Micropattern Gas Detectors for the CMS Experiment’s Muon System Upgrade: Performance Studies and Commissioning of the first GEM Detectors

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The work I carried out during the PhD is focused on the upgrade of the muon system of the Compact Muon Solenoid (CMS) experiment with Micropattern Gas Detectors (MPGDs).

The discovery potential of the experiments at the Large Hadron Collider (LHC) is strictly related to the delivered luminosity, hence the LHC has an upgrade program in order to increase the instantaneous luminosity in the next years. It plans to enhance it up to about five times the nominal value by 2025 and to deliver about 3000 $fb^{-1}$ of integrated luminosity in the next ten years of operation, an order of magnitude higher than the one collected since the first physics run in 2011 until now.

On the other hand, the LHC upgrade represents a major challenge for the experiments, as the high radiation dose and event pileup would degrade their performance if they don’t undergo an upgrade program involving several aspects as well. One example is the necessity to improve the CMS muon system in the region close to the beam direction to allow maintaining a trigger performance at least as high as during previous LHC runs, but also to compensate for possible performance losses of the existing muon detectors due to aging effects after years of operation. The upgrade of the muon system with Gas Electron Multiplier (GEM) detectors, involving three new muon stations (GE1/1, GE2/1 and ME0), serves this goal. In addition, it will also extend the muon system closer to the beam direction, increasing its total acceptance and hence the discovery potential of several physics channels.

Throughout the PhD I first took part in the R&D on MPGDs for the upgrade of CMS muon system, in particular in the development and characterization of the first prototypes of Back to Back GEM detector and Fast Timing Micropattern detector for the ME0 station, presented in chapter 3. They have been considered to cope with the challenges characteristic of this station, represented by the necessity to instrument a small available space with six detector layers and the capability to handle the high background rate present in that forward position. Then I continued my work participating in the commissioning and integration of the first GEM detectors – the GE1/1 slice test – into the CMS experiment, described in chapter 4. The installation of the full GE1/1 station is scheduled in 2019-20, but a demonstrator made of ten detectors was installed already at the beginning of 2017 and was operated in 2017-2018 with the goal to acquire installation and commissioning expertise, to develop the integration into the CMS online system and to prove the operability of the system in the CMS environment. The GE1/1 slice test represents a peerless test bench to get ready for the installation of the complete GEM subsystem. Finally, currently I am also carrying out some trigger studies to understand how to use the ME0 station, which will extend the muon system to higher pseudorapidity, to trigger specific physics channels in the extended region where no other muon station is present. The first preliminary results are presented in chapter 5.
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Chapter 1

Introduction

1.1 The CMS experiment at the LHC

The Compact Muon Solenoid (CMS) experiment is a multi-purpose experiment at the Large Hadron Collider (LHC) at CERN. The LHC provides head-on collisions of proton (but also ion) beams, initially with energy up to about 7 TeV and a luminosity up to about 75% of the nominal value of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. Recently, it has reached proton beam center-of-mass energies of about 13 TeV and has exceeded the nominal luminosity, and plans to provide beams with even higher energy and luminosity in the future.

By studying the product of such collisions, the CMS experiment aims to shed light on the mathematical consistency of the Standard Model at energy scales above about 1 TeV, but its most exciting purpose is to investigate the various alternatives to the Standard Model that foresee new symmetries, new forces or new constituents. Possibly, new discoveries could eventually open the way toward a unified theory.

The LHC collides bunches of protons every 25 ns. The beam luminosity, i.e. the number of particles in a beam crossing a unit surface per unit time, determines the rate of interactions $\frac{dN}{dt}$ taking place, which is proportional to the luminosity $\mathcal{L}$ and the interaction cross section $\sigma$ according to $\frac{dN}{dt} = \sigma \mathcal{L}$. At the design luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ on average 20 inelastic collisions are superimposed to the event of interest, resulting in $\sim 1000$ charged particles emerging every 25 ns to be detected and processed by the CMS experiment. The superimposition of more inelastic collisions is referred to as pileup, and the use of high-granularity detectors with good time resolution is necessary in
order to mitigate its effects. As a result, the CMS experiment is made up of a large number of detector channels, resulting in millions of electronic channels with very good synchronization. On top of that the large flux of produced particles leads to high radiation levels, requiring radiation-hard detectors and front-end electronics.

In addition to the aforementioned technical requirements, the structure of the CMS detector must clearly satisfy also the requirements to meet the LHC physics programme, namely:

- concerning the muon detection, good muon identification and momentum resolution over a wide range of momenta and angles, good dimuon mass resolution, ability to determine unambiguously the charge of muons with $p < 1\, TeV$
- in the inner tracker good charged-particle momentum resolution and reconstruction efficiency
- for the detection of electromagnetic particles, good electromagnetic energy resolution, good diphoton and dielectron mass resolution
- wide geometric coverage, $\pi^0$ rejection and efficient photon and lepton isolation at high luminosities
- efficient triggering and offline tagging of $\tau$ and $b$-jets
- good missing-transverse-energy and dijet-mass resolution.

The design of CMS detector has been studied in order to meet such requirements and it will be explained in section 1.3. In particular, as the experiment’s name suggests, it stands out for the use of a high-field solenoid and for the detection of muons which is of central importance to CMS.

1.2 Physics at the CMS experiment

The first major physics run took place in 2011-2012. Data collected during this period, corresponding to $\sim 25\, fb^{-1}$, have already lead to a vast amount of physics results. Despite the large quantity of results, several questions are still open and the search for their answers continues. After a two-years break, the second physics run started in 2015 and will continue until the end of 2018, after which further long shutdowns and datataking periods are scheduled, aiming to improve the previous results and shed light on the open questions.
1.2. Physics at the CMS experiment

1.2.1 The Higgs Boson

The most relevant result is the observation of a new particle of mass $\sim 125 \text{ GeV}$ by the ATLAS and CMS Collaborations in 2012 [2, 3], identified as the Higgs Boson, representing a step forward toward the understanding of the origin of the elementary particle masses. Figure 1.1 shows some Higgs boson decay candidates, in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow ee\mu\mu$ channels.

![Figure 1.1](image)

Figure 1.1: Candidate events for the Higgs decays $H \rightarrow \gamma\gamma$ (top) and $H \rightarrow ZZ^* \rightarrow ee\mu\mu$ (bottom). In the top panel the green lines represent two reconstructed photons, in the bottom panel the green and red lines pointing towards the center of the detector represent two reconstructed electrons and two reconstructed muons respectively [4].
1. Introduction

This observation has started an extensive study of its properties to verify in detail that the observed characteristics of this particle are in agreement with the ones predicted by the Standard Model for the Higgs Boson.

According to the Standard Model the Higgs boson has a non-zero coupling to all massive particles, hence it can be produced by several mechanisms in proton-proton collisions. The most relevant ones at the LHC are summarized in figure 1.2. Among these, so far the most studied production mechanisms are the gluon-gluon fusion process, which has the largest cross section at the LHC, followed by the vector-boson-fusion, with the second largest cross section, and the associated production with an electroweak vector boson $W$ or $Z$ (Higgs-Strahlung). Recently, also the production in association with top quarks has been observed, providing an opportunity to study the Higgs boson coupling to the top quark.

![Figure 1.2: Leading order diagrams for Higgs boson production mechanisms at the LHC: gluon-gluon fusion (a), vector-boson-fusion (b), Higgs-Strahlung (c), production in association with top quarks (d).]

The Higgs boson characteristics under study include the measurement of its production rate in all the observed decay channels, the determination of its coupling strength to fermions and bosons, a precise measurement of its mass from the 4-lepton and $\gamma\gamma$ final states and the study of its spin-parity assignment. CMS has so far obtained significant signals from five different decay modes of the Higgs boson: the decays to weak boson pairs one of them being off-mass-shell $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$, decays to photon pairs, to
b-quark pairs, and to $\tau$-lepton pairs. In particular, the decays in the first channels were established with more than 5 standard deviation significance. Some examples are shown in figure 1.3. Other rarer decays, like $H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu$ are expected also to become accessible to direct measurements in the future.

Studies in the Higgs sector have provided compelling evidence that the spin and parity of the boson are indeed $0^+$. In addition, by using a combination of theory predictions for the decays and production, the coupling of the Higgs boson to a set of particles have been determined. They are summarized in figure 1.4 and clearly show the unique mass dependance expected for the Higgs field. The coupling to the top quark is not yet available, but appears to be within reach through the $t\bar{t}H$ production process. Finally, since the Higgs boson could decay to low mass particles that have not been observed, some limits on the “invisible” width of the Higgs boson have been placed.

Open questions related to the Higgs Boson, not explained by the Standard Model, still exist, and their answer require the existence of new physics. For example, its scalar nature presents some theoretical challenges: radiative corrections to the Higgs should cause the mass to increase to very high values. This growth could be cancelled by new physics at masses not too far from 1 TeV. Even if measurements show that the 125 GeV Higgs boson behave like a SM Higgs, measurements of its properties are not very precise and could leave space for deviation from perfect SM behaviour. Possible deviations could be caused by the interaction with other forms of matter, like the dark matter, that could lead to answering some open fundamental questions, like the matter-antimatter asymmetry in the universe.

For these reasons, a detailed study of the 125 GeV Higgs boson to a much higher level of statistical precision is an imperative in the CMS physics program.

### 1.2.2 Physics Beyond the Standard Model

**Supersymmetric theories.** Many searches have been performed on the 2011-2012 data looking for new physics, but no evidence of physics Beyond the Standard Model (BSM) has been found so far. One BSM theory is the one known as supersimmetry (SUSY), claiming that every SM particle has a supersymmetric partner whose spin is lower by 1/2 unit. SUSY is a broken
1. Introduction

Figure 1.3: Top: $\gamma\gamma$ mass spectrum. The top and bottom panels show the distribution without and with the subtraction of the background respectively. Bottom: mass spectrum of four leptons. From left to right, the three peaks are the decay of the $Z$ boson, the Higgs boson decaying into $H \rightarrow ZZ^* \rightarrow l^+l^-l'^+l'^-$, the di-boson production of two $Z(l^+l^-)$.

symmetry, because SUSY partners have not been observed yet and so, if they exist, they must have masses higher than the ones accessible at accelerators. According to the theory, the lightest SUSY particle does not interact with
ordinary matter and at LHC experiments will result in events with large missing transverse energy $E_T$, taken as one of the main experimental signatures of SUSY. SUSY could provide the answers to some of the fundamental questions of particle physics: SUSY particles not much heavier than 1 TeV are candidates for the cancellation of the growth of Higgs mass from radiative corrections; under some assumptions, SUSY particles are also candidates for dark matter particles, as many theories predicts that the lightest SUSY particle has to be stable, electrically neutral and weakly interacting with the particles of the Standard Model.

The production rate and decays of SUSY particles depend on their mass spectrum, so the searches have to investigate a vast range of possibilities. Figure 1.5 shows an example of production cross-sections as a function of mass for particles from the Minimal Supersymmetric Standard Model (MSSM), a model considering only the minimum number of new particle states and new interactions consistent with phenomenology. So far, the lack of observation of SUSY particles at LHC has allowed to exclude some particles, like the gluinos (the SUSY partners of gluons) and squarks (the SUSY partners of quarks) with masses below 1 TeV foreseen in some simplified models, but some other scenarios are still possible, e.g. models with third generation squarks ($sbottoms$...
and stops) with masses below 1 TeV are still compatible with data.

Figure 1.5: Cross sections for the production of SUSY particles of the Minimal Supersymmetric Standard Model as a function of their masses [5].

A summary of the SUSY limits obtained from 2011-2012 data is shown in figure 1.6. SUSY theories also predict the existence of more Higgs-type particles, so far not observed at the LHC as well.

**Precision Measurements of Electroweak Observables.** Another approach to discover new physics is to make precision measurements of rare decays that are well-predicted in the Standard Model. At centre-of-mass energies of proton-proton collisions of 7 TeV and above, decay rates and electroweak interactions parameters can be determined with unprecedented accuracy, challenging theoretical prediction. If new physics exists, it may either enhance or suppress such decay rates.

An example are the rare decays $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$, that are heavily suppressed in the SM mainly due to the absence of flavor-changing neutral-current diagrams at tree level. Their total predicted branching fractions are as small as $B(B_s^0 \rightarrow \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$ and $B(B^0 \rightarrow \mu^+\mu^-) = (1.1 \pm 0.1) \times 10^{-10}$ [6]. Such decays can receive additional contributions from new physics, in the form of exchange of new virtual particles, resulting in an increase of the decays rates depending on the values of the new physics parameters. CMS has searched for the rare decays in the full Run 1 dataset (2011-2012), consisting in 5 $fb^{-1}$ of 7 TeV collisions and 20 $fb^{-1}$ of 8 TeV collisions, observing an excess of $B_s^0 \rightarrow \mu^+\mu^-$ decays corresponding to a branching
1.2. Physics at the CMS experiment

Figure 1.6: Summary of the mass limits for SUSY particles obtained from 2011-2012 CMS data.
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Figure 1.7: Total production cross section of final states including $W$ and $Z$ bosons, top quarks and Higgs bosons. Red markers represent the result of measurements on Run 1 data, blue (green) markers represent theoretical predictions at 7 TeV (8 TeV). Single boson production cross sections of processes including at least one to at least four hadronic jets with $E_T > 30$ GeV and $|\eta| < 2.4$ are also shown.

Fraction of $B(B_s^0 \to \mu^+\mu^-) = 3.0^{+1.0}_{-0.9} \times 10^{-9}$, consistent with the expectations of the SM, and no significant $B^0 \to \mu^+\mu^-$ signal, setting an upper limit of $B(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ at 95% confidence level. These results place very strict constraints on new physics models.

Other examples of precision measurements concern the production cross sections of the $W$ and $Z$ bosons, and the top quark measurements. In the former case, several studies have been performed, all of them leading to excellent agreement with theoretical predictions, available at the next-to-leading order (NLO) and next-to-next-to-leading-order (NNLO) in perturbative QCD. A summary of results in this field on Run 1 data is shown in figure 1.7 [8]. Concerning the top quark, instead, Run 1 data have allowed CMS to measure with great accuracy (equal or smaller than the uncertainties of the NLO estimates) the top pair production cross section in 7 a 8 TeV proton-proton collisions using different final states. Several measurements of top quark mass have also been produced using several strategies, whose results are summarized in figure 1.8 and whose combined result result in a measured top quark mass
1.3. Structure of the CMS detector

Before going into details, let us specify the coordinate system adopted by CMS, which will also be used throughout this thesis. Its origin is located at the nominal collision point at the center of the detector, that is approximately shaped like a cylinder rotated in order to have a horizontal main axis. The $y$-axis points vertically upward and the $x$-axis points radially inward toward the LHC center. Consequently the $z$-axis lies along the beam direction, with the positive direction pointing toward the Jura mountains. In addition, the azimuthal angle $\phi$ measured in the $x$-$y$ plane from the $x$-axis is also often used, and the radial coordinate in the $x$-$y$ plane is denoted by $r$. Finally, the angle $\theta$ is the polar angle measured from the $z$-axis and the pseudorapidity is defined as $\eta = -\log \tan \frac{\theta}{2}$.

$m_t = 173.49 \pm 0.36 \pm 0.91 \text{ GeV} [9].$

Figure 1.8: Top quark mass determination by the CMS experiment. Results of measurement on different subset of data (2010, 2011, 2012) and using different strategies.
Figure 1.9: Schematic representation of the CMS detector showing all its subdetectors and main components.

1. Introduction
The superconducting solenoid. One of the main features of the CMS detector is its magnetic field configuration, that has been chosen to measure precisely the momentum of high-energy charged particles, and also drives the detector design and layout. The overall layout of the CMS detector is shown in figure 1.9. It is 21.6 m long and has a diameter of 14.6 m, and it weights of 12500 t in total.

To provide the necessary large bending power magnets based on superconducting technology are used. A superconducting solenoid 13 meters long and with 6 meters of inner diameter providing an intense magnetic field of 4 T sits at the core of the CMS detector. The solenoid has a bore 6.3 m in diameter, is 12.5 m long and weights 200 t. Its winding is composed of 4 layers, providing a $12 \, T \cdot m$ bending power before the muon system. The magnetic flux is returned through a 12500 t steel yoke made of 5 wheels in the barrel and 3 disks per endcap, as shown in figure 1.9.

Inside the magnet coil the inner tracker and the calorimeters are accommodated, while the muon detectors sit in-between the yoke wheels and disks.

The inner tracker. The inner tracker covers a cylindrical volume 5.8 m long and with a diameter of 2.6 m. It’s designed to provide a precise and efficient measurement of charged particle tracks emerging from the collisions and a precise reconstruction of secondary vertices. It’s the subdetector closest to the interaction region, where inevitably there’s a high track multiplicity (about 1000 particles per bunch crossing at the LHC design luminosity of $10^{34} \, cm^{-2} s^{-1}$).

In order to deal with this, the inner tracker is equipped with 10 barrel layers of high-granularity, fast-response and precise silicon microstrip detectors, such that particle trajectories can be identified reliably and attributed to the correct bunch-crossing. In addition, close to the interaction region three layers of silicon pixel detectors are placed at radii between 4.4 cm and 10.2 cm, whose goal is to improve the measurement of the impact parameter of charged-particles tracks and the position of secondary vertices. In the endcaps, two disks of pixel detectors and three plus nine disks of strip tracker complete the system on each side, extending the acceptance of the tracker up to $|\eta| < 2.5$. In total, the CMS tracker is equipped with about 200 $m^2$ of active silicon detectors, the largest silicon tracker ever built. Figure 1.10 shows the expected resolution of transverse momentum, transverse impact parameter and longitudinal impact parameter for single muons of transverse momenta $p_T = 1, 10, 100 \, GeV$ as a
function of pseudorapidity.

![Graphs showing Inner Tracker resolution as a function of pseudorapidity for single muons with transverse momenta $p_T = 1, 10, 100$ GeV]}

Figure 1.10: The Inner Tracker resolution of transverse momentum $p_T$ (top-left), transverse impact parameter $d_0$ (top-right), longitudinal impact parameter $z_0$ (bottom) as a function of pseudorapidity $\eta$ for single muons with transverse momenta $p_T = 1, 10, 100$ GeV [10].

**The electromagnetic calorimeter.** The electromagnetic calorimeter (ECAL) of the CMS detector measures the energy of electromagnetic particles. It’s a hermetic homogeneous calorimeter, located right outside the inner tracker, made of 61200 lead tungstate ($PbWO_4$) crystals in the central barrel part and
1.3. Structure of the CMS detector

7324 crystals in each of the two endcaps, covering up to $|\eta| < 3.0$ in pseudorapidity. Its thickness is larger than 25 radiation lengths ($X_0$). $PbWO_4$ crystals have been selected because their high density (8.28 g/cm$^3$), short radiation length (0.89 cm) and small Molière radius (2.2 cm) result in a fine granularity and compact calorimeter. In addition the scintillation decay time of the crystals is of the same order of magnitude of the LHC bunch crossing time (about 80% of the light is emitted in 25 ns). These features make them an appropriate choice for operation at LHC. To detect scintillation light, ECAL is equipped with silicon avalanche photodiodes (APDs) in the barrel region and vacuum phototriodes (VPTs) in the endcap region.

The ECAL energy resolution is expressed with a stochastic ($S$), noise ($N$) and a constant ($C$) term through the function

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2.$$  

The energy resolution for incident electrons measured in a beam test is shown in figure 1.11.

![Figure 1.11: The ECAL electron energy resolution $\sigma(E)/E$ as function of the electron energy. The measurement has been performed in a beam test using an array of 3 x 3 crystals, in which the electron beam was narrowed to a 4 x 4 mm$^2$ region with electrons hitting on the central crystal. The stochastic ($S$), noise ($N$) and a constant ($C$) terms obtained fitting the measured resolutions are given in the plot [1].](image-url)
1. Introduction

A preshower system is also installed in front of the endcap ECAL to identify neutral pions $\pi^0$ in the endcaps within a fiducial region $1.653 < |\eta| < 2.6$. It also helps to identify electrons against minimum ionizing particles and to improve the position determination of electrons and photons.

![Figure 1.12: The HCAL jet transverse-energy resolution as function of the transverse energy $E_T$, for different pseudorapidity regions. The region $|\eta| < 1.4$ corresponds to jets detected in the barrel calorimeter, the region $1.4 < |\eta| < 3.0$ to detection in the endcap, and $3.0 < |\eta| < 5.0$ to jets in the very forward region [1].](image)

**The hadron calorimeter.** The hadron calorimeter (HCAL) is located behind the tracker and the electromagnetic calorimeter and inside the magnet coil. It’s a brass/scintillator sampling calorimeter covering up to $|\eta| < 3.0$ in pseudorapidity. Wavelength-shifting (WLS) fibres are embedded in the scintillator tiles to collect and convert the scintillation light and channel it to hybrid photodiodes (HPDs), photodetectors able to operate in high axial magnetic field such the CMS one. The presence of the ECAL and the solenoid restrict the available space in the radius range $1.77 \ m < R < 2.95 \ m$ from the beam direction. Therefore the barrel region is also equipped with a complementary outer hadron calorimeter or *tail-catcher* (HO) outside the solenoid to ensure to sample hadronic showers with nearly 11 hadronic interaction lengths. Consequently the HCAL thickness varies in the range $7 - 11$ interaction lengths $\lambda_I$ depending on $\eta$, or $10 - 15 \ \lambda_I$. 


1.3. Structure of the CMS detector

with the HO included.
An iron/quartz-fibre calorimeter based on Cherenkov light, the forward calorimeter, covers up to $|\eta| < 5.2$ to ensure full geometric coverage for the measurement of the transverse energy in the event.

Figure 1.12 shows the jet transverse-energy resolution for different pseudorapidity regions.

The muon system. The CMS experiment has decided to lay special emphasis on the detection of muons. Apart from the relative ease in the detection of muons, muons are less affected by radiative losses in the tracker material than electrons, resulting in a better mass resolution for decays with final multiple muons. Hence the choice of realizing a precise and robust muon system for muon identification, momentum measurement and triggering.

The muon system is located outside the superconducting magnet. Even in this region, the return field is large enough to saturate 1.5 $m$ of iron, allowing four muon stations to be integrated in this zone, both in the barrel and the endcaps of the experiment. Muon detectors use 3 different types of gaseous detectors: several layers of aluminium drift tubes (DTs) are installed in the barrel region up to $|\eta| < 1.2$ grouped in 4 stations, cathode strip chambers (CSCs) are installed in the two endcap regions at $0.9 < |\eta| < 2.4$ also grouped in 4 stations; in addition, in the current muon system configuration, they are complemented by resistive plate chambers (RPCs) both in the barrel and in the endcap. The latter produce a fast response with good time resolution but coarser position resolution, to help measuring the correct beam-crossing time especially at full luminosity and to help resolving ambiguities in making tracks from multiple hits in a chamber. In other words, RPCs add redundancy to the muon system. The muon system configuration allows to cover with no acceptance gaps the full pseudorapidity interval $|\eta| < 2.4$, resulting in efficient muon identification over the range $10^\circ < \theta < 170^\circ$. Figure 1.13 shows the offline reconstruction efficiency for single-muons, which is typically 95 – 99% except for some drops at $|\eta| = 0.25$, 0.8 and 1.2 caused by the transitions between two DT wheels and between the DT and CSC systems.

As the muon system is of central importance in this thesis it will be further explored in the next sections.
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Figure 1.13: Muon reconstruction efficiency for different transverse momenta $p_T$ as a function of pseudorapidity. In the top panel only hits from the muon system with a vertex constraint are used for the reconstruction (standalone reconstruction), in the bottom panel hits from both the muon system and the inner tracker are used (global reconstruction) [1].

1.4 The Muon System

Muon final states represent an excellent opportunity to recognize signatures over the very high background rate at the LHC. One typical example is the

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decay of the Higgs boson $H \rightarrow ZZ$ or $H \rightarrow ZZ^*$, where the products in turn decay into four muons. For this reason this decay has been called a gold plated channel for the detection of the Higgs boson. As previously mentioned, the reason is that muons are relatively easy to detect and, as they have smaller radioactive losses than electrons in the tracker material, the best four-particle mass resolution is obtained if all four final leptons are muons. The same considerations apply also to other decays, for examples coming from SUSY models. These considerations justify the CMS interest in a precise and robust muon measurement.

The muon system has multiple goals: muon identification, momentum measurement and triggering. The latter two rely on the high-field solenoidal magnet and its flux-return yoke. In addition, the yoke also works as hadron absorber to reduce the background for the muon identification.

The muon detection technologies introduced in section 1.3 are explained in more detail. An overview of one quadrant of the CMS experiment, including all subdetectors of the muon system, is shown in figure 1.14.

### 1.4.1 Drift Tubes

The CMS barrel muon detector uses drift chambers as tracking detectors. This choice was possible due to the low backgroud and the uniform and low intensity magnetic field present in the barrel region, where the latter is mostly contained in the steel yoke. The basic element of the drift chambers is the drift cell, a tube with a $4 \, cm \times 1.3 \, cm$ rectangular profile and $2.5 \, m$ long filled with gas, along which a $50 \, \mu m$-thick anode wire is stretched, as shown in figure 1.15. A positive voltage is applied to the wire and a negative voltage is applied to the cell walls to produce a drift field as shown in figure 1.15. When a muon passes through the gas volume, ionization electrons drift towards the anode wire where they are multiplied and collected. By registering the hit position along the wire and by calculating the muon’s original distance away from the wire, the 2D position of the crossing muon is reconstructed. The drift cells are offset by a half-cell width with respect to their neighbour to avoid dead spots in the efficiency. The drift chambers are arranged in four concentric cylinders around the beam line, for about 195000 sensitive wires in total.

DT chambers are organized in the CMS barrel in five wheels along the $z$ direction. Each wheel is subdivided into 12 sectors and in each sector there
1. Introduction

Figure 1.14: Cross-sectional view of one quadrant of CMS. In the muon system, the DT stations (MB1-MB4) in the barrel are shown in green, the CSC stations (ME1-ME4) are shown in blue, and the RPC stations are shown in red.

are four layers (one inside the yoke, one outside the yoke, and two of them embedded within the yoke iron) labeled MB1, MB2, MB3, and MB4. The layout of the DT chambers in the CMS barrel in shown in figure 1.16. In turn, each DT chamber is made of three or two superlayers (SL), a stack of four layers of rectangular drift cells staggered by half a cell. The two outer SLs have wires oriented parallel to the beam line to provide measurements in the magnetic bending plane \( r - \phi \). If present, the third (inner) SL instead has wires oriented orthogonal to beam line in order to measure the \( z \) coordinate along the beam. This layer SL is not present in the fourth station, which provides only \( \phi \) measurements.

1.4.2 Cathode Strip Chambers

Cathode Strip Chambers (CSCs) use multiwire proportional chambers in which one cathode plane is segmented into strips running across wires. Wires and
1.4. The Muon System

strips are oriented in different directions, in order to allow for a bidimensional readout. An avalanche developed on a wire induces on the cathode plane a distributed charge of a known shape. It is possible to reconstruct the track position along a wire with a precision of $50 \mu m$ or better by interpolating fractions of charge picked up by different strips (about a tenth of a strip) [12]. A close wire spacing determines a faster chamber response. A schematic representation of the principle of operation of a CSC is shown in figure 1.17. A chamber is made of six layers of wires sandwiched between cathode panels, so each chamber provides six bidimensional measurements.

The CSCs are shaped in trapezoidal chambers and arranged to form four disks (stations) placed between the iron disks of the endcap return yoke. Sorted by ascending distance from the interaction point, the disks are named ME1, ME2, ME3 and M34. All the disks are composed of two rings (e.g. ME2/1 and ME2/2) apart from the first disk ME1, which has three rings of chambers (ME1/1, ME1/2, ME1/3). The layout of the CSC chambers in the CMS muon endcap is shown in figure 1.18.

The chambers’ shape is trapezoidal and the readout is arranged in order to provide $\phi$ and $r$ coordinates, with wires running at an approximately constant spacing to measure the $r$ coordinate and strips running radially in order to
measure the $\phi$ coordinate, as shown in figure 1.19.

The motivation for measuring the $r - \phi$ coordinates is that this system is best suited for evaluating the muon momentum. Indeed, the bending observed in the endcap of a fixed $p_T$ muon track is $\eta$-dependent. Simulations have shown that the sagitta expressed in linear coordinates changes by larger factor (about five) from $\eta = 1.6$ to $\eta = 2.4$ for fixed $p_T$ muons, against a change of about a factor two using the $\phi$ coordinate in the same conditions. So expressing the sagitta in $\phi$ coordinates is less $\eta$-dependent than expressing it in $x$ coordinates, making $\phi$ a more natural coordinate for measuring $p_T$. 
For triggering purposes, first the position of hits on each plane is determined (within a half-strip uncertainty), then a look-up table is used to match the observed six-plane pattern of the half-strips to the most probable track coordinate. Wire signals also provide high-efficiency bunch-crossing determination, by picking the most frequent bunch crossing identification out of four track segments from the four muon stations linked to one track.

### 1.4.3 Resistive Plate Chambers

Resistive Plate Chambers (RPC) are gaseous parallel-plate detectors with a time resolution comparable to that of scintillators [13], well-suited for fast space-time particle tracking, and with a good spatial resolution. A standard RPC gap consists of two parallel plates 2 mm thick made of High Pressure...
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Figure 1.18: Cross-sectional view of one quarter of the CMS muon endcap, showing the layout of the CSC chambers [1].

Figure 1.19: Schematic layout of a cathode strip chamber made of 6 gas gaps. The cut-out on the top panel reveals the orientation of cathode strips (in red) and a few anode wires (in yellow).
1.4. The Muon System

Laminates (HPL) impregnated with phenolic resin (bakelite) and pressed at high pressure and temperature. The resulting plates have a bulk resistivity of $10^{10} - 10^{11} \, \Omega \cdot \text{cm}$. They are located 2 mm apart and their outer surfaces are coated with conductive graphite painted out to form the HV and ground electrodes. Copper readout strips are separated from the graphite coating by an insulating PET film. The electrode resistivity mainly determines the rate capability, while the gap width determines the time performance.

The CMS RPC consists of double gap RPC, referred to as up and down gaps, with common read-out strips located in-between, as shown in figure 1.20. The total induced signal is the sum of the two single-gap signals, allowing to operate them at lower gas gain with an effective detector efficiency higher than the efficiency of a single-gap.

![Diagram of a CMS RPC](image)

Figure 1.20: Schematic representation of a CMS RPC made of two gaps. The up and down gaps and their common readout strips are shown. On the single-gap level also the RPC basic components are visible (bakelite, graphite and PET layers, readout strips).

RPCs can be operated in different modes depending on the high voltage applied. The so-called streamer mode, in which the electric field is intense enough to generate discharges localized near the primary ionization of the crossing particle, is not suitable for the operation at LHC as the achievable rate capability is too low ($\sim 100 \, \text{Hz/cm}^2$) in this operational condition. At CMS, RPCs are instead operated in avalanche mode, i.e. with an appropriate gas mixture, at a lower high voltage to reduce the amplification and introducing a robust signal amplification at the front-end level. This allows to reduce the amount of charge produced in the gaps, hence to increase the rate capability.
by more than an order of magnitude with respect to the streamer mode.
Six layers of RPC are embedded in the barrel yoke, while four layers of RPC
are installed in the endcap up to $\eta = 2.1$.

The trigger based on RPC detectors has three basic goals: identify candidate muon tracks, assign them a bunch crossing and estimate their transverse momenta.

1.5 The CMS trigger system

Depending on the beam luminosity, several collisions occur at each crossing of bunches in proton-proton and heavy-ions collision at LHC. For example, at the nominal design luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$ approximately 20 collisions take place for each bunch crossing. As the beam crossing interval is 25 ns (40 MHz), collisions are produced at a rate of about 1 GHz at the nominal design luminosity. It’s impossible to store and process all the data associated with all produced events, so a significant rate reduction is necessary.

This is the goal of the trigger system. The trigger system is a physics event selection process, organized into two steps:

- the **Level-1 (L1) Trigger** is based on custom-designed, largely programmable electronics. It uses coarsely segmented data coming from the calorimeters and the muon system, while holding the high-resolution data in pipelined memories in the front-end electronics. The design output rate of the L1 Trigger is 100 kHz, which assuming a safety factor of three translates in practice to a maximal output rate of 30 kHz. For flexibility reasons the L1 Trigger is implemented in FPGA technology, but also ASICs and programmable lookup tables (LUTs) are widely used for speed, density and radiation resistance requirements.
- the **High-Level Trigger (HLT)** is a software system implemented in a filter farm of $\sim 1000$ commercial processors. It has access to the complete readout data and can perform complex calculations similar to those made in offline analysis software, if required for interesting events. HLT algorithms usually evolve with time and experience.

1.5.1 The Level-1 Trigger

The L1 Trigger has local, regional and global components.
1.5. The CMS trigger system

**Local Triggers**, or Trigger Primitive Generators (TPG), use energy deposits in calorimeter trigger towers and track segments or hit patterns in muon chambers. Information coming from calorimeters and the muon system are combined using pattern logic to determine trigger objects in limited spatial regions, like electrons or muon candidates, ranked and sorted. The rank is a function of energy or momentum and quality, indicating the level of confidence attributed to the L1 parameter measurements. The latter is determined based on detailed knowledge of the detectors, the trigger electronics and the amount of information available.

**The Global Trigger** includes the Global Calorimeter Trigger and the Global Muon Trigger. The latter determine the highest-rank calorimeter and muon objects respectively across the entire experiment and pass them to the Global Trigger. The Global Trigger is the top entity of the L1 Trigger hierarchy and decides whether to reject an event or to accept it and pass it to the HLT for further evaluation. The decision of the Global Trigger is based on algorithm calculations and depends on the readiness of the subdetectors and the DAQ, provided by the Trigger Control System (TCS).

A schematics of the architecture of the L1 Trigger is shown in figure 1.21.

![Figure 1.21: Schematics of the decision flow of the CMS Level-1 Trigger [1].](image)

**1.5.2 The Muon Trigger**

All the muon subsystems (DT, CSC, RPC) take part in the trigger.
Local Trigger. Each of them provides local trigger information in different forms:

- the barrel DT chambers provide track segments in the $\phi$ projection and hit patterns in the $\eta$ projection
- the endcap CSC provides three-dimensional track segments
- DT, CSC and RPC all identify the bunch crossing from which an event originated.

The electronics of the DT local trigger has four basic components: the Bunch and Track Identifiers (BTI), the Track Correlators (TRACO), the Trigger Servers (TS) and the Sector Collectors (SC). The BTIs are interfaced directly to the front-end electronics; using signals from wires they generate a trigger at a fixed time after a muon’s passage and then search for coincident, aligned hits in the four planes of DTs in each superlayer (a stack of 4 layers of drift cells). The association of hits is based on the fact that there is a fixed relation between drift time of three adjacent planes [14]. Then tracks are determined from associated hits, defined by position and angular direction. The achieved spatial and angular resolution of one BTI are better than $1.4 \, mm$ and better than $60 \, mrad$ respectively. The TRACO, instead, correlates track segments measured in the DT superlayers measuring the $\phi$ coordinate. If a correlation is found, a new segment with improved angular resolution is defined. At most two track segments per bunch crossing are transmitted to the TS by each TRACO. Finally, the goal of the TS is to perform a track selection in a multitrack environment. It uses two components, one for the transverse projection (TS$\phi$) that processes the output from the TRACO, and one for the longitudinal projection (TS$\theta$) that processes directly the output of the PTI coming from the $\theta$-type superlayers.

Regional Muon Trigger. For the Regional Muon Trigger the DT and CSC Track Finders are used. They join segments to build tracks and assign them physical parameters. RPC trigger chambers build their own track candidates based on regional hit patterns.

Global Muon Trigger. The Global Muon Trigger eventually combines all the information coming from all muon subdetectors, producing an improved momentum resolution and efficiency with respect to measurements coming only from the stand-alone systems.
1.6 The Upgrades of LHC and CMS

1.6.1 Overview

In the first physics run in 2011 and 2012 the LHC has reached a peak luminosity of \( 7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \), reaching more than 75% of its design luminosity, and has delivered an integrated luminosity of about 25 \( fb^{-1} \) to the ATLAS and CMS experiments. A vast quantity of physics results has been published (more than 300 publications from the CMS Collaboration), of which the most important result is the observation of a new particle with mass \( \sim 125 \text{ GeV} \) identified as the Higgs boson. The observation of the Higgs boson has started a detailed study of its properties.

In addition to the Higgs boson studies, many questions exists that are currently still open, from the origin of elementary particles masses to the nature of dark matter and the existence of unified fundamental forces. Many proposals for new physics exist, trying to address such questions. So far, searches undertaken with data taken in 2011 and 2012 did not reveal evidence of physics Beyond the Standard Model (BSM) yet. An approach for discovering new physics is to make precision measurements of rare decays well-predicted by the SM, as new physics would enhance or suppress their decay rate.

Precision Higgs studies and searches for new physics strongly demand for higher luminosity. Following these needs, the LHC has planned to achieve higher peak and integrated luminosity. On the other hand, this enhanced luminosity is well above the one for which CMS was designed. Consequently an extensive campaign has started to upgrade the CMS detector in order to maintain the efficiency, resolution and background rejection at the new LHC luminosity.

As both the LHC machine and the experiments will require access to the accelerator tunnels and experimental areas in order to revise their apparatuses, the plan is to alternate long periods of data taking (Run-I, Run-II, etc.) with long shutdowns periods (LS1, LS2, LS3, etc.) during which no collisions will be delivered and accesses to upgrade the experimental machinery will be possible (figure 1.22).

In particular, the data-taking period in 2011-2012 is referred to as Run-I, and the ongoing data-taking started in 2015 and ending in late 2018 is referred to as Run-II. Right now, in summer 2018, the delivered luminosity is a bit ahead of schedule. In early Run-II CMS has experienced an average pileup
(PU) of about 25 inelastic interactions per bunch crossing, which is the operating scenario for which CMS was designed, but as expected from the schedule during Run-II the luminosity has already overcome its nominal value. To cope with this first increase in luminosity CMS has already undergone some upgrades known as CMS Phase-I Upgrade [15], involving the Pixel detector, the Hadron Calorimeter and the hardware Trigger [17,18,20].

![Scheduled LHC performance](image)

Figure 1.22: Scheduled LHC performance in the period 2010-2035, showing the projected peak luminosity (red dots, left scale) and integrated luminosity (blue line, right scale). LS1, LS2, LS3, LS4 and LS5 are long shutdowns, during which the LHC will not deliver collisions. According to the schedule, the maximum peak luminosity of about $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ will be reached after LS3 in 2025 [4].

The LHC upgrades that will be carried out during the LS3 by 2023 will produce the most significant increase in luminosity, hence the LHC era that will follow is referred to as High Luminosity LHC (HL-LHC) or Phase-II. The LHC proposal in this period is to provide proton beams with an instantaneous of luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a potential peak value of $2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ at the beginning of fills. This operational condition should allow to deliver $250 \text{ fb}^{-1}$ per year for 10 years of operation. The PU in these conditions will significantly rise becoming a major challenge for the experiments, that could undergo performance degradation due to a high radiation dose and the very high pileup. The CMS upgrade program for Phase-II has been setup in order to address the challenges coming from HL-LHC.
1.6.2 CMS operation at the HL-LHC

In the HL-LHC era the CMS performance would deteriorate due to two main factors: the radiation damage caused by the high integrated luminosity and a too high pileup of events caused by the high instantaneous luminosity.

**Radiation damage.** At the HL-LHC the collisions rate will be about $5 \times 10^9 \text{ s}^{-1}$. The high particle fluxes produced by collisions will cause a significant damage progressively degrading the detector performance. The annual dose delivered per year to the detector in the HL-LHC era will be comparable to the total dose of all LHC activities from the every beginning of the LHC program to LS3. Source of radiation includes different particle types: charged particles (mainly pions) produce ionization in the detectors and undergo nuclear interactions that produce cascades of additional particles, photons (mainly from $\pi^0$ decays) produce $e^+e^-$ pairs in the beam pipe material or in the tracking system or produce electromagnetic cascades in the calorimeters, in addition particles are backscattered from the calorimeters, escaping from cascades inside them, spreading out reaching other detector components. In particular neutrons may travel long distances while slowing down and scattering many times in the CMS detector. In their interactions, neutron can produce photons and electrons. As a result, within the CMS detector volume a relatively uniform background in space and time of very low energy neutrons, photons and electrons is produced, with no more correlation with the original bunch structure of collisions. Simulations are used in order to predict the magnitude and composition of radiation at different luminosity values, while the impact of different particle types on detector performance is obtained from test beam measurements, special radiation exposures and also from Run-I experience, from which first effects of radiation damage are already visible. An example of expected radiation levels predictions in the CMS detector under HL-LHC conditions is shown in figure 1.23, which shows the distribution of absorbed dose over the CMS detector for an integrated luminosity of 3000 $fb^{-1}$.

Effects of absorbed dose vary from subdetector to subdetector. In silicon detectors, radiation produces defects in the lattice that change the bulk electrical properties of the material. Consequently a higher voltage is necessary in order to reach the full depletion of charges, i.e. to make the detector fully
1. Introduction

Figure 1.23: Absorbed dose in the CMS within the CMS detector and cavern after an integrated luminosity of 3000 $fb^{-1}$. $Z$ and $R$ are the distance along the beamline and the transverse distance from the beamline respectively [21].

sensitive to crossing ionizing particles, eventually reaching unsustainable levels and forcing operation with partial depletion, resulting in lower signals. For calorimeters, that in CMS are mainly made of scintillating $PbWO_4$ crystals or plastic scintillating tiles with wavelength-shifting fibers, radiation causes loss of transmission of the media through which light must pass (while scintillation process itself seems not to be altered by the radiation). This loss can be high, even more than 90 %, causing a reduced energy resolution.

**High Pileup.** At the nominal luminosity during HL-LHC the average number of interactions in a single bunch crossing (BX) is about 140. Simulations [22] show that most of them are soft or “peripheral” collisions that do not contribute to the search for new physics at the 0.1–few TeV scale. They produce low transverse momentum ($p_T$) particles and very little energy in the CMS detector. The other – smaller – fraction of interactions consists instead in hard collisions, in which high $p_T$ particles that may come from new high mass objects are produced, and represents the fraction of collisions of interest for physics. Unfortunately the presence of tracks from on average 140 collisions can confuse or degrade triggers and the offline reconstruction of the hard
1.6. The Upgrades of LHC and CMS

interactions. Higher pileup produces many more hits in the tracking detectors, causing mismeasured or misidentified tracks, and extra energy to the calorimeter measurements associated with the collisions that contains a hard scatter to be reconstructed. In addition, some phenomena of interest feature isolated leptons, i.e. leptons having very little activity around them. A high pileup can provide energy or tracks not due to the hard collision of interest and can make isolated leptons appear non-isolated. Finally, pileup of course confuses the trigger and the offline interpretation of events and it increases the amount of data to be read out and the execution time for the reconstruction of events in the HLT and offline analysis.

1.6.3 The Phase-II Upgrade of the CMS detector

The CMS Phase-II Upgrade is an upgrade program foreseen in order to maintain the excellent performance of the detector in terms of efficiency, resolution and background rejection for all the physics objects used in the data analysis, that would otherwise deteriorate during HL-LHC without an appropriate improvement. All subsystems will face some issues for which some remedies have been proposed and are being developed.

Modifications for the Phase-II Upgrade include:

- the completion of the fourth layer of endcap muon detectors (only partially implemented in Run-I)
- improvements in the electronics of the muon system
- the installation of new stations in the muon endcap based on Gas Electron Multiplier detectors
- the replacement of the 3-layer barrel and 2-disk endcap pixel detector with a 4-layer barrel and 3-disk endcap pixel detector
- a longitudinal segmentation in the barrel and endcap hadron calorimeters
- the replacement of the HPDs for the hadron calorimeters with Silicon Photomultipliers (SiPMs)
- the replacement of single anode photomultipliers in the HF with multi-anode photomultipliers
- the modernization and upgrade of the trigger and data acquisition systems in order to handle higher volumes of data.

At this moment, many of such upgrades have been partially or completely implemented during the End of Year Technical Stops (EYETS) that regularly
took place every year since Run 2 has started in 2015, approximately in December and the following months.

**Inner tracker and calorimeters.** Indeed, performance projections based on Run-I data and the exposure of components to radiation levels matching the HL-LHC doses have clearly shown that the tracker and endcap calorimeters must be replaced for Phase-II. This also allows to address the issues associated with high PU, as the new tracker will have increased granularity and will allow to maintain the excellent tracking efficiency during HL-LHC to determine the original p-p collision points for all charged particles. The granularity of both the outer tracker and the pixel system will be increased by about a factor 4. Improvementes have been carried out also to obtain a much lighter Outer Tracker, hence an improved $p_T$ resolution and a lower rate of $\gamma$-conversions. The complete replacement of the pixel tracker is one of the upgrades that have currently been already implemented (YETS 2016-2017), and it’s ready for operation since March 2017.

The same considerations apply to the new endcap calorimeter, that will also be replaced in order to provide optimized segmentation and improved energy resolution, especially for jets. The new calorimeter is called High Granularity Calorimeter (HGCal) and has electromagnetic and hadronic sections with excellent transverse and longitudinal segmentation, to provide detailed three dimensional images of the showers. The electromagnetic part will be made of $\sim 30$ tungsten and copper plates interleaved with silicon sensors as active material with sizes of less than $1.0 \ unit$, for a depth of $25X_0$. The hadronic part will have a front section of 12 brass and copper plates interleaved with silicon sensors, for a depth of $3.5 \ unit$, that will contain the shower maximum. The front section will be followed by a “backing hadron calorimeter” whose design will be similar to current HE detector (brass plates interleaved with plastic scintillating tiles, readout with a wavelength shifting fiber). The total hadron calorimeter depth will be about $\sim 10 \ unit$. The installation of the new HGCal is scheduled during the LS3 starting in 2024.

**Level-1 Trigger.** The enhanced luminosity will raise the trigger rate to an unacceptable level. Nevertheless, an efficient event selection is a key prerequisite to benefit from increased luminosity. In particular, a continued use of low transverse momentum $p_T$ trigger thresholds will be necessary. A sufficient
trigger rate reduction without loss of efficiency can be accomplished by improving the $p_T$ resolution already at L1 trigger level and by mitigating the effect of combinatorial background coming from PU. It is therefore necessary to introduce the tracking information already at L1, using algorithms similar to those currently implemented in the HLT and using precise momentum measurements. Such a “tracking trigger” will require a new hardware architecture, hence an upgrade in the electronics. Anyway, in order to maintain the required efficiency for all the important physics channels, it will also be necessary to increase the trigger acceptable rate, in particular for triggers involving hadrons and photons, which are more sensitive to high PU.

**Forward region.** A major goal of the HL-LHC program is the measurement of processes with small production cross-sections or decay branching ratio. To this end, specific upgrades in the forward regions of the detector are necessary in order to maximize the physics acceptance as much as possible.

On one hand the muon system will be equipped with new muon chambers in order to ensure proper trigger performance within the current coverage. Indeed currently in the region $1.5 < |\eta| < 2.4$ the muon system is only equipped with CSC, lacking redundancy despite it’s a challenging region for muons in terms of backgrounds and momentum resolution. Therefore it has been proposed to complement these four CSC stations with additional muon stations using new detector technologies with higher rate capability to maintain good L1 muon trigger acceptance in this forward region. For the first two stations, where the magnetic field is reasonably high, Gas Electron Multiplier (GEM) chambers have been chosen, since a good position resolution will improve momentum resolution for the standalone muon trigger and will improve the matching with tracks in the global muon trigger. The last two stations, instead, will be equipped with low-resistivity Resistive Plate Chambers (RPC), with lower granularity but good timing resolution, in order to mitigate background effects.

On the other hand also the extension of the muon system coverage has been proposed, with a tagging station up to $|\eta| \approx 3$ in order to allow a significant acceptance gain for multi-muon final states. The latter installation will be possible after the new endcap calorimeter will be installed, leaving some available space behind it. GEM technology has been selected also for this purpose. Not only the muon system, but also the tracker will be extended up to $|\eta| \approx 4$: this will help mitigating PU effects in jet identification and energy measurements,
improving measurements of the total energy and missing energy. In addition
the b-tagging acceptance will be increased and the most important production
regions for the Vector Boson Fusion and the Vector Boson Scattering processes
will be covered by the extended tracker.
Chapter 2

The GEM Upgrade of the CMS Muon System

2.1 Motivation

The CMS muon system was originally designed based on three technologies, as described in detail in section 1.3. It’s a highly hermetic and redundant system, that uses DTs in the barrel up to $|\eta| < 1.2$ and CSCs in the endcaps in the region $1.0 < |\eta| < 2.4$ to provide precision measurements and L1 trigger. In addition, RPCs are used to provide redundant trigger and coarse position measurement both in the barrel and in the endcaps, but were installed only up to $|\eta| < 1.6$ because their rate capability is not suitable for the high background particle rates at higher pseudorapidity.

Unfortunately this configuration will not allow to achieve an acceptable L1 trigger rate for muons with $p_T < 25 \text{ GeV}$ after LS2 without introducing substantial efficiency losses in the endcap region, that represents more than a half of the overall CMS muon coverage.

In order to perform reliably and reconstruct tracks unambiguously and efficiently, the muon system needs to provide a sufficiently large number of hits measured along the particle’s trajectory. During Phase 2 the background and particles rates crossing the CMS detector will be very high, making the association of individual hits to tracks and thus the event reconstruction a major challenge, both for the muon trigger and the offline analysis, especially in the forward direction at high pseudorapidity. Hence large background rates, but also the degradation of some muon detectors that may occur in the next
20 years, can cause individual detector layers to fail in the muon identification. Under these conditions, a reliable muon reconstruction can be met only if the number of hits recorded for a single particle is sufficiently large, and if both the spatial resolution and the time resolution are very good. Hence it is necessary to add other detectors in the muon system, possibly of a different type of the present ones to avoid them to suffer a similar degradation.

Figure 2.1 shows a comparison of the average number of muon layers with reconstructed hits for the Phase 1 system and the expected neutron flux at HL-LHC as a function of pseudorapidity, providing a qualitative idea of the need to introduce more chambers in the forward region. Indeed, the latter is the one with the highest neutron flux – from one to almost three order of magnitudes higher than in other regions – but also the one with least number of reconstructed hits.

![Figure 2.1: Average number of φ-measuring muon layers with reconstructed hits (black dashed line, left scale) for the Phase 1 muon system and neutron flux expected during HL-LHC (blue line, right scale) [16].](image)

As explained in section 1.6.3, the installation of new stations based on Gas Electron Multiplier (GEM) technology in the forward muon endcap is part of the upgrade program setup for the Phase II operation in the challenging environment of the HL-LHC. Such technology has been selected because GEM detectors can be operated well at high particles fluxes, even higher than those expected during HL-LHC in the region they are destined to, with spatial and time resolution suitable for the upgrade’s goals.
2.1. Motivation

The upgrade with GEM detectors involves three new stations: the GE1/1, GE2/1 and ME0 stations (figure 2.2) to be installed in the first, second, and in front of the first muon endcap respectively at different eta coverages. Depending on the station, they will use a stack of a different number of chambers, i.e. stacks of triple-GEM detectors. Their details – eta coverage, spanned angle by a single chamber, number of detector layers – are summarized in table 2.1. Referring to figure 2.1, the introduction of the GEM stations will add two more hits in the regions covered by the GE1/1 and GE2/1 stations, and six hits in the position of the ME0 station. In this way, the number of hits per track will increase from six to ten (including also the contribution of the iRPC chambers) depending on pseudorapidity. The GEM technology is presented in section 2.2, and the three stations will be examined in depth in the next sections.

Figure 2.2: Schematic representation of a quadrant of the CMS detector, showing the muon detectors whose installation is scheduled for the Phase II Upgrade. In particular, the GE1/1, GE2/1 and ME0 GEM stations are shown in red, while DTs, CSCs, RPCs and improved RPCs (iRPCs) are shown in yellow, green, light and dark blue respectively. On the axes, $z$ and $R$ represent the distance from the interaction point along the beam direction and perpendicularly to it respectively [23].

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2. The GEM Upgrade of the CMS Muon System

<table>
<thead>
<tr>
<th>station</th>
<th>station coverage</th>
<th>chamber coverage</th>
<th>layers</th>
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<td>\eta</td>
<td>&lt; 2.18$</td>
</tr>
<tr>
<td>GE2/1</td>
<td>$1.6 &lt;</td>
<td>\eta</td>
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</tr>
<tr>
<td>ME0</td>
<td>$2.0 &lt;</td>
<td>\eta</td>
<td>&lt; 2.8$</td>
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Table 2.1: Eta coverage, angle spanned by a single chamber, number of chamber layers for the three GEM muon stations GE1/1, GE2/1, ME0.

The impact on the trigger efficiency introduced by the upgrade of the forward muon system at $2.1 < |\eta| < 2.4$ is shown in the top graph in figure 2.3, where a clear improvement is visible with respect to the trigger efficiency obtained only with the CSC stations. The efficiency will increase from about 80% up to about 90%. In the same region, much lower trigger rates will be achieved, thanks to a better muon identification and momentum measurement, as shown in the bottom graph in figure 2.3.

In addition, the capability of measuring muon directions in the first and second muon stations also allows to trigger more efficiently on highly displaced muons, i.e. muons originated far from the primary vertex, displaced from the interaction point of $O(1) m$ (figure 2.4).

2.2 The GEM Technology

2.2.1 Micropattern Gas Detectors

Gas Electron Multiplier (GEM) detectors are one example of Micropattern Gas Detectors (MPGDs) [26]. The most attractive feature of gas detectors is the possibility to realize radiation detection and imaging able to cover large detection volumes with a low material budget with respect to other types of detectors. Gas detectors are currently extensively employed at the LHC, the Relativistic Heavy Ion Collider (RHIC), and other advanced High Energy Physics (HEP) experiments. On the other hand, “classical” gas detectors, e.g. wire chambers, drift tubes, resistive plate chambers and others, have some limitations. In particular, they usually show performance losses under high particle fluxes and high rates and have a limited spatial resolution.

The invention of MPGDs, in particular the Gas Electron Multiplier [27] (GEM), the Micro-Mesh Gaseous Structure [28] (Micromegas), and other micro-
2.2. The GEM Technology

Figure 2.3: Muon trigger efficiency (top) for threshold $p_T > 15\ GeV$ as a function of the true muon $p_T$ and Level-1 muon trigger rate (bottom) as a function of the muon trigger $p_T$ threshold, for the prompt muon trigger in the pseudorapidity region $2.1 < |\eta| < 2.4$, with and without GEM chambers [16].

Pattern detector schemes offers the possibility to develop new gaseous detectors that overcome the aforementioned limitations, with unprecedented spatial resolution, high rate capability, large sensitive area, operational stability and radiation hardness. The basic concept of MPGDs is the use of smaller basic cell sizes compared to classical gas counters, whose finer pitch and fast collection of positive ions offer an intrinsic higher rate capability, excellent spatial resolution of the order of tens of microns, and time resolution in the nanosecond range. Their production is based on modern photo-lithographic technologies, that could make them suitable also for industrial production.
2. The GEM Upgrade of the CMS Muon System

2.2.2 The Gas Electron Multiplier

The basic element of GEM detectors is the GEM foil, shown in the left image of figure 2.5. The GEM foil is a 50 $\mu$m-thick polyimide foil, cladded on both sides with a thin conductive layer of copper and regularly perforated with biconical holes in an hexagonal pattern. For the CMS GEM detectors, the holes diameter and spacing are 70 $\mu$m and 140 $\mu$m respectively. When a voltage difference of a few hundreds volts is applied between the two conductive surfaces, an electric field of the order of 60 – 100 kV/cm is produced inside the holes.
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The GEM foil is operated in an appropriate gas mixture. When an electron enters a hole, the electric field is strong enough to allow avalanche multiplication to take place inside the hole (figure 2.5 right). A stack of several GEM foils, few millimeters apart, allow to obtain avalanche multiplication in multiple steps, with the advantage to apply a reduced voltage to each GEM foil and hence decrease the possibility of electrical breakdowns, yet maintaining a high total charge amplification, as the charge gains of individual foils multiply to produce the total gain of the stack.

![Figure 2.5: Left: picture of a GEM foil acquired with a scanning electron microscope. The hole pattern is clearly visible. Right: Illustration of the avalanche production inside a GEM hole.](image)

In particular, GEM detectors for the CMS muon system upgrade are *triple-GEM detectors*, i.e. they use a stack of three GEM foils, that can reach a total charge amplification factor up to $10^5$. The detector is completed, on the two extremities of the GEM stack, by a drift cathode on one side and finely segmented electrodes on the other one, as shown in figure 2.6. The readout plane is grounded and a decreasing voltage is applied to the conducting surfaces up to the drift cathode. Hence an almost constant electric field is produced between the foils, between the first foil and the cathode and between the last foil and readout. When a particle crosses the detector volume it can produce a primary ionization in the gas molecules; the primary electrons drift towards the readout and undergo avalanche multiplication when they encounter the first foil; the multiplied charge is then transferred to the next foils and further multiplied. The amplified charge induces a signal on the readout electrodes.
that is read out by sensitive electronics. A schematic representation of a triple-GEM and its working principle is shown in figure 2.6.

![Schematic of a triple-GEM](image)

Figure 2.6: A cascade of three GEM foils. The three GEM foils (GEM 1, GEM 2, GEM 3), the drift cathode and the readout are shown.

### 2.2.3 Detector Performance

GEM technology is not new within the particle physics community: GEM detectors have already been used for long term operation in several physics experiment, i.e. the COMPASS [29], PHENIX [30], STAR [31], TOTEM [32] and LHCb [33] experiments. Experience gained in such experiments and their detector performance have contributed to choose GEM technology also for the upgrade of the forward CMS Muon Endcap.

**Other experiments.** The COMPASS experiment, the pioneer for GEM technology, has successfully operated at CERN SPS 30 $\times$ 30 $cm^2$ triple-GEM detectors for tracking in a high-rate environment up to 2.5 $MHz/cm^2$ (about 1000 times the expected rate for the CMS GE1/1). They used 3/2/2/2 $mm$ gap sizes, Ar/CO$_2$ 70:30 gas mixture, and operated two OR’ed GEM trackers at a gas gain around 8000 for a total (OR’ed) efficiency of 97.5%. In five years of operation (2002-2007) the COMPASS GEM detector have accumulated a total charge of about 200 $mC/cm^2$ without showing any gain drop, and x-ray tests in which a total charge of 700 $mC/cm^2$ was accumulated did not show any gain drop either. In addition, in 2008-2009 COMPASS also operated some five small-size GEM detectors exposed to muon rates up to 12 $MHz/cm^2$ and
achieved 7 ns time resolution [34,35].

At RHIC, the PHENIX experiment successfully operated 20 medium-size triple-GEM detectors in pure CF$_4$ [36], and the STAR experiment equipped 24 medium-size triple-GEM detectors for tracking using industrially produced circular foils since 2012 [37]. At the LHC, the TOTEM experiment employs 20 medium-size semi-circular triple-GEM detectors, which by the end of 2012 had integrated a total ionizing dose of about $5 \times 10^4$ Gy while performing as expected, and the LHCb experiment employs 12 pairs of medium-size triple-GEM detectors, with 3/1/2/1 mm gap sizes operated with an Ar:CO$_2$:CF$_4$ 45:15:40 gas mixture, as inner section of the M1 muon station in front of the calorimeters sustaining rates up to 500 kHz/cm$^2$. The latter detectors run at a gain of about 4300, with a time resolution of 4 ns and efficiency of 97 – 99% in a 20 ns time window for OR’ed signals from paired detectors. The most irradiated LHCb GEM detector in 2010-2012 has accumulated 120 mC/cm$^2$ (equivalent to 20 years of HL-LHC for the GE1/1 station) without signs of aging.

Such High Energy Physics and Nuclear Physics experiments show that the GEM technology is robust for the use in high-rate experiments. The major step represented by the CMS GEM prototypes is moving from systems with a small number of medium-size detector, to the production of a large quantity of large-size, well-performing detectors.

**CMS Dedicated R&D.** The CMS GEM Group has carried out a series of beam tests at CERN and Fermilab and with X-ray sources over a five-year R&D period to study in great detail the performances of several generations of GE1/1 prototypes. The main performance results are shown below. Such studies usually refer to the GE1/1 station, as it is the first station scheduled for the installation in the CMS muon system. Of course, the results of such campaigns can be appropriately extended also to the other GEM stations for the upgrade of the CMS Muon Endcap.

A typical measurement that has been performed on all GE1/1 prototypes is the gain measurement. It is based on the hit rate ($R$) and anode current ($I_a$) measurements at a given voltage applied to the detector when the detector is irradiated with a fixed rate of incident X-rays. Their measurement has been performed with a methodology similar to one described in section 3.2.1. The hit rate $R$ is the rate of hits measured by the detector under irradiation. As-
2. The GEM Upgrade of the CMS Muon System

Assuming that the average number of primary electrons produced per measured hit is \( N_p = E / W_{\text{gas}} \), where \( E \) and \( W_{\text{gas}} \) are the energy of the incident photons and the mean energy to produce an electron-ion pair in the gas mixture respectively, then the detector’s gain \( G \) is calculated as the ratio \( G = I_a / N_p e R \). The gas gain measured for a GE1/1 prototype with a Ar:CO\(_2\) 70:30 and a Ar:CO\(_2\):CF\(_4\) 45:15:40 gas mixture\(^1\) as a function of the drift voltage is shown in figure 2.7. A gain of the order of \( 10^4 \) has been reached with both gas mixtures.

Note that in figures 2.7, 2.8 and 2.9 the performance is shown as function of the drift voltage. As the voltage is distributed to the detector’s electrodes through a voltage divider, a variation of the drift voltage also implies a proportional variation of the voltage applied to all the electrodes.

Detection efficiency measurements have been performed in different beam tests at CERN and at Fermilab, showing a plateau efficiency of 98% for the Ar:CO\(_2\)::CF\(_4\) 45:15:40 gas mixture with a pion beam and 97 – 97.8% efficiency for the Ar:CO\(_2\) 70:30 gas mixture depending on the readout system. An example of efficiency measurement with Ar:CO\(_2\) 70:30 gas mixture is shown in figure 2.8.

The spatial resolution for GE1/1 prototypes with radial strips with pitch of 455 \( \mu m \) has been measured to be 137 \( \pm 1 \) \( \mu \text{rad} \), very close to the expected intrinsic resolution of 455 \( \mu \text{rad}/\sqrt{12} = 131 \) \( \mu \text{rad} \) [23]. For example, for the GE1/1 station the limit on spatial resolution imposed by trigger performance is 300 \( \mu \text{rad} \), safely enough greater than the measured resolution.

The timing performance has been measured for a 10 \( \times \) 10 \( cm^2 \) triple-GEM detector equipped with double-mask GEM foils and for real-size GE1-1 prototypes. GEM foils are produced using photolithographic techniques, in which the copper-clad polyimide substrate is coated on both sides with photoresist that will transfer the hole pattern to the foil under UV exposure. Typically such coating is applied on both sides (double-mask GEM foils), and in order to produce the correct hole geometry it is important to align the photoresist on the GEM foil sides within 10 \( \mu m \). With this technique the larger the detector, the more difficult it is to correctly align of the photoresist. Hence for

\(^1\)Ar has been chosen because, as a noble gas, it has a high specific ionization and allows to obtain avalanche multiplication at lower fields than other molecules and it’s cheaper than other nobles gases. CO\(_2\) acts as a quencher. In addition, Ar:CO\(_2\) gas mixtures have been chosen because they show a time response good for tracking and triggering. CF\(_4\) improves the time response, it’s non flammable, non-corrosive, non-toxic and has a good compatibility with many materials used in gaseous detectors, but it has a high Global Warming Potential (GWP).
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Figure 2.7: Measured hit rates (triangles) and gas gains (diamonds) as a function of the high voltage applied to the drift electrode of a GE1/1 prototype, operated with a Ar:CO$_2$ 70:30 (blue) and a Ar:CO$_2$:CF$_4$ 45:15:40 (red) gas mixture [23].

the production of the large-size GEM detectors for the CMS muon system, the single-mask photolithography has been used. In this technique, the GEM pattern is transferred from the photoresist only to one side of the GEM foil, removing any need for alignment. Studies have been performed in order to determine the differences between foils produced with the two techniques and to verify that the performance of foils produced with the single-mask technique are suitable for CMS goals, for example in [38, 39]. For the smaller-size detector, the timing resolution at maximum detector efficiency has been measured with a TDC, and varies between 8 ns and 4 ns for different gases and drift distances (figure 2.9). The timing measurement of the real-size detector has been performed at CERN in 2012 using the asynchronous beam from the SPS, by counting the fraction of hits in adjacent 25 ns time bins triggered by a timing hardware that selects events within a 2 ns time window. It has been seen that 95% of hits occur within the correct 25 ns clock cycle. In order to extract the timing resolution information from this distribution, one considers that the observed distribution should be a $\delta(t)$ function smeared with a gaussian and binned in 25 ns bins. The width $\sigma$ of the gaussian that best reproduces the
2. The GEM Upgrade of the CMS Muon System

Figure 2.8: Efficiency to charged particles as a function of the high voltage applied to the drift electrode of a GE1/1 prototype, operated with a Ar:CO$_2$ 70:30 and measured in a central sector of the detector. The signal is read out with APV chips, the three curves correspond to different cuts applied to the strip charges in order to simulate the VFAT2 threshold behaviour. The best fits performed with a sigmoid function are also shown [23].

This procedure has lead to a measured timing resolution for a real-size GE1/1 triple-GEM detector operated with Ar:CO$_2$:CF$_4$ 45:15:40 of 6 $\text{ns}$ on the efficiency plateau (figure 2.10). As the GE1/1 chambers will be composed of two stacked triple-GEM detectors (a superchamber, see section 2.3), the overall timing resolution of a GE1/1 superchamber should be $6 \text{ ns}/\sqrt{2} = 4 \text{ ns}$. Eventually, comparing this result with the small-size detector measurements in figure 2.9, one can expect a time resolution for a superchamber operated with Ar:CO$_2$ 70:30 to be about 8 $\text{ns}$.

Further performance measurements include the rate capability, which is evaluated performing gain measurements while irradiating the detector with high-intensity sources. Results show that the gas gain is stable over four orders of magnitude of incident particle rate up to 100 $\text{MHz}/\text{cm}^2$, above which it begins to drop.

Among the other studies not shown here, we can mention the performance
2.3 The GE1/1 station

Figure 2.9: Timing resolution of a $10 \times 10 \text{ cm}^2$ triple-GEM detector equipped with GEM foils produced with the double mask technique, as a function of the electric field $E_{\text{drift}}$ applied to the drift gas gap. The timing resolutions are measured with a TDC. The two curves show the time resolution for a detector with 3/2/2/2 mm (3/1/2/1 mm) gaps spacings from the drift electrode to the readout using a Ar:CO$_2$ 70:30 (Ar:CO$_2$:CF$_4$ 45:15:40) gas mixture [23].

in high magnetic fields, stating that the latter should not influence the detector performance, the discharge probability and the detector aging, for which some preliminary studies have been performed and some more detailed measurements are still ongoing.

2.3 The GE1/1 station

The GE1/1 station will be installed during the LS2 (2019-2020) in the first endcap muon station in the region $1.6 < |\eta| < 2.2$ to help maintaining an acceptable forward muon triggering and reconstruction during HL-LHC. It will be the first station radially encountered from the beam direction in the first muon endcap, as shown in figure 2.2. It consists of 72 ten-degree chambers per endcap, using triple-GEM detectors. A ten-degree chamber will be composed of a pair of triple-GEM detectors, combined to form a Superchamber or Gem-
2. The GEM Upgrade of the CMS Muon System

Figure 2.10: Timing resolution of a real-size triple-GEM GE1/1 detector as a function of the high voltage applied to the voltage divider. The timing resolutions are measured for a detector with 3/1/2/1 mm gaps spacings from the drift electrode to the readout using a Ar:CO$_2$:CF$_4$ gas mixture [23].

in$_i$, in order to provide two measurement planes to complement the existing ME1/1 detectors and maximize the muon detection efficiency.

**Magnetic field.** The muon trajectories are more bent by the magnetic field in the first muon station, where the latter is stronger, while in the next stations the muon bending is smaller because the magnetic field lines bend around the endcap flux return (figure 2.11). In the position of the CSC ME1/1 and GE1/1 stations, the magnetic field also varies with the pseudorapidity within the stations coverage. As a result, the magnetic field along a muon’s trajectory crossing them varies along its path, making the $p_T$ reconstruction more difficult.

**Background.** In addition, high background particle rates complicate signal identification, besides possibly having an impact on the detector performances themselves. The dominant contribution to the background is given by neutrons produced in interactions of hadrons with the beam pipe and the structures in the very forward region (HF calorimeter, beam collimator and shieldings), and secondary particles arising from the interaction of neutrons with matter. In figure 2.12 the simulated neutron flux as a function of position at a luminosity of $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ is shown. The spectrum of these long-lived neutrons ranges
2.3. The GE1/1 station

Figure 2.11: Magnetic field expected in the CMS muon endcap during LHC Phase 2 in the GE1/1 region produced by OPERA simulation. The dashed rectangles indicate the location of the GE1/1 station. The left plot shows the field strength and field lines, the right one shows the polar angle $\theta_B$ of the magnetic field vector (i.e. the angle between the magnetic field and the CMS $z$-axis). Regions coloured in blue correspond to $\theta_B = 0^\circ$, the pink ones indicate $\theta_B > 15^\circ$ [23].

from thermal energies to a few GeV. In addition, the slow neutron capture by nuclei leads to photon emission and, consequently, to electrons and positrons (figure 2.13) capable of producing detectable signals in gas detectors. Such background particles, when hitting detectors, can be detected depending on the detector sensitivity to that particle type and energy. A high occupancy and measured hit rate can lead to inefficiencies in detector response, degraded resolutions and momentum measurements, or even make the detector inoperable. The latter troubles strongly depend on the detector technology and are addressed in section 2.2, where it is shown that GEM detectors are suitable for operating in high background environments. In addition a high background also lead to a high measured hit rate. In figure 2.14 the expected hit rate per GE1/1 chamber for an instantaneous luminosity is shown. A high hit rate leads to an unacceptably high rate of track misreconstructions that contribute to the trigger rate. Therefore, the background flux level and its evaluation is a key factor for correctly evaluate not only the detector performance and aging, but also the trigger performance.
The GEM Upgrade of the CMS Muon System

Figure 2.12: Map of the simulated neutron flux as a function of position in a portion of the CMS detector, overlaid to the schematics of the detector elements. The flux is normalized to an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [23].

Figure 2.13: Simulated neutron (blue), photon (red) and electron (green) flux in the GE1/1 region as a function of pseudorapidity at a luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [23].

**Level 1 Trigger.** Because of the features of the magnetic field and the high background rate at high pseudorapidity, the contribution to the trigger rate within the GE1/1 coverage is particularly large and difficult to control. The GE1/1 chambers will work in conjunction with the existing CSC chambers to measure the muon bending angle, as shown in figure 2.15. This will result in
2.3. The GE1/1 station

Figure 2.14: Expected hit rates associated with the backgrounds induced by long-lived neutrons in a GE1/1 chamber as a function of pseudorapidity, at a luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ [23].

an increased path length traversed by muons within the first muon station with respect to the one through the 6 layers of CSC ME1/1 only (11.7 cm), namely by a factor $2.4 - 3.5$. The increased path length will significantly improve the L1 stand-alone muon trigger momentum resolution, hence drastically reducing its contribution to the overall L1 muon trigger rate, as shown in figure 2.16. This will allow to reach the goal of maintaining a L1 muon trigger thresholds at low $p_T$ values, keeping a high efficiency for capturing interesting physics processes featuring soft leptons. For example, it will be possible to preserve the L1 single muon trigger threshold at $12 - 14 \text{ GeV}$.

In summary, the GE1/1 station targets the following improvements:

- it measures the combined CSC-GEM bending angle at trigger level to reduce the rate of mis-measured muons
- it improves the tracking performance in a challenging region featured by the highest background rates and reduced magnetic bending power
- it establishes sufficient redundancy in the region $1.6 < |\eta| < 2.2$ as part of the overall Phase 2 forward muon improvement plan.
2. The GEM Upgrade of the CMS Muon System

2.3.1 GE1/1 chambers minimum requirements

In order to meet the desired trigger and physics performances, some fundamental requirements on the detector performance of the GE1/1 chambers are necessary. They are:

- maximum geometric acceptance within the given CMS envelope
- rate capability of 10 kHz/cm$^2$ or higher
2.4. The GE2/1 station

- single-chamber efficiency of 97% or higher for the detection of minimum ionizing particles
- angular resolution of 300 $\mu$rad or better on the measurement of the bending angle $\Delta \phi = \phi_{GE1/1} - \phi_{ME1/1}$
- timing resolution of a single chamber of 10 ns or better
- gain uniformity of 15% or better across a chamber and between chambers
- no gain loss due to aging effects after 200 $mC/cm^2$ of integrated charge.

As explained in section 2.2, the performance of GEM detectors meets such requirements.

2.3.2 The Slice Test

The GE1/1 station is also the first station that will be chronologically installed in CMS. For this reason, the installation of five chambers has been anticipated during the Year-End Technical Stop that has taken place in late 2016/early 2017, in order to provide first operational experience and to start addressing the process of integrating the new GEM station into the CMS datataking and control system. Chapter 4 will be dedicated to the Slice Test, representing as a key part of my PhD work.

2.4 The GE2/1 station

The second project of the GEM-based upgrade of the CMS muon system regards the GE2/1 station. It will be located in the muon system’s endcap, in the second ring encountered from the interaction point and the first one from the beam direction, as shown in figure 2.2. The GE2/1 station will be composed of 18 2-layered chambers per endcap, each one covering $20^\circ$ in $\phi$. The total pseudorapidity coverage will be $1.6 < |\eta| < 2.4$. The installation of the GE2/1 station is the second one to take place in time, in 2022-2023.

The motivation for the installation of this station is analogous to the one of the GE1/1 station, applied in a different region: the addition of redundancy allows for a reduction of the L1 trigger rate and an enhanced muon reconstruction, besides allowing to maintain the existing envelope mitigating aging effects of the CSC detectors. The GE2/1 station will measure the bending angle together with the existing CSC ME2/1 station, in a way similar to the one of the GE1/1-ME1/1 stations. Figure 2.17 shows the reconstruction efficiency of
the local trigger primitive \((\text{stub})\) for a perfectly working existing CSC system at 140 PU compared to the same efficiency in presence of the GE2/1 (and RE2/1) station. In the first case, a degradation in the stub reconstruction causes the fraction of muon candidates with a low number of reconstructed stubs to increase. Consequently, the stub reconstruction efficiency drops below 90\%, the frequency of mismeasured muon \(p_T\) increases, and the trigger rate also increases. Figure 2.17 also shows that the presence of the GE2/1 (and RE2/1) station restores the local reconstruction efficiency.

Initially, also a second type of MPGD, the micro-Resistive WELL detector \([43]\) \((\mu\text{-RWELL})\) was considered as detector technology for this station. The \(\mu\text{-RWELL}\) detector is a spark-protected single amplification stage MPGD, whose amplification stage is very similar to a GEM foil, but it’s embedded through a resistive layer in the readout board. A cathode electrode, defining the gas gap for conversion and subsequent drift of the charges, completes the detector design (figure 2.18). This detector design allows for a higher gain of a single GEM foil, as normally in GEM detectors about 50\% of the multiplied charge impacts on the bottom side of the foil and is lost, while this design allows to promptly collect all the multiplied charge through the copper dot at the bottom of the WELLs. In addition, also the ions contribute to the forma-
tion of the signal, while in typical GEM detectors the ion component is largely shielded by the GEM foils. However the distinctive advantage of this technology is that the detector is composed of very few components, not requiring complex and long assembly procedures like stretching or gluing, or mechanical parts like internal support frames.

Figure 2.18: Top: schematic representation of the amplification stage and readout of a $\mu$-RWELL detector. It consists of a GEM-like foil embedded in a readout printed circuit board (PCB) plane through a resistive deposition. The copper on the bottom side of the foil is patterned in order to create small copper dots in correspondence of each WELL structure. [43] Bottom: schematic representation of a $\mu$-RWELL detector. A cathode electrode defines a gas gap for conversion and drift of the charges [43].

Eventually, it has been decided to use the triple-GEM technology also for the GE2/1 station, with the same layout of the gaps of 3/1/2/1 mm, in order to benefit of the R&D already performed for the GE1/1 station and the experience gained in all fields, from the well-known performance, to production and assembly procedures and sites, and to the installation and operation experience gained during the Slice Test. The GE2/1 chambers will cover a much
larger surface than the GE1/1 ones, representing the largest GEM detectors ever built.

2.5 The ME0 station

After the installation of the new High Granularity Calorimeter foreseen in 2024, a new slot approximately 30 cm long in the $z$ direction will become available in the endcaps in the position closest to the interaction region, extending in the pseudorapidity region $2 < |\eta| < 2.8$. The third GEM-based muon station, the ME0 station, has been proposed for the installation in such position (figure 2.2).

The ME0 station has a substantial difference with respect to the other two GEM-based stations, driven by the fact that the muon system is currently uninstrumented at $|\eta| > 2.4$: it will partially overlap with the existing muon system, and partially extend beyond it. Hence it represents a great opportunity to extend the acceptance of the muon system by $(10 - 20)\%$ and collect a larger fraction of events showing final muons in the very forward region.

At $|\eta| < 2.4$ the station can help sustaining triggering at current trigger thresholds and improving muon reconstruction, working together with the existing muon station as already explained for the GE1/1 and GE2/1 stations. Instead, in the $|\eta| > 2.4$ region the muon reconstruction can’t work in conjunction with other muon chambers like the other two GEM stations and the ME0 station needs to be able to perform a standalone reconstruction. The inclusion into the Level-1 trigger of the information at $|\eta| > 2.4$ coming from the ME0 station is still under development. In addition, the background rate at the position of the ME0 station is much higher than the one sustained by the other GEM stations, as shown in figure 2.19.

As a consequence, the ME0 station will consist in six layers of triple-GEM detectors in order to cope with the above challenges: the presence of six planes of detection will allow to build an ME0-only segment and reject background hits not associated to the segment direction.
2.5. The ME0 station

![Graph](image)

Figure 2.19: Estimated Background Hit Rate for an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for the three GEM stations. The calculation, performed with a combination of FLUKA+GEANT4 simulations, considers the contribution of background neutrons, photons, electrons and positrons weighted according to the detector sensitivity and shows the total contribution for each GEM station [16].

### 2.5.1 Impact on physics in the forward region

Several physics channels with final muons in the forward region, both in the Standard Model and beyond it, will benefit from the muon system extension provided by the ME0 station. Among these, there are the $H \rightarrow ZZ^* \rightarrow 4\mu$ decay, a golden channel for the complete reconstruction of the Higgs boson with low background, the double parton scattering resulting in two $W$ bosons with the same charge that decay into $W \rightarrow \mu\nu$, the production of a tau decaying into $\tau \rightarrow 3\mu$, and others.

To understand the potential of the muon system extension, two of the aforementioned examples are presented in the following: the $H \rightarrow ZZ^* \rightarrow 4\mu$ and the $\tau \rightarrow 3\mu$ decays.

**The $H \rightarrow 4\mu$ decay.** Concerning the first decay, $H \rightarrow ZZ^* \rightarrow 4\mu$, a study [40] on the performances of this analysis with the CMS detector upgraded for the HL-LHC has been performed. This study compares two different Phase II
configurations of the CMS detector, referred to as configuration 3 and configuration 4: the former foresees a new tracker and forward electromagnetic calorimeter, but the current detector acceptance, the latter instead foresees the electromagnetic calorimeter, the hadronic calorimeter and the muon system extended from $|\eta| < 2.4$ to $|\eta| < 4.0$. The latter has highlighted that most of the signal muons fall outside the acceptance of the CMS detector of Run 1, as shown in the top graph in figure 2.20. As a consequence, configuration 4 would bring a significant increase of efficiency due to the increased angular acceptance, that translates into a larger number of expected events with the same integrated luminosity. Figure 2.20 bottom shows the four mass distribution obtained with the two considered configurations with an integrated luminosity of 3000 fb$^{-1}$ and a pileup of 140 events. The resulting relative selection efficiency increase is more than 40%.

More recent studies, focused on the impact of ME0 station on the $H \rightarrow ZZ^* \rightarrow 4\mu$ channel, have shown that 15% of signal muons fall within the ME0 acceptance, and in particular 8% falls in the newly instrumented region at $2.4 < |\eta| < 2.8$. In addition they have a soft $p_T$ spectrum, so that it is challenging to separate them from pileup without losing selection efficiency on the signal.

**The $\tau \rightarrow 3\mu$ decay.** In the Standard Model the $\tau \rightarrow 3\mu$ decay has a very small branching ratio ($B \sim 10^{-40}$), made possible only via higher order contributions involving neutrino oscillations, and is immeasurably small. Instead this decay becomes accessible in some exotic models, with branching ratio up to $10^{-9}$, in which case it could be within experimental reach. For example, the $\tau \rightarrow 3\mu$ decay is of utmost interest because it’s one of the cleanest Lepton Flavour Violation (LFV) decay channels, involving for example processes like $\ell \rightarrow \ell'\gamma$ or $\ell \rightarrow 3\ell'$. Currently, the best experimental upper limits on this decay come from the Belle and LHCb Collaborations, that set a limit of $2.1 \cdot 10^{-8}$ (90% CL) [41] and $4.6 \cdot 10^{-8}$ (90% CL) [42] respectively.

Tau leptons usually come from B/D decays, with very low momenta and boosted in the very forward direction, and so the muons from their decay, that show up in three quite collimated soft muons in the forward region. Therefore it is evident that the muon system extension and its improved performance can amazingly increase the potential of exploiting this decay channel. Recent studies show that increasing the muon system up to $|\eta| \sim 3$ would increase the
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Figure 2.20: Top: Distribution of the pseudorapidity $\eta$ of the most forward muon among the $4\mu$ produced in the $H \rightarrow ZZ^{*} \rightarrow 4\mu$ decay, after event selection with the configuration 4 detector (empty red) and for the irreducible background $ZZ \rightarrow 4\mu$ (solid red). The dashed vertical lines indicate the acceptance of the configuration 3 detector [40].

Bottom: Four muon mass distribution for the signal $H \rightarrow ZZ \rightarrow 4\mu$ (solid lines) and the irreducible background $ZZ \rightarrow 4\mu$ (filled histograms), with 3000 $fb^{-1}$ and a pileup of 140 events, for the configuration 3 (blue) and configuration 4 (red) scenarios [40].

signal acceptance by a factor 2.9. In addition, the enhanced capabilities of the upgraded muon system to trigger on and to reconstruct low-momentum muons
will also help to enhance sensitivity to this search.

Figure 2.21 shows the trimuon mass distribution for signal and background built with events with at least one muon reconstructed by the ME0 detector, with all selection cuts applied, obtained in a recent preliminary study [16] focused on the impact of the ME0 station. Despite the high pileup of 200, the distribution has no tails and is picked correctly. With 3000 \( fb^{-1} \) to be delivered during the HL-LHC, an exclusion sensitivity in absence of signal of \( B < 3.7 \times 10^{-9} \) (90\% CL) is expected, while the expectation for the 5\( \sigma \)-observation sensitivity is \( B = 1.1 \times 10^{-8} \). Without the ME0 station, 4000 \( fb^{-1} \) would be necessary to reach the same sensitivity.

![Figure 2.21: Trimuon invariant mass \( m_{3\mu} \) for a \( \tau \rightarrow 3\mu \) signal (red) with \( B(\tau \rightarrow 3\mu) = 2 \times 10^{-8} \) and background (blue) containing at least one muon reconstructed by the ME0 detectors. The trigger requires one tracker muon and two segments in the first muon endcap station, where ME0 segments in the \( 2.4 < |\eta| < 2.8 \) range have \( \delta p_T/p_T \sim 40 \), and a trimuon invariant mass \( m_{3\mu} < 3 \text{ GeV} \) [16].](image)

2.5.2 Effect of the time resolution

Muons in the ME0 station are reconstructed by matching tracker tracks in local \( x \) and \( y \) position, as well as in global direction in the bending plane \( \phi \). When at least three hits are observed in a region \( \Delta \eta \times \Delta \phi = (0.02 \times 0.05) \text{ rad} \), 
2.5. The ME0 station

A segment is built. Two categories are distinguished, depending on the angle with respect to the tracker track: we have a Tight ME0Muon if $\Delta \phi < 0.15$ or a Loose ME0Muon if $\Delta \phi < 0.50$. A segment is built using the reconstructed hits. An ME0 segment has an associated time, represented by the average of the times of the reconstructed hits used to build it. The time uncertainty of the segment depends both on the number of hits used $N_{\text{hits}}$ and the detector time resolution $\sigma_t$, being $\sigma_t/\sqrt{N_{\text{hits}}}$.

A high background rate characterizes the position of the ME0 station. Background hits can be wrongly used in the construction of a segment in the ME0 station, leading to a wrong time estimate of the segment and a wrong segment direction, causing a wrong reconstructed muon $p_T$, typically confusing high-$p_T$ tracks with lower-$p_T$ tracks.

The reconstruction efficiency of Tight and Loose ME0Muons for a nominal ME0 chamber based on triple-GEM technology with a strip pitch of 0.455 mrad$^2$ and a time resolution of 8 ns is shown in figure 2.22. The efficiency clearly worsens at higher pseudorapidity, as an effect of the higher background. Indeed, background hits used to reconstruct a segment are spatially close to each other, but some of them are clearly separated in time. Both the segment’s time assignment and direction are affected, the latter leading to lower reconstructed $p_T$ and hence an inefficiency. It is then interesting to investigate whether the timing information can be used in order to separate background hits from signal hits.

The background can be divided into prompt background, that can be either In-time (IT PU) or Out-Of-Time (OOT PU), and non-prompt background, composed by neutrons. Background from neutrons can be efficiently eliminated requiring hits in a minimum of three layers to define a segment. IT PU comes from events at BX=0, the same of the considered event, while OOT PU comes from bunch crossings preceding or following the considered one, in which slower or faster tracks can be mistakenly included in the BX=0. Some studies of the contribution of the IT and OOT PU have been performed, in order to understand their effect on the reconstruction efficiency of ME0Muons. The goal was to understand whether it is possible to discriminate the background hits using the timing information, especially at high $\eta$ and, if so, what would

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2The strip pitch is expressed in mrad because the GEM chambers have a one-dimensional readout with radial strips along the $\phi$ direction. In particular, the strip pitch increases with the distance from the beam axis, while the angle between the strips is constant. Hence, expressing the strip pitch in mrad is the most natural choice.
be the necessary detector time resolution.

To study the OOT component, a time clustering of hits used to build ME0 segments has been introduced, whose time windows varies between $(1 - 30) \, ns$ depending on the considered time resolution. In particular, a hit was accepted only if its hit time $t_i$ was in the range $[-3 \sigma_t - 0.8, \, +3 \sigma_t + 0.8]$, depending on the detector time resolution $\sigma_t$. The resulting efficiency for Tight ME0Muons as a function of the detector time resolution, in absence of neutron background, is shown in figure 2.23. The use of the timing information introduces the largest improvement at high pseudorapidity, where it is more desirable. In addition, the improvement has a plateau for time resolution smaller than few nanoseconds. Similar considerations apply also to the Loose ME0Muons.

The IT background component, instead, creates real tracks that can be confused with the signal tracks. To study the IT component, a real signal track coming from the $H \to ZZ^* \to 4\mu$ decay has been taken as a reference (for example the one with highest $p_T$), and the distribution of the difference

Figure 2.22: Efficiency for Tight (blue) and Loose (red) ME0Muons as a function of pseudorapidity $\eta$ [4].
2.5. The ME0 station

Figure 2.23: Efficiency for Tight ME0Muons using only hits whose time $t_i$ is in the range $[-3\sigma_{t,d} - 0.8, < t > +3\sigma_{t,d} + 0.8]$, as a function of the detector time resolution for different pseudorapidity values. The bottom part shows the difference between the efficiency with and without the use of the timing information (i.e. the values in figure 2.22). A Drell-Yan sample with PU 140 has been used, without neutron background, but with In-Time and Out-Of-Time pileup.
between its arrival time and the arrival time of other signal tracks or IT pileup muons has been realized for different detector time resolutions $\sigma_t$. The resulting distributions for time resolutions of 50 $ps$ and 100 $ps$ at pileup of 200 are shown in figure 2.24. It is clear that a time resolution of 100 $ps$ is not enough to distinguish tracks from IT pileup from signal tracks, but a smaller time resolution is necessary in order to achieve this goal adding a cut on the timing information.

From the above studies it was concluded that very high time resolution would be necessary in order to reject the IT PU, of the order of $\sim 30$ $ps$ with a six-layered ME0 station, or $\sim 100$ $ps$ for a 10-layered ME0 station. Instead, in order to reject OOT PU a lower time resolution would be sufficient. This can be explained observing that OOT hits are slower than signal hits, while IT hits are much faster and in time with the signal, hence the former component can be more easily discriminated also with a poorer time resolution.

Figure 2.25 shows a comparison of the efficiency for tight ME0Muons, that was shown in figure 2.22, and the same efficiency with the introduction of a time clustering window of 1.5 $ns$ and a detector time resolution of 100 $ps$. The efficiency results to be highly improved all over the pseudorapidity range, also in the challenging region a highest pseudorapidity. These studies have motivated the interest for the development of the Fast Timing Micropattern [44] (FTM), featuring a better time resolution than triple-GEM detectors, as an optional technology for the ME0 station.

2.5.3 Choice of the detector technology

It has been explained that the ME0 station must be composed of six detector layers. Anyway the need for a multilayer structure is not trivial, as the available space in the $z$ direction is very limited. Solutions investigated include the attempt to reduce the detector components’ thickness in order to compress the six layers into the available space, and the possibility to build a more compact Back to Back (B2B) GEM detector. In addition, motivated by the advantages of using a fast detector explained in section 2.5.2, the Collaboration at first also took part in the development of the Fast Timing Micropattern [44] (FTM) detector as an option for the detector technology to use for the ME0 station.

The working principle of the FTM detector and the R&D performed on these new Micropattern Gas Detectors – the B2B and the FTM detector – are
Figure 2.24: Time distribution of the arrival time of the signal (red) and the In-Time pileup (blue) at PU200 for detector time resolution of 100 ps (top) and 50 ps (bottom). The histogram is filled with the difference between the arrival time of a reference real track signal and the arrival time of a real track signal or a pileup muon.
Figure 2.25: Efficiency for Tight ME0Muons with no use of the time of the reconstructed hits (blue, as in figure 2.22) and clustering the hits in a time interval of 1.5 ns for a detector with time resolution of 100 ps (red), as a function of pseudorapidity.
2.5. The ME0 station

presented in chapter 3, representing a large part of my PhD work.

Eventually it has been decided that the new FTM detector was too young to be ready for using it for the ME0 station, and the interest for this specific application was restricted only to GEM detectors. Among the mentioned solutions, currently the baseline technology for the ME0 station is the “classical” triple-GEM detector.
Development and Performance of New Micropattern Gas Detectors

The detector technology chosen for the ME0 station must be able to cope with its distinctive challenges, in particular the ability to sustain the high background rate present in that region in terms of rate capability and longevity as well as a performance good enough to reach the physics goals. Moreover, the new detector must have multiple detector layers and must fit in a thin available space. Recently CMS has decided to use the classical configuration of triple-GEM detectors, properly modified in order to realize a compact six-layered structure, as baseline technology for the ME0 station. Nevertheless at first CMS participated in the R&D on types of MPGDs other than classical triple-GEM detectors, that were considered as candidates for the ME0 station: the Fast Timing Micropattern (FTM) detector [44], a completely new type of MPGD whose most attractive feature is the excellent time resolution, and the Back to Back (B2B) GEM detector, a GEM detector with a new compact design conceived for applications with space limitations. The two technologies and the R&D performed are described in this chapter.

3.1 The Back to Back GEM detector

One way that CMS also considered at first was to use the GEM technology for the ME0 station, but developing a new design able to meet the space con-
constraints. The result of this activity is the Back to Back (B2B) GEM detector, consisting in one single detector made of two independent triple-GEM detectors, each one with its own stack of three GEM foils and its own readout board. They are positioned specularly with readout planes at the two opposite ends of the detector, with a common drift cathode positioned at the center of the system, as shown in figure 3.1. This idea allows to reduce the space occupied by two triple-GEM detectors, to fit smaller spaces like the one available for the ME0 station in the CMS muon endcap.

![Figure 3.1: Schematic representation of the design of a Back to Back GEM detector. It is composed of two triple-GEM detectors, whose drift cathodes are on the opposite surfaces of a shared PCB located at the center of the system. The other detector stages, i.e. the GEM foils and readout boards, are located specularly from the center towards the outside. The prototype under study was composed of two triple-GEM detectors with gap spacings of 3/1/2/1 mm, also shown in the figure.](image)

A first prototype, shown in figure 3.2, has been built at CERN to verify the feasibility of such a new design. The prototype is composed of two triple-GEM detectors with \((10 \times 10) \text{ cm}^2\) active area and 3/1/2/1 mm gaps spacing, enclosed in the same gas tight frame. The voltage is applied to the GEM foils surfaces and the drift cathode through a miniaturized divider on a ceramic substrate (figure 3.3 right), whose resistors values are the same selected for the GE1/1 chambers and are shown in figure 3.3 left. This allows to power one triple-GEM detector using one single high voltage (HV) channel, whose voltage is then distributed commensurately to all detector electrodes by the divider. A
3.1. The Back to Back GEM detector

Printed Circuit Board (PCB) plane is located at the center of the B2B detector and is coated with copper on both sides, each one being the drift cathode for one of the two triple-GEM detectors (figure 3.1). In this prototype the two sides are in electrical contact, so that the same voltage is applied at the two drift cathodes. As a result, the HV distribution has been realized in order to supply the same voltage in parallel to the two dividers as shown in figure 3.4, so that also all the other detector stages of the two triple-GEM detectors have the same voltage applied, i.e. the same amplification and drift fields at the same time. Powering the two triple-GEM detectors with the same voltages is made necessary by the fact that in this prototype the drift cathodes are not insulated from each other, but in principle this is not a necessary feature for the B2B detectors, that could be realized keeping the powering of the two triple-GEM detectors completely independent. In the configuration of the prototype under study one single HV channel and two separate dividers are necessary to power both the triple-GEM detectors.

Figure 3.2: The Back to Back GEM detector prototype under study.

Each triple-GEM detector of the B2B detector has its own readout plane, consisting in a PCB boards with 128 parallel strips with 800 \( \mu m \) pitch. The directions of the strips on the two boards are rotated by 180° with respect to each other, so that the two triple-GEM detectors provide one dimensional position measurements in perpendicular directions. The signal is collected by two connectors per triple-GEM detector, i.e. 4 connectors are used in total for the
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Figure 3.3: Left: Diagram of the ceramic divider used to distribute the high voltage to the detector electrodes. The values of the resistors and the corresponding connections to the electrodes are shown. For example, GEM1 Top and GEM1 Bot indicate the upper and lower copper-coated surfaces of the first GEM foil respectively. Right: The miniaturized divider on a ceramic substrate used to distribute the HV, soldered on one of the external PCB boards of the Back to Back detector. The same divider developed for the GE1/1 chamber has been mounted on the Back to Back GEM detector.

entire B2B detector. For the most simple measurements, not requiring position resolution, connectors providing the analog OR’ed signal coming from all connected strips were used (figure 3.5). In this case, the signal needs to be further processed by a preamplifier and amplifier chain. Instead, for measurements in which the one dimensional position resolution is necessary, VFAT2 [52] chips were used. Two VFAT2 chips per triple-GEM detector were used, each one reading the signal collected by 64 strips. A VFAT2 is a highly-integrated 128 channel front-end chip developed for the charge-sensitive readout of multi-channel silicon and gas particle detectors, capable of providing fast trigger information, digitized data storage and formatting. A VFAT2 has both analog and digital functions, which traditionally are instead available as different components. In addition it performs front-end amplification with programmable internal calibration. It was specifically designed to work in the high radiation environments present at CERN experiments. The next generation of VFAT chips, the VFAT3 chips, have been selected also for the front-end system of the GE1/1 station in the CMS muon endcap.
3.2 Characterization of the B2B detector in laboratory

Figure 3.4: Simplified schema of the powering circuit of the Back to Back GEM detector prototype. One single HV channel supplies in parallel two dividers, each one powering a different triple-GEM detector. The maximum negative voltage, provided by the power supply, is applied to the two drift cathodes being in electrical contact with each other.

Figure 3.5: Connectors providing the logical OR of the signal collected on the strips of the readout board of one triple-GEM (labelled as GEM2).

3.2 Characterization of the B2B detector in laboratory

The very first characterization of the first Back to Back detector prototype took place in the CMS GEM laboratory at CERN. Its goal was to put the
3. Development and Performance of New Micropattern Gas Detectors

detector into proper operation and first of all it consisted in the design and realization of the powering scheme and the verification of the operation of electrical connections. Then we moved to the observation of the first signals produced by the detector and its basic characterization. For this first set of measurements, mainly focused on commissioning the detector rather than verifying that its performance satisfies CMS goals, the dividers used to power the two triple-GEM detectors had different resistor values with respect to the final configuration, summarized in figure 3.6.

Figure 3.6: Schema of the divider with resistor values used for the first measurements in laboratory.

In the first period my activity in the laboratory has focused on modifying the powering circuit and connections of the detector in order to find the most stable configuration. Indeed, the only constraint was that the two triple-GEM detectors should be powered with the same voltage, as the voltages applied to the drift cathodes were not independent. The exact circuit to be used for realizing this situation had to be chosen, and properly realized on the detector itself. Also, it has been necessary to modify and correct the grounding of the detectors and power supply, and to correct some defects of the connections integrated on the boards. The most stable configuration found is shown in figure 3.7. The negative high voltage supplied to the detector is first filtered to reduce the signal noise introduced by the power supply. One filter, shown in figure 3.8 b, is directly mounted on the detector itself. In addition in all mea-
measurements performed a second filter is used, consisting in the circuit shown in figure 3.8a enclosed in a metal box located directly after the HV power supply. The filtered HV is then applied to the end of the ceramic dividers close to the drift cathodes, and to the drift cathode itself through a 6.5 MΩ resistor. The other end of the dividers, instead, is grounded (figure 3.7). In order to distinguish the two sides of the B2B detector, i.e. the two triple-GEM detectors, their readout and their powering, the two triple-GEM detectors have been arbitrarily labelled as GEM1 and GEM2. The high voltage connector and the on-board filter are located on the side where the powering of GEM2 is realized. The reference ground and the filtered high voltage are then distributed to the other sides of the detector – the powering circuit of GEM1 and the readout of GEM1 and GEM2 – as visible in figure 3.7.

As the filters on the HV cause a voltage drop on the high voltage actually applied to the divider with respect to the value erogated by the power supply, we always refer to the current flowing through the divider $I_{\text{div}}$ to determine the detector’s powering configuration. Indeed, the voltage applied to each electrode can be simply deduced using the relation $V = RI_{\text{div}}$, selecting the value of $R$ according to the resistor values shown in figure 3.3 left. Twice the value of the current flowing through each divider is provided directly by the power supply, that measures the sum of the currents flowing through the two dividers.

### 3.2.1 Detector’s Rate and Gain

The next step was the verification of the basic operation of the detector through rate and gain measurements. The hit rate and the detector’s gain have been measured exposing the detector to a $^{109}$Cd source, emitting 22 keV photons, with an activity of the order of $\sim MBq$ as a function of the applied voltage. The $^{109}$Cd source emits photons of about 22 keV and 88 keV and electrons of different energies from few keV up to about 88 keV [46]. The source is encapsulated within a cylindrical collimator approximately with 4 cm diameter and 3 cm height, allegedly in its center, and the radiation is collimated through a hole on the bottom of the cylinder, whose center is approximately 1.25 cm from the axis of the cylinder. The measurements are performed on GEM1 and GEM2 separately, as the $^{109}$Cd source is placed on top of the detector, on the back of the readout board of the triple-GEM under study, as shown in
Figure 3.7: Circuit of the powering scheme (a) including the filters installed on the high voltage (HV) channel, and its realization on the detector board. The on-board filter is mounted on the side where GEM2 is powered (b), the filtered HV is then brought to the side where GEM1 is powered (c). In figures (b) and (c) also the dividers and input gas line are visible. The parts shown in figures (a) and (b) are mounted on the external PCB boards closing the detector, on the PCB surface facing inwards, and are accessible by rotating the detector upside down by 180°.
3.2. Characterization of the B2B detector in laboratory

Figure 3.8: Circuits of the filters used on the high voltage channel.

To move to the next triple-GEM detector and perform the same measurement in the same conditions it is necessary to rotate the detector, so that the readout board of the other triple-GEM detector is facing upwards, and place the $^{109}$Cd source on top of the rotated detector.

Figure 3.9: Picture of the detector prepared for a rate or gain measurement. A grid has been superimposed on the active area in order to determine better the position of the source within such area.

The detectors were powered with a N470 [47] high voltage supply and the readout chain for the rate measurement was composed of an ORTEC 142 PC [48] preamplifier, followed by an ORTEC 474 [49] amplifier (set with $inte$-
grate and differentiate time constants of 100 ns), a 621AL discriminator \(^1\) [50] (width of output signals set to 20 ns) and a N1145 scaler [51], as shown in figure 3.10. A rate measurement at a given high voltage applied is the difference between the hit rate measured with and without source, using the average of three different measurements. For the gain measurement instead the readout chain is very simple, and consists in connecting a Keithly 6487 picoammeter directly to the detector’s output. As the output current fluctuates, I have realized a LabView program to measure its average value. It performs a set of \(N\) independent measurements, separated by a fixed time \(d\), while showing and adding in the plot the measured values in real-time. As this picoammeter can operate in different ranges depending on the order of the input current, the program selects the appropriate range to be used automatically according to the detected input current and performs the measurement in the most precise mode available (zero correct). When the measurement is over or interrupted, it calculates the average current value and its standard deviation using the performed measurements. Typically, the current measurements of the B2B detector are averaged over \(N = 300\) measurements separated by \(d = 300\) ms. Eventually, the gain \(G\) of the detector can be calculated from the current and rate measurements as

\[
G = \frac{I_{\text{net}}}{N_p e R_p}
\]

where \(I_{\text{net}}\) is the difference between the current measurements performed with and without the \(^{109}\)Cd source at the same voltage applied, \(e\) is the elementary charge, \(R_p\) is the net hit rate measured at full detector efficiency and \(N_p\) is the average number of primary electrons produced inside the detector per measured hit. The average number of primary electrons \(N_p\) produced in the detector operated with Ar:CO\(_2\) 70:30 gas mixture is estimated as

\[
N_p = E_q \left[ \frac{0.70}{W_{\text{Ar}}} + \frac{0.30}{W_{\text{CO}_2}} \right]
\]

\(^1\)The threshold was set by looking at the signals from the amplifier on an oscilloscope to determine the amplitude of the smallest signals in presence of the source and the maximum amplitude of noise signals without the source and to verify that the ranges of their amplitudes are well separated for the majority of signals. This allowed to determine the ideal threshold value in \(mV\), to estimate the signal frequency with the oscilloscope and to verify that the electronic chain used is able to separate the signal pulses from the noise effectively. Then the threshold of the discriminator was adjusted in order to be as small as possible providing a close-to-zero hit rate without source. The measured hit rate in presence of the source was verified to be compatible with the expected value.
where $E_\gamma = 8.3$ keV, based on the assumption that the incident radiation is inducing the emission of 8.3 keV photons from the copper inside the detector [53,54], that in turn causes the primary ionization of the gas mixture, and $W_{Ar}$ and $W_{CO_2}$ are the mean energies to produce an electron-ion pair in Ar and CO$_2$ respectively.

Figure 3.10: Schematics of the readout chain used for the rate measurement.

In figure 3.11 the rate measurements for GEM1 and GEM2 are shown. The full scan in high voltage has been performed with the source positioned at the center and in a corner of the active window. The trend curves shown and the voltage range corresponding to the rate plateau appear to be consistent between the two positions. In addition, the curves show that the configuration in which the total divider current is 1435 $\mu$A (717.5 $\mu$A flowing through each divider) is in the middle of rate plateau, indicating that at this operating value the detector is working at full efficiency. Hence, this voltage has been chosen to perform also a position scan, to verify if the response of the detector in terms of efficiency is uniform across its active area. The positions considered on the active area are roughly shown in figure 3.12, consisting in some positions close to the corners and in-between them. The rates measured in other positions of the active area are systematically smaller than the rate measured in its center, of about (3 – 11)% for GEM1 and (3 – 6)% for GEM2.

Similarly, in figure 3.13 the current measured on the readout of GEM2 exposed to the $^{109}$Cd source and the calculated gain are shown as a function of the total divider current. The full scan in current is performed with the source located at the center of the active area, while a full efficiency working point was selected for a position scan similar to the one performed for the rate measurements. The measured gain is up to about $\sim 10^4$, coherent with typical gains of triple-GEM detectors with this configuration. The resulting trend as function of the divider current is in general compatible with an exponential growth. If on one hand the trend of the measured gain is as expected, on the other hand large variations of the detector’s gain within its area of the order
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Figure 3.11: Measured hit rate on the GEM1 (top) and GEM2 (bottom) triple-GEM detectors operated with Ar:CO$_2$ 70:30 gas mixture exposed to a $^{109}$Cd source, as a function of the total current flowing through the two dividers (twice the current flowing to one divider). The full scan in divider current has been performed with the source at the center of the active area (blue) and in one corner (red). At the divider current of 1436 $\mu$A the hit rate measurement has been performed for different positions of the source on the detector’s active area (green).

of (1 – 26)$\%$ are observed.

After the first characterization in laboratory, the two dividers used to dis-
3.2. Characterization of the B2B detector in laboratory

Figure 3.12: Schema of the positions on the detector’s active area used for position scan of the rate and current measurements. The external square frame represents the $(10 \times 10) \text{ cm}^2$ active area of the detector, while the red circles roughly indicates the positions considered within that area. The distances within the active area are not to scale.

tributed the high voltage have been replaced with the same dividers selected for the GE1/1 chambers, whose resistor values are shown in figure 3.3. Indeed, a goal was to verify that the detectors composing the B2B detector maintained a performance comparable to the traditional triple-GEM detectors already developed for the GE1/1 chambers. Using the same voltage divider has allowed to directly compare performance results to the existing performance studies carried out on the GE1/1 chambers. This configuration remained for the rest of the measurements performed on the prototype, including the test beam described in section 3.3.1. The basic measurements of detector rate and gain have been repeated with the new dividers (figure 3.14), both to verify the integrity of the connections and to find the new operational point of the detectors. As this measurements were preliminary to the test beam, a new naming convention is used to identify the two triple-GEM detectors – X axis GEM and Y axis GEM – referring to different orientation of the readout strips. The X and Y axis are chosen accordingly to the coordinate system that was used in the test beam.

3.2.2 Summary and discussion

The first prototype of Back to Back detector was put into operation and characterized in laboratory. Its response in terms of rate and gain was evaluated. Both triple-GEM detectors have been operated with Ar:CO$_2$ 70:30 gas mix-
Figure 3.13: Gain of the GEM2 detector as a function of the sum of the total divider divider current (blue), calculated from the current curve and the measured hit rate at full efficiency. The best fit (dashed blue line) performed with the function $Ae^{bx}$ and the resulting parameters (bottom-right box) are also shown. At the divider current of 1436 $\mu$A the gain measurement has been performed for different positions of the source on the detector’s active area (green). The detector was operated with Ar:CO$_2$ 70:30 gas mixture and exposed to a $^{109}$Cd source.

They showed the typical response of triple-GEM detectors and a gain compatible with values in literature [23], so we can conclude that the detectors in the configuration of the B2B detector are operational. Anyway the operation is clearly not uniform across their active surface, as highlighted both by the rate and gain measurements.
3.3 Test Beam studies on the B2B detector

3.3.1 Test beam setup

The B2B detector prototype has also been studied in a test beam that took place at CERN at the end of 2016, in the experimental area H8 at CERN North Area (NA) receiving beam from the Super Proton Synchrotron (SPS). A high-energy and high-resolution proton beam up to momentum $p = 450$ GeV and $\Delta p/p_{\text{max}} = \pm 1.5\%$ is provided by the SPS. Secondary particles beams composed either of hadrons, muons or electrons up to $400$ GeV momentum are also available. The beam is delivered in separated spills $(4.8 - 9.6)$ s long every $(14 - 18)$ s, and each spill can contain up to $2 \times 10^8$ particles.

The test beam setup includes, in addition to the detector under study, other two triple-GEM detectors for tracking (hereafter trackers) and some organic scintillators for triggering. The coordinate system has been chosen in order to have the $x - y$ plane parallel to the detectors’ surfaces and readout boards, and the $z$ axis coincident to the beam direction. A picture and a schema of the experimental setup are shown in figures 3.15 and 3.16.
Figure 3.15: Top: the experimental setup of the test beam in the H8 experimental area at CERN.
Bottom: a detail of the experimental setup, showing the Back to Back detector positioned in its slot of the experimental setup.

The triple-GEM detectors for tracking have $(10 \times 10) \, cm^2$ active area,
Figure 3.16: Schema of the experimental setup of the test beam. The top view is represented, corresponding to the $xz$ plane. The $y$ axis consequently lies perpendicular to this plane, pointing towards the ceiling. The back to back detector is represented in red, the trackers in blue and the scintillators in black. The beam arrives along the positive direction of the $z$ axis. The beam crosses in the order the first tracker ($tracker1$), the first scintillator ($S1$), the Back to Back detector, the second scintillator ($S2$), the second tracker ($tracker2$) and eventually the third scintillator ($S3$). All detectors are positioned with the active area perpendicular to the beam direction.

3/2/2/2 mm gaps spacing and are operated in Ar:CO$_2$ 70:30 gas mixture. Each one has a bidimensional readout composed of 256 parallel strips both in $x$ and $y$ direction with 400 $\mu$m pitch. By measuring the $x$ and $y$ coordinates where an incident particle has crossed each tracker, it is possible to determine the direction of such particle, extrapolate it along the $z$ direction, and determine on which position $(x, y)$ it should have crossed the B2B detector. Throughout the test beam the trackers have always been powered at their operational voltage at full efficiency.

The scintillators for triggering consist in three detectors with $(10 \times 10)$ cm$^2$ active area, with high efficiency to the beam particles and fast time response. Once they are correctly aligned with the trackers and the detectors under study, it is assumed that particles traversing them also pass through the other detectors of the setup, hence a signal produced in coincidence in the three scintillators is used to trigger the acquisition of data in the entire system. In addition, in case of very high particles fluxes it was also possible to add the
coincidence of a fake trigger with a rate of about $2.3\ kHz$. The fake trigger consists of a signal with a precise frequency that can be added in coincidence to the trigger produced by the three scintillators, limiting the rate of triggered events to its frequency (in this case it can be limited to $2.3\ kHz$). This feature has been introduced in order to keep the rate of collected data below the maximum rate tolerated by the data acquisition system of the test beam. When necessary, this tool has been activated during data taking for high incident particle rates.

The signals from the B2B detector and the trackers is read by VFAT2 chips. Two VFAT2 chips are used per axis per detector, i.e. each tracker is read by 4 VFAT2 chips in total – 2 for each axis – and the B2B detector is read by 4 VFAT2 chips in total – 2 for each triple-GEM detector. In this context we will refer to the $x$ or $y$ axis in order to identify the triple-GEM detectors composing the B2B detector ($x$ axis or $y$ axis GEM). The VFAT2 chips have 40 MHz signal sampling, that must be taken into account for timing measurements, as we will see in section 3.3.3.

The signal collected by VFAT2 chips is then processed by a TURBO system [55], consisting in a stand-alone system for the Control and Data Acquisition of VFAT front-end ASIC for small and medium sized testing system, initially developed for the TOTEM experiment. It uses TURBO boards, shown in figure 3.17, controlled through USB ports by a PC running a LabView software interface, that not only allows to adjust the programmable parameters of the VFATs, but also provides the possibility to see real time the ongoing data acquisition. This allows to perform VFAT control, standard calibration scans (e.g. threshold and latency scans), Data Acquisition and basic data monitoring through the same interface. For example, the interface has been used to verify real-time if the detectors were centered with the beam or, at least, their active area contained the main core of the beam, and move them slightly in the $xy$ plane in order to correct their position. Each TURBO board can interface up to 8 VFATs. In the test beam setup, three TURBO boards have been used, allowing in total to control up to 24 VFAT2 chips.

### 3.3.2 Detector Efficiency with tracking

The most precise measurement of detector efficiency is performed using the bidimensional information coming from the trackers and comparing it with
3.3. Test Beam studies on the B2B detector

Figure 3.17: One of the three TURBO boards used for DAQ system of the test beam.

the position measurements of the $x$ and $y$ axis GEMs of the B2B detector. The basic principle is shown in figure 3.18: a signal in coincidence in the three scintillators indicates that a beam particle has traversed them and all the detectors installed in the setup. This signal triggers the acquisition of data on the trackers and the B2B detector, positioned at different $z$ positions. The data collected by trackers, positioned at $z = z_1$ and $z = z_2$, provide the coordinates of the passage of the particle $(x_1, y_1)_{z=z_1}$ and $(x_2, y_2)_{z=z_2}$. This information is used to reconstruct the straight trajectory of the particle in the $xz$ and $xy$ planes and then to extrapolate the position $x_{B2B}$ (or $y_{B2B}$) where the particle is expected to be detected by the $x$ axis GEM (or $y$ axis GEM) of the B2B detector. Some tolerance on the difference between the measured and the expected position is necessary, due to the spatial resolutions of the trackers, that induce an error in the expected position, and of the B2B detector itself. Signals measured on the trackers and the B2B detector are strip clusters, i.e. groups of adjacent strips on which a signal has been detected.

In practice, the workflow for the calculation of the efficiency based on the system’s tracking capability is divided in three main steps:

1. software alignment of the detectors

2. determination of the standard deviation of the residuals

3. efficiency calculation.
3. Development and Performance of New Micropattern Gas Detectors

Figure 3.18: Schema of the principle for the calculation of the efficiency based on the tracking capability of the system. The schema is represented in the $xz$ plane, hence involves only the $x$ axis GEM. The same schema in the $yz$ plane would instead involve the $y$ axis GEM. In the $xz$ plane, tracker1 and tracker2 provide two points of particle’s trajectory, $(x_1, z_1)$ and $(x_2, z_2)$. Then trajectory in the $yz$ can be deduced, represented by the orange line. Hence, the hit on the $x$ axis GEM of the B2B detector is expect to lie on this trajectory, in the position $(x', z_x)$, shown in orange. The measured hit, if present, lies in the vicinity of such extrapolated position, with coordinates $(z_x, x_{B2B})$, represented in blue. The distance along the $x$ axis between the measured and extrapolated hit is the residual $x_R$.

1. **Software alignment of the detectors.** Before starting to apply the procedure to reconstruct the particle’s trajectory and use it to measure the detector’s efficiency, it is necessary to align the trackers and the B2B detector with each other. Indeed, in the preparation of the setup they have roughly been aligned in order to be centered as much as possible with the beam, but the local coordinate systems of each detector are still not perfectly superimposed. The final alignment is performed via software. In the software alignment the coordinate system of tracker1 is chosen as a reference, while the reference systems of tracker2 and the B2B detector will be aligned to it. Calling $x^j_i, y^j_i$ the measured coordinates before the correction, where the index $i$ runs over the events $i = 1...N_{events}$ and the index $j$ over the detectors $j = 1..N_{det}$, the cor-
rected coordinates $x_{c,j}^i, y_{c,j}^i$ are obtained through the following transformations

for $j = 1$  
$x_{c,1}^i = x_1^i$ $y_{c,1}^i = y_1^i$ (reference tracker)

for $j = 2...N_{\text{det}}$  
$x_{c,j}^i = \cos \theta_j^0 x_j^i + \sin \theta_j^0 y_j^i + x_j^0$  \tag{3.3}
y_{c,j}^i = -\sin \theta_j^0 x_j^i + \cos \theta_j^0 y_j^i + y_j^0$

that correct both for translational and rotational misalignment. Hence, to apply the correction it’s necessary to determine the six parameters $\theta_2^0, x_2^0, y_2^0, \theta_3^0, x_3^0, y_3^0$.

The correction parameters are the ones that minimize the total chi square $\chi^2_{\text{tot}}$, i.e. in the case of the test beam setup:

$$\chi^2_{\text{tot}} = \sum_{i=1}^{N_{\text{events}}} \left( \chi^2_{x_i} + \chi^2_{y_i} \right)$$  \tag{3.4}

where

$$\chi^2_{x_i} = \sum_{j=1}^{3} \frac{(x_{c,j}^i - a_x^i x_j^i - b_x^i)^2}{\sigma^2_{x_j}}$$  \tag{3.5}

$$\chi^2_{y_i} = \sum_{j=1}^{3} \frac{(y_{c,j}^i - a_y^i y_j^i - b_y^i)^2}{\sigma^2_{y_j}}$$  \tag{3.6}

$\sigma_x$ = $\frac{C_S}{\sqrt{12}}$ ($\sigma_y$ = $\frac{C_S}{\sqrt{12}}$) is the cluster size of the measured strip cluster $C_S$ divided by the square root of 12, and $a_x^i, b_x^i$ ($a_y^i, b_y^i$) are the coefficients of the linear fit in the $zx$ ($zy$) plane through the experimental points for each event $i = 1...N_{\text{events}}$

$$x = a_x^i x_z + b_x^i z$$

$$y = a_y^i y_z + b_y^i z.$$  \tag{3.7}

Note that the above equations 3.7 represent the particle trajectory for each event.

Some examples of profiles of the beam traversing the trackers and the B2B detector are shown in figure 3.19. Some empty regions are present: the ones close to borders are caused by the alignment of the three scintillators for trig-
gering, while thinner regions in-between the beam profile are due to damaged channels of the VFAT2 reading the involved strips or damaged strips of the detector. In particular by changing the positions of the VFAT2 chips on the detectors, we determined that the empty lines visible on tracker2 are due to some damaged VFAT channels (their positions move with the VFAT), while the vertical central hole present at the center of the B2B detector is due to some damaged strips of the detector itself (they don’t move when the VFAT is replaced). Where possible, we tried to locate damaged VFAT2 chips in order to produce the empty regions as far as possible from the beam core. In addition, as the presence of such empty regions affects the quality of the reconstruction of the strip clusters, the alignment and the analysis have been performed restricting only to clusters measured in the upper-right quadrant, which is in good condition for all detectors. In addition, only unambiguous events with a single cluster both on the $x$ and $y$ axis for all detectors have been used for the software alignment procedure.

The alignment problem has been solved performing the $\chi^2_{tot}$ minimization with MINUIT. Some of the detectors mounted on the setup have been moved twice during the test beam, so three different sets of correction parameters have been found, for the three different subset of measurements, shown in table 3.1.

<table>
<thead>
<tr>
<th>set</th>
<th>$\theta_2^0$ (rad)</th>
<th>$x_2^0$ (mm)</th>
<th>$y_2^0$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(8.5 \pm 0.7) \cdot 10^{-4}$</td>
<td>$(4.73 \pm 0.01) \cdot 10^{-1}$</td>
<td>$(5.17 \pm 0.02) \cdot 10^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>$(13.0 \pm 0.7) \cdot 10^{-4}$</td>
<td>$(6.33 \pm 0.01) \cdot 10^{-1}$</td>
<td>$(5.25 \pm 0.02) \cdot 10^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>$(13.3 \pm 1.1) \cdot 10^{-4}$</td>
<td>$(4.97 \pm 0.02) \cdot 10^{-1}$</td>
<td>$(4.87 \pm 0.03) \cdot 10^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>set</th>
<th>$\theta_3^0$ (rad)</th>
<th>$x_3^0$ (mm)</th>
<th>$y_3^0$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(-5.42 \pm 0.14) \cdot 10^{-4}$</td>
<td>$-2.862 \pm 0.003$</td>
<td>$-3.330 \pm 0.004$</td>
</tr>
<tr>
<td>2</td>
<td>$(-8.61 \pm 0.15) \cdot 10^{-3}$</td>
<td>$-3.815 \pm 0.004$</td>
<td>$-3.409 \pm 0.004$</td>
</tr>
<tr>
<td>3</td>
<td>$(-8.92 \pm 0.22) \cdot 10^{-3}$</td>
<td>$-2.980 \pm 0.005$</td>
<td>$-3.153 \pm 0.006$</td>
</tr>
</tbody>
</table>

Table 3.1: Parameters to perform the software alignment of measured coordinates through the transformations 3.3, obtained minimizing the total chi square 3.4. For each parameter three different values are given, to be applied to different subsets of measurements.

An example of beam profiles after the correction is shown in figure 3.20. All the next steps have been performed using the corrected coordinates calculated according to the trasformation 3.3.
3.3. Test Beam studies on the B2B detector

Figure 3.19: Examples of beam profiles taken with tracker1 (left), tracker2 (center) and B2B detector (right). In order to reconstruct the bidimensional beam profile on the right, information coming both from the $x$ and $y$ axis GEM have been used, even if they are not located exactly in the same position along the $z$ axis, only to give an indicative visual representation of the beam traversing the B2B detector. Blank lines visible on tracker2 are due to damaged VFAT channels, while the central blank area in the beam profile of the B2B detector is due to some damaged detector's strips.

2. Determination of the standard deviation of the residuals. The goal of this step is to evaluate the spread of the position of the strip clusters measured on the B2B detector around the expected position extrapolated from the reconstructed trajectory provided by the trackers.

The same quality conditions of the strip clusters used for the software alignment are also applied in this step: the clusters in the clean upper-right quadrant of the detectors’ area and events with a single cluster measured both on the $x$ and $y$ axis have been used. Of course, the corrected coordinates are considered.
Figure 3.20: Example of beam profiles after the software alignment. The plots show the distribution of the position of the strip clusters detected on tracker1 (red), tracker2 (blue) and B2B (green) detector along the $x$ direction (top) and the $y$ direction (bottom).

Once the trajectories (equations 3.7) have been determined, the extrapolation of the expected positions of the hits $x'_i$, $y'_i$ on the $x$ and $y$ axis GEMs is straightforward. The residuals of each hit $x_R = x_{c,i}^{B2B} - x'_i$ ($y_R = y_{c,i}^{B2B} - y'_i$) can be computed and their distribution is then fitted with a gaussian distribution. Some examples of residual distributions are shown in figure 3.21.
3.3. Test Beam studies on the B2B detector

The sigma $\sigma_x$ and $\sigma_y$ of the best fits will be used to determine the maximum accepted distance in the efficiency calculation.

Figure 3.21: Distribution of the residual distance of the measured hit position on the Back to Back detector from the the expected position extrapolated by the track reconstruction provided by the two trackers. The top and bottom plots show the the distribution of residuals along the $x$ and $y$ direction respectively. The red curves show the best fit to the data of a gaussian distribution.

Note that the sigma of the distribution of residuals is of the order of 310 $\mu m$, while the expected spatial resolution of each triple-GEM of the B2B detector is expected to be smaller, namely about $800 \mu m/\sqrt{12} = 231 \mu m$. The reason is that the sigma of the distribution of residuals is affected also by the spatial resolution of the trackers. Indeed, the precision of the reconstructed trajectory increases with the number of trackers used and a good precision is necessary in order to estimate the spatial resolution of the detector under study. In
principle, if the track was reconstructed with negligible error with respect to
the spatial resolution of the detector under study, the sigma of the distribution
of the residuals would be the spatial resolution of the detector under study.
In the case of this test beam it was not possible to include in the setup more
than two trackers – the minimum amount in order to determine straight lines
in the $xz$ and $yx$ plane. Hence the sigma of the distribution of residuals has a
big component coming also from the track reconstruction.

3. Efficiency calculation. Finally, the last step is the efficiency calculation.
In order to calculate it, it is necessary to count the number of coincidences $T$ in
trackers and the number of triple coincidences $N$ in the trackers and the Back
to Back detector. We have calculated three different efficiencies: the efficiency
of the $x$ axis triple-GEM only, of the $y$ axis triple-GEM only, and of their
logical AND, i.e. efficiency in detecting the same event on both triple-GEM.

The number of coincidences $T$ in the trackers is the number of events in
which a particle has been detected by both trackers. Quality selections applied
are the request of the presence of one single strip cluster on both axis of both
trackers, the use of the good upper-right region of the detectors, and also using
only events in which the distance between the measured cluster position on the
two trackers is smaller than 1 cm, i.e.

$$|x_{c,i}^{(1)} - x_{c,i}^{(2)}| < 1 \text{ cm} \quad |y_{c,i}^{(1)} - y_{c,i}^{(2)}| < 1 \text{ cm}$$

The latter condition has been introduced because the trajectories are supposed
to be almost parallel to $z$ axis, and too tilted tracks could be produced by noise
hits.

To calculate the number of triple coincidences $N$ in the trackers and the
Back to Back detector, only events selected as coincidences $T$ in the trackers
are considered as candidates for a triple coincidence. The condition to select
triple coincidences varies if one wants to compute the efficiency of the $x$ axis
GEM, of the $y$ axis GEM or of their logical AND:

- to calculate the efficiency of the $x$ axis GEM, a triple coincidence is
counted if there is at least one strip cluster measured on the triple-GEM
satisfying $|x_{c,i}^{BB} - x_{i}'| < 3\sigma_x$
- to calculate the efficiency of the $y$ axis GEM, a triple coincidence is
counted if there is at least one strip cluster measured on the triple-GEM

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satisfying $|y_{c,i}^{B2B} - y_i^0| < 3\sigma_y$

- to calculate the efficiency of the logical AND, a triple coincidence is counted if there is at least one strip cluster on the $x$ axis GEM satisfying $|x_{c,i}^{B2B} - x_i'| < 3\sigma_x$ and one strip cluster on the $y$ axis GEM satisfying $|y_{c,i}^{B2B} - y_i'| < 3\sigma_y$

where $x_i'$, $y_i'$ are the expected coordinates provided by tracking and $\sigma_x$, $\sigma_y$ are the parameters obtained by the best fits of the residual distributions in the previous step. Eventually, the efficiency $\varepsilon$ is the ratio

$$\varepsilon = \frac{N}{T}.$$  \hspace{1cm} (3.8)

In figure 3.22 the efficiencies of the $x$ and $y$ axis GEMs and their logical AND obtained as described are shown, as a function of the divider current. Operating the detector with a Ar:CO$_2$ gas mixture the efficiency plateau is reached above about 675 $\mu$A divider current, corresponding to an efficiency of about 96.5% or greater for one triple GEM and of (93.8 $\pm$ 0.1)% for their logical AND. If operated with a Ar:CO$_2$:CF$_4$ 45:15:40, the efficiency plateau is located above about 750 $\mu$A divider current, corresponding to $>96.6$% efficiency for a triple-GEM and 94.1% efficiency for their logical AND.

### 3.3.3 Timing performance

The test beam also allowed to evaluate the time resolution of the Back to Back detector prototype. The VFAT2 chips also provide 8 S-Bits, fast-OR trigger outputs produced grouping the 128 channels of a chip into 1, 2, 4 or 8 sectors. Each S-Bit is the OR performed on one sector, hence carrying low granularity but fast information. S-Bits produced from the fast-OR of all channels of a VFAT2 chip have been used for timing measurements.

In figure 3.23 the location on the B2B detector of the VFAT2 chips, numbered from 0 to 3, is shown. In particular VFAT0 and VFAT1 read the strips of the $x$ axis GEM and VFAT2 and VFAT3 read the strips of the $y$ axis GEM (we drop the usual index “2” in VFAT2 to avoid misunderstanding). Consequently, it is possible to combine the S-Bits with logic operations in order produce signals for the following events:

- some hit has been registered in the $x$ axis GEM, produced as the logical OR of VFAT0 and VFAT1 S-Bits, in the following referred to as “VFATX”
3. Development and Performance of New Micropattern Gas Detectors

Figure 3.22: Efficiency of the $x$ axis GEM detector (blue squares) of the B2B detector, its $y$ axis GEM detector (green squares) and their logical AND (green triangles) as a function of the current through one divider, when the detector is operated with Ar:CO$_2$ 70:30 (top) and Ar:CO$_2$:CF$_4$ 45:15:40 gas mixture (bottom). The efficiency has been calculated selecting hits whose positions is compatible with the one expected from the reconstructed trajectory. The dashed curves show the best fits to such data performed with the function $A/(1 + \exp \left[ \frac{B - x}{C} \right])$, whose parameters $A$ resulting from the fits are shown in the bottom-right boxes.

- some hit has been registered in the $y$ axis GEM, produced as the logical OR of VFAT2 and VFAT3 S-Bits, in the following referred to as “VFATY”
- some hit has been registered by at least one VFAT on the $x$ axis and one on the $y$ axis, produced as the logic condition (VFAT0 & VFAT2) OR (VFAT1 & VFAT2) OR (VFAT0 & VFAT3) OR (VFAT1 & VFAT3), in
3.3. Test Beam studies on the B2B detector

the following referred to as “AllVFATs”. In other words, it represents the logic AND between the two triple GEM detectors that are part of the B2B detector.

![Diagram of VFAT chips connected to the Back to Back detector](image)

Figure 3.23: Schema of the VFAT chips connected to the Back to Back detector. VFAT0 and VFAT1 are connected to the $x$ axis GEM, VFAT2 and VFAT3 are connected to the $y$ axis GEM.

The timing performance is obtained from the distribution of the measured arrival time of one of the aforementioned signals with respect to the trigger signal produced by the scintillators. An example of raw distribution of arrival times, as directly measured and without any further processing, is shown in figure 3.24. The width of the raw data distribution is influenced by the time resolution of the Back to Back detector, the signal sampling frequency of 40 MHz of the VFATs and the time resolution of the scintillators’ trigger. As the latter contribution is negligible with respect to the other ones, the raw data is expected to be distributed according to a gaussian distribution whose sigma is the timing resolution of the B2B detector convoluted with a step function with 25 ns width. The raw data distribution is fitted with such function, and the sigma of the gaussian component is taken as the time resolution measurement. Figure 3.25 shows a comparison between the sigma obtained fitting the raw distribution of arrival times with a simple gaussian distribution and the one obtained from the gaussian part of the convolution, for the AllVFATs signal. The overall difference is of the order of 2 – 3 ns.

In figure 3.26 the resulting time resolution as function of the divider current, operating the detector with Ar:CO$_2$ 70:30 and Ar:CO$_2$:CF$_4$ 45:15:40 gas mixtures is shown. In both cases the time resolution improves with higher divider current, i.e. with increasing detector gain. In particular, for the Ar:CO$_2$
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Figure 3.24: Example of raw data of the arrival time of the signal obtained from S-Bits with respect to the trigger provided by the scintillators. The sigma of this distribution is affected by the detector time resolution, the signal sampling frequency of the VFATs and the time resolution of the scintillators’ trigger.

70:30 it reaches 6 ns measured at 705 $\mu$A per divider and 5 ns measured at 755.5 $\mu$A per divider with the Ar:CO$_2$:CF$_4$ 45:15:40 gas mixture. In figure 3.27 the results obtained for AllVFATs with the two different gas mixtures are directly compared. It is evident that a slightly better time resolution is achieved with the Ar:CO$_2$:CF$_4$ 45:15:40 gas mixture, for which it is necessary to apply higher field values (higher divider currents). The latter behaviour is coherent with the rate, gain and efficiency measurements, that have also shown that the efficiency plateau and a gain of the order of $10^4$ is reached at higher field values with this gas mixture with respect to the gas mixture without CF$_4$.

3.3.4 Detector efficiency without tracking

The same setup used for the timing measurements can be used also to perform a less-sofisticated measurement of the detector efficiency. Indeed, in order to calculate the ratio 3.3.2, one can take:

- the number of coincidences $T$ as the total number of coincidences in the three scintillators
- the number of triple coincidences $N$ as the total number of events collected in the histogram of arrival times. Note that events are inserted in the histogram only if there is a coincidence in the three scintillators
3.3. Test Beam studies on the B2B detector

Figure 3.25: Comparison between the sigma resulting from the best fit of the raw data with a gaussian distribution (blue) and sigma of the gaussian component (red) obtained fitting the raw data distribution with a gaussian distribution convoluted with a step function 25 ns width, as a function of the divider current. This example is obtained from the signal All VFATs, i.e. the logical AND of the two triple-GEM detectors of the Back to Back detector, operating the detector with a Ar:CO$_2$ 70:30 gas mixture (top) and Ar:CO$_2$:CF$_4$ 45:15:40 (bottom).
Figure 3.26: Time resolution for detectors operated with Ar:CO₂ 70:30 (top) and Ar:CO₂:CF₄ 45:15:40 (bottom) gas mixtures as a function of the divider current, for the x axis GEM (obtained from the signal VFATX, in blue), the y axis GEM (from signal VFATY, in green), and for their logical AND (from signal AllVFATs, in red).
3.3. Test Beam studies on the B2B detector

Figure 3.27: Comparison of the time resolution of the logical AND of the $x$ and $y$ axis GEM operated with Ar:CO$_2$ 70:30 (red) and Ar:CO$_2$:CF$_4$ 45:15:40 (blue) gas mixtures as a function of the divider current. The curves are the same shown in figure 3.26, obtained from the signal $AllVFATs$. 

Figure 3.27: Comparison of the time resolution of the logical AND of the $x$ and $y$ axis GEM operated with Ar:CO$_2$ 70:30 (red) and Ar:CO$_2$:CF$_4$ 45:15:40 (blue) gas mixtures as a function of the divider current. The curves are the same shown in figure 3.26, obtained from the signal $AllVFATs$. 

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and the signal produced from the S-Bits. For example, for the raw data shown in figure 3.24 it is \( N = 16661 \).

Figure 3.28 shows both the efficiency of the logical AND of the \( x \) and \( y \) axis GEM detectors calculated with tracking (as described in section 3.3.2) and without tracking as described above. In particular, the efficiency without tracking has been computed from the distribution of arrival times of the signal AllVFATs.

The trends of the efficiency curves measured in the two ways are in good agreement with each other. The efficiency values measured without tracking are systematically higher, namely by about 3.5% at the efficiency plateau. This behaviour is reasonable because the event selection with this algorithm is looser than in the algorithm with tracking, as it will be discussed in section 3.3.5.1.

3.3.5 Summary and discussion

The test beam allowed to investigate the detector performance in terms of efficiency and time resolution. All measurements have been performed with two different gas mixtures, Ar:CO\(_2\) 70:30 and Ar:CO\(_2\):CF\(_4\) 45:15:40, and for the \( x \) and \( y \) axis GEM separately as well as their logical AND. It has been measured that an efficiency of 96.5% or greater is achieved for a single triple-GEM detector at the efficiency plateau using a method that poses a constraint on the position of the measured hit, and an efficiency of about 94% for their logical AND according to the same method. Depending on gas mixture, the measured time resolution of one triple-GEM detector is up to 7 ns (Ar:CO\(_2\) 70:30) or 6 ns (Ar:CO\(_2\):CF\(_4\) 45:45:40).

3.3.5.1 Detector efficiency

The efficiency measured with tracking for a triple-GEM detector of the B2B detector with the Ar:CO\(_2\) (Ar:CO\(_2\):CF: 4) gas mixture is 96.5\%\(\pm\)0.1\% (96.6\%\(\pm\)0.2\%) for the \( x \) axis detector and 96.6\%\(\pm\)0.1\% (98.1\%\(\pm\)0.2\%) for the \( y \) axis detector. As they have been obtained with the VFAT2 ASICs at a fixed 25 ns window (latency) with respect to the trigger by the scintillators, they represent efficiency values within a time window of 25 ns. The efficiency measured with a “standard” GE1/1 detector with a similar experimental setup [60], shown in figure 2.8, is 96.9\% – 97\%. Similar values (about 98\%) have also been obtained for triple-GEM detectors with (10 \(\times\) 10) cm\(^2\) active area in [59] for
3.3. Test Beam studies on the B2B detector

Figure 3.28: Comparison of the efficiency of the logical AND of the two triple-GEM detectors measured using hits close to the reconstructed trajectory (squares and crosses) and using the same setup for timing measurements (circles and diamonds) that doesn’t use any information from tracking. The comparison is shown as a function of divider current, for detectors operated with Ar:CO$_2$ 70:30 (blue) and Ar:CO$_2$:CF$_4$ 45:15:40 (red) gas mixtures. The dashed curves show the best fits performed with the function $A/(1 + \exp \left( \frac{B-x}{C} \right))$, whose parameter $A$ is the efficiency reached at curve’s plateau. The parameters $A$ resulting from the best fits are shown in bottom-right box.
both gas mixtures. These measurements are compatible with each other and with the measurements described in this chapter within the variations that can be observed detector by detector. In addition, the efficiency measured with the B2B triple-GEM detectors could have been slightly underestimated, due to some dead zones visible in figure 3.19. The shape of such dead zones, consisting in perfectly parallel lines, suggest that they must be caused by damaged strips or damaged VFAT2 channels and are not due to an intrinsic inefficiency or issue of the detector itself. Triggered events detected by a triple-GEM under study in which the particle’s trajectory passes through these zones have been considered in the efficiency calculation as “not detected”, because the hit positions has been misreconstructed (and rejected by the tracking algorithm) or the hit has not been registered at all. The estimation of this contribution depends on the beam profile, that was not constant during the test beam campaign, but assuming that events are more concentrated in the beam core crossing the central part of the active area and considering the ratio of the “insensitive” to “sensitive” areas as visible in figure 3.19, its contribution should be as small as 1-2%. Even with such eventual small variation, the measurements remain in good agreement with the ones proposed for the comparison.

The efficiency measured without tracking has been performed only for the logical AND of the two GEM detectors composing the B2B detector. Figure 3.28 shows the comparison of such efficiency curve as a function of the divider current obtained with and without the tracking. The curves obtained with the two methods overlap very well at low efficiency values, but the ones measured without tracking (in the figure, with TDC) increase faster and reach the plateau at an efficiency about 3%-4% higher than the one obtained with the tracking method.

As anticipated before, this result is due to the fact that the method without tracking is looser than the other one. First of all, there’s no spatial constraint on the position of the hit reconstructed on the detector under study. In case a particle is not detected by a GEM of the B2B detector, any noise hit on the (10 × 10) cm$^2$ active area of the detector randomly happening in coincidence with a triggered event would be wrongly identified as a detected particle. Hence some events in which the particle is not actually detected may be counted as “detected”, increasing the total measured detector’s efficiency. A second process may also have happened, involving events in which more than one particle crosses the setup in the same 25 ns time window. With
the tracking algorithm, such events have been excluded selecting only the ones with a single cluster both on the $x$ and $y$ axis of the tracker detectors. The method without tracking, instead, simply counts if at least a hit was reconstructed by the B2B detector in a fixed 25 $ns$ window with respect to the scintillators’ trigger pulse, regardless the position and number of clusters on the tracker detectors and on the detector under study. In this case, there may have been events in which two particles cross the setup in the same 25 $ns$ time window and part of them is not completely reconstructed by the B2B detector. Such events are considered as a unique event, and the logic may wrongly consider them as “detected” or “not detected” by the device under study. Also this effect can contribute to increase the total measured efficiency. Anyway, its impact depends both on the particle rate and on the detector’s efficiency. In the case of triple-GEM detectors the detection efficiency is close to 100%, so we expect that the contribution of these processes can’t be very high. For example, supposing a detector efficiency of 98%, 7.7% of the events with two particles in the same 25 $ns$ window succesfully identified as “detected” by the AND logic include at least one track not fully reconstructed (i.e. not detected by any of the two detectors). The evaluation of the impact of this process on the measured efficiency depends on the rate of events with two tracks. To evaluate such rate we can refer to the measured trigger rate, as the trigger system provided by three plastic scintillators has a time resolution smaller than 70 $ps$ (see for example [56], where the measured time resolution of a similar trigger system composed of two plastic scintillators is $\sim 70$ $ps$) and consequently is able to measure a particle rate much higher than 40 $MHz$. The highest event rates measured by the trigger system during the test beam were of the order of $\sim 20$ $kHz/cm^2$ in the core region of the beam (with the finger scintillator included in the trigger logic). The product $2$ $kHz/cm^2 \times 100$ $cm^2 = 2$ $MHz$ is the resulting rate on the entire detector’s active area, that can be taken as the upper limit of the particle rate through the setup during the test beam. With such rate, the average time between two consecutive particles is $1/2$ $MHz = 500$ $ns$, 20 times higher than the time window of 25 $ns$. This value has been obtained from the hit rate upper limit, hence the average time between particles $\Delta t$ should have remained $\Delta t < 500$ $ns$ during the test beam. It is clear that the probability of having two particles crossing the setup in the same 25 $ns$ window should be low enough to have a small impact on the measured efficiency. To be more precise, we can sup-
pose that the number of crossing particles in a fixed time window follows a Poisson distribution: when the average number of particles crossing the setup within 25 ns is $\lambda = 2 \, MHz \times 25 \, ns = 5 \cdot 10^{-2}$, the probability of having a second particle in a 25 ns time interval in which there’s at least one particle is $p = \frac{\lambda^2 \exp(-\lambda)}{2(1-\exp(-\lambda))} = 2.4 \cdot 10^{-2}$.

To estimate the impact on the efficiency measurement, let’s consider that the efficiency measurement $\varepsilon$ is calculated as the ratio $\varepsilon = N/T$ (equation 3.3.2), where $T$ is the number of triggered events and $N$ the number of such events in which there’s at least one cluster detected on both the GEM detectors of the B2B detector (i.e. their logical AND). To take into account both particles in the events with two crossing particles, the efficiency should instead be the ratio

$$\varepsilon' = \frac{N'}{T'}$$

where $N'$ and $T' > T$ include the information of both the particle tracks is such events. In particular, the number of triggered events should be increased by the number of events with two tracks, hence $T' = T + pT$. To correct the numerator $N$, let’s notice that the latter has been increased by the wrong amount only in the following two cases:

1. both tracks produce a reconstructed hit in each triple-GEM detectors.
   
   In this case the logic has incremented $N$ only by one, while it should have been incremented by two

2. one track produces a reconstructed hit only in the $x$-axis GEM, the other track produces a reconstructed hit only in the $y$-axis GEM (or vice versa).
   
   In this case the logic has incremented $N$ by one, but it should not have been incremented.

In all other cases the logic has incremented $N$ by the correct amount. If the intrinsic efficiency of each triple-GEM detector is $\varepsilon_0 = 98\%$, case 1 happens on average in $c_1 = \varepsilon_0^2 = 92.24\%$ of the events with two tracks. Case 2 happens on average in $c_2 = 2\varepsilon_0^2(1 - \varepsilon_0)^2 = 0.08\%$ of the events with two tracks. Hence, the numerator should be corrected with $N' = N + pTc_1 - pTc_2$. Finally, the corrected efficiency measurement becomes

$$\varepsilon' = \frac{N'}{T'} = \frac{N + pTc_1 - pTc_2}{T + pT} = \varepsilon \frac{1}{1 + p} + \frac{p(c_1 - c_2)}{1 + p}.$$  (3.10)

From the above equation it is clear that the entity of the correction depends
on the particle rate (through the parameter \( p \)) and on the detector’s intrinsic efficiency \( \varepsilon_0 \) (through the parameters \( c_1 \) and \( c_2 \)). Supposing \( \varepsilon_0 = 98\% \) for the GEM detectors composing the B2B detector and a particle rate of 2 MHz, the measurements \( \varepsilon = 97.5\% \) (Ar:CO\(_2\):CF\(_4\)) and \( \varepsilon = 98.0\% \) (Ar:CO\(_2\)) after the correction become \( \varepsilon' = 97.4\% \) and \( \varepsilon' = 97.9\% \) respectively. It turns out that with a detector efficiency close to 100\% as for GEM detectors and a particle rate of 2 MHz, this effect is responsible for increasing the measured rate by only 0.1\%.

We can conclude that the second process mentioned above can’t cause the difference of about 3%-4% observed between the efficiency measurement with and without tracking. The main contribute must instead be given by the first process, the presence of noise hits that can’t be rejected in the method without tracking.

### 3.3.5.2 Timing performance

The time resolution mainly depends on the drift velocity, which depends on the gas mixture and the electric field. In particular, the theory predicts an intrinsic time resolution

\[
\sigma_t = \frac{1}{nv_d}
\]

where \( n \) is the average number of primary clusters per unit length generated by an ionising particle inside the gas. The number of clusters per unit length of the two considered gas mixtures are 3.3 \( mm^{-1} \) (Ar:CO\(_2\) 70:30) and 5.5 \( mm^{-1} \) (Ar:CO\(_2\):CF\(_4\) 45:15:40) \[58\]. The drift velocities for the used and other common gas mixtures as a function of the electric field are shown in figure 3.29. As the gas mixture with CF\(_4\) shows both a higher drift velocity and average number of primary clusters, equation 3.11 predicts a better time resolution for detectors operated with the Ar:CO\(_2\):CF\(_4\) gas mixture with respect to the Ar:CO\(_2\). The time resolution measured with the B2B detector are consistent with this prediction.

For the above reasons, to compare the time response of the B2B detector with existing results, it is the case to refer it to the electric field in the drift region. For example, with the Ar:CO\(_2\):CF\(_4\) gas mixture a time resolution of 6 ns for a single triple-GEM detector was reached at 2.9 kV/cm (775 \( \mu \)A of divider current, and electric fields of 3.4/3.4/4.8 kV/cm in the transfer1/transfer2/induction gaps). A similar measurement on a “standard”
triple-GEM detector with the same active area of the B2B detector, the same gap spacing and the same gas mixture was performed during the R&D for the GE1/1 chamber (shown in Chapter 2) and it’s reported in figure 3.30 as a function of the drift field. The measurements performed with the B2B detector have been added to the plot (red circles) for comparison. Similar measurements, performed on a detector with the same active area and gap spacings, are available in [57] in the framework of an R&D activity performed for the LHCb experiment and are shown in figure 3.31. In figure 3.32, instead, time resolution measurements performed on a full-size GE1/1 prototype are shown. All these timing measurements, performed with the same gas mixture (Ar:CO$_2$:CF$_4$), have also been added to figure 3.30 to facilitate their comparison (blue empty circle for the LHCb measurements, purple circles for the GE1/1 measurements).

The collected measurements span a quite large range: the best values of each campaign span from 4 ns to about 7 ns, with the value measured with the B2B detector lying inside this interval. The most evident factor influencing
3.3. Test Beam studies on the B2B detector

Figure 3.30: Timing resolution of a $10 \times 10 \, cm^2$ triple-GEM detector equipped with GEM foils produced with the double mask technique, as a function of the electric field $E_{\text{drift}}$. The other electric fields were fixed at $3/3/3 \, kV/cm$ (transfer 1/transfer 2/induction gap). The two curves show the time resolution for a detector with $3/2/2/2 \, mm$ ($3/1/2/1 \, mm$) gaps spacings from the drift electrode to the readout using a Ar:CO$_2$ 70:30 (Ar:CO$_2$:CF$_4$ 45:15:40) gas mixture [23] [59]. Measurement obtained with the Ar:CO$_2$:CF$_4$ 45:15:40 with the B2B detector (red circles), with a full-size GE1/1 prototype (purple circles) [60] and by the LHCb Collaboration (blue empty circle) [57] have been added for comparison.

Two sets of measurements shown in figure 3.30 also show a different slope. A possible reason to explain such differences is that measurements in [57, 60] (green and blue markers) have been performed varying only the drift electric field and keeping all the other voltage values constant, after having optimized them. For the B2B detector instead (red markers), the voltage is distributed through a voltage divider, implying that all electric fields are

\[ E_d = 3.5 \, kV/cm, \]

while the other measurements did not reach such value$^2$.

\[ E_d = 3.5 \, kV/cm, \]

$^2$The timing measurements with the B2B detector have been performed at values of the drift electric field corresponding to the detector's efficiency plateau.
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Figure 3.31: Best time distributions obtained for \((10 \times 10) \, \text{cm}^2\) triple-GEM detectors operated with two different gas mixtures. The rms of the distribution and the drift \((E_d)\), transfer \((E_t)\), induction \((E_i)\) electric fields are reported on the plots. The sum of the voltage applied to the GEM foils is 1325 V for Ar:CO\(_2\):CF\(_4\) and 1230 V for the Ar:CO\(_2\) gas mixtures [57].

Figure 3.32: Time resolution as a function of the electric field in the drift gap for a full-size GE1/1 prototype operated with Ar:CO\(_2\) 70:30 (green) and Ar:CO\(_2\):CF\(_4\) 45:15:40 (purple) gas mixtures [60].

changing together with the drift electric field. For the set of measurements in [60] this is not specified. In addition, different readout electronics have been used, whose characteristics typically influence the timing performance. The response of the front-end electronics to the induced signals should also be taken into account in order to fully understand the timing performance of a detector. In particular, measurements performed on CMS prototypes (in [59, 60] and in this chapter) used VFAT2 chips optimized for CMS needs, that requires a time
3.3. Test Beam studies on the B2B detector

resolution of a single chamber of 10 ns or better. Finally, also the data analysis may have an influence on the timing measurements. For example, with the VFAT2 chips it is necessary to remove the effect of the 40 MHz sampling from the time distribution of the raw data, as performed in section 3.3.3 for the analysis of the data acquired with the B2B detector. This analysis is based on the hypothesis that the “real” arrival times, without the smearing introduced by the sampling, are distributed according to a gaussian distribution, whose sigma is taken as the time resolution of the detector. Other studies, for example [57, 61] have shown that the arrival time distribution has a clear asymmetry with a tail toward large times, as visible in figures 3.31 and 3.33. Depending on the voltage applied to the GEM foils, entries at early times may also appear (usually 1-2% of the total events), known as the bi-GEM effect, i.e. the amplification of ionization electrons produced in the first transfer gap, out of time with respect to electrons produced in the drift gap by \( g_t/v_d \) (where \( g_t \) is the transfer gap size and \( v_d \) is the drift velocity) [61]. An example of a time distribution with the bi-GEM effect is shown in figure 3.33. This effect can be controlled by adjusting the voltage applied to the GEM foils.

\[
\text{Figure 3.33: Time distributions of signals obtained with a Ar:CO}_2\ 70:30 \text{ gas mixture, showing a bi-GEM effect at early times. The rms of the distribution is 9.7 ns [61].}
\]

The analysis method applied to remove the effect of the sampling introduced by the VFAT2 chips doesn’t allow to see the distribution of the “real” arrival times and to see if the result of the gaussian fit matches such distribu-
tion, apart from verifying the value of the resulting chi square and the general agreement with the entire set of measurements. In addition, as the arrival times distribution has a tail at large times, it would be probably ideal to reduce the range of the gaussian fit in order to exclude such tail, like it’s done for example in [62]. Anyway there’s not an effective way to determine the range for the best fit in the case in which only the distribution smeared by the 50 MHz sampling is visible.

In addition, if within the CMS R&D the time resolution is represented by the sigma of the gaussian distribution, the time resolution in the considered studies [57, 61] within the LHCb Collaboration use the root mean square (rms) of the time distribution as the detector’s time resolution. A comparison between the two methods is performed in [62] showing that, if applied to the same data, they lead to a difference in the measured time resolution of more than 1 ns. In this study the gaussian fit is performed on a range that excludes the tail at late times.

To conclude, the above considerations suggest that a direct comparison between different measurements present in literature is not trivial, as many factors not totally under control influence the result. Anyway the measured time resolution with the Ar:CO$_2$:CF$_4$ 45:15:40 is in good agreement with a similar measurement performend on a full-scale GE1/1 detector [60] with a drift electric field of 3 kV/cm. It is approximately 2 ns worse than the lowest values reported in literature with the same gas mixture, but this can be explained by the different drift electric field and by the above discussion. Similar considerations apply also to the results obtained with the Ar:CO$_2$ 70:30 gas mixture.

### 3.4 The Fast Timing Micropattern detector

In the initial phases of its life, CMS took part in the development of the Fast Timing Micropattern (FTM) detector, a MPGD detector whose novel idea consists in polarising WELL structures using only resistive coating. This feature allows to use an architecture based on a stack of several layers, each one having its own drift and amplification stages, but read out from the same external readout board through the capacitive couplings. The main advantage arising from this architecture is the dramatic improvement of the timing performance, provided by the competition of the ionisation processes in the different drift
Figure 3.34: Time distribution (top) of signals and time resolution (bottom) as a function of the voltage applied to the GEM foils obtained with a triple-GEM detector operated with a Ar:CO$_2$:CF$_4$ 45:15:40 gas mixture. In the top plot, the best fit with a gaussian distribution is performed on a time range excluding the right tail of the distribution. The time resolution values in the bottom plot are obtained from the same time distributions, using the sigma of the gaussian fit as shown in the top plot (Sigma) and the rms of the time distribution (Std) [62].

regions, as shown in figure 3.35. Indeed, for a single MPGD layer with a clear division of the conversion/drift gap and the amplification region, the timing resolution is dominated by fluctuations of the nearest distance $d_{near}$ of the primary ionisation processes to the region where the electron amplification takes place. The drift velocity of the gas $v_d$ determines the arrival time, hence the contribution of $d_{near}$ to the timing resolution shows $\sigma_t = 1/nv_d$, where $n$ is the average number of primary clusters per unit length generated by an ionising particle inside the gas. For the structure of the FTM detector, instead, the
timing performance is dominated by the fluctuation of the nearest primary ionization among all the layers and depends on the total number of layers $N_D$:

$$\sigma_t = \frac{1}{n v_d N_D}.$$  \hfill (3.12)

Figure 3.35: Schematic drawing of the principle determining the time resolution of the FTM detector [44].

I took part in the R&D activity on the FTM detector performed at CERN with the participation of CMS Collaboration. When I started my PhD, the very first FTM prototype had just been studied in laboratory and was about to be tested in a two-week test beam at CERN, so I joined the activity around the analysis and discussion of the test beam data.

A schematic representation of the first prototype of FTM detector, with an active area of approximately $20 \text{ cm}^2$ and composed of two independent layers, is shown in figure 3.36. Each amplification region is made out of two kapton foils:

- a 50 $\mu$m thick foil perforated with inverted truncated-cone-shaped holes with bases of 100 $\mu$m and 70 $\mu$m and pitch of 140 $\mu$m. The foil is coated with DLC technique in order to reach a specific resistance of about 800 $M\Omega/\square$ (200 $M\Omega/\square$ measured)
- a 25 $\mu$m thick foil with a resistivity of 2 $M\Omega/\square$.

The two foils are stacked together simply due to the electrostatic force induced when they are polarized. A conversion region 250 $\mu$m thick is ensured by coverlay pillars with 400 $\mu$m diameter and 3.3 mm pitch.

The two layers can be powered independently, and the signal can be read out either from the readout electrode or from the drift electrode through a capacitive coupling.
3.5 Characterization of the FTMv1 in laboratory

A picture of the first detector prototype is shown in figure 3.37.

Figure 3.36: Transverse view of the first CMS prototype of the FTM detector. Its active area is approximately 20 cm² and it’s composed of two independent layers of drift-amplification stages. The amplification stage of each layer is made, from bottom to top, of a 25 μm-thick polyimide foil with a resistivity of $2 \, M\Omega/\square$ and a 50 μm-thick polyimide foil coated with diamond-like carbon (DLC) technique in order to have $\approx 800 \, M\Omega/\square$ surface resistance foil perforated with inverted truncated-cone-shaped holes (top base and bottom base 100 μm and 70 μm respectively). The drift gaps of each layer are 250 μm thick. The signal could be picked up both from the readout and the drift electrode [45].

3.5 Characterization of the FTMv1 in laboratory

The FTM detector prototype was first tested in laboratory under X-ray irradiation [63]. The source is an X-ray tube using a Ag cathode filament and a Be end window. The emitted spectrum shows a continuum component in the 3 – 50 keV energy range with some peaks at about 22 keV and 25 keV. The emission can be regulated adjusting the tube’s applied voltage and current. First of all, the production of a signal has been verified. Figure 3.38 shows the signal read out both from the readout and drift electrodes under X-ray irradi-
3. Development and Performance of New Micropattern Gas Detectors

Figure 3.37: Picture of the first prototype of FTM detector. This picture was taken during its disassembly, after the PCB used as support and hosting the HV connections was removed.

The electronic chain was composed of an ORTEC 142PC preamplifier and an ORTEC 474 amplifier.

Figure 3.38: Signals produced by the FTM detector collected from the readout (blue) and the drift electrode (orange, inverted) measured with an oscilloscope. Each point is the average of 10 acquisitions of the scope.
3.5. Characterization of the FTMv1 in laboratory

3.5.1 Linearity and transparency

The linearity of the detector has been measured irradiating it with X-rays varying the X-ray gun current, as the emitted flux is proportional to its current. The readout chain is the same used for the acquisition of the signals, followed by a discriminator and a scaler. Figure 3.39 and 3.40 show the measured hit rate with both layers powered and only one layer powered respectively. The trend of the measured hit rate as a function of the tube current is clearly linear. In addition, signals are detected both from the readout and the drift electrodes also when only one layer is powered: this indicates that the detector is transparent and signals can be measured also when produced in the layer farther from the electrode where they are read out. In addition, the hit rates in figure 3.39 are very well superimposed, while the overlapping is not perfect in figure 3.40. The perfect overlapping of the curves, meaning that the same hit rate has been measured from both electrodes, would be an indicator of the complete transparency to signals. Anyway, it also depends on the thresholds used to discriminate signals, and it is not possible to eliminate this contribute from the hit rate measurement. Finally, the hit rate measured when only layer2 is powered (figure 3.40 right) is in general smaller than the hit rate measured with only layer1 powered (figure 3.40 left), probably indicating a problem on layer2. This hypothesis will be confirmed also by the test beam measurements.

3.5.2 Scan in electric field

The hit rate was measured as a function of both the drift field and the amplification field, keeping the other one at a fixed value. The experimental setup is the same described for the previous measurements, using the same X-ray tube as source and the same readout chain.

Drift field. The scan in drift field is shown in figure 3.41. It has been performed powering only layer1 and applying to the amplification field a constant electric field of $110 \, kV/cm$. The hit rate shows a maximum in the $(2 - 4) \, kV/cm$ and decreases both for higher and smaller electric field. This behaviour is similar to the one observed with $\mu$-RWELL detectors [43]. The reason for the decrease at high electric field is that if latter is too high, a big amount of electric field lines in the drift region end on the upper surface of the amplification layer causing the electrons from primary ionization to collide on
Figure 3.39: Measured hit rate from the readout (blue) and the drift (red) electrodes as a function of the current applied to the X-ray tube. The measurements are performed with both layers powered, with electric fields applied to the drift and amplification regions of $2 \text{kV/cm}$ and $110 \text{kV/cm}$ respectively. The detector was operated with Ar:CO$_2$ 80:20 gas mixture.

Figure 3.40: Measured hit rate from the readout (blue) and the drift (red) electrodes as a function of the current applied to the X-ray tube. The measurements are performed with only layer1 powered (left) and only layer2 powered (right). The electric fields applied to the drift and amplification regions of the powered layer are $2 \text{kV/cm}$ and $110 \text{kV/cm}$ respectively. The detector was operated with Ar:CO$_2$ 80:20 gas mixture.

that surface, instead of being collected inside the holes and multiplied. Hence, the measured hit rate decrease if the drift electric field becomes more intense.
3.5. Characterization of the FTMv1 in laboratory

On the left part of the plot, instead, it is expected that measured hit rate decreases together with the applied field, reaching a zero hit rate for a zero drift electric field. A non-zero hit rate instead is measured in this condition, while it is necessary to apply a negative drift field in order to measure a zero hit rate. In this case, a COMSOL simulation [63] has showed that the reason is that even if there’s no field applied, some electric field lines exit from the amplification holes and reach the top of the drift region. Hence, in the drift region a small electric field is present allowing to collect some primary ionization in the amplification region. It is necessary to invert the applied field in order to suppress the collection of primary charge.

![Graph showing hit rate vs. drift field](image)

Figure 3.41: Measured hit rate from the readout (blue) and the drift (red) electrodes as a function of the drift electric field. The source was an Ag X-ray tube. The measurements are performed with only layer1 powered and an amplification field of 110 kV/cm. The detector was operated with Ar:CO₂ 80:20 gas mixture.

**Amplification field** As the charge amplification increases with the applied voltage, the measured hit rate is clearly expected to increase for increasing amplification voltage (or, equivalently, amplification field). For the spectrum of deposited energy produced with an Ag X-ray gun, the measured hit rate typically stops increasing above a certain amplification field and reaches a plateau, meaning that above that field value the detector is working at full efficiency. The same is expected for the FTM detector. The hit rate measured
powering only layer1 and with a constant drift field of 2 V/cm is shown in figure 3.42. The measured hit rate increases as expected, but unfortunately it was not possible to reach the plateau because at about 120 kV/cm the detector became unstable. This is may happen because at that value the breakdown voltage is reached. Anyway, if we compare the maximum voltage applied with the expected breakdown voltage, it is interesting to observe that the maximum voltage applied is bigger than the latter. We suppose that the reason could be that usually breakdown voltages are calculated for conductive electrodes, while the use of resistive material could allow to overcome this limit and push the voltage farther before reaching the breakdown.

Figure 3.42: Measured hit rate from the readout (blue) and the drift (red) electrodes as a function of the amplification electric field. The source was an Ag X-ray tube. The measurements are performed with only layer1 powered and a drift field of 2 kV/cm. The detector was operated with Ar:CO\textsubscript{2} 80:20 gas mixture.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{hit_rate.png}
\caption{Measured hit rate from the readout (blue) and the drift (red) electrodes as a function of the amplification electric field. The source was an Ag X-ray tube. The measurements are performed with only layer1 powered and a drift field of 2 kV/cm. The detector was operated with Ar:CO\textsubscript{2} 80:20 gas mixture.}
\end{figure}

\section*{3.5.3 Detector’s Gain}

**GEM-like measurement.** The detector’s gain measurement has been performed taking example from other two types of MPGDs, the $\mu$-RWELL detector and the GEM detector. For these two detectors the gain is typically measured in two different ways. The gain measurement for GEM detectors is

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{gain.png}
\caption{Gain measurement for GEM detectors.}
\end{figure}
explained in section 3.2.1. We recall here the formula:

\[ G = \frac{I_{\text{net}}}{N_peR_p}. \]  

(3.13)

The application of this method is not simple in this case, as it was not possible to reach the plateau during the rate measurement scanning the amplification field. Hence, we can only use the maximum measured rate, that underestimates the rate at plateau. In addition, the calculation of the number of primary electrons \( N_p \) is performed supposing that the energy of incident photons is entirely absorbed inside the drift volume, which is not ensured for a 250 \( \mu m \) thick drift gap.

**\( \mu \)-R WELL-like measurement.** In the method applied for \( \mu \)-R WELL detectors, the gain measurement is obtained from two current measurements, with and without amplification field applied, maintaining the detector under X-ray irradiation and the same drift field applied. The measured current is \( I = GRN_pe \) in both cases, where \( G \) is the detector’s gain, \( R \) the measured hit rate at full efficiency, \( N_p \) the average number of primary electrons produced per photon and \( e \) is the elementary charge. When the amplification field is zero it is \( G = 1 \) (no amplification) hence the ratio of the two measured currents gives exactly the detector’s gain:

\[ G = \frac{I_{\text{HVon}}}{I_{\text{HVoff}}} = \frac{GR_pN_pe}{R_pN_pe}. \]  

(3.14)

The big advantage of this method is that it is not necessary to estimate the average number of primary electrons \( N_p \), neither to measure the hit rate \( R_p \) at full efficiency, which in the particular case of this FTM prototype could not be measured.

Current measurements are performed on the bottom side of the amplification region, the closest point to the production and collection of the multiplied charge in the detector. They range from about 100 \( pA \) to 800 \( pA \) for an applied amplification field in the \((75 – 110) kV/cm\) range. The resulting gain, obtained with the two different methods, as a function of the amplification field is shown in figure 3.43 (GEM-like measurement) and 3.44 (\( \mu \)-R WELL-like measurement).

The main difference between the two measurements is that the \( \mu \)-R WELL-
Figure 3.43: Gain of layer1 (blue) and layer2 (red) calculated using formula 3.13 as a function of the amplification field. The source was an Ag X-ray tube. A constant drift field of 2 $kV/cm$ is applied. The detector was operated with Ar:CO$_2$ 80:20 gas mixture.

Figure 3.44: Gain of layer1 (blue) and layer2 (red) calculated using formula 3.14 as a function of the amplification field. The source was an Ag X-ray tube. A constant drift field of 2 $kV/cm$ is applied. The detector was operated with Ar:CO$_2$ 80:20 gas mixture.
like measurement results in a big disparity between the gain of the two layers, with layer1 reaching a gain of the order of $10^4$ and layer2 only up to about 10. A difference between the two layers will be confirmed also by other measurements, shown in the next sections. With the GEM-like measurement, instead, both layers reach a gain up to about $10^3$, with layer1 increasing slower than layer2. Measurements confirm that an amplification is taking place, with a dependence on the amplification field applied, even if the correctness of the exact values and the procedures applied are still not completely clear and under discussion.

3.5.4 Detector’s Efficiency

The efficiency has been evaluated in laboratory using cosmic rays. The setup is the same used for the test beam described in section 3.3.1, rotated by 90°. As the active area of the FTM detector is much smaller than the scintillators used to trigger cosmic rays, an additional finger scintillator with $(2 \times 3) \, cm^2$ active area was added to the setup. The efficiency is calculated as

$$\varepsilon = \frac{N}{T}$$

(3.15)

where $T$ is the number of events detected in coincidence in the scintillators, and $N$ the number that is detected also by the FTM detector. The readout chain is the same used for the rate measurement, composed by a preamplifier and an amplifier, whose signal is then discriminated and processed appropriately by a logic unit. The resulting efficiency, as a function of the drift field, is shown in figure 3.45. In this case both layers were powered, in order to measure the overall efficiency of the detector, and the signal was read out from the readout electrode.

The efficiency appears very low, not greater than about 16%. A low efficiency was expected, as the width of the drift region is only 250 $\mu m$. We can try to estimate the expected efficiency as follows: a Garfield simulation [63] has determined that the average number of primary ionization clusters of a $3 \, GeV$ muon in a Ar:CO$_2$ gas mixture is about $33 \, cm^{-1}$, hence $\lambda \approx 303 \, \mu m$. Consequently the maximum achievable efficiency to such muons, i.e. the probability of having at least one ionization within 500 $\mu m$ (the total drift length of the two layers), is $\varepsilon \lesssim 1 - \exp \frac{-500 \, \mu m}{303 \, \mu m} = 81\%$. Similarly, the maximum efficiency of a single layer shall be $\varepsilon \lesssim 56\%$. The measured efficiency is much smaller than the reference value for the overall detector. If we suppose that layer2,
Figure 3.45: Measured efficiency of the FTM detector as a function of the drift field using cosmic rays. Both layers were powered with the same fields applied, the amplification fields was fixed at 120 kV/cm. The signal is read out from the readout electrode. The detector was operated with Ar:CO$_2$ 80:20 gas mixture.

that has shown to perform worse than layer1 in the previous measurements, is not working properly, the measured efficiency remains much lower the above limit of 56%.

This observation is anyway compatible with the fact that we could not reach the rate plateau in the rate measurement in figure 3.42, indicating that even in the best operational conditions we can apply (optimized drift field and high amplification field) the full efficiency is not reached.

This observation raises an important point. The electronics used to read out signals produced by the FTM detector is the same that we typically use for triple-GEM detectors. On the other hand, the amplification stage of the FTM is provided by a single layer, providing an amplification somehow comparable to the one provided by a single GEM foil of a triple-GEM detector. Hence the total gain of the FTM detector is reasonably expected to be smaller than the gain of a triple GEM detector. The electronics used the read out the signal may be optimized for detectors producing a bigger charge on the readout and not for a detector with a single-stage amplification and a smaller gain like the FTM detector. Hence this is a first hint that the development of the FTM
detector must require the development of a suitable readout electronics.

The efficiency measurement has been repeated also processing the signal with a second readout chain, used during the test beam for the timing measurement described in section 3.6.1. The latter is a non-shaping electronics with a worse S/N ratio, but it is a faster (linear) electronics, necessary in order to reach a good time resolution. On the other hand, the worse S/N also results in a measured efficiency even smaller than the one shown in figure 3.45, which was instead obtained with a slowlier electronics performing signal shapting with a good S/N ratio. As the time response of the FTM detector is its most attractive feature, it is of outmost interest to develop an electronics both with a gain high enough to process the charge produced by the FTM detector and also able to maintain its fast response. The R&D on the FTM detector has continued outside CMS activities after the latter has stopped participating in its development. In particular, on this topic the R&D has recently lead to the development of a chip with the goal to satisfy such requirements, the FAst Timing Integrated Circuit (FATIC) chip [64].

3.6 Test beam studies on the FTMv1 detector

At the end of 2015 the first FTM prototype has been studied in a test beam carried out at the SPS H4 beam line at CERN North Area with muon and pion beam. Again, the setup is the same described in section 3.3.1, equipped also with the (2 × 3) cm² finger-PMT for triggering mounted just behind the active area of the FTM detector. The test beam allowed to give an estimate of the achievable time resolution.

3.6.1 Timing performance

We shall recall that the time resolution of the FTM detector is expected to be dependent on the total number of layers. The device under study has two layers, hence the measure has to be referred to a detector with this number of layers, while a better performance shall be achievable with a prototype with more layers in the future. In particular, according to formula 3.12 the expected time resolution for this 2-layers prototype operated with an Ar:CO₂ gas mixture (n ≈ 33 cm⁻¹ and v_d ≈ 7 cm/μs) is about 2 ns.

The time resolution of the trigger system has been measured prior to the
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test beam campaign in order to evaluate its contribution to the timing measurement, and it has turned out to be of the order of 100 $\text{ps}$. This contribution has not been subtracted from the presented data. In addition, note that the acquisition system used a time-to-digital converter working in COMMON-STOP mode, hence the $x$ axis of the time arrival distributions is inverted, where not differently specified.

As anticipated in section 3.5.4, the electronics chain used to read out the signal of the FTM detector is different than the one used in laboratory, as a faster one was necessary to perform timing measurements. In this case the electronic chain was composed of a Cividec broadband amplifier [65] and a linear Lecroy 612AM amplifier [66], then discriminated and fed to the appropriate logic units and to the TDC, together with trigger signal. Neglecting the contribution of the trigger system, the time resolution is taken as the sigma of the gaussian fit of the arrival time distribution.

Some examples of arrival time distribution observed with muon and pion beams are shown in figure 3.46. They are acquired with the whole detector powered, so that the measured time resolution includes the effect of the $N_d = 2$ number of layers, and in the best possible working condition achievable, i.e. amplification fields of 120 $\text{kV/cm}$ and drift fields of 7 $\text{kV/cm}$ (muon beam) and 8 $\text{kV/cm}$ (pion beam). The resulting time resolution is 2.4 $\text{ns}$ with muon beam and 1.7 $\text{ns}$ with pion beam (operating the detector with a Ar:CO$_2$ 70:30 gas mixture), very close to expected value of 2 $\text{ns}$. Note that the number of events in the arrival time distributions is low because the detector has low efficiency, as previously explained.

A different data analysis was also carried out with the goal to perform some noise rejection on the data and obtain a cleaner distribution. To produce the distributions in figure 3.46 signals detected on the drift electrode (in coincidence with the trigger signal produced by the scintillators) have been used. However signals are expected to be measured both on the readout and drift electrodes. Hence in the second analysis events detected in coincidence on both electrodes have been selected. This procedure should not reject any muon event with respect to the previous one, but should add some noise rejection. In this case, for each event the average of the arrival time of the two signals detected on the two electrodes has been inserted in the distribution. Figure 3.47 shows the distribution of the arrival time of signals measured for the pion beam. The resulting time resolution is 1.6 $\text{ns}$, compatible with the
3.6. Test beam studies on the FTMv1 detector

Figure 3.46: Distribution of the arrival time of the signals read out on the drift cathode of the FTM detector measured with muon (left) and pion (right) beam. Both detector’s layers were powered. The detector was operated with a Ar:CO\textsubscript{2} 70:30 gas mixture.

previous result.

Figure 3.47: Distribution of the average of the arrival time of signals measured in coincidence on the readout and drift cathode of the FTM detector, measured with pion beam. Both detector’s layers were powered. The detector was operated with a Ar:CO\textsubscript{2} 70:30 gas mixture.

The time response has been evaluated also as a function of the drift field applied, shown in figure 3.48. The operating conditions are the same explained for previous measurements. According to formula 3.12, a variation of the drift field causes a change in the time resolution due to the dependence on the drift
velocity $v_d$. In the considered range of electric field, the latter varies between about $(6.5 - 7.5) \mu s$ [67], i.e. by about 14%. Hence the time resolution is expected to improve by about 0.3 ns in the drift field range of $(2 - 7) \text{kV/cm}$. A small variation of the order of this value is visible, even if the trend is not perfectly clear. Anyway, we might operate the detector in a condition at the limit of the validity of formula 3.12, as the total drift length is small, and only ionization events close to amplification region can contribute to the production of signals, possibly biasing the measurement. In addition, the uncertainty on measurements is very close to the variation to be observed, due to the low statistics available, caused by the detector’s low efficiency.

Figure 3.48: Time resolution of the FTM detector as a function of the applied drift field. Signals are read out on the drift electrode, with muon (red) and pion (blue) beam. Both detector’s layers were powered. The detector was operated with a Ar:CO$_2$ 70:30 gas mixture.

Finally, we have compared the response of the two layers. A set of measurements was performed powering either only layer1 or layer2, or both of them. Results are shown in figure 3.49. One evident effect is that layer2 shows a different behaviour once more: in the case of pion beam, the error on the measurement is much larger than the errors on the other measurements because the statistics of events was particularly low, confirming that layer2 has lower efficiency than layer1 and may not be working properly; in the case of muon beam, this effect was so large that it was not possible to perform the measurement, hence it is missing from the plot. Apart from statistics-related
problems, the two measurements performed with pion beams are compatible with each other. The relevant observation is that there is no big difference between the measurements with one single layer or both layers powered. This could be due to the fact the layer2 is working at low efficiency, hence its signals do not really contribute in the competition between the two layers to get the fastest signal, and the time resolution is mainly determined by layer1. In this case, the reason for the time resolution being as good as about 2 ns, may lie again in the fact the shortness of the drift length is performing a cut only on the fastest signals.

3.6.2 Summary and discussion

The first FTM prototype was tested under X-ray irradiation and a test beam with muon and pion beam. Clear indications of its operation were provided by the X-ray irradiation, as the measured rate is clearly linearly dependent on the incident flux, and the agreement of rate values measured on the two cathodes supports it electrical transparency. Also the behaviour of the measured rate as a function of the electric fields applied is well understood and compatible with the expectations. Gain and current measurements clearly show that there is amplification inside the well structures, even if we don’t have established yet the most appropriate procedure to measure the exact gain value.

Unfortunately, this prototype can’t operate at high efficiency, both intrinsically due to the length of the drift region (setting a upper limit of $\varepsilon \lesssim 81\%$) and due to the operational conditions that don’t allow to reach the efficiency plateau before overcoming the breakdown voltage. The maximum achievable efficiency, depending on the operational conditions, is of the order of 20%. Timing measurements have shown a time resolution of the order of $1.5 – 2.5 \text{ ns}$ when the detector is operated with Ar:CO$_2$ 70:30 gas mixture [45], but the construction of a new, more efficient prototype and with more layers would help to better interpret these results.

3.7 Next FTM detector prototypes

3.7.1 Preliminary considerations

In 2016 the R&D campaign around the FTM detector continued, still with the involvement of the CMS Collaboration. The next step was to build a second
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Figure 3.49: Comparison of the time resolution of the FTM detector measured with only layer1 (left), only layer2 (center) or both layers (right) powered, measured with pion (top) and muon (bottom) beam. Signals are read out on the drift electrode. Fields applied to the powered layer(s) are 8 $kV/cm$ (drift field) and 120 $kV/cm$ (amplification field). The detector was operated with a Ar:CO$_2$ 70:30 gas mixture.

improved prototype. There were several features we could focus on with the next versions:
3.7. Next FTM detector prototypes

- efficiency
- gain
- number of layers
- active area

The active area is, probably, the least interesting topic at this point of the R&D, during which we were still investigating the technology itself. Instead, increasing the number of layers is fundamental in order to study the dependence of the time resolution from the number of layers, a feature of outmost interest. The presence of several layers also helps the goal to increase the detector’s efficiency, as the latter depends on the total drift length. In order to approach 100% efficiency, a total ionization gap thickness of about \((3 - 4) \text{ mm}\) is necessary. The efficiency is improved also by increasing the drift distance of a single detector layer. Nevertheless, increasing the drift distance of a single layer without increasing the number of layers would also lead to worse time resolution, introducing also the contribution of primary ionization electrons produced further away from the amplification region. Hence, the preferable solution is to increase the number of layers.

As a consequence, the design of the FTM version 2 (FTMv2) was based on a modular structure, on top of which new layers can be inserted. It could host up to 12 layers with independent high voltage connections.

Increasing the gain is a more delicate task. Obviously, the detector’s gain is increased with more intense amplification fields, but this operation is limited by the breakdown voltage, as already seen in the first prototype. An alternative is to increase the depth of the WELLs where the amplification takes place. Considering the availability of kapton from the manufacturer, the choice has fallen upon kapton foils 125 \(\mu\text{m}\) thick. Figure 3.50 shows the gain as a function of the distance from the WELL’s bottom for kapton foils 50 \(\mu\text{m}\) thick (first prototype) and 125 \(\mu\text{m}\) thick (new prototype) for different amplification fields. According to such curves, with the first prototype a gain of about \(10^3\) should have been reached with an amplification field of 120 \(kV/cm\) (detector operated at its limit), while a gain more than 5 orders of magnitude higher should be achieved with the same applied voltage in the second prototype. A gain of the order of \(10^4\), comparable to the gain of a triple-GEM detector, should be obtained applying 70 \(kV/cm\), corresponding to a voltage of 875 V. We are interested in knowing if this value is below the limit set by the breakdown voltage, or if it is not reachable. The breakdown voltage for a given gas is
a function of the distance between the electrodes and the gas pressure, and according to the Townsend theory [68] it can be calculated as

\[ V_b = \frac{B pd}{\log A pd - \log [\log (1 + 1/\gamma)]} \]  \hspace{1cm} (3.16)

where \( p \) is the gas pressure, \( d \) is the distance from the cathode, \( A \) and \( B \) are coefficients related to the variations of the first Townsend coefficient as a function of the electric field and the distance \( d \) from the cathode, only depending on the gas, \( \gamma \) is the second Townsend coefficient, slightly depending on the electrodes material [69]. The resulting Paschen curve, i.e. the breakdown voltage as a function of the \( pd \) product, calculated for the Ar:CO\(_2\) gas mixture is shown in figure 3.51. At the atmospheric pressure (101325 Pa reference value), for the new prototype it is \( pd \approx 13 \text{ Pa} \cdot \text{m} \). Hence, according to figure 3.51 the breakdown voltage would be \( V_b \approx 700 \text{ V} \) (56 kV/cm). The voltage necessary to obtain a gain of \( 10^4 \) is bigger than the breakdown voltage by 25%, while a gain smaller than \( 10^3 \) is expected close to the breakdown voltage. Anyway it is worth noticing that according to figure 3.51 the expected breakdown voltage for the first FTM prototype with 50 \( \mu \text{m}\)-deep WELLs was in the most favourable case 450 V (90 kV/cm), while in practice it was possible to apply a voltage up to 600 V (120 kV/cm) before the detector started being unstable. This means that the breakdown voltage was overcome by 33%, possibly due to the fact that the Paschen curves are obtained for conductive electrodes, while the FTM detector uses resistive materials. Supposing that the next prototype would show the same behaviour, it could be possible to apply an amplification field large enough to reach a gain of \( 10^4 \). Given the shortage of alternatives in the choice of the kapton width, it is worth trying a detector with this configuration.

### 3.7.2 Second FTM prototype

It happened that, due to delays in the procurement of the material, we first realized a version whose structure was different than planned. As the kapton foils with 125 \( \mu \text{m} \) thickness were not yet available, we realized the amplification region using a PCB layer 200 \( \mu \text{m} \) thick covered by a resistive graphite layer with standard serigraphy techniques, up to a surface resistivity of the order of \( (5 - 10) \text{ M}\Omega/\square \). The holes in the PCB foils were realized with a standard
Figure 3.50: Gain as a function of the distance from the bottom of WELL, for WELL depths of 50 \( \mu \text{m} \) (top) and 125 \( \mu \text{m} \) (bottom) and different amplification fields applied.
Figure 3.51: Paschen curve for the Ar:CO$_2$ 70:30 gas mixture for different values of the parameter $\gamma$ [63].
drilling technique, operated at the machine’s limit, that provided cylindrical holes with 200 \( \mu m \) diameter and 500 \( \mu m \) pitch. The active area, also determined by the drilling machine’s limits, had a circular shape with 4 \( cm \) diameter (about 12 \( cm^2 \)). The amplification stage, in this case, was more similar to a thick-GEM foil \([70]\). In order to build up the structure of the detector, each drilled foil was placed on a similar (not drilled) PCB foil, covered with resistive layers on both sides, one resistive layer representing the bottom of the amplification region and the other one the drift cathode of the underlying layer. The two types of PCB foils are shown in figure 3.52. The resulting structure of this FTM prototype is shown in figure 3.53.

Figure 3.52: PCB foils used to realize the FTMv2 detector. The first type (left), used to realize the amplification region, is covered with holes at the center, visible in the picture as a lighter circle, and covered with a resistive layer only on one side. The second type (right) is not drilled and is covered with a resistive layer on both sides.

The holes visible on the external frame shall host the pins that distribute the voltage to all cathodes and on which foils are inserted during the assembly. Each pin traverses vertically the stacked PCB foils through such holes, from the readout board up to the foil to which it needs to apply the voltage. The correct foil shows a circuit trace in correspondence of the correct hole, as visible on the right of the external frame in figure 3.52 left and on the top of the frame in figure 3.52 right. A HV pin is soldered to such trace in correspondence of the hole, and the trace in turn applies the voltage to the resistive layer by means of a circular copper track on the external edge of the resistive layer. The
Figure 3.53: Schematic view of the structure of the FTMv2 detector, showing the materials used and the width of the amplification and drift stages.

detector’s structure, designed to be completely modular, is shown in figure 3.54. It can host up to 12 detector layers with independent voltage connections. Two readout boards are used, one on top and one at the bottom of the detector. Each readout board is equipped with 200 parallel copper strips, aligned in perpendicular directions with respect to each other on the top and bottom of the detector, to be read out by four connectors in total (two per readout board).

The prototype was initially equipped with four layers with a ionization gap thickness of 250 $\mu m$ each, for a total drift region of 1 $mm$. The ionization gap was provided by a PCB mesh acting as spacer shown in figure 3.55, with small grooves to allow the gas circulation.

This thick-GEM-like FTM detector was expected to provide a large gain and to be more efficient than the previous version. We have tried to operate it with different gas mixtures, namely Ar:CO$_2$ in 70:30 and 98:2 proportions and Ar:CO$_2$:CF$_4$ 45:15:40. Also pure neon was used, as it should provide a large charge production at low electric fields. Anyway we were not able to reach a stable operation of the detector.

We faced some problematic behaviours. Some signals were produced when the
3.7. Next FTM detector prototypes

Figure 3.54: Schematic representation of the modular structure of the FTMv2 detector.

Figure 3.55: PCB mesh acting as spacer for the drift regions of the FTMv2 detector.
detector was irradiated, but they were only visible for a short time, of the order of few minutes up about ten minutes, and then disappeared. It was necessary to wait some time, of the order of 30 minutes, before it was possible to see signals again. This behaviour was observed also with low incident particle fluxes, so that we were not in the condition to perform any deep characterization of the detector. In addition, there was also a dependence on the incident particle flux: if we started to observe signals with low particle flux and then increased the incident flux in order to see an increase in the signals rate, they started instead to reduce and then disappear completely at high particle fluxes. These behaviours seem to show that the detector becomes inactive with a correlation to the charge produced inside it.

In addition, big signals were visible even without source, with frequencies ranging from tens of $Hz$ up to $kHz$, like if discharges were happening inside the detector. A second strange observation concerns the breakdown voltage. For 200 $\mu m$-thick WELLs, according to figure 3.51 the breakdown voltage should
be about \( V_b \approx 1000 \text{V} \) (50 kV/cm) if the detector is operated with a Ar:CO\(_2\) gas mixture. In practice, we were able to apply a little less than 1000 V before the detector started to be unstable. Apparently, in this configuration the observed limit is consistent with the prediction, while for the first FTM prototype it was possible to overcome the predicted breakdown voltage by about 33%.

Some hypotheses that could explain these behaviours have been made. One possibility was that the production of charge inside the detector is changing the distances between the electrodes. Indeed, once the detector is powered, the electrostatic force generated pushes the stack together. Anyway, when the detector starts producing charge, the distribution of charge may change the electric field inside it, causing the electrodes to oscillate around the planar position.

Secondly, after disassembling this prototype we have noticed two effects, both on the bulk and drilled PCB foils:

- the bulk PCB foils were damaged in correspondence of the active area of the detector. In figure 3.57 left, a damage clearly shaped along the circular active area is visible
- the drilled PCB foils show (figure 3.57 right) a halo lighter in colour around the active area. In addition, in this region the resistivity changed, resulting to be about an order of magnitude higher.

The damage of the bulk PCB foils was most probably caused by the discharges inside the detector. The clearer halo instead could have been caused during the cleaning procedure. Indeed, once a PCB foil is drilled, it is necessary to remove the drilling leftovers from the holes. This is done washing and brushing it with a water and soap mixture. The damage was most probably caused by the mechanical action of the brush, that has scratched the resistive layer, also changing its surface resistivity.

Based on the above observations, not long after we tried to re-assemble the detector replacing the PCB foils with new ones. We replaced the material used for the resistive coating with resistive kapton (instead of graphite). The amplification layer still needed to be drilled in order to realize the holes. In addition, a rigid PCB layer was added on top of the stack in order to push it together. Anyway no significant improvement was observed with this variations, and the detector remained unstable and subject to discharges.

Further ideas to improve this version can come from the comparison with its close relative, the THick GEM (THGEM) [71]. THGEMs have a structure
Figure 3.57: PCB foils after disassembling the detector. The bulk foil (left) shows a damage clearly following the shape of the active area, the perforated foil (right) shows a lighter halo in the central region.

Figure 3.58: Picture of a typical THGEM electrode, with 0.4 mm holes, 1 mm distance between the holes and 0.1 mm etched rim [71].

similar to GEM detectors, but with dimensions rescaled by about a factor 10. Holes are typically mechanically drilled, with sub-millimeter diameter holes, spaced by a fraction of a mm on PCBs, with the addition of the Cu-etching of rims around the holes typically 0.1 mm in size. A picture of a THGEM foil is shown in figure 3.58.

The main difference between a typical THGEM and a classical GEM are the dimensions. The FTMv2 has dimensions that are halfway between the two objects. The WELL depth of the FTMv2 is half the thickness of typical THGEM, and also hole diameters are one third smaller. Both foil thickness and hole diameters have an important influence on the detector’s gain. Figure 3.59
3.7. Next FTM detector prototypes

Figure 3.59: Gain curves of a THGEM as function of the amplification voltage for different foils widths \((t)\) and hole diameters \((d)\). The maximum applied voltage corresponds to a discharge every 30 seconds. The hole pitch is 1 mm, holes have rims. The detector was operated with Ar:CO\(_2\):CH\(_4\) 89:10:1 gas mixture. The curves were obtained with a collimated \(^{55}\)Fe X-ray source [72].

shows gain curves measured on THGEMs with different holes diameter and foil thickness. It is clear that the smaller the hole diameters, the higher is the maximum achievable gain. In addition, it also shows that a thinner thickness allows to obtain the same gain with a lower applied voltage. Hence, the difference in the hole patterns should in principle favour the maximum achievable gain of the FTMv2 rather than a standard THGEM. Nevertheless, reducing the foil width also reduces the value of the breakdown voltage for the widths we are considering (figure 3.51), so that a condition in which the competition of the two processes allows to reach an acceptable gain must be found.

In addition, the holes dimensions and foil width are not the only evident difference of the FTMv2 from THGEMs: for the latter, rims are typically performed on the holes’ edges. It turns out, that rims are essential for THGEMs in order to reduce edge discharges, allowing to apply higher fields and hence achieving higher gains. Figure 3.60 shows the dependence of the maximum achievable gain of a THGEM as function of the rim size, showing that gain in-
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Figure 3.60: Maximum achievable gain of a THGEM as a function of the holes’ rim size. The THGEM has 0.4 mm width, holes diameter of 0.3 mm and holes pitch of 1 mm [71].

Figure 3.61 shows some gain curves of a THGEM thinner than standard ones, whose dimension are the same of the FTMv2, apart from the holes pitch and the presence of rims. It shows that the maximum gain achieved, for example, with a pure Ar mixture is of the order of $\sim 3000$, giving an idea of the order of magnitude that could be achievable in this configuration adding hole rims. It is still to be verified, anyway, that the available electronics would be able to adequately process signals produced by a detector with a gain of the order of few $10^3$.

In addition, also structural and production issues should be considered. Indeed, the hole diameters and pitch have been determined by the machine’s limit. It is possible that operating the latter at its operational limit has lead to imperfections in the structure of the holes, that disturb the correct operation of the amplification region. We did not have the opportunity to observe with a microscope the holes produced drilling the PCB, but other studies on GEM and THGEM with resistive cathodes (RGEMs and RETGEMs) have reported that a simple drilling procedure of PCB covered with resistive kapton left micro-particles of kapton inside the holes, and they modified the drilling procedure.
3.7. Next FTM detector prototypes

Figure 3.61: Gain curves of a thin THGEM as function of the amplification voltage for different gas mixtures. The thin THGEM PCB is 0.2 mm thin and has hole diameter of 0.2 mm, hole pitch of 0.5 mm and very small rims of (5 – 10) μm. The curves were obtained with a collimated $^{55}$Fe X-ray source [72].
adding an intermediate step involving gluing and then etching a Cu layer on top of the resistive kapton in order to avoid this effect [73]. A similar problem may have been encountered also in the production of the last prototype described. Also the hypothesis of the structural problem mentioned above, according to which the electrodes may be oscillating around their position as a consequence of the spatial charge produced, can’t still be completely ruled out, as there is no certainty that the PCB added to push down the stack was enough to limit the electrodes movements.

3.8 Recent updates on the FTM detector

The detector R&D on technologies to be used for the CMS muon upgrade is of course influenced by the LHC schedule. The FTM detector was initially considered for the ME0 station, to be installed in 2024. In 2016 it has been decided that this technology, albeit interesting, was too young in order to be well understood and ready to be manufactured in large-scale detectors in time for being used for ME0 station. Hence, the CMS Collaboration has stopped participating in its development.

For completeness, I report here the major steps of the R&D that has been performed after this decision, in which we did not participate directly. A new prototype was produced in 2017, whose basic idea was to go back to the amplification structure of the first prototype. As already argumented in its performance studies, a problem with this design was that the gain of a single-stage amplification was too low for the available front-end electronics. Hence, the choice of going back to a FTMv1-structure came together with the choice to develop a dedicated electronics.

This further prototype uses 50 \( \mu \text{m} \)-thick kapton foils, covered on one side with DLC using a sputtering technique, and on the other side by a Flexible Copper Clad Laminate (FCCL). Biconical holes with diameter of about \( \sim 70 \ \mu \text{m} \) and pitch of 140 \( \mu \text{m} \) were obtained by etching. As the active area was not limited by the drilling machine anymore, this prototype has an active area of \( \sim 20 \text{ cm}^2 \), about twice the area of the previous versions. The resistivity of the DLC layer after etching is of the order \( \sim 500 \ \text{M}\Omega/\square \). The prototype has four layers with 250 \( \mu \text{m} \) drift length each, for a total drift length of 1 mm. This prototype was realized using same modular design of the previous version, able to host up to 12 layers, but some new features were introduced:
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each amplification foil is stacked on an insulating plane, composed of two 50 \( \mu m \)-thick kapton layers reinforced by a 100 \( \mu m \)-thick FR4 layer in-between them, and covered with DLC on both sides (with a surface resistivity of about \((30 - 50) \ M\Omega/\square\)). Coverlay pillars, located on the bottom of the insulating planes, have been added to ensure planarity. The overall detector is closed between two PCB layers, containing the readout strips. The connectors have been replaced with \textit{Samtec} connectors, that provide a unique rugged ground at their center. The signal path length has been optimized, placing the readout connectors directly on top and bottom of the active area in order to reach better signal-to-noise ratio. In addition, the gas input has been placed on top of the PCB to force the gas to flow through all the layers. A schematic representation of this prototype is shown in figure 3.62.

![Schematic representation of the last FTM prototype.](image)

Preliminary tests performed at the beginning of 2018 with an X-ray source have firstly shown that the detector can be operated in a stable configuration.
They successfully established its linearity with a procedure similar to the one described in 3.5.1, and verified that the measured current increases exponentially with the applied amplification voltage. Unfortunately, the tests have also shown that experimental setups with X-ray irradiation are not suitable for the characterization of detectors with small drift gap and no copper in contact with the gas volume. Hence a UV laser facility is being set up in order to test it in laboratory. Characterizing it in laboratory is of course necessary before deciding to move it to test beam campaigns.

Concerning the dedicated electronics, the FAsT Timing Integrated Circuit (FATIC) [64] Application Specific Integrated Circuit (ASIC) is being developed by the INFN-Bari CAD Team. It incorporates a fully integrated amplifier, shaper and discriminator circuit, to extract and digitize the charge and time information from the FTM analog signals. The data are then synchronously acquired by the MOdular System for Acquisition, Interface and Control (MOSAIC) [74], which is also used to write the parameters in the FATIC registers. The first version of the FATIC chip was characterized and used to perform some first measurements. The comparison between its performance and the FTM requirements have led to improvements for the design of the second version of the chip, that is under development.

3.9 Conclusions

Some MPGDs different from the “simple” triple-GEM detectors have been considered at first for the ME0 station, namely the Back to Back GEM detector and the FTM detector. For both of them interesting results were obtained, that have also been publicly shown at conferences.

The first technology considered, the Back to Back GEM detector, goes into the direction to take advantage of the already well-known GEM technology, re-designing this detector in order to meet limited space constraints. Only the first prototype of Back to Back detector, with \((10 \times 10) \, \text{cm}^2\) active area, has been realized at this time. It was built to verify the feasibility of realizing GEM detectors according to this new design and their proper operation. Some disuniformity of response across its active area has been observed, but nevertheless it has been proved that the B2B detector is operational and its overall performance is successfully compatible with the performance of traditional triple-GEM detectors, like the ones developed for the GE1/1 station.
3.9. Conclusions

described in [23]. As next steps, bigger detectors should also be realized and the reason of the disuniformity should be addressed in the construction of other prototypes. It could be useful to disassemble it and verify the integrity of the foils and the planarity of the components in PCB. Also the uniform stretching of the foils could be investigated, hence reassembling it and improving the mechanical support could lead to an improved uniformity. An interested point to be investigated is the realization of prototype in which the two sides of the drift cathode are not in electrical contact, so that the two triple-GEM detectors can be operated at independent voltages. This would be necessary for real applications, first of all because the exact working point changes from detector to detector, and also because keeping them independent would improve the flexibility of the detector. Recently the activity around this prototype is not having any follow-up, as the choice for the ME0 station is going toward the “classical” triple-GEM detector with some adjustments in order to realize the necessary six-layered compact structure.

The second MPGD considered, the FTM detector, is a novel concept of MPGD, whose most attractive feature is the very good time resolution, expected to be much better than GEM detectors. The activity with the participation of CMS was around the very first prototypes ever realized. Hence, it has mainly focused on realizing the first working detector with the minimum size and number of layers necessary to prove its working principle. A basic goal that has been successfully reached. Many other steps in its R&D program were planned, and we had several ideas on how to improve it. Unfortunately this technology, born approximately in 2015, has revealed to be too young for CMS purpose of using it for the ME0 station. Before it will be ready for this application, it will be necessary to deeply understand its operation and to demonstrate the feasibility of realizing larger-scale high-efficiency detectors, besides their adequate performance in terms of time and spatial resolution, rate capability and longevity. This represents a long R&D program to be ready before 2020, when the prototype for the ME0 station must be well defined. Hence the development of this technology has been abandoned for this specific application in the CMS experiment, in favour of the already well-known GEM technology, and is now being pursued within other projects.
3. Development and Performance of New Micropattern Gas Detectors
The GE1/1 Slice Test

4.1 The GE1/1 Slice Test

The installation of the full GE1/1 station is foreseen during the LS2 (2019-20), in time for the Run 3 scheduled in 2021. The installation of a complete new station is necessarily a delicate task, involving several technical challenges. First of all the installation of the detectors and their services into an existing system with the goal of bringing them to operation in the best possible shape, moreover the realization of the control systems of the new detector and services, which on one side should allow the inclusion of the new station in the existing automation systems to coordinate the activity of LHC and CMS subdetectors, and on the other hand they should also ensure the safety of the detectors themselves. Finally, the realization of the Data Acquisition (DAQ) system and the interface to operate it which must lead to the integration of the GE1/1 DAQ into the global DAQ of CMS to acquire data together with the other subdetectors.

For the above reasons, the GE1/1 activity started already in 2017 with the installation of the slice test, to allow acquiring installation and commissioning expertise, proving the system’s operational conditions and developing the integration into the CMS online system.

4.2 System overview

The Slice Test consists in the early installation of a small fraction of the GE1/1 chambers, precisely 5 superchambers among the 36 superchambers in the neg-
4. The GE1/1 Slice Test

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Version</th>
<th>HV supply</th>
<th>Readout</th>
<th>Gas line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemini01</td>
<td>short</td>
<td>multi-channel</td>
<td>version 2 (2017)</td>
<td>channel 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>version 3 (2018)</td>
<td></td>
</tr>
<tr>
<td>Gemini27</td>
<td>short</td>
<td>single-channel</td>
<td>version 2</td>
<td>channel 2</td>
</tr>
<tr>
<td>Gemini28</td>
<td>long</td>
<td>single-channel</td>
<td>version 2</td>
<td>channel 2</td>
</tr>
<tr>
<td>Gemini29</td>
<td>short</td>
<td>single-channel</td>
<td>version 2</td>
<td>channel 3</td>
</tr>
<tr>
<td>Gemini30</td>
<td>long</td>
<td>single-channel</td>
<td>version 2</td>
<td>channel 3</td>
</tr>
</tbody>
</table>

Table 4.1: Summary table of the main features of the Slice Test chambers.

ative muon endcap, as shown in figure 4.1 and 4.2. Their installation took place during the 2016-2017 Year-End Technical Stop, two years in advance of the installation of the complete GE1/1 station starting in 2019. Four of them are positioned almost vertically at 6 o'clock, numbered from 27 to 30, and one of them is positioned at three o'clock, numbered 01, for a total of 50 instrumented in the negative endcap for the Slice Test. In the slice test, a 10° GE1/1 chamber with two layers of triple-GEM detectors is referred to as a Gemini, dropping the term Superchamber used in production activities. Currently the negative muon endcap is instrumented with Gemini01 and Gemini27 to Gemini30. The two triple-GEM detectors of each Gemini are distinguished between layer1 and layer2 (e.g. Gemini01L1 and Gemini01L2), layer1 being the closest one to interaction point. The length of the GE1/1 chambers alternates between long and short versions in order to maximize the coverage in pseudorapidity; Gemini01, Gemini27 and Gemini29 are short versions of the detectors, while Gemini28 and Gemini30 are long ones.

The main features of the Slice Test chambers are summarized in table 4.1 and are explained in detail in the next sections.

4.2.1 High Voltage

Apart from the location, the main difference between Gemini27 to Gemini30 and Gemini01 is the high voltage supply. Indeed, each layer of Gemini27-30 is powered by a single high voltage channel, provided by a CAEN A1526N module [75] already widely used in high energy physics experiments. In these chambers the voltage is distributed to the detector electrodes through a ceramic divider like the one in figure 3.3. Gemini01 instead is powered with a CAEN A1515TG module [76], a multi-channel power supply providing 14 HV channels.
4.2. System overview

Figure 4.1: Schematic drawing of the negative muon endcap, showing the location of the five Slice Test superchambers (or Gemini). Four of them are installed close to each other in the Slot 1, one of them is located horizontally in Slot 2. Short and long superchambers are shown in blue and pink respectively. Slot 1 includes counterclockwise Gemini27, Gemini28, Gemini29 and Gemini30. Gemini01 is located in Slot 2.

(7 channels per layer) to power independently the seven electrodes of each layer of one Gemini chamber.

The chambers of the complete GE1/1 station that will be installed in 2019-20 will all be powered with the multi-channel power supply. Nevertheless, for the Slice Test a mixed HV system was chosen because no installation of HV cables within the existing CMS endcap was necessary for chambers powered with the single-channel voltage supply, as some extra HV cables had already been installed in the past in view of a possible future upgrade of the RPC subsystem in this region and were already available for this use. Only Gemini01 was equipped with the final multi-channel power supply to start gain experience with this HV module.

The multi-channel HV module has been specifically designed for GEM detectors, and in the case of the GE1/1 station one module powers both layers of one Gemini. In particular, groups of seven channels are already internally stacked so that the user should set the desired voltage with respect to the previous channel, while the voltage absolute values are computed by the mod-
4. The GE1/1 Slice Test

Figure 4.2: Pictures of the nose in the negative endcap where the slice test chambers have been installed. The positions where they have been inserted are indicated by the red rectangles. Gemini27 to Gemini30 have been installed almost vertically below the beam line (left picture), Gemini01 has been installed horizontally (right picture).

...ule. For example, if the user wants to apply 350 V to the GEM3 foil and 400 V to the drift field between this foil and the readout, it is enough to set those values to the respective channels and the module will apply 400 V to the bottom side of the foil and 750 V to the top side of the foil; if the user later decides to switch off the drift field, by setting the respective HV channel to 0 V the top and bottom sides of the GEM3 foil will be powered with 0 V and 350 V respectively by the module. This feature allows to easily operate individual channels without manually taking into account the interdependence of the voltage absolute values between the different channels. The introduction of this module has some advantages with respect to the standard CAEN A1526N module: it allows to adjust individually the voltage applied to every single electrode of the detector (on the contrary, if a single HV channel with ceramic divider is used the ratios between the electrodes voltages are fixed), to monitor their status individually and, where necessary, it allows to exclude...
possible problematic channels keeping the remaining channels powered (in the configuration with one single HV channel either all or none of the detector electrodes can be powered). In addition, the current observed through the single-channel HV supply is mainly determined by the divider’s equivalent resistance and is of the order of 700 $\mu$A. This configuration does not allow to observe current fluctuations due to discharges taking place inside the detector. The current observed through the multi-channel power supply instead is approximately zero, allowing for a greater sensitivity to such discharge events.

The use of the multi-channel supply has anyway some drawbacks: operating the detector through a single-channel supply is indeed much simpler, a lot of experience in operating such modules is already available within many experiments and a lot of well-tried control systems to learn from already exist within the CMS experiment itself. Instead for the new multi-channel supply everything needs to be created from scratch, from a user-friendly interface to handle a big amount of channels per detector to a complex automation system necessary to operate them safely within the CMS experiment. The development of the Detector Control System (DCS) and automation related to the multi-channel supply was one of the tasks of my PhD and is described in detail in sections 4.4 and 4.5. The development of a robust control system and operational experience with the multi-channel module during the slice test is of outmost importance, as the final configuration of the GE1/1 station foresees to use only this module for all the GE1/1 chambers.

### 4.2.2 Readout system and low voltage

The first version of the readout system of the slice test chambers is based on VFAT2 ASICs [77], and is still used for four of the five chambers. Instead, at the beginning of 2018 Gemini01 was replaced with a chamber equipped with the most recent version of the on-detector data acquisition (DAQ) electronics based on VFAT3 ASICs [78]. The two versions are referred to as version 2 and version 3 respectively.

A schematic representation of the layout of the version 2 GEM DAQ electronics is shown in figure 4.3. The readout of one chamber is divided into twenty-four readout sectors, each one read-out by its own ASIC chip. The on-board electronics is hosted on the GEM Electronics Board (GEB), a large multilayer PCB plane covering the entire detector. The 24 VFAT2 hybrids,
4. The GE1/1 Slice Test

one per GEM readout sector, are accommodated on the GEB together with an Optohybrid (OH) board, a Virtex-6 FPGA providing the data acquisition and slow control functionality for the ASIC chips. On the back-end, a micro-TCA (uTCA) crate hosts an AMC13 advanced mezzanine card for the propagation of Trigger Timing and Controls (TTC) signal to the CTP7 mezzanine card, also hosted in the uTCA crate, which is linked to the OH board via fiber links.

Figure 4.3: Schematic drawing of the version 2 DAQ electronics. The 24 readout sectors with their VFAT2 chips and the OH board on the GEB are shown, as well as the uTCA back-end crate.

The main differences between the version 2 and version 3 electronics are the generation of the ASIC chips, a new GEB design and a new OH board. The VFAT3 ASIC has an improved performance, communication protocol and data formatting block, especially designed to accommodate the operation conditions of the high luminosity LHC and to meet the constraints of the upgraded CMS detector. The latest version GEB has been redesigned to be split into two parts in order to simplify the manufacturing process and mechanical issues during the assembly. As a consequence, also the OH board has been redesigned in order to work as a bridge between the two parts of the GEB and is located
4.3. Operating the multi-channel power supply

in the middle of the chamber. The back-end electronics is instead unchanged between the two versions of the electronics.

Three different low voltage channels are necessary to power the version 2 readout system: 2.5 V to power the VFAT2 chips and two LV channels, of 2 V (OH2V) and 3.4 V (OH4V) respectively, are necessary to power the OH. This is no longer true for the version 3 of the electronics, that has been designed in order be powered only by one LV channel providing 6 V.

4.2.3 Gas system

The slice test chambers are operated with a Ar:CO₂ 70:30 gas mixture. For the slice test three gas lines are in use, two of them supplying in series Gemini27-Gemini28 and Gemini29-Gemini30, and the third one supplying Gemini01. The presence of gas in the gas lines is constantly monitored by two flowcells per gas line, measuring the input and the output flow. The gas is stored and sent into the mixer in the Surface Gas eXperiment Building (SGX), a dedicated room for the gas system at CMS on surface level. The gas mixture is then sent underground to the gas racks in the Underground Service Area (USC55) through 235 m-long pipes. The location of this room is beneath the surface, but still at a higher level than the Underground eXperimental Cavern (UXC55) where the CMS experiment lies. Eventually, the gas is delivered to detectors in the experimental cavern UXC55 through 70 m-long pipes. A schematic representation of the gas system is shown in figure 4.4.

4.3 Operating the multi-channel power supply

It is useful to give a quick review about some operational aspects related to the multi-channel power supply in order to understand better the next sections. This paragraph is not intended to give an exhaustive description of the device, for which the best reference is of course the manufacturer’s manual [76], but only to mention some peculiarities that have turned out to have important consequences on the development of the control system and automation.

One feature to mention is the board mode, which can be either GEM or FREE. In GEM mode when one of the seven channels connected to the same detector is turned on (or off), also all the other six channel are also turned on
(or off) following the OnOrder (OffOrder) settings. The latter setting is an integer number settable for all channels, specifying the powering order for each channel. In FREE mode, instead, the seven channels can be turned on or off independently from each other.

For the slice test chambers we have decided to power the detectors following a precise order, that is $G_3\text{bot}$, $G_2\text{bot}$, $G_1\text{bot}$, Drift, $G_3\text{top}$, $G_2\text{top}$, $G_1\text{top}$ when the chamber is being turned on or to a higher total voltage, and the opposite order when it’s being turned off or to a lower voltage. To understand this choice, I anticipate that during normal operation the detector is either in a standby state, i.e. with zero voltage applied to the GEM foils and drift field close to the operational value, or ready for physics. Powering first the GEM foils and then adjusting the drift fields allows to bring the detector ready for physics faster. On the contrary, when it needs to be switched off or to standby state the selected order brings the detector to a state without charge amplification.

Figure 4.4: Schematic drawing of the slice test gas system. The gas mixture is produced in the Surface Gas eXperiment Building (SGX), then sent to the gas racks in the Underground Service Area (USC55) and eventually to detectors in the Underground eXperimental Cavern (UXC55).
faster.
The desired powering order can be obtained the easy way operating the board in GEM mode and setting the OnOrder and OffOrder settings as desired. Anyway, we can’t only rely on this option, as we may encounter the situation in which due to some failure an HV channel can’t be switched on anymore. If we only relied on the board’s GEM mode, it would not be possible to skip one or more voltage channels. The automation software I’ve realized in order to follow the desired powering order independently from the board mode is explained in section 4.7.

The second important feature is the procedure to ramp the channels voltage, either to adjust a single voltage value or to turn on or off an entire detector layer. When powered and working, the current through an HV channel of the multi-channel supply is very small, much less then 1 $\mu$A (see figure 4.23), even though some bigger spikes can be observed. Instead during ramping the channels current is much higher and the $I_0$ limit used for normal operation could cause some channels to trip while ramping. Hence, our standard procedure is to raise the $I_0$ limit to a greater value, typically 50 $\mu$A, only for the time necessary to ramp the voltage, and then to lower it back to a value safe for the normal detector operation. In addition, as one single chamber ramping may induce currents also in the other six voltage channels, we usually apply the high current limit to all seven channels.

4.4 The Detector Control System

The CMS experiment was originally composed of eight subdetectors, to which the GEM subdetector will be added: Pixel, Tracker, Preshower and Electromagnetic Calorimeter (ECAL), Hadronic Calorimeter (HCAL), Drift Tubes (DT) Resistive Plate Chambers (RPC) and Cathode Strip Chambers (CSC). Each subdetector has its own Detector Control System, designed according to its specific needs, which ensures to operate correctly and safely each system and to control the whole CMS experiment.

The CMS DCS is based on SIEMENS SIMATIC WinCC Open Architecture (WinCC OA) [79], previously known as Prozess Visualisierungs und Steuerungs System (PVSS). WinCC OA is a SCADA [80] system for the visualization and operation of processes and machines, allowing for customized functionalities, designed for large scale applications and also widely used for
industrial and commercial applications. It also allows to realize multi-user and redundant systems, as necessary for CMS use. In addition, at CERN the Joint Controls Project team (JCOP) [81], the result of a collaboration between the four LHC experiments and the CERN IT/CO group, built a controls framework based on WinCC OA integrating the requirements of the LHC experiments, known as JCOP framework [82]. The JCOP framework provides a set of guidelines as well as software tools for the developers of the Control Systems for CERN experiments.

The GEM DCS represents an isolated case of a CMS subdetector’s control system built from scratch in recent years, requiring a big effort. The GEM DCS can be ideally divided into three main parts: one part to monitor the gas system, one part to monitor and control the single-channel HV and LV and one part to monitor and control the multi-channel HV. I have been in charge of the development of the part related to the multi-channel HV. In the following sections an overview of the basic features of the main parts of the DCS is given. Currently all of them have reached an almost final design for the slice test, even if some minor changes and updates are always possible and being developed according to the feedback and needs coming from the daily operation experience.

The gas panel. The main panel for the monitoring of the gas system is shown in figure 4.5. No action is possible on the gas system, as the hardware of the CMS gas system is centrally controlled only by the CERN gas group [83]. From the subdetector’s point of view, the gas panel can only show the actual status of all the components of the gas system, which is of utmost importance both for the health of the detectors and to ensure their proper operation with the desired performance. The gas panel is mainly based on a color code to give a visual summary picture of the overall state of the gas system, according to which green means that values are in a good range, yellow means that the values are still acceptable but in a suspicious range and red that they are in an unacceptable range most probably because of some problem. Directly accessible from the main panel are the values of input and output flows measured by the flow cells of all gas lines, the state of the gas rack and the state of the gas mixer. They are organized in different sections:

- in the bottom left part of the panel the Services section includes the state of the Mixer the Exhaust and the access to some functionalities reserved
The Detector Control System

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to expert users. The Exhaust has been implemented in the DCS but this
functionality is not used during the slice test as it is an open system, i.e.
the output gas is released in the atmosphere

- the top right part of the panel is the Gas Racks section. For the slice
test only one gas rack is used, numbered X2S31/61
- in the bottom right part of the panel is the Flow Cells section. Each rect-
gle represents a gas line, whose color indicates if the input/output flows
and their difference are in a good range. As explained in section 4.2.3
only three out of six implemented gas lines are used for the slice test,

Hovering the mouse on each rectangles shows the total input and output
flows measured by the flowcells on that gas line.

In addition, from all sections of the gas panel it is possible to open some
pop-up windows showing in detail all the parameters related to such elements,

i.e. the gas racks pressures, the mixer percentages, flows, ratios and pressures
and the environmental parameters, always accompanied by a color code to
help understand if they’re in a good range. Also trending plots for all these
parameters are available. As a problem in the gas system may require an
immediate reaction to prevent possible damage to the detectors, when any
value goes outside its good range an immediate notification is sent to a list
of people, including the dedicated shifter in the CMS control room. Alarm
thresholds for the gas system can be adjusted, masked and handled from the
Expert section of the panel, reserved only to users with special rights.

The single-channel HV and LV panel. The monitoring and control of
the high voltage of the chambers powered with the single-channel HV supply
and of the low voltage is possible through the panels shown in figure 4.6. Each
layer is graphically represented by a trapezoid like the one in figure 4.6a, which
summarizes the actual voltage and current on the HV channels and the three
LV channels used to power that detector layer and its electronics. In addition,
for a better interpretation of the values the background color changes according
to the channel status between green (channel on), yellow (channel ramping),
red (channel in error, e.g. tripped) and grey (off). A simple user has access
only to buttons in the lower part of the trapezoid that allow to switch on or
off the HV and LV channels, but can’t manually modify any other setting.

As will be explained in section 4.5, the voltage setting and the current limit
Figure 4.5: The gas panel of the GEM DCS. It is divided into four sections: Services, Gas Racks, Flow Cells, and Each Section. Each section has some buttons that open windows showing more detailed information. For example, on the right, the window opened by the Global Settings button in the Gas Racks section is shown. In particular, in this example, the gas rack is in a warning state.
are changed automatically according to the LHC state. As the GEM DAQ is constantly under improvement during the slice test, it is often necessary to powercycle the LV in order to reset the electronics. For this reason also a *Powercycle LV* button has been added, that automatically powercycles the three LV channels as necessary: a precise powering order is followed, and the powercycling is iterated until the correct current value is measured on all LV channels. Finally, trending plots pop up by clicking on each voltage channel. In addition, expert users have also access to the panels shown in figure 4.6 b and 4.6 c, that allow to change the settings of each voltage channel manually. Of the two available panels, one gives access only to the most used settings (figure 4.6 b) and one gives access to the all the possible settings (figure 4.6 c). The latter panel has been adapted from a standard panel provided by the JCOP framework to monitor and control voltage channels. Sending automatic alerts has been implemented also for the single-channel HV and LV, for example in case of channel trips, overcurrent or overvoltage, hardware failures, and other problematic situations.

**The multi-channel HV panel.** My first goal in the development of the DCS to monitor and control the multi-channel HV was the implementation of the panels shown in figure 4.7, 4.8, 4.9 and 4.10. The idea was to make all the monitorable values and the available settings accessible, so that any action on the board and its channels was possible and any parameter was visible from such panels without the need to access them with a different interface in any situation. The representation would anyway be better organized, showing the most interesting information first, and logically grouped according to the organization in separate triple-GEM detectors. Indeed in the case of the single-channel HV there is a simple one-to-one relationship between a hardware high voltage channel and a chamber layer, so that the realization of the panel showing the state of one chamber was straightforward. A fully detailed display was also already available in the JCOP framework (figure 4.6 c). Instead for the chambers supplied with the multi-channel HV the state of one single detector layer is determined by seven voltage channels, and displaying the basic parameters of all of them would result in a crowded collection of information. Also using the ready-for-use panels by the JCOP framework would mean opening seven different panels, one per HV channel, in order to manually change the settings of one detector layer.
Figure 4.6: Panels to monitor and control the single-channel HV and the LV channels.
4.4. The Detector Control System

I have then introduced a display (figure 4.7) in which the information coming from all the channels is summarized in a detector-like view. If necessary, the user can access the complete details of the interested channels by clicking on the buttons available in the bottom part. This main panel simply uses a set of led for each detector layer:

- four of them are error leds, which light up in red if any of the seven HV channels supplying that layer undergoes an overcurrent (OvC led), an overvoltage (OvV led), an undervoltage (OnV led) or a trip (Trip led)
- the color of the Status led depends on the status of the seven HV channels. If all of them are off it’s grey, if all of them are powered it’s green, if they are in a mixed state it’s yellow.

Ideally, the error leds should always be grey and the status leds should always be green, as during normal operation the detectors are always powered and only the voltage setting may change according the LHC state.

In section 4.2.1 it was explained that there’s a one-to-one relationship between HV boards and Gemini chambers: for this reason the board operating mode has also been inserted in the summary panel of one Gemini. Eventually, the buttons give access to the complete details of the 14 voltage channels powering the chamber (Monitor button), to a panel allowing to change the settings applied to all channels (Change Settings button) and to the trending plots of the main parameters of the 14 channels and of the board.

![Figure 4.7: Summary panel of the state of the high voltage of one Gemini chamber powered with the multi-channel HV supply. In the example none of the 14 channels supplying Gemini01 are undergoing any error, Gemini01L1 is entirely OFF and Gemini01L1 is entirely ON.](image)

The panel opened by the Change Settings button has two tabs, shown in
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figures 4.8 and 4.9. The first tab is divided in three main sections: one for the board settings and two for some settings of the channels of layer1 and layer2. Once opened, all values are initialized to the current ones. They can be edited to the desired new value, and all the changes will be applied all together only after clicking on the “Apply” button of that section. In this way, one can first edit manually the new settings of one entire chamber layer, having the complete view of the entire detector, before applying them. In addition, the need to click the “Apply” button prevents from immediately applying any new incorrect value typed by mistake. In addition, while a user changes the text of the OnOff column to modify that setting, the text color always indicates the actual state of the channel, i.e. it remains red until it’s off and green until it’s on.

In the very first version of this panel the three columns Vmon, Imon, I0 readback on the right part of the panel where not implemented, and have been added later for convenience after some operational experience. Indeed, after having applied a new setting the user may be interested in knowing when this value has been actually received or if it’s being processed. This feedback is not really necessary for the V1, V0, I1, RUP, RDWN, TripTime settings, but it is very useful for the I0 settings and when the channels are ramped up or down. Indeed, as explained in section 4.3 during a voltage ramping the current Imon is much higher than during normal operation, hence before applying a new voltage value or switching on/off any channel it is necessary to increase the current limit I0 on all channels to avoid the detector to undergo an overcurrent or a trip. Only after this change, the new voltage can be applied or any channel can be switched on/off. Hence, for practical use it was useful to have the possibility to check the I0 value directly from the Change Settings panel. The Vmon and Imon columns have been added for similar reasons: it is clearly useful to have the possibility to follow real-time the ramping of the voltage channels once it has started, and to bring back the current limit to a lower value once the ramping has finished. In addition, a fast button to change all the seven I0 limits at once has also been implemented (Set I0 to ALL) to facilitate this procedure.

For detectors powered with the multi-channel power supply, the working point of one detector layer can be expressed, for example, as the total voltage applied to the detector, i.e. the potential difference between the drift cathode and the readout, which is grounded. This value is the sum of the the voltages set to
all seven voltage channels. Equivalently, a second way to express the working point can also be used, which refers to the current that would flow through the voltage divider if the detector was powered with a single HV channel\textsuperscript{1}. We call the two values equivalent divider voltage $V_{eq}$ and equivalent divider current $I_{eq}$. It is possible to convert one to other simply using the total divider’s equivalent resistance $R_{\text{div}}$, i.e. $V_{eq} = R_{\text{div}} I_{eq}$. The voltage to be set to each voltage channel of the multi-channel supply can be determined similarly knowing the values of the divider’s resistors. Hence, first of all the total sum of the $V0$ settings and of the $V\text{mon}$ values is shown underneath the respective columns, in the first case to show the equivalent divider current corresponding to the inserted setting and in the second case to show the current value of the equivalent divider voltage. In addition, two fast ways to set new voltage values to all seven channels has been implemented. Typing the desired equivalent divider current and then clicking on the \textit{Set Divider Current to ALL} will automatically compute and write into the $V0$ cells the corresponding voltage values, rather than inserting them one by one. Similarly, the button \textit{Set Divider Voltage to ALL} does the same if the equivalent divider voltage is inserted.

Finally, other buttons for fast actions have been implemented. The \textit{switch all on} and \textit{switch all off} buttons are shortcuts to change the \textit{OnOff} settings of all seven channels to \textit{On} or \textit{Off} at once. The last three buttons allow to save or load custom configurations of settings. They have been implemented in the panel but are disabled in the slice test DCS, but they can anyway be enabled and used in other applications. For example, in the production chain of the 144 detector for the complete GE1/1 station several \textit{quality controls} are foreseen. For some of them a DCS has been realized, in which these panels developed for the Slice Test have also been employed.

The tab shown in figure 4.9 completes the settings panel, containing the remaining settings not shown in the tab described above. I have preferred not to squeeze all of them in one single panel, but to collect the settings used less often in a different panel. The organization and functioning of this tab is

\textsuperscript{1}For detectors powered with a single HV channel the working point is typically expressed in terms of the current through the voltage divider, while the use of the total voltage is avoided. The reason is that, due to the presence of filters between the voltage supply and the detector and the value of the current through the HV cables up to about 700 $\mu$A, a voltage drop on the filter is present. Hence the voltage erogated by the supply is higher than the one really applied to the detector. For detectors powered with the single HV channel the working point is unambiguously expressed only in terms of the measured current.
4. The GE1/1 Slice Test

Figure 4.8: First tab of the DCS panel that allows to modify most of the settings of a multi-channel board and its voltage.
4.4. The Detector Control System

similar to the previous one.

Figure 4.9: Second tab of the DCS panel that allows to modify some settings of the voltage channels of a multi-channel board.

The last panel realized for the multi-channel power supply is the one opened by the *Monitor* button from the main panel, shown in figure 4.10. This is a *passive* panel, meaning that no change to the system can be performed from it. Indeed it offers an exhaustive view of the actual values of all the existing parameters, organized by detector layers. The *Change Settings* panel already offers enough feedback on the system status for most activities, together with the FSM and the alerts messages sent in case of errors. Anyway in case of necessity from here it is possible to display and check the actual value of all parameters without exception. In particular, the most useful part is probably the upper-right part section: a matrix of error leds is present, that turn red in case any of the channels undergoes one of those errors. In case of a detector layer in error, this matrix allows to identify the exact channel having a problem.
4. The GE1/1 Slice Test

and its nature. Actually the overcurrent, overvoltage, undervoltage and trip errors are just the most common ones, but they are not all possible errors. Any other type of error can be identified from the Status value, shown on the right of the led matrix. A legend of such numbers is also accessible from this panel.

Finally, also the multi-channel power supply alerts are sent at the occurrence of many types of errors.

4.5 The CMS and LHC automation

We have introduced so far the part of the DCS dedicated to the manual operation of the system. It’s important to have a tool allowing to intervene manually on the system, but most of the time detector subsystems are not operated manually. In periods of data taking, but also in other machine conditions, the LHC goes through a sequence of states to which all the experiments and their subsystems must react properly. In principle they must be ready to take data efficiently during collisions, but they also need to go to a safe state when it is requested by possibly harmful LHC conditions. These reactions shall happen automatically as soon as they are necessary. The automation is achieved through two different tools: the DCS Finite State Machine (FSM) and the DCS Detector Protection.

The FSM allows to control entire subdetectors as single objects through predefined global actions reacting to the LHC changes of state. In broad terms the FSM is an abstract machine that can have only one state at a time, among a finite number of possible states. The CMS FSM has a tree hierarchy, whose nodes can be either logical units, control units or, if they are at the lowest level of the tree, device units. In this context I’ll skip the difference between logical and control units, that is important from the development point of view but it’s not interesting for the purpose of this description. The state of a logical or control node inside the tree is defined by the states of its children. In addition it is possible to give a command to such node, that will consequently propagate an action to its children, i.e. execute a command on them. As an effect of the received action, the state of the children may be re-evaluated and changed, and in turn also the state of the parent node will be re-evaluated according to the new state of its children. The number and names of the states, the rules defining the state transitions, the list of available commands in each
Figure 4.10: DCS panel that allows to monitor the actual values of the parameters of a multi-channel power supply.
state and their effect on children are all programmed by the developer. At the very bottom part of the FSM tree are the device nodes, that don’t propagate command to any child, but usually act on a piece of hardware. If a node or device unit in a certain state receives a command that is not declared among the state’s actions, then that command is ignored. A simple example of a FSM structure for a LHC experiment is shown in figure 4.11.

An important feature of the FSM structure is that commands propagate only down the tree, while states propagate only upwards. In order to be able to send such commands, one user shall take one node of the FSM. In this way he will be able to control the tree from there down, either sending commands from the highest node he’s owning that will be propagated down the tree, or sending commands directly to a node or device at a lower position. Only one person at a time can own an FSM tree.

This mechanism is the one driving the automation of CMS subdetectors. Each subdetector has designed its own DCS with its FSM. The upper node of each subdetector can be included in the central CMS FSM, controlled from a single operator station in the CMS control room. The subdetectors upper nodes must follow a set of conventions and rules on the states and commands in order to be compatible with the central DCS and correctly communicate with it, while the peculiar necessities of each subdetector can be implemented down their FSM tree. By taking the CMS node the operator will own all the subdetectors and have control on the whole CMS detector. He has the possibility to send some pre-defined global actions to the subdetectors, whose effects have been decided and programmed by the subdetector experts. If necessary, he can partition out the tree of a subsystem to delegate its operation to a sub-detector expert, that at that time can take control of its FSM tree.

The automated actions – not manually sent by the shifter – are propagated down the FSM tree when there’s a change in the LHC or beam state (see section 4.5.1) according to each subdetector’s automation matrix (see section 4.5.2). In order for the command to reach a subdetector and be propagated down it’s tree, it is necessary that its FSM is centrally owned by the shifter in the control room or, briefly speaking, in central.

The second mechanism to accomplish the automation is the detector protection. The detector protection does not rely on the FSM on purpose, but acts directly on the involved datapoints. Its goal is to ensure that all subdetectors are locked in a safe mode whenever a potentially dangerous situation
Figure 4.11: Example of a simple control system based on a Finite State Machine [85]. The subdetectors’ FSM trees are part of the central DCS FSM. Each subdetector develops its own tree hierarchy. The nodes shown in the example are control units (CU). The tree of each subdetector ends with device units (DU), whose actions directly act on the hardware. The arrows indicate the direction of commands (top-down) and the propagation of state (bottom-up).

exists. For this purpose the FSM is not an adequate tool, as the real effect of a propagated command depends on several factors, for example whether the subdetector is in central or not when the LHC or beam change of state requires such reaction, or if the subdetector top node is in a state able to process the received command. The detector protection is used in situations in which it is desired that the subsystems always react regardless any other factor.

4.5.1 LHC operation

The operational activity of the LHC is traditionally described by two modes: the accelerator or LHC mode and the beam mode. The LHC mode provides a general overview of the machine activity. Within a specific LHC mode a sequence of tasks in a strict order is executed, called the LHC cycle. The phase of the machine cycle is summarized by the beam mode. A number of LHC modes exist, like proton physics, ion physics, proton-nucleus physics, machine development, beam setup, and many others. For example, in periods of the year during which the accelerator is providing proton-proton collisions and the experiments may collect proton-proton data, the LHC mode is proton physics. If no problems is encountered, the typical LHC cycle in proton physics, leading to collisions inside the experiments, is as follows:
4. The GE1/1 Slice Test

1. during setup there is no beam in the LHC ring

2. at injection probe beam one ring is injected with beam, with the goal to establish a safe beam with a given lifetime

3. injection physics beam begins when the machine has been optimized and a circulating beam with appropriate lifetime has been obtained; the LHC is ready for higher intensity beams

4. prepare ramp, ramp follow the injection, during which the beam is ramped; when the ramping is over the beam state changes into flat top

5. the last preparations for proton collisions happen in squeeze and then in adjust

6. in stable beams collisions take place in the experiments

7. a physics fill is interrupted at beam dump, followed by ramp down.

4.5.2 The automation matrix

All CMS subdetectors shall automatically react to the changes of the LHC or beam modes. Such reactions are driven by the automation matrix, a two-entry table in which the automatic action to be performed for each machine-beam mode combination is stored. For example, a part of the GEM automation matrix for proton physics is shown in table 4.2.

Actions starting with “go to ...” are trasmitted to the subsystems as FSM commands. Their actual effect depends on whether the system was in central and the original state of the subsystem (and possibly on other checks). “Protected” actions instead are always executed, regardless the state of the subdetector, and lock some parameters to the target value to avoid to be modified.

4.6 The GEM Finite State Machine

A schema of the FSM realized for the slice test is shown in figure 4.11. It is organized following a logical structure of the subdetector’s parts, whose main parts are the low voltage system (GEM_LV), the high voltage system (GEM_HV) and the gas system. In particular I have personally developed
4.6. The GEM Finite State Machine

<table>
<thead>
<tr>
<th>Setup</th>
<th>Injection Probe Setup</th>
<th>Injection Physics Setup</th>
<th>Prepare Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROTON PHYSICS</td>
<td>do nothing</td>
<td>protect standby</td>
<td>protect standby</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ramp</th>
<th>Flat Top</th>
<th>Squeeze</th>
<th>Adjust</th>
<th>Stable Beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROTON PHYSICS</td>
<td>protect standby</td>
<td>protect standby</td>
<td>go to physics</td>
<td>go to physics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam Dump</th>
<th>Ramp Down</th>
<th>Cycling</th>
<th>No Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROTON PHYSICS</td>
<td>do nothing</td>
<td>nothing</td>
<td>nothing</td>
</tr>
</tbody>
</table>

Table 4.2: Part of the automation matrix of the GEM subsystem for the Proton Physics LHC mode.

The structures of the low voltage and high voltage sub-trees are very similar, showing in the first level all the Gemini chambers and on the next level the two layers. Currently, in the LV sub-tree all layers of Gemini27 to Gemini30 end up with three low voltage channels, i.e. the three LV channels necessary to power their on-board readout system. The LV of Gemini01 currently uses only voltage channel, hence the sub-trees of Gemini01L1_LV and Gemini01L2_LV end up with only one voltage channels. Similarly, also in the GEM_HV sub-tree there are some differences in the structure of the GEMINI27_HV to GEMINI30_HV branches and the GEMINI01_HV. The sub-trees of the chambers equipped with the voltage divider and powered with a single HV channel are very simple, as each detector layer is a device unit acting directly on the HV channel powering that layer. Instead, for each chamber layer supplied with the multi-channel power supply seven different HV channels power a detector layer, each one with its own device unit in the FSM tree. I have added one additional device unit, called Gemini01LXConfigurer, on the same level of the seven HV channels. Its role is described in detail in section 4.7.
To the device units, the same applies to the gas channels in the Gas System sub-tree, where only sub-tree of Channels has been expanded down. The trees not expanded in the schema have the same structure. The device units, located at the very end of each branch, are shown in yellow. For brevity, in the GEM HV and GEM LV sub-trees only some of the GEMINI chambers are shown, and only the sub-trees of GEMINI01L1 HV, GEMINI27L1 HV, and GEMINI01L1 HV have been expanded down to the device units. The trees not expanded in the schema have the same structure.
4.6. The GEM Finite State Machine

4.6.1 The Gas System FSM sub-tree

The GEM Gas System sub-tree has a substantial difference with respect to the LV and HV sub-trees of the FSM: no actions are programmed at any level of its tree. Hence it is not used to perform any action and it does not receive any command following the automation matrix, but it’s used only to monitor the gas system component’s.

The GEM Gas System sub-tree is divided into two main parts, the GEM Mixer and the Gas Distribution. The device units at the end of their subtrees are connected to several parameters, whose values can be either in a good, warning or bad range. The device units called *Stepper* are connected to a status integer representing the state of a different part, rack or mixer of the gas system. For each gas line used in the slice test (*Channel2, Channel3* and *Channel4* in figure 4.12), the input and output flow of each line together with their difference are monitored. The *Argon* and *CO2* device units in the GEM Mixer sub-tree are connected to percentage values of the Argon and CO2 in the gas mixture.

The states of the device units depending from the aforementioned parameters are propagated up the tree to the main mode of the gas system. As a result, the latter can be in three different states:

- *Running*, if all the parameters are in a good range
- *Warning*, if any of them is in a suspicious range
- *Not Running*, if any of them is in a bad range.

4.6.2 The High Voltage FSM sub-tree

The device units. To understand how the FSM is programmed, let’s start from the device units at the bottom of the FSM tree. Each device unit of the HV sub-tree is connected to a different voltage channel. Both the single-channel and the multi-channel HV device unit have six different possible states with the same meaning, each one shown in a different color:

1. TRIPPED (red), if the the channel has tripped

2. ERROR (red), if the channel is in any other faulty state different from tripped, i.e. *maxV*, *external disable* (for the multi-channel supply HV channels), *calibration error* or *unplugged*. A channel is in ERROR state also if it’s in none of the other states listed here.
3. WARNING (orange), if the channel is undergoing an overcurrent, over-voltage or undervoltage

4. RAMPING_UP (yellow) if the voltage applied to the channel is ramping up

5. RAMPING_DOWN (yellow) if the voltage applied to the channel is ramping down

6. STANDBY (light blue) if the channel is correctly powered with a voltage lower than the operational value, at which there is basically no charge amplification inside the detector

7. ON (green) if the channel is correctly powered with a voltage high enough to consider the detector operational and ready for physics

8. OFF (light blue) if the voltage channel is off.

All the possible actions to be performed on the HV device nodes are listed below:

- SWITCH_OFF, that switches off the channel by changing the onOff settings to off
- GO_TO_STANDBY, that aims to bring the HV channel to STANDBY state. For the single-channel supply, this is achieved first by setting the standby voltage of 2500 V and then setting the current limit $i\theta$ to the correct value. Indeed, the current of a single-channel voltage supply is determined by the ohmic behaviour of the divider $I = V/R_{\text{div}}$, hence a lower voltage applied determines a lower current measured on the HV channel. The current limit needs also to be raised or lowered when the voltage applied is raised or lowered
- SWITCH_ON, that aims to bring the HV channel to the ON state. In this case, for the single-channel supply it is necessary to first increase the current limit $i\theta$ and then to apply the new voltage setting

Not all the above actions are always available. Instead, in each of the possible states of a device unit a different set of actions is available. The list of the combinations of states and possible actions is summarized in table 4.3, while in figure 4.13 the possible states and state transitions of an HV device unit are represented. We have decided to forbid the direct transition from OFF to ON for safety reasons, and to force always to go through the STANDBY
4.6. The GEM Finite State Machine

<table>
<thead>
<tr>
<th>State</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIPPED</td>
<td>SWITCH_OFF</td>
</tr>
<tr>
<td>ERROR</td>
<td>SWITCH_OFF, GO_TO_STANDBY</td>
</tr>
<tr>
<td>WARNING</td>
<td>SWITCH_OFF, GO_TO_STANDBY</td>
</tr>
<tr>
<td>RAMPING_UP</td>
<td>SWITCH_OFF, GO_TO_STANDBY</td>
</tr>
<tr>
<td>RAMPING_DOWN</td>
<td>SWITCH_OFF, GO_TO_STANDBY</td>
</tr>
<tr>
<td>STANDBY</td>
<td>SWITCH_OFF, GO_TO_STANDBY, SWITCH_ON</td>
</tr>
<tr>
<td>ON</td>
<td>SWITCH_OFF, GO_TO_STANDBY, SWITCH_ON</td>
</tr>
<tr>
<td>OFF</td>
<td>SWITCH_OFF, GO_TO_STANDBY</td>
</tr>
</tbody>
</table>

Table 4.3: List of actions available in all states of a high voltage device unit.

state before reaching the ON state. As a consequence, in the OFF state only the SWITCH_OFF and the GO_TO_STANDBY actions are available, while in the STANDBY and ON state all commands are available. In faulty states and during ramping no SWITCH_ON action is available. In particular in the TRIPPED state only the SWITCH_OFF action is available.

The logical units. Having defined how the device units located at the end of the GEM_HV tree are programmed, we can now move up the tree and show how the logical units that build the FSM nodes are programmed. The possible states of the FSM nodes are the same of the device units, i.e. TRIPPED, ERROR, WARNING, RAMPING_UP, RAMPING_DOWN, STANDBY, ON, OFF. They are computed according to the following general rules:
Figure 4.13: Schematic drawing of the possible states and state transitions of an high voltage device unit. Error states are shown below the schema because they can happen at any time from any state. The colors used to represent the states are the same visible from the DCS when the FSM device is in that state.

- when all the children are in the ON (or OFF, or STANDBY) state, the node is also in the ON (or OFF, or STANDBY) state
- when the children are in a mixed stated the state with lower voltage is propagated upwards. For example, if one child is in the ON state, one child is in the OFF state and one child is in the STANDBY state, the upper node shall be in the OFF state. This choice has been done with the goal to immediately highlight the presence of any channel not ready for physics. The contrary, i.e. put in evidence any channel that is still ON whenever it is expected to be in STANDBY state for safety reasons, should not be necessary if the detector protection is properly working
- when any of the children is in an ERROR (or TRIPPED, or WARNING) state, the ERROR (or ERROR, or WARNING) state is propagated to the upper node.
- when more children have different faulty states, the priority is order is TRIPPED, ERROR, WARNING. For example, if one child is in the ON
4.6. The GEM Finite State Machine

<table>
<thead>
<tr>
<th>State</th>
<th>Condition</th>
<th>Target State</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANY</td>
<td><em>Any</em> child in state KILLED</td>
<td>KILLED</td>
</tr>
<tr>
<td></td>
<td><em>Any</em> child in state TRIPPED and NAC</td>
<td>TRIPPED</td>
</tr>
<tr>
<td></td>
<td><em>Any</em> child in state ERROR and NAC</td>
<td>ERROR</td>
</tr>
<tr>
<td></td>
<td><em>Any</em> child in state WARNING and NAC</td>
<td>WARNING</td>
</tr>
<tr>
<td></td>
<td><em>Any</em> child in state RAMPING_UP and NAC</td>
<td>RAMPING_UP</td>
</tr>
<tr>
<td></td>
<td><em>Any</em> child in state RAMPING_DOWN and NAC</td>
<td>RAMPING_DOWN</td>
</tr>
<tr>
<td></td>
<td><em>Any</em> child in state OFF and NAC</td>
<td>OFF</td>
</tr>
<tr>
<td></td>
<td><em>All</em> children in state STANDBY and NAC</td>
<td>STANDBY</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ON</td>
</tr>
</tbody>
</table>

Table 4.4: List of state rules of the logical units of the GEM_HV FSM sub-tree. The acronym NAC is the abbreviation for none of the above conditions.

...state, one is in the TRIPPED state and one is in the WARNING state, the upper node goes to the TRIPPED state (the latter state has the priority over the WARNING state).

Based on the above principles, the complete resulting schema of state transitions of logical units is summarized in table 4.4.

The actions available in the logical units, i.e. the FSM nodes of the tree, are the same actions available for the device units. In general, they just propagate to their children the same command they received. In section 4.7 it will be explained that for the nodes Gemini01L1_HV Gemini01L2_HV this result is achieved through the use of the GEM Configurator. The actions available in each state are the same of the device units, listed in table 4.3.

4.6.3 The Low Voltage FSM sub-tree

The design of the low voltage FSM tree is very similar to the one of the high voltage described in section 4.6.2. Indeed, they are both intended to operate on voltage channels. From FSM point of view the main differences between high voltage and low voltage channels are that:

- there is no STANDBY state foreseen for the low voltage channels. The applied voltage can correspond either to the ON state or to the OFF state, no intermediate voltage value is foreseen
- as the voltage applied is of the order of few volts, the transitions between the ON and OFF state (and viceversa) is basically instantanous, hence no RAMPING_UP or RAMPING_DOWN state is foreseen.
4. The GE1/1 Slice Test

Hence the device and logical units used in the low voltage FSM tree are a simplified version of the ones used in the high voltage FSM tree, described in section 4.6.2. Their behaviour can be easily obtained removing all the STANDBY, RAMPING_UP, RAMPING_DOWN states and the GO_TO_STANDBY action from tables 4.3 and 4.4.

4.7 The FSM of the multi-channel supply

In principle the behaviour of the FSM operating the detectors supplied with the multi-channel power supply is in principle the one described in section 4.6.2 for the high voltage. In practice, its implementation is complicated by the fact that one chamber layer is supplied by seven different channels, that must be powered up following a precise order, and powered down in the opposite order. To give a practical example, when a command SWITCH_ON passes through the GEMINI01L1_HV node (see figure 4.11), we would like it to be first propagated to the Gemini01L1_G3bot and to no other children until Gemini01L1_G3bot has reached the ON state (or in any other state, in case the command failed). Only at this point we would like the command to be processed by the next child in the desired order, which Gemini01L1_G2bot. Again, the SWITCH shall be given to the next child, Gemini01L1_G1bot, only when Gemini01L1_G2bot has finished processing it, and so on.

FSM objects are described using the State Manager Language (SML), that allows detailed specification of the objects such as their states, actions and associated conditions. There’s no way to obtain that a command sent to an object A is suspended until an object B has terminated to process a command or has reached a new state. An alternative idea, could be to program the GEMINI01L1_HV node to send the command only to the first child, and then to delegate each child to send the command to the next HV channel when it has finished processing the command. This is not possible to be programmed only with the use of the SML, as device units don’t propagate commands, and they could not propagate them on objects on the same level in the FSM, but anyway this behaviour could be achieved with some smart programming of their actions. However, adding this feature on the action of a single high voltage device unit would interfere in cases when the command is given directly to one voltage channel in the FSM by a user. Alternatively, one could also think to rely on the board mode of the multi-channel power supply (see section 4.3).
4.7. The FSM of the multi-channel supply

If the latter is set to GEM mode, even if the commands are propagated at the same time to all seven channels, the board itself will force the execution to take place in the programmed onOrder or offOrder. Anyway, this system has a drawback: we would be forced to use the board only in GEM mode, giving up the possibility to use it in FREE mode. On the other end, the FREE mode would be necessary in case in the future there will be the necessity to exclude single HV channels. So, a different solution would be preferable.

Hence, I solved this problem using two tools: the GEM Configurator device unit and a GEM Configurator Control Manager. The former is a new device unit introduced on the same level of the seven HV channels of one detector layer, the Configurator, as visible in figure 4.11. The latter instead is basically a script that is always running in background, independent from the FSM. The combined use of these two objects allows to ramp the seven HV channels through an FSM command following the correct powering order, without affecting the code of the actions of single high voltage device units. In addition, it works with the board set either in GEM or FREE mode. This is a brief workflow of the adopted solution, also represented in figure 4.14:

1. a detector layer has to execute a command (for example, GEMINI01L1HV has to process the command SWITCH_ON)

2. the command is propagated only to the child of type configurator, no command is propagated directly to the seven device units connected to the seven HV channels

3. the configurator device unit changes the outValue of the datapoint to which is connected to the appropriate value

4. the new outValue triggers the execution of a script inside the GEM configurator control manager, which gives the appropriate FSM command externally to the HV channels FSM objects in the correct order

5. when the command has been given to all channels, the outValue is restored to the default value.

4.7.1 The GEM Configurator Device Unit

The GEM Configurator is a device unit to be installed on the same level of the voltage channels device units. It acts on a custom variable (a datapoint,
4. The GE1/1 Slice Test

Figure 4.14: Workflow of the interaction between the GEM Configurator device unit in the FSM and the GEM Configurator CTL manager in order to give the FSM commands to the device units of the HV channels in the proper order.

DP) of type GEMCaenConfigurator that has two integer elements (datapoint elements, DPEs): the inValue and the outValue. There’s one DP for each configurator, i.e. one for each chamber layer powered with the multi-channel supply. Hence in the slice test system only two of these DPs are necessary, one per layer of the Gemini01L1 chamber.

The state of the configurator FSM device object depends only on the inValue. Its state can be either WAITING, when no command is being processed and
4.7. The FSM of the multi-channel supply

<table>
<thead>
<tr>
<th>State</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAITING</td>
<td>if inValue=1</td>
</tr>
<tr>
<td>APPLYING</td>
<td>if inValue=0</td>
</tr>
<tr>
<td>ERROR</td>
<td>any other case</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Action</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWITCH_ON</td>
<td>set* outValue=1</td>
</tr>
<tr>
<td></td>
<td>*unless the detector protection is fired</td>
</tr>
<tr>
<td>GO_TO_STANDBY</td>
<td>set outValue=2</td>
</tr>
<tr>
<td>SWITCH_OFF</td>
<td>set outValue=0</td>
</tr>
</tbody>
</table>

The three actions are available in the APPLYING and WAITING states.

The states and actions of the GEM Configurator device unit are summarized in table 4.5.

the unit is in idle waiting for a command, or APPLYING, if a command has been received and is currently being processed. Also an ERROR state has been defined, which in principle should never happen, unless the mechanism is not working correctly and the \textit{inValue} goes out of the expected range.

The \textit{outValue} is the DPE on which the commands of this object act. It is updated whenever a command is received from the upper node. As a consequence, the GEM configurator control manager reacts to any change of the \textit{outValue}, as described in section 4.7.2.

4.7.2 The GEM Configurator Control Manager

In WinCC OA it is possible to have some \textit{managers} constantly running in background, i.e. processes responsible for specific tasks. I have installed a Control (CTL) manager, a dedicated runtime environment that processes programs written in the Control programming language of WinCC OA, here called \textit{GEM Configurator Control Manager}.

This manager, that is always running, monitors the DPEs \textit{outValue} on which the configurator device unit acts, and executes a script whenever one of such DPEs changes values. When this condition takes places, the script executes the following actions:

1. the desired action and target state are determined by the \textit{outValue}, for
example $\text{outValue} = 1$ means that the action to perform is SWITCH\_ON and the target state is ON (as listed in table 4.5)

2. the current state of FSM node of the layer involved is compared with the target state, in order to determine the powering order. For example, if the current state is STANDBY and the target state is ON, the powering order starts with the HV channel G3bot and ends with G1top. Instead, if the current state is ON and the target state is STANDBY, the powering order is inverted

3. set the $\text{inValue}$ to 0. In the FSM, this will cause the involved configurator device unit to change its state into APPLYING

4. the current limit $i_0$ of all seven HV channels is raised to 50 $\mu$A, to prepare them to be ramped without tripping (as explained in section 4.3)

5. a loop over the seven HV channels starts in the proper powering order, executing the following steps at each iteration

   (a) check whether the considered channel is disabled in the FSM. If so, skip it

   (b) set the current limit $i_0$ of the already processed channels to 50 $\mu$A again

   (c) check whether the device unit of the considered channel is already in the target state. If so, skip it

   (d) externally execute the desired FSM command to the device unit of the considered channel. In the FSM, this will cause the involved HV channel device unit to change its state into RAMPING\_UP or RAMPING\_DOWN, and then into the target state when the ramping is over

   (e) wait until the above device unit has reached the target state. It may happen that due to some external problem the channel never reaches the target state, causing the program to wait forever. Hence, a maximum waiting time of 40 s is set, after which the execution continues regardless the actual state of the device unit. In addition, during the waiting time the $\text{outValue}$ is also monitored. If the latter changes to a new value, the execution of this script will abort immediately (and the execution for the new $\text{outValue}$ will start)
4.7. The FSM of the multi-channel supply

(f) move to the next channel in the loop

6. check the beam mode (physics or cosmics) and the target state, in order to decide the current limit $i_0$ to be set on all channels at the end of the ramping

7. set the new current limit $i_0$ to all seven HV channels

8. set the $inValue$ to 1. In the FSM, this will cause the involved configurator device unit to change its state into WAITING

9. after 20 seconds, unless the $outValue$ has not changed meanwhile (i.e. a new command has been sent), the same current limit $i_0$ is set again to all seven HV channels. Instead, if the $outValue$ changed during the waiting time, abort the execution of this script.

In particular, to understand why step 5b is executed, it is necessary to look at the code of the actions of the channels device units. For example, if the command SWITCH_ON is given to an HV channel, the action script will first raise the channel current limit $i_0$, then apply the new $v_0$ setting, then it will wait for the end of the voltage ramping and finally it will set the current limit $i_0$ back to the proper low value. Hence, every channel that is considered in the loop will have, at the end, a low $i_0$ current limit inadequate for the voltage ramping. On the contrary, in this situation we would like the current limits $i_0$ of all seven channels to remain high and adequate for the voltage ramping until all seven HV channels have reached the target state. If this is not the case, the chamber may unnecessarily trip. Hence, step 5b is performed in order to ensure all current limits $i_0$ to be high enough until the complete ramping of the chamber is over. Step 9 instead has been added after some operational experience: I have observed that sometimes the new $i_0$ setting is not correctly applied to all seven HV channels, i.e. from time to time one or few of them are not correctly updated. Hence the application of the new current limit is repeated twice to ensure that it is correctly applied to all HV channels.

The FSM foresees the possibility to exclude nodes or devices. As a result, the upper node will not execute any command on the excluded node or device, and the excluded node will not be taken into account to compute the state of the upper node. In figure 4.15 is shown an example of node that has been excluded from the FSM. In this figure the node GEMIN01L1_HV, child of
the GEMINI01_HV, has been excluded from the FSM. As a result, the upper node is in STANDBY state, while if the child was not disabled it the upper node would be in OFF state according to states rules. In addition, when a SWITCH_ON command will be given to the upper node, the latter will be propagated only to the GEMINI01L2_HV node.

The same considerations also apply to the GEMINI01L1_HV and GEMINI01L2_HV nodes, whose children are the seven devices units acting on the HV channels and the configurator. The presence of the configurator device object does not affect the state of its upper node, as it is not considered in the computation of the upper node state. Concerning the exclusion of the excluded children from the propagation of the commands, the step 5a in the script of the configurator manager has been specifically introduced in order to preserve this feature.

The FSM of the multi-channel as described has been implemented in the GEM DCS of the slice test at the end of 2017, and it is working without issues and successfully since then.

Figure 4.15: Example of one FSM node displayed in the GEM DCS. In this example the FSM node GEMINI01_HV has been expanded. The two children, GEMINI01L1_HV and GEMINI01L2_HV, are also visible. In particular, the cross on the right of the node GEMINI01L1_HV means that the latter has been disabled in the FSM.

4.8 The GEM Detector Protection system

The operation of the protection system relies on the existence of an input condition, i.e. a boolean input variable, that is set to true when a situation requiring a protected action occurs, and is set back to false when this situation is over. In addition it is also necessary to identify one or more variables (output DPEs) to be set to a precise value and locked to such value until the input condition remains true (or fired). Locking a variable means that the
4.8. The GEM Detector Protection system

Concerned DPEs cannot be changed, neither through the FSM nor from the DCS panel nor anywhere else in DCS. For example, the detector protection is typically used to put the high voltage to STANDBY when LHC starts the injection, as programmed by the automation matrix (see Table 4.2). In such a case, one typically chooses the $v_0$ setting of the HV channels as output DP to be locked to the standby voltage. It is possible to create more than one detector condition depending on the same input variable. After a condition has been fired and the output DPEs have been locked, a verification is executed. Some DPEs and an expected value must be defined. Such DPEs are usually not the same used as output DPEs. In the previous example, one could for example set the $v_{Mon}$ value of the HV channels as verify DPEs, and expect them to be smaller than the standby voltage (plus some tolerance). This verification is typically used by the other CMS subsystems to participate in the handshake (see Section 4.9). Anyway the GEM slice test, whose control system is considered under development and in a test phase, does not participate to the handshake, so the verification (even if programmed) is not used for any purpose.

The presence of an input condition, the choice of the output DPEs and the value to assign them, as well as the choice of the verify DPEs and the verify function are basic requirements in order to realize a basic detector protection. In addition, it is also possible to define a PRE_FIRED and a POST_FIRED function, to be executed right before and after setting and locking the output DPEs respectively, and a PRE_GONE and a POST_GONE function, to be executed right before and after releasing the locked DPEs. A simple schema of the basic workflow of a detector protection condition, without the verification, is shown in Figure 4.16. In case more detector protection conditions linked to the same input condition exist, all their PRE_FIRED (or POST_FIRED, PRE_GONE, POST_GONE) are executed in sequence, following the creation order of the conditions, before moving to the next step in the workflow shown in Figure 4.16.

Protected actions foreseen in the GEM automation matrix are all PROTECTED STANDBY triggered by the same input variable. The latter is not controlled by the local GEM DCS but is provided and controlled by the central DCS. As the high voltage is supplied to the detectors in two different ways, either with the single-channel or the multi-channel supply, it has been necessary to develop two different detector protection systems to obtain the protected
standby of the high voltage. The two protection system are triggered by the same central input condition. Notice that our policy was to lock only the $v_0$ setting of the high voltage channels, but not to lock the $onOff$ setting. In this way, the result is that if a channel is powered the *only allowed* value is the standby voltage. On the other hand, it is always possible to switch off a chamber during a protected standby.

### 4.8.1 The Detector Protection for the single-channel power supply

The standby condition for the detectors supplied with the single-channel power supply is defined at 2500 V erogated by the voltage supply for all chambers. At this voltage the electric fields inside to the GEM foils are to low for the charge multiplication to take place, hence the detector is considered in a safe state, even if it is not completely OFF. The use of a non-zero voltage for the STANDBY state allows to bring the detectors ON and ready for physics more quickly as soon as they shall be switched on and get ready for physics. At the voltage of 2500 V the current of each high voltage channel is about 470 $uA$, mainly determined by the value of the voltage divider used to distribute the voltage to the cathodes. The exact value of the current varies in range of about $\pm 5 \mu A$ with respect to the above reference value. Hence, the current limit $i0$ used in the STANDBY condition also slightly varies chamber by chamber. Such values, as well as the value for the ON states, are stored in dedicated recipes saved in an ORACLE Conditions database, from where they can be loaded when necessary. We use to load those values not directly to the $v0$ and $i0$ settings of the channels, but to the $v1$ and $i1$ settings: in this way as soon
4.8. The GEM Detector Protection system

as they are loaded they will have no effect, but they will available to be copied to the proper settings when necessary.

As the voltage value to be applied is the same for all high voltage channels, it is straightforward to use the $v_0$ settings of all HV channels as output DPEs to be locked at the value of 2500 V. The current limit $i_0$ instead must be adjusted in the PRE_FIRED and POST_FIRED functions. The resulting structure of the detector protection for the single-channel power supply works as follows:

- firstly, in the PRE_FIRED function the recipe for the STANDBY condition is loaded. This step has no real effect on the system, but only stores the proper current limits into the $i_1$ settings and makes them accessible for later. The function waits until the loading of the recipes is succesfull, in order to avoid the execution of the next steps with not up-to-date settings.

- secondly, in the PRE_FIRED function a loop over all HV channels searches for channels whose actual voltage is smaller than 2500 V and already sets the $i_0$ current limit to the value stored in $i_1$. This step is performed because a smaller voltage should also have a smaller current limit, and the chamber would trip as soon as a higher voltage is applied if the current limit was not increased. The function waits until the new $i_0$ setting is observed as actually written in the hardware

- the detector protection sets the $v_0$ settings to 2500 V to all HV channels, and locks them

- eventually, the POST_FIRED function waits for the HV channels to stop the voltage ramping, and sets the current limits $i_0$ to the values stored in the setting $i_1$.

As soon as the input condition will be released, the voltage settings $v_0$ will also be released. Every time the code is programmed to wait, for example for the recipe to be loaded or for a new current limit $i_0$ setting to be actually written in the hardware, a maximum waiting time is always set, in order to avoid to hold the script forever in case the target condition is never reached.

4.8.2 The Detector Protection for the multi-channel power supply

Also in the development of the detector protection, the case of the multi-channel power supply is more complicated because of the presence of seven
4. The GE1/1 Slice Test

Table 4.6: Definition of the STANDBY state for the chambers powered with the multi-channel power supply.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Voltage setting [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>740</td>
</tr>
<tr>
<td>G1top</td>
<td>0</td>
</tr>
<tr>
<td>G1bot</td>
<td>285</td>
</tr>
<tr>
<td>G2top</td>
<td>0</td>
</tr>
<tr>
<td>G2bot</td>
<td>575</td>
</tr>
<tr>
<td>G3top</td>
<td>0</td>
</tr>
<tr>
<td>G3bot</td>
<td>310</td>
</tr>
<tr>
<td>Sum</td>
<td>1910</td>
</tr>
</tbody>
</table>

The GE1/1 Slice Test

high voltage channels per chamber. For such detectors, the concept of the STANDBY condition is the following: the three voltage channels supplying the GEM foils (G1top, G2top, G3top) have no voltage applied in order to suppress the charge multiplication, while the four voltage channels producing the electric fields in-between the GEM foils, the drift field and the transfer field (Drift, G1bot, G2bot, G2bot) can be powered with the same values used in the ON state. As the operational voltage used in the ON state is detector-dependent, the direct application of this rule would also produce different STANDBY voltage settings for each detector. In addition, if we think to re-use the same system also with the full GE1/1 station equipped with 144 triple-GEM detectors, the total number of settings would raise to an incredibly large amount. This is though not necessary, as it is enough that in STANDBY the detectors are in a safe condition from which they can quickly be powered up to the ON state. In addition, the concept of the detector protection requires a set of DPEs to which the same value shall be applied and locked, and the use of a large amount of different settings would make the implementation of the detector protection far too much complicated. Hence, the above rule has been simplified, by setting the same voltage to all channels of the same type, chosen to be roughly a bit smaller than the average value of each channel type. The resulting definition of the STANDBY voltage is shown in table 4.6.

This definition of the STANDBY state reduces the number of voltage settings to seven values, or to four values if one considers the multiple zero voltage settings. Concerning the scalability to the complete GE1/1 system, the number of voltage settings to realize the STANDBY condition does not increase.
4.8. The GEM Detector Protection system

regardless the size of the system, hence this definition will be applicable also when the complete GE1/1 system will be installed.

A second difficulty is also present, that is the need to apply the standby voltage to the seven HV channels of each detectors following the proper powering order.

The adopted solution to achieve the protected standby condition for the chambers powered with the multi-channel supply is to use seven different detector protection conditions, one per HV channel type. One condition, the one setting and locking to standby the first channel type in the sequence (G1top), is linked directly the central input condition. Further six local input variables have been created in the local DCS project, each one acting as input condition for one of the remaining 6 channel types. In order to accomplish the correct powering order, in the POST_FIRED function of the each condition the input variable of the channel type to be ramped next is set to true. On the contrary, all the local input conditions are set to false as soon as the central one is set to false, in order to release all the HV channels at the same time as soon as the protected standby is no longer necessary.

In addition, as explained in section 4.3 it is necessary to increase the $i\theta$ current limit of all seven channel before starting to ramp the voltage on the first channel type, and to set it back to the proper limit for the STANDBY condition once all of them have reached their standby voltage. Hence, the current limits $i\theta$ are all increased in the PRE_FIRED function of the first condition to execute (G1top channel type), and set to a lower value in the POST_FIRED function of the last condition to execute (G3bot channel type).

Some other precautions must be inserted, like aborting the process in case the central input condition is released before the entire chain of conditions has been executed to its end, and the possibility to restore $i\theta$ current limits to an appropriate value in that case. Indeed, if the entire workflow did not reach the POST_FIRED function of the last condition, the current limits $i\theta$ would remain set to the high value for the ramping of the detectors, with the detectors being partially or entirely ON.

Hence, I have developed two different designs of detector protection configurations, one for G1top channel type directly depending on the central input variable, and one for the other six channels types depending on local input variables. The complete configuration of the detector protection of the first is as follows:
1. the PRE\_FIRED function sets all \( i0 \) current limits of all channel types to high value, preparing the system for the voltage ramping. Before exiting, it also waits to check that the new settings have been actually written in the hardware.

2. the output datapoint to be locked are all channel05 and channel12 of all the multi-channel power supply board found in the system. The output value to set and lock is \( 0 \) V in this case.

3. the POST\_FIRED waits for the channels to stop ramping and for the \( vMon \) to be as expected within some tolerance (\( vMon < 5 \) V). If during the waiting time the input variable is released, abort the process. After all channels have ramped to the expected voltage, the input variable of condition2 is set to \( true \).

4. when the central input variable is released, the POST\_GONE function waits for all channel to stop ramping. Then it will evaluate the proper current limit \( i0 \) to set on each layer according to the voltage applied on the GEM foils and to the data-taking condition (beam or cosmics physics). If meanwhile the input variable changes, the process is aborted.

In particular, step 3 triggers of the next input condition to be executed according to the powering order, that will bring the G2top channel types to protected standby. Step 4 has been inserted in order to put a safe current limit in the extraordinary case – that from time to time may happen – that the input conditions is fired for a short time and the time in which it is active is not long enough to bring all channels to the standby voltage. In that case, the configuration of the voltage channels will be mixed, with some of them in STANDBY and some of them in the previous state (typically ON). In this case, the current limit to set depends on whether the GEM foils are ON or STANDBY. If any of them is ON, then the current limit \( i0 \) is set to the operational value, that in turn depends on the data-taking condition (beam or cosmics physics). If all GEM foils are in STANDBY, then the current limit \( i0 \) is set to the standby value. Notice that the POST\_FIRED function is always executed, also when the detector protection is fired for a normal duration. In this case, it will simply re-assign the current limit \( i0 \) was in the POST\_FIRED function of condition 7.
4.8. The GEM Detector Protection system

<table>
<thead>
<tr>
<th>Condition</th>
<th>Input</th>
<th>Output channels</th>
<th>Expected vMon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>central</td>
<td>05,12 (G1top)</td>
<td>&lt; 5 V</td>
</tr>
<tr>
<td>2</td>
<td>local</td>
<td>03,10 (G2top)</td>
<td>&lt; 5 V</td>
</tr>
<tr>
<td>3</td>
<td>local</td>
<td>01,08 (G3top)</td>
<td>&lt; 5 V</td>
</tr>
<tr>
<td>4</td>
<td>local</td>
<td>06,13 (drift)</td>
<td>&lt; 745 V</td>
</tr>
<tr>
<td>5</td>
<td>local</td>
<td>04,11 (G1bot)</td>
<td>&lt; 230 V</td>
</tr>
<tr>
<td>6</td>
<td>local</td>
<td>02,09 (G2bot)</td>
<td>&lt; 580 V</td>
</tr>
<tr>
<td>7</td>
<td>local</td>
<td>00,07 (G3bot)</td>
<td>&lt; 315 V</td>
</tr>
</tbody>
</table>

Table 4.7: Definition of the STANDBY state for the chambers powered with the multi-channel power supply.

The second type of detector protection conditions only use the POST_FIRED function. Its design is the following:

- the output datapoints to be locked depend on the specific condition and are shown in table 4.7
- the POST_FIRED function waits for the output channels to finish ramping and to reach the expected voltage value. Then the input variable for the next condition is set to true. If during the waiting time the input variable has changed, abort the process.

In the above descriptions, every time a function is programmed to wait for a condition to be reached, a maximum waiting time is always set, so that if the action in question fails the function will not hang forever.

A simplified schema of the overall workflow of the detector protection for the chambers powered with the multi-channel power supply, showing only the main steps, is shown in figure 4.17. I have already programmed the verify function in view of the future when the GEM subsystem may be included in the LHC handshake. The detector protection condition for the G1top channel type, depending directly on the central input variable, acts on the G1top channels but performs the verification on the G3bot channels. According to the powering order, the latter channels are the last ones to reach the standby voltage, hence the verify function will positively answer only if the entire chain...
4. The GE1/1 Slice Test

Figure 4.17: Simplified schema of the design of the detector protection for the chambers powered with the multi-channel power supply. The main concepts and how they are concatenated are shown.
of conditions has successfully been executed to its end. The full chain has been programmed in such a way that, if for any reason one step fails, the chain of the detector protection conditions is interrupted, hence the G3bot channels will be at voltage standby only if all the other channels are also at standby voltage. In the extraordinary event that the chain did not come to its end – so far never observed – the DCS shifter in the control room should call a subdetector expert in order to check the reason and fix the problem.

4.9 Inclusion into the central CMS DCS

The FSM and the detector protection, the tools allowing for the automation and implying the possibility to run unattended, were the last features to be added to the control system, so that at beginning DCS consisted only in the panels for the user control. In addition, in the first months of slice test the system could only be ON if attended by a GEM expert, as the DCS, the alert system, and probably the GEM crew itself were considered in a test phase.

Reaching the current situation has implied several steps. When the FSM and the detector protection have been deployed, the GEM subdetector was immediately included in the central CMS DCS. Initially a dedicated test system was created, mimicking the central one, through which the GEM DCS could receive the LHC and beam changes of state and start following the automation matrix. This was done in order to give us the possibility to test our FSM and detector protection, integrating some time of operation in a “close-to-real” running system in order to address and solve any issue. In addition, we had to adapt them in order to be consistent with the CMS DCS operational requirements.

After the test phase, in December 2017 the GEM FSM and detector protection were included in the real central CMS DCS. Since then the detectors are automatically operated and, in particular, the first activities in this condition with beam inside LHC were performed in March 2018. Since approximately May 2018 the system has been considered safe and stable enough to run unattended, relying on the correct operation of the automation system and the alert system.

Nevertheless, as the slice test is only composed of a small amount of detectors and is a test installation, its inclusion in central is still not exactly like the other subdetectors in order to avoid that its presence in the central CMS
DCS could interfere with the normal CMS operation. There are two differences between the GEM subsystem and other ones:

1. the GEM subsystem does not participate in the LHC handshake

2. the error states of the top node of the GEM FSM are not propagated up to the central CMS node.

The handshake is a procedure between the LHC and the experiments, according to which an injection warning is sent to the experiments before LHC starts the injection. The experiments shall answer, allowing the injection only after subdetectors confirm that they are safe and ready for the injection. This answer is based on the verification of the detector protection systems of all subdetectors. The second condition, i.e. avoiding the GEM subsystem to propagate its errors to CMS through the FSM, has been achieved with the introduction of a dummy node in the FSM, as shown in figure 4.18. When a command arrives from the CMS node, it is propagated down to the GEM node, to its children and finally to the GEM_CMS_DUMMY and the GEM_ENDCAP_Minus. The latter is the upper node of the GEM subsystem shown in figure 4.12, that will further propagate the command to the GEM hardware causing it to react accordingly. The former node instead has no real effect on any hardware, but simply changes its state into the expected one whenever it receives a command. For example, if the command GO_TO_PHYSICS is sent, the GEM_Dm node always becomes READY_FOR_PHYSICS.

The GEM node is programmed in a way that commands are propagated down to both children so that the GEM subsystem can receive commands from central and follow the automation matrix, but its state only depends on the GEM_Dm node so that the state of GEM_ENDCAP_Minus node (through the GEM_E node) cannot be propagated up to the CMS node. In this way, any ERROR state in the GEM upper node will not affect the state of the CMS node in the central FSM.

4.10 The DAQ system

The VFAT chip is a synchronous chip with 128 identical channels, designed to sample at the LHC clock frequency of 40 MHz. It has two main goals: triggering, by providing a fast regional hit information to be used in the Level-1
trigger, and tracking, by providing a precise spatial hit information for a triggered event. Each channel has its own chain composed of a preamplifier and a shaper whose signal is then discriminated against a settable threshold. Its operation can be summarized as follows: if a threshold is reached on a given bunch crossing on one channel, a binary pulse, whose duration can be stretched over multiple clock cycles, is generated. A fast hit information with fixed latency is provided to the trigger system, formatting the output of 128 channels into the logical-OR of two adjacent strips (hence reducing the number of sent bits by a factor two). Instead, upon the reception of a Level-1 Accept (L1A), the full granularity information of an event is stored with the information of the time elapsed from the L1A reception in units of bunch crossings (BX Counter) and the number of L1A received (Event Counter). The latency parameter, described in the following, determines which event needs to be transferred.

In order to prepare the DAQ system and verify its status and readiness, several scans and calibrations are performed regularly. The routine mainly consist in threshold scans, latency scans and s-curves scan.

### 4.10.1 Calibration

**Threshold scan.** The first parameter to adjust is the threshold, to be set according to the noise induced on the VFAT by the system and channels. This
is the goal of threshold scans, to be run in absence of beam. For a given set of threshold values, the noise of each threshold value is defined as the ratio of events containing hits to the total amount of collected events. An example of an ideal threshold scan is shown in figure 4.19 top, where the noise decreases with higher thresholds. The lowest threshold with zero noise is desirable to be selected as parameter.

Figure 4.19: Top: example of ideal threshold scan, representing the percentage of events with hits as a function of the applied threshold [86]. Center: example of ideal latency scan, representing the percentage of events with hits as a function of the applied latency [86]. Bottom: example of S-curve on one channel with a given threshold, representing the fraction of events with hits as a function of the injected charge [86].
Latency scan. Once the threshold is set, the next parameter to adjust is the latency, determining the correct bunch crossing when a L1A is received. This calibration is done in presence of beam. The latency is a programmable parameter containing the information of the delay, in bunch crossing units, between the digitization of an event and the arrival of a L1A. It represents the response time of the system, which is typically a fixed delay. In this case, for a given set of latency values the ratio of events with a hit to the total number of events is counted. As the latency is the delay of the signal with respect to the L1A and the detector response is fixed, if the latency is too low or too high the hit is missed. The latency value that maximizes the above ratio is optimal. An example of ideal latency scan is shown in figure 4.19 center.

S-curves. S-curves characterize the response of channels as a function of the collected charge and threshold. For a given threshold settings, a charge pulse is injected into each channel and ratio of events with hits to the total number of events is measured. An example is shown in figure 4.19 bottom. S-curves indicate at which amplitude of the injected calibration pulse signals start to become visible with a given threshold. In the example, charges smaller than 40 VFAT2 units are not visible, while the turn-on value, at which 50% of injected signals are detected, is 44 VFAT2 units. This scan allows to translate the threshold value, expressed in VFAT2 units, into the correspondent calibration pulse height in VFAT2 units, represented by the turn-on value. The threshold value can then be converted into a charge, used to evaluate the equivalent noise charge of the system.

The response of individual channels displays a dispersion around a central value, indicating that the effective threshold is not constant across a VFAT chip. This dispersion may introduce a bias, that can be eliminated equalizing the front-end response. This is achieved through individual registers that adjust the threshold values channel by channel. Figure 4.20 shows an example of trimming performed on one VFAT mounted on a chamber of the slice test.

Some of the first physics data detected with the slice test GEM detectors in 2017 are shown in figure 4.21. They represent the count of produced S-Bits, the fast OR’ed output produced by the chips for triggering, as a function of the elapsed time from a L1A accept received from CMS, taken during a run of cosmics and a collision run. They both show a peak at a delay of approximately ~ 170 bunch crossings, indicating that the slice test chambers
Figure 4.20: Example of S-curves taken before (top) and after (bottom) adjusting the individual channel registers to trim the 50% response point of the same calibration pulse. Each plot shows the fraction of events with hits per VFAT channel and per injected calibration pulse. These curves were taken on the VFAT in position 0 of the Gemini01L2 chamber in 2017, when still equipped with the VFAT2 version of the chip.

have also detected the muon event triggered by CMS.
Figure 4.21: Example of distribution of delays between observed S-Bits and a received L1A for cosmic muon data (top) and collision data (bottom), integrated over all VFAT positions.
4.11 System performance

Approximately in the first year of the slice test the GEM subsystem mainly performed only local runs.
Since approximately summer 2018 the chambers Gemini27 to Gemini30, equipped with version 2 electronics, have started to participate in the CMS global runs, so that currently the slice test chambers can both collect data in local runs independent from the CMS data taking, and collect data included in the global CMS data acquisition. The inclusion into the global DAQ system is not yet completely automatic and some manual interventions are still necessary, nevertheless with the supervision of an expert on the GEM side it is possible to prepare the system for the global CMS runs. Currently, by mid-September 2018 more than 14 fb$^{-1}$ have been collected in 2018 with the GEM subsystem included and stable.

4.11.1 Stability

One of the first system properties that was possible to analyze since the very beginning of the slice test is the stability of the system, in terms of applied voltage and currents measured on the low voltage and high voltage channels powering the system. Indeed, such values are stored in an Oracle database by the DCS and are available since the very first version of the DCS was deployed, at the beginning of 2017.

After an initial debugging period performed with the help of CAEN engineers, in particular to solve some firmware issues on the multi-channel board that were causing the latter to go into error states and to switch off the detectors, a stable operation of the HV and LV system was successfully achieved, both outside collisions and during collisions. Some examples of stability plots of low voltage and high voltage supplied with the standard HV supply are shown in figure 4.22. The curves of the low voltage channels are clearly divided in periods with different voltage and current: the LV has remained on for all the considered period except for a short moment on the 14$^{th}$ of April, but the operation alternated between standby and running periods, during which the voltage and current change accordingly. When VFATs are in sleep mode the current is about 2 A, while during runs it increases up to about 6.5 A.

Concerning the chambers powered with the multi-channel supplied, in section 4.2.1 it was explained that this configuration provides a more sensitive
4.11. System performance

Figure 4.22: Stability plots of the low voltage channel (top) powering the GEB and VFATs of Gemini28L1 over ten days in April 2017 and of the high voltage channel (bottom) powering the same chamber over 7 hours in September 2017 during an LHC fill with collisions. Blue data series represent the actual voltage (right scale), red data series the monitored current (left scale). Data are automatically stored into an Oracle database by the DCS when a value changes, hence this determines the sampling of points. Values must be considered unchanged until the next point in a data series.
monitoring of the charge produced inside the detector. Indeed, at instantaneous luminosities approximately bigger than $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ we could observe a clear dependence of the measured current from the instantaneous luminosity itself, which instead is not visible on HV channels using the standard HV supply and the divider to distribute the voltage to the detector electrodes. An example is shown in figure 4.23. We are currently investigating whether a precise relationship between the instantaneous luminosity and the detector currents exist.

### 4.11.2 Detector Performance

As mentioned above, since few months the GEM subsystem is participating in the global CMS runs. This has allowed to start performing the first performance studies on the subsystem. Results shown are very recent and still under improvement, besides not yet fully understood.

**Efficiency.** One important performance to evaluate is the detector’s efficiency. A first measurement is shown in figure 4.24, showing the efficiency per eta partition of the slice test chambers Gemini27 to Gemini30, evaluated on a collision run taken in July 2018. The average efficiency per chamber varies between approximately $(50 - 60)\%$, with maximum measured efficiencies per eta partition of about $\sim 74\%$ and lower eta partitions (further away from the beam direction) displaying the lowest efficiencies. A low efficiency was expected, as it has already been addressed that this version of the electronics has a high intrinsic noise that forces to set high thresholds. In particular, the maximum amplitude of noise pulses is comparable to the amplitude of the smallest signals. Hence, a threshold high enough not to select noise pulses is also bigger than some real signals. For this reason the efficiency measured with the slice test chambers is smaller than the detector intrinsic efficiency. The role of the electronics on the low measured efficiency is also confirmed by the dependence on the eta partition. Indeed the effect is bigger at low eta partitions, closer to the front-end electronics where the intrinsic noise is higher. A new version of the electronics aimed at fixing this issue is already under development.

**Hit rate.** A second fundamental study is the hit rate measurement. The background rate increases with the beam luminosity, hence as a consequence also the measured hit rate shall increase with the instantaneous luminosity.
4.11. System performance

Figure 4.23: Measured current $i_{Mon}$ (coloured curves, left scale) on all seven channels powering the electrodes of Gemini01L2 while ON and ready for physics, superimposed to the beam instantaneous luminosity (grey, right scale) during an LHC fill with collisions. In the period considered the initial instantaneous luminosity is $1.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and diminishes to $0.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in about 13 hours.
The verification of such behaviour is an indicator of the correct operation of the detectors. In figure 4.25 a measurement of the background hit rate is shown, performed on data taken during a physics of mid-August 2018. The hit rate has a clear dependence on the beam instantaneous luminosity. Anyway in principle all detectors should show the same hit rate, no dependence on the chamber or on the layer is expected. Indeed, there should be a dependency on the pseudorapidity, i.e. on the eta partition, but the hit rates shown are averaged over the entire detectors’ surface. The hit rate curves of five of the eight chambers overlap and are in good agreement with each other, in the upper part of the plot; three of them instead show lower hit rates. The reason is currently under investigation. Apparently there is also no clear correlation with the chamber efficiency shown in figure 4.24, showing that the three chambers with lowest hit rate have an overall efficiency of about $(54 - 55)\%$ but, for example, Gemini29L1 has the lowest efficiency $(50.08\%)$ but displays one of the highest measured hit rates. There is also no evident drop in efficiency in the highest eta partitions, where a bigger background rate is expected, that
4.11. System performance

could motivate a reduced background hit rate. Anyway, crosschecking the efficiency values shown in figure 4.24 may not be meaningful, as the efficiency calculation is performed on muons, while the background rate is induced by a larger spectrum of particles, to which the detector’s response is in general different. Further analysis are currently ongoing to investigate the differences of the measured background hit rates between the chambers. Another point to be mentioned, is that the electronics may have not been optimized during the analysed fill. In particular a not ideal value of the monostable pulse length (the duration of the signal in units of bunch crossing) could not have been used, causing a systematic error that is rescaling the measured hit rate of all chambers. Also for this reason, more studies to clarify the correct background hit rates are ongoing.

Figure 4.25: Measured hit rate per slice test chamber equipped with VFAT2 ASICs as a function of the instantaneous luminosity.
4.12 Conclusions and future perspectives

The GE1/1 slice test is being a very fruitful experience in view of the full installation of the GE1/1 station next year, and also of the other GEM stations that will be installed later in the future. It allowed the team to face the integration problem on a small system, acquire the expertise necessary to achieve it and gain lots of operational experience. The possibility to perform the integration process of a reduced GEM subsystem into the CMS system should allow, in the future, to include the entire GEM subsystems more smoothly from all points of view.

4.12.1 The Detector Control System

Concerning the DCS, the experience gained during the slice test has been fundamental both in order to understand the needs of an effective DCS, to improve our knowledge of the software and how to implement the tools necessary for the operation within the entire CMS experiment, besides starting to address and solve the difficulties faced in these processes.

This first version had been conceived starting from the experience gained on small systems, made of one or few detectors, and without a deep knowledge of the existing CMS central DCS and its rules. Also, in the development of the DCS a challenge was represented by the inability of testing it in a full hardware scale prior to the installation in the CMS environment. Hence, often only the deployment of a new part of the control system in the production project could show unexpected issues, followed by the need to insert additional features. Consequently after the DCS deployment several details have been reviewed and adjusted according to the operational experience. The resulting version is currently running stable and being used daily.

In addition, now that we know the most important needs of a control system, how to implement them, and already have developed the basic pieces of control codes and tested them widely during the slice test, we can also focus on realizing a more attractive and better organized design of the DCS. The design of the DCS of the entire GE1/1 system is already ongoing, involving a larger team in deep contact with us, the developer of the very first control system of the GE1/1 slice test, in order to profit of the experience we gained in this first experience.

Concerning the future plans, during the long shutdown starting in 2019
the installation of the full system composed of 72 Gemini chamber will take place. The DCS will have to be extended in order to safely and efficiently control such a larger system. The high voltage and low voltage systems of the full GE1/1 station will be more similar to the ones currently used for the Gemini01 chamber. The realization of its DCS system will of course be based on the one developed and improved during the slice test experience. From the point of view of the panels for the user control, the main panel will have to be optimized in order to visualize a larger system. Such visualization shall give a clear summary view of the entire system at one glance and rapidly highlight the presence of problems in one of its part. From there, one shall be able to access the panels to control single items of the system, down to single detectors’ HV and LV, single mainframes, single gas lines. Detailed panels can be taken from the ones developed for the slice test, widely tested and ameliorated according to the users’ requests.

Concerning the GEM FSM, there is still a feature to develop that has not been introduced in the slice test DCS, i.e. the majority. The latter is a logic according to which at least $m$ out of $n$ children must be in error, in order for the upper node also to go into an error state. In the current FSM, a single child in error would move its parent node into an error state. As the system of the slice test is very small – only 5 Gemini chambers – the latter feature has not been implemented, but it will be necessary to introduce it in the DCS of the entire GE1/1 system.

Eventually, the structure of the FSM used in the slice test is designed according to the system’s logical view, but we are discussing whether it would be better to switch to an hardware view, or even to implement both of them. In any case, the structure or at least the objects developed for the slice test FSM can be also widely reused for the complete GE1/1 system. The same applies also for the detector protection.

4.12.2 The DAQ system and Detector Performance

The slice test data acquisition system has been operated to take data both in local and global runs. In particular, the GEM subsystem can participate in the global CMS DAQ since the beginning of this summer. We have started to analyze the data collected, whose detailed analysis is in a full swing in this period. The capability of correctly detect cosmic muons and muons from col-
4. The GE1/1 Slice Test

Collisions were verified. Some of the first detector performance studies are shown. In particular, chambers show an average efficiency of $(50 - 60\%)$, while an efficiency to muons close to $100\%$ is expected for triple-GEM detectors, and a background hit rate consistent with luminosity is observed, together with large variations (up to a factor 2) between different chambers. The low efficiency is most probably due to the high noise in the version of the electronics currently mounted on the slice test chambers, in which the amplitude of noise signals is comparable to signal produced by muons. This forces to use a threshold excluding also a part of the real signals. The development of a new version to solve this issue is already ongoing. The difference in the measured background hit rates is being investigated, both on the side of the calculation algorithm and on the side of the parameters used in the electronics. In general, results are very recent and not yet fully understood and possibly to be improved, but they can anyway confirm the proper operation of the detectors. Efforts are being done in order to improve the understanding of the results and hence the overall performance.

In addition, it is currently possible to run the GEM subsystem included in the global CMS DAQ, with a strong participation of experts in order to prepare the system and verify its status. Further debugging and development of the DAQ system and electronics is ongoing in order to allow to run stably and smoothly in central.
Chapter 5

A Trigger Study for the ME0 Station

5.1 Introduction

5.1.1 The ME0 station

The ME0 station, already introduced in section 2.5, will be installed in the region $2 < |\eta| < 2.8$ of the muon system endcap, partially overlapping with the existing muon system (up to $|\eta| < 2.4$) and extending it to higher pseudorapidity. Hence, at $|\eta| < 2.4$ it can work in conjunction with the existing muon system like the GE1/1 and GE2/1 stations, while beyond this value a different trigger system needs to be developed. In order to compensate for the lack of muon detectors in the latter region, the ME0 station will consist of six detector layers, instead of two layers like the other two GEM stations.

5.1.2 L1 trigger for specific analyses

Trigger and event reconstruction are made more difficult by the harsh environment characteristic of the ME0 region and rapidly increasing with pseudorapidity, as shown in figure 2.19. Consequently, in the extended muon system range a standalone L1 trigger can not be realized due to unsustainably high rates in this very forward region.

However, muon segments identified in this region can still be used as a part of multi-object topological L1 triggers dedicated to specific physics analyses. This concept is currently not implemented in CMS and would represent a
completely new feature for the L1 trigger, since multi-objects are currently built only up-stream in the L1 chain, in the Global Muon Trigger and Global Trigger.

This chapter presents a preliminary trigger study focused on the ME0 station. The goal is to evaluate its capability to detect physics channels with final muons in the very forward region in a first simple $p_T$ assignment and trigger version, and to suggest new features and improvements. The study focused on the $\tau \to 3\mu$ decay, one of the most interesting physics channels that could benefit from the muon system extension provided by the ME0 station, already mentioned in section 2.5.1.

5.1.3 The $\tau \to 3\mu$ decay

In the Standard Model the branching ratio of the $\tau \to 3\mu$ decay is immeasurably small, of the order of $\mathcal{B}(\tau \to 3\mu) \sim 10^{-40}$, only possible via higher order contributions involving neutrino oscillations like the one shown in figure 5.1. Anyway several exotic models predict branching ratios up to $10^{-11} - 10^{-8}$ [87–91], that could be within experimental reach. For example, an extended minimal SUper GRAvity (mSUGRA) scenario exposed in [87] foresees branching ratios up to $\mathcal{B} \sim 3 \cdot 10^{-11}$, or the Standard Model with additional heavy right-handed Majorana neutrinos or left-handed and right-handed neutral isosinglets studied in [90] predicts up to $\mathcal{B} \sim 10^{-10}$, technicolour models with non-universal $Z'$ exchange predict up to $\mathcal{B} \sim 10^{-8}$ [91], and others. They all lie below the strictest experimental limit on the $\tau \to 3\mu$ decay, posed by the Belle experiment, of $\mathcal{B}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}$ [41].

Figure 5.1: Example of one-loop $\tau \to 3\mu$ decay in the Standard Model involving neutrino oscillations.
5.2. Tau production at the LHC

During the HL-LHC lifetime 3000 \( fb^{-1} \) are expected to be delivered, corresponding to the production of about \( 5 \cdot 10^{14} \) tau leptons, begging for a \( \tau \to 3\mu \) search. For example, for a branching ratio of this decay of the order of \( 10^{-8} \) about \( 5 \cdot 10^6 \) decays are expected to be produced during HL-LHC. In table 5.1 the number of expected decays for some of the theoretical branching ratios predicted by different exotic models mentioned above are summarized. They approximately vary in the range of \( 10^3 - 10^6 \) expected decays depending on the branching ratio predicted by the model.

The relative rates for the production of hadronic taus at the LHC are collected in table 5.2. The main source of tau leptons comes from the decay of the \( B \) and \( D \) mesons, whose final muons are significantly boosted in the forward region. Within CMS, analyses are ongoing on the dataset collected in 2016,

\[
\begin{array}{|c|c|}
\hline
\mathcal{B}(\tau \to 3\mu) & \text{decays} \\
\hline
10^{-10} & 4.76 \cdot 10^4 \\
3 \cdot 10^{-11} & 1.43 \cdot 10^4 \\
10^{-11} & 4.76 \cdot 10^3 \\
\hline
\end{array}
\]

Table 5.1: Number of \( \tau \to 3\mu \) decays expected over the HL-LHC lifetime (3000 \( fb^{-1} \) of integrated luminosity) for different theoretical predictions of the branching ratios of the decay process.

\[
\begin{array}{|c|c|c|}
\hline
\text{meson} & \text{mass (GeV)} & \text{relative tau yield} \\
\hline
D_s & 1.97 & 72\% \\
D^+ & 1.87 & 3\% \\
B^+ & 5.28 & 11\% \\
B^0 & 5.28 & 11\% \\
B_s & 5.37 & 3\% \\
W & 80.4 & 10^{-4} \\
Z & 91.2 & 2 \cdot 10^{-5} \\
\hline
\end{array}
\]

Table 5.2: Relative rates of taus (charge conjugated states included). Rates for hadronic taus are obtained with PYTHIA Minimum Bias process, rates for W/Z-produced taus are obtained by NNLO W/Z cross sections and the branching ratios of \( W \to \tau\nu \) and \( Z \to \tau\tau \).
corresponding to about 33 $fb^{-1}$ of integrated luminosity, on tau leptons coming from the $D$ and $B$ mesons decay and also on tau leptons from the $W \rightarrow \tau \nu$ process, whose advantage is represented by the production of harder final muons. Anyway, with the current detector configuration only 1.3% of signal events have all three final muons lying the current detector acceptance [93]. Instead, first studies [16] focused on the impact of the ME0 station (see section 2.5.1) have shown that the increased muon acceptance up to $|\eta| \sim 3$ would increase the signal acceptance by a factor 2.9, and that events with at least one muon reconstructed by the ME0 detector during HL-LHC ($3000 \, fb^{-1}$) could lead to an exclusion sensitivity in absence of signal of $\mathcal{B} < 3.7 \cdot 10^{-9}$ (90% CL) and an expected 5$\sigma$-observation sensitivity of $\mathcal{B} = 1.1 \cdot 10^{-8}$ [16]. Without the ME0 station, 4000 $fb^{-1}$ would be necessary to reach the same sensitivity.

In total, 83% of the tau leptons produced at LHC comes from the decay of the $B^0$ or the $D_s$ mesons. The present study, hence, was performed using as signal tau leptons from the decay of the $B^0$ and $D_s$ mesons. In particular, the use of tau leptons coming from the $W$ and $Z$ bosons would have been of advantage as their high mass would result in harder final muons, easier to trigger than soft ones. Unfortunately (see table 5.2), their relative rates are smaller than $10^4$. Added to the fact that we are looking for a rare decay whose branching ratio is smaller than $\sim 10^{-8}$, the $W$ and $Z$ decay channels have not be considered for this study because the number of events of interest traversing the ME0 station produced during HL-LHC is very small.

5.2.1 Signal simulation

To produce signal datasets, proton-proton collisions at a center of mass energy of 13 $TeV$ were simulated, forcing only one $B^0$ (or $D_s$) per event, if present, to undergo the full decay chain $B^0(D_s) \rightarrow \tau \rightarrow 3\mu$. Only events with the latter decay have been kept, while all other events have been rejected. In this way, a dataset containing a single $B^0(D_s) \rightarrow \tau \rightarrow 3\mu$ decay per event was generated. In addition, to focus the study on the capability of the ME0 station to trigger such events, some datasets were generated with the additional request for at least one muon in the pseudorapidity range $1.8 < |\eta| < 3$.

Datasets are produced with the CMSSW [94] framework, a collection of software that performs simulation, calibration, alignment and reconstruction.
of events inside the CMS detector. The produced signal datasets don’t only contain the process at the generator level, but a full simulation was performed. In particular, once the collision and its products are generated, the outgoing particles are run through a detailed simulation of the CMS detector. They are propagated inside the CMS detector and its magnetic field, so that their interaction within the detector materials is simulated, secondary (tertiary, etc.) particles are generated and charges particles’ trajectories are bent by the magnetic field. Focusing on the ME0 detector, the interaction of particles within the ME0 chambers was also simulated. The detector electronics response is modeled, so that digis mimic the experimental raw data that are produced from the latter interactions. Digis contain the digital information of every single readout strip on which a signal was detected. The entire simulation chain described is available in the CMSSW framework. Then digis are further processed to produce reconstructed hits and segments, as explained in section 5.3.

Table 5.3 shows the fraction of $\tau \to 3\mu$ decays originated by the $B^0$ and $D_s$ mesons with at least one, two or three final muons from the tau lepton decay in the pseudorapidity region covered by the ME0 station (a bit larger, to take into account also muons that could reach the ME0 station due to scattering in experiment’s materials), with no cut on the muon momentum. They give an estimate of the number of events that can be collected depending on the number of muons requested in the ME0 station: they vary from about $\sim 1.8 \cdot 10^6$ ($\sim 1.8 \cdot 10^5$) events if the loose condition of only one muon in the ME0 station region is applied for a branching ratio of $B(\tau \to 3\mu) = 10^{-8}$ ($B = 10^{-9}$), to about $\sim 2.3 \cdot 10^5$ ($\sim 2.3 \cdot 10^4$) events with the strictest condition of all three final muons in the ME0 station region, with the same branching ratio. Anyway, these numbers represent an upper limit, as they don’t take into account the muon momentum, so that they may consider muons falling in the eta range of interest but too soft to reach and traverse the ME0 station and be actually detected.

The eta distributions of the muons from the tau decay originated by the $B^0$ ($D_s$) meson are shown in figure 5.2 (figure 5.3), as well as the distributions of their transverse momentum $p_T$. As above, only events with at least one final muon in the range $1.8 < |\eta| < 3$ and no cut on the muon momentum were considered for these distributions. The peculiar $|\eta|$ distributions in the bottom plots are an effect of this selection performed on the pseudorapidity of the final muons. Green distributions ($Muon3$) are filled with muons with
### Table 5.3: Fraction of $\tau \rightarrow 3\mu$ events originated by $B_0$ and $D_s$ mesons showing at least one, two or three muons ($N_\mu$) from the tau decay in the range $1.8 < |\eta| < 3$, and total number of such events expected during HL-LHC (integrated luminosity of 3000 fb$^{-1}$) for different values of the branching ratio $B(\tau \rightarrow 3\mu)$. No cut on the muon momenta or transverse momenta is performed.

<table>
<thead>
<tr>
<th>meson</th>
<th>fraction</th>
<th>$N_\mu \geq 1$ events if $B = 10^{-8}$</th>
<th>events if $B = 10^{-9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>47.3%</td>
<td>247708</td>
<td>24771</td>
</tr>
<tr>
<td>$D_s$</td>
<td>44.3%</td>
<td>1517208</td>
<td>151721</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>1764916</td>
<td>176492</td>
</tr>
</tbody>
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<table>
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<tr>
<th>meson</th>
<th>fraction</th>
<th>$N_\mu \geq 2$ events if $B = 10^{-8}$</th>
<th>events if $B = 10^{-9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>22.0%</td>
<td>115411</td>
<td>11541</td>
</tr>
<tr>
<td>$D_s$</td>
<td>20.3%</td>
<td>696186</td>
<td>69619</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>811597</td>
<td>81160</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>meson</th>
<th>fraction</th>
<th>$N_\mu = 3$ events if $B = 10^{-8}$</th>
<th>events if $B = 10^{-9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>6.4%</td>
<td>33424</td>
<td>3342</td>
</tr>
<tr>
<td>$D_s$</td>
<td>5.6%</td>
<td>193016</td>
<td>19302</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>226440</td>
<td>22644</td>
</tr>
</tbody>
</table>
the largest $p_T$ both in the top ($p_T$ distributions) and bottom ($|\eta|$ distributions) plots, blue (Muon1) and red (Muon2) distributions are filled with muons with the smallest and medium $p_T$ respectively. The distributions obtained in the two cases – decay chains originated by the $D_s$ or $B^0$ mesons – are very similar, showing three quite collimated muons with low transverse momenta, whose $p_T$ distributions are peaked below or at approximately $\sim 1$ GeV, and in any case with almost all muons with $p_T < 4$ GeV.

To allow evaluating trigger selections based on the pseudorapidity information, figure 5.4 shows the pseudorapidity difference between pairs of muons from the decay of the tau lepton. The pseudorapidity coverage of the ME0 station is $\Delta \eta = 0.8$, so it is interesting to verify how many muon triplets or pairs are produced within this $\eta$ distance. As above, the same events with at least one muon in the range $1.8 < |\eta| < 3$ and no cut muon momentum were used to populate the distributions. The average distance in pseudorapidity between the three muons is $\Delta \eta \approx 1.3$, with 74% (73%) of muon triplets showing $\Delta \eta_{3\mu} > 0.8$, indicating that approximately 25% of events may show all three muons traversing the ME0 station. The distance between muon pairs shows that about 66% (65%) of muon pairs falls inside the angle $\Delta \eta_{\text{max-med}} < 0.8$ and about 28% (26%) of pairs falls inside $\Delta \eta_{\text{med-min}} < 0.8$, for muon triplets originated by the $B_0$ ($D_s$) meson. Eventually, 92% (for decays originated by both mesons) of events have at least one muon pair within the $\Delta \eta_{\text{max-med}} < 0.8$ distance.

### 5.3 Muon reconstruction in the ME0 station

In the geometry used for this study, the ME0 station is composed of 18 ME0 modules per endcap, each one equipped with 6 detector layers with a trapezoidal shape with bases 21.9 cm and 52.7 cm. The center of the station is 527 cm from the origin of the CMS global coordinate system along the $z$ direction. The readout is composed of 284 strips along the $\phi$ direction, i.e. radially from the beam line, with a pitch of $\Delta \phi = 0.455$ mrad. A local coordinate system is used, having the $x$ axis along the global $\phi$ direction and parallel to the chamber base and the $y$ axis along the radial direction and parallel to the strips. Along the local $y$ direction, each chamber is divided into 8 eta partitions, covering approximately $\Delta \eta \approx 0.1$, allowing for a coarse position measurement in the local $y$ direction. The layout of the ME0 station and chambers is shown
Figure 5.2: Transverse momentum $p_T$ (top) and pseudorapidity (bottom) distribution of the final muons produced in the $B^0 \rightarrow \tau \rightarrow 3\mu$ decay chain. Only events in which there is at least one final muon in the range $1.8 < |\eta| < 3$ have been considered. No cut on the muon momenta or transverse momenta is performed. The distributions are normalized to the total number of events. The blue distribution ($\text{Muon1}$) is built with the muons with smallest transverse momentum, the red distribution ($\text{Muon2}$) with muons with the second highest transverse momentum, the green distribution ($\text{Muon3}$) with muon with the highest transverse momentum, in both plots.
5.3. Muon reconstruction in the ME0 station

Figure 5.3: Transverse momentum $p_T$ (top) and pseudorapidity (bottom) distribution of the final muons produced in the $D_s \rightarrow \tau \rightarrow 3\mu$ decay chain. Only events in which there is at least one final muon in the range $1.8 < |\eta| < 3$ have been considered. No cut on the muon momenta or transverse momenta is performed. The distributions are normalized to the total number of events. The blue distribution ($\text{Muon1}$) is built with the muons with smallest transverse momentum, the red distribution ($\text{Muon2}$) with muons with the second highest transverse momentum, the green distribution ($\text{Muon3}$) with muon with the highest transverse momentum, in both plots.
Figure 5.4: Distributions of the difference in pseudorapidity between pairs of muons produced in the decay of the tau lepton. The blue distributions represent the eta difference between the muon with maximum and minimum pseudorapidity ($\eta_{\text{max}} - \eta_{\text{min}}$), the red ones represent the eta difference between the muon with maximum and medium pseudorapidity ($\eta_{\text{max}} - \eta_{\text{med}}$), the green ones represent the eta difference between the muon with medium and minimum pseudorapidity ($\eta_{\text{med}} - \eta_{\text{min}}$). The top plot shows the distributions for muons originated from the $B_0$ meson, the bottom plot from $D_s$. All distributions are normalized to the total number of events. Events with at least one final muon in the range $1.8 < |\eta| < 3$ are used, no cut on the muon momenta or transverse momenta is performed.
5.3. Muon reconstruction in the ME0 station

Figure 5.5: Left: schematic representation of the ME0 station in one endcap of the muon system. Right: exploded view of an ME0 chamber, with 6 detector layers and 8 eta partitions.

<table>
<thead>
<tr>
<th>Eta partition</th>
<th>Height (cm)</th>
<th>$\Delta \eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.76</td>
<td>0.100</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.113</td>
</tr>
<tr>
<td>3</td>
<td>11.69</td>
<td>0.100</td>
</tr>
<tr>
<td>4</td>
<td></td>
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<td>8</td>
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</tbody>
</table>

Table 5.4: Dimensions of the eight eta partitions of an ME0 chamber.

In the position of the ME0 station the magnetic field is very low, hence the trajectory followed by muons traversing it is basically straight. Instead, the relevant trajectory bending as an effect of the magnetic field takes place before muons reach the ME0 station, mainly in the Tracker. Traversing an ME0 chamber, a muon is detected by some of the detector layers (see figure 5.6). Typically a segment is built from the detected hits if at least 3 hits are found in a region $\Delta \eta \times \Delta \phi = (0.05 \times 0.02)$ rad. A ME0Muon is constructed by matching a track reconstruction in the Tracker [92] to the segment built in the ME0 station, requiring the latter to be close to the Tracker track within $\Delta x < (3\sigma_x \text{ OR } 2 \text{ cm})$ and $\Delta y < (3\sigma_y \text{ OR } 2 \text{ cm})$, where $\sigma_x$, $\sigma_y$ are the
5. A Trigger Study for the ME0 Station

Figure 5.6: Schematic representation of the working principle of the ME0 station. The six detector layers are represented in light blue. A muon traversing an ME0 chamber is detected by some of the six layers, as represented by the purple dots. A segment passing through the measured hits, represented by a brown dashed line, is built.

propagated track covariance and the segment errors summed in quadrature.

In this study the goal is to introduce, for the first time in CMS, an ME0-only trigger algorithm not using Tracker tracks, so a different trigger path, explained in the following, was used.

The readout electronics is intended to be digital, so signals from ionizing particles are represented by the fired strips (digis). In the trigger path the concept of pad is also introduced by merging two adjacent strips, hence reducing the granularity by a factor two. Segments, instead, are built using the reconstructed hits in each ME0 layer, that are clusters of adjacent strips or pads. Both reconstructed hits made of digis and pads were studied, in order to evaluate the possibility to use a position measurement with smaller granularity in the L1 trigger, represented precisely by reconstructed hits made of pads.

When travelling across the experiment towards the muon station, muons follow a circular motion around the vector of the magnetic field, whose radius is inversely proportional to the intensity of the magnetic field and directly proportional to the particle momentum. The $p_T$ assignment in this study is based on the measurement of the bending angle $\Delta \phi$ in the ME0 chambers, the observable used to measure the rotation undergone by the particle. In this context the bending angle $\Delta \phi$ is defined as the angle of the segment reconstructed in the ME0 station with respect to a reference direction (see figure 5.7). The latter is the direction from the interaction point (the origin of the global coordinates) towards the point where the segment crosses the first
5.3. Muon reconstruction in the ME0 station

Figure 5.7: Schematic representation of the measurement of the bending angle $\Delta \phi$ as used in the present study. The orange line is the muon’s trajectory, the brown dashed line is the reconstructed segment built on the reconstructed hits shown as purple dots, the dashed black line connectes the interaction point (IP) to the point where the reconstructed segment crosses the first detector layer. The bending angle $\Delta \phi$ is the angle between the segment and the latter direction.

detector layer. The higher is the bending angle, the smaller the muon $p_T$.

In particular, we are interested in determining whether a muon’s $p_T$ overcomes a certain threshold. This selection is performed on the bending angle of the reconstructed muon, applying the condition $|\Delta \phi| < \Delta \phi_{thr}$. Threshold values are defined in order to select muons with the threshold $p_T$ with an efficiency of 95% and are determined in section 5.3.1.

Analysis are performed using the CMSSW [94] framework. Before the read-out of the ME0 chambers was implemented in the simulation of CMSSW to provide a realistic detector simulation of the digis, pseudo-digis were used in the first analyses involving the ME0 station. The interaction of particles with the detector gas volume produces simulated hits, from which pseudo-digis were obtained by smearing their position with the spatial and time detector resolutions.

In this study, the signal datasets containing the $\tau \rightarrow 3\mu$ decay and the prompt muon datasets used to determine the $p_T$ thresholds (used in sections 5.3.1 and 5.4) were realized ad-hoc and use realistic digis and pads to build reconstructed hits and segments in the ME0 station. Instead, the trigger rates presented in section 5.5 were obtained from already existing central datasets, where only the reconstruction based on pseudo-digis was available.

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5.3.1 Evaluation of the bending thresholds

The first step of the study was the determination of the thresholds on the bending angle $\Delta \phi$ for different muon $p_T$ values. For example, to determine the bending threshold $\Delta \phi_{\text{thr}}$ corresponding to a threshold of 5 $GeV$, only tracks of muons with $p_T = 5$ $GeV$ are considered and the distribution of their bending angles measured in the ME0 station is built. The threshold $\Delta \phi_{5\text{GeV}}$ is defined as the value for which 95% of such tracks satisfies $|\Delta \phi| < \Delta \phi_{5\text{GeV}}$.

To evaluate the bending thresholds a set of datasets containing a single muon per event with a fixed transverse momentum $p_T$ was generated. Five different datasets were generated for transverse momenta $p_T = (3, 5, 10, 20, 50)$ $GeV$. The full simulation chain, from the simulated hits to the reconstruction of segments was performed, in two different versions. As it has not been determined yet if the L1 trigger based on the ME0 station will use digis or pads, both versions were realized, in order to compare the results obtained with the two different granularities. The resulting bending angle distributions for different muon transverse momenta are shown in figures 5.8 top (using digis) and 5.9 top (using pads). Muons with smaller $p_T$ are on average more deviated as expected, with the mean bending angle varying from about 0.03 $rad$ for 3 $GeV$ muons to about 0.001 $rad$ for 50 $GeV$ muons. However the distributions have standard deviations of about (0.02 – 0.03) $rad$ and are not clearly separated both for the reconstruction based on pads and digis.

The distributions were used to determine the thresholds on the bending angles, summarized in table 5.5. As the bending angle distributions are not well separated, the thresholds are not very selective and still include high fractions of muons with smaller $p_T$, as visible in figures 5.8 bottom and 5.9 bottom, that show the fraction of muons with different $p_T$ selected at the various $\Delta \phi_{\text{thr}}$ cuts that have been identified. For example, the bending angle threshold to select 95% of muons with $p_T > 20$ $GeV$ also collects about 70% of muons with $p_T = 3$ $GeV$. No appreciable difference is visible between the usage of the digi or pad based reconstruction.

5.4 Evaluation of the trigger efficiency

The trigger efficiency of a specific trigger algorithm is defined as the ratio of the triggered events over the total number of events of interest. The efficiency
5.4. Evaluation of the trigger efficiency

Figure 5.8: Top: distributions of the bending angles of ME0 segments for muons with different transverse momenta $p_T$, normalized to the total number of events. Segments are built using reconstructed hits made from digis.

Bottom: fraction of muons with a given $p_T$ selected as a function of the cut on the bending angle $\Delta \phi_{thr}$. The fractions are obtained from distributions in the top plot.
Figure 5.9: Top: distributions of the bending angles of ME0 segments for muons with different transverse momenta $p_T$, normalized to the total number of events. Segments are built using reconstructed hits made from pads. Bottom: fraction of muons with a given $p_T$ selected as a function of the cut on the bending angle $\Delta \phi_{thr}$. The fractions are obtained from distributions in the top plot.
5.4. Evaluation of the trigger efficiency

<table>
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<th>Digi-based reconstructed hits</th>
<th>Pad-based reconstructed hits</th>
</tr>
</thead>
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<tr>
<td>$p_T$ (GeV)</td>
<td>$\Delta \phi_{thr}$ (rad)</td>
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<tr>
<td>50</td>
<td>0.0404</td>
</tr>
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</table>

Table 5.5: Bending angle $\Delta \phi_{thr}$ cuts in order to select the 95% of muons with different transverse momenta $p_T$, for segments built on reconstructed hits made with digis (left) or pads (right).

evaluated in this study is always referred to the trigger capability of the $\tau \rightarrow 3\mu$ decay with at least one muon in the eta acceptance $1.8 < |\eta| < 3$, without cuts on the muon momenta. This implies that a fraction of tau decays are not triggerable by definition. So the efficiency is used to determine the effective cross section of the $\tau \rightarrow 3\mu$ production that can be used.

Several trigger selections were considered using the thresholds determined in section 5.3.1. They are divided into three main categories:

- **single muon**, requiring at least one segment satisfying the cut on $\Delta \phi$
- **double muon**, requiring at least two segments satisfying the $\Delta \phi$ cuts
- **triple muon**, requiring at least three segments satisfying the $\Delta \phi$ cuts.

In each category, different combinations of $\Delta \phi$ cuts were used, corresponding to setting different thresholds on the transverse momentum $p_T$ of the muons. As high $p_T$ thresholds still collect a considerable fraction of low $p_T$ muons, also thresholds up to 50 GeV were used even if the final muons have transverse momenta of the order of few GeV or less.

In addition, not only selections based on $\Delta \phi$ cuts were used, but also the quality of the segment and the eta partition were considered. Two variables were introduced:

- the quality of the segment $q$ indicates how many reconstructed hits $n_{RH}$ are used to build the segment, where $q = 0$ if $n_{RH} = 4$, $q = 1$ if $n_{RH} = 5$, $q = 2$ if $n_{RH} = 6$
- the veto $\eta_{veto}$ poses a restriction on the position of the origin of the segment, which is the point where the segment crosses the center of the ME0 chamber along the $z$ direction. $\eta_{veto} = 0$ means no restriction on the position of the origin, allowing for segments at any $\eta$ position along
the chambers. \( \eta_{\text{veto}} = 1 \) excludes segments whose origin is in the highest eta partition, \( \eta_{\text{veto}} = 2 \) excludes segments whose origin is in the 7th or 8th eta partition, \( \eta_{\text{veto}} = 3 \) excludes segments whose origin is in the 6th, 7th or 8th eta partition.

Finally, in all cases it was also requested that segments’ origins were in the same chamber or in adjacent chambers.

A large number of selections was applied with different combinations of the \( p_T \) thresholds. The efficiencies of some of them are shown in figures 5.10 and 5.11 obtained from signals originated from the \( B^0 \) and \( D_s \) mesons respectively. They are obtained from segments produced on digi-based reconstructed hits. Each efficiency plot shows the trigger efficiency for the selection either of a single, double or triple muon, as a function of the \( \eta_{\text{veto}} \). Different curves are obtained with a different request on the segment qualities \( q \) and different \( p_T \) thresholds. The trigger efficiencies obtained with thresholds \( p_T > 10 \text{ GeV} \), an intermediate threshold value among the considered ones, and the most restrictive \( p_T > 50 \text{ GeV} \), are shown. All efficiencies are referred to the \( \tau \to 3\mu \) decays with at least one final muon in the region \( 1.8 < |\eta| < 3 \) and no cut on muon momenta, i.e. to the events listed in the upper part of table 5.1. Similar efficiency plots obtained from segments produced on pad-based reconstructed hits can be found in appendix A. They are in general slightly smaller than efficiencies from segments produced on digi-based reconstructed hits.

Figures 5.10 and 5.11 show that the trigger efficiencies vary approximately in the range \((0.001 - 20)\%\). In general there’s a small dependence on the \( p_T \) thresholds. This is explained by figure 5.8, showing that thresholds don’t provide a net selection of muon momenta, whose bending angle distributions are not well separated. Similarly, also \( q \) has a small impact on the trigger efficiency, indicating that posing a more restrictive selection on segments’ quality would have no big impact on the trigger efficiency (of the order of a factor 2-3). Indeed, about \( \sim 100\% \) of the considered segments are built with at least 4 reconstructed hits, among which about \( \sim 75\% \) of them are built with 6 reconstructed hits, \( \sim 18\% \) with 5 reconstructed hits and only about \( \sim 7\% \) with 4 reconstructed hits.

The biggest impact on the trigger efficiency is instead introduced by the \( \eta_{\text{veto}} \), changing the efficiency by one order of magnitude or more. In particular, at higher \( \eta_{\text{veto}} \) the efficiency reduces significantly, consistent with the fact that a higher \( \eta_{\text{veto}} \) is rejecting \( \tau \to 3\mu \) decays in eta partitions at higher pseudorapid-
5.4 Evaluation of the trigger efficiency

Figure 5.10: Trigger efficiencies for $\tau \to 3\mu$ decays originated from the $B_0$ meson with at least one final muon in the region $1.8 < |\eta| < 3$ (and no cut on the muon momentum), as a function of the veto $\eta_{\text{veto}}$, requiring at least one (top left), two (top right) or three (bottom) segments with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on digis.
Figure 5.11: Trigger efficiencies for pi^0 decays originated from the D^- meson with at least one final muon in the region |y| < 3, and no cut on the muon momentum, as a function of the veto veto, requiring at least one (top left), two (top right), or three (bottom) segments with \( p_T > 10 \text{ GeV} \) (full markers) or \( p_T > 50 \text{ GeV} \) (open markers). Efficiencies using segments with quality \( q = 0 \) (blue), \( q = 1 \) (red), and \( q = 2 \) (green) are shown. The reconstructed hits used to build segments are based on digis. Two curves end outside the plot area because for those values the efficiency is zero.
5.5 Evaluation of the trigger rates

We are interested in evaluating the trigger rates that would arise from the trigger selections shown in section 5.4, to understand if they would be acceptable. During HL-LHC an instantaneous luminosity of $\sim 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ is expected, with a peak luminosity up to $\sim 2 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$, corresponding to an event pileup up to about 200. Hence trigger rates were evaluated on central datasets with pileup of 200, and are shown in figure 5.13.

For comparison, figure 5.12 shows the trigger rates for muons expected during HL-LHC in the forward region of the upgraded muon endcap, in the region $2.1 < |\eta| < 2.4$ next to the extended muon acceptance, as a function of the $p_T$ threshold. For example, for the upgraded detector the trigger rate for muons with $p_T > 5 \text{GeV}$ is of the order of 100 kHz, it decreases down to about $10 \text{kHz}$ for a threshold of $p_T > 10 \text{GeV}$ and down to 1 kHz for a threshold of $p_T > 50 \text{GeV}$ [16]. These values shall be compared to the single muon trigger rates in this study.

**Single muon.** Figure 5.13 top left shows that any selection based on a single muon must be ruled out, as the resulting trigger rates are bigger than 3 MHz.

**Double muon.** For trigger algorithms based on two segments (figure 5.13 top right) the only way to keep the trigger rate at least below 100 kHz is to apply a veto $\eta_{\text{veto}} \geq 2$, i.e. to exclude segments in the last two eta partitions of the chambers and accepting muons only up to about $|\eta| \lesssim 2.6$ or 2.5. From figures 5.10 and 5.11, they correspond to trigger selection efficiencies for $\tau \rightarrow 3\mu$ in the range of few $10^{-4}$ to few $10^{-3}$.
5. A Trigger Study for the ME0 Station

Figure 5.12: L1 muon trigger rates for prompt muons for the Phase-1 and Phase-2 (upgraded) muon endcap at an event pileup of 200 as a function of the muon trigger $p_T$ threshold in the region $2.1 < |\eta| < 2.4$ [16].

**Triple muon.** Trigger rates expected from triple muon selections (figure 5.13 bottom) are the only possibility to use segments located in more eta partitions. Without restrictions on the eta partition ($\eta_{veto} = 0$) the best achieved trigger rate is 76 kHz, corresponding to trigger selection efficiencies for $\tau \rightarrow 3\mu$ of few $10^{-4}$. In order to further reduce the trigger rate it is necessary to exclude events in one or more eta partitions at high pseudorapidity. The lowest trigger rate obtained in this study is down to 10 kHz (strictest selections in the triple muon triggers), at which the efficiency to the $D_s$ channel drops to zero and the efficiency to the $B_0$ channel is $(1.4 \cdot 10^{-3})\%$. One of lowest trigger rates sensitive to both channels is 36.2 kHz (50.2 kHz), obtained excluding only the last eta partition for segment quality $q \geq 2$ and thresholds $p_T > 50 \text{ GeV}$ ($p_T > 10 \text{ GeV}$), at which trigger efficiencies are of the order of $\sim 10^{-2}\%$.

Hence, trigger rates of the order of $\sim kHz$ are not achievable with the considered selections. Trigger efficiencies corresponding to trigger rates in the range $(10 - 100) kHz$ are in the range $(10^{-3} - 10^{-1})\%$.

5.6 Some example cases

In this section we consider some of the trigger selections described above:

- *case1*, selecting events with two segments with thresholds $p_T > 50 \text{ GeV},$
5.6. Some example cases

Figure 5.13: Trigger rates at PU200 as a function of the veto $\eta_{veto}$, requiring at least one (top left), two (top right) or three (bottom) segments with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on ME0PseudoDigis.
segment quality \( q \geq 2 \) and veto \( \eta_{\text{veto}} = 3 \)

- *case2*, selecting events with three segments with thresholds \( p_T > 10 \text{ GeV} \),
  segment quality \( q \geq 1 \) and veto \( \eta_{\text{veto}} = 3 \), i.e. excluding muons beyond about \( |\eta| > 2.5 \)

- *case3*, selecting events with three segments with thresholds \( p_T > 50 \text{ GeV} \),
  segment quality \( q \geq 2 \) and veto \( \eta_{\text{veto}} = 1 \), i.e. excluding only one of the eight eta partitions.

They have been chosen because they correspond to reasonable trigger rates if compared to the observed range of \((10 - 100) \text{ kHz}\) and involve both triple and muons selections and different restrictions on the eta partitions.

The main features of the example cases and the total number of triggered events expected during the HL-LHC are summarized in table 5.6. The expected number of observed events is calculated as

\[
N_{\text{obs}} = N_\tau f_\tau B(\tau \to 3\mu) \varepsilon_\eta \varepsilon_t
\]  

(5.1)

where \( N_\tau \) is the number of tau leptons produced during HL-LHC with an integrated luminosity of 3000 \( fb^{-1} \), \( f_\tau \) is the fraction of tau leptons produced by the decay of the considered meson (see table 5.2), \( B(\tau \to 3\mu) \) is the branching ratio of the \( \tau \to 3\mu \) decay, \( \varepsilon_\eta \) is the fraction of such decays with at least one final muon in the region \( 1.8 < |\eta| < 3 \) to which the trigger efficiencies are referred (see table 5.3) and \( \varepsilon_t \) are the trigger efficiencies shown in section 5.4.

Figure 5.14 shows the expected number of observed events with the three selections as a function of the branching ratio of the \( \tau \to 3\mu \) decay, together with the total number of \( \tau \to 3\mu \) decays expected during HL-LHC. The latter prediction includes tau leptons produced over the entire solid angle, also at \( \eta \) values not covered by the ME0 chambers. Figure 5.15 instead allows to compare the triggered events only to the tau leptons produced in the \( \eta \) region of interest, for the three considered example cases. On one hand, it confirms that the eta region in which they are sensitive to the \( \tau \to 3\mu \) decay extends beyond \( |\eta| > 2.4 \). On the other hand, the algorithms considered here allow to trigger only a small fraction of the decays present in this region.
5.6. Some example cases

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<tr>
<td><strong>total</strong></td>
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<td>122</td>
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Table 5.6: Number of $\tau \to 3\mu$ decays expected over the HL-LHC lifetime (3000 fb$^{-1}$ of integrated luminosity) for different branching ratios of the decay process.

Figure 5.14: Expected number of $\tau \to 3\mu$ decays produced during HL-LHC and expected number of triggered events for three different trigger algorithms as a function of the branching ratio of the decay $B(\tau \to 3\mu)$. 

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5. A Trigger Study for the ME0 Station

Figure 5.15: Number of $\tau \to 3\mu$ decays originated from the $B_0$ (dark blue) and
$D_s$ (light blue) mesons as a function of the pseudorapidity of the tau lepton $|\eta_\tau|$, together with the number of events triggered by three different algorithms (top plot). The total number of events is arbitrary, but the distributions are scaled to each other. The bottom plot shows the trigger efficiency of the same algorithms in the top plot as a function of $|\eta_\tau|$. 

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5.7 Conclusions and future prospects

In the extended region of the muon system at $|\eta| > 2.4$ that will become accessible with the ME0 station a specific L1 trigger needs to be developed. Indeed, the absence of other muon detectors and the harsh environment in this position make it impossible to realize a standalone L1 trigger in this very forward region. A proposed solution, not yet implemented in the CMS L1 trigger so far, is the development of L1 triggers dedicated to specific physics analyses, in which muon segments are part of multi-object topological triggers. Several physics channels, showing final muons in the forward region, would benefit from the trigger capability of the ME0 station.

The study performed is the first step in the development of such specific trigger algorithms to use in the extended muon system range. The muon reconstruction and trigger algorithms adopted are not the definitive solution, but rather preliminary studies to start addressing the main difficulties and their order of magnitude and to suggest changes in the reconstruction and trigger algorithms that could lead to an improved performance.

For example, this preliminary study highlights that the most difficult region to handle is represented by the last eta partitions, as trigger rates rapidly increase with the contribute of the highest eta partitions. It was necessary to use strict trigger selections in order to keep one of the lowest achievable trigger rates, at the cost of a lower efficiency. Hence, one of the main goals of improved reconstruction and trigger algorithms must be achieving a better trigger rate reduction without loosing a large fraction of events of interest.

The muon reconstruction used in this study is based on a very simple evaluation of the bending angle using only the information from the ME0 station. Similarly, also the considered trigger algorithms only look for segments reconstructed in the ME0 station. In order to achieve a better trigger performance, it is my intention to investigate the effect of both these choices:

- the bending angle in this study is measured with respect to the direction connecting the interaction point to the segment’s position on the first ME0 layer. This was done because there’s no other muon detector at $|\eta| > 2.4$ to measure the bending angle with, similarly to the GE1/1-ME1/1 or GE2/1-ME2/1 systems, and a pure stand-alone ME0 algorithm was tried. The upgraded Tracker, instead, will extend up to $|\eta| < 4$. So it would be interesting to study if the tracks measured by
the Tracker can be effectively used to achieve a more effective bending measurement hence a better \( p_T \) resolution. In addition, it would also be interesting to study the impact of a different spatial resolution of the ME0 chambers;

- in this first study, focused on triggering the \( \tau \to 3\mu \) decay, the considered algorithms have searched up to three segments in the ME0 station. Nevertheless a large fraction of events with at least one final muon in the eta region covered by the ME0 station show one or two muons outside this range. Hence the introduction of two or three muons detected in the nearby stations (CSCs and GEMs) in the trigger algorithms could significantly increase the number of triggered events. I plan to perform further studies in order to understand an effective way to include the CSC, GE1/1 and GE2/1 stations to the trigger of the \( \tau \to 3\mu \) decay at the very end of the muon system and evaluate the improvement led by this combination on the trigger efficiency.

In addition, also the possibility to apply different selections in the last eta partitions could be taken into account in order to handle the high trigger rate coming from them. Another idea could be to verify that the total sign of the three final muons is \( \pm 1 \) based on the sign of the bending angles, if a sufficient resolution on their measurement is achieved.

Finally, some considerations should be made also on the datasets used. The segment reconstruction in the ME0 station used for the evaluation of the trigger rates is different from the one used in the rest of the study. The results should anyway give the order of magnitude of the trigger rates, but some discrepancies from the exact rate values obtained with the modified reconstruction are possible.
Chapter 6

Conclusions

The presented work touches several steps of the upgrade of the muon system of the CMS experiment with GEM detectors.

The first part is focused on the R&D on MicroPattern Gas Detectors (MPGDs), in particular on the branch that has started after the big effort to develop triple-GEM detectors for the GE1/1 station, extending the interest also to similar types of MPGDs. As the GE1/1 station was the first one scheduled for the installation in the timeline, its R&D was also the first one in the timeline of the GEM R&D program. A longer window for the R&D for the other stations, to be installed after 2022, was available. In this period, even short, CMS took an interest also in the micro-Resistive WELL (μ-RWELL) detector for the GE2/1 station, the Fast Timing Micropattern (FTM) detector and the Back to Back (B2B) GEM detector for the ME0 station. In such a short time, of the order of a couple of years for the FTM detector and about a year for the Back to Back GEM detector, the study began with the first small-size prototypes, explained in detail in chapter 3. Positive results were reached in both cases, but still leaving room for further work.

Concerning the FTM, a completely new technology, the work necessarily started with the very basic goal to verify its working principle. The capability of detecting particles, the time resolution and the transparency of the detector with two layers were successfully established with the very first prototype, of reduced size and the minimum amount of layers. Given these fundamental results, next steps involved the production of prototypes with more layers and/or a larger active area and drift gap, in order to study the dependency of the above results on the number of detector layers. Anyway, as this technology is very recent,
proving its performance was not the only concern, but also its structure, in terms of materials and dimensions, and construction and assembly procedures need to be investigated in order to obtain a correctly working detector. Hence the R&D program on the FTM detector was too long in order to obtain a well-known and under control detector technology in time for the application in the GEM upgrade, so the R&D program within the CMS activities ended in 2016, but still remained of interest for CMS.

The situation was different for the Back to Back GEM detector, representing an option to make triple-GEM detectors fit a smaller space as necessary for the ME0 station. In this case, the detector technology was already very well known and the R&D could start from a more advanced knowledge, and the work mainly consisted in adapting it into a new more compact design having the same performance of the “classical” triple-GEM detector. The overall performance of the detector achieved this goal, nevertheless it is smaller in proximity of the edges of the detector’s active area. Next steps in the development of the detector would have been addressing the reason for such disuniformity and to build bigger prototypes. But after less than one year of activity the R&D on this prototype ended, in favour of another solution for the ME0 station.

For both detectors technologies, a good starting point was reached, but further work shall be carried out within a different project or for other applications with a longer timeline. As regards the choice of the technology for the GE2/1 and ME0 stations, the preference has been to use GEM detectors for all of them. Indeed, using three different detector technologies for the three stations would of course require three times the work, in terms of detector R&D, development of the full design of the detectors for the CMS stations, the acquisition of the expertise in operating all three technologies, the study and understanding of how each one performs in the CMS environment. Choosing the same technology and building a uniform GEM subsystem allows, instead, to focus on controlling one single technology, share the experts and knowledge among all three stations, and also re-use the construction techniques and sites put together for the GE1/1 station.

The major detector R&D phase is now over, with remaining activities mainly focused on aging studies, that require a long charge integration time, and setups in laboratory used for testing. The largest fraction of current activities in laboratories concern the production and testing of the chambers under
construction in order to instrument the full GE1/1 station.

In 2017 the GEM project has gone forward and has reached a new milestone with the GE1/1 slice test: the first installation of GEM detectors in the CMS experiment. With the slice test the problem of integrating a completely new system into the existing CMS experiment has been faced for the first time. The integration problem mainly involves the Detector Control System (DCS), responsible for the safe control and operation of the subsystem, and the Data AcQuisition system (DAQ). The DCS for the slice test was deployed in several steps, during which we adjusted it according to the users needs and the central DCS rules and addressed and solved problems highlighted by the operation. The slice test experience allowed us to learn the CMS DCS environment and its fundamental rules, how to achieve particular system behaviours, and supplied us with ideas on how to realize a larger-scale control system for the complete GE1/1 installation, besides lots of field tested parts of DCS that can be reused or adapted for this goal. The DAQ system is also operational. At the beginning of the slice test it was possible to perform only local runs, and the slice test on-field experience allowed to improve and develop it and to reach the capability, few months ago, to finally run included in the global CMS runs. The work on the DAQ side is still very active: running in central is not yet completely smooth and automated, and some issues possibly affecting the detectors’ performance remain. These points are being addressed and under constant investigation and improvement.

The overall slice test experience is being fundamental in order to prepare us for the installation and operation of the full-size GEM subsystems and have a realistic forecast of the necessary work, from several points of view.

The GE1/1 station represents the pioneer GEM station under different aspects, from the detector R&D, the study of the inclusion into the CMS trigger system and the impact on its performance, to the installation into CMS, the commissioning within the experiment and the first on-field operations. Many of them can be transferred also to the other two GEM stations. One aspect that is characteristic only of the ME0 station and has not been developed yet is a trigger system not relying on the measurement of the bending angle in tandem with a second muon station, to apply in the extended muon system range where the ME0 station will be the only muon detector. The latter is necessary in order to benefit from the extended muon system. In particular, a standalone L1 trigger in this region is not feasible as it would result in
unsustainably high trigger rates. A completely new concept for the L1 trigger was proposed, using muons segments as part of multi-object topological L1 triggers dedicated to specific physics analyses. The development is at an early stage, on which a first preliminary study, exposed in chapter 5, was carried out. The latter is a starting point, that allowed to address the main difficulties of this task and provided ideas to investigate in order to develop the trigger techniques to apply in the forward extended region of the muon system.
Appendix A

Trigger efficiencies

Trigger efficiencies for trigger algorithms using segments built on reconstructed hits made from pads, as explained in section 5.4, for $\tau \rightarrow 3\mu$ decays originated from the $B^0$ (figures A.1 to A.3) and $D_s$ (figures A.4 to A.6) mesons.

Figure A.1: Trigger efficiencies for $\tau \rightarrow 3\mu$ decays originated from the $B_0$ meson with at least one final muon in the region $1.8 < |\eta| < 3$, as a function of the veto $\eta_{\text{veto}}$, requiring at least one segment with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on pads. Two curves end outside the plot area because for those values the efficiency is zero.
A. Trigger efficiencies

Figure A.2: Trigger efficiencies for $\tau \rightarrow 3\mu$ decays originated from the $B_0$ meson with at least one final muon in the region $1.8 < |\eta| < 3$, as a function of the veto $\eta_{\text{veto}}$, requiring at least two segments with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on pads. Two curves end outside the plot area because for those values the efficiency is zero.

Figure A.3: Trigger efficiencies for $\tau \rightarrow 3\mu$ decays originated from the $B_0$ meson with at least one final muon in the region $1.8 < |\eta| < 3$, as a function of the veto $\eta_{\text{veto}}$, requiring at least three segments with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on pads. Two curves end outside the plot area because for those values the efficiency is zero.
Figure A.4: Trigger efficiencies for $\tau \rightarrow 3\mu$ decays originated from the $D_s$ meson with at least one final muon in the region $1.8 < |\eta| < 3$, as a function of the veto $\eta_{\text{veto}}$, requiring at least one segment with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on pads. One curve ends outside the plot area because for those values the efficiency is zero.

Figure A.5: Trigger efficiencies for $\tau \rightarrow 3\mu$ decays originated from the $D_s$ meson with at least one final muon in the region $1.8 < |\eta| < 3$, as a function of the veto $\eta_{\text{veto}}$, requiring at least one two segments with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on pads. One curve ends outside the plot area because for those values the efficiency is zero.
Figure A.6: Trigger efficiencies for $\tau \rightarrow 3\mu$ decays originated from the $D_s$ meson with at least one final muon in the region $1.8 < |\eta| < 3$, as a function of the veto $\eta_{\text{veto}}$, requiring at least one three segments with $p_T > 10$ GeV (full markers) or $p_T > 50$ GeV (open markers). Efficiencies using segments with quality $q \geq 0$ (blue), $q \geq 1$ (red), $q \geq 2$ (green) are shown. The reconstructed hits used to build segments are based on pads. One curve ends outside the plot area because for those values the efficiency is zero.
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