Commissioning, Operation and Performance of the CMS Resistive Plate Chamber System

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Proefschrift ingediend tot het verkrijgen van de graad van Doctor in de Wetenschappen: Natuurkunde
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Our present understanding of elementary particle physics is the result of over a century of experimental and theoretical progress going hand in hand. Early on, collisions were an important asset in the discovery and understanding of particles, starting with the observation of the positron [1] and muon [2] in the thirties from collisions of highly energetic cosmic particles with nuclei in the earth’s atmosphere. Soon accelerators were developed to explore the world of particle physics through an abundance of man-made particle collisions, increasing precision and energies over the years.

A succession of theoretical predictions and experimental discoveries in this field led to the development of the Standard Model of Particle Physics during the sixties and seventies. Ever since, this theory of elementary particles and their interactions has been challenged, and it proved to accurately describe measurements as well as successfully predict for example the discovery of the top quark and the tau neutrino. More recently, a Higgs boson was added to this list [3, 4] using the ATLAS and CMS detectors at the Large Hadron Collider.

This chapter will give a brief introduction to the main characteristics of the Standard Model of Particle Physics and the challenges it holds (section 1.1). Section 1.2 goes on to describe how the Large Hadron Collider was built as a discovery machine to probe for new physics using the four experiments installed at its collision points (section 1.3).
Figure 1.1: Elementary particles and their masses as presented in the Standard Model of Particle Physics (a) [5], and the interactions (blue lines) of the fermions (ovals) through the bosons (circles) (b) [6].

1.1 Physics Motivation

1.1.1 The Standard Model of Particle Physics

The Standard Model of Particle Physics (SM) is a Quantum Field Theory (QFT) that describes the known elementary particles and their interactions. Within the SM, all matter consists of fermions, namely the leptons and quarks. These spin $\frac{1}{2}$ particles are grouped in three generations, with particles differing only in mass (fig. 1.1a). Stable matter consists only of particles from the first generation, due to the unstable nature of the heavier variants. Each generation adds two leptons and two quarks to the equation, along with their antiparticles.
The leptons come in six flavours: the electron and electron-neutrino ($e^-$, $\nu_e$) in the first generation, the muon and muon-neutrino ($\mu^-$, $\nu_\mu$) in the second, and the tau and tau-neutrino ($\tau^-$, $\nu_\tau$) in the third generation. For each lepton, there is an antiparticle with opposite charge. The quarks consist of the up and down quarks ($u$, $d$) in the first generation, the strange and charm quarks ($s$, $c$) in the second, and the bottom and top quarks ($b$, $t$) in the third generation.

The fundamental interactions take place between particles that carry an interaction-specific charge through the exchange of gauge bosons. The weak interaction requires a weak isospin charge, and is mediated by the charged $W^+$ and $W^-$, and the neutral $Z^0$ boson. The photon ($\gamma$) is responsible for the electromagnetic interaction, and interacts with all electrically charged particles. Finally, the gluon ($g$) is the gauge boson for the strong force. Only the quarks and the gluon itself carry the color charge associated with this interaction.

The fourth known fundamental interaction, gravity, is not part of the SM. While it is experienced as a strong force at human scale and above, it becomes negligible at the scale of particle physics experiments when compared to the other three interactions.

These particles and interactions are contained in a relativistic Quantum Field Theory. The electromagnetic and weak interactions are combined in the Electroweak (EWK) theory, and the strong interaction is described by Quantum Chromodynamics (QCD). The mass of particles is added to the SM by the electroweak symmetry breaking through the Brout-Englert-Higgs mechanism, which gives rise to the Higgs boson ($H$) and adds mass to the weak gauge bosons. The fermions gain mass through Yukawa couplings with the $H$ boson.

### 1.1.2 Beyond the Standard Model

While successful at the observed collision energy ranges, there is a general consensus that the Standard Model of Particle Physics can not be the ultimate description of nature.

From a somewhat aesthetic point of view, many physicists believe a unified theory should exist from which the known interactions emerge after spontaneous symmetry breaking. While the SM establishes this for the electromagnetic and weak interactions, no theory has been devised to add the strong interactions. At present the gauge couplings do not meet at higher energies, making unification impossible in this framework. Also the gravitational interaction should be added from this point of view, as its strength becomes relevant towards the Planck scale ($\Lambda_P \approx 10^{19}$ GeV).

The introduction of the SM Higgs boson also opens the fear for excessive fine-tuning to constrain the quantum corrections to the Higgs mass. This is known as the Hierarchy problem.
Also from other fields challenges to the SM arise: astrophysical and cosmological measurements strongly suggest the existence of dark matter and dark energy. Neither can at present be explained using the constituents of the SM.

Inspired by these known challenges, several theories have been devised to extend or replace the SM. As an example, a promising set of models considers a broken Super Symmetry (SUSY), a symmetry between bosons and fermions. With the introduction of these bosons, the quantum corrections to the Higgs mass would cancel out naturally, solving the Hierarchy problem. It also provides the means to unify the strong and electroweak interactions. Like other theory candidates, it comes with a spectrum of new particles, including some candidates for dark matter. One of the goals of the Large Hadron Collider and its experiments is to probe for the range of new particles that are introduced with these theories, through their discovery or their influence on known interactions.

1.2 The CERN Large Hadron Collider

Installed in the tunnels of the former Large Electron-Positron Collider (LEP) accelerator at the European Organization for Nuclear Research (CERN) (Geneva, Switzerland), the Large Hadron Collider (LHC) accelerates two proton beams in opposite directions along a 26.7 km path, some 100 m underground.

A Discovery Machine  Considering the challenges the SM poses at present, the Large Hadron Collider was designed as a discovery machine. This implies colliding at high energy, to increase the cross section for the heavy resonances. The loss of energy through synchrotron radiation excludes the use of the lighter electron and positron for this purpose. Using protons does however mean that the collisions have complex final states: the partons taking part only carry a variable fraction of the proton momentum leading to interactions of variable center-of-mass energy. The use of proton-proton collisions ($pp$), rather than proton-antiproton ($p\bar{p}$), allows for high intensity beams, increasing the collision rates and as such decreasing the minimal cross section that can be probed.

The Accelerator Complex  The LHC cannot accelerate the protons from the ground up. Instead, it relies on a chain of accelerators present at CERN (fig. 1.3).

Starting from a bottle of hydrogen gas, hydrogen atoms are stripped of their electrons, and the resulting protons are accelerated by a linear accelerator, Linac 2, to 50 MeV. This beam is then injected in the Proton Synchrotron Booster (PSB), in turn accelerating the protons to 1.4 GeV, followed by the Proton Synchrotron (PS) where they reach 25 GeV. The final acceleration before reaching the LHC is provided by the Super Proton Synchrotron (SPS), which delivers 450 GeV protons to the LHC.
1.2. The CERN Large Hardron Collider

Figure 1.2: Predicted Standard Model of Particle Physics cross sections at the Tevatron collider (dashed line at $\sqrt{s} = 1.96$ TeV) and the LHC collider (lines at $\sqrt{s} = 7$ TeV (2011), 8 TeV (2012) and 14 TeV (design)) as a function of the centre-of-mass energy $\sqrt{s}$ [7]. The discontinuities at 4 TeV are due to the switch from $p\bar{p}$ to $pp$ collisions at that energy.
Figure 1.3: Overview of the CERN accelerator complex [8].
The LHC then accelerates the beams in separate beam pipes for each direction to a maximum energy of 7 TeV per proton, before starting collisions with a center-of-mass energy of up to $\sqrt{s} = 14$ TeV at the different experiments. The acceleration takes place in four straight sections along its circumference (fig. 1.4) in Radio Frequency (RF) cavities. Along the eight arcs, 1232 superconducting dipole magnets producing an 8 T magnetic field bend the protons to their circular trajectory, and 392 superconducting quadrupole magnets focus the beams to counteract dispersion. The proton bunches, each containing $O(10^{10})$ protons, are arranged in 3564 buckets per beam, commonly referred to as one Bunch Crossing (BX). At the nominal $f_{\text{rev}} = 11.246$ kHz, the 3564 buckets per beam give rise to a 24.95 ns BX separation, which makes for a 40.08 MHz BX frequency. For most of the 2012 fills, 1368 buckets contained colliding bunches of protons, each with $O(10^{10})$ protons.
Chapter 1. Physics at the CERN Large Hadron Collider

Luminosity  A key parameter of a particle collider is its *instantaneous luminosity*, $\mathcal{L}$ (cm$^{-2}$ s$^{-1}$). It gives access to the expected number of events $\langle N \rangle$ for a cross section $\sigma$ under investigation through

$$\langle N \rangle = \sigma \int \mathcal{L}(t) \, dt.$$  (1.1)

The instantaneous luminosity is defined by the LHC proton beam parameters. Assuming a Gaussian beam distribution, it is given by [9, 10]

$$\mathcal{L} = \frac{N_b^2 \gamma_r}{4 \pi \epsilon_n \beta_*} n_b f_{\text{rev}} F$$  (1.2)

where $N_b$ is the number of particles per bunch, $n_b$ the number of bunches per beam, $f_{\text{rev}}$ the revolution frequency, $\gamma_r$ the relativistic gamma factor, $\epsilon_n$ the normalized transverse beam emittance, $\beta_*$ the beta function at the collision point and $F$ the geometric luminosity reduction factor due to the crossing angle at the Interaction Point.

Over a physics run, the instantaneous luminosity will degrade as particles are lost in collisions, beam-gas interactions and in the collimators. It can be approximated by an exponential decay process

$$\frac{d\mathcal{L}}{dt} = -\frac{1}{\tau} \mathcal{L},$$  (1.3)

or

$$\mathcal{L}(t) = \mathcal{L}_0 e^{-\frac{t}{\tau}}$$  (1.4)

with $\mathcal{L}_0$ the instantaneous luminosity at the start of the run. Minimum lifetimes were between 0.5 h and 10 h in 2012, depending on the fill conditions [11].

Figure 1.5 shows the integrated luminosity delivered to the Compact Muon Solenoid during the 2010-2012 running periods.

1.3 The LHC Experiments

Considering the complexity and the cost of the LHC accelerator complex, it is important to make the most of its scientific reach. For this reason, the accelerated protons collide at four points along its circumference, as illustrated in fig. 1.4.

Two independent general-purpose experiments have been set up to investigate the proton-proton collisions: at P1, ATLAS\(^1\) [13] has been installed, and at P5 one finds the Compact Muon Solenoid (CMS) [14]. They have been designed to address the aforementioned challenges, starting with the Higgs boson discovery and searching for physics beyond the SM.

In the ALICE\(^2\) experiment [15], lead-ion collisions are studied to improve our understanding of the quark-gluon plasma. The Large Hadron Collider Beauty Experiment (LHCb) experiment specializes in the study of bottom-quark physics and CP violation.

\(^{1}\)A Toroidal LHC Apparatus Experiment

\(^{2}\)A Large Ion Collider Experiment
Figure 1.5: Cumulative integrated luminosity versus day delivered to CMS during stable beams for pp collisions at 7 TeV and 8 TeV centre-of-mass energy in 2010-2012 [12]. It accounts for the luminosity delivered from the start of stable beams until the LHC requests CMS to turn off the sensitive detectors to allow a beam dump or beam studies. Given is the luminosity as determined from counting rates measured by the luminosity detectors. These detectors have been calibrated with the use of the van-der-Meer beam-separation method, where the two beams are scanned against each other in the horizontal and vertical planes to measure their overlap function.
Two smaller experiments are installed near ATLAS and CMS, respectively Large Hadron Collider Forward Experiment (LHCf) [16] and Total Elastic and Diffractive Cross Section Measurement (TOTEM) [17]. The first studies particle showers close to the beam pipe to test models of particle showers as present in astroparticle physics. The latter is interested in the total cross section of proton collisions by measuring up to high pseudo-rapidity (cf. section 2.1.1).
Chapter 2

The CMS Experiment at the LHC

At one of the Interaction Points of the LHC, Point 5 (P5), the CMS experiment [14] has been installed. As one of the two general-purpose experiments at the LHC, it is designed to detect a wide range of event signatures. This chapter will go through the different detector technologies in use to detect the photons, electrons, charged and neutral hadrons and muons (section 2.1). Section 2.2 introduces the trigger system in use to select relevant events, as well as the basics of the Data Acquisition System. Section 2.3 and section 2.4 give a brief overview of the online control and monitoring software, and the offline analysis software architecture.

2.1 The CMS Detector

Built as a general-purpose collider experiment, CMS follows a classic layout with an inner tracking detector, followed by Electromagnetic and Hadronic Calorimeters, and muon chambers on the outside. These layers are organized in a barrel region, consisting of cylindrical coaxial layers around the beam pipe, and two endcap regions with disks closing the barrel region. The detector components were chosen to meet the LHC physics programme requirements [14], which translates into

- a tracker close to the Interaction Point (section 2.1.3) to provide high charged-particle momentum resolution, and allow τ and b jet tagging,

- a hermetic Electromagnetic Calorimeter (section 2.1.5) to ensure good electromagnetic energy resolution, with significant material thickness in radiation lengths\(^1\) over a short distance, and with the granularity to achieve sufficient π\(^0\) rejection and

- a hermetic Hadronic Calorimeter (section 2.1.4) to measure the energy of charged and neutral hadrons with significant material thickness in nuclear interaction lengths\(^2\), allowing for good missing transverse energy (\(E_{\text{miss}}^T\)) resolution.

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\(^1\)The radiation length, \(X_0\), is the mean distance over which a high-energy electron loses all but \(1/e\) of its energy by bremsstrahlung, and 7/9 of the mean free path for pair production by a high-energy photon [10].

\(^2\)The hadronic equivalent of \(X_0\), \(\lambda_I \approx A^{1/3}/\rho \approx 35\,\text{g cm}^{-2}\)
Precise muon detection and identification that allows the measurement of momenta up to 1 TeV is achieved with an extensive muon system (section 2.1.6) outside a significant amount of absorber material, and

a single 3.8 T superconducting magnet (section 2.1.2) allows the momentum assignment of charged particles throughout CMS.

An overview of these detectors and their key characteristics is shown in fig. 2.1, and the most relevant features are explained in the following paragraphs. A detailed description of the CMS experiment can be found in [14].

### 2.1.1 The Coordinate System

The global coordinate system of CMS has its origin in the Interaction Point (IP). A right-handed coordinate system is used with the $X$-axis pointing towards the center of the LHC ring, the $Y$-axis pointing upwards, and the $Z$-axis along the beam pipe. Throughout this thesis, capitals will be used for these coordinates to differentiate them from the local coordinate systems of single detectors.
Because the LHC provides hadron collisions, the different energy fraction of the parton leads to an unknown total energy. Because of this, one is mainly interested in the transverse components of the total and missing energy. This same feature also leads to a potentially longitudinally boosted center of mass. As a consequence, quantities invariant under such boosts are used, such as the transverse momentum $p_T$. Along the beam pipe, the $Z$-direction, the difference in pseudorapidity

$$\eta = -\ln\left(\tan \frac{\theta}{2}\right)$$

(2.1)

between two particles is approximately invariant under such a boost for ultra-relativistic particles. Here, $\theta$ is the polar angle between the particle momentum and the $Z$ axis. It is accompanied by the azimuthal angle $\phi$, with the $X$-axis at $\phi = 0$, to form a spherical coordinate system.

2.1.2 The Superconducting Magnet

As suggested by its name, the Compact Muon Solenoid uses a superconducting solenoid to achieve accurate $p_T$ measurements for charged particles crossing the detector. This 12.5 m long solenoid produces a magnetic field of 3.8 T, and to contain it outside its 6 m diameter, it is surrounded by a 12 500 tonnes steel return yoke. The three coaxial yoke layers of the barrel are interspersed with the muon detectors, allowing for significant muon track bending between them. Outside the magnet, the barrel yoke is organized in five separate dodecagonal wheels along $Z$ (YB-2 to YB+2), which can be moved on high-pressure air pads to create space between them and give access to the installed detectors. The same is true for the three steel endcap disks on each side of the experiment (YE-1 to YE-3 and YE+1 to YE+3).

2.1.3 The Inner Detector

The CMS inner tracking system is a silicon-based detector, designed to measure the trajectories of charged particles very precisely. It consists of an inner silicon pixel detector within a distance of 20 cm from the beam pipe, providing 100 by 150 $\mu$m pixels arranged in three barrel layers and two endcap layers. The resulting 66 million active elements span a length of 98 cm.

Surrounding the pixel detector are 10 barrel layers and 12 forward layers of silicon strip detector, covering the region up to 116 cm from the beampipe, along 5.6 m with 9.3 million channels. Several strip layers (barrel) and rings (endcap) are instrumented with a second micro-strip detector module mounted back-to-back with a stereo angle of 100 mrad, such that the strip detector also provides two-coordinate measurements in at least $\approx 4$ hits for $|\eta| < 2.4$. 
Depending on the interactions to which they couple, the particles are detected and potentially stopped as demonstrated, allowing for identification. The known particles with the lifetime to make it into the detector are photons and electrons, mostly stopped by ECAL, charged pions, kaons, protons and neutrons that should be stopped by HCAL, and muons that cross the full detector. Missing transverse energy $E_{\text{miss}}^T$ points to particles escaping undetected, like neutrinos.

2.1.4 The Electromagnetic Calorimeter

In the next layer, the energy of the electrons and photons is measured by the Electromagnetic Calorimeter (ECAL). The ECAL subdetector covers the pseudorapidity range $|\eta| < 3.0$ with 61200 lead tungstate (PbWO$_4$) crystals in the barrel, read out by Avalanche Photodiodes (APDs), and 7324 crystals in the endcap region, read out by Vacuum Phototriodes (VPTs).

The crystals are arranged side by side with their axes pointing slightly away from the Interaction Point to avoid cracks. The length of the crystals corresponds to 25.8 radiation lengths ($X_0$), in the barrel and 24.7 $X_0$ in the endcaps, stopping most electrons and photons such that they deposit all their energy while traversing the crystals. The barrel region consists of 36 supermodules with $20 \times 85$ crystals each, covering $\Delta\eta \times \Delta\phi = .0174 \times .0174$ or a 22 by 22 mm$^2$ front-face cross section. The endcaps feature two Dees each, holding 3662 crystals with a front-face cross section of 28.62 by 28.62 mm$^2$.

An additional sampling calorimeter in the endcaps, the Preshower (PS), is installed to improve the resolution in order to resolve the two photons of a $\pi^0$ decay: behind a two lead radiators of 2 and 1 $X_0$ each, two layers of silicon strip sensors are configured orthogonally to measure the electromagnetic showers.
2.1.5 The Hadronic Calorimeter

The Hadronic Calorimeter (HCAL) is a sampling calorimeter that initiates a cascade of secondary particles for the high-energy hadrons by alternating layers of non-magnetic brass absorbers and fluorescent scintillators. It consists of a coaxial barrel region up to $|\eta| < 1.3$ (HB, 5.4 to 10.6 $\mu$), an endcap region up to $|\eta| < 3$ (HE) and a forward region further down the beam pipe at 11.2 m that increases the coverage up to $|\eta| < 5.2$ (HF).

The limited space for stopping power in the barrel region is overcome with an additional calorimeter outside the solenoid up to $|\eta| < 1.3$ (HO) that uses the coil and a 19.5 cm layer of steel yoke as absorber.

Between the brass absorber plates ($\approx 5$ cm for HB, $\approx 8$ cm for HF), scintillator tiles with a segmentation depending on $\eta$ from $\Delta \eta \times \Delta \phi = .087 \times .087$ to $.17 \times .17$ produce the optical signal that embedded wavelength-shifting fibres take to Hybrid Photodiodes (HPDs). The total amount of light summed over the layers of tiles within a given region is a measure for the passing particle’s energy.

2.1.6 The Muon System

Another key feature of the CMS experiment is its extensive muon system. As a powerful handle to the signature of interesting events, the trigger and reconstruction capabilities for muons are very important. The hermetic design of the calorimeters means that very little of the hadronic showers leaks into the system, leaving a clean muon identification system.

The CMS muon system consists of three types of detectors (fig. 2.3). The Drift Tube Chambers are used in the barrel region ($|\eta| < 1.2$), where the occupancy and background noise are low, and the residual magnetic field is uniform and mostly contained in the return yoke. In the endcap regions, muon rate, neutron-induced background rates and the magnetic field dictate the use of Cathode Strip Chambers ($0.9 < |\eta| < 2.4$). Both systems consist of gaseous drift chambers, and provide precise space and time measurements.

The Resistive Plate Chamber (RPC) system covers both the barrel and endcap regions ($|\eta| < 1.61$) and provides an independent measurement for triggering purposes with a coarser space resolution but a fast time response for unambiguous BX assignment. It is described in detail in chapter 3.

**Drift Tube Chambers** The Drift Tube Chambers (DTs) are gaseous particle detectors built with 13 by 42 mm$^2$ rectangular drift cells (fig. 2.4b). A $\not= 50$ $\mu$m gold-plated stainless steel wire serves as the anode at 3.6 kV, and two 50 $\mu$m thick aluminum electrodes on the short edges of the drift cells serve as cathodes ($-1.8$ kV). The long edges contain 50 $\mu$m thick aluminum field electrodes at 1.8 kV. The cells span the full length or width of the chamber of $\approx 2.4$ m.
Figure 2.3: The Muon System of CMS. The Drift Tube Chamber layers are indicated in blue, Cathode Strip Chamber layers in green, and the Resistive Plate Chambers with red arrows. In the forward region, light and dark shades indicate the positions in even and odd sectors, which for the Cathode Strip Chambers overlap with 5 strips. For the Drift Tube Chambers, the lighter shades indicate layers measuring the $\eta$ coordinate instead of the $\phi$ coordinate. The magnetic field is strongest in the steel return yoke.
2.1. The CMS Detector

Figure 2.4: Illustration of the Drift Tube Chamber chambers. (a) shows a schematic view of a DT chamber [19]. Two superlayers measure the $\phi$-coordinate, and one superlayer measures the $\eta$-coordinate. A honeycomb plate separates the two $\phi$-superlayers and provides rigidity. (b) shows a single DT cell and its drift lines and isochrones [19].

The electrons and ions created by a passing muon will drift towards and away from the anode wire respectively. After a maximum drift time of 380 ns through the 85% Ar / 15% CO$_2$ gas mixture, the electrons reach the strong electric field close to the wire and the resulting avalanche creates an electrical signal on the anode wire.

The full barrel region is equipped with 4 coaxial layers of DTs (stations MB1 to MB4), with one DT in each of the 12 sides of each dodecagonal wheel (sector), and an additional separation in the outer layer of the top and bottom sector. Inside a DT, the position of the passing muons is measured in 3 superlayers consisting of four staggered layers each, with wires along $Z$ in the outer superlayers, and along $\phi$ in the middle suyperlayer$^3$ (fig. 2.4a). Combining the information from the different layers, a DT achieves a 100 $\mu$m resolution.

Cathode Strip Chambers The Cathode Strip Chambers (CSCs) are also gaseous particle detectors, this time combining cathode strips running along $\eta$, and perpendicular anode wires measuring the $\eta$ coordinate. These multiwire proportional chambers consist of seven cathode panels, interleaved with six anode wire planes in the 9.5 mm gaps (fig. 2.5). They are operated at an anode wire voltage of 2.9 to 3.6 kV, in a 50% CO$_2$, 40% Ar, and 10% CF$_4$ gas mixture. Using a 8.4 to 16 mm strip pitch and a wire-distance of 2.5 to 3.16 mm depending on their location, they provide a 75 to 150 $\mu$m resolution.

They are installed over the full 360$^\circ$ $\Delta\phi$ span in 4 layers (ME1 to ME4) and up to three rings as illustrated in fig. 2.3.

$^3$MB4 only has the 8 layers measuring the $\phi$ coordinate.
Section 2. The CMS Experiment at the LHC

Figure 2.5: Illustration of the Cathode Strip Chamber chambers. (a) shows a cut-away diagram of a CSC chamber with few of its anode wires, indicating the cathode strip and anode wire directions [19]. (b) shows a cross-sectional view of the gas gap in a CSC, with a schematic illustration of the gas ionization avalanche and induced charge distribution on the cathode strips [19].

2.2 The CMS Trigger and Data Acquisition System

The high luminosity and collision rate provided by the LHC, arriving in trains of ≈20 MHz for a total rate of ≈15 MHz in 2012, mean the CMS subdetectors produce the equivalent of ~15 TB s⁻¹ of data after zero-suppression. Data at these rates cannot be fully processed and stored at this rate.

Since only a fraction of these events provide insight into the physics processes under investigation, the CMS Trigger and Data Acquisition System (TriDAS) is designed to reduce this rate by selecting events based on their content (fig. 2.6). This selection is made in two steps. First, the Level One Trigger (section 2.2.1) selects relevant events at a rate of $\mathcal{O}(100\,\text{kHz})$ [20] using dedicated hardware, after which the detector channels have to be read out and sent to a commercial processor farm. There, the High Level Trigger further reduces the event rate to $\mathcal{O}(100$ to 800 Hz) [21, 22] (section 2.2.2). Selected events are then written to disks and tapes, and distributed among the data tiers across the globe to be processed by end-users.
2.2. The CMS Trigger and Data Acquisition System

![Diagram of CMS Trigger System]

2.2.1 The Level One Trigger

The first stage of online event selection is performed by the Level One Trigger (L1T) system. This system consists of dedicated electronics that receive data of a subset of the CMS detector channels every 25 ns, to process the full 40 MHz rate at which collisions may occur. The L1T traces back photons, electrons, muons and jets, and calculates the total and missing transverse energy $\Sigma E_T$ and $E_T^\text{miss}$ that give an idea of the total energy involved and hint at high-energy neutral particles crossing the detector unnoticed. These trigger objects are sent to the Global Trigger (GT).

At present, the L1T system follows a tree-like structure, going from local detector-specific processing, via regional triggers, to global triggers (fig. 2.7). Using the local hits, segments and clusters, the regional systems attempt to locate particle passages throughout the detector. The global processors combine these objects, sort them and provide them to the GT that takes a final decision, distributed as the Level One Accept (L1A) signal.

This decision has to arrive 128 BX (3.2 µs) after the actual Bunch Crossing, the time during which readout buffers can contain the data corresponding to an event. A large portion of this time actually goes into the transmission to and from the Underground Service Cavern (USC55) where the Trigger-dedicated hardware is located. Most of the hardware logic is implemented in custom Application Specific Integrated Circuits (ASICs) and programmable Field-Programmable Gate Arrays (FPGAs), using Look-Up Tables (LUTs) where possible to minimize processing time.
Figure 2.7: Outline of the Level One Trigger. The calorimeter systems (red) and muon systems (blue) each combine their trigger objects in a global trigger, and the Global Trigger combines that information with independent technical triggers to decide whether or not to send an event to the High Level Trigger. $E^\text{miss}_T$ indicates the missing transverse energy, $H_T$ the scalar transverse energy sum of all jets above a programmable threshold.
2.2. The CMS Trigger and Data Acquisition System

2.2.1.1 The Level One Calorimeter Trigger

The Calorimeter Trigger System measures local energy deposition sums in the ECAL and the HCAL detectors for common $\eta - \phi$ regions, called the calorimeter towers, using dedicated circuits on the readout electronics. For the ECAL, these sums are accompanied by a fine-grain bit, indicating if a large fraction of the summed energy came from two out of five adjacent ($\eta$) strips (five crystals along $\phi$). These Trigger Primitives are transmitted to the Regional Calorimeter Trigger (RCT), where each crate covers half the detector for a 40° opening angle and identifies $e$, $\gamma$ and hadron jet candidates in $4 \times 4$ tower regions. Finally, the Global Calorimeter Trigger (GCT) receives these trigger primitives and sends the four best candidates of each category to the GT, along with total and missing transverse energy.

To support the Global Muon Trigger, the RCT also transmits two bits indicating if energy deposits are compatible with the passage of a Minimum Ionizing Particle (MIP), or if a region is compatible with an isolated muon.

2.2.1.2 The Level One Muon Trigger

The different CMS muon detectors each have their own system for detecting and roughly reconstructing the passage of a muon. For the CSC and DT detectors, this process takes place in two phases [23, 24]: local triggers reconstruct track segments, and the track finders combine that information.

**DT and CSC Local Triggers** The first stage is performed in on-chamber electronics, and aims to reconstruct local track segments pointing towards the IP.

The DT does this by finding drift cells with coincident aligned hits in three out of four layers of a superlayer, within a group of nine drift cells (fig. 2.8). A mean-timer technique matches the hits to a straight-line segment, and a BX is assigned. These segments are matched between the two outer superlayers comparing them with pre-computed patterns, and sorted by momentum. This information is combined with the segments from the middle layer where possible and up to two segments in each chamber are collected for the DT Track Finder (DTTF).

In the CSCs, signals on cathode strips are combined per layer to achieve a half-pitch resolution, and a coincidence of four layers is required to create a segment (fig. 2.9). This is executed in a crate on the balconies. For the anode wires, 10 to 15 wires are ORed in a single channel, and again segments are selected using a four-out-of-six logic, this time in on-chamber electronics. To assign a BX, the coincidence takes place in two steps: when two layers have coincident hits, a segment pre-trigger is fired and the BX is assigned. The segment trigger is final if another two layers give a signal within the next
50 ns, to allow for the drift time. The $\eta$ and $\phi$ segments are combined in Trigger Mother Boards (TMBs) on the balconies, where also the ORed signals from the neighbouring RPCs arrive (section 4.2.1) to resolve ambiguities. Up to three segments per chamber can be transmitted to the CSC Track Finder (CSCTF).

**DT and CSC Track Finders** The Track Finders build the segments into tracks, assign them their $p_T$ and transmit up to four candidates to the Global Muon Trigger (GMT). For the DTTF, this is achieved by extrapolating the segments to neighbouring chambers using LUTs, and looking for matching segments within a given window around the projection. The matching segments are then linked in a series and joined into muon candidates. The CSCTF tries to match segments pairwise for consistency with a single track, and then tries to match the segment pairs into a single muon track. In the overlap region, local track segments are shared between DT and CSC.

The final muon candidates are assigned a $p_T$ using LUTs, and the coordinates at the second station are used to assign $\eta$ and $\phi$ coordinates. The muon candidates are assigned a quality that depends on the number and location of the contributing segments. Both Track Finders then send up to four muon candidates each to the Global Muon Trigger.

**RPC Muon Trigger** For the RPC detectors spanning the $|\eta|$ range up to 1.61, up to four muon candidates are traced back in both regions. The Pattern Comparator algorithm used for this is detailed in section 4.1.
2.2. The CMS Trigger and Data Acquisition System

Figure 2.9: Overview of the CSC local trigger [14]. (a) The charges on the different cathode strips within a layer are combined to give 1/2-strip-pitch resolution hits. To these hits, a local segment is matched. (b) For the anode wires, 10 to 15 wire signals are ORed, and a segment is matched to the resulting hits. (c) The BX assignment is performed by requiring two or more coincident hits, and the segment is completed if at least four layers have fired within the next 50 ns.

Global Muon Trigger The three described muon triggers provide CMS with a two to three-fold redundancy, depending on the $|\eta|$ region. By combining the information from the three muon triggers, the Global Muon Trigger (GMT) attempts to improve the muon trigger efficiency and purity, reduce the trigger rates and suppress the background.

To do so, the GMT collects up to four candidates from both the DTTF and the CSCTF, as well as four muons from both the RPC barrel and endcap regions. These muons are described by their $p_T$ and charge, their $\eta$ and $\phi$ coordinates at the second station and the aforementioned qualities. In addition, it receives quiet bits (to indicate the energy deposition in the calorimeters is below a given threshold) and MIP bits (to indicate an energy deposit compatible with a MIP crossing) from the GCT for $\Delta \eta \times \Delta \phi = 0.35 \times 0.35$ calorimeter regions.

After synchronizing these inputs, barrel RPC and DT candidates are matched by calculating the distance at the second muon station, $\Delta r = \sqrt{w_\eta (\Delta \eta)^2 + w_\phi (\Delta \phi)^2}$ using appropriate weights for $\eta$ and $\phi$ depending on the region. During 2012 data taking, the following logic was used to assign the merged candidate its $p_T$ [25]:

- In the barrel region,
  - if $|\eta| > 0.7$ and the RPC candidate quality is zero, the $p_T$ of the DT candidate is used.
  - Otherwise, the minimum $p_T$ is assigned to the merged candidate.

- In the forward region,
  - the CSC $p_T$ is used if its quality is three.
  - Otherwise, the minimum $p_T$ is used.
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Next, duplicate candidates in the overlap region, where the other combinations are possible (except RPC barrel and endcap), are cancelled out. The resulting candidates are then extrapolated to the calorimeter region, to set its MIP and isolation bits using the GCT data.

The final muon candidates are assigned a new quality, which in 2012 followed the following logic [25]:

- Quality 3: unconfirmed CSC candidates with a CSC quality of 1 (2) for $|\eta| > 1.3$ ($1.2 < |\eta| < 1.5$ and $|\eta| > 1.8$)
- Quality 5: unmatched RPC candidates
- Quality 6: unmatched DT and CSC candidates
- Quality 7: matched RPC-DT and RPC-CSC candidates

The candidates with quality 3 are rejected in the Global Trigger Single Muon triggers.

2.2.1.3 The Global Trigger

The Global Trigger (GT) is the final step of the Level One Trigger, and issues the L1A signal for selected events. This decision-taking is performed based on the candidate particles and quantities from the GCT and GMT, as well as a set of up to 64 Technical Triggers, special-purpose direct trigger signals from sub-detectors or TOTEM. Like for the GMT, the logic is implemented in FPGAs and can be adjusted.

The core logic of the GT is performed by the Global Trigger Logic (GTL) module. This card applies up to 128 so-called algorithms intended to match different physics event signatures. For each algorithm, it tests if one or more candidate particles or quantities comply with a given set of restrictions – be it a lower threshold on $p_T$, quality, $E_T$, cuts on the allowed charge or the presence of MIP or isolation bit, $\eta$ and $\phi$ ranges, or even cuts on the $\Delta \eta$ or $\Delta \phi$ between candidate particles. These restrictions form a condition, and the final algorithm is a logical expression of one or more condition results.

Inside the Final Decision Logic (FDL) card, each of these algorithm decisions can be deterministically prescaled (cf. section 6.3.1), depending on the abundance of corresponding events at a given instantaneous luminosity, or even masked. A logical OR of the resulting decisions with (potentially masked or prescaled) Technical Trigger decisions or vetos defines the final Level One Accept (L1A) decision, which is distributed by the L1 Trigger Control System (TCS) to the detectors to trigger full readout.

The outcomes for the different algorithms go on to serve in logical expressions that initiate corresponding High Level Trigger paths.
2.2. The CMS Trigger and Data Acquisition System

2.2.2 Readout and the HLT

**Readout** Upon the arrival of a L1A signal from the GT via the Timing, Trigger and Control System network, detector-specific Front-End Drivers (FEDs) send the digitized information of the detectors for the corresponding BX over S-LINK64s to the Front-End Readout Links (FRLs), encapsulated in the Common Data Format (CDF). The FRLs combine this data into an event fragment, and send them from the USC55 to the surface Surface Control Room (SCX) (push).

**Event Builder** The data of up to 8 event fragments with the same BX is then assembled by the FED Builder switching network in the buffers of the Readout Unit (RU). The resulting super-fragments enter another switching network, the Readout Builder, that in turn assembles them into a full event record in the Builder Units (BUs) (pull). This network is managed by the Event Manager.

**Event Filter** From there, the full events are sent to the Filter Unit (FU) PCs, where the High Level Trigger (HLT) processing is executed. Based on the software for offline analysis, CMS Software (CMSSW), it performs an accurate reconstruction of physics objects using combined sub-detector information to match requested event signatures. Depending on the abundance, the logical expressions that initiate different HLT paths can again be prescaled deterministically, this time before any calculations are performed.

**Trigger Throttling System** The arrivals of L1A decisions is a stochastic process, and while most parts within the TriDAS can cope with rates well above the average, full buffers may occur. To prevent this, Trigger Throttling System (TTS) signal can by sent to the GT both by the FEDs (synchronous with the Timing, Trigger and Control System clock, sTTS), and the RUs (Asynchronous TTS, aTTS) [26]. The GT will limit L1A rates accordingly until the TTS warning is cleared.

2.2.3 Timing, Trigger and Control System

During data taking, all subsystems of the CMS detector need to be informed when bunches cross, and which events to read out. Within those subsystems it’s important to assign time frames to the matching event and merge data from different parts of the detector correctly. This can be achieved using a common clock and event counters throughout the relevant electronics. This synchronisation is mediated by the Timing, Trigger and Control System (TTC) network.
**LHC clocks** The main clock is naturally defined by the LHC bunch passages, which are well determined in the LHC RF system at Point 4 (P4). From there, two clocks at the bunch-passage frequencies in both directions are transmitted over optical fibres to the LHC experiments and the CERN Control Center (CCC) [27, 28]. A third reference clock corresponds to the bunch-passage frequency at the target energy, and two additional signals stand for the target orbit frequencies in both directions.

CMS receives the clocks and orbit signals in the RF Receiver Module (RFRX), and after selection of a bunch clock and an orbit signal by the RF to TTC Interface Module (RF2TTC)\(^4\), the TTC Electrical Fanout Module (TTCcf) distributes what is to be the main clock and orbit pulse for the CMS readout and trigger electronics. In the absence of LHC beams, the RF2TTC uses an internal clock at 40.078 MHz.

**CMS clocks** The CMS TTC system distributes the clocks, along with time-critical messages, to the subdetector electronics. It consists of two time-division multiplexed (TDM) channels, A and B, transmitted over optical networks. The first channel distributes exclusively the L1A signals, while the B channel allows for specific broadcast or addressed control signals. Both channels are assigned a bandwidth of \(\approx 40\) Mbit s\(^{-1}\), as defined by the bunch clock from the RF2TTC. The RF2TTC’s orbit clock is sent through the B channel in the form of a bunch-counter reset command.

**CMS TTC architecture** The CMS optical TTC network is divided into independent partitions, each originating at a TTC CMS Interface (TTCci) module. These modules can either be controlled by the central TCS as a whole, or in up to eight independent partition groups, or by a preassigned subdetector’s Local Trigger Controller (LTC). This allows subdetectors to run independently with private triggers for commissioning purposes.

A TTCci receives L1A and so-called B-Go commands from the TCS or its LTC and translates them to the partition-specific TTC channel B control words. A TTC Encoder and Transmitter (TTCex) module encodes the two TTC channels using a clock received from the TTCcf, and through optical splitters these commands are broadcast to the partition’s electronics.

Other commands carried by the B channel include [30]

- a start and stop command to start and stop data taking,
- an orbit counter reset, usually sent at the beginning of a run,
- an event counter Reset, sent after a resync,
- a test enable command, to initiate calibration procedures,
- a resync command, to start emptying trigger and readout buffers or pipelines, and

\(^4\)In practice, the reference clock is used as main bunch clock when beam is present.
2.3 CMS Online Software

The CMS detector and its electronics comprise a vast system with many flexible components that need to cooperate. To manage the different servers and applications that provide control and monitoring, it has been organized in a hierarchical structure with common Finite State Machine (FSM) states throughout the tree.

LHC Beam Synchronous Timing System   An independent TTC network carries the LHC Beam Synchronous Timing System (BST) data from the CCC to the different experiments. Via its A channel it also transmits the orbit turn clock, while its B channel contains the LHC Global Positioning System (GPS) time and details on beam and bunch types, energies, counters and states. This information enters CMS via the Central TCS and the LTCs, and it is stored in event data. The RF2TTC module also uses a BST input to aid in clock selection.

- a hard reset command, used to trigger firmware and configuration reloading to avoid Single Event Upsets (SEUs) piling up [31].
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Run Control and Monitor System The top of the control system is implemented using the Run Control and Monitor System (RCMS) framework. Implemented in the Java language, it organizes the system in Function Managers (FMs) in a hierarchical control tree, and provides the user with web-based Graphical User Interfaces (GUIs). A central FM node steers the FMs for the sub-systems using a common FSM, but any FM can be controlled independently.

A set of services are accessible to the FMs [32]:

- a security service for authentication and user account management,
- a resource service for storing and delivering configuration information of online processes,
- access to remote processes via resource proxies,
- error handlers,
- a log message application to collect, store and distribute messages, and
- Job Control to start, stop and monitor processes in a distributed environment.

Information about which configuration to use is organized in global configuration keys, to which subsystems can link their own. This allows for the operation of the full detector by a limited number of central shifters.

Cross Platform Data Acquisition The software platform used for the online software is XDAQ (Cross Platform Data Acquisition) [33], implemented in C++. It is designed to provide the distributed platform needed to control the electronics and run the Data Acquisition (DAQ) components. Each XDAQ executive can load different applications and provides the developer the means to allow efficient communication among distributed applications using peer-transport like SOAP\(^5\) over HTTP and binary Intelligent Input/Output (I2O) over TCP or in-memory. Miscellaneous tools also ease the implementation of things like a web-based GUI, centralized logging, FSMs and service discovery.

Trigger Supervisor Apart from the sub-detectors, also the L1T has a node that handles the different L1T systems homogeneously as Trigger Supervisor (TS) cells [34] (cf. section 5.2).

Detector Control System Another subsystem consists of the CMS Detector Control System (DCS), which is responsible for the slow control of the different subdetectors. The full DCS is implemented in the WinCC Open Architecture SCADA Tool (WinCC-OA), formerly known as PVSS\(^6\), a common characteristic for the LHC and its experiments.

\(^5\)Simple Object Access Protocol
\(^6\)Prozessvisualisierungs- und Steuerungs-System
2.4 CMS Offline Software

This distributed system allows control, monitoring and archiving of critical components like power supplies, gas supplies and sensors, compatible with several industry standards. To achieve a homogeneous system, CERN uses the Experiments’ Joint Controls Project (JCOP) framework on top with tools and guidelines for developers.

Data Quality Monitoring  The task of verifying the trigger and detector operation is carried out by the Data Quality Monitoring (DQM) system [35]. Using a subset of the data analysed by the HLT in the online system, as well as states published by the other online software, histograms and other quantities are filled and served to the shifters in a web-based GUI. Offline, more thorough analysis can be performed by the offline DQM on Tier-0, the first tier in the computing resources architecture that receives, stores and distributes data from the HLT and performs the first calibration and reconstruction.

It also performs subsystem-specific algorithms to alert shifters and flag data valid or invalid for physics analysis.

2.4 CMS Offline Software

Once the detector data has been compiled per event and enters the HLT, it is handled by the CMS Software (CMSSW) Framework [36]. CMSSW is a modular event-driven C++ software framework, with an Event Data Model (EDM) and services for simulation, calibration and alignment.

Starting from a source module, it allows for easy integration of event-driven modules with predefined interfaces for filtering or analysis of data, as well as further production in producers. The latter gives a unified storage model for the unpacking of RAW CDF data and the reconstruction of physics objects, as well as handling simulated events. An output module selects what used or produced data is kept for storage, and depending on the final event content the resulting ROOT data files are organized in different data tiers (RAW, RECO, AOD or DQM and calibration-specific mixes) [37].

CMSSW also gives access to detector conditions and calibration information in an object-oriented fashion, based on Database (DB) tables linked either to the Run/Luminosity Section (LS)7 identifier or a timestamp. This data is made available worldwide to the LHC Computing Grid using a Frontier Distributed DB caching system [38], and is grouped for different running or simulation conditions in global tags for ease of use.

7A time unit of $2^{18}$ beam revolutions for conditions was implemented in CMS as one Luminosity Section (LS), equivalent to 23.31 s.
Chapter 3

The CMS Resistive Plate Chambers

Given the key role of muons in the selection of events, the fast Resistive Plate Chambers are a crucial part of the CMS experiment. This chapter goes through the working principle of this detector (section 3.1), as well as the design and implementation of the CMS RPC system (section 3.2). The author took an important role in the commissioning of services related to the RPCs in CMS.

3.1 Resistive Plate Chambers

3.1.1 Gaseous Particle Detectors

From the early stages in particle detection for High Energy Physics (HEP) experiments, gaseous particle detectors have played a crucial role. Throughout the years, they have evolved from the single-wire proportional counter introduced by Rutherford [39], to a wide range of fast, efficient detectors with a fine resolution at a reasonable cost [40]. They also brought the particle tracking detectors from photographic to fully electronic devices, a major step for the analysis capabilities of experiments. From the advent of the multiwire proportional chamber [41] onwards, they enabled the discovery of a high number of particles.

Despite the broad range of gaseous particle detectors, the principle remains broadly the same. As particles cross a gaseous medium, they ionize its constituents. The resulting electrons and ions are then accelerated by an electric field, and through secondary ionization the electrons may cause an avalanche. The avalanche can grow to a streamer or a spark from anode to cathode depending on the electric field, the geometry and the gas in use. The propagation of these free charge carriers induces a signal on readout electrodes, which depending on the layout and electronics can give a fine grained position and time information about the particles’ path.
Chapter 3. The CMS Resistive Plate Chambers

3.1.2 Resistive Plate Chamber Development

The cylindrical geometry of early gaseous detectors set a severe limit on the feasible time resolution. The introduction of planar detectors with uniform electric fields resolved this by increasing the amplification region to the full gas gap, eliminating the drift region.

In the early seventies, a parallel plate chamber using one plane with high-resistivity ($10^9$ to $10^{10}$ $\Omega$ cm) was developed and successfully applied in a time-of-flight experiment [42, 43]. The resistive glass plate effectively limited the area of the electrode discharge around the signal, allowing for high-rate applications. In addition, the electric field drops locally due to the slow recharging, limiting the avalanche development.

In the early eighties, the advantages of resistive plates met with the wide availability of High Pressure Laminate (HPL) planes made with melamine or phenol resins (Bakelite), as Santonico et al. built parallel plate chambers consisting of two high-resistivity bakelite planes containing a low-pressure gas mixture [44]. In addition, the introduction of the avalanche mode for RPCs [45, 46] in the nineties increased its rate capabilities by an order of magnitude to the kHz cm$^{-2}$ range. These developments made RPCs an affordable solution for large-area high-rate experiments, and led to the Resistive Plate Chambers as used in CMS.

3.1.3 Resistive Plate Chamber Working Principles

3.1.3.1 Passage of a Muon through an RPC

When a relativistic muon crosses the RPC gas volume, it predominantly interacts with the gas molecules through the electromagnetic interaction. The mean energy loss rate through ionization and excitation for relativistic heavy charged particles ($m \gg m_e$) is described by the Bethe-Bloch equation [10] (fig. 3.1),

$$ -\frac{1}{\rho} \frac{dE}{dx} = \frac{e^4}{4\pi \epsilon_0^2 m_e c^2} Z^2 N_A Z A \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 E_{\text{max}}}{I^2} - \beta^2 - \delta (\beta \gamma) \right], $$

(3.1)

where

- $\rho$ is the density of the material,
- $e$ is the charge of the electron,
- $\epsilon_0$ the dielectric constant of the vacuum,
- $c$ the speed of light,
- $z$ the charge of the incident particle,
- $N_A$ Avogadro’s number,
Figure 3.1: Energy loss $\frac{1}{\beta} \frac{dE}{dx}$ for positive muons in copper as a function of $\beta \gamma = \frac{p}{mc}$ [10]. The increasing contribution of the density effect with muon momentum is illustrated ($\delta$, green dashed). $E_{\mu c}$ represents the muon critical energy, at which energy losses due to radiation (orange, dotted) and ionization (red, dot-dashed) are equal. The energy of a MIP is also indicated.

- $Z$ the atomic charge number of the material and

- $A$ the atomic number of the material.

- $\beta = \frac{v}{c}$ is the velocity of the particle in units $c$, and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$.

$I$ represents the mean excitation energy, and $E_{\text{max}}$ is the maximum energy transfer in a single collision of the particle with mass $m$ and momentum $p$,

$$\frac{2m_e p^2}{m^2 + 2\gamma m_e m + m_e^2}. \tag{3.2}$$

Polarization of the medium screens the long-distance interaction of the particle, truncating the rise in energy loss expected from the extending electric field with higher energy. This is called the density effect and is contained in $\delta (\beta \gamma)$.

It should be noted that eq. (3.1) describes the mean energy loss. The energy loss through a given $pdx$ is a stochastic process following the long-tailed Landau distribution, which implies the most probable value is well below the predicted mean (cf. [10]).
While other effects contribute to the energy loss of the particle, it is the loss of kinetic energy through excitation and ionization of the gas atoms and molecules that enables the RPC to detect the passage of a muon. The excited atoms can either emit a photon when returning to the ground state, emit an Auger electron or cause ionization through collision (Penning effect). The photon can in turn either be absorbed by an atom if its energy exceeds the minimum ionizing potential, as such ionizing it through the photo-electric effect, or it can escape undetected.

3.1.3.2 Avalanche Development

Electron Multiplication The electron-ion pairs along the muon track, the primary clusters, are the free charge carriers that initiate Townsend avalanches as the electrons are accelerated in the electric field $E$ and cause further ionization.

Given the limited energy loss, consecutive ionizations are independent and the number of primary clusters $n_c$ follows a Poisson distribution [47],

$$P(n_c) = \frac{(g \lambda_{\text{eff}})^{n_c}}{n_c!} e^{-g \lambda_{\text{eff}}}$$  \hspace{1cm} (3.3)

for gap width $g$ and $\lambda_{\text{eff}} = \frac{\lambda}{\cos \phi}$, the effective number of primary clusters $n_c$ per unit $z$ for a particle incident at angle $\phi$ with respect to $z$. This also defines the distributions of the positions $z_j$ of primary cluster $j$,

$$P(z_{j, 0}) = \lambda_{\text{eff}} \frac{(z \lambda_{\text{eff}})^{j-1}}{(j-1)!} e^{-z \lambda_{\text{eff}}}.$$  \hspace{1cm} (3.4)

The development of the electron cascades from these clusters is driven by the Townsend ionization coefficient $\alpha$ and the attachment coefficient $\beta$, respectively describing the average number of electron-ion pairs created, and the average number of electrons attached to form a negative ion according to [48]

$$\frac{dn_j}{dz} = (\alpha - \beta) n_j,$$  \hspace{1cm} (3.5)

where $z$ is the position along the electric field and $n_j$ the number of electrons from primary cluster $j$.

Different models exist to describe the fluctuations of the avalanche development and their impact on the signal induction [49, 47]. For constant $\alpha$ and $\beta$, one approximation assumes an exponential avalanche development with total charge [47]

$$q_e (z) = \sum_j n_j e^{(\alpha - \beta)(z - z_{j, 0})}$$  \hspace{1cm} (3.6)

at position $z$ for primary clusters $j$ with initial number of electrons $n_{j, 0}$, where $q_e$ is the electron charge. The factor $M_j$ accounts for the stochastic fluctuation, and the Polya distribution is reported to give good agreement of simulation and experiment.
Signal Induction  Using Ramo’s theorem [50], the current induced on an electrode by the movement of the resulting electrons in the electric field can thus be calculated as a function of the weighting field $E_w$ and the drift velocity $v_d$ [47]

$$i(t) = -v_d \cdot E_w \sum_{j} q_e M_j n_j,0 e^{(\alpha - \beta)(t - t_j,0)}.$$  \hspace{1cm} (3.7)

High Voltage Correction  The Townsend ionization coefficient $\alpha$ is reported to have a functional dependence on $E_P$, leading to an approximate High Voltage (HV) correction for the environmental pressure of [51, 52]

$$V_{\text{eff}} = \frac{P_0}{P} \frac{T}{T_0} V_{\text{app}},$$  \hspace{1cm} (3.8)

with an additional term $\propto \ln \frac{P}{P_0}$ suggested in [53] based on eq. (3.6) and the Korff approximation for $\alpha$,

$$\frac{\alpha}{P} = A \exp \left( -B \frac{E}{P} \right).$$  \hspace{1cm} (3.9)

3.2  The CMS Resistive Plate Chambers

3.2.1  Detector

CMS uses double-gap Resistive Plate Chambers, with each 2 mm gas gap formed by two parallel HPL bakelite electrodes (bulk resistivity $\rho \sim 1 \times 10^{10}$ to $6 \times 10^{10}$ $\Omega$ cm) (fig. 3.2). A 35 to 40 $\mu$m coating of linseed oil on the inside smoothens the surface [54] and quenches Ultraviolet (UV) photons [55]. A $10 \times 10$ cm$^2$ grid of $\varnothing$ 8 mm Polyvinyl Chloride (PVC) spacers keeps a constant gap width throught the chamber. On the outside a lower-resistivity graphite coating ($\sim 10^5$ $\Omega$/cm$^2$) acts as the electrode connected to the High Voltage.

The gaps are placed one on top of another with common copper readout strips in between at ground level (fig. 3.2), separated from the graphite by mylar sheets. They are operated in avalanche mode to safeguard the time resolution at high rates ($\sim 1$ kHz/cm$^{-2}$).

The gas mixture, kept at 21 $^\circ$C, is composed of three components.

- 95.2 $\%$ C$_2$H$_2$F$_4$ (R-134a) acts as the carrier gas, and ensures a high primary cluster density $\lambda^{-1}$ ($\sim 5$ mm$^{-1}$ vs $\sim 2.5$ mm$^{-1}$ for argon) while maintaining the effective Townsend coefficient $\eta = (\alpha - \beta)$ [56].
- 4.5 $\%$ iC$_4$H$_{10}$ (isobutane) is added as a quencher gas to absorb UV photons from molecule de-excitation.

\footnote{The electric field inside the detector when setting the electrode under study at unit voltage, and connecting the others to ground [50].}
Chapter 3. The CMS Resistive Plate Chambers

Figure 3.2: Cross-section of a CMS Resistive Plate Chamber. The top gap mirrors the bottom one.

- 0.3% SF$_6$ controls the excess $e^-$ through its high electron affinity, contributing to the attachment coefficient $\beta$ and suppressing streamer probability [57]

A 35%–40% humidity is added to maintain the bakelite resistivity, which increases as the bakelite dries out [58].

To reduce the consumption of the gases, a necessity given the significant Global Warming Potential (GWP) of R-134a and SF$_6$, the gas mixture is circulated in a closed loop with a 5 to 10% fresh mixture injection [59, 60]. This circulation brings a pollution of the gas with it, that could increase currents in the RPCs as well as present chemically reactive impurities like hydrocarbons, HF, F$^-$ and Freon-type molecules [61]. A set of gas purifiers installed above ground reduces these and successfully allows for a 90 to 95% recirculation factor [62]. In addition to a gas chromatograph, a stack of RPCs above ground – exposed to cosmic rays – continuously monitors the recirculated gas mixture before and after the purifiers, as well as the fresh mixture [63].

3.2.2 Layout and Naming Convention

Regions, Stations and Layers ($R$, $Z$) The detector layout of the RPC system within CMS is mainly driven by the need to trigger on the transverse momentum of passing muons. Because the transverse momentum $p_T$ is measured with the bending of the muon in the CMS magnetic field, this requires a muon to cross a minimum of three layers. Since no detector has a 100% efficiency, and single layers can not provide full $\phi$ coverage due to mechanical restrictions, a fourth layer has been added to this requirement. Ideally, these layers are interleaved with the steel return yokes, to ensure a maximum muon track bending between them.

In the barrel region ($RB$) the muon chambers are organised in four coaxial stations ($RB1$ through $RB4$), interleaved with the steel return yokes (fig. 2.3). In practice, low-$p_T$ muons do not reach the outer return yokes. Therefore, the inner two stations each consist of a layer of DTs sandwiched between two layers of RPCs (named in and out). The outer two stations each consist of one layer of RPCs and one layer of DTs.
3.2. The CMS Resistive Plate Chambers

The two endcap regions \( RE^+ \) and \( RE^- \)\(^2\) are each composed of three steel disks holding a total of 3 RPC planes (numbered \( RE+1 \) through \( RE+3 \) on the positive \( Z \) side, and \( RE-1 \) through \( RE-3 \) on the negative). A fourth layer of RPCs has been installed during the LHC First Long Shutdown (LS1) \( (RE-4 \) and \( RE+4 )\).

**Sectors (\( \phi \)), Wheels (\( Z \)) and Rings (\( \eta, R \))** The full barrel is divided in 12 sectors along \( \phi \), as dictated by the mechanical construction of the CMS return yokes. The constant \( \Delta \phi \) division creates increasingly big chambers with \( R \), so the third and fourth layer are divided in two subsectors along \( \phi \) where possible \((- \) and \(+ \))\(^3\). The top sector 4 has an additional separation for RB4 into \(--, -, +, ++\) with increasing \( \phi \).

For mechanical stability and feasible RPC-sizes, the endcap disks are divided in 36 sectors along \( \phi \)\(^4\).

The barrel yoke is further organized in the five moveable wheels along \( Z \) \((W-2 \) to \( W+2 \)). Inside each wheel, every layer and (sub)sector has one rectangular chamber – one aluminum frame containing four gas gaps.

The endcap layers have two concentric rings each along \( R \) (labeled ring \( R2 \) and \( R3 \))\(^5\), consisting of 36 trapezoidal chambers. The chambers of the inner ring on the first layers \((RE+1/R2 \) and \( RE-1/R2 \)) alternately sit in front of and behind the corresponding CSC.

**Rolls (\( \eta, R \)) and Readout Strips (\( \phi \))** The surface area of the strips, and thus their length, is defined by a limit on the background rate per strip, which would increase the probability of random coincidences resembling a muon. The length is further restricted by the time-of-flight difference and the signal propagation time along the strip, as well as the change in muon bending along \( \eta \) for the endcap regions, visible from the changing magnetic field in fig. 2.3.

These considerations result in a division of each chamber along \( \eta \) in two to three \( \eta \)-partitions \((rolls)\), resulting in strip lengths of 57 to 125 cm in the barrel and 47 to 79 cm in the endcap region. They are labeled \( backward \) and \( forward \) in the barrel region, or \( backward, central \) and \( forward \) in the reference layers \((section 4.1)\). The 36 10\(^\circ\) trapezoidal chambers in each endcap ring consist of three rolls, labeled \( A \), \( B \) and \( C \) with increasing \( \eta \).

The \( \Delta \phi \) coverage of a single strip defines the \( p_T \)-resolution of the RPC Pattern Comparator \((PAC) \) trigger \( (section 4.1)\), but is limited by the achievable cluster size. For these reasons, the system has been designed to have \( R \)-projective strips covering \( \Delta \phi \approx 18\,45'' \) where possible, running along the beam axis in the barrel region and radially in the endcap region. For the endcap region this logic can be followed exactly, such that every roll

\(^2\)Also called the \( forward \) region, or \( forward \) for \( RE^+ \) and \( backward \) for \( RE^- \).
\(^3\)Sector 9 and 11, where the wheels are supported, do not have the necessary space in RB4.
\(^4\)Except for the future inner ring, planned to contain 20\(^\circ\)-chambers.
\(^5\)\( R1 \) refers to the descoped ring that will instrument \( 1.61 < |\eta| < 2.1 \) for phase II.
Chapter 3. The CMS Resistive Plate Chambers

<table>
<thead>
<tr>
<th>Strip width ($\Delta \phi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>track bending (required momentum resolution)</td>
</tr>
<tr>
<td>multiple scattering and energy losses</td>
</tr>
<tr>
<td>cluster size</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strip length ($\Delta \eta$)</th>
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</thead>
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<tr>
<td>signal propagation time along the strip (BX assignment)</td>
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<tr>
<td>change of the bending with $\eta$</td>
</tr>
<tr>
<td>change of $\eta$ due to non-$r\phi$ bending</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strip area (number of strips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of channels (cost)</td>
</tr>
<tr>
<td>complexity of the trigger processor (feasibility)</td>
</tr>
<tr>
<td>number of interconnections (feasibility)</td>
</tr>
<tr>
<td>capacitance</td>
</tr>
<tr>
<td>occupancy</td>
</tr>
<tr>
<td>probability of random coincidences of background hits</td>
</tr>
<tr>
<td>mechanics of the chamber</td>
</tr>
</tbody>
</table>

Table 3.1: Determination of the RPC granularity [64]. Dominant upper and lower limits are marked with $\Downarrow$ and $\Uparrow$ respectively.

(10°) has a plane of 32 trapezoidal strips. For the barrel region chambers have to fit in the return yokes, leaving gaps in $\phi$ within a layer. Within each chamber the strips are chosen to have a constant width, leading to a somewhat smaller $\phi$-span for strips near the chamber edges.

A full description of the granularity requirements is given in [64], and summarized in table 3.1.

3.2.3 Services

The main services for the RPCs are controlled by the RPC Detector Control System (DCS) [65, 66]. The RPC DCS is controlled through the central CMS DCS, which in turn follows the RCMS FSM state changes (fig. 5.5, cf. section 2.3). A summarized state of the RPC system is reported upwards this hierarchy.

An extensive WinCC-OA GUI also gives the shifter the options of controlling the system through FSM state transitions at different nodes of two trees – respectively describing the hardware tree or the detector layout – always affecting nodes further down the tree. Additional panels give access to individual power supply boards and channels.
3.2. The CMS Resistive Plate Chambers

Optimized settings for all components are stored in and loaded from DB, as well as monitoring data. To limit disk-usage, all parameters are assigned a deadband, and only changes that exceed this deadband are stored. Data relevant for offline analysis are translated to C++ objects and transferred from the Online Master Database System (OMDS) to ORCON\textsuperscript{6}/ORCOFF\textsuperscript{7} using the Populator of Condition Objects (PopCon), such that they can be used from CMSSW.

3.2.3.1 Power Supply System

The power supply system takes care of the HV that creates the electric field in the RPCs, and the Low Voltage (LV) to power the on-detector Front-End (FE) electronics and the Link Boxes (section 4.2.1). Many of its components have to endure the residuals of the CMS magnetic field outside the steel yokes, as well as significant radiation levels ($\sim 0.4$ to $0.8$ Gy for $5 \times 10^3$ fb$^{-1}$ [67]). Therefore, a distributed power supply system is in use, minimizing the number of components in the Underground Experimental Cavern (UXC55), and with radiation-tolerant magnetic-field-resistant power supplies manufactured by CAEN.

The system is built around the CAEN Embedded Assembly System (EASY) [68], with four independent SY1527 mainframes installed in the USC55 and controlled by RPC DCS through an OPC\textsuperscript{8} server. During commissioning periods, control can be taken through a telnet interface with these mainframes, overriding the DCS system.

The mainframes are fitted Branch Controller boards, to each of which up to six EASY crates are connected. While the crates are physically connected as a line, the EASY system effectively implements a star topology. This is achieved by using a fifty wire connection for an eight wire bus, and shifting the communication wires by one section between input and output at each crate.

The power supplies have on-board safety restrictions, including both hardware and software limits, and more advanced safety mechanisms are implemented in the RPC Detector Control System to react on temperature rises and cooling, gas or other auxiliary system failures. The central Detector Safety System (DSS) system [69] implements further global safety actions, through a programmable alarm-action matrix.

**High Voltage** For the High Voltage, the barrel and endcap region each have a mainframe in the USC55. The EASY crates in turn host CAEN A3512N HV modules, capable of supplying 12kV at 1 mA on 6 floating channels, well beyond CMS RPC requirements, monitoring with a precision of 1 V and 0.1 µA. Each channel is then split in two (barrel region) or four (endcap region) channels before a HV cable runs from the USC55 to the UXC55. Because each channel serves one layer of gaps in a double-gap RPC, malfunctions on one side can be eliminated from the USC55 while access to the UXC55 is limited.

\textsuperscript{6}Offline Reconstruction Condition Database, Online subset
\textsuperscript{7}Offline Reconstruction Condition Database, Offline subset
\textsuperscript{8}OLE for Process Control
Cluster size versus atmospheric pressure [70]. In red, early 2011 data shows a linear correlation between the cluster size and atmospheric pressure. In blue, late 2012 data shows the cluster size is stable at \(\approx 1.85\) after application of eq. (3.10).

**HV Correction**

While temperature changes in the cavern can be limited, the pressure follows the environment. Therefore, a pressure correction according to eq. (3.8) has been in use for the CMS RPCs through an automatic procedure in DCS.

Taking into consideration the cluster size \(N_{CLS}\) as a function of the pressure \(P\) however, it became clear\(^9\) that the HV correction formula overestimates the overall effect of the pressure.

As a first approximation, the pressure dependence of the cluster size is linear both before and after this correction is introduced,

\[
N_{CLS} (V_{app}, P) = a (V_{app}) (P - P_0) + b,
\]

where \(b\) is the cluster size at \(V_{eff}, P_0\).

With the two aforementioned measured linear dependencies,

\[
a (V_{eff}) (P - P_0) + b = a_1 (P - P_0) + b
\]

\[
a \left( V_{eff} \frac{P}{P_0} \right) (P - P_0) + b = a_2 (P - P_0) + b,
\]

and assuming \(a (V_{app})\) is linear in \(V_{app}\), constant cluster size \((a (V_{app}) = 0)\) corresponds to

\[
V_{app} = \left( \frac{a_2}{a_2 - a_1} - \frac{a_1}{a_2 - a_1} \frac{P}{P_0} \right) V_{eff}.
\]

This can be translated to a reduction of the correction by taking into account only a fraction \(\alpha_0 = \frac{a_1}{a_1 - a_2}\) of the pressure change [70]:

\[
V_{app} = \frac{P_0 + \alpha_0 \Delta P T_0}{P_0} \frac{T}{T} V_{eff}.
\]
3.2. The CMS Resistive Plate Chambers

Pressure Correction done every 40V variation
Pressure Correction done every 15V variation
Pressure Correction done every 3V variation

Figure 3.4: RPC Barrel efficiency over the 2011-2012 data [70]. The pressure correction has been introduced gradually as shown by the legends. A zoom on the last period is shown, when pressure correction was applied more fine-grained, and eventually using eq. (3.10) from late 2012.

This empirical correction was implemented by the end of 2012 under the name $\alpha$-correction, and the resulting cluster size distribution for $\alpha_0 = 0.8$ can be found in fig. 3.3, while fig. 3.4 shows the evolution of the efficiency under different pressure correction conditions.

To remove the inherent dependency of $\alpha_0$ on the chosen $P_0$ within this formula, one can introduce a pressure offset

$$\beta_0 = \frac{1 - \alpha_0}{\alpha_0} P_0 = -\frac{a_2}{a_1} P_0,$$

constant in the region of interest, resulting in

$$V_{\text{eff}} = \frac{P_0 + \beta_0}{P + \beta_0} T_0 V_{\text{app}}.$$

Low Voltage and Environmental Sensors The two other mainframes take care of the Low Voltage crates in the balconies of the UXC55, housing LV supplies for the Link Boxes (CAEN A3009) and Front-end electronics (CAEN A3016), as well as Analog-to-Digital Converters (ADCs) (CAEN A3801A) for on-chamber temperature sensors, gas-line temperature sensors, and on-yoke temperature and humidity sensors. Each device is powered by two LV channels, serving the analog and digital components. Inside an RPC chamber, a FEB Distribution Board (FDB) distributes the LV – as well as an I\textsuperscript{2}C communication line – to the Front-End Board (FEB), the latter responsible for detecting the RPC avalanches (cf. section 4.2.1).
The FDB distributes the LV passively, and the I²C line is controlled through the Link System (cf. section 5.1). Because the FEBs have additional temperature sensors on AD7417 ADCs, these are sent to the RPC DCS via the XDAQ-PVSS SOAP Interface (PSX) (cf. section 5.1).

The trigger and readout system in the USC55 is powered locally through the Versa Module Eurocard (VME) crates.

### 3.2.3.2 Gas System

The gas supply system is controlled by the CERN LHC-Experiments Gas Control Systems (GCS) group, also with a WinCC-OA-based system. The RPC DCS extracts relevant parameters to adjust HV settings in case of gas supply problems, made accessible via the Data Interchange Protocol (DIP)\(^\text{10}\). For prompt actions – for example a dangerous increase of isobutane content – Programmable Logic Controllers (PLCs) can cut gas supply and stop the HV supplies directly at the mainframes.

\(^{10}\)A DIP publisher and consumer is provided on top of WinCC-OA as part of the JCOP framework.
As muons leave trails of avalanches in the RPC gas gaps, a chain of electronics records the hits, traces back the muons and selects interesting events. To get the most out of the luminosity the LHC delivers, this process has to be repeated for every Bunch Crossing (25\, ns), with high constraints on the system’s performance and reliability.

This chapter describes the CMS RPC Trigger and Data Acquisition algorithms used to achieve this, as well as the hardware implementation.

4.1 The RPC Muon Trigger Algorithm

To identify muons in the RPC detector real-time every 25\, ns, recorded hits are compared with predefined hit patterns by the Pattern Comparator (PAC). Given the vast number of strips, the possible tracks muons can follow through the RPC system, and the rate at which the RPC trigger has to identify them, parallelization of this process is inevitable. Taking the muon trajectories through the CMS detector into consideration, a geometric partitioning in both $\eta$ and $\phi$ closely related to the detector layout proves to be the natural choice. The amount of data the patterns constitute and the transfer of candidates between the consecutive processing units dictate a correlated binning of muon candidate parameters.

**PAC Segmentation and Binning**  From the trigger point of view, the RPC subdetector is divided into so-called towers along the $\eta$-coordinate. The $\eta$-coverage of each tower is defined by the strip length in the reference layer, as depicted in fig. 4.1, which allows for an unambiguous $\eta$-coordinate assignment to the muon candidates. Because this division does not match the strip positions and lengths in other layers, a tower-processing unit also takes the strips into account that overlap with its $\eta$-range. Contributing strips within a layer at the same $\phi$-angle are combined in a logical strip, that is considered fired if any of its constituting strips gives a signal.
Figure 4.1: Cross-section of a quadrant of the CMS RPC subdetector. Each arrow represents a strip in this plane (physical sector 1). For trigger purposes, the RPC subdetector is divided into 25 towers along $\eta$ (delineated by the blue dashed lines), matching the strip lengths in the reference layers (red wiggly arrows). Each tower consists of 144 logical cones along the azimuthal angle. Outside the reference layers the strips don’t match the tower’s $\eta$-ranges, and are combined in a logical strip. As an example, the strips contributing to towers 3, 7 and 11 are highlighted in blue. In the forward region, the strips in lighter shades represent the even physical sectors.
4.1. The RPC Muon Trigger Algorithm

<table>
<thead>
<tr>
<th>index (n)</th>
<th>(p_{T,n}) (GeV/c)</th>
<th>index (n)</th>
<th>(p_{T,n}) (GeV/c)</th>
<th>index (n)</th>
<th>(p_{T,n}) (GeV/c)</th>
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<tr>
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<td>15</td>
<td>14.0</td>
<td>23</td>
<td>45.0</td>
<td>31</td>
<td>140.0</td>
</tr>
</tbody>
</table>

Table 4.1: The Level One muon \(p_T\)-scale, indicating the lower \(p_T\) bound for each 5-bit index. The scale is common for the DTTF, the CSCTF, the RPC PAC and the GMT.

For the azimuthal segmentation, eight adjacent strips in the reference layer constitute one of the 144 \(\phi\)-segments (2°30'). Outside the reference layer, the resulting pyramidal \((\Delta \eta \times \Delta \phi)\) segments (logical cones) are extended along \(\phi\) with neighbouring strips to account for the curvature of muons in the magnetic field (fig. 4.2).

This strip-oriented segmentation defines the \((\Delta \eta \times \Delta \phi)\)-binning of both the patterns and their corresponding muon candidates. Using the segment position in the reference layer is in accordance with the GMT specifications, that demand \((\eta, \phi)\) muon coordinates at the second station for ease of matching with the DTTF and CSCTF candidates [71, 72].

For the transverse momentum, a common 5-bit non-linear \(p_T\)-scale has been fixed for the different Level One (L1) muon triggers with the requirement that at every \(p_T\)-threshold a 90\% trigger efficiency is reached [71, 72]. The \(p_T\)-scale was chosen as a rounded logarithmic scale to achieve constant rate-ratios from bin to bin [73] (table 4.1, fig. 4.3).

PAC Pattern Generation The patterns of fired logical strips are produced following the trajectories of Monte Carlo (MC) generated muons through CMS, assuming 100\%-efficient RPC chambers. Starting above the highest \(p_T\)-threshold \((p_{T,n}=31)\), muons with identical hit patterns are grouped. For every logical cone the most frequent patterns are assigned \(p_T = p_{T,n}\) until a fraction of muons

\[
\frac{N_{p_{T,sel}}}{N_{p_{T} \geq p_{T,n}}} \gtrsim 0.9
\]

is selected. These steps are then repeated for the following \(p_T\)-thresholds, always taking into account the previously selected patterns. This procedure ensures the GMT \(p_T\)-scale requirement is fulfilled by design.

For low-\(p_T\) muons, multiple scattering increases the number of possible muon tracks coming from a given initial \(p_T\) and direction significantly. Since the track bending is highest at low \(p_T\), two to four adjacent logical strips can be combined (logical OR) in super strips to reduce the number of patterns, while maintaining a reasonable \(p_T\)-resolution.
## Logical sectors in the endcap region

### Figure 4.2: Logical sectors in the endcap (a) and barrel region (b), delineated by blue dashed lines and labeled with their corresponding Trigger Crate (TC) (cf. section 4.2.2). Each arrow represents one physical sector (endcap) or one chamber (barrel), with strips pointing into the plane of the page.

The data arriving in the second Trigger Crate (TC1) is marked in dark blue, the data copied from the next Trigger Crate in light green. As an example, the strips taken into account for the fifth \( \phi \)-segment of the second logical sector (orange background) are overlined in orange.
4.1. The RPC Muon Trigger Algorithm

Figure 4.3: Level One GMT single muon (a) and dimuon (b) cross sections during the 2012D run for the different \( \eta \)-regions relevant for the RPC system. Only Luminosity Sections with an integrated luminosity per event \( \mathcal{L}_e \) of 0.303 to 0.360 mb\(^{-1}\) were used, with an average and standard deviation of \( (0.344 \pm 0.063) \) mb\(^{-1}\). The binning follows the common 5-bit non-linear \( p_T \)-scale (table 4.1). The methods used are clarified in chapter 6, and the error bars are the corresponding 95% confidence intervals.

A further reduction in the number of patterns – this time without a loss in accuracy – is achieved by merging patterns with the same assigned \( p_T \) and the same sign that differ only by an adjacent strip in one layer.

**PAC Logic** Looking at real data, the limited efficiency of the RPCs leads to incomplete patterns. As a trade-off between the efficiency, the \( p_T \)-resolution and the fake muon rates, a pattern needs matching hits in at least three out of three (four) stations in the endcap (barrel) region, or in all four inner layers (barrel only). For low \( p_T \) candidates, hits in three inner layers suffice. The three-station requirement implies that hits on both sides of two or more iron yokes are measured, thus ensuring the track-bending can be measured for high \( p_T \) candidates. To mark the effect of this trade-off, candidates are assigned a 2-bit quality

\[
\text{quality} = \# \text{ layers} - 3.
\]

**PAC Algorithms** Implementing a logical function for every valid layer-combination of each pattern would result in expensive FPGA requirements. Therefore, this classical approach is replaced by an economical algorithm for part of the patterns [74]. In this algorithm, patterns with the same sign and \( p_T \) are grouped by combining the contributing logical strips within each layer (logical OR) (fig. 4.4). The triggerability and quality of a group are defined using the same logic as for normal patterns, but considering fired layers instead of strips. If a group qualifies, logical strips in empty layers are all considered fired and a single AND operation for each pattern in the group is applied to the modified input.
Chapter 4. The CMS RPC Trigger and Data Acquisition System

Figure 4.4: FPGA-logic-saving RPC PAC algorithm exemplified for a logical cone in the barrel region (a) and its main flaw (b). Instead of calculating the quality for each pattern in the group, the quality is calculated once for the logical OR of the contributing strips in each layer, empty layers are filled with pseudo-hits, and a simple logical AND is calculated with each pattern in the LUT. Only one pattern of the group is shown here as a gray path. In case a spurious signal coincides with a track in a missed layer, that same track will be missed.

Using this algorithm, valid pattern matches can be missed if a higher-quality modified input doesn’t match any pattern in the group. This scenario can be caused by a logical strip within the group that gives an unrelated signal in a layer where the muon didn’t fire a strip, or by a missing pattern.

**Ghost Busting and Sorting** Due to the overlap of the logical cones in both $\eta$ and $\phi$ outside the reference layer, the trail of a muon can match patterns in more than one logical cone. To stay below the expected dimuon rate above a given $p_T$-threshold, the occurrence of these so-called ghosts should not exceed 0.5% of the actual muon rate [75].

The trail left in the best matching logical cone contains at least the hits it’s neighbouring logical cones handle. Therefore, the ghost busting algorithm only keeps the pattern with the highest quality. In case adjacent candidates with equal quality remain, the highest-$p_T$ candidate survives to secure sensitivity at high $p_T$.

According to the GMT specifications, the PAC can send up to four muon candidates for the endcap region ($|\text{tower}| > 7$) and the same number for the barrel region ($|\text{tower}| \leq 7$) [72]. The four candidates with the highest quality – and for equal quality the highest $p_T$ – are selected for each region.

**Heavy Stable Charged Particle Trigger** Intended for synchronization during the first beams, the ability to combine the hits of multiple BX was foreseen in the RPC Pattern Comparator. This feature, and the fact that collisions were only provided every second BX during the first running period, made it possible to add a trigger option specifically for Heavy Stable Charged Particle (HSCP) as follows (fig. 4.5).
4.2 The RPC TriDAS Hardware Architecture

The high mass of these particles causes them to move slower through the CMS experiment. This means they leave trails in the RPC detectors both within the regular time window and 1 BX later. By reducing the latency for the RPC PAC with respect to the Beam Pick-up Timing for Experiment (BPTX) signal by 1 BX, and using the RPC hits of two consecutive BXs, the PAC becomes sensitive to both on-time muons and slow HSCPs. While this does introduce duplicate muon candidates, the reduced latency combined with the BPTX veto assures that only the correct triggered event will pass the GT.

4.2 The RPC TriDAS Hardware Architecture

The RPC Trigger and Data Acquisition System’s data flow can be split up in three stages. During the first stage, hits are collected and synchronized with the LHC clock (section 4.2.1). The second stage traces back muon candidates and passes this information to the L1 Trigger chain (section 4.2.2). The final stage consists of assembling the data for readout whenever the Global Trigger sends out a Level One Accept signal (section 4.2.3).
4.2.1 Detector Readout

Front-End Boards  The signals induced on the RPC strips when an ionizing particle traverses its gas gap are collected by up to 18 on-detector Front-End Boards (FEBs) per RPC (fig. 4.6). Depending on the region, the FEBs contain 2 or 4 custom ASICs, the so-called FEB Chips. These FEB Chips handle 8 strips each. The strips are connected to the channels of the FEB Chips by Kapton foils (barrel region) or coaxial cables (endcap region) on one end. The barrel strips are terminated with a resistor on the other end to avoid reflections.

The FEB Chip’s design (fig. 4.7) is governed by two requirements, namely the threshold uniformity and the timing performance over the wide dynamic range of the RPC signals (20fC to 20pC) [76]. The first requirement is met by amplifying signals in the threshold region with a high gain, resulting in ~2mV/fC up to about 100fC, while passing on to a lower gain for bigger charges. A threshold discriminator then performs a charge selection by comparing the amplified signal to a programmable threshold level and arming a single-shot circuit. However effective for selection, this technique suffers an unacceptable amplitude time-walk of ~10ns for the aforementioned dynamic range. This problem is overcome by feeding an RC-differentiated signal to a zero-crossing discriminator, which brings down time-walk below 1ns and fulfils the second requirement.

A coincidence gate receives both results, and triggers a monostable that defines the output-signal length (~100ns). For the duration of the output-signal, afterpulses are ignored. Finally, an LVDS (Low-Voltage Differential Signaling) line driver transmits the resulting pulses over twisted pair cables to the LBox backplanes in the balconies at the periphery of the CMS return yokes.
4.2. The RPC TriDAS Hardware Architecture

Figure 4.7: Single-channel block diagram of the CMS RPC FEB Chip [76]. The different stages are explained in section 4.2.1.

For every 4 LVDS (Low-Voltage Differential Signaling) lines starting from the FEB, one line runs from the LBox to the FEB. When a pulse is transmitted over this line, a signal is presented at the inputs of the corresponding channels. This feature is used during Commissioning of the RPCs (section 5.5).

To ensure safe detector operation and optimise the detector performance, every FEB can be configured and monitored through an I²C interface (section 5.1.2). The main FEB parameters consist of the discriminator threshold, implemented as a Threshold Voltage ($V_{Th}$), and the output pulse width, defined by the Monostable Voltage ($V_{Mon}$). Both $V_{Th}$ and $V_{Mon}$ are common for the 8 channels of one FEB chip. Power-on default values have been preset before installation using PCB mounted potentiometers, and during the detector configuration phase they are replaced using commercial on-board Digital-to-Analog Converters (DACs). Likewise, ADCs on the FEBs give access to the actual values. To measure $V_{Mon}$, a voltage divider is needed to match the ADC range, so only half the resolution remains. For safe operation each FEB has at least one temperature sensor.

Link System Through the backplane of an LBox, Link Boards (LBs) receive the LVDS pulses. Each LB handles the data of up to 12 FEB Chips, corresponding to one chamber (3 rolls) in the endcap region, or one roll in the barrel region\(^1\). A full LBox defines one or two link sectors of a wheel or disk, which determines its connection to the Trigger Crates (TCs) (section 4.2.2). The link sectors were chosen to minimize cable lengths and their definition is illustrated in fig. 4.8.

The first step in processing the chamber signals is to synchronize the hits with the LHC BXs. A TTC Receiver ASIC (TTCrx) [77] on every LB provides two 40 MHz\(^2\) clock signals with adjustable phase shift, as well as the LHC BXs. The phases of the first two clocks are adjusted to build a time window ($\leq 25$ ns). The incoming hits, i.e. the rising edges of the FEB pulses, have to arrive within this window to be assigned to the same data frame. The duration of these time windows mainly depends on variations in RPC locations (muon time-of-flight), strip lengths, and FEB-LBox cable lengths.

---

\(^1\)Except in stations RB3 and RB4 (bar RB4/S10), where two subsectors share an LB.

\(^2\)The actual frequency depends on the TTC distributed frequency; cf. section 2.2.3.
Figure 4.8: Definitions of the sectors in the Link System and the Trigger Crates. The arrows correspond to the link sectors denoted in the respective circles, numbered 1 to 12. The dark blue boxes represent the Link Boxes connected to the first logical sector (TC0), the light green boxes to the second one (TC1). As RE+1 (RE-1) and RE+2 (RE-2) are both installed on yoke YE+1 (YE-1), their link sectors are installed in common Link Boxes. RE+3 (RE-3) and RE+4 (RE-4) share Link Boxes on YE+3 (YE-3). In the reference layers RE+2 and RE-2, where the logical cones don’t overlap, the link sectors are shifted by $20^\circ$ to avoid splitting their optical outputs in the Trigger Crates. The lighter shades in the logical sectors are used for logical cone extensions outside the reference layer.
4.2. The RPC TriDAS Hardware Architecture

The 96 channels in the data frame of each LB are compressed by grouping them in partitions of eight and applying a zero-suppression at partition-level. For every three LBs, the middle one collects the data of its two neighbours\textsuperscript{3} via a front plane. This so-called Master Link Board (MLB) is identical to its neighbouring Slave Link Boards (SLBs), with the exception of a Gigabit Optical Link (GOL) and a laser diode. It performs a final synchronization by adding per-LB delays and assigning the data frames to the correct LHC BX. The multiplexed data is then serialized by the MLB’s GOL and transmitted to the USC55 over \(\sim 100\) m optical fibres [78].

Every 25 ns, the data describing one partition can be transmitted. Because more than one partition may have fired strips, up to 8 partitions can be transmitted during consecutive BXs along with their delay to recompile them further on. In case more than 8 partitions were fired, an additional End-Of-Data (EOD) bit is set to indicate partitions are lost. While this should rarely happen, this bit is stored in the RAW datasets to verify its occurrence.

The synchronization, compression and multiplexing are executed by a Static Random-Access Memory (SRAM) Field-Programmable Gate Array (FPGA) on the LB, named the SynCoder. A Flash memory on the LB stores the firmware and registers for the SynCoder. This allows fast reloading of the firmware onto the more SEU-prone SRAM whenever a TTC Hard Reset is broadcast (section 5.1.2, section 5.1.3).

In the first endcap stations, an additional output on every LB is used to send information about hits and timing to the CSC Trigger Mother Board (TMB) via the RPC-Anode Local Charged Track Trigger (ALCT) Transition Board (RAT) (section 2.2.1.2). The same output is used in the barrel region for the RPC Balcony Collectors (section 4.3).

4.2.2 Muon Trigger

**Trigger Crates** The optical fibres coming from the MLBs are connected to Splitter Boards (SBs) in the USC55. These boards with passive optical splitters are located in the Trigger Crates (TCs), and distribute the signals to a set of Trigger Boards (TBs). Inside a Trigger Board, the optical signals are deserialised by TLKs. FPGAs, named OPTO, synchronise the data to compensate for the fiberlength-dependent delays. The resulting data frames are duplicated to serve both a Readout Mezzanine Board (section 4.2.3) and three to four PAC mezzanine boards.

Each PAC daughterboard houses one FPGA which applies the PAC algorithm to a 30° \(\phi\)-segment (logical sector) of one tower. The algorithms, logic and patterns are all compiled into the firmware from VHDL (Very-High-Speed Integrated Circuit Hardware Description Language) descriptions, leading to a separate firmware for each PAC FPGA. A complete logical sector, spanning the 12 logical cones in all 25 towers, is handled by the Trigger Boards in one TC. To reduce the length and number of optical links, the logical sectors are rotated with respect to the link sectors by 20°, and start at \(\phi = 5°\) [79] (fig. 4.8).

\textsuperscript{3}Except for stations RB3 and RB4 (bar RB4/S04 and RB4/S10), for which every second LB is an MLB.
Chapter 4. The CMS RPC Trigger and Data Acquisition System

**Ghost Buster and Sorter (GBS)** The ghost busting and sorting takes place in 4 separate stages to avoid collecting all candidates in one device.

The first step is executed on the Trigger Board by the Trigger Board GBS (TB GBS). This FPGA collects the $4 \times 12$ candidates the PAC FPGAs produced: one for each logical cone, with $p_T$ set to zero for void candidates. For each tower it only keeps the cones with the highest (quality, $p_T$, sign) among $\phi$-adjacent groups of valid candidates. The candidates gain 2 bits of data for the following passes, stating whether they are connected to a border of the tower by their location or through eliminated adjacent candidates. This information, called the Ghost Buster Data (GBData), allows for the same ghost busting algorithm along $\phi$ further on, without the need to transfer all candidates.

Along $\eta$, each candidate eliminates candidates in the neighbouring towers at the same $\phi$ bin or differing by at most one cone. For the second pass, the four highest (quality, $p_T$, sign) candidates are forwarded to the TC backplane along with their $\eta$ and $\phi$ coordinates, and there the same ghost busting along $\eta$ is performed for the adjacent towers of different TBs.

**Sorter Crate** For the third stage, the four best candidates of each TC are sent to one of two Half Sorter Boards (HSBs) in the Sorter Crate (SC). The HSB applies the same $\phi$ ghost busting logic to neighbouring towers, this time using the GBData to verify if candidates are adjacent or were connected through a contiguous set of candidates. Once again the four best candidates are selected, this time separately for the barrel and the endcap region. In the final stage, they continue from the HSBs to the Final Sorter Board (FSB), where the number is further reduced to four candidates per region. The Global Muon Trigger combines these muon candidates with those from the DTTF and CSCTF (cf. section 2.2), and the resulting candidates continue to the Global Trigger to contribute to the L1T algorithms.

**4.2.3 Data Acquisition**

Until a final Global Trigger decision arrives, the subsystems are expected to synchronise and buffer data from all Bunch Crossings. For each L1A, the CMS DAQ expects the data of the corresponding event to be delivered by the subsystem’s Front-End Drivers (FEDs) to a set of Front-End Readout Links (FRLs) over the S-LINK64s, encapsulated in the Common Data Format (CDF) (section 2.2).

Since the PAC trigger uses all available information from the RPCs, there is no need for a separate hardware branch to collect the data right up to the TBs. On these devices, the compact data frames coming from the MLBs are already synchronised by the OPTO devices. The remaining tasks of buffering, assembling and transmitting the data are performed by two types of devices: the Readout Mezzanine Board and the Data Concentrator Card.
4.3. The RPC Technical Trigger

**Readout Mezzanine Board**  Inside the TB, the Readout Mezzanine Board (RMB) receives an LVDS copy of the data sent from the OPTOs to the PAC mezzanines. This FPGA groups the data per BX using the partition delays and adds the originating optical link to the dataframes. The data are then delayed and queued awaiting an L1A signal on the TTCrx.

The RMBs can be configured to pass on a window of up to $N_{\text{BX}} = 8$ BXs for every L1A. One RMB can handle up to 12 optical link inputs. Given the MLB capabilities, the data is limited to at most $(N_{\text{BX}} + 7)$ partitions. In case of overlap, the data preceding an accepted Bunch Crossing will preferentially be assigned to the previous L1A, as the data of each Bunch Crossing can only be sent once.

A GOL Opto-Hybrid (GOH) on the TB finally collects and transmits the accepted data over optical fibres from the RMB to one of three Data Concentrator Cards (DCCs) in the DCC/CCS Crate (cf. section 5.1).

**Data Concentrator Card**  The DCC is a board developed by the CMS ECAL group, where it also acts as the FED [80]. Its generic hardware implementation allows it to be adopted for the RPC DAQ, be it with adjusted firmware. Apart from the obligatory FED S-LINK64 (data transmission) and LVDS Fast Signals Port (sTTS), it contains 9 Input Handler (IH) FPGAs, an Event Merger (EM) FPGAs and an Event Builder (EB) FPGA [81].

The data flow from the Input Handlers to the Event Merger is divided over three buses, handling three IHs each, and is orchestrated by the Event Builder. When the latter receives an L1A signal from a TTCrx, it cycles over the Input Handlers, one IH at a time per bus, with the requests to send the data of one BX to the EM. The EM stores the three input queues and sends the full event data preceeded by a CDF header and followed by a CDF footer to the S-LINK64, from where it goes to the corresponding FRL.

### 4.3 The RPC Technical Trigger

To spend as little delivered luminosity as possible on commissioning the CMS detector, a considerable part is achieved with cosmic muons. Both the algorithms and interconnections of the L1 RPC PAC Trigger are however optimized to identify muons produced during LHC collisions, i.e. originating near the IP. While the PAC performs well as a cosmic muon trigger by loading custom patterns onto the PAC FPGAs, this design puts higher geometric constraints on the tracks than imposed by the physical layout of the RPC detector. In addition, cosmic muons also arrive during collisions but remain undetected or are misidentified as collision muons by the PAC.
To overcome these limitations, and to add a debugging tool for the existing system, a separate RPC Technical Trigger has been installed in the barrel region. This system uses the CSC RAT output on the Link Boards, which were originally only used in the forward region.

The logic of the RPC Technical Trigger is mainly embedded in two devices: the RPC Balcony Collector and the Technical Trigger Unit [82].

4.3.1 RPC Balcony Collector

The CSC output of an LB is programmed to transmit an OR of the synchronised RPC signals of its $\leq 96$ strips, resulting in a single bit per roll\(^4\) per BX. A front-panel on each half LBox collects and delivers this data to an RPC Balcony Collector (RBC), of which one is housed in every second LBox to keep the overall cost low. This implies that every RBC has access to the data of two link sectors.

**Local Trigger** An FPGA on the RBC applies a first trigger algorithm on these signals based on a majority rule for the six barrel layers. This so-called Local Trigger processes the two sectors independently. Obviously, this algorithm imposes a strong geometric constraint on the muon tracks.

Both the required majority and the number of BXs taken into account per event can be selected during configuration. All 26 to 28 input signals of the RBC, along with the two local trigger results, are serialized by a GOL and sent to USC55 over an optical fibre.

4.3.2 Technical Trigger Unit

The optical signals of the 30 RBCs arrive in Technical Trigger Units (TTUs), housed in the Sorter Crate. These boards deserialize the inputs, synchronize the hits with the LHC clock and apply trigger algorithms to find the muon tracks. Apart from the actual trigger algorithms, these functions are mostly identical to those of the Trigger Boards, and the TTU devices were consequently implemented as a copy of the latter.

Since only 72 bits can be handled per OPTO for every BX, only 12 out of 18 optical inputs on the TB can be used. This implies the need for three TTUs, and in practice each handles one or two wheels. One PAC mezzanine suffices to process the trigger algorithms for one wheel, so only two daughterboards are installed per TTU.

The results from the three TTUs are collected in a backplane, where the final logic is applied and 8 Technical Trigger bits are assembled and sent to the GT over LVDS.

At present four trigger algorithms are implemented.

\(^4\)Except in stations RB3 and RB4 (bar RB4/S10), where two subsectors share an LB.
Local Trigger A first algorithm applies the same per-sector majority logic on the barrel layers as the RBCs. While this may seem redundant, it allows to improve the algorithm over time by loading new firmware on the TTU PAC FPGAs, which can not be done for the RBCs without a prolonged access to UXC55. One such improvement consists of the extended sector mode, in which the majority is applied on pairs of adjacent sectors.

Tracking Algorithm The second algorithm performs tracking over a full wheel [83]. During a first pass it looks for a first seed in the outermost fired layer in the highest possible sector. Then, step by step, a search is made for hits in layers and sectors adjacent to the previously found hit, increasing the track length by one for each step. This tracking restarts with the next seed whenever a track ends, until a configurable number of steps is reached. The decision for the processed wheel is positive if any of the found tracks reaches a minimum track length.

This algorithm fails if a layer was not fired — be it due to inefficiency, masking or dead strips. To partly overcome the shortcomings of both this algorithm and the TTU Local Trigger, the final wheel decisions consist of the logical OR of both algorithm outputs. These 5 results comprise Technical Trigger bits 26 to 30 (wheels +2 to -2), and an OR of all wheels goes to bit 24 [84].

Pointing Trigger Another feature of the RPC Technical Trigger, as requested by CMS, involves looking for cosmic muons that cross the tracker volume. To this end, an algorithm similar to the RBC majority logic is applied first. For the top sectors 2 to 6 the logic remains, but the bottom sectors 8 to 12 are each extended with their two neighbouring sectors to account for muon track bending in the magnetic field. The decisions of these algorithms are serialized and sent to the TTU backplane, which checks for a top-bottom coincidence in opposite sectors.

To broaden the acceptance, the top-bottom coincidence doesn’t need to be intra-wheel, which would only point to the tracker volume near wheel 0. An inter-wheel check for coincidence connects wheel 0 to any other wheel, and negative with positive wheels not further than three wheels separated. To account for the time needed for a muon to pass through the complete CMS detector, the results of the top sectors are delayed by 1 BX.

The final result constitutes Technical Trigger bit 25.

Prompt-Muon Trigger A last algorithm in the TTU has been designed to select low-\(p_T\) muons that don’t reach the outer layers (RB3 and RB4). While useful in the early collision days, its use is now superseded by the PAC and its added low-\(p_T\) logic.
The scale and flexibility of the RPC Trigger and Data Acquisition System implies the need for an extensive control and monitor system. To bring the detector in an operational mode, optimized firmware and register values are loaded. Once running, various hardware and software components monitor and diagnose the performance of the system, and data relevant for safe operation are forwarded to the Detector Control System. Given the hostile environment (magnetic field, radiation), fast detection and recovery of induced malfunctions is essential.

This chapter describes the hardware and software architecture used to achieve these goals, with a key interest in the front-end components. The author played an important role in the development of the RPC online software, concentrated mainly on the front-end electronics, and developed two generations of a wide range of commissioning tools used both before the first LHC run as during the LHC First Long Shutdown.

5.1 The RPC TriDAS Control Hardware Architecture

The communication hardware used for the RPC Trigger and Data Acquisition System can be divided in three branches.

The first branch is responsible for communication with the USC55 electronics, and allows direct access from computers at P5 designated to the RPC system. The second branch, be it hosted by the previous, provides access to the Link System and front-end electronics in the UXC55. The third branch constitutes the RPC TTC partition (cf. section 2.2.3), and is necessary for synchronisation and integration in the L1T and DAQ systems.
5.1.1 Underground Service Cavern

As described in section 4.1, the Underground Service Cavern hosts the Trigger Crates, the Sorter Crate and the DCC/CCS Crate, all 9U VME crates. To simplify long-term maintenance, the different CMS groups use a common solution to communicate with the USC55 VME crates: underground computers are connected to the VME buses through CAEN VME-PCI (Peripheral Component Interconnect) optical link bridges [85]. A total of five computers are equipped with these links for the RPC TriDAS, each connected to up to three crates. Within CMS the use of a common Hardware Access Library (HAL) for these links is encouraged [86].

To access firmware-specific registers on the FPGAs, the RPC TriDAS uses a custom developed framework called Internal Interface (II) [87, 88]. Rather than keeping track of registers in VHDL and describing their names, addresses, sizes and bit meanings in text or XML files loaded at runtime, both the VHDL communication layer and C++ register descriptions are generated from a single II definition file. The C++ code contains the descriptions as static variables along with a memory mapping, eliminating name lookup at runtime and avoiding crashes when registers are added or removed.

5.1.2 Link System

Underground Service Cavern to Underground Experimental Cavern Communication with the UXC55-based Link System is established using a set of token rings hosted by Front-End Controllers (FECs) [89]. Originally developed for the CMS Tracker control system, several subsystems have adopted this technology. Eighteen FECs, installed on Clock and Control System (CCS) boards in the DCC/CCS Crate, serve a token ring each, corresponding to one side of a CMS return yoke (detector tower). Through optical links, they are connected to radiation hard Communication and Control Unit ASICs (CCU-25s) [90] on Control Boards (CBs) in the balconies. Copper interconnections between the CBs close the rings.

To initiate communication, a FEC sends out a token to its ring that is forwarded from node to node, be it a CCU node or a FEC node. A node that needs to transmit data intercepts the token and replaces it with a data frame that circulates the ring. The destination node replaces a symbol in the data frame to confirm reception, and upon receipt the original transmitter will circulate an empty token again. As the ring host, the FEC will initialise and diagnose the network, as well as cope with errors. To deal with the obvious weakness of a communication ring with physically inaccessible nodes, a secondary path connects the CCU-25s, alternately skipping one node (fig. 5.1). Every node can be programmed to use the second line.
5.1. The RPC TriDAS Control Hardware Architecture

**Figure 5.1:** Redundant CCU ring [91] The optical fibres run between the USC55 FECs and selected UXC55 CBs, and are converted in the Digital OptoHybrids (DOHs). When a node fails, its neighbouring nodes will switch to the B-ring.

**Control Boards to Half Link Boxes** Given the price of the CCU-25s, only the CBs were fitted with them to act as CCU nodes. Other UXC55 RPC TriDAS electronics are accessed indirectly: each Half Link Box holds one CB that handles the communication with the corresponding set of ≤ 9 LBs in that Half LBox, the matching FEBs and, where applicable, an RBC (fig. 5.2). The memory bus and Parallel Input/Output (PIO) on the CB’s CCU-25 give direct access to its CB Initialisation Controller (CBIC) and CB Programmable Controller (CBPC).

To keep the complexity of the different FPGAs on the CBs, LBs and RBCs affordable, they are implemented as SEU-prone SRAM FPGAs. This implies that the firmware has to be reloaded periodically to minimize the impact of SEUs [31], as well as after powercycles. To be able to initialise this process, one radiation tolerant Flash FPGA, the CBIC, loads and configures the firmware of the CBPC and Link Board Controllers (LBCs). This firmware can either be loaded from an on-board Flash memory, or through the CCU ring. While loading over CCU is a slow process, it brings the possibility to debug firmware without access to the cavern, and new stable firmware can be written to the Flash memory in the same way.

Once initialised, the CBPC and LBCs handle further communication on and between the CB and LBs via a Control Bus on the LBox front plane [91, 92].

**Control Boards to Front-End Boards and RPC Balcony Collector** Communication with the FEB Distribution Boards (cf. section 3.2), FEBs and the RBC is mediated by Inter-Integrated Circuit (I²C) lines hosted by the CB. While the CCU-25 does provide I²C channels, its lack of support for multi-byte operations dictated a separate I²C controller module on the CBPC, based on an OpenCores VHDL implementation [93].
Figure 5.2: The Link Box control system, showing the Control Board and Link Board FPGAs and ASICs, along with their control buses \[92\]. Communication is initiated through either the CCU ring or the TTC network. The DOH is only present in the CBs directly connected to the Front-End Controller, and a Multiplexer (MUX) connects it to the CCU-25. The Link System FPGA represents the SynCoder mentioned in section 4.2.1.
5.1. The RPC TriDAS Control Hardware Architecture

![Diagram of the RPC TriDAS Control Hardware Architecture](image)

**Figure 5.3:** Example data transfer over an I²C bus containing the most relevant communication possibilities between master (dotted red) and slave (dashed blue). The master writes two bytes to a slave, and reads two bytes from the same or another slave. The lighter shades are repetitions of the previous line for clarity. SDA transitions need to occur while SCL is low, except for the Start (S), Stop (P) and Restart (Sr) conditions (gray). Clock Stretching (CS) is demonstrated on a byte level, but can also occur on a bit level for low speed modes. Every byte is sent from most to least significant bit, followed by an acknowledgement or an absence thereof from the receiver. Slave devices either have a 7-bit or a 10-bit address, and for the latter 2 bytes need to be broadcast.

The I²C bus [94] allows for bidirectional communication with several master and slave devices over a two wire bus — the Serial Data Line (SDA) carrying the data and the Serial Clock Line (SCL) forwarding the communication clock from master devices. Both lines are to be connected in open-drain or open-collector mode, and are by default pulled up with resistors or using a current source. Master devices initiate and terminate data transfers, generate clock signals and address slaves. The SCL is pulled down by the master periodically, and while the SCL is down, the transmitter can change the SDA level to set the value of the following bit. The protocol permits slave devices to hold the SCL down and as such stretch the clock to pause communication in case time is needed to execute requests. These features are exemplified in fig. 5.3.

To cover the distance from the periphery of the ⌀ 15 m wheels and disks to the RPCs, and yet limit the logic in the FDBs, LVDS connections carry the exact I²C communication from the CB to the FDBs. The number of LVDS pairs has been limited to three per I²C bus: the SDA runs bidirectional over two lines, the SCL unidirectional from CB to FDB. This comes at the expense of the I²C-native clock stretching, an issue resolved by anticipating the necessary delays in the communication software.

**FDB to FEBs and redundant I²C lines** The FEB Distribution Boards are fitted with multiplexers for every I²C bus they serve. While this is a mere protection against accidental communication in the endcap region, in the barrel region it adds the possibility to switch between the default CB I²C buses (up to 3 per FDB) and the additional I²C lines provided...
by the Drift Tube Chamber Chamber Control Boards (CCBs) [95, 96]. These are housed in on-detector DT minicrates. An optical CCB/FDB ground isolation on the FDB introduces the same conversion from two bidirectional lines to three unidirectional lines as for the CB lines, again resulting in one-way SCL propagation.

**Link Boards to FEBs** For every eight LVDS channels transferring data from FEB to LB, two twisted pairs run from LB to FEB within the same connector. When the LB drives an LVDS pulse to the FEB over these lines, the FEB generates a test pulse on four corresponding channels. While this doesn’t reveal information on the used thresholds, it does allow to deduce cable lengths, to test the full readout chain and to fulfil commissioning tasks (cf. section 5.5).

### 5.1.3 Timing, Trigger and Control System

The RPC TriDAS comprises one TTC partition, and is equipped with its own Local Trigger Controller to take over from the Central Trigger Controller during local runs. It can receive trigger signals from the TTU, the FSB and selected TCs, and can be configured to transmit L1As from those to the TTCci. The RPC’s TTCci receives L1A and B-Go commands from either system and broadcasts them over the local TTC network.

**Local TTC Network** Within the Trigger and Data Acquisition chains, several steps require the LHC clock and CMS event counters: the Link Boards have to assign the hits to the correct Bunch Crossings, and in order to compile the data of different LBs in the next steps of the trigger and readout chain, they are accompanied with a BX number. To this end, the LBs use the TTC Bunch Counter Reset Command (BC0) to keep a synchronous bunch counter up to date. As for the other B-Go commands [97],

- Event Counter Reset Commands (EC0s) are used in the DAQ chain from the RMB onwards to add the event number to the hit data,

- HardReset commands are necessary to initiate the firmware reloading on UXC55 FPGAs simultaneously with other subsystems to minimize deadtime,

- ReSync commands reset and clean RMB and DCC input buffers and

- TestEnable commands initiate test pulses to be sent from the LBs to the FEBs.

The A-channel L1As are needed by the RMBs and DCCs to decide what data to compile and send to the S-LINK64s. Finally, an additional RPC-specific TTC B-channel command starts the diagnostic readout.
This means the TTCci needs to distribute the TTC network to the LBoxes, the TC and the SC. For the Link Boxes, every CB is fitted with an optical receiver that feeds the TTC signals to its TTCrx and to a clock fanout (fig. 5.2). The fanout provides the TTC clocks and commands to the Link Board TTCrx’s through the LBox front panel. The TC backplanes each contain a TTCrx and redistribute clock and commands via the TC GBS.

**Trigger Throttling System**  The Trigger and Data Acquisition System handles data flows that are prone to statistical fluctuations. Even though the buffers are built to handle detector occupancies and L1A rates well above the expected, fluctuations can lead to full buffers. For the LBs and RMBs, transmission bandwidth constitutes the limiting factor. Flags are added to data in case hits were omitted to avoid overflows [81]. The DCC on the other hand is able to inform the TCS about its input buffer occupancy by publishing its state through the sTTS to avoid data corruption.

### 5.2 The RPC TriDAS Control Software Architecture

While an independent Online Software Interface is developed by every subsystem to communicate with its hardware, common frameworks are used throughout the CMS Trigger and Data Acquisition System to enable a centralized structure. This section will give a brief introduction on these frameworks before detailing the RPC-specific implementation.

#### 5.2.1 Software Framework

##### 5.2.1.1 Cross Platform Data Acquisition

The control over the RPC TriDAS hardware is distributed over several computers, but in practice they should behave as one system, synchronously with the other parts of CMS. To achieve this, the Online Software Interface (OSWI) has been embedded in XDAQ (Cross Platform Data Acquisition) [33], a C++ framework under active development at CERN and used throughout the CMS TriDAS.

Within this framework, each XDAQ process, called a *context*, can load several *applications* at runtime from shared libraries. The context configuration — including the applications to load, their parameters, and Uniform Resource Identifiers (URIs) of other contexts or web services — is described in an Extensible Markup Language (XML) format. The context provides the means for communication between different applications: for fast and efficient data exchange it implements binary I2O messaging over TCP/IP\(^1\), mainly used in DAQ data transfers, while for regular Remote Procedure Calls (RPCs), the Simple Object Access Protocol (SOAP) over HTTP is used. In addition, the context connects Common Gateway Interface (CGI) requests over HTTP to application-defined

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\(^1\)For local data exchange, I2O messages are passed via a First In First Out (FIFO) buffer in memory.
Figure 5.4: Web user interface automatically built from Trigger Supervisor components. The menu on the left shows the components grouped by type. The main page exemplifies available actions in the RPC TS Cell’s CellOperation.

web-based GUI. Other tools are included in the XDAQ framework to ease development (threading, serialization, DB access, logging, application monitoring...). This results in a distributed system of web service applications, operating conform several World Wide Web Consortium (W3C) standards.

As a central logging framework, XDAQ provides the open-source log4cplus package [98]. This package, porting the capabilities of the log4j library (log for Java) to C++, gives the user a uniform framework for logging messages to streams that can be defined after compilation — the user here being a software developer. In addition, it allows messages sent to a logger to be rerouted to different user-defined appenders. To ease development, the CMS TriDAS infrastructure provides the means to store log4cplus messages in database.

5.2.1.2 Trigger Supervisor

On top of the XDAQ framework, the Trigger Supervisor (TS) has been built for use by the Level One Trigger [34]. This system brings uniformity among the LiT XDAQ applications by introducing common SOAP interfaces and a homogeneous web-based GUI.

The TS system is organized as a hierarchical tree of Cells. Each Cell is a XDAQ application, aware of the Cells it must operate one level down the tree, called its xhannels. Furthermore, the Cells use a common description for the Finite State Machine used for operation (called CellOperation), RPCs (CellCommands), and custom web user interfaces (CellPanels). This allows the framework to build a surrounding dynamic web-based GUI, giving access to the different components (fig. 5.4). The framework also adds tools that allow custom web GUIs to use Dojo Toolkit\(^2\) widgets and update them using Asynchronous JavaScript and XML (AJAX).

\(^2\)An open-source javascript toolkit for client-side web development.
5.2. The RPC TriDAS Control Software Architecture

On top of the subsystem-defined Cells, a Central Cell translates the RCMS state transitions requested by its Function Manager to the corresponding L1T-specific FSM transitions (cf. fig. 5.5). For local activities, each Cell can be operated on using its web-based GUI, always affecting Cells further down the tree.

5.2.2 Application Structure

The RPC TriDAS communication software constitutes two branches in the CMS Run Control and Monitor System: the RPC Trigger Supervisor (TS) Cell and the RPC Function Manager (FM). The RPC TS Cell supervises the Trigger Crates, the Sorter Crate and the Link Boxes. The RPC FM handles the Data Concentrator Cards (fig. 5.5). The RPC TS Cell follows up the CellOperations of the Central TS Cell, and in turn manages 31 RPC TS worker Cells, listed in its xchannel configuration. These Cells, all XDAQ applications implemented in the TS framework, are organized according to the hardware access they provide: each of the 12 TCs is assigned one Cell, each of the 10 barrel and 8 endcap CCU rings (detector towers) is handled by a worker, and one Cell deals with the SC.

The DCC is the only node controlled by the RPC FM, which is a first level RCMS Function Manager.
Figure 5.5: The nodes in the RCMS FSM tree relevant for the RPC subsystem. The applications with direct hardware access are marked in red (dashed). The DT application belongs in the DT subdetector’s tree, but is depicted here to clarify the hardware access for the artificial DT Tower. The gray background is wrapped around the applications that access the Configuration Database through the Java application. The XDAQ-PVSS SOAP Interface (PSX) messages are SOAP messages following the PSX XML Schema; the Extended External Data Representation (EXDR) messages are SOAP messages with an EXDR attachment.
5.2. The RPC TriDAS Control Software Architecture

Unlike most CMS subsystems, access to DB is granted by a Java application, rather than a XDAQ-native TStore application. The application connects to the Configuration Database (ConfDB), a DB in the OMDS, using Hibernate [99] to retrieve hardware and configuration descriptions mapped to Java objects. Access is initiated by SOAP requests from the XDAQ applications, and the Java objects serialized in the SOAP response are deserialized to C++ objects.

5.2.3 Application Lifecycle

The lifecycle of an RPC hardware handling TS Cell is shown in fig. 5.6. Once initiated, the Finite State Machine takes over to handle further actions, apart from those defined in CellPanels. This ensures the system can be operated as part of the CMS TriDAS without the continuous need for RPC experts. Since the transitions are requested using asynchronous SOAP messages or GUI interactions, they should be seen as states themselves occupied between request and completion confirmation.

It should be noted that the DCC handling XDAQ application is at present a plain XDAQ application with separate FSM states and transitions, but the general picture stands.

**Initialise**  The first step in the application lifecycles is contained in their construction as the applications are started. The processes are managed by a CMS-wide process controller, which starts and stops registered applications on the different machines. A process monitoring tool (watchdog) periodically polls their availability using SOAP messages.

Among the 32 RPC hardware-handling XDAQ applications, only few distinct types are implemented: either the application handles a detector tower in the Link System, a Trigger Crate, the Sorter Crate or the Data Concentrator Cards. Within these application classes, one has to recognise however that the diverse RPC geometries dictate different hardware structures and implementations. At startup, each application is made aware of the hardware it controls by retrieving a hardware description from the Configuration Database.

The DB stores the hardware description categorized in three core device tables [100]: crates, boards and chips. Chips have a foreign key matching the board that hosts them, and their position on the board. The same goes for boards and crates. Using Hibernate, this information, combined with device-specific data from several tables, is converted to a Java device hierarchy. After being exchanged using SOAP messages, this data allows the hardware application to construct an internal representation of the active hardware devices and the routes to control them. This dynamic approach ensures a scalable system, and allows for adjustments in case of problems. Since changes need to be traceable, entries in tables are always accompanied by their creation timestamps, and at any time the most recent instance is used.

The Halted state is reached when every application has built a software representation of the hardware it serves and has initiated the communication channels.
Figure 5.6: Finite State Machine states (solid, blue) and transitions (dashed, green) as defined in the RPC TS configuration operation FSM. Transitions are states in themselves, occupied between transition request and completion confirmation SOAP messages.

An additional state, *Configured but not Synchronized*, has been added specifically for the RPC sub-system. This state and its transition states are seamlessly added to the Central TS Cell *Configuring* state.
5.2. The RPC TriDAS Control Software Architecture

**Configure**  During configuration, firmware is loaded to FPGAs where necessary and configurations from DB are written to the FPGAs and ASICs, or updated in Flash memory in the UXC55-based hardware. The firmware and configuration settings choices are made based on the configuration key sent down the FSM tree along with the configuration request by Run Control or intermediate nodes.

In practice, the *Configuring* state is a composite state for the L1T RPC subsystem. An additional state, *Configured but not Synchronized*, has been added because different components need to be fully configured before the MLB GOLs are activated and the links are synchronized. The resulting substates are invisible for the Central TS Cell: the RPC TS Cell forwards both a *Configure* and a *Synchronize Links* request to its nodes during the CMS *Configuring* transition.

Once running, TTC HardReset commands initiate FPGA firmware reloading and configuration loading from Flash memory in the UXC55. This keeps SEUs in the FPGAs SRAM from piling up, which could potentially corrupt data taking (cf. section 2.2.3).

**Enable**  When preparing a datataking run, subsystems are sent the request to *Enable* along with the next run number. As the previous step prepared the hardware for collisions, cosmics or testing procedures, this step is mainly about readiness of monitoring and diagnostic tools. These are activated to detect potential problems, report them to shifters and experts and where possible resolve them to safeguard data quality.

As part of the FPGA firmware, diagnostic modules have been implemented in the different RPC TriDAS stages. These modules consist of counters that keep track of the RPC hits (LBs, TCs and DCCs) and PAC muon rates (TCs and the SC), as well as the occurrence of transmission errors between them. Their multitude and complexity dictates processing of this data in the online software before presenting it to shifters. Rates are compared with expected values to issue warnings. Live histograms with average and peak values, as well as history plots, are generated using ROOT (fig. 5.7). Since these diagnostic tools run regardless of L1A signals, essential data is stored. Offline software reprocesses e.g. LB strip counters to locate those with abnormal rates and understand the RPC hit rates throughout the detector.

In addition, register values that indicate the states of ASICs are monitored where available (TTCrx, GOL...).

Online analysis of the results is summarized in a state for the different hardware device observables, defined in software as their *monitorables*, assuming values *Ok*, *Warning* or *Error*. *Ok* is used when no problems could be detected, and in case of *Warning* and *Error*, short messages are added to describe the problem. These states and messages are published by the different TS Cells in FlashLists, mixed type tables used in the XDAQ environment to publish application variables. They are collected by the RPC TS Cell using SOAP to give the shifter access from one GUI entry point. Important potential problems, along with possible interventions or people to contact, are forwarded to the central shifter who has the task of looking after the full CMS Level One Trigger system.
5.3 Front-End Control System

The Front-End control differs from the other RPC TriDAS hardware communication in that

- it doesn’t require configuration key specific configurations,
- it’s less prone to SEUs [101],
- with its $\approx 6 \times 10^3$ FEBs it outnumbers the other parts of the TriDAS system\(^3\) and
- it doesn’t follow the default crate-board-chip hierarchy.

Nevertheless, the Front-End electronics are accessed through the Link System, and they constitute an intrinsic part of the RPC TriDAS.

In the original software design, access to the FEBs was provided through a synchronous SOAP interface on the Link System’s detector tower XDAQ applications. Access information and locations of FEBs were accordingly loaded in a separate central application, and configurations were chosen manually. This design and its implementation lead to several problems:

\(^3\)For example, the FEB to LB ratio is 4.88, the latter being the next most numerous RPC TriDAS board.
5.3. Front-End Control System

- Speed: by far the main problem, with a duration of ≈30 min to configure the FEBs of the full system.

- Resource availability: both the requesting application and the tower application’s indispensable CGI/HTTP and SOAP/HTTP interfaces were inaccessible for the duration of an action.

- Data presentation and persistence: all results were presented to the user in huge flat tables and discarded afterwards.

These problems guided the requirements for a new implementation, and a thorough solution was achieved by reimplementing the FEB access in the RPC Tower Cells, changing both the implementation of the hardware access algorithms (section 5.3.1 and section 5.3.2) and the software infrastructure and application interfaces (section 5.4).

5.3.1 Hardware Access Controllers

Three I\(^2\)C interfaces were foreseen at the start of the new implementation: Command I\(^2\)C (CI\(^2\)C) and Block I\(^2\)C (BI\(^2\)C) on the CBPC, and the redundant DT I\(^2\)C line on the CCB. The BI\(^2\)C and DT line introduce an important difference with respect to the original implementation, namely asynchronous hardware access requests: rather than receiving results at the end of each I\(^2\)C command, commands need to be queued and results arrive when execution is explicitly requested or when the software controller decides execution is needed - whichever occurs first. In addition, the speed of the BI\(^2\)C compared to the CI\(^2\)C demands the addition of delay commands to anticipate clock stretching.

Given these changes and the new overall implementation, the full FEB I\(^2\)C communication protocol was reviewed and trimmed wherever possible.

**Command vs Block I\(^2\)C** — As mentioned in section 5.1.2, the CBPC contains an OpenCores-based module to provide I\(^2\)C access to the FEBs. This module has to be addressed one I\(^2\)C-command at a time by the software controller and polled for results — hence the name Command I\(^2\)C.

To minimize the data sent over CCU, the additional BI\(^2\)C controller has been implemented in the CBPC firmware. Rather than sending I\(^2\)C commands one by one — repeating addresses of FECs, CCU nodes and CBPC registers at every command, poll for readiness and result retrieval — a group of commands can be sent to a contiguous block of memory. As the CCU protocol has foreseen the transfer of memory blocks, this method reduces addressing overhead and polling for completion. The drawback is the aforementioned asynchronous hardware access and the possible failure of complete blocks when a single command fails.
To cope with these changes, a new C++ I^2C interface was implemented. Rather than returning a result or throwing an exception for an I^2C request, an I^2C register with input, output, and success or failure methods is used, optionally reduced to the bare minimum as can be useful when access is restricted to CI^2C. Commands can also be grouped, implying the software controller promises not to break the group of commands over separate blocks. Staged commands will be executed either on request or when they outnumber a block. The controller will then run the queued groups and ungrouped commands that fit inside a block and execute the corresponding response methods. The grouping of commands has the additional advantage that execution of commands can be stopped if one command failed, rather than failing or timing out on each command individually in CI^2C mode.

Block I^2C and Command I^2C have also been combined in a single client with the same interface. The client allows runtime selection of either firmware controller, with an optional fallback to CI^2C for failing blocks.

**Redundant DT I^2C line**  For the DT I^2C line, a software controller with the same interface has been implemented that communicates directly with the DT CCB servers. It was found however that the availability of DT resources and maintainability of the separate RPC and DT code would benefit from using XDAQ provided Inter-Process Communication. For this reason, a SOAP/HTTP solution is being developed during LS1.

### 5.3.2 FEB System Integration

#### 5.3.2.1 Initialisation

In correspondence with the other hardware, Front-End electronics were reimplemented as boards and chips built from ConfDB descriptions. The application-specific device hierarchies are built from FEB and FEB Chip tables, and translated to a set of FEBs containing 2 to 4 chips each using Hibernate. Given the difference between barrel and endcap FEBs, an additional layer was added in software named a FEB Part. The FEB Part corresponds to one barrel FEB or half an endcap FEB.

The hardware description of the FEB Distribution Boards has not been added to the ConfDB because their descriptions can be reconstructed from the FEB descriptions. While the barrel FDBs serve three independent I^2C lines, the communication software lists them as three separate devices. This doesn’t lead to ambiguities because only the PCB, the LV supply and DT I^2C line are common, all secondary for CB-FEB communication purposes. Since access to one FDB never occurs in parallel, the splitting is valid for the DT line too, this time tripling the multiplexer. To simplify switching between the different I^2C controllers, an abstract FEB Access Point (FAP) was implemented as the FDB host that interfaces to whichever I^2C providing device is in use.

On top of the FEB hardware tree, a FEB System was added to provide a simple global interface to the objects and methods from the different software components.
5.3. Front-End Control System

5.3.2.2 Configuration and Monitoring

Like for the other RPC TriDAS control systems, configuration and monitoring requests are passed down the device hierarchy within each application, here from FEB System to FEB Chip, and executed for each device that’s listed in the request. To minimize CCU traffic, I²C commands are postponed at every step in order to merge them where possible.

In the original design, the state of each FEB in software was tightly connected to its hardware state, requiring an explicit application reset in the case of FEB powercycles. Decoupling these states implied additional I²C commands, but the overall configuration and monitoring time still decreased.

In both the barrel and endcap FEBs, a significant discrepancy has been found between the values set by the DACs for $V_{\text{Th}}$ and $V_{\text{Mon}}$ (cf. section 4.2.1), and those read back by the ADCs. Independent measurements of the levels turned out to be closer to the ADC values [102]. To overcome this, the configuration algorithm used to consist of a sequence of writing to the DAC, reading the ADC and writing a corrected value to the DAC. It was found however that these offsets remain constant over time (fig. 5.8), so they were implemented as part of the individual FEB Chip configurations in the ConfDB.

**Figure 5.8:** Stability of the measured difference between ADC and DAC voltages for FEB $V_{\text{Th}}$ (small red squares) and $V_{\text{Mon}}$ (big blue squares). To increase the ADC range for $V_{\text{Mon}}$, a voltage divider doubles it ranges and halves its resolution. The values have been shifted for clarity by $\pm10\text{ mV}$ as displayed by the guidelines.
5.3.2.3 Speed

The decentralisation of the FEB System to the different RPC Towers Cells has the important benefit of enabling parallel hardware access with less Inter-Process Communication (IPC) overhead. The bottleneck of the original implementation was defined by the transfer rates over a single CCU network and the FE hardware access. Since the VME link serving the FECs was far from flooded, parallelization of the access to tower-level increased configuration speed significantly (fig. 5.9). A proof of concept had been achieved within the original software structure, implemented by sending the synchronous SOAP requests in separate threads from the central application, reaching configuration times of about 7 minutes. This did not release the RPC Tower Cells communication interfaces though. At present, the full system can be configured in less than 140 seconds.

5.3.2.4 Resource Availability

The access obstruction to applications and hardware for the duration of the FE configuration and monitoring actions is the second problem addressed by the parallelisation. This is now reduced in time and moved from obstructing access to the full application interfaces, to blocking a mutex that grants hardware access to the various software components. This is still unacceptable though during nominal operation: centrally induced state transitions
5.3. Front-End Control System

Figure 5.10: FEB Control CellPanel in the RPC Trigger Supervisor Cell. While access to the application is already restricted, asking expert confirmation before activating critical panel subsections has proven to avoid problems when new shifters arrive. The displayed log messages concern both RPC TS Cell - Tower Cell communication and reports collected from the individual Tower Cells. The individual RPC Tower Cells contain similar panels. To give users clear indicators on the impact of their activities, actions are made accessible through buttons while textual hyperlinks are reserved to guide them to other content.

would be too slow in case FEB actions are started before by experts or shifters. To overcome this, the FEB System includes both pause, resume and interrupt functions. Using these, TS operations will be handed the hardware access mutex after finishing a minimal number of queued commands. In practice this means the thread running a configuration or monitoring action finishes the current FEB, and the corresponding FAP is handled again when resuming.

5.3.2.5 FEB Control Panel

Unlike the other devices, configuration is not initiated by the TS FSM. Instead, a dedicated TS CellPanel (FEB Control) in the RPC Trigger Supervisor sends out asynchronous requests with the command and a configuration key to its xchannels of the RPC Tower Cell type (fig. 5.10). A similar panel is available in the individual RPC Tower Cells. Monitoring can be initiated from the same panels, but it is also integrated into the hardware monitoring during the TS FSM enabled state.

The thresholds and monostable settings have been adapted to each FEB Chip and are linked with a nominal running configuration key. To allow for commissioning activities, for example data-taking threshold scans, additional keys and configurations have been added to the ConfDB and the user is offered a list of keys to choose from. To ensure a dynamic and responsive GUI, action requests are negotiated with the XDAQ applications using AJAX.
To collect more than just success or failure in the FEB Control Panel, a remote log4cplus appender/logger has been developed to collect the most relevant messages from the Tower Cells in the TS. Its inner working is similar to the Publisher described in section 5.4.1.3. To display log messages in the web interface, an additional log4cplus appender was implemented that generates the necessary HTML and JavaScript code. For uniformity, the same colors and icons are used as for the hardware states (section 5.4.1.1).

### 5.4 Front-End Control System Application Interfaces

Within any system running full-time, efficient problem tracing is indispensible. Since this system contains \( \approx 6 \times 10^3 \) FEBs hosting \( \approx 15 \times 10^3 \) FEB Chip, flat state representations and logging are inadequate. In addition, this vast number would render the table representation of the FlashLists used for other hardware cluttered, thus obscuring existing monitorables for shifters. The main application interface requirements this system should satisfy can be summarized as follows:

- a shifter should promptly spot problems,
- an expert should easily understand their source,
- parameters should be logged and stored in the Conditions Database and
- parameters relevant for safe detector operation should be available for the RPC Detector Control System.

Section 5.4.1 will go through the tools built to enable such a system, and section 5.4.2 will present the resulting application interfaces.

#### 5.4.1 State, Log and Parameter Bookkeeping

To ease the bookkeeping of states, logs and parameters, several interfaces were devised that ensure that hardware items

- are part of one or more hardware-representing trees,
- have a state (section 5.4.1.1),
- contain a log of events (section 5.4.1.2) and
- have a publisher (section 5.4.1.3).

This collection allows to easily log events, update states, route data seamlessly within and among applications and automatically build a clear web-based GUI.
The tree is implemented such that it is defined by its nodes, rather than by a container. This way a less intrusive structure can be built, maintaining the regular crate-board-chip hierarchy. At each node, bidirectional C++ iterators can be created with undefined or predefined iteration depth.

### 5.4.1.1 Hardware States

In analogy with the LogLevels of log4cplus, devices, and where applicable parameters, have been assigned a State taking values

- **Ok** the device is configured and found to be working,
- **NotSet** no communication has taken place that defines the device’s state,
- **Info** something is wrong, but without important consequences  
  e.g. a FEB DAC offset differs slightly from the ConfDB value,
- **Warn** something is wrong, problems may occur later on  
  e.g. a FEB threshold differs from the configuration value,
- **Error** problems occurred  
  e.g. high temperature, communication problems . . . , or
- **Unknown** preserved for aliases not found in the event tables,

with corresponding color codes and icons for GUI purposes. With the devices organized in a tree, a device keeps track of both its own state and the worst state further down the tree, called its parent state.

### 5.4.1.2 Logging Mechanism

Given the vast number of hardware components, a compact logging mechanism was implemented compatible with log4cplus. The system starts from the knowledge that return values and possible failures are predefined — worst case scenario even unexpected failures should be handled to keep all applications running. Rather than just printing runtime messages to loggers and distributing text strings for given events, their severity level and corresponding explanations are stored in predefined tables and assigned a category, id and named alias.

Using these, short calls like `log("event_alias")` or `unlog("event_alias")`

- send the appropriate reports to the associated log4cplus logger,
- update the device’s event list in a compact way, storing a timestamp and an event id,
• update the state of the device and its parents, and

• efficiently publish the event to other applications.

This system allows for clear GUI features, as well as for selective configuration and monitoring depending on the runtime device history.

5.4.1.3 Parameter Publisher

Important FEB System parameters are collected in a single XDAQ application, called the FEB Collector, for two reasons. First it allows to give the shifter an overview of the full system and easy access to parameters, states and reports without interfering with the critical hardware accessing applications. Secondly, certain parameters need to be stored in the Conditions Database and sent to the RPC Detector Control System. Because the service foreseen for XDAQ-PVSS interaction — the XDAQ-PVSS SOAP Interface (PSX) — is memory, CPU and network traffic consuming, the FEB Collector acts as a buffer on a computer with lower resource occupation and no critical hardware access.

To push data to the Collector, minimal XML messages with Extended External Data Representation (EXDR) attachments are used instead. To keep the overhead from both the XML envelope and EXDR type tagging minimal, events and parameter changes are collected in each RPC Tower Cell until either a maximum amount of data or a maximum duration since the first parameter arrival is reached, whichever occurs first. In par with the importance of resource availability mentioned before, this transmission takes place in a separate thread. To achieve this, a thread-safe FIFO queue was implemented and the XDAQ WorkLoop was generalized to run on objects rather than function pointers.

While this inter-application publisher contains a lot of background activity, the publisher interface itself was deliberately kept simple and is used for less complex intra-application communication too.

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4 EXDR is a binary data representation with smaller encoding sizes and faster processing time than XML. It is based on the Internet Engineering Task Force (IETF) External Data Representation (XDR) standard [103] and has been extended within the XDAQ framework to work with most of the serialization methods used for XML.
5.4. Front-End Control System Application Interfaces

5.4.1.4 XDAQ-PVSS SOAP Interface

Once collected in the FEB Collector, the data from the 18 Tower Cells is used to give shifters an overview, and selected data is forwarded to PVSS using the XDAQ-PVSS SOAP Interface (PSX). The PSX service itself is provided as a XDAQ package, and is maintained centrally for the different subsystems. The interchanged PSX messages are SOAP messages following the PSX XML Schema in their Body. When the PSX application receives the PSX messages, it accesses the PVSS DataPoints through a PVSS API Manager (cf. section 3.2.3).

The FEB Collector uses the same queue and thread infrastructure as the Towers Cells, this time to minimize the SOAP envelope overhead for the PSX messages.

5.4.2 User Interfaces

Two different representations of the RPC FE electronics are familiar for shifters and experts. On the one hand, the location of problems is easiest to spot by the shifter envisaging the FEB System as a direct mirror of the RPC chambers. On the other hand, a problem is best understood and resolved by the expert falling back on the hardware tree that serves the device in question. Both representations have been implemented.

5.4.2.1 RPC Tower Cells

The RPC Tower Cells contain the actual hardware tree, and therefore the expert view on the hardware is provided from these applications. This user interface was implemented before the TS layer was added throughout the RPC TriDAS, and as a consequence the web-based GUI detaches itself from the usual TS menu-panel GUI. Nevertheless, an expert can access it from within the FEB Control CellPanel.

To give the expert a prompt overview of problems, specific icons are used to show the state of each device, and their background is adjusted to represent the parent states. The iterators for the hardware trees allow the application to quickly go through the hardware tree and skip full branches or individual leaves depending on their parent or individual state respectively. This allows for a severely reduced overview when desirable, limited to the problematic devices (fig. 5.11a).

Accessing single devices in the tree, their event log and registered parameters are available as shown in fig. 5.11b.
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Figure 5.11: Example FEB System GUIs in the RPC Tower Cells. On the left one sees the full system, filtered for a minimum state value of Info as selected in the Minimum state menu. For clarity, icons are used for device states, background colors for their parent state. Any device level can be clicked and generates the same interface: an event log on top, followed by the registered parameters and the devices further down the device tree. On the right an example FEB Chip is shown.

5.4.2.2 RPC FEB Collector

The FEB Collector receives both the parameters and the log events from the Tower Cells. Part of this data — the temperatures, $V_{Th}$ and $V_{Mon}$ parameters — are forwarded to the RPC DCS and stored in Conditions Database (CondDB). All latest values and log events are in addition kept in memory for the shifter’s customary detector overview.

To achieve this, the devices have been organized in the chamber-roll-FEB hierarchy, with separate states for the different parameters. With the use of a broadly supported XML based vector image format, Scalable Vector Graphics (SVG), the application dynamically creates a pictorial overview of the complete RPC subdetector (fig. 5.12). This representation is color coded with the different chamber parent states, for the full chamber or any of its parameters. In addition, SVG permits separate elements to be hyperlinkable, so shifters can click their way from the picture to the chamber or wheel components (fig. 5.13). Each component can again be clicked to get a specific event log (fig. 5.14).

Like for the RPC Tower Cells, component lists can be filtered by their state.
Figure 5.12: Detector overview of FEB states as shown in the FEB Collector. Hovering a chamber will show its name; clicking the chamber, wheel or disk it will guide the shifter to a list of the corresponding FEBs. The shown picture gives an overview of the final states; using the menu on the left, states for separate parameters can be shown.

Figure 5.13: List of devices in RE+2 as shown in the FEB Collector, filtered for a minimum state value of Info. The icons show the overall and parameter states of each FEB.
5.5 Front-End Commissioning Tools

An important characteristic of commissioning periods is continuous change. Hardware is added, software modified, and database tables are adapted accordingly. This environment implies that the commissioning-dedicated software and storage should be as independent as possible, where possible allowing for stand-alone analysis.

To address these issues, an additional package has been developed in the online software for a generic description of hardware setups. Keeping minimal dependencies, it features full tracking of the setup, the commands and device-specific properties and parameters. Offline it can be used to further investigate problems, leaving the online system operational.

Being integrated in the online software, the hardware commissioning tests are presented to the end-user through TS panels.

Applied to the RPC system, it has been used for commissioning the FE electronics.

5.5.1 Hardware Description Package

The Hardware Description Package (HWD) describes the hardware in use as a System of Devices. Its philosophy is contained in the Relational Database Management System (RDBMS) diagram in fig. 5.15.
Figure 5.15: Database diagram for the Hardware Description Package. Bold, underlined columns represent the primary keys, foreign keys can be recognised by the leaving arrow. Further details can be found in section 5.5.1.

Direction takes one of three values (input, output, bi-directional), and property, observable and configurable act as booleans. The datatypes are predefined as integer, float, text and blob.
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The first part describes what hardware is present in the current System. Because it is used here for single tests, this part is static and registered at the start. Adding timestamps as part of the Primary Key to SystemDevice and Connection would make it fully dynamic.

The second part, labeled Configuration, deals with the Properties and Parameters of the hardware, and boils down to the device addresses and hardware register values. The Parameters are grouped in DeviceTypeConfigurations and Configurations. Because Properties are mere static Parameters, the same architecture is recycled. In principle also this part could be implemented statically, with an incrementing number of Configurations. However, because many System Configurations are very similar for commissioning tests, a Devices’ DeviceConfiguration can change over time within the same Configuration. While for a long-term system one would usually introduce tables for every ParameterType, Parameter or DeviceType, the short-timed nature of commissioning tests is served well by a one-table-per-DataType layout.

The Monitoring part is used to register what Configurations are applied, globally or locally, and what values are read from the observable Parameters.

In accordance with the RPC online software, all actions on the hardware are translated to either a Configuration or Monitoring. Translating the heavily normalized table structure to C++, the memory impact is kept to a minimum by design.

Finally, to simplify data analysis, the Snapshot was introduced. This stores a timestamp and its SnapshotType, and allows to mark key moments during a test. As a tradeoff between accuracy and ease of use, all timestamps represent the Unix Time in microseconds.

Given the commissioning-environment, this table architecture is implemented in SQLite3 [104] database files, allowing for standalone analysis on a snapshot of the system in use. To overcome the lack of hash-function in SQLite3, an optimized implementation of Murmur3A [105] was added and is used to avoid duplicate text and blob entries in the tables, drastically minimizing also Configurations.

The C++ implementation of this description includes the relevant equivalent classes, with automatic type deduction and translation for the DataTypes. The necessary Structured Query Language (SQL) queries are implemented in a HardwareStorage class, making the use of this layer transparent. Online, the Devices are registered in their current setup, and all tests are run using the Configuration and Monitoring commands. Offline, the user simply loads the System from the SQLite3-file and loops through the Snapshots. As Snapshots are selected, the Devices in memory automatically assume the configurations and observable values, as well as the States defined in the online System (section 5.4.1). Being Parameters, the observable values are assumed behind the scenes, exploiting the (Device)Configuration implementation.
5.5.2 RPC Front-End Commissioning

All RPC electronics located in the UXC55 have been described according to the HWD C++ implementation, using classes that translate actions and access the existing software. The same code is used offline by the analysers.

5.5.2.1 Connectivity Test

While production and installation of the RPCs is executed with high care for detail, the number of connections and hardware addresses make it an error-prone process. An important and elaborate test of the RPC system is therefore the verification of all connections. For the FE electronics, this includes the signal cables and the I\textsuperscript{2}C cables, resulting in well over a hundred connectors in every LBox.

Because the communication and the signals of the FEBs go through separate lines, one can be used to test the other, leaving only simultaneous swaps of both the I\textsuperscript{2}C and signal cables of a full chamber or roll (cf. section 5.1.2). Since the I\textsuperscript{2}C connectors go to the CBs and the signal cables to the LBs, this kind of swap is unlikely. The algorithm in place brings down local signal thresholds below electronic noise levels, and verifies if the origin of high rates corresponds to the requested signal connector. Alternatively, thresholds are brought below and above the onset of the built-in pulsers (section 4.2.1), which are then triggered at high rate ($sim160$ kHz) through the signal readout cables.

To give the user a wide range of options, most parameters can be adjusted before running the test through the TS FEB Commissioning Panel (fig. 5.16b). This also gives the user the option to select only part of the detector (fig. 5.16a). The offline analyser application suggests possible swaps or missing channels, and produces plots for visual verification (fig. 5.17) on the chamber, Link Board and Link Box levels. This technique has been used in the commissioning of the RE4 upgrade throughout LS1, as well as for the validation of the existing RPC system after interventions.

5.5.2.2 FEB Configuration

Profiting from the FEB Commissioning Panel, an additional form allows the configuration and monitoring of selected FEBs, optionally storing the output. This is used extensively during on-chamber interventions, and the option to auto-correct for the $V_{\text{TH}}$ and $V_{\text{Mon}}$ offsets ensured a functional detector during Global Runs, before the necessary DB tables were filled.
Figure 5.16: The TS FEB Commissioning Panel, showing the Roll Selection (a) and the options for the three FEB Commissioning tests in use (b). The progress of a test can be followed, and a test can safely be paused or interrupted (c).
Figure 5.17: Example result of the FEB Connectivity Test. This is an obvious case of a swap, as suggested by the snippet from the textual output and verifiable from the visualization. The colored blocks on the bottom correspond to the FEB Chips with low threshold, so the connector where the noise should be visible. The low rates are a result of some signals coming through at high threshold.

These plots are simplified through an option in the FEB Connectivity Test Analyser, hiding further information on where exactly to find the connectors.
5.5.2.3 Threshold Scan

Once the connectors are in place, it is important to understand the FEBs are behaving as expected, while access is granted. Since this usually happens before any cosmic muon or collision data can be recorded, the FEB Threshold Scan was introduced. This test applies thresholds from a range of values, and measures the rates recorded by the LBs at every step. In this way, one can

- spot $I^2$C communication problems,
- verify the rates at different thresholds, with or without the pulsers,
- measure the $V_{Th}$ and $V_{Mon}$ offsets (section 5.3.2), and
- locate problematic FEB Chips and so-called dead and noisy strips.

The online user interface is an extension of the previously mentioned FEB Commissioning panel. The offline analyser for the FEB Threshold Scan produces textual output that tells the user where to find any of the listed problems, how to reach the hardware in the cavern, and what $V_{Th}$ and $V_{Mon}$ offsets should be sent to database. Like for the FEB Connectivity Test, a series of plots brings a clear view on the potential issues (fig. 5.18).
5.5. Front-End Commissioning Tools

Figure 5.18: Example output of the FEB Threshold Scan.
In (a) and (b) one sees the threshold distribution before and after offset correction. At low threshold, rates are high and the measured threshold is slightly influenced. One chip is visible for which the I^2C communication is faulty.

The second series shows the distribution of the threshold at which strip signal rates are suppressed to below 10 kHz, without (c) and with (d) the use of the pulsers.

(e) and (f) show the rates per channel in a linkboard at different thresholds without and with the use of the pulsers respectively. The selected channels are indicated to distinguish dead strips from those channels that are not connected to a strip. For the given picture, one strip is dead in the corresponding chamber.

These plots are simplified through an option in the FEB ThresholdScan Analyser, hiding further information on where exactly to find the LBs channels and RPCs strips.
Performance of the CMS RPC Detector and Trigger

The performance of the RPC detectors within CMS is relevant in two fields: muon reconstruction and the L1 trigger. For muon reconstruction, the timing, efficiency and resolution of individual detectors are the most important features. For trigger purposes, the RPC subsystem as a whole should be considered, which involves the detector response as well as the performance of the PAC muon recognition and the produced muon rates.

While not the first analysis of the CMS RPC performance, this chapter will narrow the gap between the performance on one side, and the hardware involved on the other, and explore ways to extend the reach. To obtain this, finer time-granularity is achieved by combining data where possible, and allowing a bias or sacrificing precision elsewhere. To clarify the interpretation, comparisons will be made with previous results.

This chapter will go through the datasets, reconstruction algorithms and tools needed to deduce the performance of the RPC chambers and the rates of the trigger in a prompt fashion.

6.1 Data Selection

6.1.1 Data Tiers and Data Sets

Evaluating the detector performance of the RPC detector requires access to objects available in – or reconstructable from – the RAW or RECO data tiers (section 2.4). This includes

- the hits, clusters and local tracks contributing to muon tracks (RECO),

- the detector responses (RAW), and

- the L1T objects (RAW, RECO).
While one could go for a low-bias dataset, a robust option is to take advantage of the redundancy of the CMS muon system (section 2.1.6). Naturally, this restricts the results for the RPCs to the (geometric) acceptance of the Drift Tube Chambers and Cathode Strip Chambers, but this restriction complies mostly with the need for those detectors in accurate offline muon reconstruction, as well as the common layout of the RPCs on one side and the DTs and CSCs on the other.

### 6.1.1.1 RPCMonitor

**Selection**  For the detector analysis, the choice is made to use the `RPCMonitor` dataset. The content of this dataset is restricted to the data from the muon detectors and the trigger crates, and it is seeded by the logical expression $\text{L1\_SingleMu7 OR L1\_SingleMu14\_Eta2p1 OR L1\_SingleMu16\_Eta2p1}$ – L1T algorithms requiring a single muon candidate with the given $p_T$ in GeV/c, the last two restricted to $|\eta| < 2.1$. The limited content of this dedicated dataset allows for a low prescale, which was set to 10 (section 6.3.1) for 2012D data on HLT path `AlCa_RPCMuonNormalisation`, on top of the L1 prescales on the mentioned triggers$^1$ (fig. 6.1).

**Content**  While this dataset is only available labeled as RAW, it doesn’t strictly abide by the original definition of this data tier. Instead of the Common Data Format from the FEDs, it contains the muon-system data after a minimum translation to so-called digis, as well as the result of local reconstruction. For RPC, these are individually fired strips (digis), and contiguous groups of fired strips with their coordinates within CMS after local reconstruction, called RecHits. For the DT and CSC systems, they consist of fired strips and wires, and locally reconstructed segments. Also the L1 muon candidates from the GMT and the subsystems are stored, as well as the decisions of the L1T algorithms and HLT paths after prescaling.

**Custom Filtering**  In addition to the muon selection (section 6.2), the L1\_SingleMu7 is further restricted to $|\eta| < 2.1$ in accordance with the other two L1T algorithms. Only the `AlCa_RPCMuonNormalisation` HLT path is used. To reduce the selection dependency on the RPC detector and trigger, the data is further filtered to only allow events that would have been triggered by the fictional L1\_SingleMu7\_Eta2p1 for GMT candidates without the use of the PAC.

$^1$AlCa stands for Alignment and Calibration. For specific studies, the self-explanatory `AlCa_RPCMuonNoHits` and `AlCa_RPCMuonNoTriggers` are available in the same dataset with a lower prescale of 2 in 2012D data.
6.1. Data Selection

Figure 6.1: High Level Trigger cross sections for paths seeded by GT algorithms using GMT and technical triggers only. It is clear that the three last paths deliver by far the greatest number of events, be it without muon selection at the HLT and limited event content. Only Luminosity Sections with $\mathcal{L}$, 0.303 to 0.360$\text{mb}^{-1}$ were taken into account, with an average and standard deviation of $(0.344 \pm 0.030)\text{mb}^{-1}$.
Chapter 6. Performance of the CMS RPC Detector and Trigger

6.1.1.2 L1Accept

Selection  To reconstruct the rates produced by the L1 muon triggers, another dataset is necessary. While rates for L1T algorithms are kept in the FDL module and stored in Database, this does not provide information on their correlations and the L1 muon or calorimeter object compositions. A minimal dataset, named L1Accept\(^2\), seeded by the occurrence of any Level One Accept (L1A), is maintained by CMS to study the behaviour of the trigger and the cross sections of HLT seeds.

Content  The L1Accept dataset only contains the GT crate data, including L1 muon candidates from the GMT and the subsystems, and the decisions of the L1T algorithms and HLT paths after prescaling. However, this results in a vast amount of data given its prescale of 10 (section 6.3.1) in 2012D data for its sole HLT path, DST_Physics seeded by any L1A.

Custom Filtering  As will become clear in section 6.3.1, using this data without prior assumptions on L1T correlations requires the unprescaled decisions. While these are not contained in this dataset, the ingredients to run the GT emulator can be reconstructed to produce them. This obviously has only been applied here for muon-seeded algorithms, so this dataset has been reduced to the clean muon triggers – those seeded exclusively by the GMT candidates and the Technical Triggers, excluding other conditions (fig. 6.2).

6.1.1.3 Commissioning

The Commissioning dataset is used only to estimate the impact of End-Of-Data (EOD) occurrences in the Link Boards (section 4.2.1). As its name states, it is intended for commissioning and is as such readily available in the for analysis uncommon RAW dataformat. The need for another dataset stems from the lack of truly RAW data in the RPCMonitor dataset, and the omission of EOD information in RPC digi data. Because of its limited impact, only the subset passing HLT_L1SingleMuOpen and HLT_L1SingleMu12 are used here – two HLT paths that only add a prescale to their L1T equivalents.

6.1.2 Conditions

In addition to the event data in the EDM root-files, data from the CondDB are used to reconstruct the running conditions.

\(^2\)Often referred to by its stream-name NanoDST.
6.1. Data Selection

Figure 6.2: Level One Trigger cross sections for algorithms using GMT and technical triggers only.
- Names ending in \( \text{er} \) or \( \text{Eta2p1} \) refer to their restricted \(|\eta| < 2.1\);
- \( \text{HighQ} \) requires high quality muon candidates, excluding quality 4;
- and \( \text{WdEta} \) means the two muon candidates stay within a maximum \( \Delta\eta \).

Only Luminosity Sections with \( \mathcal{L} = 0.303 \) to \( 0.360 \text{mb}^{-1} \) were taken into account, with an average and standard deviation of \((0.344 \pm 0.030) \text{mb}^{-1} \).
6.1.2.1 Luminosity

**Pixel cluster counting** The luminosity measurement used for CMS physics analysis is based on the occupancy of the tracking detectors at the core of CMS, with a method called *pixel cluster counting* [106]. It is based on the number of clusters fired in the pixel detector, whenever the BPTX signals the presence of the proton bunches – implemented as the **L1_ZeroBias** trigger. It assumes a constant pixel cluster cross section \( \sigma_{cls} \), giving an instantaneous luminosity \( \mathcal{L} \) for a mean number of clusters per event \( n_{cls} \)

\[
\mathcal{L}(t) = \frac{n_{cls}(t)}{\sigma_{cls}} n_b f_{\text{rev}} \tag{6.1}
\]

where \( n_b \) is the number of colliding bunches per beam, and \( f_{\text{rev}} \) the LHC revolution frequency of 11.246 kHz. \( \sigma_{cls} \) is called the *visible cross section*, calibrated by means of *Van der Meer* scans [107].

**Forward HCAL** Another method to determine the instantaneous luminosity uses the CMS Forward Hadronic Calorimeter HF (section 2.1.5). It provides a real-time luminosity measurement with a 1% statistical accuracy in less than 1 s [106]. It is however subject to calibration drift and shows a non-linear pileup dependency. With proper calibration, it has been used before the availability of the pixel cluster counting with an uncertainty of 4.4% [108]. Its availability from the CMS Software (CMSSW) makes it the measurement of choice for this analysis, and it was rewritten to allow multiple-run analysis and reduce DB queries.

**Integrated Luminosity Per Event** The parameter of choice to indicate the ability of the LHC machine to produce collisions is naturally expressed by the instantaneous luminosity \( \mathcal{L} \). While this quantity fits perfect with the time-integrated measurement, as well as the rate-defined capabilities of the HLT, it hides aspects of trigger performance because of the variable number of colliding bunches in the LHC (fig. 6.3, fig. 6.4). As a solution this work will often use the *mean integrated luminosity per event*\(^3\) – rather than per unit of time – and refer to it as \( \mathcal{L}_e \). Given the total inelastic cross section, \( \sigma_{\text{inel}} \), it also gives an indication of the expected pile-up,

\[
\langle n_{pu} \rangle = \mathcal{L}_e \sigma_{\text{inel}} \tag{6.2}
\]

---

\(^3\) While strictly speaking one could argue to use *bunch crossing* instead of *event*, the term *bunch crossing* is generally used to refer to the 24.95 ns time interval between two potential bunch positions (buckets) in the LHC.
6.1. Data Selection

Figure 6.3: Integrated Luminosity $\int \mathcal{L}$ as measured by HF for the different LHC beam filling configurations during 2012D, shown for the Integrated Luminosity per Event $\mathcal{L}_e$ as a function of the Instantaneous Luminosity $\mathcal{L}$.

Figure 6.4: Effective cross section of the L1_DoubleMu_12_5 as a function of the instantaneous luminosity and the integrated luminosity per event. This L1T algorithm requires at least one 12 GeV/c and one 5 GeV/c muon candidate from the GMT. Four out of six colliding-bunches configurations can be distinguished visually. Each run has been split in $\approx 155$ LS blocks ($\approx 1\text{ h}$) to produce one measurement each, with a lower limit of 40 LS.
Figure 6.5: Evolution of the number of RPC strips declared dead and masked by the offline Noise Tool, after fluctuation suppression based on the run-length. Local spikes correspond to additional chambers switched off for a few runs due to operational reasons. The minimum number of LSs per run to declare a strip dead (120 LSs) or alive (60 LSs) are indicated with the two horizontal black lines. Only Luminosity Sections approved for muon physics are counted for each run, while the width is the full run duration.

6.1.2.2 RPC Conditions

RPC dead and masked strips In 2012, no unambiguous data was made available in DB to follow the masking of strips in the Link Boards. While the masks and their entry-date are added, the masks are only applied after a configuration of the Link System, occurrences of which are not stored. Given the limited changes, a fixed list of dead and masked strips is used to merge strips into RecHits in case fired strips are separated by a missing strip.

For this study, a custom list has been compiled to better approximate the true resolution and efficiency of the RPCs. It uses the per-run assessment of strip-states by the so-called Noise Tool [19], which analyses the output of the Link Board histogramming feature (section 5.2.3). To diminish the influence of statistical fluctuations or short-lived problems, 120 LSs are required to declare a strip dead, while 60 LSs suffice to declare a strip alive. The run-lengths are calculated using the CMS official lists of Luminosity Sections declared good for muon physics, and the resulting evolution can be seen in fig. 6.5.

These strip states are stored in a CMSSW-compliant SQLite3 Conditions Database (CondDB), and are automatically loaded for the custom RPC hit reconstruction.
6.2. RPC Detector Performance

For the post-LS1 running periods, an exact DB-solution is foreseen to track the masked strips.

**Services and Environment**  Because no HV scans are analysed in this work, and temperature fluctuations are limited, only the environmental pressure has been added in a CMSSW-compliant SQLite3 DB.

### 6.2  RPC Detector Performance

#### 6.2.1  Methods

Previous analyses of the RPC detector performance using the RPCMonitor dataset have usually been restricted to straight-line extrapolations of CSC and DT segments to the nearest RPCs. This has some advantages and disadvantages. On the one hand, the low magnetic field outside the return yoke allows for these projections, and reduces complexity. On the other hand, being only dependent on a single chamber, it is susceptible to fake segments. Furthermore, the RE3/R2:C and RE2/R3:A rolls are excluded by this method given the limited CSC coverage nearby (cf. fig. 2.3).

**Muon Selection**  To overcome these problems, this work will use muon reconstruction and propagate the muon-matched segments. While standalone muon reconstruction – using only the muon system outside the solenoid – is readily available, it’s the combination with a track from the inner tracker to a global muon that defines the muons for physics analyses [109, 110]. Given the dataset content however, standalone muons are the only choice. This does have an impact on the $p_T$ resolution and purity. The muon tracks are further corrected for the beamspot-position as stored in the Conditions Database. NPCs are explicitly excluded from this reconstruction to avoid a bias.

To ensure quality, the selection criteria shown in table 6.1 are applied to these muon tracks – closely modelled by existing selection criteria on global muon candidates. The first two requirements and the third are correlated, as the refit to the beamspot improves the impact-criteria at the cost of the goodness-of-fit.

**Muon Segment Propagation**  To locate the crossing of the muon path with RPCs, the segments contributing to the muon track are propagated to the RPC layers using *Stepping Helix Propagation*, which takes into account the magnetic field and the material effects [111]. This is the default propagator used within CMS for reconstruction outside the tracker volume. From every RPC layer-crossing, the nearest track segment is located and, if necessary, the propagation to potential RPC rolls within that layer is repeated from there.
Chapter 6. Performance of the CMS RPC Detector and Trigger

| Cut | Value | \(|\eta| < 0.83\) | \(0.83 < |\eta| < 1.24\) | \(0.83 < |\eta| < 1.61\) |
|-----|-------|-----------------|-----------------|-----------------|
| 0 Total | | 1.00 | 1.00 | 1.00 |
| 1 Transverse Impact | \(d_{xy} < 0.3\) cm | 1.00 | 1.00 | 1.00 |
| 2 Longitudinal Impact | \(d_z < 20.0\) cm | 1.00 | 0.99 | 1.00 |
| 3 Track Fit | \(\chi^2/\text{ndof} < 10\) | 0.72 | 0.77 | 0.89 |
| 4 Segments | stations > 2 | 0.57 | 0.49 | 0.70 |
| 5 Transverse Momentum | \(p_T > 2.0\) GeV/c | 0.57 | 0.49 | 0.70 |
| 6 Uniqueness | \(\Delta\eta^2 + \Delta\phi^2 > 0.05\) | 0.57 | 0.49 | 0.69 |

Table 6.1: Muon selection criteria. The first two exclude cosmic muons, the third ensures the muon track matches the segments, and the fourth makes for reliable muon identification and \(p_T\) reconstruction. The uniqueness excludes muons reconstructed from the same segments to confirm requirement 4.

Propagating the segments to the RPCs implies an error on the final state. This is due to the propagation of uncertainties on the original position and momentum, the stochastic behaviour of material effects and energy loss fluctuations. As a consequence, a propagated hit near a chamber border means a hit took place with limited probability.

To calculate this probability, the spatial uncertainties are assumed bivariate gaussians on the RPC surface and are efficiently integrated within the bounds of the rectangular barrel (using \([112, 113]\)) or the trapezoidal forward chambers (numerical integration with gauss-legendre quadrature). To calculate the probability a layer was hit, the convex polygon intersections of projections of one chamber on the neighbouring along the muon path are taken into account. The integration is then reduced to the trapezoidal case by slicing the polygon.

Only hits with an error \(\sigma_x < 10\) cm and \(\sigma_y < 10\) cm are taken into account, with a probability of \(\geq 99\%\) to hit the roll under study. While lower probabilities could be included, the roll efficiency for different probabilities drops faster than the probability, indicating error underestimation, poor alignment or efficiency problems near the borders. Given the dimensions of a roll, the latter is improbable, but further investigation is pending.

Hit Matching Hit matching, like most object matching for this work, has been performed using the Munkres \([114]\) algorithm, finding the smallest sum of distances between objects. Using the appropriate definitions for the distance, its affinity for number of matches over smaller distances can be tuned. While in most scenarios this will translate to a simple smallest-distance matching, this is achieved in the first step of the algorithm without wasting computation time. On the other hand, it solves potential ambiguities.
Given the uncertainty on possible error underestimation, only propagated hits with an error \( \sigma_x \leq \frac{w}{\sqrt{12}} \) are taken into account to calculate the resolution of an RPC with pitch \( w \). For resolution calculation, matching is allowed within a \( 28 \sigma_x \) band, after combining the initial theoretical error from the clustersize \( \sigma_x = \frac{CLS \times w}{\sqrt{12}} \) and the uncertainty on the propagated hit. For efficiency calculation, matching is limited to a \( 7 \sigma_x \) band – worst-case scenario this translates to two strips. The low noise background rates limit the introduced error (cf. fig. 6.9).

When no hits are found, the algorithm will look for hits that came one or two BXs early or late, to assess the timing of the RPC system.

### 6.2.2 Results

#### 6.2.2.1 Efficiency and Cluster Size

The efficiency of the CMS RPCs as it stands today is the result of annual High Voltage scans during which the HV-dependency of the RPC is assessed. After correcting for the pressure dependence (eq. (3.8)), a sigmoid is fitted to the efficiency curve (fig. 6.6a),

\[
\varepsilon = \frac{\varepsilon_{\text{max}}}{1 + e^{-\lambda(HV_{\text{eff}} - HV_{50})}},
\]

where \( \lambda \) gives an indication of the slope of the sigmoid, and \( HV_{50} \) is the High Voltage at which half the maximum efficiency \( \varepsilon_{\text{max}} \) is reached. These values are then used to define the working point of the roll under study, maintaining the high efficiency of the plateau region but avoiding high streamer-probability.

Figure 6.6 shows the results of such a campaign, and is the starting point for data taking – and thus this study.

The corresponding efficiency distribution of the RPC rolls using the muon propagation method is shown in fig. 6.7. A minimum efficiency resolution of 2.0% at 90\% was used (equivalent to 3.3\% at 50\% for the standard normal approximation), but no rolls failed this requirement. Unlike the previous method, no rolls are excluded by definition, but it has to be noted that RE3/R2:C still has a low occupancy due to the geometric coverage of the CSC.

Future studies on RPCMonitor data could lower the standalone 3-station muon requirement to a 2-station requirement and benefit from the availability of MIP data from the GCT in the GMT data record to increase the occupancy in this region. One can also extend the `AlCa_RPCMuonNormalisation` path with `AlCa_RPCMuonNoHits` and `AlCa_RPCMuonNoTriggers` to increase the sample without introducing a bias using the same equations for the combination of triggers as in section 6.3.2.
Chapter 6. Performance of the CMS RPC Detector and Trigger

Figure 6.6: (a) shows the sigmoidal behaviour of the Resistive Plate Chamber for three example HV scans, averaged over the barrel and endcap regions [115]. Changes in the number of broken and recovered chambers and chips are taken into account in the errors. (b) shows the resulting efficiency distribution for all RPC rolls in 2012, measured using the extrapolation method and excluding broken channels [115].

Figure 6.7: RPC Efficiency Distribution using 2012D RPCMonitor data for the barrel (a) and endcap (b) region. The RE3/R2-C and RE2/R3-A rolls were excluded in the extrapolation method (green). Roll classification comes from detector-expert maintained lists, and may not contain all 2012D changes.
6.2. RPC Detector Performance

To understand the impact of the $\alpha$-correction (eq. (3.10)), both the efficiency and the cluster size are shown as a function of the pressure in fig. 6.8. Given the approximate $1/p$ dependence of the effective HV, it is clear that the overcorrection before its introduction is cancelled by the $\alpha$-correction.

The presence of the monostable on the FEB chips suppresses afterpulses, rendering it impossible to detect them. To have an idea of how the RPC behaves in the proximity of a hit, the two neighbouring strips on each side have been monitored after each matched hit. By shifting wheels or rotating over a given angle, four similar strips can be probed to understand the same behaviour without hit. The result is shown in fig. 6.9, and both the next-BX hit and the random probing give very similar results, suggesting the hits can be ascribed to the nominal background rate.

6.2.2.2 End-Of-Data

If no match can be found to a propagated hit, the same algorithm will check if an EOD-bit was set in the corresponding LB for that BX. As mentioned, this test can not be executed on the RPCMonitor dataset where RAW data is missing, but it has been applied to the Commissioning dataset. Figure 6.10 indicates a negligible impact on the efficiency.

6.2.2.3 Timing

The timing of the RPC hits are defined on a Link Board-level: while the LB can delay hits, the MLB has to send them altogether over a single optical link at the correct BXs. Therefore, it makes more sense to measure the arrival of hits on a per-LB level, rather than per roll. It should be noted that only hits within the designated time window $\leq 25\text{ ns}$ are measured, so true calibrations should be dealt with using full or shifting windows. Nevertheless, the high efficiency of the rolls indicates on-time signal arriving, and the result is shown in fig. 6.11

6.2.2.4 Resolution and Cluster Size

From the design of the RPC detector, the cluster size has been taken into account to maintain an appropriate resolution for the detector (section 3.2). While the mean cluster size has been shown above, fig. 6.12 shows its distribution for the barrel and endcap region. Its effect on the resolution can be seen in fig. 6.13, where the final resolution obtained through a gaussian fit is shown. The resolutions are expressed in strip-pitch-units (table 6.2) defined at the propagated point in the roll. For the trapezoid endcap rolls, this varies along $y$. 

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Figure 6.8: Efficiency and Cluster Size for the barrel and endcap regions as a whole, measured at different pressures $P$. Errors are 95%-intervals, using Clopper Pearson for efficiencies. Each measurement corresponds to a contiguous set of $\approx 155$ LS with a minimum of 40 LS. In blue the measurements before the $\alpha$-correction are indicated, in green after. The correlation due to the overcorrection for pressure is clearest for the cluster size, as well as its suppression with the new correction.

It should be noted that the cluster size depends on the muon incident angle, and hence the muon $p_T$. Therefore, different results will be obtained for different datasets, yet the trend should remain.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Pitch (cm)</th>
<th>Layer</th>
<th>Pitch (cm)</th>
<th>Layer</th>
<th>Pitch (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE1/R2:C</td>
<td>1.737</td>
<td>RE*/R2:C</td>
<td>1.946</td>
<td>RB1in</td>
<td>2.289</td>
</tr>
<tr>
<td>RE1/R2:B</td>
<td>2.093</td>
<td>RE*/R2:B</td>
<td>2.230</td>
<td>RB1out</td>
<td>2.452</td>
</tr>
<tr>
<td>RE1/R2:A</td>
<td>2.379</td>
<td>RE*/R2:A</td>
<td>2.551</td>
<td>RB2in</td>
<td>2.756</td>
</tr>
<tr>
<td>RE1/R3:C</td>
<td>2.927</td>
<td>RE*/R3:C</td>
<td>2.918</td>
<td>RB2out</td>
<td>2.952</td>
</tr>
<tr>
<td>RE1/R3:B</td>
<td>3.293</td>
<td>RE*/R3:B</td>
<td>3.296</td>
<td>RB3</td>
<td>3.524</td>
</tr>
</tbody>
</table>

Table 6.2: The strip pitch in the different RPC regions.
Figure 6.9: Probability to find a strip fired near a matched RPC hit, one BX after the muon crossed (any of 2 contiguous strips on either side). As shown, it is compatible with randomly searching for fired strips in a similar region of the detector (any of 4 contiguous strips).
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**Figure 6.10:** EOD bits matched to muons without matching hit in the corresponding roll. Distribution using 2012D Commissioning data, restricted to L1_SingleMuOpen OR L1_SingleMu2.

**Figure 6.11:** Timing on a per-hit and a per Link Board level. In the hit matching procedure, priority is given to on-time hits, within a 7 \( \sigma \) band (approximately two strips for small propagation errors). The missing LBs are those for which no hits were recorded.
6.3 Level One Muon Trigger Cross Sections

As mentioned in section 2.2.1.3, the L1T Final Decision Logic board prescales the algorithm and technical triggers to reduce the event rate processed by the HLT. In turn, the High Level Trigger applies prescales for individual paths with abundant event signatures. Under nominal running conditions, the instantaneous luminosity provided by the LHC will decrease according to eq. (1.4). To optimize the use of the detector readout capabilities and HLT processing power, the prescales of both the L1T and HLT systems can be adjusted simultaneously between Luminosity Sections by selecting a new *prescale column* from prescale table, thus keeping trigger rates at reasonable levels. This column links to a predefined set of L1T and HLT prescales.

This presents a challenge for the reconstruction of original rates and cross sections. While for many physics analyses HLT paths will have no or single-level prescales, trigger studies on L1 reconstructed objects can benefit from combinations of prescaled paths.

The following section will describe prescaler implementations and estimate event weights and confidence intervals for the different types (section 6.3.1). The effect of logical expressions on effective weights is described in section 6.3.2.

**Figure 6.12:** Distribution of the average and rms cluster size per roll in the barrel and endcap regions. The missing rolls are those for which no hits were recorded.
Figure 6.13: RPC resolutions expressed in strip-pitch for the barrel layers, with a fitted gaussian in gray and its standard deviation mentioned. The strip pitches are listed in table 6.2. Contributions of individual rolls have been shifted with the mean of individually fitted gaussians on the residual distributions. It is clear that from clustersize \( \text{CLS} \geq 4 \), the resolution deteriorates quickly. This is in turn responsible for the tails in the overall residual distribution.
6.3. Level One Muon Trigger Cross Sections

6.3.1 Estimating the Number of Events before Prescalers

6.3.1.1 Definitions

Consider a trigger firing $n$ times during an experiment, of which $m$ events are selected by a prescaler designed to reduce the number of triggered events by a factor $P$. Such a prescaler is usually implemented in one of two ways, referred to as deterministic and non-deterministic prescaling:

- the *Deterministic method* uses a trigger counter $i$, starting at a fixed or random value and passing only triggered events for which $(i \mod P) = 0$;
- for the *Non-Deterministic method*, a random number generator produces $0 \leq r < 1$ for each triggered event and selects those events for which $0 \leq r < P^{-1}$.

Methods to estimate the original number of triggered events $n$ in either scenario are described.

6.3.1.2 Deterministic Prescaler

When using the deterministic prescaler with a random initial counter value, a number of triggered events will be lost before the first one passes the prescaler. This number follows a uniform distribution running from $0$ to $P - 1$. The same is true for the triggers following the last selected event.

Adding the two independent uniform distributions to the $((m - 1)P + 1)$ triggers encompassed by the $m$ selected triggers, one finds the expectation value and variance

\[
\langle n \rangle = mP \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \qu
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\[
\langle n_2 \rangle = mP \quad \langle n_1 \rangle = mP \quad V_{n_1} = mP (P - 1). \tag{6.9}
\]

The second experiment is ruled by the probability to contain \( n_2 \) triggers after the last selected event and before the end of the experiment, given no more events are selected by the prescaler within \( \{ n_1 + 1, \ldots, n_1 + n_2 = n \} \). The probability to end after any triggered event in the range \( \{0, 1, \ldots, i - 1\} \) is uniform, where \( i \) denotes the next prescaler selected event had the experiment been continued. If a maximum of \( N \) triggered events occur after
the last selected event, the probability that the prescaler skips \( n_2 \) triggered events before the end of the experiment is given by

\[
\frac{(1 - P^{-1})^N}{N + 1} + \sum_{i=n_2+1}^{N} \frac{P^{-1} (1 - P^{-1})^{i-1}}{i}
\]  
(6.11)

with parameters numerically calculable from their definition. For \( P \ll N \), which can be expected from the goal of prescales, this becomes

\[
\sum_{i=n_2+1}^{\infty} \frac{P^{-1} (1 - P^{-1})^{i-1}}{i},
\]  
(6.12)

and for the prescales used in this work, the parameters can then be approximated as

\[
\langle n_2 \rangle \approx \frac{P - 1}{2},
\]  
(6.13)

\[
V_{n_2} \approx \frac{5P + 1}{12} (P - 1),
\]  
(6.14)

as can be seen from fig. 6.14. In the opposite scenario, \( N \ll P \), the first term in eq. (6.11) would dominate and lead to a uniform distribution with

\[
\langle n_2 \rangle \approx \frac{N}{2},
\]  
(6.15)

\[
V_{n_2} \approx \frac{(N + 1)^2 - 1}{12}.
\]  
(6.16)

Since both experiments are independent, the general non-deterministic prescale-scenario will results in a probability to cover \( n \) events of

\[
\sum_{n_1=m}^{n} \binom{n_1 - 1}{m - 1} P^{-m} (1 - P^{-1})^{n_1-m} \sum_{i=n_1+1}^{\infty} \frac{P^{-1} (1 - P^{-1})^{i-n_1-1}}{i-n_1}
\]  
(6.17)

with parameters

\[
\langle n \rangle \approx mP + \frac{P - 1}{2},
\]  
(6.18)

\[
V_n \approx \left( mP + \frac{5P + 1}{12} \right) (P - 1).
\]  
(6.19)

Confidence levels For a confidence level \( (1 - \alpha) \), it is possible to guarantee the coverage probability \( p \). Given an experiment with \( n \) triggered events and non-deterministic prescale \( P \) is repeated, the confidence interval of a fraction \( (1 - \alpha) \) of the experiments should contain \( n \). This means that, considering the binomial distribution of \( m \),

\[
p(m_{\text{low}} < m < m_{\text{up}} \mid n_{\text{low}} (m) < n < n_{\text{up}} (m)) = 1 - \alpha.
\]  
(6.20)

This can be translated to an interval for \( n \) given \( m \) as

\[
I_{1-P^{-1}} (n_{\text{up}} - m, m + 1) \leq \frac{\alpha}{2}
\]

\[
I_{1-P^{-1}} (n_{\text{low}} - m + 1, m) \geq 1 - \frac{\alpha}{2}
\]  
(6.21)
where $I_z(a,b)$ is the Regularized Incomplete Beta Function [116]. Note that these boundaries correspond to the bounds for $n$ when describing the negative binomial distributions of the two extreme scenarios,

- $n \leq n_{\text{up}}$ for the case that an event passed the prescaler immediately after the run, and
- $n_{\text{low}} \leq n$ for the case that the last event passing the prescales marked the end of the run.

$n_{\text{low}}$ and $n_{\text{up}}$ can be calculated from these relations using `boost::math::ibeta_invb` [117]. Figure 6.15 shows the actual coverage for a $1 - \alpha = 68.27\%$ and $95.45\%$ confidence level for a range of prescales.

The prescales in this work will often be combined (cf. section 6.3.2), resulting in different weights each behaving like a non-deterministic prescale. Rather than storing separate counts $m$ for every weight and using eq. (6.21), a normal approximation will be used around the estimator in eq. (6.18) with

$$\sigma_n = \sqrt{\left(m + \frac{3}{2}\right) P (P - 1)},$$

(6.22)

a variation on eq. (6.19) to account for its low coverage at low $m$. The corresponding $68.27\%$ and $95.45\%$ confidence levels coverages are displayed in fig. 6.16. Figure 6.16 compares the errors for both techniques at a $68.27\%$ and $95.45\%$ confidence level.

**Non-Deterministic after Deterministic Prescaling** The variation introduced by a deterministic prescaler ($P_1$) is completely defined at the start and end of the experiment, independent of the selected events. Therefore it can be added to the variation on the non-deterministically prescaled trigger ($P_2$), resulting in

$$\langle n \rangle \approx m P_1 P_2 + P_1 \frac{P_2 - 1}{2},$$

(6.23)

$$V_n \approx P_1^2 \left( m + \frac{3}{2} \right) P_2 \left( P_2 - 1 \right) + \frac{P_1^2 - 1}{6}.$$  

(6.24)

**6.3.1.4 Prescalers in CMS**

In the case of CMS, the L1T uses deterministic prescales with fixed seed. Run starts and prescale changes reset the counter to zero\(^4\). Since the number of prescale changes is far less than the number of lumisections, as there are only 9 columns in the prescale tables used most commonly, eq. (6.4) and eq. (6.5) are used for all lumisections. This introduces a bias $\sim \frac{P-1}{2}$ in the lumisections for which a prescale change was initiated, accounted for in the variance by using eq. (6.5) rather than eq. (6.7). For the full run this becomes negligible.

\(^4\)In practice they count down and are loaded with $P^1$
Figure 6.15: Comparison of the coverage of the confidence intervals produced with the exact method (eq. (6.21)) and the normal approximation (eq. (6.22)) at a 68.27% (a) and 95.45% (b) confidence level. The blue and red indicators on the color bars correspond to the lower limits of the exact method and normal approximation respectively.
Figure 6.16: Comparison of the width of the confidence intervals produced with the exact method (eq. (6.21)) and the normal approximation (eq. (6.22)) for the $1 - \alpha = 68.27\%$ and $95.45\%$ confidence levels.

The CMS HLT uses deterministic prescales with pseudo-random seeds.

While CMS does not use non-deterministic prescalers, most scenarios will need the non-deterministic error calculation.

On the one hand, the DST_Physics HLT prescale in the NanoDST stream should be interpreted as non-deterministic when considering individual L1 triggers. This is a consequence of the independence of consecutive events. The same goes for the L1_ZeroBias prescale.

For the same reason, additional time-independent requirements on top of deterministically prescaled triggers will result in non-deterministic prescaler behaviour. Finally, also the binning of any measurable not directly correlated with the trigger induces non-deterministic behaviour, again a consequence of the independence of consecutive events.

Terms independent of the number of passing events $m$ in the different estimators for $n$ and $V_n$ are supposed to be added for a total running period over which is integrated. Since prescales can change during such a period, their values should be weighted accordingly. Assuming the cross-section $\sigma$ under study is constant, the effective prescale can be calculated from

$$P_{\text{eff}} = \frac{n}{m} = \frac{\int \mathcal{L}(t)\sigma \, dt}{\int \mathcal{L}(t) \frac{\sigma}{P(t)} \, dt} = \frac{\int \mathcal{L}(t) \, dt}{\int \frac{\mathcal{L}(t)}{P(t)} \, dt}. \quad (6.25)$$
The variances listed above account for the error introduced reconstructing the observed number of events from the recorded number. They do not account for the distribution of the number of observed events given the nature of the cross-sections of underlying physics processes and trigger behaviour.

6.3.2 Event Weights for Prescaled Triggers in Logic Expressions

The prescaling of L1T and HLT decisions cuts back on the size of datasets for any given trigger. While desirable for the restricted computing and storage capabilities, and tuned for different physics analysis, it also limits the data available to understand the trigger behaviour for added constraints on time, collision or environmental factors.

This section calculates weights needed to reconstruct the original composition of events passing a desired logic expression of unprescaled trigger decisions, starting from selection criteria on the prescaled decisions. The logic selection expression is assumed to be inclusive of the logic expression under study, if it were to act on unprescaled decisions.

While unprescaled decisions are not stored in CMS, both the cases where the unprescaled decisions are known and unknown are handled. This clarifies the choice of running the L1T emulator for trigger studies.

6.3.2.1 Definitions

Consider a set of triggers $T_i$ and their corresponding prescales $P_i > 0$. The probability to find a trigger pattern $X$ after prescaling, given a trigger pattern $Y \supseteq X$ before prescaling, approaches

$$\prod_{i \in \{Y \setminus X\}} (P_i - 1) \prod_{j \in Y} P_j^{-1}, \quad (6.26)$$

where the lower case indices $i, j, \ldots$ denote the individual fired triggers and the upper case $X, Y, \ldots$ combinations thereof. It should be noted that this assumption reduces the prescaling to independent probabilities $P_i^{-1}$. While this is in agreement with the definition of non-deterministic prescaling, for deterministic prescalers this implies that

- the number of events $\gg P_i$ (or the number of recorded events $\gg 1$),
- prescaler counters should not be in phase, and
- the intrinsic requirement that events are independent, or no correlation exists with the prescale counters.

The goal consists of calculating weight $w_m$ for every recorded event $m$, such that the number of unprescaled events passing expression $E_Y$ is given by

$$N_{E_Y} = \sum_n E_Y (Y_n) = \sum_m E_X (X_m) w_m \quad (6.27)$$
where $Y_n$ is the unprescaled fired trigger combination for event $n$, and $E_Y(Y)$ evaluates to 1 if combination $Y$ passes the expression $E_Y$, and 0 otherwise. Analogously, the logic selection expression $E_X(X)$ evaluates to 1 if prescaled trigger combination $X_m$ for recorded event $m$ passes the selection expression $E_X$, and 0 otherwise.

The aforementioned restriction on the logic selection expression translates to $E_Y(Y) \Rightarrow E_X(Y)$.

**6.3.2.2 Weights without Knowledge of Unprescaled Trigger Decisions**

To derive event weights when unprescaled trigger results are unknown, the weights in eq. (6.27) should depend on $X$ only. The relation between the number of events with a given trigger pattern $X$ after prescaling ($M_X$ measurements) and those before ($S_Y$ sources with pattern $Y$) is given by

$$M_X = \sum_{Y \supseteq X, i \in \{Y \setminus X\}} (P_i - 1) \prod_{j \in Y} P_j^{-1} S_Y. \quad (6.28)$$

Writing $P'_i = (P_i - 1)$ and $S'_Y = \prod_{i \in Y} P_i^{-1} S_Y$, this can be expanded as

$$M_0 = S_0 + \sum P'_i S'_i + \sum \sum P'_i P'_j S'_{i,j} + \sum \sum \sum P'_i P'_j P'_k S'_{i,j,k} + \cdots$$

$$M_i = S'_i + \sum P'_j S'_{i,j} + \sum \sum P'_j P'_k S'_{i,j,k} + \cdots$$

$$M_{i,j} = S'_{i,j} + \sum \sum P'_k S'_{i,j,k} + \cdots$$

$$M_{i,j,k} = S'_{i,j,k} + \cdots, \quad (6.29)$$

where it’s understood that duplicate indices in a single term are inherently impossible. Picking an $S'_Y$ and summing consecutive lines in eq. (6.29) gives

$$S'_Y = \sum_{X \supseteq Y, i \in \{X \setminus Y\}} \prod_{i \in \{X \setminus Y\}} (1 - P_i) M_X$$

$$S_Y = \sum_{X \supseteq Y, i \in \{X \setminus Y\}} \prod_{i \in \{X \setminus Y\}} (1 - P_i) \prod_{j \in Y} P_j M_X.$$ 

Finally, writing eq. (6.27) as a function of $M_X$ or $S_Y$ gives

$$N_{E_Y} = \sum_{X} E_X(X) w_X M_X \quad (6.30)$$

$$= \sum_{Y} E_Y(Y) S_Y \quad (6.31)$$

$$= \sum_{Y} E_Y(Y) \sum_{X \supseteq Y, i \in \{X \setminus Y\}} \prod_{j \in Y} (1 - P_i) \prod_{j \in Y} P_j M_X. \quad (6.32)$$

In practice, only $E_X(X) M_X$ are measured, which implies that eq. (6.32) can only be used if $E_Y(Y) \Rightarrow E_X(X)$. The weights for $M_X$ needed to reconstruct the number of events passing the expression unprescaled can now be written as

$$w_m = w_{X_m} = E_X(X_m) \sum_{Y \subseteq X_m} E_Y(Y) \prod_{i \in \{X_m \setminus Y\}} (1 - P_i) \prod_{j \in Y} P_j. \quad (6.33)$$
These weights may differ considerably in both size and sign for different $X$, leading to unstable estimates induced by overlap of the contributing triggers.

### 6.3.2.3 Weights with Knowledge of Unprescaled Trigger Decisions

In case the unprescaled trigger results are known, one can start from eq. (6.26), writing $S_Y$ as a sum of its contributions to $M_X$

$$S_Y = \sum_{X \subseteq Y} \prod_{i \in (Y \setminus X)} (P_i - 1) \prod_{j \in Y} P_j^{-1} S_Y$$

and reconstruct $N_E$ from the second identity in eq. (6.27). The contributions to $M_X$ for which $E_X(X) = 0$ will disappear from these sums, and the weight for a recorded event $m$ with unprescaled trigger pattern $Y_m$ becomes

$$w_m = w_{Y_m} = E_Y(Y_m) \sum_{X \subseteq Y_m} \frac{E_X(X)}{\prod_{i \in (Y_m \setminus X)} (P_i - 1)}. \quad (6.34)$$

While the weights will still differ in size, they will always be positive.

Every trigger pattern $Y$ passing the expression $E_Y$ can be regarded as a separate class of events, of which only a fraction $w_Y^{-1}$ is kept. Because no assumptions have been made about the prescales in section 6.3.2 being integer, the same error calculation can be used for the weights $w_Y$.

### 6.3.2.4 Prescaler-Induced Event Weights in CMS

As it’s clear eq. (6.34) is the weight of choice, the Global Trigger Emulator has to be used when reprocessing the data to derive the missing unprescaled decisions.

Equation (6.34) is tedious to calculate, especially since prescale set indices, prescales, L1T and HLT triggers, unprescaled and prescaled trigger decisions are spread over several EDM Data Formats, Event Setup Data Records and the EDM Provenance. To ease this process, the SimpleTrigger package was developed.

On the one hand, SimpleTrigger consists of a series of EDM objects to store the necessary information:

- for each run it stores in a compact and uniform way
  - HLT Streams, DataSets and Paths,
  - HLT Expressions,
  - HLT and L1T Masks and Prescales,
• for each LS it keeps track of
  – the active Prescale Index,
  – the Instantaneous Luminosity and other relevent Beam and Data-Taking information provided by the CMSSW LumiProducer,
• and for every event it stores
  – if an HLT was run, and
  – the unprescaled and prescaled decisions for each of the triggers.

On the other hand, it provides tools to
• interpret textual infix expressions of the L1T and HLT triggers,
• store, evaluate and describe the resulting compact postfix description,
• calculate the event weights according to eq. (6.33) or eq. (6.34) and
• evaluate the luminosity-related data on the fly should the official calibration be improved.

### 6.3.3 L1 Muon Trigger Cross Sections

#### 6.3.3.1 Methods

To calculate the cross sections of the RPC and GMT at different $p_T$, the L1Accept dataset is used. The logical expression used to select events and calculate their weight is given as

\[
\text{DST\_Physics AND } (L1\_SingleMu?? \text{ OR } L1\_SingleMu7 \text{ OR } L1\_SingleMuOpen \text{ OR } L1\_ZeroBias) \tag{6.35}
\]

where $L1\_SingleMu??$ is replaced with the lowest-$p_T$ unprescaled single muon trigger in $(L1\_SingleMu12, L1\_SingleMu16, L1\_SingleMu20)$ for single-muon trigger studies, or the lowest-$p_T$ unprescaled double muon trigger from $(L1\_DoubleMu\_10\_Open, L1\_DoubleMu\_12\_5)$ for double-muon related studies.

In the order shown in eq. (6.35), the unprescaled L1 algorithm trigger decisions are always inclusive of the next, apart from the double-muon trigger with $L1\_SingleMu7$. While unprescaled decisions do not exist for HLT paths, \text{DST\_Physics} is true by definition. This means that the number of classes is reduced to four or five, simplifying bookkeeping.

It should be noted that adding for example the eta-restricted triggers to this expression would increase the number of classes, and the offset introduced with the estimators $\langle n \rangle$ in section 6.3.1, but bring an overall reduction to the weight of each event. The reason for this is the lack of knowledge about the number of triggers missed before the first event of
6.3. Level One Muon Trigger Cross Sections

![Graph](image)

**Figure 6.17**: Effective cross section as a function of $p_T$ for the RPC L1 muon candidates during the first 155 LSs ($\approx 1$ h) of Run 206246, with 68% confidence intervals. The effective cross section as measured by the full 2012D L1_ZeroBias sample for similar $\mathcal{L}_e$ is shown for reference (0.216 to 0.245 mb$^{-1}$).

The sensitivity indicates the offset in the mean introduced in eq. (6.17), with a 68% confidence interval in gray, and gives an indication of the maximal sensitivity given the integrated luminosity. It is clear that the introduction of the weights does not suppress this, but for high $p_T$, more events are added with significantly smaller weights. As a consequence, measurements converge to the full-sample-values faster where they are higher than the offset.

While binning was kept fine to illustrate the offset-effect, coarser binning can be used to reduce it.

While for the GMT the effect can be suppressed through the knowledge that certain $p_T$ thresholds coincide with the GT thresholds, this is not true for the other subsystems of the L1 muon trigger.

### 6.3.3.2 Results

**Quality** Figure 6.18 shows the efficacy of this method with a stack of the qualities contributing to the RPC PAC candidate distributions. The quality $\geq 3$ histograms show the minimum sensitivity in the overlap and forward region, as this quality can not be reached there by lack of RPC layers.

**Cluster Size** The muon rates produced by the RPC PAC depend on the efficiency and clustersize of the contributing detector. How the clustersize can influence the $p_T$ assignment is illustrated in fig. 6.19: as the Pattern Comparator does not recognise clusters as such, but instead looks at each strip individually, its affinity for high-$p_T$ muons shifts the strip used in the selected pattern towards the edge of the clusters. As the clustersize increases, also the efficiency increases and the combined effect is illustrated in fig. 6.20.
Figure 6.18: Effective cross section of the RPC PAC muon candidates as a function of their $p_T$ in the different $\eta$ regions. It is clear that only three layers are available in the forward region, resulting in zero-quality candidates only.

The lower-right plot shows the cross section for double-muon RPC PAC candidates. The $>10^{-4} \text{mb}^{-1}$ area where $p_{T,2} > p_{T,1}$ is a consequence of the zero-count offset. While it can be ruled out, it is left as an indicator of the sensitivity of the measurement.

Only Luminosity Sections with an integrated luminosity per event $L_e$ of 0.303 to 0.360 mb$^{-1}$ were used, with an average and standard deviation of $(0.344 \pm 0.030)$ mb$^{-1}$. 
Figure 6.19: Strip used in the muon pattern selected by the PAC as reported by the emulator, from the available strips in clusters with size two, three and four, for the different barrel layers and depending on the charge of the candidate. The preference for one side along $\phi$ is consequence of the PAC priority for high-$p_T$ muon candidates. Only candidates with $p_T \geq 16$ GeV/c are taken into account, because lower-$p_T$ patterns combine multiple strips per layer.
Figure 6.20: Effective cross section for a range of $p_T$-thresholds on the RPC PAC muon candidates as a function of the mean of the clustersize distributions in respectively the barrel, the global and the endcap region.
Each measurement corresponds to a contiguous set of $\approx 155$ LS with a minimum of 40 LS.
6.3. Level One Muon Trigger Cross Sections

Figure 6.21: The cross section of L1 muon candidates with $p_T \geq 10$ GeV/c as a function of $\eta$ and $\phi$. Particularly in the RPC endcap, the three-out-of-three logic results in gaps when one chamber malfunctions (c). This effect is not clear from CSC cross section (d), but the GMT does filter out the lower quality candidates resulting in similar gaps (b). When combined (a), the GMT shows reasonable rates for the full coverage.

**PAC impact on the GMT** On the one hand, the candidates from the different L1 muon trigger systems make for a stable system, as they act complementary to catch local inefficiencies (fig. 6.21).

On the other hand, the combined candidates from the RPC, CSC and DT systems make for a stable muon candidate cross section, as depicted in fig. 6.22. It should be noted, that when one subdetector is removed, as demonstrated for the RPC, the muon candidate rates become susceptible to the $p_T$ overestimation of one system with a less sharp GMT cross section as a result (fig. 6.23).
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\[ p_T \geq 5 \text{ GeV/c} \]
\[ p_T \geq 10 \text{ GeV/c} \]
\[ p_T \geq 18 \text{ GeV/c} \]
\[ p_T \geq 35 \text{ GeV/c} \]
\[ p_T \geq 60 \text{ GeV/c} \]
\[ p_T \geq 100 \text{ GeV/c} \]

**Figure 6.22:** Effective cross section for a range of \( p_T \)-thresholds on the GMT muon candidates, both running with (data) and without (emulation on data) the RPC PAC contribution. Without RPCs, the rates show increased cross section fluctuations, as shown in fig. 6.23. The slow decrease for high-\( p_T \) at low \( \mathcal{L} \), though well within the error, could be explained by the decreasing integrated luminosity for the same measurement duration. Because of this, the long-tail effect on eq. (6.18) becomes visible. Each measurement corresponds to a contiguous set of \( \approx 155 \) LS with a minimum of 40 LS.

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6.3. Level One Muon Trigger Cross Sections

Figure 6.23: Change in cross section distributions of the GMT when using or ignoring PAC candidates.

In the barrel region, the addition of RPC candidates to the GMT sharpens the cross section, and lowers it through the minimum-$p_T$ logic (cf. section 2.2.1.2). In the forward region, cross sections increase with the addition of RPC candidates to the GMT because of the different GMT logic in that region: the CSC $p_T$ is used for high-quality CSC candidates, which remain, and low-quality CSC candidates are added by RPC confirmation.
Summary and Conclusions

Over the past few years, the Compact Muon Solenoid (CMS) experiment has successfully dealt with the collisions the Large Hadron Collider (LHC) has delivered. While this is most obvious through the numerous physics analyses and results that are still being produced well in LHC First Long Shutdown, the reliability of the detector and trigger ensured the necessary data is available.

In the search for new physics, some interesting events distinguish themselves through their muonic signatures. With its strong magnetic field, CMS is capable of measuring the transverse momentum of muons with high precision through its extensive tracker and muon system. This thesis dealt with one subdetector in the muon system, the Resistive Plate Chamber (RPC), and its muon trigger, the RPC Pattern Comparator.

**Resistive Plate Chambers** The RPC detector is a gaseous resistive parallel-plate chamber, with a high electric field over its gas gap. The CMS RPC are operated in avalanche mode, which means that the ionisation by passing particles causes multiplication of the accelerated electrons in avalanches, but falls short of causing a streamer.

In CMS, these RPCs are installed in three to six layers outside its solenoid, and work together with Drift Tube Chambers (DTs) and Cathode Strip Chamber (CSC) to detect the passage of muons. They measure their transversal momentum thanks to a 3.8 T solenoid, causing a strong magnetic field in particular in the iron return yokes interleaved with the muon chambers.

**RPC Pattern Comparator** This muon detection not only has to be performed when analysing data, it also has to take place in real-time during the collisions to pre-select events. All three dedicated muon detectors generate up to four muon candidates each at the 40 MHz of the LHC clock to deal with the high-rate bunch crossings. These are combined by a Global Muon Trigger (GMT) and serve the CMS trigger system.

For the RPCs, this is accomplished by a Pattern Comparator (PAC) that runs on FP-GAs\(^5\) and compares the RPC hits to predefined patterns, corresponding to simulated muon traces.

\(^5\)Field-Programmable Gate Arrays
Before the first LHC collisions, as well as during the LHC First Long Shutdown, the RPC detector had to be prepared on many levels.

**Hardware** To start with, all of its hardware had to be in place and functional. With \( \mathcal{O}(10^3) \) chambers, each in need of gas supplies, High Voltage for its electric field, Low Voltage for its electronics and cables for control and readout, this is a complex system with the potential for a wide range of human errors. In addition, several parameters had to be tuned before the arrival of LHC collisions. The commissioning activities surrounding each of these services constitute the first part of this PhD, with a main responsibility for the commissioning of front-end electronics.

**Online Software** The control system for this detector has been organized in several hierarchies, where each node can be accessed for local activities, and the system can be easily controlled as a whole through its Finite State Machine. A Detector Control System handles the safety-critical services, and is implemented in an LHC-wide common platform running on WinCC-OA\textsuperscript{6}. The control of the Trigger and Data Acquisition System is implemented in C++ on top of the Cross Platform Data Acquisition (XDAQ) framework, alongside Java components for Database access, and is detailed in chapter 5.

The second stage of this PhD involved development of software in the latter category, improving the speed and reliability of the Front-End control and monitoring, and adding persistence for critical parameters. Over the years, experience has proven the developed web interfaces and Finite State Machines give an adequate handle on the detector.

**Commissioning Software** With the end of LHC First Long Shutdown near, the commissioning software developed with the PhD experience in commissioning and online software development has proven itself effective, speeding up certain activities from hours to minutes. Given the rate at which new RPCs have been installed, and the duration of access to existing hardware, this has been indispensable.

**Detector Performance** While an extensive set of tools had been developed to assess the RPC performance, an attempt has been made in the final stage of this PhD to further exploit the available data to the benefit of the detector and triggers. In particular the Pattern Comparator cross section estimates have been improved greatly over previous calculations, opening the way to correlate them with the detector performance. For the detector performance, a new set of tools has been developed with the potential of reaching previously uncalibrated areas.

\textsuperscript{6}WinCC Open Architecture SCADA Tool
Outlook  During LHC First Long Shutdown, an additional layer of RPCs has been installed, part of which has been assembled in Ghent. Where the past few months have been about integrating these chambers and their services into the existing system, the first operational tests with cosmic muons are ongoing at the time of writing.

Software is a fast evolving subject, particularly when one considers the web-based interfaces used for the online and commissioning software. While HTML5 was in early development when part of the online software was being developed, the latest versions of the XDAQ framework in use adopted features that can now be considered stable enough to enhance the user experience and ease data presentation. This trend can and should be followed in the RPC Trigger and Data Acquisition System control software.

While some results have been obtained already, the tools introduced in chapter 6 have the potential to aid in the further understanding and tuning of the detector parameters.
Nederlandstalige Samenvatting

Ons huidig begrip van elementaire deeltjesfysica bouwt op de experimenten en theorieën van duizenden natuurkundigen sinds de jaren dertig. Dit leidde in de jaren zestig en zeventig tot de ontwikkeling van het Standaard Model van de deeltjesfysica, een theorie gedreven door de quantummechanica, relativiteitstheorie en de indrukwekkende experimentele resultaten uit die periode. Niet alleen beschrijft deze theorie de krachten en deeltjes die tot dan werden ontdekt, ze voorspelde ook nieuwe deeltjes waarvoor nog enige decennia aan experimentele vooruitgang nodig waren.

Recent werd ook een Higgs boson aan deze lijst toegevoegd, ontdekt door de Compact Muon Solenoid (CMS) en ATLAS\textsuperscript{7} experimenten in 2012, beide geïnstalleerd aan de CERN\textsuperscript{8} Large Hadron Collider (LHC).

Hoewel het Standaard Model een accurate beschrijving blijkt voor de bestaande experimenten, zijn er nog steeds open vragen. Zo bevat de theorie slechts drie van de vier fundamentale krachten: de zwaartekracht wordt niet beschreven. Verder zijn er in het Standaard Model geen deeltjes die \textit{donkere materie} kunnen verklaren. Ook zijn er nog problemen in de theorie waarvoor potentiële oplossingen een resem aan nieuwe deeltjes voorspellen.

Naast het Higgs boson, is de zoektocht naar die verdere nieuwe deeltjes een belangrijke drijfveer voor de bouw van de Large Hadron Collider en zijn experimenten. Aangezien deze deeltjes een hoge massa hebben en slechts een kleine kans om te worden geproduceerd, moet de LHC terugvallen op een zeer hoge frequentie aan proton-proton botsingen, met bovendien een groot aantal botsingen tegelijkertijd. Welke nieuwe deeltjes er ook mogen verschijnen, de detectors die de eindproducten observeren zullen steeds terugvallen op de detectie van een kleine subset aan gekende deeltjes.

De hoge frequentie betekent dat de detectors zeer performant en stabiel moeten zijn: in een korte onderbreking worden vele potentiële botsingen gemist. Aangezien geen netwerken, processors of bestaande opslagcapaciteit deze frequentie kunnen bijhouden, is maat snelle detectie ook een adequate data reductie nodig die de interessante botsingen selecteert. Dit is de taak van de zogenaamde trigger, die op basis van een gereduceerde reconstructie van de eindproducten nagaat of een botsing al dan niet moet worden bijgehouden.

\textsuperscript{7}A Toroidal LHC Apparatus Experiment
\textsuperscript{8}European Organization for Nuclear Research
Het werk beschreven in deze thesis concentreert zich op een van de subdetectoren van het CMS experiment, met name de Resistive Plate Chamber (RPC) detector. Deze detector bestaat uit twee resistieve platen die een gas insluiten, en detecteert een deeltje wanneer het gas erdoor wordt gelioniseerd. De resulterende elektronen worden dan versneld en vermenigvuldigd in een elektrisch veld, wat leidt tot een elektrisch signaal in daarvoor voorziene elektroden langs de platen.

Resistive Plate Chambers zijn in CMS opgenomen om iedere $25\,\text{ns}$ de muon deeltjes te detecteren die kunnen duiden op relevante botsingen voor de huidige studies. Bijgevolg is de detector voorzien van een uitgebreid systeem om de detector uit te lezen, alsook om deze muonen te traceren met behulp van specifiek ontwikkelde hardware en firmware en zo de trigger te informeren.

In een eerste luik van het doctoraatsonderzoek werd na de installatie van de RPCs ervoor gezorgd dat deze detectors naar behoren werken, dit zowel vóór de eerste ingebruikname van de LHC als gedurende de huidige periode voorzien om de versneller en de detectors klaar te maken voor de toekomst. Hiervoor werden de basisvoorzieningen voor de detector gecontroleerd en bijgesteld – van het gas waarin de muonen hun sporen achterlaten door ionisatie en het elektrische veld dat deze deeltjes moet versnellen, tot de elektronica die zorgt dat de signalen kunnen worden uitgelezen, of de duizenden connectoren die ervoor zorgen dat deze signalen kunnen bijdragen aan het experiment. Aangezien er bijna duizend RPCs zijn geïnstalleerd, betekent dit dat vele testen moesten worden geautomatiseerd.

Daarnaast draagt dit doctoraatswerk ook bij aan de software die de elektronica van dit grote aantal detectors aanstuurt en de werking ervan opvolgt. In het verlengde van die taak werden ook applicaties ontwikkeld die de connecties tussen de onderdelen verifiëren, de werking van de individuele onderdelen nagaan en controleren of de juiste elektronische componenten worden aangesproken. De geïmplementeerde software brengt een drastische reductie in uitvoeringstijd en een hogere precisie bij de installatie, de commissioning en het gebruik van de CMS RPCs.

Tot slot werd ook de performantie van deze subdetector en zijn muon tracering onderzocht. Aan de ene kant werd hiervoor nagegaan in welke mate de instellingen van de RPCs invloed hebben op hun detectievermogen. Dit gebeurde aan de hand van muonen gereconstrueerd met de data van verschillende CMS subdetectors. Daarnaast werd nagegaan in welke mate dit de frequentie van de trigger beïnvloedt.


Bibliography


Bibliography


AOD
Data Tier containing Analysis Object Data, a subset of the RECO relevant for physics analysis.

Ghost
Ghosts are fake muon candidates usually created when different trigger elements receive hits or track segments of the same, real muon.

Link sector
A link sector is defined by the Link System chamber connections, and spans a $30^\circ$ $\phi$-segment. It corresponds to the chambers connected to one Link Box (LBox), with the exception of RE+3 and RE-3 where one LBox serves two link sectors. In the barrel region the link sectors and physical sectors coincide, and are usually referred to as sectors.

Local Trigger
A trigger algorithm implemented in the RPC Balcony Collector (RBC) that applies a per-sector majority rule on the six barrel layers.

Logical segment
A logical segment as defined by the RPC trigger system spans 8 strips along $\phi$ in the reference layer ($2^\circ\ 30'$).

Logical sector
A logical sector as defined by the RPC trigger system spans a $30^\circ$ $\phi$-segment.

Logical cone
A logical cone as defined by the RPC trigger system spans a logical segment for a single tower.

OPTO
An FPGA used on the Trigger Board programmed to synchronise the data coming from three TLKs, using the time signature embedded in the data frames.

Physical sector
A physical sector is defined by the CMS yoke and RPC, DT and CSC chamber layout. It spans a $30^\circ$ $\phi$-segment in the barrel region or $10^\circ$ $\phi$-segment in endcap region. In the barrel region the link sectors and physical sectors coincide, and are usually referred to as sectors.

RAW
Data Tier containing detector data after online formatting, the Level One Trigger result, High Level Trigger (HLT) decisions, and some of the higher level quantities calculated during HLT processing.
**Glossary**

**RECO**

Data Tier containing reconstructed objects (tracks, vertices, jets, electrons, muons...) and reconstructed detector hits, clusters and local tracks.

**Roll**

A roll consists of the contiguous set of strips in a CMS RPC with the same $\eta$-range. It is also referred to as an $\eta$-partition.

**S-LINK64**

A 64-bit asynchronous serial link between the Front-End Drivers (FEDs) and the Front-End Readout Links (FRLs).

**Tier-1**

The second tier in the computing resources architecture. It receives part of the Tier-1 RAW data, archives it on tape and processes it up to the Analysis Object Data (AOD) data tier.

**Tier-0**

The first tier in the computing resources architecture. Located at CERN, it accepts the RAW data from Trigger and Data Acquisition System (TriDAS), distributes it to the Tier-1 sites and archives it to tape. It also processes the data to generate a first, prompt calibration and reconstruction.

**TLK**

The TLK2501 is a 1.5 to 2.5 Gbit/s Transceiver by Texas Instruments

**Tower**

A tower as defined by the RPC trigger system spans an $\eta$-range corresponding to the RPC strip length in the reference layer.
# Acronyms

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<td>Analog-to-Digital Converter</td>
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<td>LHC Beam Position Monitor</td>
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<td>Control Board (CB) Initialisation Controller</td>
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<td>CBPC</td>
<td>CB Programmable Controller</td>
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*Signal initiating transmission of data over the Timing, Trigger and Control System (TTC) B channel, cf. TTCvi specifications.*

Four electrostatic button electrodes positioned symmetrically around the beam-pipe.

[118]: Two BPMs located on each side of CMS, at ±175 m from the nominal Interaction Point (IP). They provide highly efficient (>99.99%) detection and accurate timing of the proton bunches as they approach CMS.
Acronyms

**CCC**  CERN Control Center  
**CCS**  Clock and Control System  
*The Electromagnetic Calorimeter (ECAL)/Preshower equivalent of the Tracker Front-End Controller (FEC)*  
**CCU**  Communication and Control Unit  
**CCU-25**  Communication and Control Unit ASIC  
**CDF**  Common Data Format  
**CERN**  European Organization for Nuclear Research  
**CGI**  Common Gateway Interface  
**CI**  Command I  
**CLS**  Cluster Size  
**CMS**  Compact Muon Solenoid  
**CMSSW**  CMS Software  
**CondDB**  Conditions Database  
**ConfDB**  Configuration Database  
**CP**  Charge Parity  
**CPU**  Central Processing Unit  
**CSC**  Cathode Strip Chamber  
**ALCT**  Anode Local Charged Track Trigger  
**CSCTF**  CSC Track Finder  
**RAT**  RPC-Anode Local Charged Track Trigger (ALCT) Transition Board  
**TMB**  Trigger Mother Board  
**CTC**  Central Trigger Controller  
**DAC**  Digital-to-Analog Converter  
**DAQ**  Data Acquisition  
**DB**  Database  
**DCC**  Data Concentrator Card  
**EB**  Event Builder  
**EM**  Event Merger  
**IH**  Input Handler  
**DCC/CCS Crate**  Versa Module Eurocard (VME) crate containing Data Concentrator Card (DCC) and Clock and Control System (CCS) modules  
**DCS**  Detector Control System  

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<td><strong>DIP</strong></td>
<td>Data Interchange Protocol</td>
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<tr>
<td><strong>DOH</strong></td>
<td>Digital OptoHybrid</td>
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<td><strong>DQM</strong></td>
<td>Data Quality Monitoring</td>
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<tr>
<td><strong>DSL</strong></td>
<td>Dispersion Suppressor Left</td>
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<td><strong>DSR</strong></td>
<td>Dispersion Suppressor Right</td>
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<td><strong>DSS</strong></td>
<td>Detector Safety System</td>
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<td><strong>DT</strong></td>
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<td><strong>EASY</strong></td>
<td>Embedded Assembly System</td>
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<td><strong>EDM</strong></td>
<td>Event Data Model</td>
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<td><strong>EOD</strong></td>
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<td><strong>EWK</strong></td>
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<td><strong>EXDR</strong></td>
<td>Extended External Data Representation</td>
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<td><strong>FDL</strong></td>
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<td><strong>FE</strong></td>
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<td><strong>FIFO</strong></td>
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<td><strong>FM</strong></td>
<td>Function Manager</td>
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*Global Trigger module that applies the final OR on technical and algorithm triggers, and applies prescales and masks*
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<td>Fast Merge Module</td>
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<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
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<td><strong>HLT</strong></td>
<td>High Level Trigger</td>
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<tr>
<td><strong>LS</strong></td>
<td>Luminosity Section</td>
</tr>
<tr>
<td></td>
<td><em>2^{18} orbits or ( \approx 23.31 \text{s} )</em></td>
</tr>
<tr>
<td><strong>LS1</strong></td>
<td>LHC First Long Shutdown</td>
</tr>
<tr>
<td><strong>LSS</strong></td>
<td>Long Straight Section</td>
</tr>
</tbody>
</table>
LTC  Local Trigger Controller ........................................................... 26, 27, 64
LUT  Look-Up Table ................................................................. 19, 22, 47
LV  Low Voltage ................................................................. 39, 41, 49, 74, 130
LVDS  Low-Voltage Differential Signaling ........................................ 49, 50, 51, 54, 55, 56, 63, 64
MC  Monte Carlo ................................................................. 45
MIP  Minimum Ionizing Particle .................................................. 21, 23, 24, 33, 103
MUX  Multiplexer .......................................................................... 60
OLE  Object Linking and Embedding ................................................. 39, 152
OMDS  Online Master Database System ............................................ 38, 69
OPC  OLE for Process Control ..................................................... 39
ORCOFF  Offline Reconstruction Condition Database, Offline subset ........ 38
ORCON  Offline Reconstruction Condition Database, Online subset .......... 38
OSWI  Online Software Interface .................................................. 65
P1  Point 1 .................................................................................. 8
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P5  Point 5 ................................................................................ 8, 11, 59
PAC  Pattern Comparator ......................................................... 22, 37, 43, 45, 47, 48, 53, 54, 55, 56, 57, 71, 93, 94, 121, 125, 129, 130
PC  Personal Computer ............................................................. 25
PCB  Printed Circuit Board .......................................................... 74, 150
PCI  Peripheral Component Interconnect ....................................... 59, 76, 150, 152
PCI Special Interest Group
PIO  Parallel Input/Output ............................................................ 60
PLC  Programmable Logic Controller ........................................... 42
PMT  Photomultiplier Tube .......................................................... 154
PopCon  Populator of Condition Objects ........................................... 38
PS  Proton Synchrotron ............................................................... 4
PS  Preshower ............................................................................ 14
PSB  Proton Synchrotron Booster .................................................. 4
PSX  XDAQ-Prozessvisualisierungs-und Steuerungs-System (PVSS) Simple Object Access Protocol (SOAP) Interface ........................................... 41, 68, 80, 81
PVSS  Prozessvisualisierungs- und Steuerungs-System .......................... 28, 41, 68, 80, 152, 155
PVC  Polyvinyl Chloride ............................................................... 35
QCD  Quantum Chromodynamics .................................................. 3
**Acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFT</td>
<td>Quantum Field Theory</td>
</tr>
<tr>
<td>RAM</td>
<td>Random-Access Memory</td>
</tr>
<tr>
<td>RBC</td>
<td>RPC Balcony Collector</td>
</tr>
<tr>
<td>RC</td>
<td>Run Control</td>
</tr>
<tr>
<td>RCMS</td>
<td>Run Control and Monitor System</td>
</tr>
<tr>
<td>RCT</td>
<td>Regional Calorimeter Trigger</td>
</tr>
<tr>
<td>RDBMS</td>
<td>Relational Database Management System</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RF is used to refer to LHC P4, where the LHC RF cavities are located that provide the required acceleration field for ramping the beam energy up to 7 TeV and for keeping the colliding proton beams tightly bunched [119].</td>
<td></td>
</tr>
<tr>
<td>RF2TTC</td>
<td>RF to TTC Interface Module</td>
</tr>
<tr>
<td>RFC</td>
<td>Request for Comments</td>
</tr>
<tr>
<td>RFRX</td>
<td>RF Receiver Module</td>
</tr>
<tr>
<td>Receives the RF timing signals from P4</td>
<td></td>
</tr>
<tr>
<td>RMB</td>
<td>Readout Mezzanine Board</td>
</tr>
<tr>
<td>rms</td>
<td>root mean squared</td>
</tr>
<tr>
<td>ROOT</td>
<td>ROOT's Rapid Object-Oriented Technology Data Analysis Framework</td>
</tr>
<tr>
<td>RPC</td>
<td>Resistive Plate Chamber</td>
</tr>
<tr>
<td>RPC</td>
<td>Remote Procedure Call</td>
</tr>
<tr>
<td>RU</td>
<td>Readout Unit</td>
</tr>
<tr>
<td>SB</td>
<td>Splitter Board</td>
</tr>
<tr>
<td>SC</td>
<td>Sorter Crate</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>SCL</td>
<td>Serial Clock Line</td>
</tr>
<tr>
<td>SCX</td>
<td>Surface Control Room</td>
</tr>
<tr>
<td>SDA</td>
<td>Serial Data Line</td>
</tr>
<tr>
<td>SEU</td>
<td>Single Event Upset</td>
</tr>
<tr>
<td>A non-destructive radiation-induced state change in a micro-electronic device</td>
<td></td>
</tr>
<tr>
<td>SM</td>
<td>Standard Model of Particle Physics</td>
</tr>
<tr>
<td>SOAP</td>
<td>Simple Object Access Protocol</td>
</tr>
<tr>
<td>A protocol specification for exchanging structured information, formatted with XML, usually sent over Hypertext Transfer Protocol (HTTP) on the Transmission Control Protocol (TCP) transport layer, as is the case for XDAQ</td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td>Super Proton Synchrotron</td>
</tr>
<tr>
<td>Acronyms</td>
<td>Description</td>
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<tr>
<td>----------</td>
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</tr>
<tr>
<td><strong>SQL</strong></td>
<td>Structured Query Language</td>
</tr>
<tr>
<td><strong>SRAM</strong></td>
<td>Static Random-Access Memory</td>
</tr>
<tr>
<td><strong>SUSY</strong></td>
<td>Super Symmetry</td>
</tr>
<tr>
<td><strong>SVG</strong></td>
<td>Scalable Vector Graphics</td>
</tr>
<tr>
<td><strong>TB</strong></td>
<td>Trigger Board</td>
</tr>
<tr>
<td><strong>TC</strong></td>
<td>Trigger Crate</td>
</tr>
<tr>
<td><strong>TCP</strong></td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td><strong>TCP/IP</strong></td>
<td>TCP transport over Internet Protocol (IP)</td>
</tr>
<tr>
<td><strong>TCS</strong></td>
<td>L1 Trigger Control System</td>
</tr>
<tr>
<td><strong>TDM</strong></td>
<td>Time-Division Multiplexing</td>
</tr>
<tr>
<td><strong>TIM</strong></td>
<td>Timing Module</td>
</tr>
<tr>
<td><strong>TOTEM</strong></td>
<td>Total Elastic and Diffractive Cross Section Measurement</td>
</tr>
<tr>
<td><strong>TRACO</strong></td>
<td>Track Correlators</td>
</tr>
<tr>
<td><strong>TriDAS</strong></td>
<td>Trigger and Data Acquisition System</td>
</tr>
<tr>
<td><strong>TS</strong></td>
<td>Trigger Supervisor</td>
</tr>
<tr>
<td><strong>TTC</strong></td>
<td>Timing, Trigger and Control System</td>
</tr>
<tr>
<td><strong>BC0</strong></td>
<td>Bunch Counter Reset Command</td>
</tr>
<tr>
<td><strong>EC0</strong></td>
<td>Event Counter Reset Command</td>
</tr>
<tr>
<td><strong>TTCcf</strong></td>
<td>TTC Electrical Fanout Module</td>
</tr>
<tr>
<td><strong>TTCci</strong></td>
<td>TTC CMS Interface</td>
</tr>
<tr>
<td><strong>TTCex</strong></td>
<td>TTC Encoder and Transmitter</td>
</tr>
<tr>
<td><strong>TTCrx</strong></td>
<td>TTC Receiver ASIC</td>
</tr>
<tr>
<td><strong>TTCvi</strong></td>
<td>TTC VME Interface</td>
</tr>
<tr>
<td><strong>TTS</strong></td>
<td>Trigger Throttling System</td>
</tr>
<tr>
<td><strong>aTTS</strong></td>
<td>Asynchronous TTS</td>
</tr>
<tr>
<td><strong>sTTS</strong></td>
<td>Synchronous TTS</td>
</tr>
<tr>
<td><strong>TTU</strong></td>
<td>Technical Trigger Unit</td>
</tr>
<tr>
<td><strong>URI</strong></td>
<td>Uniform Resource Identifier</td>
</tr>
<tr>
<td><strong>USC55</strong></td>
<td>Underground Service Cavern</td>
</tr>
<tr>
<td><strong>UV</strong></td>
<td>Ultraviolet</td>
</tr>
<tr>
<td><strong>UXC55</strong></td>
<td>Underground Experimental Cavern</td>
</tr>
<tr>
<td><strong>VHDL</strong></td>
<td>Very-High-Speed Integrated Circuit Hardware Description Language</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>VME</td>
<td>Versa Module Eurocard</td>
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<tr>
<td>VPT</td>
<td>Vacuum Phototriode</td>
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<tr>
<td>W3C</td>
<td>World Wide Web Consortium</td>
</tr>
<tr>
<td>WinCC-OA</td>
<td>WinCC Open Architecture SCADA Tool</td>
</tr>
<tr>
<td>XDAQ</td>
<td>Cross Platform Data Acquisition</td>
</tr>
<tr>
<td>XDR</td>
<td>External Data Representation</td>
</tr>
<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
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</table>

*Photomultiplier Tubes (PMTs) having a single gain stage.*

*Formerly known as PVSS*