



UNIVERSIDAD DE SONORA

DEPARTAMENTO DE INVESTIGACIÓN EN FÍSICA

MEASUREMENT OF THE LUMINOSITY IN PROTON-PROTON COLLISIONS AT THE CMS EXPERIMENT OF THE LARGE HADRON COLLIDER

THESIS

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF:

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BY:

ASHISH SEHRAWAT

DIRECTOR:

DR. JOSE FELICIANO BENITEZ RUBIO

HERMOSILLO, SONORA

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Abstract

The Pixel Cluster Counting (PCC) luminosity measurement method has emerged as a reliable offline technique for luminosity measurement developed for the CMS experiment. The PCC method is studied for its precision in luminosity measurement using 2017, 2018 and 2022 datasets. The results of these studies demonstrate that the PCC luminosity measurement method is stable and linear. Final systematic uncertainty achieved on luminosity measurement for 2018 and 2022 datasets are 2.2% and 1.4% respectively. Moreover, the clusters and coincidences counting algorithms and their optimization for the Phase II High Luminosity LHC (HL-LHC) luminosity measurement are also developed, using simulated datasets for the proposed Phase II pixel detector. Linearity of the Tracker endcap pixel (TEPX) and Disk 4 Ring 1 luminometers is expected to be within 1% (offline) up to a pileup of 200 and their statistical precision per second is about 0.1% at pileup 200.

Declaration

I, Ashish Sehrawat, solemnly affirm that the doctoral thesis entitled "Measurement of the Luminosity in Proton-Proton Collisions at the CMS Experiment of the Large Hadron Collider," submitted for the completion of the Doctorado en Ciencias (Física) at the Universidad de Sonora, is my original work. It has not been submitted for any degree or examination at another university.

The results and discussions presented in Chapter 5 of this thesis are part of the collaborative work published as "Luminosity measurement in proton-proton collisions at 13.6 TeV in 2022 at CMS," CMS Collaboration, 2024, CMS PAS LUM-22-001, accessible at <https://cds.cern.ch/record/2890833>.

The outcomes of Chapter 6 are included in "The Phase-2 Upgrade of the CMS Beam Radiation Instrumentation and Luminosity Detectors," by the CMS Collaboration, technical report, CERN, Geneva, 2021, available online at <https://cds.cern.ch/record/2759074>. These contributions are properly cited and recognized within this document.

This thesis has been prepared with strict adherence to ethical standards of academic conduct. All sourced information has been appropriately cited to respect the intellectual property rights of original authors. This work has been supported by the Universidad de Sonora and the Consejo Nacional de Ciencia y Tecnología (CONACYT), to whom I extend my deepest gratitude for their support.

By signing below, I certify the authenticity and originality of the work submitted herein and affirm all statements made as true and based on my research findings.

Ashish Sehrawat

14 April 2024

New Delhi, India

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Chapter 1

Introduction to collider experiments

Collider experiments are a type of particle physics experiment that typically involve high energy collisions of electrons or protons. These collisions can lead to the creation of new particles or the detection of new phenomena, providing insight into the fundamental nature of matter. Colliders are designed to accelerate particles to nearly the speed of light and guide them along a circular or linear path using magnetic fields. By colliding particles, physicists can study the resulting particle showers and detect the products of the collision using complex detectors. Two important parameters in the collider experiments are energy and luminosity. Collider experiments have played a crucial role in advancing our understanding of particle physics and continue to be a vital tool for scientific exploration.

1.1 Luminosity and its importance in particle physics

Luminosity is a measure of the number of particle collisions that occur per unit area per unit time. In particle physics, luminosity is a crucial parameter that determines the rate at which interesting particles may be produced in a collider experiment [1].

The instantaneous luminosity of a collider for head-on collisions is given by the following equation:

$$L_{inst} = \frac{N_1 N_2 f}{A} \quad (1.1)$$

where N_1 and N_2 are the number of particles in each beam, f is the frequency of bunch crossings, and A is a parameter that takes into account the overlap between the two beams that is the product of beam size.

The importance of luminosity in particle physics lies in its direct relationship with the production rate of particles of interest. The production rate of a given particle is the product of the luminosity and the cross-section of the process. Thus, luminosity directly affects the ability to detect rare events. Additionally, precise measurements require a large number of collisions to be able to statistically determine the properties of the particles being studied.

The rate (R) of a given particle can be expressed as:

$$R = \sigma L_{inst} \quad (1.2)$$

where L_{inst} is the instantaneous luminosity, and σ is the cross-section of the process that produces the particle. The cross-section is a measure of the probability that a given process will occur, and it is typically a very small number, on the order of picobarns (10^{-36}cm^2). In order to achieve high luminosity, particle accelerators use various techniques to increase the number of particles in the beams and focus them to a small cross-sectional area. This is done by using superconducting magnets to guide the particles along a circular path and keep them confined to a small area. Another technique is to use radio frequency cavities to accelerate the particles to higher energies increasing the frequency of bunch crossings. In high-energy particle accelerators, such as the Large Hadron Collider (LHC) at CERN, the integrated luminosity is typically measured in units of inverse femtobarns (fb^{-1}), which is a measure of the total number of collisions per unit area during the course of an experiment. The importance of luminosity can be seen in the many discoveries that have been made in particle physics due to high luminosity experiments. For example, the discovery of the Higgs boson at the LHC was made possible by the high luminosity of the collider, which allowed physicists to observe the rare Higgs boson signal over the background noise of other particles. In addition to discoveries, high luminosity experiments are also important for precision measurements. For example, the precise measurement of the properties of the top quark, the heaviest known elementary particle, benefits significantly from the large number of collisions at the LHC. These collisions provide a robust dataset that reduces the uncertainty in the top quark mass measurement, allowing for more precise determination than were possible at the Tevatron.

1.2 Motivation for precision luminosity measurement

In particle physics, the luminosity of colliding beams is a crucial measurement as it provides information about the rate at which rare processes occur and enables precise measurements of particle properties such as cross-section and couplings to fermions and

bosons. Luminosity depends on several variables, including the number of protons in each beam, the size and shape of the beams, and their relative positioning. A slight change in any of these variables can significantly alter the luminosity. Therefore, it is crucial to measure the luminosity with high precision.

Precision in luminosity measurement allows for the accurate determination of the Standard Model parameters, such as the masses of fundamental particles and the strength of their interactions (coupling constants). These parameters are critical for making precise predictions about particle behavior in high-energy collisions. By refining these parameters, physicists can enhance their understanding of the universe fundamental structure and forces. High precision luminosity measurement increase the ability to observe rare processes that occur at very low rates. Such processes might be signatures of new physics beyond the Standard Model, including new particles or forces. Distinguishing these rare events from the background noise is crucial for advancing our understanding of the universe. The electroweak theory, which unifies the weak nuclear force and electromagnetism, makes precise predictions about the production and decay rates of W and Z bosons. Accurate luminosity measurements are essential for comparing these theoretical predictions with experimental data. Any discrepancies could indicate new physics or the need for adjustments within the Standard Model. Quantum Chromodynamics (QCD) describes the strong force, one of the four fundamental forces. Experiments that measure jet production rates and other phenomena related to the strong force depend on precise luminosity measurements for validating QCD predictions. This understanding is crucial for both the theoretical framework and for interpreting results of particle collision experiments. High precision in luminosity measurement allows experimental results to be benchmarked against theoretical models with greater accuracy. This benchmarking is essential for validating or refuting theories about the fundamental constituents and forces of the universe.

Improving the uncertainty in luminosity measurements is essential for many physics analyses. It is a dominant factor in the measurement of Higgs Boson cross sections and couplings to other gauge bosons and fermions projected for High luminosity (HL)-LHC era, as shown in Fig. 1.1. As such, the uncertainty in cross-section and coupling measurements cannot be better than the uncertainty in luminosity measurement. Therefore, ongoing efforts are focused on improving the precision of luminosity measurements, with the pixel detector at CMS being a key component of this effort. By reducing the luminosity uncertainty, physicists can make more precise measurements of particle properties and potentially discover new physics beyond the Standard Model.

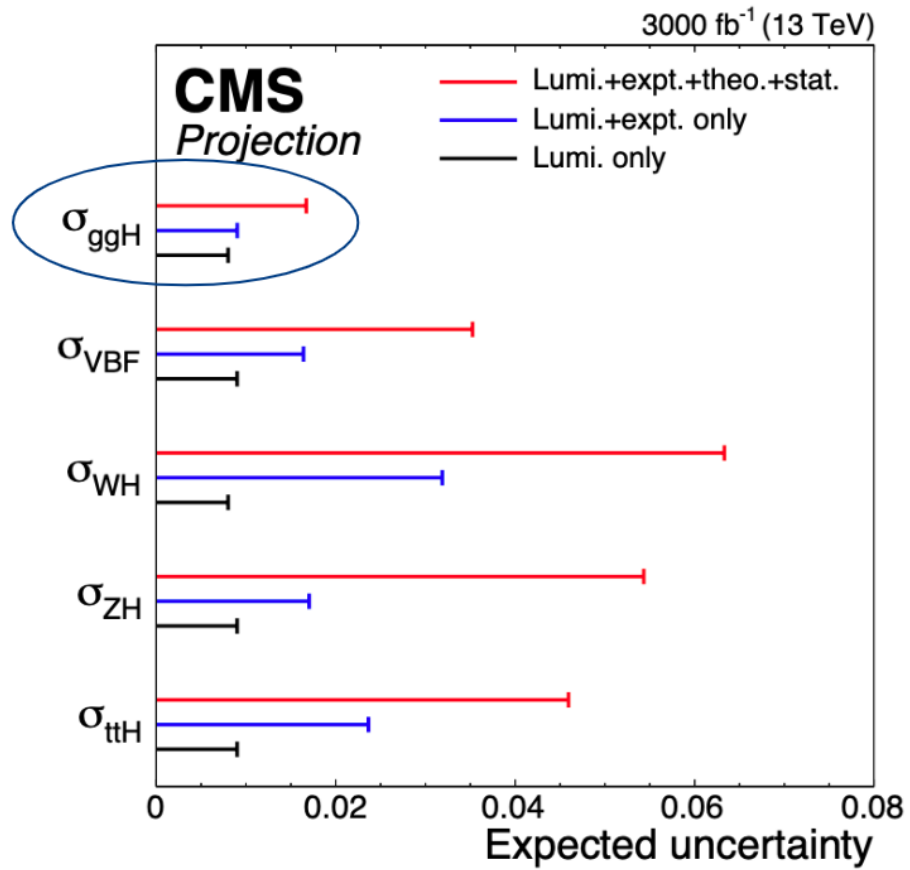


Fig. 1.1 Higgs boson production processes cross section projected uncertainty. In the most precisely measured Higgs boson production process, gluon fusion (ggH), luminosity uncertainty will dominate other experimental systematic uncertainty at the HL-LHC [2].

1.3 Large Hadron Collider and the CMS Experiment

The CERN accelerator complex consists of a series of accelerators that work together to produce beams of particles at ever-increasing energies. These beams are then fed into the Large Hadron Collider (LHC) for further acceleration and collision. The first step in the accelerator complex is the Linac 2, a linear accelerator that produces beams of protons with an energy of 50 MeV (mega-electronvolts). The protons are then sent to the Proton Synchrotron Booster (PSB), which accelerates them to an energy of 1.4 GeV (giga-electronvolts). From there, the proton beams are sent to the Proton Synchrotron (PS), which further accelerates them to an energy of 25 GeV. The next step in the complex is the Super Proton Synchrotron (SPS), which accelerates the protons to an energy of 450 GeV. The SPS also produces beams of heavy ions, such as lead nuclei, which are used for experiments in nuclear physics and other fields. Finally, the proton beams are sent to the LHC, where they are accelerated to their maximum energy of 6.5 TeV per proton.

The LHC consists of a 27-kilometer ring of superconducting magnets, which guide two counter-rotating beams of protons to collide at four different locations around the ring, where four major experiments, ATLAS, the Compact Muon Solenoid (CMS) experiment, ALICE and LHCb are located as shown in Fig. 1.2. The protons are organized into "bunches," with each bunch containing around 100 billion protons. The bunches are spaced apart by 25 nanoseconds, and the LHC can contain up to 2,808 bunches per beam. The bunches in the LHC are designed to have a beam current of 0.55 amperes. It uses radiofrequency (RF) cavities to accelerate the proton beams. The RF frequency used is 400 MHz, which corresponds to a wavelength of 75 centimeters. The LHC uses quadrupole magnets to focus the proton beams and keep them tightly collimated. The LHC uses a total of 1,232 superconducting dipole magnets to bend the proton beams around the circular accelerator ring. The dipole magnets are cooled to a temperature of 1.9 Kelvin (-271.3°C) using liquid helium, and are capable of producing a magnetic field of up to 8.3 tesla. The LHC's detectors record data from proton-proton collisions at a rate of around 40 million bunch crossings per second, but only a tiny fraction of these are actually recorded for analysis. The LHC operates at a vacuum pressure of around 10^{-13} atmospheres, which is lower than the pressure on the surface of the moon.

The CMS experiment [4] is a multi-purpose particle detector that is designed to detect and study the particles produced in the collisions at the LHC. The CMS detector is a complex instrument that consists of several layers of sub-detectors, each designed to detect different types of particles and measure different properties of the particles. The CMS detector consists of a tracker, an electromagnetic calorimeter, hadron calorimeter, and a muon detector.

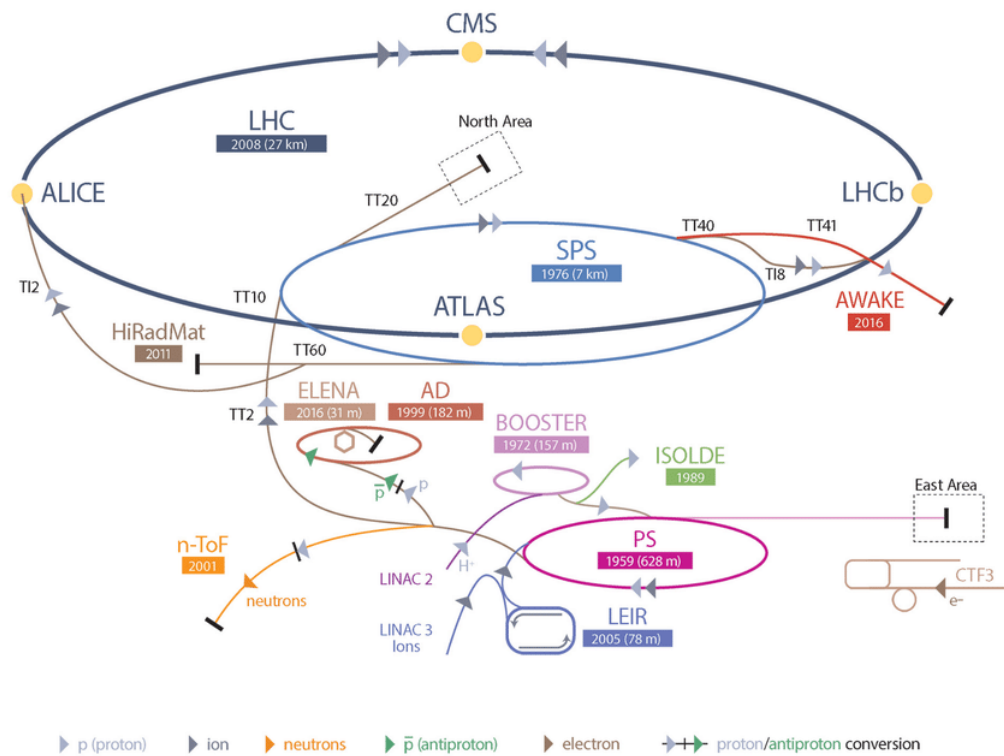


Fig. 1.2 CERN accelerator complex consists of Linac 2, Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), Super Proton Synchrotron (SPS) and Large Hadron Collider (LHC) which is the accelerator chain for proton physics at the LHC. LHC ring showing four interaction points where the ALICE, ATLAS, LHCb and CMS detectors are stationed [3].

- The tracker is a cylindrical detector made up of two main subsystems: the pixel detector and the silicon strip detector [5]. The pixel detector, the innermost subsystem near the interaction point, is crucial for precise track reconstruction and vertex identification. It includes four barrel layers and two endcap regions with hybrid pixel detector modules. These modules consist of a silicon sensor, segmented into roughly $100 \times 150 \mu\text{m}^2$ pixels, and readout electronics. When charged particles pass through the sensor, they create electron-hole pairs that induce a current, which is amplified, shaped, and digitized. The upgraded pixel detector used in Run 2 contained over 120 million pixels, ensuring high granularity and hit efficiency. The pixel detector has a $4.8 \mu\text{m}$ and $7.99 \mu\text{m}$ spatial resolution along $100 \mu\text{m}$ and $150 \mu\text{m}$ pixel pitch respectively [6]. The silicon strip detector surrounding the pixel detector provides extra tracking points for improved track reconstruction. It comprises of the Tracker Inner Barrel and Disks (TIB/TID) and the Tracker Outer Barrel and Endcaps (TOB/TEC). Silicon strip sensors, segmented into strips with a pitch of 80 to $205 \mu\text{m}$, generate electron-hole pairs like the pixel detector. The signals are then processed by the readout electronics.
- The Electromagnetic Calorimeter (ECAL), a part of the CMS detector, is crucial for measuring the energy of photons and electrons from collisions. The ECAL contains over 75,000 lead tungstate (PbWO_4) crystals arranged cylindrically around the interaction point. When photons or electrons hit the crystals, they generate a secondary particle shower, producing scintillation light proportional to the energy of the incoming particle. By assessing this light in each crystal using avalanche photodiodes and vacuum phototriodes [7], the ECAL can precisely determine the energy of the incoming particle. The ECAL covers a pseudorapidity range $|\eta| < 3.0$ ¹, facilitating measurement of particles at various angles to the beam axis. Its arrangement includes a barrel region and two endcap regions. The PbWO_4 crystals vary in size and orientation in these regions to match particle trajectories. They are sufficiently long to absorb incoming particle energy. The ECAL boasts an energy resolution of less than 0.5% for 50 GeV electrons and less than 1% for 100 GeV photons. This precision results from the small crystal size, the PbWO_4 crystals' high light yield, and advanced calibration procedures. Moreover, it has excellent timing resolution, crucial for differentiating between particles from the same collision and rejecting background events.
- The Hadron Calorimeter (HCAL) [8] in the CMS detector, positioned outside of the Electromagnetic Calorimeter (ECAL), measures the energy of hadrons—particles comprised of quarks and gluons bound by the strong nuclear force. Since hadrons

¹The pseudorapidity η is calculated as $\eta = -\ln(\tan(\frac{\theta}{2}))$ and ranges from $-\infty$ to $+\infty$.

are abundantly produced in high-energy LHC collisions, the HCAL design focuses on absorbing their energy for measurement. It is composed of alternating layers of brass, for energy absorption, and plastic scintillator, for light emission when particles pass through for the barrel and endcap calorimeters. HF uses quartz fibers and steel as active and passive components, respectively. Photodetectors convert this light into a measurable electrical signal. The Barrel HCAL, also known as HB in CMS, is the main part of the HCAL that is centered around the beam pipe and extends outwards. The pseudorapidity range for this section of the calorimeter is $|\eta| < 1.3$. The Endcap HCAL, or HE, is designed to capture particles emitted at larger angles from the beam pipe, extending the coverage of the barrel region. The pseudorapidity range of the Endcap HCAL is $1.3 < |\eta| < 3.0$. The Forward HCAL, or HF, is situated at both ends of the detector to capture particles produced at the smallest angles to the beam direction. The pseudorapidity range of the Forward HCAL in the CMS experiment is $3.0 < |\eta| < 5.2$.

- The Muon Chambers [9] are a vital part of the CMS detector. Designed to detect a variety of particles from high-energy collisions, the CMS is particularly equipped for detecting muons, highly penetrative charged particles that often evade other detection methods. Positioned on the outermost layer of the CMS detector, the muon chambers comprise three types of detectors: drift tubes (DTs), cathode strip chambers (CSCs), and resistive plate chambers (RPCs). The DTs are centrally located in the barrel region, while CSCs cover the forward and backward endcap regions. The RPCs, offering a quick trigger signal for muon detection, are found in both the barrel and endcap regions. These chambers detect muons by observing the ionization when a muon travels through the detector gas. By tracking muon trajectories, scientists can investigate the properties of these particles and explore physics beyond the Standard Model.
- The CMS experiment employs a powerful superconducting solenoid magnet, composed of niobium-titanium (NbTi) wire, to generate a strong, uniform magnetic field crucial for detecting and measuring charged particles from high-energy collisions. The wire, cooled to -268.5°C with liquid helium, becomes superconducting, carrying substantial electrical currents without heat generation. The cylindrical magnet, among the largest of its kind at 13 meters long and 6 meters in diameter, produces a 3.8 Tesla magnetic field—approximately 100,000 times stronger than Earth's magnetic field. This field bends the trajectories of charged particles as shown in Fig. 1.3, facilitating momentum measurement and aiding physicists in studying the properties of various particles.

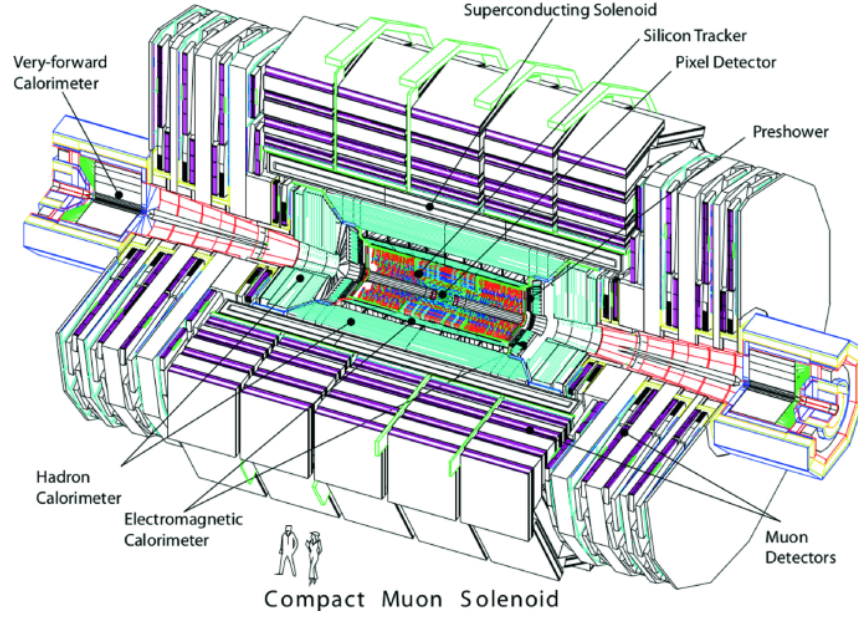


Fig. 1.3 CMS detector with all of the sub detectors showing silicon tracker, electromagnetic and hadron calorimeters and muon chambers [4].

1.4 Run 1, Run 2 and Run 3 luminosity measurement

Since the beginning of the operation of the CMS experiment, three main data-taking periods have taken place: Run 1, Run 2, and Run 3, with the latter starting in 2022 and currently ongoing. During these periods, the CMS experiment measured the instantaneous and integrated luminosity of the proton-proton collisions produced by the LHC where the integrated luminosity for each year is shown in Fig. 1.4. During Run 1, the CMS experiment achieved a peak instantaneous luminosity of up to $7.6 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$, while during Run 2, the luminosity reached a peak value of up to $2.1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. The luminosity measurements during both runs were accompanied by careful assessments of the systematic uncertainties to ensure accurate and reliable results [10–16] as shown in Table 1.1. Luminosity systematic uncertainties for heavy ion runs is shown in Table 1.2. p-Pb collisions versus Pb-p collisions systematic uncertainty are mentioned in the first two rows of the table. Inside the parenthesis, systematic uncertainty for Pb-p is mentioned, that is beam direction reversed. The last row in the table is for systematic uncertainty in Pb-Pb collision.

Table 1.1 Summary of center of mass energy, integrated luminosity, and systematic uncertainty per year in CMS.

Year	Center of Mass Energy (TeV)	Integrated Luminosity (fb ⁻¹)	Systematic Uncertainty (%)
2010	7	0.045	11
2011	7 and 8	6.1	2.2
2012	8	23.3	2.5
2015	13	4.3	1.6
2016	13	41.6	1.2
2017	13	49.8	2.3
2018	13	67.9	2.5

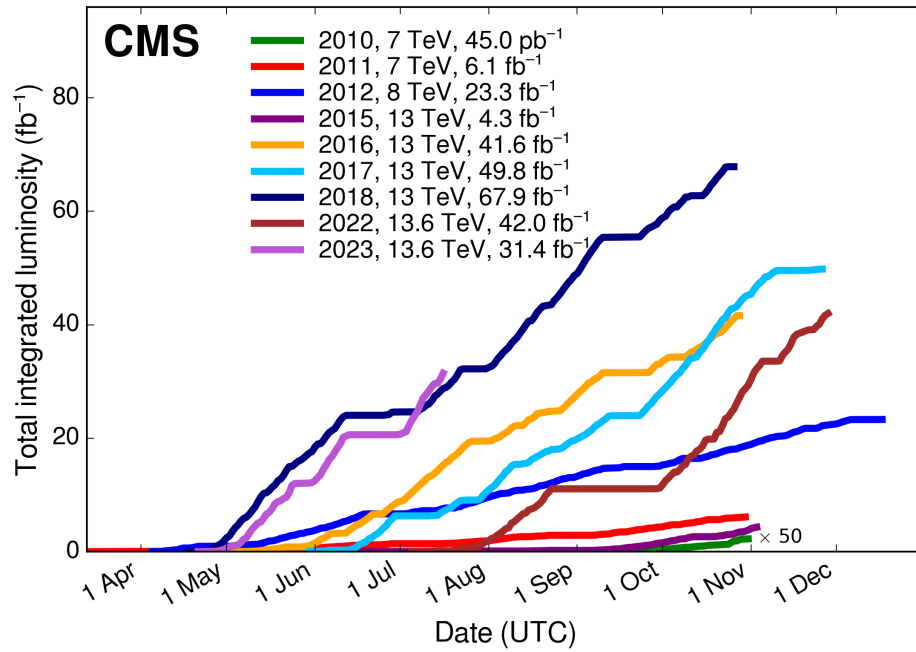


Fig. 1.4 Delivered luminosity versus time for Run 1, Run 2 and Run 3 of the CMS Experiment [17].

Table 1.2 Summary of center of mass energy and systematic uncertainty per year during the CMS pPb and PbPb luminosity measurement [18–20].

Year	Center of Mass Energy/nucleon (TeV)	Systematic Uncertainty (%)
2013	2.76	3.4(3.6)
2016	5.02	3.2(3.7)
2018	5.02	1.5

Chapter 2

Luminosity measurement at the CMS experiment

The CMS experiment employs several devices to measure luminosity, each covering specific pseudorapidity ranges and regions within the CMS detector [16]. The use of several luminometers as shown in Fig. 2.1 offers a multitude of advantages. Primarily, it ensures redundancy and acts as a backup for potential device failures, ensuring that data collection can proceed without interruption. Additionally, having multiple luminometers allows for cross-checking, providing greater consistency in results and allowing for more reliable data interpretation. These different devices enable better control over systematic uncertainties, as any discrepancies can be identified and adjusted for. Moreover, each device employs different method to measure luminosity, providing complementary information that enriches the overall understanding of particle interactions. Some luminometers recording low rates can be calibrated using others, enhancing their accuracy and utility. This holistic approach to luminosity measurement significantly improves the robustness and reliability of the data collected. In the central region, the Muon Drift Tubes (DT) luminometer is used covering a $|\eta|$ range from 0 to 1.2. The Pixel Cluster Counting (PCC) luminometer also operates in this region and extends into the forward region covering a range from 0 to 2.5. In the forward region, several devices are utilized. The Pixel Luminosity Telescope (PLT) covers the pseudorapidity range from 2.8 to 4.7. The Fast Beam Condition Monitor (BCM1F) functions in a range from 3.1 to 4.7. The Hadron forward (HF) luminometer caters to the most forward region of the CMS detector [14], functioning in the pseudorapidity range from 2.9 to 5.2 as shown in Fig. 2.2. The Radiation Monitoring System for Environment and Safety (RAMSES) are located directly behind HF.

2.1 Luminosity measurement methods

- **Pixel Luminosity Telescope (PLT)** : PLT is positioned 1.75 meters away from the interaction point. The PLT is an ensemble of 16 "telescopes". These are symmetrically distributed around the beam pipe at both sides of the detector, with each telescope being composed of three individual silicon sensor planes. A defining feature of the PLT functionality is the measurement of per-bunch instantaneous luminosity. This is accomplished by enumerating events in which all three sensor planes in a given telescope simultaneously register a hit. A specialized readout mechanism operating at the LHC full bunch-crossing frequency of 40 MHz is employed to carry out this task. The PLT has provisions for reading out full pixel data, albeit at lower frequencies. This less frequent, yet detailed data readout serves multiple purposes. It is instrumental in determining calibrations, implementing corrections, and evaluating systematic uncertainties associated with both online and offline measurements. The PLT operates in what is called the "fast-OR" mode, which detects charged particles produced in a single bunch crossing of the proton beams. In this mode, the PLT triggers on any pixel in the detector that registers a signal above a certain threshold. This signal is called the "fast-OR signal" and indicates that a charged particle has passed through the detector. The PLT uses the information from all three detector planes to reconstruct the trajectories of the charged particles produced in the collisions. This is done by analyzing the signals from the individual pixels and using algorithms to determine the path of the particle through the detector. The PLT uses a specialized algorithm called the "triple coincidence" to identify charged particles that are produced in the collisions and to reject background noise. It requires a charged particle to be detected in all three planes, which corresponds to a "triple coincidence" detection. The rate of triple coincidences is proportional to the luminosity. This helps to reduce the contribution of background noise and improve the precision of the luminosity measurement [21].
- **Fast Beam Conditions Monitor (BCM1F)** : The BCM1F is specifically designed to detect the ionization produced by charged particles passing through its diamond sensors, and to convert this signal into a measurement of the beam intensity and luminosity. During Run 2, the BCM1F consisted of 24 diamond sensors, each with an active area of 1 cm², arranged in six rings around the beam pipe. The diamond sensors are positioned very close to the CMS detector, just 10 cm away from the beam pipe. This allows the sensors to detect the charged particles produced by the proton-proton collisions. When charged particles pass through the diamond sensors, they ionize the carbon atoms in the diamond crystal, producing electrons and holes. The electrons and holes are then collected by metal electrodes embedded in the

diamond, producing a voltage signal proportional to the ionization produced by the charged particles. The voltage signal is then amplified by fast electronics and converted into a digital signal, which is sent to the CMS data acquisition system for further analysis. To measure the luminosity, the BCM1F counts the number of charged particles passing through each diamond sensor per unit time. The signal from each sensor is integrated over a short time interval (usually 25 ns), corresponding to the time it takes for a single proton bunch to pass through the sensors. The integrated signal is then converted into a measure of the instantaneous luminosity, which is proportional to the product of the number of charged particles per bunch and the collision frequency. Run3 FBCM employs silicon-pad sensors located inside the cold volume of the Tracker, leveraging the zero-counting algorithm for luminosity measurement and also offering timing information with a few nanoseconds precision for beam-induced background measurement.

- **Hadron Forward Calorimeter:** The Hadron Forward (HF) Calorimeter is a critical component of the CMS experiment. It is a subdetector that measures the energy, position and arrival time of particles produced during proton-proton collisions. The HF Calorimeter is designed specifically to measure hadron particles, which are particles made up of quarks and gluons, in the forward region (i.e., close to the beamline) of the CMS detector. The HF Calorimeter is located at the very front and back of the CMS detector, at a distance of about 11.2 meters from the interaction point. This placement allows it to cover a pseudorapidity range of 2.9 to 5.2, which is important for measuring particles produced at small angles relative to the beamline. The active material, in this case, is scintillating quartz fibers, which emit light when they interact with charged particles. The passive material is steel absorber plates, which serve to initiate hadron showers, causing the incident hadron to interact and create secondary particles. As these secondary particles pass through the scintillating fibers, they produce light, which is collected by photodetectors and converted into an electrical signal proportional to the particle's energy. Two separate algorithms are used for luminosity measurement in the HF Calorimeter, hadron forward occupancy (HFOC) and hadron forward transverse energy (HFET) based on the zero counting (ZC) method and the sum of transverse energy methods respectively.

The zero counting method is used by particle colliders to measure the luminosity. In this method, the luminosity is estimated by counting the number of events with zero particles detected in a specific region of the detector. The basic idea behind the zero counting method is that the probability of having zero particles detected in a given region of the detector is proportional to the Poisson probability of having no collisions in that region. This probability can be related to the instantaneous luminosity of the collisions through the following equations,

We consider the Poisson distribution, which gives the probability of observing a certain number of events, n , when the average number of events is λ :

$$P(n; \lambda) = \frac{e^{-\lambda} \lambda^n}{n!}$$

For zero-counting, we are interested in the probability of observing no events ($n = 0$). Substituting $n = 0$ into the Poisson distribution equation, we get:

$$P(0; \lambda) = \frac{e^{-\lambda} \lambda^0}{0!} = e^{-\lambda}$$

The probability of observing zero events, $P(0; \lambda)$, is related to the average number of events λ , which can be determined by taking the negative natural logarithm of $P(0; \lambda)$:

$$\lambda = -\ln(P(0; \lambda))$$

The average number of events per bunch crossing, λ , is related to the instantaneous luminosity, L_{inst} , and the total visible cross-section, σ_{vis} , by:

$$\lambda = L_{inst} \cdot \sigma_{vis}$$

Substituting λ in terms of L and σ_{vis} into the equation involving $P(0; \lambda)$, we get:

$$L_{inst} \cdot \sigma_{vis} = -\ln(P(0; \lambda))$$

Solving for L_{inst} gives us the equation for instantaneous luminosity based on the zero-counting method:

$$L_{inst} = \frac{-\ln(P(0; \lambda))}{\sigma_{vis}}$$

The probability $P(0; \lambda)$ can be written as the ratio $\frac{N}{N_0}$ because it is the fraction of the total number of events where zero particles are detected:

$$P(0; \lambda) = \frac{N}{N_0}$$

Substituting $P(0; \lambda) = \frac{N}{N_0}$ into the equation for L_{inst} gives us:

$$L_{inst} = \frac{-\ln(N/N_0)}{\sigma_{vis}} \quad (2.1)$$

where L_{inst} is the luminosity, N is the number of events with zero particles detected in the region of interest, N_0 is the total number of events, σ_{vis} is the visible cross-section. One advantage is that it is a simple and robust method that does not require sophisticated detectors or calibration procedures. However, it can be affected by background events, such as cosmic rays or beam-gas interactions.

The HFET algorithm measures luminosity by summing transverse energy deposits in the HF calorimeter cells. It relies on the direct proportionality between the total transverse energy and the particle flux from the interaction point. Accurate calibration of calorimeter cells is crucial for this method, as it ensures that the aggregate transverse energy accurately reflects the luminosity of the particle collisions [14].

The measurement of instantaneous luminosity, L_{inst} , using the HFET algorithm involves the following steps:

1. Initialize the total transverse energy sum:

$$\Sigma E_T = 0$$

2. For each calorimeter cell, do:

- (a) Measure the transverse energy $E_{T,cell}$.
- (b) Update the total transverse energy sum:

$$\Sigma E_T = \Sigma E_T + E_{T,cell}$$

3. Correct the total transverse energy sum for background energy:

$$\Sigma E_T = \Sigma E_T - E_{T,background}$$

4. Multiply by a calibration constant k to obtain the luminosity:

$$L_{inst} = k \times \Sigma E_T$$

The calibration constant k is empirically determined through a series of calibration procedures, van der Meer scans. The constant accounts for the proportionality between the aggregate transverse energy and the actual luminosity of the particle collisions.

- Muon drift tubes: The DT system is part of the CMS muon system. DTs in the CMS experiment are designed to accurately measure the trajectory and momentum of muons produced in proton-proton collisions at the LHC. The DT system consists of rectangular drift cells filled with a gas mixture, typically of argon and carbon

dioxide. The use of DT muon rates for luminosity measurement is based on the idea that the rate of muon production is proportional to the instantaneous luminosity. Muons come from the decay of inclusive, Z, W, top and jets. However, the DT muon rate luminometer is not independently calibrated during the van der Meer (vdM) scan due to low measured rate. It is cross calibrated with PCC or HF.

- **Pixel Cluster Counting (PCC):** The pixel detector in the CMS experiment is made up of multiple layers of silicon sensors arranged in a cylindrical shape around the beam pipe. When charged particles from the collisions pass through the silicon sensors, they create electric charge that is read out as a signal. The signals from adjacent pixels are combined to form clusters, which represent the position of the particle track in the detector. The total number of clusters detected over a certain period of time is used to estimate the luminosity. The PCC provides a precise measurement of the luminosity and is particularly useful when the collision rate is high [13].

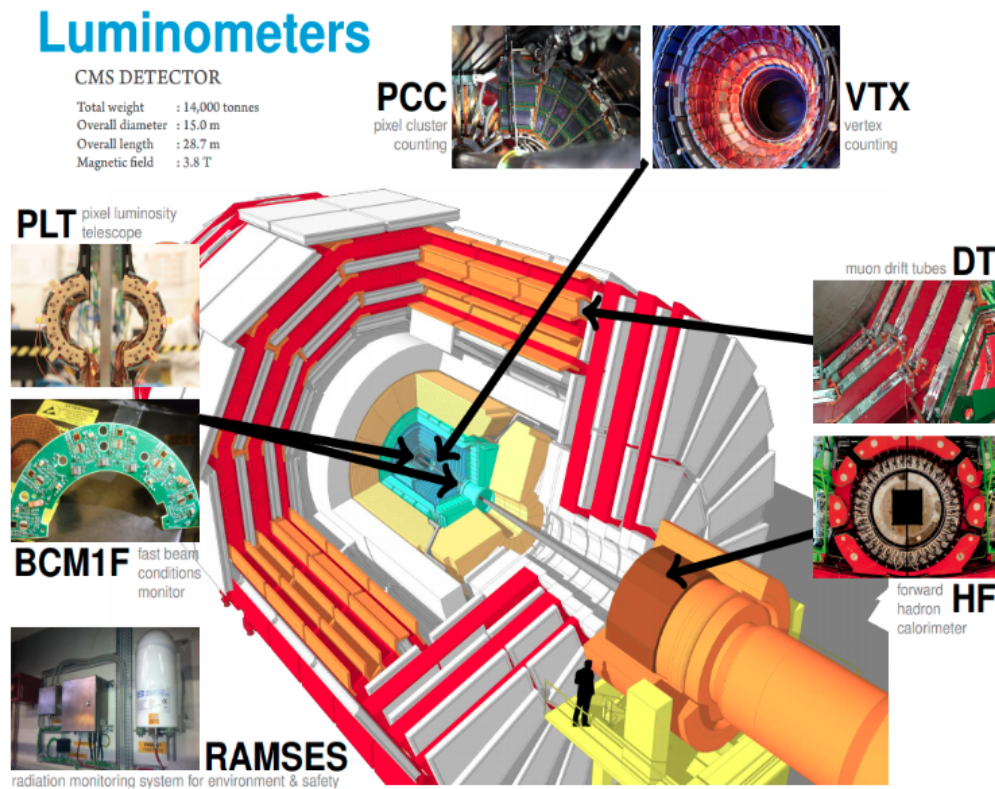


Fig. 2.1 CMS detector with all of the luminosity measurement devices showing PLT, BCM1F, HF, DT, PCC and RAMSES [22].

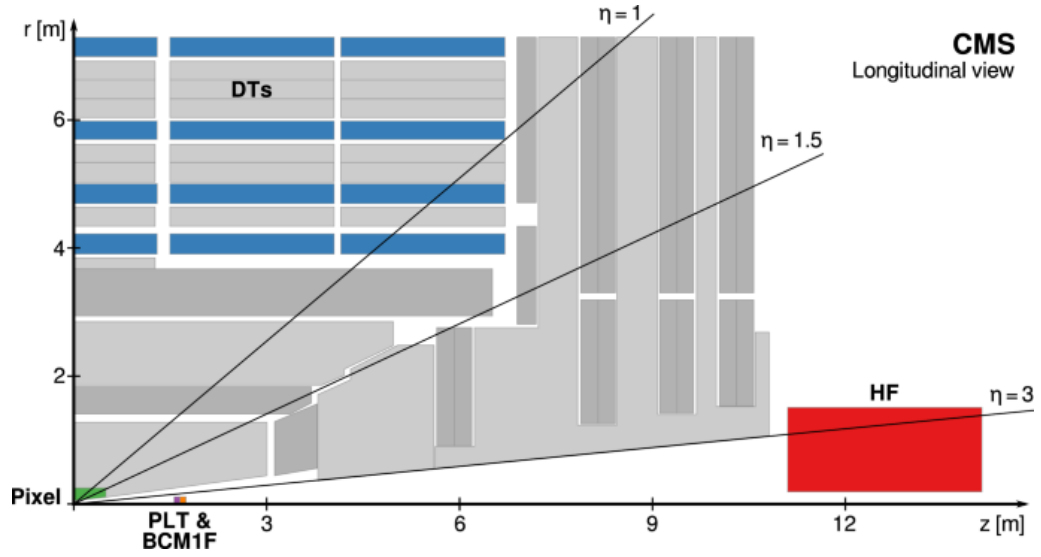


Fig. 2.2 Cross section of the CMS detector in the r - z plane showing all Run 2 luminometers PLT, BCM1F, DTs, and HF location. The two RAMSES monitors used as a luminometer in Run 2 are located directly behind HF [14].

2.2 Pixel detector

The pixel detector is one of the subdetectors of the CMS experiment that is closest to the interaction point where the proton beams collide. It consists of four barrel layers (L1-L4) at radii of 29, 68, 109 and 160 mm and three forward disks (D1-D3) on each end at distances of 291, 396, and 516 mm from the center of the detector as shown in Fig. 2.3. It is built from 1856 silicon sensor modules, 1184 modules in the barrel layers (BPIX) and 672 modules in the forward disks (FPIX) [23]. Modules for barrel layers and forward disks are shown in Fig. 2.4. Table 2.1 shows the number of modules in each pixel layer and disk. The modules in BPIX L1 are designed to handle high particle densities and radiation levels. Each module in this layer consists of a matrix of 4160 pixels, arranged in 160 rows and 26 columns. The pixel size in BPIX L1 is approximately $100 \times 150 \mu\text{m}^2$, which allows for high-resolution position measurements of charged particles. The modules in BPIX L2-4 layers are designed to withstand lower radiation levels compared to BPIX L1. Each module in BPIX L2-4 consists of a matrix of 66560 pixels, arranged in 260 rows and 256 columns. The pixel size in BPIX L2-4 is also approximately $100 \times 150 \mu\text{m}^2$. The FPIX modules are also designed to handle high particle densities and radiation levels. Each module in the FPIX consists of a matrix of 16128 pixels, arranged in 160 rows and 101 columns with same pixel size as barrel layer pixels. The pixel detector has a high position resolution, with a spatial resolution of 4.8 microns in the transverse direction and 7.99 microns in the longitudinal direction. The pixel detector also has a high time resolution, with a readout time of 25 nanoseconds. The pixel detector is capable of detecting charged particles with a wide range of energies, from a few hundred MeV to several TeV. The pixel

detector is able to operate at very high particle fluxes, with a hit rate of up to $100 \text{ MHz}/\text{cm}^2$. To achieve this high rate capability, the pixel detector uses fast readout electronics. The pixel detector is also designed to operate at a high radiation level, with a dose of up to $5 \times 10^{14} \text{ neutrons}/\text{cm}^2$ expected over the lifetime of the detector. To mitigate the effects of radiation damage, the pixel detector uses sensors made of high-purity silicon and a cooling system that keeps the detector at a temperature of -20°C . The pixel detector is used as a primary luminometer. The luminosity measurement is based on counting the number of pixel clusters produced in the detector by the proton-proton collisions. However, there are several challenges to accurately measure the luminosity with the pixel detector. One challenge is the multiple proton-proton collisions per bunch crossing (pileup). Another challenge is the possible non-linearity or instabilities of the pixel detector response, which can lead to inaccuracies in the luminosity measurement. Therefore, the motivation of this research work is to develop and test more precise techniques for measuring the luminosity with the pixel detector.

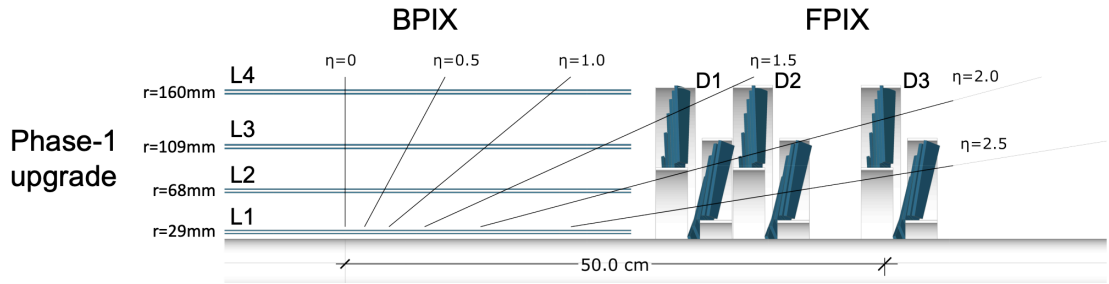


Fig. 2.3 Layout of the CMS Phase-1 upgraded pixel detector in longitudinal view [23].

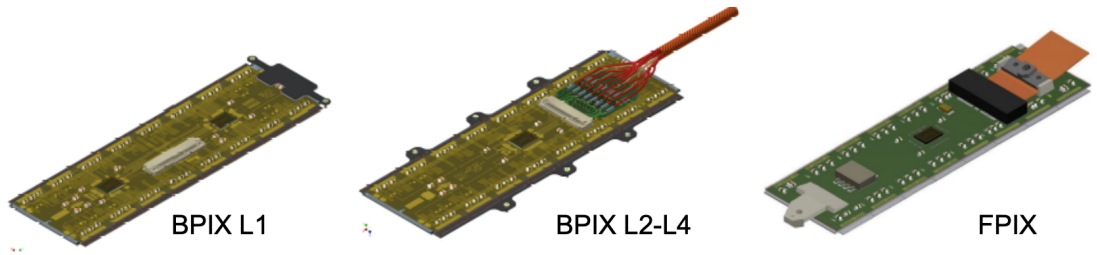


Fig. 2.4 Pixel detector modules for BPIX L1 (left), BPIX L2-4 (middle), and the FPIX detector (right) [23].

2.3 Pixel cluster counting method

The Pixel Cluster Counting (PCC) method is one of the main luminosity measurement techniques used at the CMS experiment. The PCC method is based on counting the number

Table 2.1 Number of pixel detector modules in each layer and disk.

Layer/Disk	# modules
L1	96
L2	224
L3	352
L4	512
D1 inner ring	88
D1 outer ring	136
D2 inner ring	88
D2 outer ring	136
D3 inner ring	88
D3 outer ring	136

of pixel clusters produced by the collisions in the CMS pixel detector, which is a high-resolution silicon detector located close to the collision point. The pixel detector is made up of more than 124 million pixels. The detector is designed to detect charged particles produced in the collisions, and the pixel clusters are formed when several neighboring pixels are hit by a single particle. The PCC method is based on the assumption that the number of pixel clusters produced is proportional to the number of collisions, and therefore to the luminosity. The proportionality constant is called the pixel detector visible cross section, and it can be determined with a calibration method described in section 3.1. The PCC method exclusively utilizes offline luminosity measurement, comprising two stages: the "prompt-lumi," which is delayed by a few days and employs a non-optimized module list, and the "offline reprocessed luminosity" that uses an optimized module list for enhanced accuracy. During Run 2, the PCC online role was confined to recording pixel information, with cluster reconstruction occurring offline. However, in Run 3, this process evolved, allowing clusters to be reconstructed online within the High-Level Trigger (HLT) system, subsequently recorded for detailed offline analysis. There are several steps involved in the PCC method for measuring luminosity like data acquisition, pixel cluster reconstruction and pixel cluster counting as described below.

- Pixel detector data acquisition is the process of collecting and digitizing the signals from the silicon pixel detectors in the CMS experiment. When a particle passes through the silicon pixel detector, it creates a small amount of charge in the pixel sensor. The charge is collected by the electrodes in the pixel sensor and converted into a voltage signal. The voltage signal is then digitized using an analog-to-digital converter (ADC) to create a digital signal. The ADC measures the voltage at regular intervals, called sampling intervals, and assigns a digital value to each voltage measurement. The digital signal is then stored in a buffer in the front-end electronics

of the pixel detector. The buffer is a small amount of memory that temporarily holds the data before it is transmitted to the data acquisition system. The data acquisition system continuously monitors the data from the pixel detectors to detect interesting events. When an event of interest is detected, a trigger signal is sent to the front-end electronics of the pixel detector to read out the data from the buffer. The readout electronics in the pixel detector then transmit the data to the data acquisition system using high-speed optical fibers. The data is sent in packets, called data frames, which contain information about the event, such as the time of the event, the position of the particle, and the amount of charge deposited in the pixel sensor.

- Pixel cluster reconstruction is the process of identifying groups of adjacent pixels that have been fired by a single particle passing through the detector. The first step in the pixel cluster reconstruction process is to identify individual pixel hits in the data frames obtained from the pixel detector data acquisition system. The next step is to identify "seed" pixels, which are individual pixels with a high signal-to-noise ratio. A seed pixel is defined as a pixel hit with a signal above a certain threshold, which is typically set at a few times the noise level of the pixel detector. Once seed pixels have been identified, the next step is to build pixel clusters around each seed pixel. This is done by adding adjacent pixels with a signal above a lower threshold, called the cluster threshold. The cluster threshold is typically set at a level that minimizes the number of fake clusters while maximizing the efficiency of cluster finding. After pixel clusters have been built, the next step is to split or merge clusters as needed. This is done to remove fake clusters caused by noise or overlapping particles, and to merge clusters that are split due to inefficiencies in the cluster building process. Once the pixel clusters have been identified and merged/split as necessary, they are parameterized by their position and energy. The position of the cluster is determined by the center of gravity of the pixels in the cluster, and the energy is determined by summing the signal of all the pixels in the cluster. Finally, a set of selection criteria are applied to the pixel clusters to remove any remaining fake clusters and select only those clusters that are likely to be from real particle interactions. These selection criteria typically include requirements on the size, shape, and energy of the clusters.
- The number of pixel clusters is counted over a fixed time interval, known as lumi section. One lumi section is 23.36 seconds time interval. In the pixel cluster counting process, events of interest are selected from the large dataset obtained from the CMS experiment. This is typically done using zero bias triggers that randomly select events that are coming from filled bunch crossings. After the pixel clusters have been reconstructed in each event, the next step is to count the number of clusters

in each event. This can be done using simple counting algorithms that count the number of clusters above a certain energy threshold.

- The number of pixel clusters in each event is affected by various sources of background noise. To accurately measure the number of signal clusters in each event, these background sources must be subtracted from the total cluster count.
- The number of pixel clusters is used to calculate the instantaneous luminosity using the following formula:

$$L_{inst} = \frac{N_{cl} f_{rev}}{\sigma_{vis}} \quad (2.2)$$

where L_{inst} is the bunch luminosity, N_{cl} is the number of clusters per bunch crossing, f_{rev} is the revolution frequency of the LHC, and σ_{vis} is the visible cross section of the pixel detector obtained from calibration.

The PCC method has several advantages over the other luminosity measurement methods used by the CMS experiment. The PCC method is based on the pixel detector, which has a high spatial resolution. Another advantage is its high precision and stability, as it is based on a well-understood physical process and has a small systematic uncertainty. The PCC method is also robust against pile-up, which is the presence of multiple proton-proton interactions in a single bunch crossing, as it can distinguish between pixel clusters produced by different collisions. This allows for precise measurements of the luminosity, even when the particle collision rate is high. The pixel detector has a high detection efficiency, meaning that it can detect a large fraction of the particles produced in the collisions. The pixel detector's high granularity enables precise detection of individual particles. It has a wide dynamic range, capable of measuring luminosities from low to high due to the large number of pixels.

The PCC of various layers and disks, normalized to the total PCC, as a function of lumi section can provide crucial insights into the detector's performance and stability over time and under different conditions [24]. A lumi section is a unit of data-taking time in the LHC during which the beam conditions are assumed to be stable. The luminosity delivered during each of these lumi sections can vary, leading to different levels of activity in the detector.

When these ratios are plotted against lumi sections, several key aspects can be studied:

- **Detector Stability:** Stable ratios across lumi sections suggest that the detector is functioning consistently and reliably under varying luminosity conditions. Abrupt spikes or drops could be indicative of potential problems such as radiation damage, electronic noise, or other instabilities in the detector.

- **Long-Term Performance:** By tracking these ratios over multiple lumi sections, one can monitor the long-term performance of the detector. This approach allows for the detection of gradual changes or trends, which could suggest a slow degradation of the detector components.
- **Layer/Disk-Specific Analysis:** This type of plot can reveal layer or disk-specific issues. For instance, if one layer's PCC ratio deviates significantly from the norm in high lumi sections, it might suggest that this layer is particularly sensitive to low luminosity or is underperforming.

The PCC method has been extensively tested and validated by CMS during the LHC Run 1 and Run 2, which corresponded to proton-proton collisions at center-of-mass energies of 7-8 TeV and 13 TeV, respectively. The PCC method has achieved a relative luminosity precision of about 1.5%, which is well within the design goals of CMS [16]. In the future, the PCC method will continue to be a key component of the CMS luminosity measurement strategy, as it provides a precise and robust measurement of the luminosity ratio between different datasets and periods. The PCC method will also benefit from the upgrades and improvements planned for the CMS pixel detector and the LHC, which will increase the luminosity and the collision rate, and will challenge the performance and the calibration of the PCC method. CMS is planning to install a new pixel detector as extensively discussed in Chapter 6 for the High-Luminosity LHC (HL-LHC) era, which will feature smaller pixel sizes, faster readout electronics, and radiation-hard materials. The CMS is also planning to develop new techniques and algorithms for the PCC method, such as machine learning methods, deep neural networks, and real-time analysis tools.

Chapter 3

Luminometer calibration

A prevalent technique for calibrating luminosity measurement devices is the van der Meer (vdM) scan method. This method is named after Simon van der Meer, a Dutch physicist and Nobel laureate, who developed the technique in the 1960s. These scans are performed to relate the detection rate of a given luminometer to the absolute luminosity determined from the measured beam parameters. The proportionality constant is called the visible cross section. It involves scanning the beams across each other in the horizontal and vertical planes to measure the beam overlap integral, which is proportional to the luminosity. This is done by displacing the beams in the horizontal (x) and vertical (y) planes independently while keeping the other direction fixed as shown in the left part of Fig. 3.1. The scans are performed at several different positions along the collision point, creating a series of data points for each plane. The data points collected during the scans are then fitted with suitable function like single, double gaussian as shown in the right part of Fig. 3.1 to determine the beam overlap integrals in the x and y directions. The total beam overlap is the product of the beam overlap width in the horizontal and vertical planes over the entire interaction region [25]. The total beam overlap is an essential parameter in determining the visible cross section to calculate absolute luminosity.

3.1 vdM method

In the vdM scans, rate is plotted as a function of beam separation along x and y directions that is used to determine the visible cross section σ_{vis} .

The instantaneous luminosity per bunch crossing when the crossing angle between the colliding bunches is negligible and bunches collide head on is given by the following integral [13],

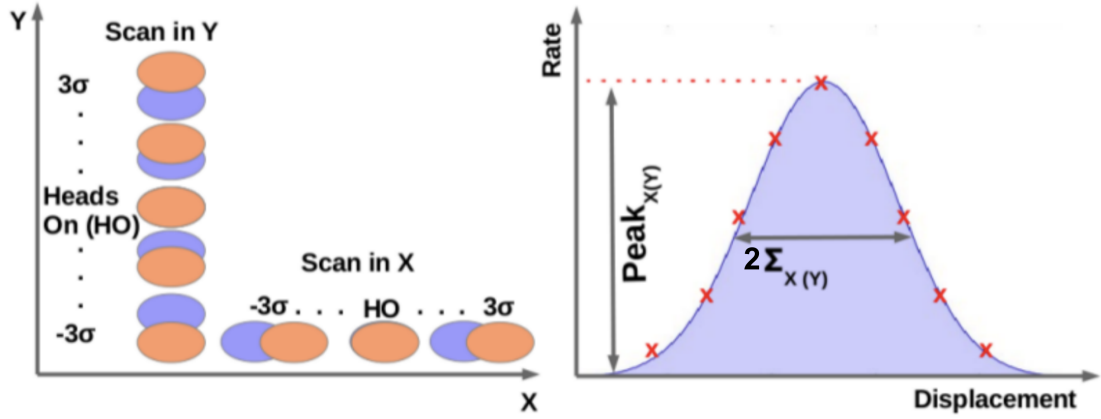


Fig. 3.1 Left: Scanning the beams across each other ($\pm 3\sigma$) in the transverse plane, horizontal (x-scan) and vertical (y-scan) directions. Right: Rate is measured as a function of beam separation [26].

$$L_b = N_1 N_2 f \int_{-\infty}^{+\infty} \rho_1(x, y) \rho_2(x, y) dx dy \quad (3.1)$$

where N_1, N_2 are the number of protons in the colliding bunches, f is the LHC orbit frequency whose value is 11246 Hz, $\rho_1(x, y)$ and $\rho_2(x, y)$ are the two dimensional particle density distribution functions for each colliding bunch in x and y directions [27].

Assuming complete factorization of particle density distribution function along x and y directions for both the bunches, we get

$$L_b = N_1 N_2 f \int_{-\infty}^{+\infty} \rho_{1x}(x) \rho_{2x}(x) dx \int_{-\infty}^{+\infty} \rho_{1y}(y) \rho_{2y}(y) dy \quad (3.2)$$

where $\rho_1(x, y) = \rho_{1x}(x) \rho_{1y}(y)$ and $\rho_2(x, y) = \rho_{2x}(x) \rho_{2y}(y)$

The vdM scan determines the bunch overlap integrals $\int \rho_{1x}(x) \rho_{2x}(x) dx$ and $\int \rho_{1y}(y) \rho_{2y}(y) dy$ by measuring pixel-cluster rate as a function of beam separation Δx and Δy along x and y directions.

$$\int \rho_{1x}(x) \rho_{2x}(x) dx = \frac{R_x(0)}{\int R_x(\Delta x) d\Delta x} \quad (3.3)$$

$$\int \rho_{1y}(y) \rho_{2y}(y) dy = \frac{R_y(0)}{\int R_y(\Delta y) d\Delta y} \quad (3.4)$$

where $R_x(0)$ is the measured cluster rate along x direction when the beam separation is zero and $R_x(\Delta x)$ is the measured cluster rate when beams are separated by distance Δx and

$R_y(0)$ is the measured cluster rate along y direction when the beam separation is zero and $R_y(\Delta y)$ is the measured cluster rate when beams are separated by distance Δy .

We define the quantities Σ_x and Σ_y :

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R_x(\Delta x) d\Delta x}{R_x(0)} \quad (3.5)$$

$$\Sigma_y = \frac{1}{\sqrt{2\pi}} \frac{\int R_y(\Delta y) d\Delta y}{R_y(0)} \quad (3.6)$$

Thus, the expression for instantaneous luminosity is given by

$$L_b = \frac{N_1 N_2 f}{2\pi \Sigma_x \Sigma_y} \quad (3.7)$$

and the PCC visible cross section defined in terms of beam parameters and rate is given by

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y R(0)}{N_1 N_2} \quad (3.8)$$

where $R(0)$ is the peak cluster rate.

3.2 Background estimation

Background contributions can arise from several sources, such as beam-gas interactions, electronic noise, cosmic rays, or other processes that produce signals in the detectors. These contributions can affect the precision of the luminosity measurement and lead to systematic uncertainties in the calibration. Beam-separation scans are performed with increased beam separations (i.e., with the beams not fully overlapped). These scans can provide an estimate of the background contributions when the beams are not colliding. Sources of machine induced backgrounds are described below.

- **Beam-gas elastic interactions:** In these interactions, beam particles scatter off residual gas molecules in the beam pipe without breaking the molecular structure of the gas. The scattered beam particle and the gas molecule maintain their initial identities but change their direction and energy. Although the primary beam particle does not produce secondary particles in this type of interaction, the scattered particle can still enter the detector, causing background noise. Maintaining an ultra-high vacuum inside the beam pipe helps reduce the likelihood of such interactions.

- **Beam-gas inelastic interactions:** In contrast to elastic interactions, beam-gas inelastic interactions involve the beam particle and the residual gas molecule undergoing a collision that alters the structure of the gas molecule. The beam particle transfers some of its energy to the gas molecule, leading to the creation of new particles or the excitation of the gas molecule. These new particles or de-excitations can generate secondary particles, which may enter the detector and contribute to the background. As with elastic interactions, maintaining a high vacuum in the beam pipe and using beam collimation systems can help minimize beam-gas inelastic interactions.
- **Beam-halo interactions:** Beam-halo refers to the particles that are not part of the beam's core but reside in the outer regions of the beam. These particles can interact with the detector materials or other elements in the beamline, such as collimators, beam pipe walls, or shielding. These interactions can produce showers of secondary particles that may enter the detector and contribute to the background. Beam-halo interactions can be mitigated using collimators to clean the halo particles from the beam and shielding the sensitive parts of the detector from direct exposure to halo particles. Additionally, continuous monitoring of the beam halo and adjusting the beam optics can help reduce the impact of beam-halo interactions.

3.3 Fit model

The Poly2G model, or the "Gaussian function with a polynomial term" model, is a fitting function that combines a second-order polynomial function and a Gaussian function. It is a versatile and flexible model that can be used to fit various types of data, including the PCC data in the context of the vdM calibration. The Poly2G model can be employed to fit the PCC rates and extract the beam parameters, beam overlap integrals and peak rates needed for the determination of the calibration constant [28]. The Poly2G function has additional degrees of freedom compared to a single Gaussian but fewer than a DG (Double Gaussian), allowing for better convergence. Test was carried out using different fit models (single gaussian, double gaussian and PolyG functions) for the 2018 PCC vdM data. Poly2G showed least χ^2/ndof that is why it is chosen as fit function as shown in Table 3.1.

	SG	DG	SuperG	PolyG
Convergence	100%	70%	100%	100%
Average chi2/ndof	2.93	2.36	2.28	1.69

Table 3.1 χ^2/ndof for different fit models

The general form of the Poly2G model is

$$F(x) = Peak \left[1 + r_2 \left(\frac{\Delta x - \mu}{\frac{\sigma}{1+r_2}} \right)^2 \right] \exp \left[-\frac{1}{2} \left(\frac{\Delta x - \mu}{\frac{\sigma}{1+r_2}} \right)^2 \right] \quad (3.9)$$

where Peak is the maximum PCC rate, μ is the mean, σ and r_2 are the fit parameters.

To determine the beam overlap Σ in this model, we calculate the area under the Poly2G curve between $-\infty$ and $+\infty$ and divide by its peak value. We integrate the Poly2G function from $-\infty$ to $+\infty$ using the substitution method.

$$z = \frac{x - \mu}{\frac{\sigma}{1+r_2}}, dx = \frac{\sigma}{1+r_2} dz \quad (3.10)$$

With this substitution, the function becomes:

$$F(z) = Peak [1 + r_2 z^2] \exp \left(-\frac{1}{2} z^2 \right) \quad (3.11)$$

The integral is then:

$$I = Peak \int_{-\infty}^{\infty} [1 + r_2 z^2] \exp \left(-\frac{1}{2} z^2 \right) \frac{\sigma}{1+r_2} dz \quad (3.12)$$

Thus:

$$I = \frac{Peak \sqrt{2\pi} \sigma (1 + r_2)}{1 + r_2} = Peak \sqrt{2\pi} \sigma$$

Dividing by the Peak value:

$$\frac{I}{Peak} = \sqrt{2\pi} \sigma$$

Following the definition presented in equations (3.5) and (3.6), the beam overlap width for the Poly2G fit function is:

$$\Sigma = \frac{\sqrt{2\pi} \sigma}{\sqrt{2\pi}} = \sigma \quad (3.13)$$

Chapter 4

Run 2 Luminosity Measurement

4.1 Dataset

For studying the performance of PCC luminometer during 2018 data taking, we have divided CMS luminosity data taking into seven periods: A, B, C, D1, D2, D3, and D4, as depicted in Fig. 4.1. Run ranges for each period are shown in Table 4.1. During period B, specifically corresponding to fill 6868, van der Meer (vdM) scans were conducted for calibrating the PCC luminometer.

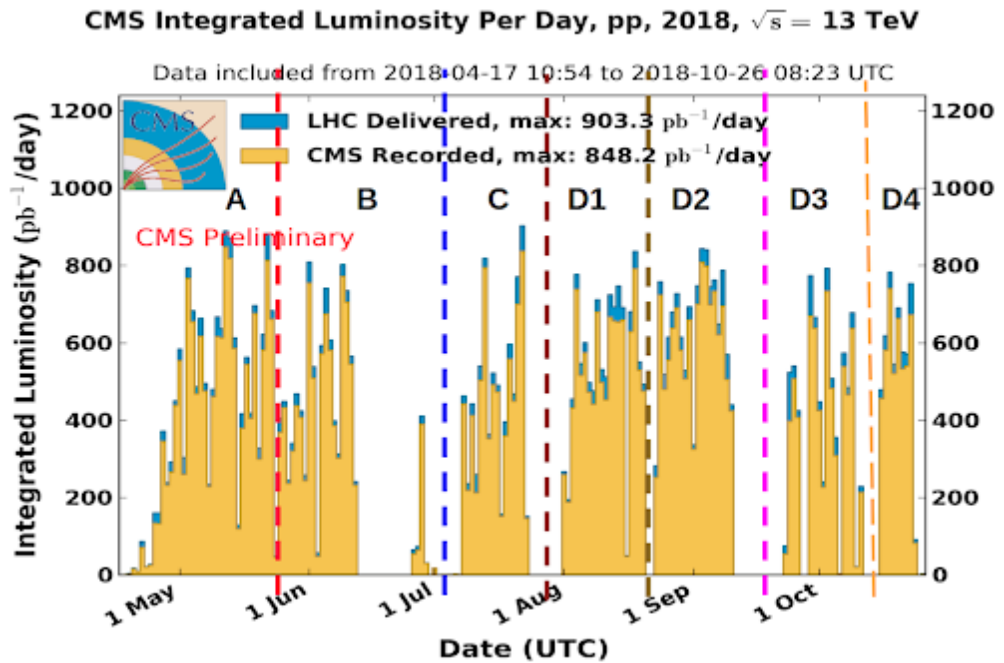


Fig. 4.1 2018 luminosity data taking periods showing data taking period boundaries and vdM calibration data (1 July in period B) [29].

Table 4.1 2018 luminosity data periods with run ranges.

Period	Run range
2018A	315252-316995
2018B	317080-319311
2018C	319337-320065
2018D1	320500-321665
2018D2	321710-322964
2018D3	323363-324420
2018D4	324564-325175

In the study under consideration, the datasets have been drawn from the Alignment and Calibration (AlCa) project, an integral component of the CMS experiment. The dataset selection includes two subsets: Random trigger and Zero-Bias. The Random trigger dataset comprises of data where trigger is applied on both colliding and non-colliding bunches. On the other hand, the Zero-Bias dataset encapsulates events that have passed the trigger system with no bias which means the colliding bunches are randomly triggered without the use of any CMS detector signal. The list of colliding bunches is detected by an independent system Beam Pick-up Timing for eXperiments (BPTX). CMS software (CMSSW) version 10_2_2 is used for reprocessing random trigger PCC dataset and 10_6_30 [30] is used for reprocessing zero bias PCC datasets.

The pixel detector records data for each bunch-crossing, though the readout rate is constrained by the trigger. During subsequent data processing, these events are consolidated into lumi sections. During each lumi section, the number of pixel clusters produced in each module is recorded and the module weights for all pixel modules are studied to track their performance over time. This helps in identifying good and bad modules, as shown in Fig. 4.2. Only pixel modules that demonstrate consistent and reliable performance throughout the entire 2018 year are considered good and included in the analysis. The pixel cluster rate, along with the visible cross section of the detector, is used to determine the instantaneous luminosity of the collider. PCC data is subsequently reprocessed. This involves the re-analysis of the data using updated or refined algorithms, calibrations, and detector conditions.

The purpose of reprocessing can be multifold:

- Improved algorithms or calibration: As experiments progress, there can be improvements in algorithms or calibration techniques used to process the raw data. This can lead to a more accurate or efficient representation of the collected data.

- Changes in detector conditions: Detector conditions might change over time due to factors like aging or upgrades. These changes can affect the interpretation of the data.
- Discovery of issues or errors: Sometimes, errors or issues in the original data processing might be discovered.

In the context of PCC data, reprocessing can lead to a more accurate luminosity measurement, which in turn can affect the interpretation of the physics results derived from the LHC data. Random trigger PCC dataset is reprocessed with new module veto list (described in section 4.2) to obtain afterglow corrections with improved module stability selections. Zero-bias dataset is reprocessed after applying afterglow corrections using same module veto list with more stringent selections on module stability to obtain PCC luminosity.

4.2 Detector module selection

The goal of minimizing instabilities in PCC luminosity measurement is to ensure precise and consistent results. To achieve this, a pixel module veto list is created for each period to keep track of bad modules. The stability of each module is determined based on the change in the ratio of module PCC and total PCC, referred to as the module weight.

By carefully analyzing the module weights and excluding the bad modules from the analysis, the instabilities in PCC luminosity measurement can be minimized. This process ensures that the data used for luminosity measurement is of high quality and can produce precise results.

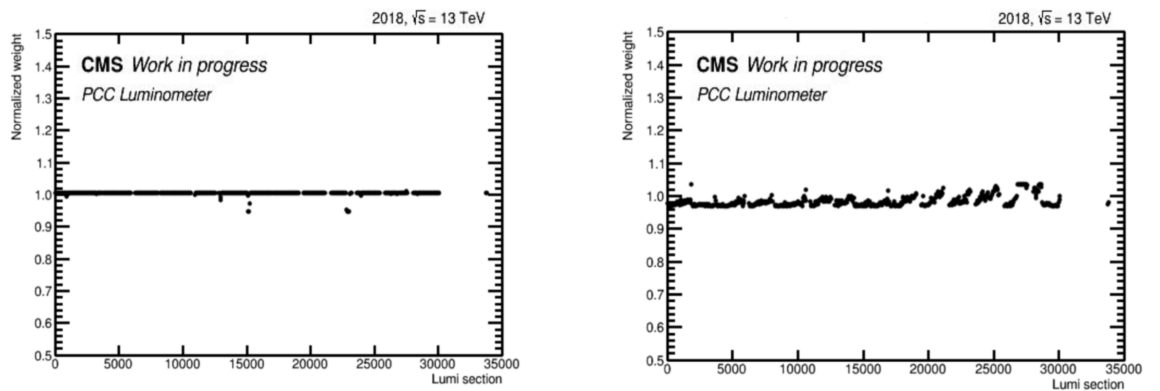


Fig. 4.2 Change in normalized module weight with time. Modules showing significant change in module weight (shown in right figure) over time having large RMS/mean values are used to make module veto list [16].

The module veto list is a list of detector modules that are excluded from the analysis of data due to their known or suspected high rate of background events or other issues that could affect the accuracy of the measurement. The following factors lead to unstable modules:

- **Radiation damage:** The harsh radiation environment in the LHC can cause damage to the silicon pixel sensors over time, leading to increased leakage currents, noise, or reduced charge collection efficiency.
- **Manufacturing defects:** Defects in the silicon material or issues during the manufacturing process can result in poorly performing pixel modules. These defects may not be immediately evident but can become more pronounced overtime.
- **Electronic noise:** Noisy electronic components or crosstalk between channels can lead to an increased number of false signals or noise in the pixel module data.
- **Temperature variations:** Temperature fluctuations can affect the performance of the pixel modules, leading to changes in their noise levels, gain, or charge collection efficiency.
- **High voltage issues:** Problems with the high voltage supply to the pixel modules can result in unstable operation, leading to erratic behavior or complete module failure.
- **Partial module failure:** A pixel module may suffer from partial failure, with some pixels or readout channels not functioning properly. This can lead to an increased number of dead or noisy pixels in the module.
- **Readout or data acquisition issues:** Errors in the readout electronics or data acquisition system can lead to data corruption or loss, affecting the performance of the pixel modules.
- **Calibration issues:** Inaccurate or outdated calibration parameters can result in incorrect measurements, leading to the appearance of abnormal behavior in the pixel module data.
- **Firmware or software issues:** Bugs in the firmware or software responsible for controlling and reading out the pixel modules can lead to abnormal behavior or incorrect measurements.
- **Mechanical or alignment issues:** Mechanical stresses or misalignments during the installation or operation of the pixel detector can affect the performance of the pixel modules or cause them to fail.

- Contamination or environmental factors: Contamination of the pixel modules by dust, moisture, or other substances can affect their performance or cause them to fail. Similarly, external environmental factors, such as magnetic fields or vibrations, can impact the operation of the pixel modules.

Module veto list consisting of bad modules is first created for period B, vdM fill and then for other periods A, C, D1, D2, D3 and D4 as follows,

Run 2018B and vdM fill:

- Poor statistics lumi sections are removed by applying selection on total PCC.
- All barrel layer 1 modules are removed as these modules are significantly affected by dynamic inefficiency effects, where the hit efficiency decreases at higher instantaneous luminosity due to the readout chip not being able to process all of the hits.
- A loose selection of 7% based on RMS/mean of module weight profile is applied where mean and RMS values are obtained from the projection of module weight profile. Modules with significantly large RMS/mean are removed with this loose selection as shown in Fig. 4.3.
- Module stability is re-evaluated based on RMS/mean values using an iterative method where in each step, appropriate selections are applied to remove bad modules (shown in Fig. 4.4) until stable luminosity is attained.

Run 2018A, C and D:

- Period B module vetolist is applied to these periods to determine remaining bad modules.
- same procedure is used as period B.
- module weight comparisons between period B and these periods is done and modules with more than 3 sigma change in module weights are removed as shown in Fig 4.5.

2% selection on RMS/mean of module weights gives the best stability for all pixel detector barrel layers and forward disks. Number of good and bad modules after this selection is shown in Table 4.2.

Figure 4.6 shows the stability plots of the relative contribution to luminosity from pixel layers/disks before and after applying the module veto in the vdM calibration period. The plots provide a comparative view of how the luminosity fraction has been impacted

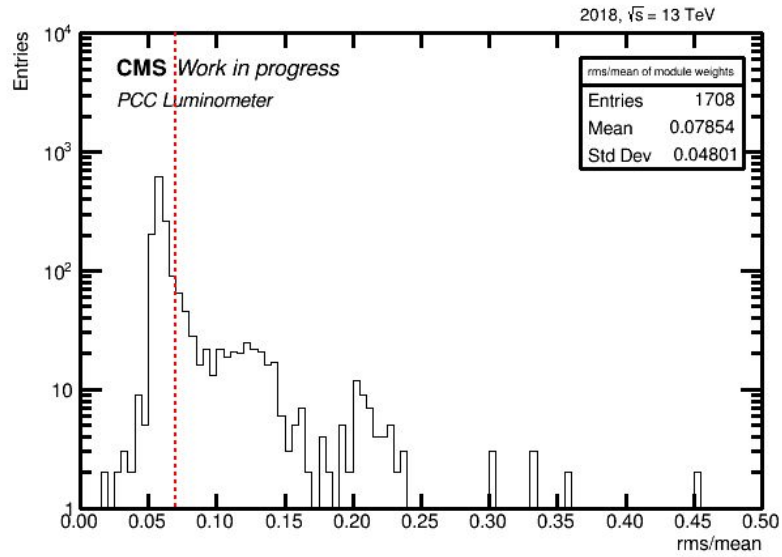


Fig. 4.3 A loose selection of 7% is applied to remove bad modules. Appropriate selections are applied in each iterative step to remove other bad modules [16].

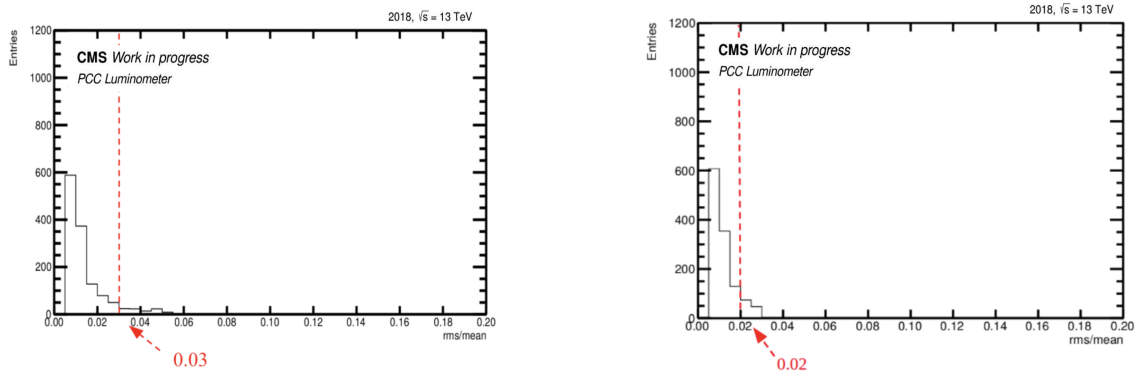


Fig. 4.4 Left: Second iteration on RMS/mean of 3% is applied to remove more bad modules. Right: Final iteration on RMS/mean of 2% is applied to obtain module veto list for each period [16].

Table 4.2 2% rms module veto list for each period showing number of good and bad modules.

Period	# bad modules	# good modules
A	1276	580
B	802	1054
C	1076	780
D1	1169	687
D2	1184	672
D3	1081	775
D4	1032	824

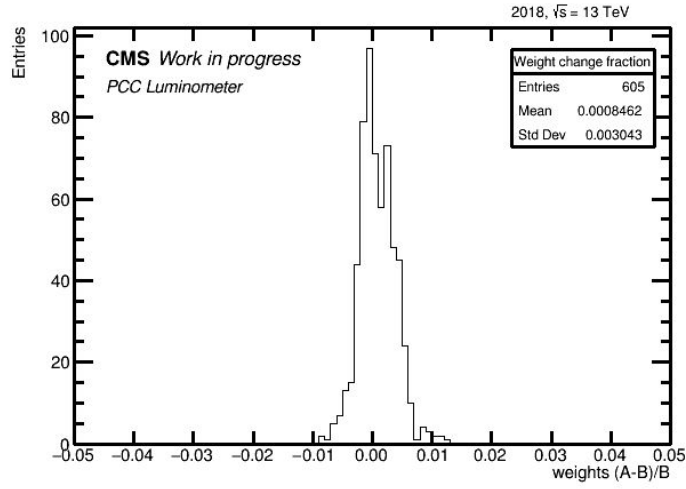


Fig. 4.5 Projection of change in module weights between period A and B. Modules showing more than 3 sigma change in module weights are added to the module veto list [16].

by the application of this veto list. The 'before' plot shows greater variability, reflecting the fluctuations in luminosity across different layers or disks during each lumi section. In contrast, the 'after' plot display a more stable profile, indicating that the module selection has effectively reduced the variance in luminosity fraction readings, enhancing data stability.

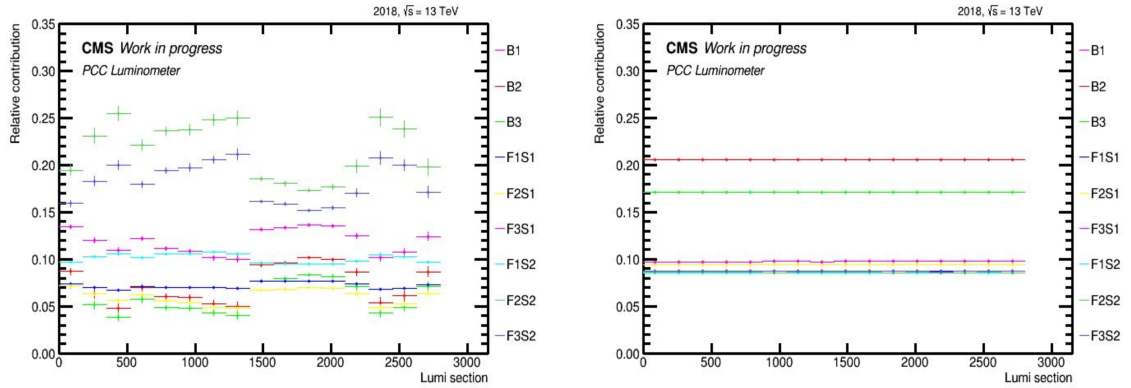


Fig. 4.6 Luminosity fraction per layer or disk (stability plots) before (no veto) and after applying the final module veto with 2% RMS/mean selection for the vdM fill 6868 data [16].

Table 4.3 shows the number of modules for a common selection over the entire year. Common module veto list is a combination of module veto list of all run periods A, B, C, D1, D2, D3 and D4. Approach to make a common module veto list is to start by combining module vetolists of period A,B and C, then combine A,B, C, D1 and so on. Less than 9% of the pixel modules remain after applying module stability selections to be used for final

Table 4.3 Final module veto list. This veto list is created by combining module veto lists for each period.

Period	# bad modules	# good modules
A + B	1276	580
A + B + C	1417	439
A + B + C + D1	1534	322
A + B + C + D1 + D2	1629	227
A + B + C + D1 + D2 + D3	1668	188
A + B + C + D1 + D2 + D3 + D4	1701	155

luminosity measurement. The total number of good modules across all layers and disks is 155.

The relative contribution to PCC luminosity from each pixel detector layer and disk without and with final module veto list is shown in Fig. 4.7.

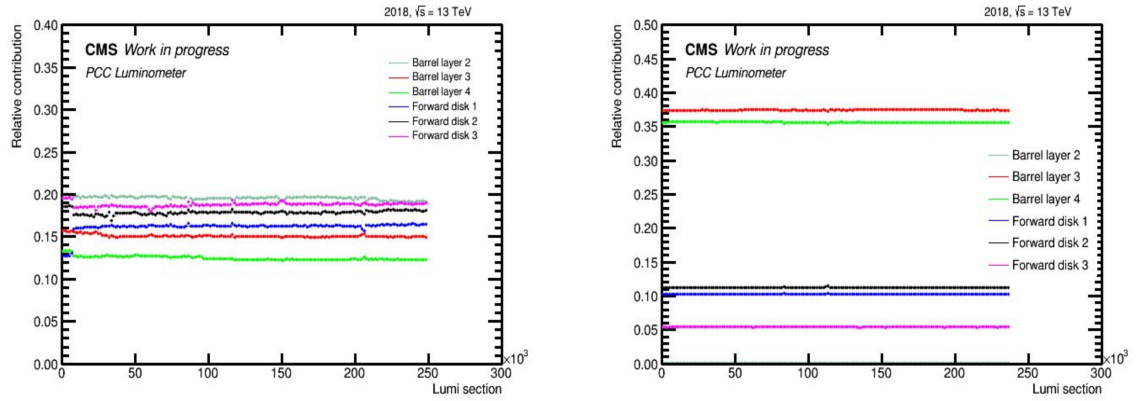


Fig. 4.7 Left: Luminosity fraction of pixel detector for various layer and disks as a function of lumi section for a module selection excluding only the BPIX Layer 0 for the full 2018 zero-bias dataset. Right: Stability profiles of pixel detector layer and disk for final module veto list [16].

Table 4.4 presents the statistics of good modules across different layers and disks for final module veto list. The layers and disks are divided into five categories: Layer 3, Layer 4, Disk 1, Disk 2, and Disk 3. For each of these categories, the number of good modules, mean, RMS, and the ratio of RMS to mean are provided. Layer 2 has no good modules. Layer 3, on the other hand, has 48 good modules with a mean value of 0.374681, an RMS of 0.000663165 and an RMS-to-mean ratio of 0.00176995, indicating low variability. Layer 4 shows a slightly larger count of good modules with 79, and similar statistical parameters to Layer 3, albeit with a slightly higher RMS and RMS-to-mean ratio, suggesting slightly greater variability. When it comes to the disk categories, Disk 1 and Disk 2 each have 10 and 12 good modules respectively. Their mean values are lower than those of the layers, as

are their RMS values, although their RMS-to-mean ratios are higher, suggesting greater relative variability in these categories. Disk 3 has the fewest good modules with only 6, and it presents the highest RMS-to-mean ratio among all categories, indicating the highest relative variability.

Table 4.4 Layer/Disk good modules and statistics for final module veto list.

Layer/Disk	Good modules	mean	rms	rms/mean (%)
Layer 3	48	0.374681	0.000663165	0.176995
Layer 4	79	0.356424	0.000724235	0.203195
Disk 1	10	0.102687	0.000535149	0.521144
Disk 2	12	0.112508	0.000460595	0.409389
Disk 3	6	0.0537002	0.000282446	0.525967
Total	155			

4.3 vdM calibration results

The calibration of luminosity measurement by the CMS experiment luminometers in the 2018 proton-proton data taking at $\sqrt{s} = 13$ TeV [16] was performed during LHC fill 6868 on June 30 and July 1, 2018 at $\sqrt{s} = 13$ TeV. Zero-bias triggers on 5 bunch pairs (BCIDs 265, 865, 1780, 2192, and 3380) recorded events at a rate of 27.7 kHz. Trigger is applied on five colliding bunches due to limitation of the recording bandwidth.

The 2018 CMS vdM scan program (shown in Fig. 4.8) was conducted in two segments, interrupted by an alarm. The first segment involved six x-y scan pairs. Two were short “emittance” scans, named “emit1” and “emit2,” where the beams were separated by $4\sigma_b$ (beam size) over 9 steps with a 10-second integration time at each step. A standard vdM scan (described in section 3.1), named “vdM1,” separated the beams by $6\sigma_b \approx 600 \mu\text{m}$ in 25 steps, with a 30-second duration per step. The “offset1” scan followed the same procedure as the standard scans but with a $\pm 1.5\sigma_b$ separation in the non-scanning direction. Lastly, two sets of “beam imaging” scans were conducted, where one beam remained fixed while the other was moved in 19 steps between $+4.5\sigma_b$ and $-4.5\sigma_b$, each lasting 46 seconds per step. The second part of the scan program was conducted in the same fill, approximately 7.5 hours later, and consisted of twelve scan pairs. This included a short emittance scan, “emit3”; beam imaging scan pairs, “imag2” and “imag3”; an offset scan pair, “offset2”; and two standard vdM scan pairs, “vdM2” and “vdM3”.

Beam Imaging Scans: Beam imaging scans are designed to measure the transverse profile of the beam. They involve moving one beam across the other in steps and measuring the interaction rate (or event rate) at each step. By doing this, the shape or “profile” of the beam in the transverse plane can be obtained. These scans allow for a detailed analysis

of the beam shape, which is essential for understanding the beam properties. In a perfect scenario, the density distributions of protons in a bunch would factorize into separate X (horizontal) and Y (vertical) components. However, real beams can have correlations between X and Y (non-factorization). Beam imaging scans help map the 2D profile of the beam and are thus essential for diagnosing and understanding any such correlations. Knowing the 2D profile of the beams is crucial when calculating luminosity, as assumptions made about the factorization of the beam profiles feed into these calculations. By using beam imaging scans, experimenters can assess the validity of the factorization assumption or correct for any observed non-factorization.

Offset Scans: They are similar to standard VdM scans but involve an intentional offset in the non-scanning direction. By comparing the results of offset scans with the results of regular scans, one can identify and correct for any systematic discrepancies that are present. Offset scans can help to assess the sensitivity of the luminosity measurement to non-factorization in the transverse plane. For example, if there are correlations between the X and Y distributions of protons (i.e., non-factorization), this could in principle affect the shape of the beam overlap region in the collision point. Offset scans, by changing the relative position of the beams, can help to assess whether such non-factorization has a significant effect on the measured luminosity.

vdM scans are typically conducted at least once a year to ensure the luminometer is correctly calibrated. The outcomes of these vdM scans, particularly the visible cross-section values, serve as a benchmark to adjust and standardize the data collected during the physics runs.

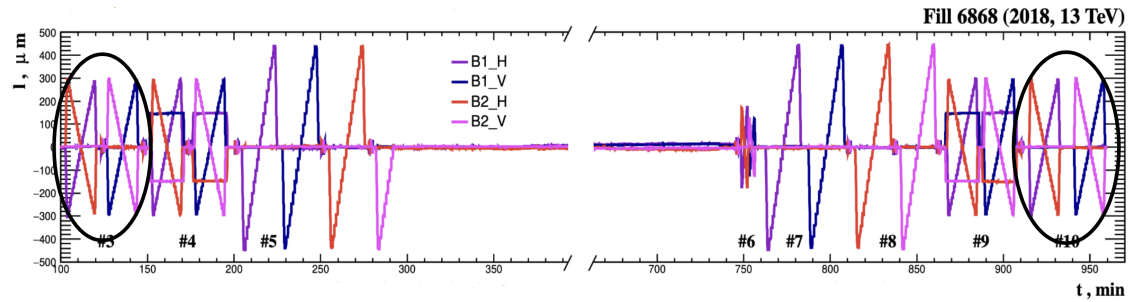


Fig. 4.8 Beam position along x and y is plotted as a function of time showing different types of scans. 3 and 10 are vdM scans, 4 and 9 are offset scans, 5, 7 and 8 are beam imaging scans, 6 is emittance scan [16].

The vdM data (LHC fill 6868) is processed using the final module selection. The background estimation for the PCC rate is done with two super-separation scans SS1 and SS2. The mean and error are obtained from the y projection of PCC rates per NB4 plotted as a function of time as shown in Fig. 4.9. The results for five different BCIDs are shown in Table 4.5, using the reprocessed PCC data for fill 6868. The overall background correction

Table 4.5 Mean for the background estimated with the SS1 and SS2 data, separately for all five BCIDs and averaged.

BCID	Mean (SS1)	Mean (SS2)
265	0.02902	0.02743
865	0.02572	0.0281
1780	0.02862	0.0286
2192	0.02729	0.02323
3380	0.02882	0.02896
Average	0.02789	0.02726

applied to raw PCC rate is 0.02757 ± 0.01987 , which is calculated by taking the average of the mean values of SS1 and SS2.

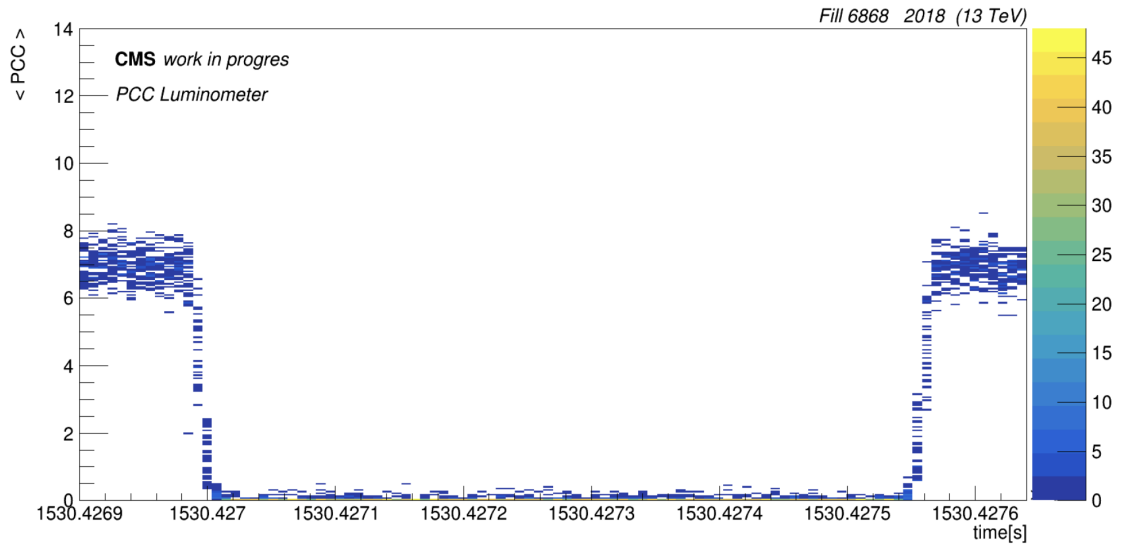


Fig. 4.9 2D histogram filled with the Avg. PCC evaluated per NB4, during head-on collisions (high part) and during the Super-Separation window (low part) [16].

Figure 4.10 displays the collision rates for a specific particle bunch as one beam is moved across another, with all necessary corrections applied. $\chi^2/ndof$ for vdM and imaging scans has an average value of 0.4514 (shown in Fig. 4.12) where the Poly2G fit model converges for all BCIDs. Peak value and beam overlap Σ_x and Σ_y along X and Y (shown in Fig. 4.11) are extracted from fit to calculate σ_{vis} . The σ_{vis} value obtained by averaging all scans for the final module veto list is $960.54 \pm 0.85(\text{stat.})$ mb.

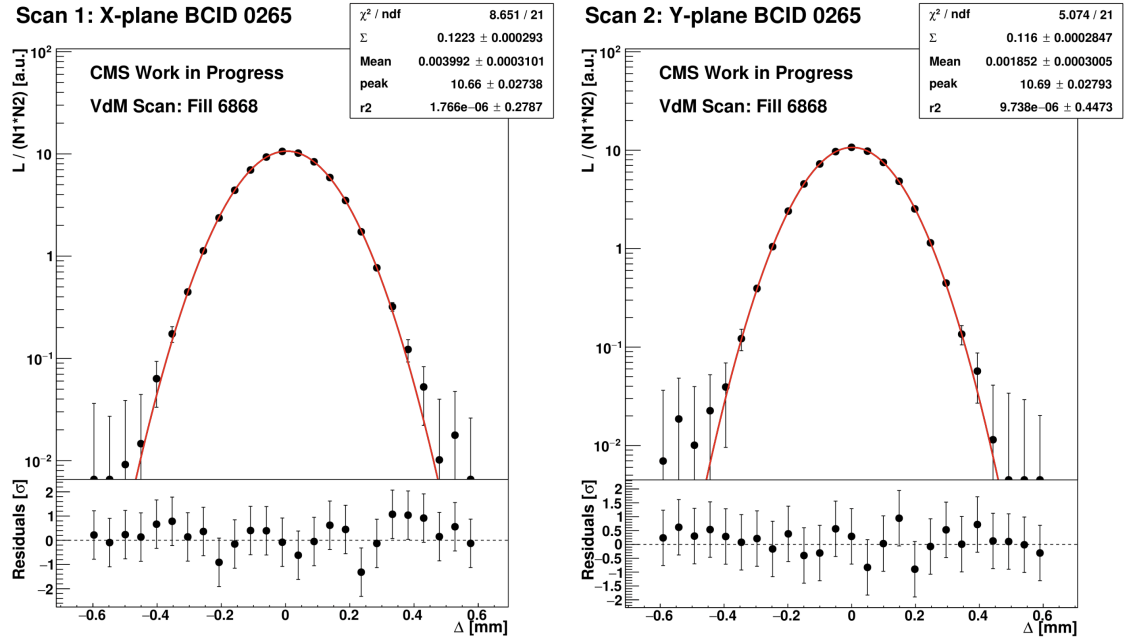


Fig. 4.10 Rates and the resulting fitted Poly2G scan curves as a function of the beam separation for a single bunch (BCID 265) as recorded by PCC for vdM1 scan in the x (left) and y direction (right). Background subtraction and the beam corrections have been applied to the raw data before the fit. Residual is defined as (Data-fit)/fit [16].

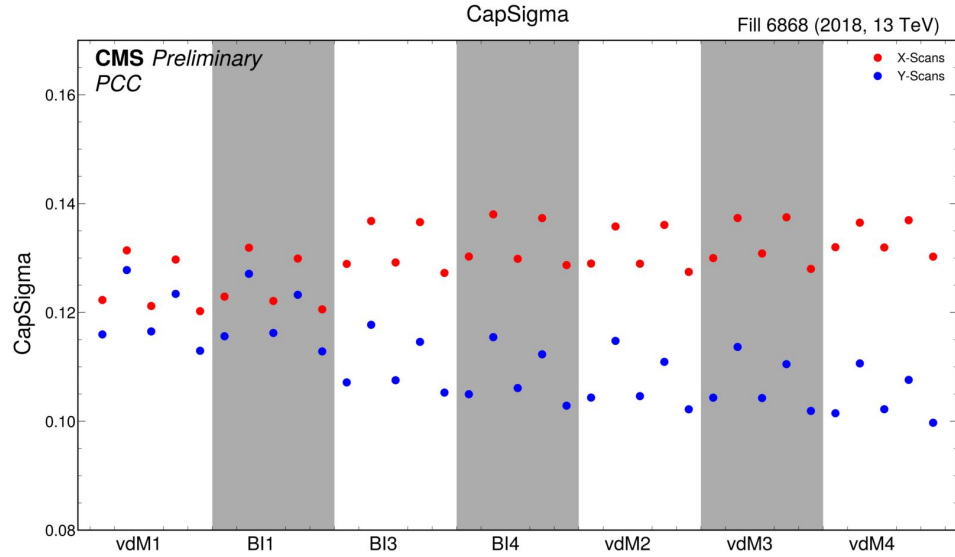


Fig. 4.11 Beam overlap widths for each vdM and imaging scans [16].

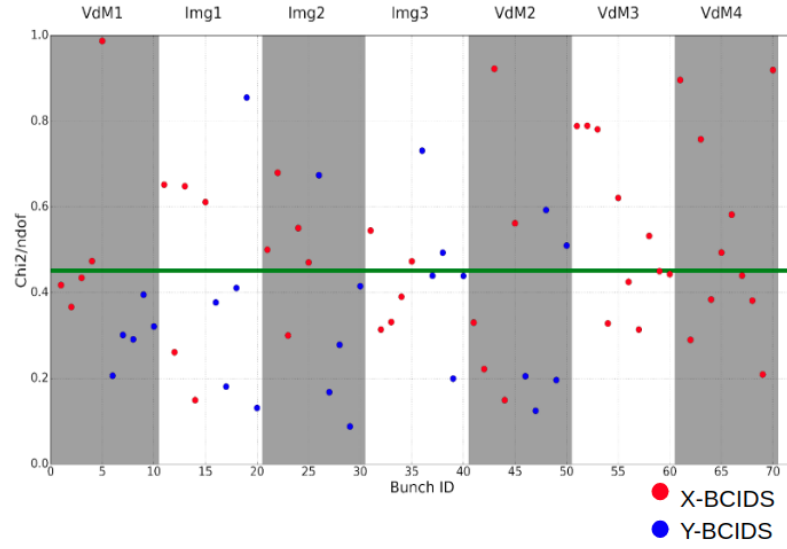


Fig. 4.12 χ^2/ndof for all vdM and imaging scans. [16].

CapSigma ratio plots of PCC with other luminometers for 2018 vdM data are shown from Fig. 4.13 to Fig. 4.16. We observe that the data points mostly hover around the ideal ratio of 1, showing that the measurement from the PCC luminometer matches well with other luminometers. However, there is some noticeable variability, especially with the HFET and HFOC luminometers.. The plots also show some differences between the X and Y scan results, suggesting that the detectors react differently based on the direction of the scan, which could be due to minor alignment issues. These effects result in deviations of the σ_{vis} which are then taken as systematic uncertainties by the bunch-to-bunch and scan-to-scan systematics. The fact that most data points are close to the ratio of 1 confirms the overall reliability of the Capsigma measurement from the PCC luminometer. A data point at 1.010 has a deviation of 1% above the expected value, 1.015 is 1.5% above expected value and a data point at 0.985 has a deviation of 1.5% below the expected value. Uncertainty in CapSigma ratio can be used to determine consistency in the visible cross section measurement for different luminometers.

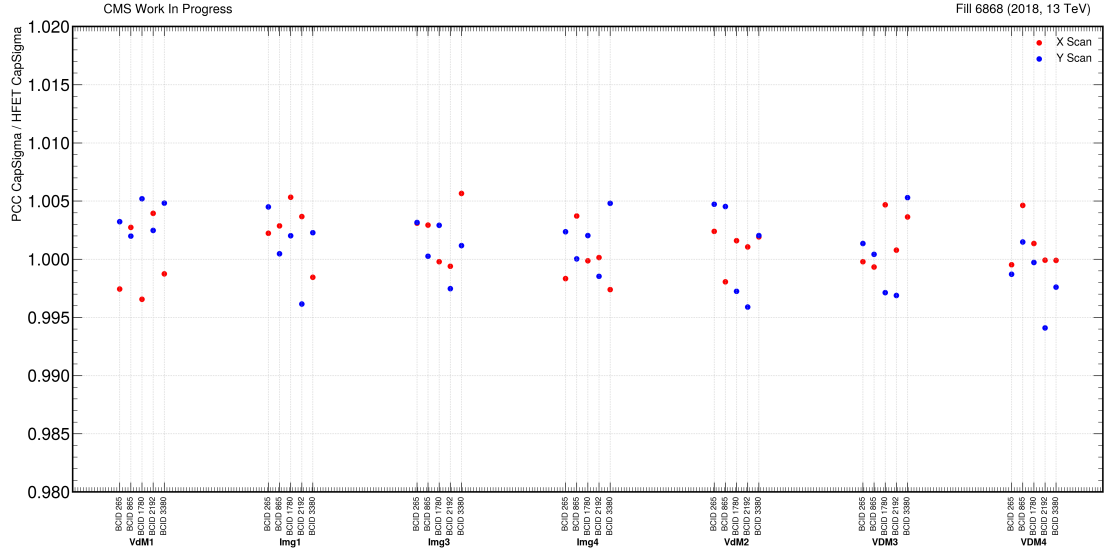


Fig. 4.13 Beam overlap widths ratio PCC/HFET for each vdM and imaging scans [16].

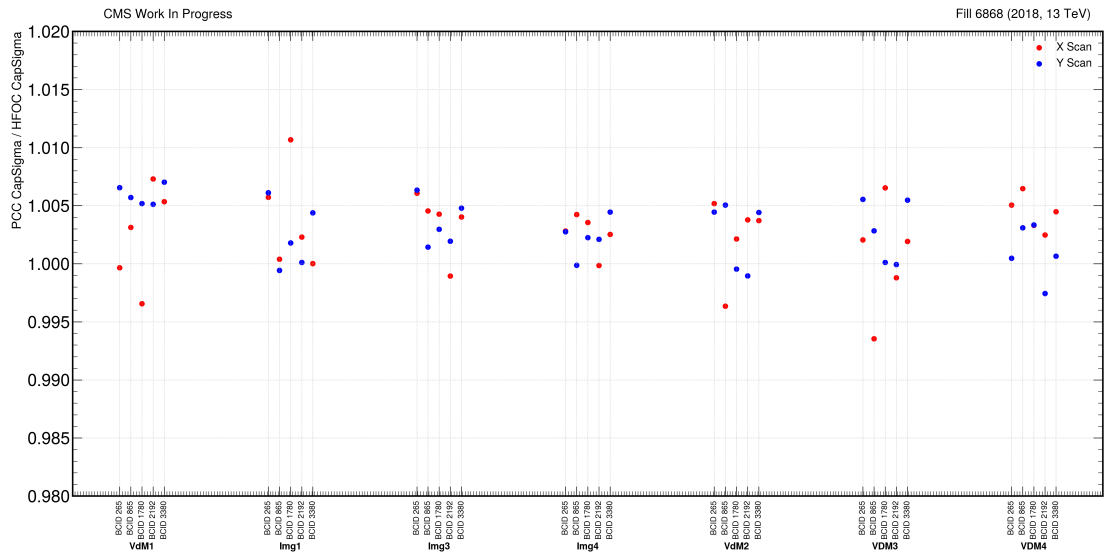


Fig. 4.14 Beam overlap widths ratio PCC/HFOC for each vdM and imaging scans [16].

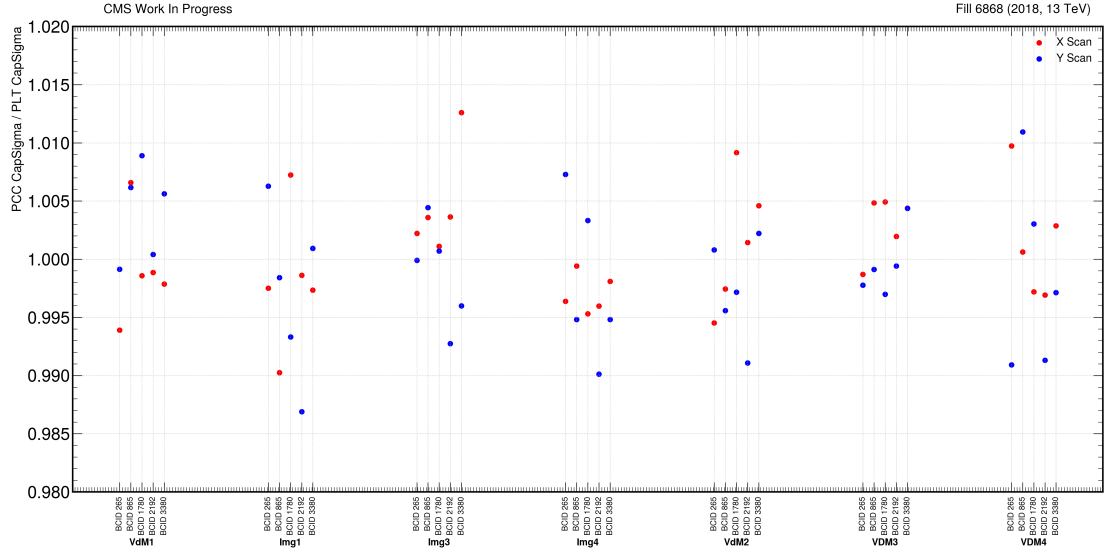


Fig. 4.15 Beam overlap widths ratio PCC/PLT for each vdM and imaging scans [16].

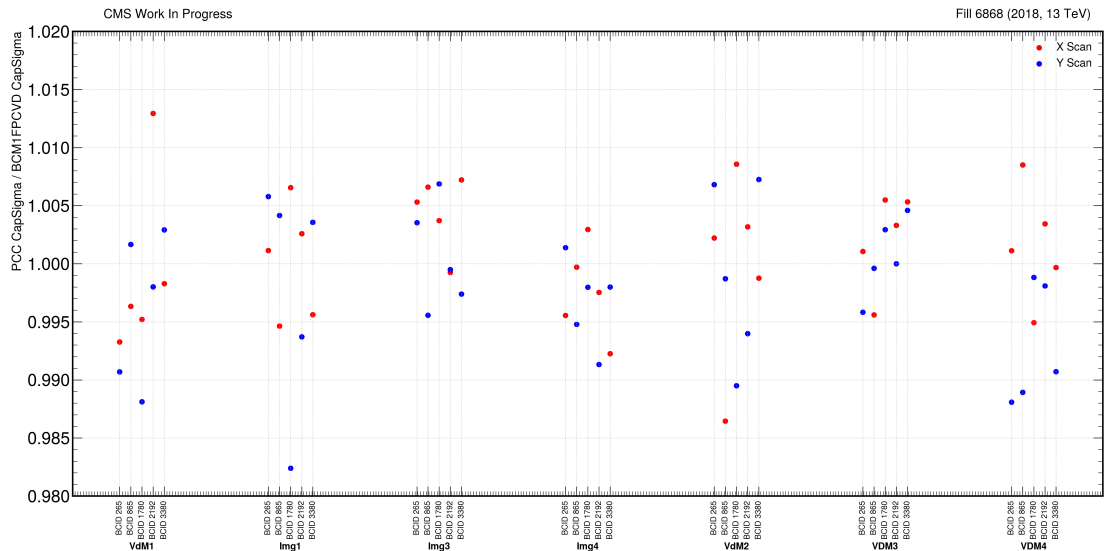


Fig. 4.16 Beam overlap widths ratio PCC/BCM1FPCVD for each vdM and imaging scans [16].

The PCC visible cross section for various bunch crossing across different scans is shown in Fig. 4.17. The data points exhibit a scatter around the mean value, with no apparent systematic bias, as they are distributed both above and below this average. While there is a certain level of precision suggested by the proximity of the points to the mean line, the varying lengths of the error bars indicate a range in measurement uncertainty. This variability in precision could be attributed to fluctuating experimental conditions inherent to each BCID.

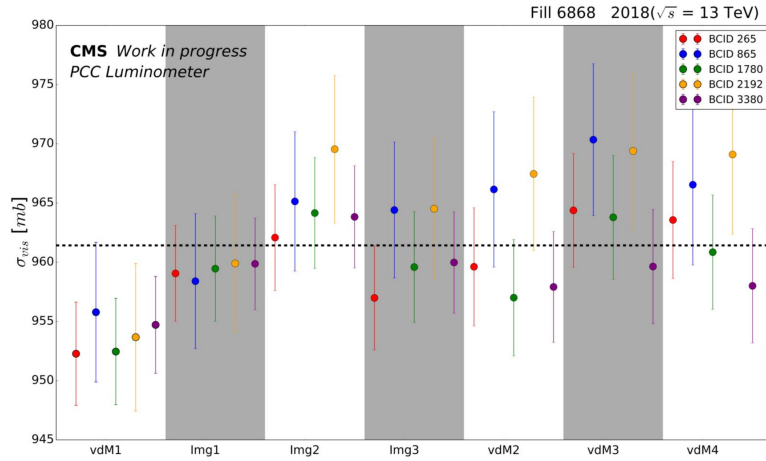


Fig. 4.17 Bunch to bunch variation of PCC visible cross section [16].

4.4 Luminosity for physics fill

The LHC operates in cycles known as "fills." A fill is a period during which the LHC is filled with protons and provides collisions for its experiments. The luminosity profile of a fill is a graphical representation of the instantaneous luminosity as a function of time for the entire duration of that fill. Before the actual data taking begins, there is a phase of beam injection, acceleration, and stabilization. During this period, no collisions are taking place, so the luminosity is zero. Once the beams are accelerated to their maximum energy and brought into collision, there is a rapid rise in luminosity. This is the point where the luminosity reaches its highest value, known as the peak luminosity. After the peak, the luminosity starts to decrease. This period, known as "stable beams", is when most of the data is collected. The reason for the decrease in luminosity over time is the reduction in the number of protons in the beams due to collisions. The rate of this decrease can be influenced by various factors, including beam dynamics, losses, and the efficiency of the collider's operation. The fill concludes when the number of protons is too low to provide useful data, or if there's a technical issue, leading to a beam dump. At this point, the luminosity drops to zero. The total duration of a fill can vary. Some fills last only a few hours, while others can extend for over a day, depending on operational efficiency and the goals for that specific fill. fill profile for fill 6961 during 2018 data taking is shown in Fig. 4.18 with

- Peak luminosity = $1.85 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- End luminosity = $0.9 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Number of colliding bunches = 2556
- Number of lumi sections = 1400

- Integrated luminosity = 0.418 fb^{-1}

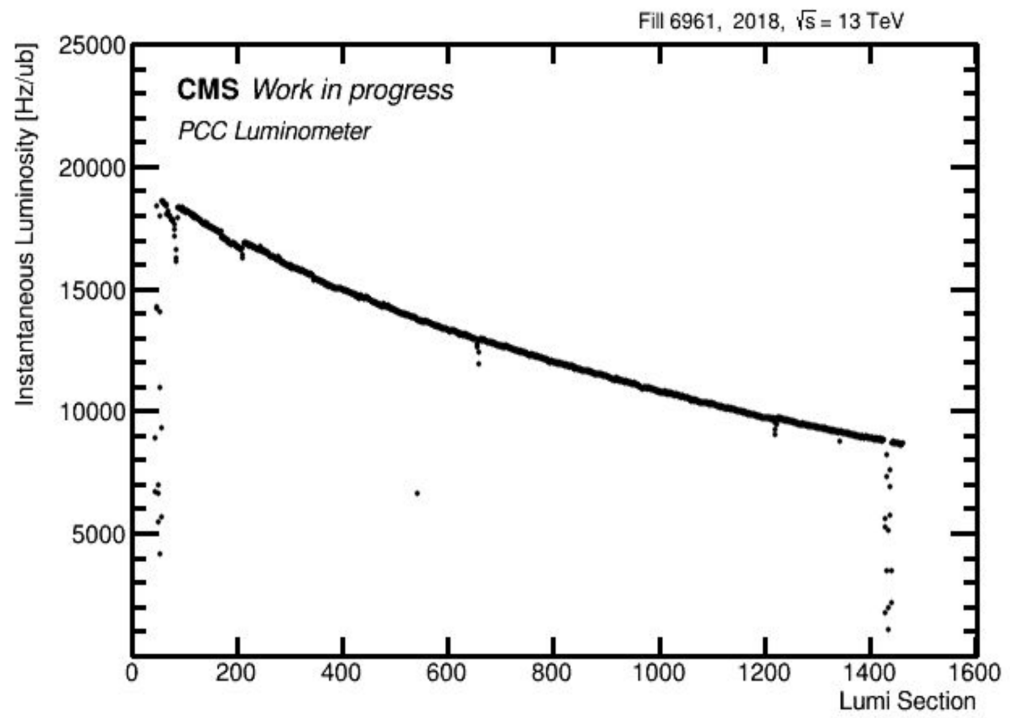


Fig. 4.18 Typical lumi profile for LHC fill during 2018 data taking period for fill 6961 [16].

4.4.1 Afterglow backgrounds

In the precision PCC luminosity measurement, understanding and rectifying the effects of afterglow is crucial. When estimating afterglow corrections, it's paramount to utilize raw PCC data obtained from both colliding and non-colliding bunches. The colliding bunches yield genuine signals representative of particle interactions, while the non-colliding bunches illuminate the background noise inherent in the system, simultaneously capturing any lingering afterglow from prior collisions. Two primary types of afterglow noise have been identified:

Type 1 Afterglow (Electronic Spillover): This noise arises due to the lingering signal waveform in silicon after an actual collision event.

Type 2 Afterglow (Activation-Induced Background): This noise is a consequence of the gradually diminishing activation of the detector. It occurs when the detector material encounters high-energy particles, leading to the creation and decay of radioactive isotopes [12].

The afterglow correction process seeks to adjust for these residual signals, which result in background added to the cluster count. The concept of 'afterglow' is intrinsically tied to the detector and the events it records, independent of the specific modules used for data collection. Thus, regardless of any module's performance or operational state, the need for consistent afterglow correction remains.

In the afterglow correction process, the following steps are involved,

- A model is constructed to mirror the afterglow tail from a single colliding bunch using the random trigger data.
- The model is then fine-tuned according to the luminosity associated with that bunch.
- In the ongoing correction process, a histogram representing the collision events and containing bunch trains is adjusted whereby the afterglow model, multiplied by the luminosity of each colliding pair, is subtracted from all subsequent collision events. This step ensures each bunch is comprehensively corrected.
- Finally, the scale factor for correction is defined by the ratio of the corrected to the uncorrected PCC. This factor is then implemented in the final PCC for the ZB data.

Moreover, pedestal correction is essential. It signifies the adjustment of baseline values in the detector due to electronics noise. This procedure ensures accurate and stable readings from the pixel detector, culminating in precision PCC luminosity measurements.

For accurately modeling the afterglow effect in raw data, a composite function is utilized. It includes parameters for the Type 1 afterglow and an exponentially decaying model for Type 2, taking both amplitude and decay width into account. The model is summed over all bunch crossings.

$$F(x) = \sum_{k=0}^{N_{\text{bcid}}} N_k [(x - k == 0) + A(x - k == 1) + B \exp(-C(x - k - 1))(x - k \geq 1)] \quad (4.1)$$

fill 9036, shown in Fig. 4.19 and encompassing 900 colliding bunches, serves as the foundation for estimating the Type 2 afterglow parameters. A fit is performed to one wagon train, then two, and finally three, refining the parameters for Type 2 afterglow and minimizing the residuals of both afterglow types. Fit plots for single train is shown in Fig. 4.20. The values of type 2 afterglow parameter amplitude (B) and decay width (C) for different wagon trains are shown in Table Fig. 4.6.

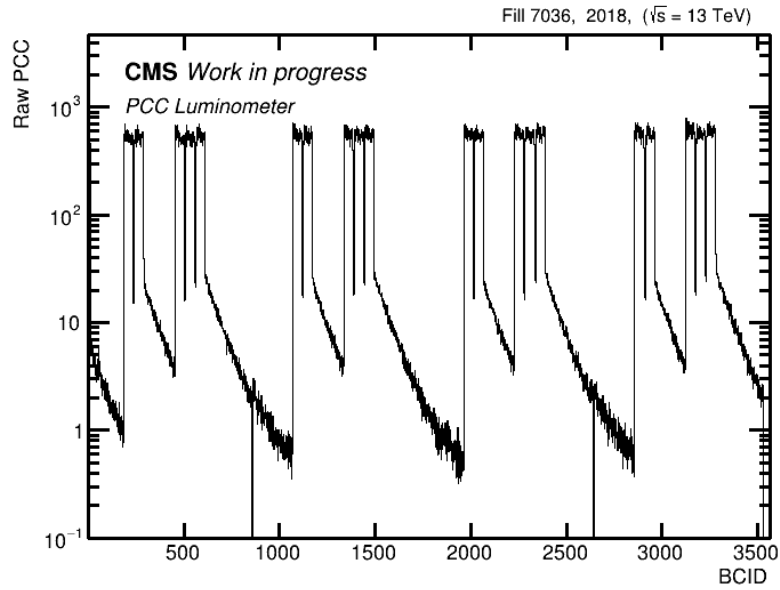


Fig. 4.19 fill 7036 pattern (900 b fill) [16].

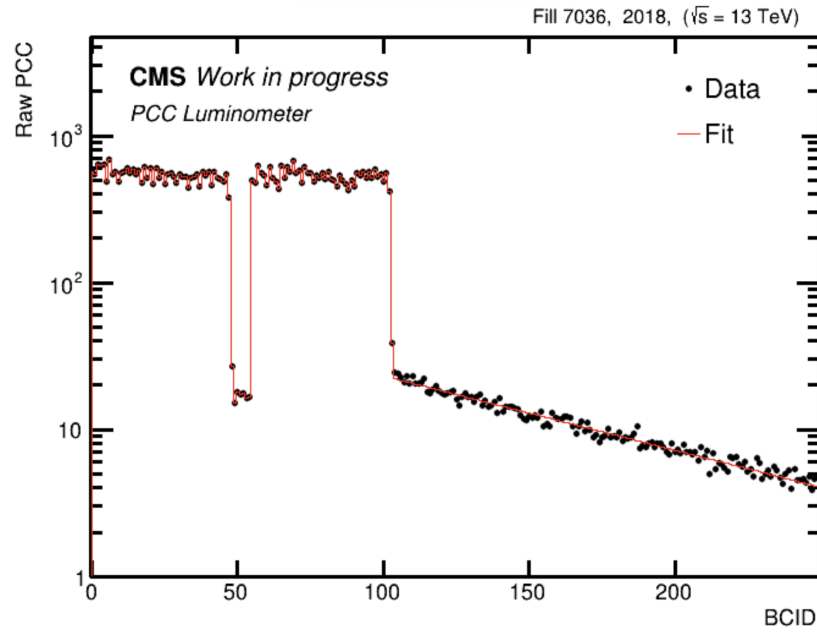


Fig. 4.20 Fit to single train to estimate afterglow parameters [16].

Table 4.6 Type 2 afterglow parameters obtained from fit to raw PCC data

# of wagon	B	C
2-wagon train	0.000813	0.01219
3-wagon train	0.0008265	0.01231

The scale factor for one 50 lumi section block in run number 315690 is shown in Fig. 4.22. It provides an overview of the afterglow scale factor applied to the raw PCC. On the left, both the raw and corrected PCC for all bunch crossings are displayed, showing the variations between the initial data and the adjusted counts. The right side specifically highlights the afterglow scale factor for a single 50 lumi section block, representing the afterglow correction applied for final module veto.

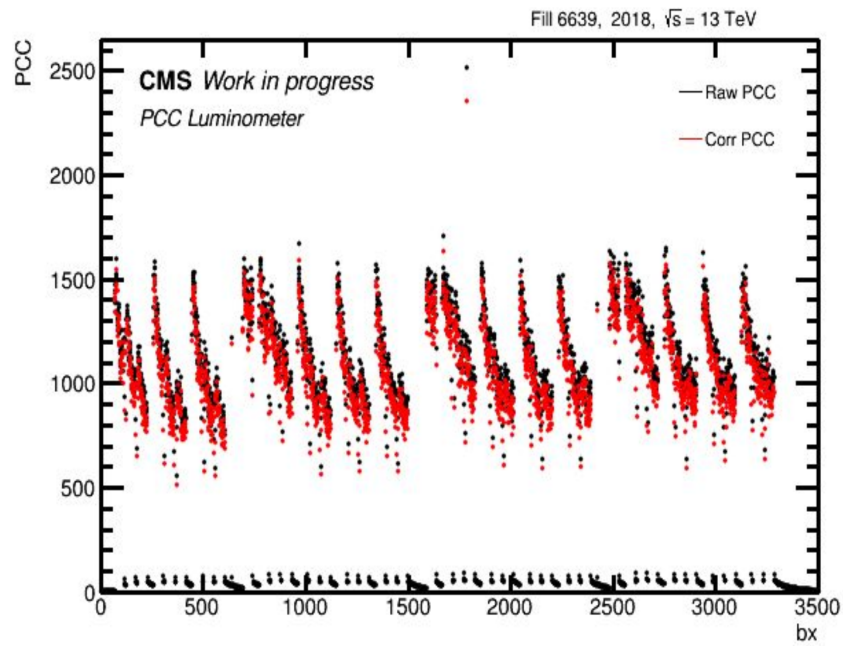


Fig. 4.21 Raw and corrected PCC rates for all bunch crossings in run 315690 [16].

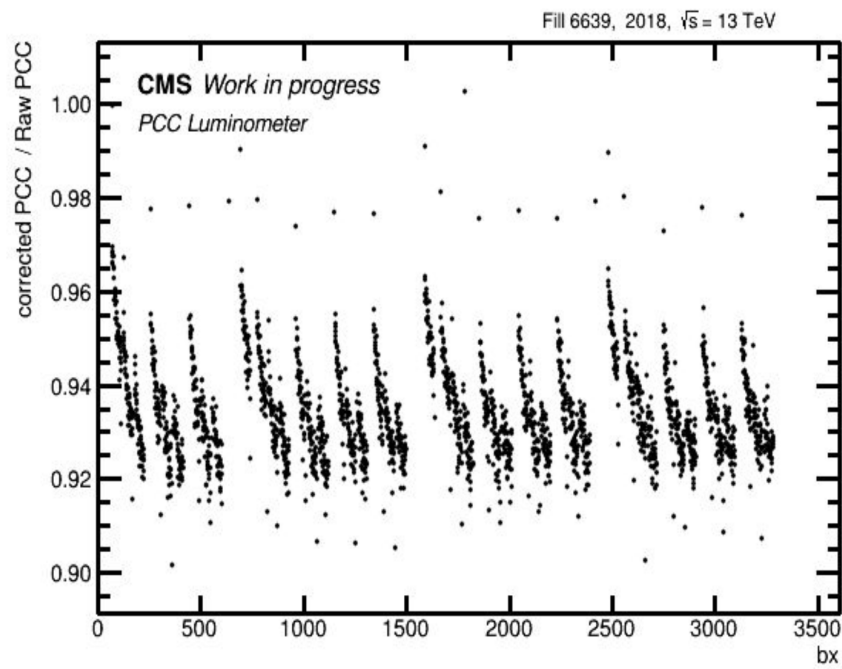


Fig. 4.22 Afterglow scale factor for one 50 lumi section block in run 315690 for the final module veto [16].

4.5 PCC instantaneous and integrated luminosity

Instantaneous luminosity is proportional to the rate of collisions at any given moment in time. It is a snapshot of the experiment performance and is represented as L_{inst} . The unit of instantaneous luminosity is often Hertz per micro barn ($\text{Hz}/\mu\text{b}$). Integrated luminosity is the accumulation of instantaneous luminosity over a specific time period. Mathematically, it is defined as:

$$\text{Integrated Luminosity} = \int (\text{Instantaneous Luminosity}) dt$$

The unit of integrated luminosity is typically inverse femtobarns (fb^{-1}). Integrated luminosity can be understood as the sum of all instantaneous luminosities over the duration of the experiment, enhancing the statistical significance of the data collected. It serves as a measure of the total number of events recorded by the experiment, crucial for robust statistical analysis. When plotted as a function of lumi sections, PCC instantaneous and integrated luminosity offer distinct yet complementary insights into the experiment's performance. In plots that feature luminosity as a function of these lumi sections, the x-axis enumerates the lumi sections while the y-axis presents the luminosity values. For instantaneous luminosity, discrete data points are plotted for each lumi section, providing immediate, lumi section specific measurements of the collision rate as shown in Fig. 4.23. These points can fluctuate based on a variety of factors, such as beam conditions or adjustments to the accelerator. On the other hand, integrated luminosity is represented by a continuously ascending curve.

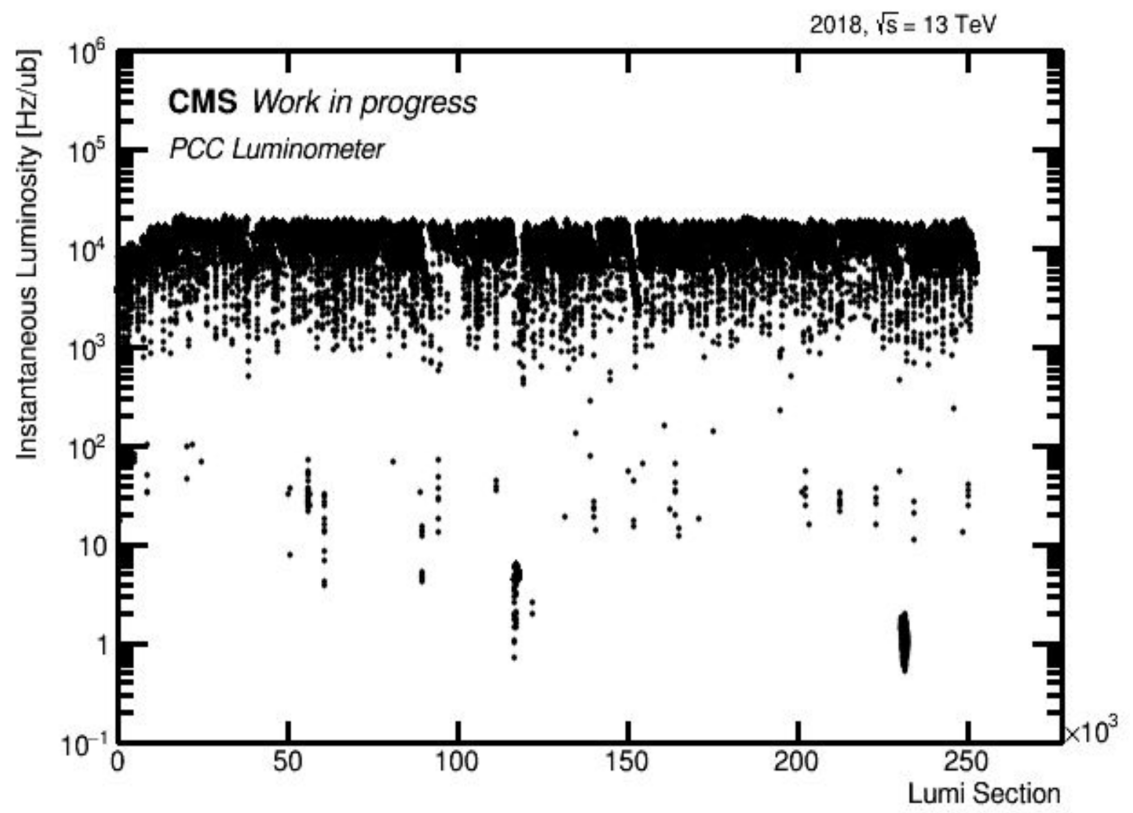


Fig. 4.23 2018 PCC instantaneous luminosity as a function of lumi section [16].

4.6 Systematic uncertainties

The luminosity measurement at CMS experiment is influenced by various systematic uncertainties. Systematic uncertainty originates from inherent biases in experimental design, instrumentation, or methodologies, consistently skewing results away from the true value. These include effects from orbit drifts, xy non-factorization, beam-beam interactions, stability issues, non-linearity of the detector response, afterglow from preceding collisions, and CMS downtime. Each of these sources can impact the precision of the luminosity determination and requires careful consideration in the luminosity's data analysis.

4.6.1 vdM calibration uncertainties

- **Orbit Drift:** Orbit drift in particle accelerators refers to the slight deviation or shift in the trajectory of circulating particle beams from their intended path. This drift can be caused by a myriad of factors, including imperfections in the magnetic fields guiding the beams, external disturbances, and even minute ground movements or temperature fluctuations affecting the accelerator components. The precision with which beams are aligned in colliders like the LHC is crucial for maximizing the number of particle collisions, and hence the luminosity. When an orbit drift occurs, the overlap of the colliding beams may become suboptimal, leading to a reduced instantaneous luminosity. This reduction can influence the effectiveness of the experiments conducted, potentially introducing uncertainties in the luminosity measurement [31]. To calculate the systematic uncertainty due to orbit drift in luminosity measurement, the process begins with measuring the particle beam positions during vdM scans using systems like DOROS BPM and arc BPMs. Corrections are applied based on linear interpolations of these positions to account for any drift from the intended paths, crucial for maintaining optimal beam overlaps and accurate collision counts. The impact of these corrections on the visible cross section is then assessed. Systematic uncertainty is estimated by comparing corrected visible cross section values from both measurement systems, with an additional peak position correction applied for discrepancies at the head-on position. This comprehensive approach consolidates the uncertainties from orbit drift and peak position corrections into a single value.
- **X-Y non-factorization:** The luminosity calibration often relies on methods that factorize the beam overlap integral into two separate integrals in the horizontal (X) and vertical (Y) directions. When this factorization is not valid or precise, the XY non-factorization comes into play. It essentially refers to the systematic uncertainty arising from the inability to perfectly separate or factorize the beam profiles in the horizontal and vertical dimensions. A variety of reasons can lead to XY non-

factorization. One of the main causes is the complex shape and dynamics of the colliding beams. While in an ideal scenario, the beams might be perfectly Gaussian in shape and independent in X and Y dimensions, real-world effects such as beam-beam interactions, intrabeam scattering, or external perturbations can introduce correlations between the two dimensions. This means that the actual overlap of the beams cannot be simply represented as a product of their profiles in X and Y. The luminosity is a direct measure of how many collisions are happening per unit of time and area, and it depends on the overlap of the colliding beams. If the beams' profiles in the X and Y dimensions are not factorized correctly, it can lead to an inaccurate representation of their overlap, thus introducing a systematic uncertainty in the luminosity measurement [32]. To determine the systematic uncertainty due to X-Y non-factorization in luminosity, a series of specialized beam imaging scans are conducted to capture the actual profiles and overlaps of the colliding beams, challenging the common assumption that beam densities in the X and Y dimensions can be independently factorized. Data from these scans are used to model the beam shapes, incorporating potential X-Y correlations using various mathematical functions. Simulated vdM scans based on these models then predict the expected luminosity, accounting for the non-factorizable nature of the beams. By comparing these predictions with actual vdM scan results which assume factorizable beam profiles a correction factor is estimated to adjust the luminosity. The systematic uncertainty related to X-Y non-factorization is finally determined by evaluating the correction factor variability and the model fit quality, ensuring the adjustment accurately reflects the true beam interactions and their impact on the measured luminosity.

- **Length scale:** Two types of scans, constant and variable separation scans, are employed to calibrate the length scale. These scans assess the position of the luminous region and juxtapose it with the nominal beam separation. Specifically, constant separation scans utilize a linear fit to align the measured positions against nominal separations, facilitating corrections in the x and y directions independently. Variable separation scans, on the other hand, provide insights into how beam interactions change with varying distances, offering a dynamic perspective. The methodology also incorporates an evaluation of various sources of uncertainty such as variations between the forward and backward parts of the scans, orbit drift during the scans, tracker misalignment, and inconsistencies in vertex position measurement. These uncertainties are quantified and subsequently combined in quadrature with statistical uncertainties to calculate the total length scale uncertainty.
- **Beam-Beam Deflection:** refers to the change in trajectory of the individual particles in the beam as they pass near each other in the interaction point, due to their

electromagnetic interaction [33]. In a perfect scenario, each beam of protons would stay focused and keep their trajectory constant throughout the process. However, when two beams cross each other, the electromagnetic fields of the protons in one beam can exert forces on the protons in the other beam, causing them to deviate from their initial trajectory [34]. Systematic uncertainty due to beam-beam deflection is computed by modeling the electromagnetic interactions that cause proton beams to deflect when colliding affecting luminosity. Sophisticated simulations predict the deflection impact, allowing for the derivation of a correction factor to adjust luminosity. This uncertainty is quantified by evaluating the correction factor variability and confidence across various conditions.

- **Dynamic β :** The beta function (β^*) in the context of particle accelerators like the LHC is a measure of the beam size at the collision point [35], and it plays a crucial role in determining the luminosity of the collisions. Lower values of β^* lead to smaller beam sizes at the interaction point and thus higher luminosity, as the probability of proton-proton collisions is increased. However, β^* is not necessarily constant during the operation of the LHC. It can vary due to factors such as changes in the accelerator's operating conditions, beam-beam interactions. When β^* changes, it can alter the size of the proton beams at the interaction point. As the luminosity is inversely proportional to the square of the beam size, a small change in β^* can lead to a significant change in luminosity. If these changes in β^* are not accurately tracked and accounted for, they can introduce uncertainties in the luminosity measurement. The challenge is that β^* is not directly observable, so its value and any changes in it have to be inferred from other measurements, such as the beam size and position, the orbit drift. The systematic uncertainty due to dynamic β effects is quantified based on beam transport simulations that incorporate both the defocusing effects of beam-beam interactions and the scaling of these effects to the actual beam energies, β settings, and measured beam widths. The correction and its uncertainty are derived from the modeling of how each beam, under the influence of the other, experiences changes in its focusing properties, thereby affecting the overlap and, consequently, the luminosity. The correction is essential to account for the fact that the presence of one beam influences the focusing properties of the other, leading to adjustments in the measured beam sizes and the calculated luminosity.
- **Beam Current Calibration:** Beam current calibration ensures that the N value (number of particles per bunch) used in the luminosity equation is accurate. If the calibration is off, the derived value of N from the instruments like beam current transformers will be inaccurate, leading to errors in the calculated luminosity L_{inst} . As the luminosity dependence on number of particles per bunch is N^2 , even small errors in beam current calibration can significantly affect the accuracy of L_{inst} [36].

The systematic uncertainty due to Beam Current Calibration is computed by considering uncertainties from two main sources: the precision of the DC Current Transformers (DCCT) measurements and the correction for spurious charges (ghost and satellite charges) that do not contribute to the luminosity. These uncertainties stem from the normalization process where Fast Beam Current Transformers (FBCT) measurements are adjusted based on the more accurate total beam current readings from the DCCT, and from the adjustments made to account for non-contributing charges detected during the calibration process. The combination of these factors determines the overall systematic uncertainty associated with calibrating the beam currents.

- **Ghosts and Satellites:** The ghost charge refers to the unintended or unexpected particles present in slots within the LHC beam that are nominally supposed to be empty. This term encapsulates the stray particles that aren't part of the primary, intended bunch structure of the beam. Ghost charges can originate from remnants of previous fills or injections into the LHC. When protons are injected and circulated within the accelerator, not all of them are perfectly grouped into the designated bunch structures. Some can linger outside the primary bunches, leading to these unintended ghost charges. The presence of ghost charges can significantly impact the luminosity measurement. Ghost charges can lead to additional, unexpected collisions when they interact with particles from the opposing beam. If these ghost-induced collisions are not accounted for, the luminosity can be overestimated. In the LHC, with its 400 MHz RF, there are 35640 RF bins, each about 2.5 ns long. Though only every tenth bin is typically filled with a particle bunch, stray particles are found in neighboring bins. These stray bunches within a ± 12.5 ns range of a filled RF bin are termed "*satellite bunches*", distinct from main bunches and can influence precision luminosity measurement [37]. The systematic uncertainty due to ghosts and satellites is computed by first measuring these spurious charges using specific detection methods, such as the LHC longitudinal density monitors (LDM) and the beam-gas imaging method, which provide an assessment of the presence of non-colliding protons within the beam. These charges, known as ghosts (protons in nominally empty bunch slots) and satellites (protons outside the main RF bucket but within the colliding bunch crossing), do not contribute to the luminosity but are included in the total beam current measurement. To accurately account for the luminosity, corrections are made to the beam intensities to exclude the contributions from these spurious charges. The correction ensures that the calculated luminosity accurately reflects only the colliding protons that contribute to collisions. The uncertainty associated with this correction is derived from the precision and variability of the measurements used to quantify the ghost and satellite charges. This

includes considering the limitations and variability inherent in the measurement methods (LDM and beam-gas imaging), as well as the fluctuating nature of these spurious charges over time and under different beam conditions.

- **Scan to Scan Variation:** Refers to the variation in experimental results obtained from different scans or measurements, which can arise from various sources such as statistical fluctuations, instrument drift, or systematic errors.
- **Bunch to Bunch Variation:** It means the σ_{vis} varies from one bunch to another bunch.

Table 4.7 provides statistical data of the PCC visible cross-section for different scans. These scans represent different data-taking periods under slightly different experimental conditions. We observe that the 'Img1' scan has the smallest relative standard deviation, implying the least variability in the measured visible cross-section compared to its mean. On the other hand, the 'vdM2', 'vdM3', and 'vdM4' scans have higher relative standard deviations, indicating greater variability.

Table 4.7 Bunch to bunch variation of PCC visible cross section. The “bunch spread” is determined as the standard deviation (STD) of the bunches divided by the mean visible cross section. SEM is the standard error on the mean

Scan	Mean	STD	(SEM/ σ_{vis}) [%]
vdM1	953621.33	1334.83	0.14
Img1	959386.63	559.37	0.058
Img3	964376.43	2502.04	0.26
Img4	960386.85	2936.50	0.31
vdM2	960566.04	4320.81	0.45
vdM3	964566.94	3928.54	0.41
vdM4	962586.52	3943.24	0.41

- **Cross-Detector Consistency:** Refers to the agreement between measurements obtained from different detectors or measurement systems. This is important for verifying the accuracy and reliability of experimental results. A head-on lumi phase during vdm fill is used. The systematic uncertainty is computed by comparing luminosity measurement across various detectors over the data-taking period. This involves analyzing the ratios of luminosity measurement between pairs of detectors, assessing their stability and linearity under different conditions, and identifying any systematic deviations. The variability and consistency between detectors are quantified, typically using the standard deviation of these ratios, after excluding periods with known issues. The overall systematic uncertainty reflects the largest observed deviations and variability among the detectors, ensuring a conservative estimate that accounts for differences in detector responses and operational conditions.

- **Background Subtraction:** Refers to the process of removing unwanted signals from a measurement or detector system that arise from sources other than the physical phenomenon of interest, such as noise, cosmic rays, or other particles. Machine induced backgrounds are subtracted from raw PCC rate as described in section 4.3.

4.6.2 Integration uncertainties

- **Stability:** Systematic uncertainties can be introduced due to time-dependent changes in detector performance and environmental conditions. These changes can be influenced by various factors, including detector aging, radiation damage, and fluctuations in noise. A comparison of PCC luminosity with HFOC luminosity as a function of time is shown in Fig. 4.24 depicting slight instabilities in PCC luminosity over time. Detector aging can result in time-dependent changes in the detector's performance. For example, as the detector ages or sustains radiation damage, its efficiency may decrease, leading to a reduction in the number of detected events for a given luminosity. The noise level in the detector can also fluctuate over time due to changes in the experimental conditions. Noise can lead to spurious signals that can be misinterpreted as genuine events, leading to an overestimate of the luminosity. Conversely, high noise levels can also mask genuine events, leading to an overestimate of the luminosity. The standard deviation of ratio of luminosity from best and second best luminometer is used as stability systematic uncertainty as shown in Fig. 4.25. The standard deviation provides a measure of the spread or dispersion of the measurements. If the measurements are stable, the spread will be small, and the standard deviation will be low. Conversely, if there are time-dependent changes in the detector performance or environmental conditions, the measurements will vary more, and the standard deviation will be higher.

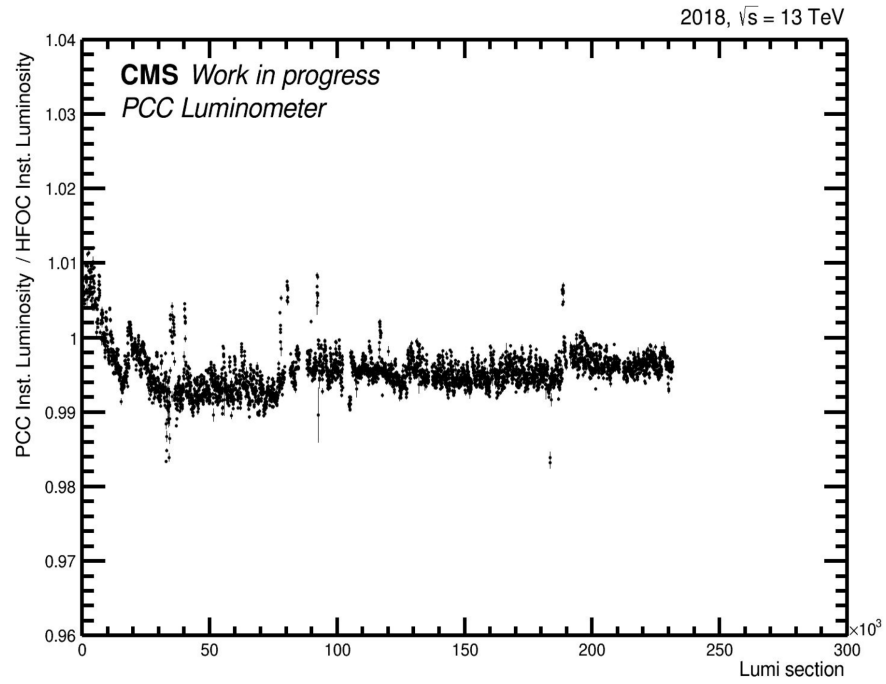


Fig. 4.24 Profile of the PCC/HFOC luminosity as a function of lumi section [16].

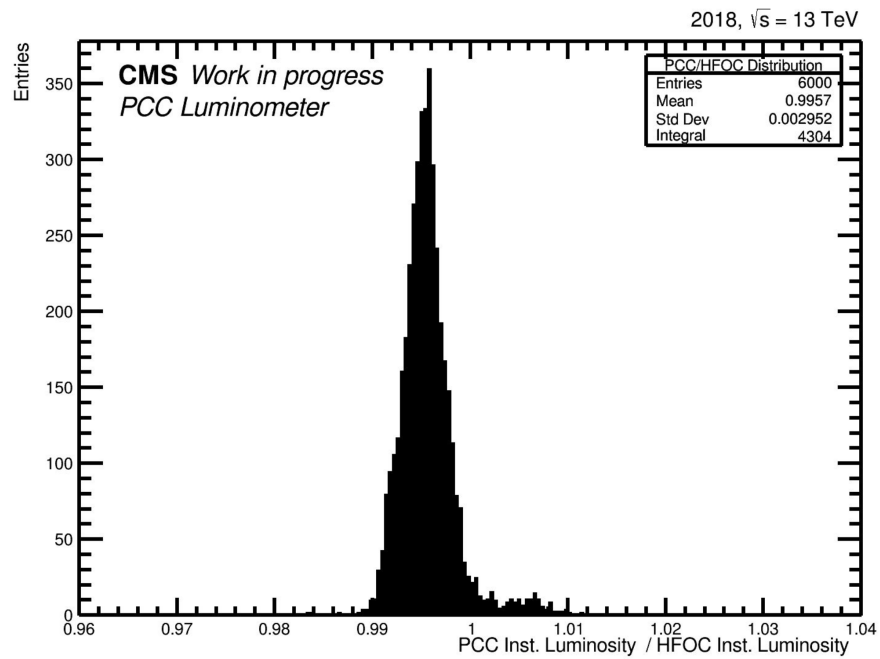


Fig. 4.25 Distribution of the ratio of PCC/HFOC luminosity evaluated per 50 lumi section blocks [16].

- **Linearity:** The response of a detector might not always be the same at different luminosity levels. In other words, a detector might respond differently when there are more particles passing through it per unit of time (higher luminosity) compared to when there are fewer particles (lower luminosity). This is particularly relevant at the high luminosities achieved. Linearity of PCC luminosity with HFOC luminosity is shown in Fig. 4.26. Pileup events are common at high luminosities and can affect the linearity of the luminosity measurement. If the detector or the counting system is unable to accurately count the number of pileup events, the count rate might not increase linearly with the actual luminosity, leading to a non-linear response.

A linear fit is done to study change in detector response at different luminosity levels. By multiplying the slope by the luminosity range (the difference between the highest and lowest luminosity levels), we obtain a measure of how much the rate is expected to vary due to non-linearity over that luminosity range. This product can be used as an estimate of the linearity systematic uncertainty in the luminosity measurement.

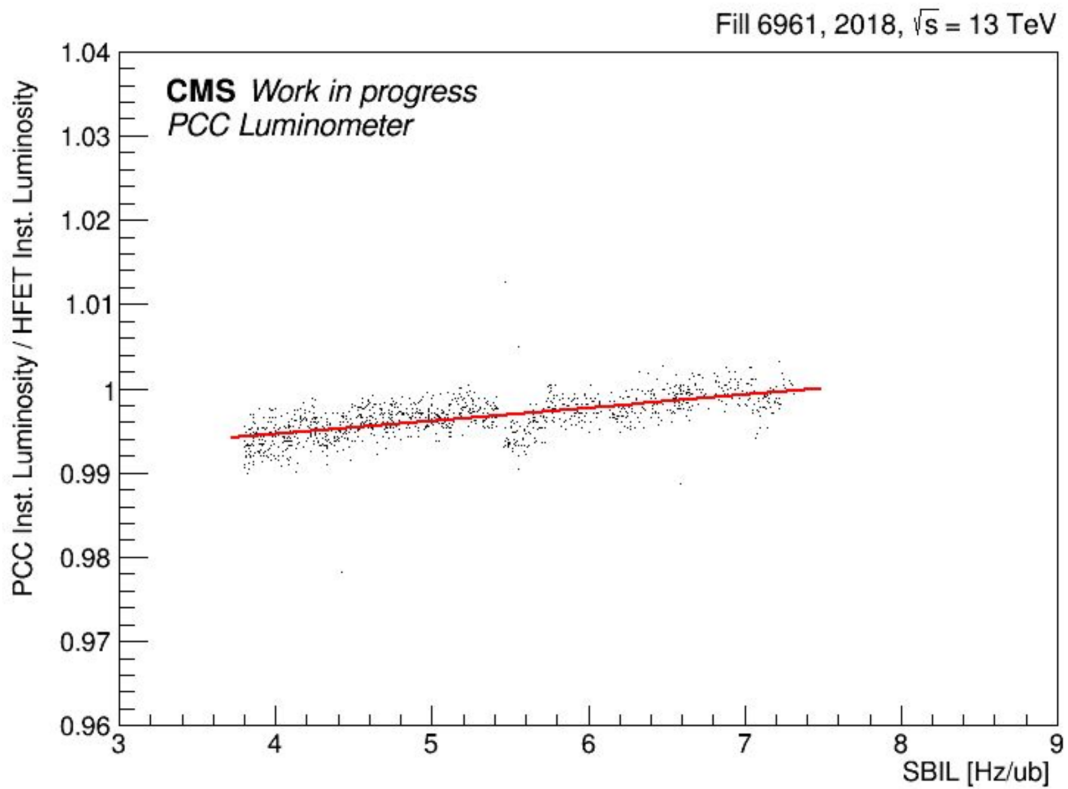


Fig. 4.26 Linearity of PCC compared to HFOC for fill 6961. Ratio of PCC/HFOC luminosity plotted as a function of HFOC luminosity to determine change in detector response over different luminosity levels. Slope of the linear fit is 0.00154614 in units of $(\text{Hz/ub})^{-1}$ [16].

- Afterglow: Systematic uncertainty due to afterglow background is determined by calculating the mean of the type 1 and type 2 afterglow residuals. Type 1 afterglow residuals are determined by the ratio of the luminosity of the first empty bunch immediately following a colliding bunch to the luminosity of the colliding bunch. Type 2 afterglow residuals focus on the luminosity of the second empty bunches after a colliding bunch, compared to the luminosity of the colliding bunch itself.

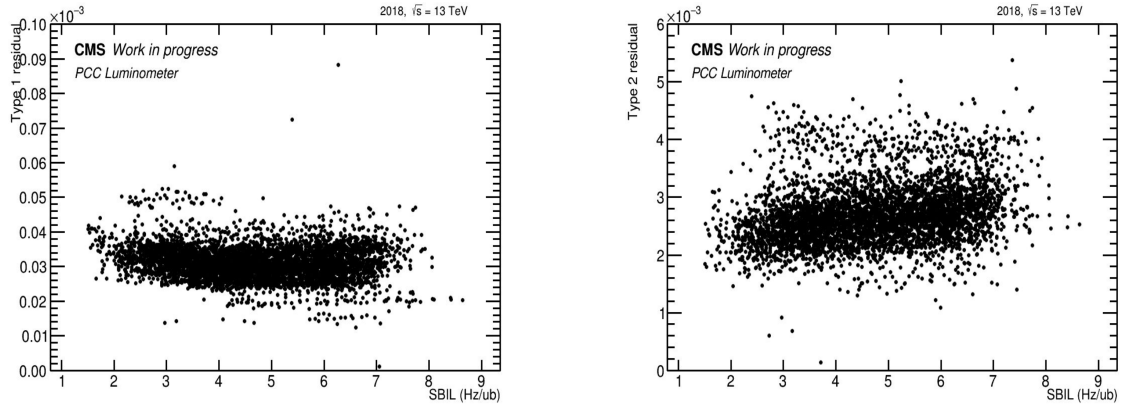


Fig. 4.27 Left: PCC afterglow correction type 1 residual as a function of instantaneous luminosity. The residual fraction is given by the ratio of the luminosity of the first empty bunch immediately following a colliding bunch to the luminosity of the colliding bunch. Right: Type 2 residual as a function of instantaneous luminosity. These are given by the ratio of the luminosity of the second empty bunches after a colliding bunch to the luminosity of the colliding bunch. Random trigger PCC dataset for all periods are used to make these plots [38].

The systematic uncertainty during 2018 luminosity measurement for final veto is shown in Table 4.8.

Table 4.8 Systematic uncertainty during calibration and physics data taking for the final veto for the 2018 PCC luminosity measurement [16].

	Systematics	Uncertainty [%]
Normalization	Length scale	0.2
	Orbit drift	0.1
	x-y nonfactorization	2.0
	Beam-beam deflection + Dynamic β^*	0.2
	Beam current calibration	0.2
	Ghost and satellite	0.1
	Scan to scan variation	0.3
	Bunch to bunch variation	0.1
	Cross detector consistency	0.5
	Background subtraction	0.1
Integration	Afterglow	0.3
	Cross detector stability	0.3
	Linearity	0.4
Total		2.2

Chapter 5

Run 3 Luminosity Measurement

5.1 Dataset

To investigate the performance of the PCC luminometer during the 2022 data collection period [39], we segment CMS luminosity data into five distinct periods: C, D, E, F, and G, as illustrated in Figure 5.1. The run ranges associated with each of these periods are outlined in Fig. 5.1. Notably, during period F, specifically during fill 8381, van der Meer (vdM) scans were implemented to calibrate the PCC luminometer. For our current analysis, we employ dataset that align with the 2022 luminosity measurement periods, specifically 2022C, 2022D, 2022E, 2022F and Run 2022G as highlighted in Table 5.1. We extracted these datasets from the Alignment and Calibration (AlCa) project, a critical aspect of the CMS experiment. The selected datasets encompass two subcategories, namely Random trigger and Zero Bias similar to Run 2 PCC dataset.

Table 5.1 Run periods, run number ranges and dates for the 2022 data taking period.

Run Period	Run Number Range	Date
C	355862 - 357401	2022-07-19 to 2022-08-12
D	357538 - 357900	2022-08-15 to 2022-08-23
E	359268 - 360327	2022-09-23 to 2022-10-14
F	360390 - 362167	2022-10-14 to 2022-11-17
G	362433 - 362760	2022-11-21 to 2022-11-28

5.2 Detector module selection

The method for selecting reliable modules based on their performance, using the module weight, is detailed in section 4.2. Its significance in identifying consistent modules are

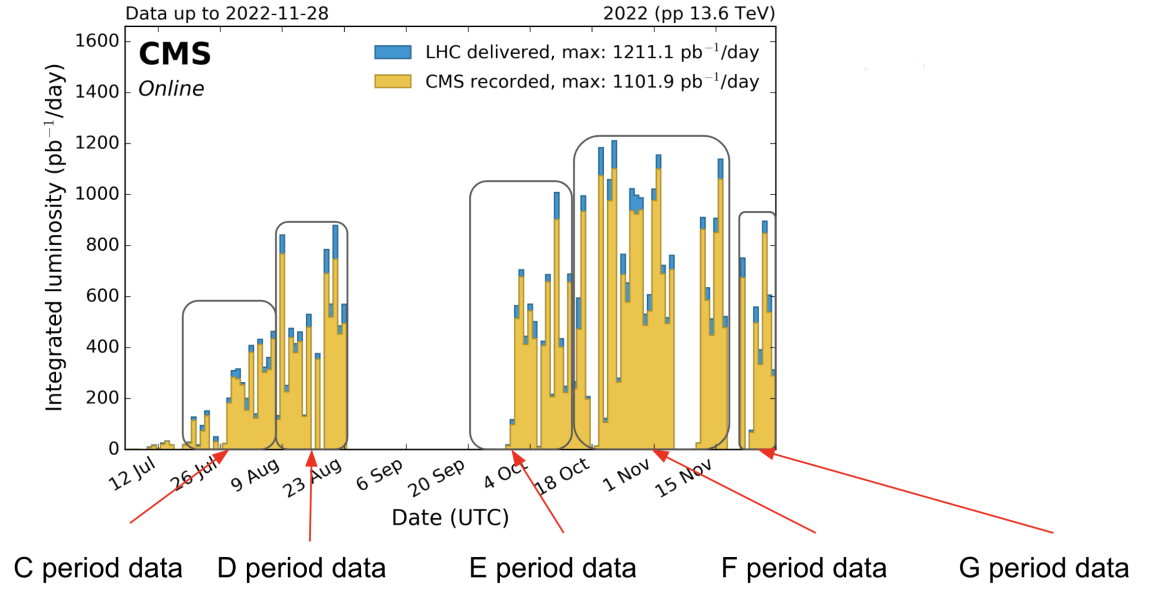


Fig. 5.1 2022 luminosity data taking periods showing data taking period boundaries.

illustrated in Fig. 5.2. Evaluations are undertaken in lumi sections. Modules with consistent performance throughout 2022 are focused upon. Unreliable modules are added to a "module veto list", ensuring their data is excluded from luminosity calculation, thus preserving data accuracy. While all modules can be part of the luminosity measurement, only around 10% withstand the rigorous selection criteria. The selection focuses on evaluating each module's stability using zero-bias dataset.

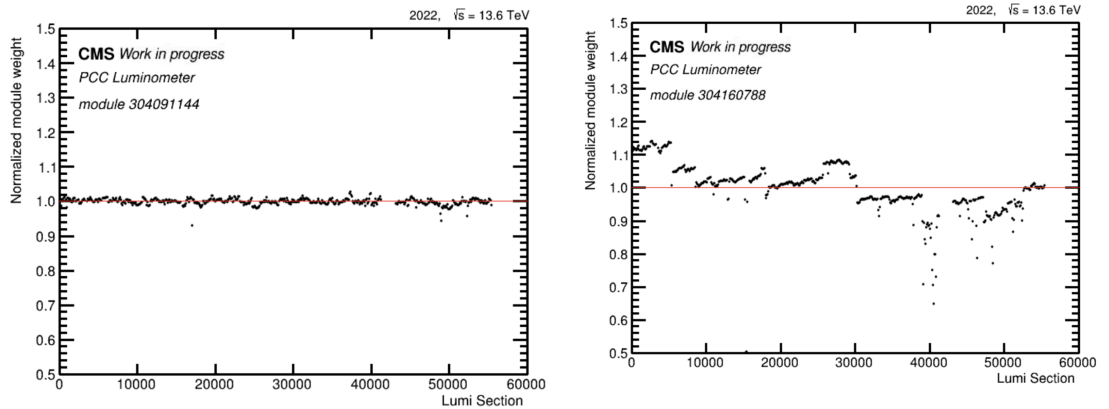


Fig. 5.2 Module weight profile as a function of lumi section showing good (left) and bad (right) module during Run 2022F. The horizontal red line is the mean of the module weight.

For module evaluation, the steps include:

1. Lumi sections with low statistics are removed based on total PCC.

2. All barrel Layer-0 modules are sidestepped due to their vulnerability to dynamic inefficiency.
3. An initial filtering removes modules with 2% average deviation of the module weight from its mean (shown in Fig. 5.3).
4. Module stability is reviewed using an iterative method. In the case of the 2022F dataset, we introduce additional criteria of 0.8%. For different data periods, the specific values used depend on how good the initial module list is.
5. The selection of modules based on their linearity relies on assessing the average deviation of the module weight v.s. the average PCC per module (shown in Fig. 5.4). This process typically requires either one or two iterations. To illustrate, during the 2022F period, we first apply a 0.4% selection criterion, followed by a more stringent 0.25% selection.

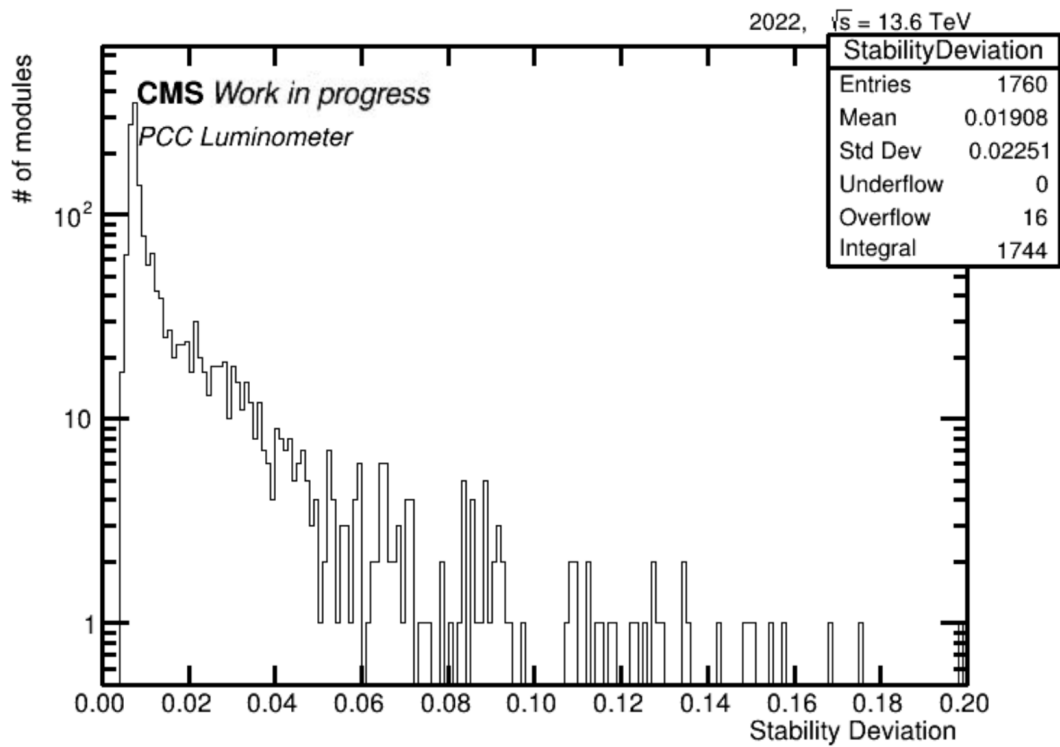


Fig. 5.3 During Run 2022F, the distribution illustrates the average deviation of the module weight over it's mean for all modules.

Table 5.2 presents a quantitative summary of malfunctioning or "bad" modules across various periods. BPIX Layer0 has 96 bad modules. As we progress through the various periods in 2022 (from F to D), there is a general trend of increasing bad modules, both for

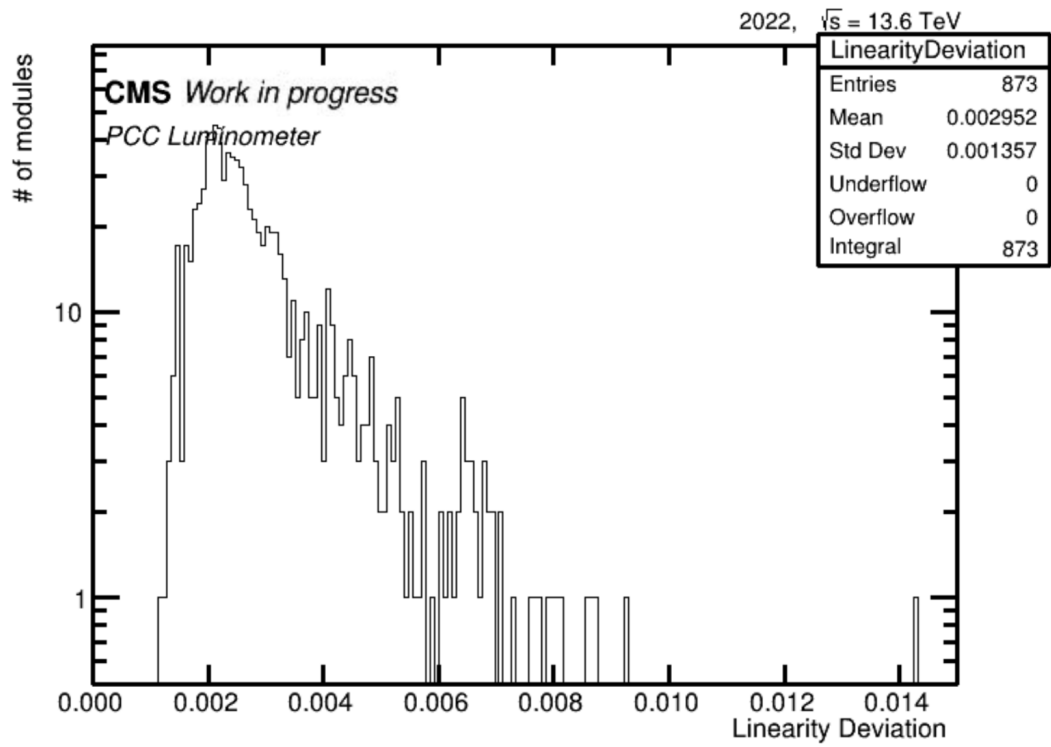


Fig. 5.4 Left: Linearity profile, module weight as a function of average PCC per module for one module in Run 2022F. Right: For all modules in Run 2022F, the distribution displays average deviations of the module weight divided by their mean derived from their linearity profiles.

stability and linearity considerations. The total number of bad modules added to the veto list grows in each period due to the sequential or iterative nature of the procedure where the veto list for each period starts with the veto from the previous period [40].

This suggests that as time progresses, the number of malfunctioning modules tends to grow. The highest number of bad modules for stability is observed in the 2022D period with 1653 bad modules. On the other hand, the 2022D period also has the highest for linearity with 1677 bad modules. The vdM fill has 1693 bad modules, which is slightly higher than those in the 2022D period for stability but slightly less for linearity. There seems to be a consistent observation that for each given period, the number of bad modules under linearity considerations is either equal to or slightly higher than those under stability considerations [40].

Table 5.2 Number of bad modules for selection on stability and linearity for various periods.

Type Or Period/Step	# of bad modules
BPIX Layer0	96
2022F Stability	983
2022F Linearity	1195
2022C Stability	1364
2022C Linearity	1484
2022E Stability	1553
2022E Linearity	1570
2022G Stability	1604
2022G Linearity	1628
2022D Stability	1653
2022D Linearity	1677
vdM fill	1693

Table 5.3 presents the number of good modules in various layers and disks of the pixel detector after a final selection process. The stability of various pixel layers and disks after removing all modules in Layer 0 and for final veto are shown in Fig. 5.5 and Fig. 5.6 respectively.

Table 5.3 Number of good modules in each layer/disk

Layer/Disk	Number of Good Modules
Layer 3	39
Layer 4	88
Disk 1	13
Disk 2	19
Disk 3	4
Total	163

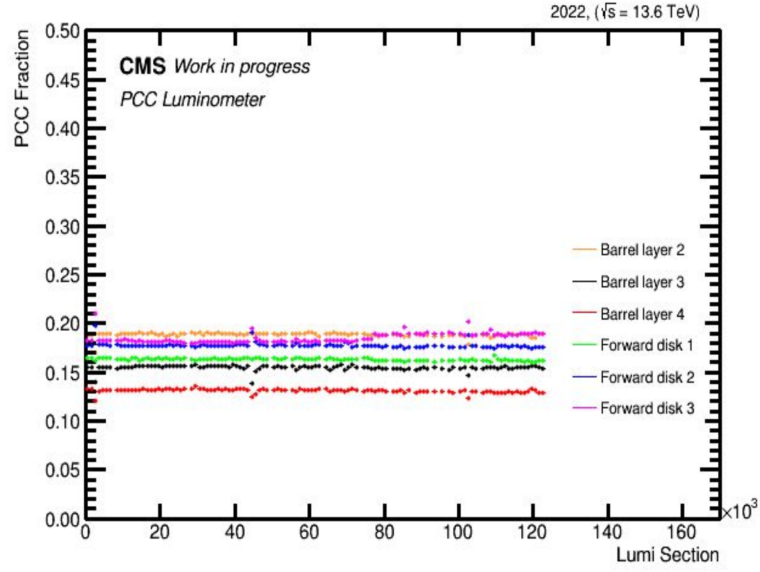


Fig. 5.5 Luminosity fraction of pixel detector for various layers and disks as a function of lumi section for the entire 2022 data with all Layer 0 modules vetoed.

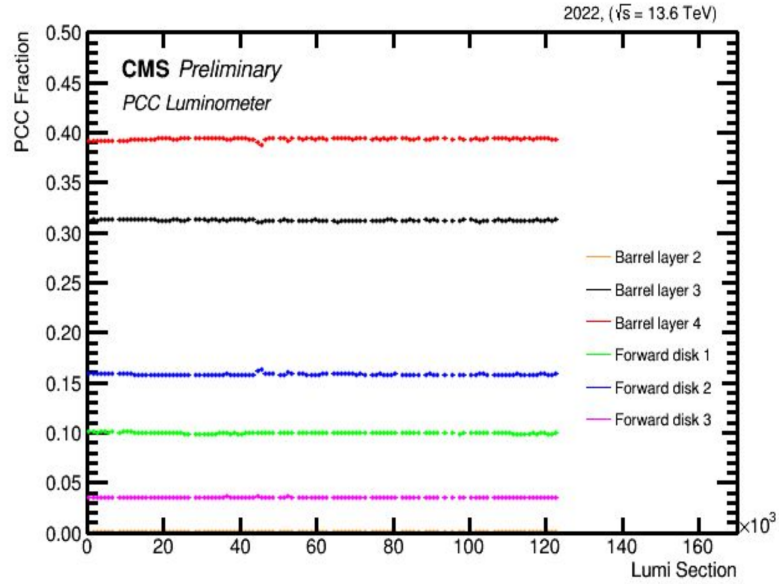


Fig. 5.6 Stability profiles of pixel detector layers and disk modules for the final module veto list.

5.3 vdM calibration results

The vdM calibration involves varying the position of the colliding proton beams horizontally and vertically and observing the changes in the event rate resulting from these shifts as a function of beam separation. This procedure allows us to determine the overlap integral of the beam profiles, which is an essential part of the absolute luminosity calculation. In the context of PCC, the event rate corresponds to the number of pixel clusters detected per unit time. Therefore, by observing how this rate changes with the beam positions, the calibration constant of the PCC luminometer can be determined.

The vdM scan was performed in November 2022, during the LHC fills 8379 and 8381. In fill 8381 on 10–11 Nov 2022, data was collected when 144 paired bunches of particles were colliding, with additional unpaired bunches also present. Various scan pairs were conducted, including four vdM scans, two Beam Imaging (BI) scans, and one length scale scan. Each of these scans consists of two examinations in the x and y transverse planes. In the vdM scan, beams were separated by a distance correlating to six times transverse beam size and then moved across each other in 25 steps. Each step lasted 30 seconds and moved the beams by half of their transverse size. For the BI scans, one beam remained fixed while the other moved in 19 steps, over a distance of up to 4.5 times its transverse size. The length scale scan involved beams being separated by a constant distance and moved in both directions in five steps. The scan program during fill 8381 is shown in Fig. 5.7.

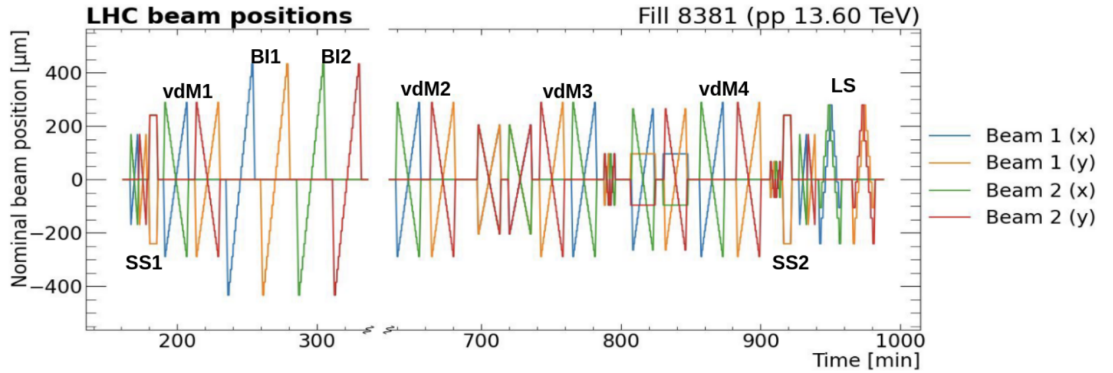


Fig. 5.7 2022 vdM calibration program. In LHC fill 8381, proton beam positions were recorded, including four vdM scans, two BI scans, one LS scan, and two SS periods [40].

The vdM calibration fit is depicted in Fig. 5.8 which depicts how the detected event rate varies as the beams are scanned across each other in the horizontal (X) and vertical (Y) directions. The rates have been fitted to a double Gaussian curve, which reflects the bell-shaped spatial distribution of the proton bunches. The peaks of these curves correspond to the maximum event rate, which occurs when the beams are perfectly overlapped. The width of the curve gives an indication of the spread of the beam in the respective direction.

In the final analysis, a floating constant is used in the fit for the background because the background from the SS1 and SS2 give inconsistent values as shown in Table 5.4.

Table 5.4 PCC background rate for five BCIDs during super separation scans 1 and 2. Average PCC background rate is calculated by averaging over all five BCIDs.

SS 1			SS 2		
BCID	Mean	SEM	BCID	Mean	SEM
282	0.03917	0.00147	282	0.07682	0.00128
822	0.03896	0.00130	822	0.077513	0.00137
2944	0.03979	0.00145	2944	0.082114	0.00178
3123	0.03788	0.00132	3123	0.075385	0.00127
3302	0.03931	0.00130	3302	0.077605	0.00139
(a) $SS1_{avg} = 0.0390 \pm 0.000613$			(b) $SS2_{avg} = 0.077902 \pm 0.00060436$		

The χ^2 statistic measures the discrepancy between the observed event rates and the values predicted by the double Gaussian fit, while ndof (number of degrees of freedom) accounts for the complexity of the fit. A value of χ^2/ndof close to 1 can be seen in the statistics box which signifies a good fit. The variation of χ^2/ndof across scans is shown in Fig. 5.9. From this plot, we can observe that the average fit quality of the data to the model, as measured by the chi-squared per degree of freedom (χ^2/ndof), is slightly above the ideal value of 1, with a mean of approximately 1.55. This suggests that the model fits the data reasonably well overall, but there may be some systematic deviation. The consistency of fit quality across different scans, both X and Y, indicates that no significant discrepancy exists between these two scanning directions within the range of values presented. The change in beam overlap width across scans is shown in Fig. 5.10. The plot reveals an asymmetry in beam overlap widths, with the X-Scans showing higher CapSigma values than the Y-Scans in all scans, indicating a larger beam width along the X-axis. The Y-Scans exhibit narrower and more uniform widths, suggesting a more stable overlap along the Y-axis. This consistent difference in the overlap widths between the X and Y scans is evident across various vdM and beam imaging scans. The PCC visible cross section is 1076 ± 0.9 (stat) mb. The bunch to bunch variation and scan to scan variation of the PCC visible cross section is shown in Fig. 5.16 and Fig. 5.17 [40].

CapSigma ratio plots of PCC with other luminometers for 2022 vdM data are shown from Fig. 5.11 to Fig. 5.15. The CapSigma ratios of PCC with BCM1F and PLT are closely centered around the ideal value of 1, indicating a high degree of measurement consistency. However, greater variability is observed in the ratios involving HFET and HFOC. The results for UTCA show moderate variability, better than HFET and HFOC but not as stable as BCM1F or PLT. Differences between X and Y scans across these luminometers indicate potential directional sensitivities or alignment issues affecting the measurements. The data mostly aligns near the 1 ratio. A data point at 1.010 has a deviation of approximately 1%

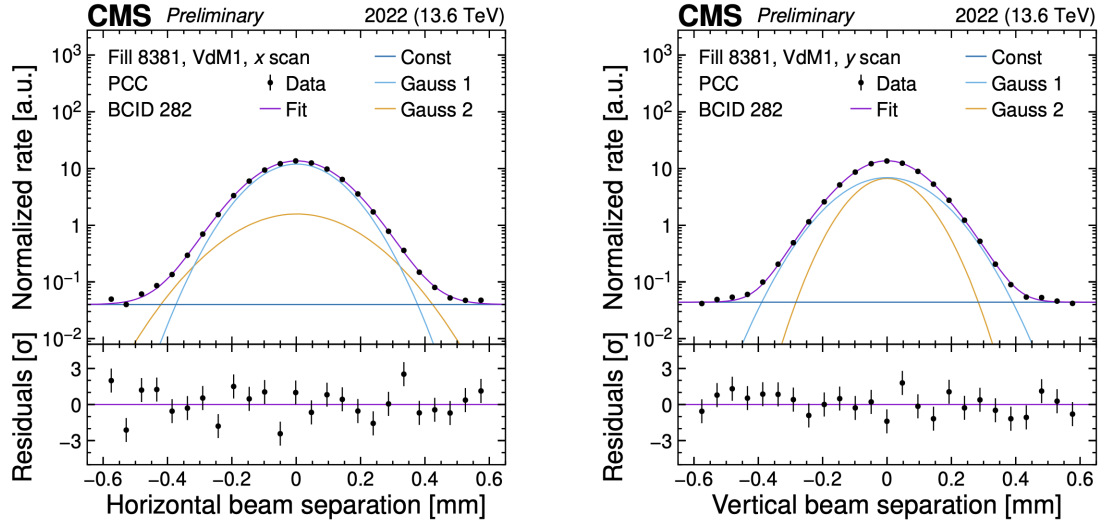


Fig. 5.8 Rates and the resulting fitted double Gaussian scan curves as a function of the beam separation for a single bunch (BCID 282) as recorded by PCC for a vdM1 scan in the x (left) and y direction (right). Beam corrections have been applied to the raw data before the fit.

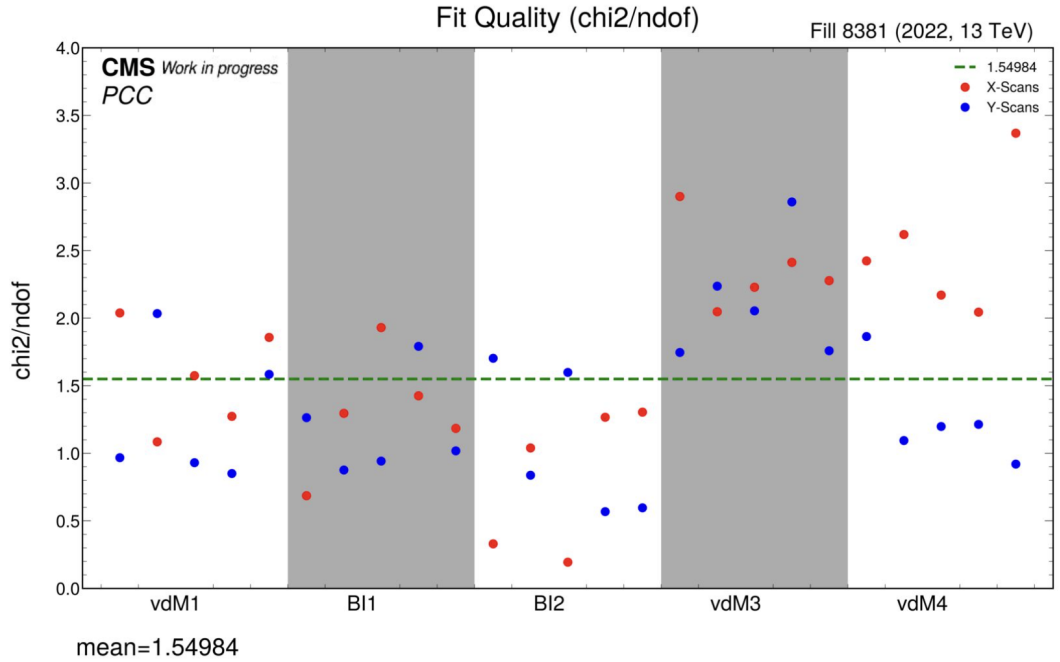


Fig. 5.9 χ^2/ndof for all vdM and imaging scans.

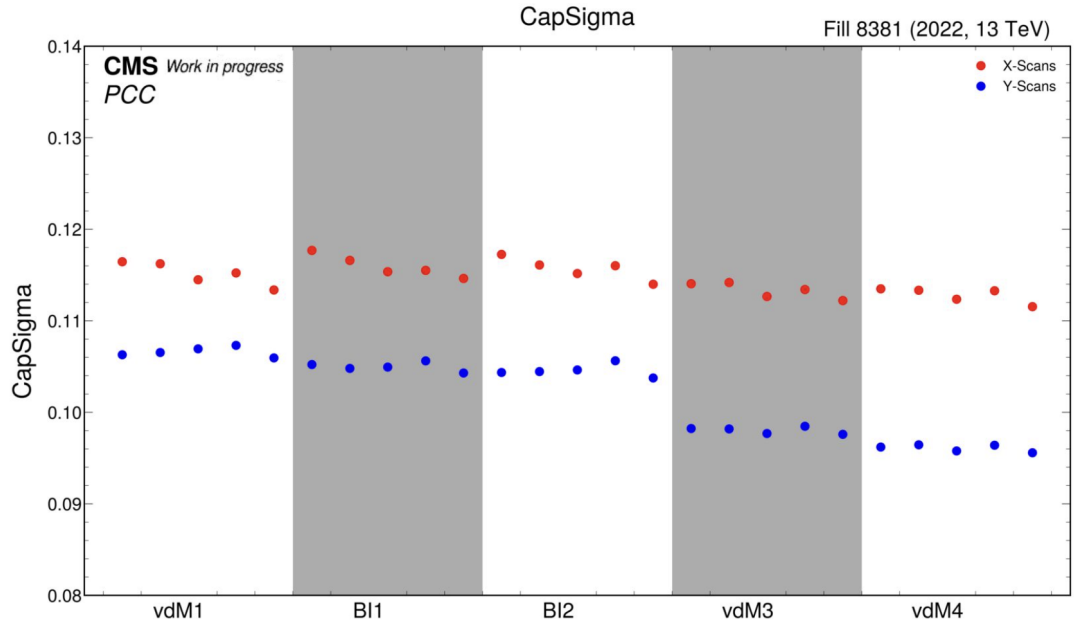


Fig. 5.10 Beam overlap widths for each vdM and imaging scans.

above the expected value, 1.015 is 1.5% above expected value and a data point at 0.985 has a deviation of approximately 1.5% below the expected value. Uncertainty in CapSigma ratio can be used to determine consistency in the visible cross section measurement for different luminometers.

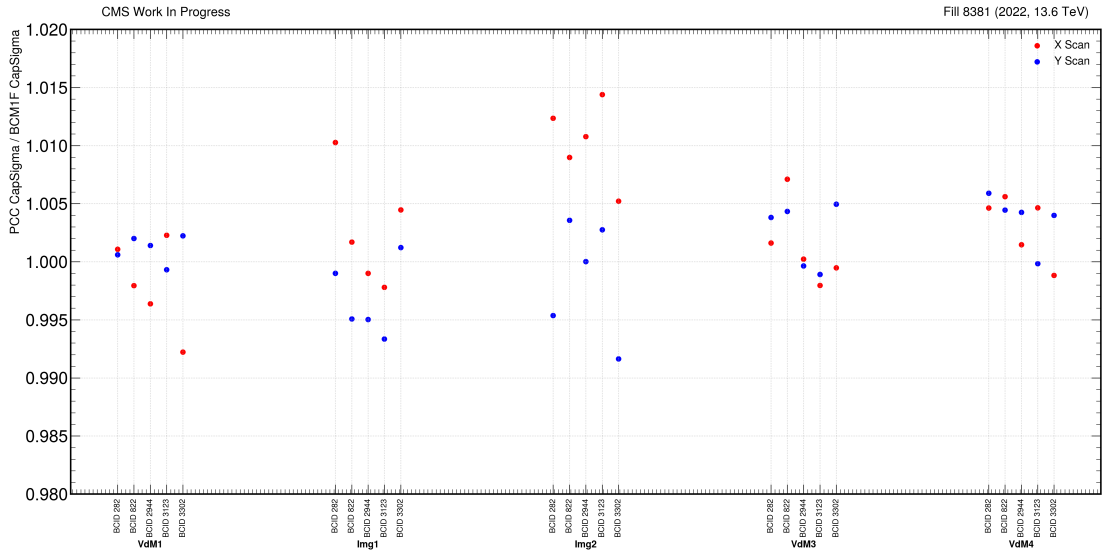


Fig. 5.11 Beam overlap widths ratio PCC/BCM1F for each vdM and imaging scans.

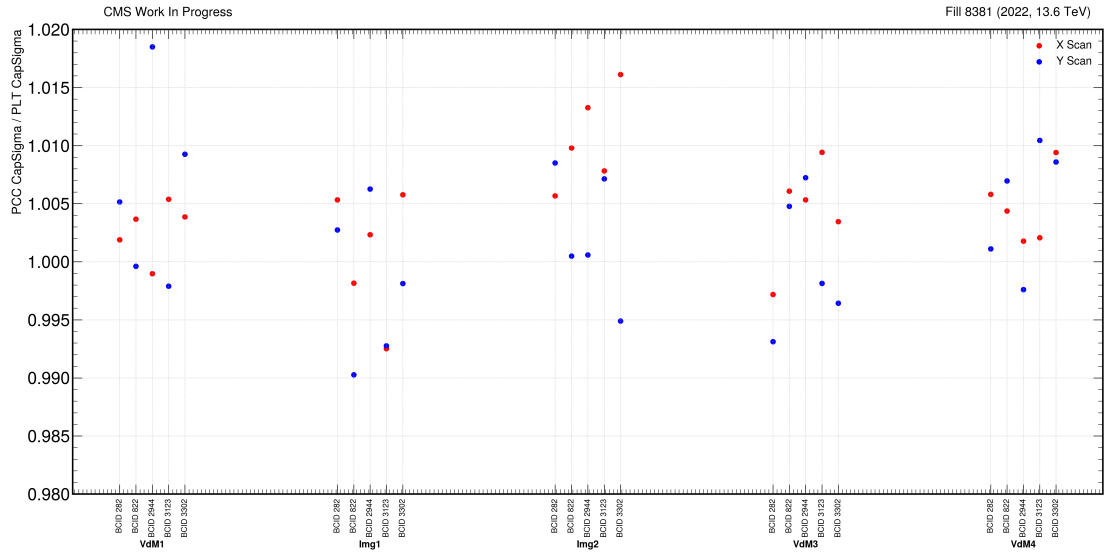


Fig. 5.12 Beam overlap widths ratio PCC/PLT for each vdM and imaging scans.

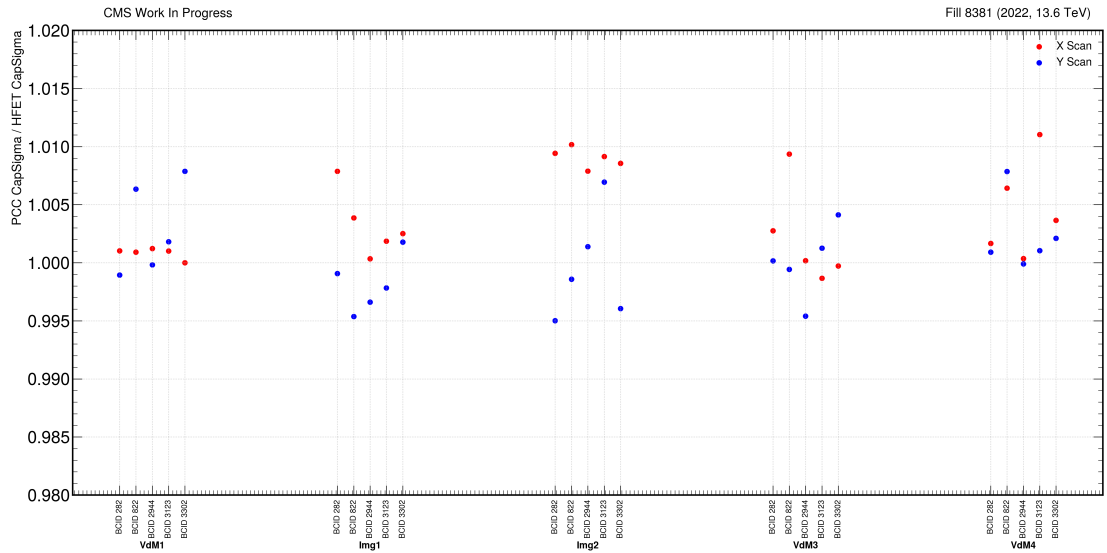


Fig. 5.13 Beam overlap widths ratio PCC/HFET for each vdM and imaging scans.

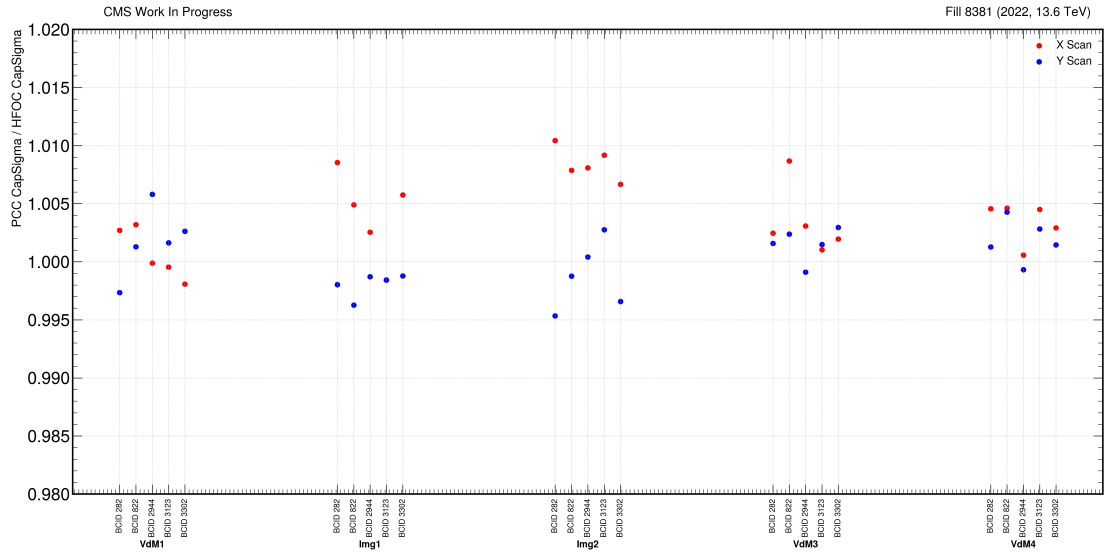


Fig. 5.14 Beam overlap widths ratio PCC/HFOC for each vdM and imaging scans.

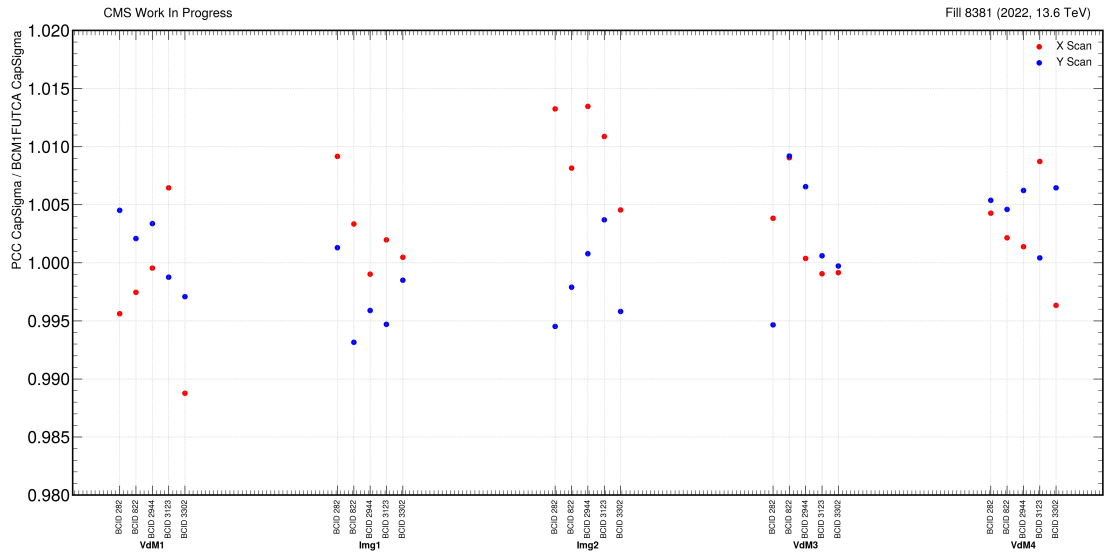


Fig. 5.15 Beam overlap widths ratio PCC/BCM1FUTCA for each vdM and imaging scans.

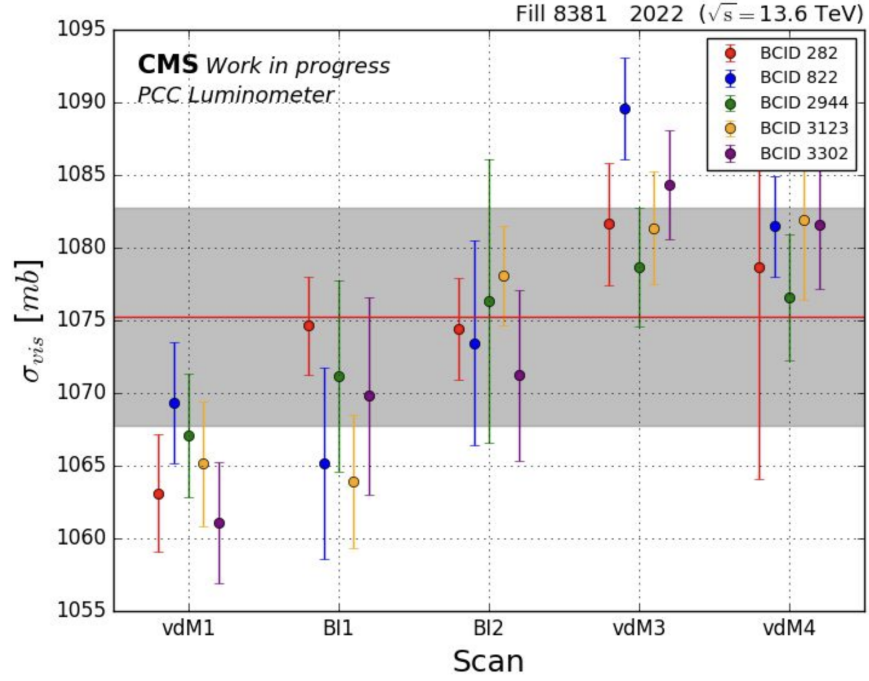


Fig. 5.16 Bunch to bunch variation of PCC visible cross section where the red line is the average value. Red band depicts the $\pm$ one RMS of the values.

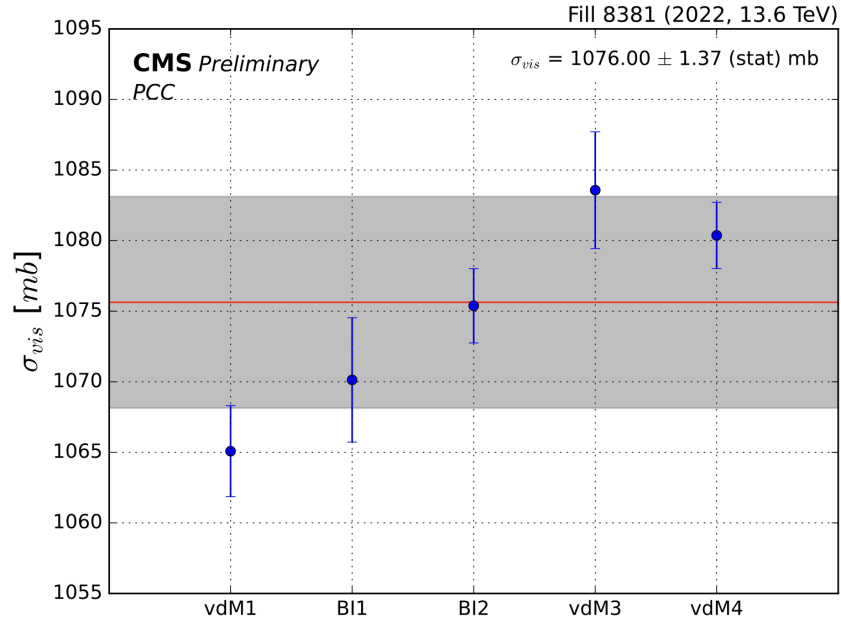


Fig. 5.17 Visible cross section per scan where red line shows the average value. Red band depicts the $\pm$ one RMS of the values.

5.4 Luminosity for physics fills

The fill cycle in Run 3 includes a leveling part in order to control the very high pileup achieved with upgraded LHC beam optics. The fill luminosity profile for fill 8395 during 2022 data taking is shown in Fig. 5.18. This fill consists of

- 2450 colliding bunches
- 2600 lumi sections
- peak luminosity of 19000Hz/ub

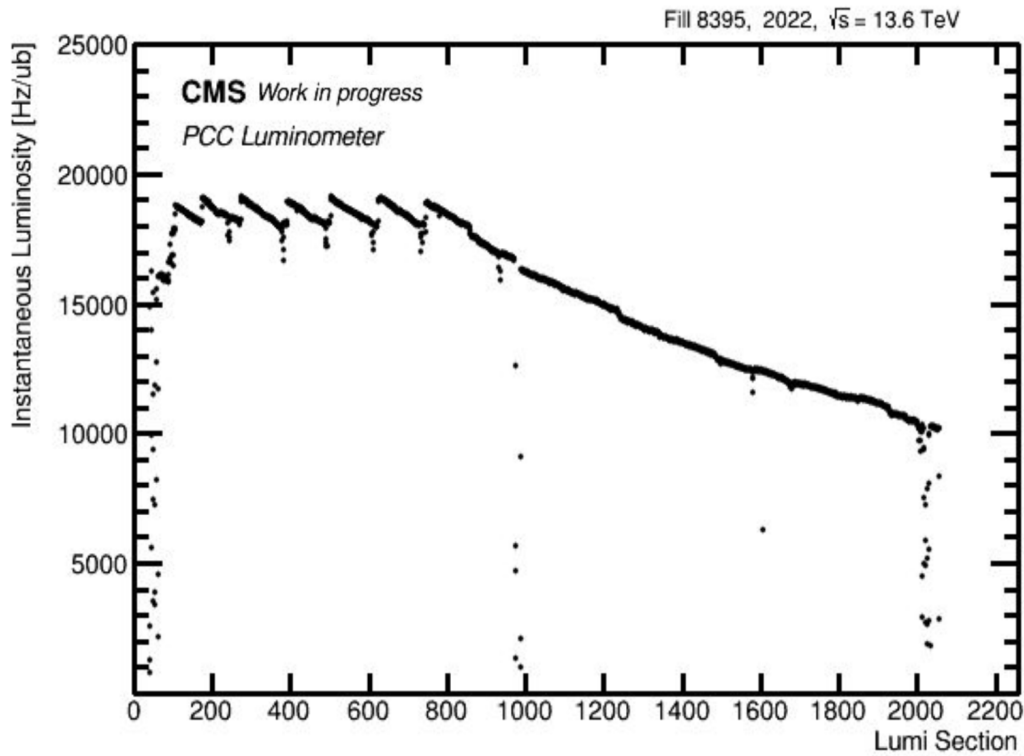


Fig. 5.18 PCC luminosity profile for fill 8395.

5.4.1 Afterglow background corrections

Corrections are introduced to the PCC measurement to mitigate background effects. The considered background contributions for physics fills are:

- **Afterglow (Out-of-time counts):**

- **Type 1:** Activations from the preceding bunch's pixels. Rectified by observing subsequent bunch clusters.
- **Type 2:** Due to the detector's material activation, modeled using an exponential decay function for non-colliding bunches post-train.

Both pedestal and type-1 parameters are determined in each 50 LS blocks.

Type-2 parameters, derived from a preceding study using Random trigger data, are presumed to remain constant during the year. The fitting template is given by:

$$F(x) = \sum_{k=0}^{N_{bcid}} N_k \left[(x - k == 0) + \alpha \cdot (x - k == 1) + A \cdot e^{-\tau \cdot (x - k - 1)} (x - k \geq 1) \right] \quad (5.1)$$

with k denoting the colliding bunch crossing and x indicating the histogram bin. 2022 PCC afterglow model uses run number 361957 for fitting the type 1 and type 2 afterglow effect in the PCC raw data as shown in Fig. 5.19. The model consists of a parameter for type 1 afterglow correction and an exponentially decaying function with two parameters, amplitude and decay width, to model type 2 afterglow correction. The fit function is summed over all bunch crossings. Fit performed for 4 wagon train is shown in Fig. 5.20 in run 361957 to compute type 2 afterglow amplitude and decay width. The values obtained for type 2 afterglow amplitude and decay parameters are 0.0008406 and 0.01047 respectively [40].

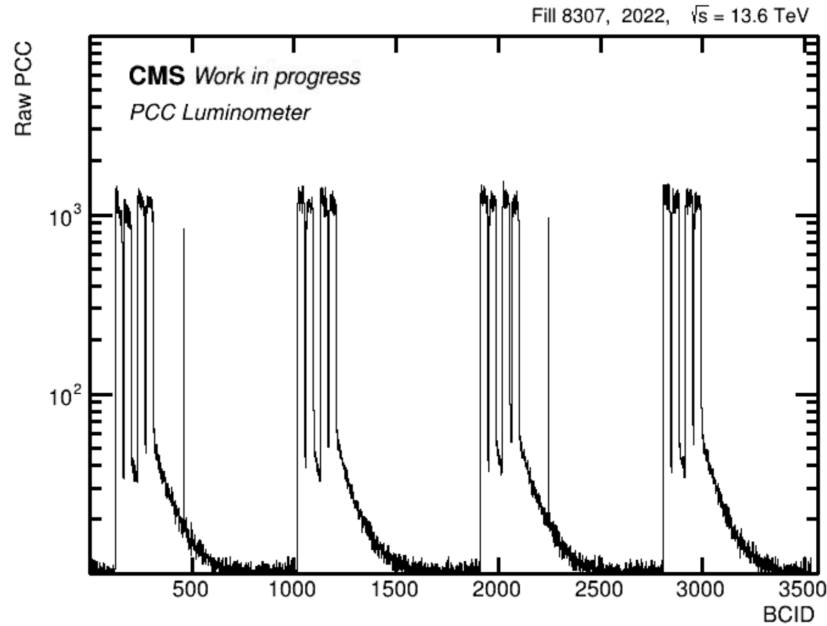


Fig. 5.19 PCC per bx for fill 8307 for one 50 LS block. The first and ninth train are used to fit the afterglow tail.

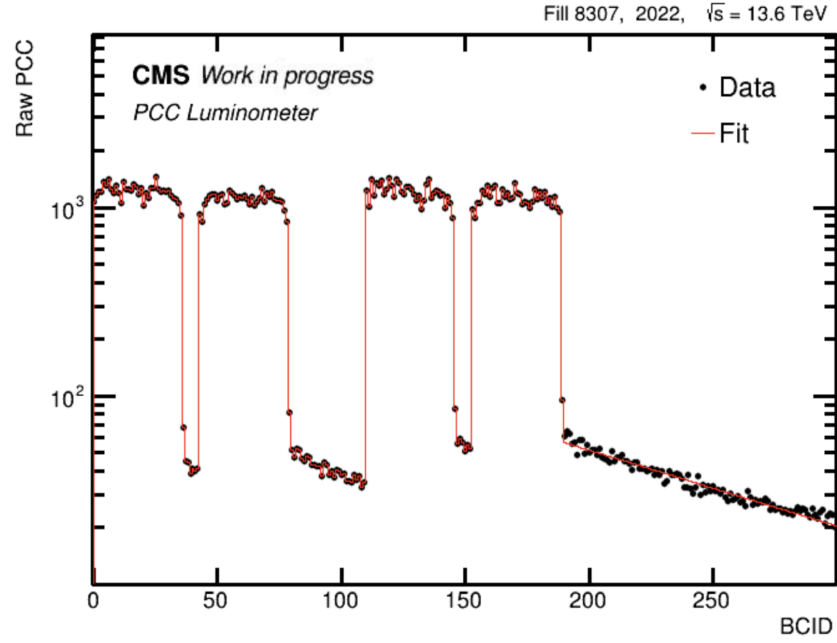


Fig. 5.20 Fit to 4-wagon train.

Background estimations are obtained from the Random trigger datasets, processed in 50 LS blocks. The corrections, determined from these backgrounds, are subsequently applied to the zero-bias data. While Type 1 residuals are minimal, Type 2 shows a slight deviation of around 0.2% as shown in Fig. 5.22.

Comparable patterns are observed for 2022 periods E, F and G. During periods C and D, data was limited to the "AICALumiPixelsEXPRESS" stream with an outdated module selection. Consequently, direct re-evaluation became unfeasible. As a solution, stored afterglow corrections evaluated in the CMS prompt calibration stage, corrected by a factor 1.008 from period E data, were applied.

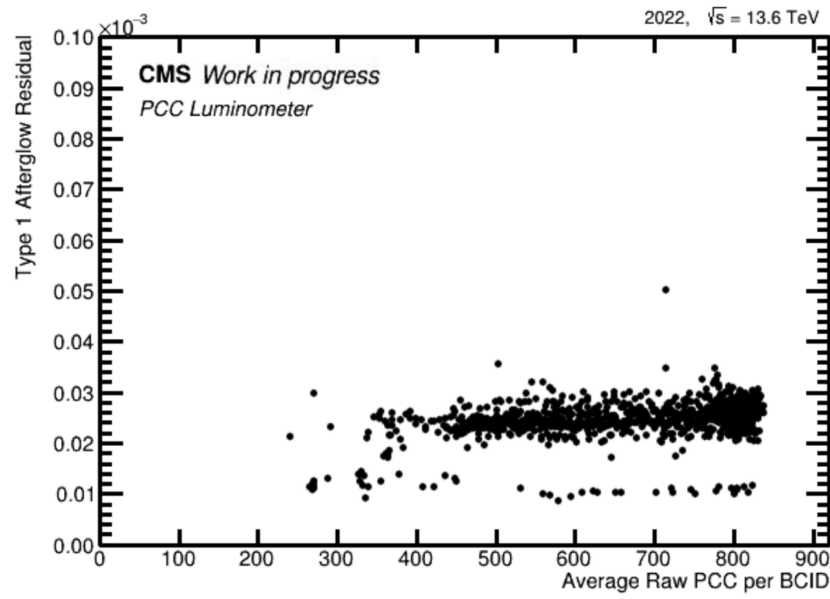


Fig. 5.21 PCC afterglow correction type 1 residual as a function of instantaneous luminosity for period Run 2022F. The residual fraction is given by the ratio of the luminosity of the first empty bunch immediately following a colliding bunch to the luminosity of the colliding bunch.

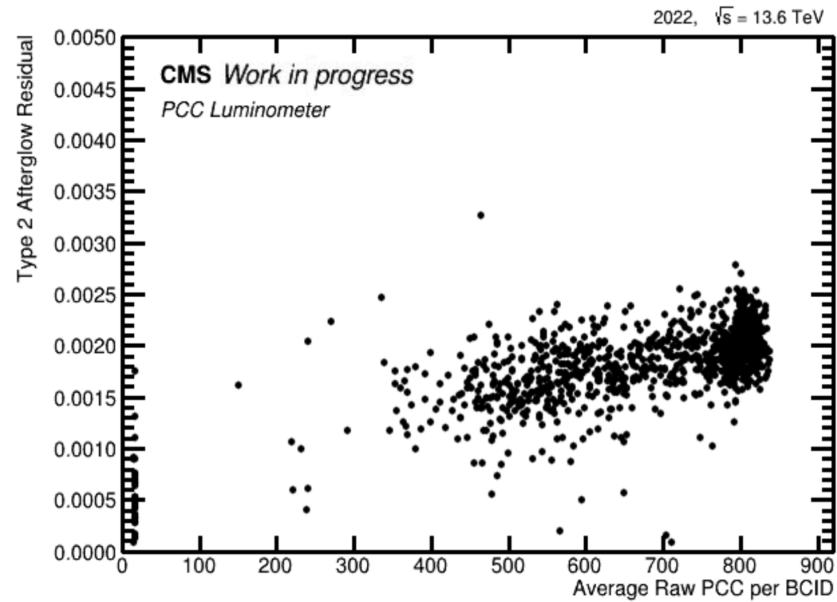


Fig. 5.22 Type 2 residual as a function of instantaneous luminosity for period 2022F. These are given by the ratio of the luminosity of the second and following empty bunches after a colliding bunch to the luminosity of the colliding bunch.

5.5 PCC instantaneous and integrated luminosity

PCC instantaneous luminosity provides a measure of the collider performance and is graphically represented in Fig. 5.23. Each fill in the graph consistently displays a sequence of characteristics related to luminosity. The process initiates with ramp-up periods, where a swift increase in luminosity is evident. This surge is subsequently followed by leveling parts, where luminosity stabilizes and plateaus. As the fill progresses, burn-off parts emerge, marked by a gradual decline in luminosity. Interspersed within the graph are notable, sharp drops to lower luminosity levels, characteristic of emittance scans. As each fill reaches its culmination, pronounced drops are observable, signifying the end of fill events. This cyclical pattern is evident across all fills, underscoring the systematic nature of the process. Integrated luminosity accumulates this data over time [40].

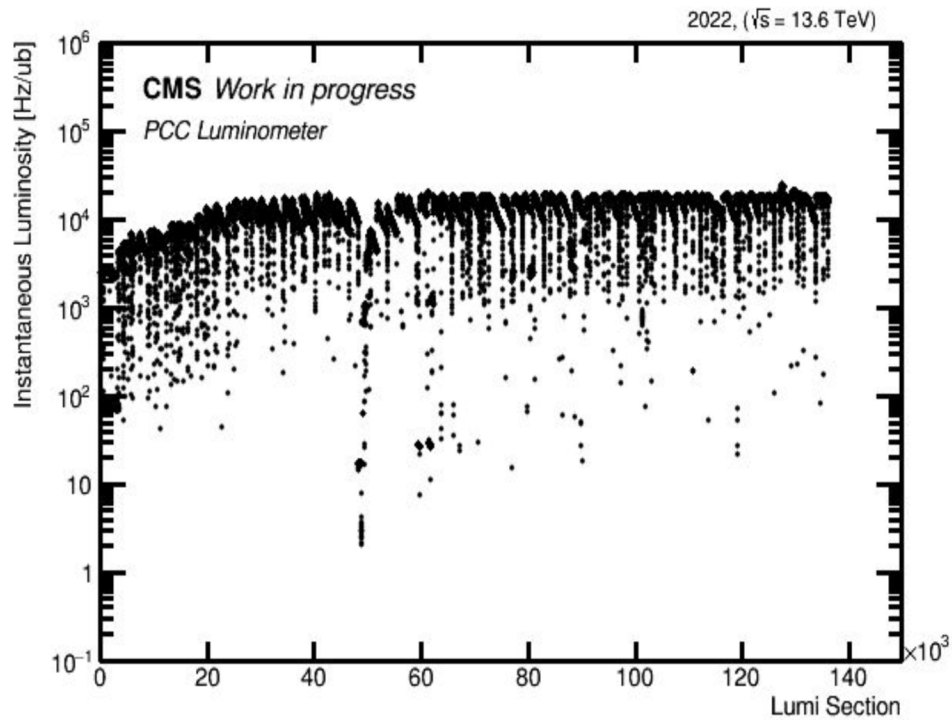


Fig. 5.23 PCC instantaneous luminosity as a function of lumi section for entire 2022 year.

5.6 Systematic uncertainties

Various sources of systematic uncertainty come into play, affecting the precision of the results. These uncertainties arise from factors such as detector calibrations, alignment, temporal drifts in the detector response, modeling of the beam conditions, and potential

nonlinearities in the detector response. Each of these factors necessitates careful calibration, modeling, and validation processes to ensure the highest accuracy in the luminosity measurement.

5.6.1 vdM calibration uncertainties

- **XY-factorization:** In the vdM calibration, the luminous area estimation, based on beam shapes, can lead to the "factorization bias." Methods to study factorization bias are
 - **Beam-Imaging Method:** By using reconstructed collision vertices, this method estimates actual beam densities, which helps in refining the vdM-based luminous area. The following equation describes the relationship between the number of interaction points (vertices) and the proton densities of two beams at specific positions.

$$N_{\text{vertices}}(x, y; \Delta x) \propto \rho_1(x + \Delta x, y) \cdot \rho_2(x, y) \otimes V \quad (5.2)$$

where

- * $N_{\text{vertices}}(x, y; \Delta x)$: Represents the number of vertices or interaction points at a given beam separation in the x and y directions. The term Δx indicates the change or step in the x-direction.
- * $\rho_1(x + \Delta x, y)$ and $\rho_2(x, y)$: Represent the proton density distributions of the two beams at specific positions. The densities indicate how many protons are present at a particular point in space.
- * $\otimes V$: Represents a convolution operation with V , the vertex resolution. It's a mathematical way to combine two functions to produce a third function, used here to account for the limitations in measuring the exact position of the vertices due to the resolution of the detectors.

Combining all steps, we get

$$\begin{aligned} \sum_{\Delta x} N_{\text{vertices}}(x, y; \Delta x) &\propto \sum_{\Delta x} [\rho_1(x + \Delta x, y) \cdot \rho_2(x, y)] \otimes V \\ &\approx \int_{\Delta x} [\rho_1(x + \Delta x, y) \cdot \rho_2(x, y)] \otimes V d\Delta x \end{aligned} \quad (5.3)$$

The number of interaction points (vertices) observed depends on the proton densities of the two beams at specific positions, the separation between the beams in the x and y directions, and the precision with which these interaction points can be measured. By studying the change in the number of interaction points as the beams are moved closer or further apart, we can know about the proton densities of the beams and their distribution in space. The convolution with V ensures that the measurements are adjusted for the limitations of the detectors.

- **Diagonal Scans:** Moving the beams at a 45° angle to the standard vdM direction in diagonal scans captures data across both x and y dimensions at the same time. This approach provides a unique view of how protons overlap and distribute in a two-dimensional plane. Instead of just seeing a linear view from one direction, the diagonal movement offers a comprehensive picture of the spread and patterns of protons in 2D.
- **Offset Scans:** In offset scans, the added separation in the direction not being actively scanned gives additional data points that wouldn't be captured in a standard vdM scan. This added separation means that the scan captures proton densities at slightly shifted positions. When combined with the regular vdM scan data, it offers a more detailed view of the proton distribution in two dimensions, helping to understand variations and potential irregularities in the 2D proton density.
- **Bunch to bunch uncertainty:** The "bunch to bunch variation of PCC visible cross section" refer to how much the measured visible cross-section (and thus, the measured luminosity) changes from one bunch crossing to another as shown in Table 5.5. Variations could arise from different factors such as varying numbers of protons per bunch, spatial distribution of protons within the bunches, and the specific conditions of the pixel detector at the time of each bunch crossing. If significant variations are observed, it may be necessary to adjust the analysis to account for these differences.

Table 5.5 Bunch to bunch variation of visible cross section (as shown in Fig. 5.16). N_b is the number of bunches in the vdM scan. SEM is the standard error on the mean.

Scan	σ_{vis} [mb]	RMS [mb]	(SEM/ σ_{vis}) [%]
vdM1	1065.09	2.89	0.1286
Img1	1070.14	3.94	0.1746
Img2	1075.38	2.35	0.1040
vdM3	1083.58	3.70	0.1616
vdM4	1080.37	2.09	0.0920

- Scan to scan uncertainty: PCC visible cross section can exhibit change from one scan to the next. These variations could be due to slight changes in the experimental conditions. The results for each scan are plotted after averaging over five BCIDs as shown in Fig. 5.17. Each point on this graph represent the result from one scan. A red line is drawn to indicate the average value of the visible cross-section over all the scans. This average value provides a useful comparison point to evaluate the consistency of the individual scan results and identify any potential anomalies or systematic errors.
- Background subtraction: Machine-induced backgrounds are studied using two super separation scans 1 and 2. A floating constant is used in each fit and the uncertainty due to the background level is directly propagated to the result in the visible cross section values.

5.6.2 Integration uncertainties

- Stability: Stability systematic uncertainties, often stem from time-variable factors such as detector aging, radiation damage, and noise fluctuations. Detectors used in high-energy physics are subject to a harsh radiation environment which can cause performance degradation over time. This degradation, if not accurately accounted for in the models, can introduce systematic uncertainties. The stability systematic uncertainty is quantified by the standard deviation of the luminosity ratio from the best and second-best luminometer. A larger spread in measurements, indicated by a higher standard deviation, represents a greater systematic uncertainty due to temporal shifts in detector performance or environmental conditions. Fig. 5.24 depicts the time evolution of ratio of luminosity values obtained from the PCC and the HFET luminometer. Each point on the x-axis represents a lumi section - a discrete time interval of data collection. The plot shows the variation in luminosity measurements across the data-taking period. This is crucial in calculating the systematic uncertainty related to stability, as any temporal fluctuations in luminosity could potentially indicate a source of uncertainty in the measurements. Fig. 5.25 shows the projection of the luminosity ratio using 50 lumi section binning strategy [40].

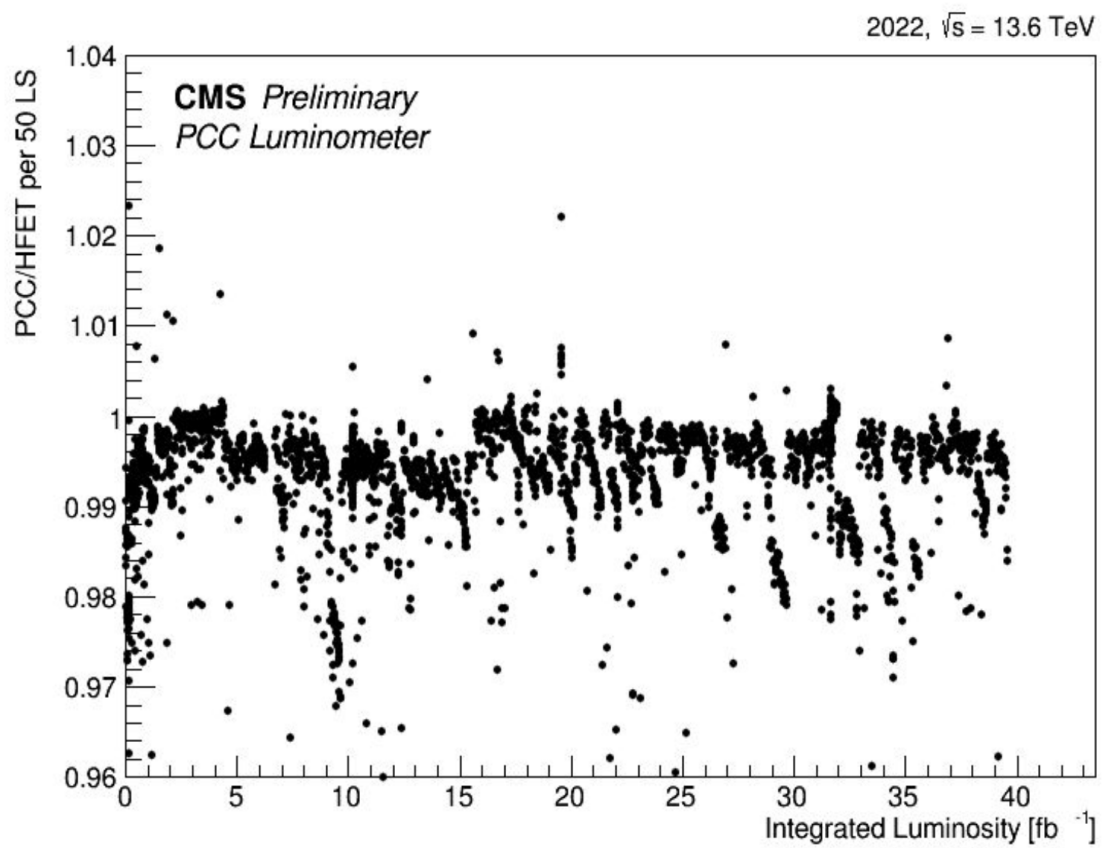


Fig. 5.24 Profile of the PCC/HFET luminosity as a function of integrated luminosity.

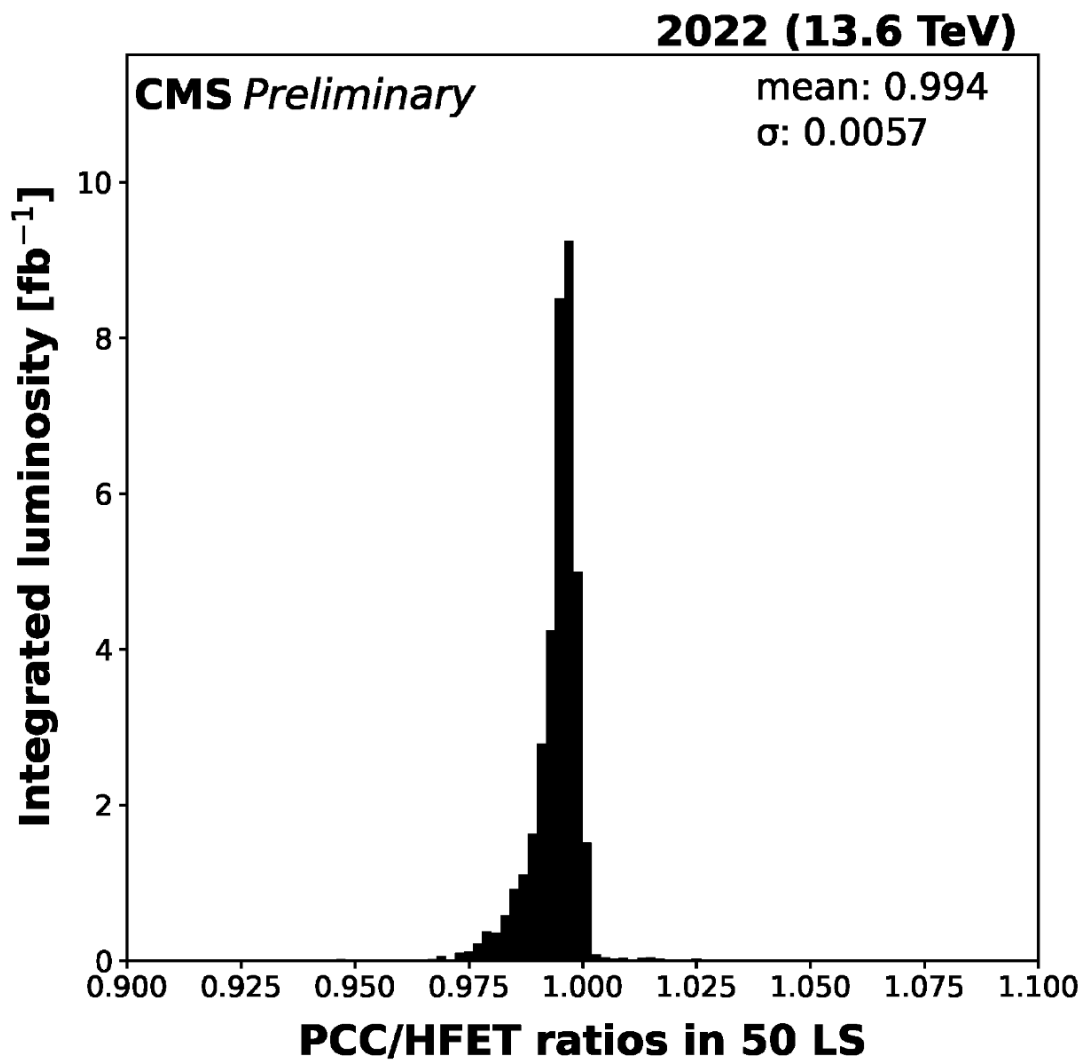


Fig. 5.25 Distribution of the ratio of PCC/HFET luminosity evaluated per 50 lumi section blocks.

- **Linearity:** Detectors in high-energy physics experiments can display varying responses at different luminosity levels, leading to non-linear behavior, especially at high luminosities. To quantify the linearity systematic uncertainty, the slope variability of the detector response against luminosity levels can be analyzed. This, combined with the luminosity range, provides a measure of the expected rate variability due to non-linearity, representing the linearity systematic uncertainty [40].

The plot in Fig. 5.26 shows the ratio of luminosity values obtained using the PCC method to those from the HFET luminometer. The values are plotted as a function of HFET luminosity. The goal of this graph is to examine potential changes in the detector response across different luminosity levels. If the detector response was perfectly linear, we do expect the ratio to remain constant across the range of HFET luminosity values. Deviations from a constant ratio indicate non-linearity in the detector response, thereby contributing to systematic uncertainties.

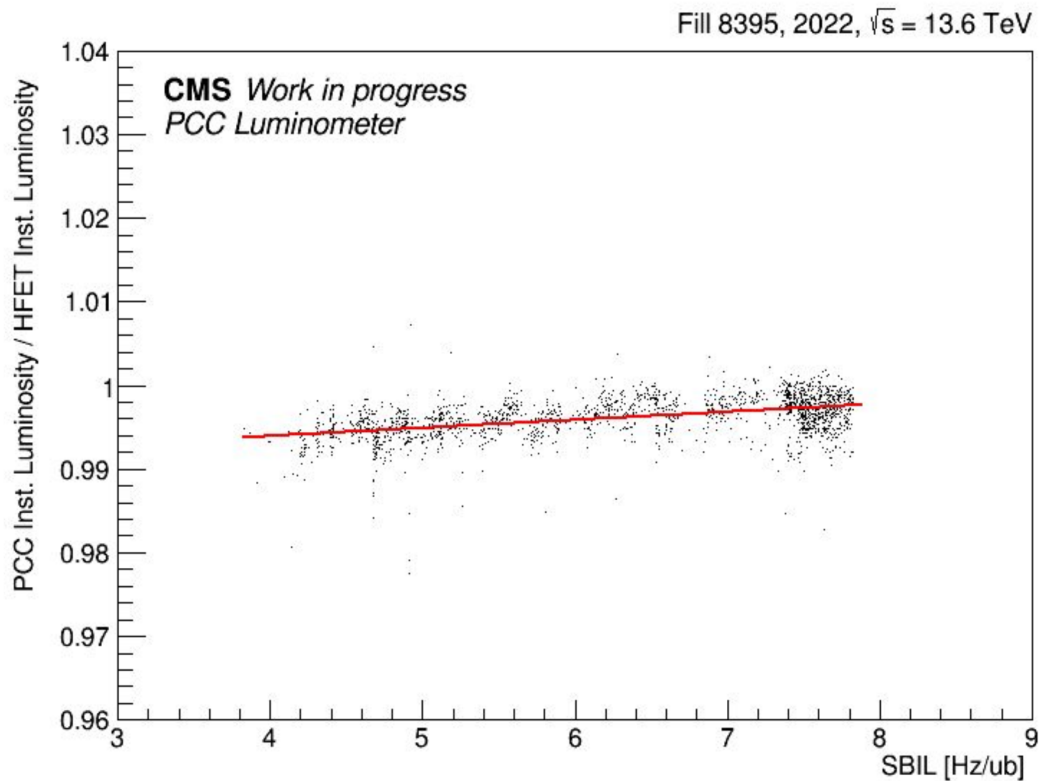


Fig. 5.26 Ratio of PCC/HFET luminosity plotted as a function of HFET luminosity to determine change in detector response over different luminosity levels. Slope is 0.00114 ub/Hz.

- **Afterglow:** Systematic uncertainties from afterglow backgrounds are derived from the means of type 1 and type 2 afterglow residuals. These are determined by comparing the luminosity of the immediate empty bunch after a collision to the

colliding bunch luminosity and comparing subsequent empty bunches' luminosity to the colliding bunch, respectively.

Table 5.6 provides a detailed breakdown of the systematic uncertainties associated with the luminosity measurement for the year 2022. Each row represents a specific correction factor, while the corresponding column indicates its associated uncertainty as a percentage.

Table 5.6 Systematic uncertainty in 2022 PCC luminosity measurement (%) [40]

Source	Uncertainty (%)
Calibration	
Beam current	0.2
Ghost and satellite charges	0.2
Orbit drift	0.1
Residual beam positions	0.3
Beam-beam effects	0.4
Length scale	0.1
Factorization bias	0.8
Scan-to-scan variation	0.5
Bunch-to-bunch variation	0.1
Cross-detector consistency	0.4
Integration	
Afterglow corrections	0.2
Cross-detector stability	0.6
Cross-detector linearity	0.5
Calibration	1.2
Integration	0.8
Total	1.4

Chapter 6

TEPX luminometer for HL-LHC

The Phase II upgrade of the CMS Tracker is a crucial project undertaken to maintain the effectiveness of the CMS experiment during the High Luminosity LHC (HL-LHC) phase, which is expected to start in 2029 [41]. The HL-LHC will significantly increase the instantaneous luminosity, leading to a higher number of proton-proton collisions per bunch crossing. Instantaneous luminosity will increase to an unprecedented value of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ which corresponds to 200 proton-proton collisions per bunch crossing, on average. This higher collision rate poses several challenges, including increased radiation levels, higher data rates, and more complex event environment. The Run 2 pixel detector will not be able to handle these extreme radiation environment, resolve nearby particle tracks and operate properly to give a reliable estimate of the instantaneous luminosity for such a high pileup. That is why it will be replaced by a new pixel detector. The Phase II upgrade of the CMS tracker comprises of two main components: the Inner Tracker (IT) and the Outer Tracker (OT) [42]. The Inner Tracker consists of three main sub-components: the Tracker Endcap Pixel detector (TEPX), the Tracker Forward Pixel detector (TFPX), and the Tracker Barrel Pixel (TBPX) detector as shown in Fig. 6.1 [43].

The Data Acquisition (DAQ) system for the Phase II CMS Tracker must handle the increased data rates and complexity associated with the HL-LHC. The HL-LHC is expected to achieve a peak luminosity which is around 5-7 times higher than the current LHC design luminosity which the DAQ system must handle. The upgraded CMS Tracker will generate a large amount of data due to the increased granularity of the pixel and strip sensors. The data rates from the tracker modules are expected to be several terabits per second (Tbps) during the HL-LHC operation. The Level-1 Trigger system in the Phase II Upgrade is designed to accept events at a rate of up to 750 kHz. The DAQ system must handle the transmission of trigger primitives to the Level-1 Trigger system and buffer the full event data until the trigger decision is made. In the Inner Tracker readout system, control signals are sent to the inner tracker at 160 Mb/s to coordinate its detection processes. It, in turn,

outputs data at 1.28 Gb/s per chip to the LpGBT, which acts as a data consolidator for up to three chips. This data is then relayed optically to the DTC board, which operates a bidirectional data exchange: 2.5 Gb/s optical down-links channel control information back to the Inner Tracker, while 10 Gb/s up-links carry processed readout data and monitoring details to the DAQ and control system. Moreover, the DTC can interface with a Lumi processor via an optional link, designed for a substantial data transfer rate of approximately 4x25 Gb/s, to handle specialized luminosity data processing. Finally, the DAQ and control system, which receives the comprehensive data at a substantial rate of 25 Gb/s, undertakes the final processing and storage of data.

The TBPX occupies the central region along the z -axis from 0 to just below 300 mm, employing 1×2 modules (modules with two readout chips) and 2×2 modules (modules with four readout chips) arranged in four layers parallel to the beam. The TFPX extends from approximately 250 mm to 1400 mm in the z -direction, with 1×2 and 2×2 modules. The TEPX covers a range from about 1700 mm to over 2600 mm and includes 1×2 and 2×2 modules. Collectively, these sub-detectors boast around 1.947 billion pixels across 13,488 pixel chips, spanning a silicon area of 4.87 square meters.

The TEPX consists of four double-disk per side with each double-disk consisting of five rings of modules as shown in Fig. 6.2. The rings have 20, 28, 36, 44 and 48 modules respectively. The first two inner rings are equipped with 1×2 modules, while the more extensive 2×2 modules are mounted on the three outer rings. This design is further enhanced by the arrangement of modules in four layers as shown in Fig. 6.3. This allows for modules to be mounted on both the front and back sides of a disk, creating an overlap in the r - ϕ direction. By mounting modules at varying radii on the two disk that form each double-disk, overlap in the radial direction (r) is also accomplished. TEPX will have better radiation tolerance, increased granularity, improved two-track separation, improved estimation of hit rate and statistical precision, extending tracking acceptance beyond $|\eta| = 4$.

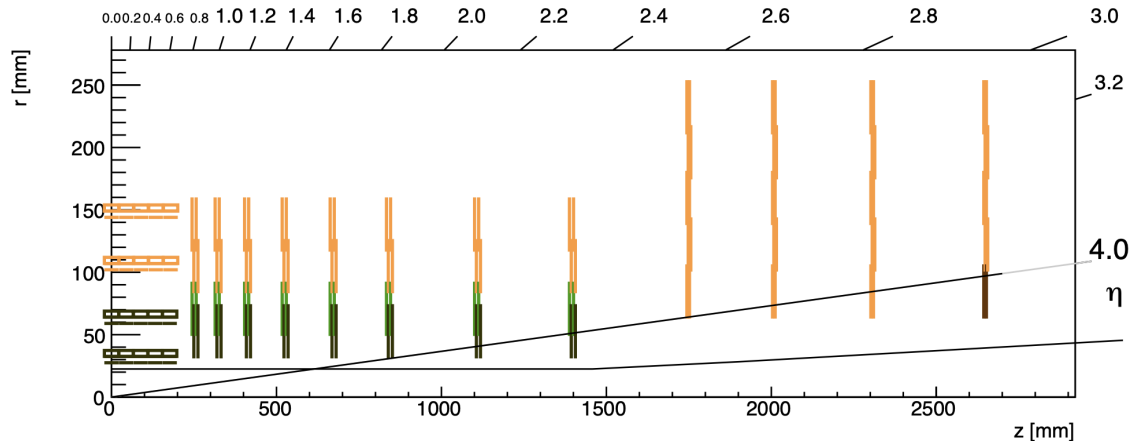


Fig. 6.1 A layout of the CMS Phase II Inner Tracker showing four TEPX disks, eight TFPX disks and four TBPX layers [44].

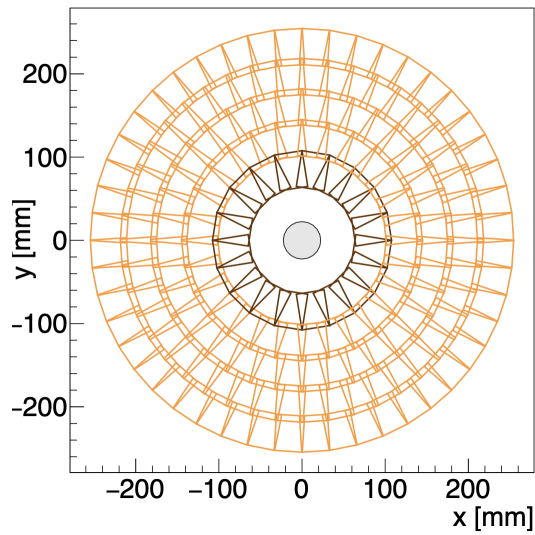


Fig. 6.2 View of one TEPX double-disk in the $r - \phi$ plane; individual pixel modules on two planes (double-disk) and five rings are outlined by orange rectangles [44].



Fig. 6.3 R-Z view of the TEPX double-disk showing the four layers of modules L1, L2, L3 and L4. Layer 1 and 3 has Ring 1, 3 and 5 modules, Layer 2 and 4 has Ring 2 and Ring 4 modules. The planes are separated in z by about 1 cm. The first plane holds modules on both front and back faces, with alternating rings to cover the gaps in r ; the second plane holds modules in the same way as the first plane, but with an offset in ϕ to cover the gaps in ϕ .

6.1 TEPX Luminometer

TEPX is designed to function as a high-precision online bunch-by-bunch luminometer, primarily using pixel cluster counting for luminosity measurement, a method involving the detection and counting of pixel clusters formed by charged particles from the proton collisions. Additionally, TEPX benefits from coincidence counting due to overlapping modules which enhances accuracy and enables systematic studies. TEPX features a sophisticated dedicated trigger system for sampling all relevant bunch crossings in an unbiased manner. This system operates at a baseline trigger rate of 75 kHz, which is 10% of the 750 kHz allocated for physics data. TEPX adapts to different operational conditions: during standard physics runs, it maintains a baseline luminosity trigger rate of 75 kHz, while during vdM scans, this rate can significantly increase, potentially up to 1 MHz [45].

TEPX Disk 4 Ring 1 (D4R1) is located in the innermost ring of the last double-disk of the TEPX and it is exclusively designed for measuring luminosity and beam-induced background (BIB). D4R1 is optimally placed due to its low radius, large active area, and high z position, making it highly efficient for these measurements. The D4R1 operational mode is distinct from the rest of TEPX [46]. It employs the entire available trigger rate and readout bandwidth, which varies based on operational mode. This capability ranges from a trigger rate of 825 kHz (similar to the rest of TEPX) up to several MHz, limited by readout bandwidth and the available e-link capacity. In nominal physics conditions, the

baseline trigger rate for D4R1 is 825 kHz, while in van der Meer (vdM) conditions, it is 2 MHz, with the potential to reach between 5 and 10 MHz in certain scenarios.

6.2 TEPX Luminometer Simulation

Simulated data samples for Phase II include full CMS detector description and use official CMS software (version CMSSW_10_6_0_patch2) which calls GEANT4 for detector simulation [47]. Pixel clusters are reconstructed using the standard CMS reconstruction algorithms [48]. It is done by converting raw data to digi format (row, column, charge) and then form clusters from digis. The samples used in simulation use single-neutrino generated events overlaid with a variable number of minimum-bias events (events with any amount of real energy detected in CMS) to simulate different pileup values. The number of simulated events used in this analysis for each pileup value is shown in Table 6.1.

Table 6.1 Events processed for each pileup

Pileup	Number of events processed
0.5	100600
1	87400
1.5	74900
2	66200
10	21800
30	10000
50	5000
100	5000
140	5000
200	5000

Fig. 6.4 shows the location of TEPX clusters in Disk 4 in the XY plane (Z is the direction of the beam) from a simulated sample with a pileup of 200 [49]. It consists of five concentric rings that are color-coded to indicate the density of clusters within the detector. It is transitioning from blue (low density) to red (high density), with the hottest regions indicating the overlap modules within the rings. The granularity of the histogram is set to 1000 for both axes and a bin size of 0.1 mm, allowing for a detailed visualization of the clusters across the disk.

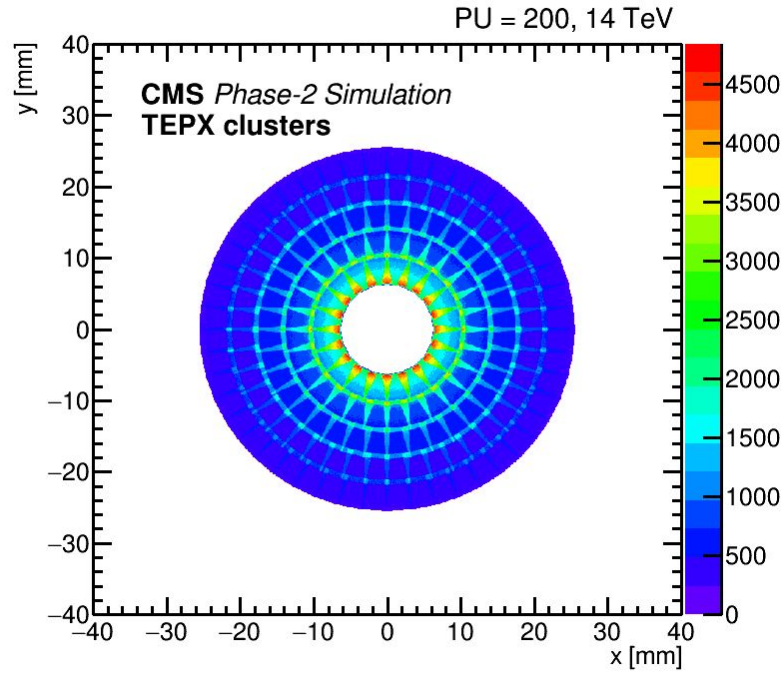


Fig. 6.4 TEPX cluster map in the XY plane for pileup 200 simulated sample having 5000 events. It shows clusters in one TEPX disk consisting of 5 rings. Hot regions are showing the module overlap. x bin size is 0.1 mm and y bin size is 0.1 mm.

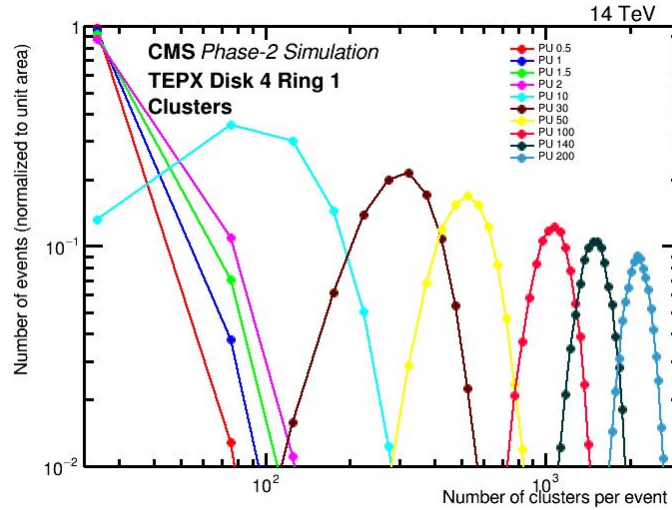


Fig. 6.5 Distribution of number of clusters for TEPX Disk 4 Ring 1 for all pileup samples.

6.2.1 Linearity of TEPX clusters

Linearity is one of the systematic uncertainties in the calculation of instantaneous luminosity and PCC visible cross section σ_{vis} . A linear relation between the mean number of clusters and pileup (PU) imply that $\langle N_{cl/pp} \rangle = \frac{\langle N_{cl} \rangle}{\mu} = \frac{\sigma_{vis}}{\sigma_{pp}}$, $\langle N_{cl} \rangle = \frac{\sigma_{vis}}{\sigma_{pp}} \mu$. Linearity indicates that the PCC visible cross section σ_{vis} does not depend on the per bunch instantaneous luminosity (ideal luminometer). In ideal scenario, σ_{vis} is not dependent on pileup, but this a potential problem with the luminometer. A non-linear relation $\langle N_{cluster} \rangle = \alpha(PU)^\gamma, \gamma \neq 1$ would add non-linear terms in the rate equation $R = \sigma_{vis} L_{inst}$ and cause σ_{vis} to vary with the per bunch instantaneous luminosity and pileup values. TEPX luminometer proposed for Phase II shows excellent linearity over entire pileup range.

The number of clusters per pp collision in Disk 4 Ring 1 varies from 0 to 2600 as a function of pileup. At pileup 200, mean number of cluster per pp collision is 2200 as shown in Fig. 6.5. The distributions follow Poisson statistics. Linearity results for simulated TEPX clusters from low to high pileup values are shown in Fig. 6.6 and Fig. 6.7. Non-linearity is within 1% for entire pileup range.

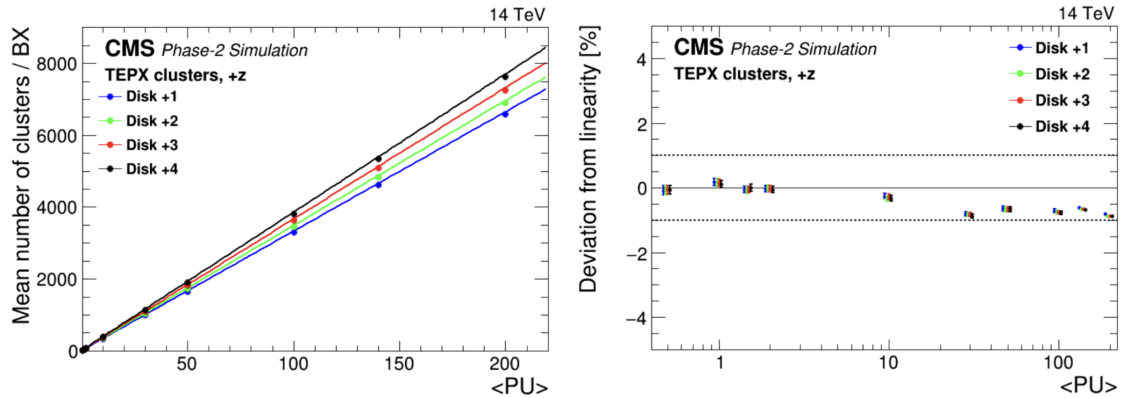


Fig. 6.6 Left: Simulated mean number of clusters for TEPX disks as a function of pileup. A line is fitted between pileup values of 0 and 2, and then extrapolated up to a pileup of 200. Right: The relative difference between the data points and the values of the fit function at the respective pileup value [44].

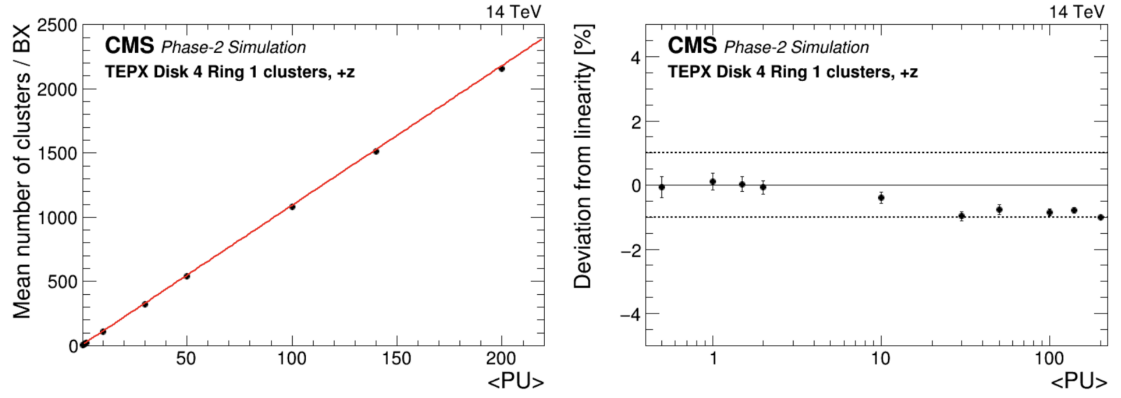


Fig. 6.7 Left: Simulated mean number of clusters for TEPX Disk 4 Ring 1 as a function of pileup. A line is fitted between pileup values of 0 and 2, and then extrapolated up to a pileup of 200. Right: The relative difference between the data points and the values of the fit function at the respective pileup value [44].

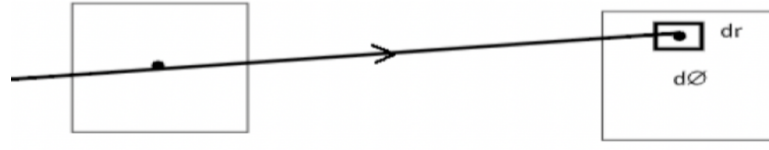
6.2.2 TEPX two-fold coincidences

Two-fold coincidences are clusters in modules overlap regions formed by modules in front layers (L1-L3) and back layers (L2-L4) separately. There are two types of two-fold coincidences namely in ϕ and r . Two-fold coincidence in ϕ involve modules overlap in the same ring of one double-disk and two-fold coincidence in r require modules overlap between successive rings of one double-disk. Two-fold coincidences are better way to distinguish between a real hit and random noise. Luminosity determination based on counting coincidences has an advantage over clusters that afterglow effects are tiny.

A new algorithm for luminosity measurement based on counting two-fold coincidences is proposed that applies selections using dr and $d\phi$ variables (shown in Fig. 6.8) to minimize non-linearity for high pileup as these variables take into account track angle and its curvature [50]. Proper selections are applied for each TEPX disk based on these variables using low pileup simulated samples and then these selections are applied to high pileup samples for suppressing fake coincidences.

We study the two-fold coincidences in ϕ for all TEPX Disk and rings using r , ϕ variable for pileup 0.5. Based on pileup 0.5 sample, a pre-selection of 0.15 mm on dr and 0.04 on $d\phi$ variable is applied in order to remove fake coincidences.

The dr , $d\phi$ distribution showing true, fake, total two-fold coincidences for Disk 4 Ring 1 for pileup 0.5 is shown in Fig. 6.9. After obtaining these distributions for all TEPX disks and rings, we carry out a fit of the true coincidences distribution (shown in red color) to obtain mean and standard deviation of these distributions. A two-standard-deviation



$$r_2 - r_1 = \sqrt{x_2^2 + y_2^2} - \sqrt{x_1^2 + y_1^2}$$

$$\phi_2 - \phi_1 = \tan^{-1}\left(\frac{y_2}{x_2}\right) - \tan^{-1}\left(\frac{y_1}{x_1}\right)$$

Fig. 6.8 r, ϕ variables used to define coincidence clusters.

selection is applied on the dr value about the mean. The mean values are shown in Table 6.2. The standard deviation values of the fit to true coincidences for all disks and rings are shown in Table 6.3. Similarly, two-sigma cut is applied on the $d\phi$ variable as well. The standard deviation values for $d\phi$ variable are shown in Table 6.4. While doing the fit, the mean value for $d\phi$ variable is set to zero. A plot of two-fold coincidences in ϕ after applying all selection based on standard deviation values of all TEPX disks and rings is shown in Fig. 6.11.

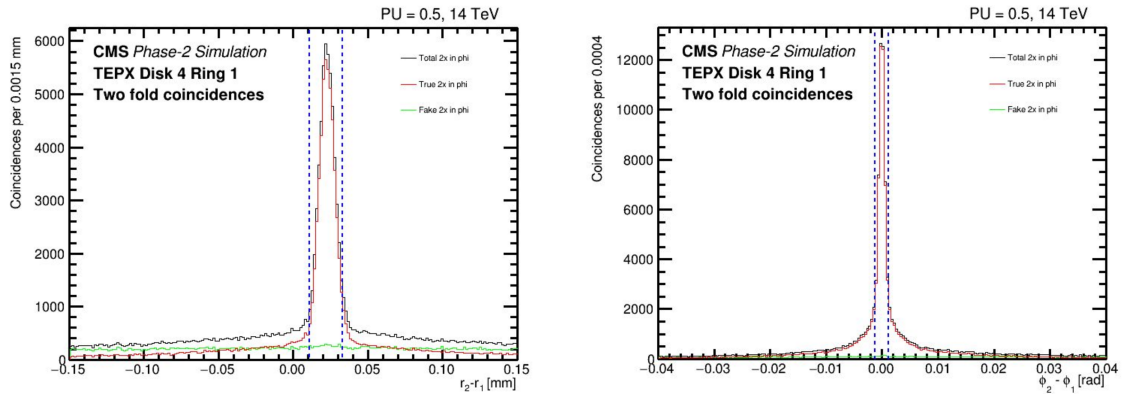


Fig. 6.9 Distribution of cluster count as a function of dr and $d\phi$ variables for pileup 0.5 for Disk 4 Ring 1. The black curve represents the total two-fold coincidence counts, the red curve depicts the true two-fold coincidence counts, and the green curve indicates the fake two-fold coincidence counts.

Table 6.2 dr mean values (mm) obtained from fit for two-fold coincidences in ϕ for all disks and rings

Disk	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5
1	0.034	0.051	0.068	0.084	0.098
2	0.030	0.044	0.059	0.073	0.085
3	0.026	0.039	0.051	0.063	0.074
4	0.023	0.034	0.045	0.055	0.064

Table 6.3 dr cut values (mm) for two-fold coincidences in ϕ for all disks and rings

Disk	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5
1	0.0064	0.0072	0.0078	0.0086	0.0088
2	0.0059	0.0066	0.0070	0.0077	0.0079
3	0.0056	0.0062	0.0066	0.0070	0.0073
4	0.0053	0.0059	0.0061	0.0067	0.0068

Table 6.4 $d\phi$ cut values for two-fold coincidences in ϕ for all disks and rings

Disk	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5
1	0.00088	0.0013	0.0015	0.0016	0.0017
2	0.00076	0.0011	0.0013	0.0014	0.0015
3	0.00068	0.00097	0.0012	0.0013	0.0013
4	0.00061	0.00088	0.0010	0.0011	0.0012

Similarly, we also studied two-fold coincidences in r which arise from module overlaps between successive rings by only considering one-to-one module overlap between first two and last two layers in one TEPX double-disk [51]. A one-to-one overlapping of modules is considered between L1L2 and L3L4 modules as shown in Fig. 6.10. Fit is done to pileup 0.5 distribution of true coincidences for both L1L2 and L3L4 coincidences in r . Fit results for all disks and rings are shown from Table 6.5 to 6.7. Similarly, two-sigma standard deviation selections are applied on dr , $d\phi$ variables. After applying all selections, the XY map of two-fold coincidences in r for L1L2 and L3L4 combined as shown in 6.12.

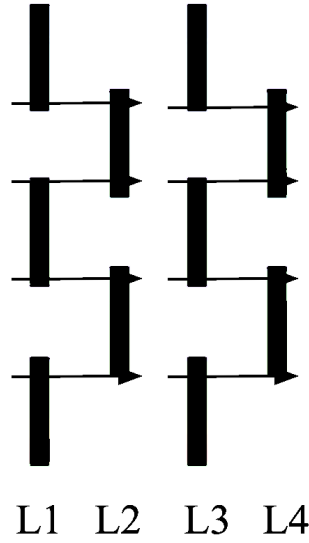


Fig. 6.10 Definition of two-fold coincidences in r from the module overlap regions.

Table 6.5 dr mean values (mm) obtained from fit to true coincidences in r

Disk	Ring			
	1-2	2-3	3-4	4-5
1	0.023	0.031	0.039	0.047
2	0.020	0.027	0.034	0.040
3	0.018	0.023	0.029	0.035
4	0.015	0.020	0.026	0.031

Table 6.6 dr standard deviation (mm) values obtained from fit to true coincidences in r

Disk	Ring			
	1-2	2-3	3-4	4-5
1	0.0045	0.0045	0.0047	0.0052
2	0.00442	0.0047	0.0048	0.0050
3	0.0045	0.0045	0.0049	0.0049
4	0.0045	0.0047	0.0049	0.0049

Table 6.7 $d\phi$ standard deviation values obtained from fit to true coincidences in r

Disk	Ring			
	1-2	2-3	3-4	4-5
1	0.00063	0.00082	0.00094	0.0010
2	0.00057	0.00076	0.00085	0.00090
3	0.00052	0.00066	0.00077	0.00083
4	0.00047	0.00059	0.00069	0.00075

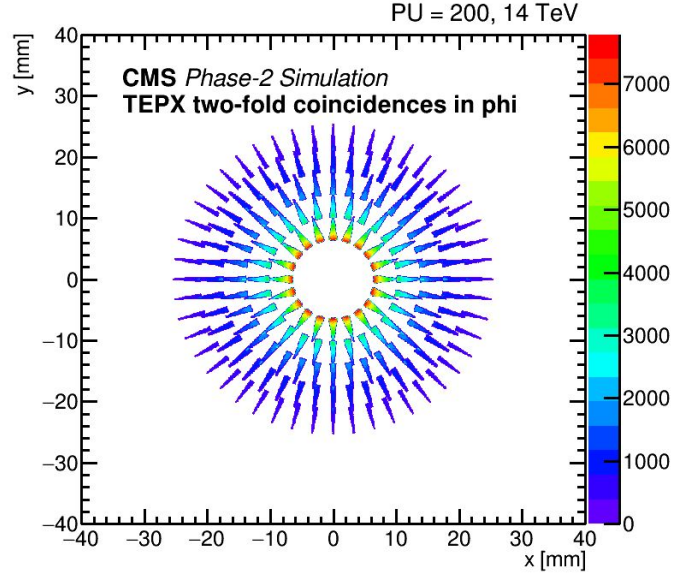


Fig. 6.11 X-Y map of reconstructed two-fold coincidences in ϕ showing module overlap regions.

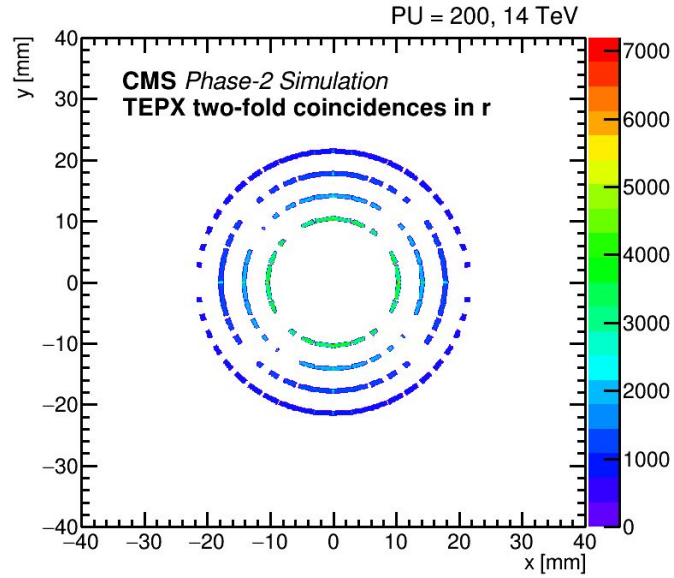


Fig. 6.12 X-Y map of reconstructed two-fold coincidences in r using the selections described in the text. We have only reconstructed coincidences in r arising from module overlap in L1L2 and L3L4. The gaps in the plot correspond to other types of two fold coincidences in r that will arise from module overlap in L1L4, L3L4 and L2L3.

The new algorithm is able to remove physics noise at high pileup as can be seen from the high efficiency values and low fake rates for Disk 4 for all rings and for all pileup samples as shown in Table 6.8 and 6.9. The fake two-fold coincidence rates for different rings in Disk 4 with a pileup of 200 are presented. The rate changes across the rings, starting from 1.1% in Ring 1 and increasing to 2.5% in Ring 4, before slightly decreasing to 2.3% in Ring 5. This variation suggests that the fake coincidences is not uniform across the rings of Disk 4, with the middle rings (Rings 3 and 4) showing a higher fake rate. There is a general trend of increasing fake rates with pileup. For instance, at a pileup of 0.5, the fake rates for "2-fold in ϕ " and "2-fold in r " are 0.78% and 0.99%, respectively. These rates gradually increase as the pileup value rises, reaching 1.85% for "two-fold in ϕ " and 1.57% for "two-fold in r " at a pileup of 200. Fake rate is defined as

$$\text{Fake rate} = \frac{\text{Number of fake coincidences (Area under the green curve)}}{\text{Total number of coincidences (Area under the black curve)}} \quad (6.1)$$

as shown in Fig. 6.9.

Table 6.8 Fake rate for Disk 4 for pileup 200

Disk 4	Fake two-fold coincidence rate (%)
Ring 1	1.1
Ring 2	1.9
Ring 3	2.0
Ring 4	2.5
Ring 5	2.3

Table 6.9 TEPX two-fold coincidences fake rate and efficiency

Pileup	Fake rate (%)		Efficiency (%)	
	2-fold in ϕ	2-fold in r	2-fold in ϕ	2-fold in r
0.5	0.78	0.99	99.21	99.00
1	0.79	1.01	99.20	98.98
1.5	0.80	1.02	99.19	98.97
2	0.79	1.02	99.20	98.97
10	0.83	1.04	99.16	98.95
30	0.94	1.09	99.05	98.90
50	1.04	1.14	98.95	98.85
100	1.31	1.29	98.68	98.70
140	1.53	1.41	98.46	98.58
200	1.85	1.57	98.14	98.42

We study the linearity of two-fold coincidences, that is how the number of two-fold coincidences change with pileup to obtain precise luminosity measurement [52]. Distribution of two-fold coincidences for TEPX Disk 4 Ring 1 for all pileup values is shown in Fig. 6.13. For pileup 200, mean two-fold coincidences is around 270. The new algorithm is able to suppress non-linearity at high pileup values as shown in Fig. 6.14 and 6.15. Non-linearity is within 1% for entire pileup range.

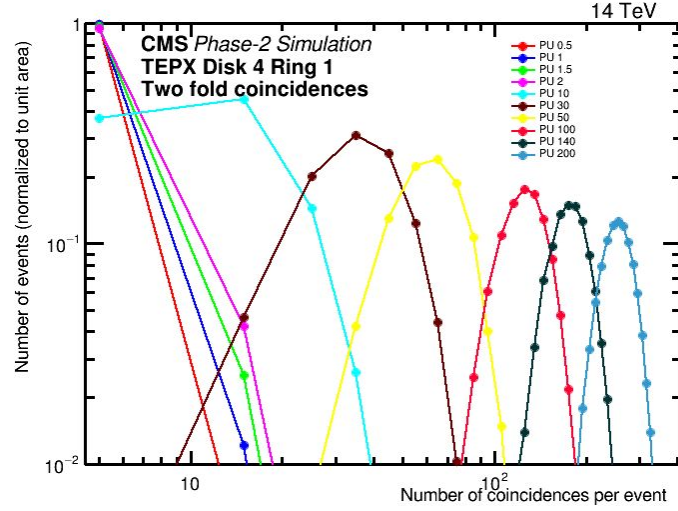


Fig. 6.13 Distribution of number of two-fold coincidences for TEPX Disk 4 Ring 1 for all pileup values [44].

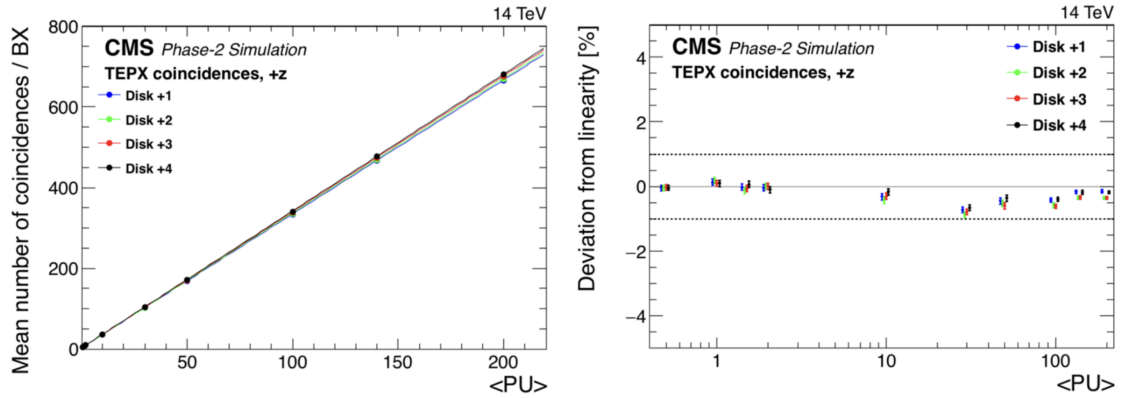


Fig. 6.14 Left: Simulated mean number of two-fold coincidences for TEPX disks as a function of pileup. A line is fitted between pileup values of 0 and 2, and then extrapolated up to a pileup of 200. Right: The relative difference between the data points and the values of the fit function at the respective pileup value [44].

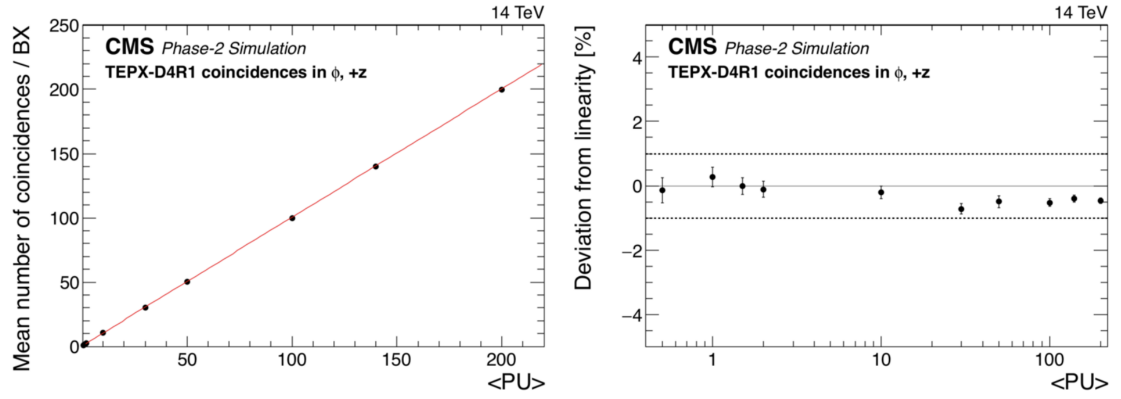


Fig. 6.15 Left: Simulated mean number of two-fold coincidences in ϕ for TEPX Disk 4 Ring 1 as a function of pileup. A line is fitted between pileup values of 0 and 2, and then extrapolated up to a pileup of 200. Right: The relative difference between the data points and the values of the fit function at the respective pileup value [44].

6.2.3 TEPX three-fold coincidences

It is possible to have three fold coincidences in TEPX detector. A three-fold coincidence refers to a situation where three hits occur in a close spatial arrangement originating from the same underlying event. In the current algorithm, we look for another cluster in the lower ring after a two fold coincidence cluster in ϕ is found. The selections used for finding three-fold coincidences using old dx, dy and dz cut variables are 0.1 mm, 0.1 mm and 0.9 mm. The XY map of three-fold coincidences is shown in Fig. 6.16. Three-fold coincidences under all pileup conditions is shown in Fig. 6.17. With the current algorithm, three-fold coincidences shows non-linearity as shown in Fig. 6.18.

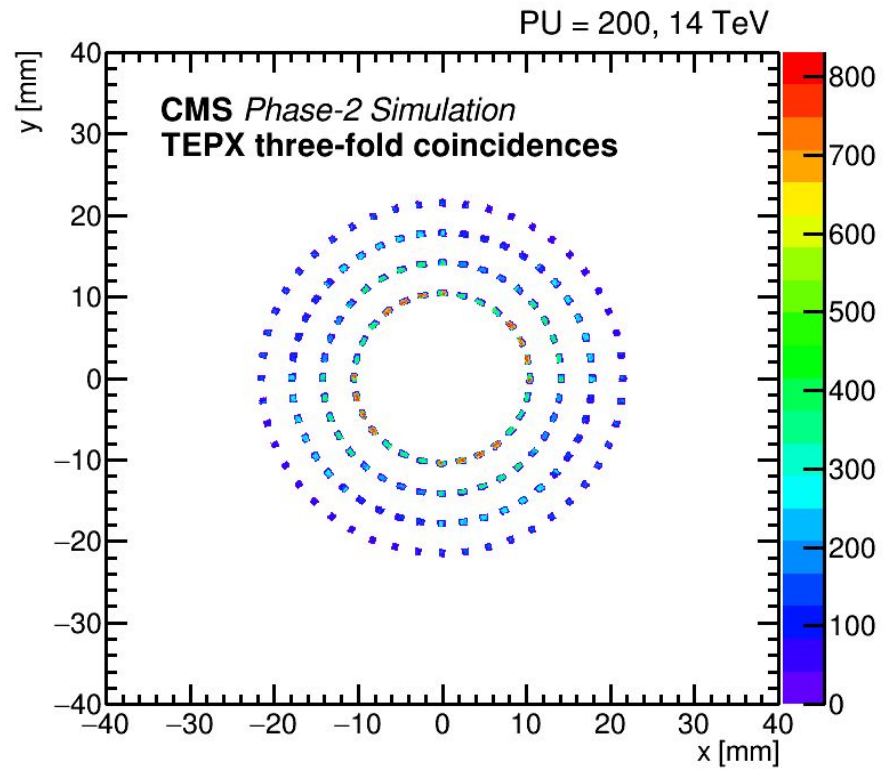


Fig. 6.16 Reconstructed three fold coincidences in all rings within TEPX double-disk.

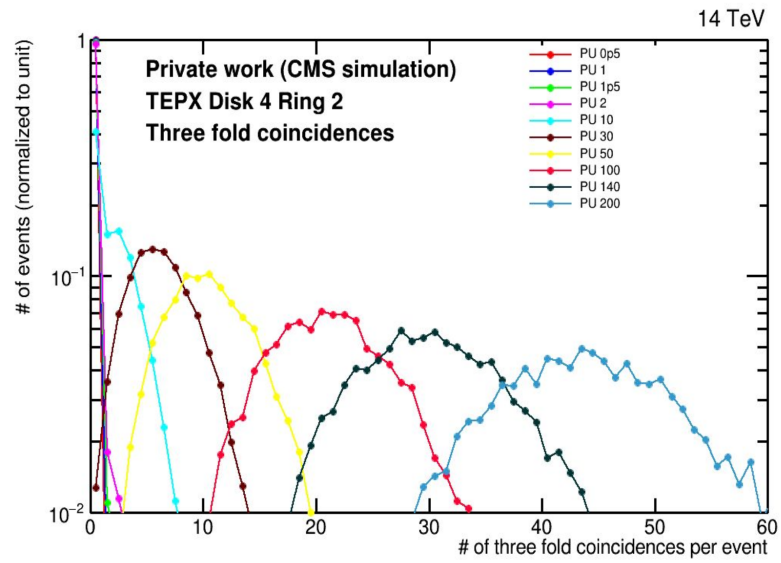


Fig. 6.17 Distribution of number of three fold coincidences for TEPX Disk 4 Ring 2 for all pileup values.

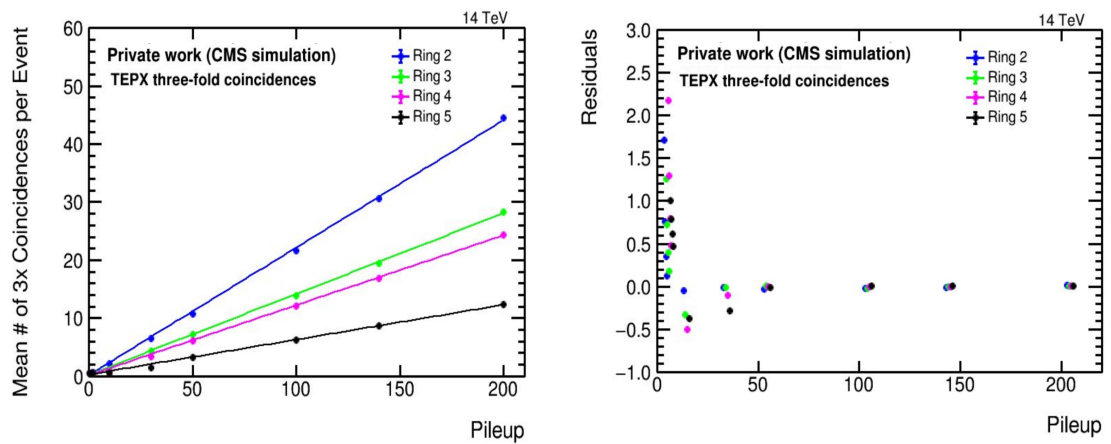


Fig. 6.18 Left: Simulated mean number of three-fold coincidences for all Disk 4 rings as a function of pileup. Right: Deviation from linearity for Disk 4 all rings, the relative difference between the data points and the values of the fit function at the respective pileup value.

6.3 Statistical precision

Statistical precision is another uncertainty that needs to be considered for precise luminosity measurement. It must be kept minimal to achieve 1% accuracy for HL-LHC luminosity measurement. The relative statistical uncertainty in % is calculated as $\frac{\sqrt{N}}{N} \times 100$ where N is the product of the number of counts per event, the trigger frequency and the time integration period.

The following tables detail the precision of event counting algorithms at a set pileup of 0.5 and high pileup scenarios across varying integration times to ensure precision luminosity measurement.

Table 6.10 Expected statistical precision (in %) in head-on collisions during typical vdM conditions with pileup of 0.5 for TEPX clusters and two-fold coincidences over different integration time period [44].

vdM (PU 0.5)	Trigger Rate (kHz)	1 bx, 1s	1 bx, 30s
TEPXD4R1 Clusters	1000	1.82	0.332
TEPXD4R1 2x Coincidences in ϕ	1000	5.98	1.09
TEPXD4R1 2x Coincidences in r	1000	11.1	2.02
TEPXD4R1 2x Coincidences	1000	5.27	0.962
TEPX Clusters	500	0.709	0.129
TEPX 2x Coincidences in ϕ	500	2.65	0.485
TEPX 2x Coincidences in r	500	4.59	0.838
TEPX 2x Coincidences	500	2.3	0.42

Table 6.11 Expected statistical precision (in %) in head-on collisions during physics conditions with pileup of 200 for TEPX clusters and two-fold coincidences over different integration time period [44].

Algorithm	Trigger Rate (kHz)	1 bx, 1s	2500 bx, 1s
TEPXD4R1 Clusters	825	0.1	0.002
TEPXD4R1 2x Coincidences in ϕ	825	0.329	0.00659
TEPXD4R1 2x Coincidences in r	825	0.61	0.0122
TEPXD4R1 2x Coincidences	825	0.29	0.0058
TEPX Clusters	75	0.0915	0.00183
TEPX 2x Coincidences in ϕ	75	0.343	0.00685
TEPX 2x Coincidences in r	75	0.593	0.0119
TEPX 2x Coincidences	75	0.297	0.00594

Chapter 7

Summary and Conclusions

The research presented in this thesis on the PCC luminometer offers profound insights and advancements in luminosity measurement. The meticulous analysis and improvement in PCC luminosity analysis, including the development of a comprehensive module veto list and innovative calibration techniques, have significantly enhanced the precision of luminosity measurement. The implementation of afterglow correction methodologies addresses residual signals, ensuring the accuracy of the PCC data. Alongside these achievements, this thesis also contributes substantially to the Phase II upgrade of the CMS detector. The Phase II upgrade is a major, multi-year project, currently in its design and development phase, with full operation expected to commence in 2029. The advancements in the PCC luminometer, combined with the upcoming Phase II upgrades, position the CMS detector at the forefront of particle physics research. The improvements in luminosity measurement techniques and detector capabilities will enable more precise and accurate experiments, paving the way for groundbreaking discoveries in understanding the fundamental forces and particles of our universe. The comprehensive approach and innovative methodologies developed in this thesis are pivotal contributions to the field, enhancing not only current research capabilities but also setting a solid foundation for future explorations in high-energy particle physics.

Chapter 1 of the thesis lays the groundwork for understanding the critical role of luminosity in particle physics, particularly in the Large Hadron Collider (LHC). The chapter highlights ongoing advancements in enhancing luminosity measurement precision, notably through the CMS pixel detector.

In Chapter 2, we provide a comprehensive overview of the methods and technologies used to measure luminosity at the CMS detector. It focuses on various luminosity measurement methods, the role of the pixel detector, and the pixel cluster counting (PCC) method. It details the importance of precise luminosity measurement for understanding particle

interactions, the challenges involved, and the advancements made in this field, particularly with the PCC method's implementation and its impact on enhancing the accuracy of luminosity measurements.

In Chapter 3, we discuss the calibration of luminosity measurement devices using the van der Meer (vdM) scan method. It explains the technique developed by Simon van der Meer for relating the detection rate of a luminometer to absolute luminosity. This involves scanning colliding beams across each other and measuring the beam overlap integral, which is proportional to luminosity. The chapter also covers background estimation to account for various sources of noise. Rate is fitted with gaussian plus polynomial model for 2018, a fitting function used to fit signal in the vdM calibration process and double gaussian model for 2022 vdM data.

In Chapter 4, the results from Run 2 (2017 and 2018) are comprehensively detailed. The visible cross section was accurately determined as 960.54 ± 0.85 (stat.) mb. A total of 155 good pixel modules were selected for the final luminosity measurement. The total systematic uncertainty is expected to be order of 2.2% which is better than LUM PAS 18 results. Work is ongoing to complete this measurement and we expect significant improvement in beam-beam systematic uncertainties.

In Chapter 5, results from the PCC luminosity measurement during Run 3 (2022) are outlined. Furthermore, a comprehensive analysis of systematic uncertainties in the luminosity measurement for the year 2022 is presented. Total systematic uncertainty is 1.4%.

Chapter 6 of the thesis on the TEPX luminometer for the High Luminosity Large Hadron Collider (HL-LHC) addresses the challenges and solutions in luminosity measurement for the anticipated HL-LHC phase starting in 2029. Advanced algorithms using dr and $d\phi$ variables effectively manage non-linearity and suppress fake coincidences at high pileup levels, maintaining non-linearity within 1% across the pileup range. Furthermore, the system achieves high efficiency and low fake rates in complex luminosity conditions. Statistical precision is also emphasized as a critical factor for achieving the targeted 0.1% in HL-LHC luminosity measurement.

7.1 Conclusions

The detailed application of the PCC method for luminosity measurement during the 2018 data-taking period is provided in chapter 4. This chapter concludes with significant achievements in precision and methodology:

- A rigorous selection process identified 155 good pixel modules from the total modules in the pixel detector.
- The visible cross-section (σ_{vis}) was precisely determined to be 960.54 ± 0.85 (statistical) mb.
- Parameters for a 3-wagon train were amplitude 0.0008265 and decay width 0.01231.
- The peak luminosity for fill 6961 is $1.85 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ and the end luminosity was $0.9 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, with an integrated luminosity for the fill recorded at 0.418fb^{-1} .
- Specific areas of systematic uncertainty investigated include:
 - Scan to scan variation: 0.3%
 - Bunch to bunch variation: 0.1%
 - Afterglow correction: 0.3% for afterglow effects.
 - Cross detector stability: 0.3%
 - Linearity: 0.4%, which assesses the change in detector response at different luminosity levels.
- A systematic uncertainty for the 2018 PCC luminosity measurement was estimated to be 2.2%.

Chapter 5 presents a detailed analysis of the PCC luminosity measurement method as applied during Run 3. The chapter outlines the methods used for data collection, calibration, addressing systematic uncertainties, and the results of luminosity measurement.

- A stringent selection process identified 163 good modules, ensuring high quality and reliability of the data used for luminosity calculations.
- The visible cross-section (σ_{vis}) was calibrated to be 1076 ± 0.9 mb (statistical), demonstrating the accuracy achieved during the vdM scans.
- Type 2 Afterglow Parameters used to model the exponential decay function for non-colliding bunches post-train were an amplitude of 0.0008406 and a decay width of 0.01047.
- The peak luminosity recorded during fill 8395 was $19,000 \text{Hz}/\mu\text{b}$, involving 2450 colliding bunches over 2600 lumi sections.

- Total systematic uncertainty was calculated at 1.4% for the 2022 measurements. Uncertainties that I focused on includes: scan-to-scan variation (0.5%) and bunch-to-bunch variation (0.1%), Detector-specific uncertainties from stability (0.6%), and linearity (0.5%). Afterglow corrections contributed 0.2% to the total systematic uncertainty, essential for minimizing errors due to residual signals.

The chapter 6 confirms that the TEPX luminometer maintains excellent linearity within 1% across a wide range of pileups, up to a pileup of 200. The statistical precision per second for the TEPX clusters is 0.1% at a pileup of 200.

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