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CMS tracker status, challenges, and performance in Run 3

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The CMS silicon tracker, consisting of the pixel and strip detectors, provides precise measurements of charged-particle trajectories in the high-luminosity environment of the CERN Large Hadron Collider (LHC). During Run 3 at $\sqrt{s}$ = 13.6 TeV, the tracker has operated stably under increasingly demanding conditions, with the average pile-up exceeding 60 interactions per bunch crossing and a total integrated luminosity more than 245 fb^{-1}. The detector maintains a high fraction of active channels, exceeding 94% across all subsystems, and delivers excellent hit efficiency, signal-to-noise ratio, and spatial resolution. Radiation effects are mitigated through increases in bias voltage. Effects such as cluster breaking in the pixel detector are addressed through updated calibrations and improved reconstruction. Overall, the CMS tracker continues to provide excellent tracking performance, ensuring reliable physics reconstruction throughout Run 3 and offering valuable operational experience for the High-Luminosity LHC detector upgrades.

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1. Introduction

The Compact Muon Solenoid (CMS) detector [1] is a general-purpose experiment at the CERN Large Hadron Collider (LHC), designed to investigate a broad range of physics processes at the energy frontier. Precise reconstruction of charged-particle trajectories is a key component of the CMS physics program, enabling accurate vertexing, momentum measurement, and particle identification. These measurements are provided by the CMS silicon tracker, which extends up to a pseudorapidity of $|\eta| < 2.5$ and is located inside a 3.8 T solenoidal magnetic field.

The tracker is composed of two main subsystems: the silicon pixel tracker and the silicon strip tracker. The pixel detector consists of a barrel (BPix) and an endcap section (FPix), providing four barrel layers and three forward disks on each end. The strip tracker surrounds the pixel detector and comprises the Tracker Inner Barrel (TIB), Tracker Outer Barrel (TOB), Tracker Inner Disks (TID), and Tracker Endcaps (TEC). In total, the full tracker includes over 16,000 silicon modules, corresponding to about 200 m^2 of active silicon area. Figure 1 shows an overview of the CMS tracking detectors.

Since the start of Run 3 in 2022, the LHC has operated at a center-of-mass energy of 13.6 TeV, reaching peak instantaneous luminosities which exceed those of Run 2. At the time of writing, the total integrated luminosity collected by CMS in Run 3 has already surpassed 245 fb^{-1}, compared to the total of 163.6 fb^{-1} recorded at 13 TeV during Run 2. The higher instantaneous luminosity and number of interactions per bunch crossing (pile-up) in Run 3 present a more demanding operational environment for the CMS tracking detectors, with the pile-up exceeding 60. These challenging conditions require good detector stability, calibration, and reconstruction to maintain excellent performance throughout data taking.

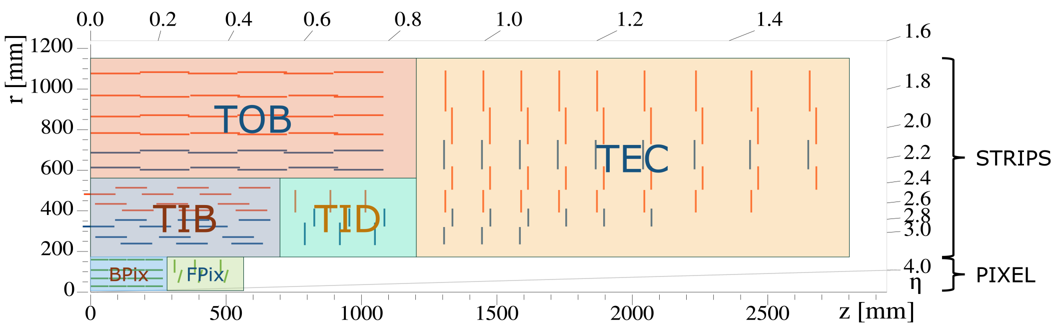


Figure 1: The CMS tracking detectors, consisting of the pixel and strip detectors. The pixel detector consists of the BPix and the FPix. The strip detector consists of the TIB, TID, TOB, and TEC. More details are given in the main text.

2. Tracker Module Design

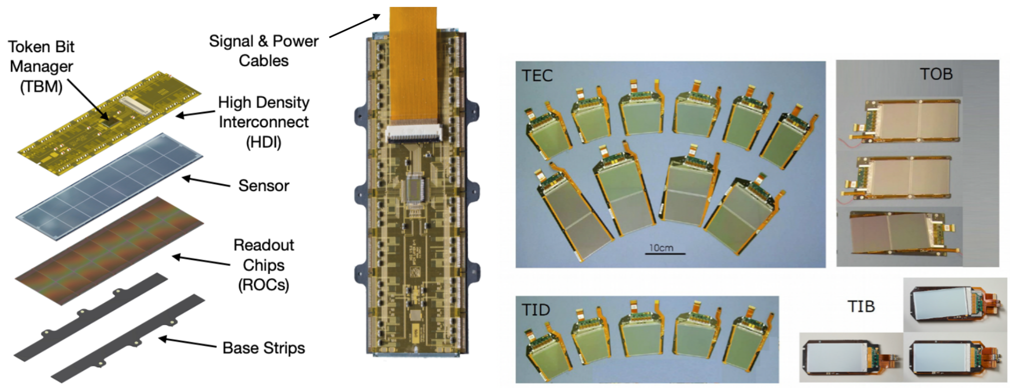
2.1 Silicon Pixel Tracker

The silicon pixel detector [2] employs planar n-in-n silicon sensors, 285 μm thick and segmented into pixels of 100×150 μm^2. Each sensor is bump-bonded to a two-dimensional array of readout chips (ROCs). The readout is managed by a Token Bit Manager (TBM), which orchestrates the communication among ROCs; two TBMs are used for BPix layer 1 to handle the higher hit rates. The TBM chip is mounted on a high-density interconnect (HDI), a printed-circuit board, that also routes high voltage to the modules (Fig. 2).

Two ROC types are deployed: PSI46dig and PROC600. The PSI46dig chip, used in BPix layers 2–4 and in the FPix disks, maintains efficiency above 90% up to hit rates of 200 MHz/cm^2. The PROC600 chip, dedicated to BPix layer 1, was optimized for the extreme hit densities near the beam line, achieving above 90% efficiency at 600 MHz/cm^2 [2].

2.2 Silicon Strip Tracker

The silicon strip tracker [3] consists of p-in-n sensors with two thicknesses: 320 μm and 500 μm. Thinner sensors are used in the inner regions. In the outer layers, two sensors are daisy-chained for longer strips. To maintain an adequate signal-to-noise ratio despite the increased capacitive noise due to larger cell size, thicker sensors are used. The tracker includes both single- and double-sided modules, the latter assembled from two single-side sensors mounted back-to-back with a 100 mrad stereo angle (Fig. 2).



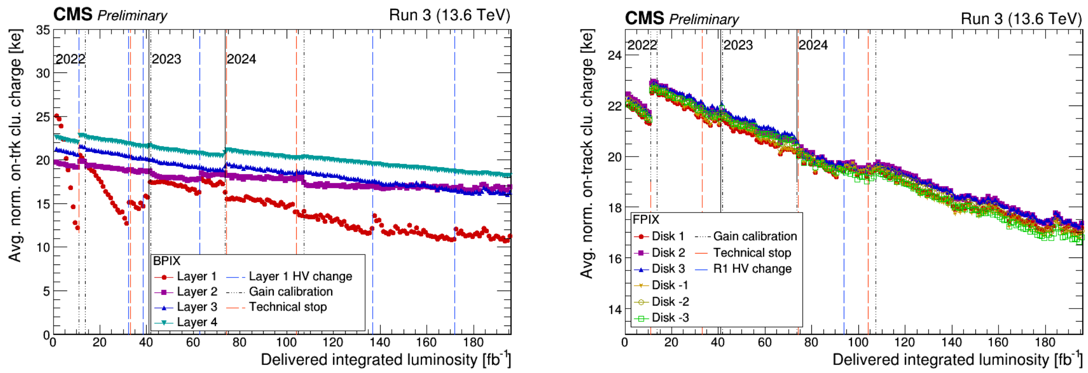
(a) (b)

Figure 2: (a) an exploded view of a silicon pixel module [2] and (b) different configurations of silicon strips modules [3].

3. Operational Challenges in Run 3 and Detector Performace

The CMS tracker has demonstrated excellent stability during Run 3. As of mid-2025, the BPix maintains approximately 96% active channels, with some localized inefficiencies due to temporarily or permanently disabled modules. A known issue affects a ϕ region of about 22.5° in BPix layers 3 and 4, related to a clock distribution problem. The FPix retains about 94% of active channels, with a region corresponding to 14 modules that currently receive no triggers. The silicon strip tracker also remains highly reliable, with around 95% of channels active overall.

The intense radiation field induces single-event upsets in the front-end electronics and the accumulated radiation damage leads to leads to higher leakage currents and increased depletion voltages in the sensors. In the pixel detector, radiation-induced charge loss has become evident, particularly in BPix layer 1, where the collected charge has dropped to about 50% of the unirradiated



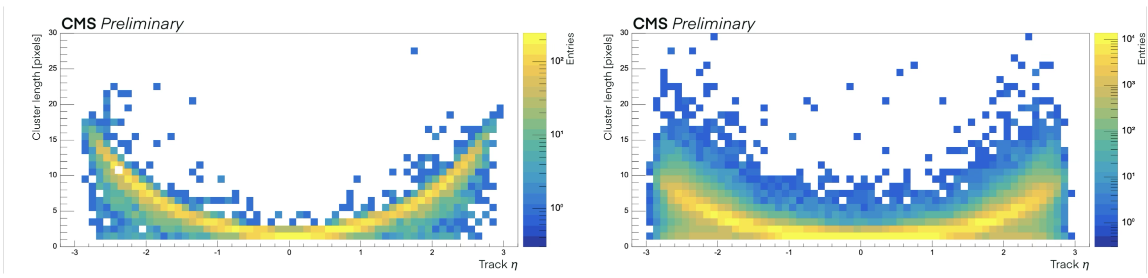
(a) **(b)**

Figure 3: Average on-track cluster charge in kilo-electron as a function of integrated luminosity for (a) BPix layers and (b) FPix disks [6].

level. The charge collection in the FPix disks is also decreasing over time but at a slower rate (Fig. 3). Regular bias voltage scans and calibration updates are performed to compensate for this degradation. As of 2025, the high-voltage settings are 600 V for BPix layer 1 and between 300–450 V for the outer BPix layers and FPix rings.

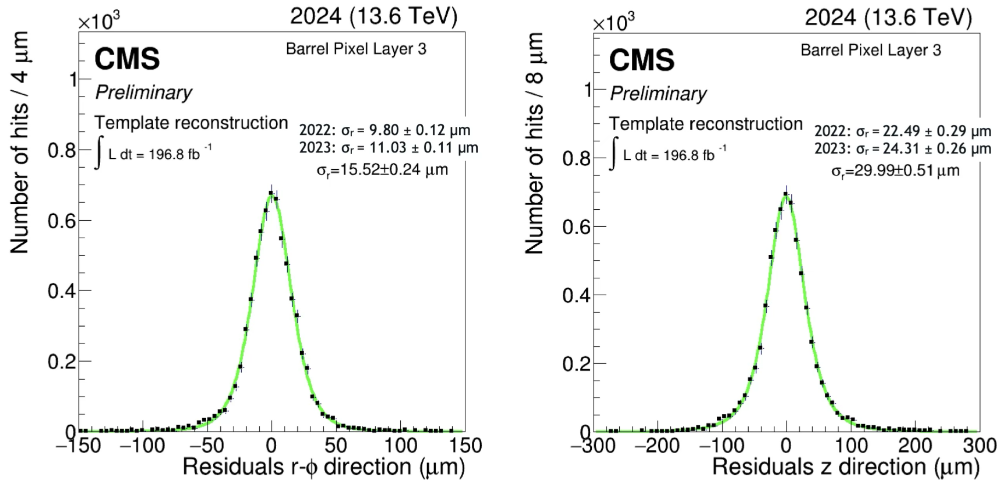
Radiation damage also leads to the so-called cluster breaking phenomenon, in which the reduced charge collection efficiency results in split and shortened clusters, especially at large pseudorapidities. This effect is visible in the on-track cluster length in the z-direction versus η distributions (Fig. 4), where the distribution in 2025 is more diffuse and shows smaller average cluster lengths compared to 2023. The degradation in the pixel hit resolution observed between 2022, 2023, and 2024 is consistent with the effects of charge loss and worsen by cluster breaking (Fig. 5). The BPix layer 1 additionally experiences an increasing rate of auto-masked channels [4] caused by readout errors; the issue is mitigated by gradually raising the power to the digital electronics (v_{dd}) of the ROCs. However, as of mid-2025, the maximum value of v_{dd} is reached. Despite these effects, the overall data quality of CMS remains of high.

The strip tracker sensors are operated over-depleted to maintain efficient charge collection and



(a) **(b)**

Figure 4: On-track cluster length in the z-direction versus η in BPix layer 1 for (a) 2023 and (b) 2025 data. The cluster breaking effect is visible as a reduction in average cluster length and increased spread at high $|\eta|$.



(a) **(b)**

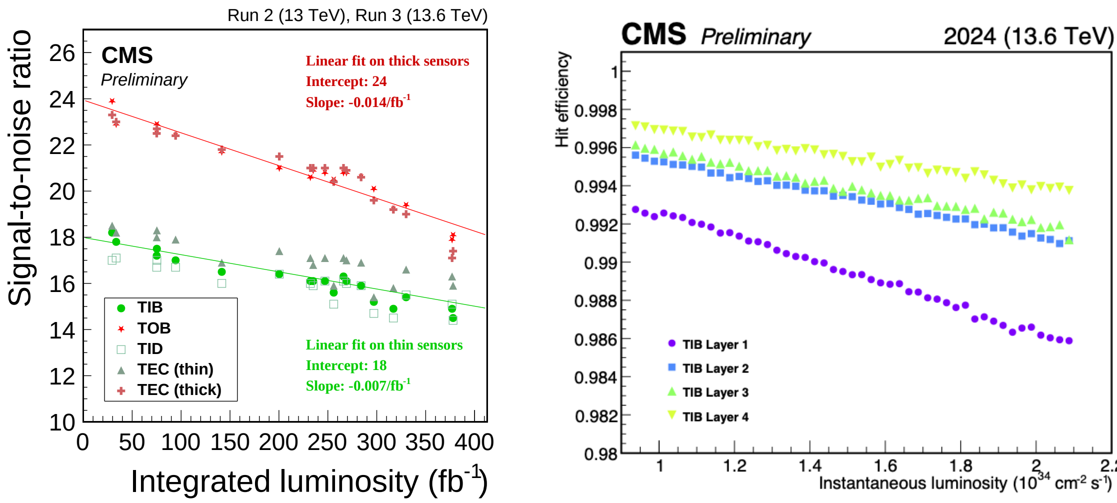
Figure 5: Hit residuals on BPix Layer 3 in 2024, compared with values from 2022 and 2023, in the (a) r–ϕ direction and (b) z direction [6].

spatial resolution after irradiation. Following type inversion in the p-in-n sensors, the depletion region develops from the sensor backside; operating above the depletion voltage ensures that it fully extends to the strip side, allowing charge generated near the strips to be collected [3]. Bias voltage scans are performed biannually across the full detector and monthly on representative modules to monitor depletion voltage evolution. By 2025, several components, such as the TOB inner layers and TEC disks 5–9, operate at 500 V (Fig. 8). The cooling set point has been decreased to −25°C since mid-2024 to reduce leakage currents. A few modules in less-efficiently cooled areas approach or have reached the 12 mA power supply limit.

Signal-to-noise ratio (S/N) remain high across all strip subdetectors. The observed decrease of S/N with integrated luminosity is consistent with the expectation from the incurred radiation damage and expected to remain above the design goal of S/N>10 through the rest of Run 3. The hit efficiency exceeds 98% for all strip layers, with a dependence on instantaneous luminosity (Fig. 6). The hit resolution scales with the strip pitch, ranging from about 10 μm for the smallest pitch to 35 μm for the largest pitch (Fig. 7).

4. Data Quality Monitoring and Anomaly Detection

To ensure high-quality tracking data, CMS employs sophisticated monitoring and certification procedures [5]. Short-duration anomalies (spanning a few luminosity sections, each 23 seconds) can occur in pixel layers or disks, potentially affecting tracking if overlapping regions are impacted. Detection methods based on machine-learning models are being developed to aid automated identification and flagging of these events. These tools improve data-taking efficiency and minimize manual intervention, ensuring stable data certification throughout Run 3.



(a) (b)

Figure 6: (a) Signal-to-noise ratio trends and (b) hit efficiency as a function of instantaneous luminosity for the silicon strips [7].

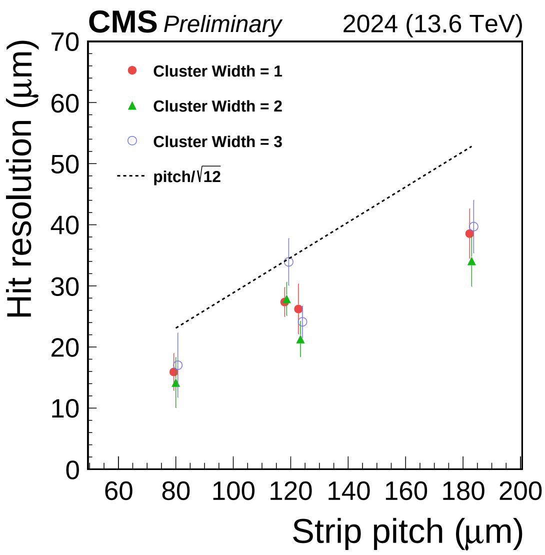


Figure 7: Hit resolution of the strips as a function of strip pitch [7].

5. Heavy-Ion Operation

In addition to proton–proton collisions, CMS successfully recorded heavy-ion collision data with neon–neon, oxygen–oxygen, and proton–oxygen collisions. Both tracking detectors operated reliably during these special runs, maintaining good efficiency and resolution despite the challenging event topologies.

6. Summary and Outlook

The CMS silicon tracker continues to deliver high-quality tracking data under the demanding conditions of Run 3 at 13.6 TeV. Both the pixel and strip subsystems maintain a high fraction of active channels and stable performance despite increasing radiation exposure. In the pixel detector, BPix layer 1 shows the strongest radiation effects, including reduced charge collection, cluster breaking, and higher auto-masking rates. The strip tracker maintains excellent signal-to-noise ratio, hit efficiency, and spatial resolution, with radiation-induced effects well within expectations. Machine-learning-based anomaly detection enhances data quality monitoring, ensuring reliable reconstruction performance.

Operational experience from Run 3 provides essential input for the preparation and future operation of the upgraded tracker at the High-Luminosity LHC, particularly in areas such as radiation mitigation, calibration procedures, and data quality monitoring. The CMS tracker remains an important component of the experiment's success as Run 3 enters its final phase.

Acknowledgments

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