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CMS Silicon Strip Tracker Performance in Run 3

Emery Nibigira, on behalf of the CMS Collaboration
University of Tennessee, Knoxville, USA
E-mail: nibigira@cern.ch

The CMS detector at the CERN Large Hadron Collider (LHC) is a multipurpose detector with capabilities to identify electrons, muons, photons, as well as charged and neutral hadrons. Its tracking system consists of two silicon based sub-detectors: the inner tracker with pixels and the outer tracker with strips. The silicon strip tracker has an active area of approximately 200 m^2 containing more than 15000 silicon modules. Results from the operation and performance of the silicon strip tracker during the LHC Run 3 data-taking are discussed. Performance metrics including evolution of bad module components, signal-to-noise ratio, hit reconstruction efficiency, and single-hit resolution, will be presented. The results affirm that the tracker sustained excellent performance throughout Run 3, thereby ensuring the high-quality tracking required for precision CMS physics analyses.

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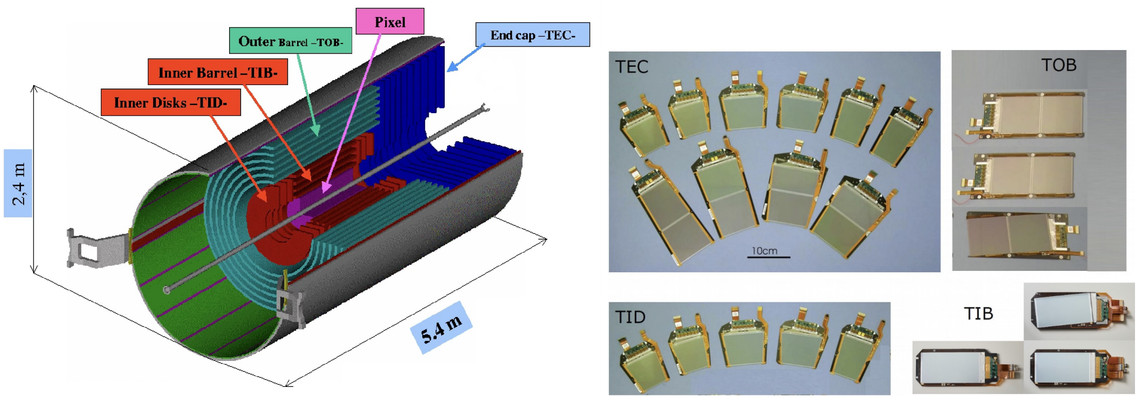
1. CMS and its Silicon Strip Tracker

The CMS detector [1] at the CERN Large Hadron Collider (LHC) is a multipurpose detector with capabilities to identify electrons, muons, photons, as well as charged and neutral hadrons. Located inside the solenoidal magnetic field (3.8 T), the Silicon Strip Tracker (SST) detects charge deposits (hits) at discrete points along the paths of charged particles arising from the collisions produced by the LHC. These hits, together with those detected in the Pixel Tracker, are used to reconstruct the trajectories (tracks) of charged particles traversing the CMS detector. The SST is equipped with 15148 individual silicon detection modules comprising 9.3 million readout strips. It is divided in the inner barrel (TIB), the inner disks (TID), the outer barrel (TOB) and outer end-caps (TEC). The layout of the Tracker substructures and various types of SST modules are shown in Figure 1. Silicon modules with a sensor thickness of 320 µm are employed in the TIB, TID, and the four innermost rings of the TEC, whereas 500 µm sensors are used in the five outermost TEC rings. The first two layers of the TIB and TOB, as well as the two and three innermost rings of the TID and TEC, respectively, are equipped with double-sided (stereo) modules. Each stereo module consists of two detector modules mounted back-to-back, with the strip orientation of one module rotated by 100 mrad relative to the other. This configuration enables the reconstruction of three-dimensional hit positions, providing the radial coordinate in the disks and the longitudinal coordinate in the barrel. The Strip Tracker modules contain one or two silicon strip sensors, the APV25 front-end chip [2], and other auxiliary ASIC for readout and monitoring. The APV25 chip has 128 amplifying channels and is designed in 0.25 μm CMOS technology to be radiation hard with low noise and a fast signal readout.



(a) (b)

Figure 1: An overview of the CMS tracker and its substructure (a), module types of the SST (b).

2. Performance of the SST during LHC Run 3

2.1 LHC Run 3

The LHC began data-taking operations with proton-proton (pp) collisions at a center-of-mass energy of 7 TeV in early 2010. The period from 2010 to 2012 is referred to as Run 1, while the years 2015 to 2018 correspond to Run 2. The total integrated luminosity of pp collisions delivered

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to CMS in Runs 1 and 2 was 192.3 fb^{-1}. At the time of publication, LHC Run 3 is ongoing since 2022 and so far ~245 fb^{-1} have been delivered to CMS at a centre of mass energy of 13.6 TeV. This increasing integrated luminosity creates challenging conditions such as high levels of radiation damage. During data-taking periods, the status of the SST is continuously monitored, and any noisy or inefficient electronic channels identified are flagged and communicated to the offline data processing chain, where they are masked prior to track reconstruction.

2.2 Bad module components

The evolution of the global fraction of module components flagged as bad for offline reconstruction for pp collisions as a function of integrated delivered luminosity is shown in Figure 2. The data include 2022, 2023, and 2024. The offset around 190 fb^{-1} corresponds to the integrated luminosity of Run 1 and Run 2. The drop in bad module fraction around 205 fb^{-1} is due to the recovery of a cooling loop in the End-caps. The several jumps in bad module fraction are due to modules whose power supplies were temporarily turned off. The trend of the fraction of bad module components shows that the fraction of active channels is similar in Run 2 and Run 3: ~96%.

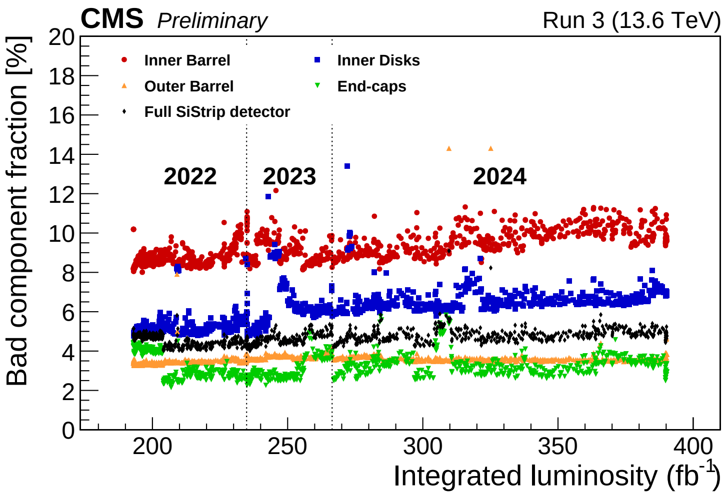

Figure 2: The evolution of the fraction of module components flagged as bad for offline reconstruction [4].

2.3 Signal-to-Noise performance

A high signal-to-noise ratio (S/N) is one of the primary indicators of good detector performance, as it unambiguously separates signals generated by charged particles from fluctuations in the detector noise. The S/N is affected by several factors, including signal processing by the readout, operating temperature, and applied bias voltage. Therefore, it is constantly monitored during detector operation. Figure 3a shows a S/N distribution for data taken in 2024. The most probable value (MPV) of this distribution is obtained by fitting it with a Landau function convoluted with a Gaussian distribution. The MPV reflects the signal-to-noise performance of the corresponding detector region. The evolution of the S/N as function of the integrated luminosity is shown in Figure 3b for different detector regions. For the TEC region, the S/N is split by sensor thickness.

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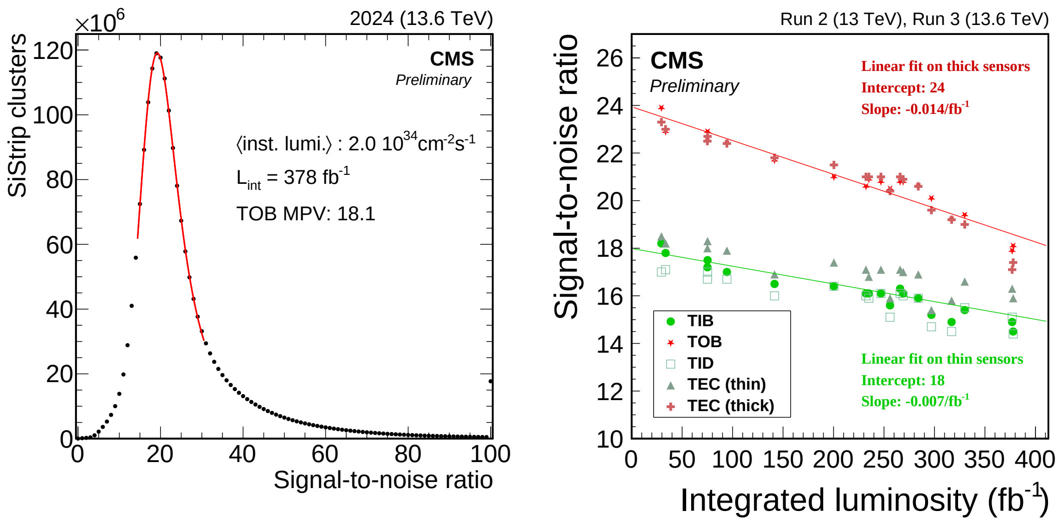
Trend lines are fitted to the two populations of thin and thick sensors. As expected from irradiation studies [3], the S/N decreases with increasing integrated fluence, reflecting the degradation of charge collection efficiency in irradiated sensors. Furthermore, the observed decrease is consistent with the expected trend from measurements in Ref. [1], ensuring good quality physics data until the design end of life of the SST (500 fb^{-1}).



(a) **(b)**

Figure 3: Signal-to-noise distribution for TOB for data taken 2024 (a) [4]. The overall signal-to-noise ratio measured in pp collisions since Run 2 as a function of the integrated delivered luminosity (b) [4].

2.4 Hit reconstruction efficiency

The hit detection efficiency is essential for accurately reconstructing particle trajectories. The hit reconstruction efficiency corresponds to the response of the sensor and readout electronics when a charged particle passes through the detector. It is defined as the ratio of detected hits to the number of expected hits associated with a reconstructed track. Routine measurements of the hit efficiency are performed using both collision and cosmic-ray data to ensure stable detector performance. These measurements rely on high-quality tracks. Selected tracks are required to have at least a transverse momentum of 1 GeV, at least eleven valid hits, and no additional trajectories within 5 mm to reduce false track-to-cluster association. Figure 4a shows the hit reconstruction efficiency measured in the TIB layers as a function of the instantaneous luminosity for pp collisions recorded in May 2024. It can be seen that the hit efficiency decreases linearly with the instantaneous luminosity. The modules in the TIB layer 1, located closest to the LHC beam, are exposed to the highest levels of radiation damage and therefore are affected the most. Despite radiation exposure, the SST preserves a hit finding efficiency exceeding 98%.

2.5 Single-hit resolution

The hit resolution is estimated using only hits from tracks passing through regions where two detector modules overlap within a layer. Selected tracks are required to have a transverse momentum

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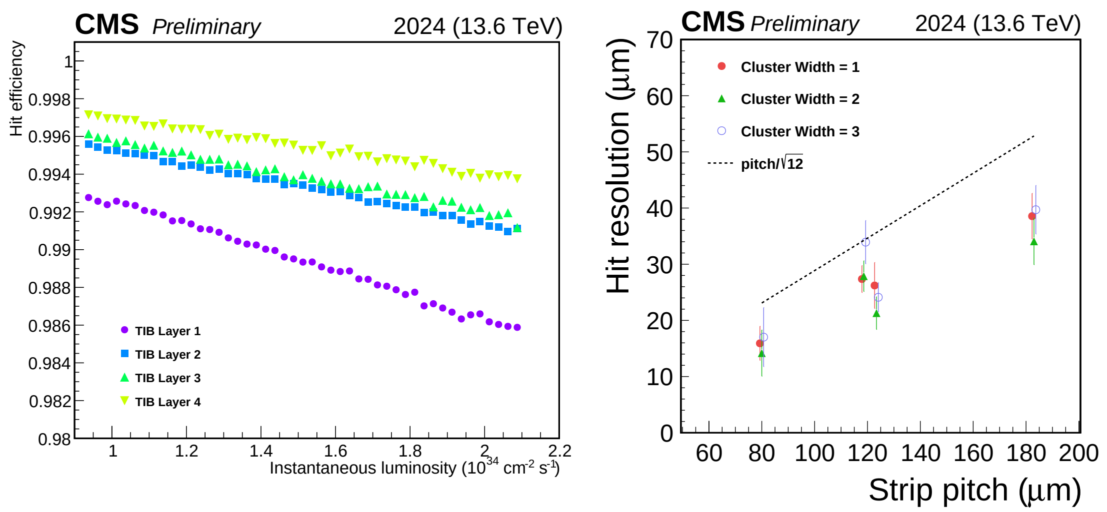

(a) **(b)**

Figure 4: Hit efficiency of the SST from four TIB layers as a function of the instantaneous luminosity (a) [5]. Strip hit resolution measured in pp collisions as function of the strip pitch, the theoretically expected resolution from a binary readout tracking detector (pitch/$\sqrt{12}$) is also displayed (b) [4].

larger than 3 GeV/c, at least eight valid hits, and a χ^2 probability of the track fit greater than or equal to 10^{-3} [4]. The resolution is calculated as:

$$\sigma_{\text{hit}} = \frac{\sqrt{\sigma^2_{\text{meas-pred}} - \sigma^2_{\text{pred}}}}{\sqrt{2}}, \tag{1}$$

where $\sigma_{\text{meas-pred}}$ is the double difference between the measured and predicted positions in the two sensors and σ_{pred} refers to the position of a predicted impact point of the track in the module. The factor of $\sqrt{2}$ in the denominator accounts for the fact that the measurement involves two sensors. The measured hit resolution is shown in Figure 4b for 2024 data and for different cluster widths expressed in units of number of strips. The resolution of a hypothetical binary readout, without analog charge measurement, is shown for comparison. This result demonstrates that the hit resolution of the SST benefits from charge sharing by adjacent strips, which is made possible by the analog readout of the charge from each channel. The resolution is significantly better than the binary limit.

3. Conclusions

The SST has successfully recorded data during LHC Run 1 and Run 2, and it is continuing to perform well in Run 3. Its performance with proton-proton collisions during LHC Run 3 has been presented. Despite ~15 years of operation and radiation damage conditions, the SST continues to deliver good quality data for physics analyses. The detector shows stable number of active channels throughout Run 2 and Run 3, above 95%. The signal-to-noise ratio, hit reconstruction efficiency, and single-hit resolution are very good and compatible with the expectations.

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