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CMS track reconstruction performance and tracking developments during Run 3

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Abstract

The efficient and precise reconstruction of charged particle tracks is crucial for the overall performance of the CMS experiment. Prior to the beginning of the Run 3 at the LHC in 2022, the first layer of the Tracker Barrel Pixel subdetector was replaced in order to cope with the high pileup environment, and significant upgrades were made to the track reconstruction algorithms. Performance measurements of the track reconstruction both in simulation and data will be presented from the collisions which occurred in 2022 and 2023. Finally we will discuss the ongoing developments to improve track reconstruction for the remainder of Run 3 and for the future.

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PROCEEDINGS OF SCIENCE

CMS track reconstruction performance and tracking developments during Run 3

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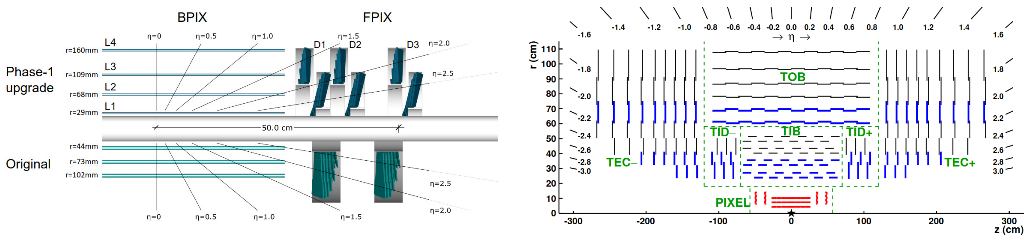

Figure 1: Layout of the CMS tracker. The figure on the left, the layout of the pixel subdetector, is from [5], the figure on the right, the overall layout of the tracker, is from [3].

1. Introduction

This presentation contains CMS track reconstruction performance results derived from proton-proton collision data collected during Run 3 at the Large Hadron Collider in 2022 and 2023. The aim is to evaluate the current performance of the CMS tracker and to commission the updated tracking software for Run 3, ensuring its operational parameters are under control and consistent with Monte Carlo simulations. These results are crucial since track information is essential for most physics analyses in CMS. This work is therefore essential to ensure the high quality of the CMS physics results.

The CMS Silicon tracker [3] [4] is immersed in a 3.8 T solenoidal magnetic field generated by the CMS magnet. Figure 1 illustrates the tracker layout. The CMS tracker includes a pixel subdetector near the interaction point, upgraded in 2017 to consist of four central layers (Barrel Pixel Detector, BPix) and three endcap disks (FPix). The pixel modules provide three-dimensional measurements of particle positions, while surrounding silicon strip modules offer two-dimensional measurements, except for the double-sided layers, highlighted in blue, that perform three-dimensional measurements. The iterative CMS track reconstruction algorithm [3] involves multiple iterations of the same reconstruction steps: seeding, pattern recognition, and final fitting. In the initial iterations, easily identifiable tracks are reconstructed, and their hits are masked in subsequent iterations, which focus on more complex topologies. Some iterations use pixel detector information for seeding, while others rely on strip detector data. Before LHC Run 3, the first layer of the Tracker Barrel Pixel subdetector was replaced to handle the expected high pileup environment [5], and the new mkFit pattern recognition algorithm was implemented [6].

For performance measurements, ZeroBias data were utilized, i.e. selected at the trigger level based only on the coincidences between proton beams. The selected tracks pass the "highPurity" [3] selection and must have $p_T > 1$ GeV. Monte Carlo events were reweighted to match the distribution of reconstructed vertices between data and Monte Carlo.

2. 2022 data/MC comparisons

2022 was the first year of data-taking at a center-of-mass energy of 13.6 TeV. The ZeroBias events analyzed were collected from July 19^{th} to October 17^{th}, 2022, except for the period from August 23^{rd} to September 27^{th}, when the P4 cooling plant at the LHC stopped due to the failure of a control card of a PLC of a ventilation equipment, causing a loss of control over the cryogenic system [7]. This interruption affected data collection for all LHC experiments. Results are presented according to the data-taking periods in the figures and are sourced from the 2022 DP Tracking Performance note [8].

Figure 2 shows the distribution of the significance of the 3D impact parameter for tracks passing the selection criteria outlined in section 1 for both data and Monte Carlo. These results are categorized by time periods and corresponding integrated luminosity following the replacement of the first layer of the Barrel Pixel Detector. The disagreement between data and Monte Carlo simulations increases from the first period (July 19^{th} to August 15^{th}) to the second (August 20^{th} to August 23^{rd}), indicating a deterioration in the performance of Barrel Pixel layer 1 due to radiation damage. The improved agreement in the last data-taking period results from increased bias voltage applied to the silicon modules in Barrel Pixel layer 1, to increase the hit detection efficiency, and updated spatial alignment of the modules.

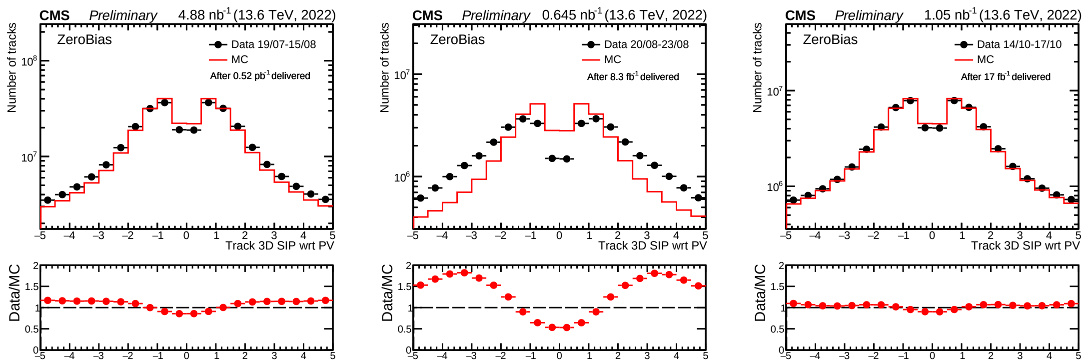

Figure 2: Significance of the 3D impact parameter in data and Monte Carlo for the different data-taking periods and after the integrated luminosity delivered since the replacement of the first layer of the Barrel Pixel Detector indicated in the figures. Results are taken from [8].

An updated track reconstruction was implemented for the first two periods mentioned. The updates include improvements in the pixel local reconstruction and spatial alignment of the tracker modules. Figure 3 shows the significance of the 3D impact parameter for a subset of the events collected from August 20^{th} to August 23^{rd}, which were reprocessed with these updates. The events is in this subset were collected from August 20^{th} to August 22^{nd}. The reprocessing significantly reduces the disagreement between data and Monte Carlo. These updates affect mostly the variables related to the impact parameters and the analyses which use them (b/tau tagging, etc.).

3. 2023 data/MC comparisons

Results are presented for two data-taking periods: May 6^{th} to June 13^{th}, 2023, and July 1^{st} to July 16^{th}, 2023, sourced from the 2023 DP Performance Note [9]. During the second period, readout issues were observed in layers 3 and 4 of the Barrel Pixel subdetector, affecting tracks with $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$ [10]. Two separate Monte Carlo samples simulating the tracker conditions were used for each period.

Figure 4 shows the distribution of the azimuthal angle ϕ for tracks passing the selection criteria in section 1. The figure on the right highlights the impact of the readout failure in layers 3 and 4.

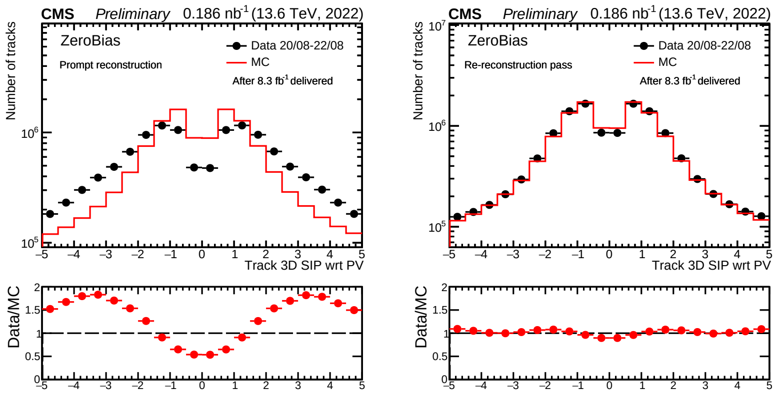

Figure 3: Significance of the 3D impact parameter distribution in data and Monte Carlo selecting only the tracks in the period in the figure for which the updated reconstruction was performed. Results are taken from [8].

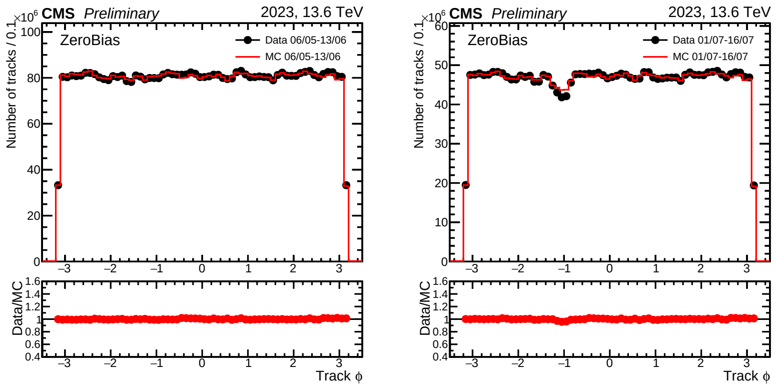

Figure 4: Azimuthal angle (ϕ) distribution in data and Monte Carlo. Results are taken from [9].

Overall, the agreement between data and Monte Carlo is good, with discrepancies around 5% in the region affected by the readout failure.

Figure 5 displays the distributions of the distance of closest approach to the primary vertex for tracks passing the selection in section 1, for both periods across the full geometric range (the first on the left, the second in the middle), along with a comparison in the pixel tracker region affected by the readout failure (on the right). The Monte Carlo distribution is narrower than the data distribution, indicating a better quality of alignment. The distribution for the second period is wider for tracks in the region affected by the readout failure, reflecting a resolution deterioration due to the missing pixel layer measurements. The disagreement between data and Monte Carlo is greater in the second period (O(30%) compared to O(20%) in the first period).

4. Upgrades to the tracking software

Updates at the High Level Trigger have been implemented to mitigate the effects of the readout failure in the layers 3 and 4 of the Barrel Pixel subdetector. At the High Level Trigger [11], track reconstruction is performed in a single iteration of the Combinatorial Kalman Filter considering

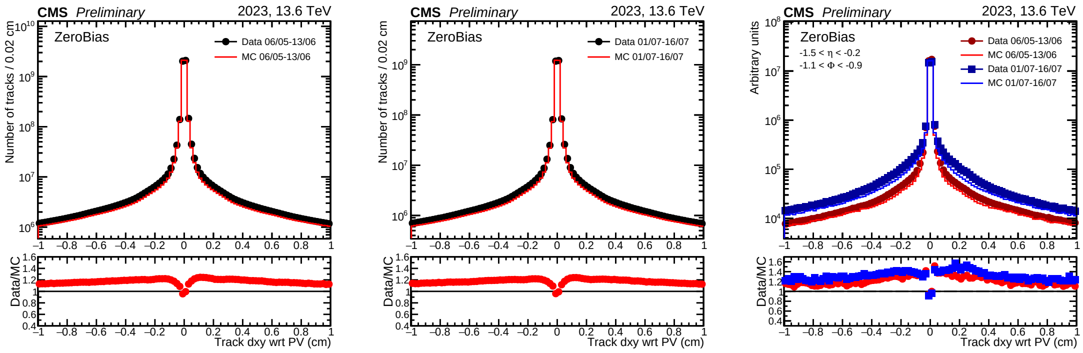

Figure 5: Distance of closest approach with respect to the primary vertex of tracks passing the selection described in the text: for the first (left) and the second (middle) period of 2023 in the full geometric range, with a comparison of the two periods in the pixel tracker region affected by the readout failure (right). Results are taken from [9].

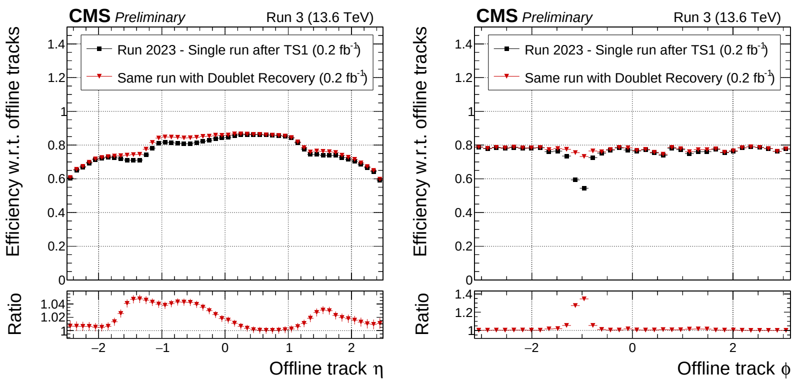

Figure 6: Reconstruction efficiency at High Level Trigger with respect to the offline reconstruction as a function of η , on the left, and ϕ, on the right, with and without the pixel doublet recovery iteration. Results are taken from [11].

tracks with least three hits in the pixel detector and $p_T > 0.3$ GeV. Starting from 2024, an additional pixel doublet recovery iteration, executed after the initial one, has been introduced: pixel doublets, created from pixel triplets that are missing a hit in Barrel Pixel layers 3 and 4, are utilized to initiate track reconstruction. Figure 6 shows the reconstruction efficiency at High Level Trigger with respect to the offline reconstruction as a function of η (left) and ϕ (right), both with and without the additional pixel doublet recovery iteration. A significant efficiency recovery can be observed when the additional iteration is included, particularly as a function of ϕ.

Updates for tracking inside the core of high$-p_T$ (O(100 GeV)) jets have been introduced for 2024. The tracking efficiency in the core of high$-p_T$ jets is affected by cluster merging due to increased occupancy and merged clusters on BPIX layer 1 at higher jet p_T, and combinatorics due to more candidate tracks and higher probability of misreconstructing tracks. CMS employs an iteration dedicated to the reconstruction of tracks inside high$-p_T$ jets. For 2024 the new DeepCore iteration[12] has been introduced: starting from the jets, a Convolutional Neural Network uses the pixel detector raw data from up to 4 layers of the pixel barrel detector (BPIX1 to BPIX4) to predict

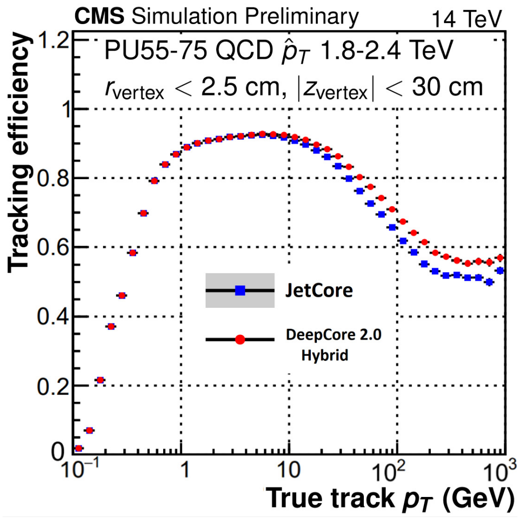

Figure 7: Reconstruction efficiency of the tracks inside the core of jets with high transverse momentum p_T (selected as described in [12]) as a function of the p_T of the tracks when the default (in blue) or DeepCore 2.0 hybrid (in red) iteration for tracking inside of high−p_T jets is used. Results are taken from [12].

the actual track crossing points on BPIX2. Unlike JetCore, the iteration used until 2023, it does not use the information on the presence of the reconstructed hits. Figure 7 displays the reconstruction efficiency for tracks in high−p_T jet cores (selected as per [12]) using all offline track reconstruction iterations. Blue points indicate efficiency with the JetCore iteration, while red points represent the hybrid DeepCore and JetCore implementation [12] implemented for tracking. An increase in tracking efficiency is noted with DeepCore, particularly significant for $p_T > 10$ GeV.

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