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CMS track reconstruction performance and tracking developments during Run 3(*)

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Summary. — The precise and efficient reconstruction of charged particle tracks is crucial for the success of the CMS experiment at the LHC. Prior to the start of LHC Run 3 in 2022, the first layer of the Tracker Barrel Pixel subdetector was replaced to cope with the high pileup environment, and significant upgrades were made to the track reconstruction algorithms. Measurements of track reconstruction performance based on data collected in 2022 and 2023 compared to simulation results are presented in this paper. This is then followed by a discussion of the ongoing developments to improve track reconstruction introduced for the remainder of Run 3 starting from 2024 and for the future.

1. – Introduction

In this presentation, we will discuss a series of findings derived from proton-proton collision data gathered by the CMS experiment 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 CMS tracking software for Run 3, ensuring that its operational parameters are accurately controlled and consistent with Monte Carlo simulations. Prior to the start of LHC Run 3, the first layer of the Tracker Barrel Pixel subdetector was replaced to cope with the high pileup environment expected in Run 3 [4], and the new mkFit pattern recognition algorithm was deployed [5]. These results are critical because track information is utilized by the majority of physics analyses in CMS, making it indispensable for ensuring the high quality of the physics output produced by the CMS experiment.

The CMS tracker [2, 3] is immersed in a solenoidal magnetic field of 3.8 T generated by the CMS magnet. It employs two technologies: as outlined in fig. 1, closer to the interaction point it is composed of pixel modules, arranged, since the Phase-1 upgrade in

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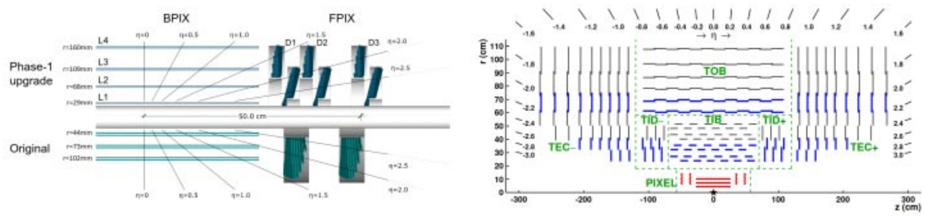

Fig. 1. – Layout of the CMS tracker. The figure on the left, the layout of the pixel detector, is from [4], the figure on the right, the overall layout of the tracker, is from [2].

2017, in 4 layers in the central region and three disks in the endcaps. These modules perform three-dimensional measurements of particle positions and are surrounded by micro-strip modules that conduct two-dimensional measurements. An exception is the blue-highlighted layers, which are double-sided and capable of performing three-dimensional measurements. For tracks reconstruction CMS uses an iterative algorithm [2]: iterations of the same reconstruction steps are performed. In the first iterations tracks which are more easily identifiable are reconstructed and their hits are masked from the subsequent iterations, depending on the iteration and some quality criteria which the reconstructed tracks have to pass, while in the latter iterations tracks from more difficult topologies are reconstructed. In some of these iterations tracks are seeded using the pixel detector information, in others they are seeded using the strip detector information.

For performance measurements, ZeroBias data were used, *i.e.*, selected at the trigger level using only the information on the coincidence of the proton beams. The selected tracks pass the "highPurity" [2] selection and have $p_T > 1$ GeV. The MC events were reweighted so that the distribution of the number of reconstructed vertices in the MC is equal to that in the data.

2. – 2022 data/MC comparisons

The year 2022 marked the inaugural data-taking period for Run 3 at a center-of-mass energy of 13.6 TeV, and during the long shutdown the innermost Barrel Pixel layer closest to the beam collisions was replaced. The ZeroBias events selected for this analysis were collected from July 19^{th}, 2022 to October 17^{th}, 2022, with the exception of the period from August 23^{rd} to September 27^{th}, because the cooling plant at P4 at the LHC stopped due to the failure of a control card of a PLC of a ventilation equipment produced the loss of control of the cryogenic system [6]. The beams were stopped during this period of time, impacting the data taking of all the LHC experiments. The results are shown as a function of the period of data taking in the figures. All the results shown are extracted from the 2022 DP Tracking Performance note [7].

Figure 2 shows the distribution of the significance of the 3D impact parameter for the tracks which pass the selection outlined above for data and Monte Carlo. These data are presented for specific time periods and corresponding integrated luminosity, measured after the replacement of the first layer of the Barrel Pixel Detector, as indicated in the figure. The discrepancy between the data and Monte Carlo simulations increases when transitioning from the first period, from July 19^{th} to August 15^{th}, to the second period, from August 20^{th} to August 23^{rd}. This suggests a deterioration of the performance of the Barrel Pixel layer 1 due to accumulated radiation damage. The improvement in the

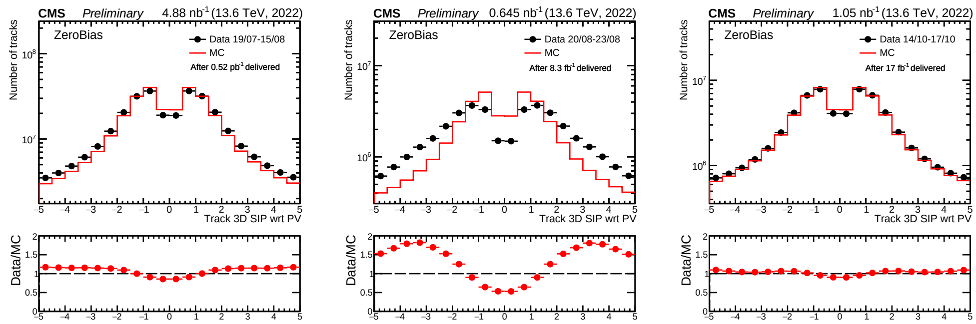

Fig. 2. – Distribution of the significance of the 3D impact parameter for data and Monte Carlo for the different periods of time and after the integrated luminosity delivered since the replacement of the first layer of the Barrel Pixel Detector indicated. Figures are taken from [7].

agreement in the last data taking period is due to an increase of the bias voltage applied to the silicon, to improve the hit detection efficiency of the detector, and to an update in the spatial alignment of the modules.

An updated version of the track reconstruction which includes improvements related to the local reconstruction in the pixels and the spatial alignment of the tracker modules was made available for the first two periods indicated above. Figure 3 shows the same distribution as in fig. 2 for a subset of the events collected from August 20^{th} to August 23^{th}, and which correspond to a period from August 20^{th} to August 22^{th}, which were reprocessed with these updates. The agreement between data and MC has significantly improved after the reprocessing. The variables related to the impact parameters (used for b/tau tagging, etc.) are the ones most affected by the reprocessing, as expected given the improvements mentioned earlier.

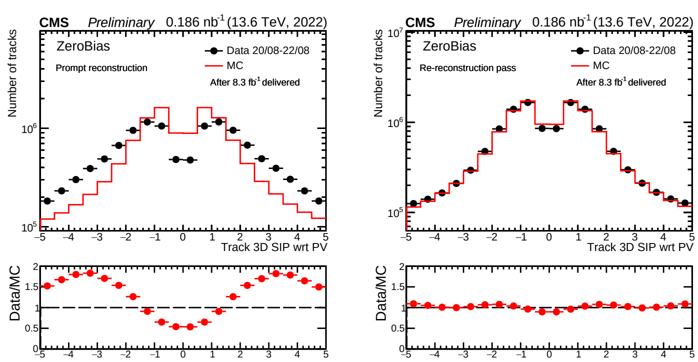

Fig. 3. – Distribution of the significance of the 3D impact parameter for data and Monte Carlo for tracks from events collected in the indicated period for which the updated recostruction was performed. Figures are taken from [7].

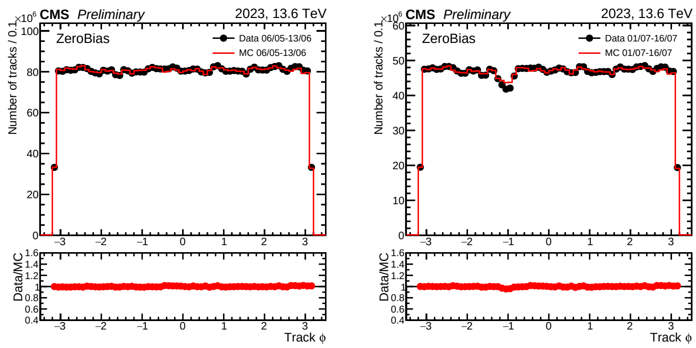

Fig. 4. – Distribution of the azimuthal angle ϕ. The figures are taken from [8].

3. – 2023 data/MC comparisons

The results are shown for two data taking periods: from May 6^{th}, 2023 to June 13^{th}, 2023 and from July 1^{st}, 2023 to July 16^{th}. These results are extracted from the 2023 DP Performance Note [8]. In the second period, readout problems were observed in the layer 3 and 4 of the Barrel Pixel tracker, with track coverage within $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$ [9]. Two different Monte Carlo samples were used to simulate the tracker conditions in the two different periods.

Figure 4 shows the distribution of the azimuthal angle ϕ for the tracks which pass the selection outlined above. The effect of the readout failure in the layer 3 and 4 of the Barrel Pixel tracker can be observed in the figure on the right. Overall the agreement between data and Monte Carlo is good and is at the 5% level in the region affected by the readout failure.

Figure 5 presents the distributions of the distance of closest approach to the primary vertex for tracks that meet the previously described selection criteria: 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, $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$ (right). It can be seen that the Monte Carlo distribution is narrower than the data distribution, indicating a better quality of alignment in Monte Carlo. The distribution is broader in the second period for the tracks with $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$, indicating the worsening of resolution due to missing pixel layer measurements. For these tracks the agreement between data and MC is worse in the second period (O(30%) compared to O(20%) in the first period).

Figure 6 shows the distributions of the number of valid hits in the pixel detector (left) and in the strip detector (right) of the tracks passing in the pixel tracker region affected by the readout failure, $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$. These distributions are sensitive to the bad tracker detector components. For the pixel detector (left), the number of tracks reconstructed with 4 good hits is well-reproduced for the first period, while for the second period the number of valid hits is lower as expected and it has a peak at 2, which is well reproduced in MC, while the agreement of MC with data in general is worse than in the first period. For the strip detector (right), the number of hits is in general overestimated in MC, but for the second data-taking period with only tracks with $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$ a significant reduction in the number of tracks with less than 4 valid hits in the strip detector can be seen, and the distribution

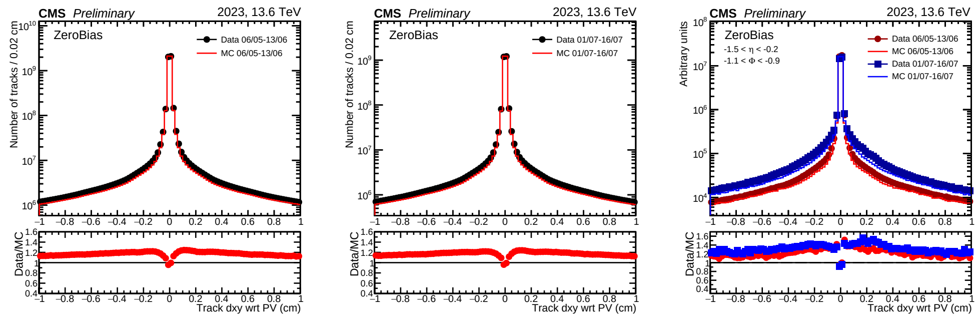

Fig. 5. – Distributions of the distance of closest approach to the primary vertex for tracks passing the selection described above: for the first (left) and the second (middle) period of 2023 in the full geometric range, with a comparison of the two periods in the pixel tracker region affected by the readout failure. The figures are taken from [8].

is shifted towards higher values: for efficient tracking, with only two active pixel layers more strip hits are effectively required. Part of the disagreement could be attributed to the fact that the Monte Carlo simulation used for these comparisons is still preliminary, not the final one to be used for CMS physics analyses.

4. – Upgrades to the tracking software

Mitigation procedures have been introduced to deal with the loss of efficiency due to the readout failure in the layers 3 and 4 of the Barrel Pixel detector. At High Level Trigger [10] the track reconstruction is performed in one iteration of the Combinatorial Kalman Filter considering tracks which have at least three hits in the pixel detector and $p_T > 0.3$ GeV. Starting from 2024, a pixel doublet recovery iteration which is performed after the initial one was added: pixel doublets, formed from pixel triplets missing a hit in Barrel Pixel layers 3 and 4, are used to initiate track reconstruction. Figure 7 shows the reconstruction efficiency at High Level Trigger with respect to the offline reconstruction as

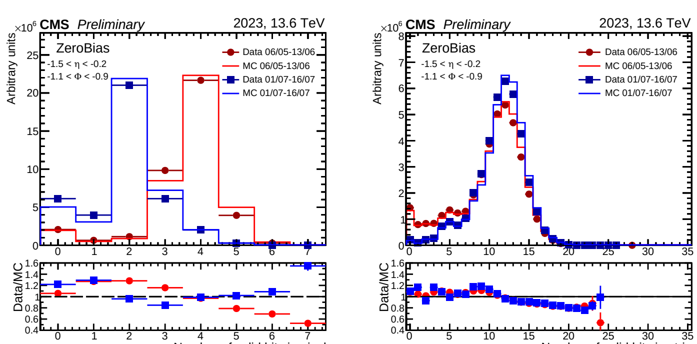

Fig. 6. – Distributions of the number of valid hits in the pixel detector (left) and in the strip detector (right) of tracks in the pixel tracker region affected by the readout failure, $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$. The figures are taken from [8].

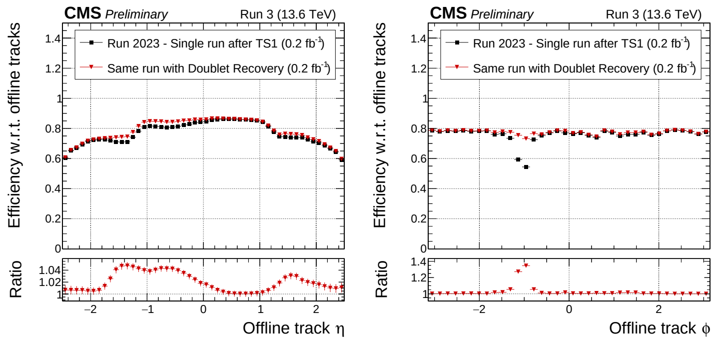

Fig. 7. – Reconstruction efficiency at High Level Trigger with respect to the offline reconstruction as a function of η (left) and ϕ (right) with and without the pixel doublet recovery iteration. The figures are taken from [10].

a function of η (left) and ϕ (right) with and without the pixel doublet recovery iteration. It can be seen that there is a significant efficiency recovery when the extra iteration is included.

In the offline reconstruction, the multiple implemented iterations already enable highly efficient track reconstruction, with iterations such as pixel doublet iteration and those utilizing the strip detector already in place. Attempts at modifying some of the iterations did not improve the overall reconstruction efficiency, if not at the cost of a significant increase in the total fake rate. Therefore no upgrades were introduced in the offline reconstruction sequence([1]).

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([1]) This was the status at the time of the presentation, since then there has been an upgrade in the iteration for track reconstruction inside high p_T jets [11].