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CMS track reconstruction performance and tracking developments during Run 3

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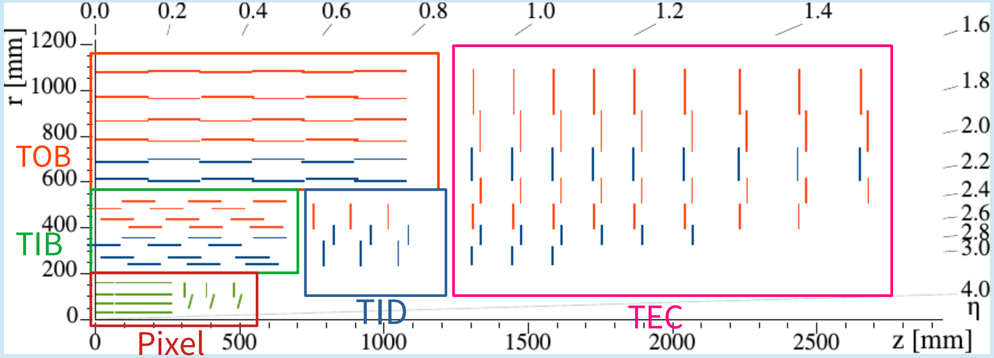
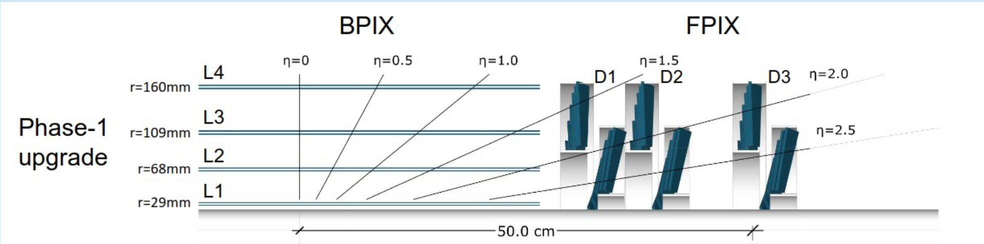
Tracking in CMS [1]

- CMS tracker immersed in a solenoidal magnetic field of 3.8 T.
- Two technologies:
  - Pixel: 4 layers in the central region (BPix) and 3 disks in the end-caps (FPix)
  - Silicon micro-strips: TIB, TID, TOB, TEC. The double-sided modules provide 3D measurements.
- CMS employs an **iterative tracking** algorithm:
  - Multiple iterations of the reconstruction steps (seeding, pattern recognition, fitting)
    - The first ones for more easily identifiable tracks (prompt and high-p_T)
    - The others look for more complex topologies (displaced and low-p_T), after having masked hits associated to already reconstructed tracks
  - Seeding step exploits either pixel only hits, or double-sided strip ones

Double-sided modules in blue



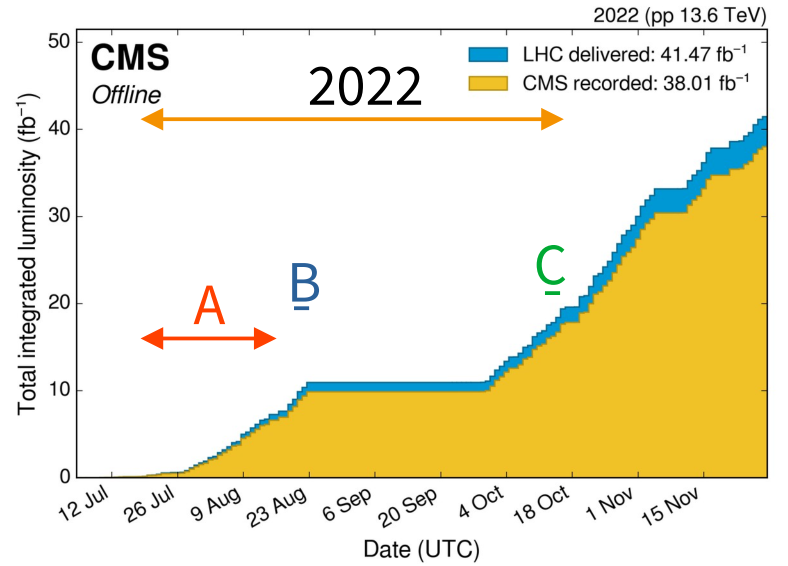


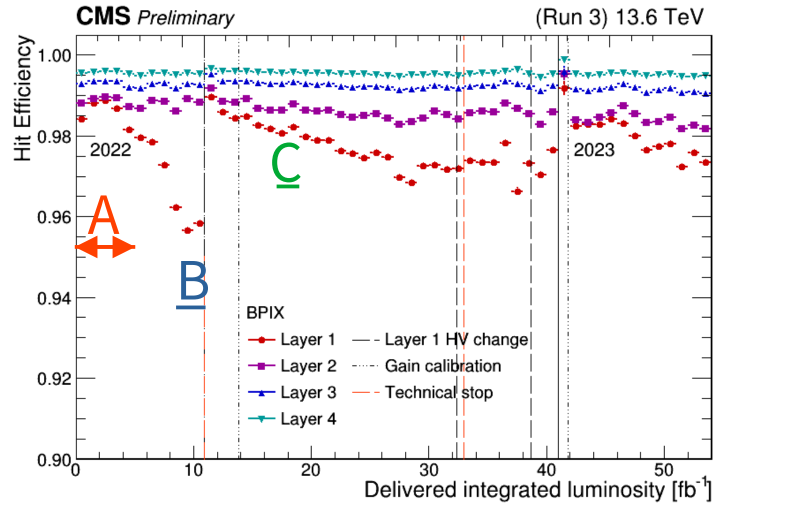
Outlook

- This presentation will show performance results about track reconstruction in CMS in 2022 and 2023:
  - This allows CMS to:
    - Commission the new CMS tracking software [2].
    - Validate the Monte Carlo simulations.
    - Validate the tracker conditions.
  - For performance measurements, ZeroBias data were used, i.e. selected at the trigger level using only the information on the coincidence of proton beams:
    - **2022** was the first year of data taking for Run 3 at a **center-of-mass energy of 13.6 TeV**, and during the long shutdown **the Barrel Pixel layer closest to the beam collisions was replaced** [3].
    - In **2023**, a **malfunction** was observed that affected **layers 3 and 4 of the Barrel Pixel detector [4]**.
- Then some of the updates to track reconstruction introduced for 2024 data taking will be presented. In particular these are:
  - The **performance improvement driven by the strategy for mitigating the Barrel Pixel detector malfunctioning.**
  - **Updates to the reconstruction of tracks inside high-p_T jets**.

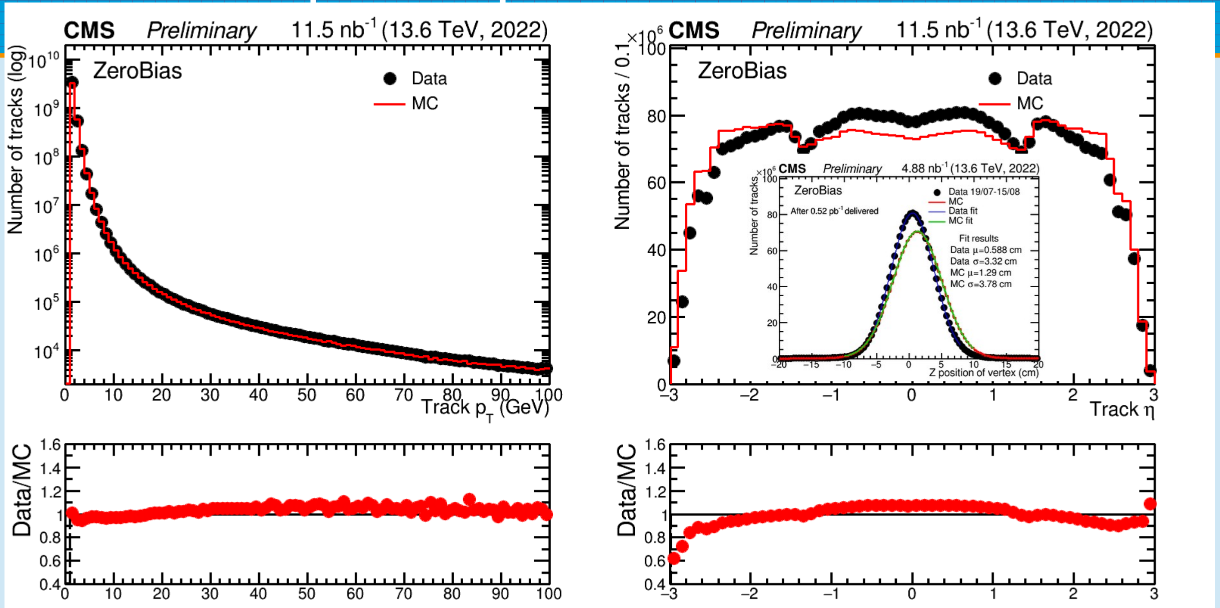
2022 data/MC comparisons

- The analysis uses ZeroBias events, the selected tracks pass the “highPurity” [1] selection and have p_T>1 GeV.
- The Monte Carlo simulation of the ZeroBias events is a **preliminary Minimum Bias simulation**.
- Events were collected from July 19th 2022 to october 17th 2022 (with the eception of the period from august 23rd to september 27th).
- MC events were reweighted so that the **distribution of the number of reconstructed vertices in MC matches than in data**.
- These results are described in the 2022 DP Tracking Performance note [5].



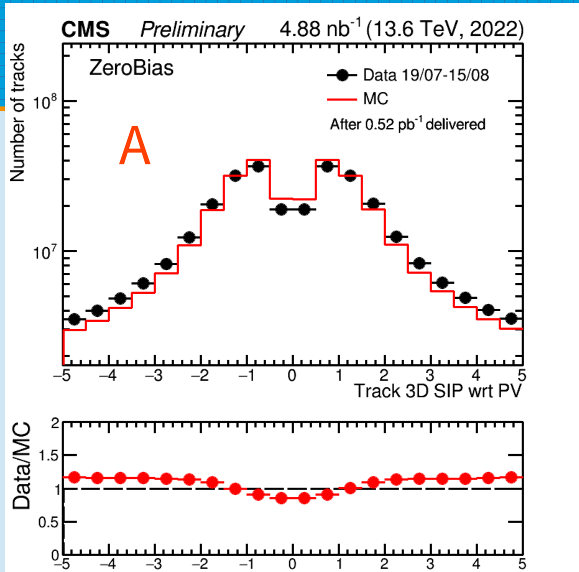


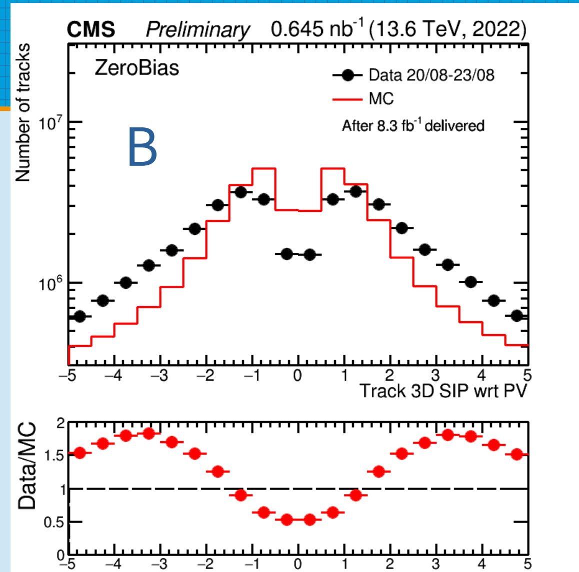
Kinematic properties

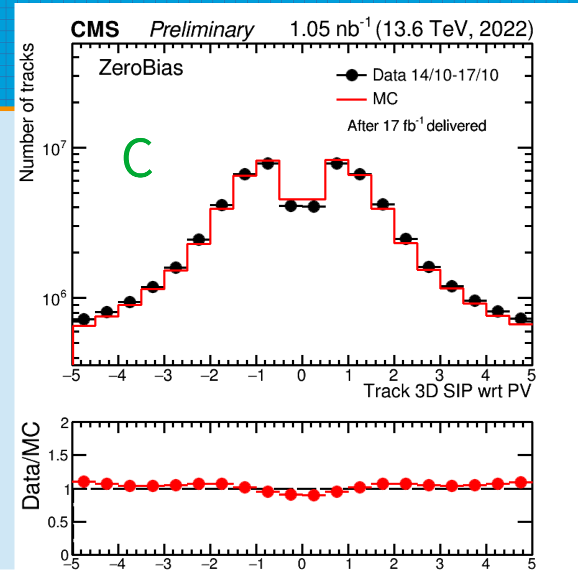


- The figures show the distributions of p_T and pseudorapidity (η) for the tracks high-purity tracks with $p_T > 1$ GeV.
- For the **p_T** distribution **the data/MC agreement is at 10%**.
- The **η** distribution **is wider in MC than in data**:
  - Probably related to the tuning **MC parameters**. The MC used is **not the final one for 2022 physics analyses**.
  - Asymmetry in |η| related to different position Z of the Beam Spot between data and MC.
- No scale factors for track reconstruction and identification are applied to the events.

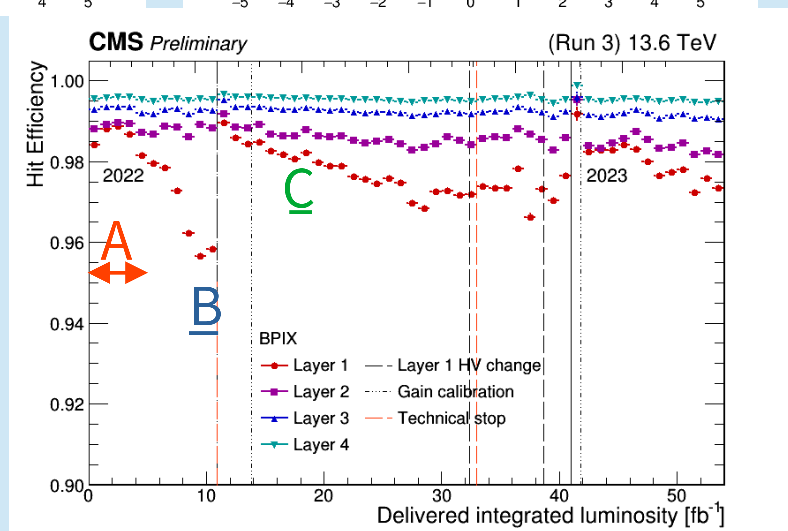
Significance of 3D IP



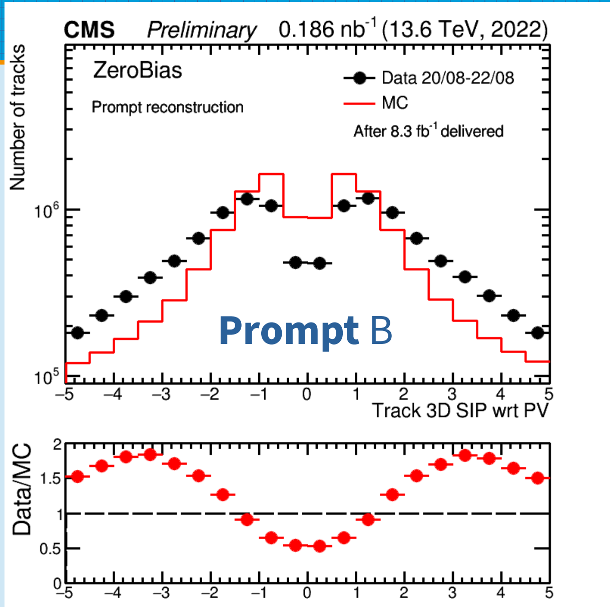


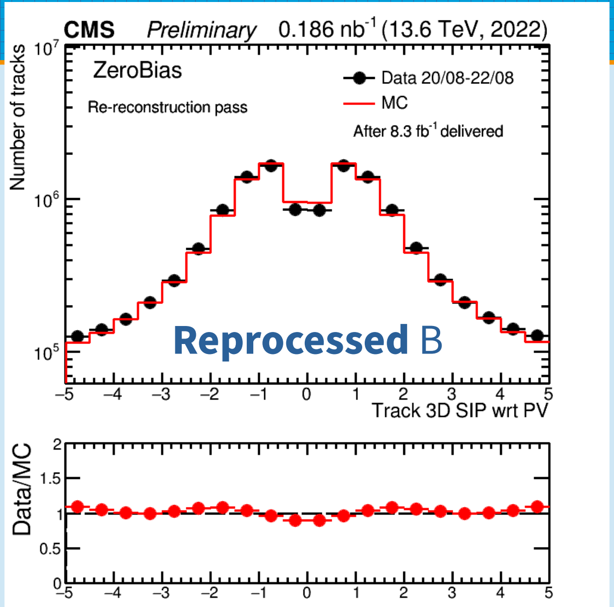


- Comparisons are shown for the different periods of time in the figures. Additionally, the figures show the luminosity that has been delivered since the installation of the new first layer of the Barrel Pixel Detector.
- **Agreement between data and MC worse when going from A to B**, due to the **aging of BPix layer 1 due to the accumulated irradiation**. Data was affected by a rapid change of the silicon properties not fully compensated by the reconstruction parameters used in the prompt reconstruction.
- **Agreement improves in C**. This is due to updates in the high-voltages on the Barrel Pixel layer 1 and in the alignment which was implemented in the data taking.



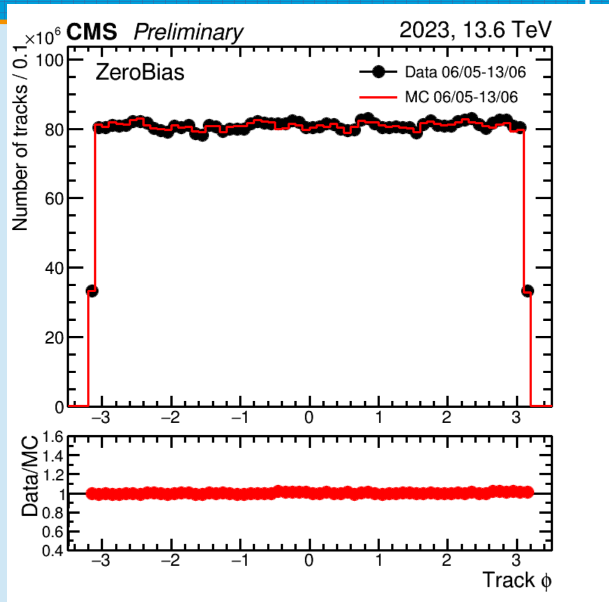
Significance of 3D IP

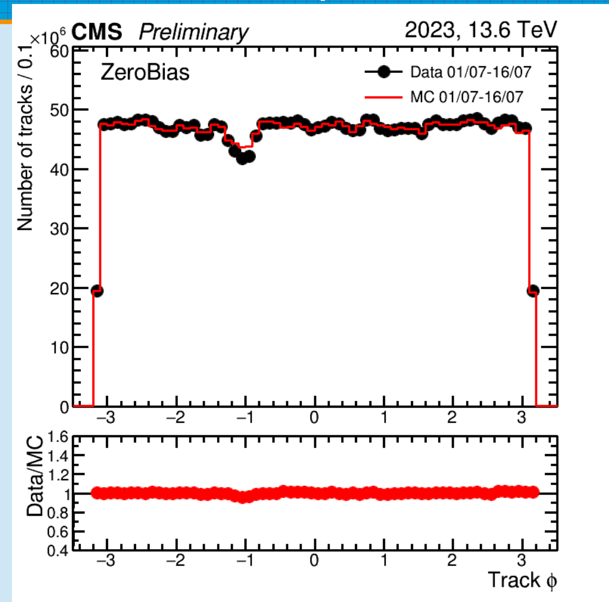




- **Considering only reprocessed data**.
- **Re-reconstruction includes updates to pixel local reconstruction and the alignment of the tracker, leading to better performance.**
- The updates introduced in the re-reconstruction have a significant impact on the variables related to the impact parameters (hence used for b/tau tagging,etc.).
- **A significant improvement for the data/MC agreement can be observed for re-reconstructed data.**

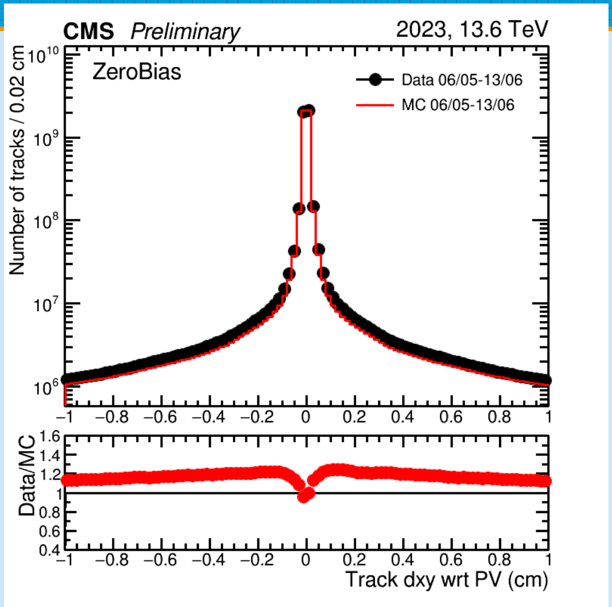
2023 Data/MC comparisons: ϕ distribution

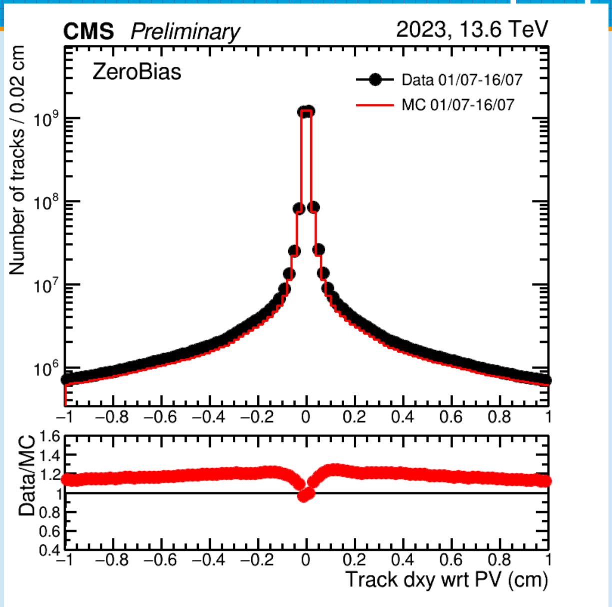


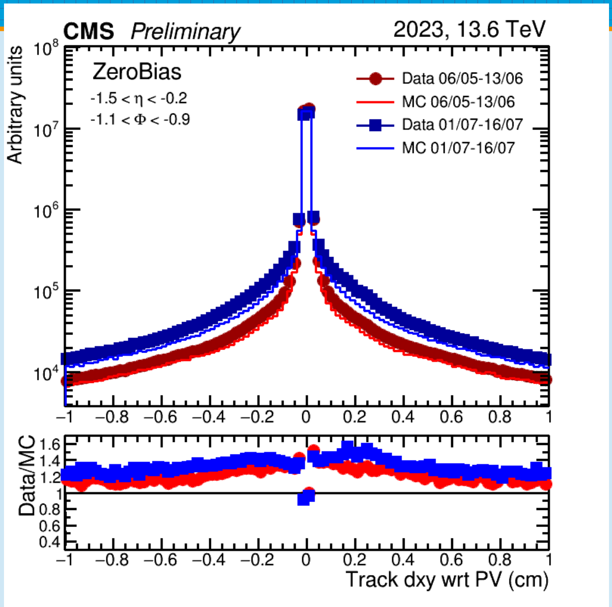


- Results of data/MC comparisons for 2023 are shown in this and the following slides. The data used are 13.6 TeV ZeroBias data collected in two periods. These results are described in the 2023 DP Tracking Performance note [6].
- **A lack of readout in pixel layers 3 and 4 of the barrel pixel tracker was observed in the second period [4].** This has an impact on the reconstruction of tracks with $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$ (hole, hereafter). Two different Monte Carlo data sets were used to simulate the different detector conditions. The effect of this readout failure can be seen in the figure on the right.
- **Good agreement between data and MC is found.**

Distance of closest approach



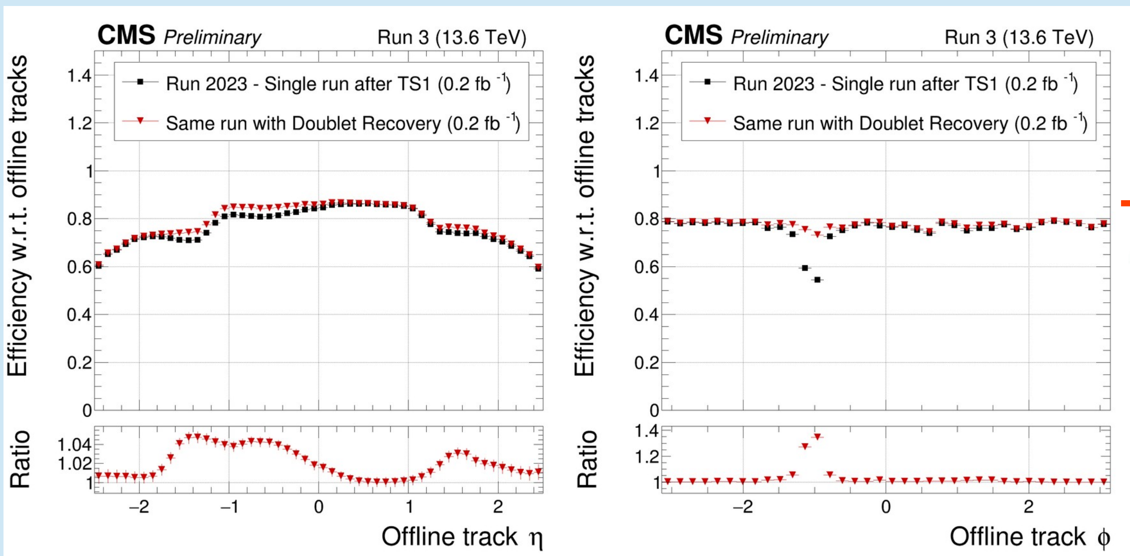




- The MC distributions are narrower than the data ones, indicating a **optimistic misalignment scenario**.
- The distribution is broader in the second period for the tracks in the hole, indicating the **worsening of the resolution due to the readout failure of the modules in layers 3 and 4**. For these tracks the agreement between data and MC is worse in the second period (approximately 30% compared to 20% in the first period).

BPIX failure: Mitigation at HLT [7]

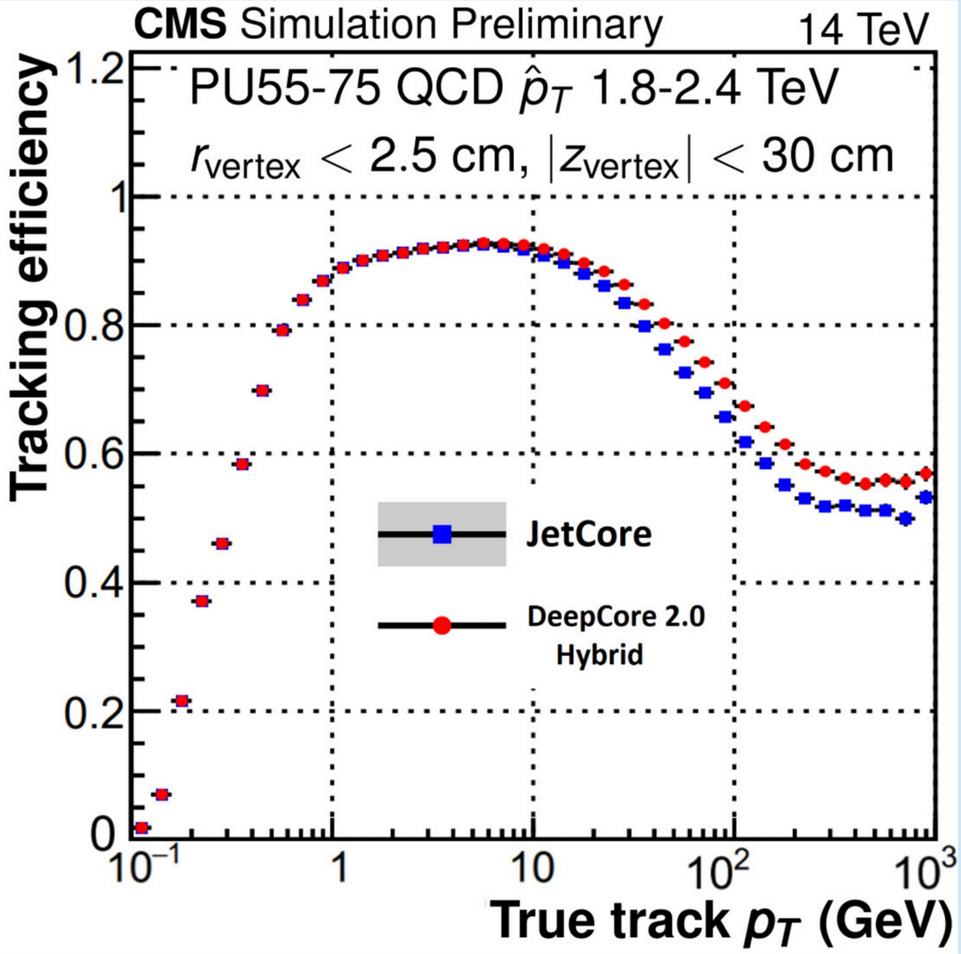
- Tracking at the HLT is performed in a single iteration considering tracks with at least three hits in the pixel detector and p_T>0.3 GeV.
- **Pixel doublet recovery iteration** added for 2024 data taking:
  - This is a "lighter" variant of what is done in the offline reconstruction (in the current form since Run 2).
- This additional iteration considers only specific combinations of pixel hit doublets. These doublets are obtained from pixel hit triplets where hits are missing in layers 3 and 4 of the Barrel Pixel Detector.
- Significant recovery in the reconstruction efficiency wrt offline reconstruction.



BPix1 + BPix2 + BPix3
~~BPix2 + BPix3 + BPix4 (*)~~
BPix2 + BPix3 + FPix1_neg
BPix2 + BPix3 + FPix1_pos
BPix3 + FPix1_neg + FPix2_neg
BPix3 + FPix1_pos + FPix2_pos

Tracking updates: DeepCore [8]

- The **tracking** efficiency **in the core of high-p_T jets** (O(100 GeV)) is **affected by**:
  - **Cluster merging**: as jet p_T increases, the occupancy and the number of merged clusters on BPIX layer 1 increase.
  - **Combinatorics**: as jet p_T increases, the number of candidate tracks and the probability to mis-reconstruct tracks in the core of jets increase.
- Introduced new **DeepCore [8]** algorithm:
  - Starting from the jets, a CNN directly uses charge deposits from up to 4 layers of the pixel barrel detector (BPIX1 to BPIX4) to predict actual track crossing points on BPIX2.
  - **It doesn't use the reconstructed hit information**, unlike JetCore.
- **Increase in overall offline tracking efficiency**.



Conclusions

- Performance results of track reconstruction in CMS in 2022 and 2023 using ZeroBias data have been shown.
- In 2022, the effects of radiation damage on the new Bpix layer 1 were observed. These effects were mitigated by updates in the reconstruction in the latter part of the year and in the reprocessed dataset.
- In 2023, the effects of the readout failure in Bpix layers 3 and 4, and the deterioration of the reconstruction of quantities related to the impact parameters, were observed.
- The effects of this readout failure were mitigated at the High Level Trigger level by adding a specific iteration to the track reconstruction sequence.
- Increase in the offline tracking efficiency when the DeepCore algorithm is used.

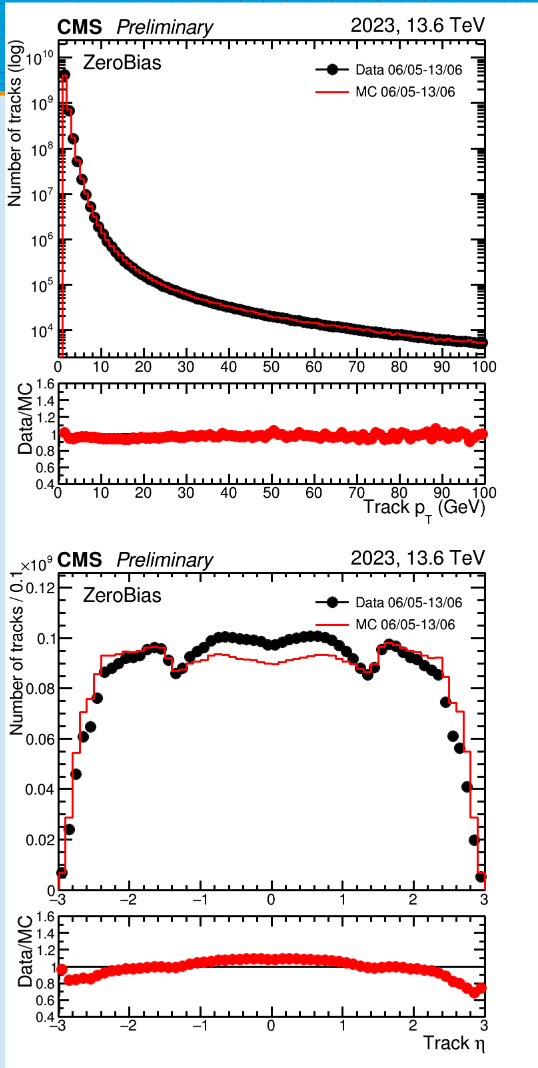
References

- [1]: Description and performance of track and primary-vertex reconstruction with the CMS tracker, The CMS Collaboration, arXiv:1405.6569v2 [physics.ins-det] 28 Oct 2014
- [2]: Performance of Run 3 track reconstruction with the mkFit algorithm, The CMS Collaboration, CERN-CMS-DP-2022-018
- [3]: The CMS Phase-1 Pixel Detector Upgrade, CMS Tracker Group of the CMS Collaboration, JINST 16 (2021) P02027
- [4]: Operation and performance of the Pixel Detector, G. Haza, CMS-CR-2023-282
- [5]: Early Run 3 tracking performance, The CMS Collaboration, CERN-CMS-DP-2022-064
- [6]: CMS tracking performance in 2023, The CMS Collaboration, CERN-CMS-DP-2023-090
- [7]: Performance of Track Reconstruction at the CMS High-Level Trigger in 2023 data, The CMS Collaboration, CERN-CMS-DP-2024-013
- [8]: DeepCore 2.0: Convolutional Neural Network for Tracking in Jets with High Transverse Momentum, The CMS Collaboration, CERN-CMS-DP-2024-003

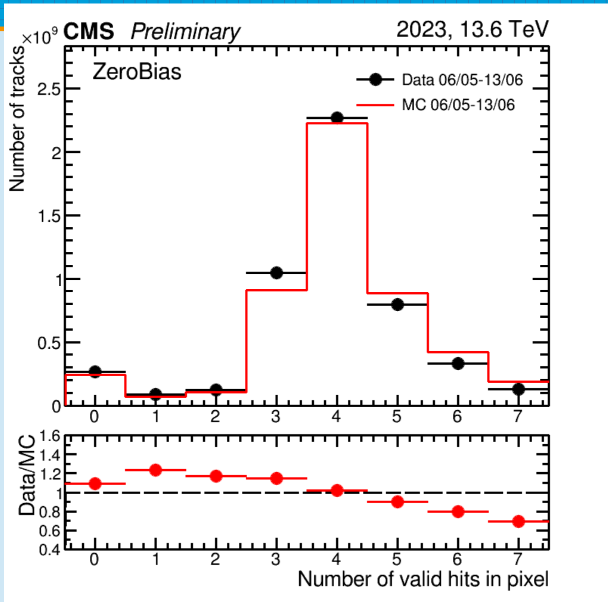
BACKUP

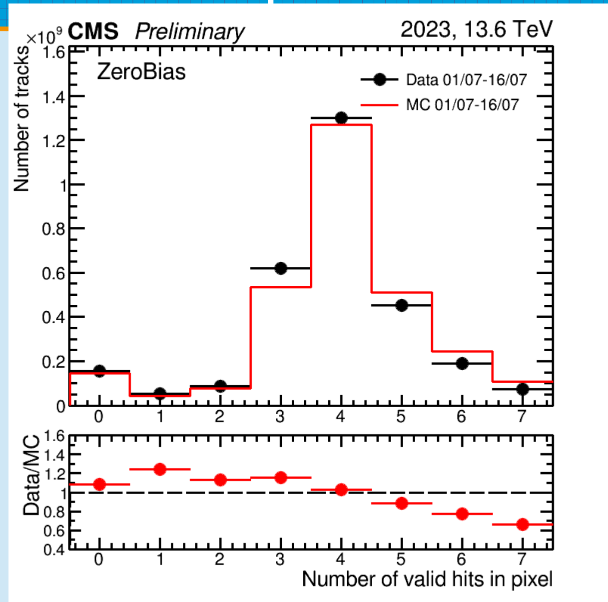
2023 data/MC comparisons

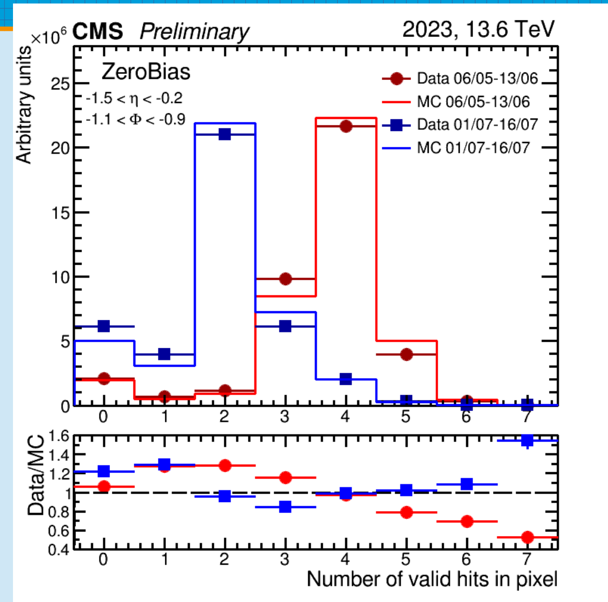
- The data used for the comparisons shown are ZeroBias data at 13.6 TeV collected in two periods, between May 6th and June 13th, 2023 and between July 1st and July 16th, 2023. In the second period, problems were observed in layers 3 and 4 of the barrel pixel tracker, impacting tracks with $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$. Different Monte Carlo data sets were used to simulate the different detector conditions in the two periods.
- The simulation of event production is identical to that used in 2022, with a similar data/MC agreement for the kinematic distributions (to be compared with slide 5 for 2022).
- These results are extracted from the 2023 DP Tracking Performance note [6].



Valid hits in the pixel detector

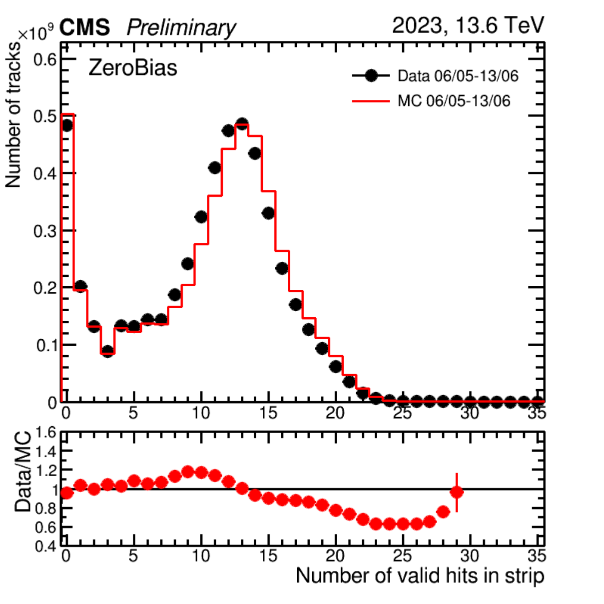


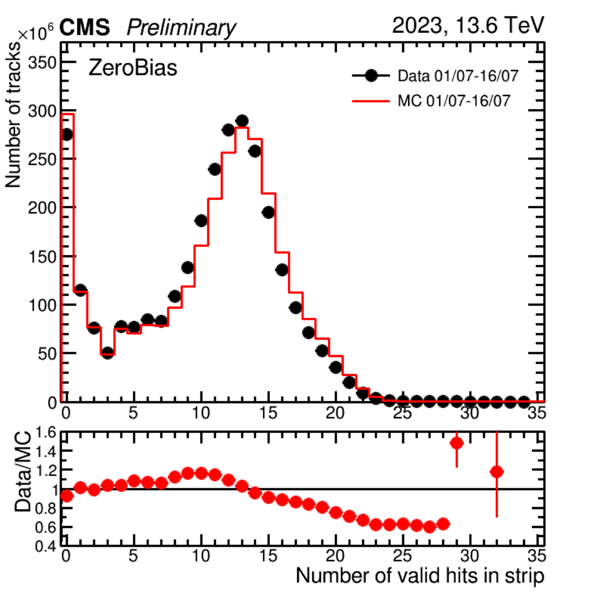


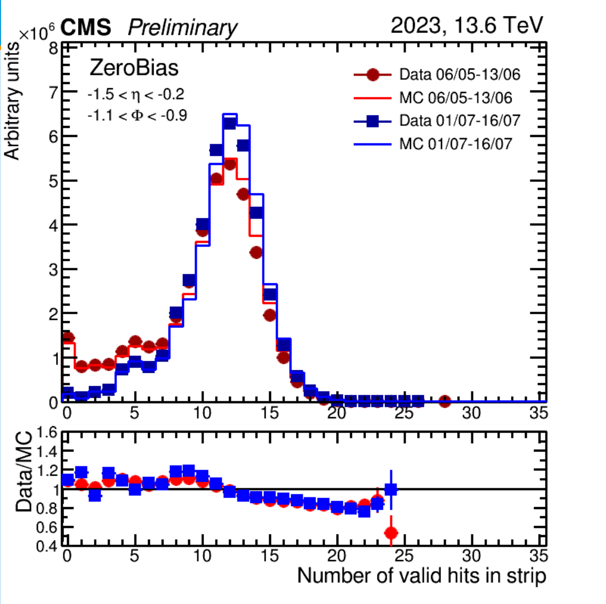


- These distributions are sensitive to the bad tracker detector components.
- The agreement has a **dependence as a function of the number of hits**, similar to what was seen in 2022. The number of tracks with **4 valid hits is well reproduced** for both periods across the full geometric acceptance and for the first period for tracks in the hole.
- For the second period for tracks in the hole: **number of valid hits is lower, with a peak at 2,** as expected because only 2 barrel layers remain in that region, and this is well reproduced in the MC, while the overall agreement is worse than in the first period.

Valid hits in the strip detector







- In general, the number of hits is overestimated, but this trend is similar to what was observed for 2022 [4]. For the second period, when considering only the tracks in the hole, **a significant reduction in the number of tracks with less than 4 valid hits is observed, and in general the distribution is shifted towards higher values**:
  - For good tracking efficiency, more hits in the strip detectors are necessary when only two pixel layers are active.

BPIX failure: Mitigation

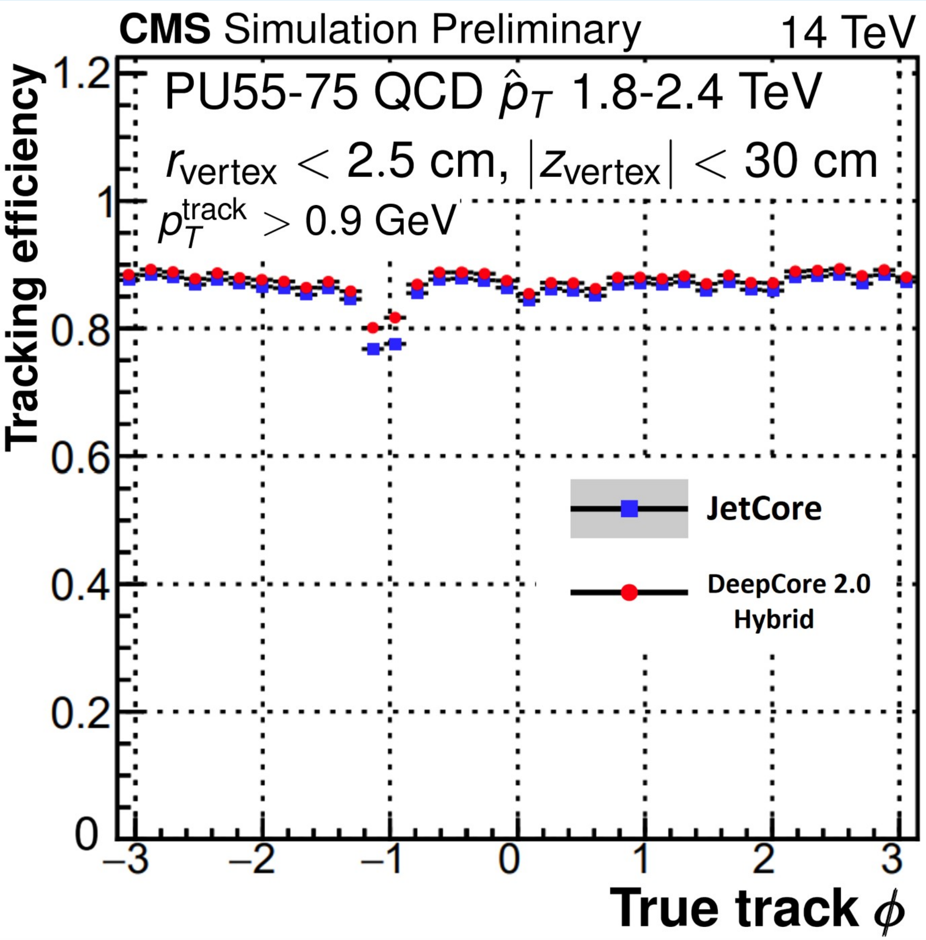
Offline

- **Pixel doublet recovery** already implemented starting from 2017
- **Retraining of the classification DNN** brought to a marginal improvement (< 0.5%), but a significant increase in the fake rate
- **Relaxing th pixelPair seeding criteria** results in a significant increase of the fake rate
- Not many improvements from **pixel-less recovery** due to failure in TIB1 in the same region

Iteration	Seeding	Target track
Initial	pixel quadruplets	prompt, high p_T
LowPtQuad	pixel quadruplets	prompt, low p_T
HighPtTriplet	pixel triplets	prompt, high p_T recovery
LowPtTriplet	pixel triplets	prompt, low p_T recovery
DetachedQuad	pixel quadruplets	displaced--
DetachedTriplet	pixel triplets	displaced-- recovery
MixedTriplet	pixel+strip triplets	displaced-
PixelLess	inner strip triplets	displaced+
TobTec	outer strip triplets	displaced++
JetCore	pixel pairs in jets	high-p_T jets
Muon inside-out	muon-tagged tracks	muon
Muon outside-in	standalone muon	muon

Tracking updates: DeepCore [8]

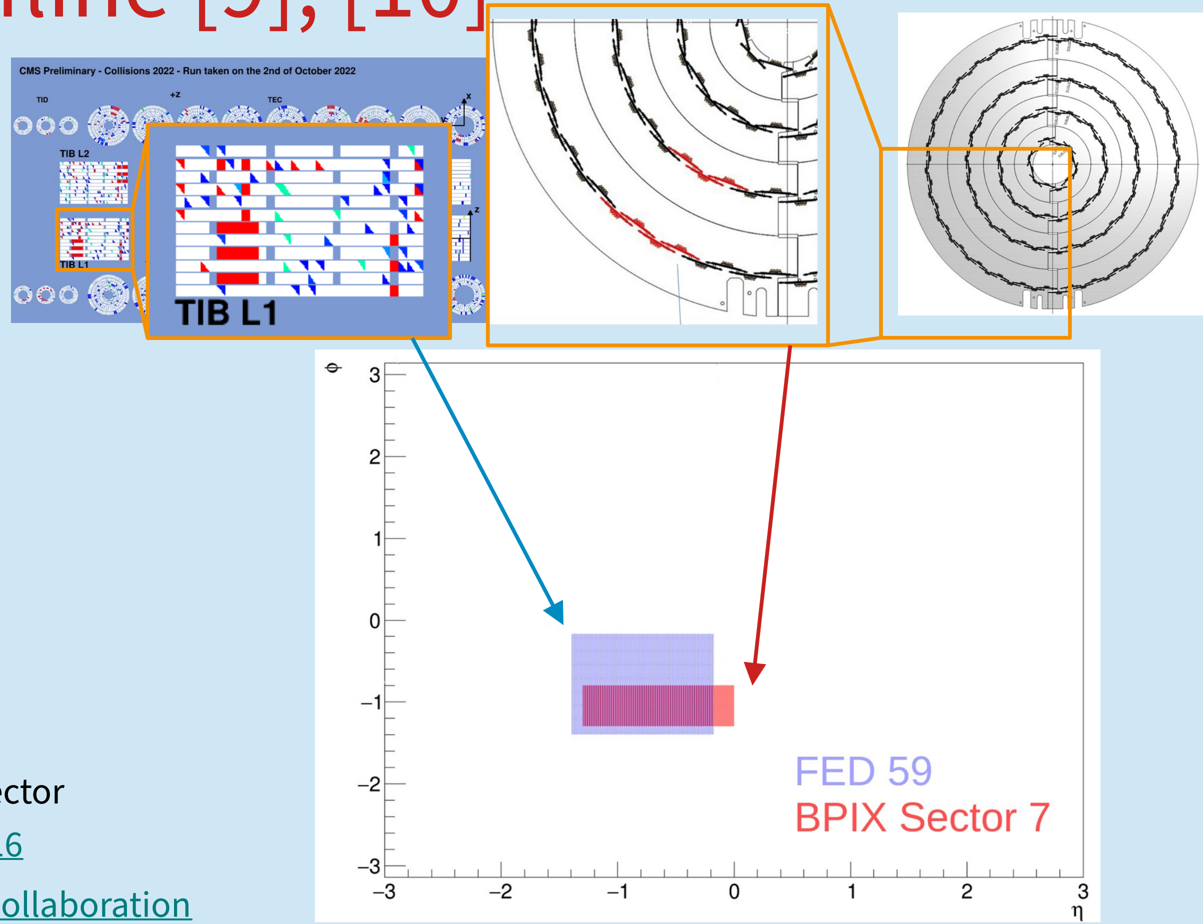
- The **tracking** efficiency **in the core of high-p_T jets** (O(100 GeV)) is **affected by**:
  - **Cluster merging**: as jet p_T increases, the occupancy and the number of merged clusters on BPIX layer 1 increase.
  - **Combinatorics**: as jet p_T increases, the number of candidate tracks and the probability to mis-reconstruct tracks in the core of jets increase.
- Introduced new **DeepCore [8]** algorithm:
  - Starting from the jets, it uses a CNN to look at the cluster charge distribution in pixel layers 1 and 2.
  - **It doesn't use the reconstructed hit information**, unlike JetCore.
- **Increase in overall offline tracking efficiency** (incidentally also in the hole).



BPIX failure: Mitigation

Offline [9], [10]

- Offline, **the different iterations that allow to have a track reconstruction with high efficiency have already been implemented** (among these pixel doublet, and iterations that used double sided strips for seeding).
- Also, failure in the overlapping regions of Bpix layers 1 and 2 and the first layer of micro-strip (already observed in the end of 2022).
- No significant gains in efficiency (unless at the cost of a significant in fake rate).



[9]: CMS Technical Design Report for the Pixel Detector Upgrade, A. Dominguez et al., CERN-LHCC-2012-016

[10]: SiStrip Bad components tracker maps, CMS Collaboration