CMS tracking performance in Run 2 and early Run 3

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A Introduction

A precise and efficient tracking is one of the critical components of the CMS physics program as it impacts the ability to reconstruct the physics objects needed to understand proton-proton collisions at the LHC.

❑ Iterative Tracking at CMS

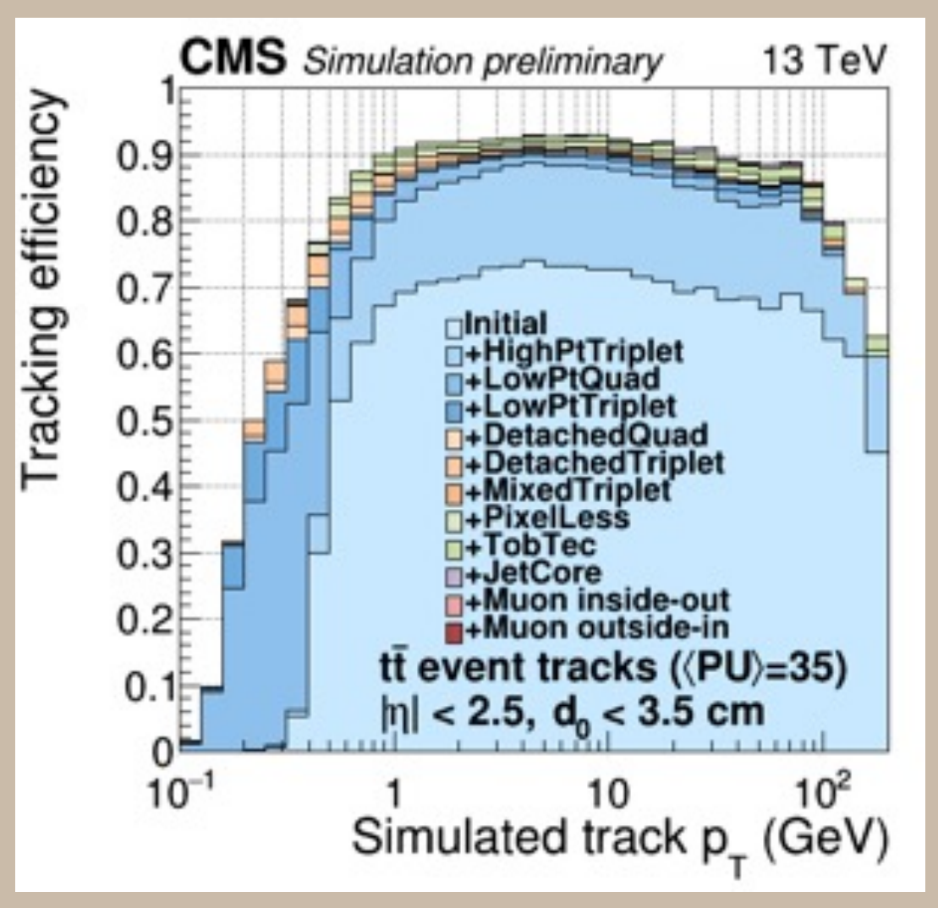
- ➢ Track reconstruction is an **iterative procedure** [1], where each step is meant for reconstructing a specific subset of tracks (prompt, low/high p_T, displaced, ...)

reconstruct the most energetic tracks [staring from the high p_T seeds].

remove hits associated to found tracks

repeat the pattern recognition w/ looser set of cuts

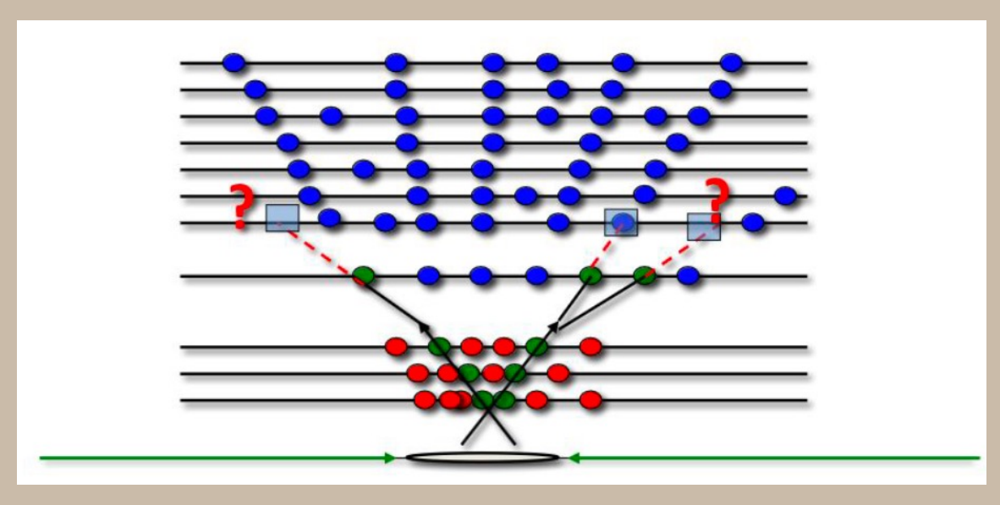
- ➢ Removing hits of found tracks reduce the combinatorial problem so that problematic tracks can be reconstructed within the CPU time budget.



B Algorithmic improvements for Run 3

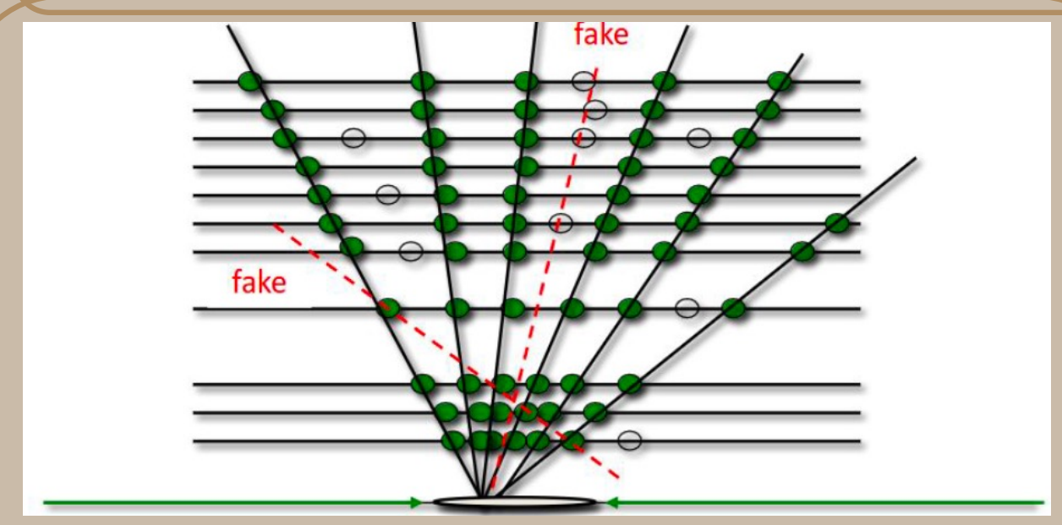
Developments during the LHC Long Shutdown 2 focused on the tracking algorithmic improvements targeted to reconstruction timing and tracking fake rate:

Track Building step: from CKF to mkFit

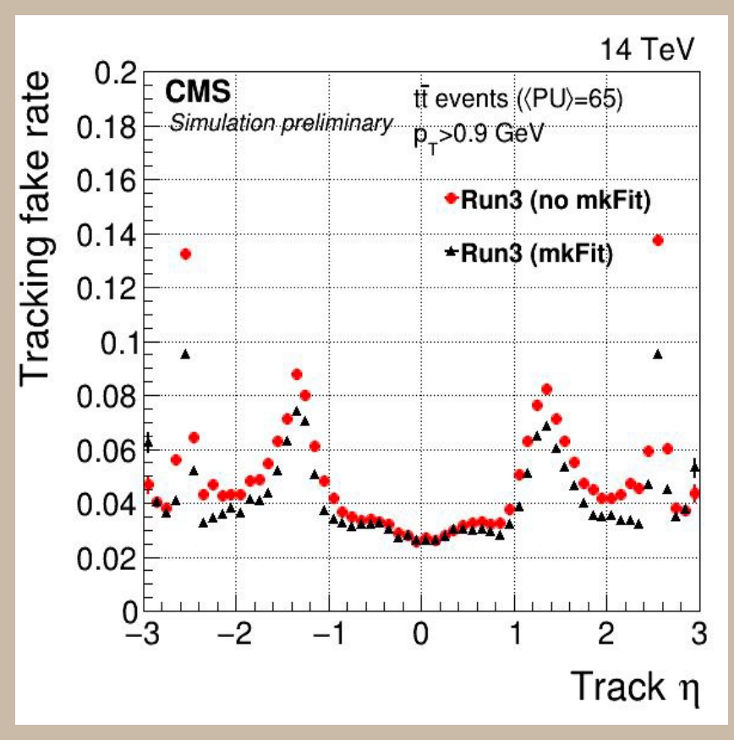


- Parallelization and vectorization at multiple levels using Kalman Filter, using the mkFit algorithm [2].

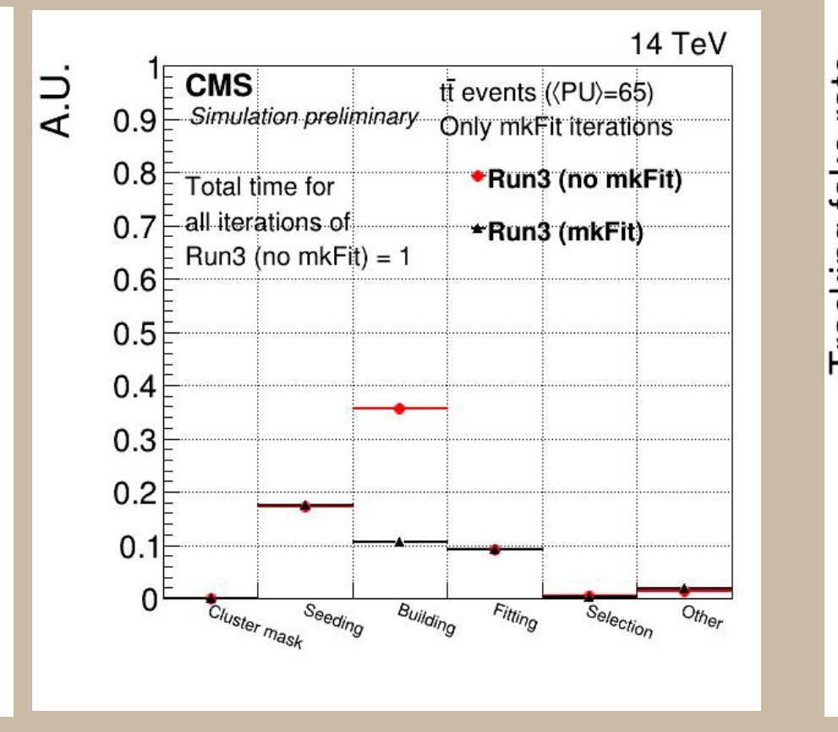
Track Selection step: from BDT to DNN



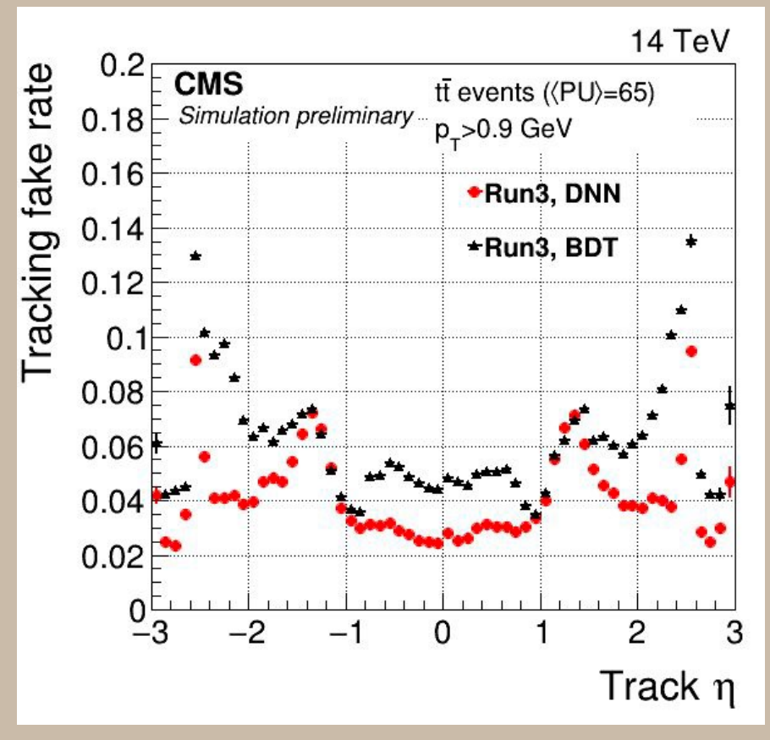
- After final fit, track quality is assessed with track classifier: from a Boosted Decision Tree to a Deep Neural Network [3].



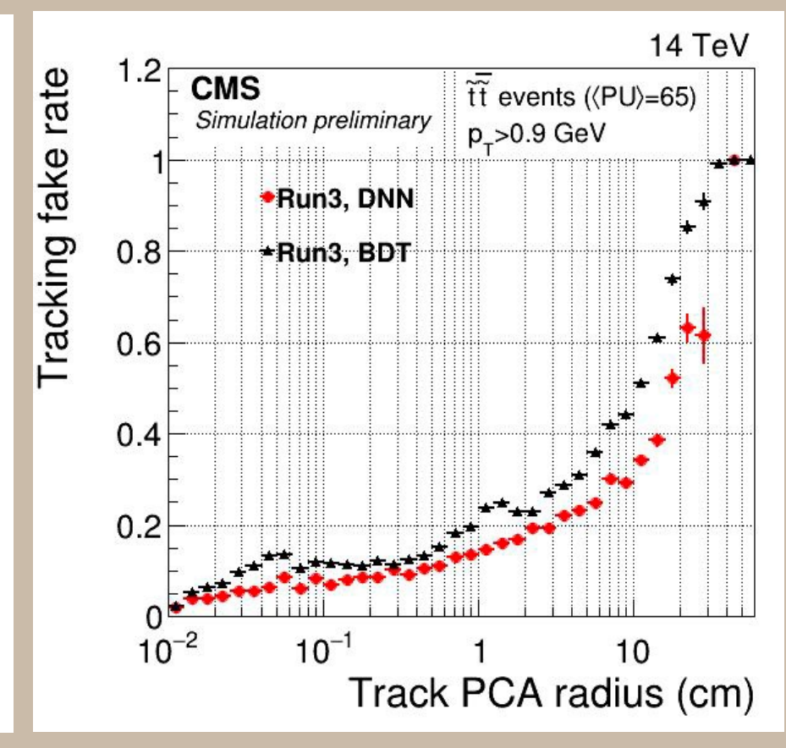
The **tracking fake rate** using **mkFit** is lower than. the one obtained with the traditional CKF tracking algorithm



Using **mkFit** allows to **reduce the track building time** by a factor of **about 3.5** considering the sum of iterations where mkFit is used.

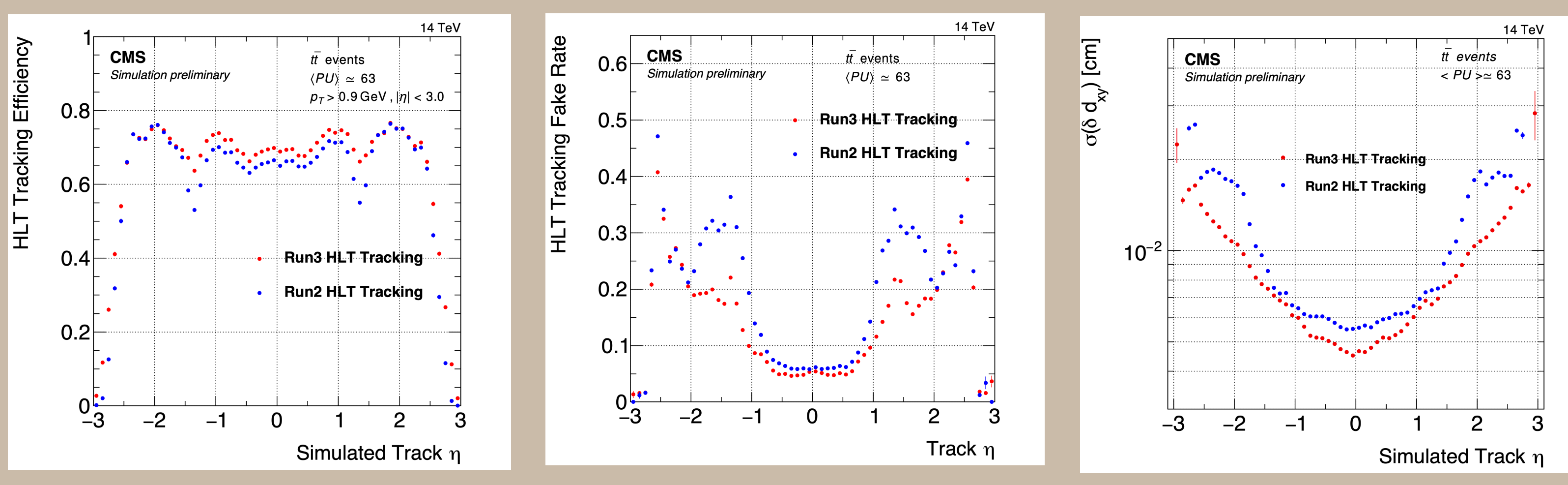


The tracking fake rate when the DNN is used is **notably lower** than the one obtained using the BDT.



The **tracking fake rate** when the DNN is used is lower than the one obtained using the BDT **across all the radii values**, with a **reduction of about 30%.**

- ➢ Since the start of Run 3, the HLT makes use of a heterogeneous computing farm to run a version of the full event reconstruction optimized for fast processing.
- ➢ In Run 3, HLT tracking is based on a single iteration of the Combinational Kalman Filter, seeded by pixel tracks reconstructed by the Patatrack algorithm [4], which can be offloaded to GPUs.

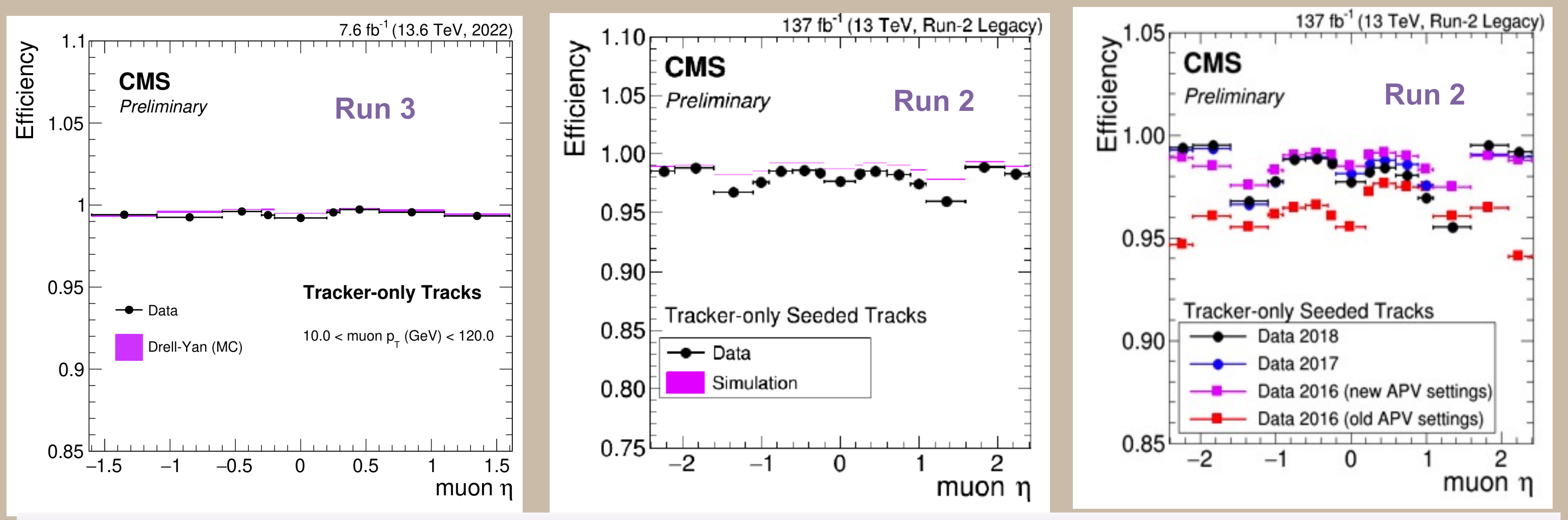


The tracking efficiency (left), tracking fake rate (middle), and the track d_{xy} resolution are shown as a function of the simulated track pseudorapidity η for the Run-2 HLT tracking (blue) and the Run-3 HLT single-iteration tracking (red) [5]. With respect to the Run 2 HLT tracking, improved efficiency, improved impact parameters resolution, and noticeable fake rate rejection in the transition region between the barrel and the endcap.

C Tracking Performance using Tag&Probe Technique

- The tag and probe method (T&P) is a data-driven technique used to measure the efficiencies from data. It is based on the reconstruction of well-known resonances, such as Z boson.
  - ➢ **Tag:** a global muon (i.e. reconstructed using both the muon chambers and the tracker) with transverse momentum $p_T \geq 27$, associated to one leg of the resonance and with a single muon trigger.
  - ➢ **Probe:** any standalone muon (i.e. reconstructed using only hits from the muon system) with at least one valid hit in the muon system (i.e. good track-hit χ^2).
  - ➢ **passing probe:** The standalone muon is matched with tracks that fulfill minimum quality requirements in $(\Delta R < 0.3)$. The matching is defined by comparing the directions at the point of the closest approach to the beamline of the two tracks.
- The (tag + passing probe) and (tag + failing probe) lineshapes are fit separately with a signal + background model.
- The efficiency is computed as the ratio between the "passing probes" and the total number of probes in the sample.

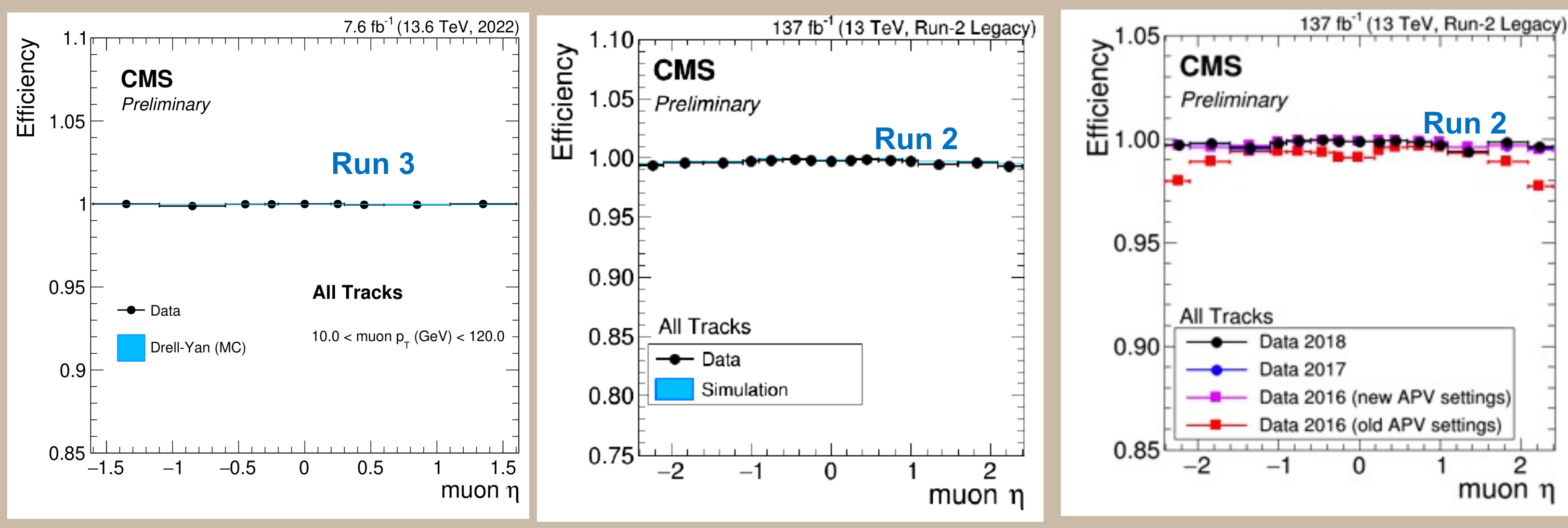
Tracker only seeded tracks



Muon tracking efficiency calculated from Z→μ+μ- events using Tag-and-Probe technique for the subset of trajectories in which the CMS tracker is used to seed the measurement (**Tracker-only seeded tracks**) [6],[7].

The final reconstructed tracks include outside-in and more relaxed inside-out regional muon iterations⇨ higher efficiency for muons.

All tracks collection



Muon tracking efficiency calculated from Z→μ+μ- events using Tag-and-Probe technique for all reconstructed muon trajectories (**All-tracks**). [6],[7].

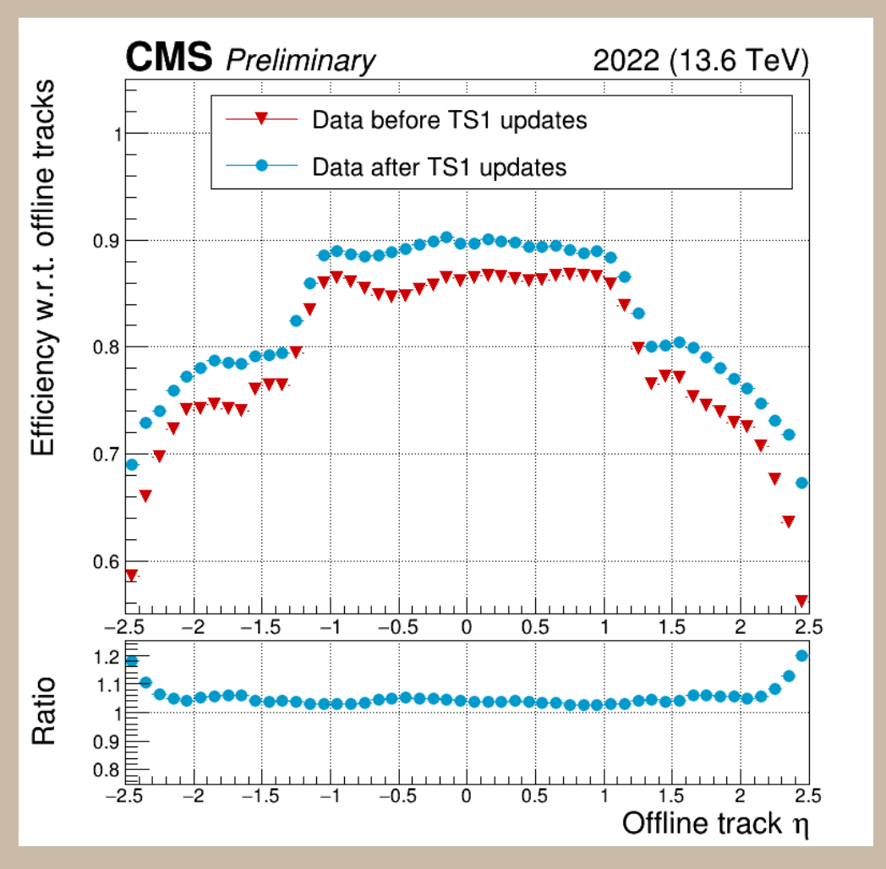
Thanks to the phase-1 pixel upgrade (adding one more layer of pixel measurements) and the new track seeding algorithm *based on Cellular Automaton (CA) technique* ⇨ increased efficiency after 2016

(*) old APV settings: pre-amplifier of the APV25 readout chip is saturated (20 fb-1 of 2016 data).
new APV settings: APV setting changed for fast recovery (16 fb-1 of 2016 data) [8].

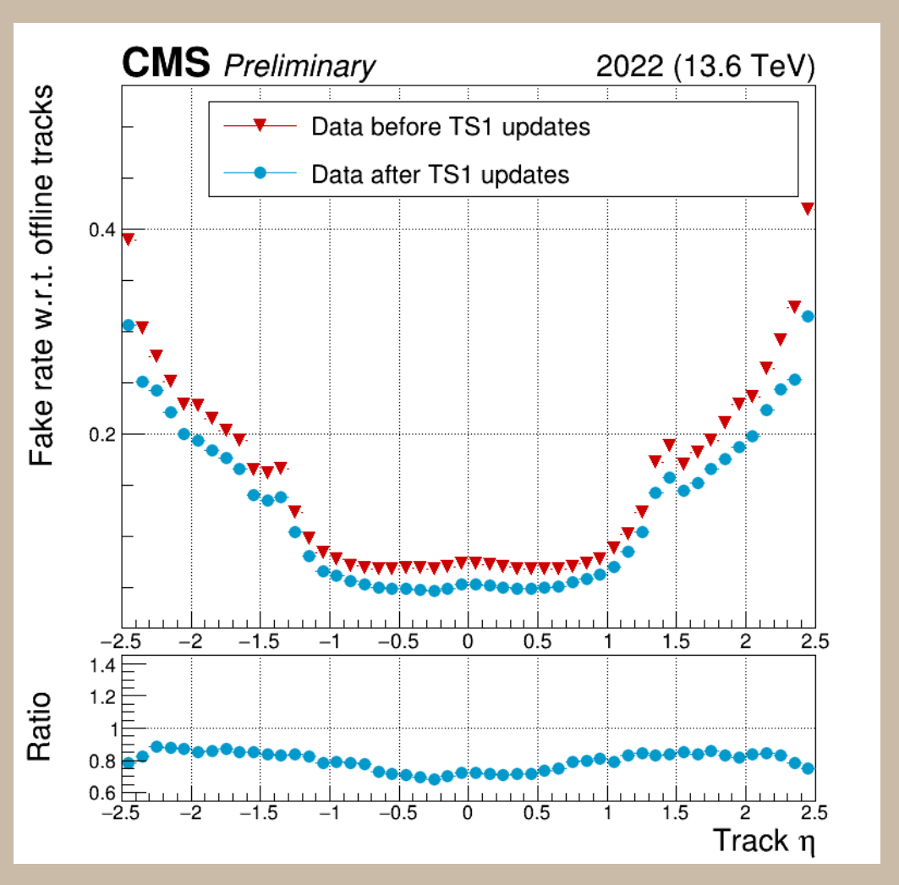
D Performance of tracking @ HLT

❑ The performance is measured using runs taken shortly before and after the first Technical Stop (TS1) of the LHC, when several updates in detector conditions took place:

- ➢ Increase in BPix L1 reverse bias high voltage (HV) from 150 V to 300 V.
- ➢ Update of the pixel cluster position estimator (CPE), as well as a new pixel detector gain calibration and a new tracker alignment.



- ✓ The HLT tracking efficiency and fake rate measured in data are defined with respect to offline tracks, i.e. tracks produced by the full offline event reconstruction, which satisfy high-purity track quality criteria [9].
- ✓ Differences in efficiency over the full η range are due to differences in efficiency in BPix L1 [9].
- ✓ The increase in fake rate at high |η| is also observed in the HLT tracking performance with respect to simulation [5].



E Conclusions

❑ Despite the challenging conditions at the LHC in Run 2 and in Run 3, the CMS Tracker has robust performance in a challenging environment ⇨ "high tracking and vertexing performance".

- ➢ Performances show a dependence of the detector as well as the algorithms used in the event reconstruction.
- ➢ The Phase-1 pixel upgrade has helped to cope with higher LHC delivered luminosity and the increased number of PU events during Run 2.
- ➢ In order to provide more precise and accurate track reconstruction sophisticated algorithms, techniques and calibrations have been developed for Run 3 which helped to cope with the excellent tracking efficiency.

F References

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