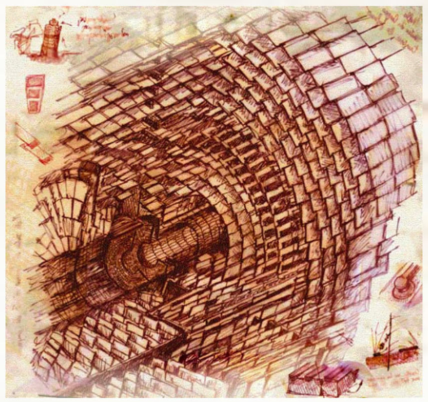
CMS track reconstruction performance during Run-2 and developments for Run-3

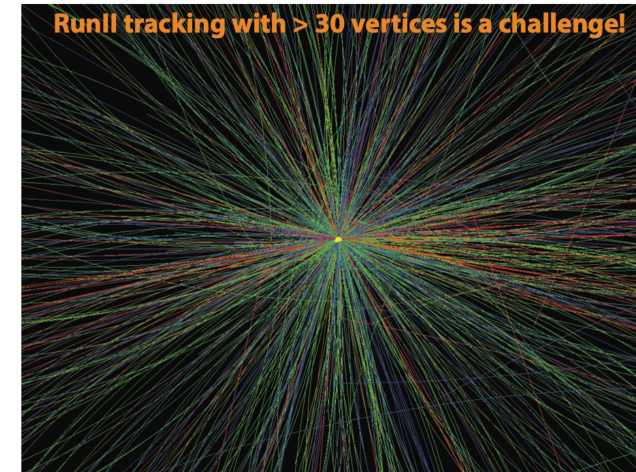


Walaa Elmetenawee[1] on behalf of
The CMS collaboration

ICHEP 2020
40th International conference on High Energy Physics
28 July -6 August 2020

[1] University & INFN Bari

CMS Tracking system: Run1+Run-2 2016

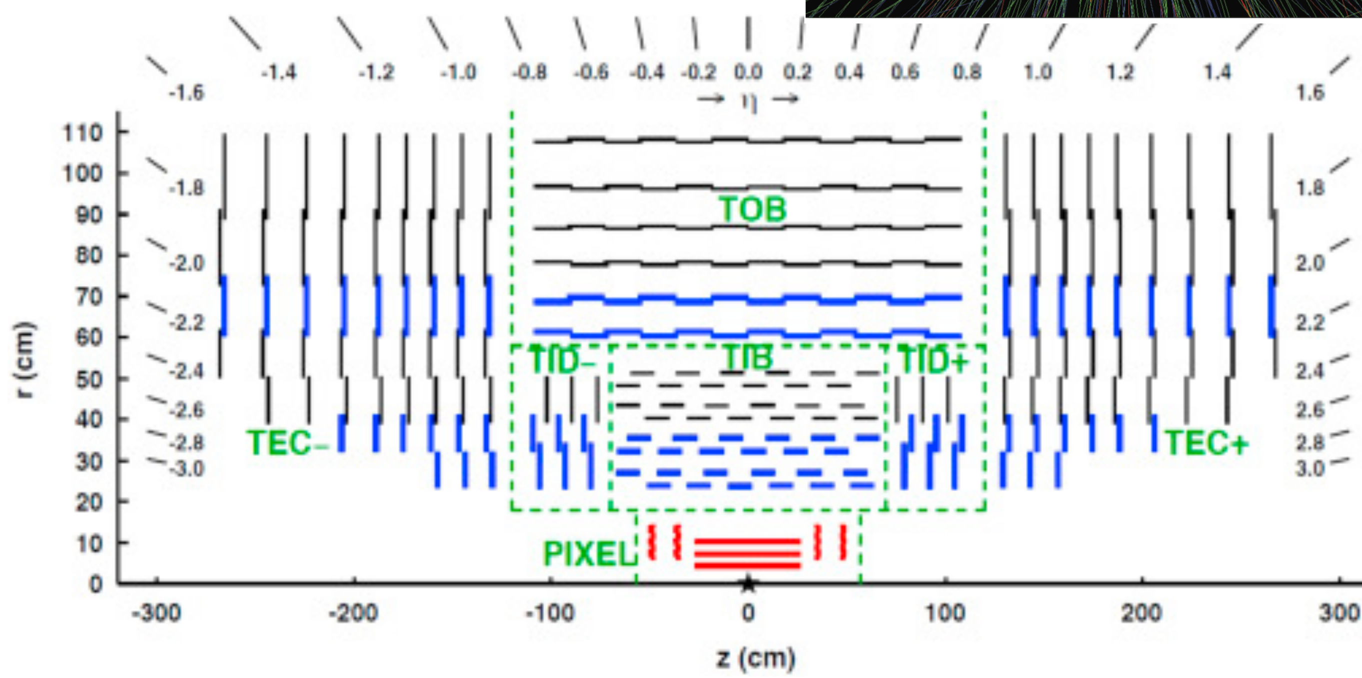


The tracking challenge at the LHC

- typically **30 charged particles** within the tracker acceptance per proton-proton collision and **~ 25-40 collisions** per event: ~**O(1000) charged particles per event** need to be reconstructed.

Largest silicon tracker ever built

- active area: ~200 m^2
- acceptance: $|\eta| < 2.5$
- immersed in a 3.8 T magnetic field



Strip detector [pitch: 80-180 μm^2]

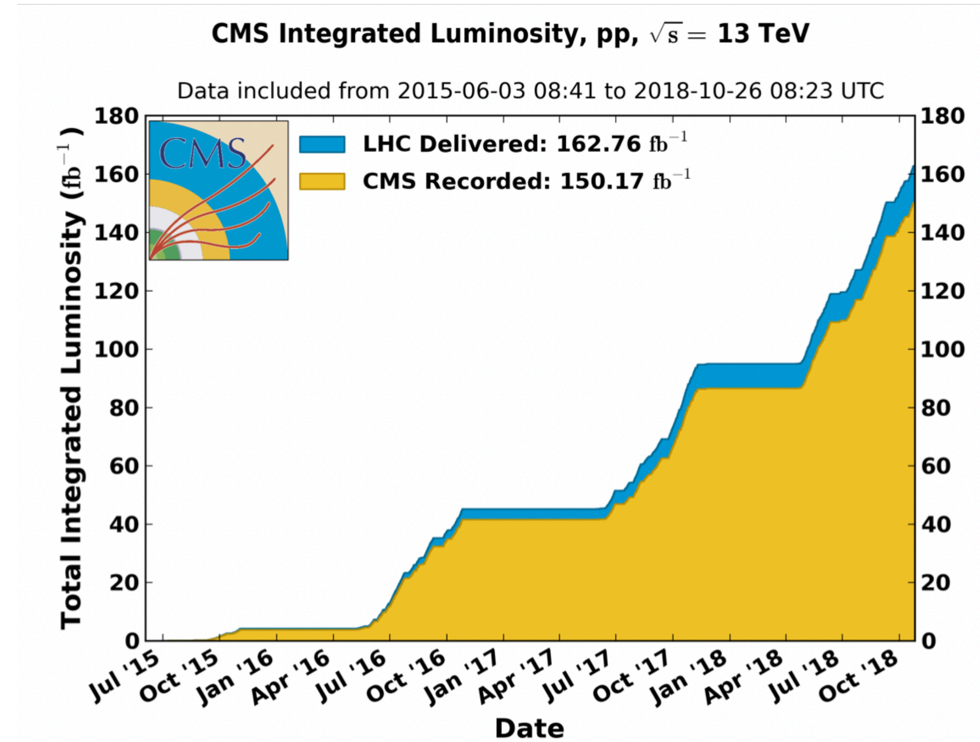
- inner Barrel (**TIB**): 4 layers
- inner Disks (**TID**): 3 (x 2) layers
- outer barrel(**TOB**): 6 layers
- endcap (**TEC**): 9(x 2) disks.
- hit resolution: (10,40) x (230,530) μm

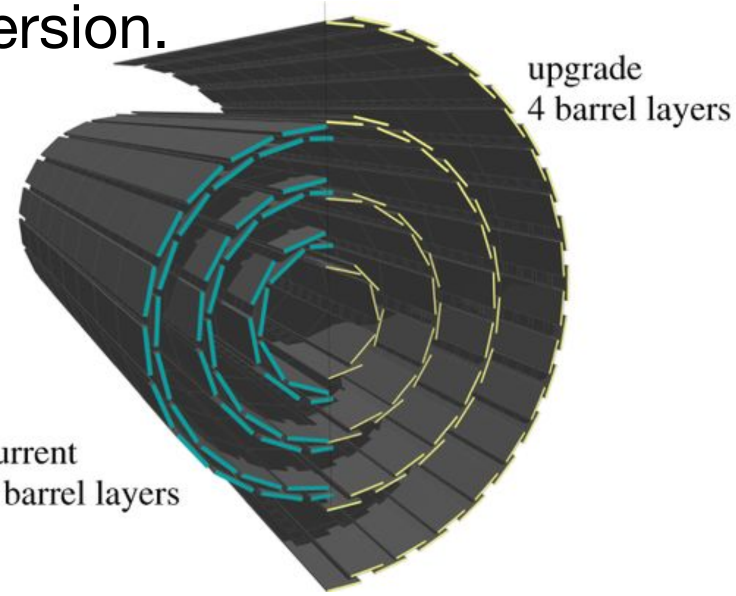
Pixel detector [100 x 150 μm^2]

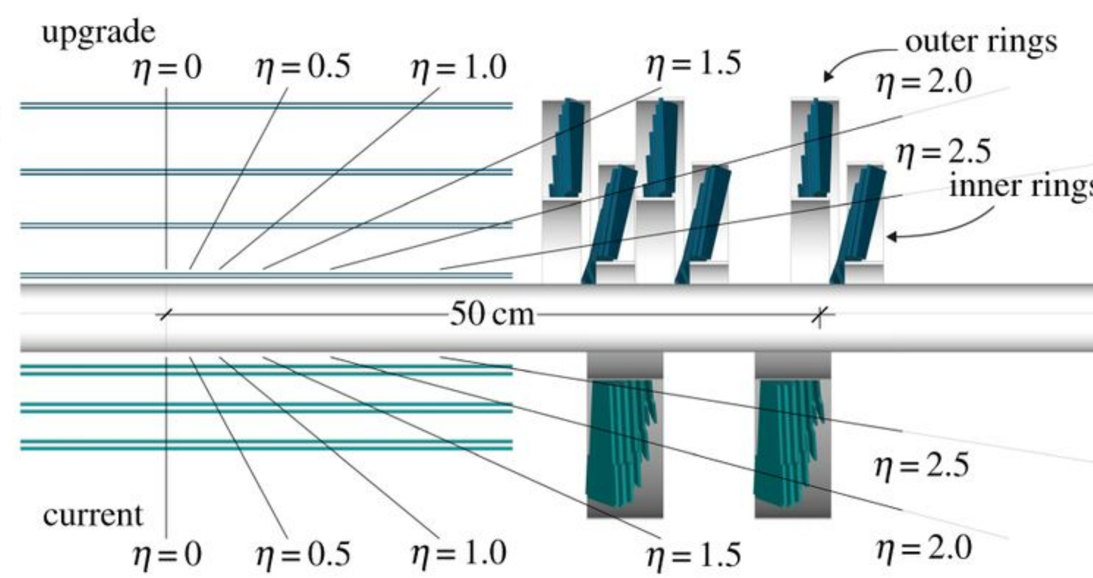
- 127 M pixels.
- 3 barrel layers.
- 2(x2) endcap disks.
- hit resolution: 10 x (20,40) μm

Tracker upgrade in 2017

- The original pixel detector replaced with a new device, the "phase-1" pixel detector to address dynamic inefficiencies in the readout chip at high rates.
- One additional tracking point, in both barrel and forward regions.
  - 4-hit seeds
  - lower fake rate!
- Smaller radius of the innermost pixel layer
  - closer to the interaction region.
  - improves tracking and vertexing performance.
- Reduced material budget
  - reduces multiple scattering.
  - reduces photon conversion.







Track reconstruction in CMS

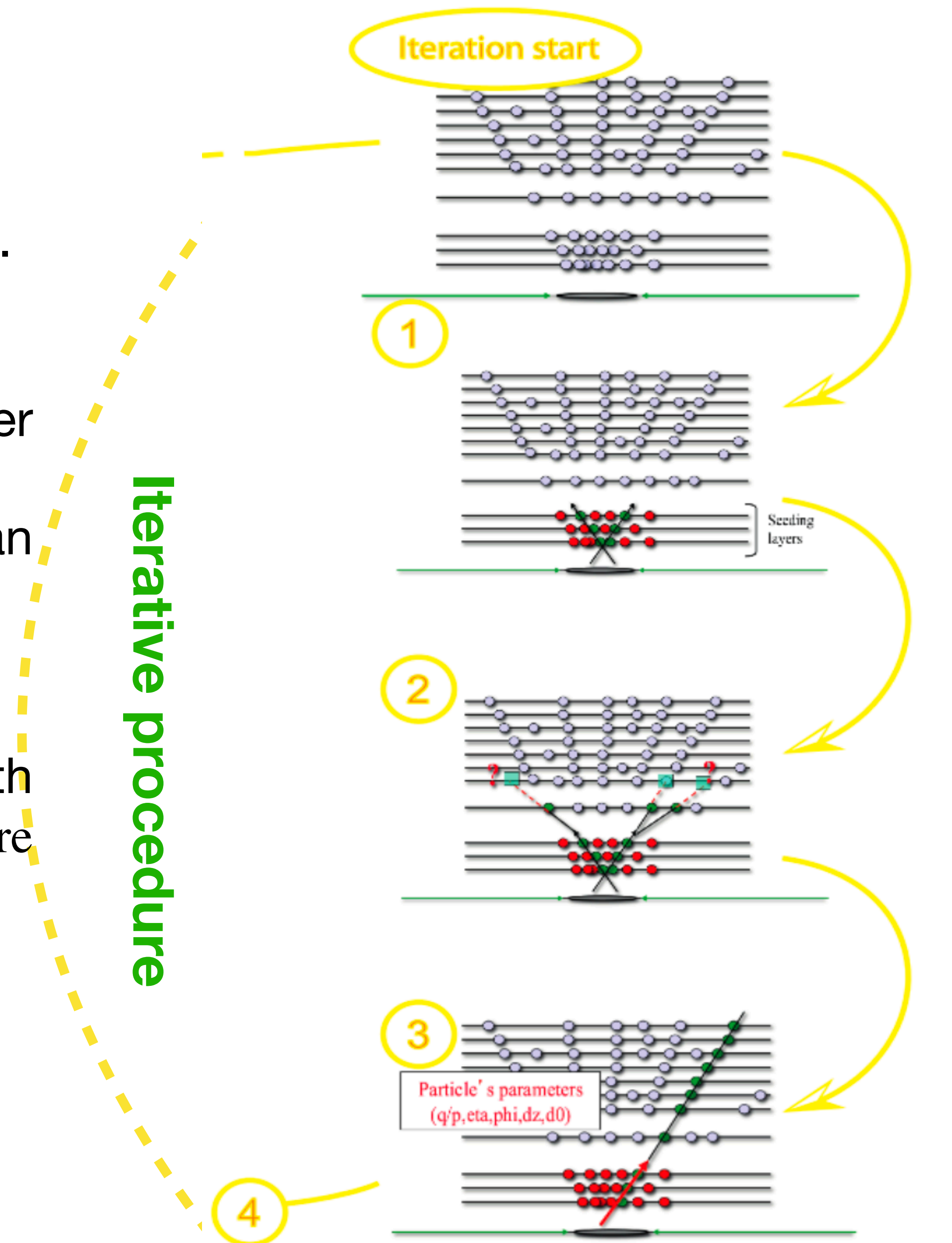
In each iteration, tracks are reconstructed in four steps:

1. Seeding:
- provides an initial track candidate and trajectory parameters.

2. Pattern recognition: (track finding)
- extrapolate current trajectory parameters to the next layer and find compatible hits and update with Kalman filter.
- continue until there are no more layers or there is more than one missing hit.

3.Final fit:
- provides the best estimate of the parameters of each smooth trajectory after combining all associated hits [outlier hits are rejected]

4.Selection:
- the track selection sets quality flags based on a set of cuts sensitive to fake tracks, on the track normalized $\chi 2$, and on its compatibility with interaction region.



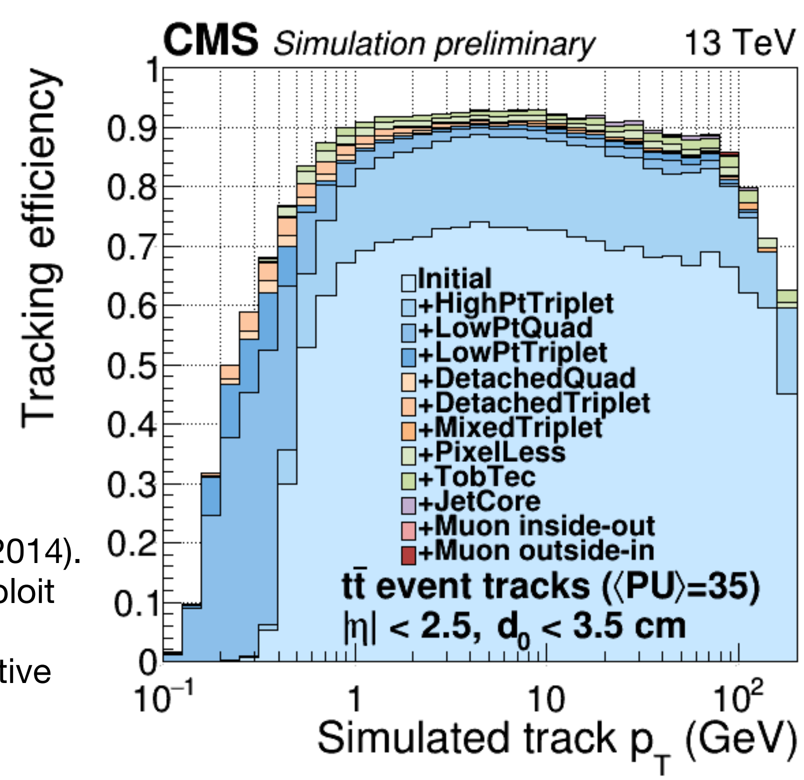
Removing hits of found tracks reduce the combinatorial problem so that problematic tracks can be reconstructed within the CPU time budget.

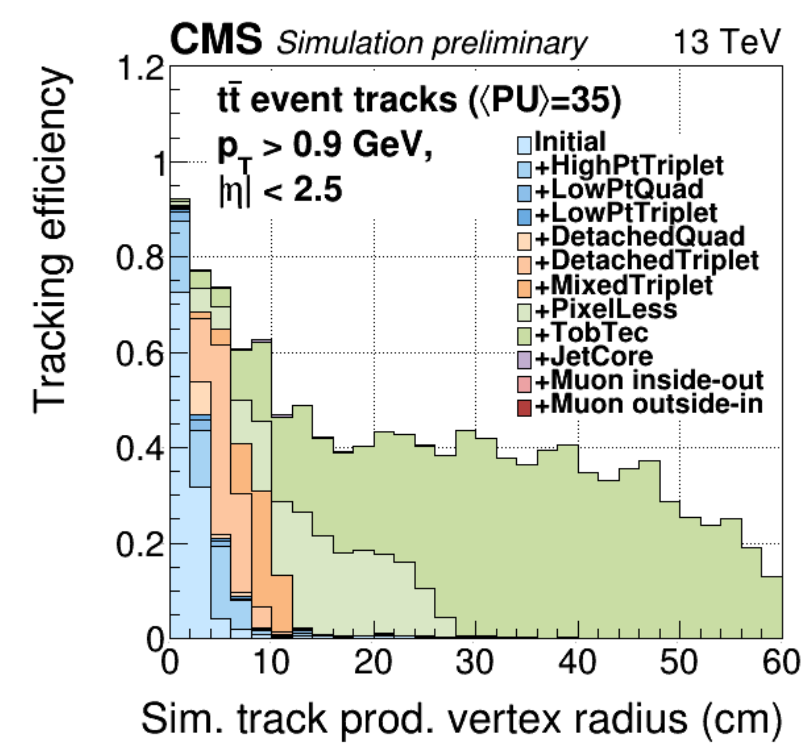
Iterative Tracking in CMS

Track reconstruction is an iterative procedure[1]**:**

- Starting with tracks with **high-p_T quadruplets**(*) that have high precision pixel hits and beam spot constraints that make it reconstructed quickly.
- Subsequent steps use **triplets,** or improve the acceptance either in p_T or in displacement.
- The the later steps use seeds with hits from the strip detector to find **detached tracks**.
- Final steps develop **special iterations**(**) to improve tracks reconstruction in **high-density environment (jets)** or using info from other subsystems (**muons**)

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

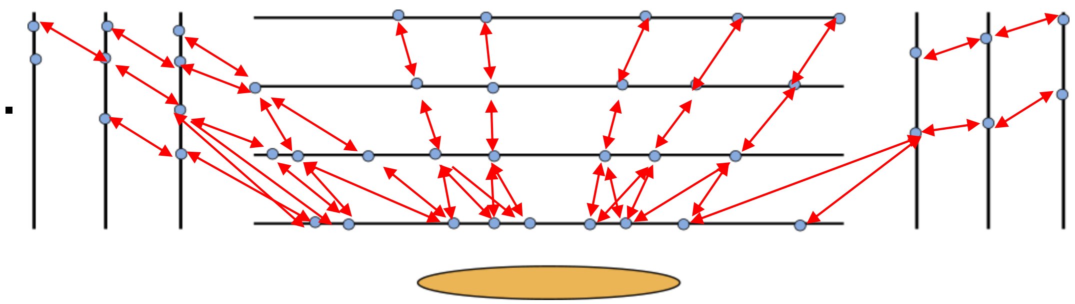


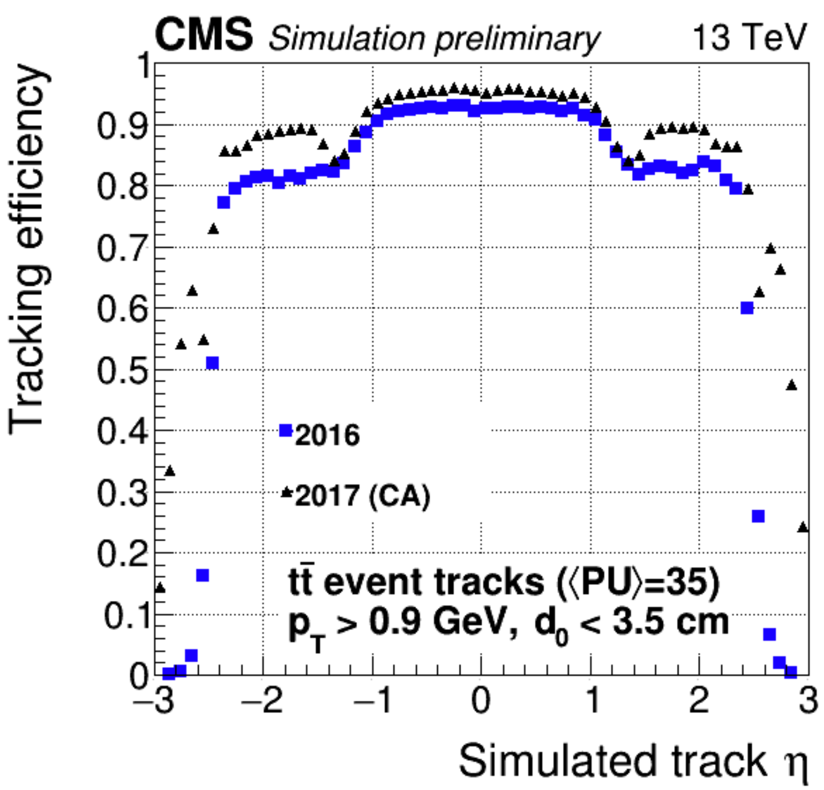


[1] CMS Collaboration, CMS-TRK-11-01, Submitted to JINST (2014).
(*) pixel quadruplets iterations are new w.r.t. run1 because it exploit the layout of the Phase1 pixel detector.
(**) jetCore and the muon seeded steps are new w.r.t. run1 iterative tracking.

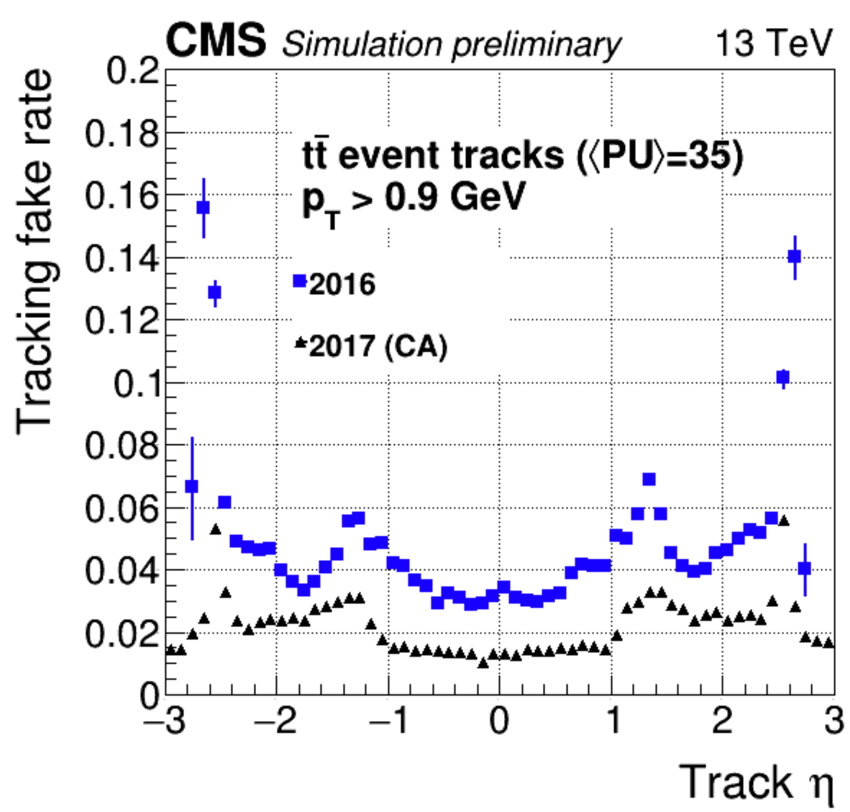
Improvements in 2017

- New track seeding algorithm based on **Cellular Automaton (CA)** technique.
  - Hit pairs are formed between detector layers.
  - Pair compatibility w.r.t. the interaction point is checked.
  - Hit N-tuplets used for seeding (triplets/quadruplets) formed from compatible pairs.

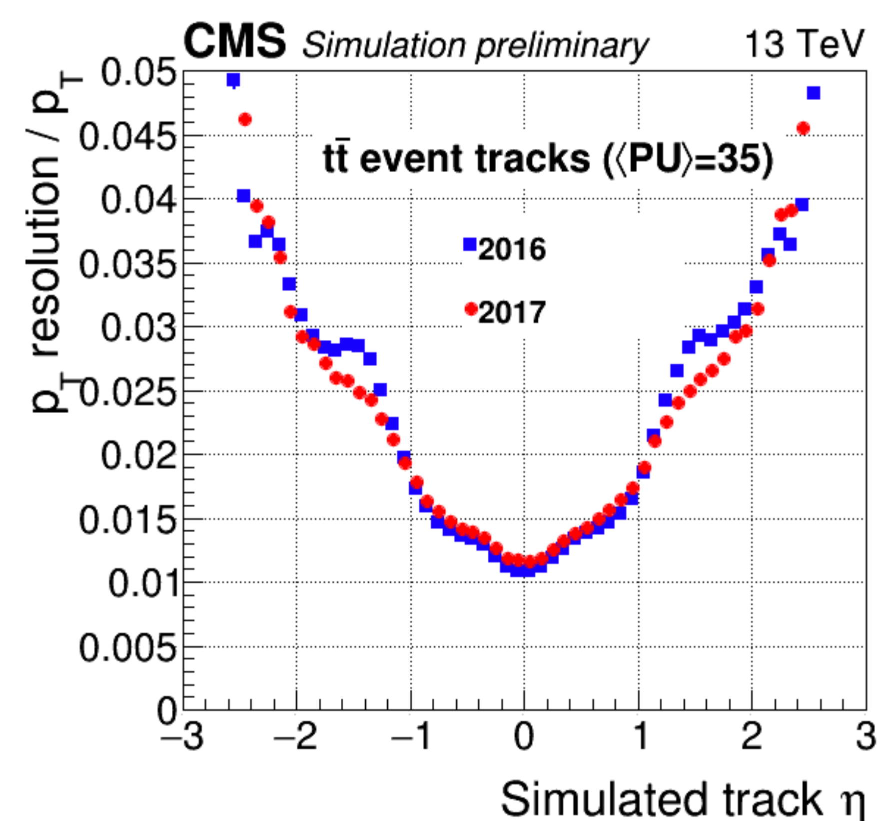




☆**Increase efficiency**



☆**Decrease fake rate**

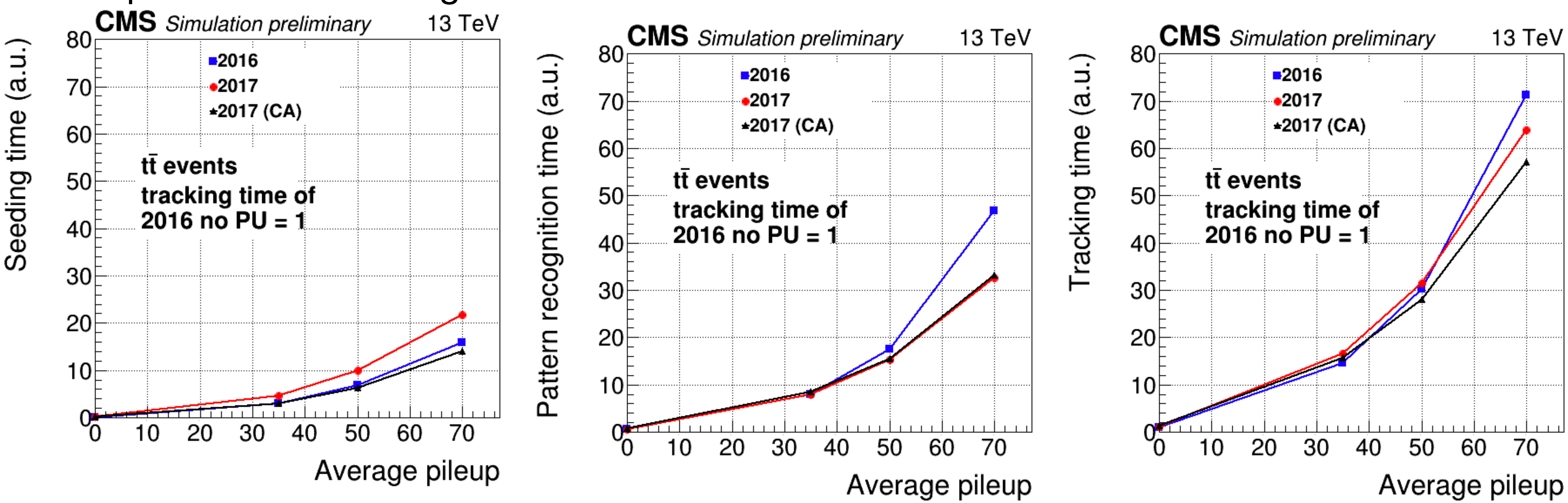


☆**Improve pT resolution**

(mainly in the transition region)

Improvements in 2017- Timing

- With the additional layers, conventional seed finding in the pixel detector would have significantly slowed down track seeding.
- Use of **CA reduces timing** back to or below the 2016 performance(*).
- Reduction in fake rate leads to **reduction of time spent on pattern recognition**, independent of seed algorithm.



Despite the increase in the number of pixel layers ~20% faster track reconstruction w.r.t. 2016 tracking @ <PU> = 70

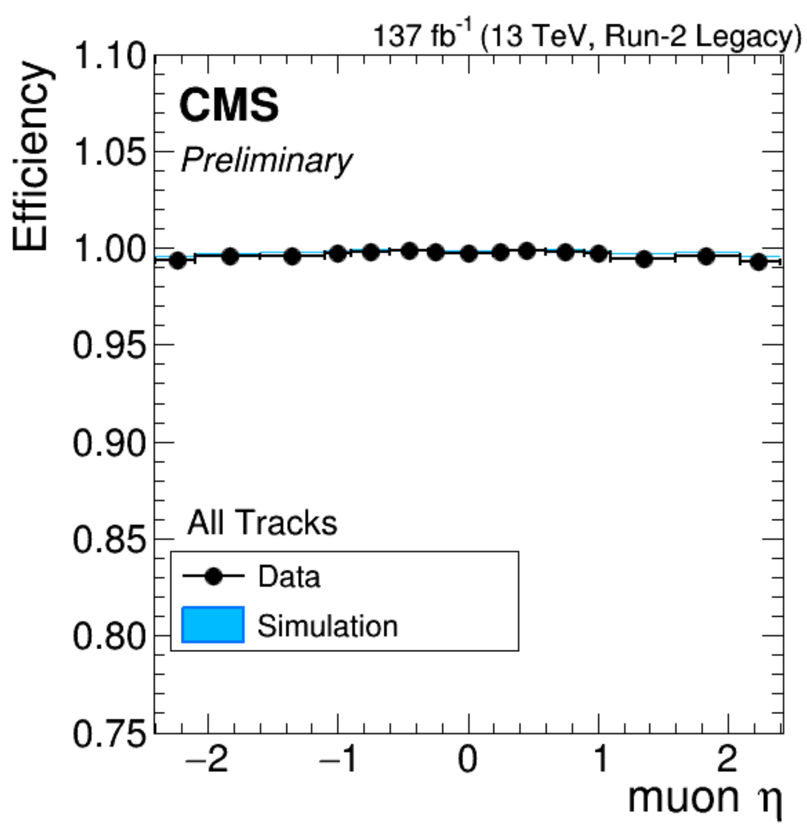
(*) In 2016 we didn't run at very high pileup

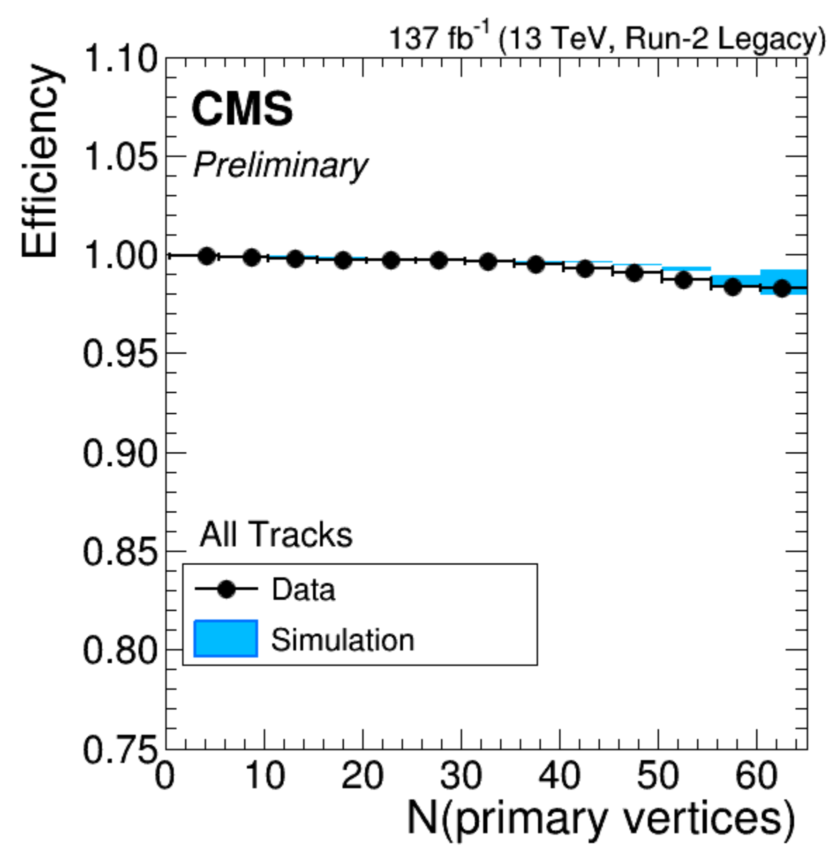
Tracking performance in Run-2 Legacy

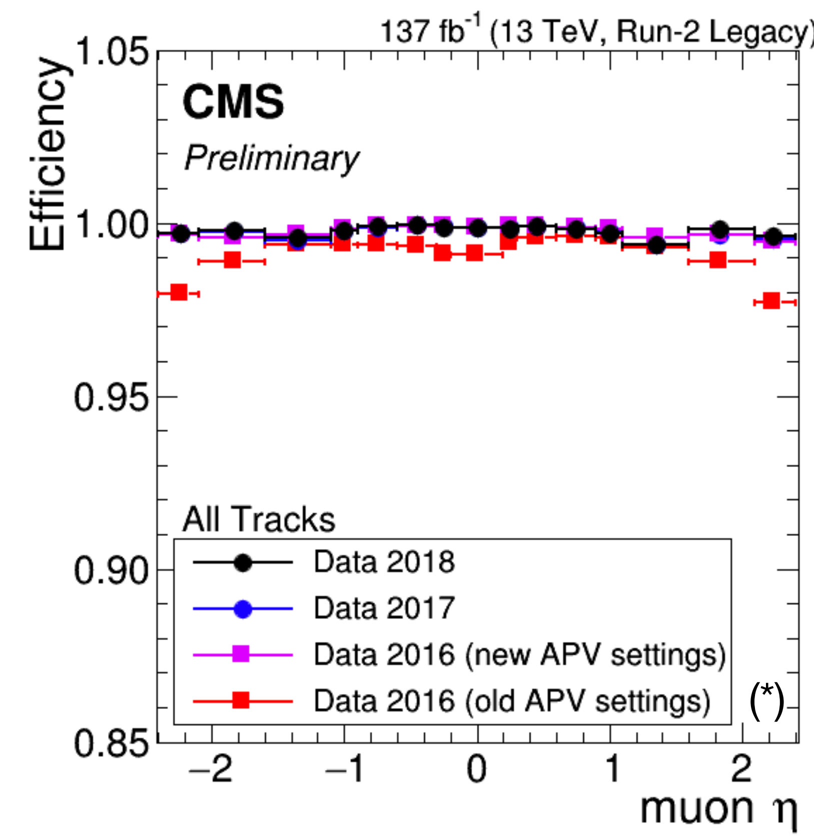
In general, **high tracking efficiency in Run-2 Legacy data ~99.9%** (despite difficult circumstances), thanks to significant improvements, which were made during both the LS1 and Run2:

new iterations, new tuning, PU mitigation, code re-engineering, **new seeding framework**, **Cellular Automaton(CA) seeding**, mitigation strategy, etc..

Good agreement of the tracking efficiency is observed for (2018, 2017, 2016 new APV settings). For 2016 old APV settings(*) a loss in efficiency up to ~2 % is found.





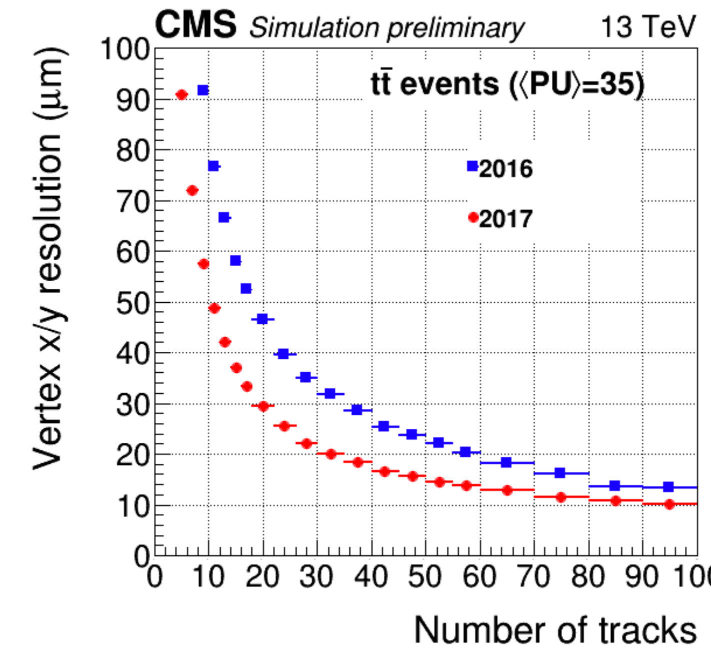


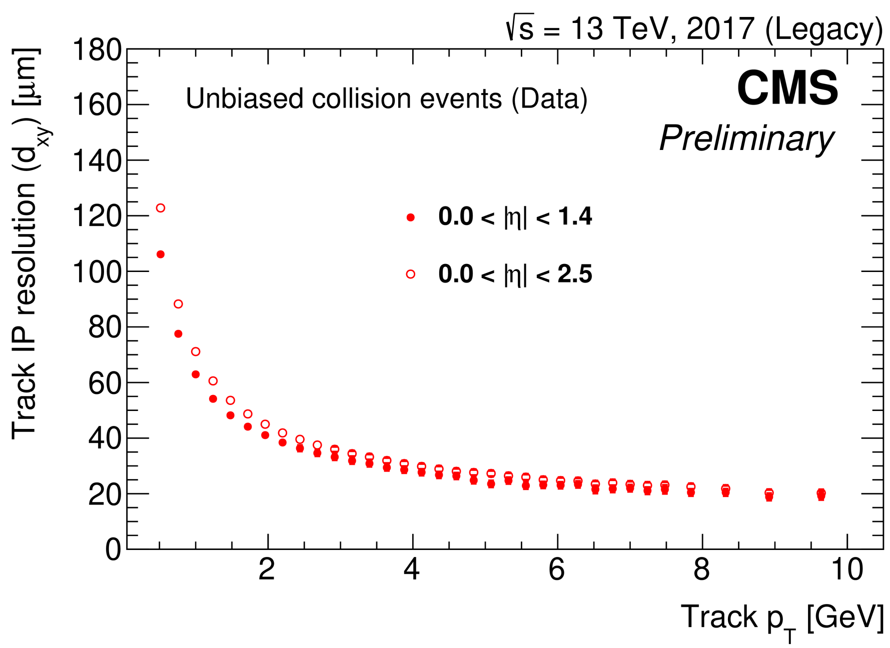
tracking efficiency calculated from $Z \rightarrow \mu^+\mu^-$ events using Tag-and-Probe technique for muon with $p_T > 0.1$ GeV

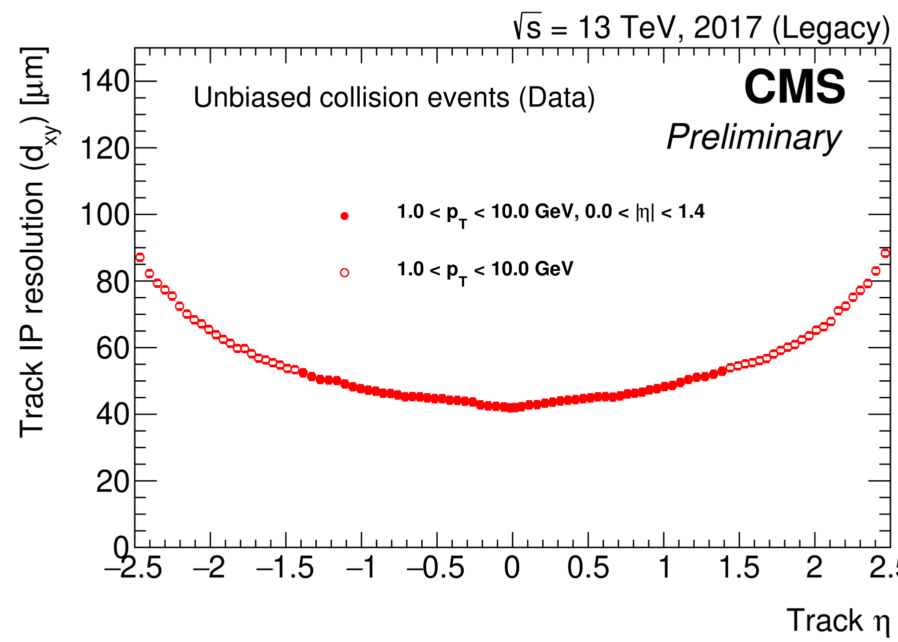
(*) old APV settings: pre-amplifier of the APV25 readout chip is saturated (20 fb^{-1} of 2016 data).
new APV settings: APV setting changed for fast recovery (16 fb^{-1} of 2016 data).

Track impact parameter resolution

- The resolution in a reconstructed primary-vertex position depends strongly on the number of tracks used to fit the vertex and the pT of those tracks.
- The 2017 vertex reconstruction shows better performance than 2016 one, Thanks to the new pixel detector!







the resolution of the transverse (dxy) impact parameter (IP) of reconstructed tracks in 2017 Legacy data with Phase-1 Tracker

Transverse track IP resolution in 2017 Legacy data (13 TeV) with Phase-1 Pixel detector:

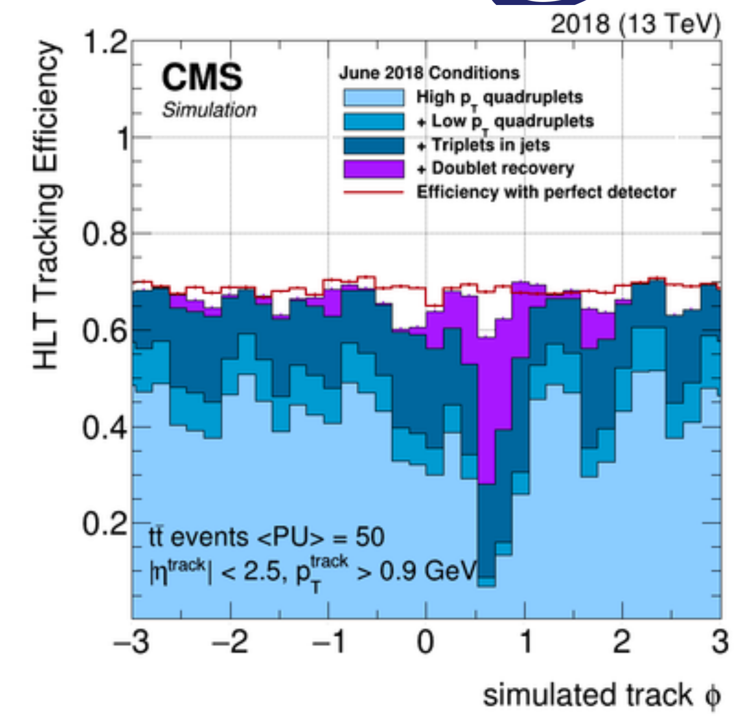
- For (pT =1-10 GeV, |**η**| < 2.5) ~ 20-75 μm
- For (pT =1-10 GeV, |**η**| < 1.4) ~ 20-65 μm (25-90 μm for Phase-0 Pixel detector).

Track reconstruction @ HLT

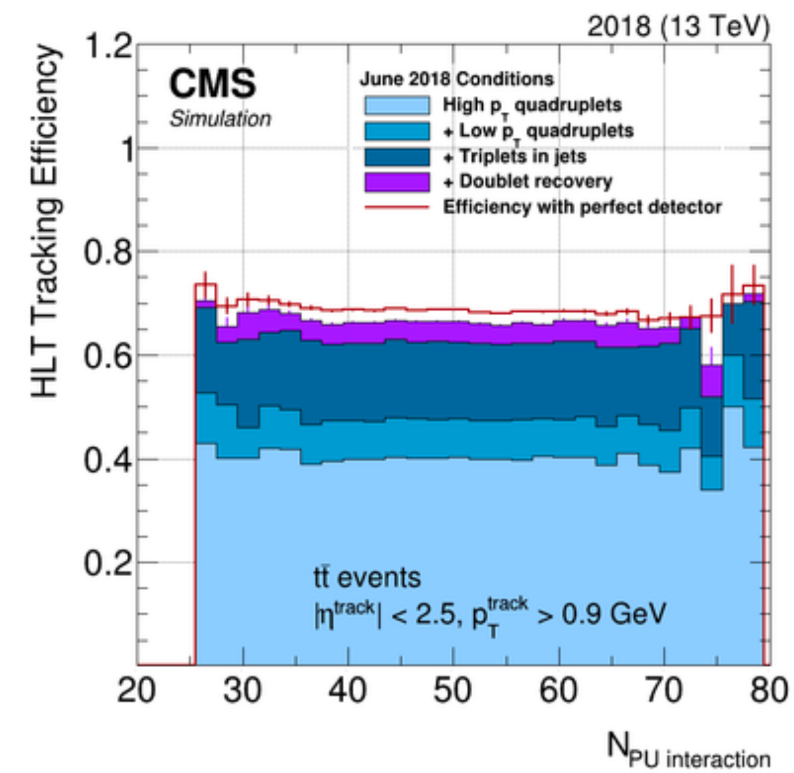
- **Tracking@HLT is a regional tracking:** reconstruct tracks only within regions of interest (around physics objects).
- **reduce #iterations** w.r.t. offline tracking.

CA seeding for PF@HLT since 2017 ➪

Iterations	Seeding	Target tracks
Iter0	Pixel tracks (quadruplets)	Prompt, hight pT
Iter1	Pixel tracks (quadruplets)	Prompt, low pT
Iter2	Pixel triplets	Recovery
doublet recovery	Pixel doublets in η-ϕ	Static doublet recovery



- During the operation in 2017, several issues with the Phase-I pixel detector where identified that lead to a non-negligible fraction of non-active pixel modules in each event.
  ➪In 2017, adopted a **Static mitigation** via dedicated iterations in specific η-ϕ regions.

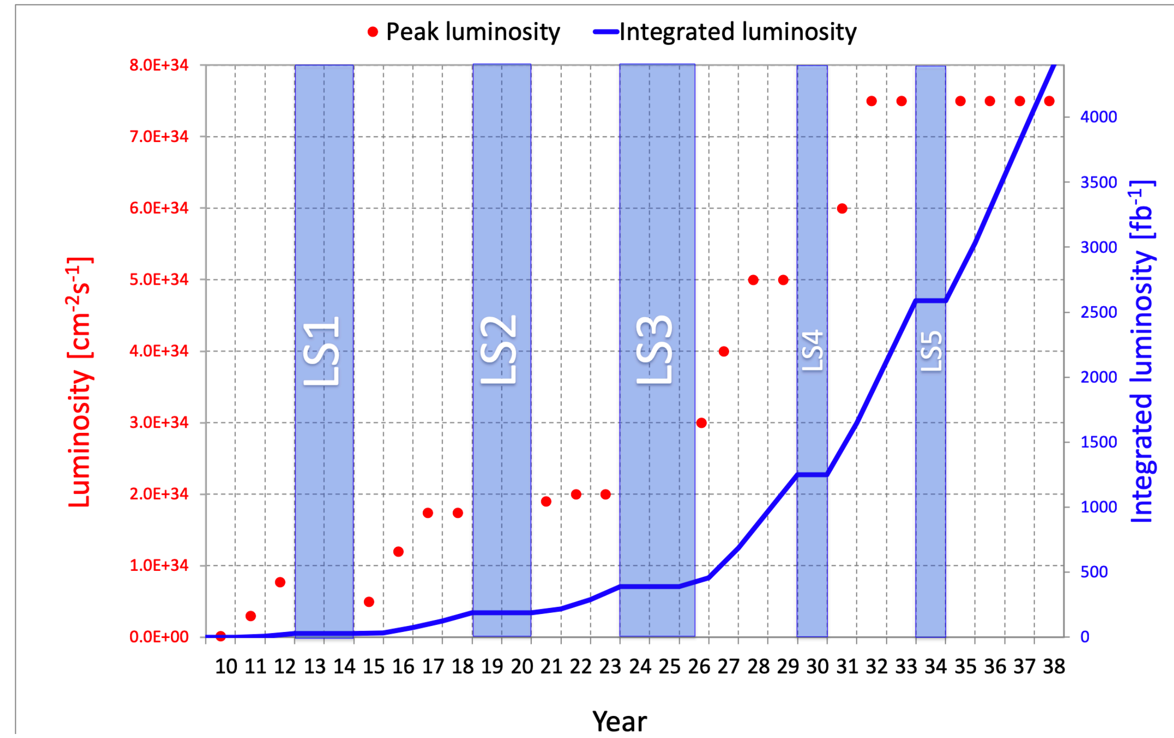


- However, recovery is insufficient for additional (dynamic) pixel issues [like the DC/DC converter issue]
  ➪In 2018, adopted the **Dynamic mitigation** of pixel issues.

efficiency is almost flat as a function of #PU

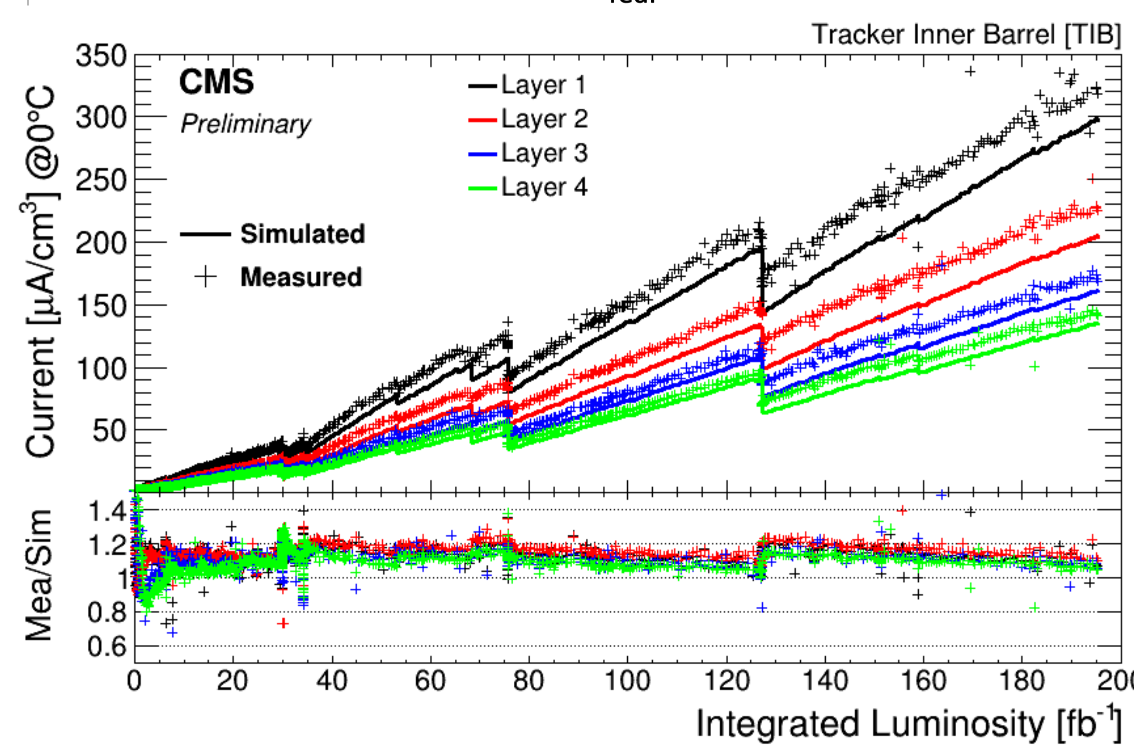
Developments for Run-3

With increasing the luminosity and consequently the accumulated radiation, there will be non negligible degradation in the tracker detector in both Pixel and Strip detectors w.r.t. the nominal performance.



➪ New developments targeting Run-3

- ☆ Developments in mitigation strategy.
- ☆ DNN track selection.
- ☆ DeepCore track seeding in jets with CNN.
- ☆ Seed cleaning with CNN.



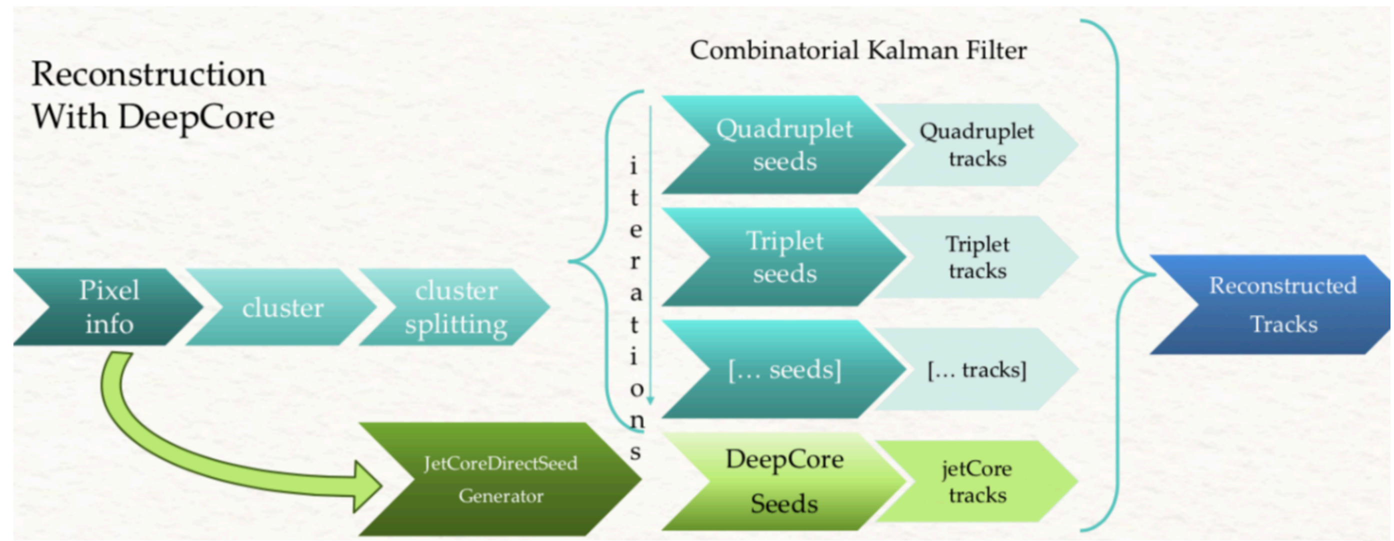
Average leakage current for TIB layers with luminosity

Developments for Run-3

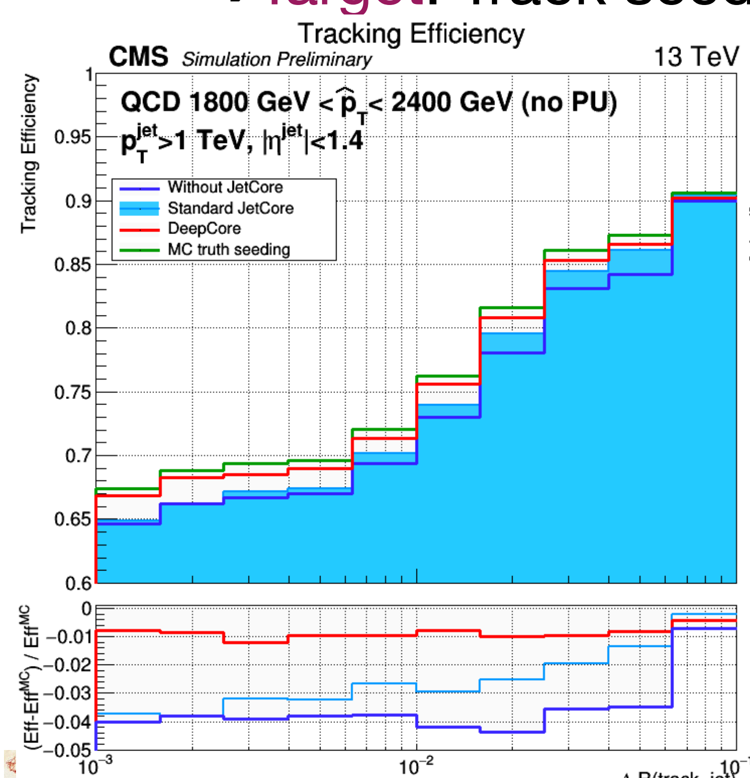
DeepCore "Tracking inside jets"

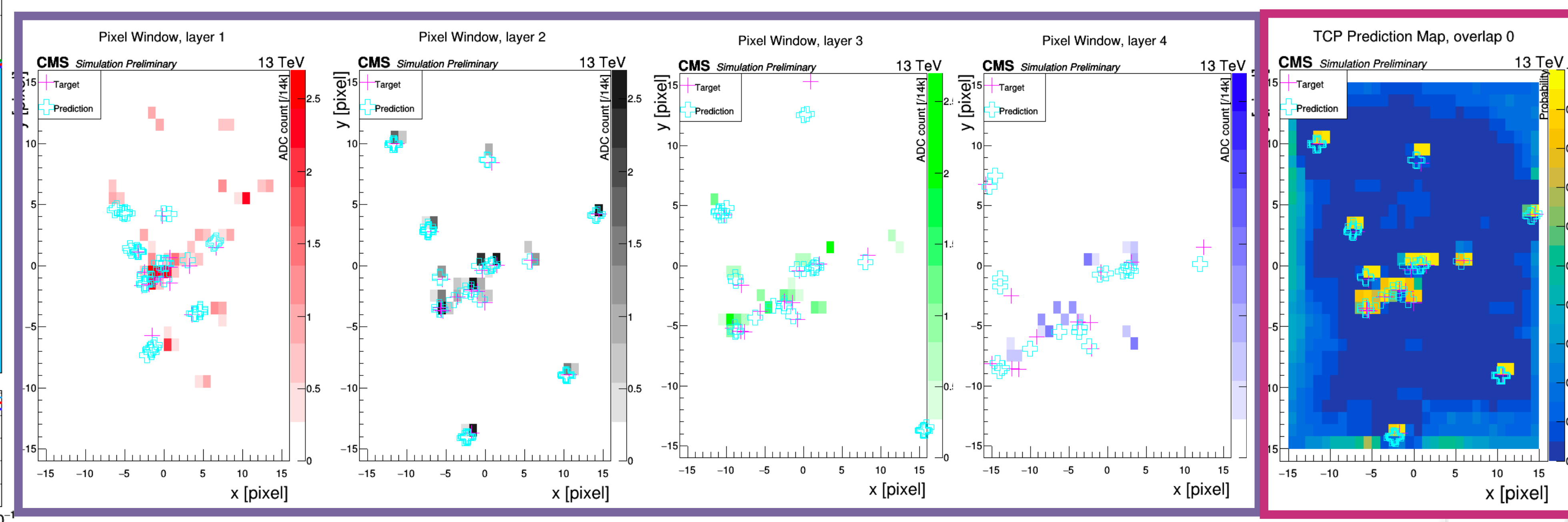
NEW approach for Run-3

- Tracking inside jets becomes inefficient over 500 GeV due to cluster merging.
- Run-3 Update: skip pixel clustering and use **Convolutional Neural Network (CNN)** to produce track seeds in the jets.
  - ➪Inputs: Jet pT and direction from Calorimeter + Pixel Raw Info.
  - ➪Target: Track seed parameters.



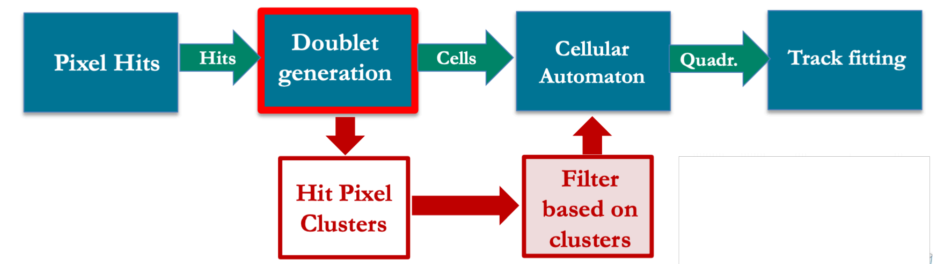
Fake rate reduction ~ 60%
Almost ideal efficiency
Seeding time reduced ~ 85%



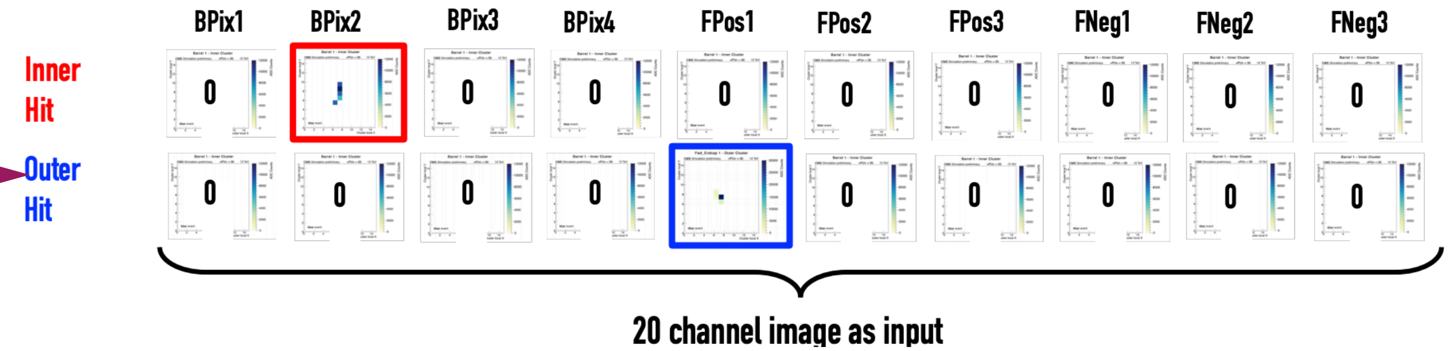


Developments for Run-3

Seed filtering using Convolutional Neural Network (CNN)

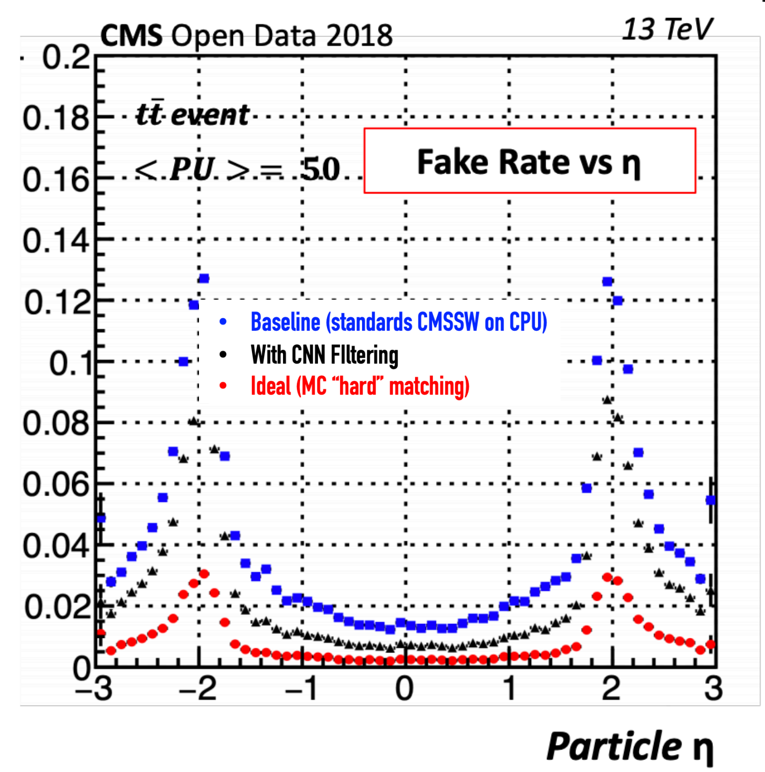


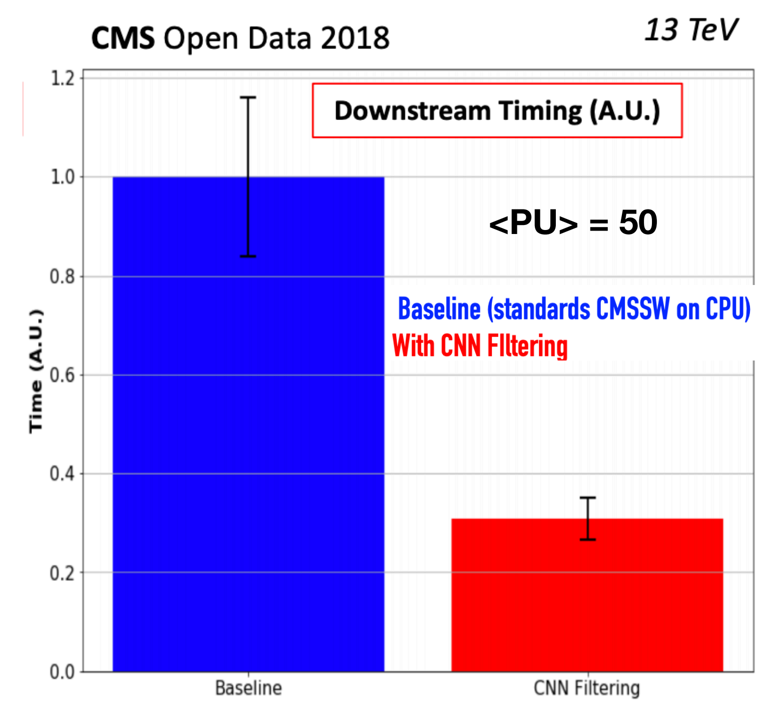
- Track seeding in the pixel detector starts with hit doublets that are formed into triplets/quadruplets to build seeds.
- Starting from doublet generation, filter the pixels clusters based on their shape.
- Inputs are maps of the pixel clusters for the hits making the doublet from 20 channels, one per each layer(4 barrel and 6 endcap).



- The test shows that the plugging-in of the CNN, would practically leave unchanged the performances of the downstream track reconstruction while heavily reducing the combinatorial fakes and thus improving the timing performance.

Fake rate reduction ~ 40%
& time reduction ~68 %





Conclusions

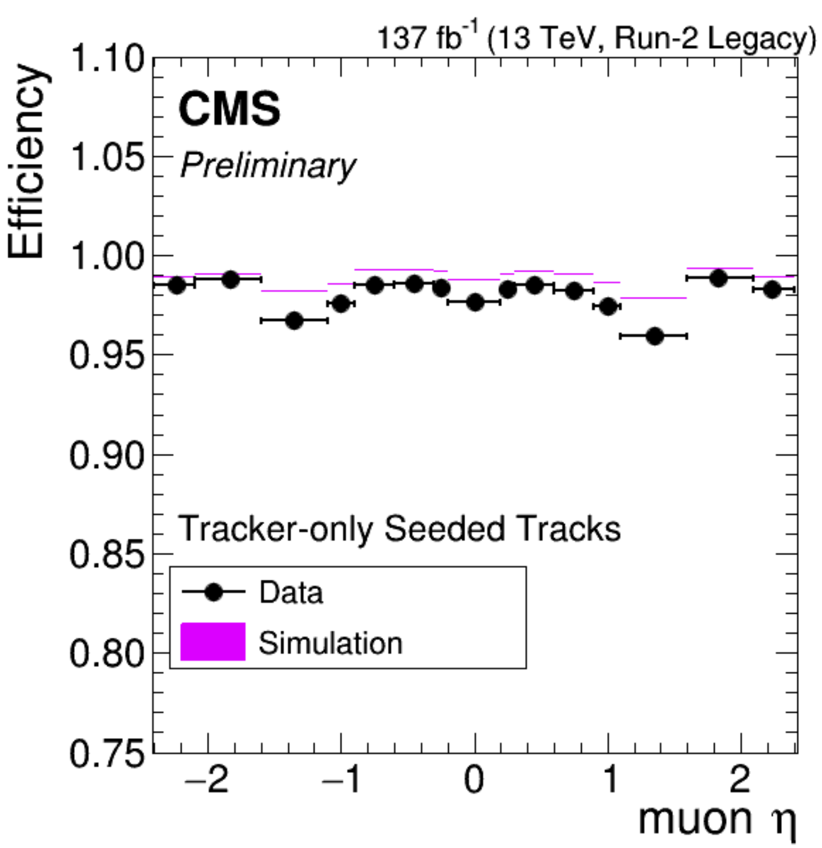
- Despite challenging conditions at the LHC in Run-2, the CMS Tracker has r**obust performance** in a difficult environment.
  (**high tracking and vertexing performance**)
- Depends on the performance of the detector as well as the algorithms used in the event reconstruction.
- The Phase 1 pixel tracker helped to cope with large lumi/PU events.
- Tracking at the HLT efficient.
- Tracking efficiency measurements based on **data-driven techniques.**

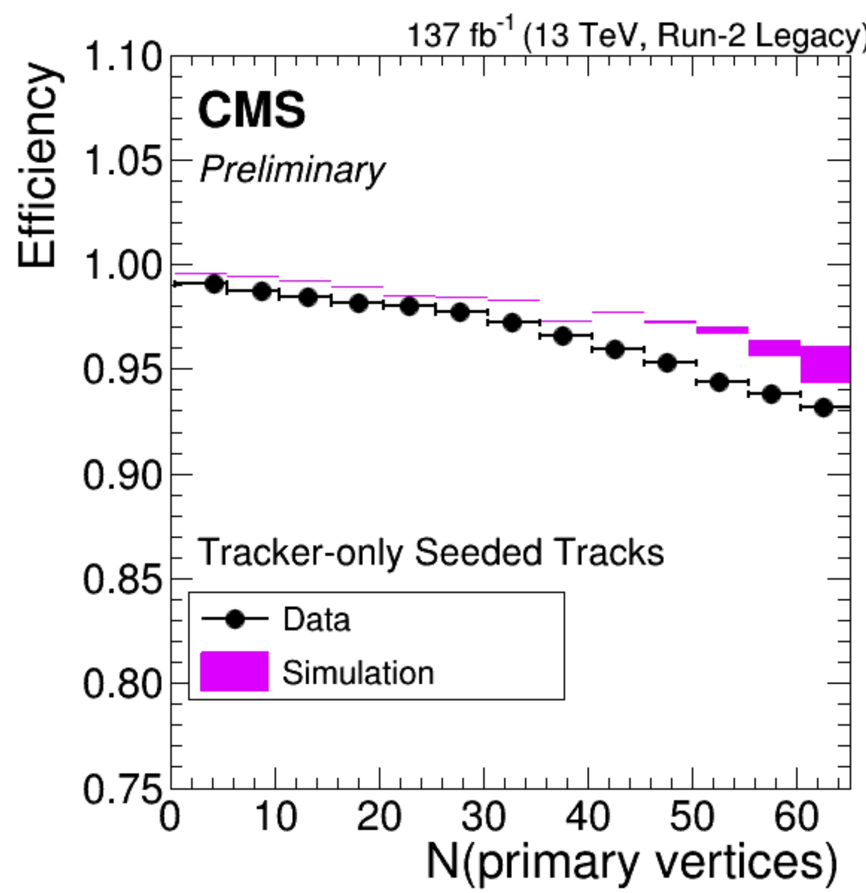
- **New developments targeting Run3**
  - Developments in mitigation strategy.
  - DNN track selection.
  - DeepCore track seeding in jets with CNN.
  - Seed cleaning with CNN.

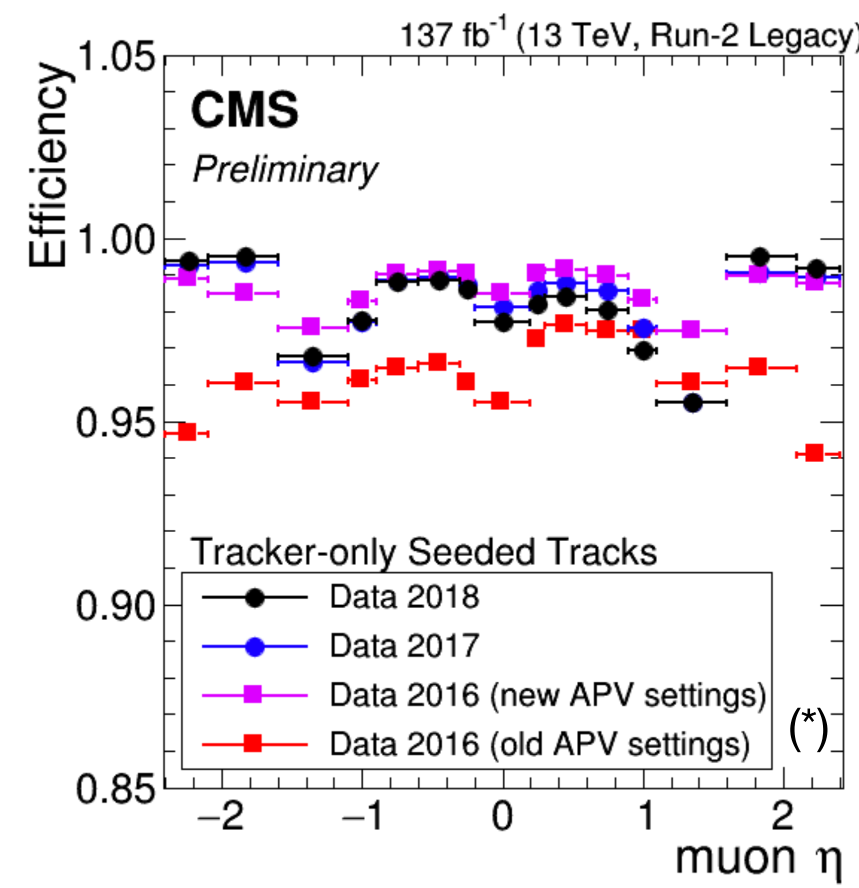
Backup

Tracking performance in Run-2 Legacy

- The tracking efficiency for **tracker-only seeded tracks** (used to reconstruct π,k,..) in Run-2 Legacy data is ~ 98%.
- The efficiency is similar for 2018, 2017, 2016 new APV settings. For 2016 old APV settings(*) a loss in efficiency up to ~ 5 % is found.





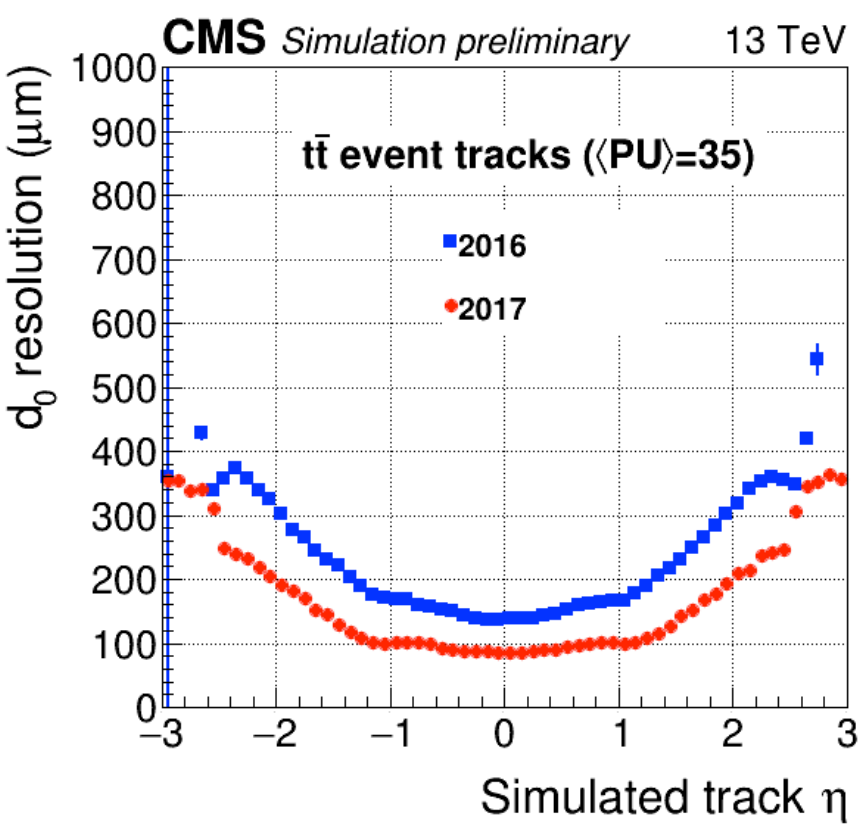


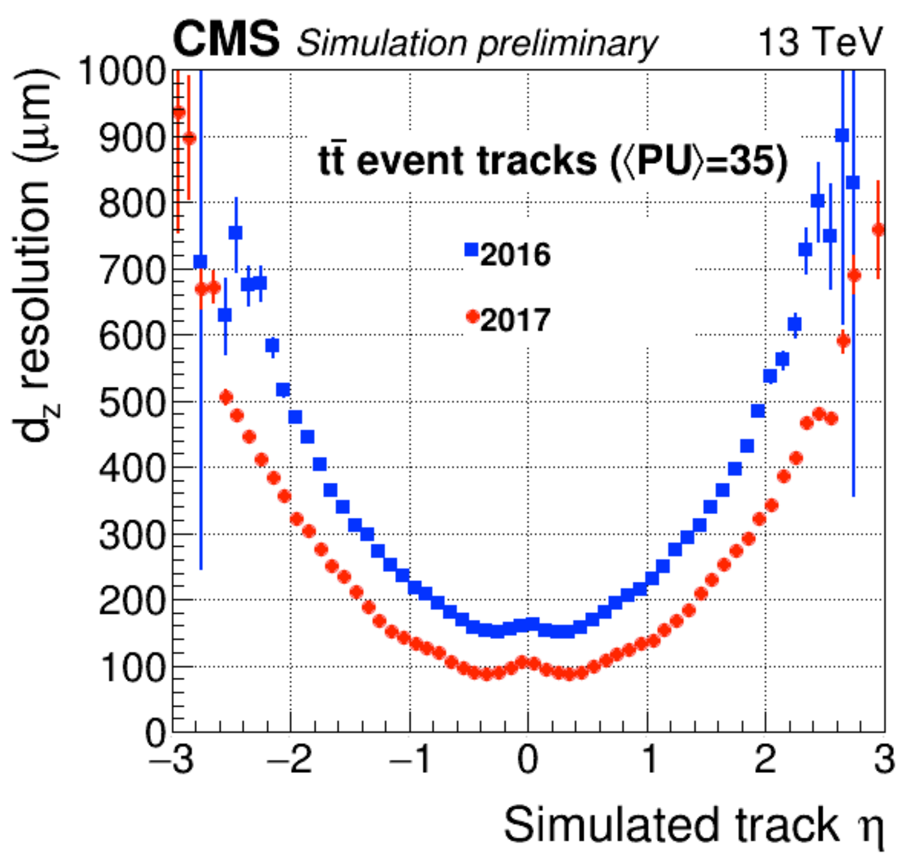
Muon tracking efficiency calculated from $Z \rightarrow \mu^+\mu^-$ events using Tag-and-Probe technique for muon with p_T >0.1 GeV

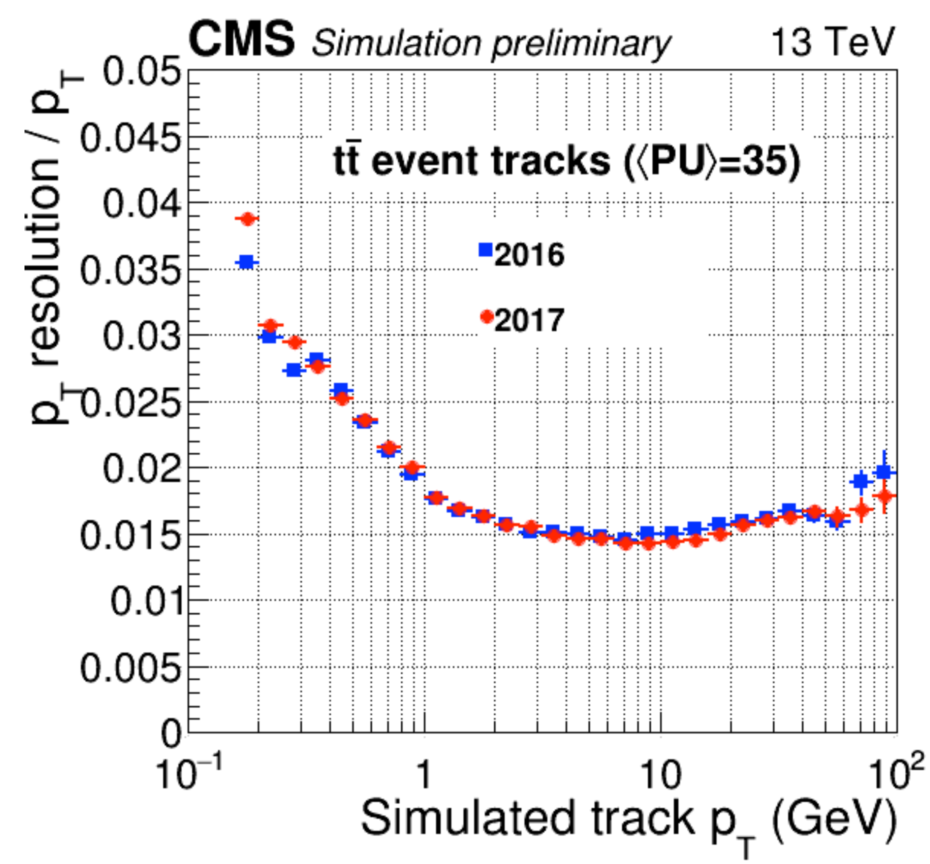
(*) old APV settings: pre-amplifier of the APV25 readout chip is saturated (20 fb^{-1} of 2016 data).
new APV settings: APV setting changed for fast recovery (16 fb^{-1} of 2016 data).

Track parameter resolution 2017 vs 2016

- Track d_0 (transverse impact point) resolution and d_z (longitudinal impact point) resolution → **better performance with the 2017 detector** over all the η spectrum.
- The p_T resolution between 2016 and 2017 are comparable.



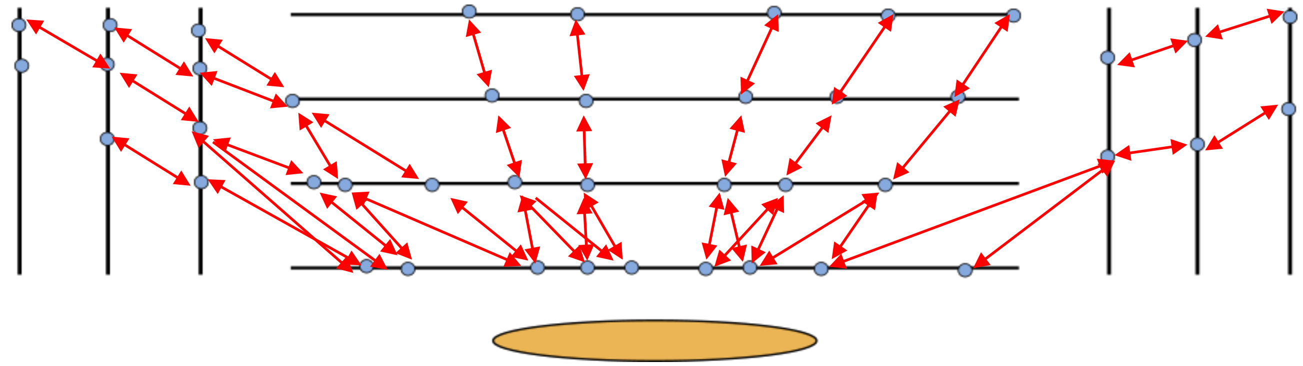




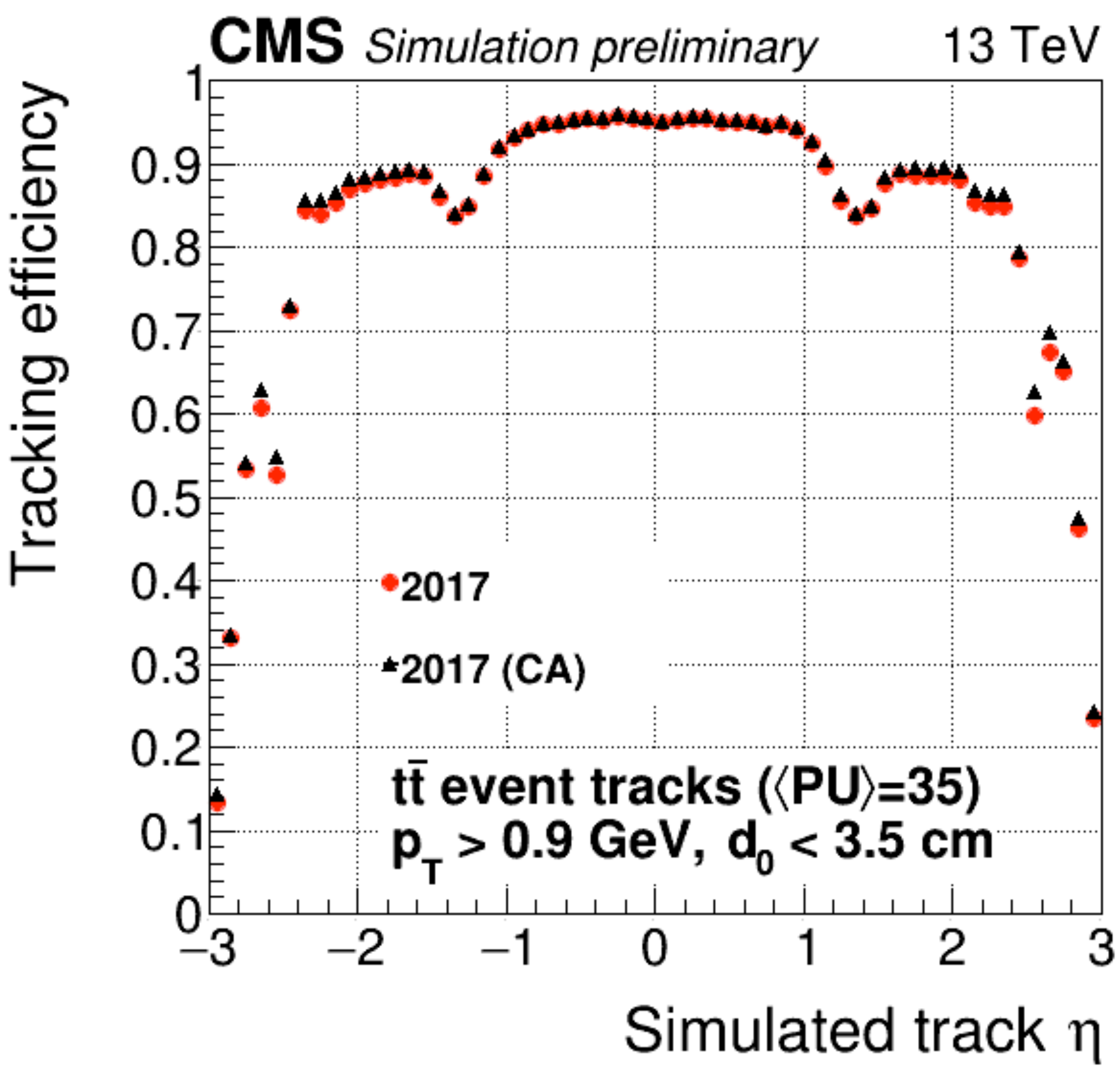
CA track seeding approach

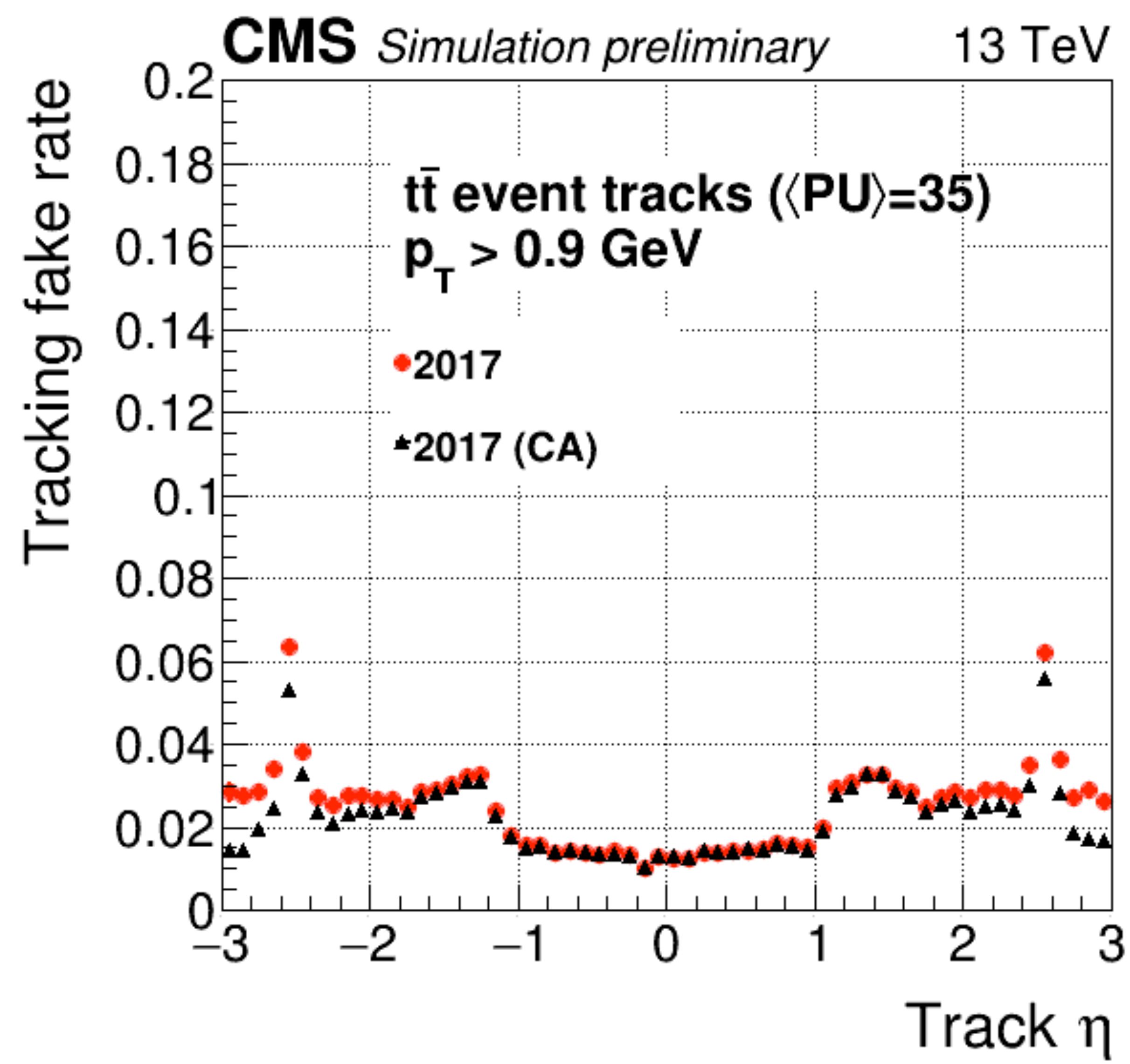
The CA is a track seeding algorithm designed for parallel architectures:

- In a CA, a network of cells evolves in discrete time steps from an initial state according to predefined rules, depending only on the values of the cells in the local neighborhood.
- A graph of all the possible connections between layers is created
- Doublets are created for each pair of layers (compatible with a region hypothesis)
- A cell is defined as a segment linking three hits.
- Neighborhood rules : pair of hits in common and similar eta
- Evolution rules: At each time step a cell increases its state if on its left it has a neighbor with the same state.
- The neighbor fit triples are joint in a longer seed
- Fast computation of the compatibility between two connected cells
- No knowledge of the world outside adjacent neighboring cells required, making it easy to parallelize.



Tracking performance with the CA

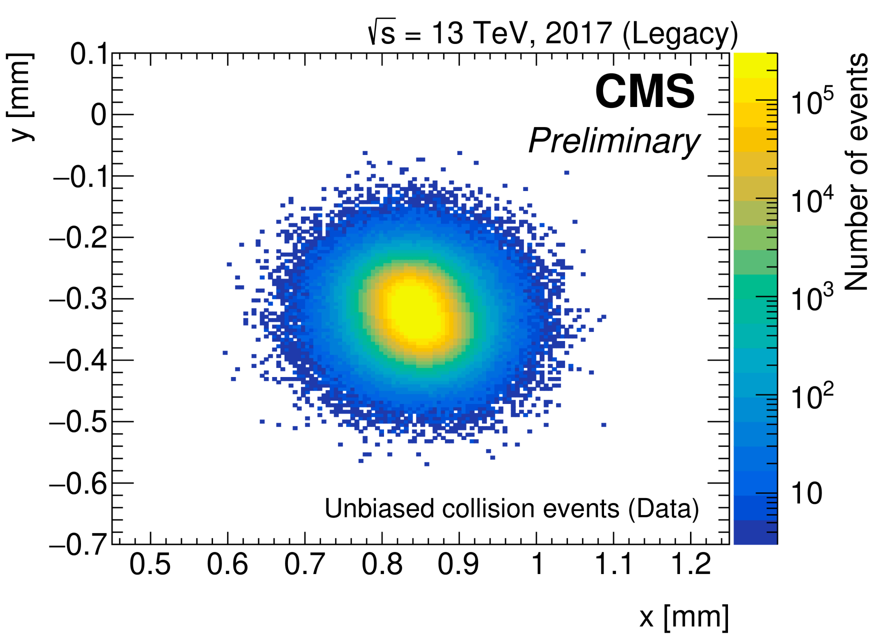


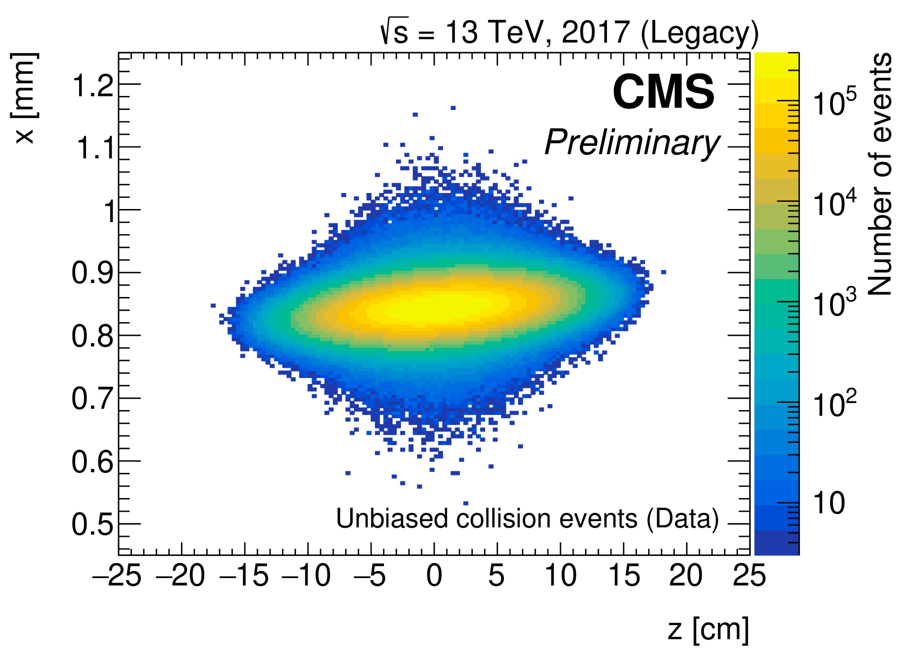


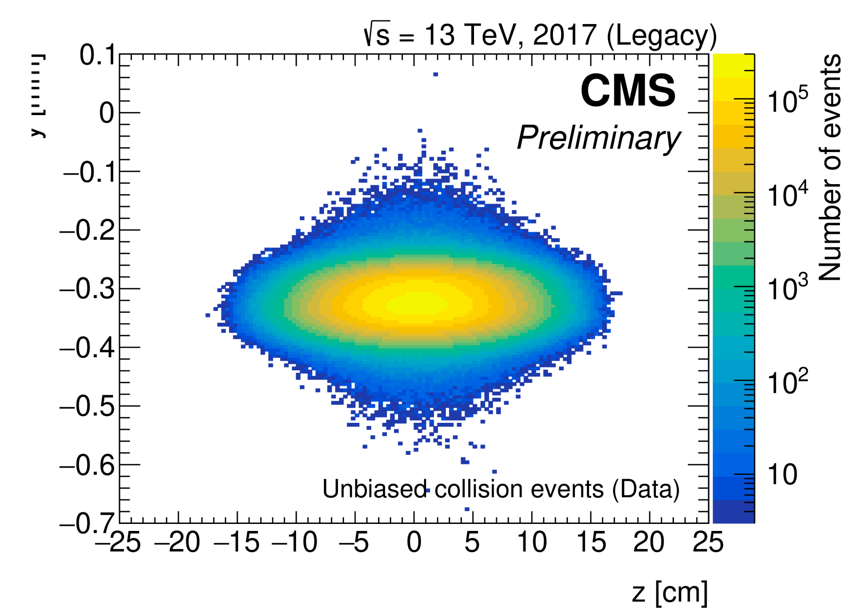
The Efficiency and fake rate improved with the CA seeding

Track impact parameter resolution

- Measure track IP with respect to the reconstructed beam spot position.
- Extract IP resolution from a multi-Gaussian fit function as σ_{IP} = FWHM/2.36
- Parametrize the measured resolution on the track pT and η.
- Beam width subtraction:
  - Beam width (the beam size measured either in x or y coordinate) is parametrized as a function of accumulated integrated luminosity.
  - The average beam width is extracted from the fit in each bin of the resultant parametrization corresponding to the periods of specific beam configuration.
  - The average beam width measured in x and y (≈10-16 μm) is subtracted from the track IP resolution
  - This correction becomes increasingly important for the very high pT tracks (≈ 10 GeV), where the intrinsic track IP resolution starts to approach the measured beam width



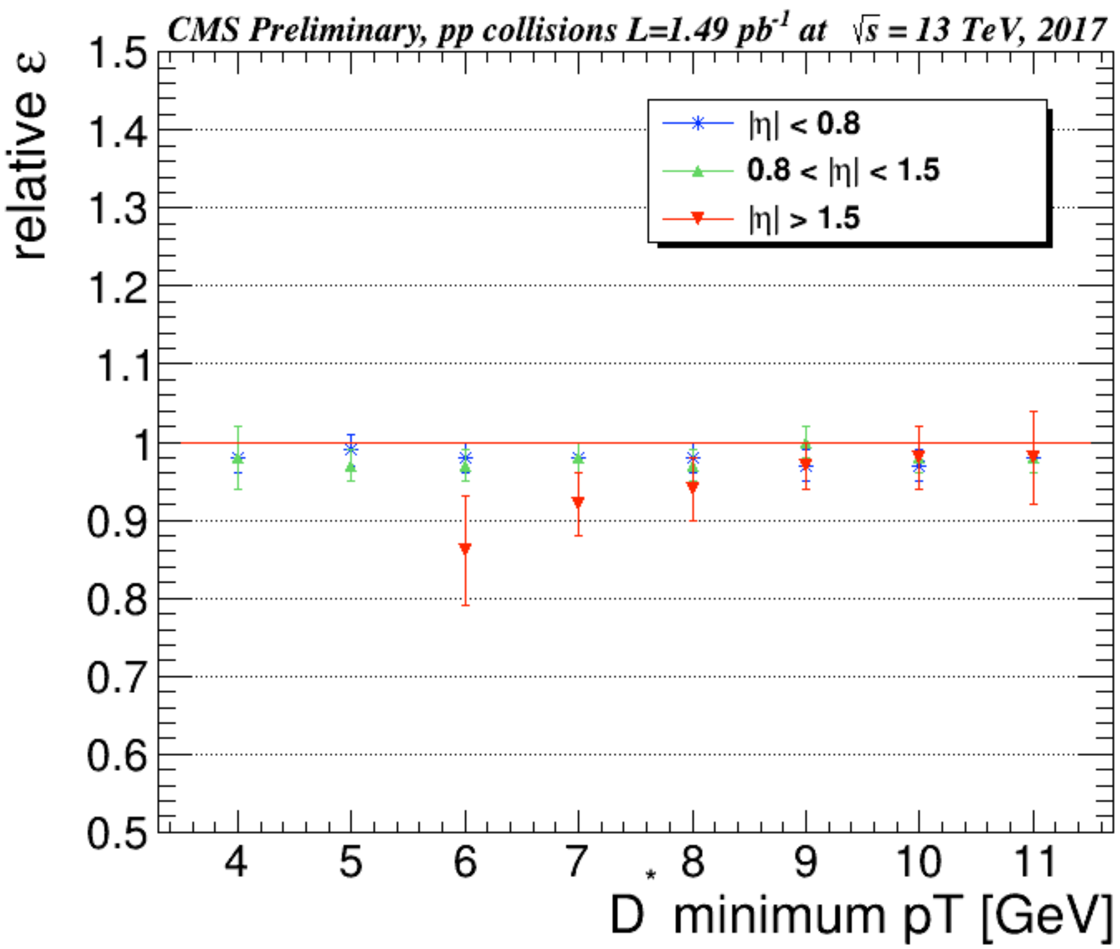


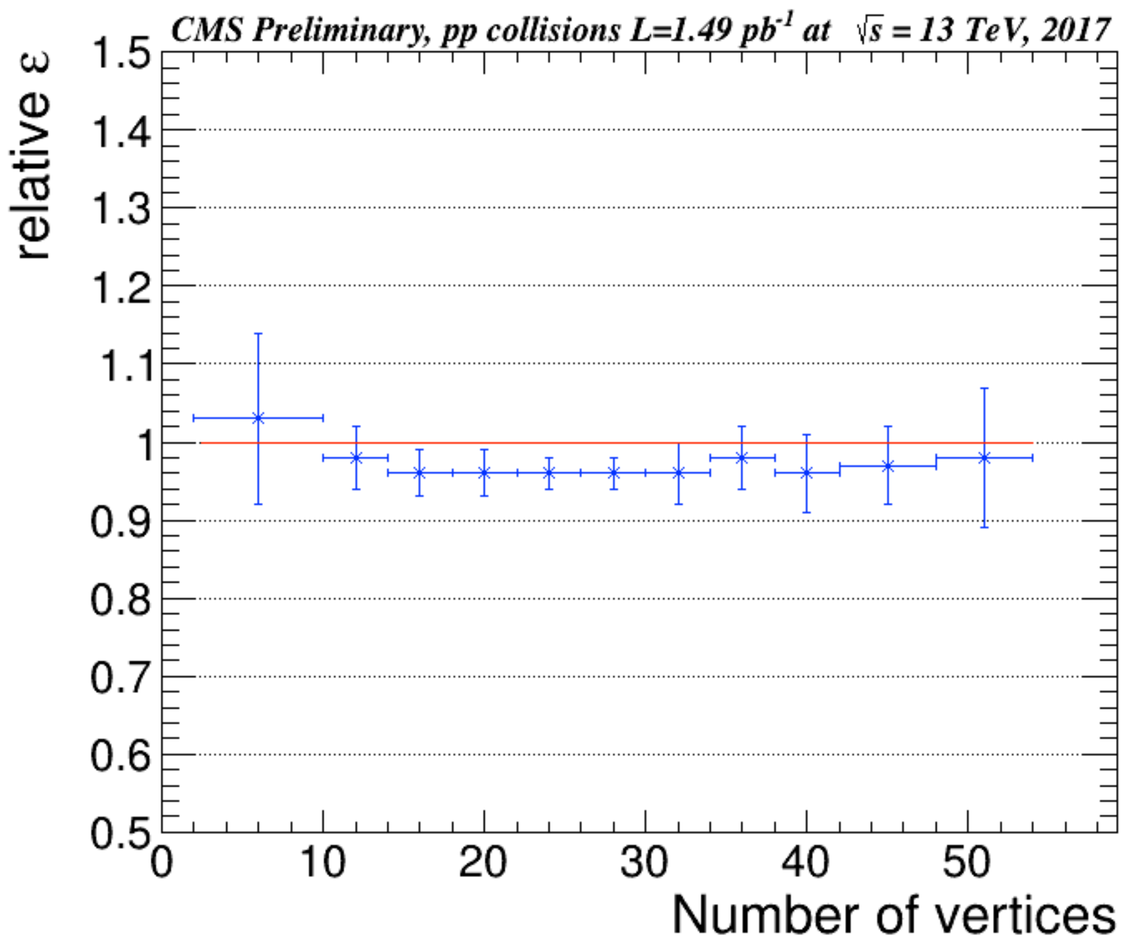


Pion efficiency with the D^* meson

From the PDG we know RPDG = 2.08 ±0.05 and then the pion relative efficiency can be evaluated as $\varepsilon_{rel} = \sqrt{\frac{R}{R_{PDG}}}$

The uncertainty of this measurement will be systematic uncertainty associated to the charged hadron reconstruction in CMS



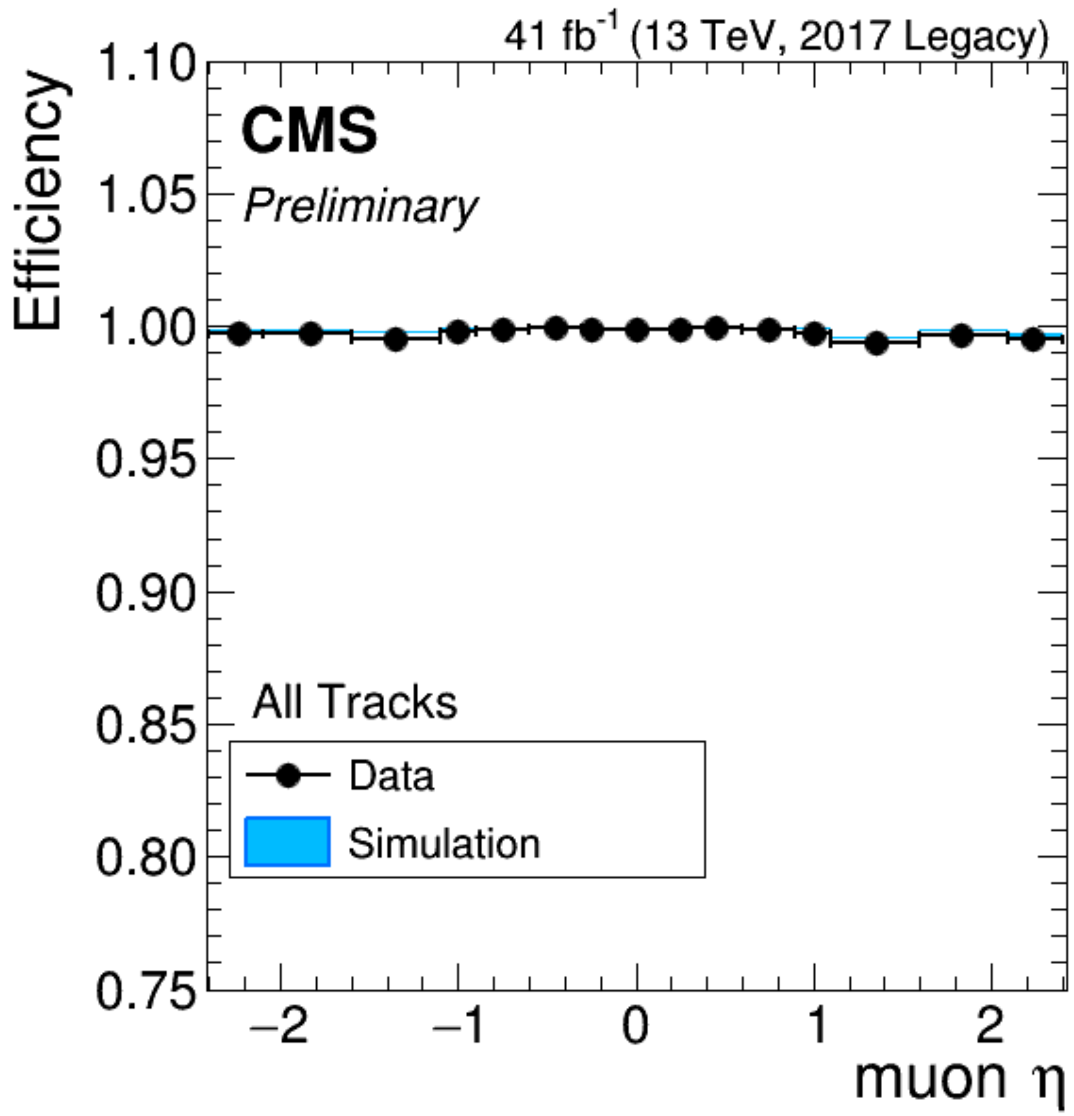


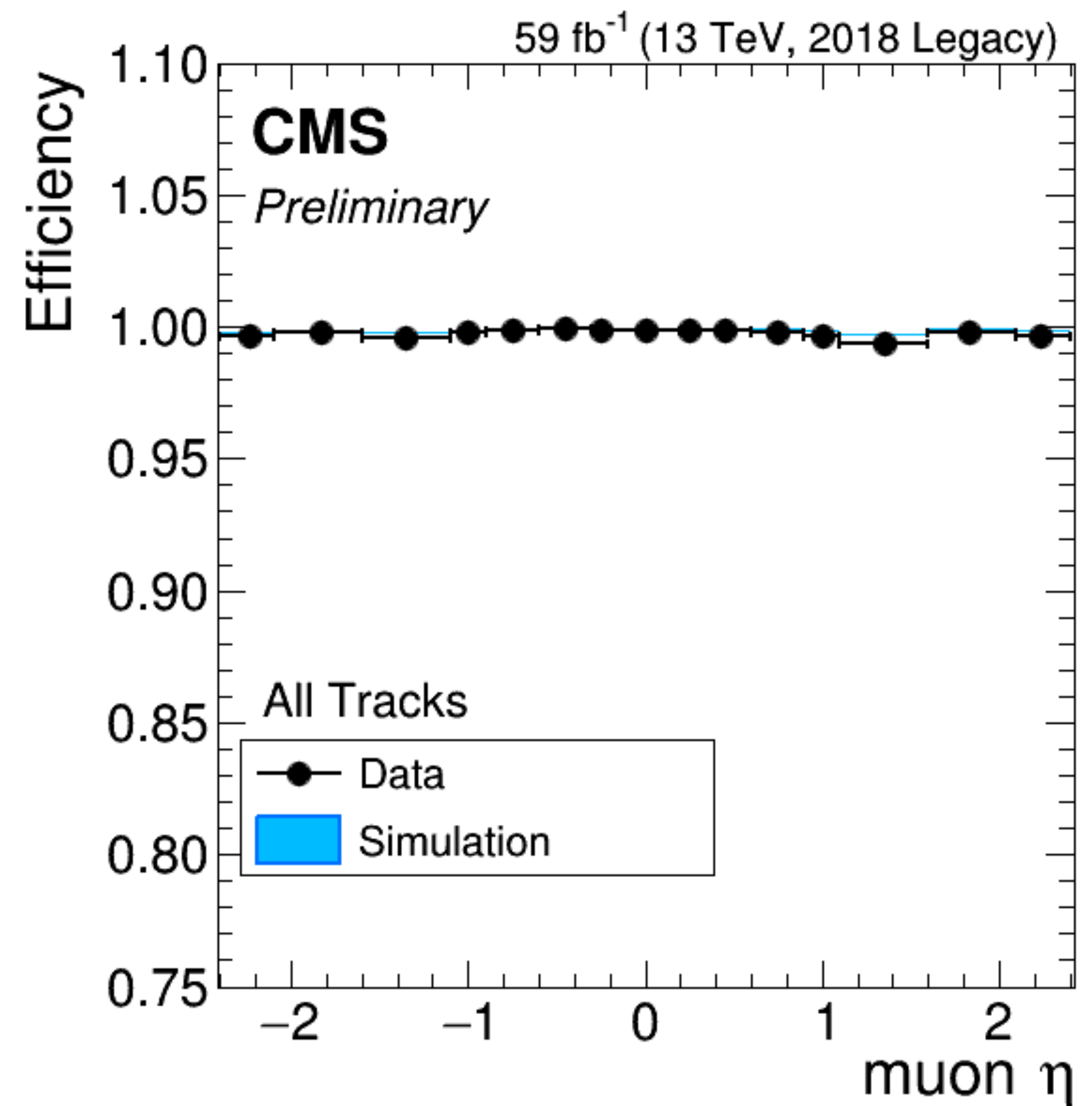
$$\boldsymbol{\varepsilon_{rel} = 0.979 \pm 0.019\ (stat) \pm 0.007\ (syst) \pm 0.012\ (PDG)}$$

The total uncertainty on this measurement is quoted as **2.4%**

Tracking performance in Run-2 using Tag-and-probe

The Tag and Probe Tool is a generic tool developed to measure any user defined object efficiency from data at CMS by exploiting di-object resonances like Z or J/Psi.

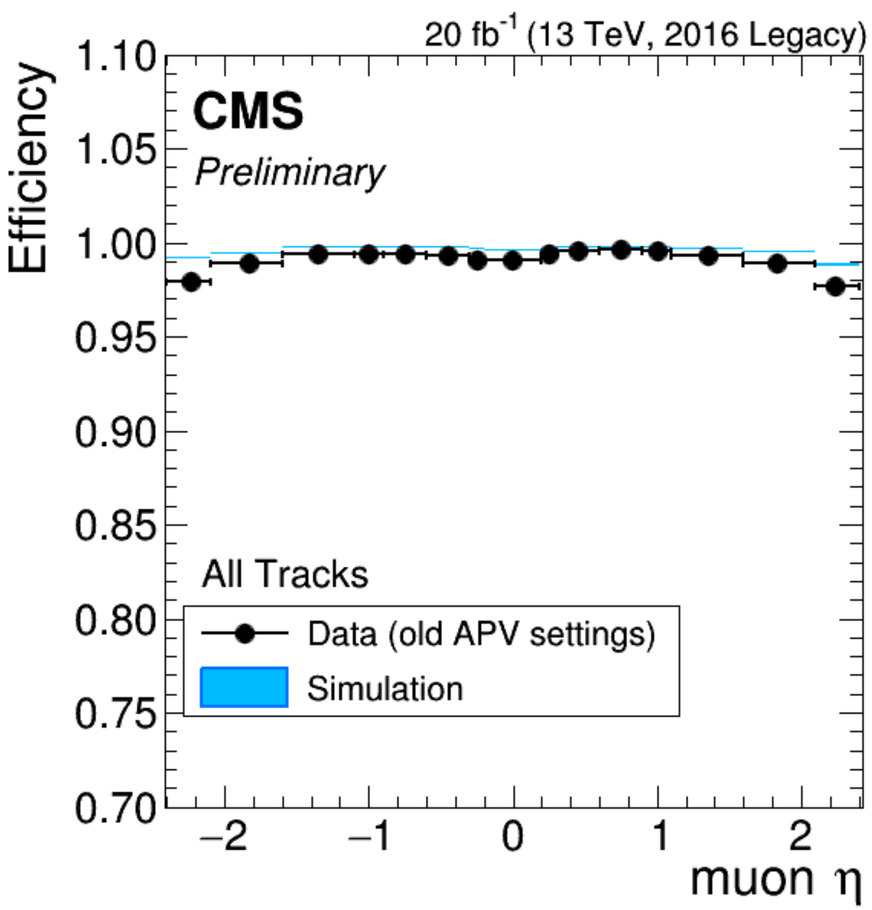


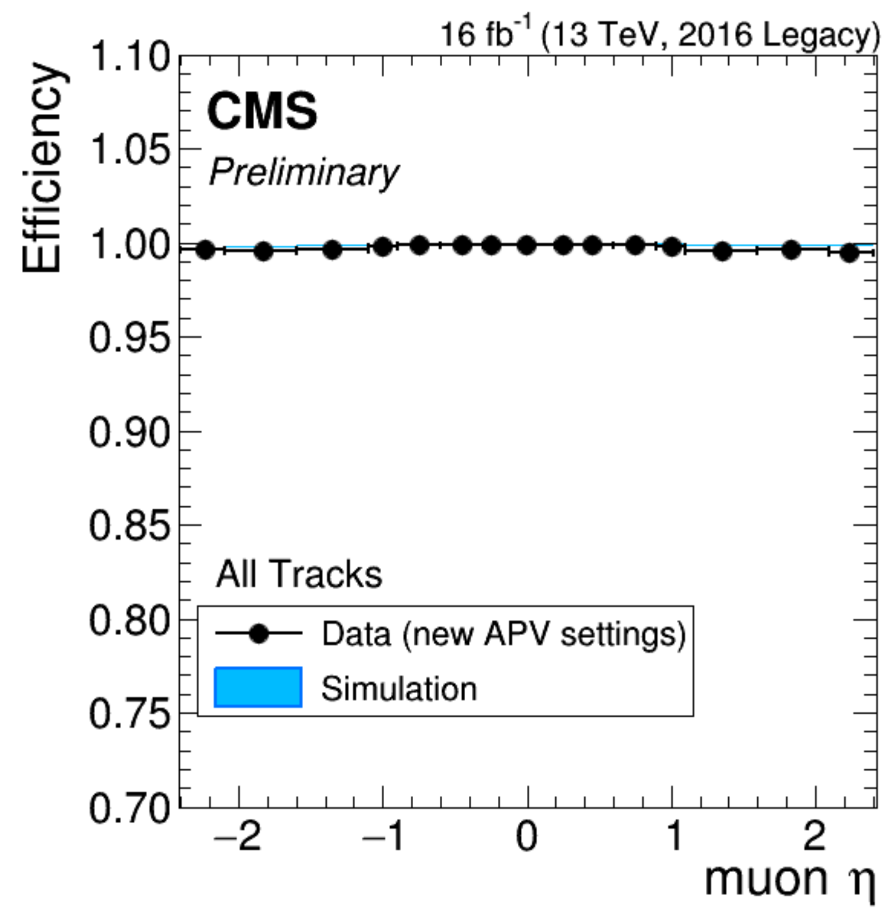


The tracking efficiency for all tracks (tracker+muon seeded) is higher than 99.5% all over pseudo-rapidity η regions for both 2018 and 2017 datasets.

Tracking performance in Run-2 using Tag-and-probe

- In late 2015 and early 2016, the Silicon Strip Tracker observed a decrease in signal-to-noise associated also with a loss of hits on tracks. This behaviour was traced to saturation effects in the pre-amplifier of the APV25 readout chip. The drain speed of the pre-amplifier was affected more strongly by the change in operating temperature than anticipated, leading to very slow discharge of the amplifier under high occupancy conditions. During this issue, about 20 fb^{-1} of 2016 data were affected, referred to as (old APV settings). The drain speed was changed to allow for faster recovery. With the new APV pre-amplifier settings, the hit efficiency is back at the same level as in Run-1, 16 fb^{-1} of 2016 data has been taken with the new settings, referred to as (new APV settings).





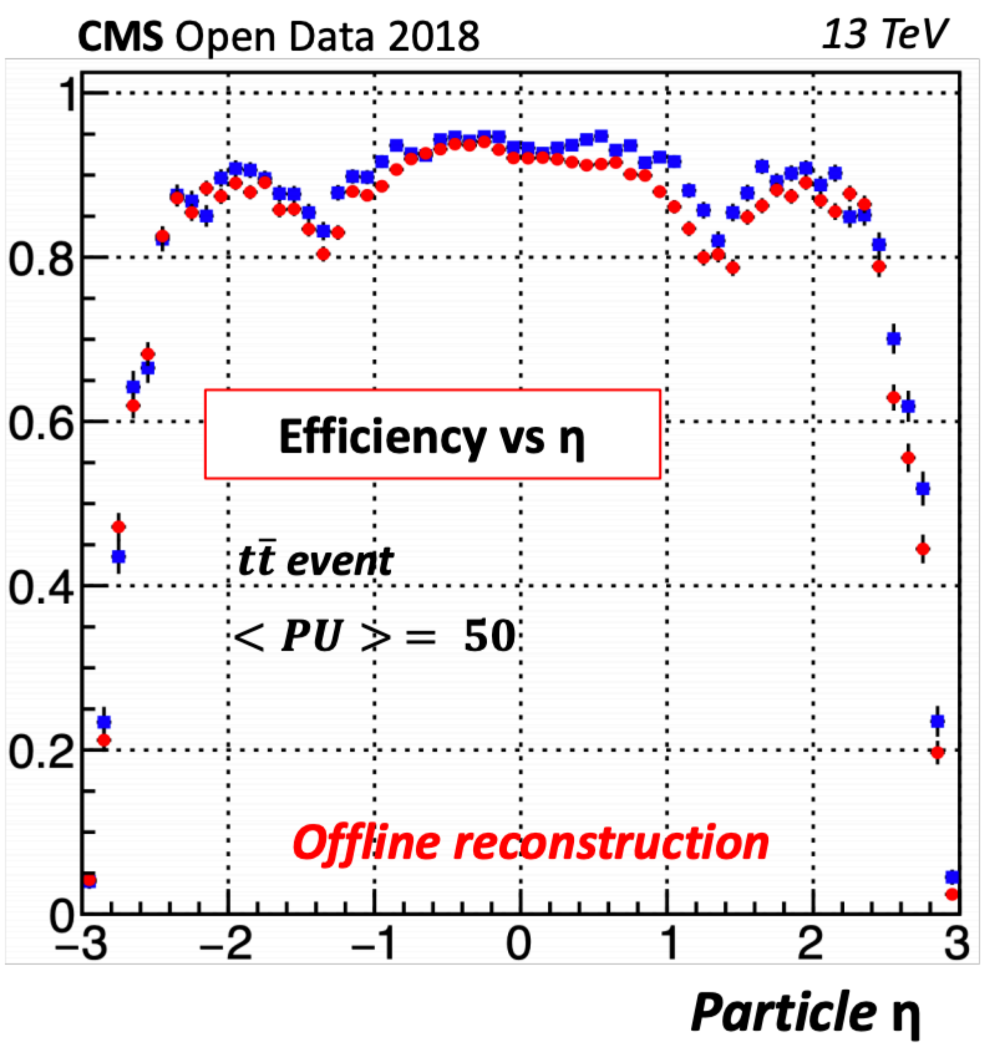
The tracking efficiency for all tracks (tracker+muon seeded) is ~ 99 % for old APV settings data increased to ~ 99.5 % for new APV settings

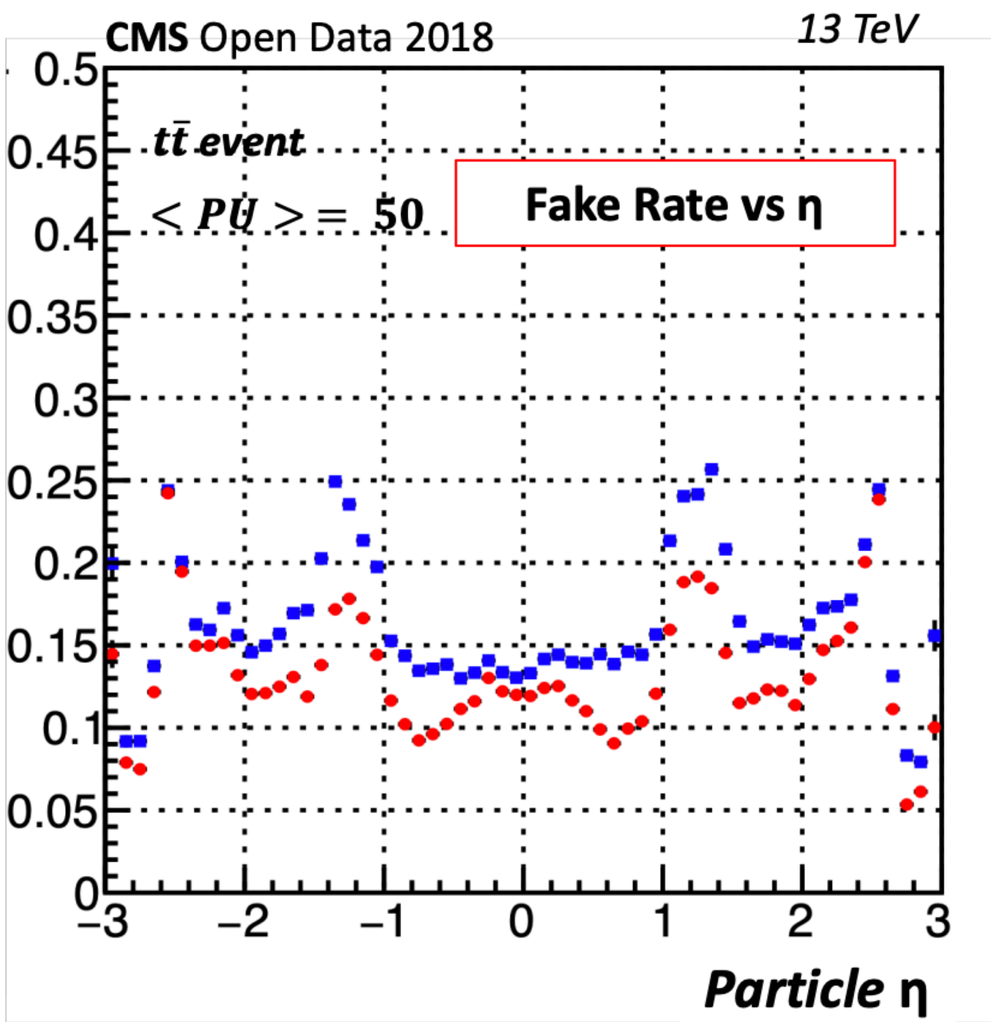
Developments for Run-3

Seed filtering using Convolutional Neural Network (CNN)

- Baseline (standards CMSSW on CPU)
- With CNN FIltering

Offline tracking efficiency





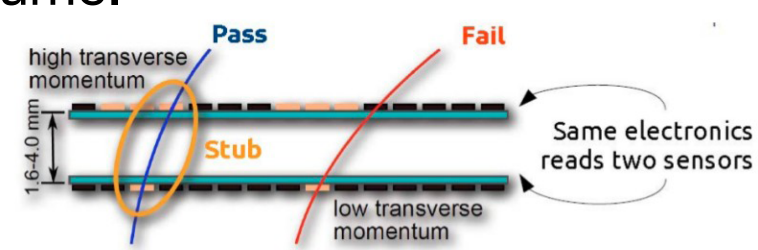
The tracking efficiency (overall ~0.9) is consistent (0.02 drop).
Network trained with Online pixel: room for improvment.

The fake rate is reduced (overall from ~0.016 to ~0.013).
Network trained with Online pixel: room for improvment.

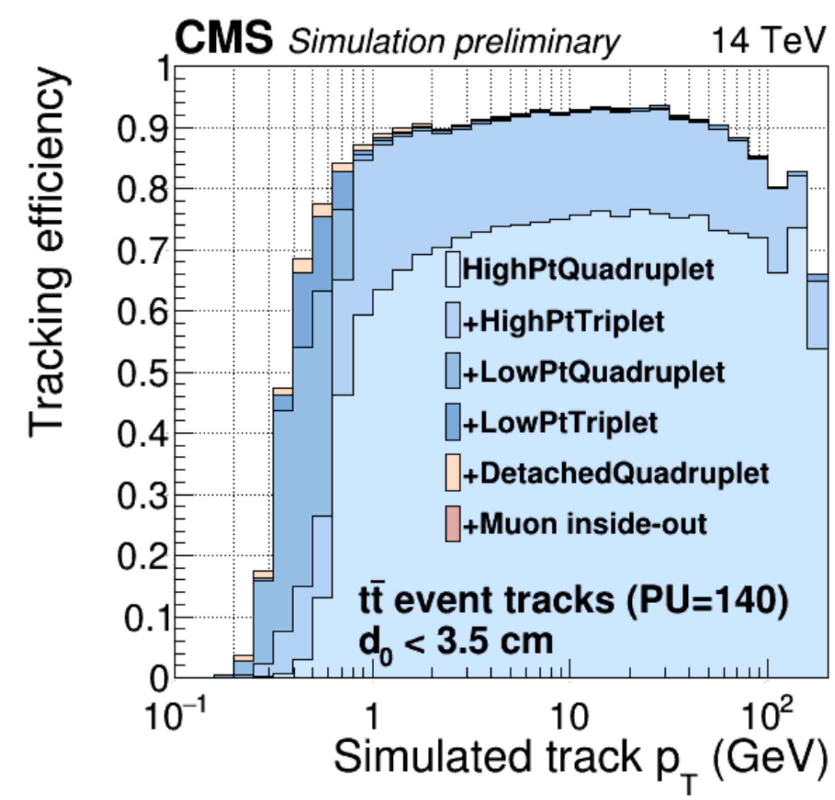
CMS tracker for Phase-2 upgrade

- Present tracker designed for an integrated lumi of 500/fb and <PU> ~ 30-50.
- **Requirements for phase-2:**
  - High radiation tolerance to operate efficiently up to 3000/fb.
  - Increased granularity to maintain channel occupancy around or below the per cent level.
  - Reduced material in the tracking volume.
  - Contribution to the Level-1 trigger.
  - Extended tracking acceptance.
  - Robust pattern recognition.

Parameters	Run-2	HL-LHC
Years	2015-2018	From 2026
Centre-of-mass energy	13 TeV	14 TeV
Instantaneous luminosity	2×10^{34} cm^{-2} s^{-1}	$5(7.5)\times10^{34}$ cm^{-2} s^{-1}
Time between collisions	25 ns	25 ns



("p_T modules") for L1 track trigger



Same efficiency at PU140 as with PU35 in current setup