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on behalf of the CMS Collaboration

Technology & Instrumentation in Particle Physics (TIPP) 2023

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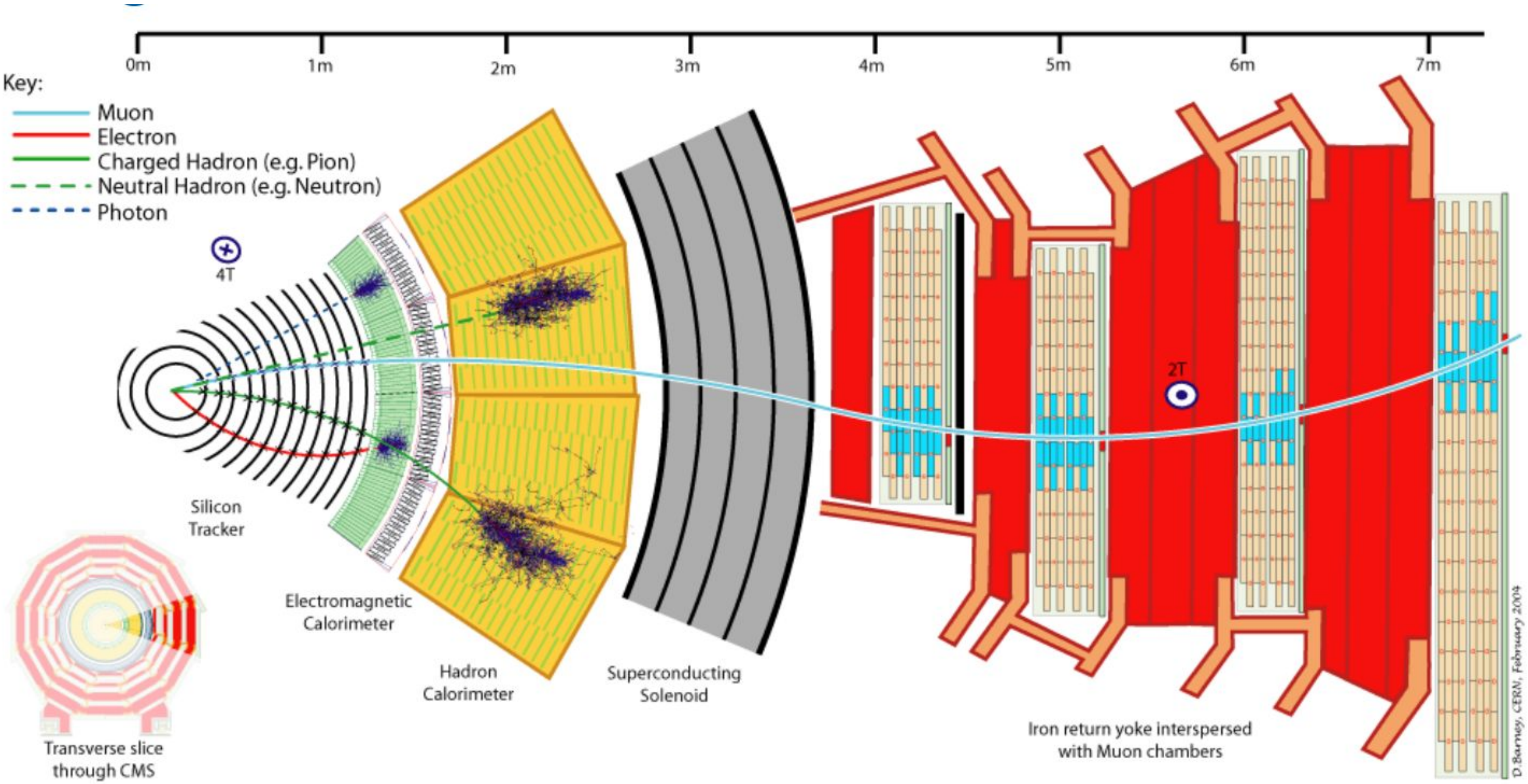
Present and Future of Tracking & Vertexing at CMS

Introduction

- Tracking at CMS for the Run 3:
  - The CMS tracking system
  - Track reconstruction overview
    - The iterative tracking
  - Algorithmic improvements for Run 3
    - The `mkFit` algorithm
    - The Track selection DNN
  - Data / Simulation agreement in Run 3
    - Performance during 2022 data-taking
  - Tracking at the HLT
    - Performance during 2022 data-taking
- Tracking for the Phase 2 upgrade:
  - The upgraded tracker
  - New developments:
    - The Line Segment Tracking Algorithm
    - Vertex reconstruction for Heterogeneous Architectures
- Conclusions & Outlook

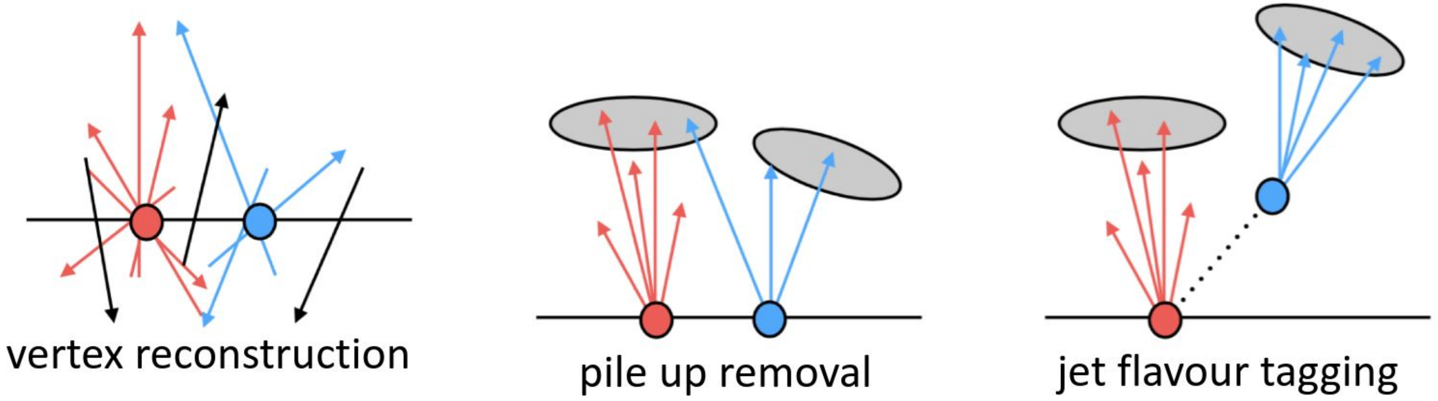
Tracking is at the heart of CMS



- Particles interact differently, so CMS is a detector with different layers to identify the decay remnants of Higgs bosons and other unstable particles;
- Even for neutrals (photons, neutral hadrons) we use (lack) of tracking information in Particle Flow
  - **Almost NO analysis in CMS would be possible without tracks.**

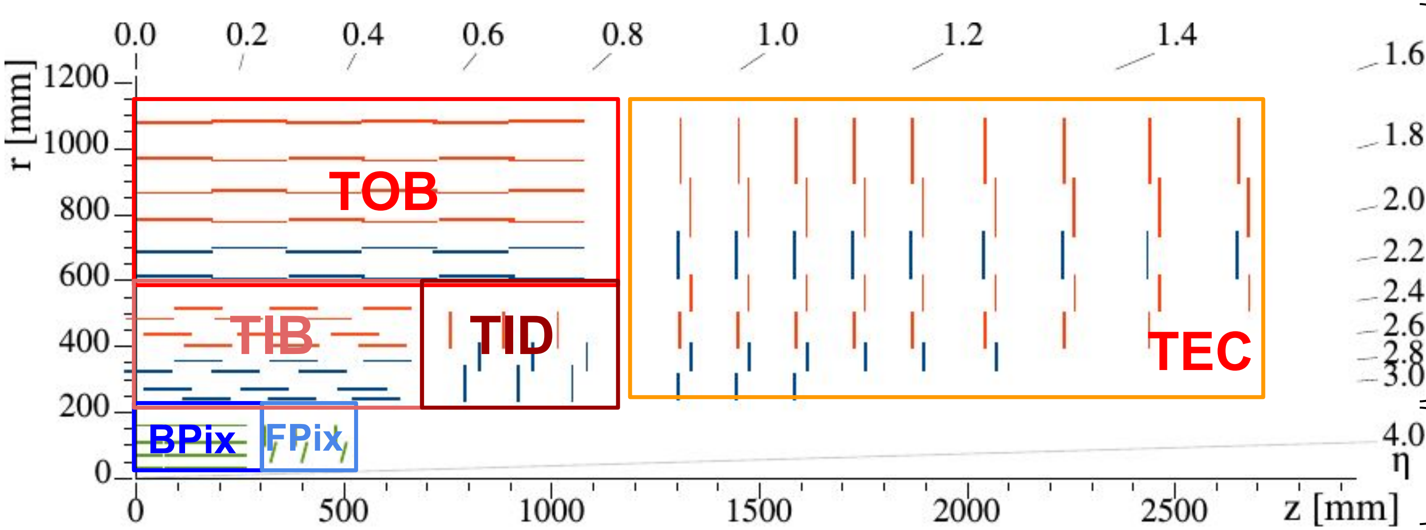
The tracking challenge at LHC

- The tracking challenge at the LHC:
    - typically 30 charged particles within the tracking volume acceptance per proton-proton collision
    - and 50-60 collisions per event: O(1500) charged particles per event;
- These need to be reconstructed:
    - with **very high efficiency** (>90% for ~GeV pions)
    - **precise** track parameters
    - very **low fake rate**: O(~ few %)
    - **quickly** (stringent CPU limits)
- Very strong requirements on track reconstruction algorithms
- Track reconstruction is not just about reconstructing charged particles:
    - used in almost every element of reconstruction



CMS Silicon Tracker

- All-silicon design:
  - Allows for high-precision charged particle tracking up to $|\eta|<3$;
  - Essential in particle identification, heavy-flavour tagging, trigger decisions, vertex reconstruction;
  - Largest Si tracker in the world: ~200 m^2 area, ~135M electronic channels
- Comprised of the Pixel (innermost parts)
  - 4 layers in the barrel (BPix) and 3 disk (FPix) in the forward regions:
    - 1,856 Pixel modules.
- and the Strips sub-detectors (outer parts)
  - 10 layers in the barrel (TIB, TOB) and 12 forward disks (TID, TEC):
    - 15,148 Strips modules.



- Micro-strip sensors
- Stereo modules (two components with a 100 mrad stereo angle)
- Analog readout

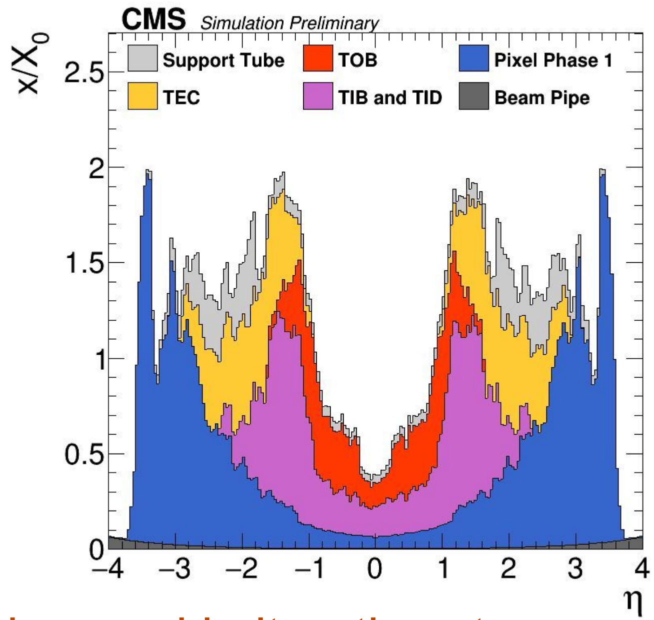
- pixel sensors
- ~124M channels
- digital readout

Track reconstruction in CMS

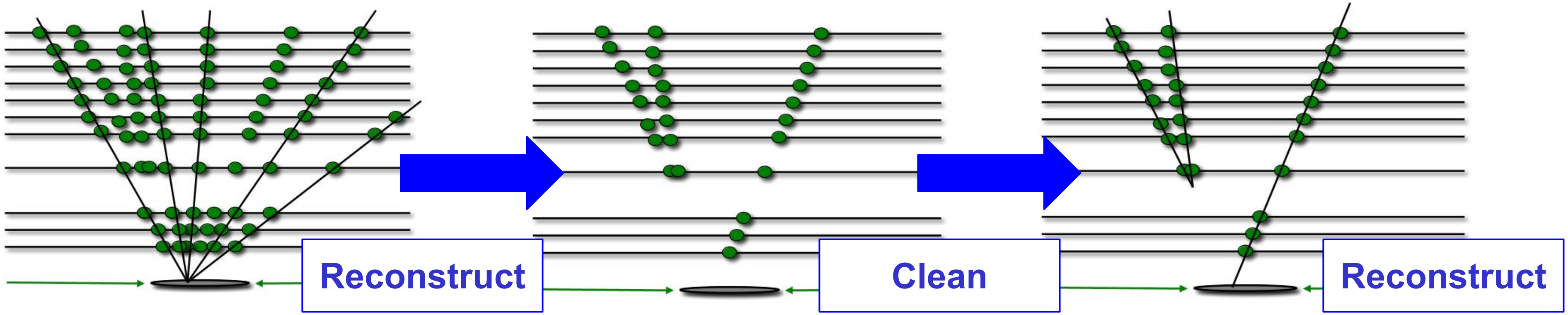
- Few, but precise measurements;
- Non negligible amount of dead material inside the tracker volume

R_{inner}[cm]	R_{outer} [m]	|η| coverage	B field [T]
3	1.1	3.0	3.8

X_0 @ |η|=0	p_T resolution @1 (100) GeV, |η|=0	d_0 resolution @1 (100) GeV, |η|=0 [μm]
0.4	0.7 (1.5)%	90 (20)

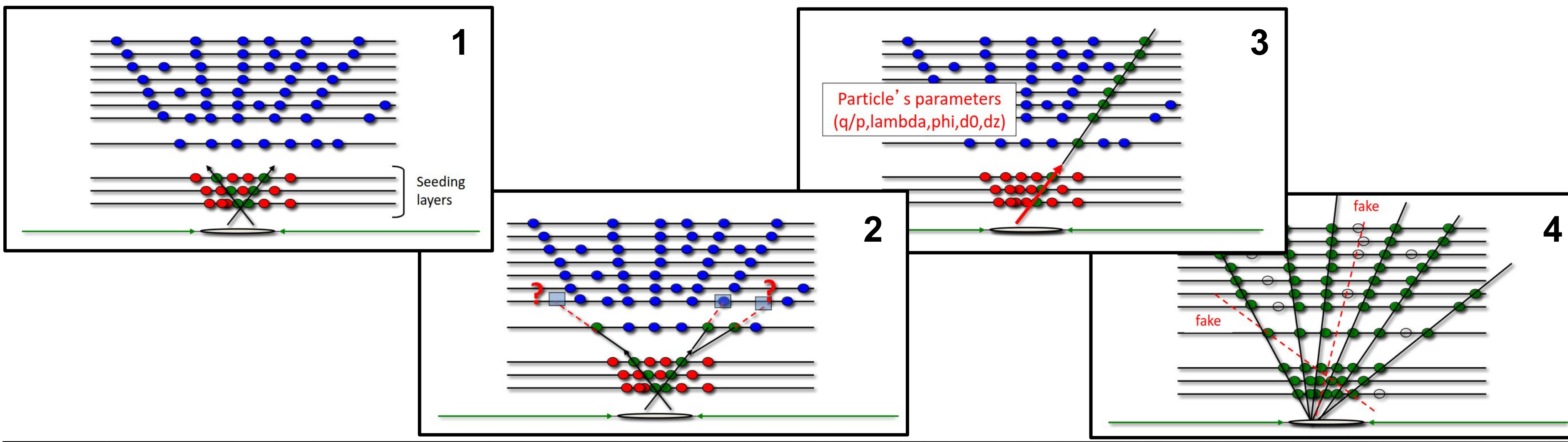


- Main tracking algorithm: Combinatorial Track Finder used in iterative steps:
  - limits the number of combinatorics in pattern recognition
  - tracking reach guarantee, w/o degrading computing performance



Track reconstruction in CMS

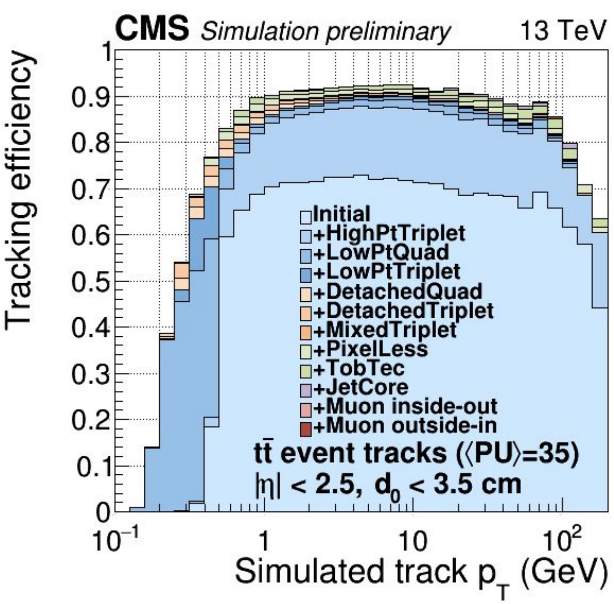
- In each iteration, tracks are reconstructed in four steps:
- **1. Seeding**:
  - provides track candidates, with an initial estimate of the trajectory parameters and their uncertainties (use combination of pixel, strip or mixed hits);
- **2. Pattern recognition**:
  - hits compatible with the predicted track position are added (Kalman update) to the trajectory and track parameters are updated;
- **3. Final fit**:
  - taking into account the B-field non uniformity and a detailed description of the material budget;
  - provides the best estimate of the parameters of each smooth trajectory after combining all associated hits (outlier hits are rejected);
- **4. Selection**:
  - sets quality flags based on a ML-based MVA with more than 20 inputs;
  - aims to reject fake tracks; tracks sharing too many hits are also cleaned as duplicates;

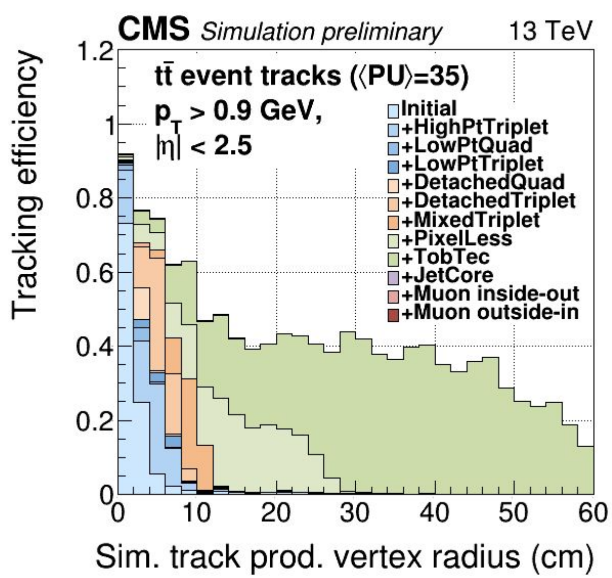


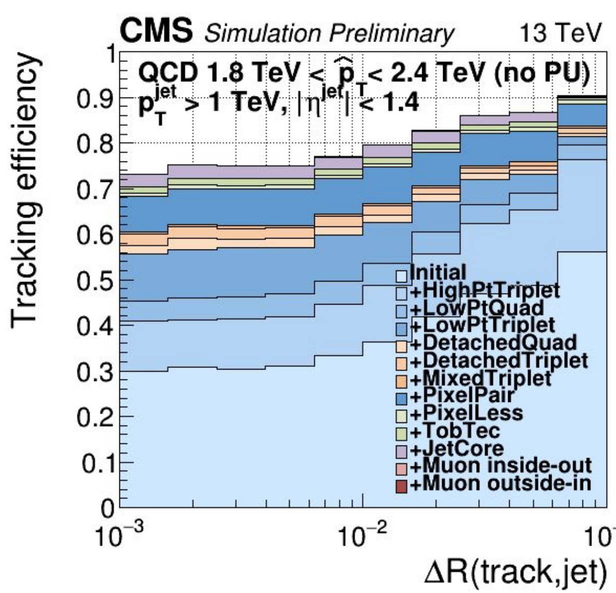
Iterative tracking at CMS

- Tracks reconstruction is an iterative procedure:
  - the InitialStep makes use of high-pT quadruplets coming from the beam spot region
  - Subsequent steps use triplets, or improve the acceptance either in pT or in displacement
  - the later steps use seeds w/ hits from the strip detector to find detached tracks,
  - final steps are dedicated to special phase-space
    - highly dense environment (i.e. within jets)
    - clean environment (i.e. 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

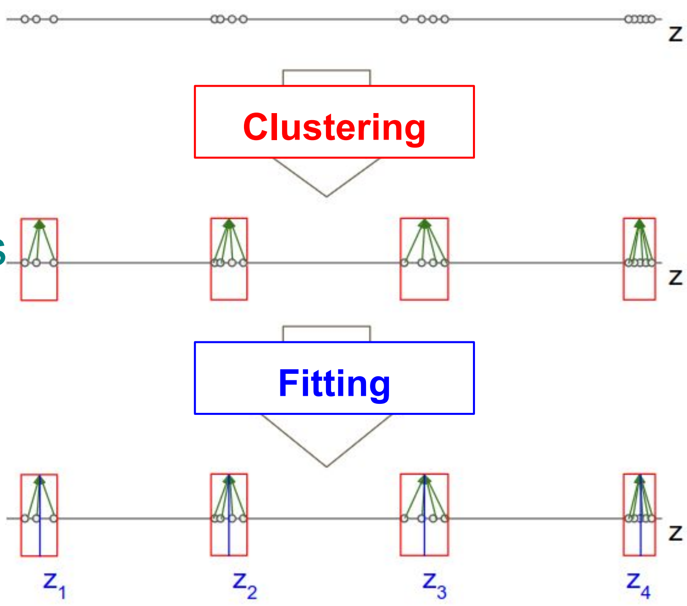






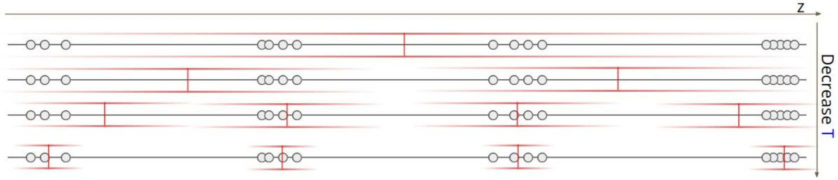
Vertexing at CMS

- CMS vertexing starts from a set of tracks.
- Then proceeds into two steps:
  - **Clustering**: group together close-by tracks in cluster candidates. The algorithm used is deterministic annealing;
  - **Fitting**: fit vertex properties of those clusters from those of the tracks. The algorithm used is Adaptive vertex fitting algorithm;



- Deterministic annealing (DA) is based on optimizing an energy (assignment) function with a penalization entropy term:
  - Starting at very high temperature (T) all tracks are assigned to one single cluster;
  - As we lower T, splitting the cluster into several becomes beneficial;
  - Iteratively update assignment probabilities P_{ik} while lowering T provides a final robust estimation of the clusters.

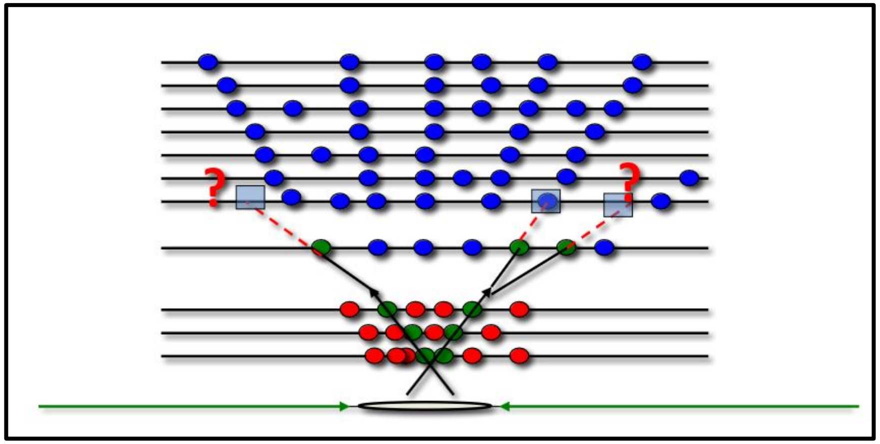
$$E - TS = \sum_{i=1}^{I} \sum_{k=1}^{K} P_{ik} \frac{(z_i - z_k)^2}{\sigma_i^2} + T \sum_{i=1}^{I} \sum_{k=1}^{K} P_{ik} \log(P_{ik})$$



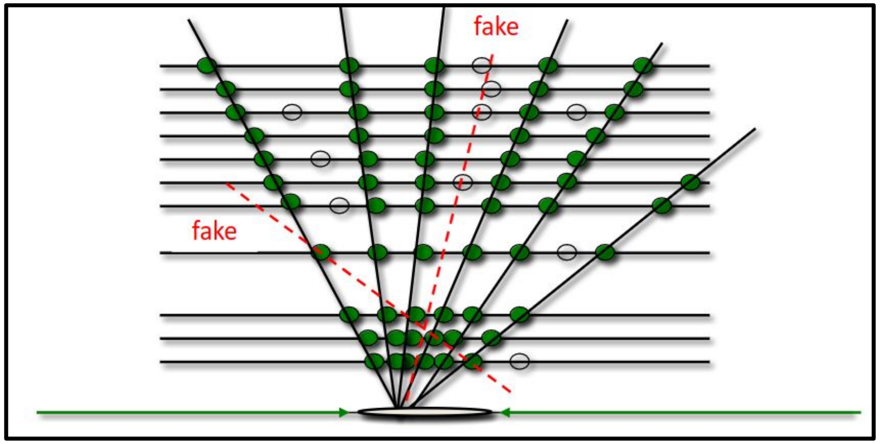
Algorithmic improvements for Run 3

- Developments during the LHC Long Shutdown 2 focused on the tracking algorithmic improvements targeted to reconstruction timing and tracking fake rate:
  - Parallelization and vectorization at multiple levels using Kalman Filter, since including the mkFit algorithm (CMS-DP-2022-018)
  - After final fit, track quality is assessed with track classifier: from a Boosted Decision Tree to a Deep Neural Network (CMS-DP-2023-009)

Track Building step: from CKF to mkFit



Track Selection step: from BDT to DNN



mkFit algorithm

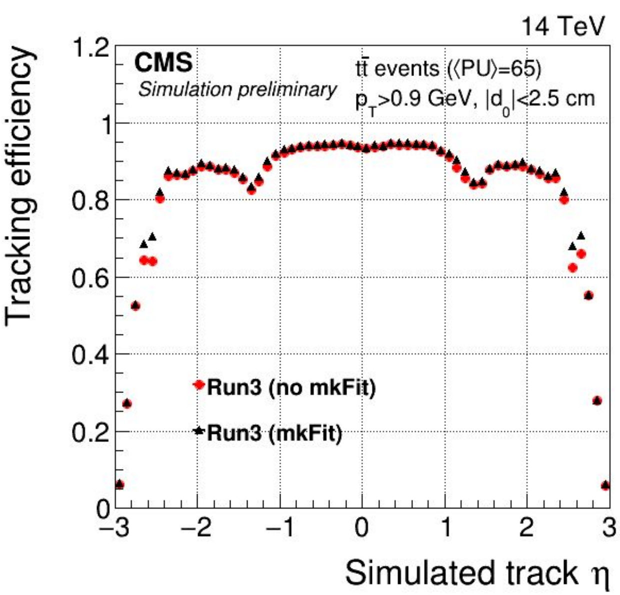
- In Run 2, the CMS track reconstruction algorithm used an iterative approach based on combinatorial Kalman Filter (CKF), consisting of twelve main iterations targeting different track topologies and seeded with different seed tracks.
- For Run 3, a new algorithm has been developed for track pattern recognition (or track building), named mkFit, that maximally exploits parallelization and vectorization in multi-core CPU architectures. This algorithm has been deployed in the CMS software for a subset of tracking iterations:
  - **InitialPreSplitting**:
    - initial iteration before splitting merged pixel clusters in dense jet environments;
  - **Initial**:
    - initial iteration;
  - **HighPtTriplet**:
    - high-pT triplet iteration;
  - **DetachedQuad**:
    - detached quadruplet iteration;
  - **DetachedTriplet**:
    - detached triplet iteration;

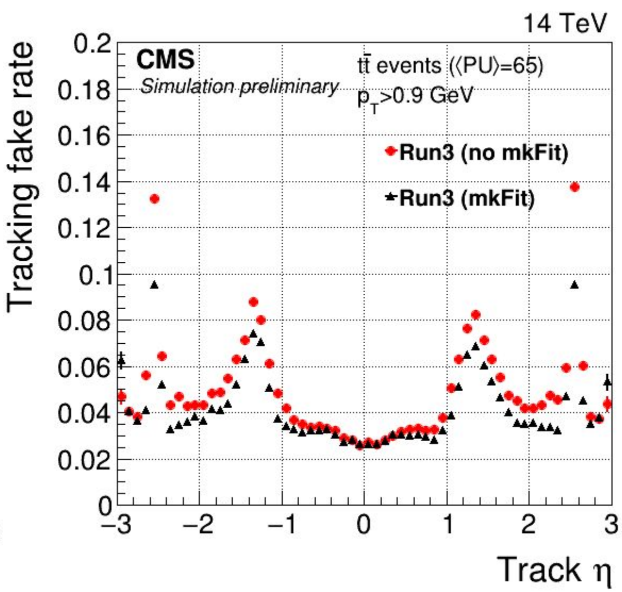
Iteration	Seeding	Target track
Initial	pixel quadruplets	prompt, high p_T
LowPtQuad	pixel quadruplets	prompt, low p_T
HighPtTriplet	pixel triplets	prompt, high p_T recovery
LowPtTriplet	pixel triplets	prompt, low p_T recovery
DetachedQuad	pixel quadruplets	displaced--
DetachedTriplet	pixel triplets	displaced-- 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

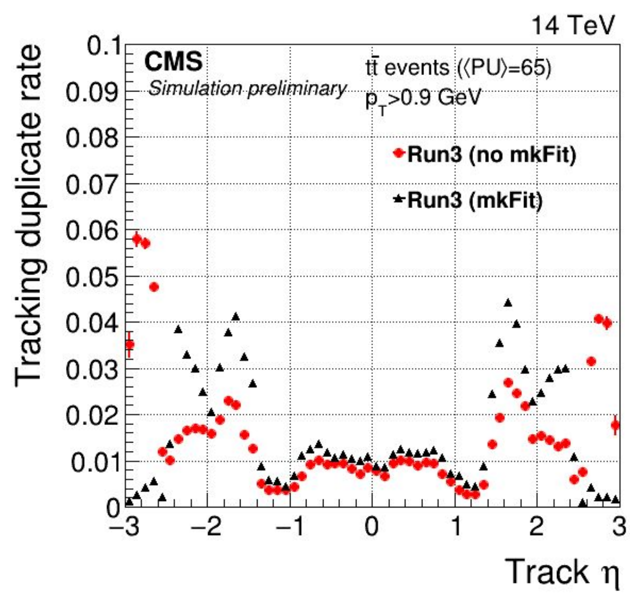
- The mkFit algorithm allows to retain a similar physics performance with respect to the traditional CKF-based pattern recognition, while substantially improving the computational performance of the CMS track reconstruction

mkFit physics performance

- The performance has been measured in a simulated $t\bar{t}$ sample with superimposed pileup events 55 to 75 (flast). The detector conditions account for the residual radiation damage due to Run 2 operations.
- When mkFit is used for track building in a subset of iterations:
  - The **tracking efficiency** is consistent with the one obtained with the traditional CKF tracking algorithm;
  - The **tracking fake rate** is on average lower than the one obtained with the traditional CKF tracking algorithm;
  - The **tracking duplicate rate** is higher than the one obtained with the traditional CKF tracking algorithm especially at 1.45<|η|<2.5, while it's lower at |η|>2.5.

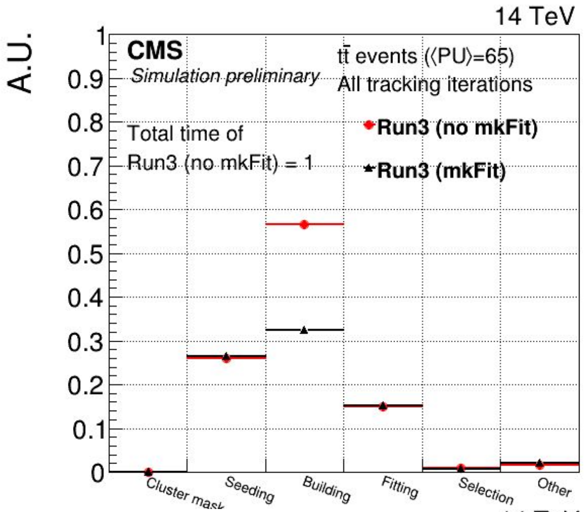




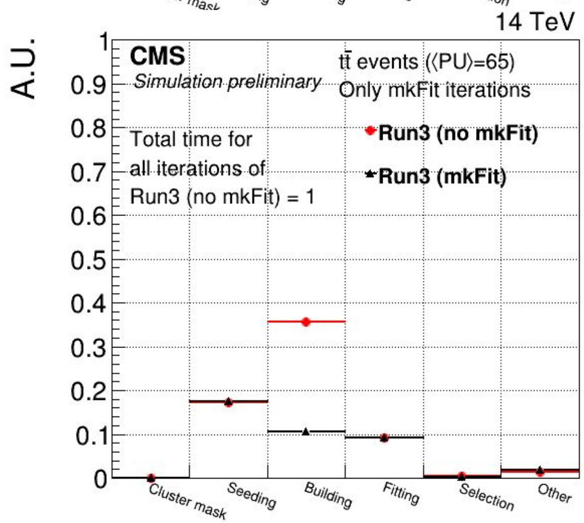


`mkFit` timing performance

- The tracking time performance has been measured in the same simulated $t\bar{t}$ sample with superimposed pileup (PU) events as for the physics performance
- Single-threaded measurements are performed with local access to the input



- Overall, using `mkFit` in a subset of tracking iterations allows to **reduce the track building time by a factor of about 1.7**, corresponding to a reduction of the total tracking time by about 25%. In Run 3, tracking has been measured to make about half of the total offline reconstruction time.
  - Thus, this translates to a reduction of the total offline CMS reconstruction time or conversely to **an increase of the event throughput by 10-15%**.

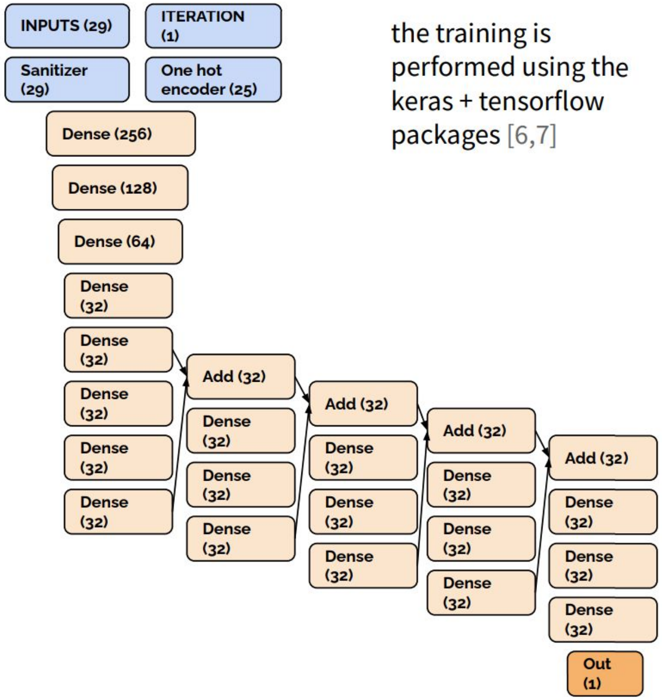


- Using `mkFit` allows to **reduce the track building time by a factor of about 3.5** considering the sum of iterations where `mkFit` is employed.
  - In individual iterations where `mkFit` is employed, this factor varies from about 2.7 to about 6.7.

Track Selection DNN

- After the pattern recognition and the fit, based on Kalman Filter techniques, high purity tracks are selected and the hits belonging to those tracks are not used in the following iterations, thus keeping the complexity of the pattern recognition under control for later iterations.
  - The track selection was gradually improved: starting with a parametric selection in Run 1, moving to a BDT in Run 2, and to a DNN in Run 3.

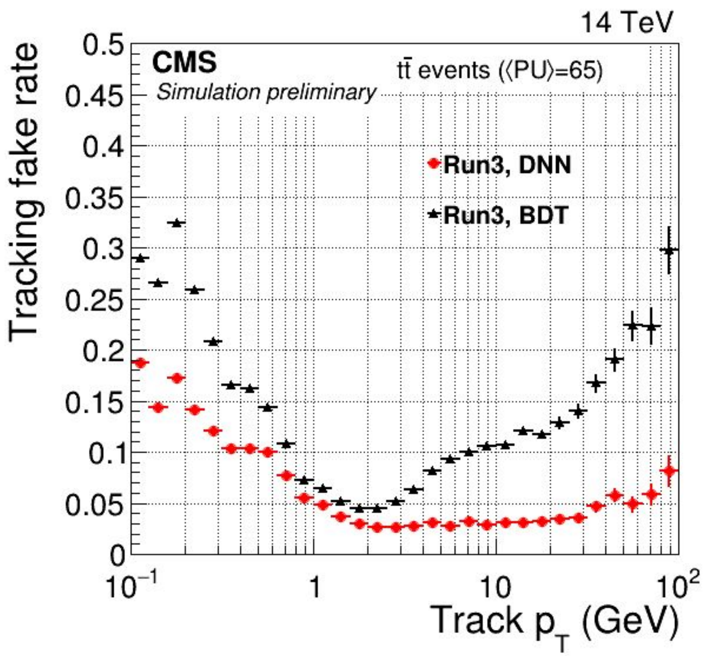
- DNN Architecture:
  - Relatively simple feed-forward network, with 5 iteration of “skip connection” and sum of the layer outputs in the downstream layers;
  - The “sanitizer” layer applies log/absolute value transformations to some of the inputs, while the “one hot encoder” converts the iteration flag into a boolean vector by category;
  - **Activations**: ELU in hidden layers, sigmoid for output;
  - **Loss function**: binary cross-entropy;

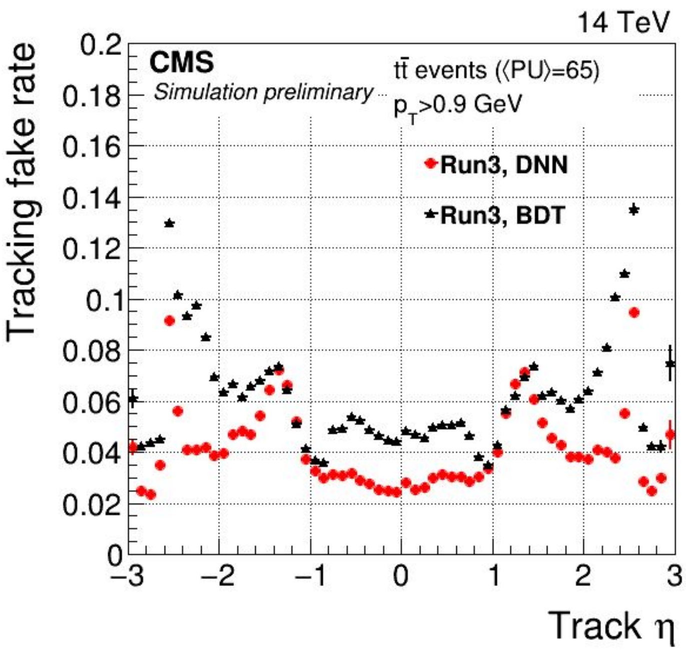


the training is performed using the keras + tensorflow packages [6,7]

DNN track selection performance

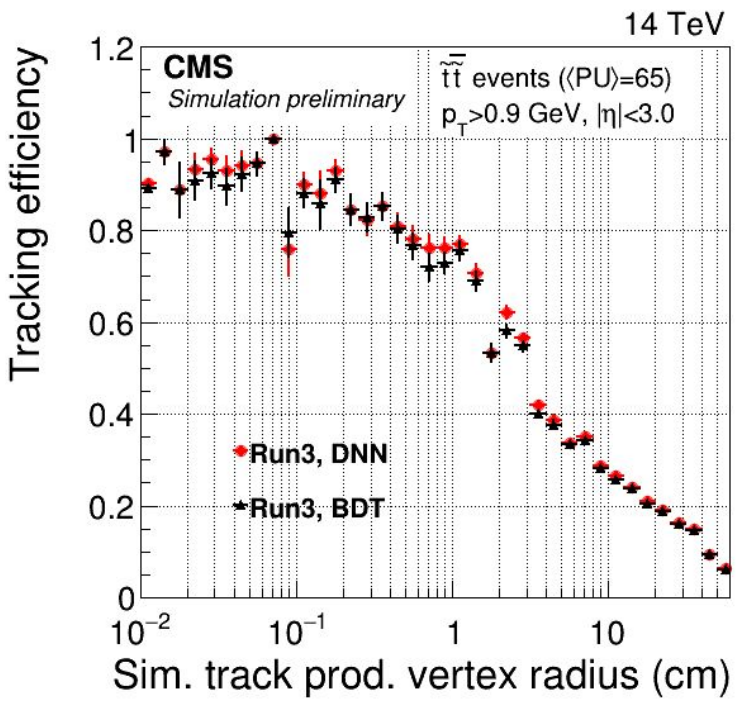
- The performance has been measured in a simulated $t\bar{t}$ sample.
  - The physics results are shown after applying the high purity BDT or DNN selection to each iteration and after merging all the tracks from the iterations into one collection.
- The tracking fake rate when the DNN is used is notably lower than the one obtained using the BDT:
  - especially for very low and very high p_T values. Overall the fake rate is reduced by about 40%.
  - the largest fake rate reductions are in the tracker endcaps (|η|>2) and in the barrel (|η|<1). The discontinuities follow the tracker regions.

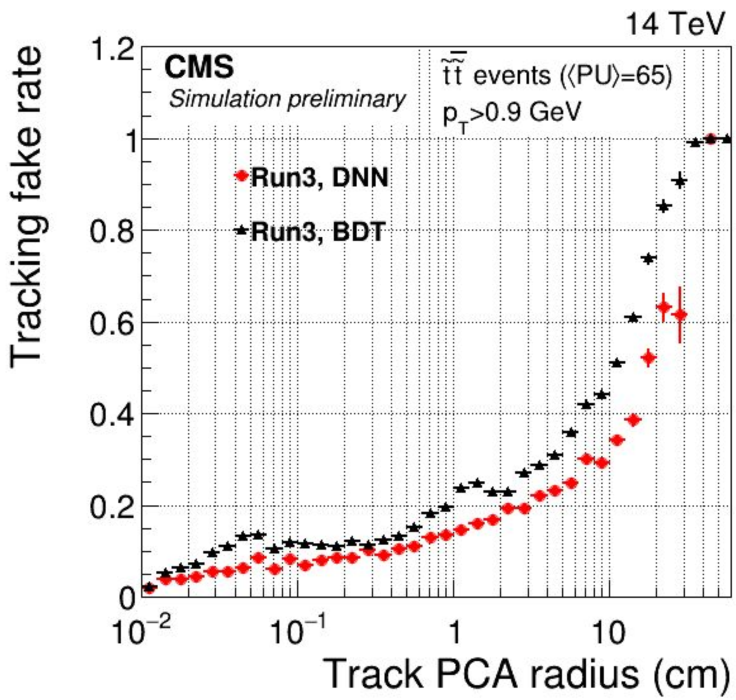




DNN track selection performance

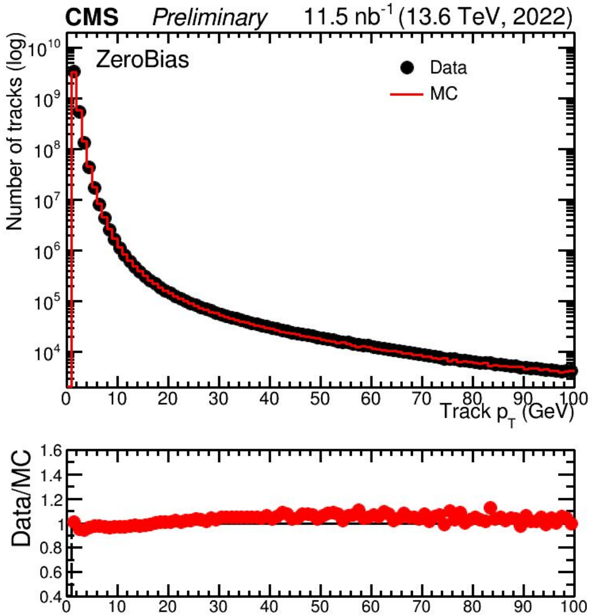
- The performance has been measured in a sample with stop-antistop production in RPV SUSY, where the stops have a significant decay length and produce displaced tracks,.
- The physics results are shown after applying the high purity BDT or DNN selection to each iteration and after merging all the tracks from the iterations into one collection.
  - The tracking efficiency when the DNN is used is consistent or slightly higher than the one obtained using the BDT at all radii.
  - 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%.

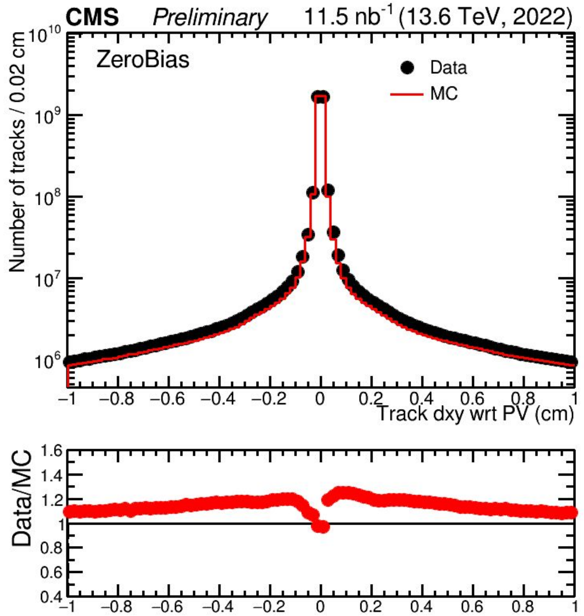


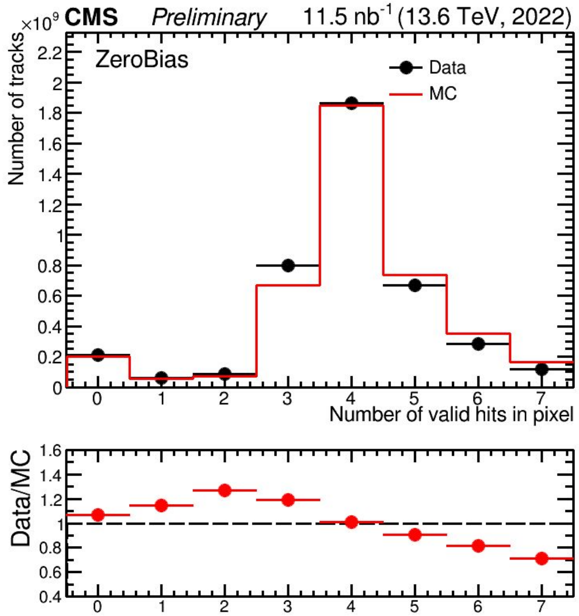


Data/Simulation agreement in Run 3

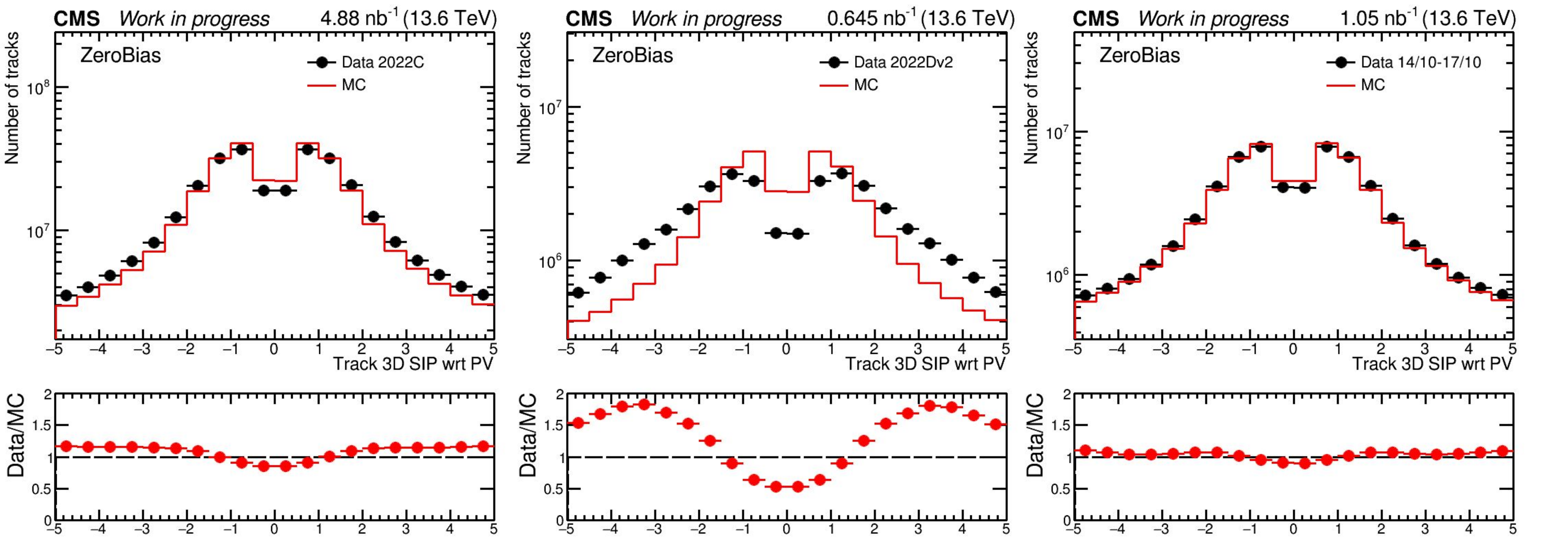
- The figures in the following show a comparison between 2022 CMS data and MC of the reconstructed track properties (documented in CMS-DP-2022-064).
  - Events used are selected with minimal trigger bias, using only the information on the beam-beam coincidence, and were collected from July 19th, 2022 to October 17th, 2022 (with the exception of the period from August 23rd to September 27th). The trigger which is used collects only a fraction of delivered events.
  - the tracks which are considered are tracks which pass the `highPurity` selection (see previous slides), with p_T>1GeV.
  - MC distributions are normalized to the number of vertices in data.
- Overall and without further corrections a **reasonable agreement** is found between data and simulation.





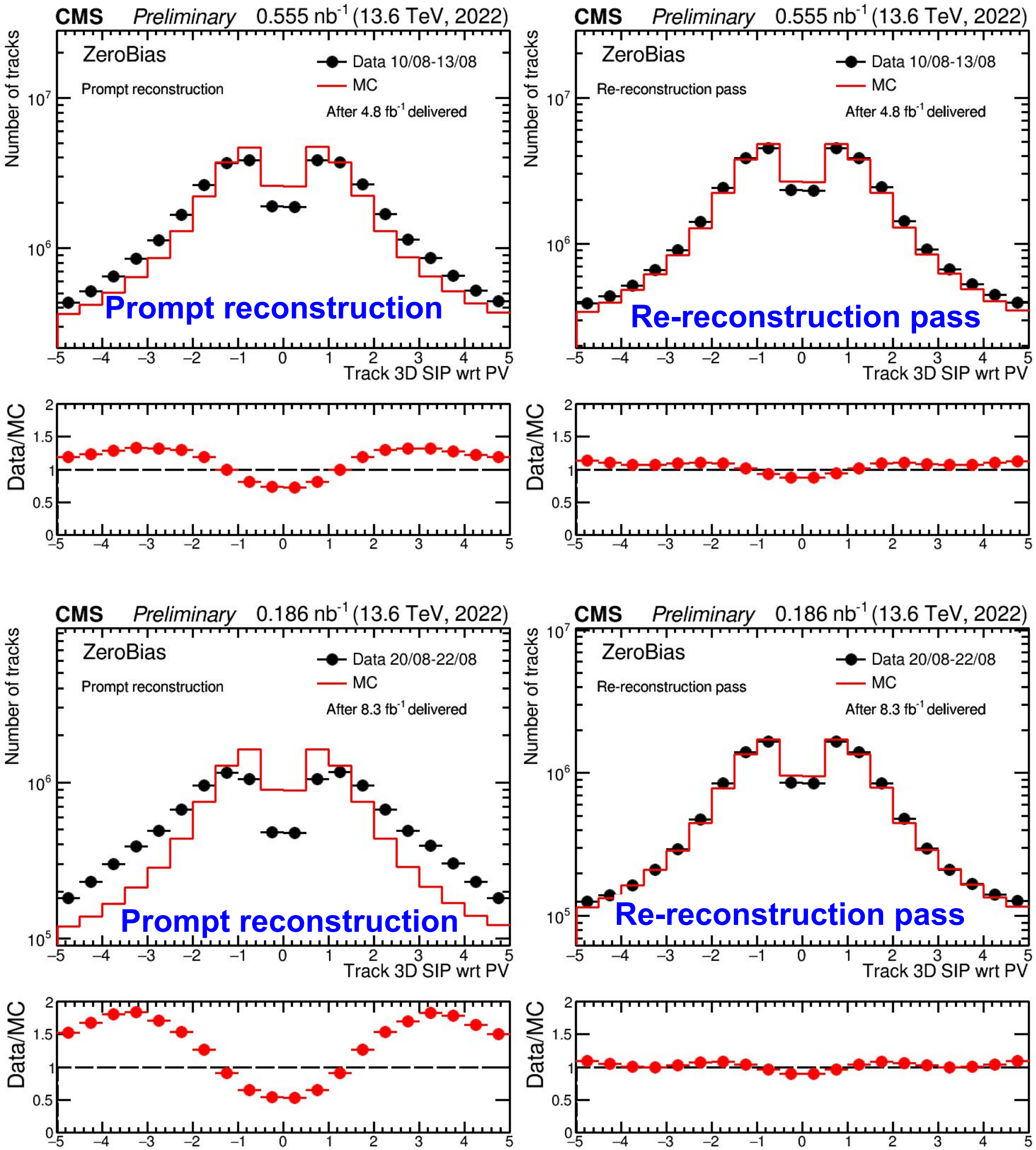


Impact parameter performance in Run 3



- The figures show the distributions of the significance of 3D impact parameters with respect to the Primary Vertex of tracks from events passing the selection described above.
- Comparisons are shown for the different periods of time shown in the figures, after the indicated luminosity was delivered since the installation of the new BPix layer 1.
  - Agreement between data and MC gets worse over time, indicating aging of BPix layer 1 due to accumulated irradiation.
  - Improvement in agreement in the latter data taking period due to an update in the high-voltages and in the alignment which has been implemented later in the data-taking.

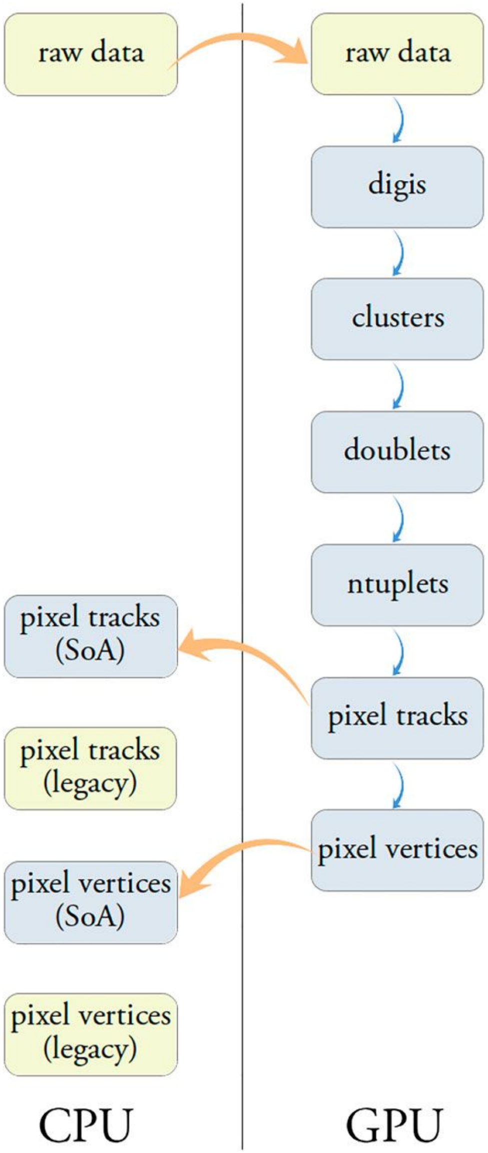
IP performance Prompt vs Re-reconstruction



- The figures show the distributions of the significance of 3D impact parameters with respect to the Primary Vertex of tracks from events, passing the selection described above.
- In this case only those events which have been re-reconstructed are considered here.
- Re-reconstruction includes updates to pixel local reconstruction and the alignment of the tracker, leading to better performance.
  - The figures on the left shows the prompt reconstruction, the figures on the right shows the re-reconstruction pass, for the period indicated and after the indicated luminosity was delivered since the installation of the new BPix layer 1.
  - Variables connected to impact parameters (hence used for b/tau tagging, etc.) are the ones most improved by the re-reconstruction conditions, as expected from the updates previously indicated.
- The agreement between data and MC is much better for re-reconstructed data.

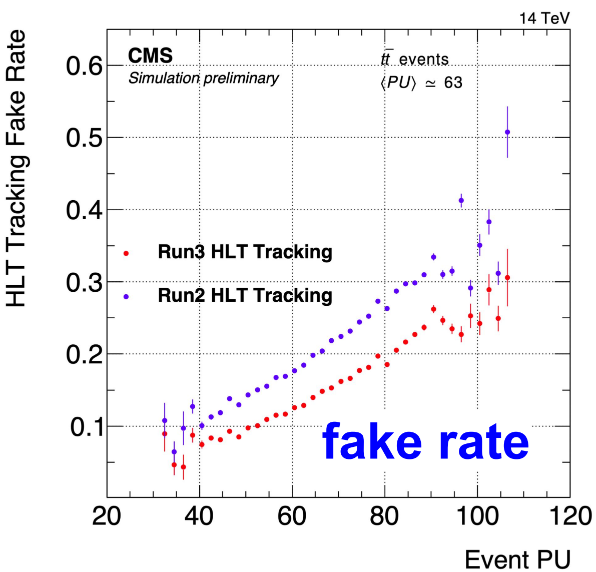
Tracking at the High Level Trigger

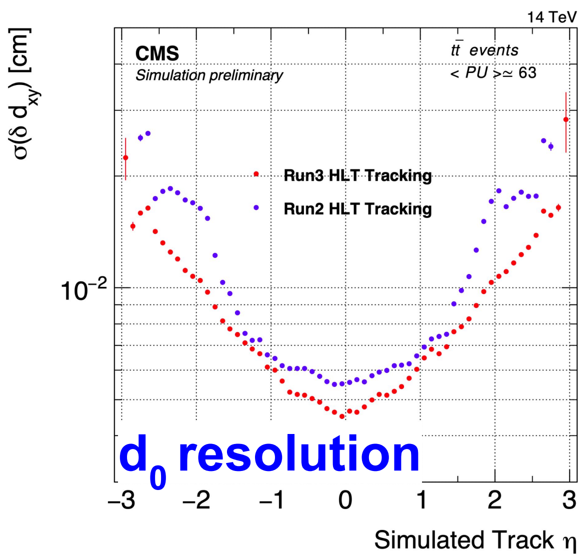
- The CMS High-Level Trigger (HLT) runs a version of the full event reconstruction optimized for fast processing.
    - Since the start of Run 3, the HLT makes use of a heterogeneous computing farm.
- In Run 3, HLT tracking is based on a single iteration of the Combinational Kalman Filter, seeded by pixel tracks reconstructed by the Patatrack algorithm (DOI:10.3389/fdata.2020.601728), which can be offloaded to GPUs.
- To be used as seeds, Patatrack pixel tracks are required to:
    - Be built with at least three pixel hits;
    - Have transverse momentum $p_T > 0.3$ GeV;
    - Be consistent with a leading pixel vertex;
- Pixel vertices from primary interactions are reconstructed at the HLT from pixel tracks with at least four hits and $p_T > 0.5$ GeV.
- The vertex with largest summed $\sum p^2_T$ of constituent tracks, is the primary vertex (PV).

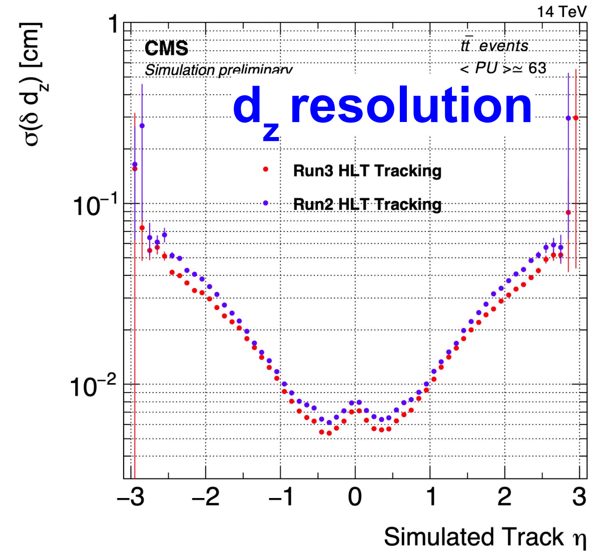


Performance of tracking at HLT

- Performance in simulation is documented in [CMS-DP-2022-014]()
- The performance has been measured in a simulated ttbar sample with superimposed pileup (PU) events.
  - The number of PU events generated follows a uniform distribution from 55 to 75. The detector conditions are simulated with no module failure and taking into account the residual radiation damage due to Run-2 operations
- Some highlights below:
  - With respect to the Run 2 HLT tracking, better fake rate rejection and improved impact parameters resolutions.

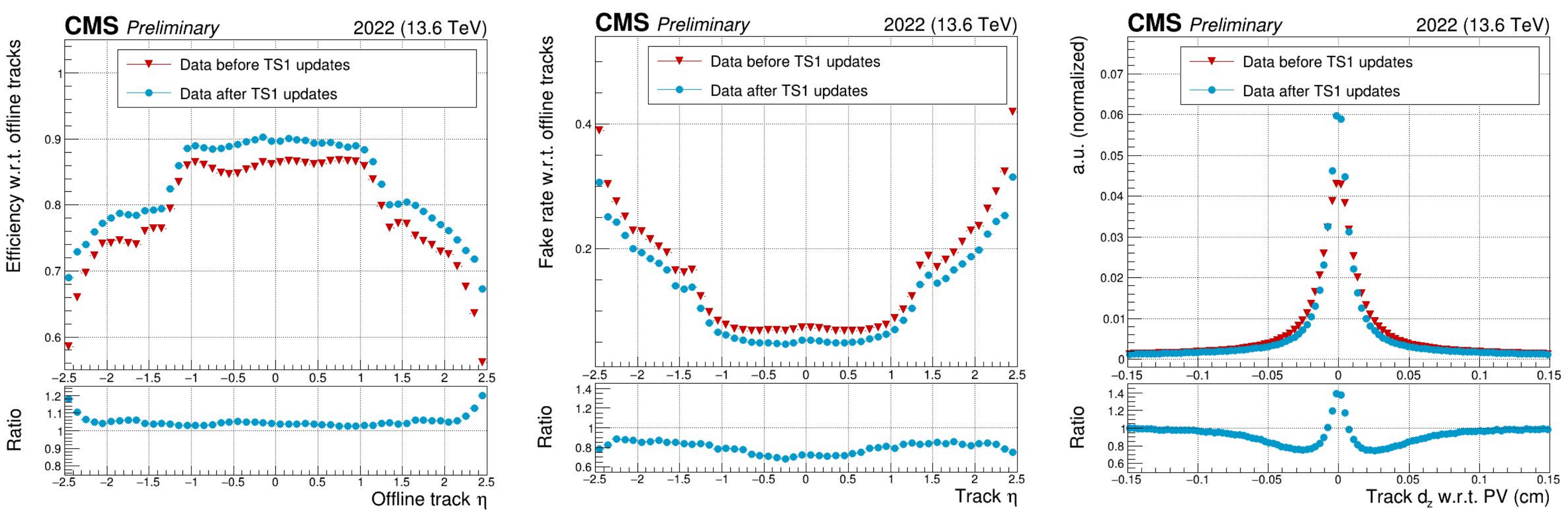






Tracking at HLT performance in 2022

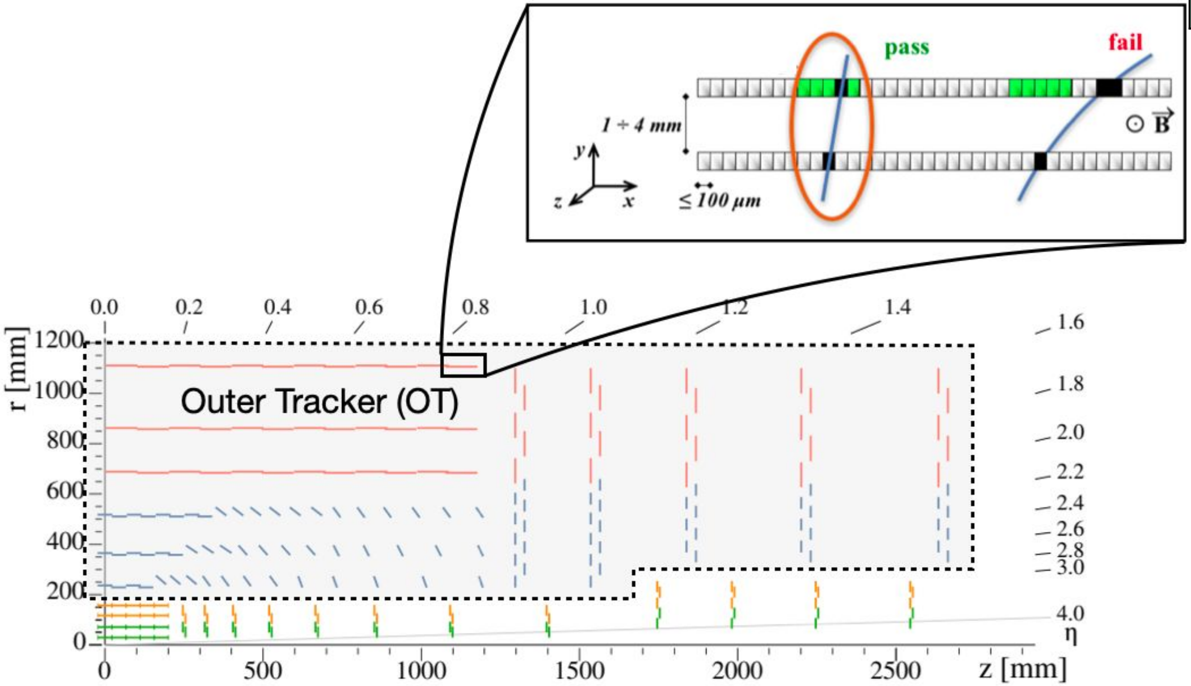
- The performance is measured (CMS DP-2023/028) in data recorded at √s=13.6 TeV in 2022, using runs taken shortly before and shortly after the first Technical Stop (TS1) of the LHC, when several updates in detector conditions took place:
  - Increase in BPix L1 reverse bias high voltage (HV) from 150 V to 300 V, with a corresponding;
  - 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.



CMS Tracker for the Phase2 upgrades

- The CMS Phase-2 Tracker will be composed of:
  - Inner Tracker: 4 barrel layer, 12 disks
    - Extended up to η = 4.0
  - Outer Tracker: 6 barrel layer, 5 disks
    - Each module consists of two closely spaced sensors allowing for an L1 track trigger (“pT modules”)

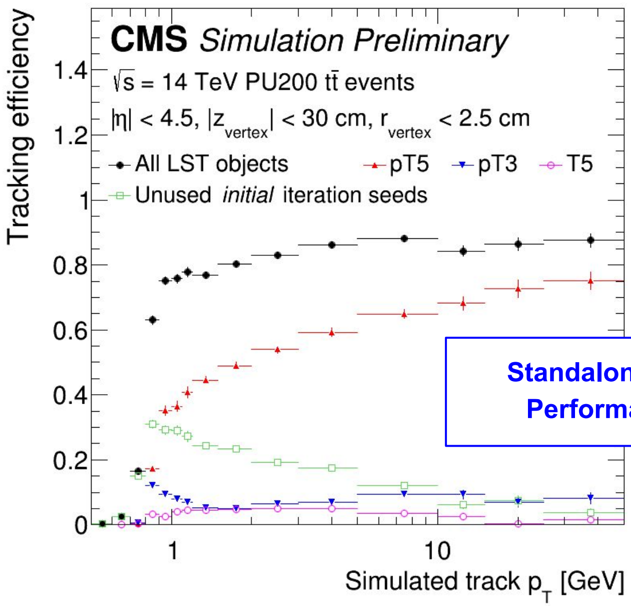
Parameters	Run 3	HL-LHC
Years	2022-2025	≥2029
√s	13.6 TeV	14 TeV
Inst. lumi	2.5 10^{34} Hz/cm^2	7.5 10^{34} Hz/cm^2
Bx rate	40 MHz	40 MHz

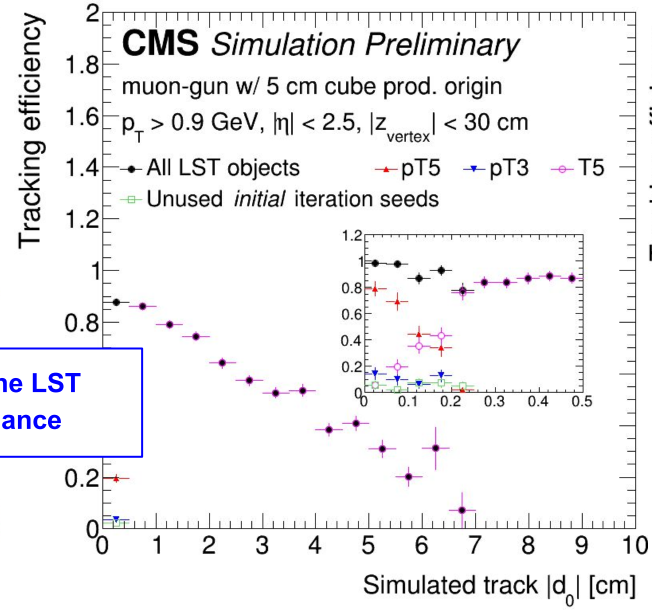


- The modules are arranged in a tilted geometry for the Barrel Layers 1,2,3.

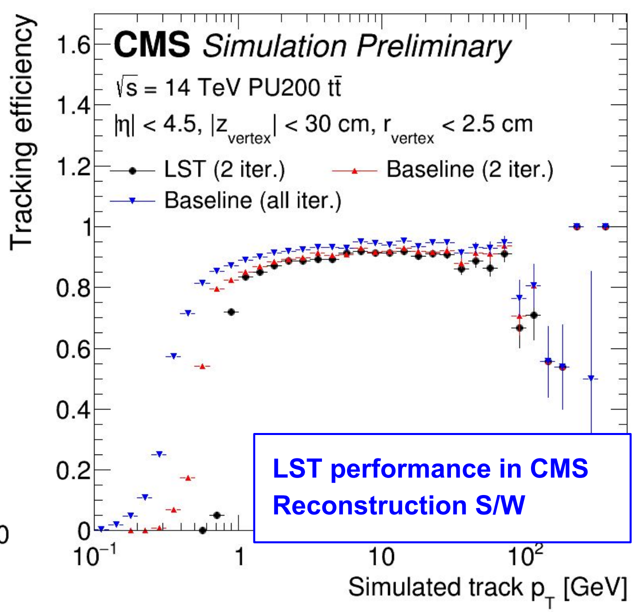
Line Segment Tracking for Phase-2

- The LST algorithm (CMS-DP-2023-019) creates following objects in OT through linking of objects:
  - MiniDoublet (**MD**): linked pair of hits in individual pT modules
  - Line Segments (**LS**): linked pair of MDs in neighboring layers
  - Triplet (**T3**): linked pair of LSs with a common MD
  - Quintuplet (**T5**): linked pair of T3s with a common MD
- Using a subset of inner tracker (IT) pixel seed iterations, (i.e. initial iteration seed, and `highPtTriplet` iteration seed), the LST algorithm creates following objects through linking of OT objects with IT seeds:
  - pixel + Quintuplet (**pT5**): linked pair of a pixel seed and a T5
  - pixel + Triplet (**pT3**): linked pair of a pixel seed and a T3 (both not in a pT5)





Standalone LST Performance



LST performance in CMS Reconstruction S/W

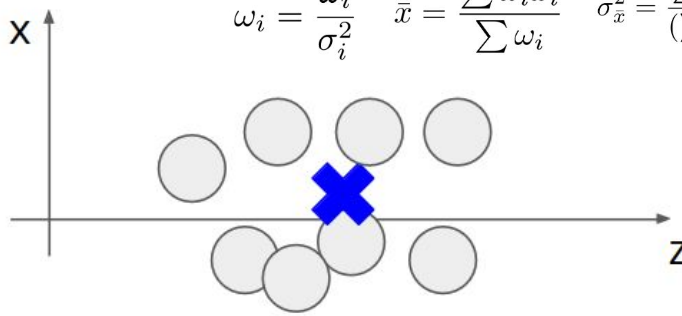
Vertexing on Heterogeneous computing

- In the Phase-2 environment both steps (clustering and fitting) in vertexing involve computations across ~1000s of tracks and ~100s of vertices.
- The legacy algorithms scale baldy.
  - Proposal to redesign them in order to fit better in a heterogeneous computing environment.
- The new clustering procedure sorts the tracks in the z coordinate, splits them in blocks of same size (set by default to 512) with a fixed overlap fraction between blocks (set by default to 0.5) and performs independently the DA along all the blocks.

- The new estimator iteratively estimates the vertex 3D coordinates and errors using the weighted mean of tracks impact point at the beamspot position and uncertainty. The iterations include an outlier rejection to improve the performance.

$$t_{i,x}^2 = \frac{(x_i - \bar{x})^2}{(\sigma_{i,x}^2 + \sigma_{\bar{x}}^2)} \quad \text{If } \forall j \ \ t_{i,j} < 3 \rightarrow \tilde{\omega_i} = 1 \quad \text{Else } \tilde{\omega_i} = 0$$

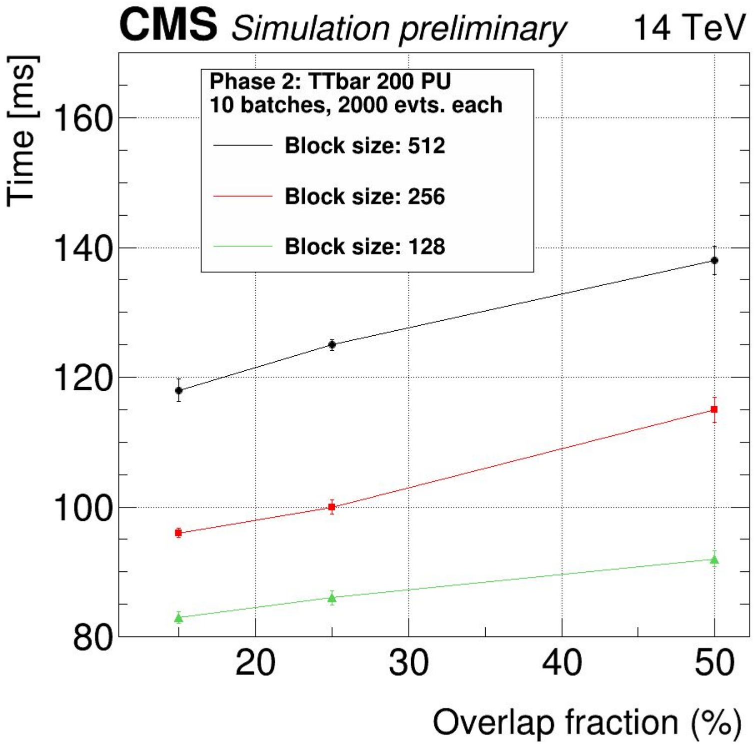
$$\omega_i = \frac{\tilde{\omega_i}}{\sigma_i^2} \qquad \bar{x} = \frac{\sum \omega_i x_i}{\sum \omega_i} \qquad \sigma_{\bar{x}}^2 = \frac{\sum \omega_i \tilde{\omega_i}}{(\sum \omega_i)^2}$$



Timing performance of new vertexing

- Performance increases already in the CPU due to the decrease in the complexity of the algorithm as we dramatically decrease the number of track-vertex association needed:

$$p_{ij}^{(n)} = \frac{e^{-\beta\left(\frac{z_i - z_k^{(n-1)}}{\sigma_i^2}\right)^2}}{\sum_{l=1}^{K} e^{-\beta\left(\frac{z_i - z_l^{(n-1)}}{\sigma_i^2}\right)^2}}$$



- Single block:
  - ~200 vertices x ~10000 tracks => 2×10^6 P_{ii} values.

- 512 track block:
  - split the 10000 tracks in 40 overlapping blocks. 40 blocks x 10 vertices x 500 tracks => 2×10^5 P_{ij} values;
    - Effectively we are transforming the problem of clustering at <PU> ~ 200 into 40 overlapping problems of clustering at <PU> ~ 10.

Conclusions & Outlook

- Tracking algorithms need to provide high-quality tracks efficiently and with an efficient usage of resources:
  - high tracking and vertexing performance in Run 3 (despite challenging conditions at the LHC);
- In order to provide more precise and accurate track reconstruction sophisticated algorithms, techniques and calibrations have been developed.
- Run 3 developments include:
  - Speed-up in the track building (`mkFit`);
  - Improve the track selection algorithm (DNN);
  - improvements at tracking at trigger level (on GPUs);
  - Monitoring of Data performance vs MC as well as online reconstruction vs offline reconstruction.
- The HL-LHC will provide unprecedented challenges in terms of track and vertex reconstruction
  - this open up a rich playground for future developments in both hardware and machine learning based tracking.
  - Two promising developments have been shown

Thanks for the attention!

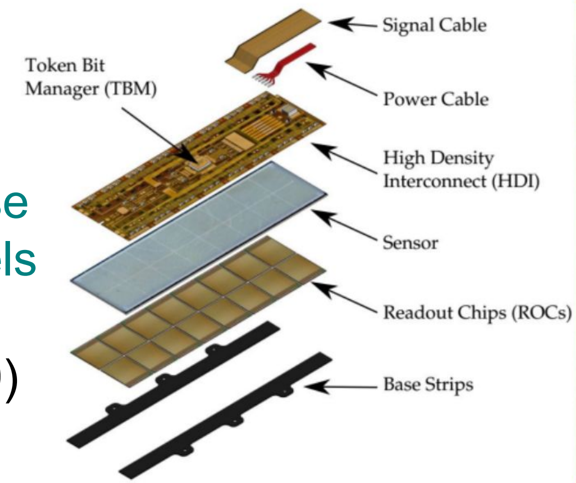
Resources

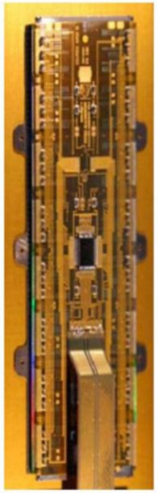
- Performance of Run-3 HLT Track Reconstruction (CMS DP-2022/014)
- Performance of Run 3 track reconstruction with the mkFit algorithm (CMS DP-2022/018)
- Primary Vertex Reconstruction for Heterogeneous Architecture at CMS (CMS DP-2022/052)
- Early Run-3 data/MC comparison to study CMS Tracking Performance (CMS DP-2022/064)
- Performance of the track selection DNN in Run 3 (CMS DP-2023/009)
- Performance of Line Segment Tracking algorithm at HL-LHC (CMS DP-2023/019)
- Performance of Track Reconstruction at the CMS High-Level Trigger in 2022 data (CMS DP-2023/028)

BACKUP

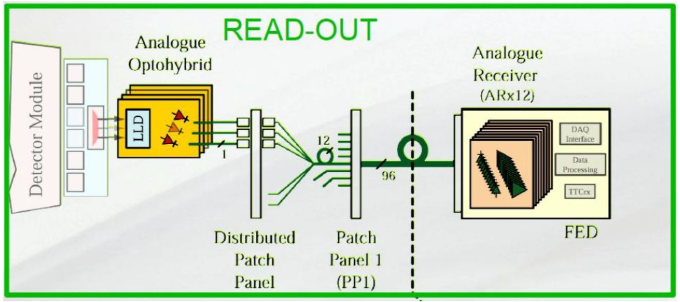
CMS Silicon Tracker: modules anatomy

- Silicon Pixel modules (Phase-1 detector):
  - $100\times150\times280\ \mu m^3$ n-in-n pixel cells used everywhere in the detector;
  - Readout Chip (ROC): 250nm CMS ASIC pulse height read-out, reads matrices of 52x80 pixels
  - Two chips employed:
    - **PSI46dig** (same architecture as Phase 0) digital readout and double column drain;
    - **PROC600** (dedicated for BPix Layer 1) dynamic cluster drain;

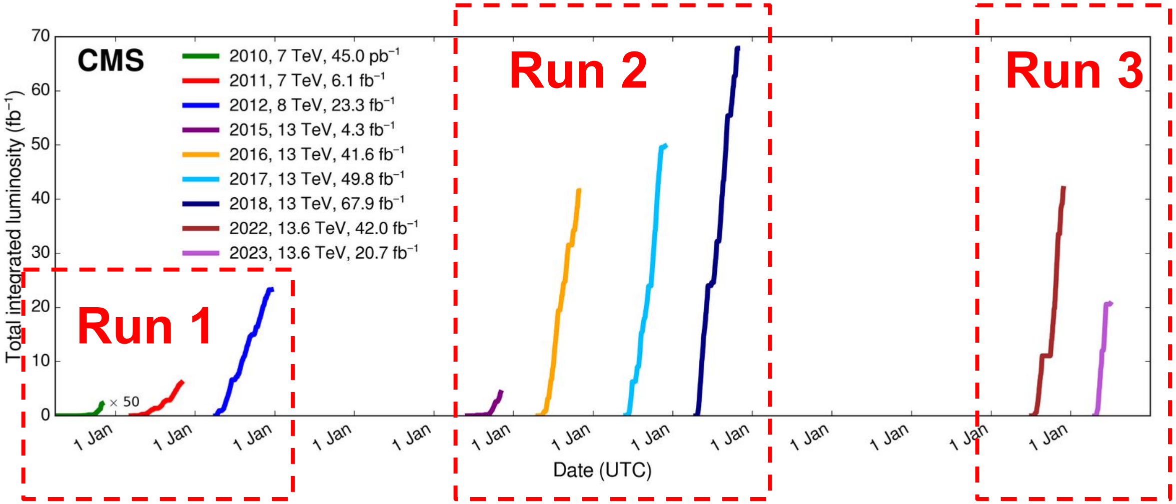


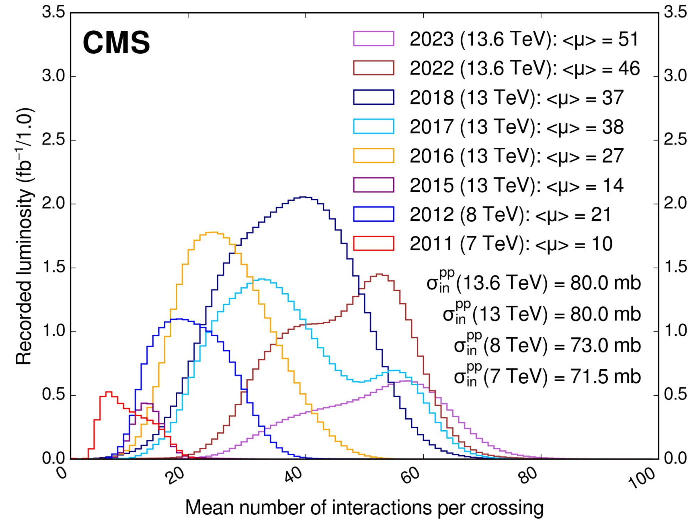


- Silicon Strip modules:
  - 320 µm Si in inner layers (TIB, TID and inner TEC rings 1-4);
  - 500 µm Si in outer layers (TOB, TEC ring 5-7) → two silicon wafers daisy-chained.
  - Analog readout with **APV25** chip.
    - Each chip reads out 128 channels.
    - Tracker module have 4 or 6 APV chips.
    - Signal from 2 chips multiplexed to a Laser Driver.

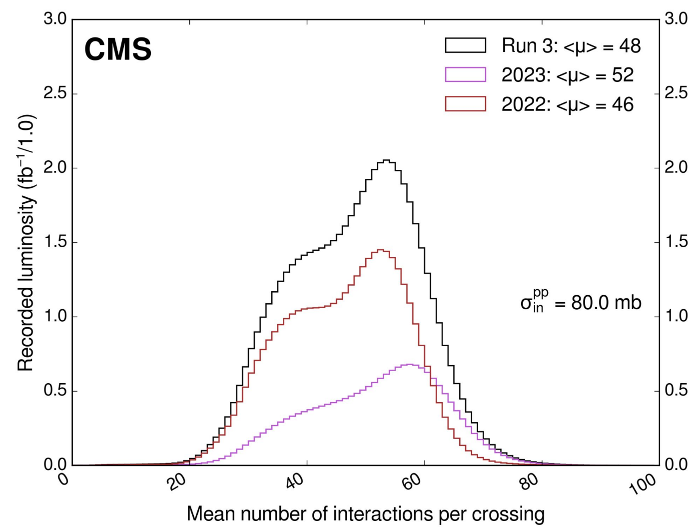


CMS Data Taking so far





- Luminosity delivered to CMS by the end of Run 2 is ~192 fb^{-1}.
- Luminosity delivered to CMS as of today during Run 3 is ~61 fb^{-1}.
  - LHC is expected to deliver around 250fb^{-1}
- Average number of pp interactions per crossing in Run 3 is 48, 52 considering only 2023:
  - Highly irradiated environment, challenging conditions for the tracking detectors.

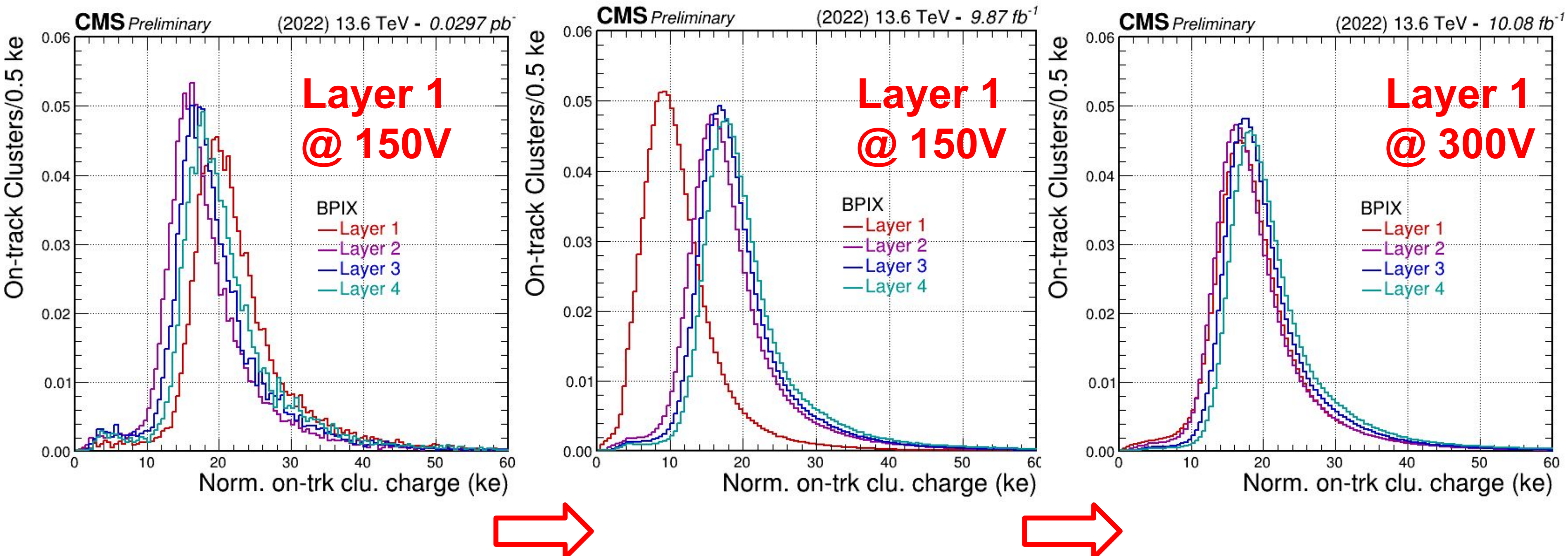


Preparation for Run 3 data-taking

- New Pixel Layer 1 installed in already in 2021:
  - Able to be operated up to 800 V compared to 600 V during Run 2
  - Enhanced front-end ASICs to improve efficiency and increase resistance against single-event upsets;
- Degradation of performance due to irradiation is expected nonetheless:
  - Especially in BPix Layer 1 due to its proximity to the LHC luminous region (29mm from the beam line);
  - Degradation visible in Pixel Hit Efficiency and Strip Signal-to-Noise ratio;
  - Effects of radiation are closely monitored, and measures are taken to mitigate the degradation;
- Routine bias voltage scans and increase of bias voltage when needed, along with routine calibrations for Pixel:
  - Adjusting temperature and bias voltage of the Strips to mitigate leakage currents;
  - Beneficial annealing during no-beam periods help improve performance;
- Improvements in online automated alignment procedure from 36 (low granularity) to ~5k parameters (high granularity) prompt calibration loop.

Radiation damage in BPix Layer 1

- Strong effect of radiation damage observed in cluster properties at the beginning of Run-3 when new layer 1 sensor were not yet conditioned.

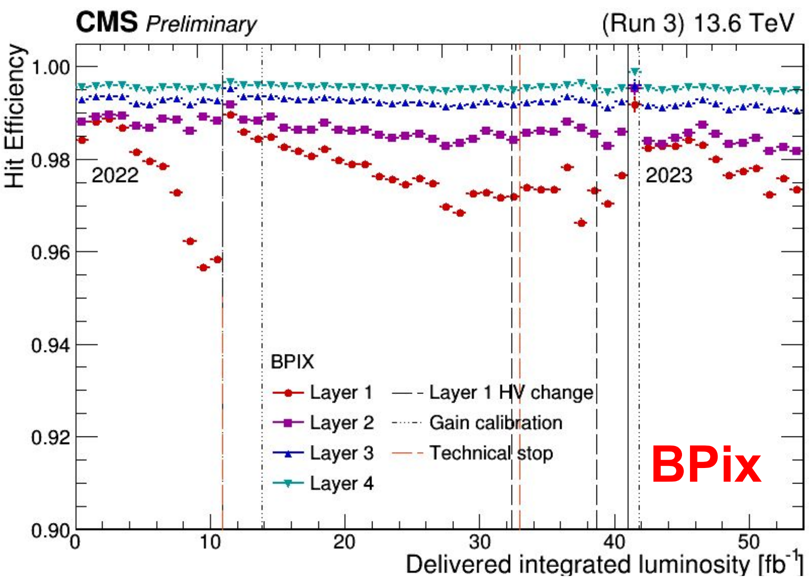


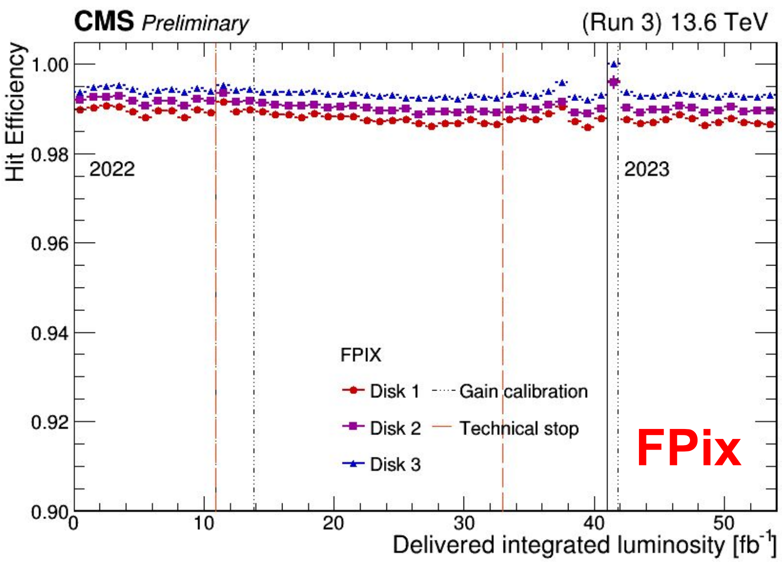
Layer 1 fully replaced during LS2, started with no radiation damage, i.e. higher cluster charges.

Large charge efficiency loss due to radiation damage observed within first 10 fb^{-1}.

Recovered by raising bias voltage from 150V to 300V.

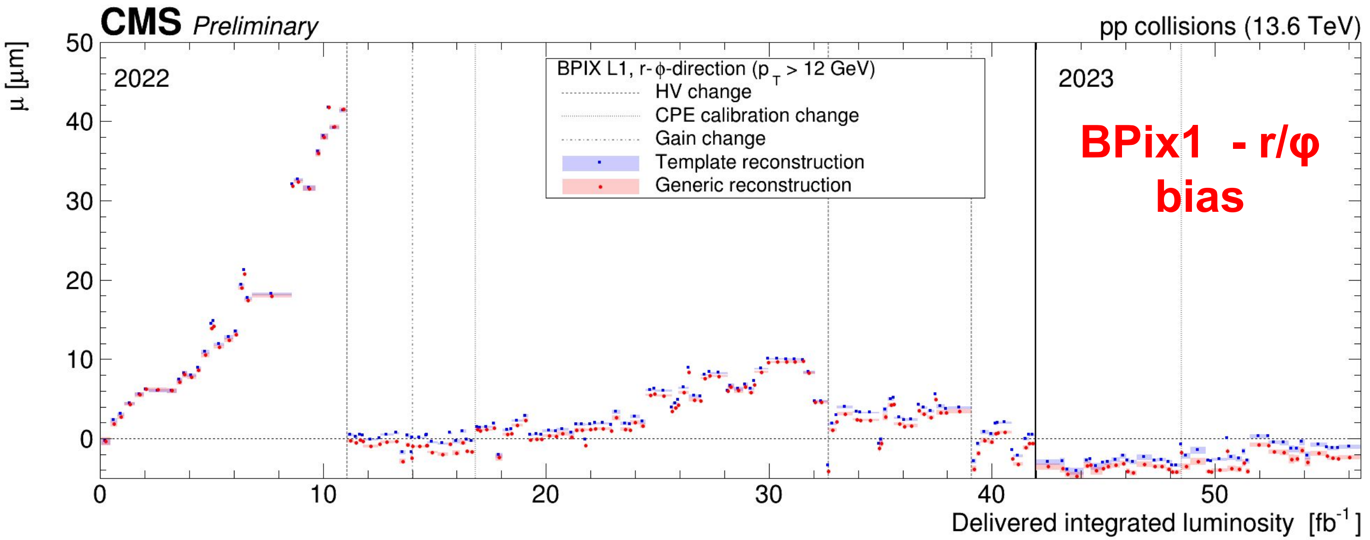
Pixel detector: evolution of hit efficiency

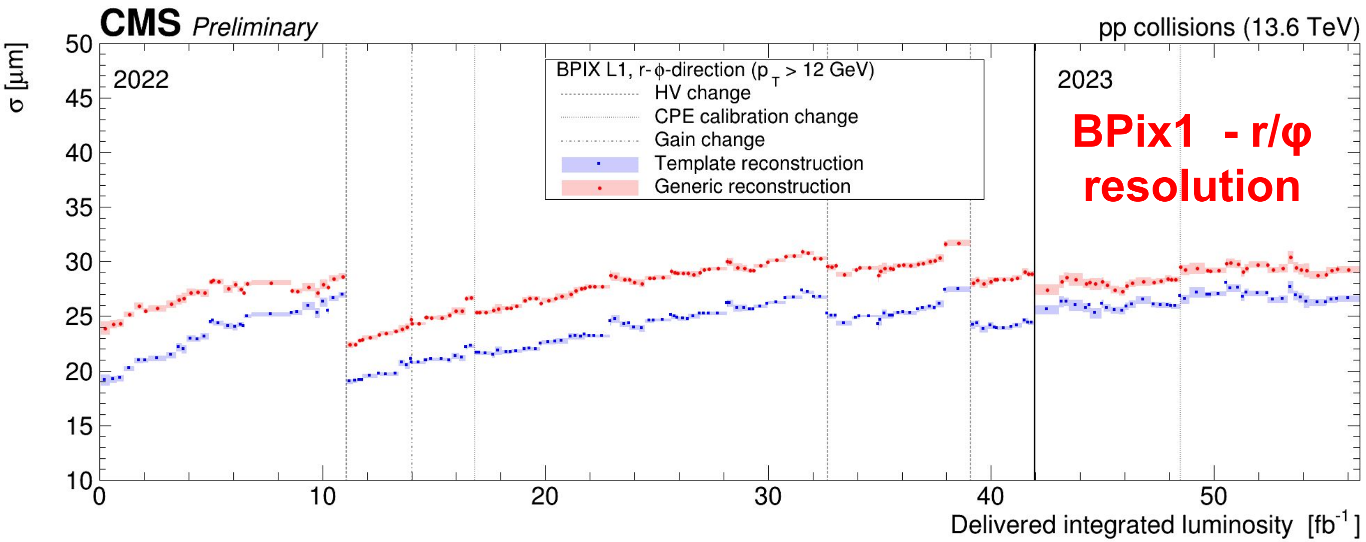




- Hit efficiency is defined as the probability to find any cluster within a 1mm window around an expected hit, independently of the cluster quality
  - Measured using muon tracks trajectories with p_T > 2 GeV
  - Bad components of the pixel detector are excluded from the measurement
- In BPix observed strong trend in hit efficiency loss in the first 10 fb^{-1} of Run 3 data-taking
  - Recovered after raising HV to 150V;
  - Further degradation until next raise in HV (to 450V);
  - Relatively stable in 2023;
- In FPix hit efficiency is stably above 98% with a very gentle slope as a function of integrated luminosity

Pixel detector: Layer 1 hit resolution





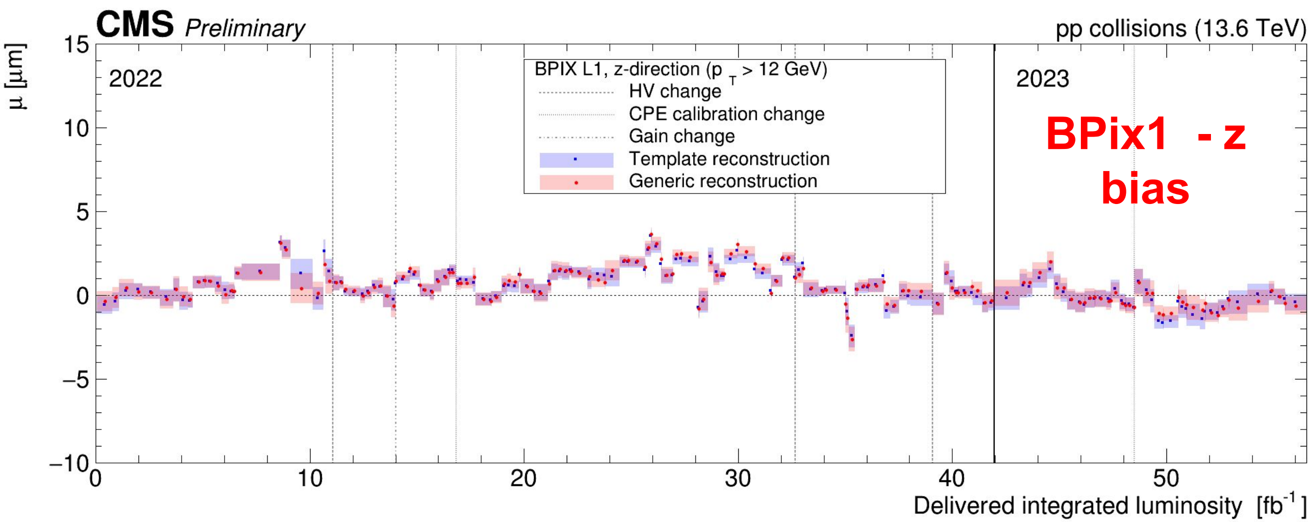
Integrated delivered luminosity since the beginning of Run 3 until the data-taking run used to produce the figures is indicated.

A strong increase of the bias is observed in the first 10 fb^{-1} while it is relatively stable in the rest of the data-taking.

Resolutions have been slightly increasing with time:

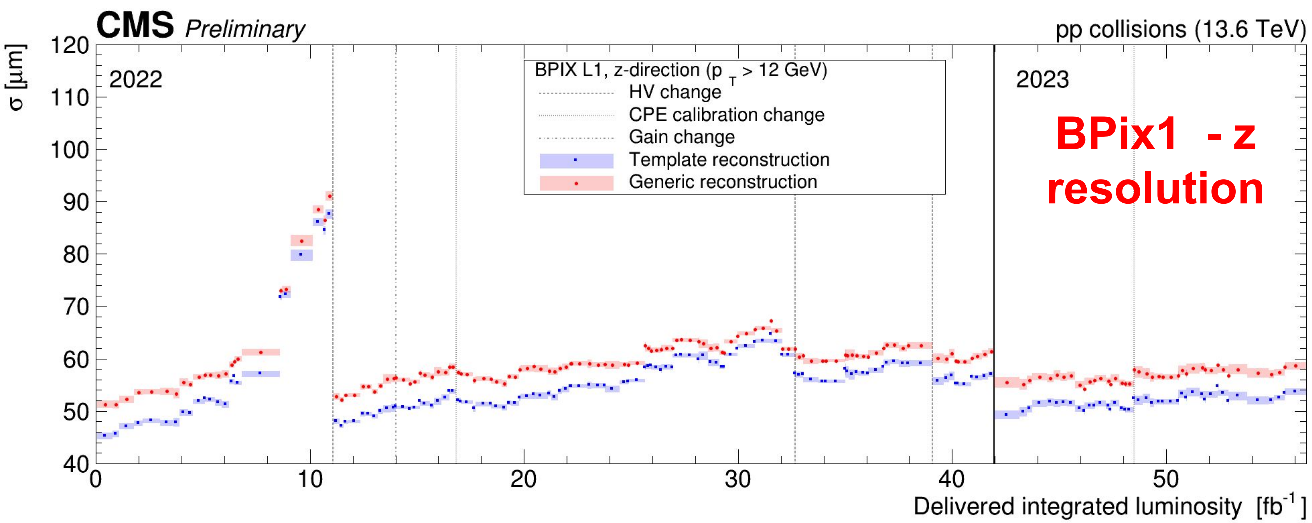
- The performance of the Template algorithm better than the Generic algorithm.

Barrel Pixel Layer 1 hit resolution



Integrated delivered luminosity since the beginning of Run 3 until the data-taking run used to produce the figures is indicated;

Bias is stable throughout Run 3.

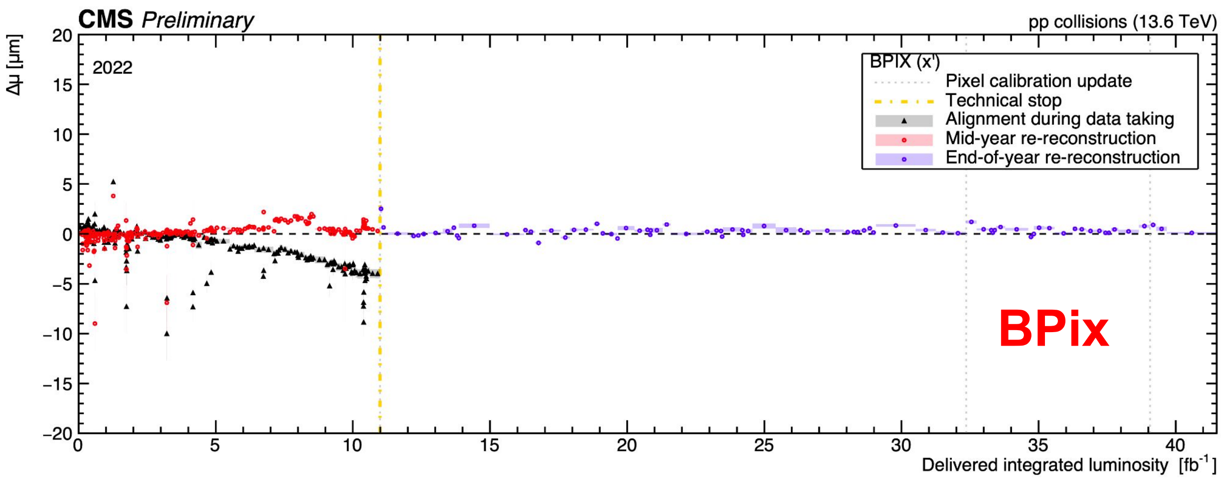


A strong increase of the resolution along z is observed in the first 10 fb^{-1} (related to cluster breakage) while it is relatively stable in the rest of the data-taking:

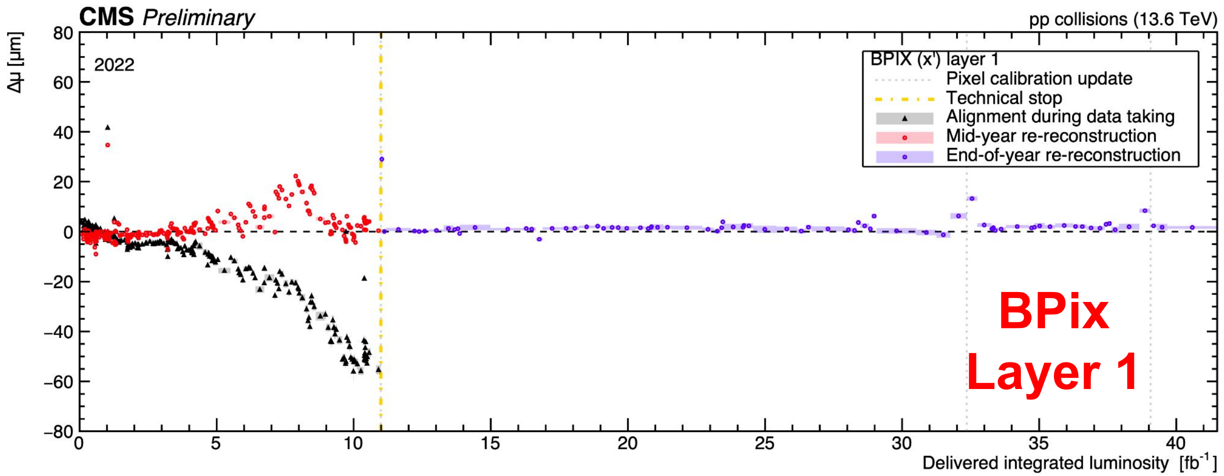
- The performance of the Template algorithm better than the Generic algorithm.

Tracker Alignment: monitoring of performance

- Online alignment with LG PCL at the beginning of data taking (black) and offline alignment after reprocessing (red)
  - Deviation from zero → Shift on LA → indication of radiation damage



- Online HG PCL corrects position bias developed during data-taking and uncorrected by local reconstruction.



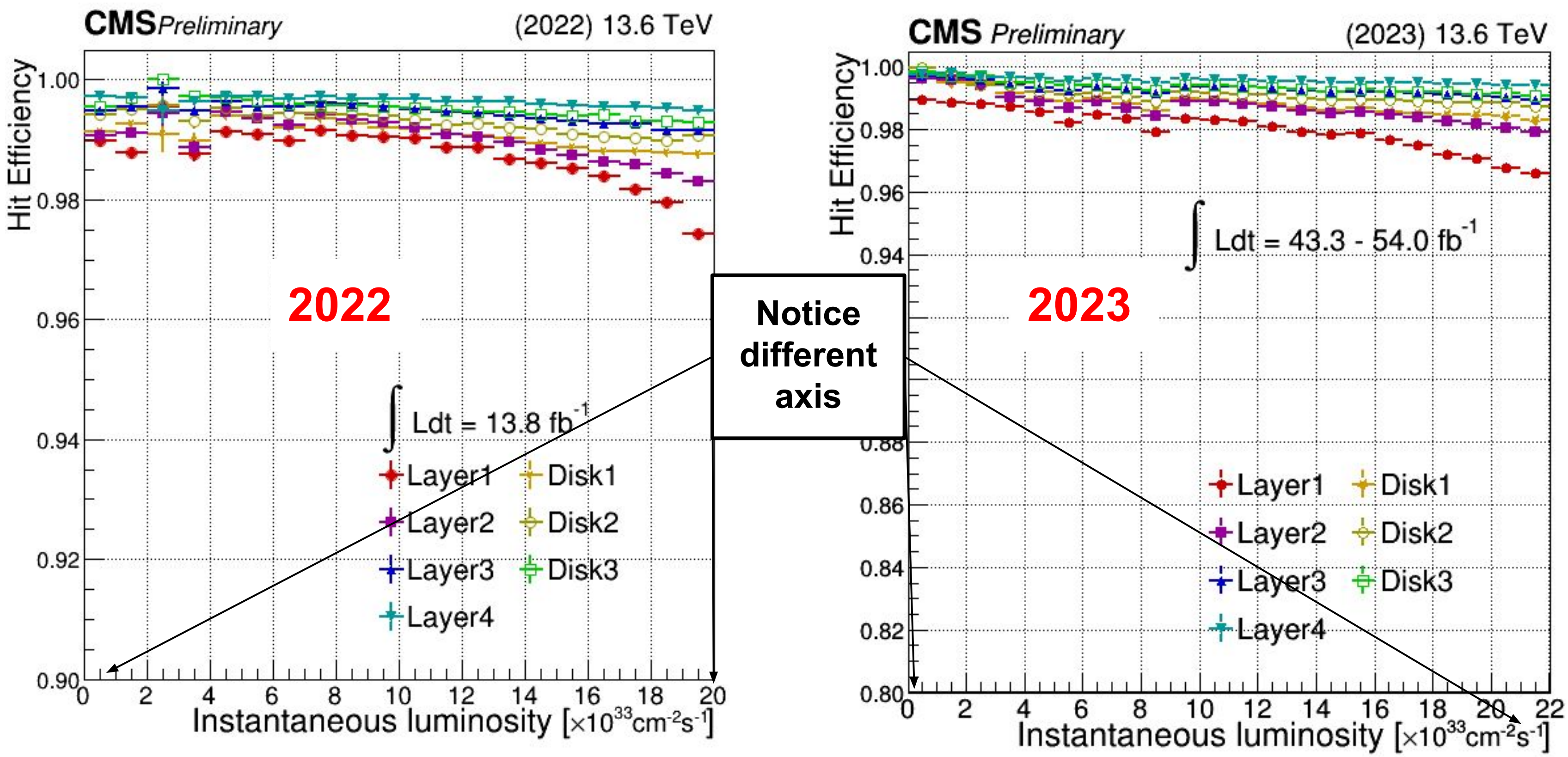
- BPIX layer 1 more affected since it's closer to the interaction point (notice different scale!).

Resources

- CMS Pixel Detector Performance in 2022: CMS-DP-2022-067
- CMS Silicon Strip Tracker Performance Results in 2022: CMS-DP-2023-030
- CMS Tracker Alignment Performance in 2022: CMS DP-2022/044, CMS-DP-2022/070
- CMS Pixel Detector Performance in 2023: CMS DP-2023/041
- CMS Silicon Strip Tracker Performance Results in early 2023:
- CMS Tracker Alignment Performance in 2023: CMS DP-2023/039

Pixel Efficiency vs Inst. Luminosity

- Hit efficiency is the probability to find any cluster within 1 mm around an expected hit independent of the cluster quality:
  - Measured using muon tracks with p_T > 2 GeV;
  - Bad components of the pixel detector are excluded from the measurement;



HV Bias Scans in Pixel Layer 1

- Four mini bias voltage scans performed in 2023 along with five scans taken in 2022 are shown at various integrated luminosities:
  - The effect of radiation damage is visible in the shift of the plateau in different scans.
  - The complex evolution of the hit efficiencies with irradiation is understood to come from multiple effects some of which are the inversion of the charge carrier type in the silicon sensor and the annealing during the periods with no data-taking.
- The trend change with bias voltage of the cluster size in x direction comes from two competing effect
  - Increase of bias voltage helps the charge collection, but also reduces the charge sharing between pixel
  - The former increases while the latter decreases the cluster size
- Operating voltage in Layer 1 at the startup was 150 V. After the second scan, it was increased to 300 V, later after 31.8 fb^{-1} scan it was increased to 350 V. In 2023 scans the operating voltage was 400 V.