Performance highlights in CMS

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on behalf of the CMS collaboration

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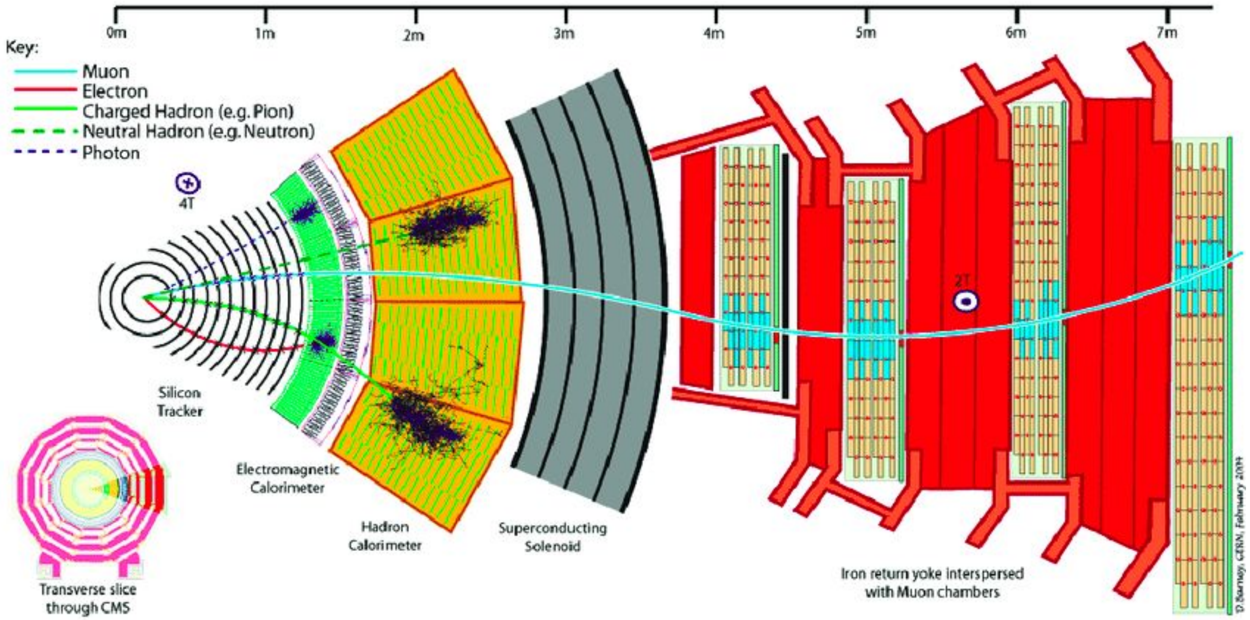
Introduction

- The CMS experiment;
- CMS data-taking so far;
- Subsystem performances:
  - Silicon Tracker performance
  - Tracking performance
  - Flavour-tagging performance
  - ECAL calorimeter performance
  - Muon reconstruction performance
- The CMS Trigger system:
  - CMS Trigger performance
- Data compression via partial online processing
- Summary & conclusions

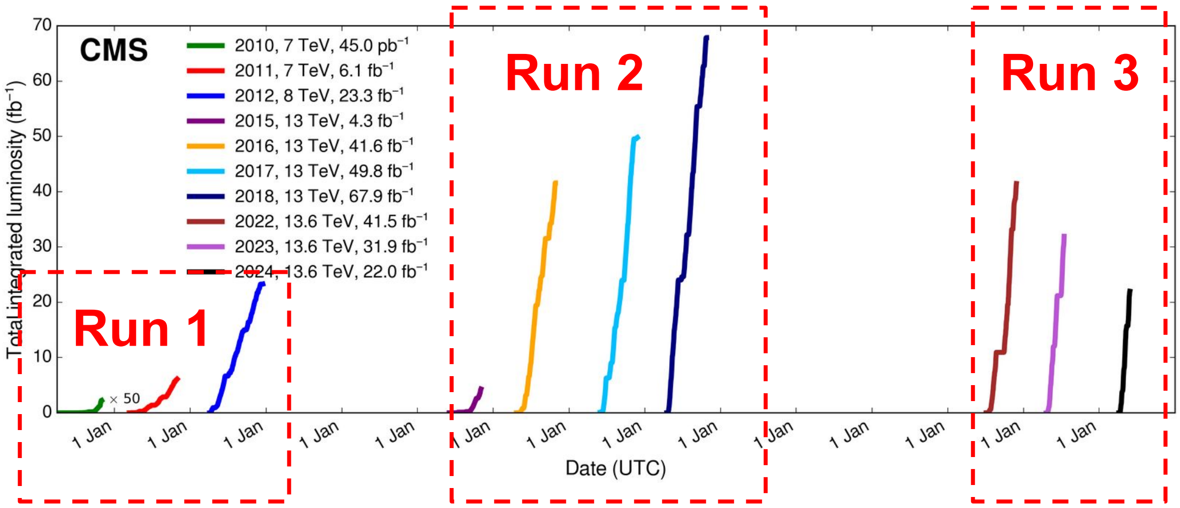
The CMS experiment

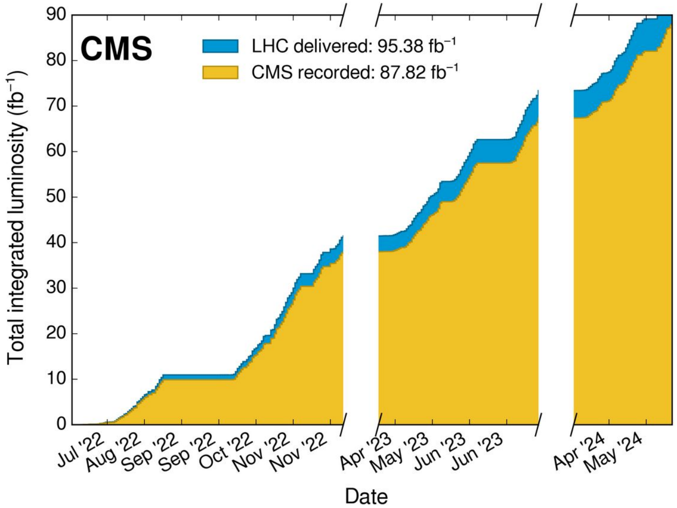
- Event reconstruction via particle flow:
  - Combine information from all sub-detectors:



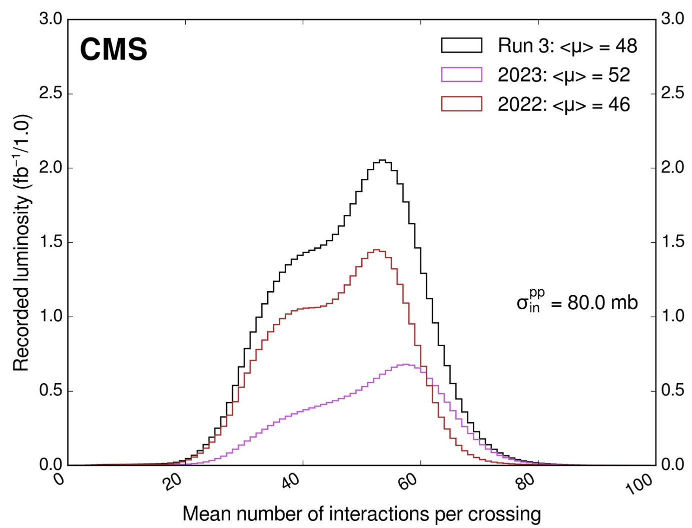
- Challenges for Run 3 data taking:
  - Radiation damage from the past
  - Increasing pileup to > 60
  - Recover - Detector maintenance
  - Upgrade experience: use technological advancements in hardware & software

CMS Data Taking so far



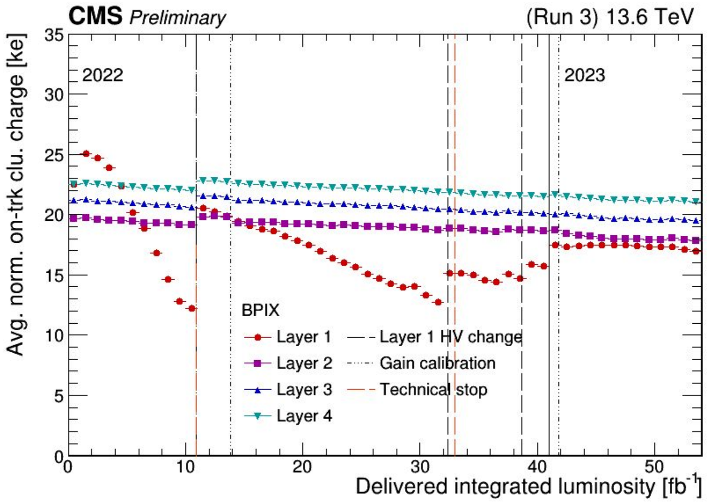


- Luminosity delivered to CMS by the end of Run 2 is **~192 fb^{-1}**.
- Luminosity delivered to CMS as of today during Run 3 is **>95 fb^{-1}**.
  - LHC is expected to deliver around 250fb^{-1}
- Average number of pp interactions per crossing passed from 46 in 2022 > 50 in 2023 and and 2024:
  - Highly irradiated environment, challenging conditions for the detectors and reconstruction algorithms.

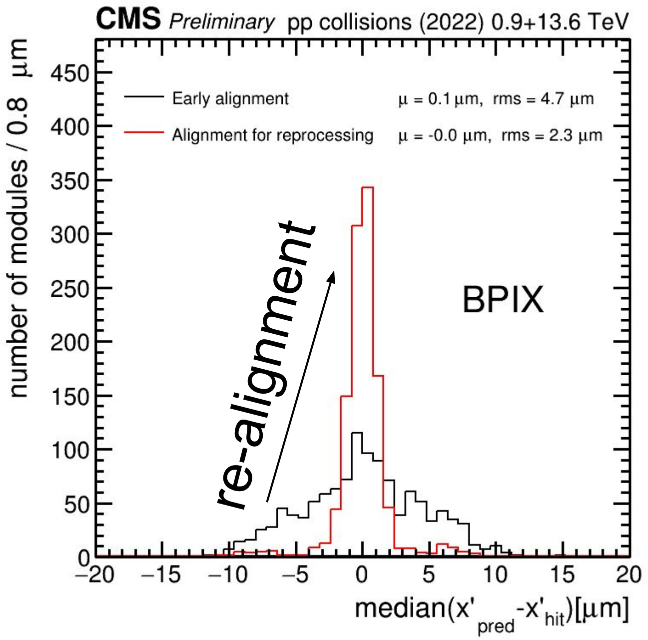


Silicon Tracker Performance

- Pixel Detector performance:
  - Extracted after end of Run 2 for maintenance during LS2;
  - New innermost layer completely new
    - Reinstalled in 2021.
  - Performance in terms of pixel cluster properties closely monitored during data-taking to study evolution of radiation damage;

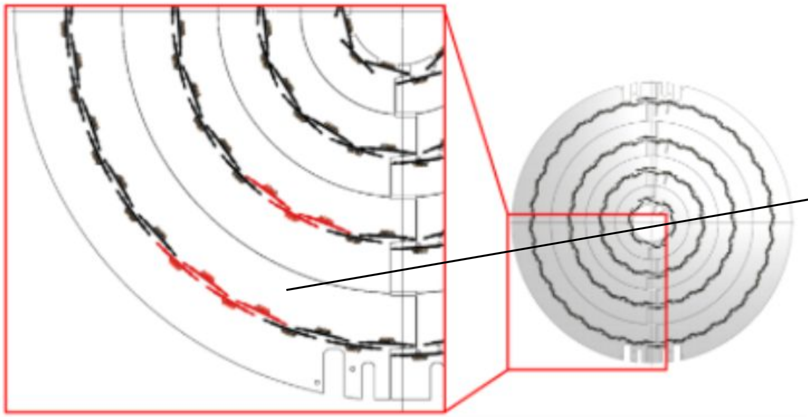


- Incremental detector alignment procedure
  - Early alignment:
    - O(100K) cosmic ray tracks;
    - O(10M) pp collision tracks at 0.9TeV.
  - Alignment for reprocessing:
    - O(10M) cosmic ray tracks;
    - O(150M) pp collision tracks at 13.6TeV.

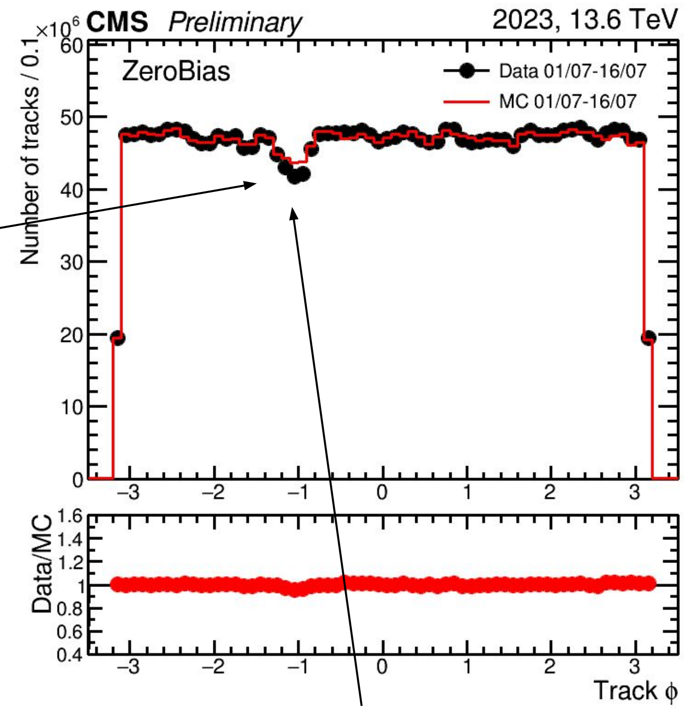


Issue in the Barrel Pixel layer 3 & 4

- After TS1 of 2023 (June 19-24): 27 modules (representing about 1.5 % of the total modules in the pixel detector) in the Barrel Pixel Layers 3 & 4 became inoperable (issue in distributing the LHC clock signals). They cover a sector in φ spanning approximately 0.4 radians (~23 degrees) in at negative pseudorapidity.



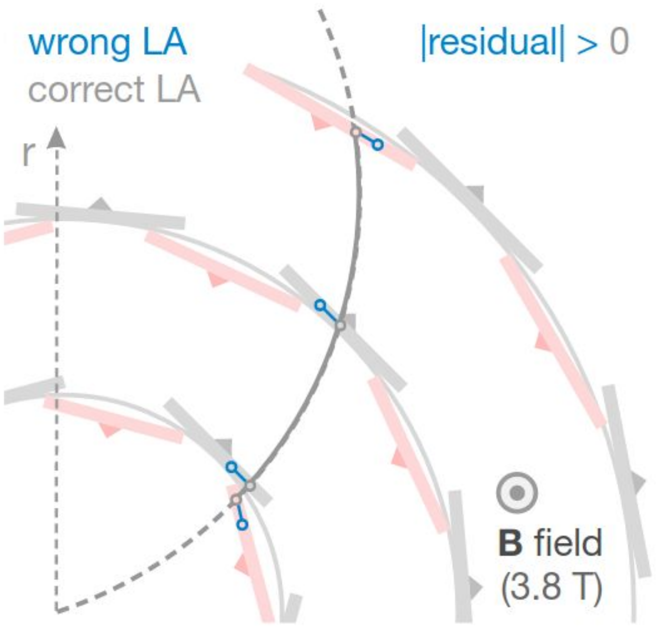
A small region in the detector has reduced efficiency in tracking

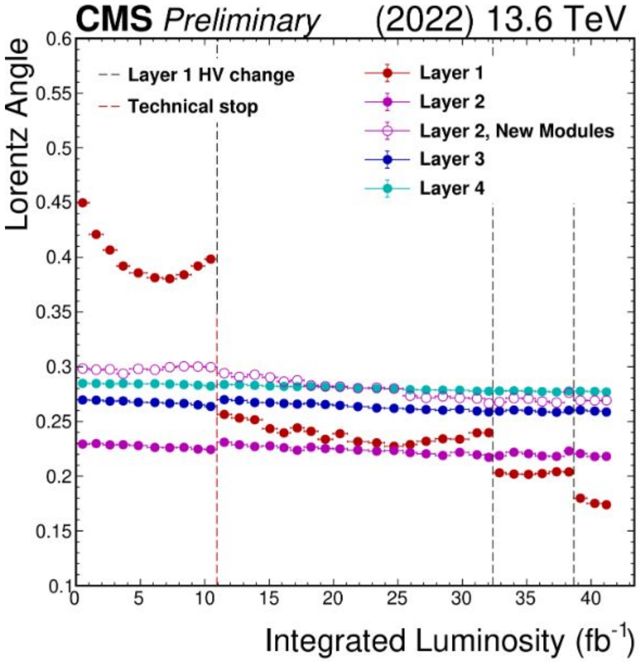


Visible effect in offline tracking reconstruction in data and simulation

Time dependence of Tracker Alignment

- Tracker needs to be realigned frequently due to several source of time variations:
  - Magnet cycles: magnet switch on and off for maintenance reasons →half-barrels and half-disks (O(mm))
  - Temperature variations: cooling operations after switching off and on the detector→ Sensors (10^{-1}mm)
  - Ageing of the modules: change of the Lorentz drift due to high radiation environment → Sensors (few μm)





During the track reconstruction, the Lorentz angle has to be taken into account to properly estimate the hit position:

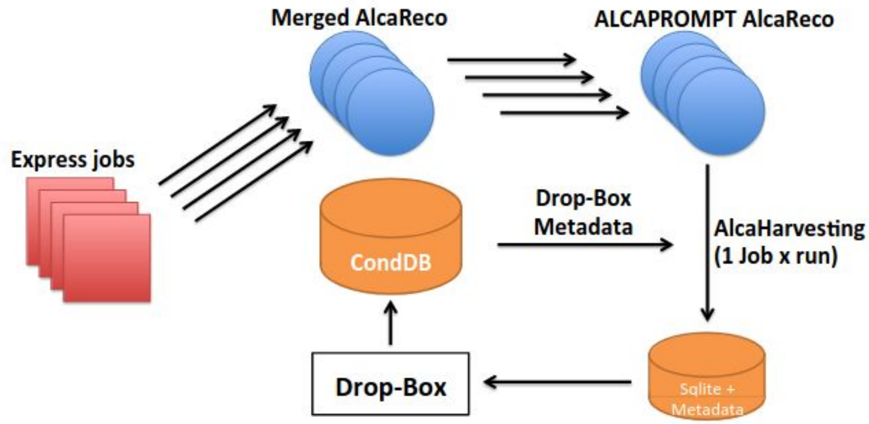
$$\Delta x' \propto \tan\theta_{LA}$$

Evolution of $\tan\theta_{LA}$ directly translates in position bias.

The Prompt Calibration Loop

- To account for shifts in the different components of the pixel detector during data taking:
  - Automated alignment workflow that provides an update of the alignment parameters within 48 hours;
  - Alignment of the pixel while the strip is fixed.

runs @Tier0



In Run 2

Low Granularity Prompt Calibration Loop (**LG PCL**)

Track-based alignment at the level of half barrels and cylinders

36 (6 d.o.f times 6 “alignables”) alignment parameters

In Run 3

High Granularity Prompt Calibration Loop (**HG PCL**)

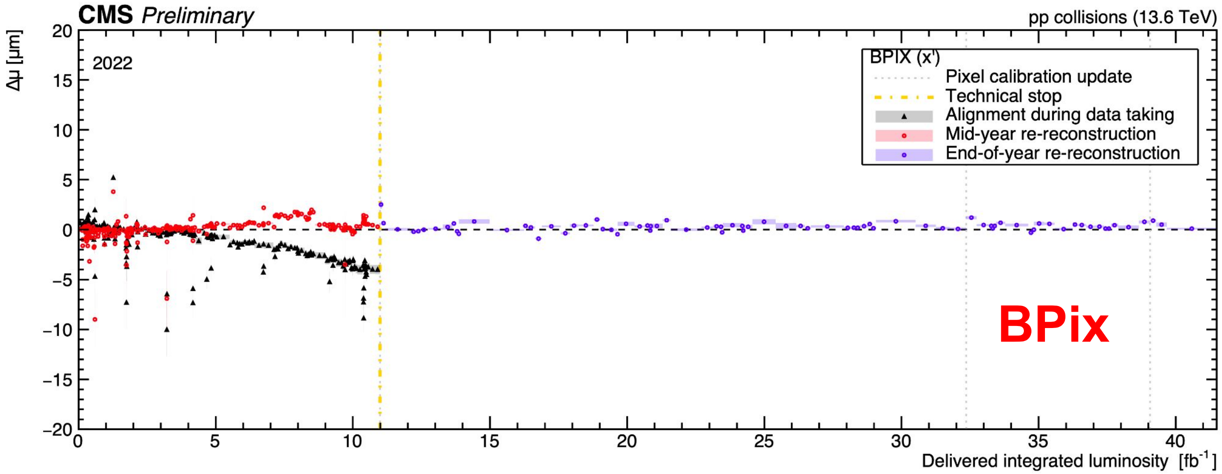
Track-based alignment at the level of ladders and panels

~ 5k alignment parameters

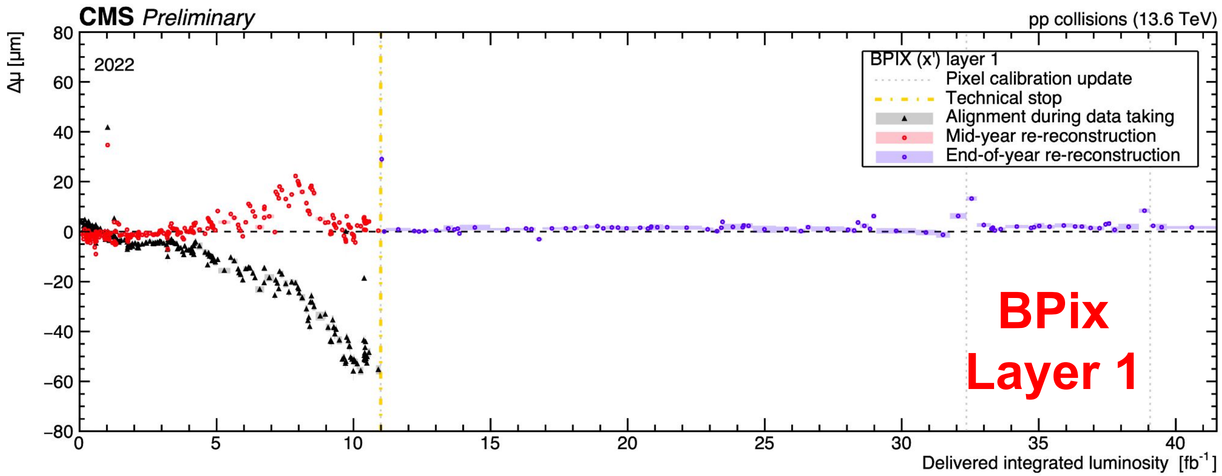
Replace some of the manual HG alignments after newpixel calibrations

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



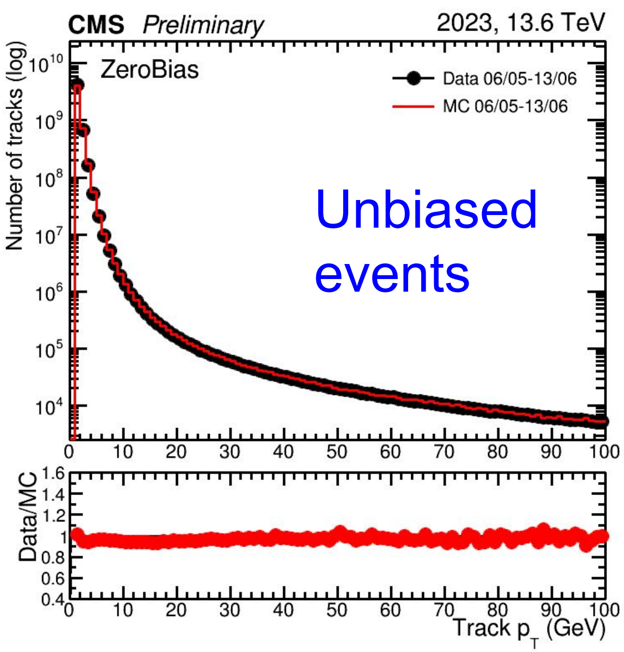
- Online HG PCL corrects position bias developed during data-taking and uncorrected by local reconstruction.

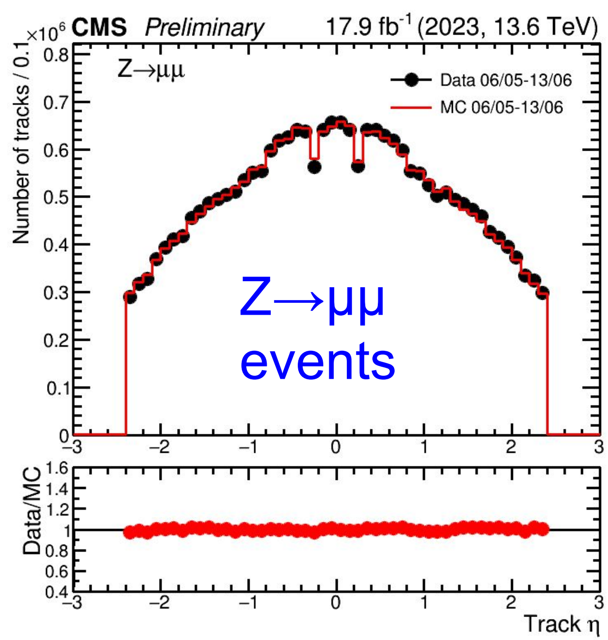


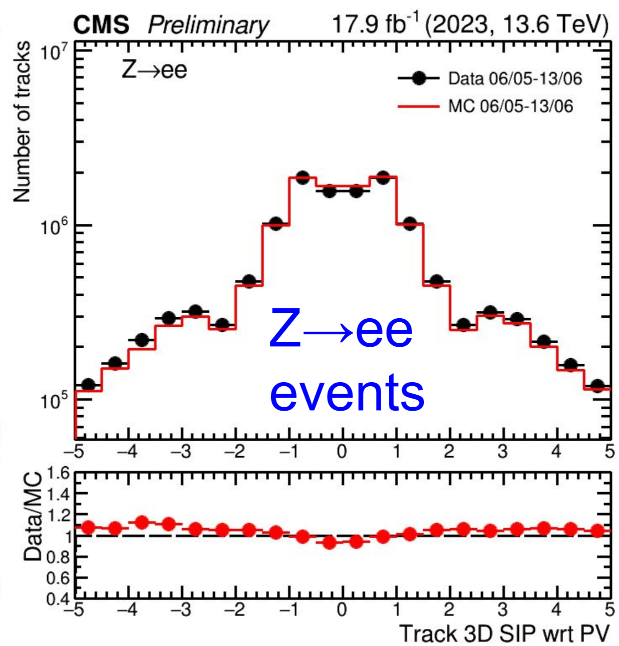
- BPIX layer 1 more affected since it's closer to the interaction point (notice different scale!).

Inner Tracking Performance

- The figures in the following show a comparison between 2023 CMS data and MC of the reconstructed track properties (documented in [CMS-DP-2023-090]).
  - the tracks which are considered are tracks which pass the high purity selection, with p_T>1GeV.
  - MC distributions are normalized to the number of vertices in data.
- Overall and without further corrections a **good agreement** is found between data and simulation on a variety of event topologies.

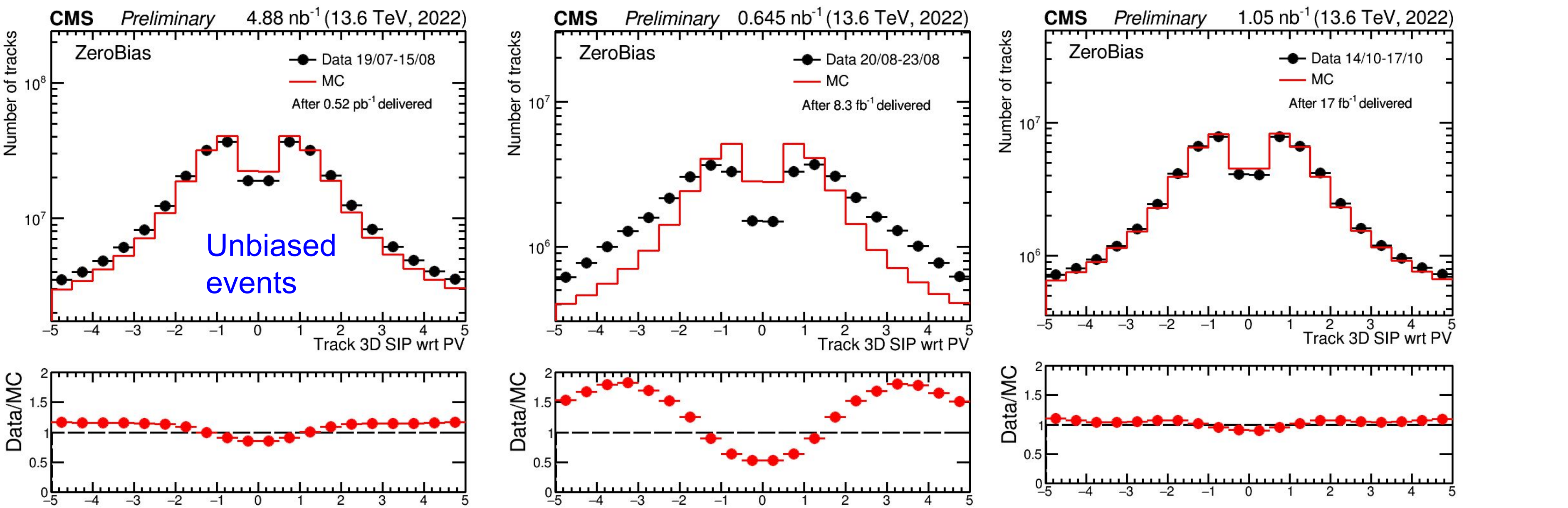






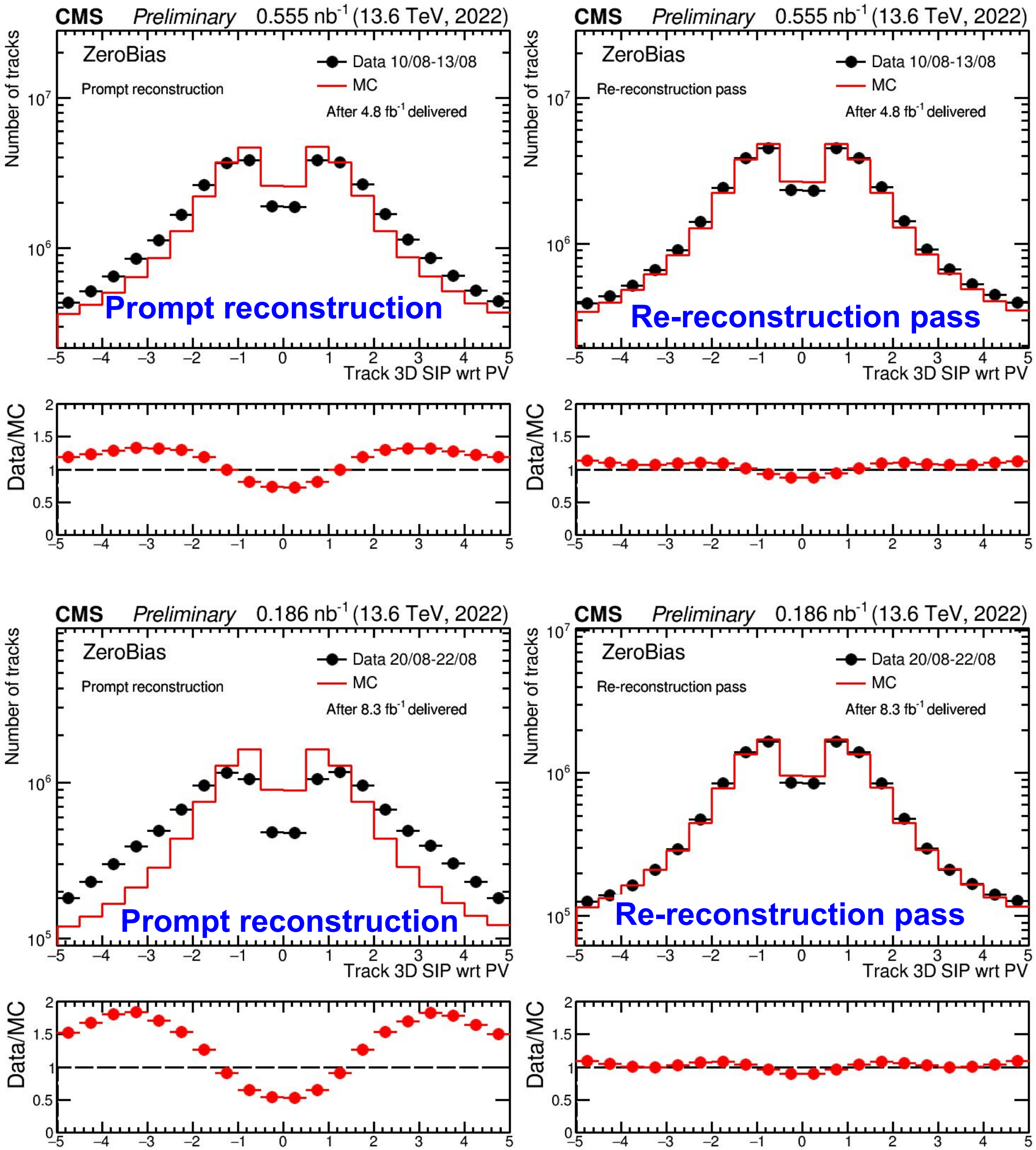
Tracking Performance and radiation damage

[CMS DP-2022/064]



- 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.

Tracking Performance in reprocessed data

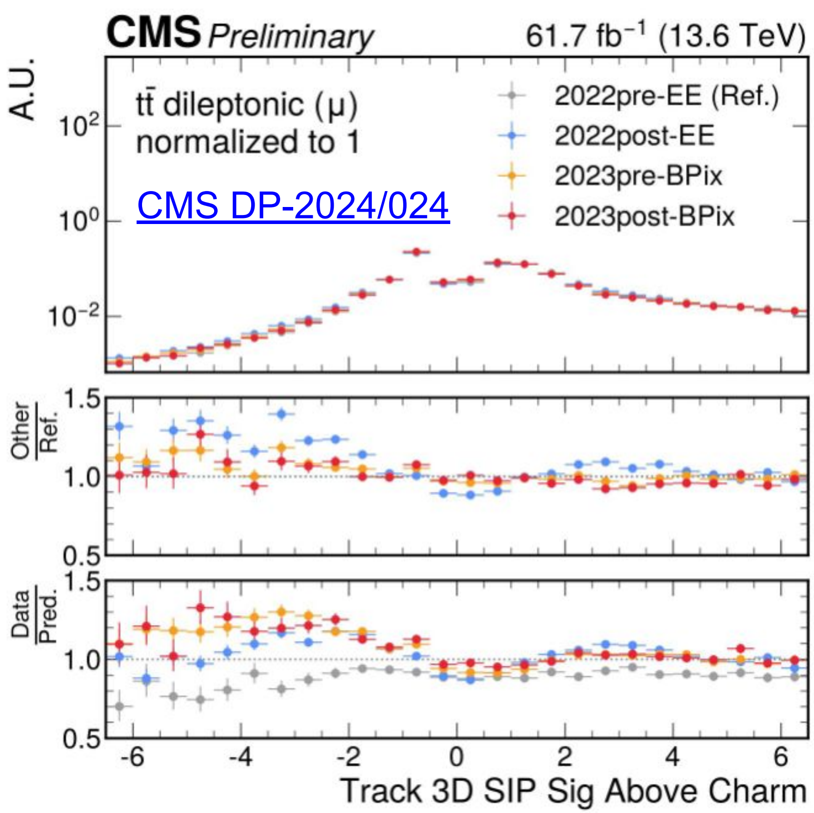


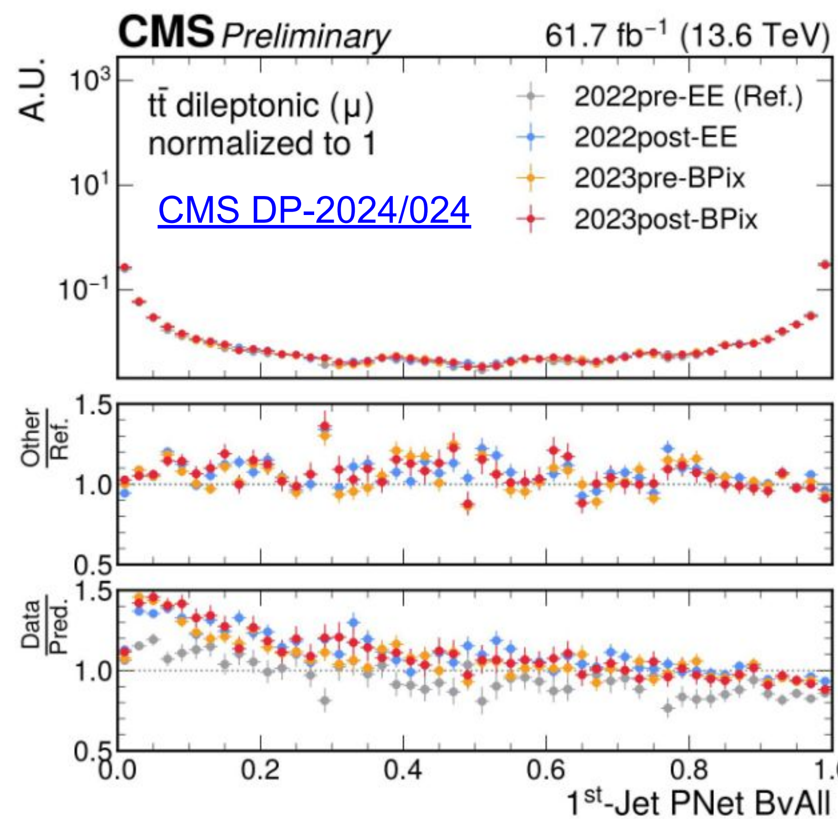
[CMS DP-2022/064]

- 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, .
  - 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.

Flavour tagging performance

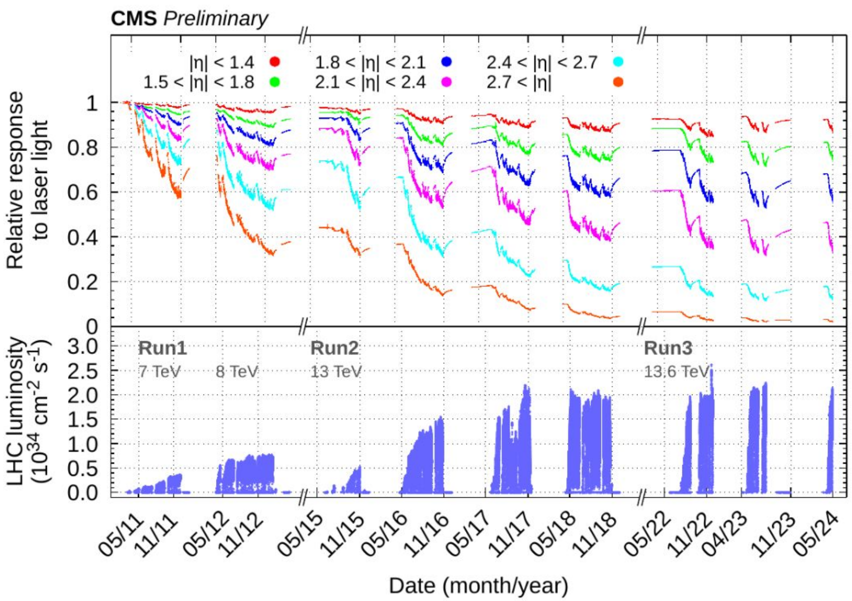
- Track 3D signed impact parameter (SIP) significance (left) and tagger scores (right) in different data-taking periods in the dileptonic $t\bar{t}$ phase space. In the first panel with the distribution normalized to 1 demonstrated as arbitrary unit (A.U.).
  - The second panel assumes the early 2022 period as reference and shows the ratio of other data-taking conditions vs. the reference. The third panel shows the Data and prediction ratios in each individual condition.



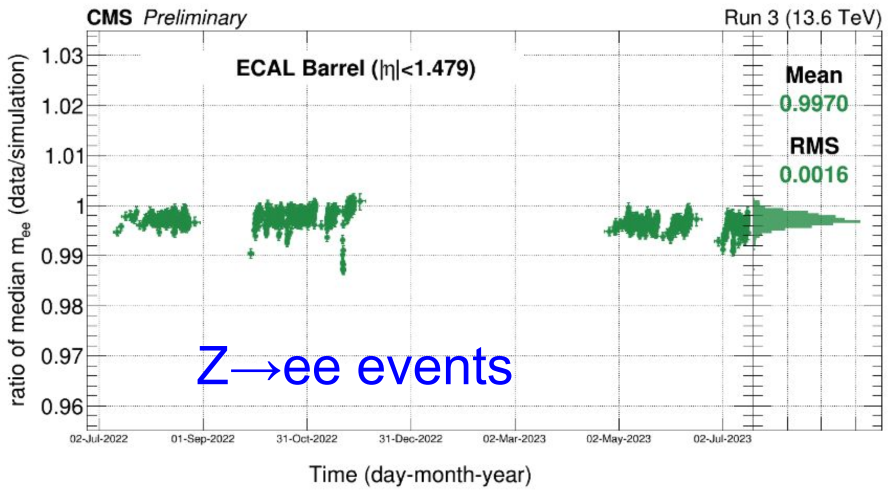


ECAL Calorimeter performance

- Relative response to laser light injected in the ECAL crystals, measured by the ECAL laser monitoring system, averaged over all crystals in bins of η in 2011 through part of 2024 data taking periods, with magnetic field at 3.8 T.
  - The response change observed in the ECAL channels is up to **15% in the barrel** and it reaches up **to 70% at |η| ≈ 2.5**, the limit of the tracker acceptance.
  - The response change **is up to 99% in the region closest to the beam pipe**.
  - The recovery of the crystal response during the periods without collisions is visible.
- Time stability of the di-electron invariant mass comparing between data and simulation for the 2022 and 2023 data-taking period using Z→ee events:
  - The plot shows the time stability of the di-electron invariant mass median ratio of data and simulation for the 2022 and 2023 datasets.
  - Both electrons are required to be in the ECAL Barrel.



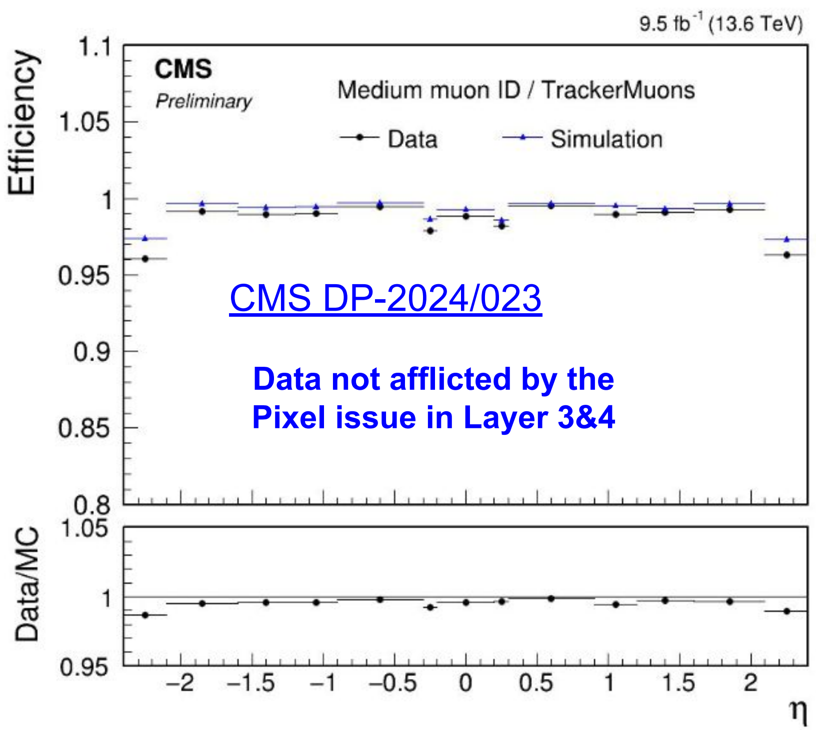
[CMS DP-2024/022]

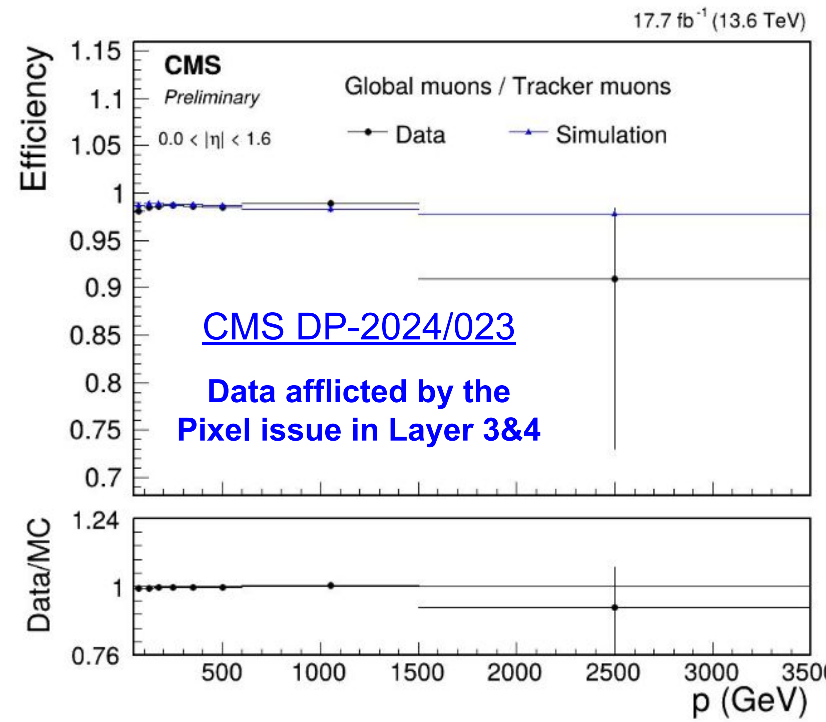


Muon reconstruction performance

- The muon ID and Isolation efficiencies are estimated by applying a tag-and-probe technique to muons from J/ψ and Z decays.
  - The selection of the tag and probe muons are optimized for three different transverse momentum regions: low p_T (<30 GeV) muons from the J/ψ decays, medium p_T (15 - 200 GeV) from Z decays, and high p_T (>200 GeV) from high-mass Drell-Yan

- Efficiency for **high- p_T muons** is estimated by applying a cut-and-count tag-and-probe technique to muons from Drell-Yan events with mass above 70 GeV.
  - Cuts are added to ensure muons originate from the same vertex, cosmics are rejected.

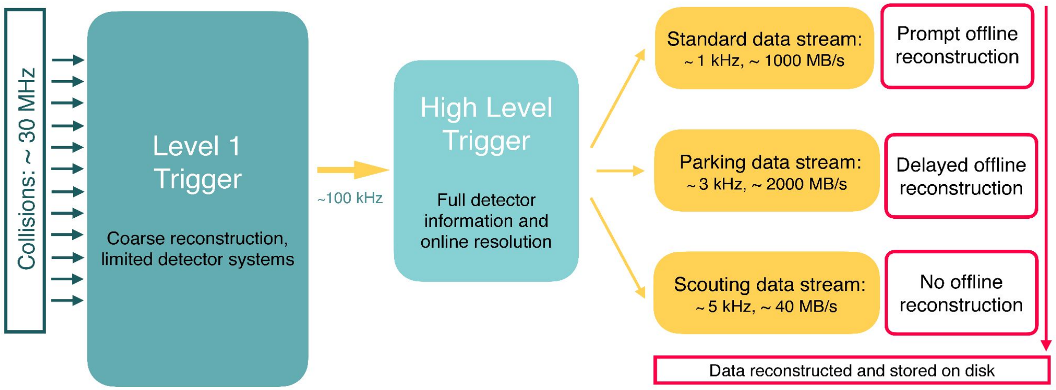




CMS Trigger System

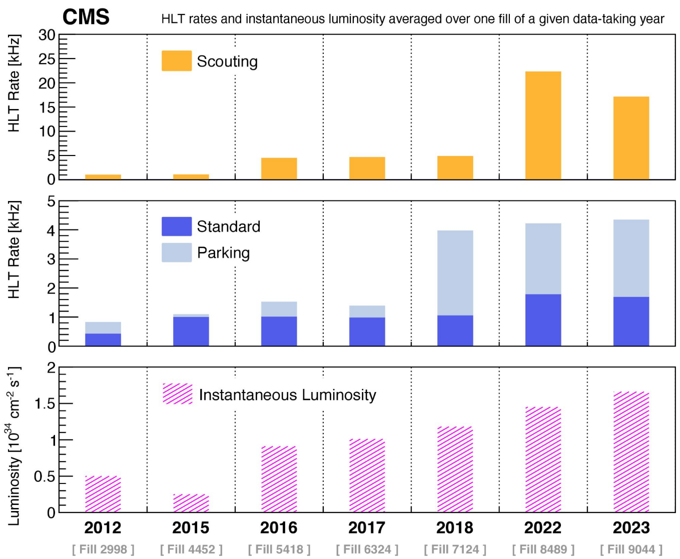
- LHC collision rate at 40 MHz:
  - Two tiered trigger system to filter events
  - Level 1 (LV1): custom electronics

Data flow for typical CMS data-taking scenario



CMS DP-2024/022

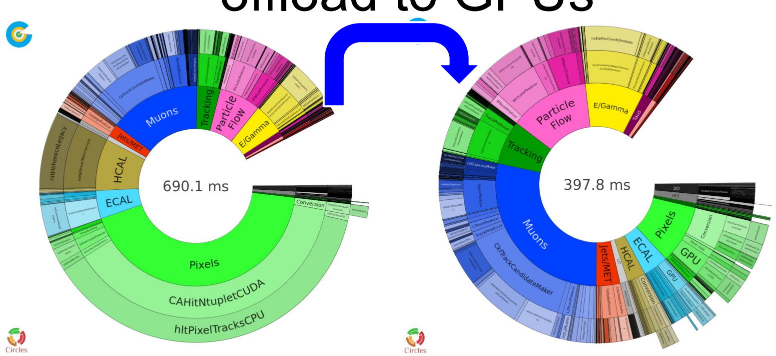
History of rates for different data streams



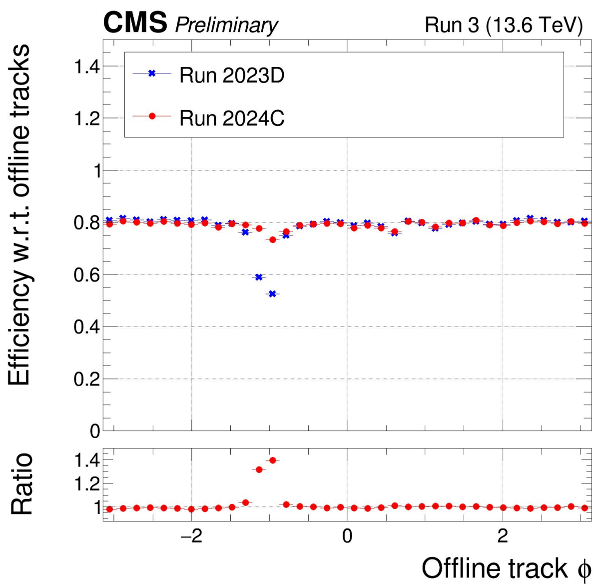
- High Level Trigger (HLT): streamlined version of CMS reconstruction
  - Gain experience with heterogeneous architectures
  - Currently offloading **~40%** of the event processing for calorimeters and pixel local reconstruction, pixel tracking and vertex reconstruction.

CMS DP-2023/004

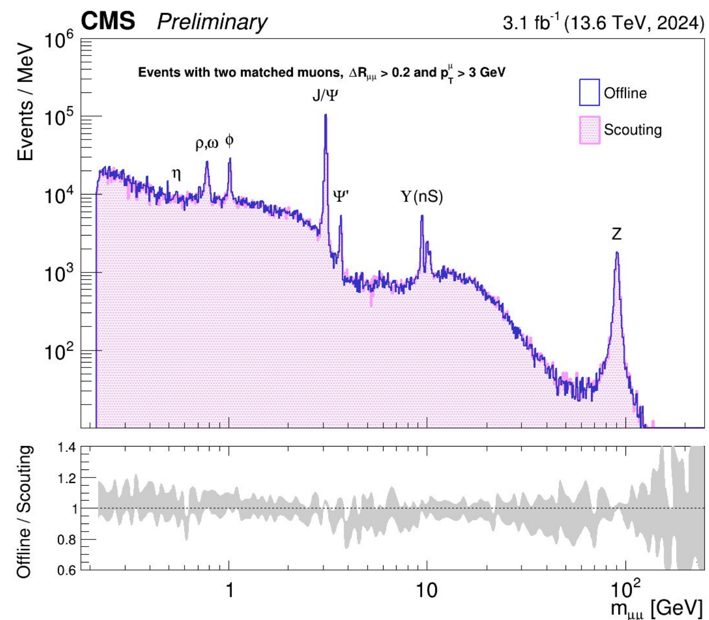
offload to GPUs

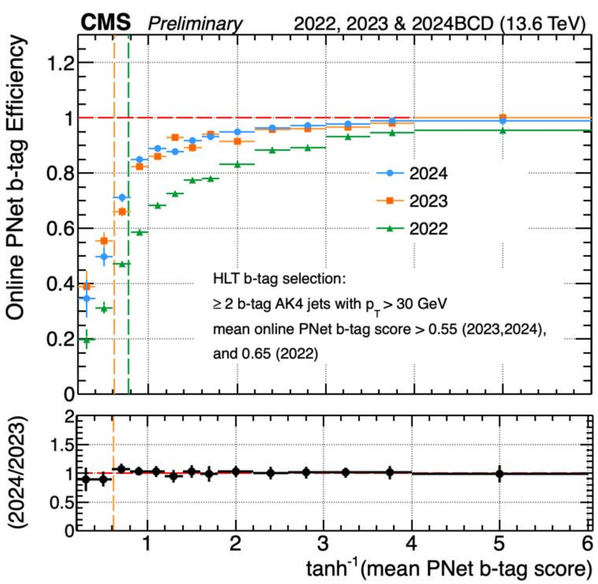


CMS HLT performance in 2024



- **Object performance:** The HLT tracking efficiency with respect to high-purity offline tracks is shown as a function of the offline track azimuthal angle φ for the later part of 2023 pp data-taking (after the technical stop) and the beginning of 2024.





- **Trigger optimization:** Online ParticleNet b-tag efficiency, as used in the High Level Trigger (HLT), as a function of the mean ParticleNet b-tag score of the two most b-tagged jets with pT > 35 GeV. The efficiency is measured in a (electron-muon) control region, and shown for 2022, 2023 and 2024 data.

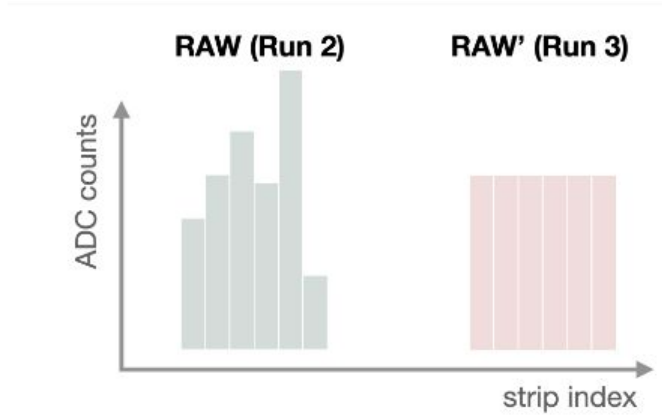
- **HLT objects reconstruction performance w.r.t offline:** Comparison of the dimuon spectra obtained with scouting (pink filled histogram) and offline (blue solid line) muons during the initial phase of the 2024 pp data-taking period

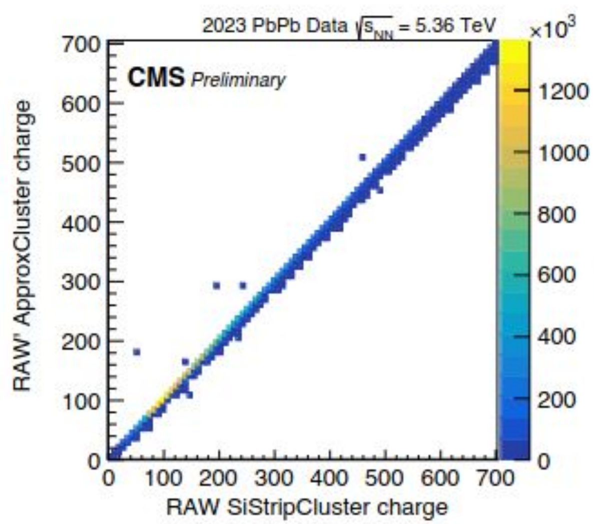
Results approved for LHCC-158

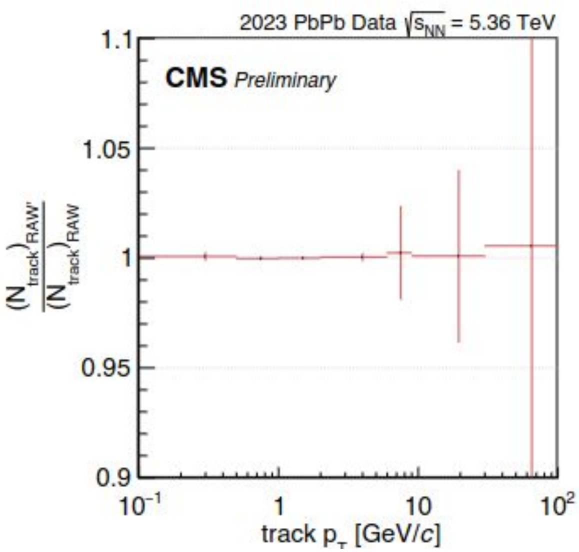
Data compression via partial online processing

- As the LHC deliver higher luminosities of proton-proton and heavy-ion collisions, the size of raw event data output begins to be a limiting factor in the number of events that can be recorded.
    - Due to large number of channels, the original silicon strip tracker (SST) data format is the largest component of the CMS raw-data size.
- A novel strategy was designed to reduce the volume of data from the SST by partially processing it in the High-Level Trigger system:
        - The **strip clustering algorithm** on the global SST, (normally part of the offline event reconstruction), is executed online.
        - Afterwards data stored in a compressed format using a rectangular approximation of the cluster properties. This lead to substantial reduction of the overall raw event size and a comparable increase in the throughput while retaining good tracking performance.
    - The approach was used **during the 2023 PbPb run.** The addition of standard lossless compression algorithms and DAQ upgrade allowed to collect significantly higher PbPb statistics compared to Run 2.

CMS DP-2024/007







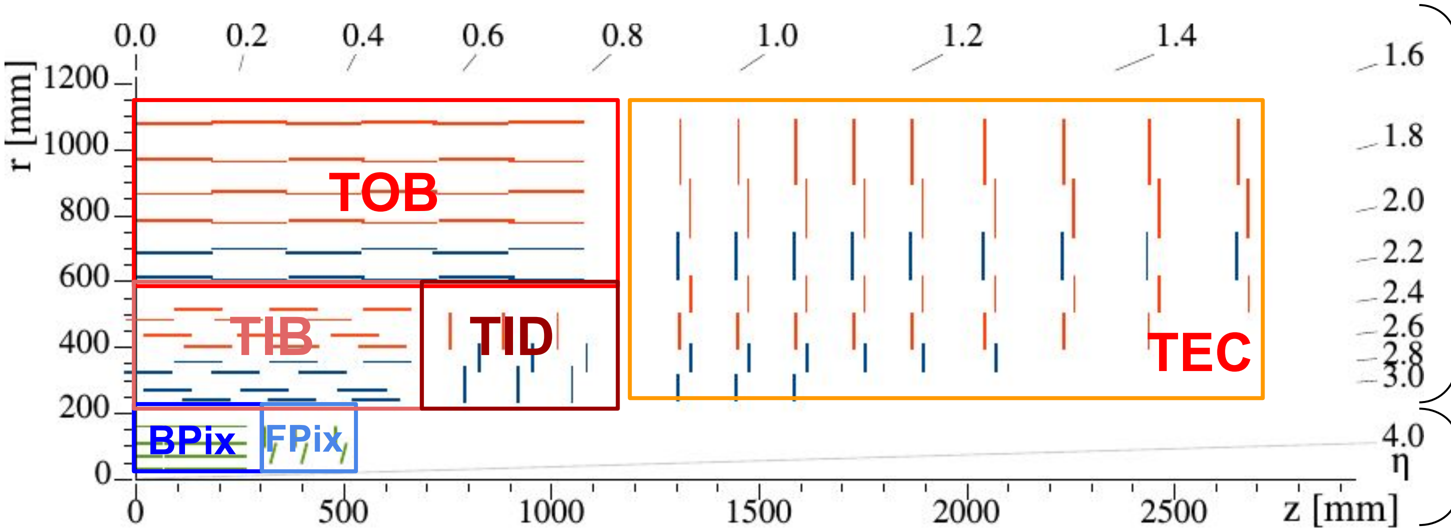
Summary & conclusions

- Successful upgrades of the CMS detector before start of Run 3
- Good quality data taken in 2022, 2023 and 2024)
  - Exploring new regimes – e.g. LLP, HH → 4b
  - New computing techniques – (e.g machine learning)
  - Many new physics results expected soon!
- Important milestones reached with regards to the HL-LHC:
  - Exploring selective data reduction techniques
  - Multi-core CPU/ GPU processing (see talk by S. Donato)
  - Transitioning into production & preparing for assembly and integration (see talk by T. Tomei)

BACKUP

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

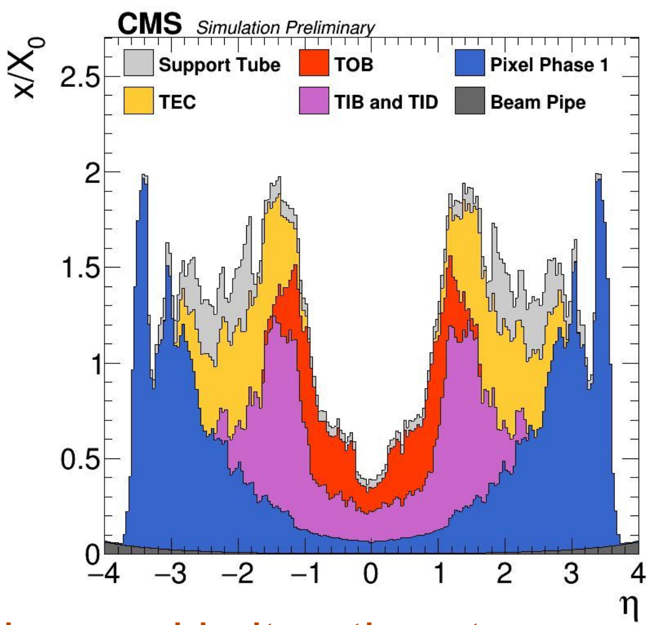
- pixel sensors
- ~124M channels
- digital readout

Track reconstruction in CMS

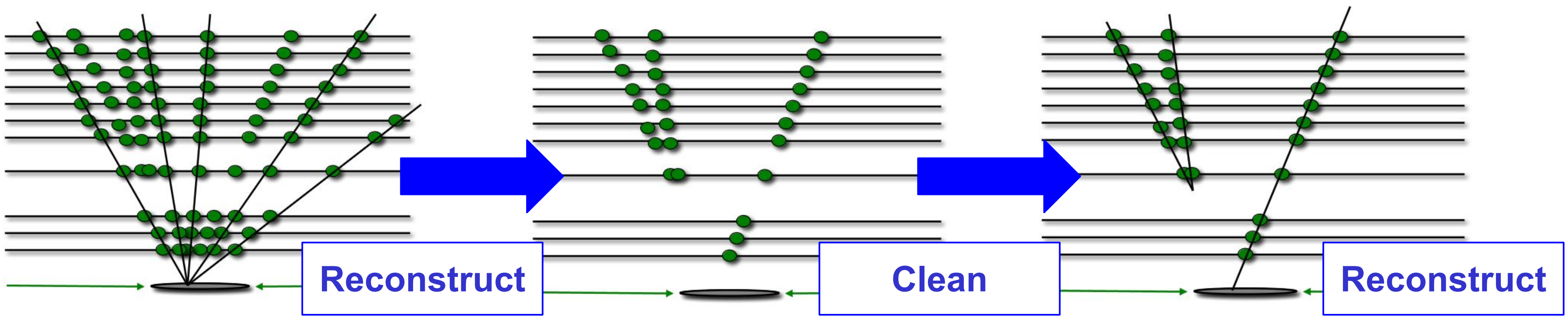
- Few, but precise measurements;
- Non negligible amount of dead material inside the tracker volume

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)

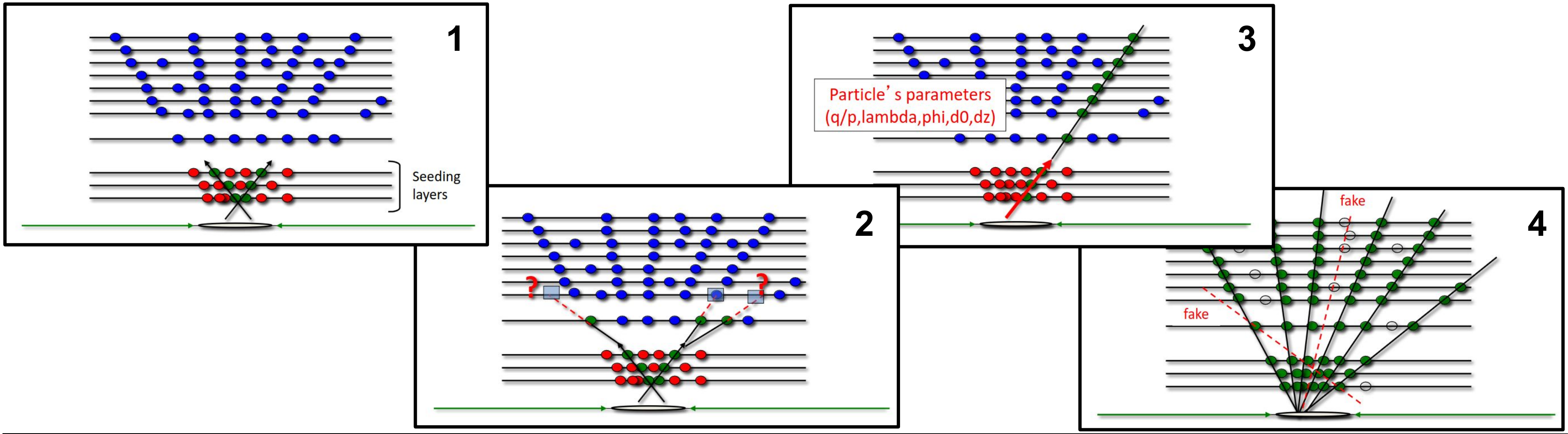


- Main tracking algorithm: Combinatorial Track Finder used in iterative steps:
  - limits the number of combinatorics in pattern recognition
  - tracking reach guarantee, w/o degrading computing performance



Track reconstruction in CMS

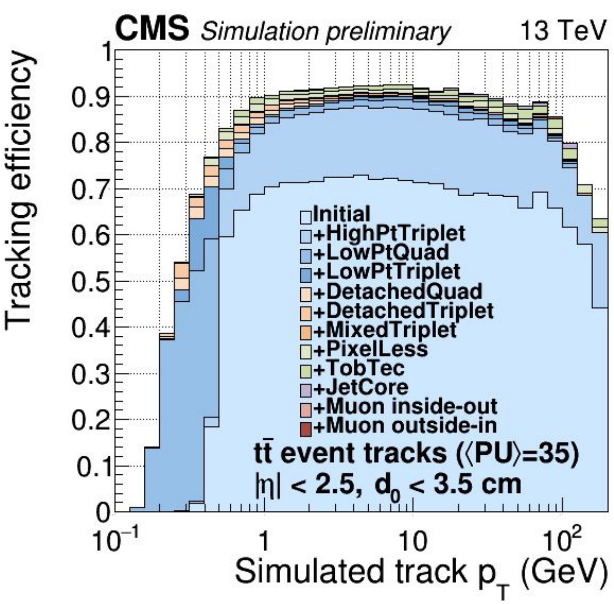
- In each iteration, tracks are reconstructed in four steps:
- **1. Seeding**:
  - provides track candidates, with an initial estimate of the trajectory parameters and their uncertainties (use combination of pixel, strip or mixed hits);
- **2. Pattern recognition**:
  - hits compatible with the predicted 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;

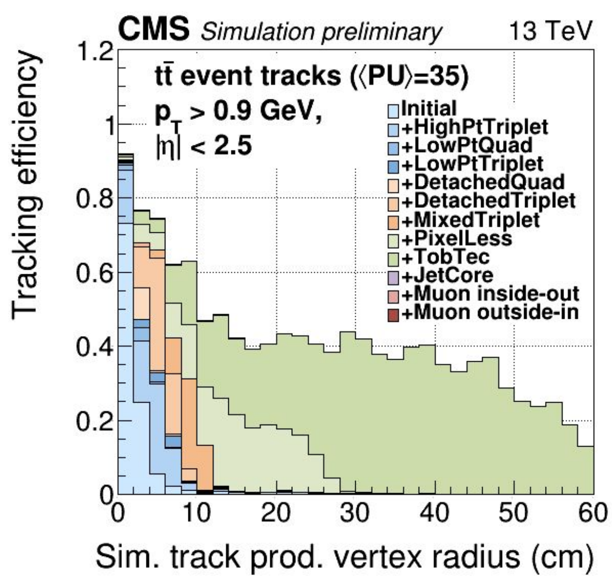


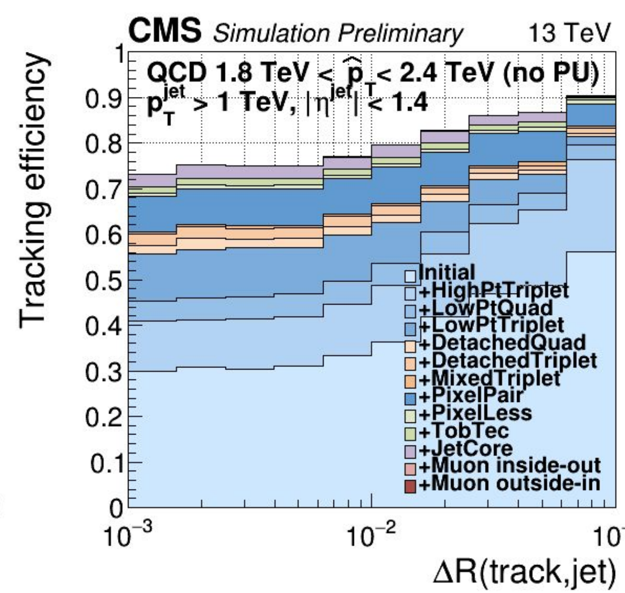
Iterative tracking at CMS

- 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



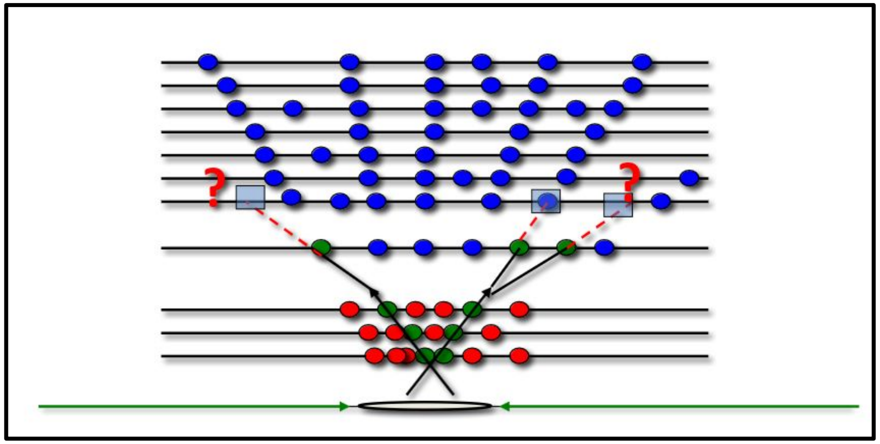




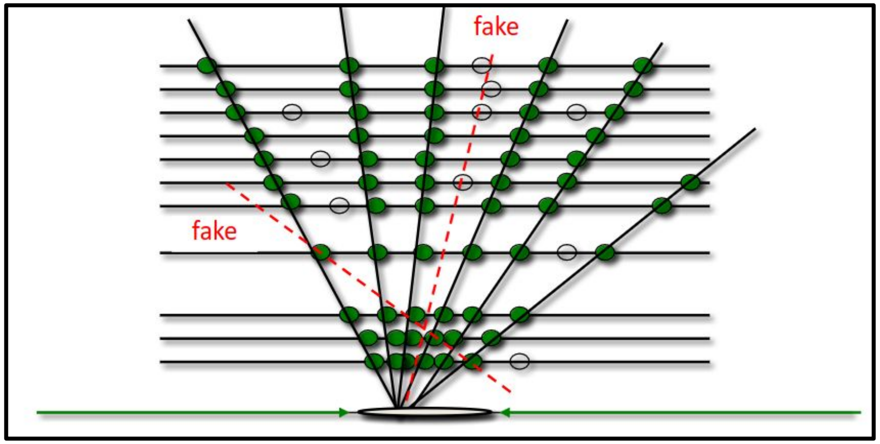
CMS Algorithms for Run 3

- 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

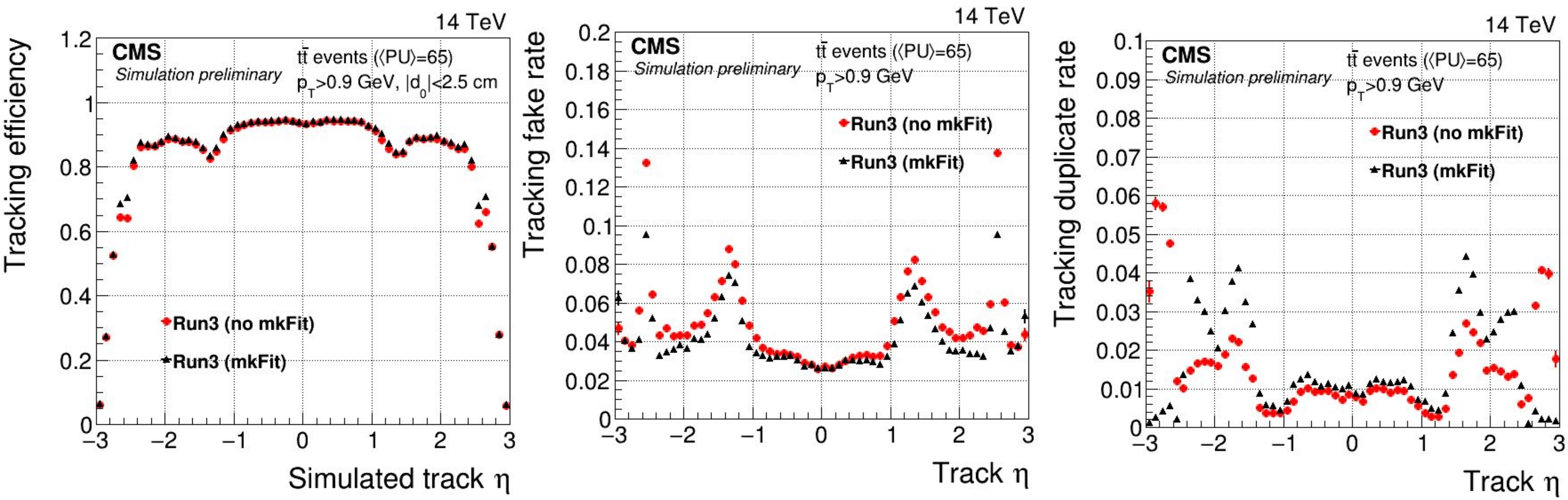
- In Run 2, the CMS track reconstruction algorithm used an iterative approach based on combinatorial Kalman Filter (CKF), consisting of twelve main iterations targeting different track topologies and seeded with different seed tracks.
- For Run 3, a new algorithm has been developed for track pattern 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

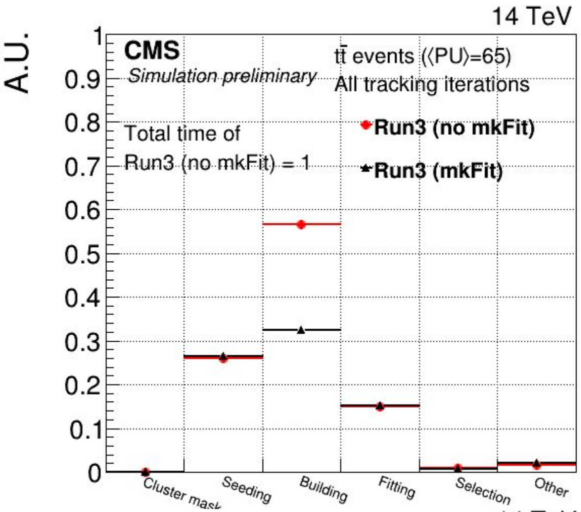
mkFit physics performance

- 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.

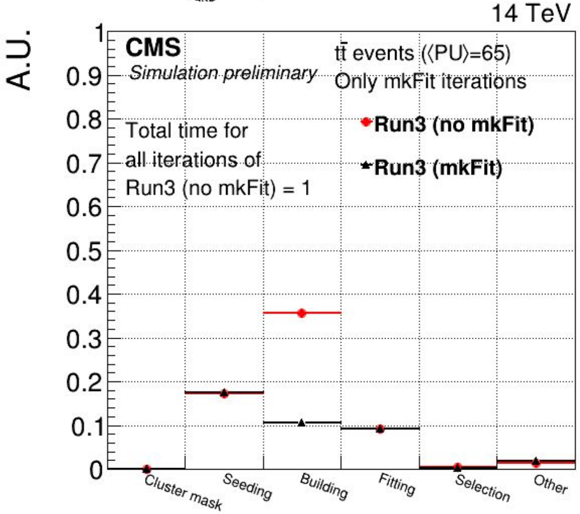


mkFit timing performance

- 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%**.

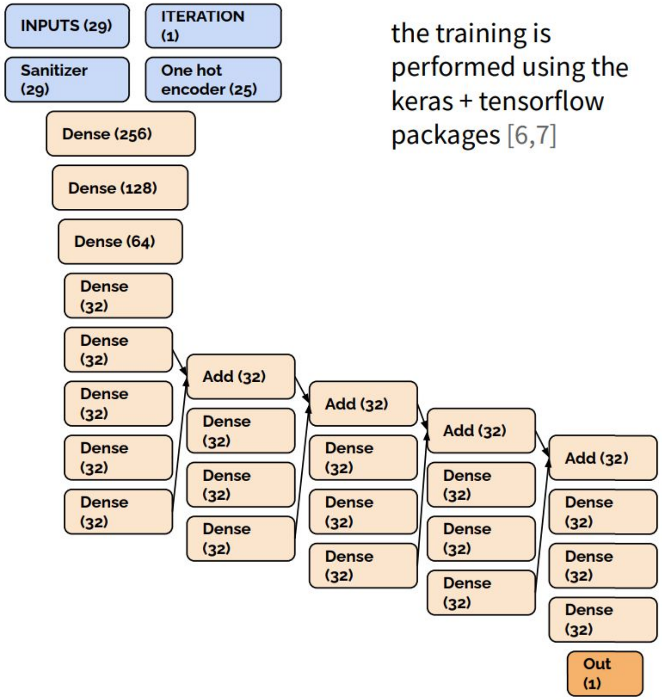


- Using `mkFit` allows to **reduce the track building time by a factor of about 3.5** considering the sum of iterations where `mkFit` is employed.
  - In individual iterations where `mkFit` is employed, this factor varies from about 2.7 to about 6.7.

CMS: 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.

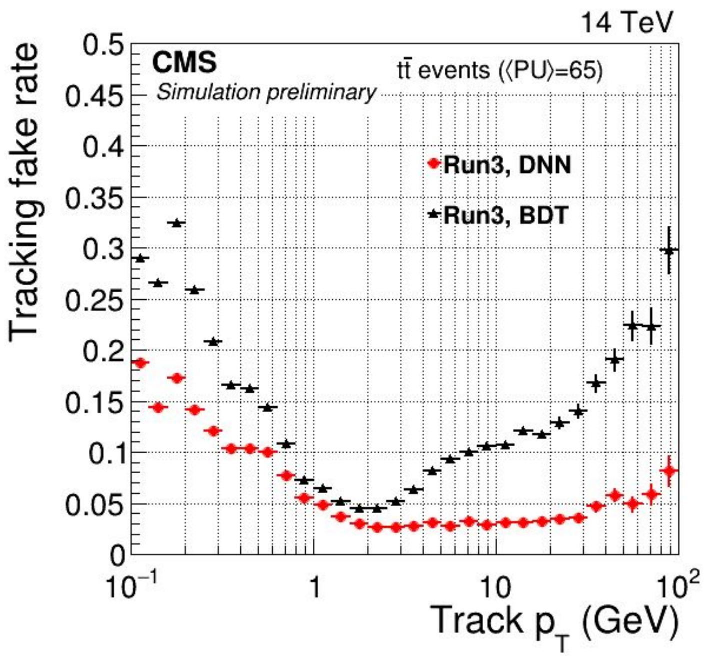
- DNN Architecture:
  - Relatively simple feed-forward network, with 5 iteration of “skip connection” and sum of the layer outputs in the downstream layers;
  - The “sanitizer” layer applies log/absolute value transformations to some of the inputs, while the “one hot encoder” converts the iteration flag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

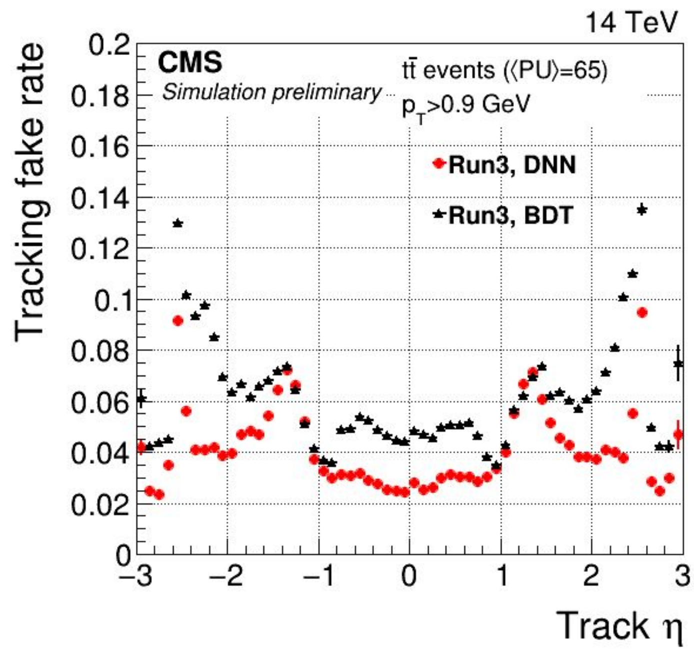


the training is performed using the keras + tensorflow packages [6,7]

CMS DNN performance

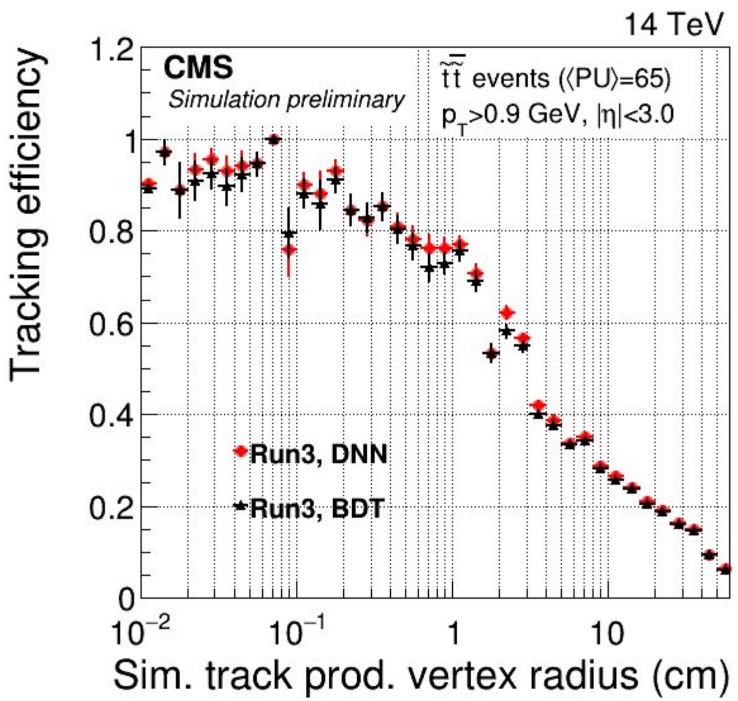
- The performance has been measured in a simulated $t\bar{t}$ sample.
  - The physics results are shown after applying the high purity BDT or DNN selection to each iteration and after merging all the tracks from the iterations into one collection.
- The tracking fake rate when the DNN is used is notably 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.

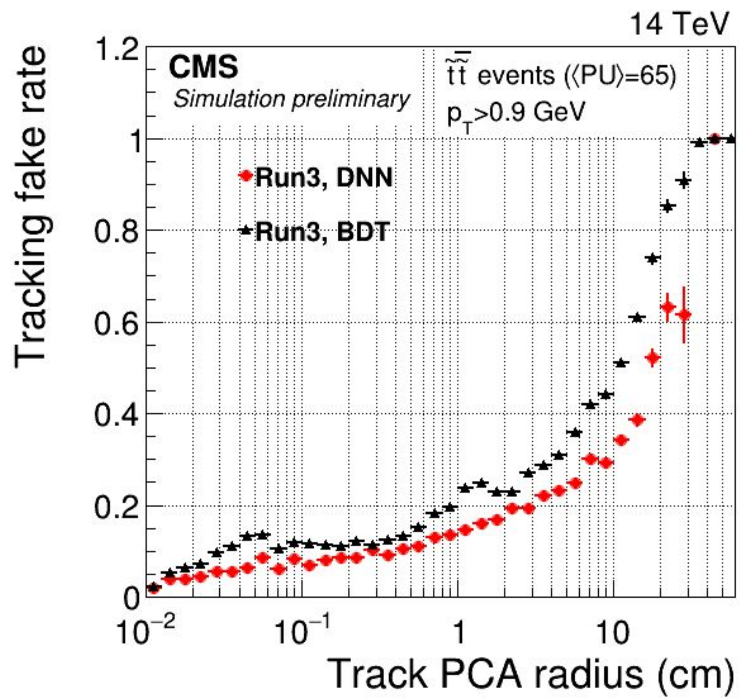




CMS: DNN track selection

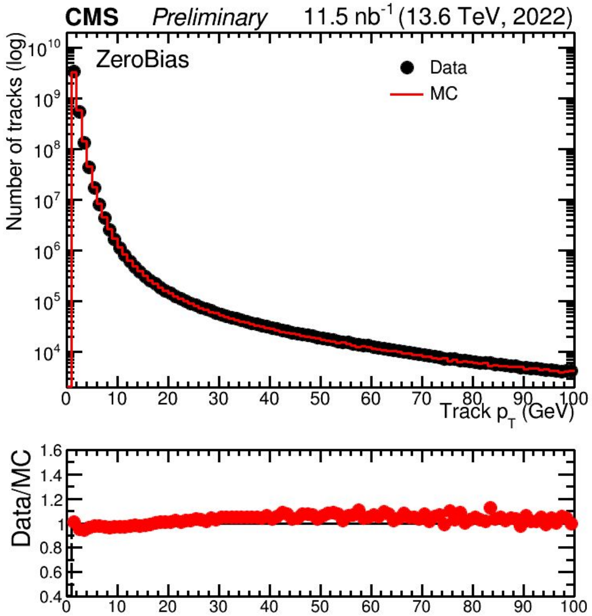
- The performance has been measured in a sample with stop-antistop production in RPV SUSY, where the stops have a significant decay length and produce displaced tracks,.
- The physics results are shown after applying the high purity BDT or DNN selection to each iteration and after merging all the tracks 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%.

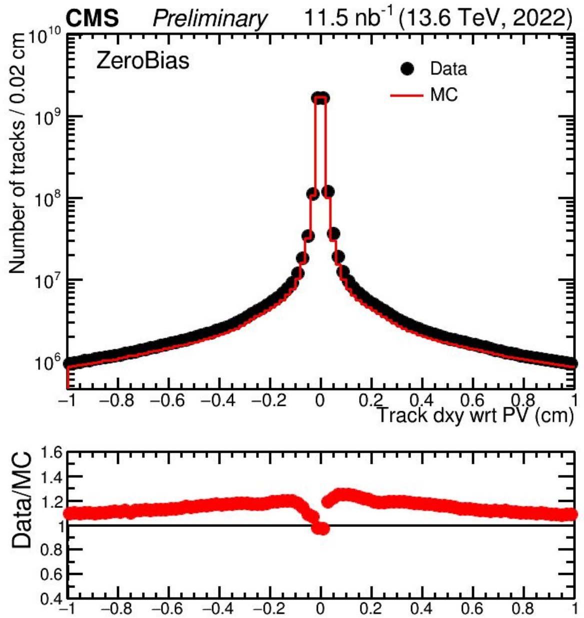


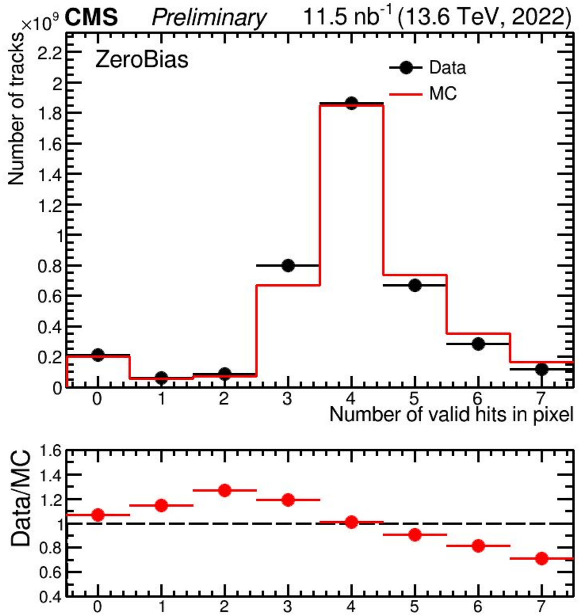


CMS Tracking Performance

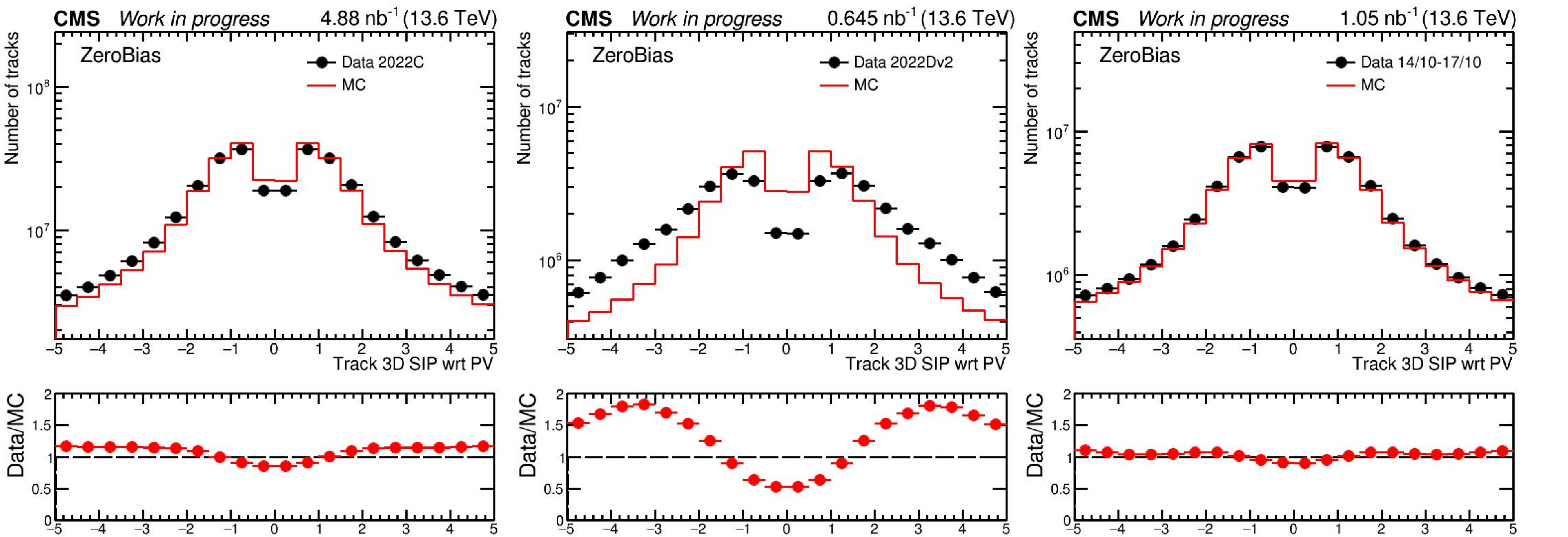
- The figures in the following show a comparison between 2022 CMS data and MC of the reconstructed track properties (documented in [CMS-DP-2022-064](CMS-DP-2022-064)).
  - Events used are selected with minimal trigger bias, using only the information on the beam-beam coincidence, and were collected from 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.





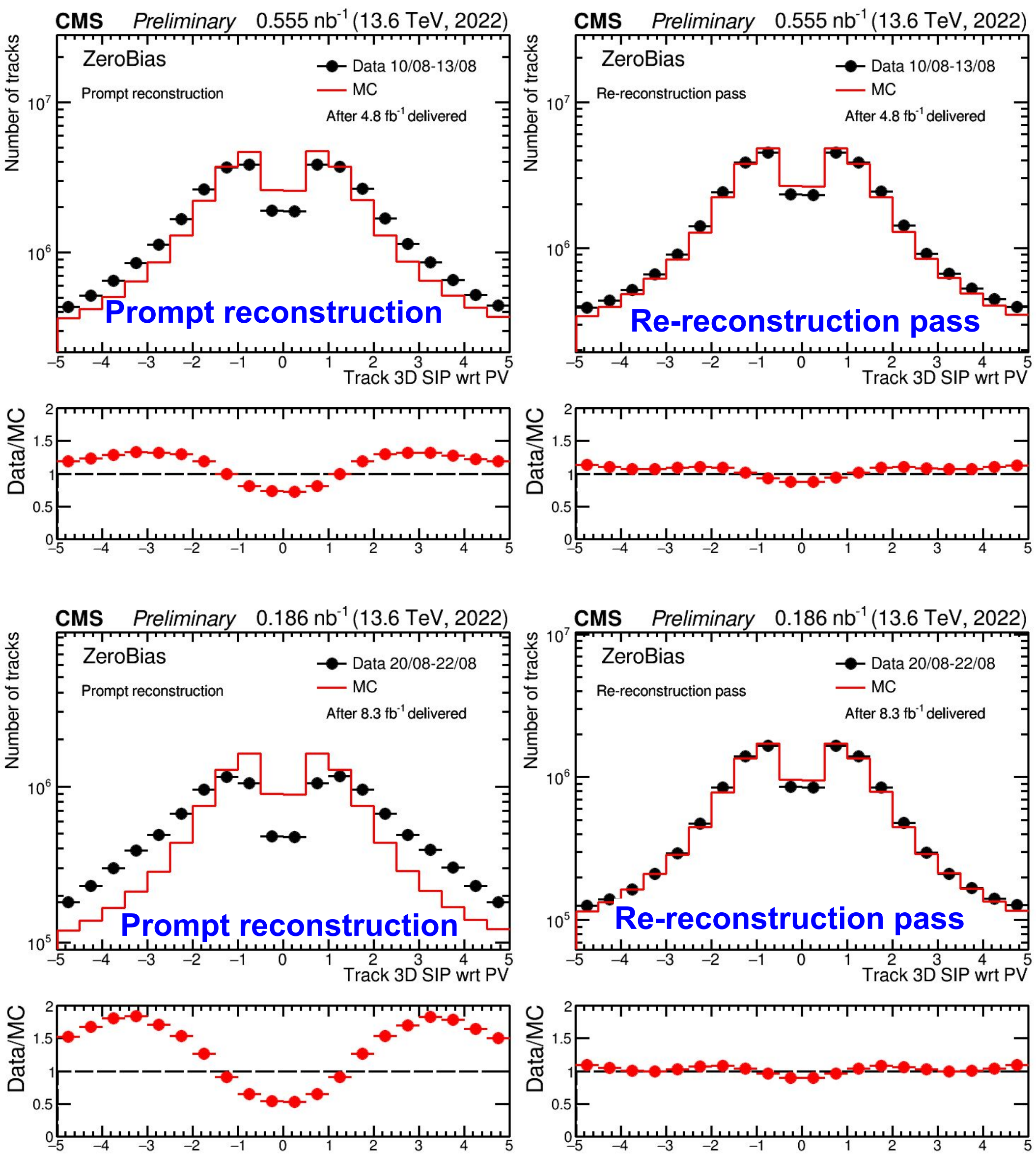


CMS Tracking Performance



- 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.

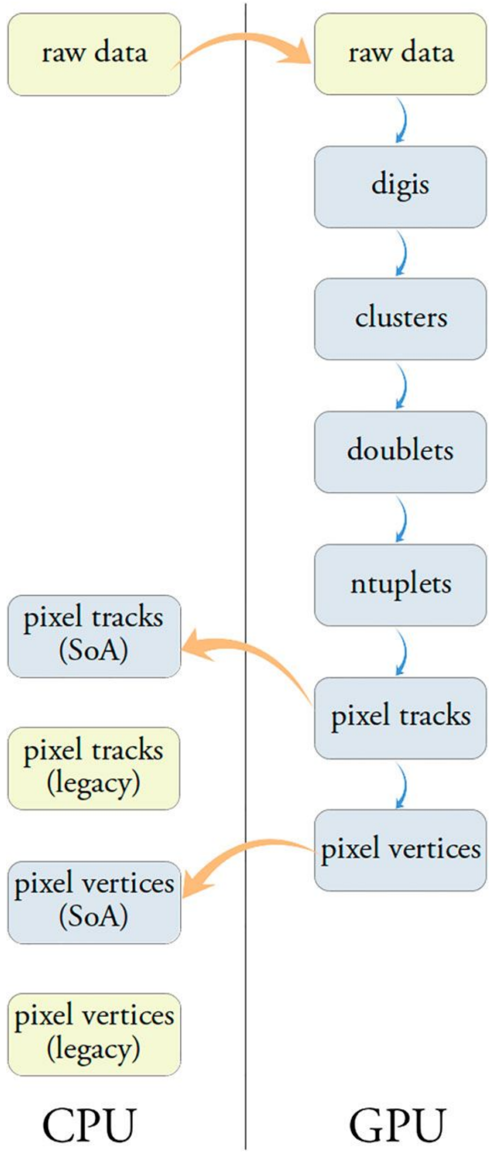
CMS: Tracking Performance



- 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.

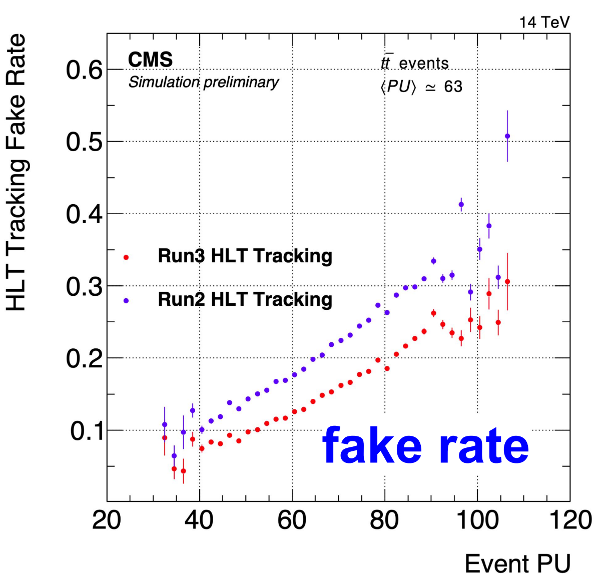
CMS: HLT Tracking

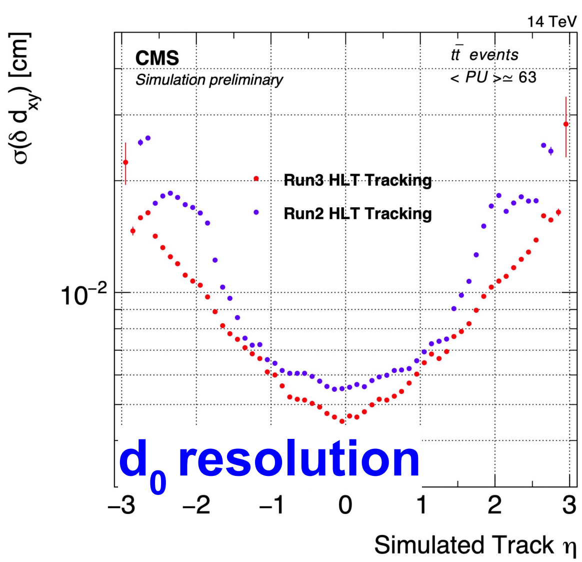
- The CMS High-Level Trigger (HLT) runs a version of the full event reconstruction optimized for fast processing.
    - Since the start of Run 3, the HLT makes use of a heterogeneous computing farm.
- In Run 3, HLT tracking is based on a single iteration of the Combinational Kalman Filter, seeded by 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).

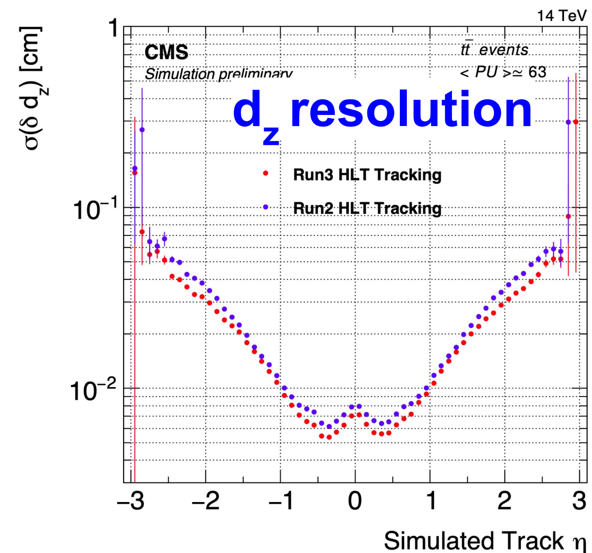


CMS TRK at HLT Performance

- 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.

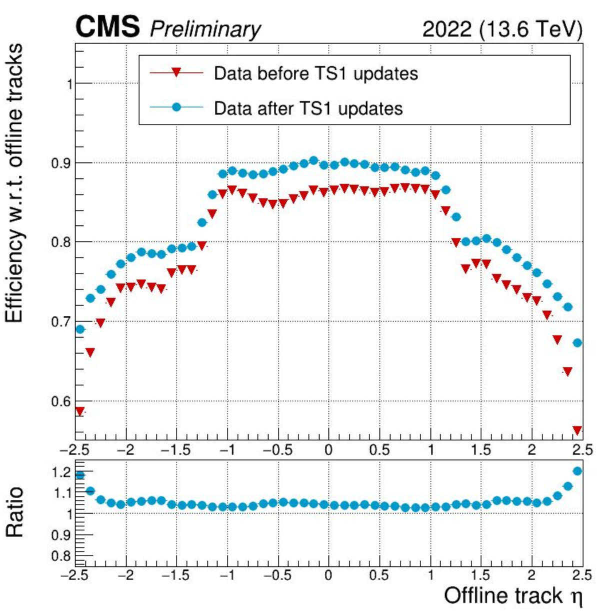


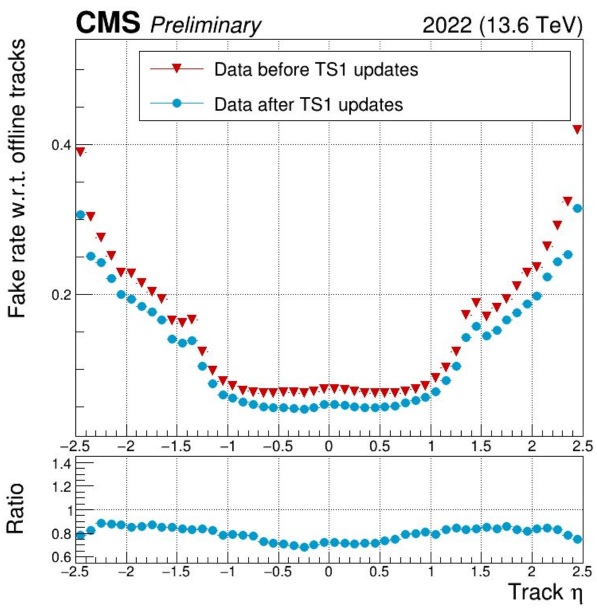


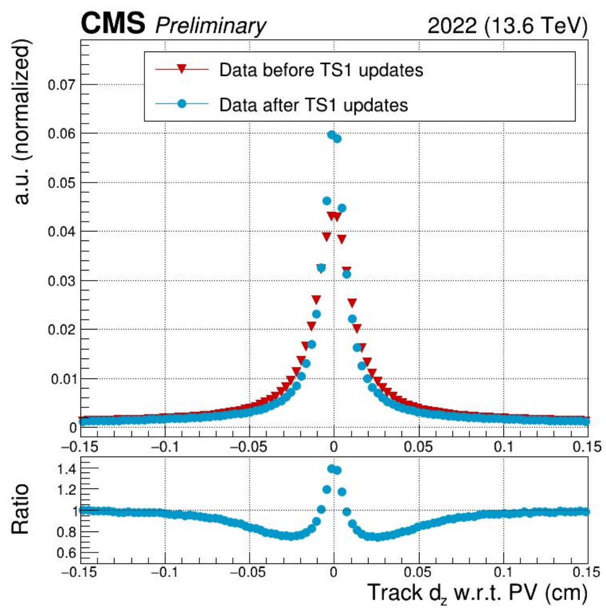


CMS TRK at HLT performance

- 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.

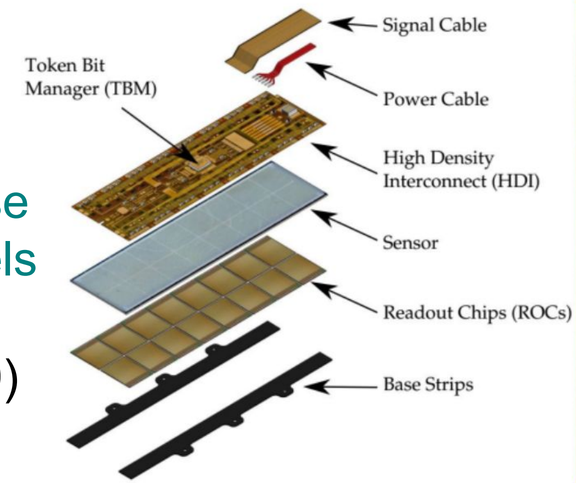


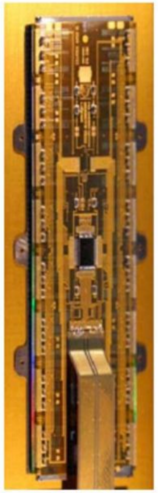


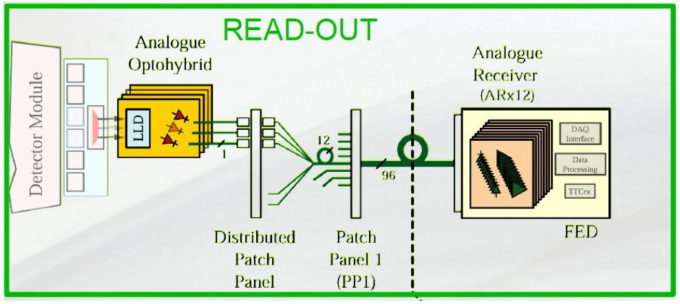


CMS Silicon Tracker

- Silicon Pixel modules (Phase-1 detector):
  - 100x150x280 μm^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 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)
- 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