Performance of the CMS Tracker in Run 3

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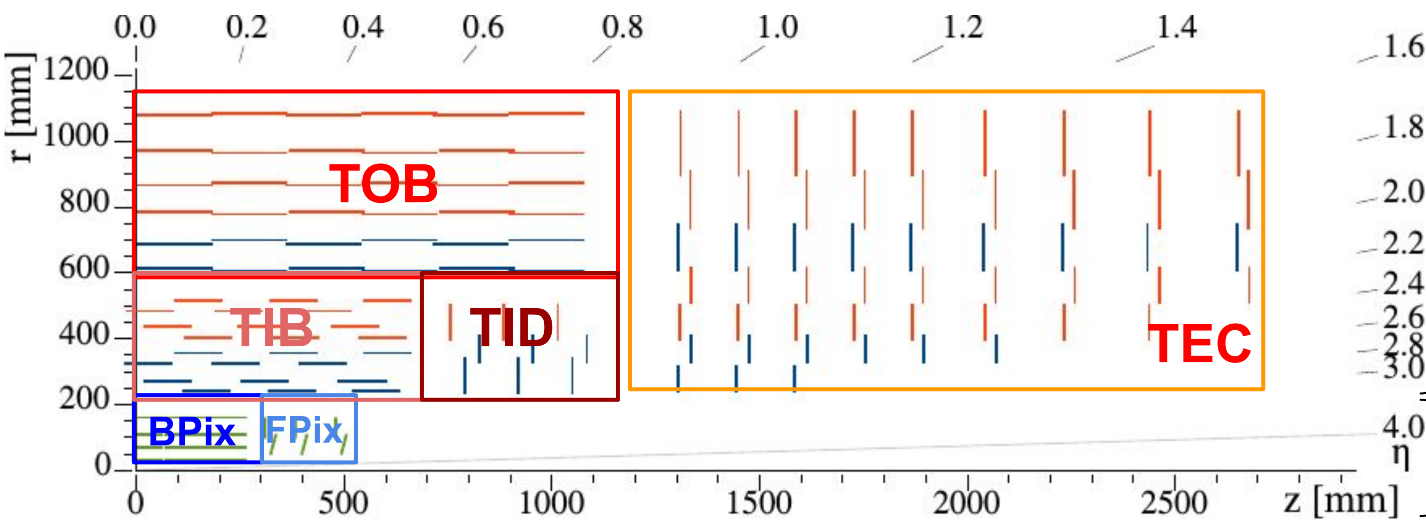
Introduction

- The CMS Silicon Tracker:
  - Silicon Pixel & Strip detectors;
  - Description of sensors and readout;
- Data taking conditions:
  - Preparation taken for Run 3;
- Detector Performance:
  - Pixel Tracker performance;
  - Strip Tracker performance;
  - Tracker alignment performance;
- Conclusions & Outlook

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.

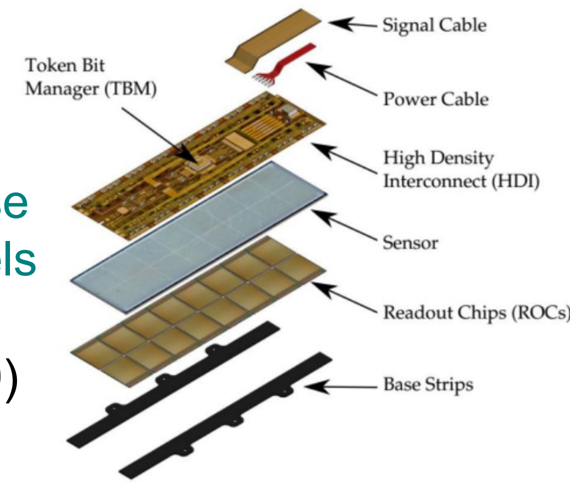


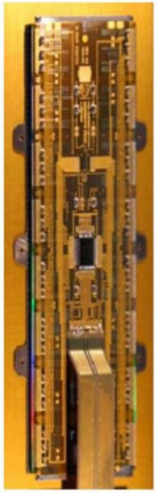
- Micro-strip sensors
- Stereo modules (two components with a 100 mrad stereo angle)
- Analog readout

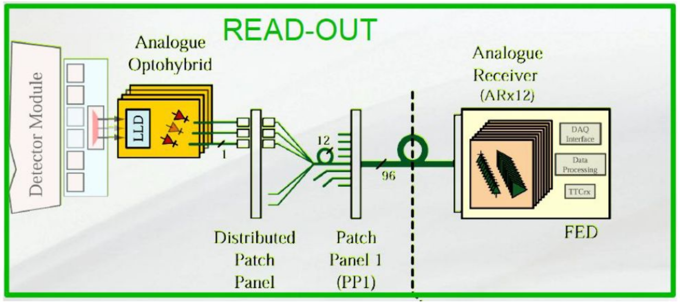
- pixel sensors
- ~124M channels
- digital readout

CMS Silicon Tracker: modules anatomy

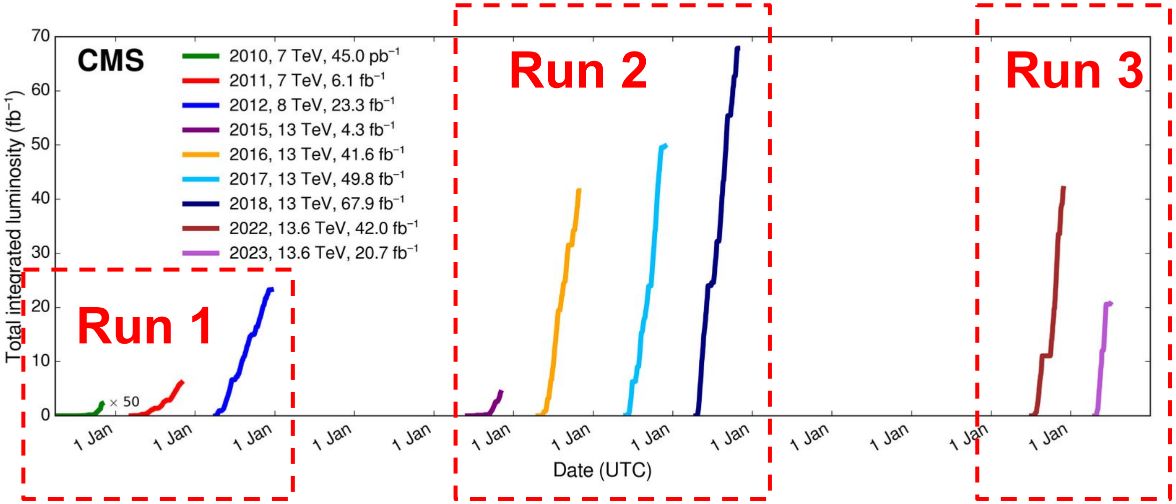
- Silicon Pixel modules (Phase-1 detector):
  - 100x150x280 μm^3 n-in-n pixel cells used everywhere in the detector;
  - Readout Chip (ROC): 250nm CMS ASIC pulse height read-out, reads matrices of 52x80 pixels
  - Two chips employed:
    - **PSI46dig** (same architecture as Phase 0) digital readout and 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.

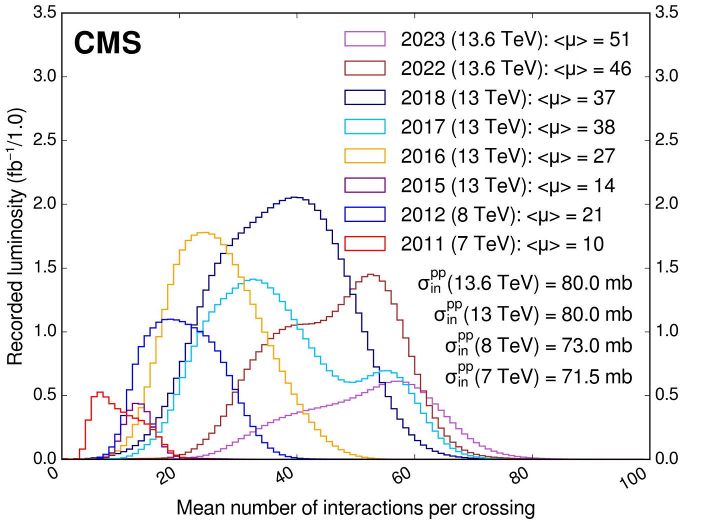




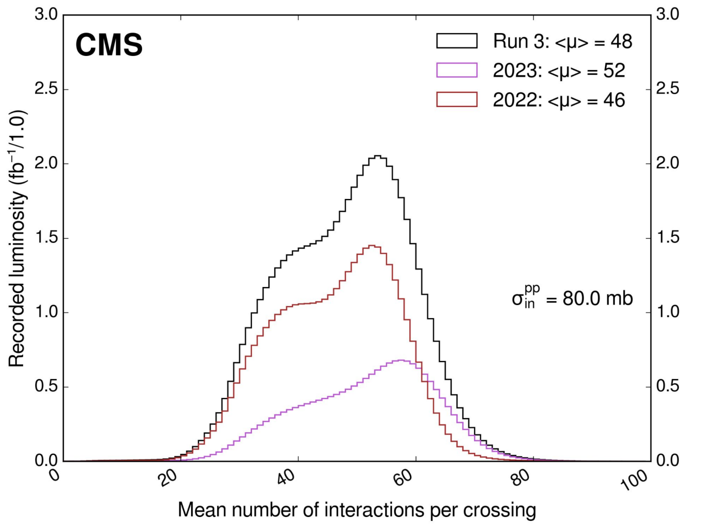


CMS Data Taking so far





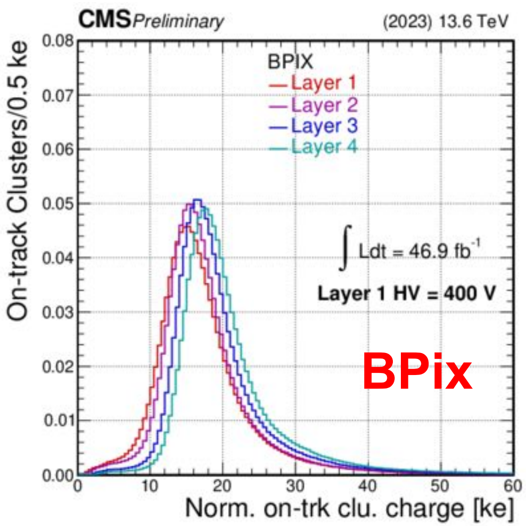
- Luminosity delivered to CMS by the end of Run 2 is ~192 fb^{-1}.
- Luminosity delivered to CMS as of today during Run 3 is ~61 fb^{-1}.
  - LHC is expected to deliver around 250fb^{-1}
- Average number of pp interactions per crossing in Run 3 is 48, 52 considering only 2023:
  - Highly irradiated environment,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

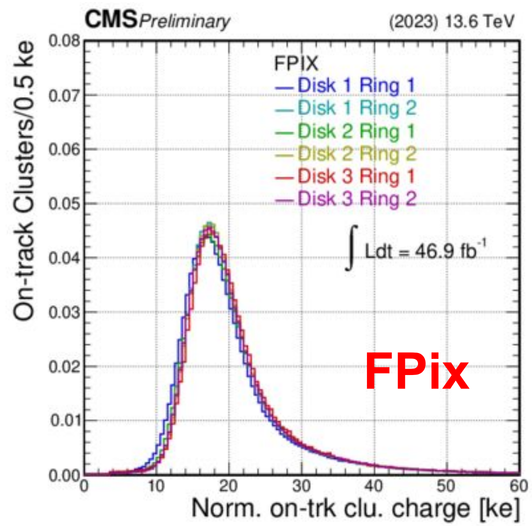


Preparation for Run 3 data-taking

- 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.

Pixel cluster properties

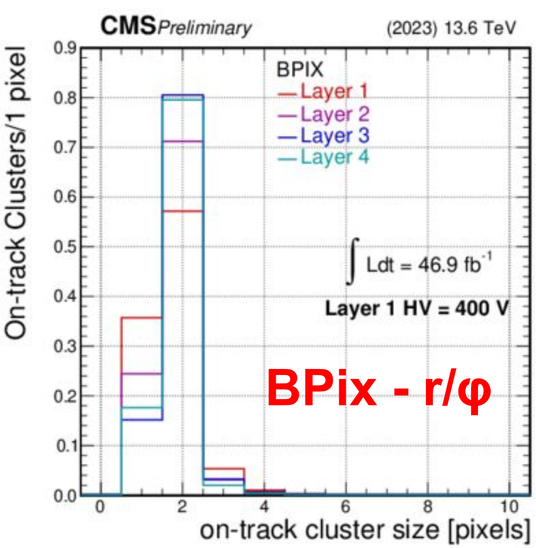


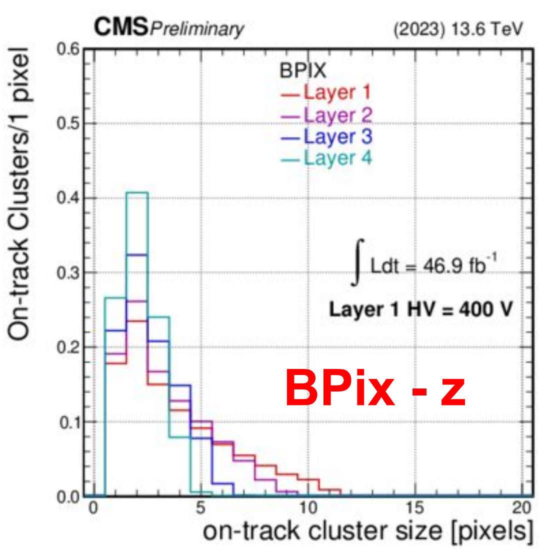


Clusters required to belong to tracks $p_T > 1$ GeV.

Cluster Charge normalized by incidence angle:

- The distributions of the normalized on-track cluster charge for each barrel pixel (BPIX) layer and Forward pixel (FPIX) disk differ because of the loss of charge collection efficiency caused by radiation damage.
- Radiation damage introduces the charge efficiency loss which is recovered by raising the HV.





Cluster Size in X direction (global r- φ)

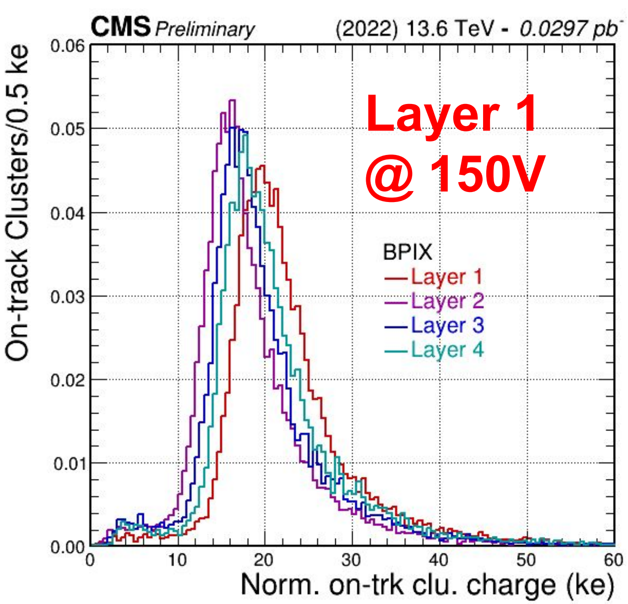
- The cluster size in X direction is determined mostly by the Lorentz charge sharing and also the geometry of the detector.
- The difference in the cluster size between layers in BPIX is expected due to the different bias voltages and consequently different Lorentz charge.

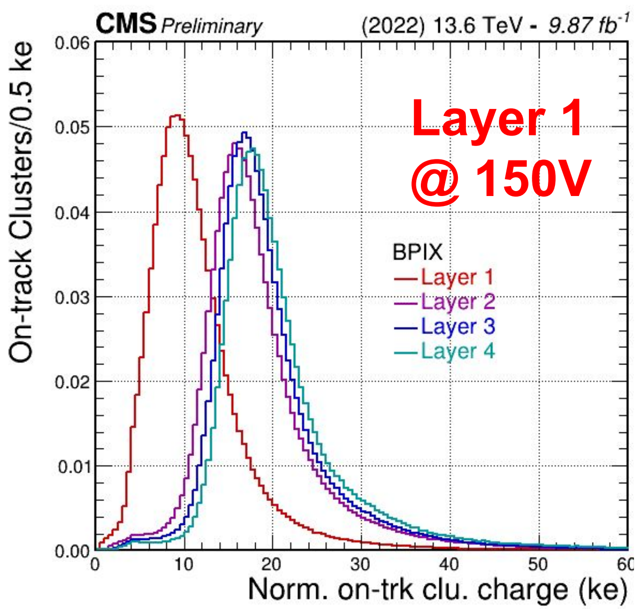
Cluster Size in Y direction (global z on the barrel)

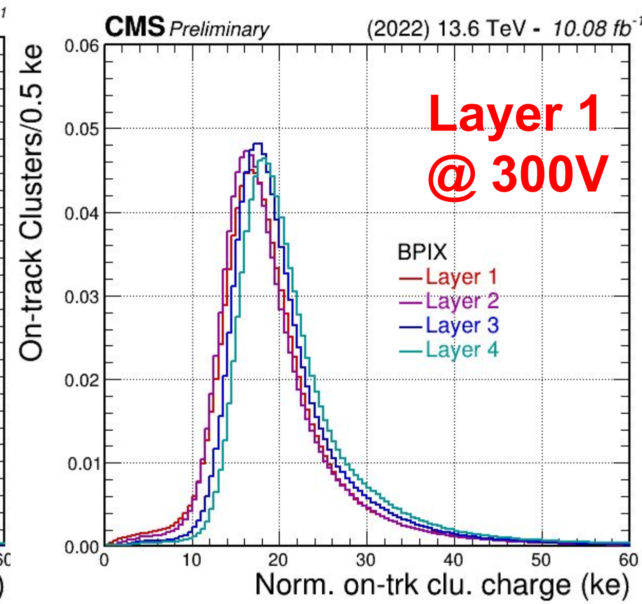
- The cluster size in Y direction is determined by the geometry of the detector: the layers closer to the beam see more shallow tracks therefore longer clusters are expected.

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.





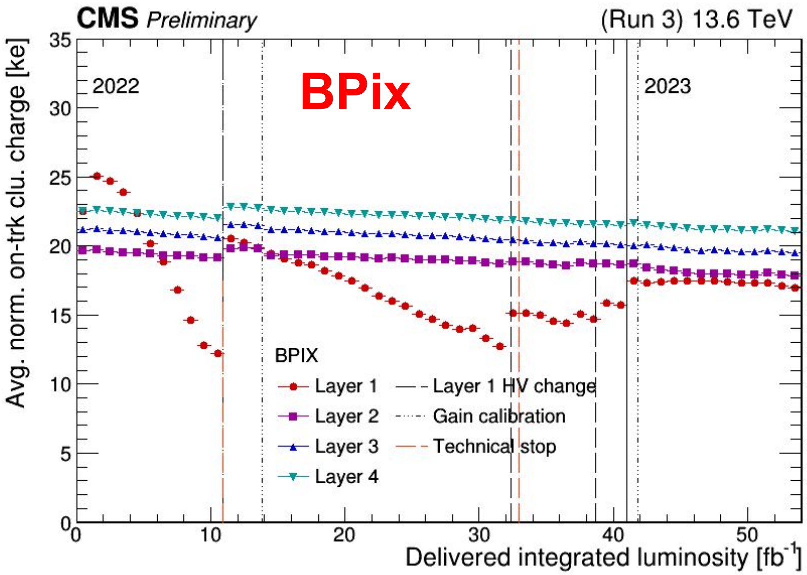


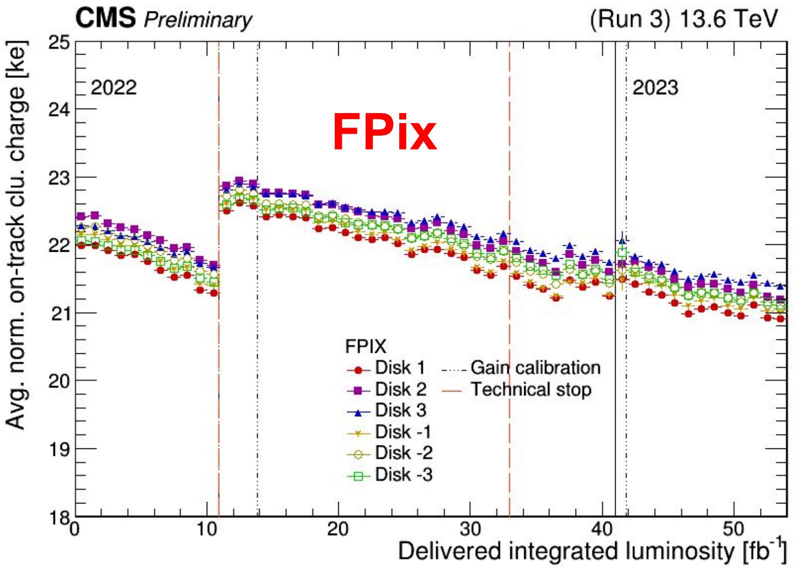
Layer 1 fully replaced during LS2, started with no radiation damage, i.e. higher cluster charges.

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 cluster charge

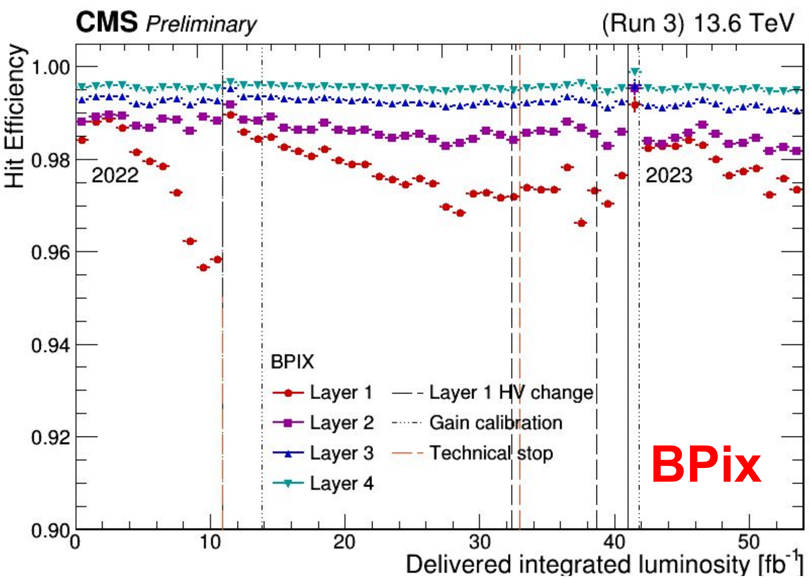


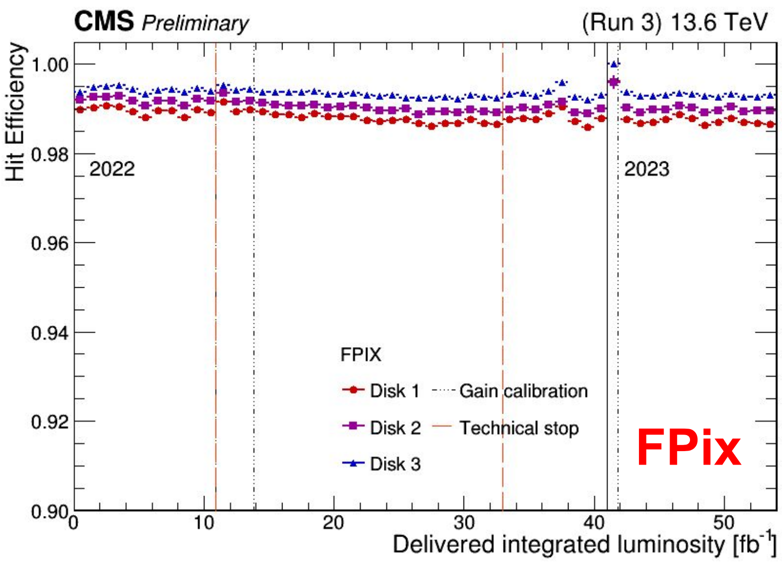


Average cluster charge normalized by incidence angle:

- Summary over all certified runs in Run 3;
- Beneficial effects of annealing can be seen for periods of technical stops or during the year-end stops:
  - The trend for Layer 1 also displays the effects of increasing the sensor HV.
- Newly replaced Layer 1 rapidly changed with irradiation in 2022 and with time became conditioned and more stable to further irradiation effects;
- The increase in charge for FPIX during the first technical stop is due to the new gain calibration:
  - The y-scale on FPIX figure spans a narrower range than on the BPIX figure

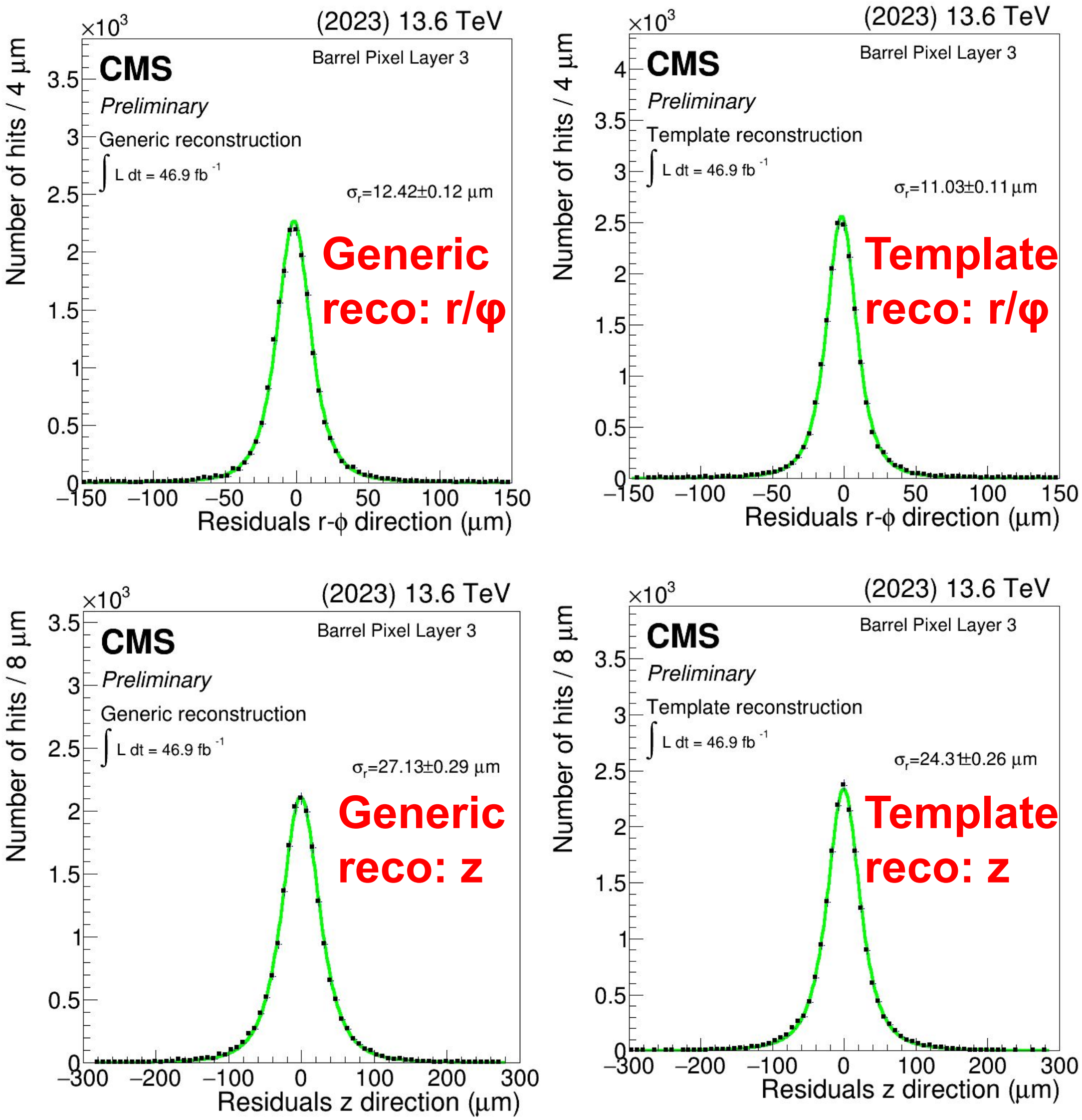
Pixel detector: evolution of hit efficiency





- 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 Hit Resolutions



Cluster positions are reconstructed with two algorithms:

- Generic: a simple algorithm based on track position and angle. Used in our High Level Triggers (HLT) and early track iterations offline.
- Template: an algorithm based on detailed cluster shape simulations predicted by PixelAV. Used in the final fit of each track in the offline reconstruction.

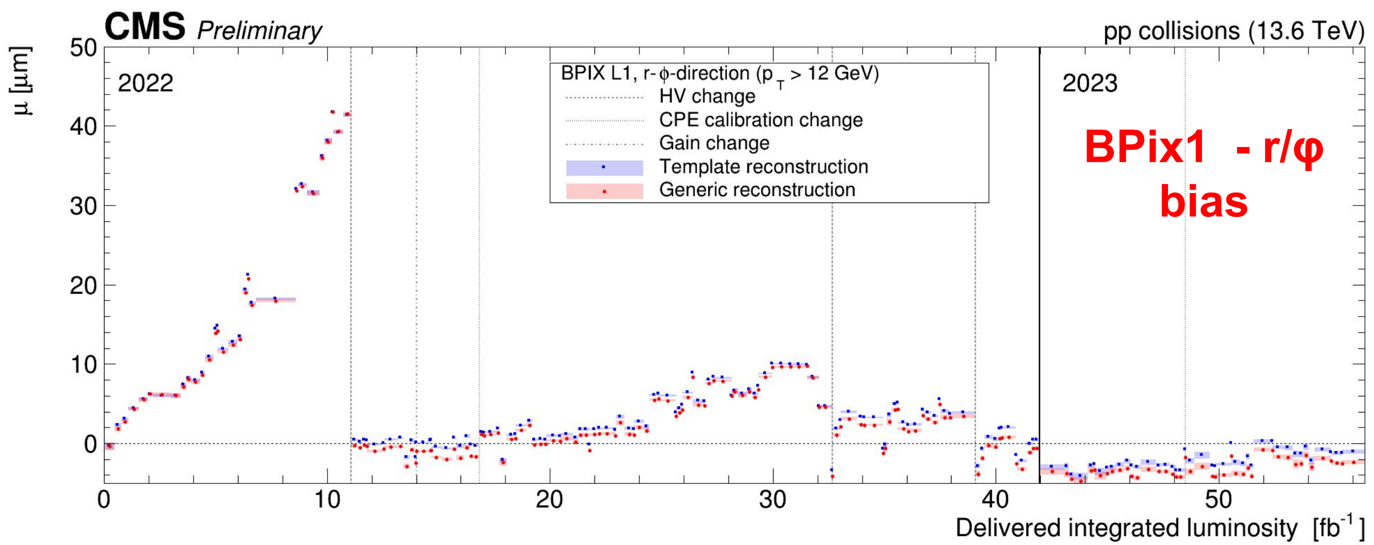
Residuals measurement using the triplet method

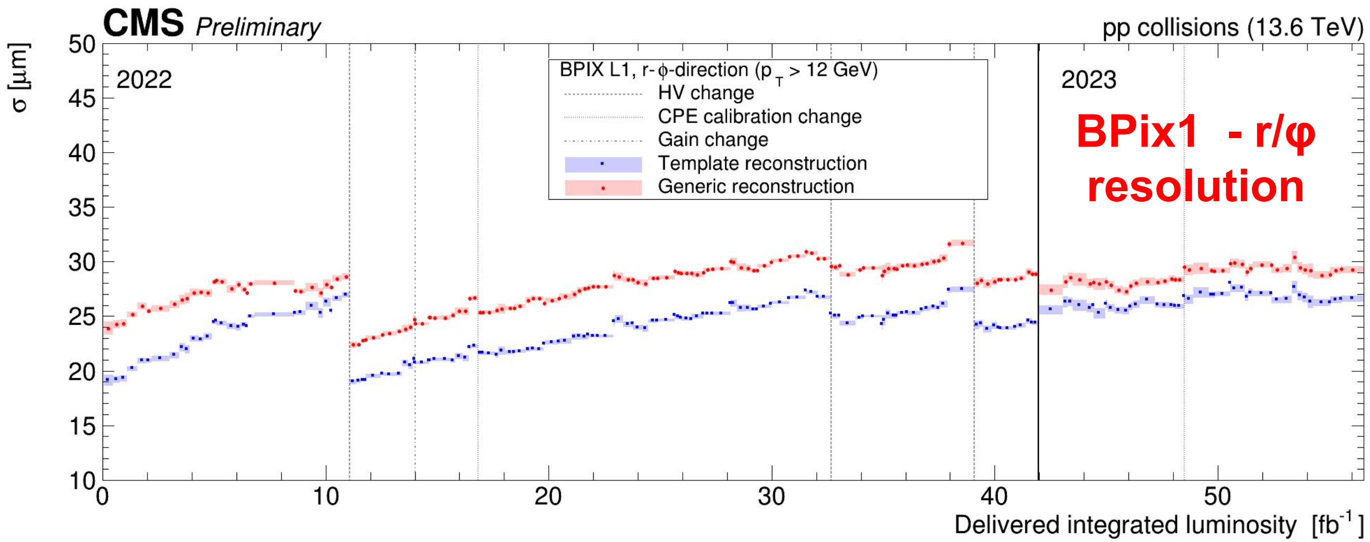
- p_T > 12 (4) GeV tracks with hits in 3 layers (disks) are selected and refitted using hits in two of three layers (disks) for the BPIX (FPIX).
- Trajectory is extrapolated to remaining layer (disk) and residuals with the actual hit are calculated for the BPIX (FPIX)
- Residual distribution fitted with the Student-t function to obtain the mean offset (μ) and resolution (σ)

Interpretation:

- Observed residual distribution is the sum of the intrinsic detector resolution and a track extrapolation error
- The performance of the Template algorithm is seen to be better than the Generic algorithm

Pixel detector: Layer 1 hit resolution





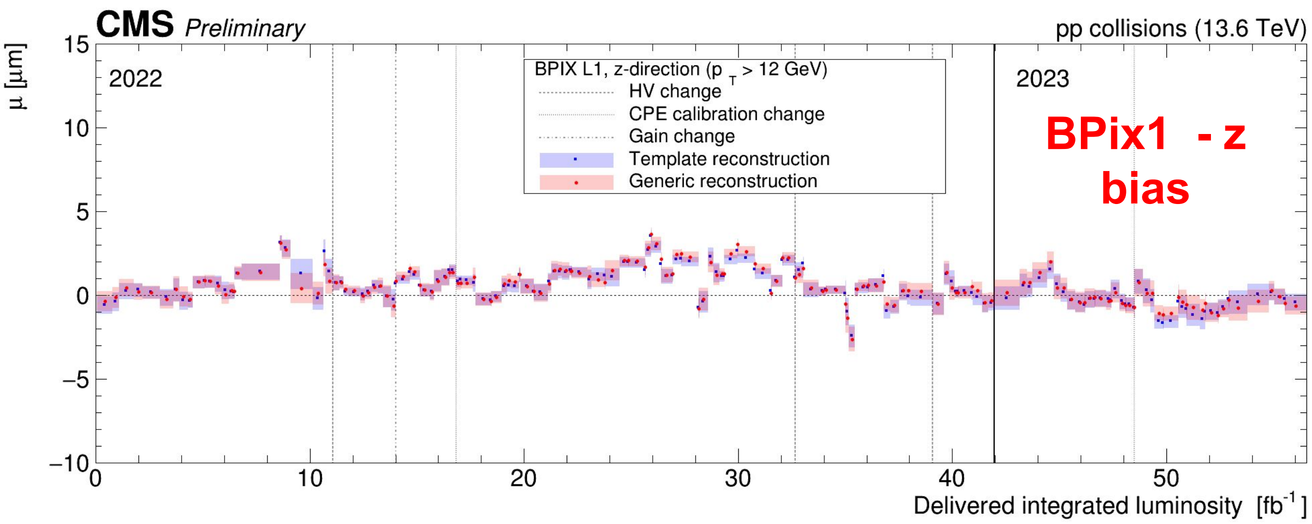
Integrated delivered luminosity since the beginning of Run 3 until the data-taking run used to produce the figures is indicated.

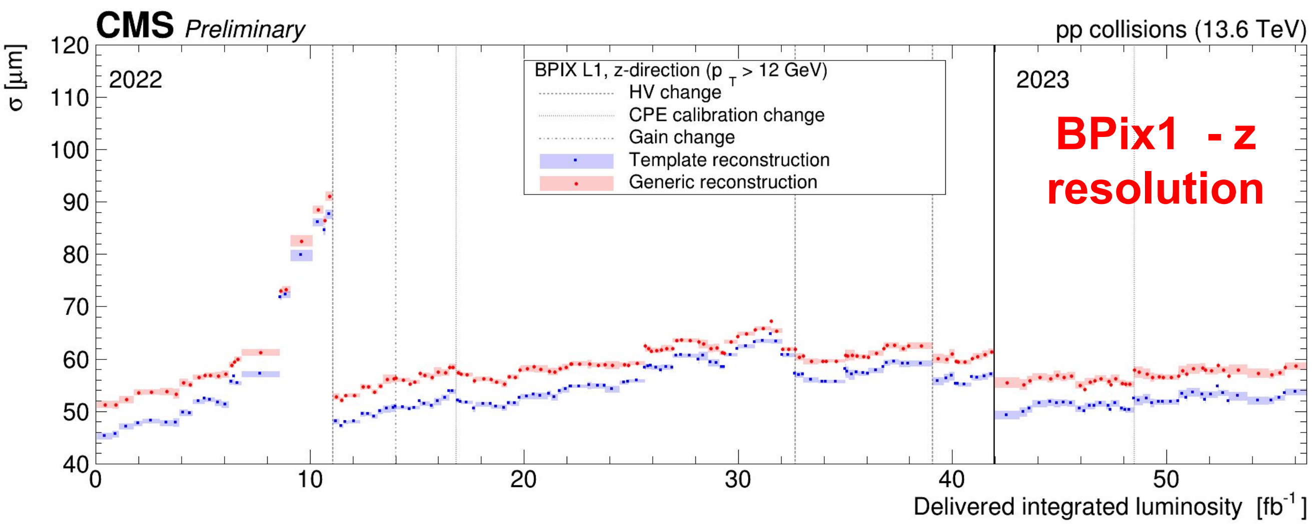
A strong increase of the bias is observed in the first 10 fb^{-1} while it is relatively stable in the rest of the data-taking.

Resolutions have been slightly increasing with time:

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

Barrel Pixel Layer 1 hit resolution





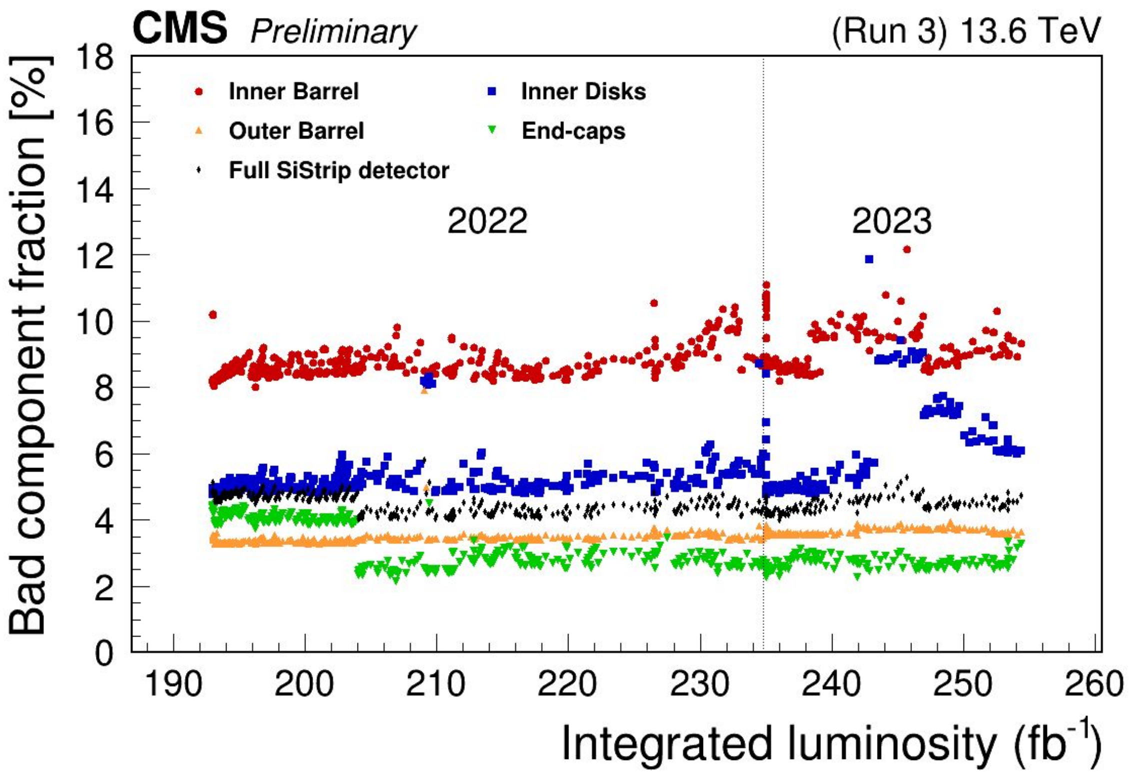
Integrated delivered luminosity since the beginning of Run 3 until the data-taking run used to produce the figures is indicated;

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.

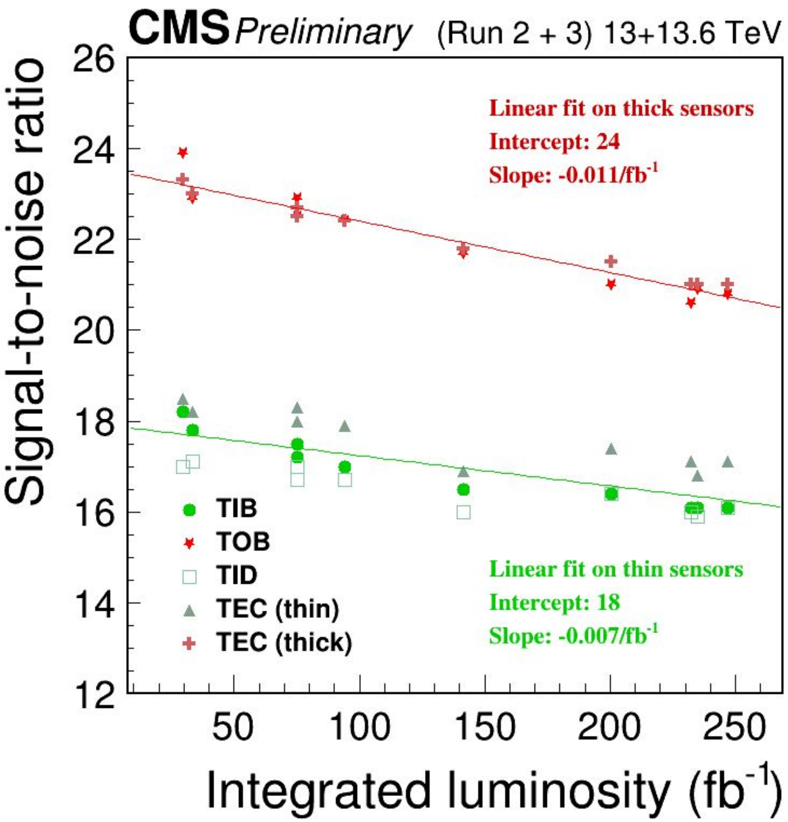
Strip Detector status - Bad components

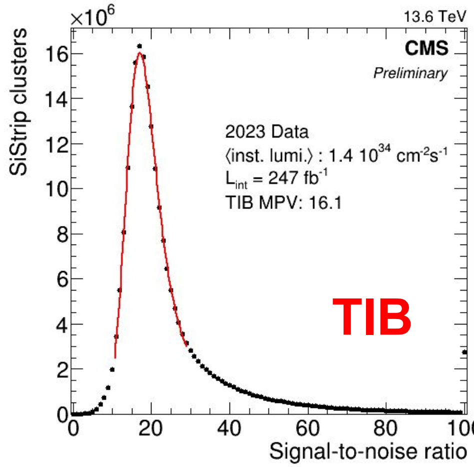


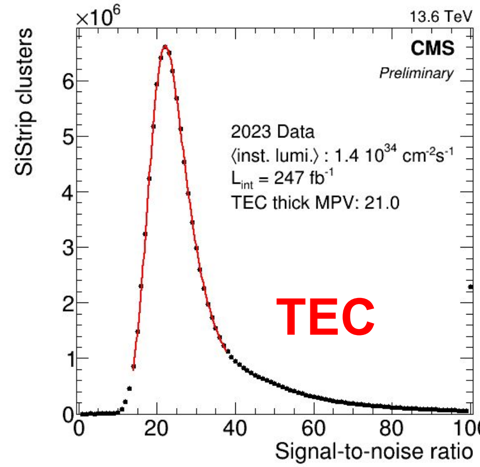
- Evolution of the global fraction of module components flagged as bad for offline reconstruction for 2022 and 2023 pp collisions at a center of mass energy of 13.6 TeV as a function of integrated delivered luminosity.

- The initial offset of 193 fb^{-1} corresponds to the integrated luminosity of Run 1 and Run 2.
  - The drop in bad module fraction around 205 fb^{-1} is due to the recovery of a cooling loop in the TEC+.
- The bad component fraction can be seen to increase for a handful of runs due to some promptly recovered issues in either data-taking or in powering.

Strip Signal over Noise Ratio



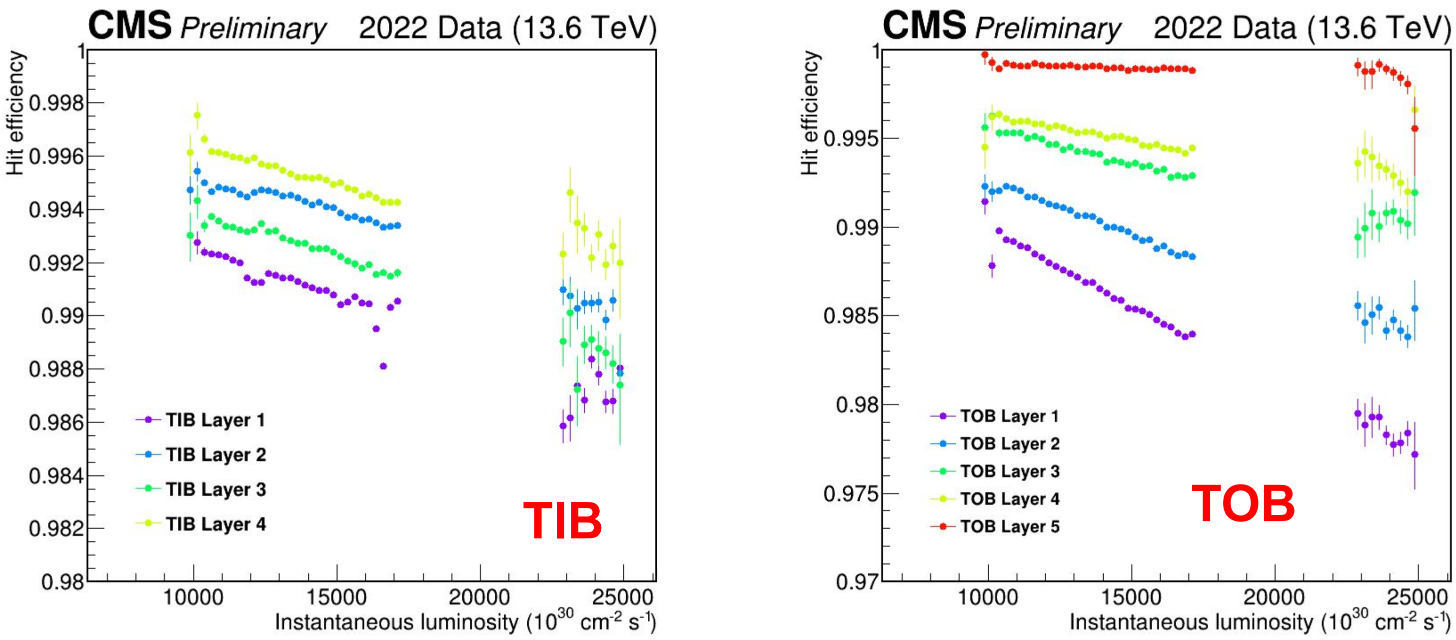




- The Signal-to-noise ratio, corrected for path length inside the silicon is shown for a 2023 13.6 TeV pp collision run where the SST was operated in deconvolution mode (nominal conditions), and cooled down to -20°C.
  - The position of the MPV of the peak is given, estimated from a fit to a Landau convoluted with a Gaussian distribution.
- The lifetime integrated luminosity of high- energy pp collisions delivered by the LHC was of 247 fb^{-1} .

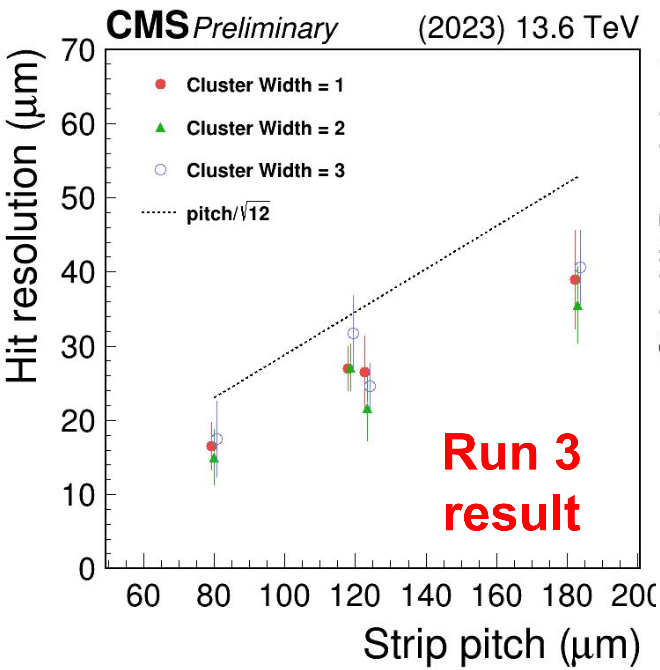
- The signal-to-noise ratio measured in pp collision since the beginning of Run 2 is reported as a function of the integrated delivered luminosity.
  - Measurements have been performed split per sensor thickness in the Tracker Endcaps (320 μm or 500 μm).
- The signal-to-noise ratio scale with integrated luminosity. The data were fitted with a linear function.

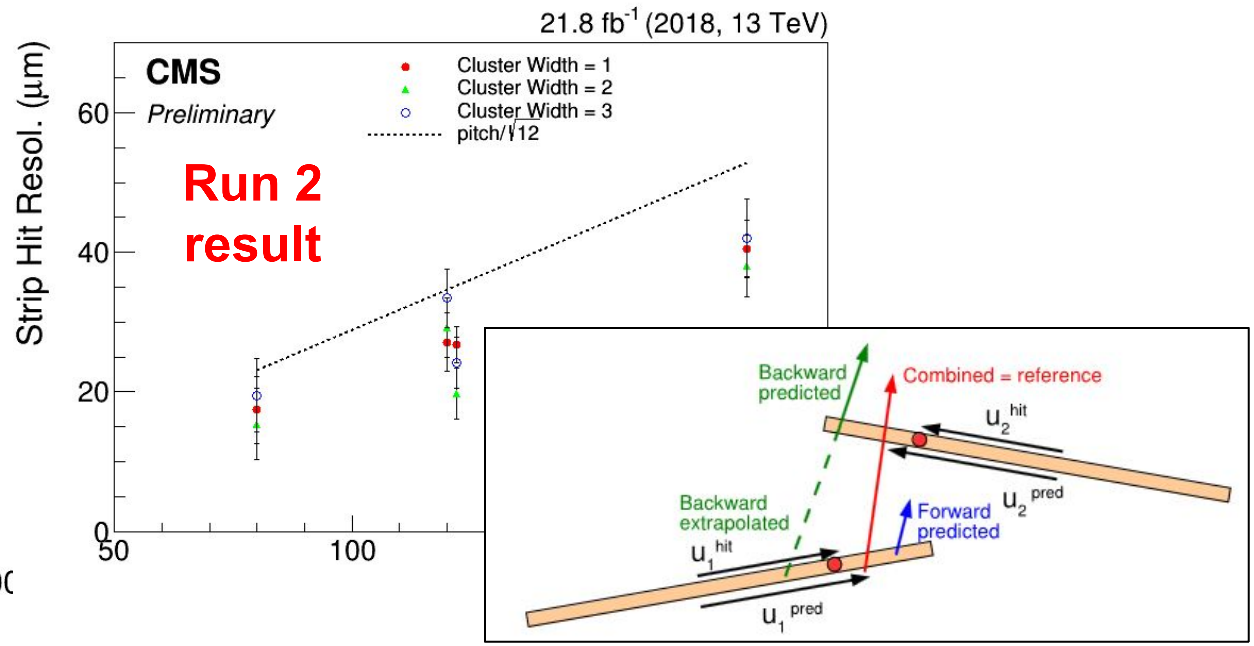
Strip Hit Efficiency



- Efficiency is measured using high purity tracks.
  - Efficiency is the fraction of traversing tracks with a hit anywhere within a range of 15 strips.
  - The modules flagged as bad are not included in the measurement.
- Eff. scales linearly with inst. lumi and pileup and is 98% even at high PU (measured in a dedicated high PU fill in 2022).
  - Run 3 startup hit efficiency is quite good comparing to Run 2.

Strip Hit Resolution

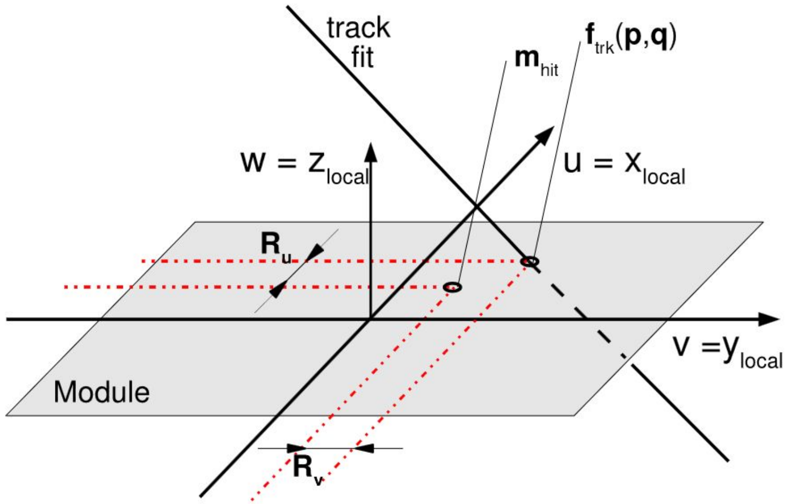




- The strip hit resolution is computed by using hits in overlapping modules of the same layer ("pair method").
- Strip Hit resolution derived with the by selecting pairs of hits in different types of overlapping sensors and for different cluster widths expressed in units of number of strips:
  - The expected resolution for a pitch/√12 is also shown for comparison, demonstrating the benefit from charge sharing due to the analogue readout → results completely inline with Run 2 expectations.

Track-based Tracker Alignment

- Goal: Determine with enough precision the position and orientation of all the modules of the tracker (20k with 6 degrees of freedom), being of few in the pixel tracker:



- Usage of tracks to align the modules following a Track-based alignment approach
  - Global fit of all parameters:

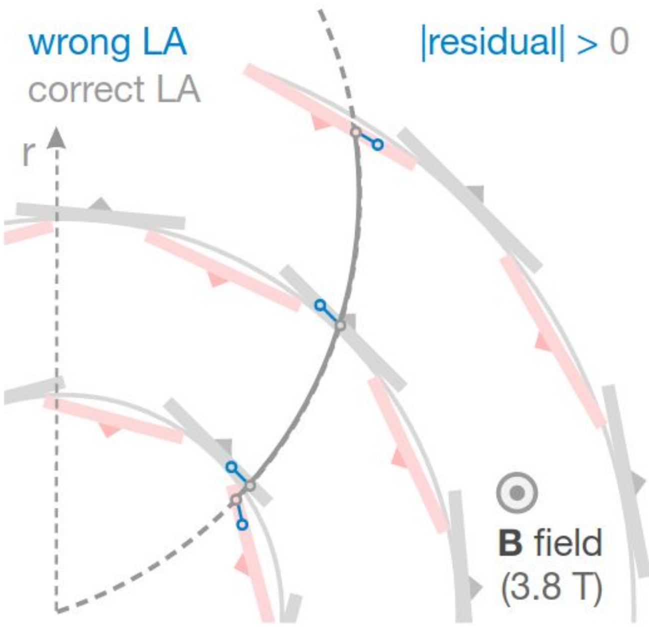
$$r_{ij}(p, q_j) = m_{ij} - f_{ij}(p, q_j)$$

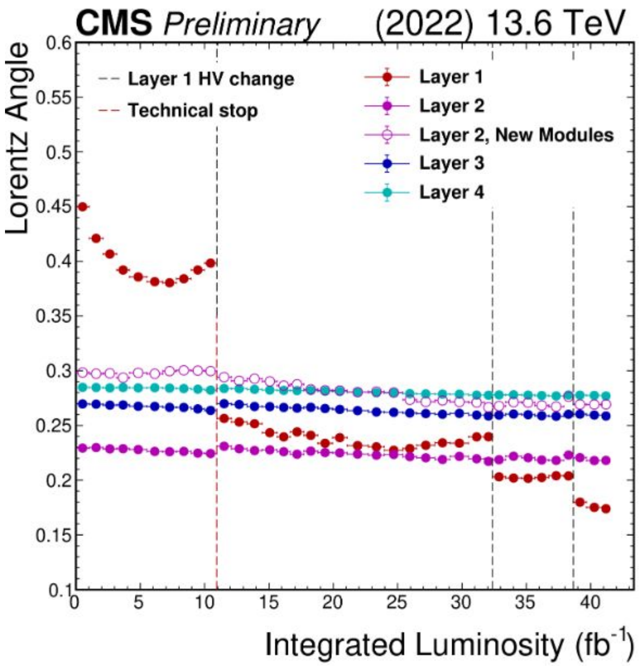
Minimisation of sum of squares of normalised track-hit residuals.

$$\chi^2(p,q) = \sum_j^{tracks} \sum_i^{hits} \left(\frac{m_{ij} - f_{ij}(p, q_j)}{\sigma_{ij}^m} \right)^2$$

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:

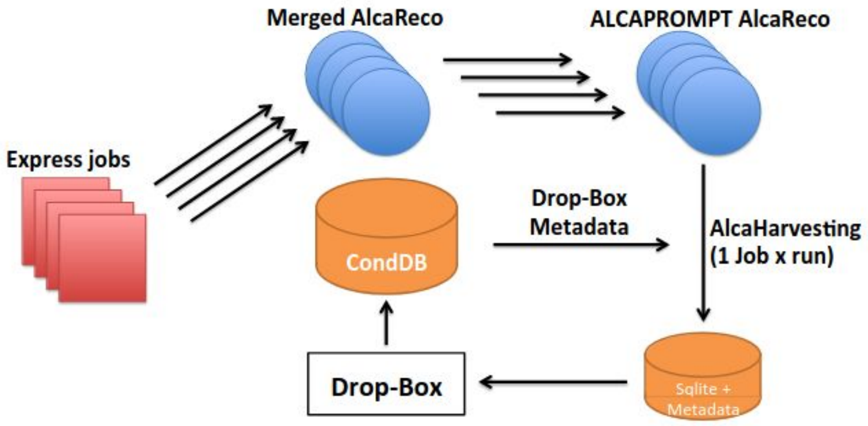
$$\Delta x' \propto \tan\theta_{LA}$$

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**)

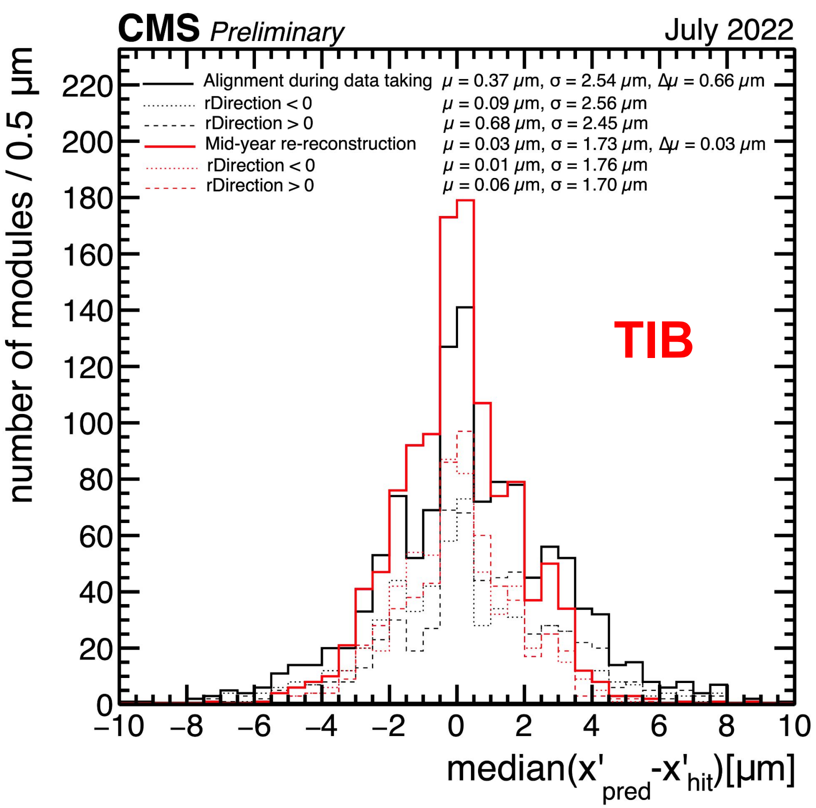
Track-based alignment at the level of ladders and panels

~ 5k alignment parameters

Replace some of the manual HG alignments after newpixel calibrations

Sensitivity to Lorentz Drift

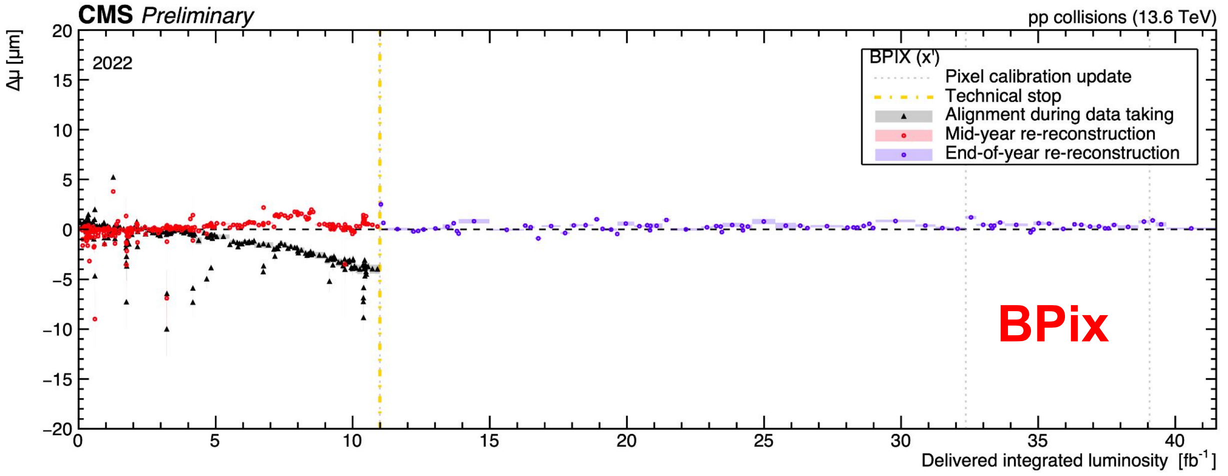
- Hit prediction obtained by fitting the track from all hits except the one under study
  - Obtain track-hit residual → Histogram of the median of the distribution



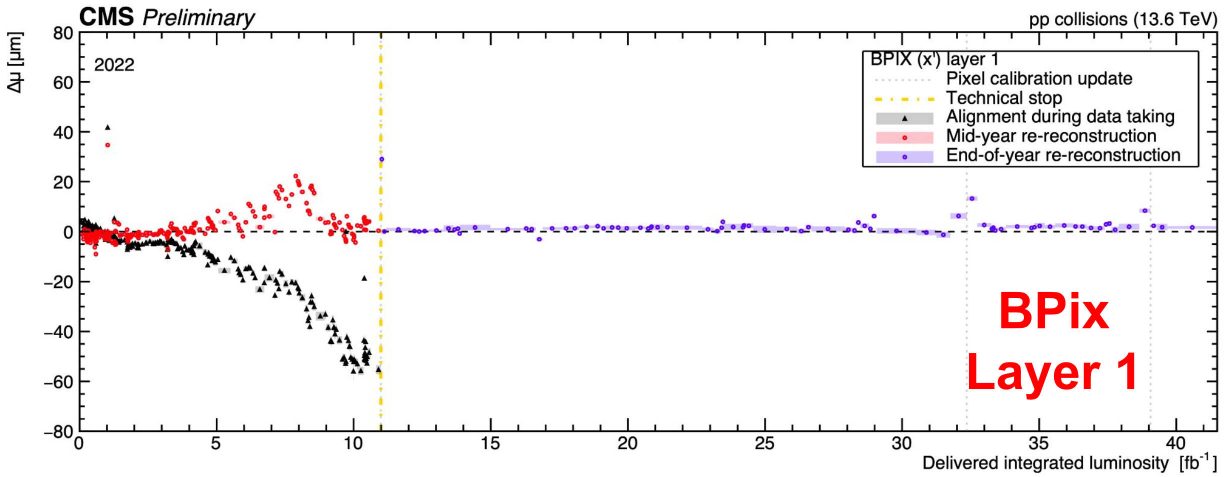
- Sign of the Lorentz Angle (LA) shift depends on the orientation of the E field
  - BPIX modules arranged in ladders (alternatively facing inward or outward w.r.t to the beamline);
  - This arrangement generates opposite shift in the hit position for inward and outward modules;
- Monitoring Δμ = difference in the mean of the inward and outward residuals distributions allows to monitor the Lorentz drift and its time dependence.

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

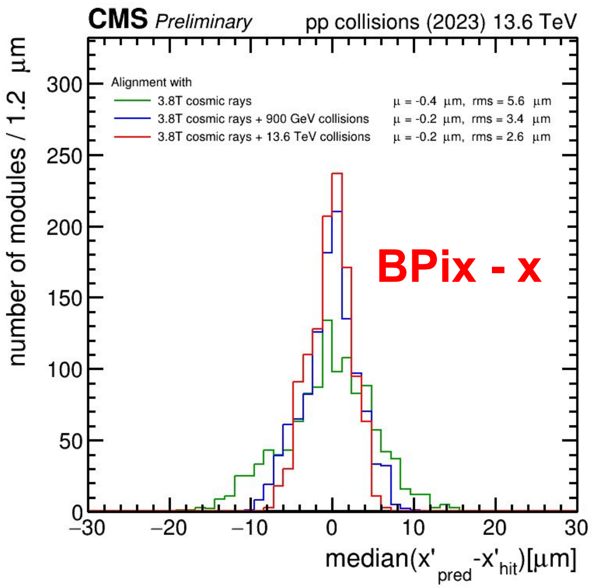


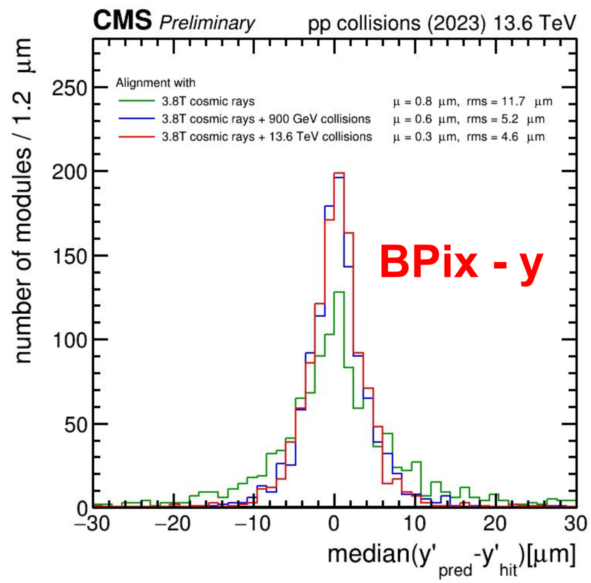
- Online HG PCL corrects position bias developed during data-taking and uncorrected by local reconstruction.

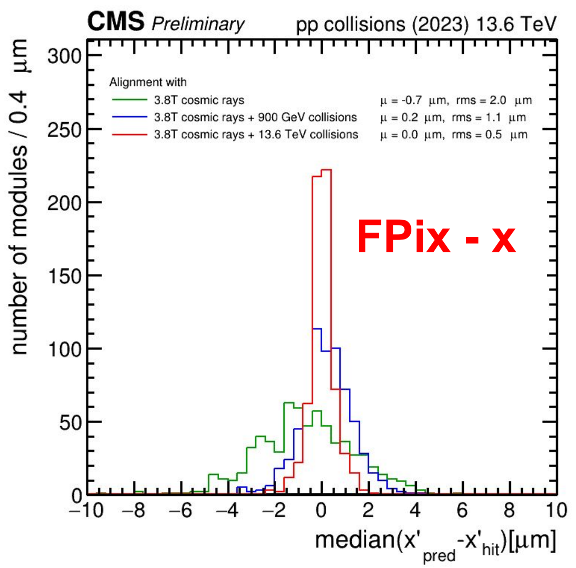


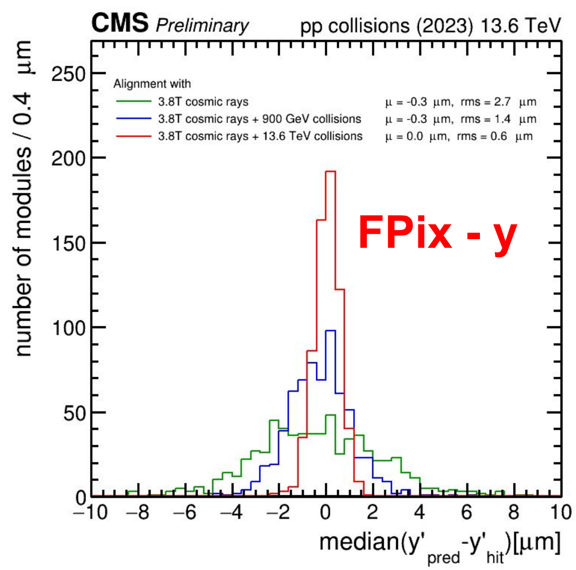
- BPIX layer 1 more affected since it's closer to the interaction point (notice different scale!).

Tracker Alignment in 2023





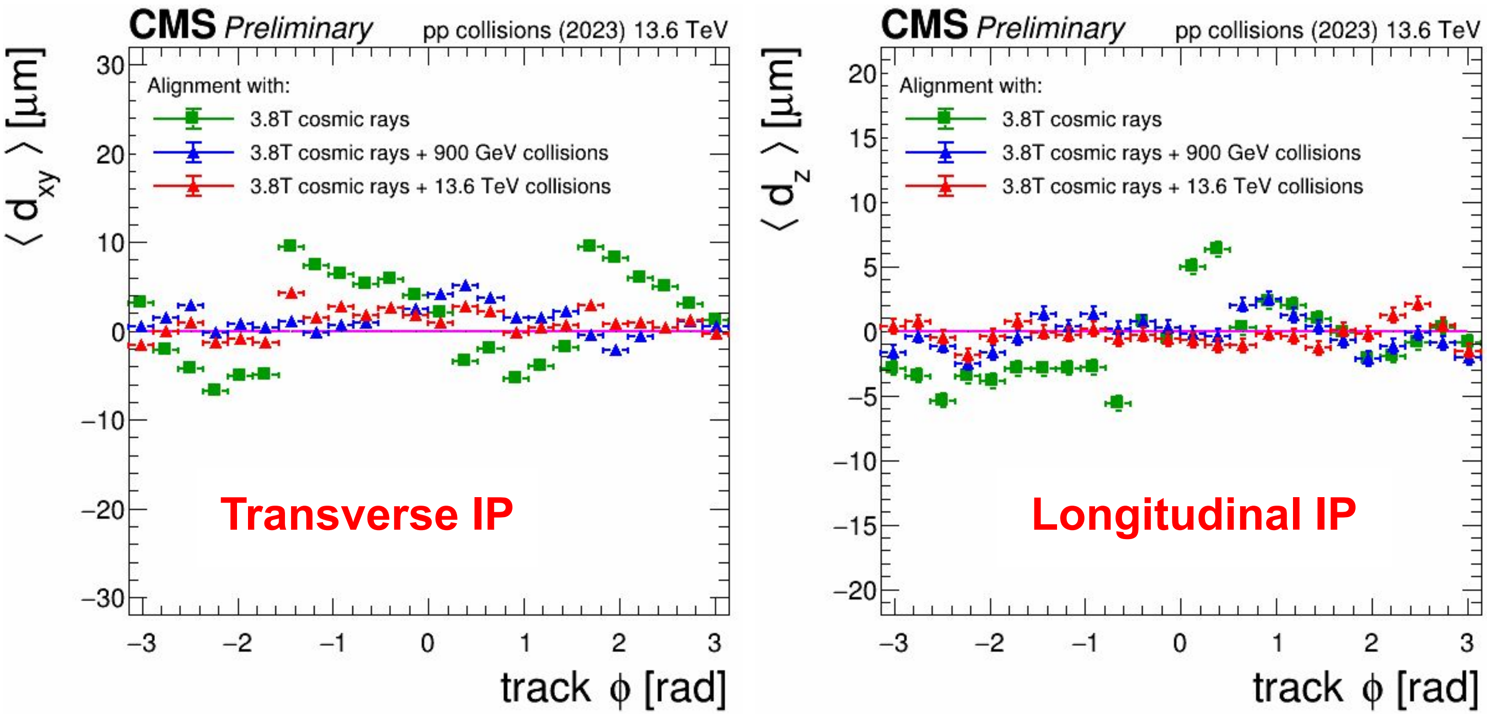




Distributions of Median Residuals (DMR):

- Median of track-hit residuals ($x'_{pred} - x'_{hit}$)is determined for a given number of tracks;
- To avoid biasing the measurement, tracks are first re-fitted while the hit under consideration is removed;
- With perfectly aligned detector, distributions are expected to be centred at zero value;
- Width of the distribution indicates local alignment precision.

Tracker Alignment in 2023



Primary Vertex (PV) validation

- Performance of track impact parameters;
- Measured using unbiased track-vertex residuals:
  - longitudinal d_z and transversal d_{xy};
  - Ideally averaged around zero;
- To avoid biasing measurement, all PV are first re-fitted while the track under scrutiny is removed

Summary

- The CMS Silicon Pixel Tracker after refurbishment with a new Layer 1 is successfully delivering high quality data in Run 3.
  - Ageing and Lorentz angle drift in silicon modules is monitored as a function of time using trends of hit efficiency and distributions of hit residuals;
- The CMS Silicon Strip Tracker operational and performing well after ~ 12 years of operation:
  - Active detector fraction was quite stable during Run 3.
  - Signal to Noise is quite stable and close to expectation.
  - Hit Efficiency and resolution also match expectations.
- The HG PCL has shown as being extremely efficient at absorbing effect of radiation damage reducing the need for manual updates of the alignment conditions and improving the quality of the alignment in the prompt reconstruction
  - HG PCL online shows stable performance in Run 3
- Studies are ongoing with data collected at 13.6 TeV this year and more results are expected by the end of this year.
  - Excellent tracking performance in the early Run 3 data taking.

Thank you for the attention!

Resources

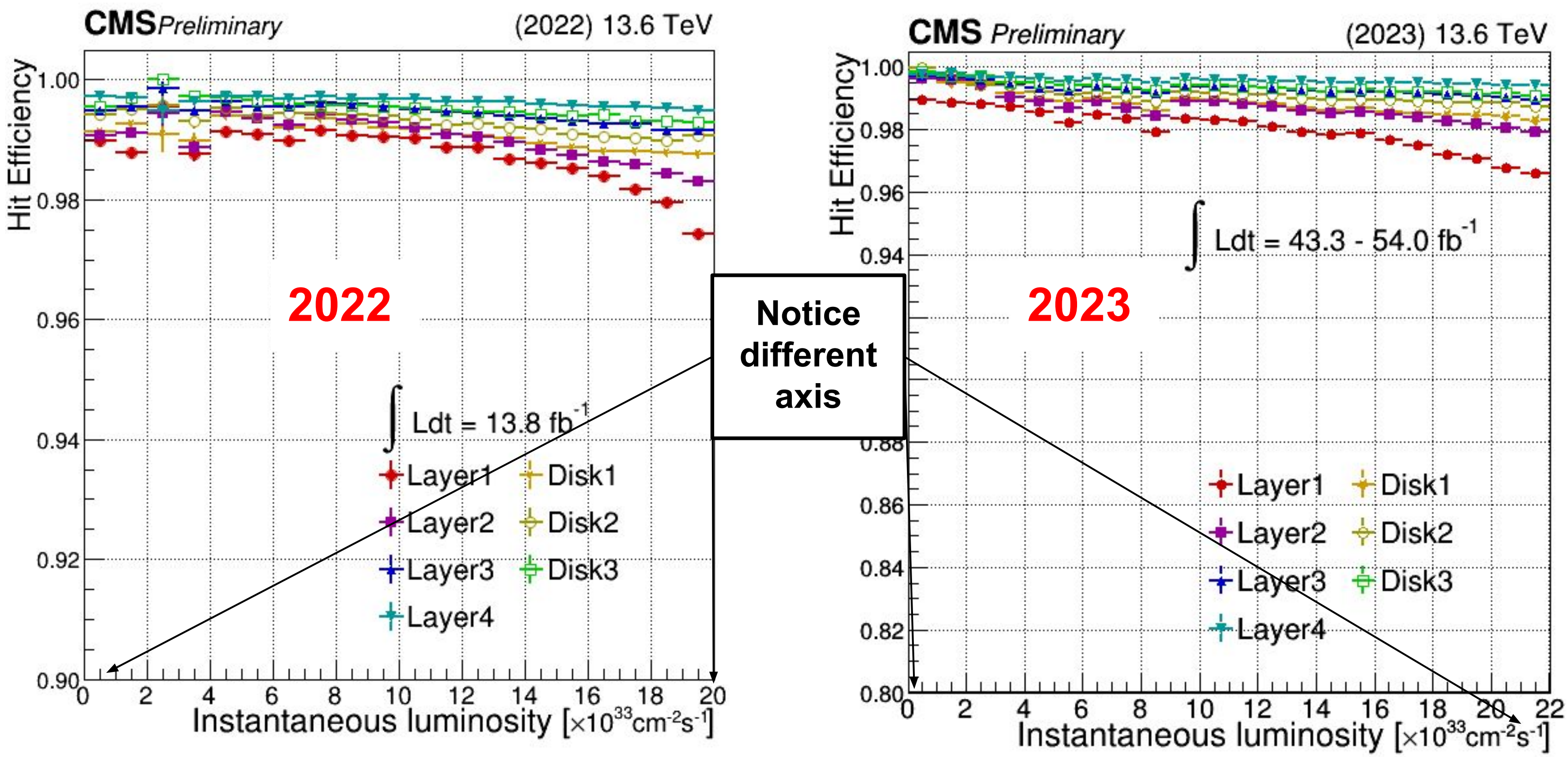
- CMS Pixel Detector Performance in 2022: CMS-DP-2022-067
- CMS Silicon Strip Tracker Performance Results in 2022: CMS-DP-2023-030
- CMS Tracker Alignment Performance in 2022: CMS DP-2022/044, CMS-DP-2022/070

- CMS Pixel Detector Performance in 2023: (DP note in preparation) https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlotsJuly2023
- CMS Silicon Strip Tracker Performance Results in early 2023: (DP note in preparation) https://twiki.cern.ch/twiki/bin/view/CMSPublic/StripsOfflineSummer2023
- CMS Tracker Alignment Performance in 2023: (DP note in preparation) https://twiki.cern.ch/twiki/bin/view/CMSPublic/TkAlignmentPerformance23

BACKUP

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.