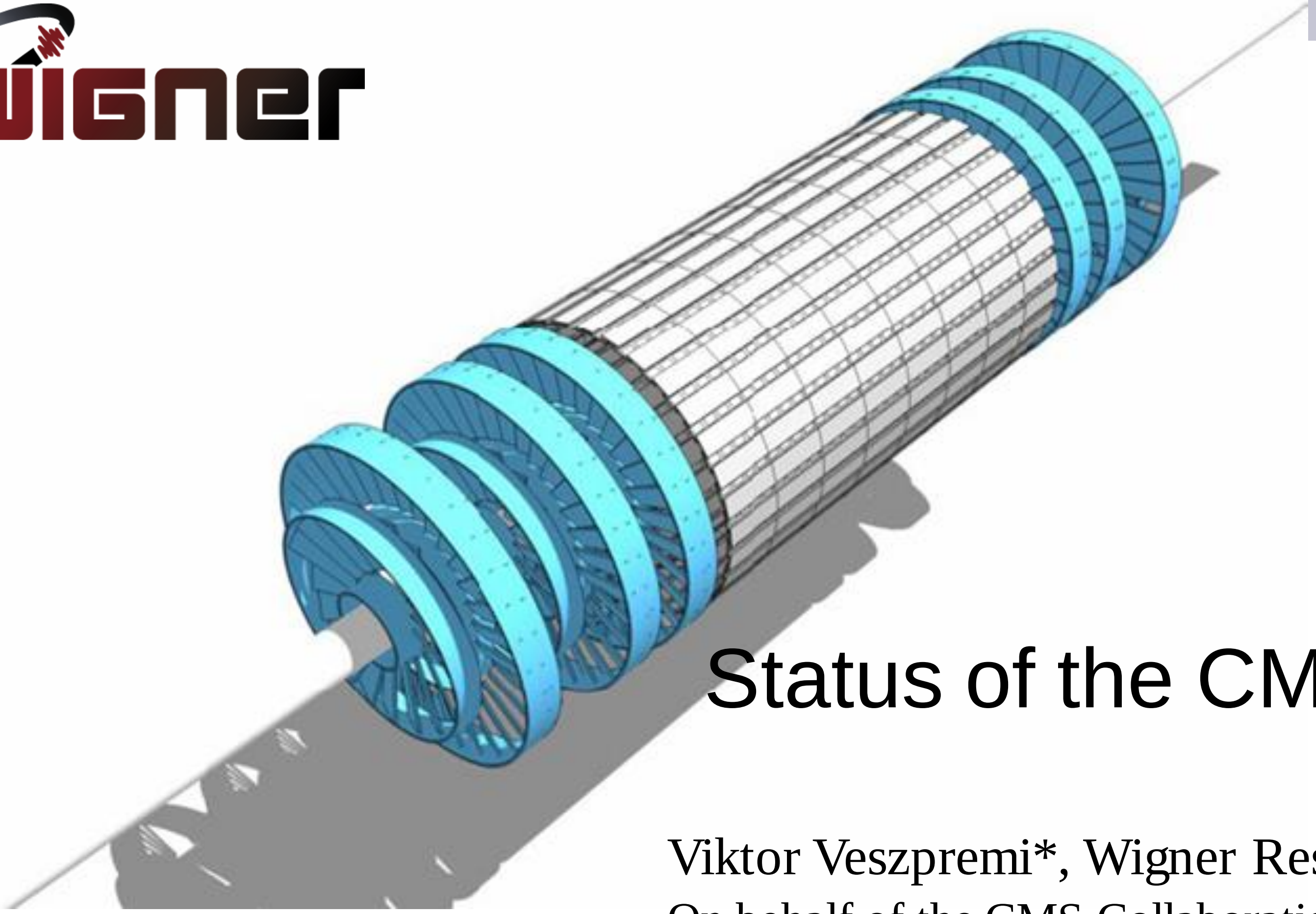


Status of the CMS Pixel Detector

Viktor Veszpremi*, Wigner Research Centre for Physics

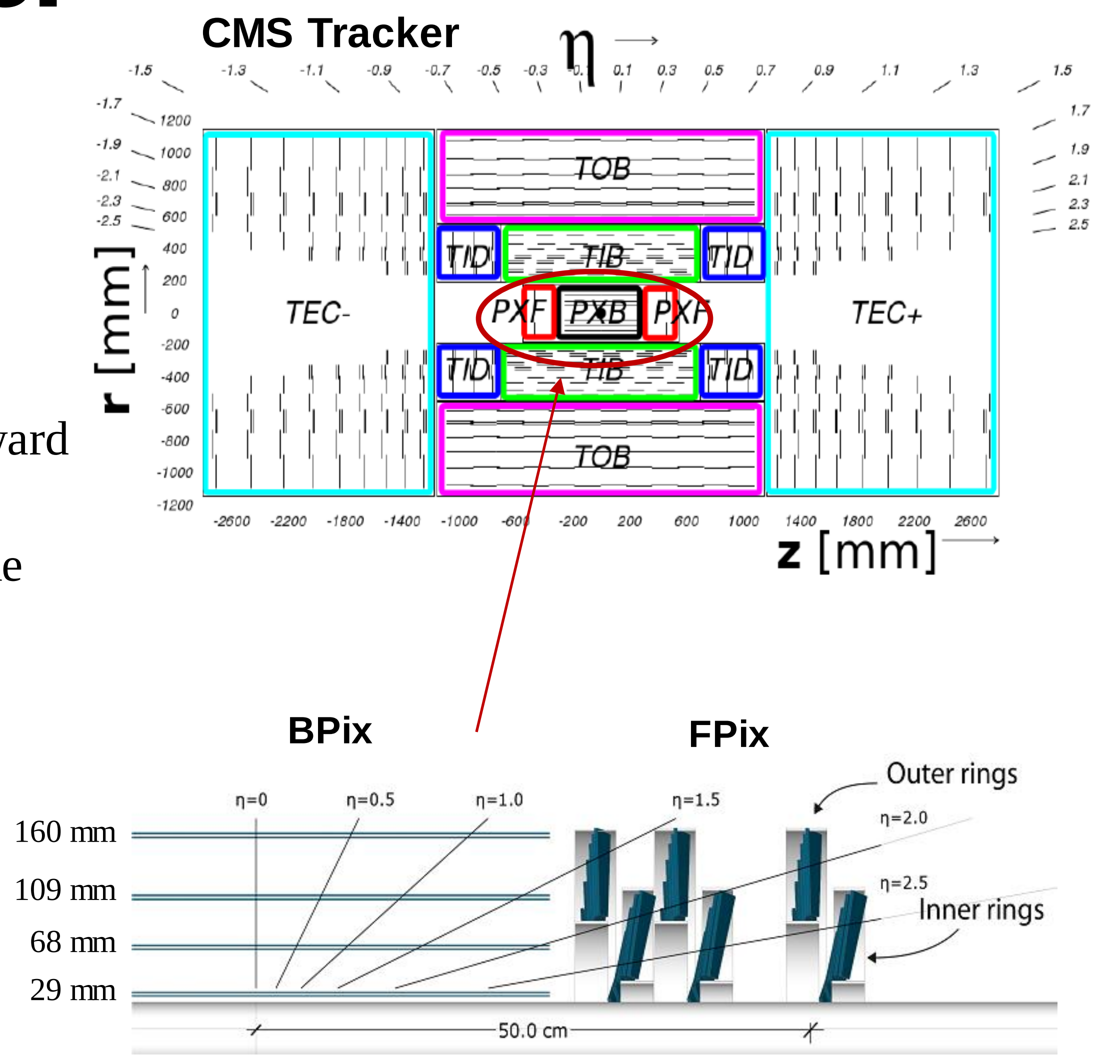
On behalf of the CMS Collaboration

PIXEL2022: 10th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging, 12-16 December 2022, Santa Fe, New Mexico, USA

*supported by OTKA K124850

The Phase 1 pixel detector

- Provides track seeds and determines primary and secondary vertex resolution
- First installed in January 2017 replacing the Phase 0 detector
  - One additional layer in barrel (BPix) and disk in forward (FPix)
  - 4-hit coverage up to η<3, made faster seeding possible by pairing hits and hit-pairs
  - Layer 4 potentially taking over role of TIB layer 1
  - Layer 1 adjusted to smaller beam-pipe diameter
- ~124 M channels, sensor covering 1.9 m^2 area
- Scheduled replacement of layer 1 after Run 2



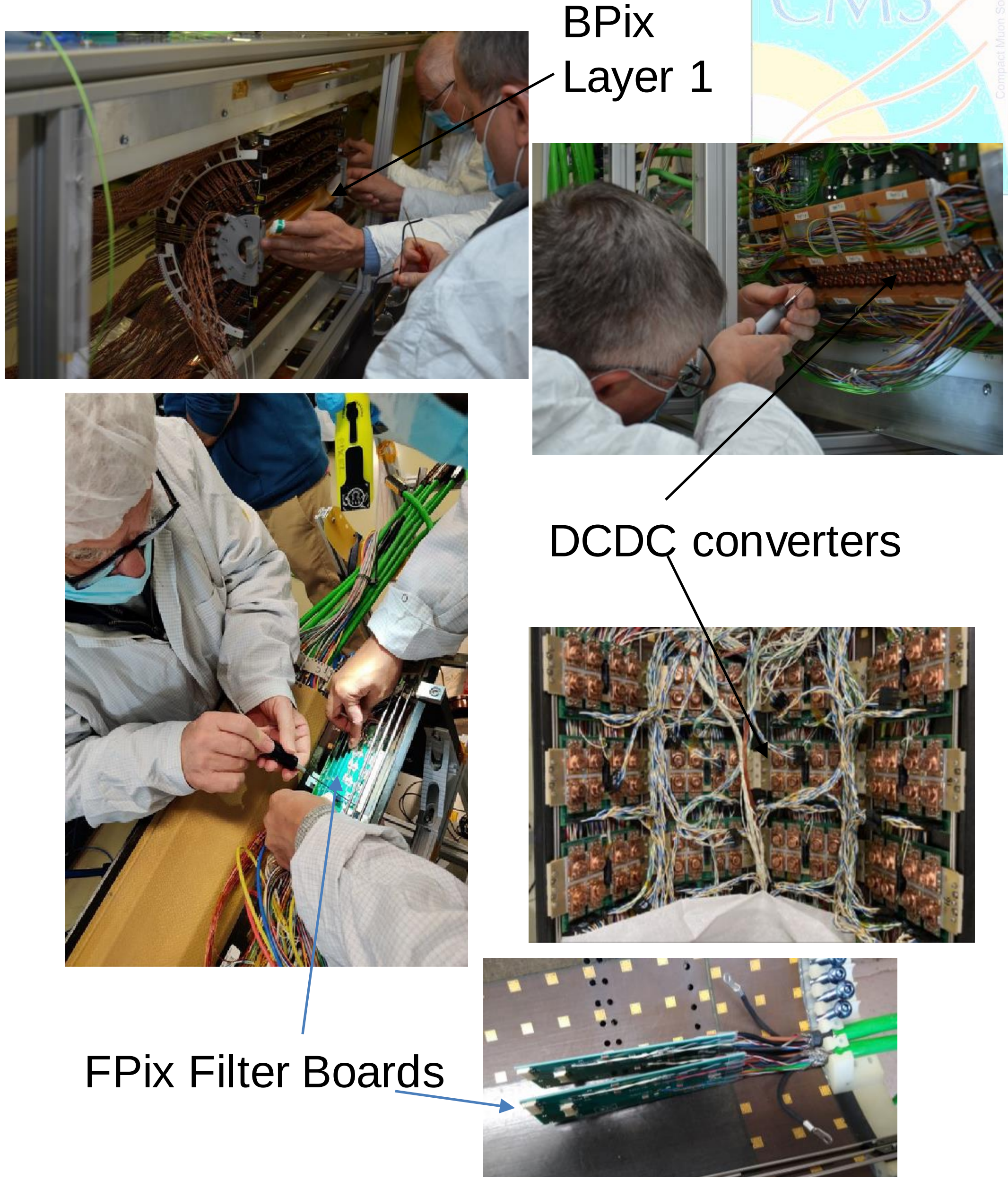
Refurbishment during LS2

- Refurbishment program carried out in LHC Long Shutdown 2 (LS2) started in 2019, otherwise detector kept cold and dry

- Barrel pixel
  - New layer 1 with updated ASICs
  - Replacement of few damaged layer 2 modules

- Forward pixel
  - Refurbished CO2 cooling connections
  - New power filter boards for better HV granularity

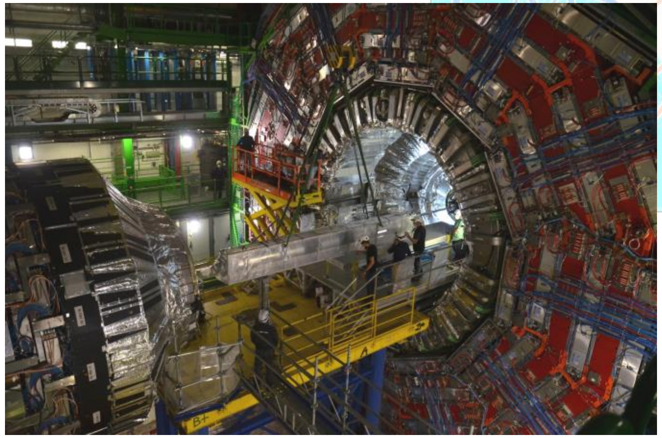
- Common
  - New DCDC converters with FEAST chip protected against failure in the disabled output state
  - HV power supplies upgraded to 800V (with max. current of 15 mA)

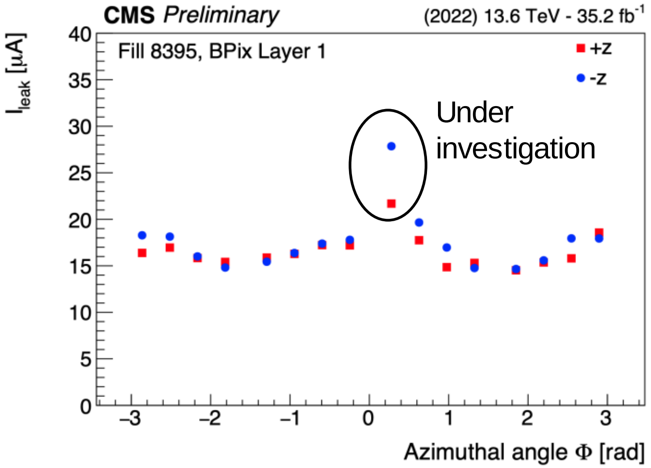


Photos by Erik Butz

Insertion and positioning

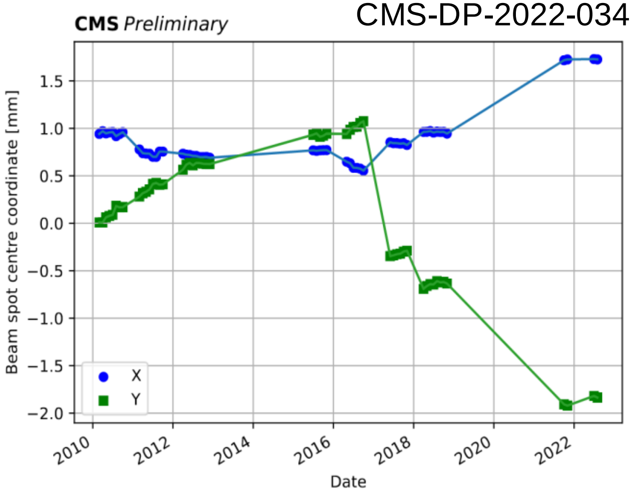
- Reinserted in June 2021
- Natural upward movement of the LHC tunnel –corrected by a 1.8 mm magnetic bump by end of Run 2
- LSS5 realignment + pixel positioning during insertion successful in order to remove magnetic bump along global Y → residual misalignment ~100 μm
- Observed > 1 mm residual beam offset along global X
  - Confirmed by increase of leakage current unevenly along ϕ
  - To be corrected by LHC during year-end technical stop





Uncorrected leakage current (per front-end chip) in each sector

CMS-DP-2022-034



Beamspot and BPix centers measured in the CMS coordinate system

Time alignment in first collisions

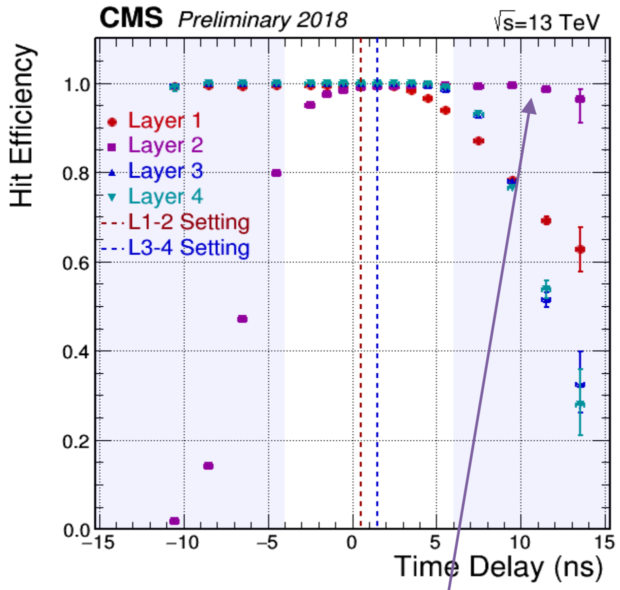
- Pixels built from two read-out chip (ROC) variants
  - FPix and BPix layers 2-4 with PSI46dig : digital readout, >90 % efficiency up to 400 MHz
  - BPix layer 1 with PROC600, digital readout, >90 % efficiency up to 600 MHz

- Internal timing different for the two chips (i.e. PROC600 is "faster")

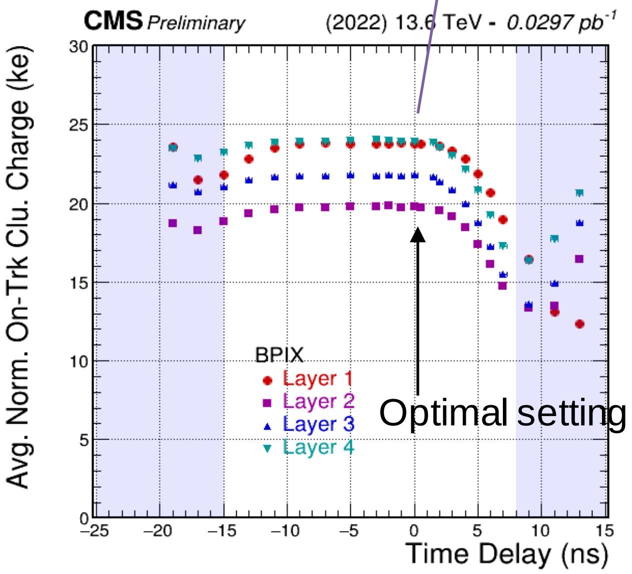
- Layer 1 and 2 share the same clock-tree due to space constraints
  - Timing was optimized for layer 1 in Run 2 : time-stamping hits as late as possible to mitigate time-walk → maximizes hit efficiency and cluster charge
  - Layer 2 read out "too early" → higher in-time threshold, lower resolution

- Newly introduced timing feature in layer 1 modules to optimize both layers separately for Run 3

CMS DP-2021/007



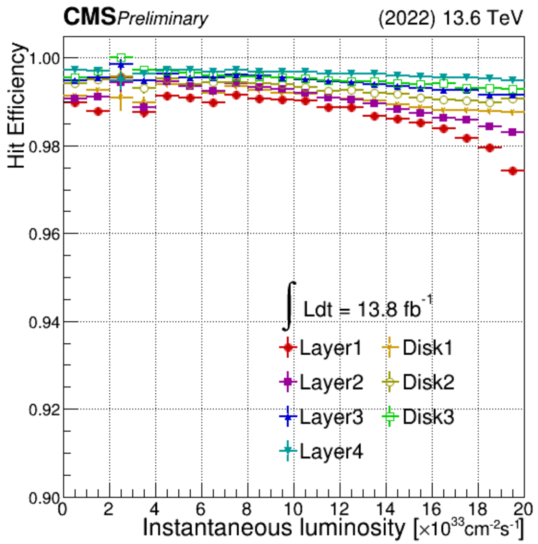
CMS-DP-2022-047



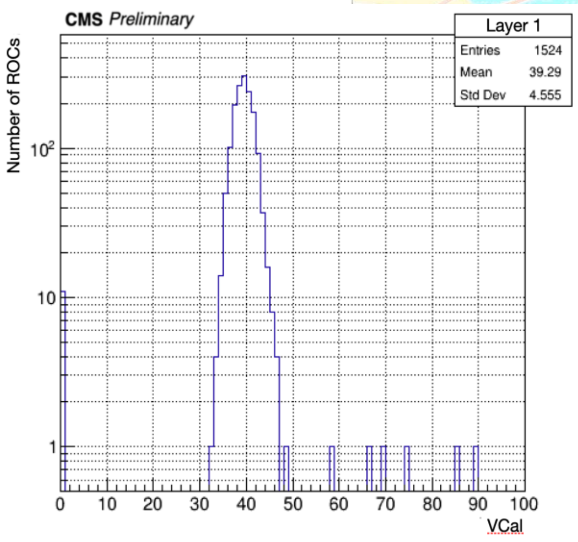
The new Layer 1

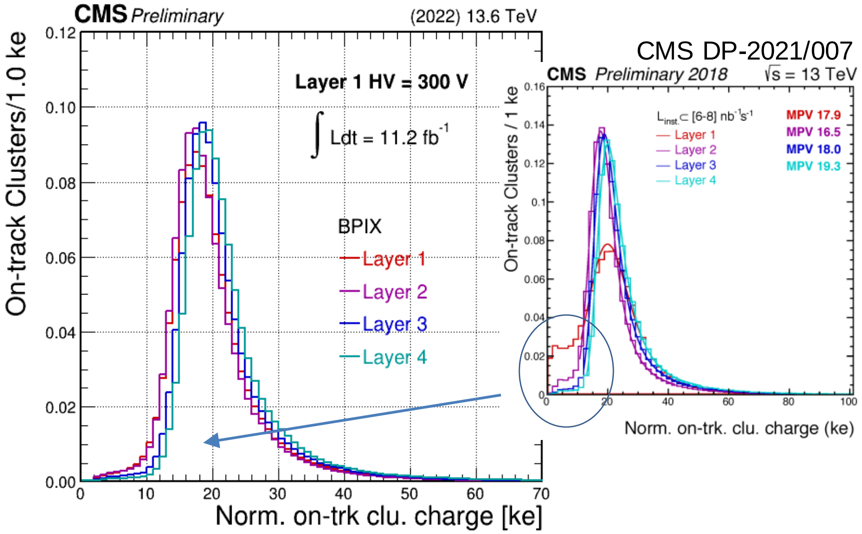
- Planned replacement was opportunity to fix a few features
- New readout chip v4
  - Fix too high dynamic inefficiency at very low and high particle rate : high inst. lumi. loss from several % to 2-3 %
  - Reduce cross-talk, improve thresholds from >3000 e- to ~2000 e-
- New Token Bit Manager (TBM)
  - New timing feature introduced
  - Improved SEU resistance against problem that put the TBM in a "stuck" state
  - Reset capabilities as a safety net
- New HDI designed to operate at higher bias voltage to extend time of operation by increasing HV

Cluster finding efficiency

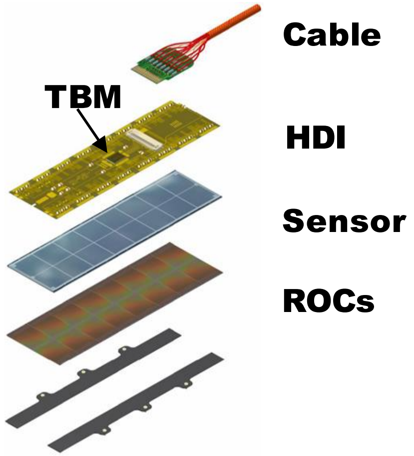


In-time threshold measured by internal charge injection



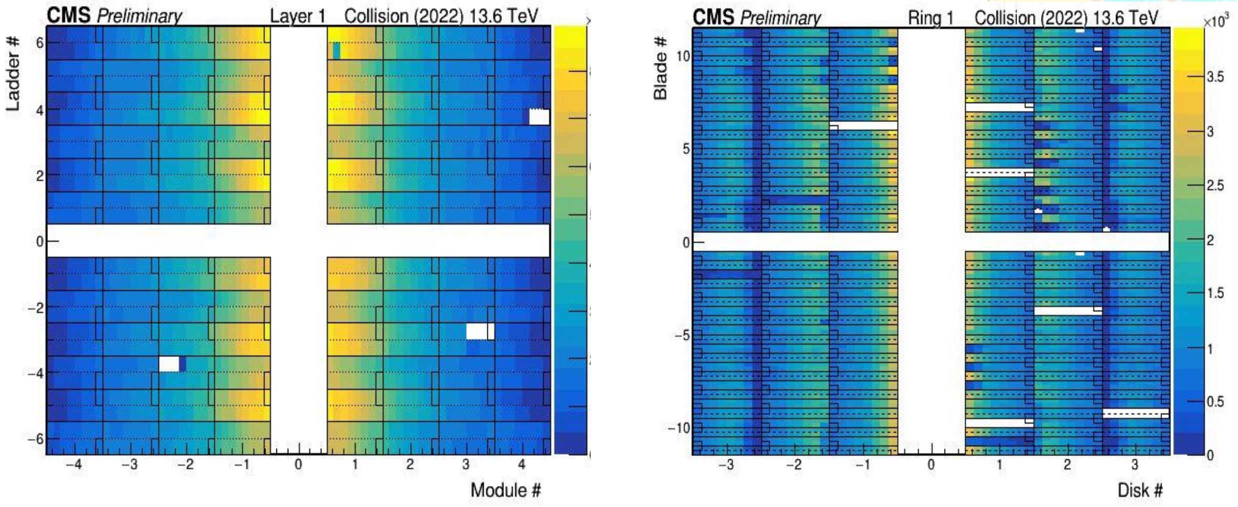


Cluster charge normalized to impact angle



Active detector fraction

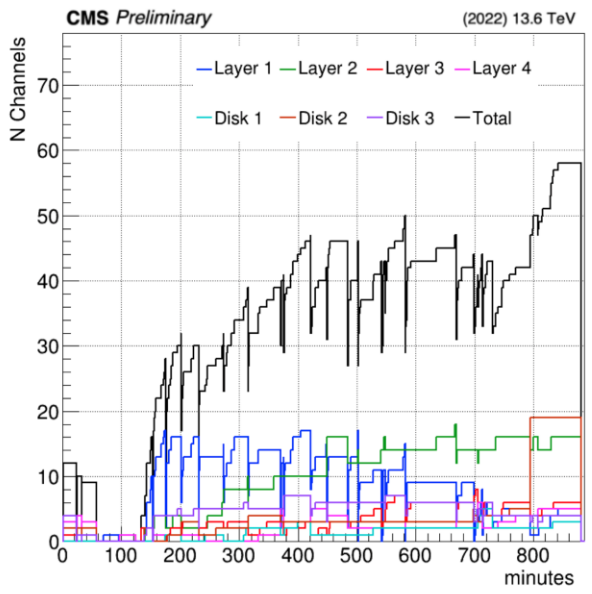
Bpix Layer 1 and Fpix cluster occupancy (CMS-DP-2022-047)



- Cluster occupancy plot with ROC binning
  - White areas (with non-zero coordinates) are permanently bad ROCs
  - Temporarily bad ROCs due to SEU also seen
  - Noisy modules in FPix due to Run 2 operation when HV was ON but LV was off

- **BPix and FPix** active fractions are **98.4 % and 98 %** after recommissioning (were 93.5% and 96.7 % before LS2 – CMS DP-2021/007)

- **Temporarily bad** channels are masked during operation → total fraction **up to 5-8 %**
  - Partially recovered by reprogramming
  - Non-layer 1 modules sometimes unrecoverable by programming (“stuck TBM”) → detector is power-cycled between fills
  - Layer 1 module masking decrease with instantaneous luminosity



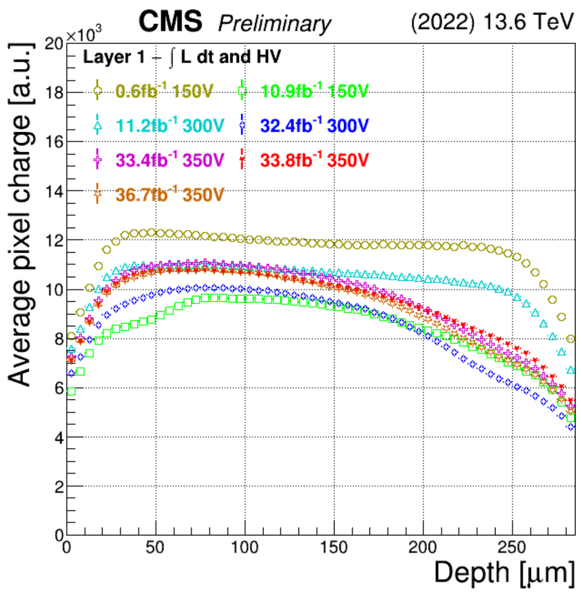
Number of read-out channels masked in the back-end in response to frequent read-out errors

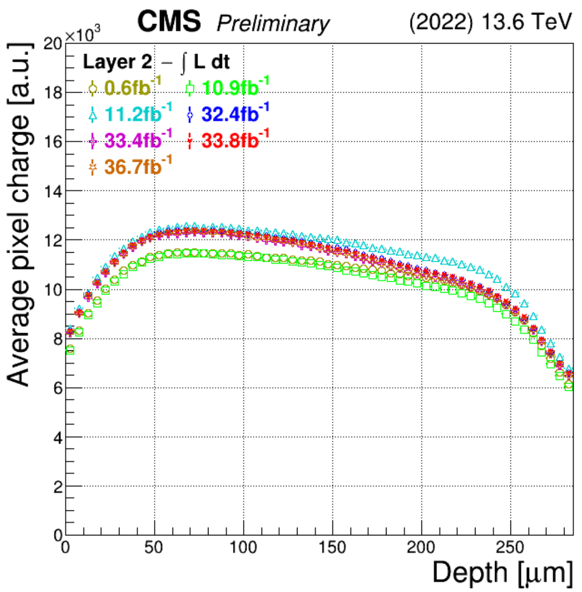
Charge collection

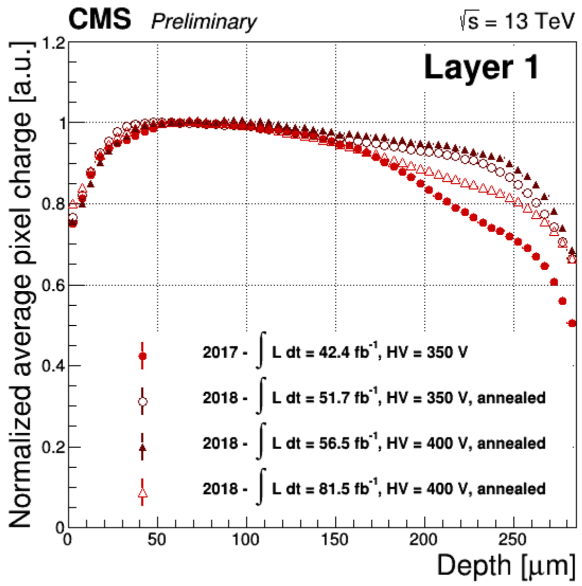
- Production depth computed from the displacement of the pixel center with respect to the track impact point and the track impact angle

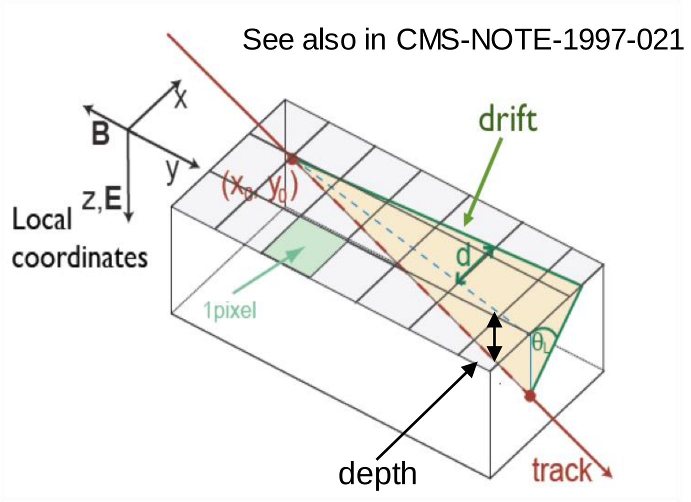
- Layer 1
  - Large drop in charge collection efficiency in the first 10 fb^{-1}
  - Recovered by increasing bias voltage from 150V to 300V
  - Further increases to 350V and 400V were applied by end of year
  - Charge loss at end of 2022 largely compatible with end of 2017

- Layer 2 (and others)
  - Annealing effects during the Technical Stop 1 (TS1)



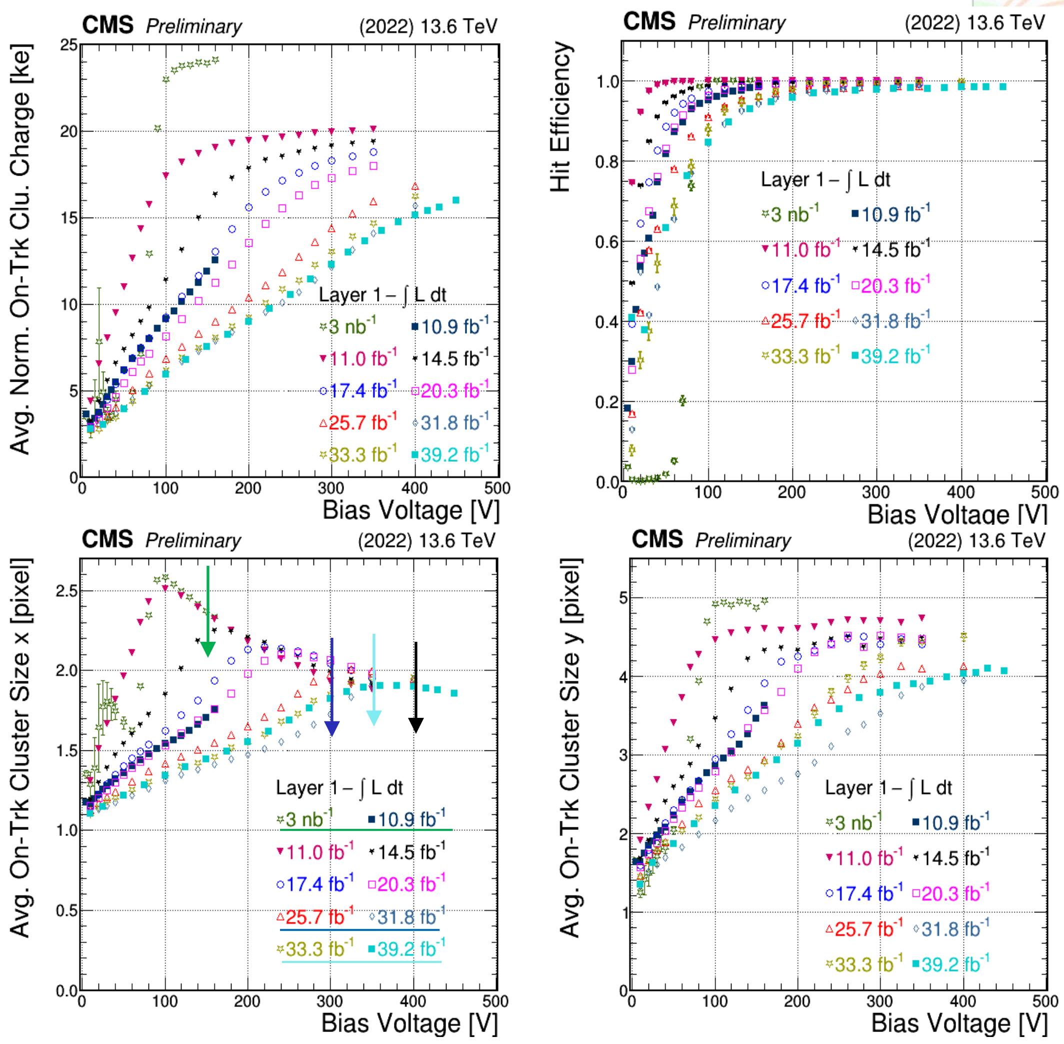






Monitoring radiation damage effects

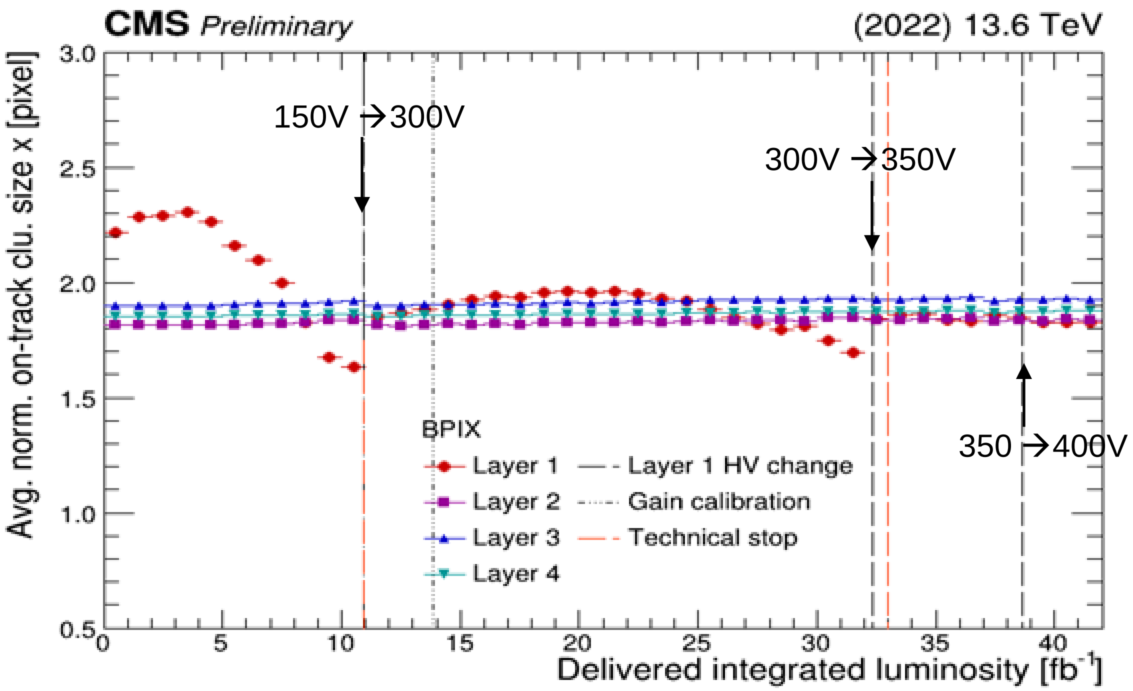
- High voltage bias scans performed multiple times a year
- Transparent "mini scans" done on single HV channels powering BPix layers 1-4 and FPix disks 1-3 modules non-overlapping in tracking (results shown for layer 1)
- Type inversion likely happened before second scan
- Operation voltage at startup was 150V, increased to 300V after second scan, and to 350V after 31.8 fb^{-1}
- Finished data-taking at 400V

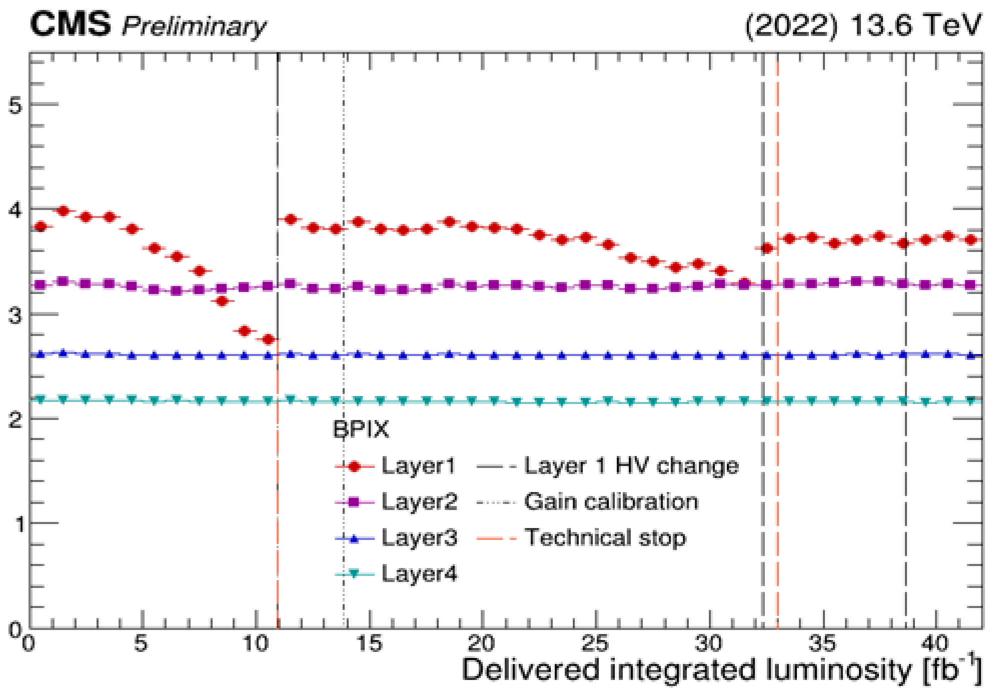


Monitoring cluster properties

- Size in local x determines resolution in the global azimuthal angle ϕ – optimal setting of HV is a balance between Lorentz Angle and charge collection efficiency

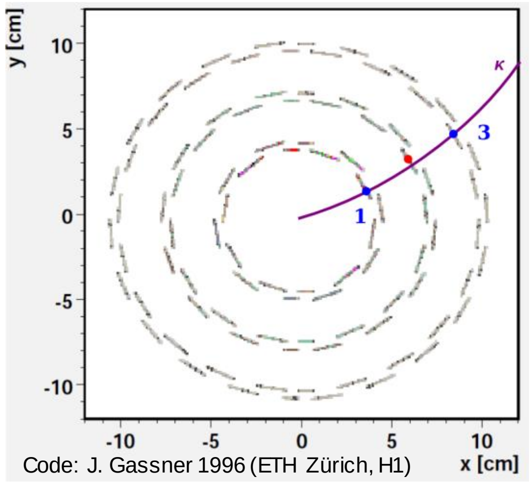
- Size in local y determines resolution in global Z – maintained relatively constant apart from initial rapid radiation effects in first 10 fb^{-1} (the first three weeks in real-time)





Estimate of the resolution

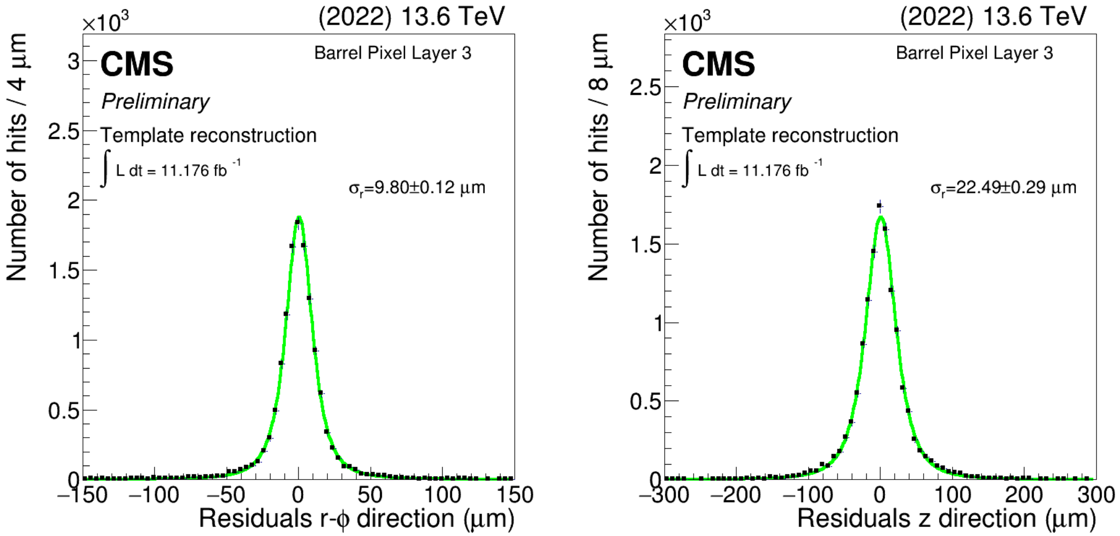
- Triplet method:
  - p_T > 12 GeV tracks with hits in 3 layers are selected and refitted using hits in two of three layers
  - Trajectory extrapolated to remaining layer, residuals with the actual hit are calculated
  - Residual distribution fitted with the Student-t function



- Template: an algorithm based on detailed cluster shape simulations predicted by PixelAv [1,2]. Used in the final fit of each track in the offline reconstruction

- Example shows residual in layer 3: propagate from hits on layer 2 and 4

- Observed residual distribution is the sum of the intrinsic detector resolution and a track extrapolation error

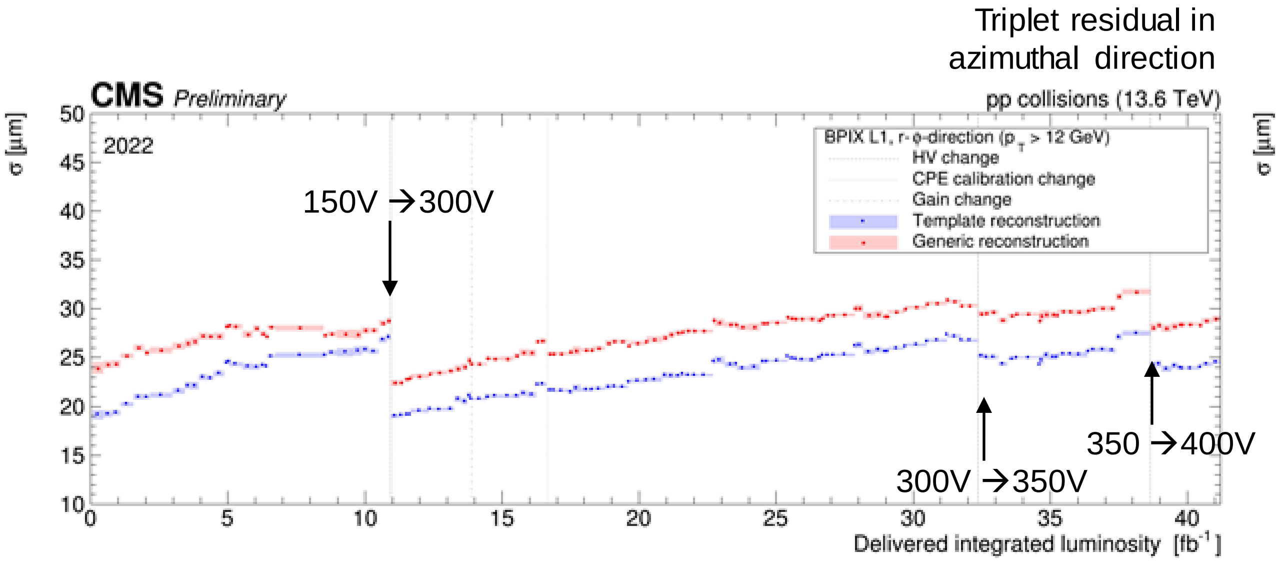


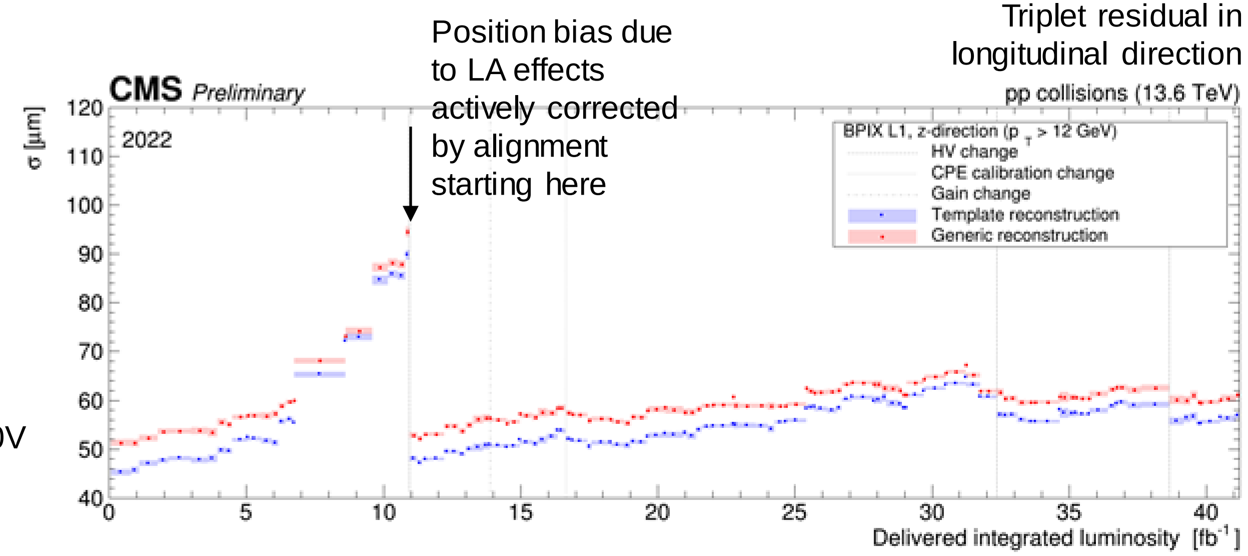
[1] M. Swartz, “CMS pixel simulations”, Nucl. Instrum. Methods, A 511 (2003), 88-91

[2] M. Swartz and D. Fehling and G. Giurgiu and P. Maksimovic, “A new technique for the reconstruction, validation, and simulation of hits in the CMS pixel detector”, PoS VERTEX2007 (2007), 035

Monitoring hit residuals in Layer 1

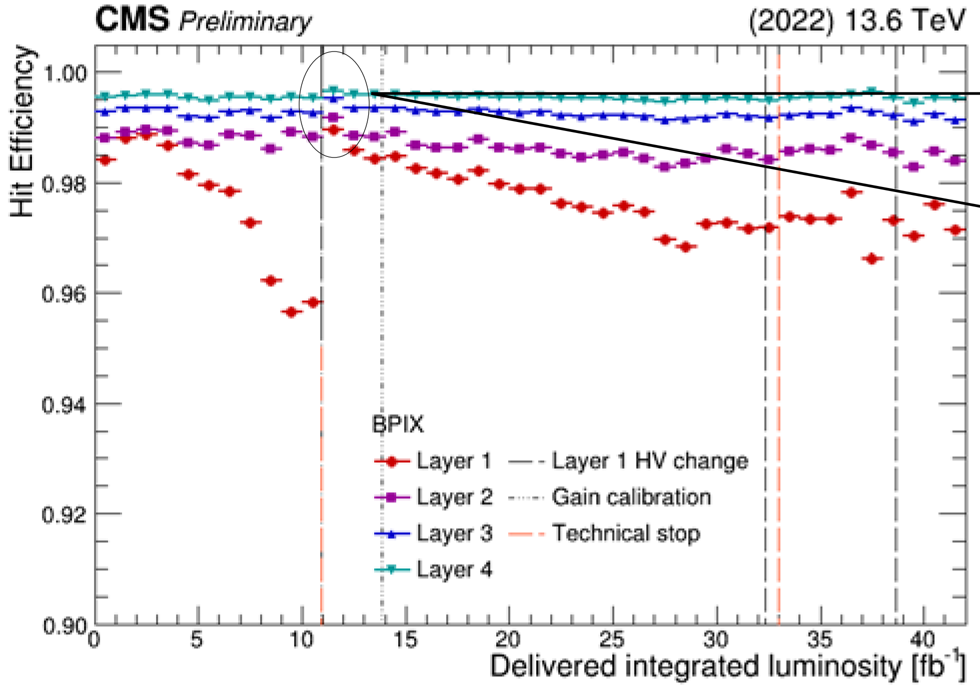
- Layer 1 triplet is weekly constrained by using hits on layer 2 and 3 → resolution is more difficult to estimate
- Improved residual w.r.t Run 2 → lower thresholds and cross-talk confirmed
- Maintained relatively constant transverse resolution, somewhat late change of HV bias for the longitudinal direction
- Note: see more on position bias due to rapid change in Lorentz Angle in the Alignment talk during this conference

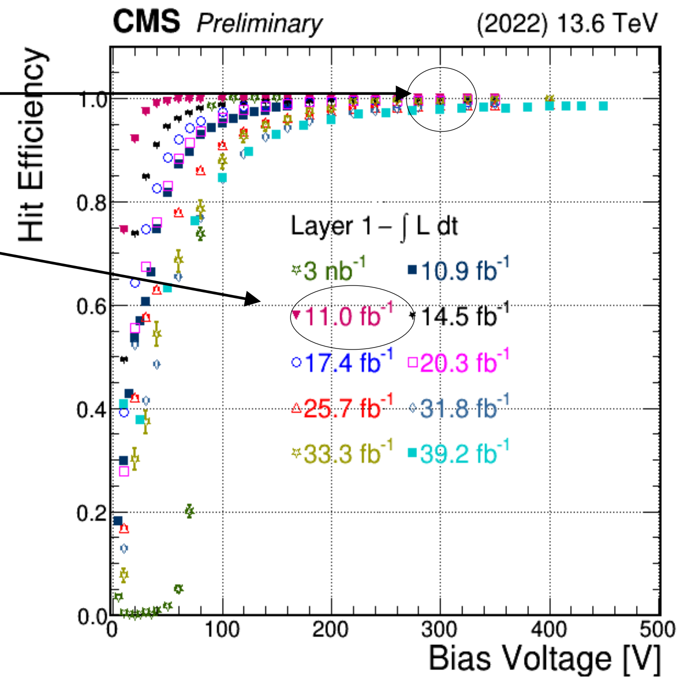




Monitoring hit efficiency

- Hit efficiency is the probability to find any cluster within 1 mm around an expected position, independent of the cluster quality
- Measured with muon tracks with p_T >2 GeV in order to remove seeding bias
- All permanent and temporarily bad components are eliminated
- Around the maximum, inefficiency is predominantly due to dynamic effects in the read-out chip
- Also observe losses due to under-depletion (mostly at large Z with particles incoming at grazing angle)





Summary and outlook

- Successful refurbishment and recommissioning followed by relatively smooth data-taking
- Very preliminary studies are available, but detector performance remains good, high active fraction
- New layer 1 fulfilled our hopes, several weak features fixed
- Radiation damage is largely compatible with earlier expectations so far
- Lower threshold in layer 1 and higher maximum bias voltage provides extended lifetime
- Studies to determine if lifetime compatible with duration of Run 3 are being updated

Extra slides

Start of data taking	Delivered integrated luminosity	Comments
23rd July 2022	0.55 fb^{-1}	Beginning of Run 3 (Layer 1 HV=150 V)
23rd August 2022	10.9 fb^{-1}	Right before TS1 (Layer 1 HV=150 V)
30th September 2022	11.2 fb^{-1}	Right after TS1 (Layer 1 HV=300 V)
03rd November 2022	32.4 fb^{-1}	Right before MD2 (Layer 1 HV=300 V)
05th November 2022	33.4 fb^{-1}	Right before MD2 (Layer 1 HV=350 V)
12th November 2022	33.8 fb^{-1}	Right after MD2 (Layer 1 HV=350 V)
16th November 2022	36.7 fb^{-1}	After MD2 and before FMD4 (Layer 1 HV=350 V)

- Table showing the information on runs used to study the cluster properties in slides 4 -11.

TS1 - Technical Stop 1
MD - Machine Development
FMD - floating MD