Tracking performance and alignment of the upgraded CMS tracker

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On behalf of the CMS Collaboration

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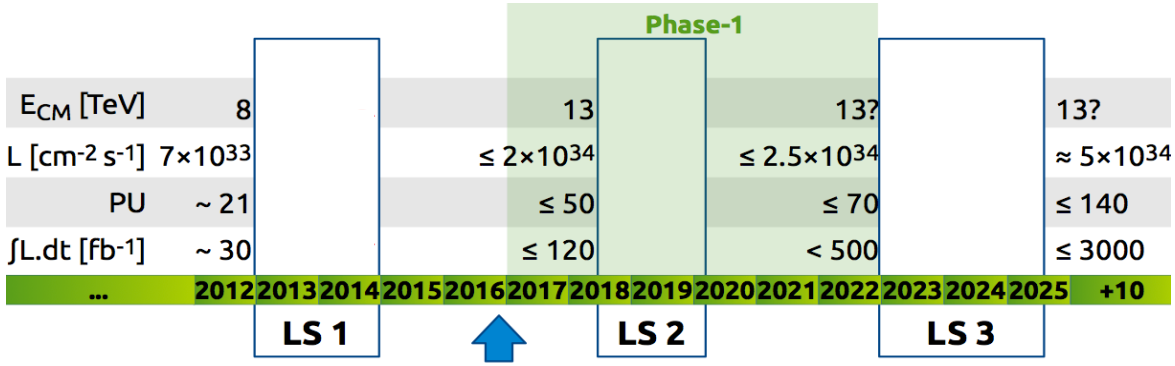
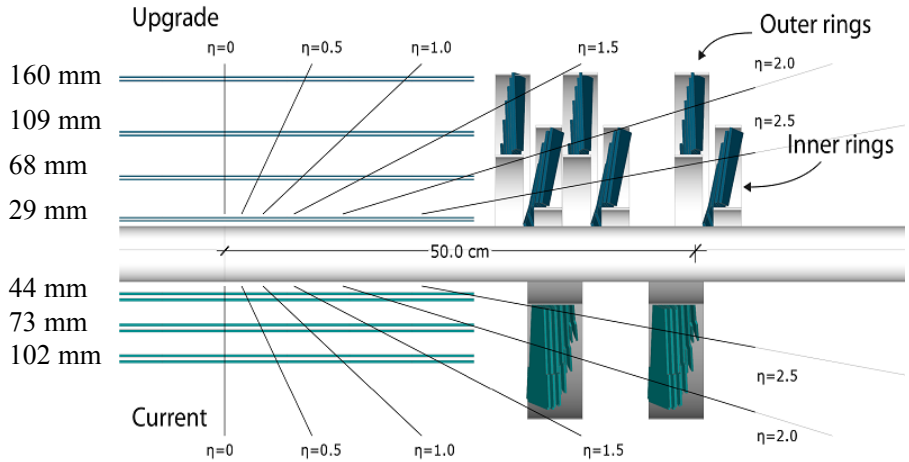
*supported by the János Bolyai fellowship of the Hungarian Academy of Sciences

Motivation for pixel upgrade



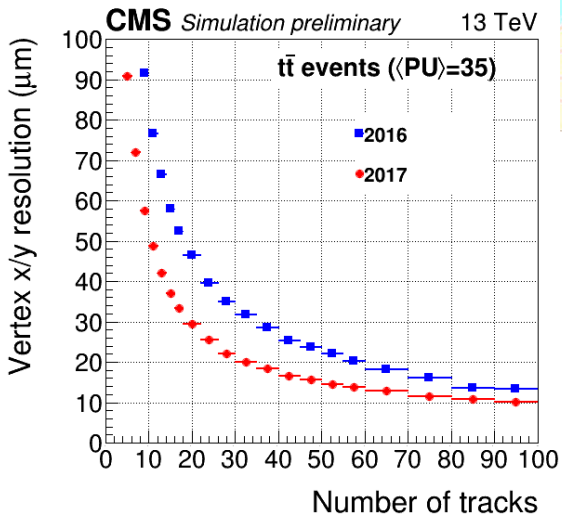
- previous detector designed to operate at 10^{34} cms^{-2}s^{-1} @ 25 ns bunch spacing
- LHC expects to reach 2.5 times that and 70 PU before LS3
- Goals
  - Sustain data-taking
  - Maintain and improve performance
  - Keep the original design wherever possible

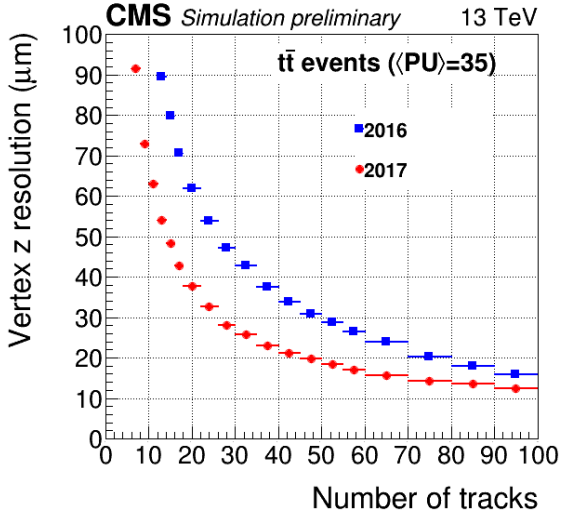
- More layers both in Barrel (BPix) and Forward (FPix) pixel in the same detector volume
  - BPix 48 M → 79 M; FPix 18 M → 45 M
- Detector and services in the same mechanical envelope
- Maintain the same or better material budget
- Quick replacement during extended TS in 2017



Advantages of Phase 1 geometry

- Increased event PU → larger multiplicity
  - More primary vertices to resolve
  - Higher hit rate in the chip
  - Increased processing time and fake-rate due to combinatorics
- Extra layers at no cost on material budget
  - Redundancy for hit loss
  - Quadruplet seeding possible
  - Better p_T resolution
- The new layout
  - Inner layer closer to beam – better impact parameter resolution
  - Outer layer closer to outer tracker – easier track propagation from pixels to first outer tracker layer



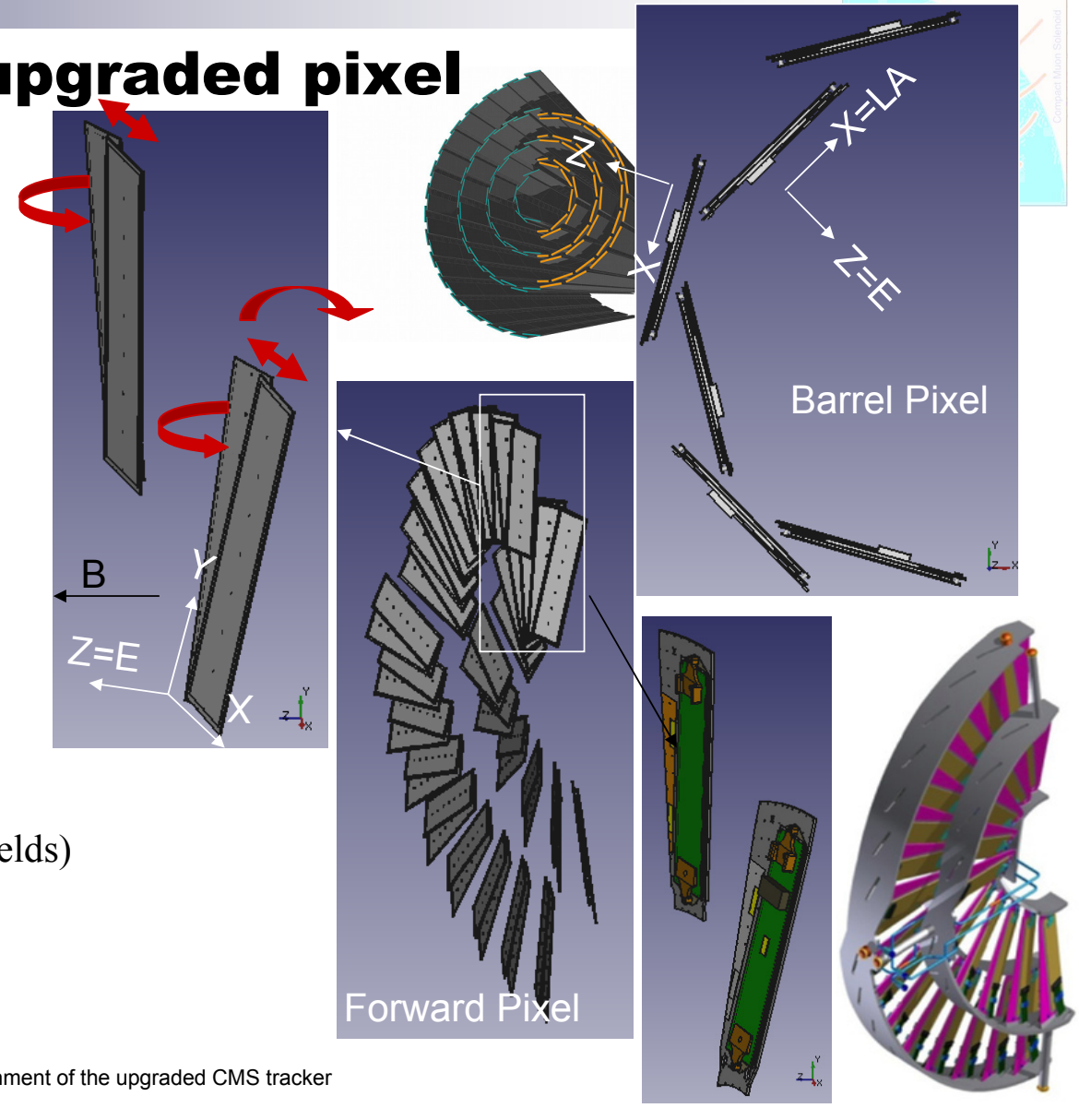


Hit reconstruction in the upgraded pixel

- Same sensor as before the upgrade:
  n+-in-n, 285 µm thick, 100x150 µm pixel size

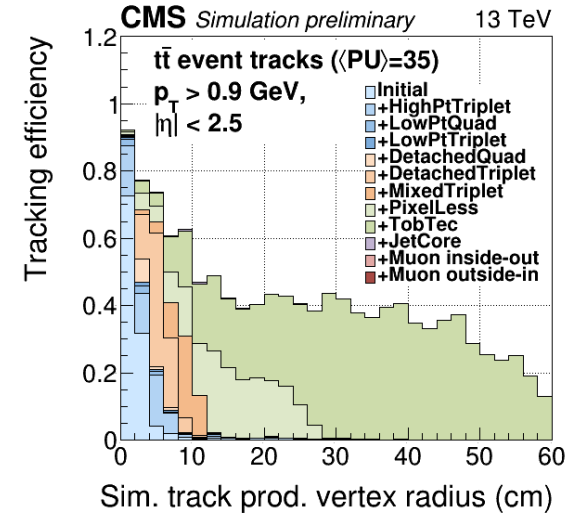
- Read out in zero-suppression mode
  - Low noise, thresholds generally lower than in previous detector
  - More radiation tolerant

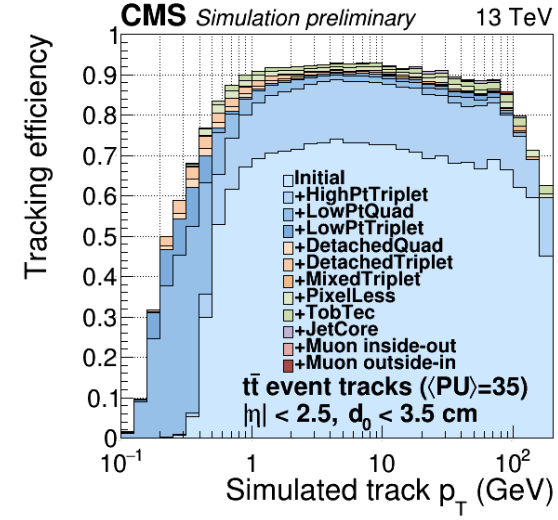
- Cluster parameterization
  - Thick sensors + magnetic field
    → significant charge sharing
    → **but beneficial for resolution**
  - BPix geometry fairly simple (perp. E- and B-fields)
  - FPix complicated, requires LA description in 8 different E-field configuration w.r.t the B-field



Tracking algorithm and seeding

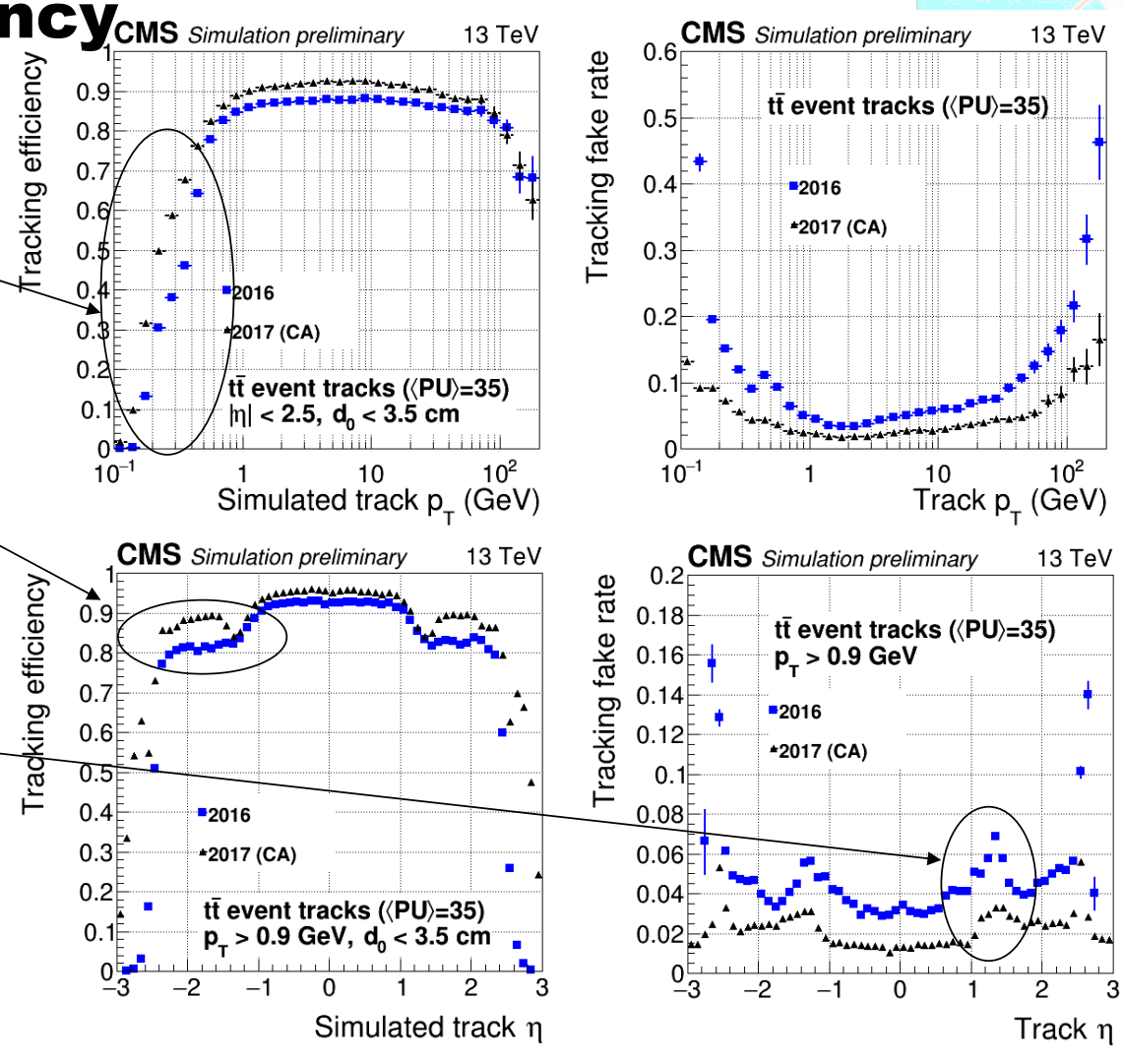
- Track reconstruction
  - inside-out, starting from hit-multiplet seeds formed in the pixel
  - outer tracker-only and muon seeds
- Trajectory building in the outer (strip) tracker using Kálmán filter
- Iterative tracking: earlier steps reconstruct better quality tracks, then remove used clusters
  - High-pt, good quality, tracks at small production radius first
  - Worse quality tracks and secondary interactions in latter steps
- New seeding algorithm developed
  - Novel approach based on Cellular Automaton(CA) techniques





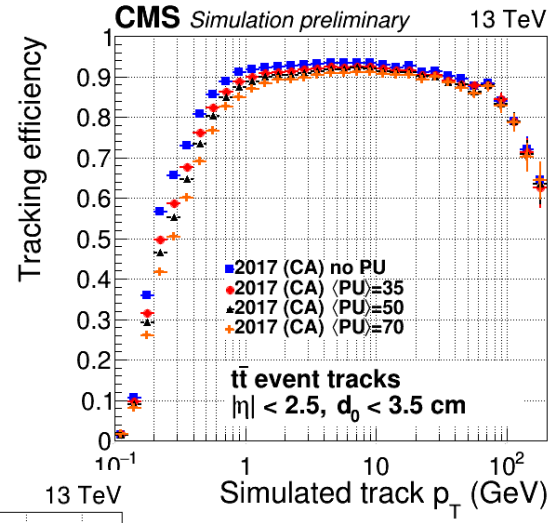
Expected tracking efficiency

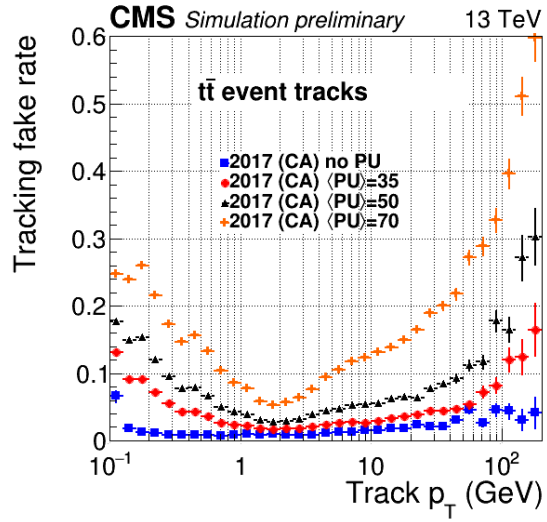
- Performance in ttbar events at sqrt(s)=13 TeV at average expected PU of 35
- Increased tracking efficiency especially at low-p_T
- Increased efficiency more significant in the forward region
  - Better eta-coverage due to additional FPix disk
- Significant reduction of fake-rate at barrel-forward transition region
  - Layer 1 has larger overlap with FPix disks
- Improvements mostly due to layout and hit detection efficiency not relying on better resolution...

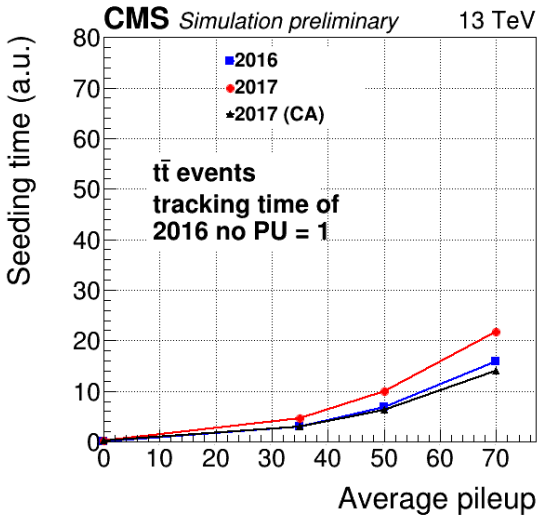


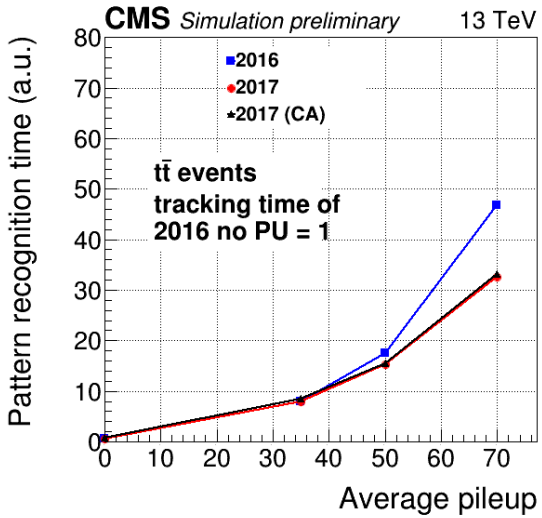
PU dependence

- Robust tracking efficiency as function of PU
  - Only tracking algorithm; hit-efficiency and bad modules are not simulated
- PU affects mostly the fake-rate





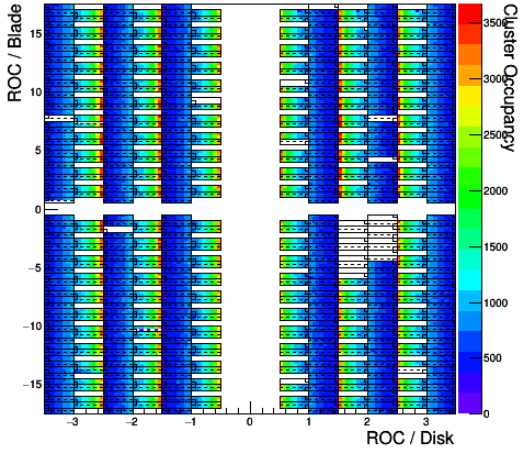


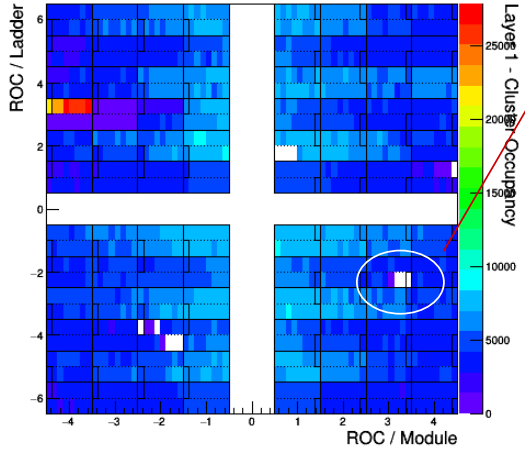


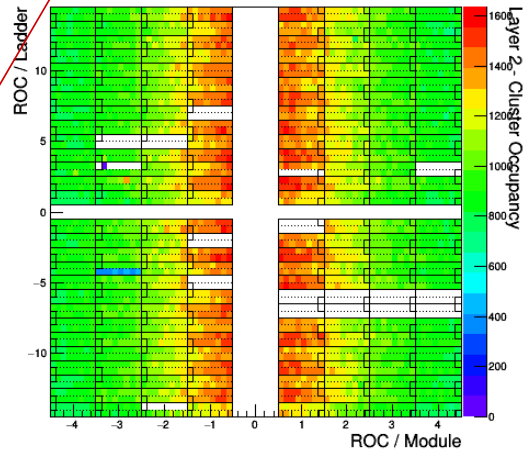
- 2016-level seeding time is preserved by CA despite increased number of layer combinations
- CA needs fewer and simpler calculations that are localized in memory

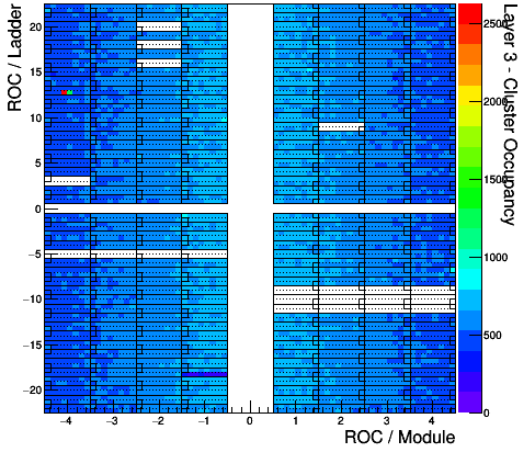
Bad components and SEU-s

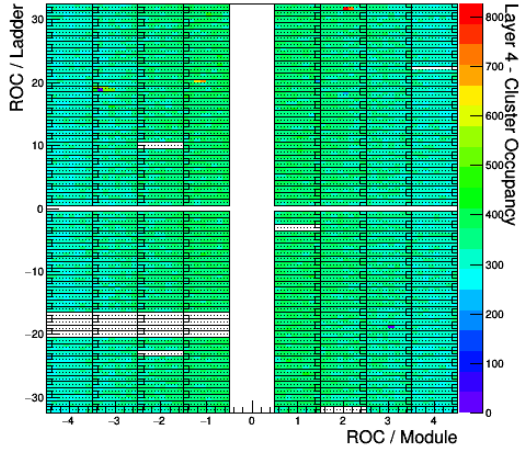
TBM core: 4 ROCs in Layer 1











- **Permanently bad** components presented on Monday by Jory
  - Tracking marks modules inactive **for the whole run**
  - → trajectory is propagated further
  - → or fall-back on triplet seeding
- **„Stuck TBM"-s** are marked by FEDs in raw data
  - → Unpacker marks chips temporarily inactive **in the event**

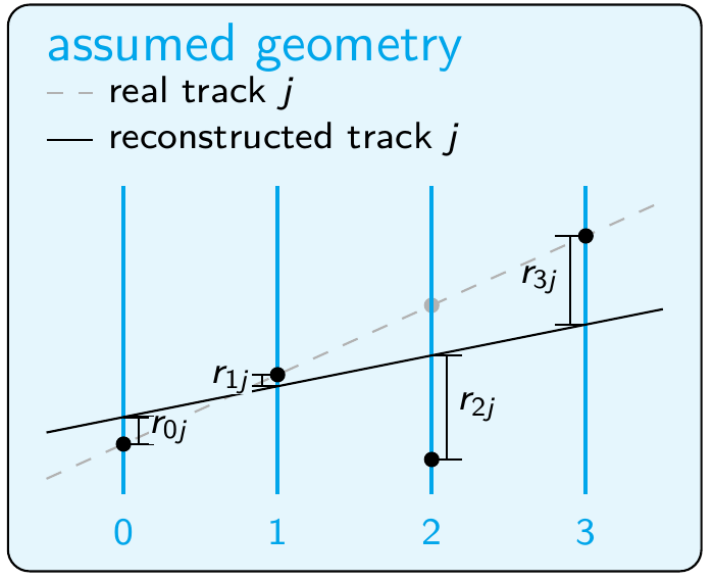
Alignment

- χ^2 of all hits in all tracks are summed up and minimized by moving positions of all modules and refitting tracks
  - Multi-dimensional fit: O($10^{5)}$ alignment parameters and up to O(10^6) track parameters
  - Two algorithms used in CMS:
    - Millepede
    - Hippy

  CMS Collaboration "Alignment of the CMS tracker with LHC and cosmic ray data " 2014 JINST 9 P06009 doi:10.1088/1748-0221/9/06/P06009

- Internal constraints defined by the construction hierarchy of the detector structure
  - Pixel/Strip detector → Pixel Half-shells → inner/outer modules within layers → individual modules

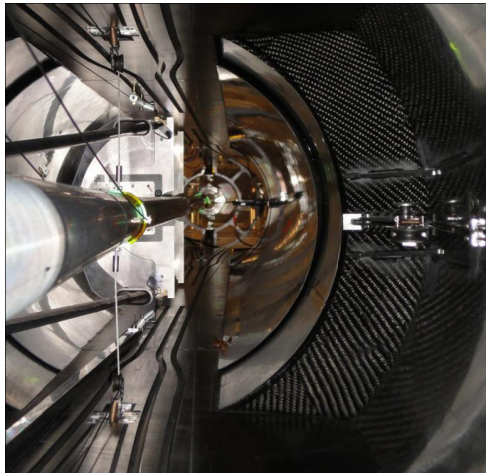
- **Higher-level structure** adjustment → fix **overall** detector **movement**
- **Inner/outer module** alignment → **cluster position bias**
- **Individual module → manufacturing spread, module curvatures**



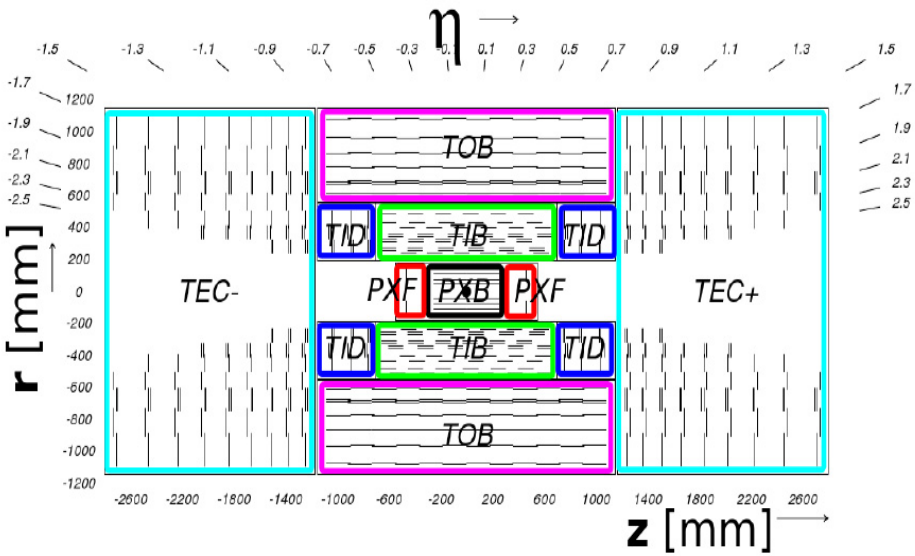
- Assumed (ideally aligned) geometry reconstructs hit at wrong position
- Track is biased → trying to cure it by minimizing

$$\chi^2 = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \frac{r_{ij}^2}{\sigma_{ij}^2}$$

Alignment strategy at start-up



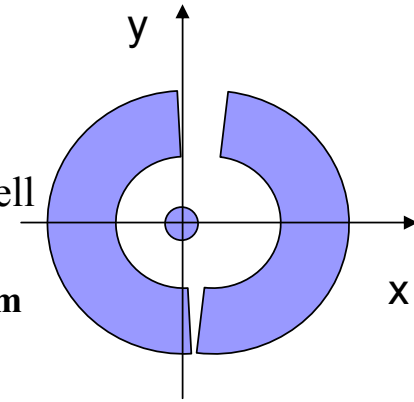
- Pixel detector inserted in „left" and „right" halves placed around the beam-pipe

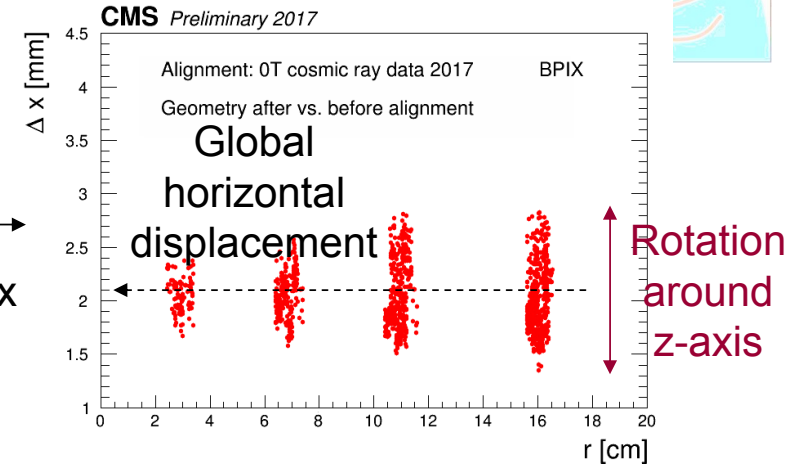


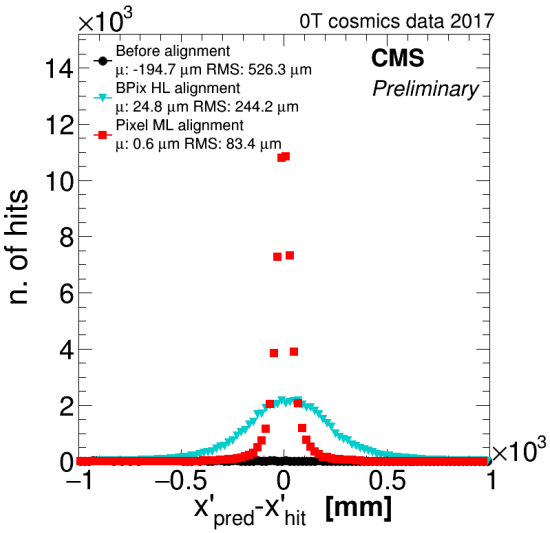
- Seeding of cosmic rays in the muon system
  → pixel is just an observer
- Based on earlier experiences, assumed no movement in strips
- Finding position of pixel
  - **Cosmic** ray muons → **high-level structure**, limited module alignment
  - **Collisions → module alignment**
  - When high-stat cosmics and muon-resonances available → **full Tracker alignment**

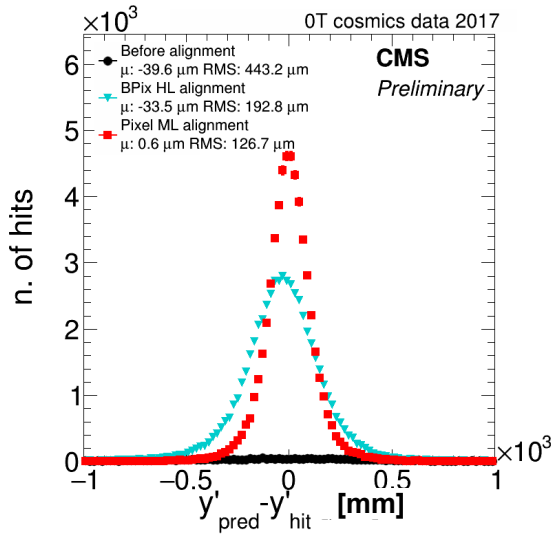
BPix: 0T cosmic ray alignment

- Expected ~1000 µm high-level, ~500 µm ladder, and ~100 µm module misalignment w.r.t initial geometry
- **Cosmic ray** illumination (from „top") **constraints** well **all high-level positions**
  - Found a **global horizontal** position mismatch of **~2 mm**
  - **r-dependent spread** implies additional **rotation**





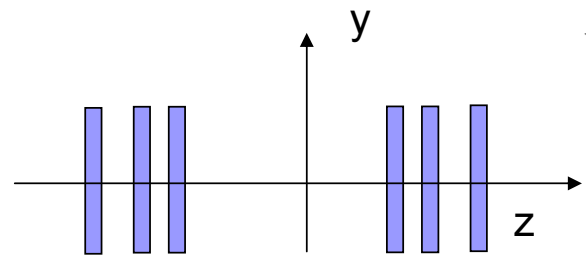


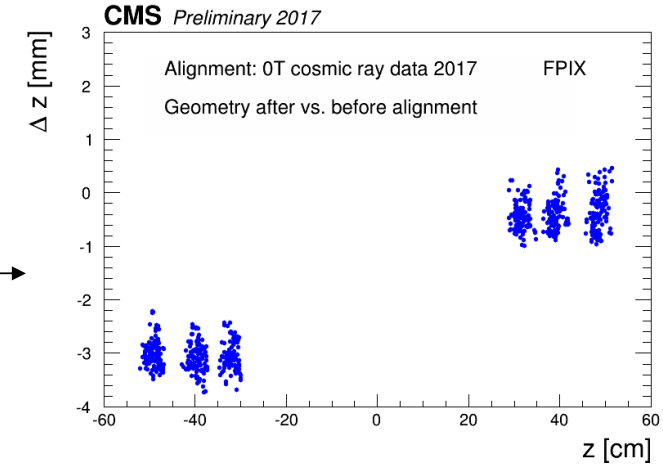


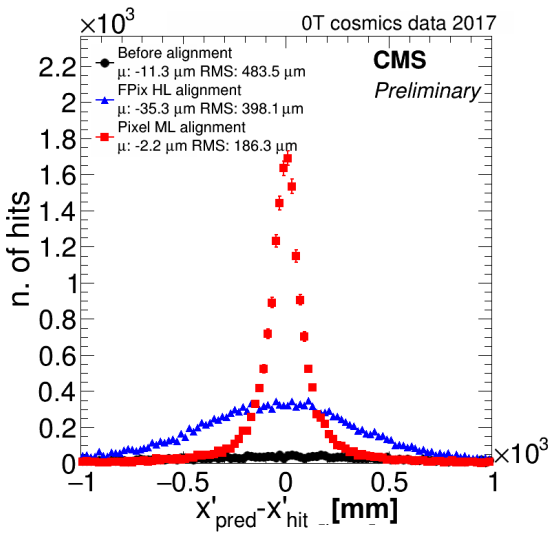
- Local coordinates (top plots)
  - x = global rφ direction
  - y = global z direction (beam axis)
- Global coordinates (bottom plot)
  - x = in the LHC plane
  - z = beam axis
  - r= radius perp. to z

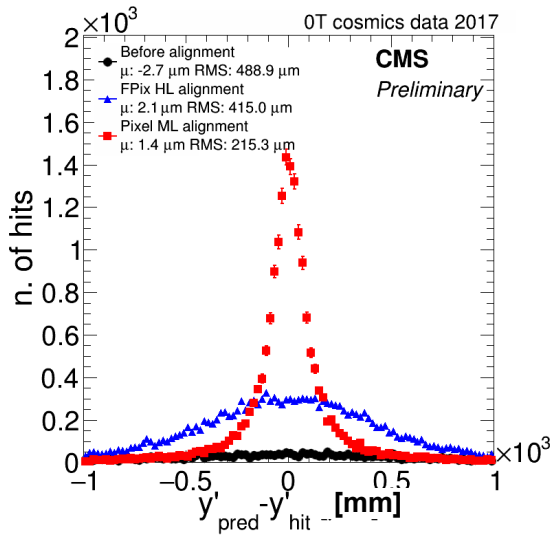
FPix: 0T cosmic ray alignment

- Expected mismatch from initial geometry model
  - up to ~500 μm in transverse plane
  - up to ~4 mm along beam axis
- **Cosmic ray** illumination **constraints z position** well (a weak mode for collision tracks)
  - Found a larger mismatch in FPix -Z









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- Global coordinates (bottom plot)
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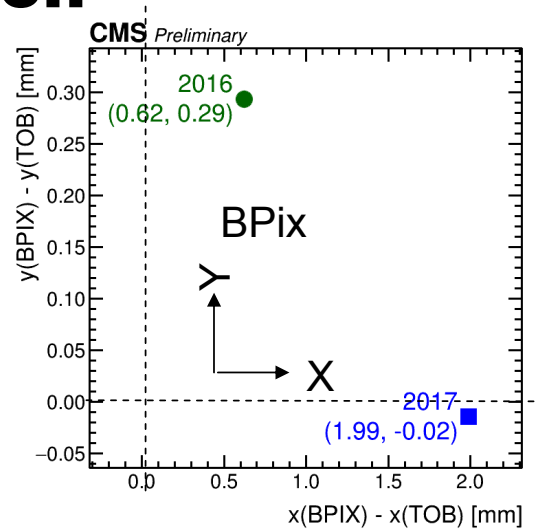
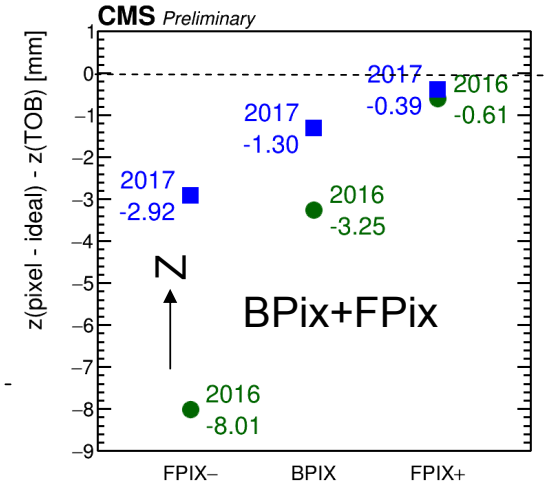
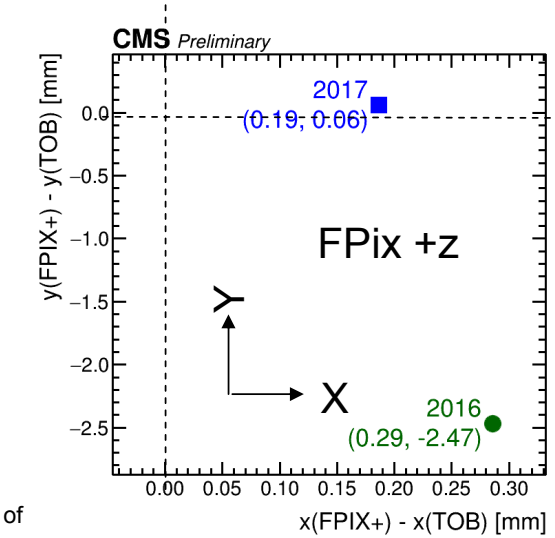
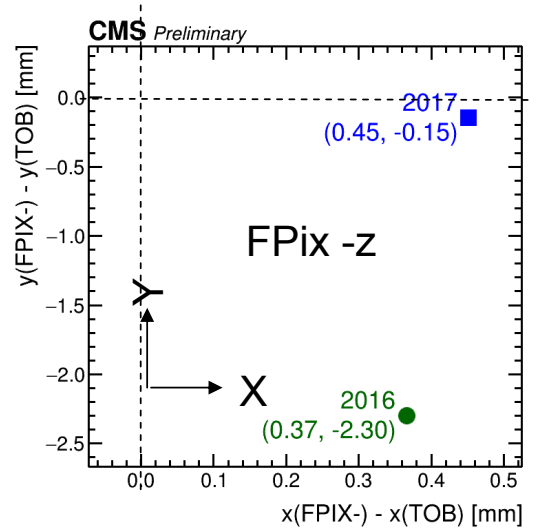
Accuracy of detector insertion

- Reference frame: barry center of the strip TOB (Tracker Outer Barrel)
- Plots show barry centers for **previous** and **upgrade** detectors
  - BPix: off horizontally w.r.t previous detector, better centered in other directions
  - FPix: at least as well or better centered in any directions





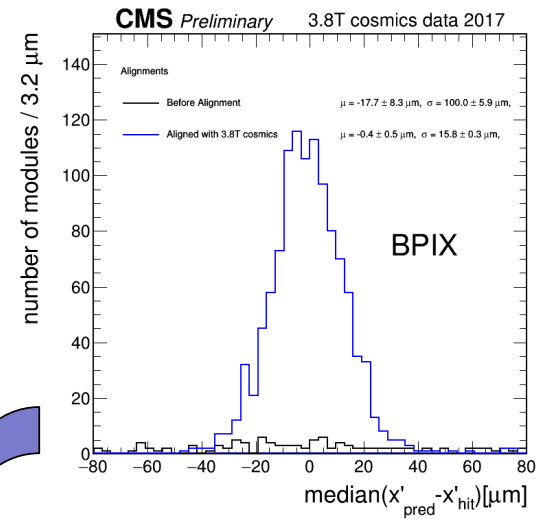


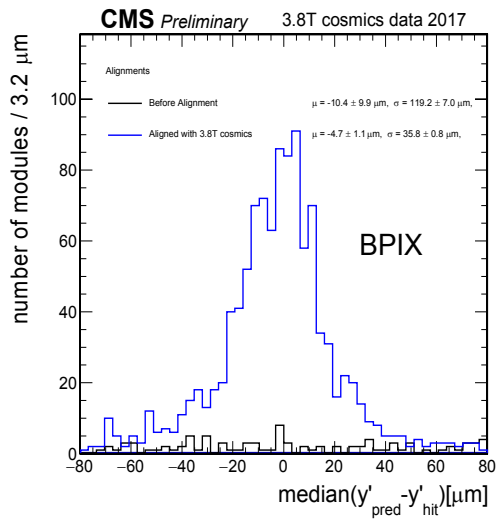


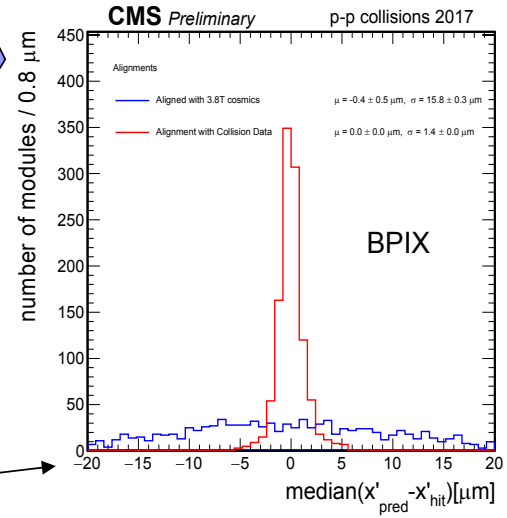
Alignment with collisions

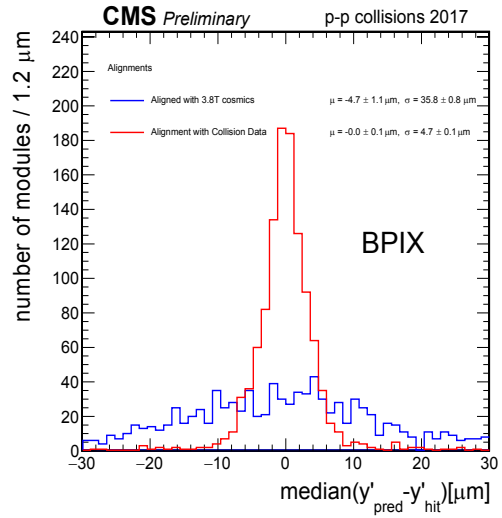
- Median of the residual distribution is computed for each module
  → spread of this value (DMR) quantifies goodness of alignment

- Great improvements in BPix
  - Sigma of DMR already much better than intrinsic resolution
  - Expect some more improvements in end-of-year, ultimate calibration





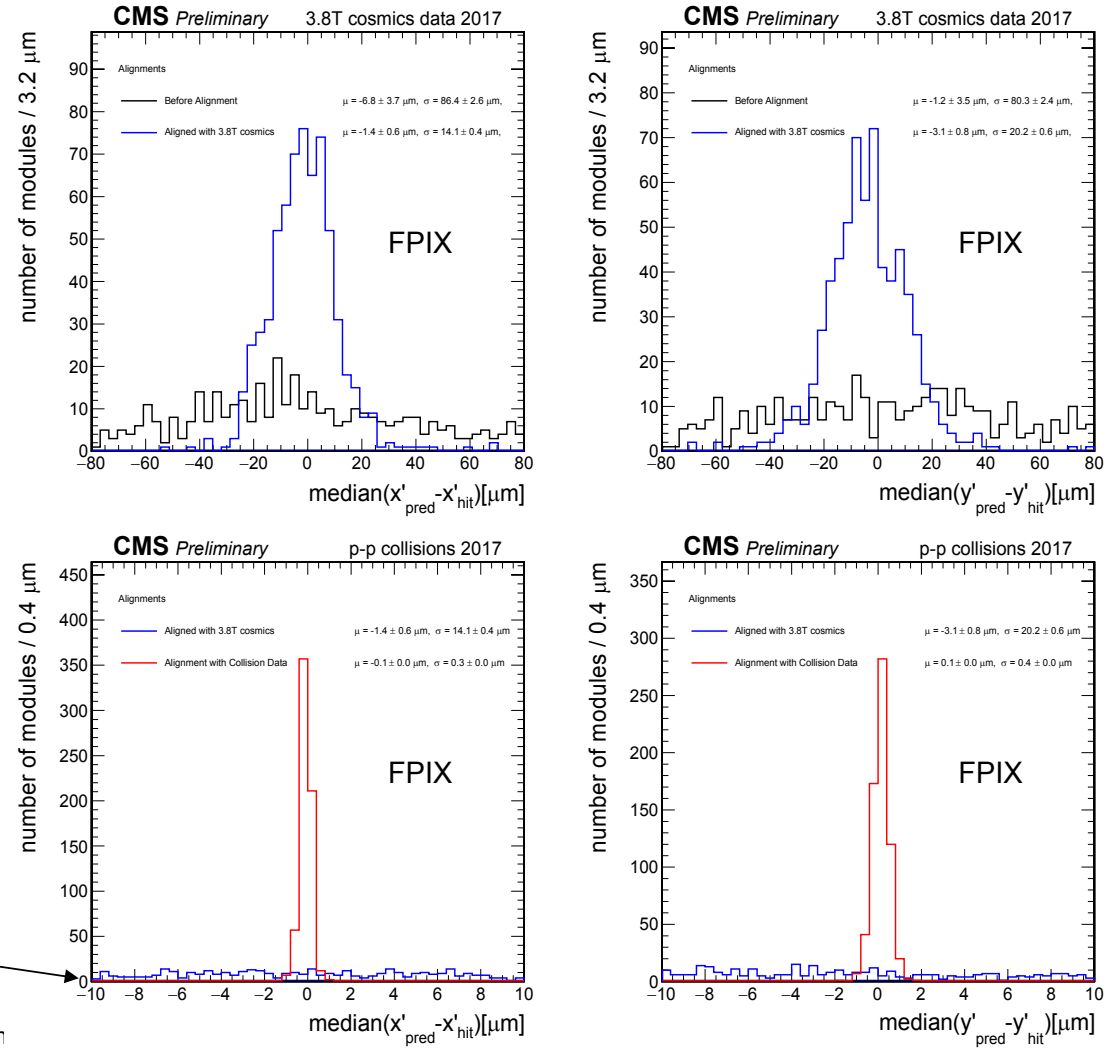




mind the scale

Alignment with collisions

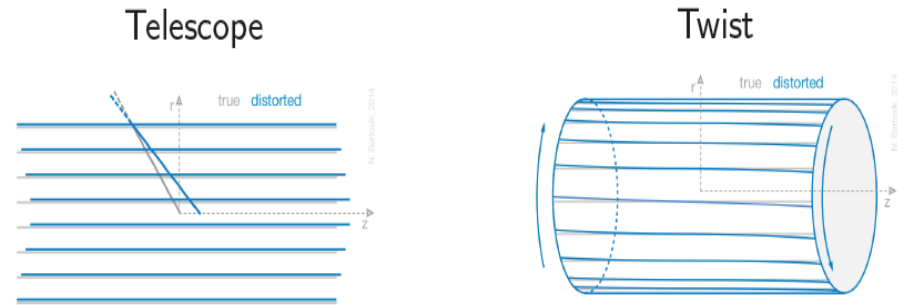
- Collision tracks closer to perpendicular in FPix → very accurate positioning in local x,y
- Sigma of DMR reached alignment of ideal Monte Carlo geometry (!)
  - Negligible w.r.t intrinsic resolution



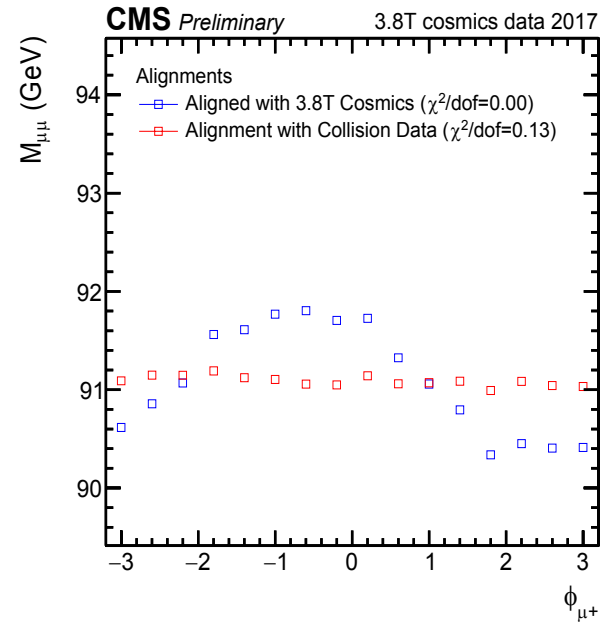
mind the scale

Full tracker alignment

- Last step of commissioning: a full strip+pixel alignment was performed
- Weak modes in alignment: movements that leave χ^2 sum invariant
  - E.g. Coherent dislocation of layers at different radii
  - Distortions
- Weak modes lead to systematic errors in track momentum → can be constrained by muon-pairs from Z-decays
- Final alignment eliminates φ-dependency of Z-mass

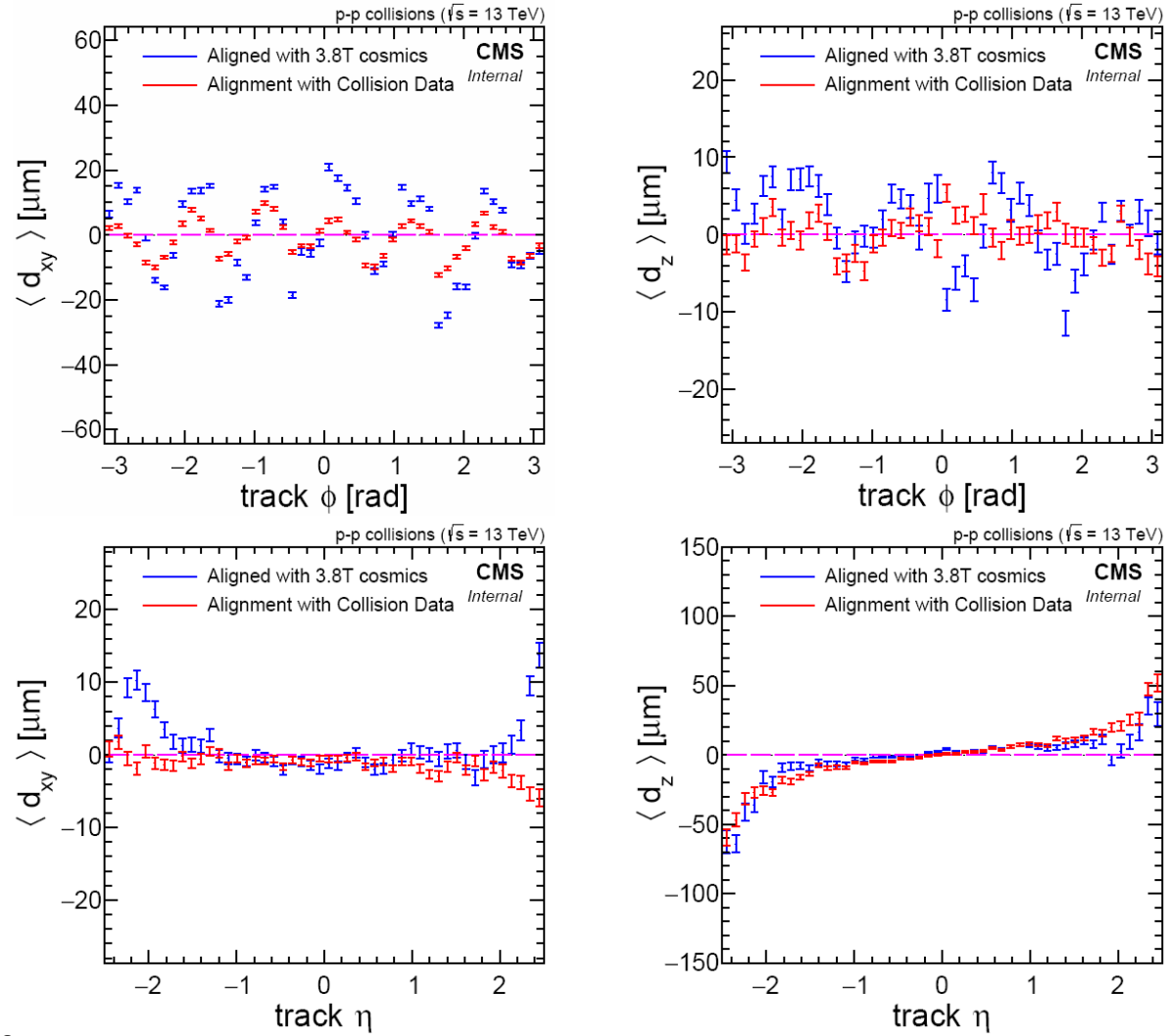


(plots from N. Bartosik's thesis)



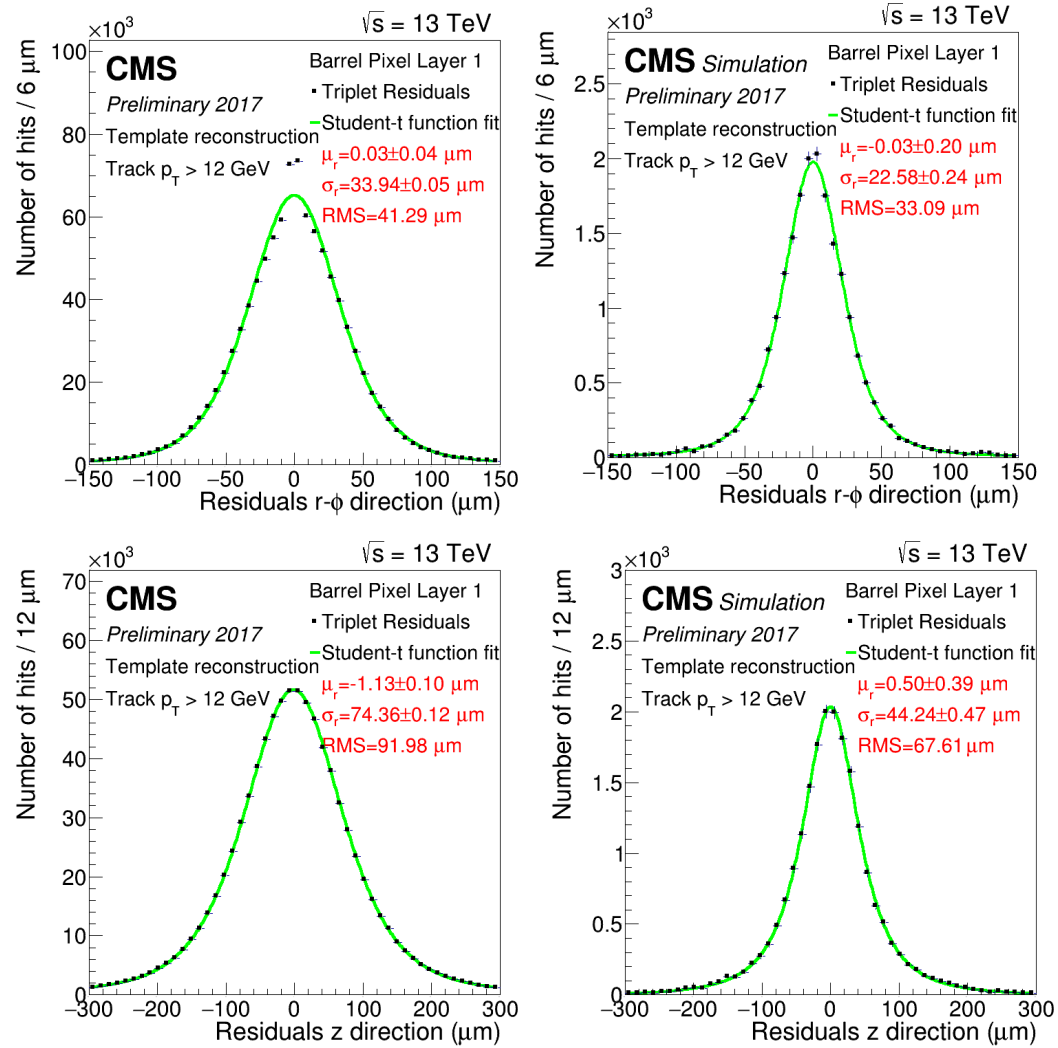
Alignment validation

- Mean impact parameter w.r.t primary vertex (PV) should be zero
  - → Systematic deviation is a sign of remaining biases
- 6-fold structure vs global φ
  - Clue: **Layer 1** is composed of 6 inner + 6 outer ladders
  - Bias comparable to expected single hit resolution
- Similar bias seen also with the previous detector right after commissioning



Layer 1 resolution

- Resolution is quantified as the residual in the hit-triplet method: tracks from 2 hits are analytically propagated to the 3rd layers
  - Large systematics on Layer 1 being the last (first) hit, but should be reproduced by MC
- Resolution so far 50-70% worse than expected
- Resolution is determined by
  - Accuracy of charge-sharing description
  - Read-out threshold
  - Hit-pixel efficiency
  - Charge collection efficiency
  - Timing



Layer 1 resolution

- In the transverse plane: prime suspect is the incorrect LA in reco, not fixed by alignment

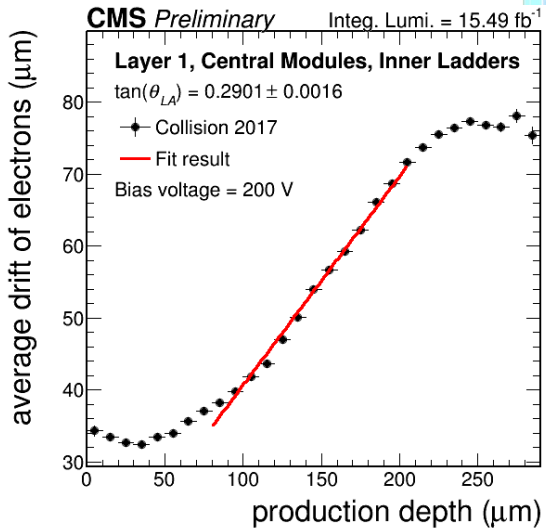
  (Note: LA is short for Lorentz force induced charge sharing – a single value is actually not sufficient to describe the mechanism)

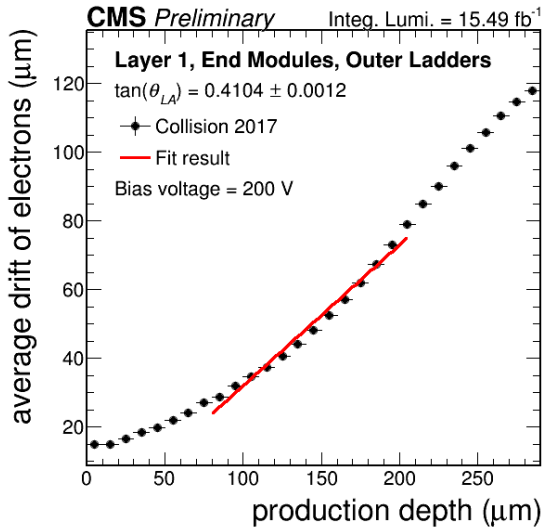
- LA is measured with the grazing angle method: displacement of charges originating at different depths
  - Used same model for the entire layer in previous detector
  - Already large variations within Layer 1 modules after 15.5 fb^{-1}

- Inconsistent LA leads to non-zero mean residual in alternating directions

  → in symmetric case to wider residual

- **Effect seems to reduce by sufficient over-depletion**



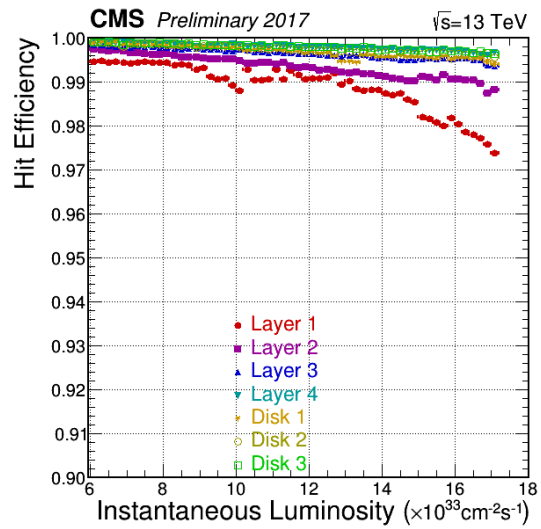


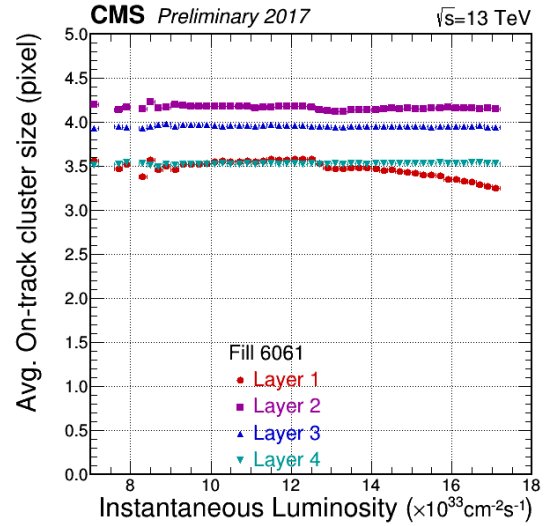
Layer 1 resolution

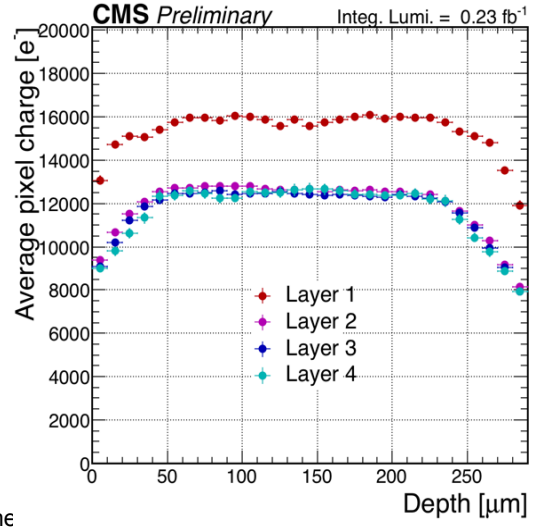
- Cross-talk in Layer 1 demands a higher threshold than designed
  → estimate ~4000 e-

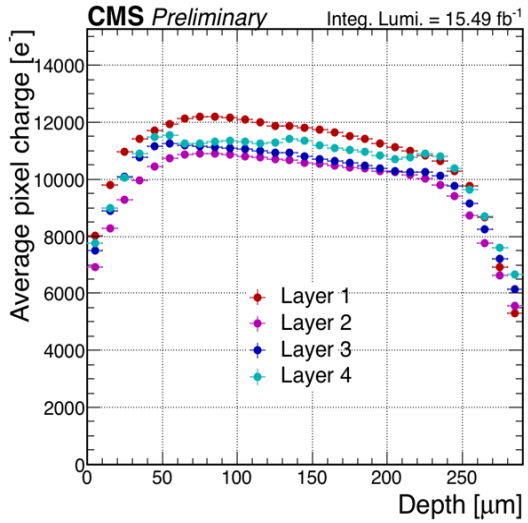
- Dynamic efficiency causes loss of pixels in clusters → affecting cluster shoulders and cluster splitting

- Already considerable radiation damage by the end of commissioning
  → signs of charge collection inefficiency even in farther layers
  → made bias voltage adjustment necessary (L1: 350V, L2: 250V, L3-4: 200V, FPix: 300V)



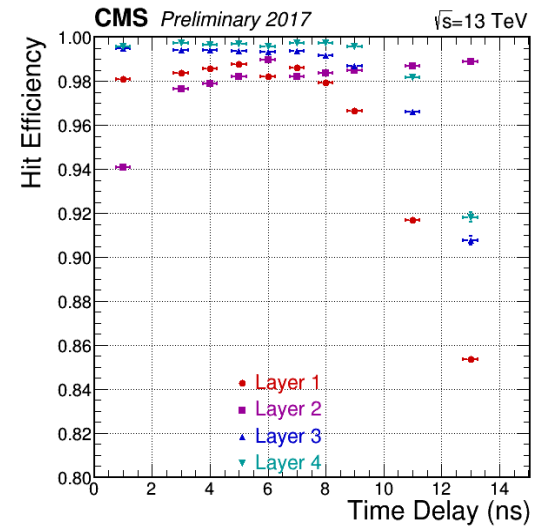


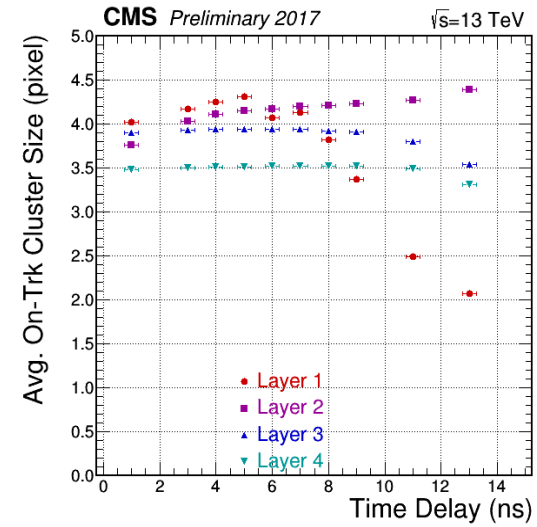




Timing effect on resolution – Layer 2

- Hit pixel pulses are buffered asynchronously along with time-stamps in units of bunch-crossing
  - Time-stamp assignment affected by clock-phase difference between chip and LHC collisions
  - Clock-phase adjusted per clock-distribution group: Layer 1+2 and Layer 3+4
  - In clock-phase scan, observed a 10-12 ns relative shift between Layer 1 (PROC600) and Layer 2 (PSI46dig) chips..
- Clock-phase is optimized to reduce time-walk effect (read-out as low charge/late pixels as allowed by the time-window)
  - Needed to optimize for Layer 1
  - A bit early for Layer 2
- Layer 2 threshold ~2500 – 3000 e- mostly due to timing
  - 1000 e- → ~1 μm worsening (seen in test beam)
- Average threshold in module testing was ~1600 e- (average 100-200 e-) → indeed achieved in Layer 3-4 and FPix





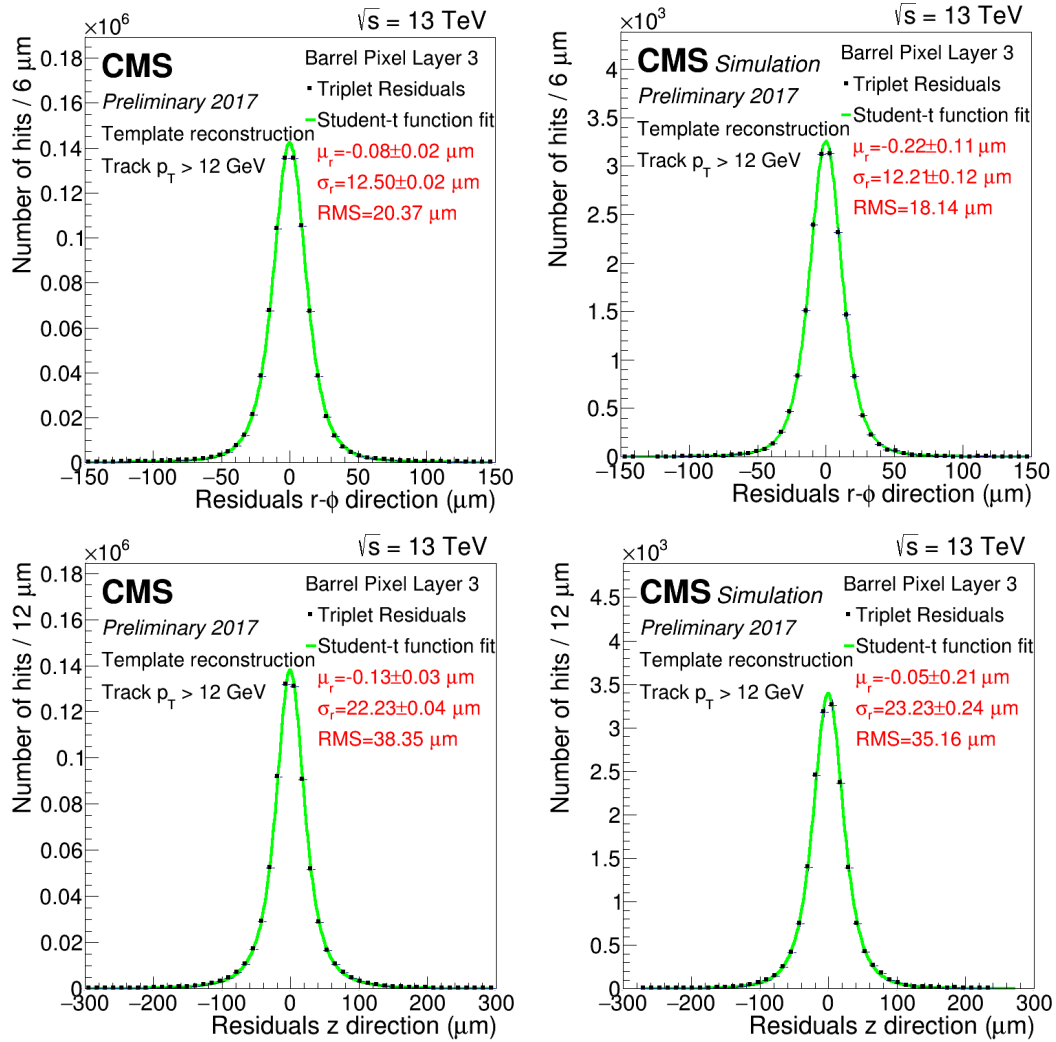
Resolution of Layer 2-4

- Compare triplet residual measurements in data and simulation
  - MC assumes perfect detector (no radiation damage, threshold 2000 e-, no pixel efficiency loss)

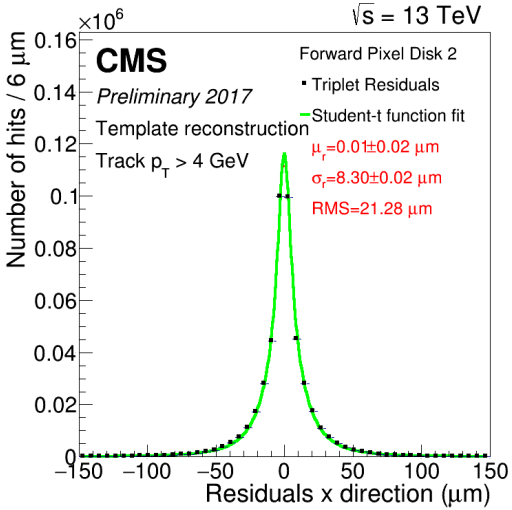
    → intrinsic resolution 6-7 μm (simhit-rechit residual width)

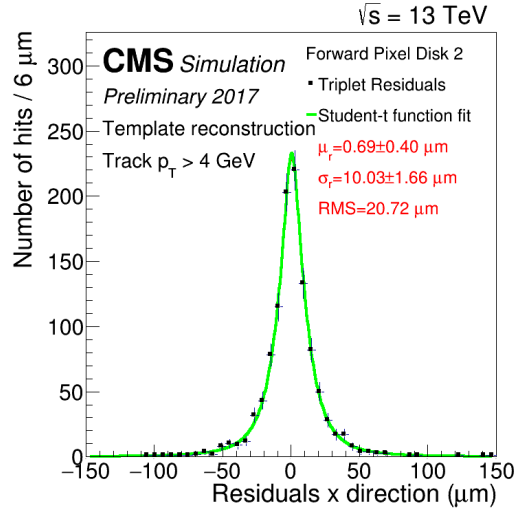
- Comparisons imply optimal performance of Layer 2-4

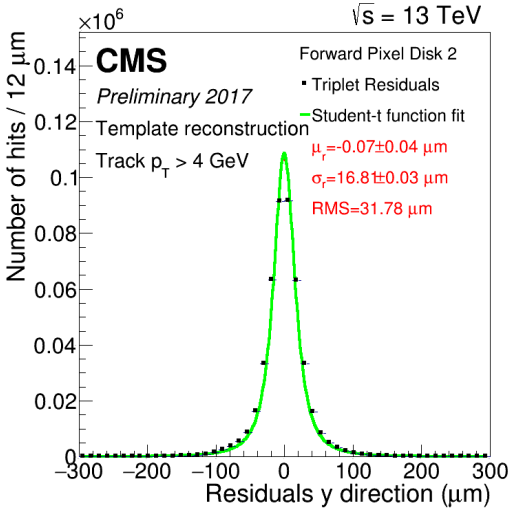
- Layer 2 still compatible with MC
  - seem to have no sensitivity to the timing issue
  - but need to keep an eye on the issue...

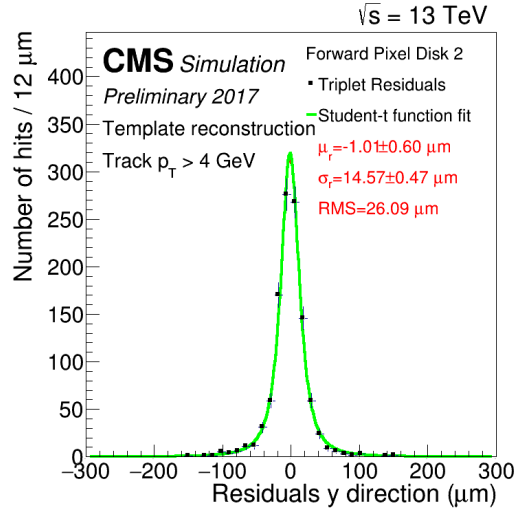


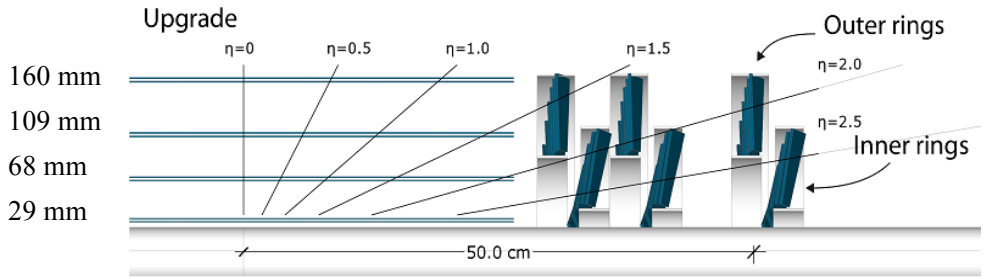
Resolution of FPix







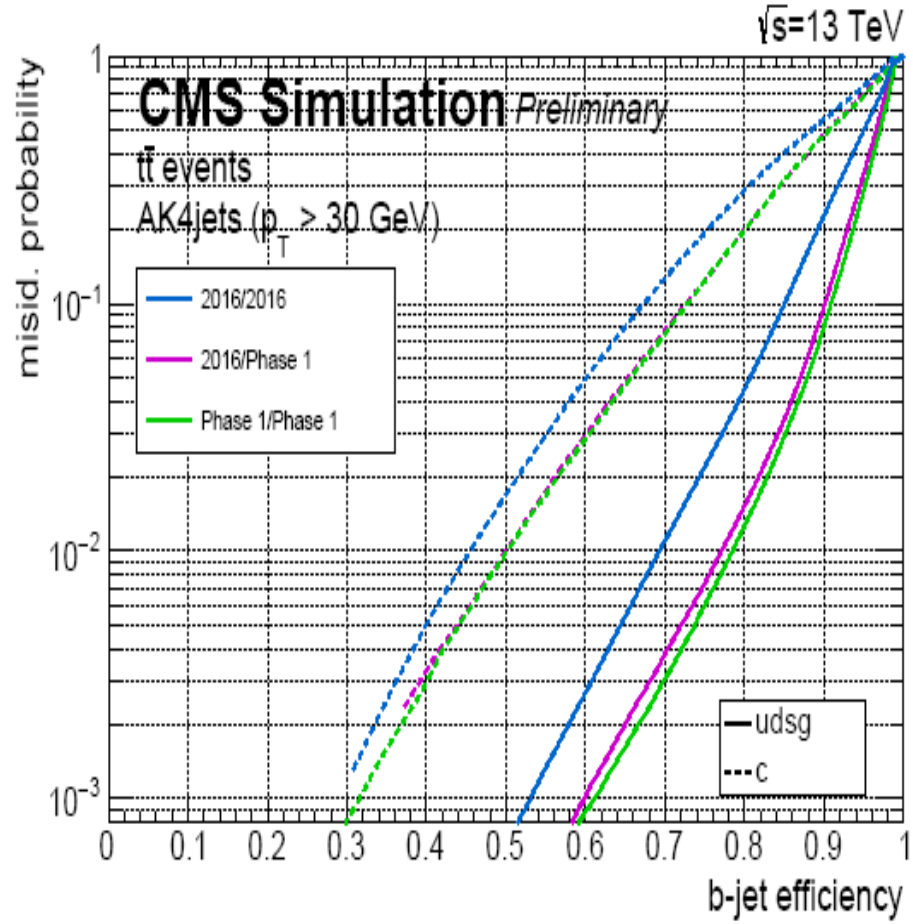




- Triplets fully in FPix
  → result independent of Layer 1
- Resolution of data in the rφ direction outperforms simulation!
  → 2000 e- in simulation is probably too pessimistic

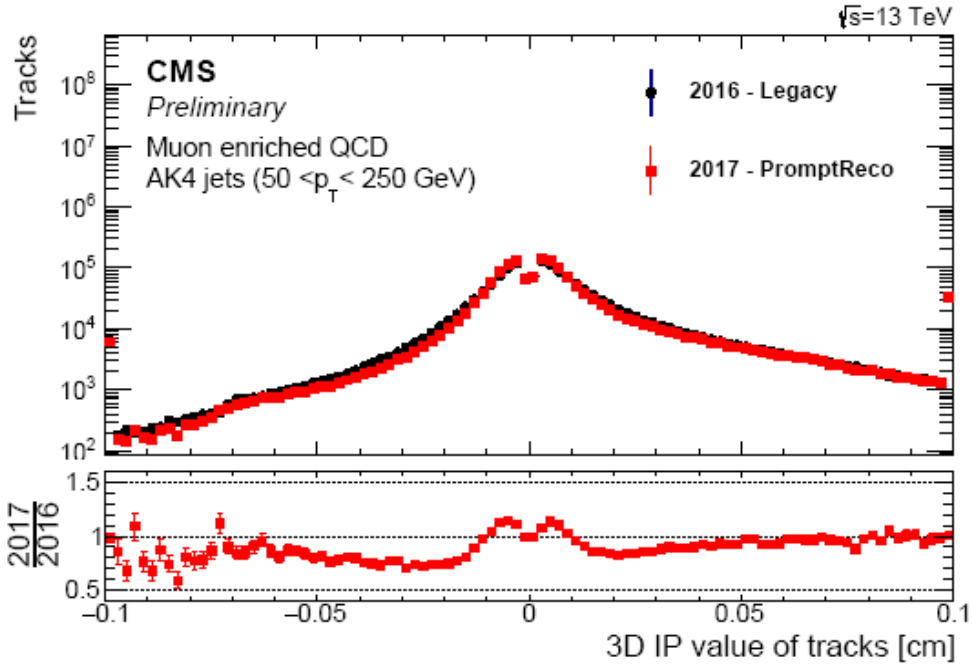
B-tagging expectations

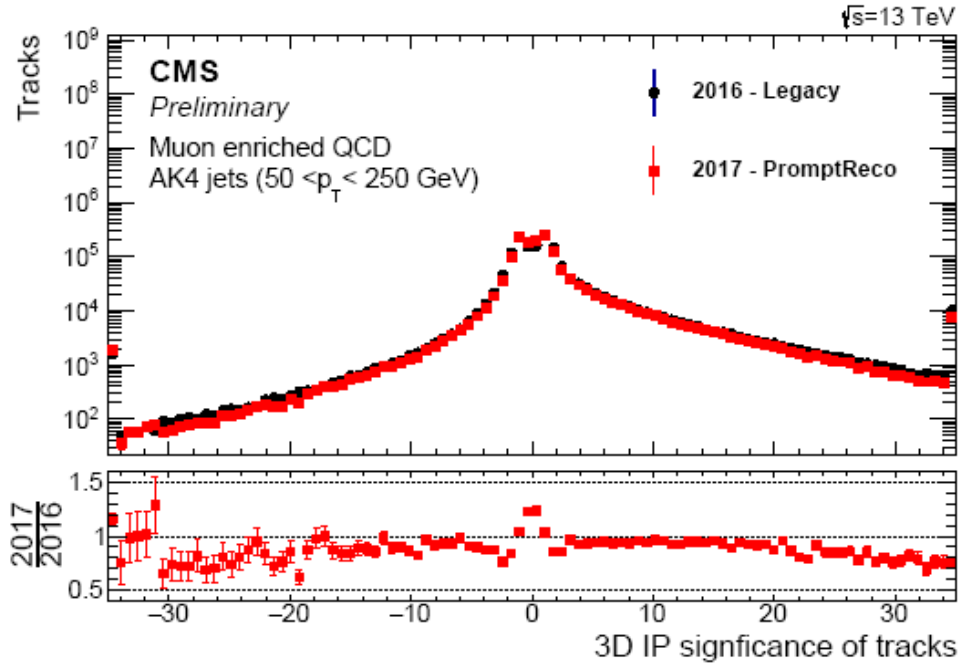
- Expected performance in simulation shown
- **Blue** vs **magenta**: improvement due to upgrade as seen in preliminary simulation (similar to TDR)
- **Magenta** vs **green**: training and retraining tagging with upgrade detector before and after finalizing reconstruction in simulation
  - Proper handling of E-field direction w.r.t the B-field
  - More accurate reco geometry
  - Updated material budget in tracking (duplicate rate seems to be rather sensitive)
  - New seeding
  - Final tuning of tracking



B-tagging in data

- Not yet at ultimate performance just being right after commissioning
- Still a bit better performance seen in 3D impact parameter
- And in one of the basic b-tag discriminator values





Summary

- Challenging times with installation and commissioning of the new Phase 1 detector: unusually short time available

- Encountered some unexpected issues, major ones being:
  - Higher threshold in Layer 1 due to cross-talk
  - Clock-phase difference between PROC600 and PSI46dig
  - Unexpected level and trend of hit efficiency loss
  - SEU-s in the TBM
  - ...each is manageable, but they all came at the same time while significant radiation damage received already while in commissioning

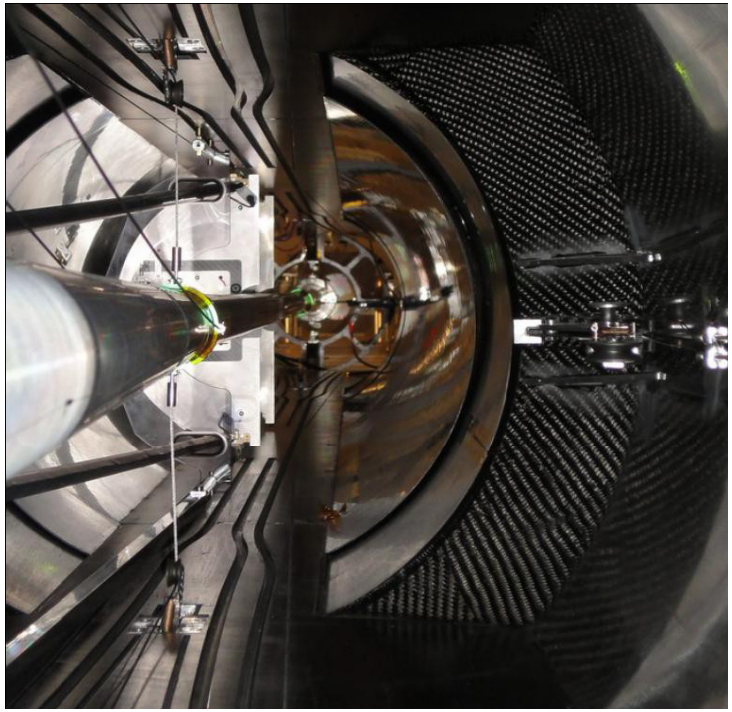
- Despite challenges, performance is already as good or better than the previous detector
  - Big fraction of improvement purely due to new geometry already present
  - Chips also perform better → the Phase 0 would have not taken $1.7*10^{34}cm^{-2}s^{-1}$ well
  - Commissioning has concluded successfully, we have a good prospect on reaching the design performance

Extra slides

Expected initial misalignment

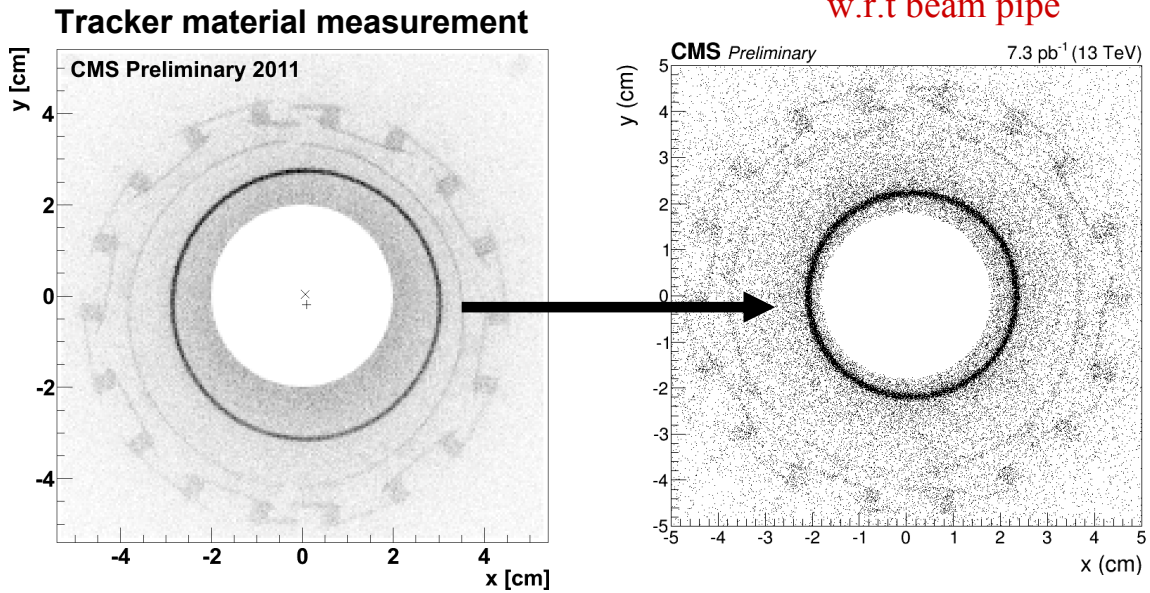
Structure	Δx [μm]	Δy [μm]	Δz [μm]
TPBBarrels	500 (uniform)	500 (uniform)	1000 (uniform)
TPBHalfBarrels	100 (uniform)	100 (uniform)	100 (uniform)
TPBLadder	500 (uniform)	500 (uniform)	500 (uniform)
TPBModule	100 (gaussian)	100 (gaussian)	100 (gaussian)
TPEHalfCylinders (+z)	250 (fixed)	250 (fixed)	-680 (fixed)
	250 (fixed)	-250 (fixed)	-720 (fixed)
TPEHalfCylinders (-z)	250 (fixed)	250 (fixed)	3940 (fixed)
	-250 (fixed)	250 (fixed)	4020 (fixed)
TPEHalfDisks	250 (uniform)	500 (uniform)	100 (uniform)
TPEBlade	300 (gaussian)	300 (gaussian)	200 (gaussian)
TPEModule	200 (gaussian)	200 (gaussian)	50 (gaussian)
StripModule	20 (gaussian)	20 (gaussian)	20 (gaussian)

The Phase 1 detector system



- Inner layer is at smaller radius, requires more clearance
- Beam pipe changed from 59 mm to 45 mm during LS1

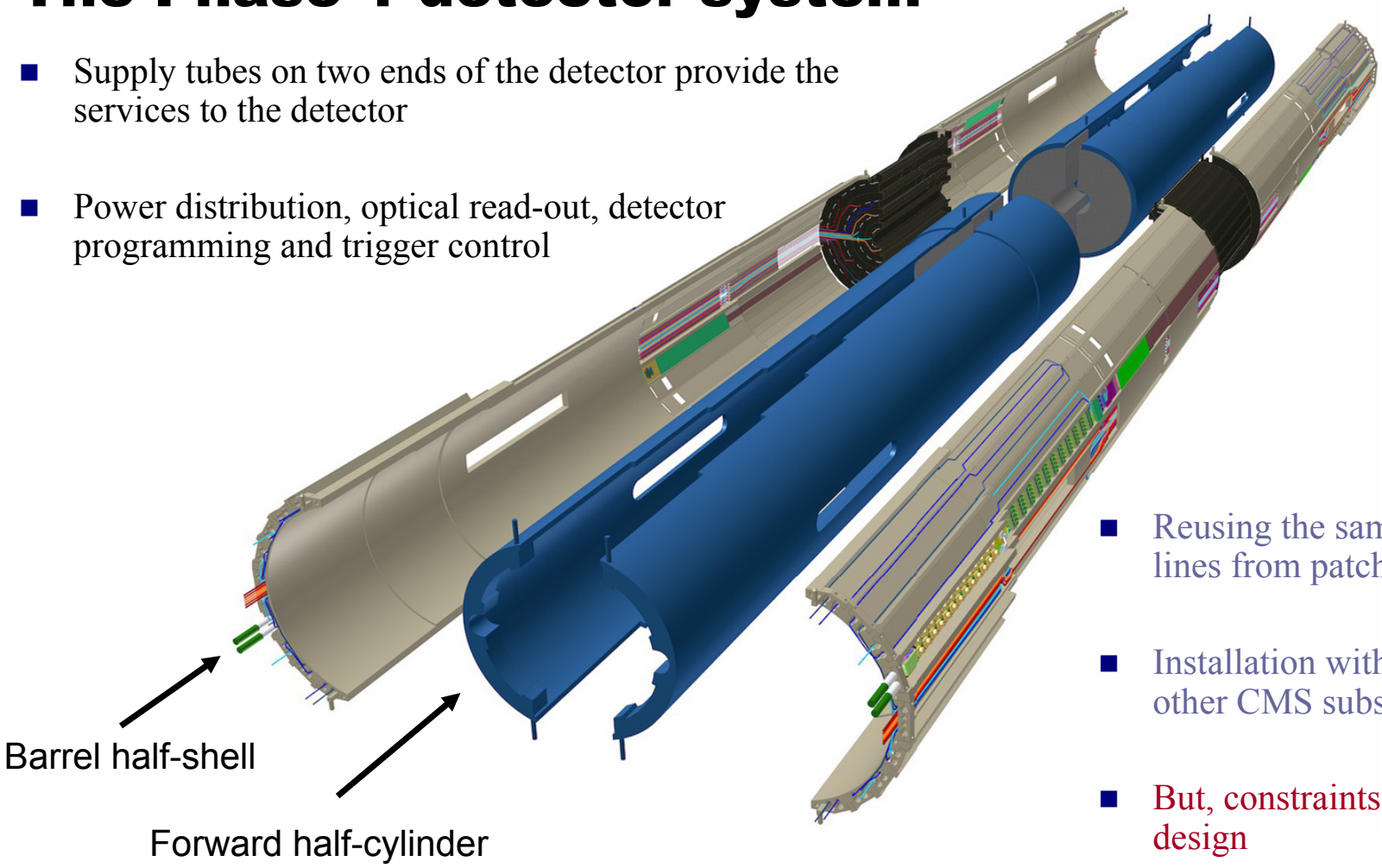
Barrel off-centered w.r.t beam pipe



- Beam pipe position was checked in 2015 running
- Nuclear interactions reconstructed by tracking; multiplicity clearly shows beam pipe and Layer 1 of the current detector

The Phase 1 detector system

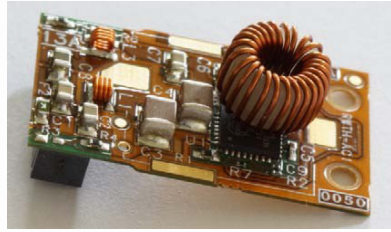
- Supply tubes on two ends of the detector provide the services to the detector
- Power distribution, optical read-out, detector programming and trigger control



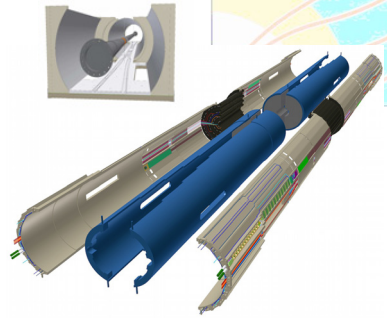
- Reusing the same power cables, fiber optic lines from patch panel
- Installation with minimum impact on the other CMS subsystems
- But, constraints imposed on electronics design

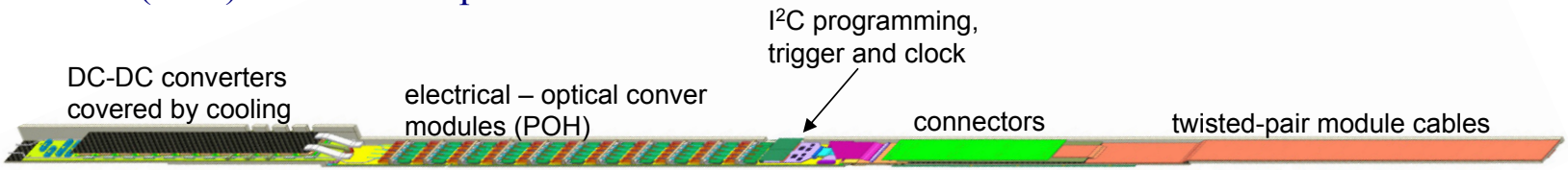
Powering and read-out

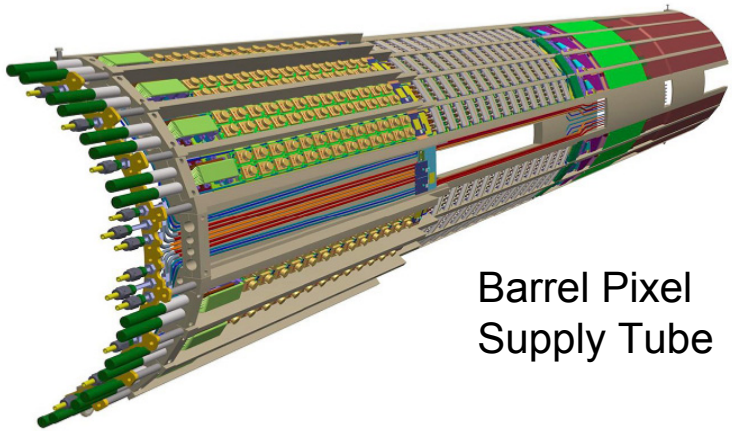
- Doubling the read-out is achieved with more modules, need more power
- Analog 3.0V and digital 2.5 V by DC-DC converters (80%) from 10 V input



DCDC converter with AMIS5 ASIC
(RF shield not mounted)





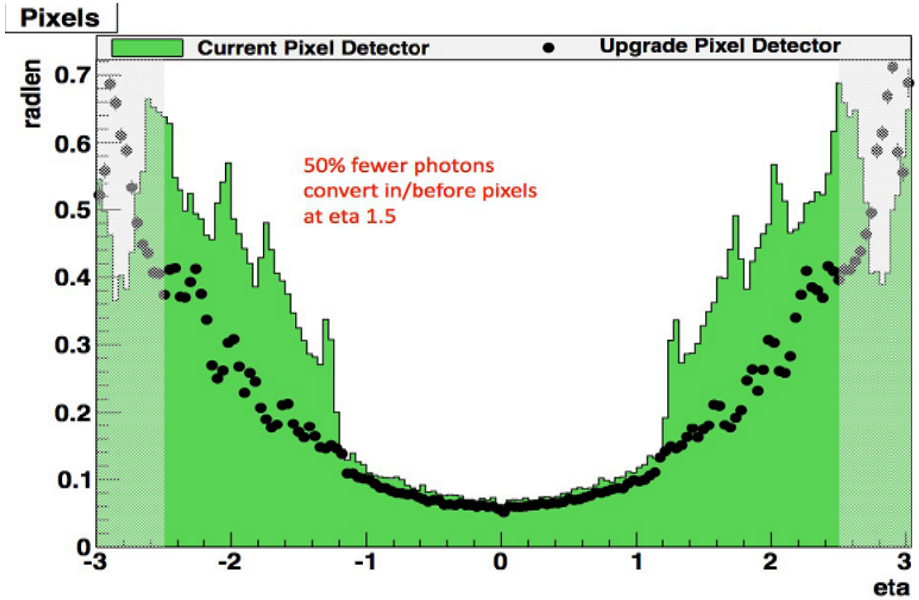


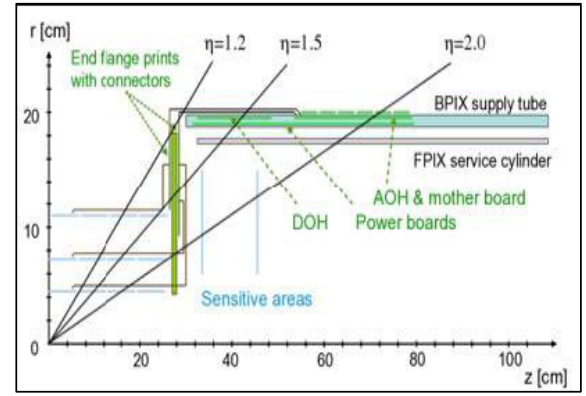
Barrel Pixel
Supply Tube

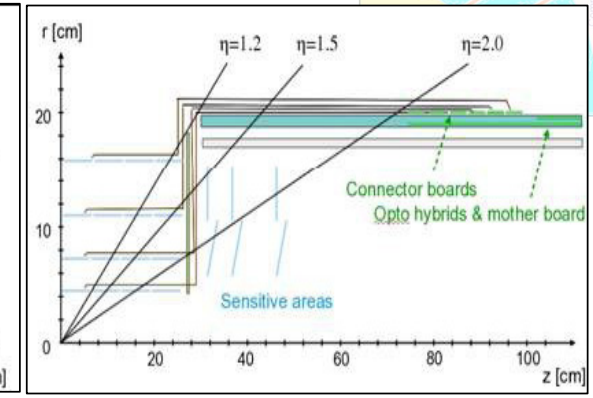
- Electronics
  - Distributes clock signal synchronized to TOF within 1 ns
  - Equally distributes data-load among back-end FPGA-s
- 8 slots per half-shell, servicing a sector of up to 39 modules
  - 6 layers of 20 mm wide PCB-s and a bundle of 56 fiber optic cables stacked within a 20 mm deep slot

Material budget

- Light mechanical support
- Smaller coolant mass
- Supply tube has much more components, but shifted away from the interaction point

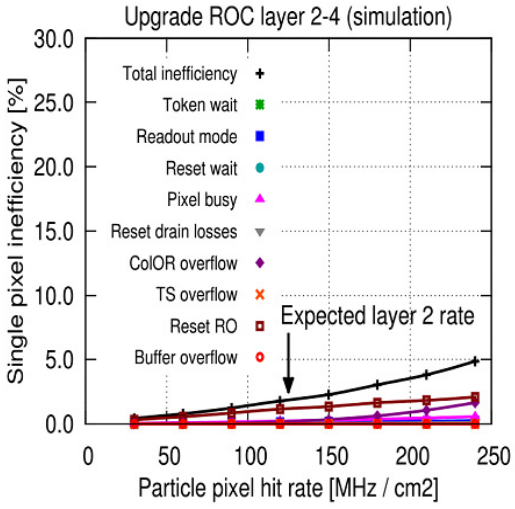


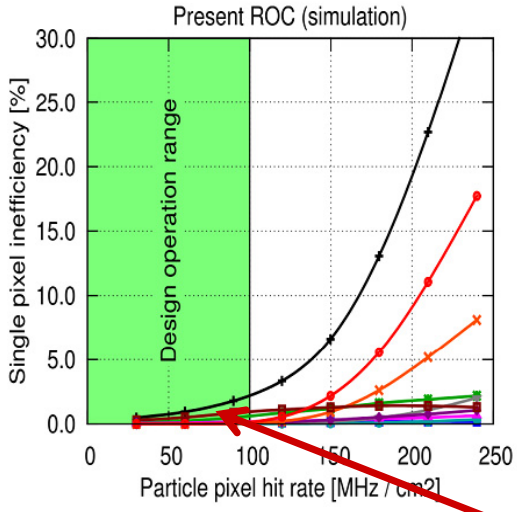




- Reduced mass, less multiple scattering and nuclear interactions
- Factor of two decrease in photon conversion between 1.1 and 2.6 in pseudo-rapidity w.r.t. current detector

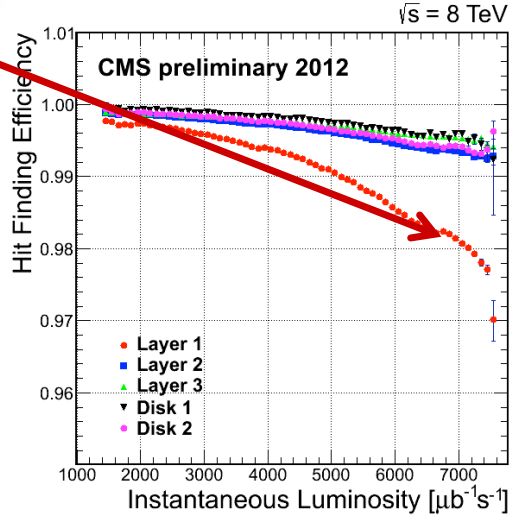
Hit efficiency

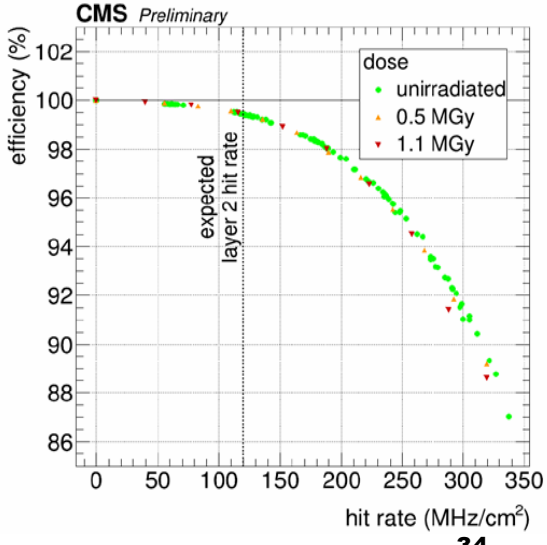




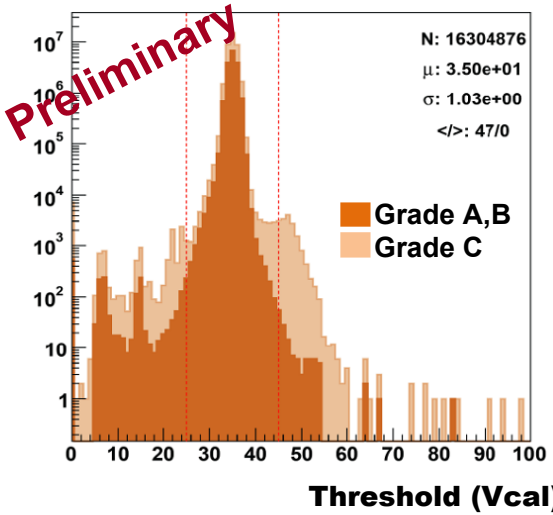
- TS and Buffer overflows, the major sources of inefficiency currently, entirely eliminated
- Typical expected rate 120 MHz Layer 2
- Chip to handle Layer 1 rate of 580 MHz is under testing

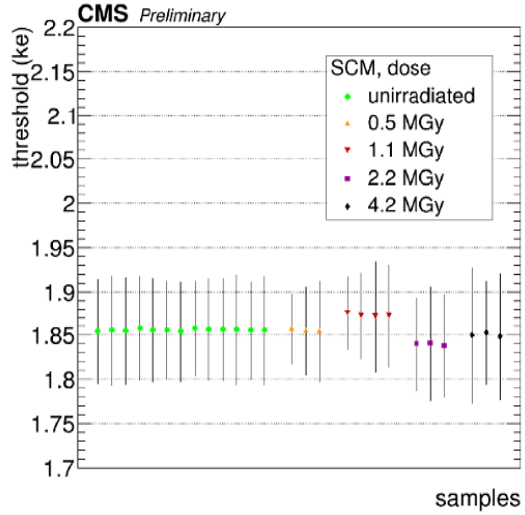
- Present detector operated at ~75 MHz/cm^2 in 2012
- 2-3% loss of measured hit finding efficiency, ~6-9% dcol loss – complicated relationship between beam test and real LHC conditions
- Performance of new Layer 2 chip is also expected to be stable with irradiation





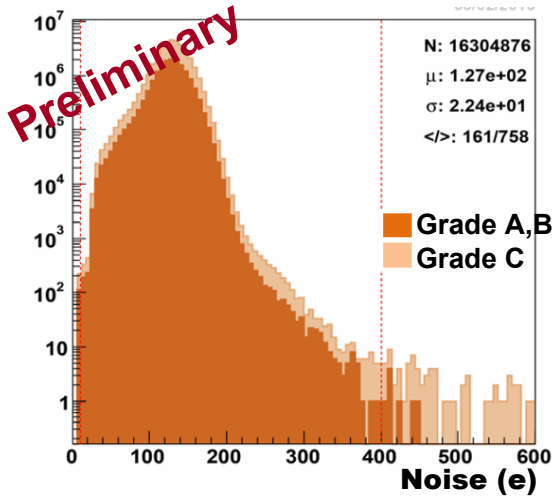
Module testing – Threshold and noise

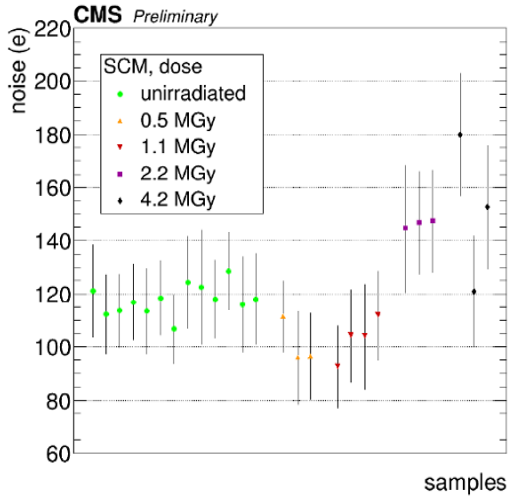




- Colors show results of grading (~90% bare and ~74% detector grade module yields)
- Average threshold ~1600 electrons (35 VCal units) from 3200 e

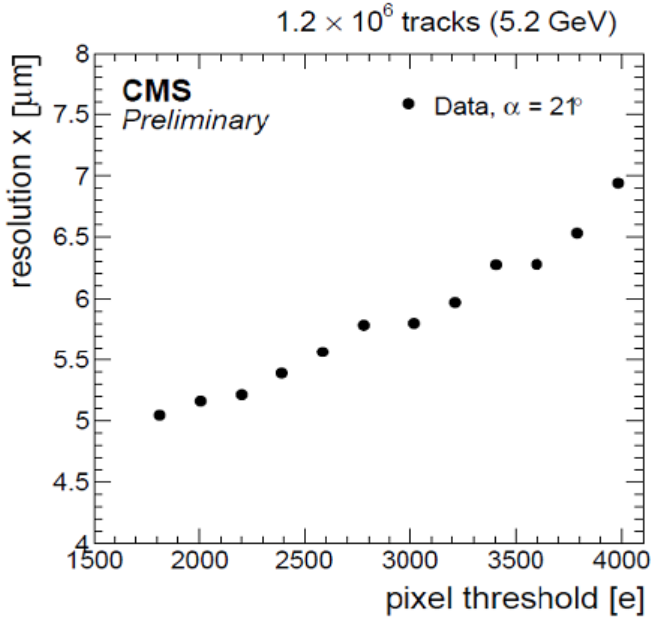
- Very stable with irradiation way beyond the dose expected after 500 fb^{-1} (1.2 MGy)
- Noise for modules qualified as detector grade (dark brown) much below threshold
- Noise stable with irradiation

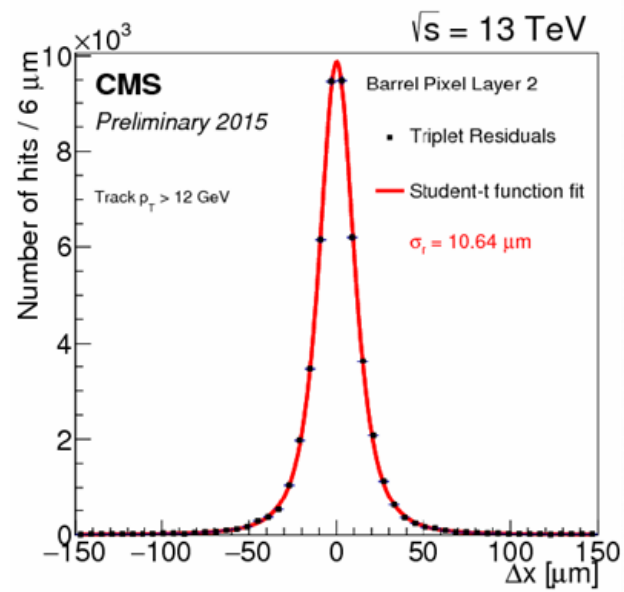


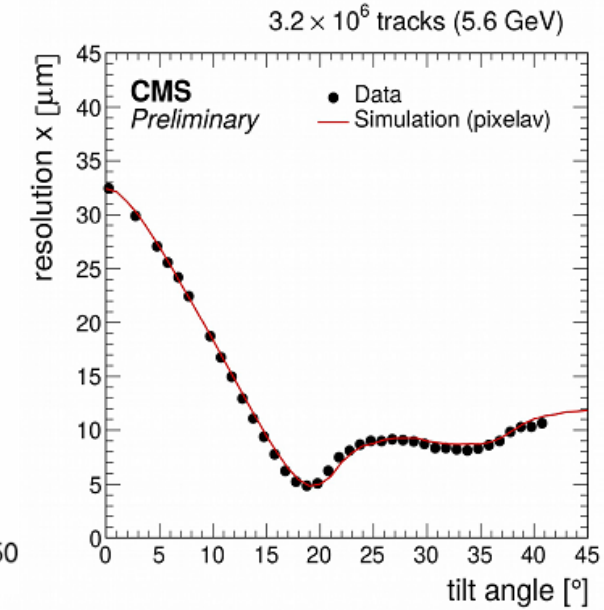


Resolution

- Cluster position resolution much better than pixel pitch due to Lorentz drift induced charge sharing
  - LA angle ~21°
- Lorentz angle decreases with higher bias voltage (moving the „wrong" way)







- Lower threshold beneficial effect is clrearly visible
- Improvements of cluster position resolution is expected from ~10.6 microns to 5 microns