CMS Tracker Operational Experience

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On behalf of the
CMS Tracker Collaboration

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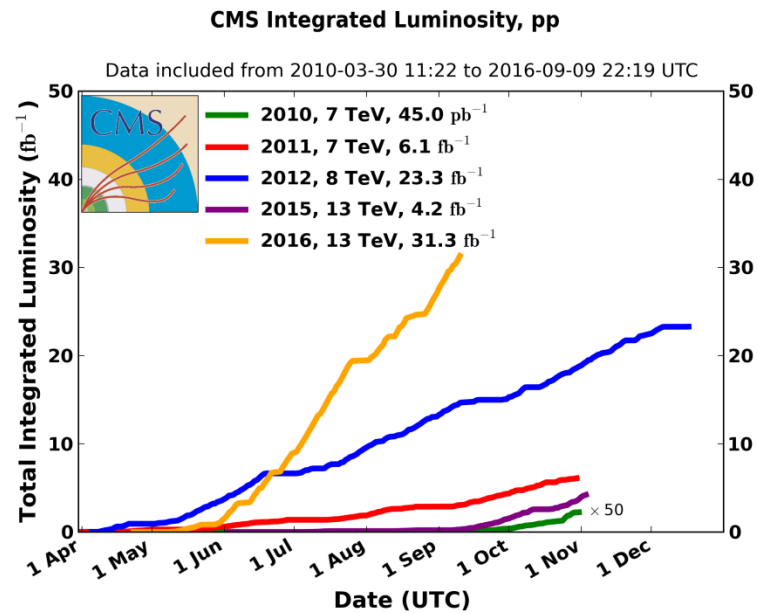
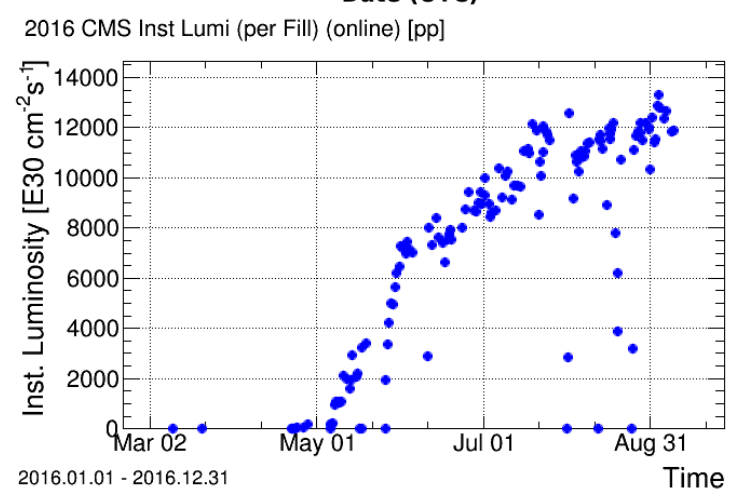
Outline

- A snapshot of LHC Run II data
- The CMS detector and Tracker overview
  - Activities in the long shutdown
- Pixel status and performance
- Strip status and performance
- Briefly:
  - Single Event Upset (SEU)
  - Alignment
  - Track reconstruction
  - Pilot blade
- Summary and conclusions

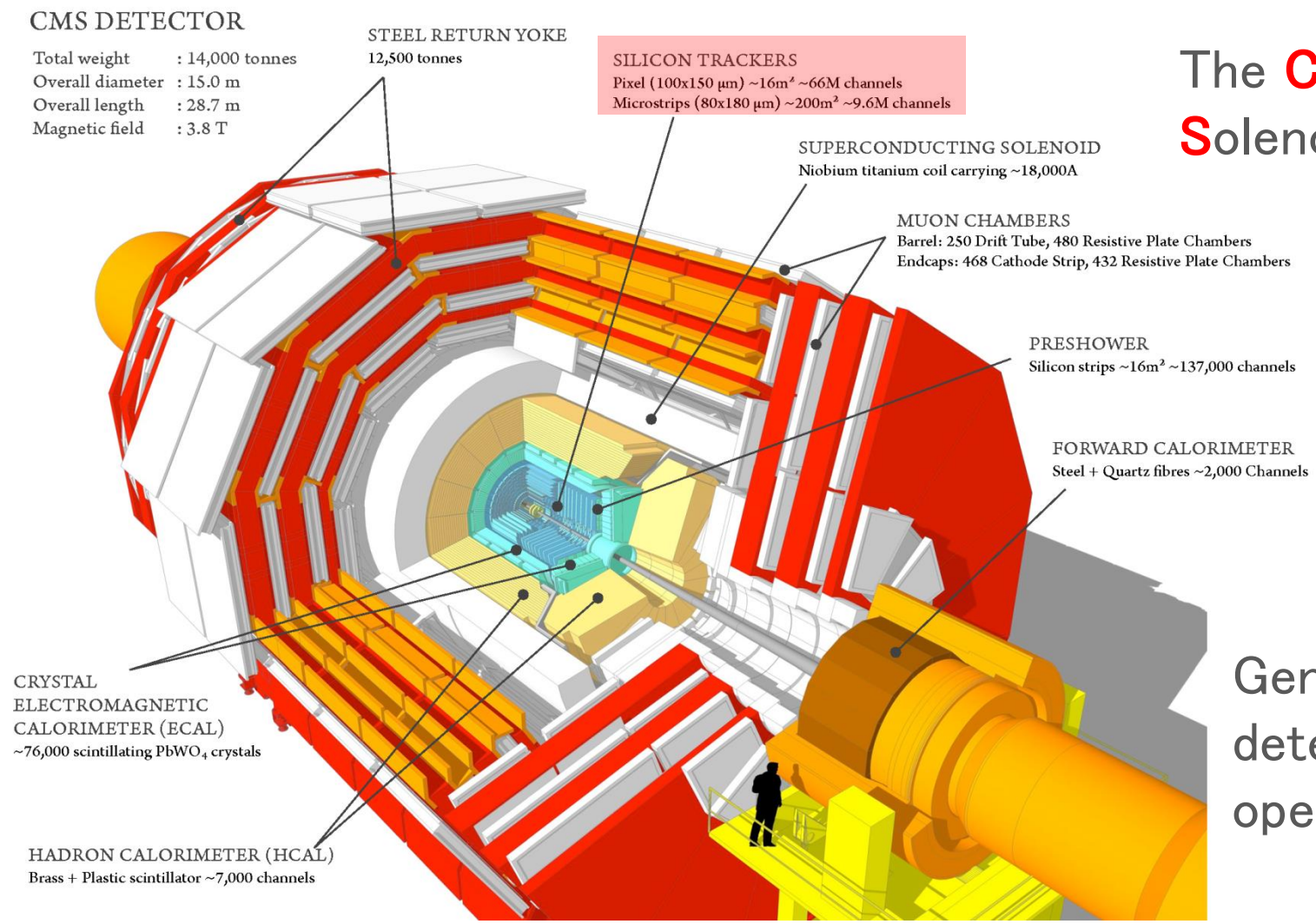
A Snapshot of Run II Data

- LHC Beam Conditions:
  - pp c.m energy 13 TeV
  - 25 ns bunch spacing
  - Max number of colliding bunches 2232
- Delivered Luminosity:
  - 31 .3 (2016) + 4.1 (2015) fb^{-1}
    - ~ 29 fb^{-1} in Run I
  - Max in a single LHC fill: 710 pb^{-1}
- Peak Luminosity:
  - 1.33 10^{34} cm^{-2} s^{-1}
    - 0.7 10^{34} cm^{-2} s^{-1} in Run I
  - ~ 20–40 hard interactions per bunch crossing (pile-up)
- LHC plan: 100 fb^{-1} by the end of 2018





The CMS detector

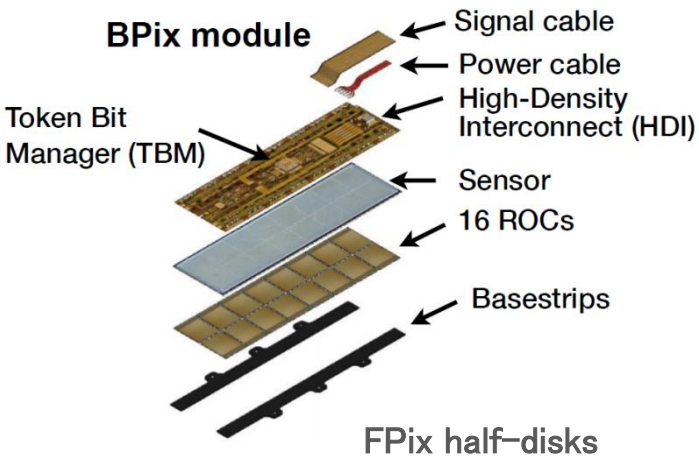


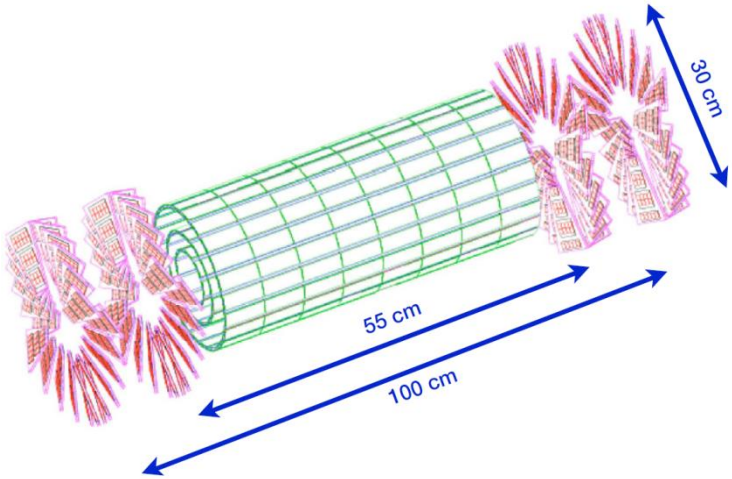
The **C**ompact **M**uon **S**olenoid

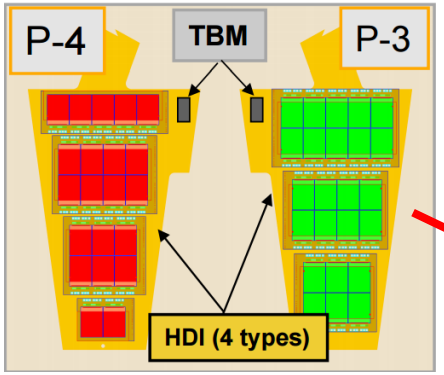
General purpose detector operating at LHC

Pixel Detector Overview

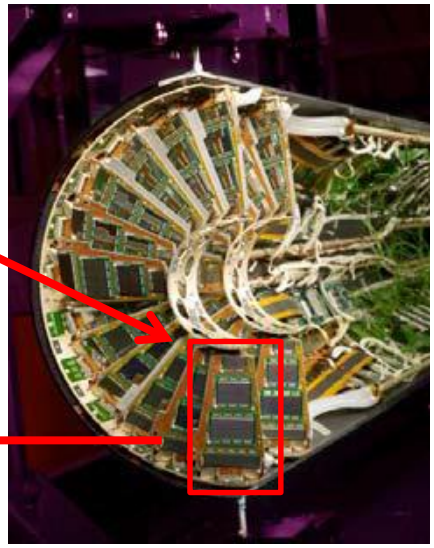
- 3 Barrel layers (BPix) (4.3, 7.2, 11 cm from IP)
- 2 Endcap disks on each end (FPix)
- 768 modules in BPix, 192 panels in FPix
- n+ implant on n bulk, 285 um thickness
- 1 Read Out Chip (ROC) serves 52 x 80 pixels
- 48 + 18 M pixels
- cell size 100 x 150 um







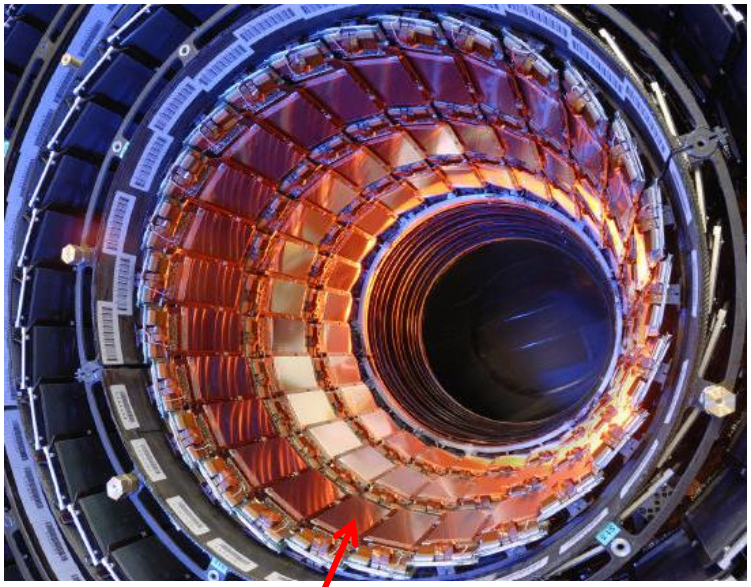
FPix half-disks

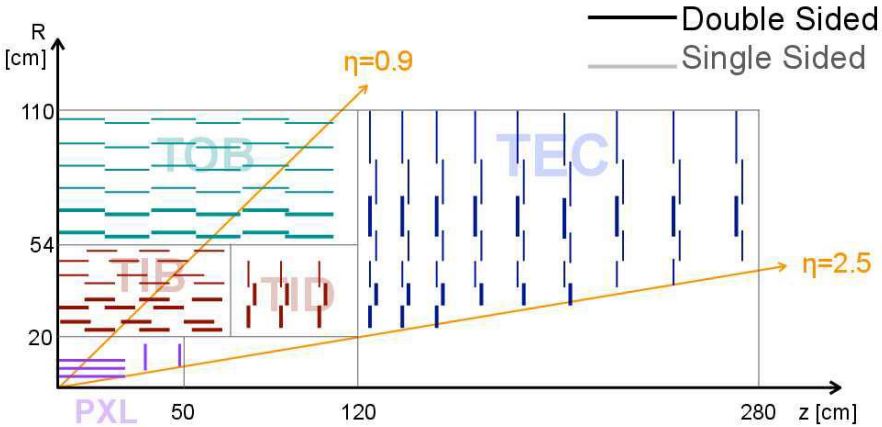


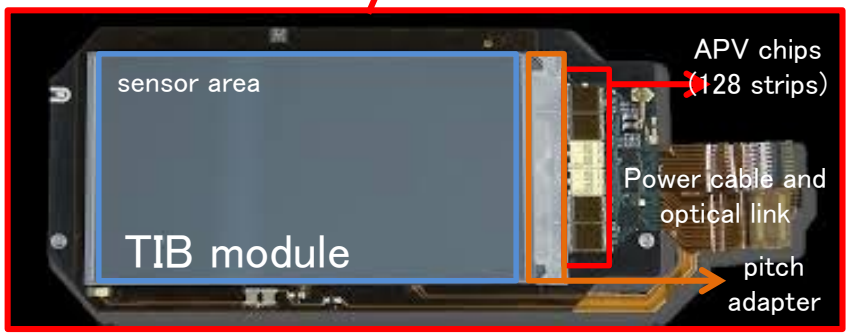
FPix "Blade" made of two counterposed **panels** with different ROC number and shape

Strip Detector Overview

- Total active area 200 m^2
  - 10 layers in the barrel (4 TIB + 6 TOB),
  - 3 inner disks plus 9 endcap disks (TID,TEC)
- 9.6 M read-out channels
- Si-strip modules:
  - p+- on-n sensors, 320/500 um thickness
  - 512/728 strips per module (4-6 APV chips)
  - Double sided modules
    - ✓ 100 mrad angle, 3D position measurement
  - strip pitch 83-205 um

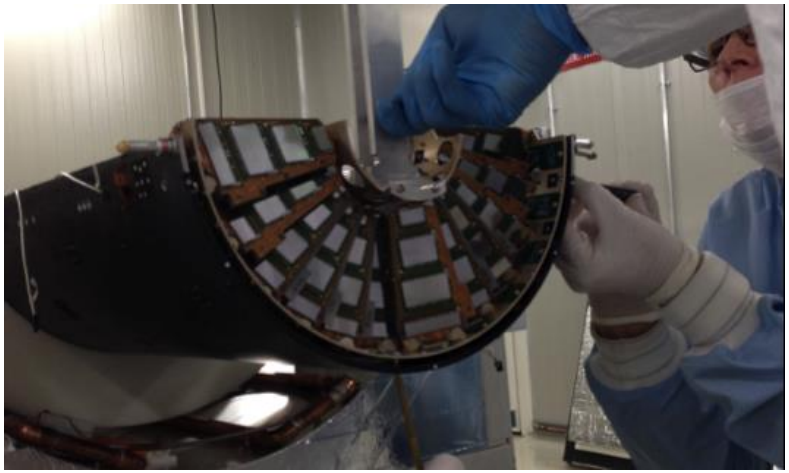


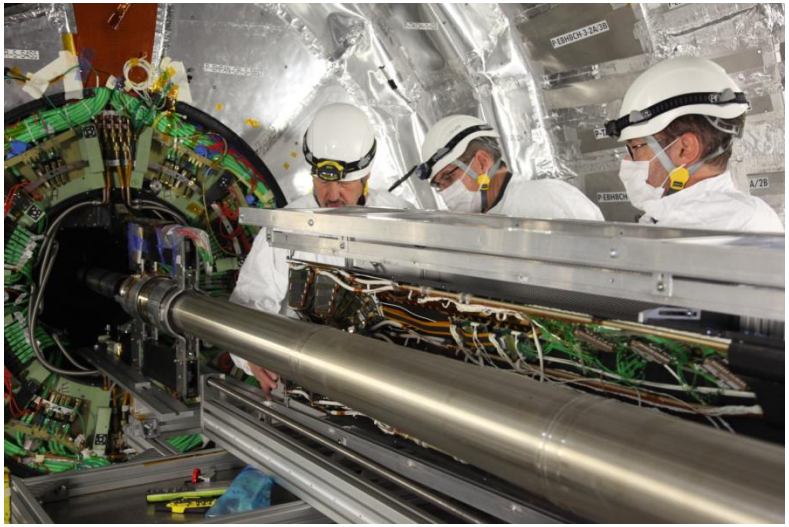




Activities in LS1

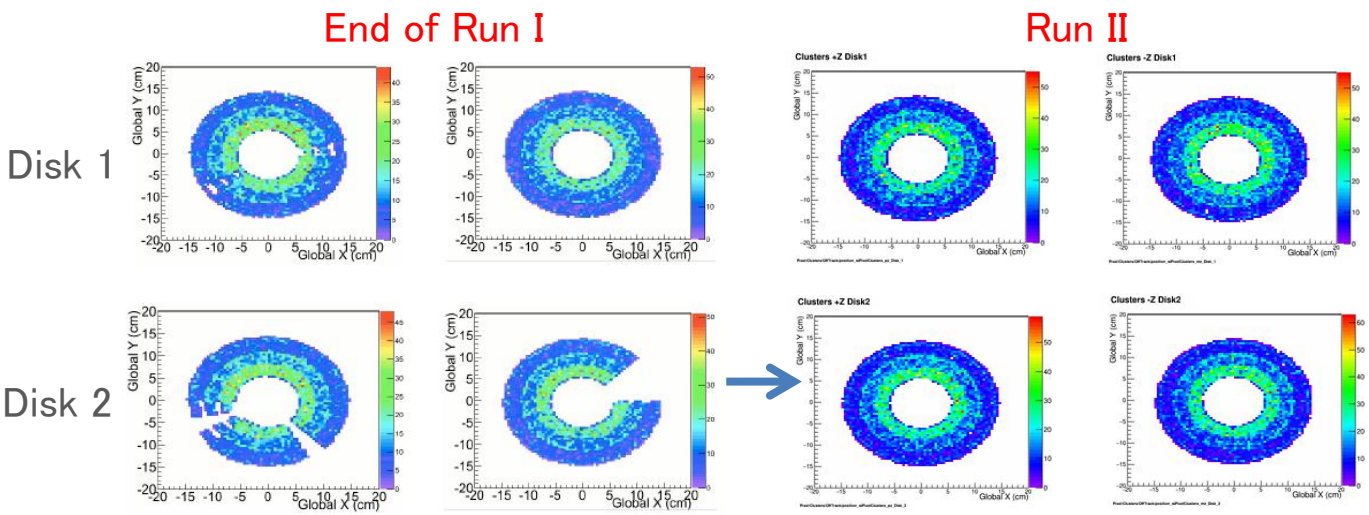
- Pixel detector repaired on surface after Run I (2013):
  - repaired faulty components (cables, optical converters)
  - 59 bad modules replaced
  - reinstalled in late 2014
- Improvement of the cooling system and humidity control
  - completely new coolig plants cabinets, improved insulation, new heat exchangers
  - new high capacity dry gas injection, insulation of tracker bulkhead and service channels completely redone
- Change of operating temperature:
  - Pixels from 0° to −10°
  - Strips form +4° to −15°
  - coolant temperatures



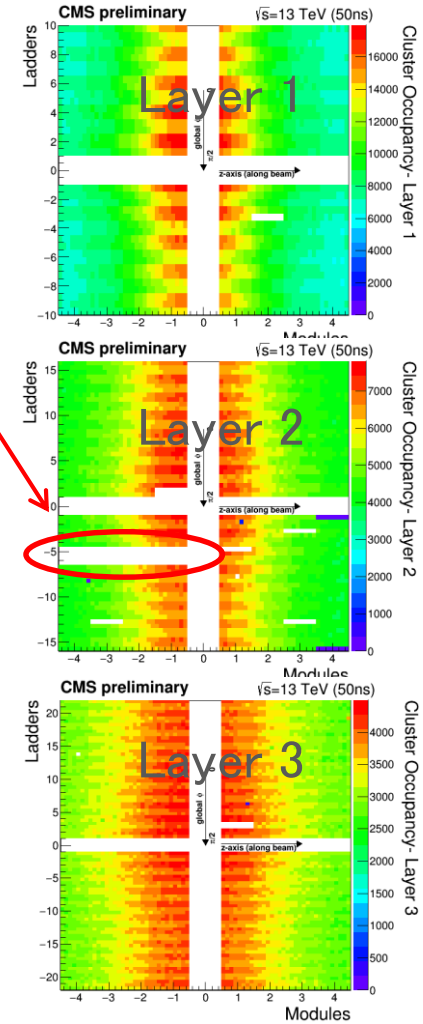


Status of the Pixel detector in Run II

- BPix Problematic sector in layer 2
  - ➢ not possible to power on at high magnetic field
- Bad components:
  - – BPix < 1.8 % (slightly better than Run I)
  - – FPix only 2 bad ROCs (99.95% good fraction)
- Increase of BPix bias voltage to 200V (150V)



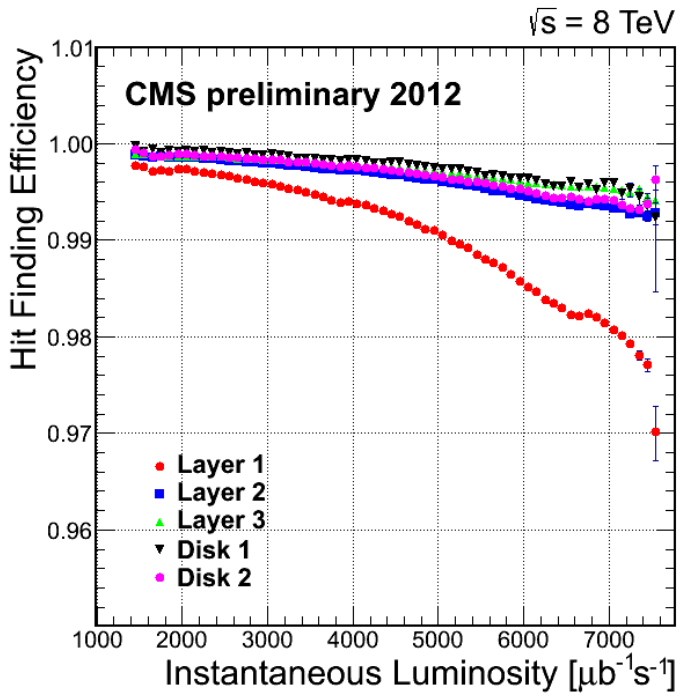
FPix cluster occupancy

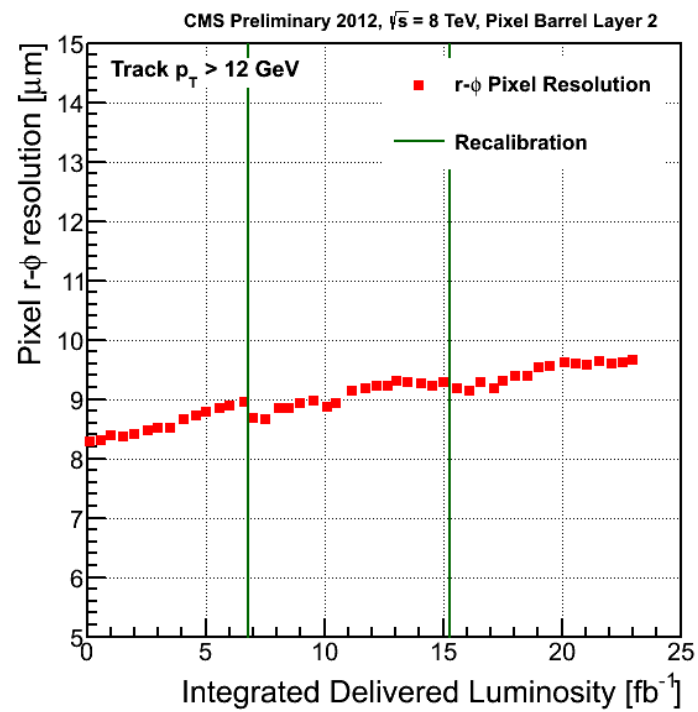


BPix cluster occupancy

Pixel Performance in Run I

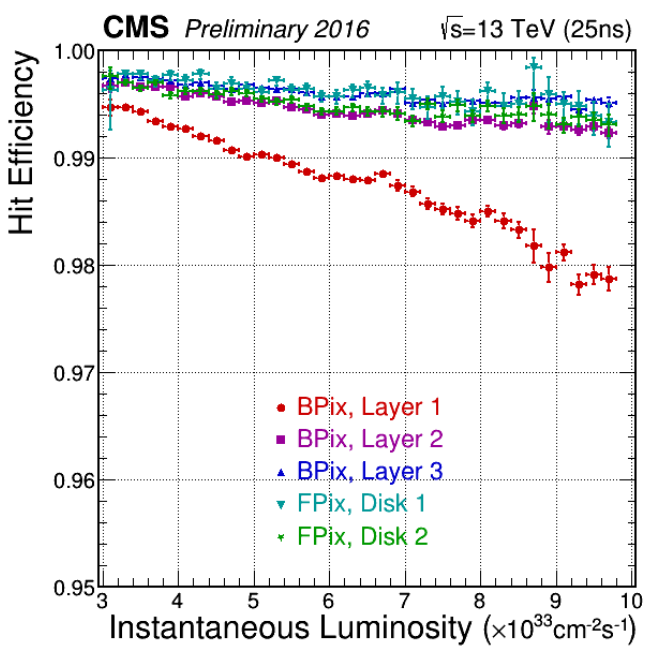
- Hit finding efficiency above 99% in outer layers
  - dynamic inefficiency observed at high lumi , affecting especially BPix Layer 1
  - ROC buffer overflow at high rate
    - Expected given the current ROC design
- Hit resolution in r−ϕ below 10 um at the end of Run I

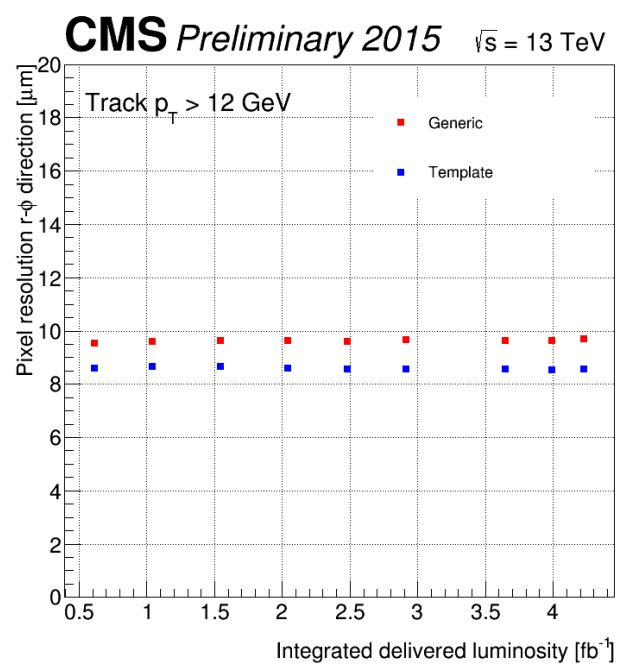




Pixel Performance in Run II

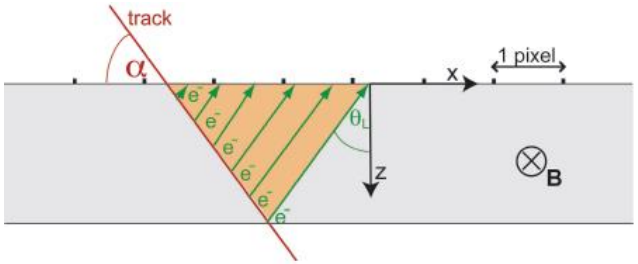
- Hit Efficiency stays above 99% for outer layers
  - Effect in Layer 1 expected given the current ROC design
  - Worst measurement of 2016 in BPix Layer 1 ~95.4% @ 1.2 10^{34} cm^{-2} s^{-1}
- Hit Resolution in $r-\phi$ < 10 um
  - Two methods used for the measurement:
    - Generic: fast estimate of the hit position (used in Online reconstruction)
    - Template: based on a detailed simulation of clusters shapes for different track incidence angles (give the best performance)

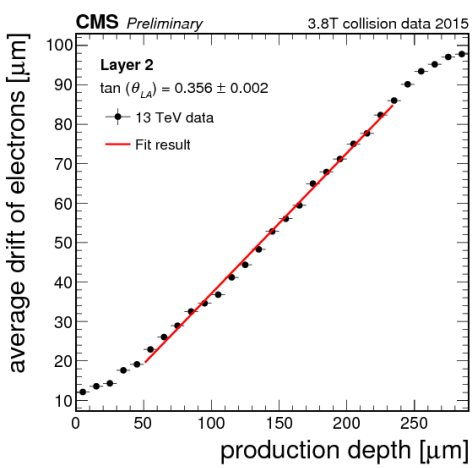


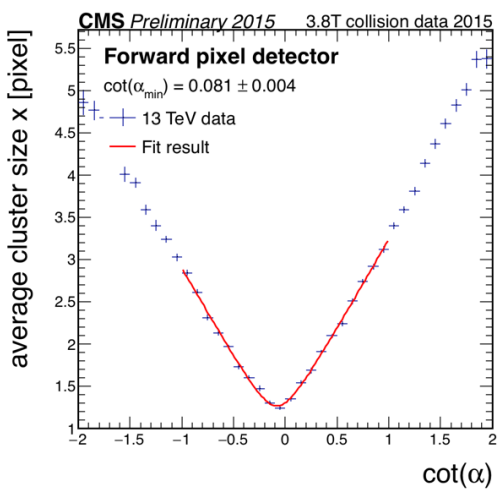


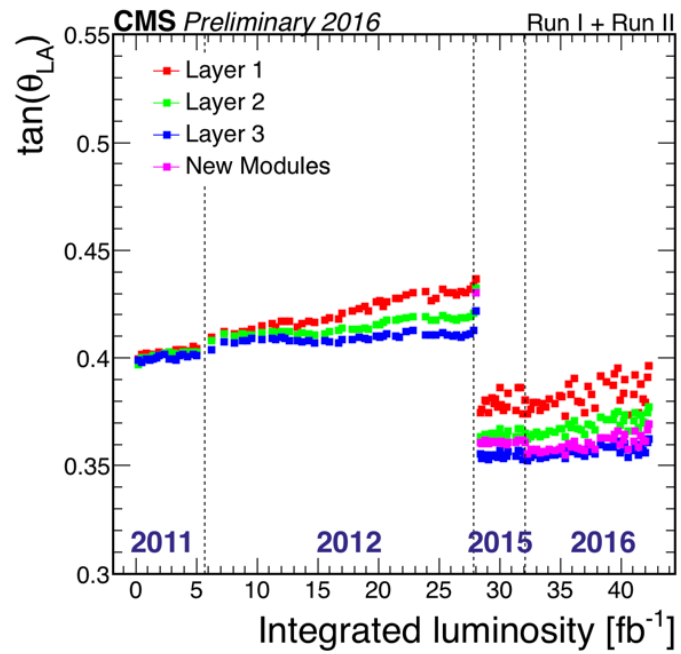
Lorentz Angle measurement

- Lorentz angle in Pixel measured after changing bias voltage to 200V
  - fundamental to achive a good hit resolution
- Two different methods:
  - Grazing angle method in BPix:
    - measurement of the drift length as a function of the depth
  - Minimum cluster size method in FPix:
    - Minimum cluster size for tracks parallel to the drift direction
  - Both methods based on good quality tracks



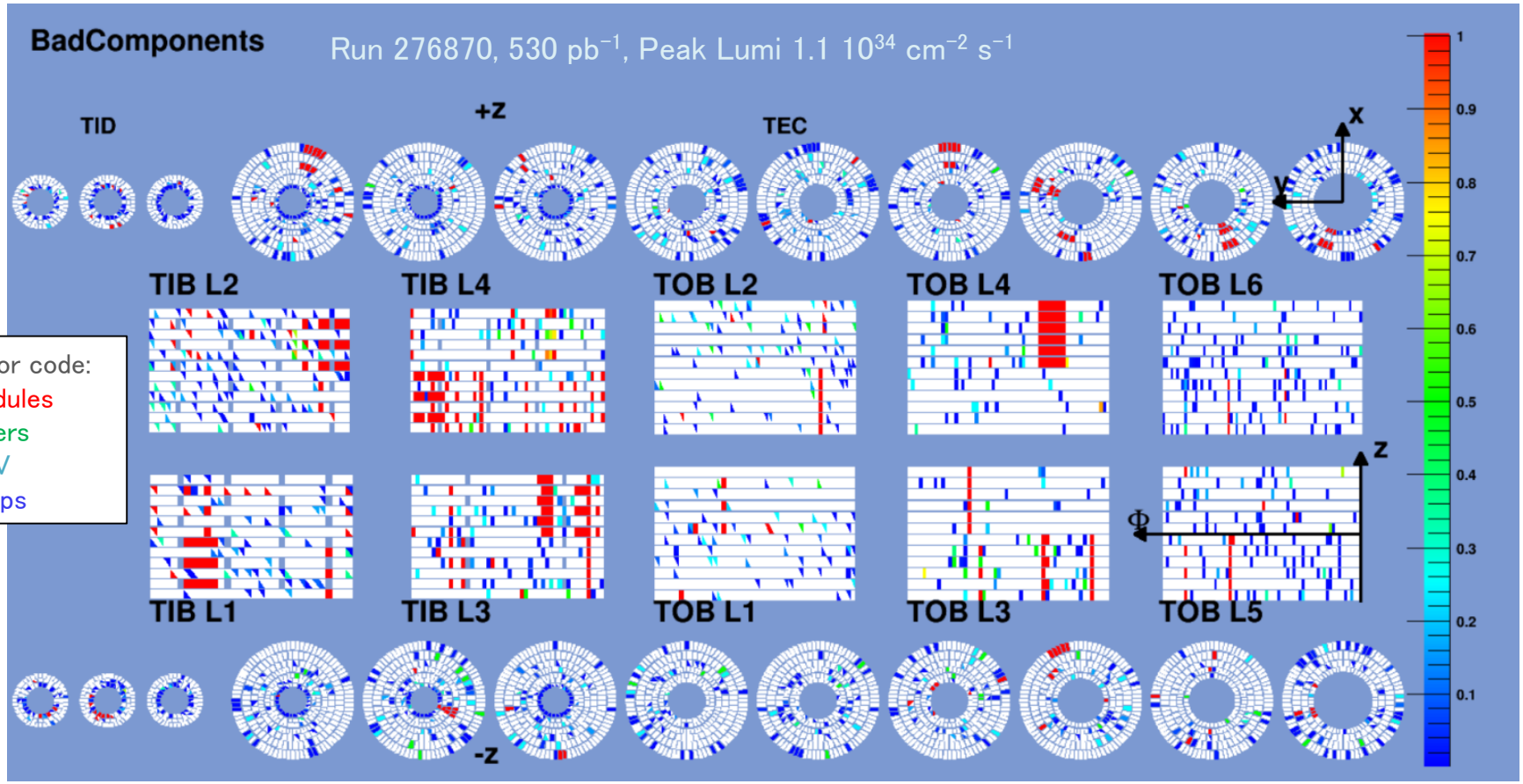






Status of the Strip Detector

- Tracker map of bad components
  - Monitored from faulty full modules (red) to single strips (blue)

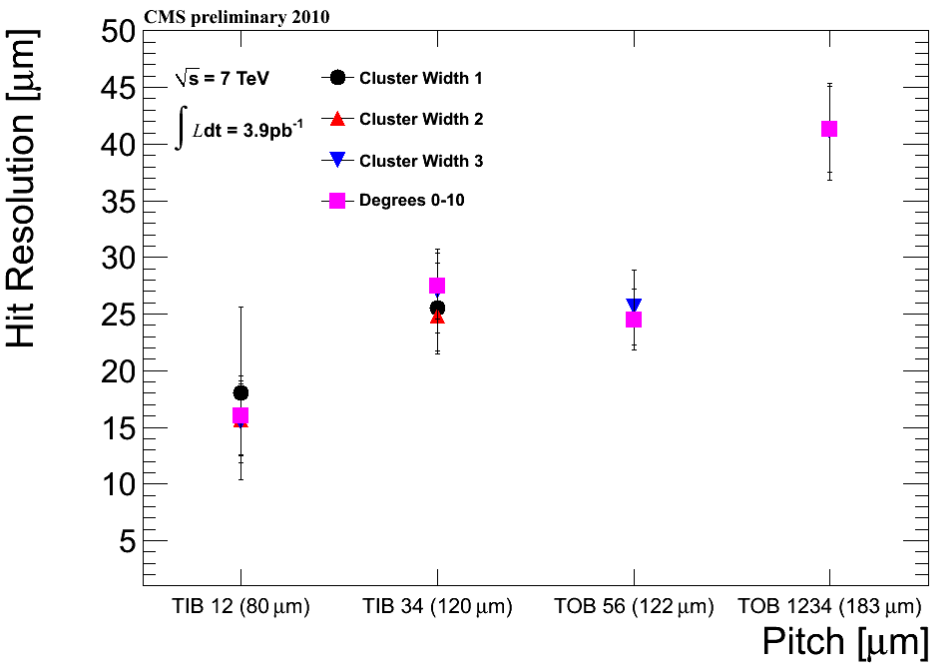


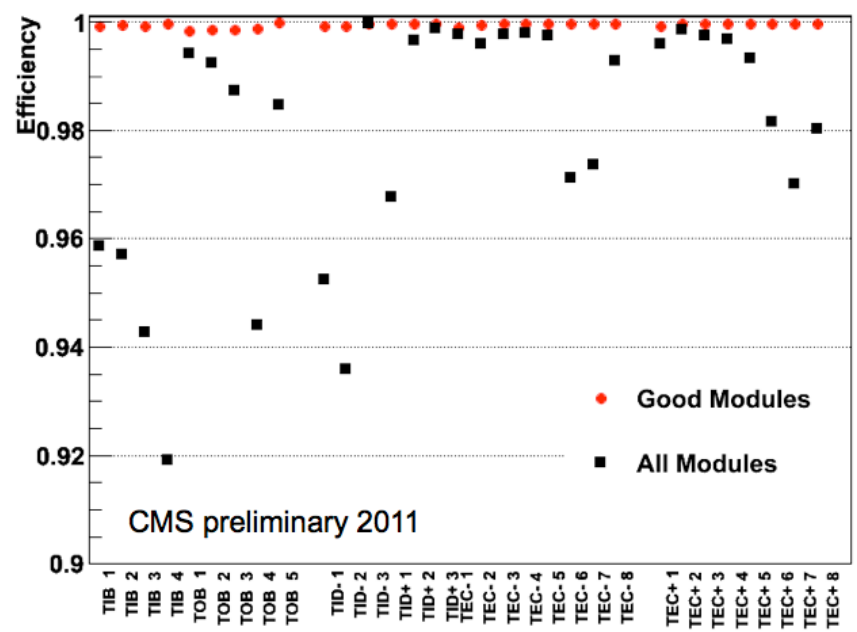
Color code:
Modules
Fibers
APV
Strips

Total fraction: 3.6–3.8% (No significant difference with respect to Run I)

Strip Performance in Run I

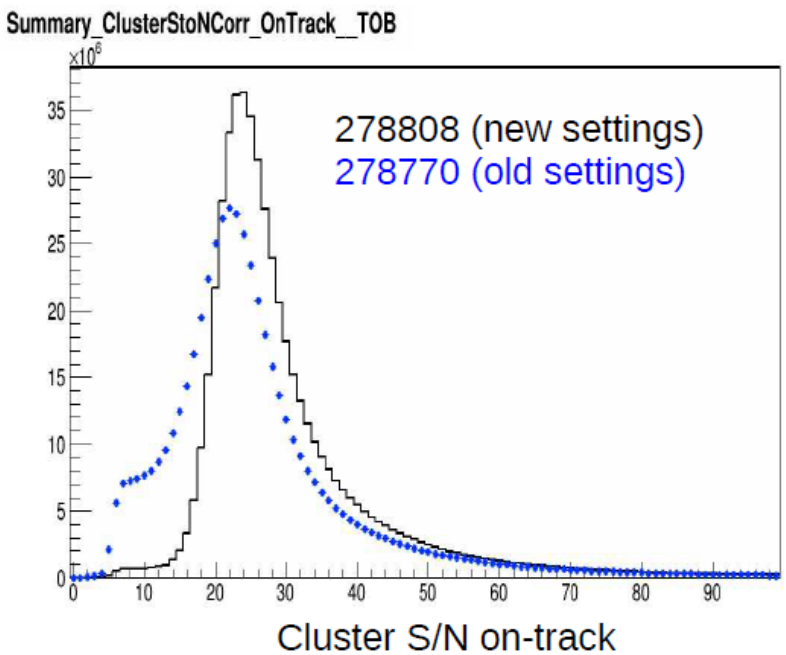
- Hit resolution in 15–42 um, depending on the pitch
  - small dependence on cluster width and track crossing angle
- Hit efficiency above 99% excluding bad components

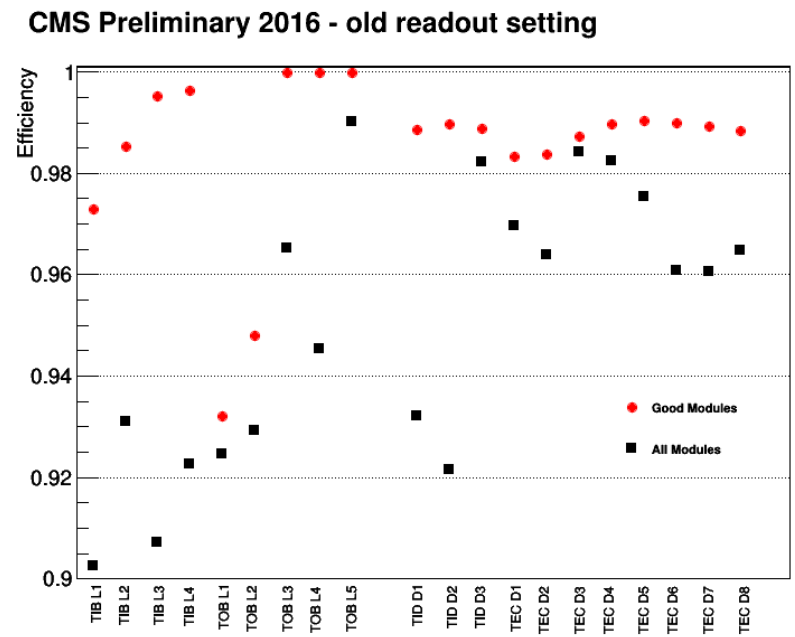




Strip Tracker Dynamic Inefficiency

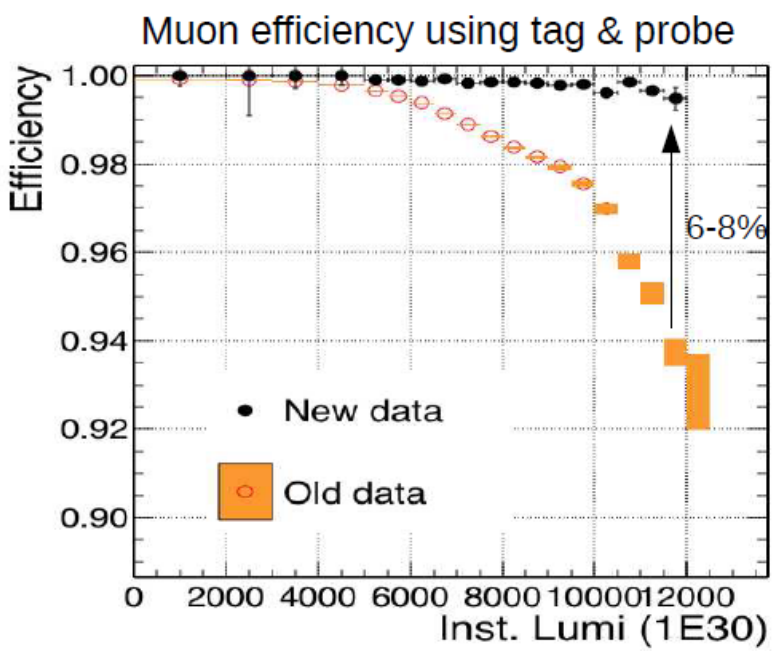
- A decrease of signal over noise ratio associated to loss of tracking hits has been observed in late 2015 and part of 2016
  - Effect increasing with Inst. Lumi. and occupancy
  - Problem was initially believed to be due to heavily ionizing particles (HIPs)
  - Finally traced to saturation effects in the pre-amplifier of the APV chip
- Fixed in mid August changing the APV chip settings, to increase the drain speed
  - About 20 fb^{-1} of data affected
    - The effect will be mitigated in reprocessing of data

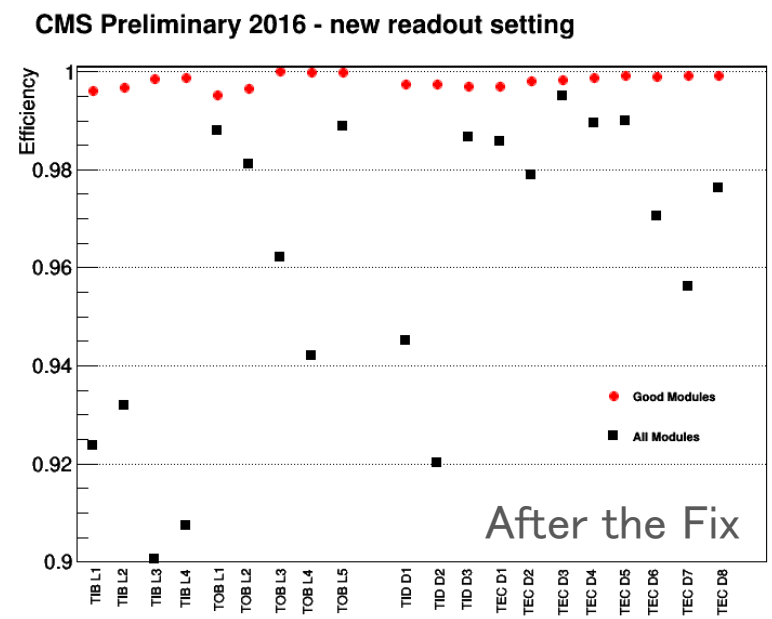




Strip Performance in Run II

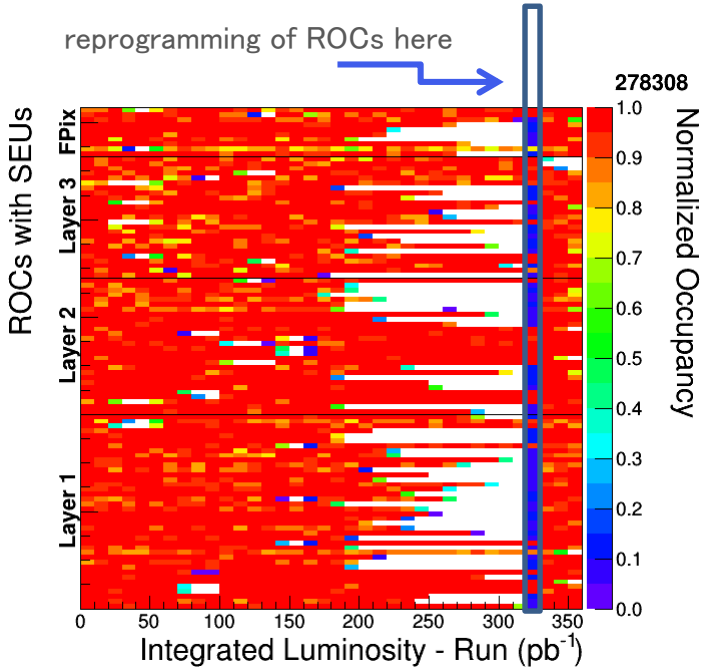
- With the new APV preamplifier settings the Hit Efficiency is back at the same level of Run I (above 99%)
  - substantial improvement especially visible in TOB L1-L2 and inner layers/rings





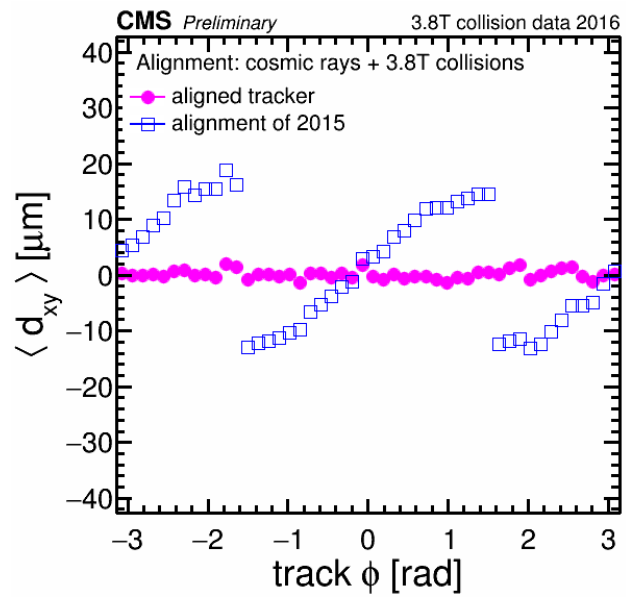
Single Event Upset (SEU) in Run II

- Single Event Upset (SEU) effects
  - SEU rate dependent on Inst. Lumi., are becoming more visible in Run II
  - more prominent in high occupancy regions (Pixels)
    - estimated a rate of 1 Pixel ROC every 2 pb^{-1}
- Automatic recovery procedure in place
  - Only for Pixel
  - inefficient ROCs are reprogrammed during the run (every 50 pb^{-1}) and fully recovered
- Effect negligible in the Strip detector
  - small trend observed in number of bad components during a fill, completely recovered after reconfiguration (done after each beam dump)
  - overall effect of few per mil with no impact on data quality

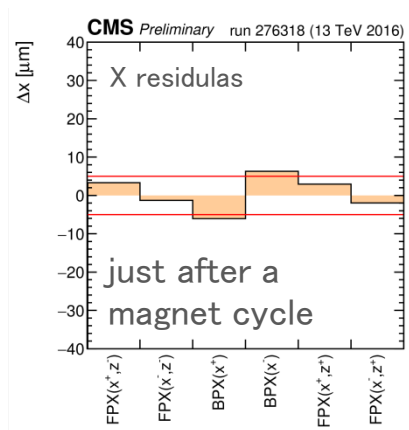


Alignment in Run II

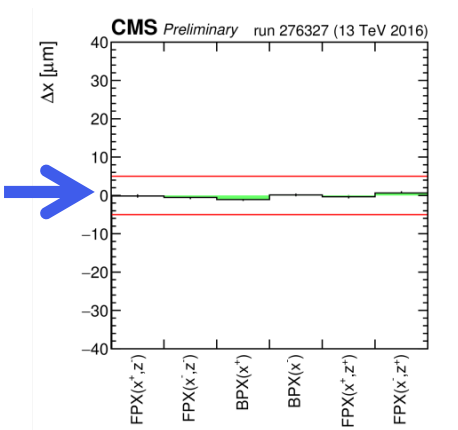
- Crucial ingredient to obtain the best performance
  - alignment of the full tracker redone in 2016 using 1 M collisions events and cosmic data
- Automatic procedure for Pixel alignment is in place since mid 2016
  - alignment is checked on a run by run basis and adjusted if necessary
  - Only for Pixel large structures: FPix half cylinders, BPix half shells
  - mostly needed in case of magnet cycle (movements in Z up to 300 um)
  - Residual movements in X up to ~10 um after magnet cycle, are reduced to few um by the automatic algorithm



Before alignment

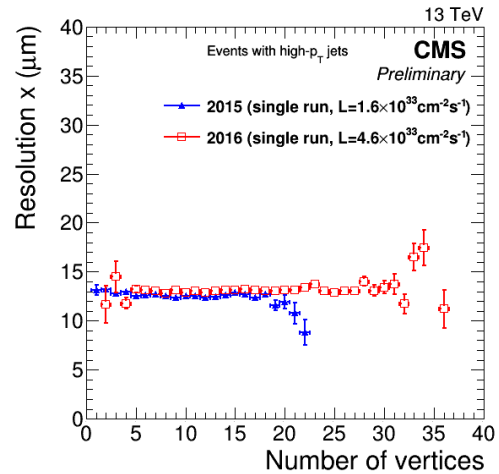


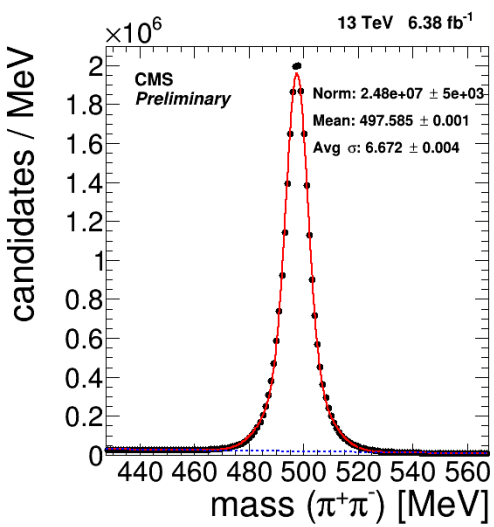
After alignment

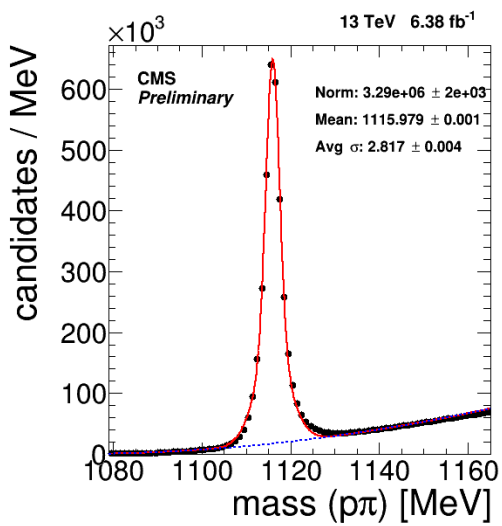


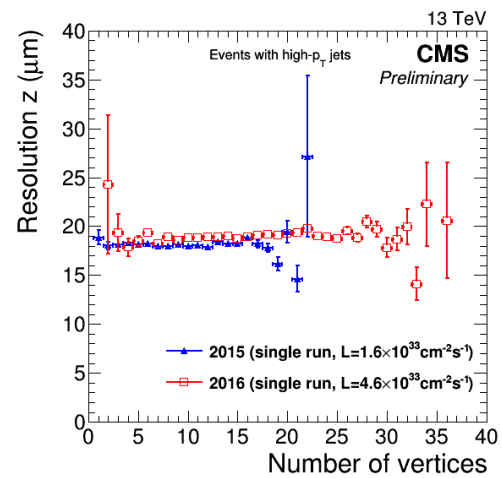
Track Reconstruction Performance

- Primary vertex resolution:
  - ~ 13 um in xy, and 19 um in z
  - degradation with increasing pile-up mainly due to Pixel dynamic inefficiency
- V0 reconstruction:
  - Only tracker information used
  - $K_S \rightarrow \pi\ \pi$, $\Lambda \rightarrow p\ \pi$
- Detectors maintains good performance even under more challenging beam conditions beyond design



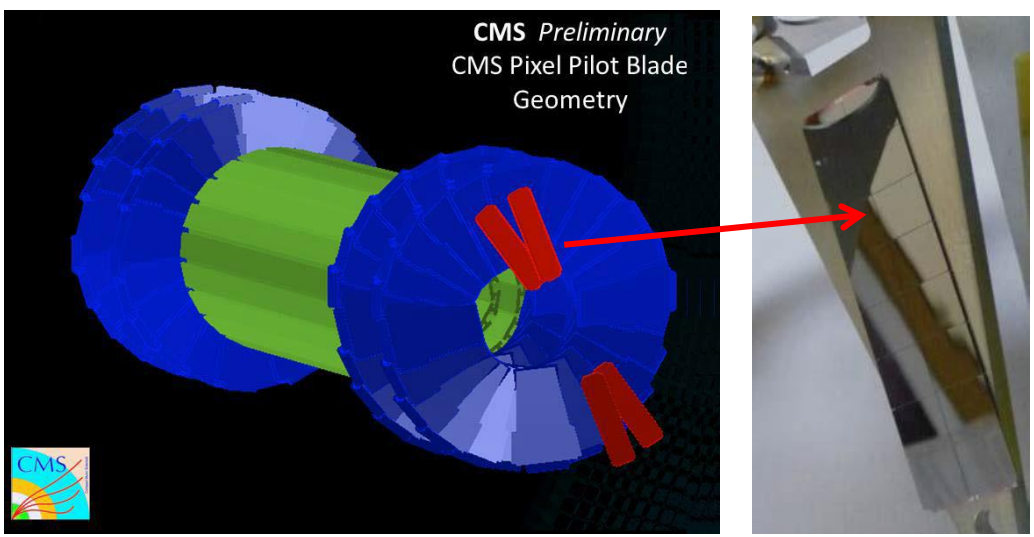


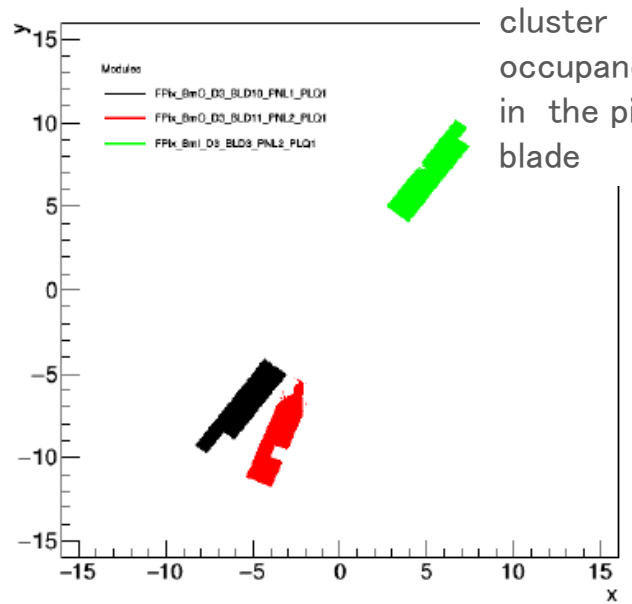




The Pilot Blade

- The CMS Pixel detector will be replaced in 2017 (Phase I)
  - upgraded Pixel detector with 4 barrel layers and 3 disks on each side
  - new digital ROC will cure dynamic efficiency losses
  - dedicated talk tomorrow by M.Verzocchi
- A "pilot blade" equipped with Phase I modules installed in 2014
  - integrated in the central DAQ and DCS systems, included in data taking as any other CMS subdetector
  - not all the ROCs commissioned (clusters not used in reconstruction)
  - fundamental input in view of the commissioning of the full detector (early 2017)





cluster occupancy in the pilot blade

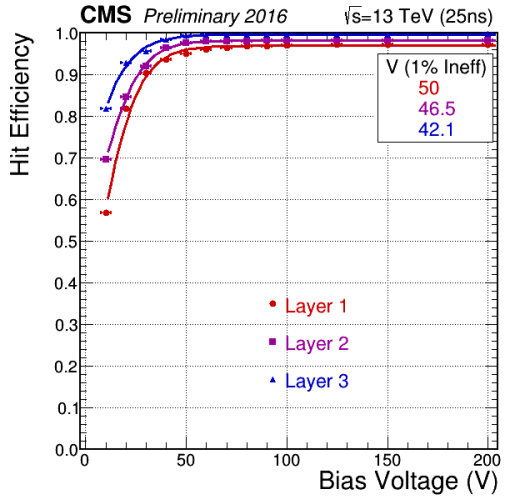
Summary and Conclusions

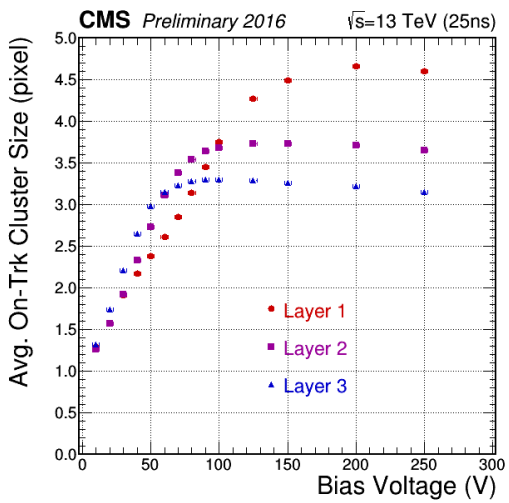
- CMS successfully taking physics data in Run II even at the highest luminosity
  - ~35 fb^{-1} already delivered over 100 fb^{-1} planned for the end of 2018
- The Tracker is operating with very good performance
  - detectors are running very stably at low temperature since LS1
- Some issues encountered running at high luminosity
  - dynamic inefficiency in Pixels (expected)
    - will disappear with Phase I detector
  - Strip dynamic inefficiency solved
    - performance back to nominal
- Track reconstruction performance stable with respect to Run I
  - good effort in developing mitigation algorithms to compensate the effect of Strip inefficiency
- Phase 1 pilot detector continues to provide valuable information towards the commissioning of the upgrade detector
- The CMS Tracker is ready to provide good quality data for the rest of 2016, looking forward for the new Pixel detector and the highest LHC luminosity.

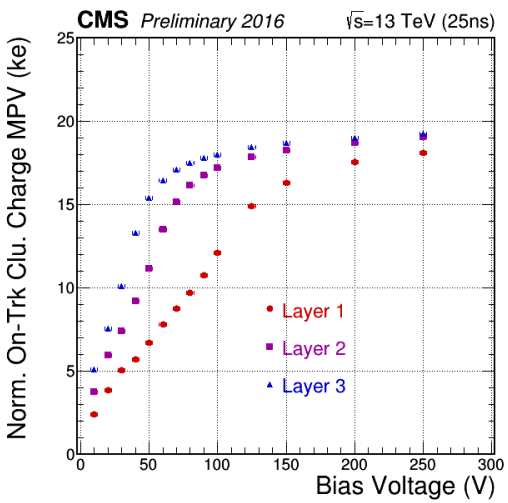
BACKUP

Pixel Performance Vs Bias Voltage

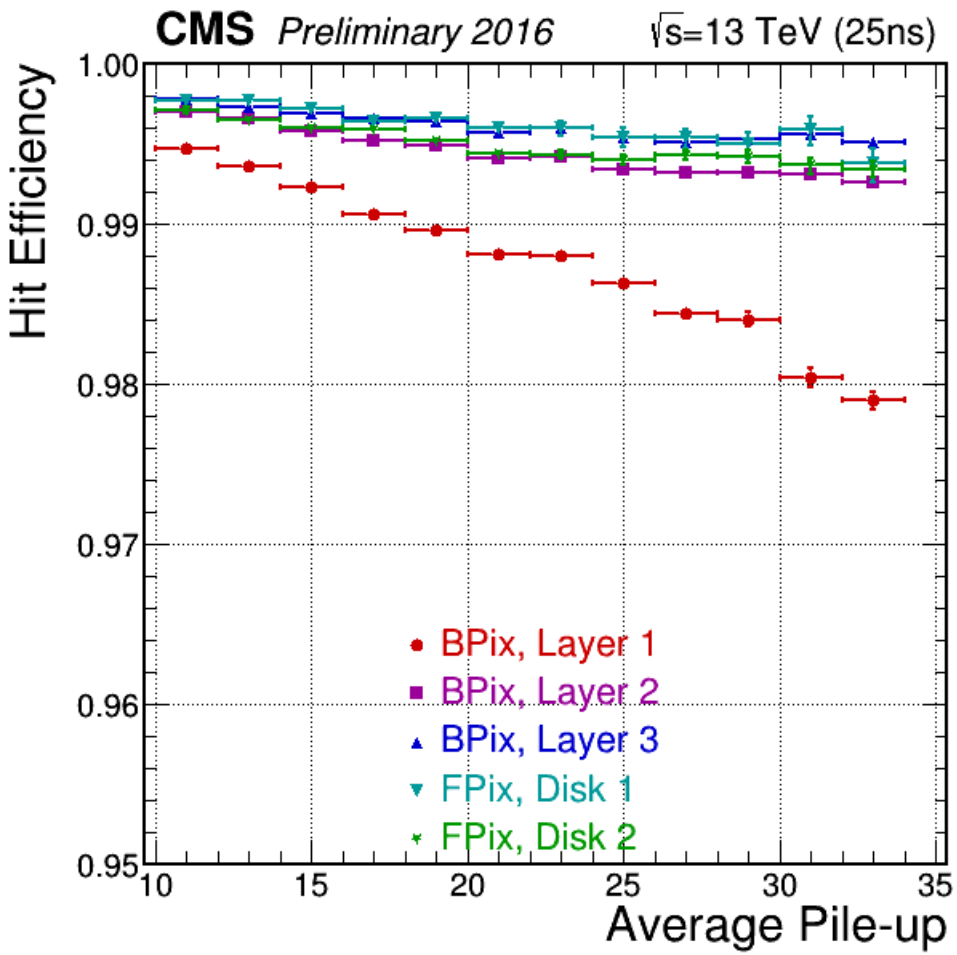
- The voltage setting in Run II was increased from 150 V to 200 V
  - In order to mitigate charge trapping effects while maintaining reasonable charge-sharing (large enough Lorentz Angle)
  - The hit efficiency reaches maximum value above 60V
  - Cluster size is near its maximum
  - The detector is fully depleted well below the operational voltage



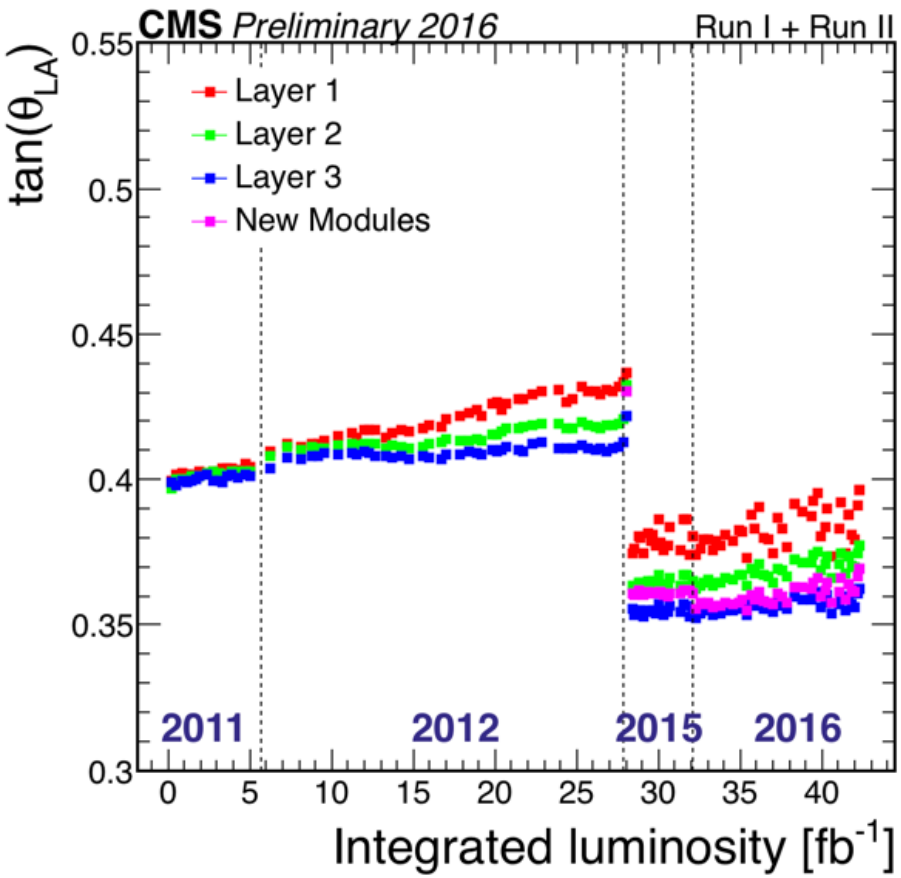


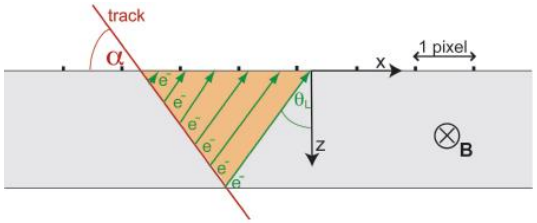


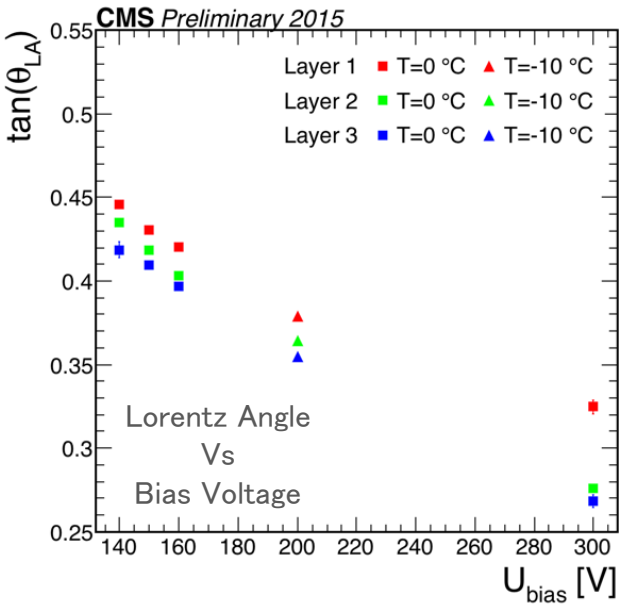
Pixel Efficiency Vs Pile Up



Pixel Lorentz Angle

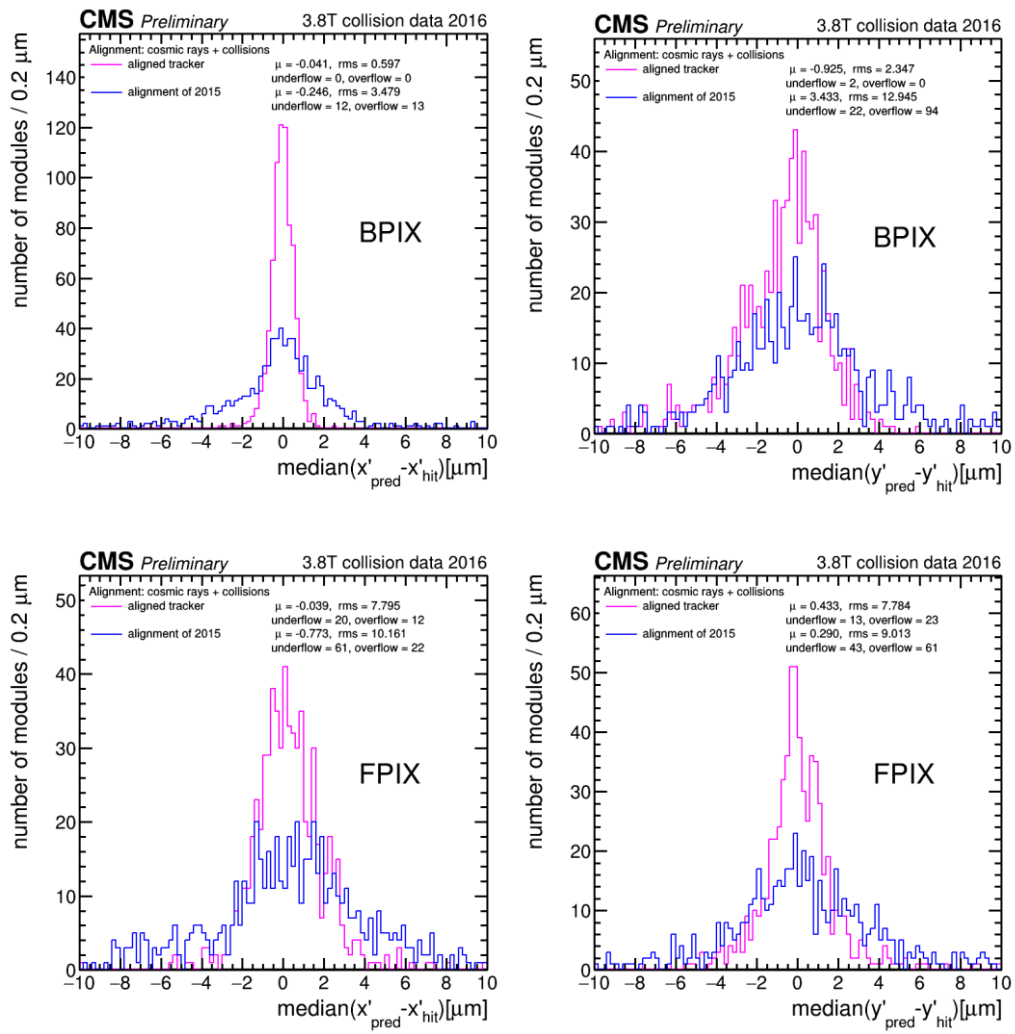






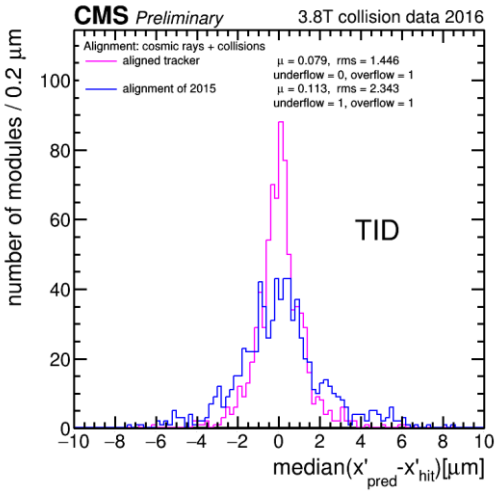
Alignment Pixel

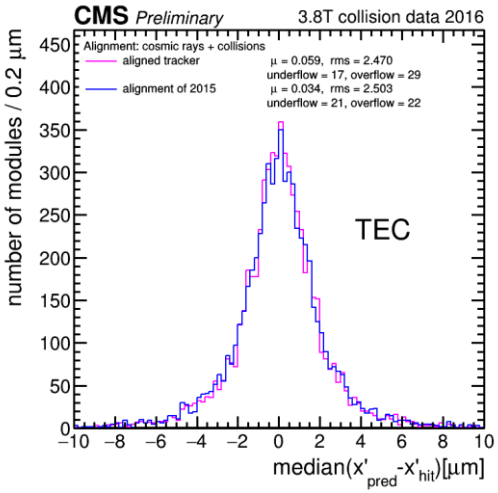
- Pixel Alignment updated after 2015:
  - very sensitive to magnetic field ramp and temperature cycles
- Track hit residuals shown here in x and y:
  - a factor 5 improvenìment in rms after alignment

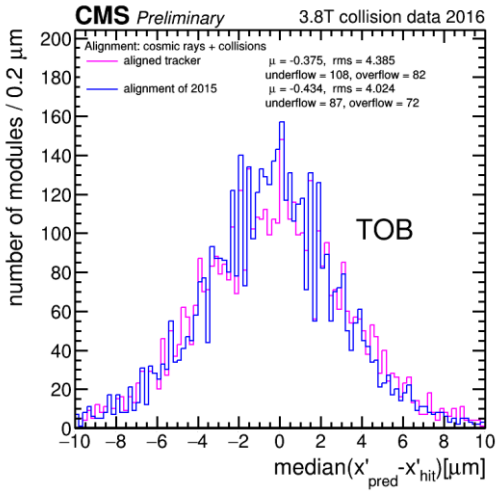


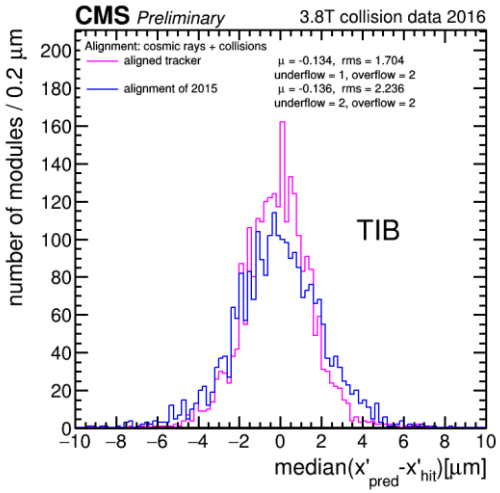
Strip Alignment

- Performed using 1 M tracks from pp collisions at 3.8T (plus cosmic muons)
- Less sensitive to magnet ramp
  - Improvement observed especially in TID disks, also TIB geometry improved
  - TOB very stable
    - ➢ used as reference in the alignment algorithms
  - TEC not aligned at module level in the new Geometry



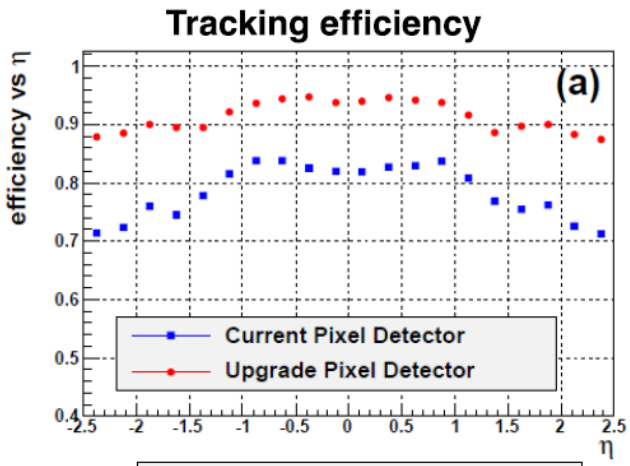




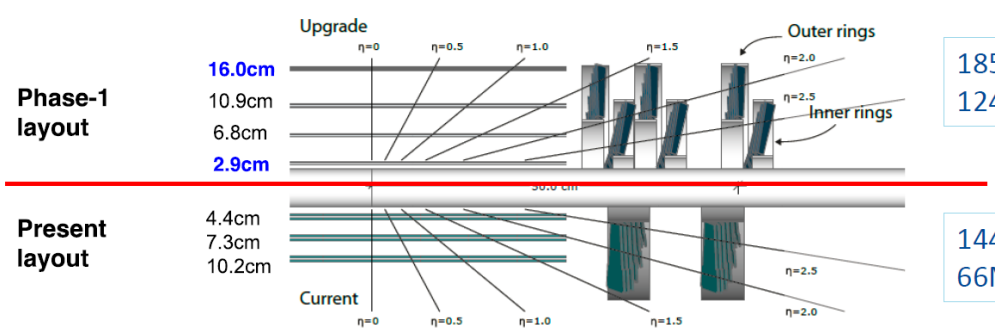


Phase I Upgrade

- New geometry:
  - 4 barrel layers and 3 disks each side
  - First layer at 2.9 cm
- Digital ROC
  - reduce buffer overflow effect
    - ➢ against dynamic inefficiency
- Reduction of material budget
  - 2 phase CO2 cooling system

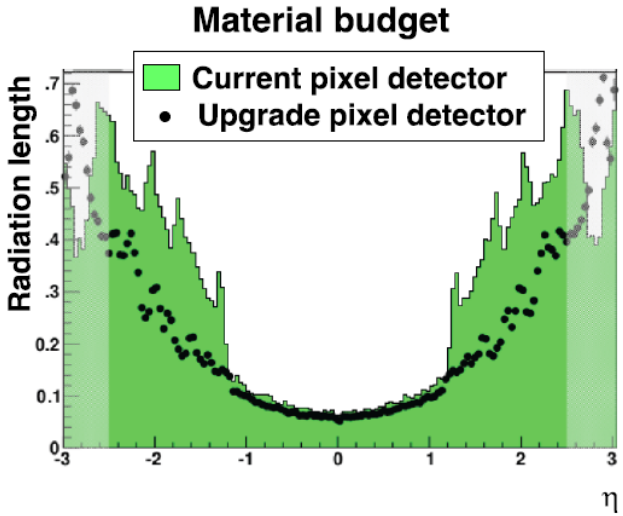


ttbar sample, 50 pileup events

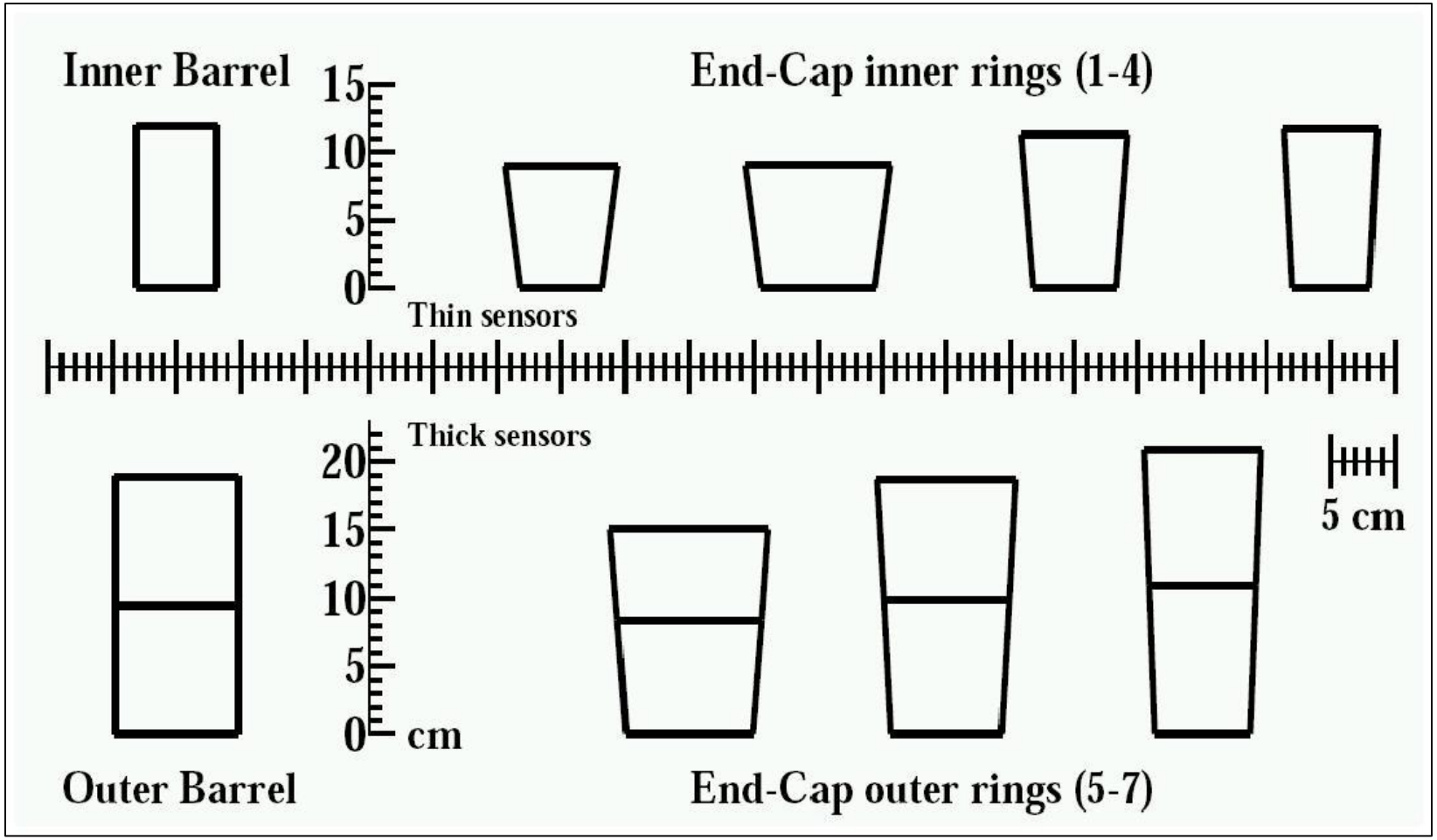


1856 modules
124M pixels

1440 modules
66M pixels



Different Shapes of Strip Sensors



People

- To guarantee smooth operations of the CMS Tracker a "shift crew" is necessary
  - Online: checking the status of the detector and DAQ system
    - 4 people per week, available 24/7
    - 2 Detector experts and 2 DAQ experts (Pixel + Strip)
  - Offline: checking quality of data and giving fast feedback in case of issues
    - 2 shifters a day (16h), coordinate by an "Offline Shift Leader".
    - 2 data quality experts (on call) as a support (Pixel + Strip)
- Total number of people involved up to now:
  - 51 in Online operations
  - 30 experts plus 54 shifters in Offline
- More than 6k shift slots covered in 2015-2016