Operational Experience with the CMS Pixel Detector

János Karancsi

On Behalf of the CMS Collaboration

Institute for Nuclear Research, H. A. S. (ATOMKI),

University of Debrecen

PIXEL 2016, Sestri Levante (Italy), 5 September 2016

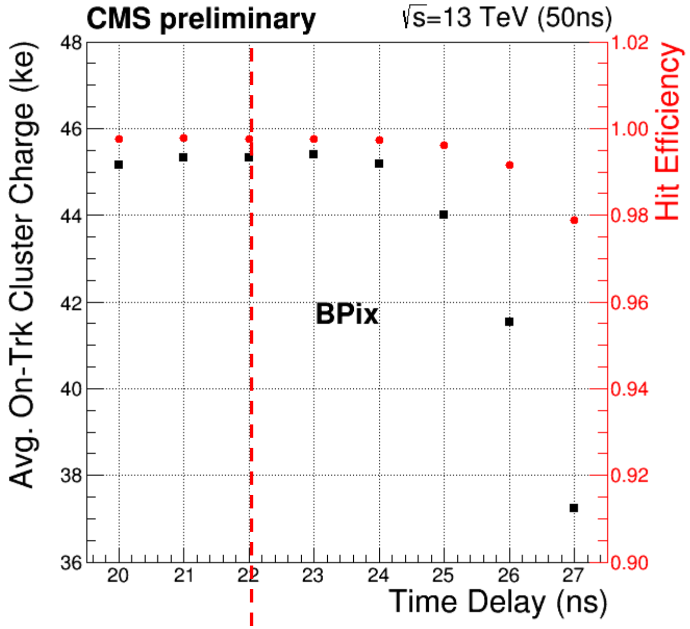
OTKA K109803

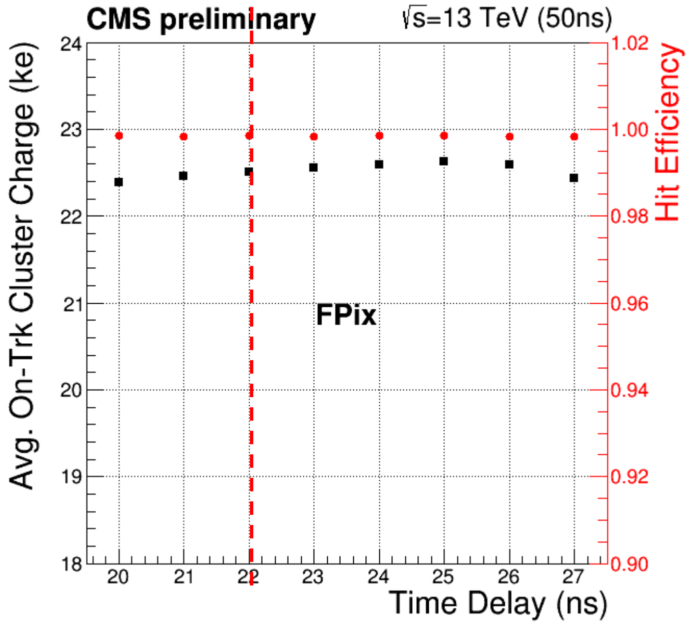
Overview

- Introduction
- Run II Startup Operations
  - Startup calibrations
  - Working detector fraction
  - High Voltage Bias scan
- Performance measurements during stable running
  - Lorentz Angle
  - Pixel Thresholds
  - Cluster properties
  - Hit resolution
  - Hit efficiency
- Inefficiencies, SEUs

Run II Startup Operations

- Modules were replaced in Long Shutdown 1
  - During Long Shutdown 1 most of the bad components from Run I were repaired
    - Forward disks were almost fully reapaired (except one chip)
    - All Barrel modules repaired/replaced with spare/new modules, but we lost ~2% shortly after the startup (More info on next slides)
- Changed operation temperature and voltage
  - Operation temperature decreased from 0 °C to -10 °C
  - Raised Barrel high voltage from 150V to 200V (More info on slide 6-7)
- Startup calibrations in Run II:
  - Most calibrations were done online in a sequence, eg:
    - Basic set of calibrations at the new temperature (Delay, baseline, AOHbias, AOHgain, FED clock phase, TBM ultra-black, ROC ultra-black, Address levels)
    - Vana calibration of the power supply
    - Threshold minimization, Pulse height optimization
    - Gain calibration
  - Time alignment was done during the first LHC Collisions @ 13 TeV
    - In 2016 we used the same settings and validated the delay setting

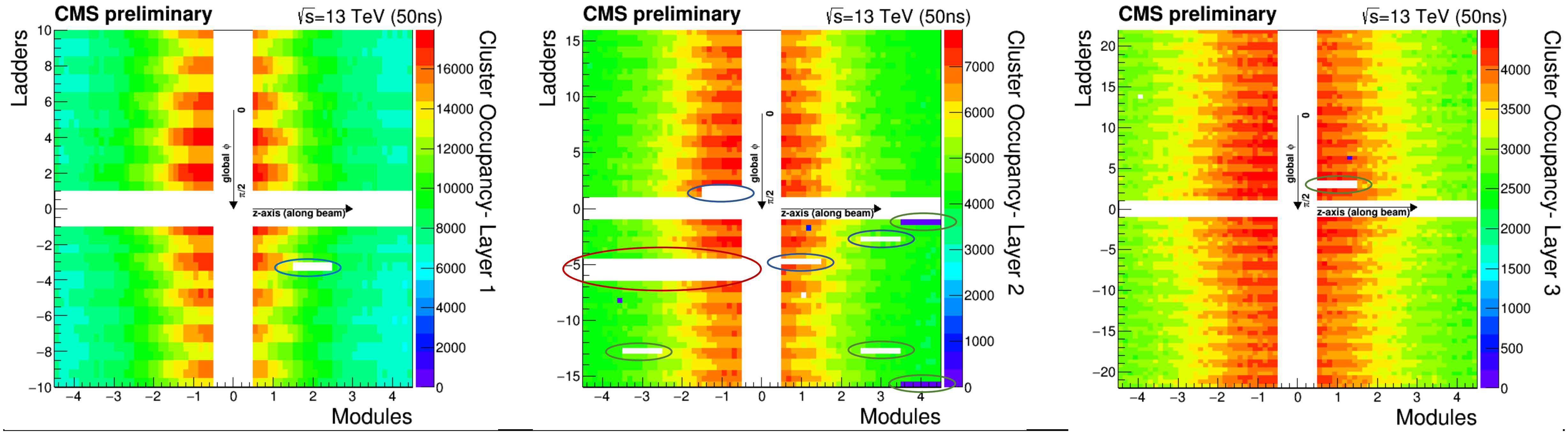




Run II Startup Operations

Cluster occupancy in Barrel Pixel modules

- All clusters are considered (independently of tracking)
- White cross-shaped area in the middle of the plots correspond to invalid ladder/module coordinates (counts start from +/-1)
- Alternating pattern along ladders are due to the staggered structure of a layer (every other ladders are closer to the interaction point in radius)
- Other white (or low occupancy) areas are due to bad modules/ROCs
  - Each bin corresponds to a ROC
  - Good detector fraction – after LS1: 98.2% (shown on plots from 2015, current status in 2016 is slightly better 98.3%)
    - A few modules had HV problems and some gave strange signals (mostly due to instabilities)
    - Lost an entire sector in a layer 1-2 quadrant, due to an undervoltage problem that is only present in high magnetic field: No solution found, but we managed to bring back layer 1 modules

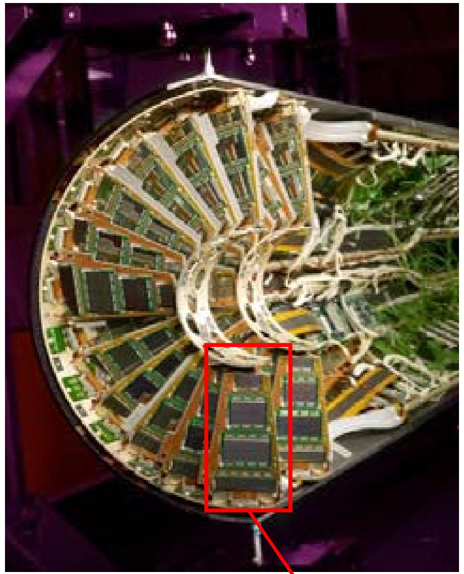


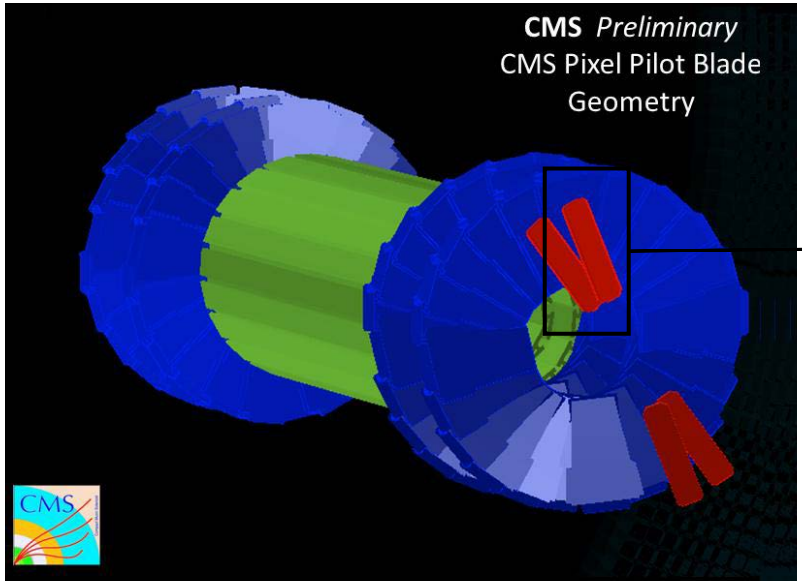
Run II Startup Operations

Cluster occupancy in Forward Pixel modules

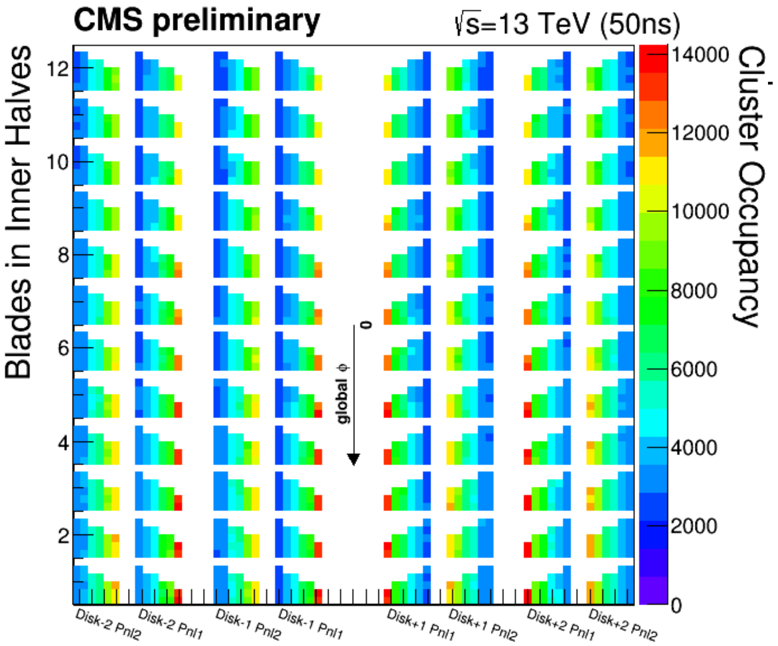
- FPix constitutes two pairs of disks on each side of the collision point along the beam-line (z) and 4 modules of the Phase I pilot system on one side
- Two panels form a blade, 12 blades form a half disk
- Triangles are due to radially increasing module sizes on each panel - Each bin corresponds to a readout chip
- The new Phase I modules are made of 2x8 ROCs
- All modules were fully repaired during LS1
    - Except for 1 ROC, which is masked
    - Good detector fraction after LS1: 99.98%

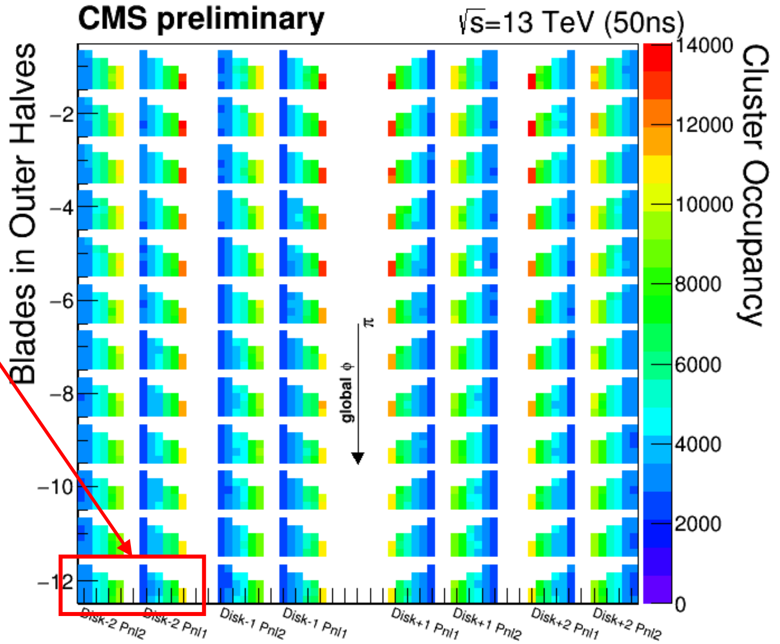
Phase 0 blade





Phase 1 pilot blade

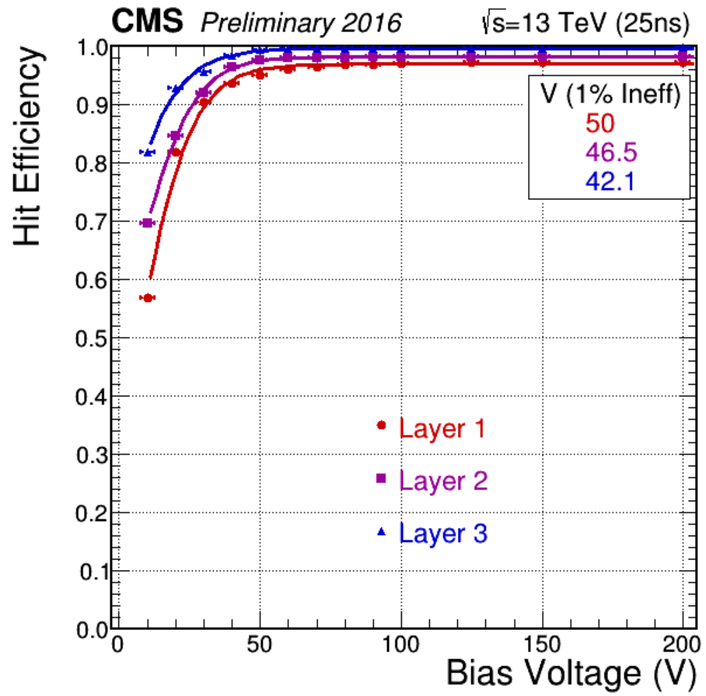


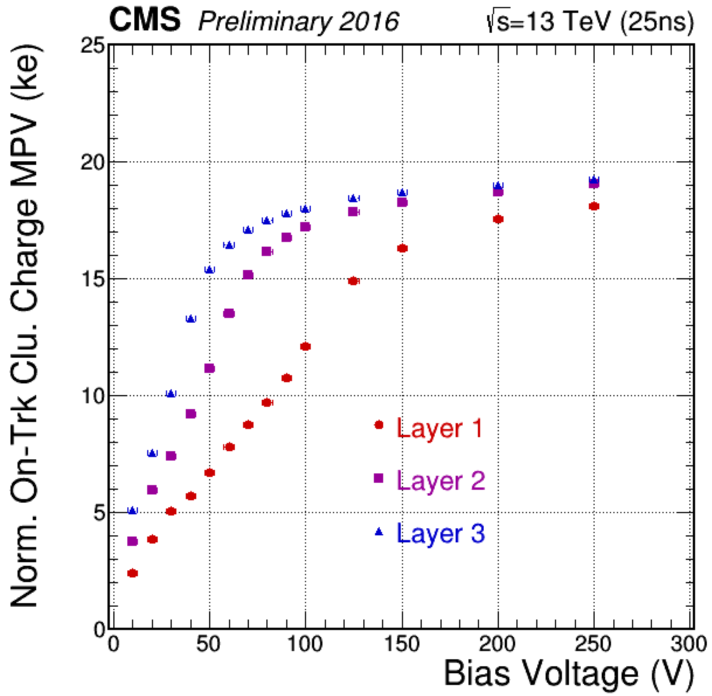


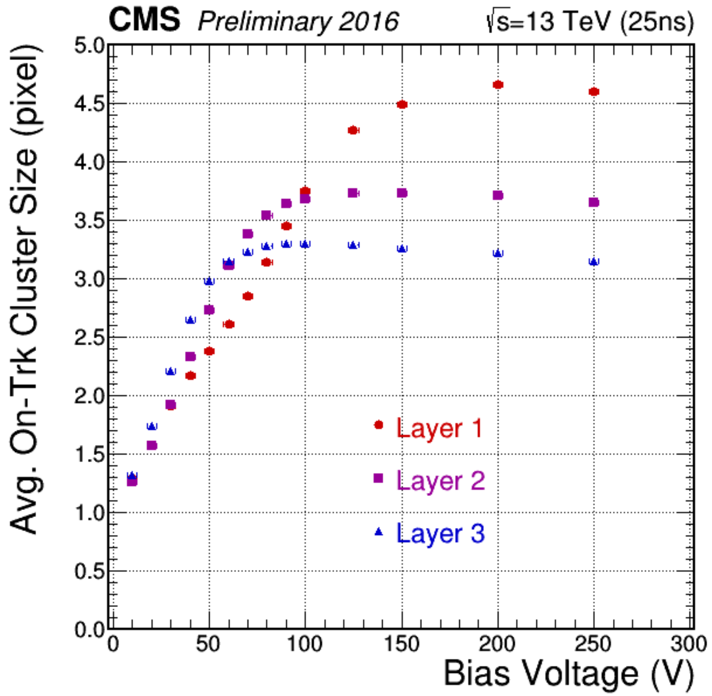
High Voltage Bias Scan

Hit Efficiency, Cluster Charge MPV and Size vs Bias Voltage

- Scans are carried out regularly, in order to see long term aging effects of the detector
  - We aim to ensure maximum efficiency while maintaining good resolution
  - The voltage setting for the barrel 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 on all layers
      Points were fitted with a turnon curve, the voltage corresponding to 1% inefficiency is shown on the top right corner
    - Cluster size is near its maximum
    - The detector is fully depleted well below the operational voltage

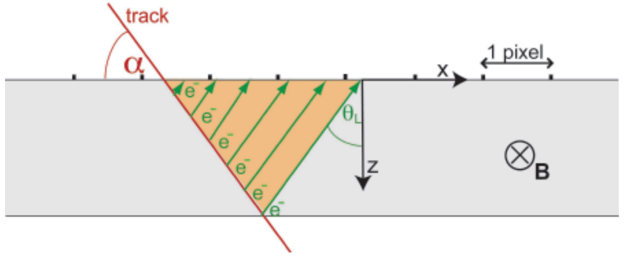


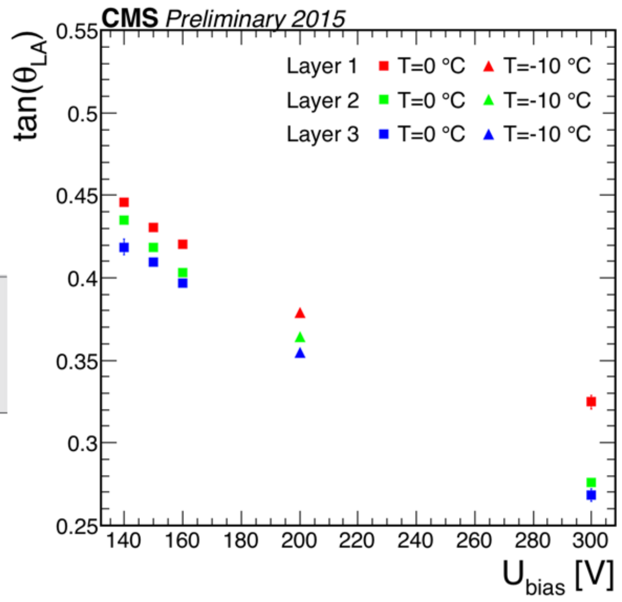




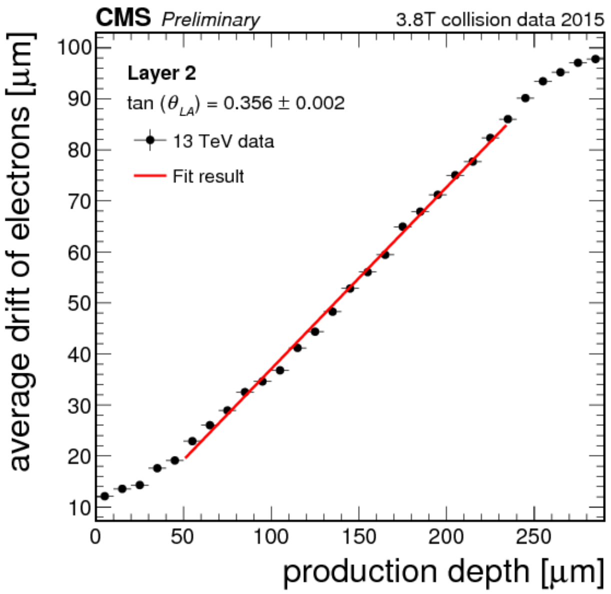
Lorentz Angle Measurement

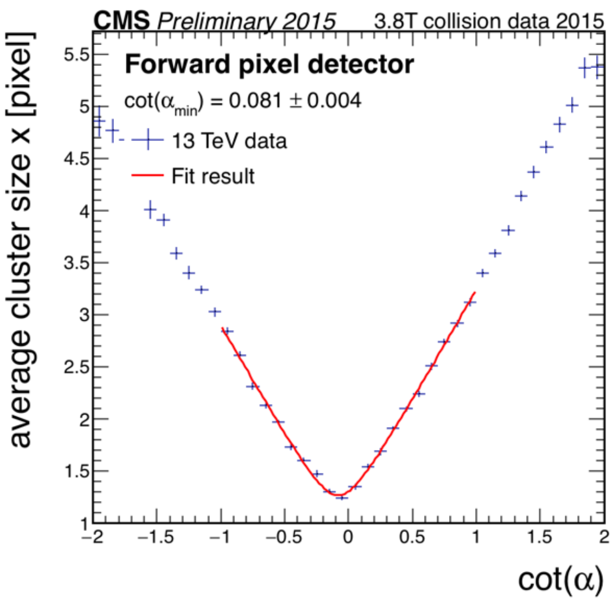
- Measurement method – Barrel – Grazing angle method (bottom left plot):
  - Uses well measured tracks to determine the drift of the electrons in pixel sensors.
  - In order to measure the drift length as a function of depth, only tracks with shallow impact angle with respect to the local y ayis (parallel to beam axis) are used, which corresponds to tracks with a high pseudorapidity.
- Forward – Minimum cluster size method (bottom middle plot):
  - Cluster size is minimal for tracks parallel to the drift direction of the charge carriers.
  - We find the minimum of the mean cluster size along the local x coordinate measured as a function of the cotangent of the incidence angle α

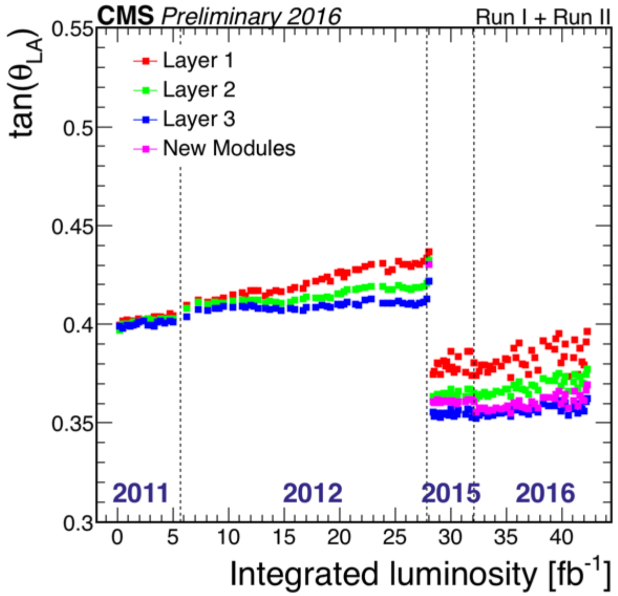




- Different voltage scan points were taken just before and after the long Shutdown I (top right plot)
- Selection requirements:
  - Good quality tracks with $p_T > 3$ GeV, $\chi^2/N_{d.o.f.} < 2$
  - Cluster charge < 120 ke$^-$ and size in y ≥ 4 (2 for Forward)
  - Hit residuals < 50 µm
  - Edge pixels excluded



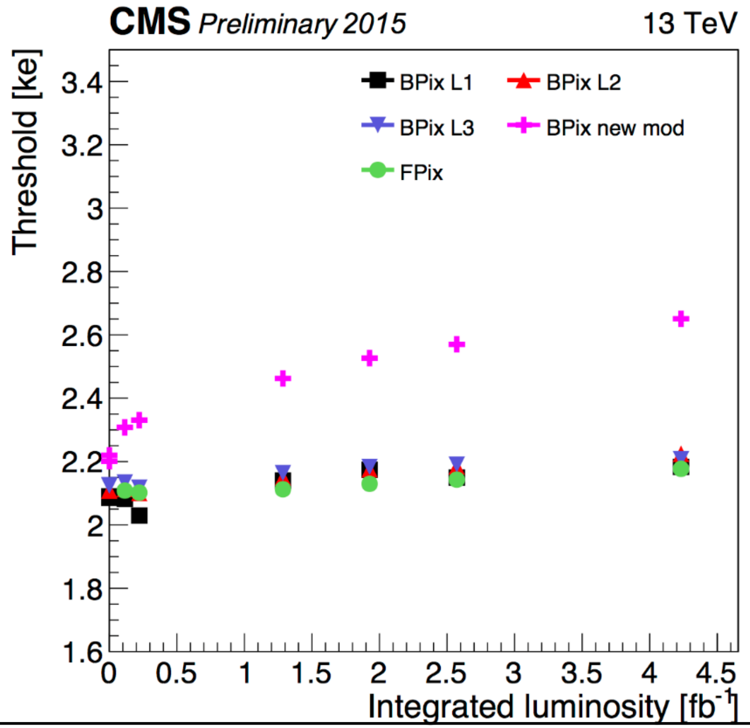


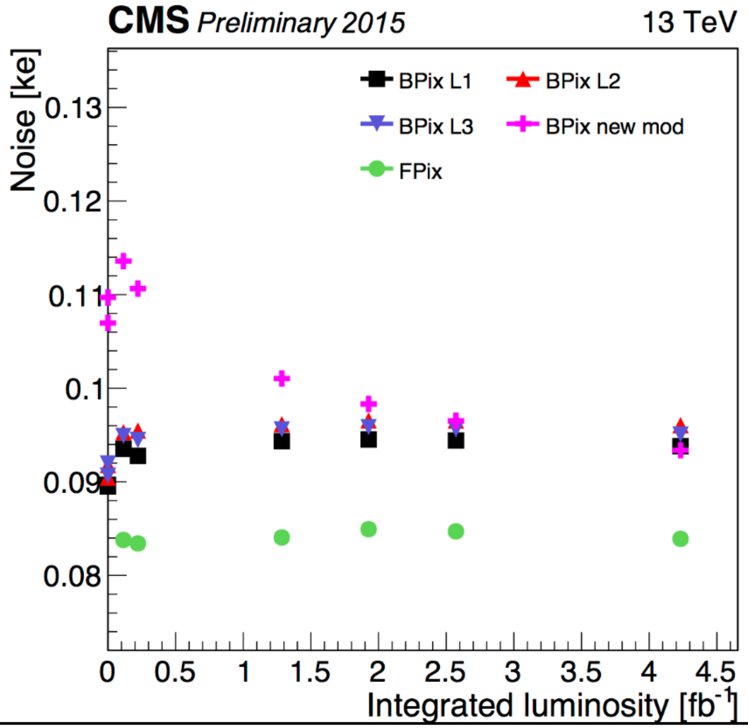


Pixel Threshold Measurement

Threshold vs Integrated Luminsoity in 2015

- The average pixel Thresholds and Noise is measured with charge injection, using the "S-Curve" method:
  - The efficiency curve is evaluated in the bunch crossing in which the charge was deposited as well as in the following one. The absolute threshold is defined as the injected charge at which the error function reaches the 50%.
- The threshold was minimized at the beginning of the year and measured periodically, they are averaged over pixel barrel layers 1, 2 and 3 and over forward pixels
- Threshold of new modules rapidly increased with radiation, consequently noise decreased and rapidly reached similar values as that of the old modules

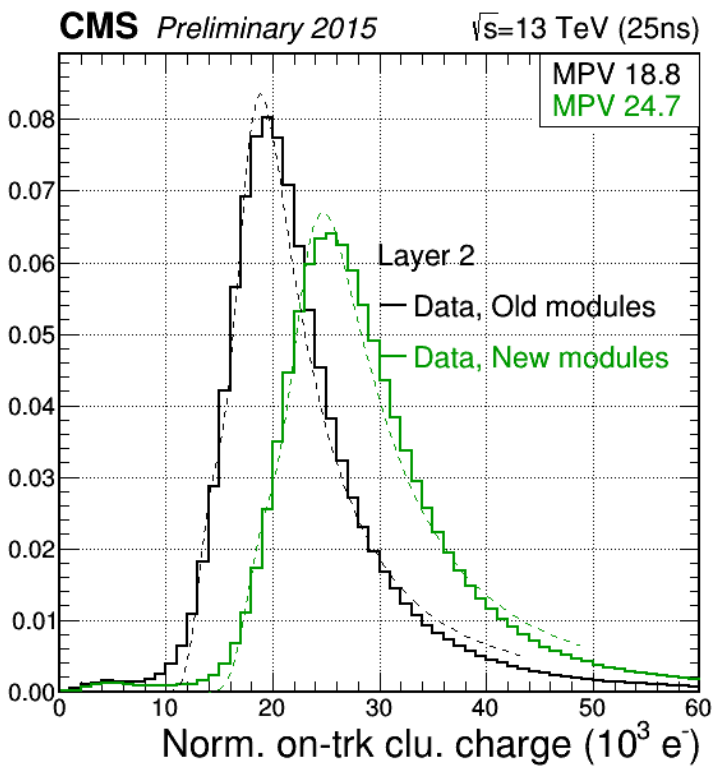


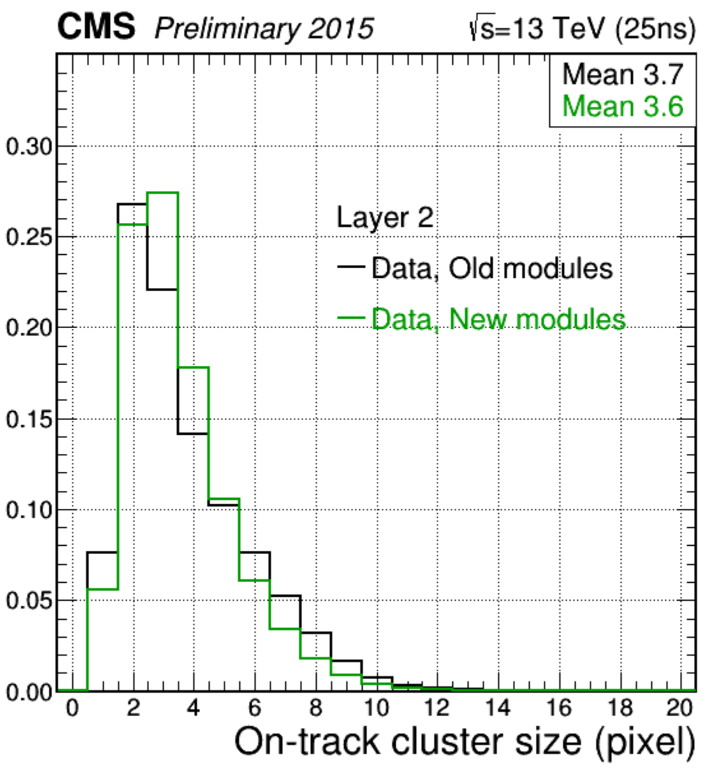


Cluster Properties - New and Old modules

On-track cluster charge MPV and Size

- Cluster properties are important in the monitoring of detector conditions
- Track selection: $p_T > 1$ GeV
- Cluster charges were normalized with impact track angle (left plot)
  - The distribution was fitted with a convulted landau and gaussian function and the most probable value extracted from the fit
- New and old modules are compared



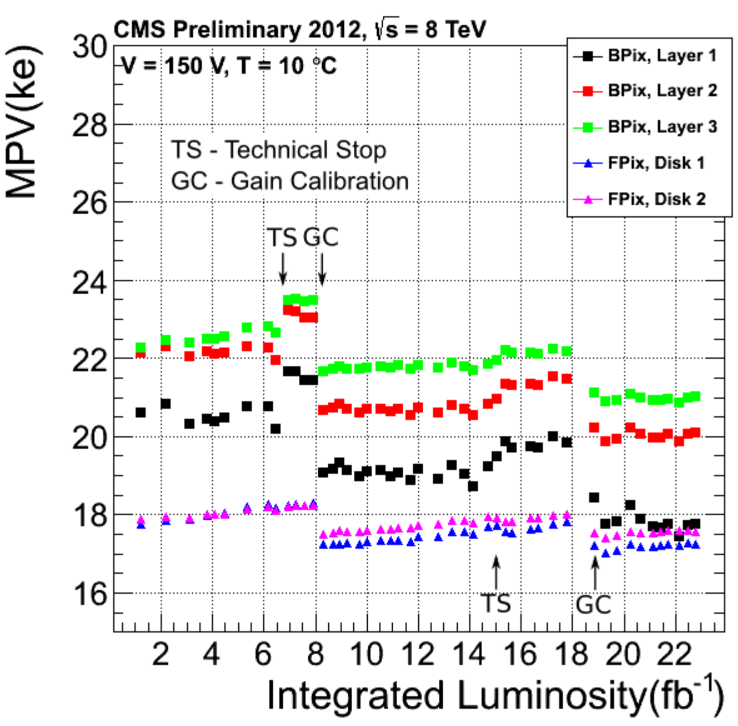


Cluster Properties - New and Old modules

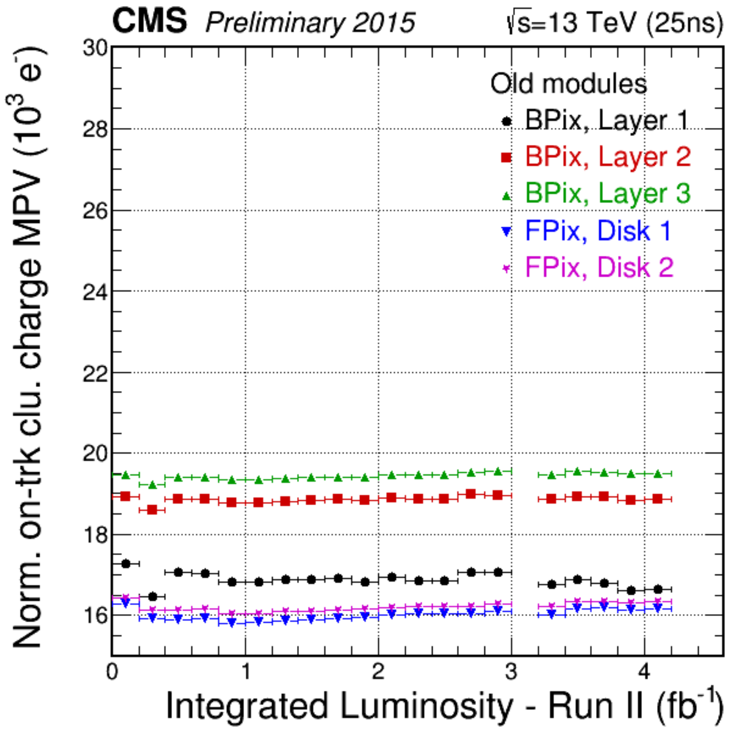
Cluster charge MPV vs Integrated Luminsity

- The normalized on-track cluster charge MPV was monitored both in Run I and Run II
- For new modules the MPV increases rapidly between online calibrations
    - Gain calibrations change the cluster charge (decrease it)
    - Only one gain calibration was done in the beginning 2015
- New modules behave just like old old ones in the beginning of Run I (MPV increases rapidly) while old ones show a saturation effect

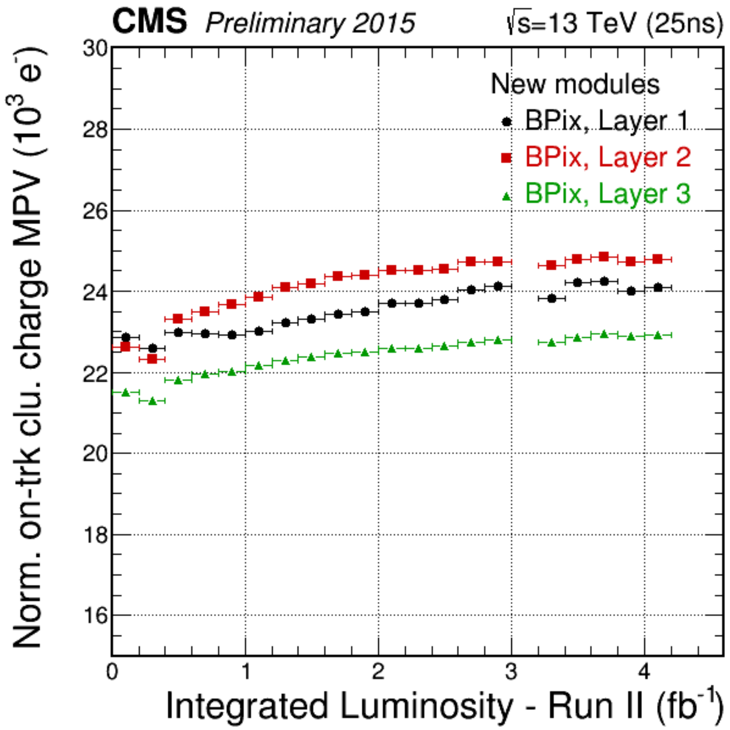
Run I



Run II – Old modules



Run II – New modules

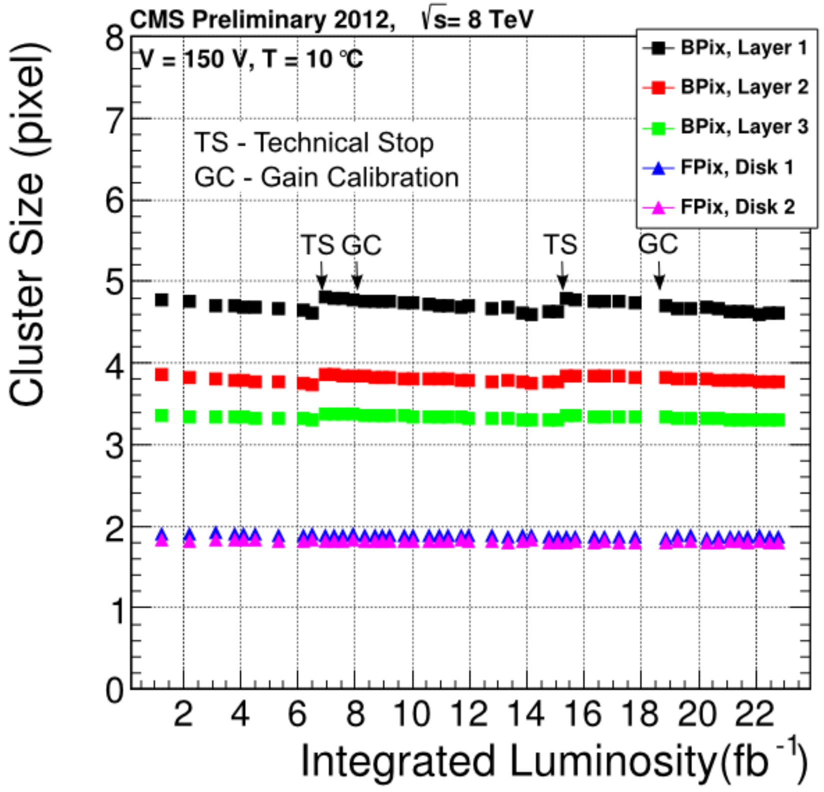


Cluster Properties - New and Old modules

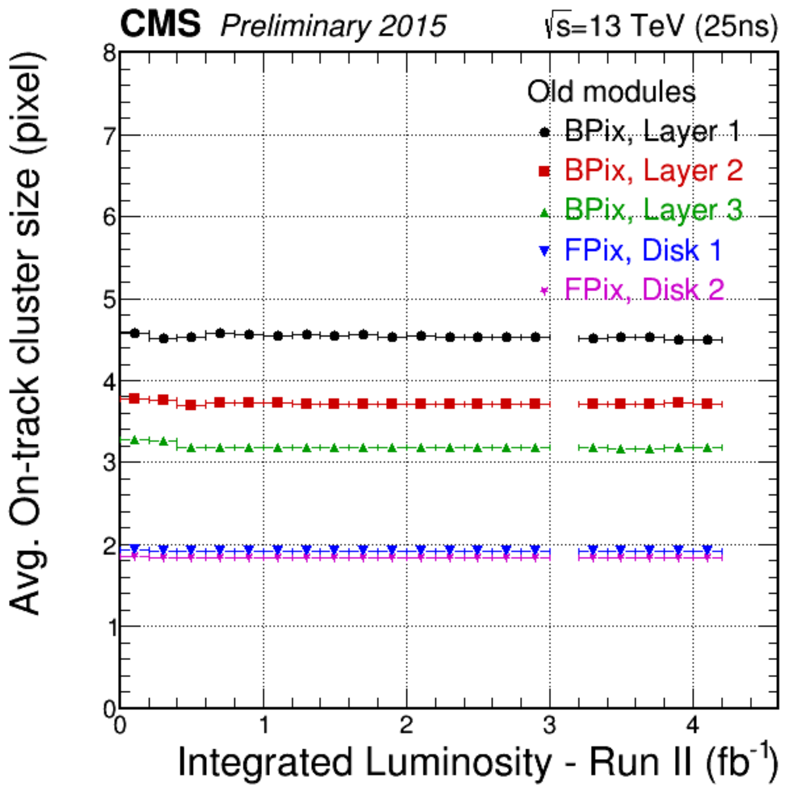
Cluster size vs Integrated Luminsity

- Cluster slightly changes during the year with radiation damage
  - In Run I, calibrations during the year seen to recover the diminished cluster size
- The average cluster size did not change much during 2015 both for old and new modules

Run I



Run II



Hit Resolution – Barrel Layers

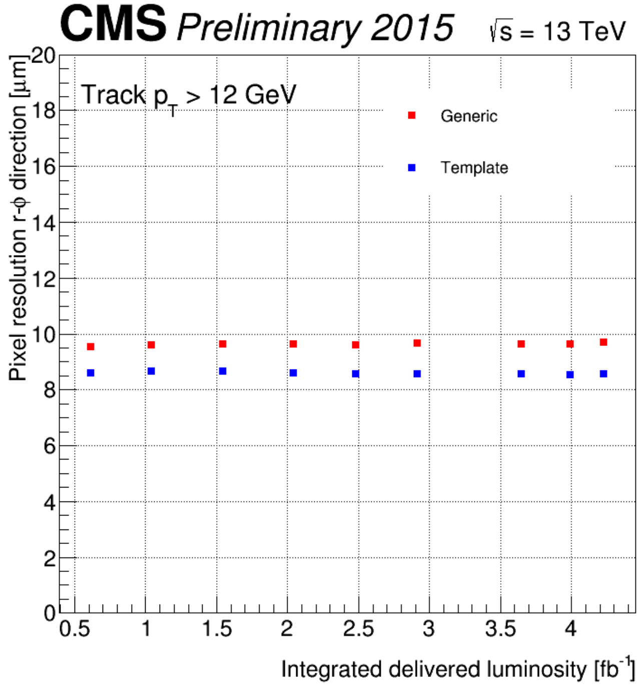
Barrel Resolution (r-ϕ and z) – Algorithm comparison

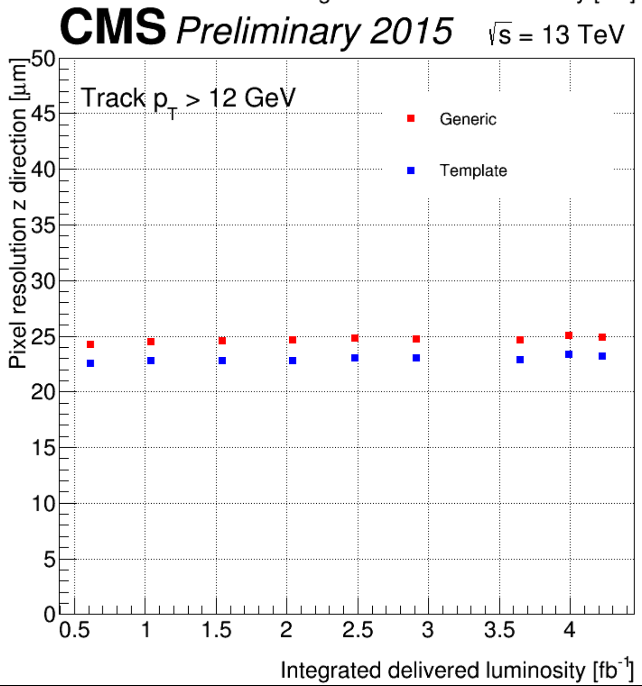
- Two Pixel Hit reconstruction algorithms are used in CMS:
  - Generic algorithm estimates the hit position based on the charge of the first and last pixels in a cluster
    - Gives very fast and relatively accurate hit position estimate (this is used in HLT)
  - Template algorithm uses predefined cluster shape templates to find a very accurate hit position
    - Based on a detailed simulation (called PixelAv) of expected pixel cluster shapes in x and y projections for different track incidence angles
    - Includes radiation damage
    - Can tell how compatible the cluster is to a given track (eg. to remove hits from delta rays)
    - Also used to split merged clusters
- Hit Resolution measurement – Triplet method:
  - Tracks with p_T > 12 GeV and hits in all three layers of the pixel barrel are selected
  - The tracks are re-fit without the hit in the middle layer
  - Then, the residual between the original found hit position and the interpolated track is calculated
  - A student-t function is fit to the distribution
  - Assuming the resolution is the same in all three layers the width of the function fit divided by $\sqrt{3/2}$ gives the intrinsic pixel resolution

  Upper plot: resolution in local x – global r-ϕ

  Lower plot: resolution in local y – global z
- The performance of the Template and Generic hit reconstruction algorithms were compared in the end of year reconstructed data:

  The template algorithm shows better performance in both directions



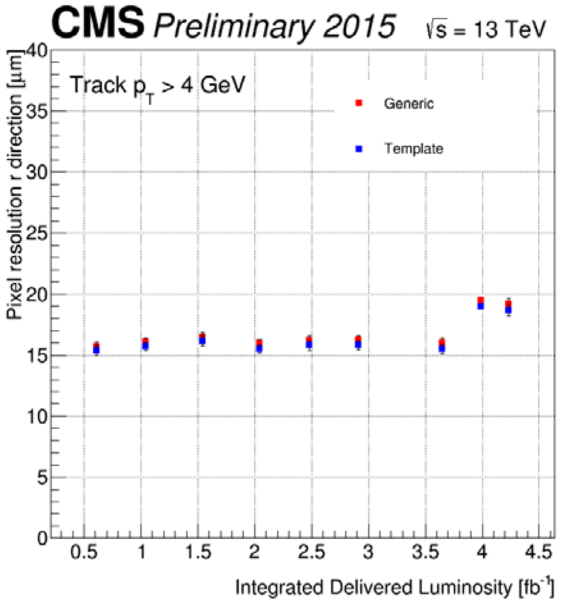


Hit Resolution – Forward Disks

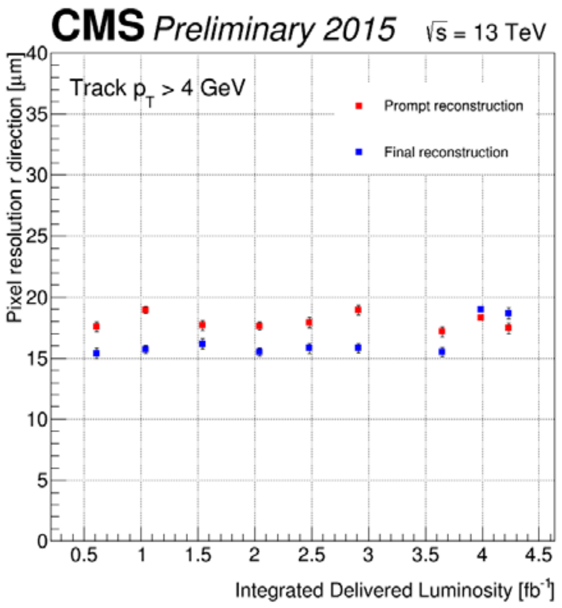
Forward Pixels Resolution (r-direction)

- Hit Resolution measurement on forward disks – Helix method:
  - Tracks with p_T > 4 GeV having hits in all two layers of the pixel forward detector and in the first layer of the pixel barrel detector are selected.
  - We cannot use the triplet method, because in the endcap region we do not have circular layers similar to the barrel
  - Instead, a helix is computed using the layer 1 and disk 2 measurement point (excluding the disk 1 hit)
  - Then, similar to the triplet method the residual difference between the hit position and the interpolated track is calculated and fitted with a student-t function to extract the width of the distribution
- The template algorithm shows superior performance also for the forward pixels
- The resolution mesurement is seen to depend slightly on the running conditions and improve with the best conditions (bottom plot)
  - Compared to the promptly reconstructed data, there was a large improvement seen on the first 7 points

Final Reco



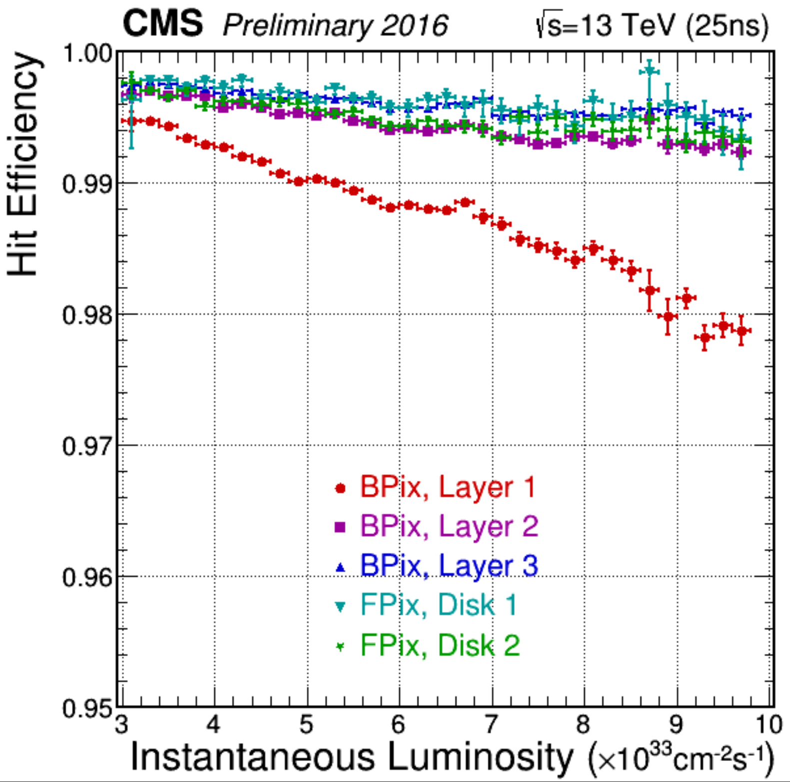
Template Algo

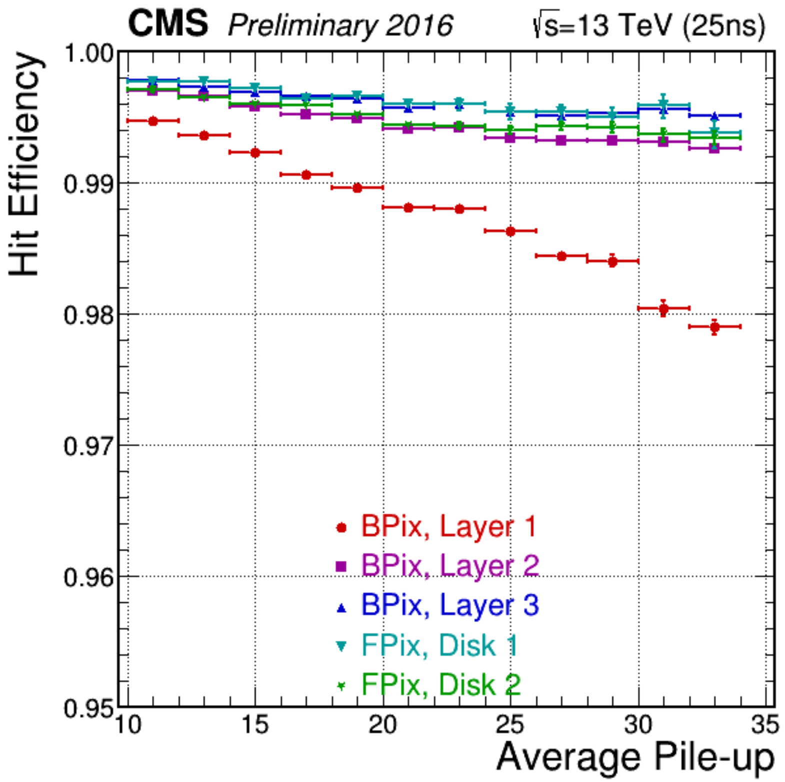


Hit Efficiency in 2016

Hit Efficiency vs Instantaneous Lumi and average Pile-up

- The limited size of the internal buffer of the readout chips cause a dynamic inefficiency that increases with the instantaneous luminosity
- This is an expected behaviour of the current readout chip design
- SEU candidates, data aquisition problems and modules on the innermost radius of Disk 1 were excluded, definition of hit efficiency can be found in the backup
- Since the pile-up increases further this year, we expect worse performance:
  - The current worst efficiency was measured on the innermost layer (~95.4% @ 1.2 x10^{34} $cm^{-2}s^{-1}$ at an avg. pile-up of ~39)
  - We simulate the main data loss (double column inefficiency)

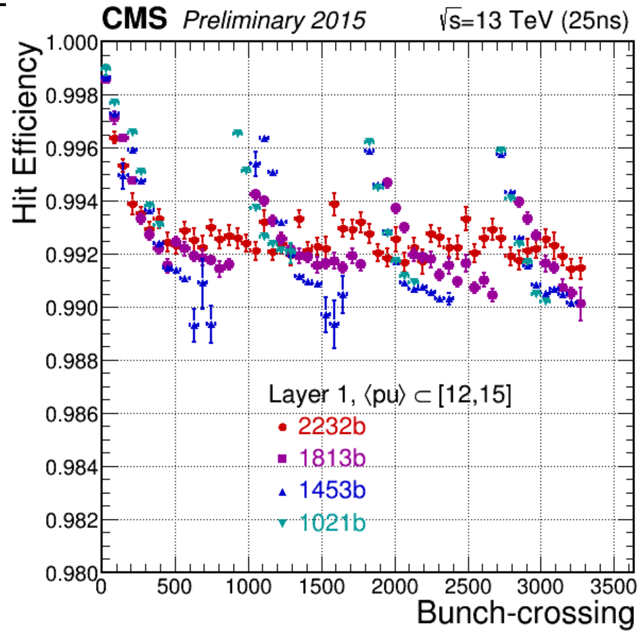




Inefficiencies, SEUs

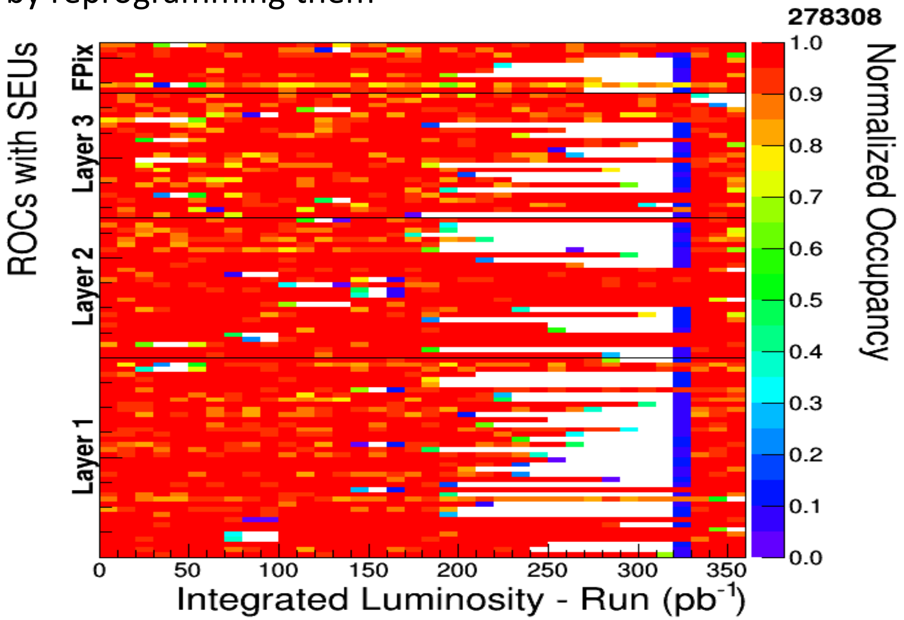
Hit Efficiency vs LHC Bunch Crossing Number – Layer 1-3

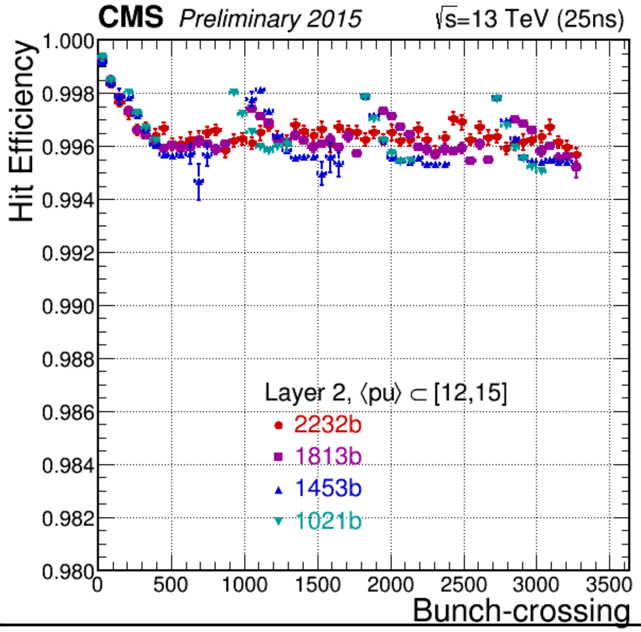
- The main souce of inefficiencies are due to dynamic data losses
- The efficiency recovers to around 100% right after the abort gap (between 3300-3600) due to the empty readout buffers
- Efficiency rapidly decreases after each gap between proton trains and reach a dynamic equilibrium after around the average trigger latency (~500 bx) when the rate of emptying and filling of buffers become similar
- The innermost layer experiences the largest influx of particles per unit area

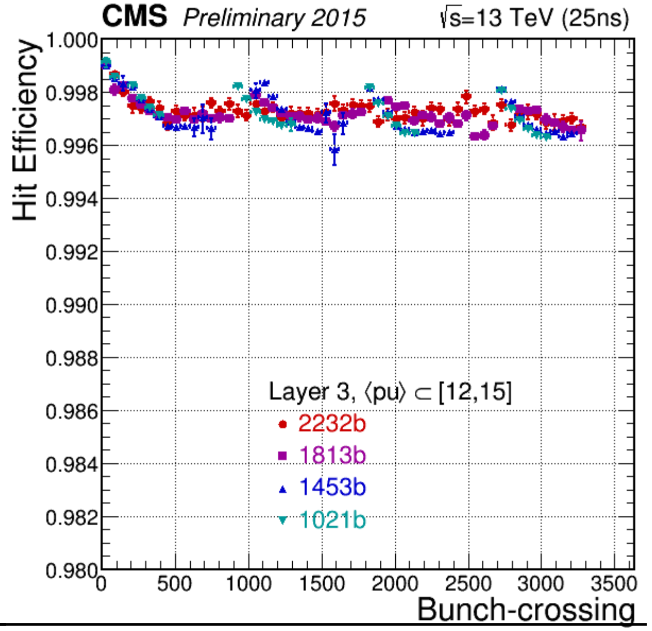


Single Event Upsets

- The rate of single event upsets affecting the readout chips in such a way that the efficiency reaches below 10% was estimated in data to be around ~1 chip per every 2 pb^{-1}
- An automatic recovery mechanism was recently introduced in order to periodically recover lost ROCs by reprogramming them







Summary

- The detector was successfully commissioned for Run II
  - Calibrations are carried out in the beginning of each year and also during the year in order to maintain good performance

- The working detector fraction is high: 98.7%
  - Due to the two layer redundancy even a missing sector is not a problem

- The overall performance of the detector is very good
  - Hit resolution is similarly good as in Run I
  - Hit efficiency is lower for the innermost layer as expected
    - Solution for the high luminosity regime is the upcoming Phase I upgrade of the detector which will provides many improvements compared to the current detector which was designed for luminosities up to 1e34
    - Largest sources of inefficiencies are simulated
    - Other layers and disks perform very well (above 99%)
  - Single event upsets that affect ROCs are mitigated by periodic reprogramming

Backup Slides

Hit efficiency definition

- Hit efficiency is the probability to find any clusters within a 500 micron area around an expected hit
  - The goal is to quantify pure sensor efficiency with tracking effects maximally removed
  - Temporary efficiency loss is observed in function of hit-rate (dynamic inefficiency most dominantly due to buffer overflow); largest effect is visible in the innermost layer (Layer 1)

- Expected hits are provided by good quality tracks
  - Associated to primary vertex with small impact parameter
  - with $p_T > 1.0$ GeV
  - Missing hit allowed only on layer under investigation (valid hits are expected on two „other” layers/disks)

- Module selection:
  - Bad read-outs removed
  - ROCs under SEU (temporarily disfunctioning ROCs) removed
  - ROC and module edges, as well as, overlap areas of adjacent modules within a layer rejected
  - Only modules with good illumination by tracks are selected

- Systematic uncertainty estimated to be ~0.3%