Radiation Experience with the CMS Pixel Detector

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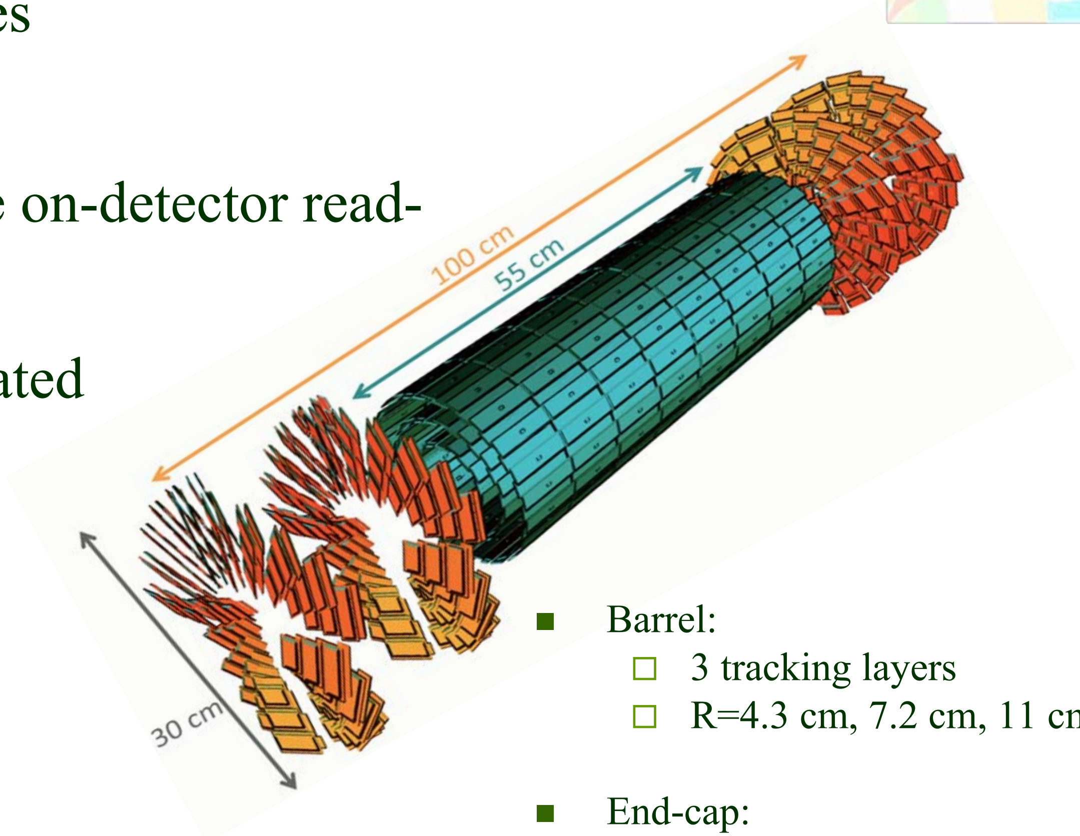
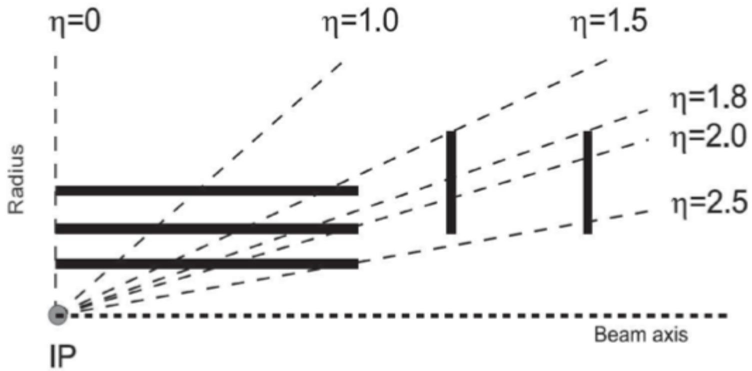
Overview

- The CMS pixel modules
- The LHC machine
- Radiation effects of the on-detector read-out electronics
- Properties of the irradiated silicon sensors
- Detector performance



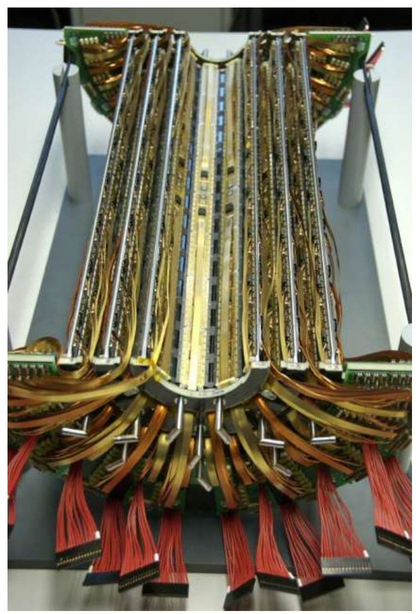
- Barrel:
  - 3 tracking layers
  - R=4.3 cm, 7.2 cm, 11 cm
- End-cap:
  - 2 disks on each side
  - Z=34.5 cm and 46.5 cm

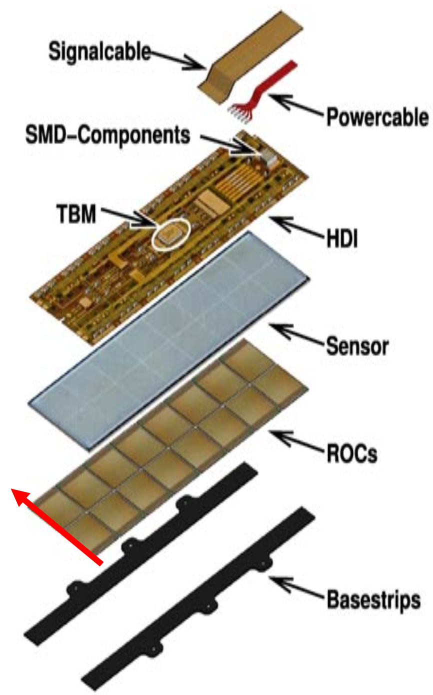
The pixel modules

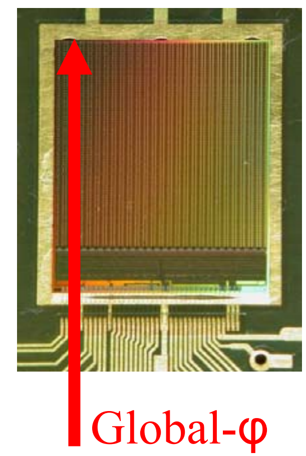


- N+-in-n sensor, 66 M pixels
- Pixel size: 100 μm x 150 μm x 285 μm
- Data sparsification of 52 x 80 pixels by Read Out Chip (ROC)

- Pixels in ROCs are arranged in 26 double columns of 160 pixels
- Double columns are aligned in the azimuthal (radial) direction in the Barrel (End-cap)

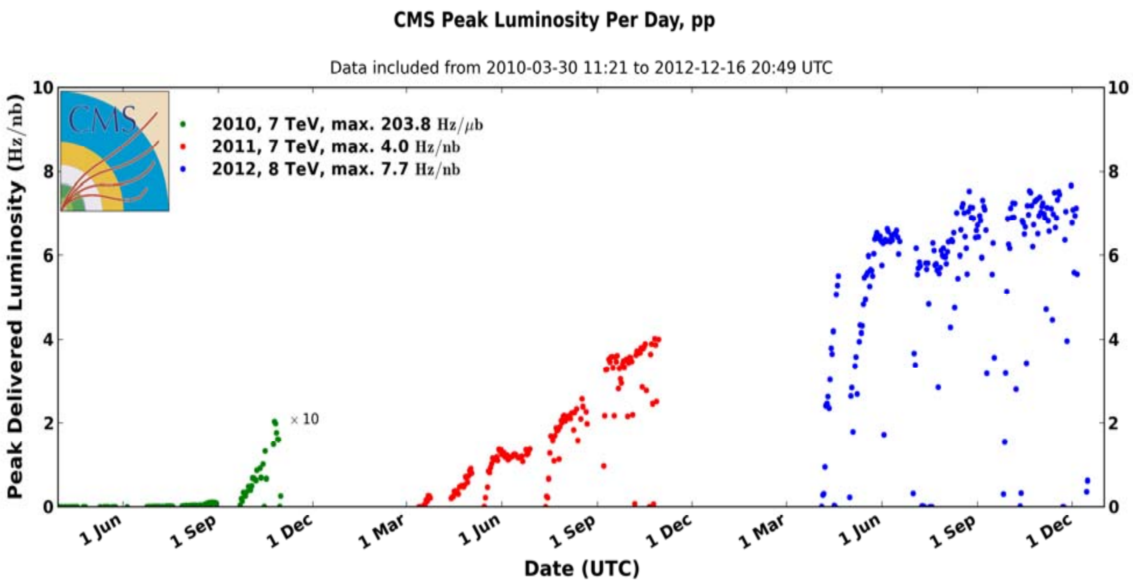






Global-φ
(Global-R)

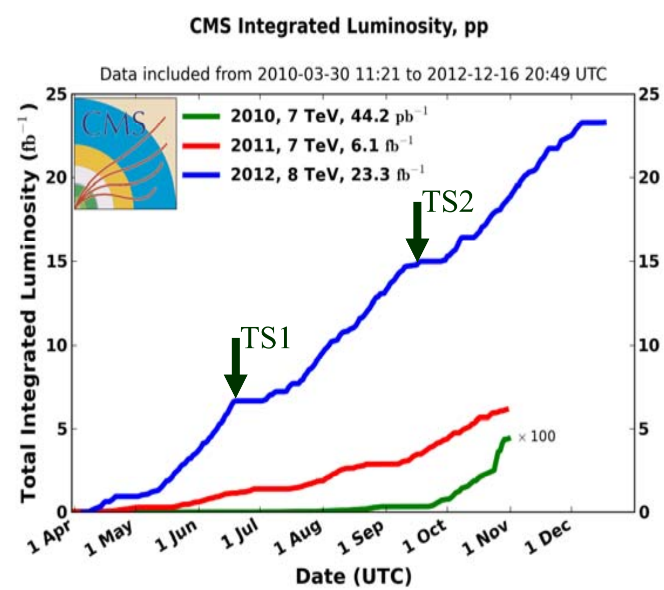
The LHC Machine



- Improving parameters over Run 1
- 50 ns bunch spacing forced high instantaneous luminosity

- Delivered pp collision data in Run 1
  - 7 TeV in 2010: 44.2 pb^{-1}
  - 7 TeV in 2011: 6.1 fb^{-1}
  - 8 TeV in 2012: 23.3 fb^{-1}

- The 2012 data-taking was interrupted by two Technical Stops (TS). Time used for
  - detector calibrations,
  - sensor studies



Radiation effects in the ROC

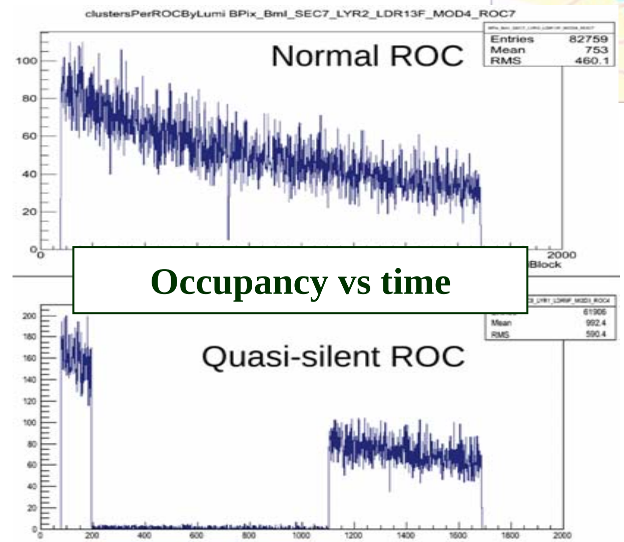
- We have observed both temporary and long-term effects on the ROCs due to irradiation
  - Temporary effects are always connected with instantaneous luminosity (pile-up), a continually changing quantity that makes consistent measurements and detector studies difficult
  - Long-term effects are parameterized by integrated luminosity

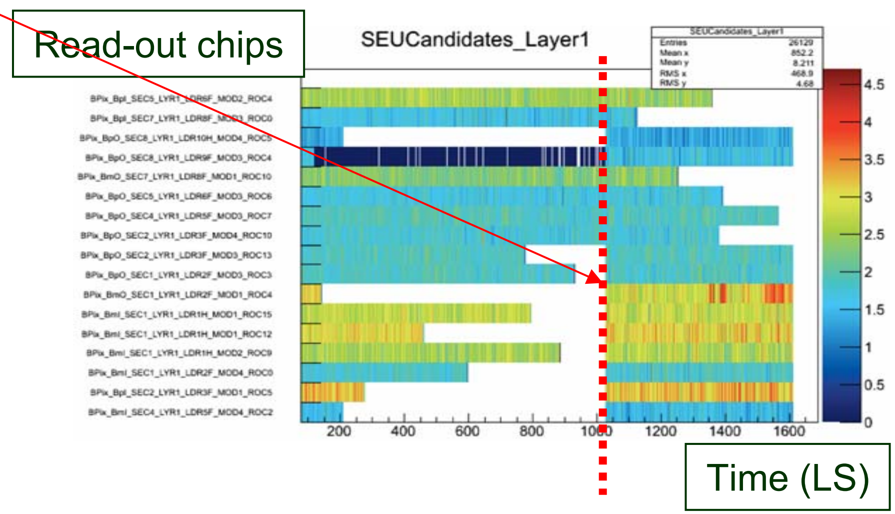
- Most significant short-term effects:
  - Single Event Upset in electronics
  - Hit buffer overflow
  - Occupancy-dependent gain calibration
  - Threshold change due to multiple hits in double columns – yet to be investigated

- Long term effects:
  - Gain variation
  - Drifting of pixel read-out thresholds

Single Event Upset

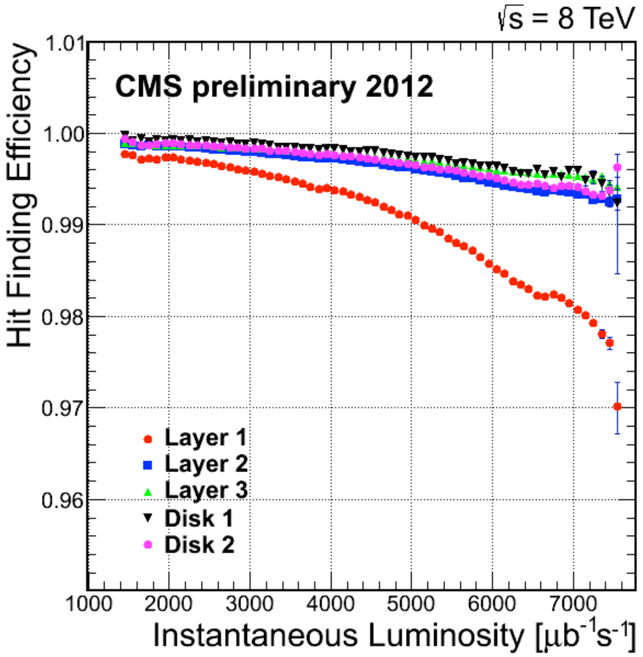
- Particles from collisions can flip bits in control registers of ROCs and auxiliary electronics (Single Event Upset)
- SEU may interrupt or degrade data taking
- Solution is reprogramming electronics triggered by
  - Read-out front end
  - Data quality monitoring (manually)
- Entire clusters are lost, results in loss of efficiency but not in changes of cluster properties

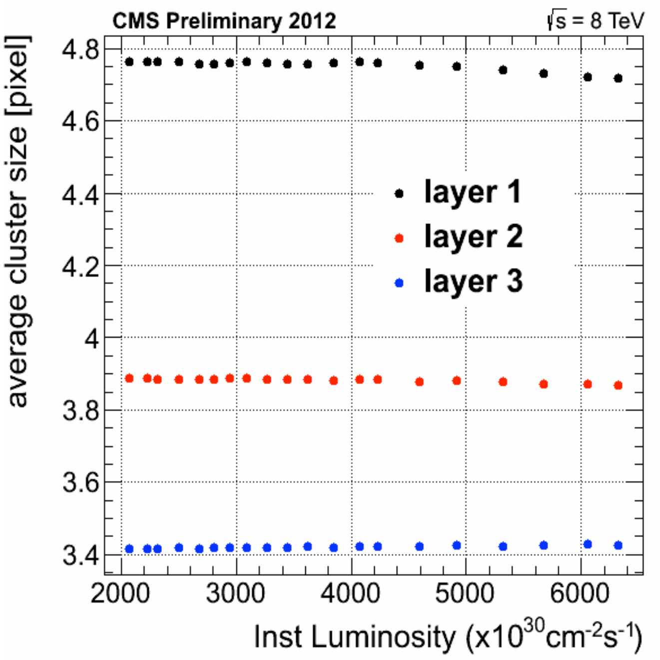




Hit buffer overflow

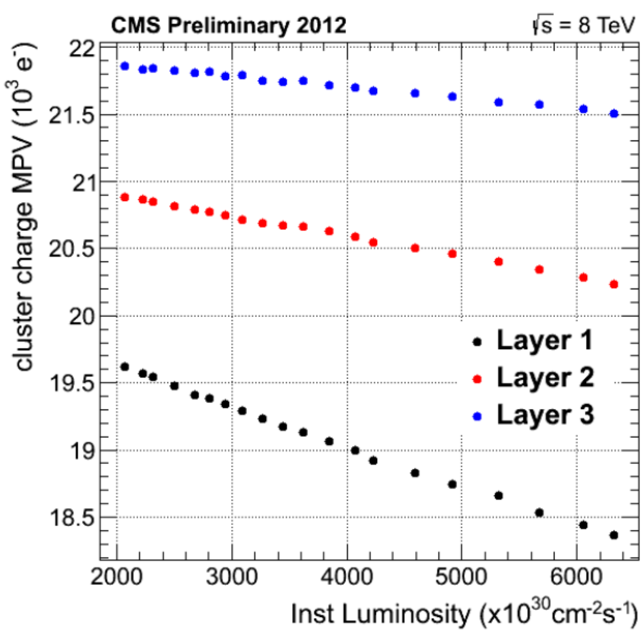
- Higher occupancy fills the internal buffers of the double columns in the ROCs faster leading to buffer overflow
  - Central region: higher chance of losing entire (small) clusters
  - Large-η: long clusters are split into smaller clusters more often
- Net effect is a slight, simultaneous decrease in cluster size and charge – impact is under investigation based on simulation

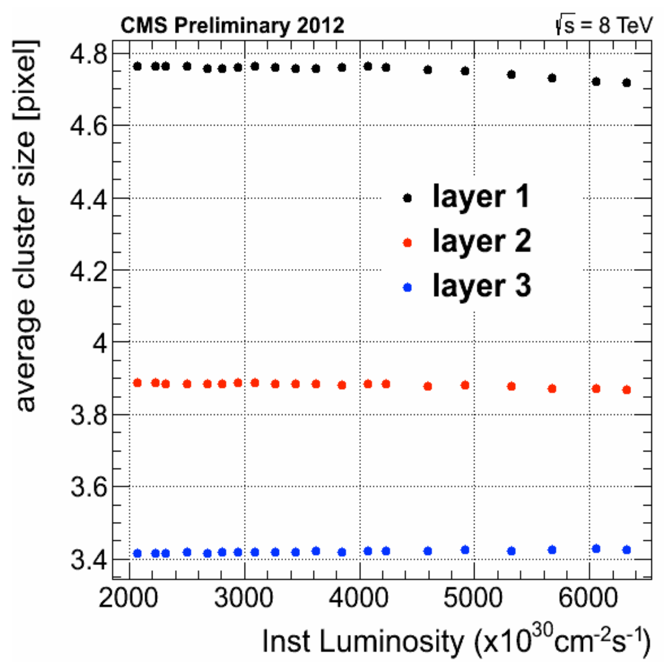




Occupancy-dependent gain calibration

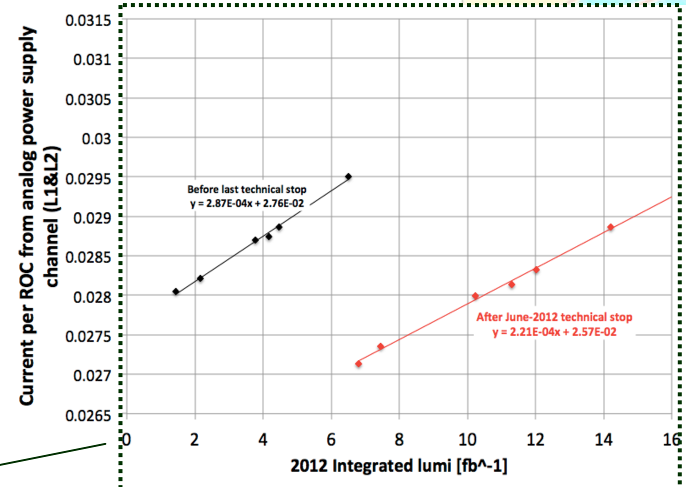
- Higher occupancy increases the power consumption and therefore the temperature in the ROCs
- Pixel charge gain calibration is temperature dependent
  - No significant change in cluster size → effect is stronger than results of buffer overflow
  - Visible on all layers
- Mechanism is not yet taken into account in simulation



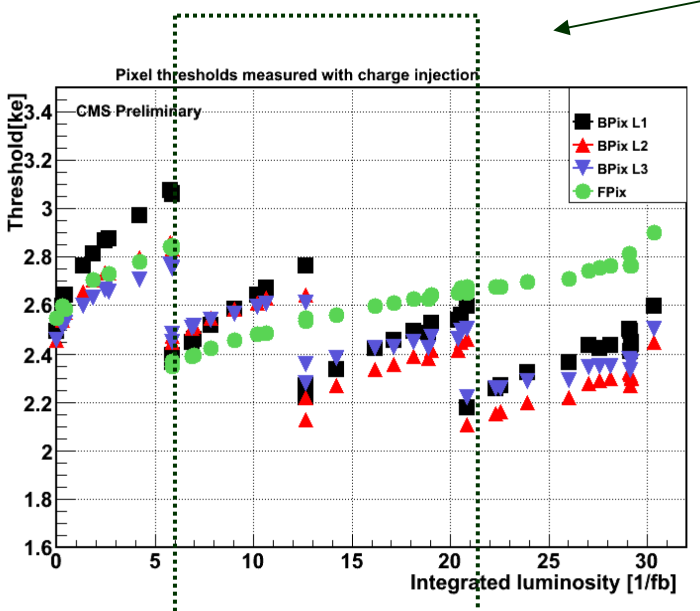


Long-term variations in threshold

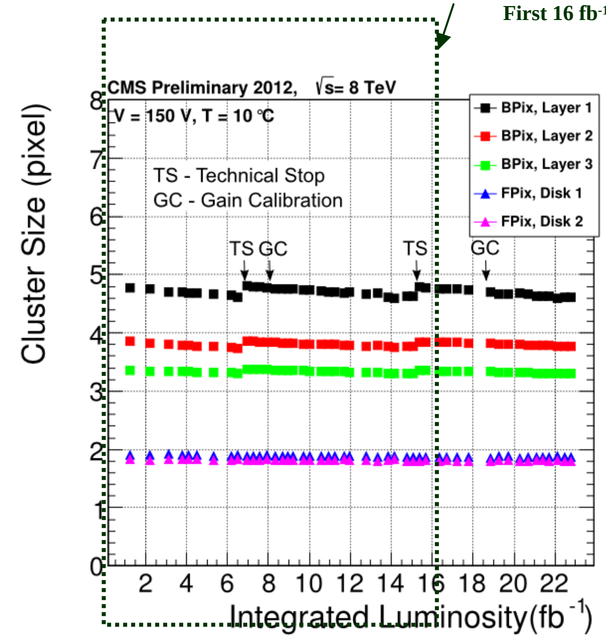
- Threshold is measured with charge injection
- Analog current increases linearly with radiation damage, possibly due to
  - change in units of the analog voltage setting
  - or a drift in reference voltage
- Slower signal rise time leads to higher threshold
  - Confirmed by decrease in cluster size



First 16 fb^{-1} in 2012



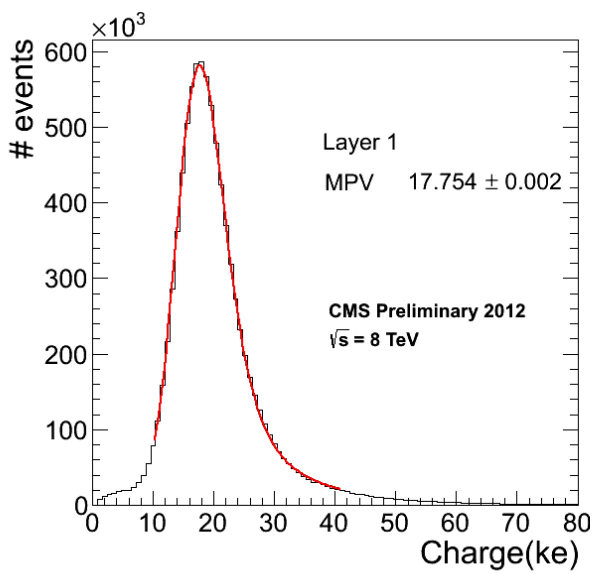
First 16 fb^{-1} in 2012

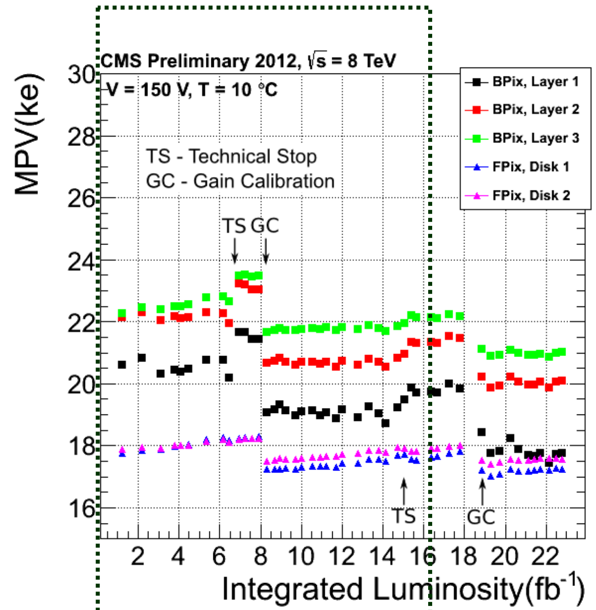


First 16 fb^{-1} in 2012

Long-term variations in gain calibration

- During technical stops in 2012 (TS) thresholds were readjusted (minimized)
  - Slightly increased luminosity in the LHC after TS is overcome by lower thresholds
- After applying cluster charge gain calibration in offline reconstruction (GC), overall MPV decreases
  - Contradicts with thresholds being lower than before TS
- Pixel charge gain is also measured by charge injection
  - Change in units of injected charge?





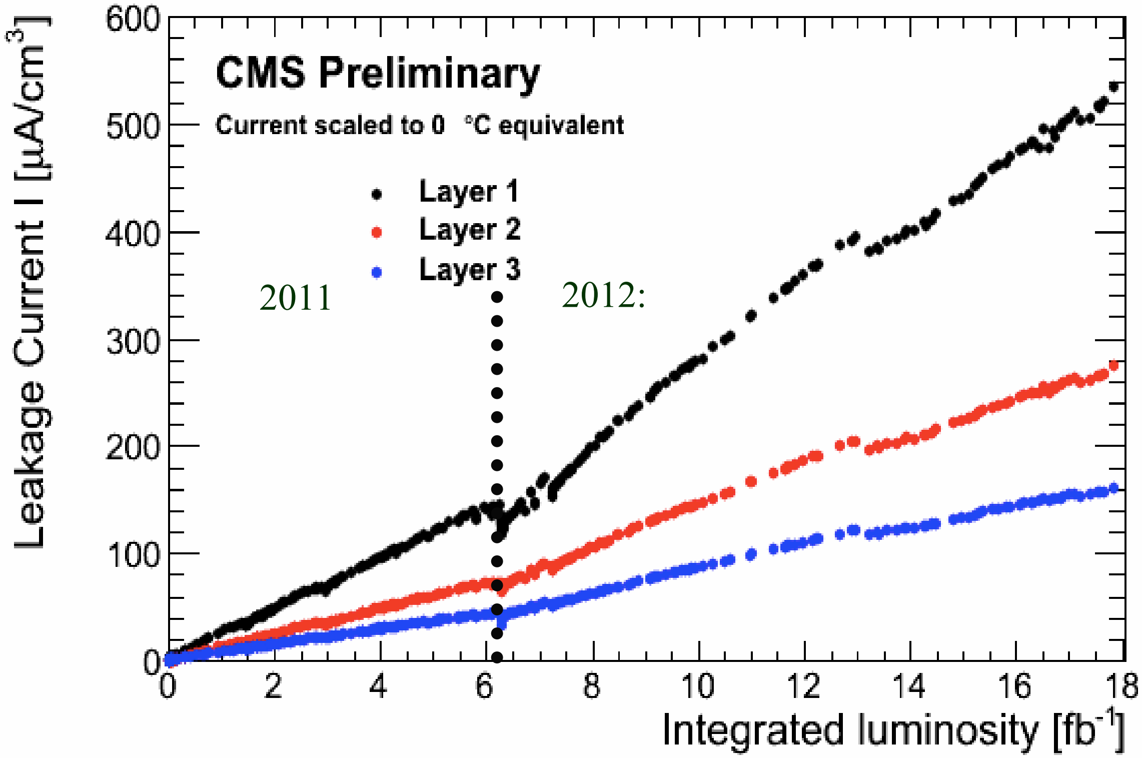
First 16 fb^{-1} in 2012

Radiation effects in the sensors

- Leakage current
- Full depletion voltage
- Charge collection profile
- Lorentz-angle

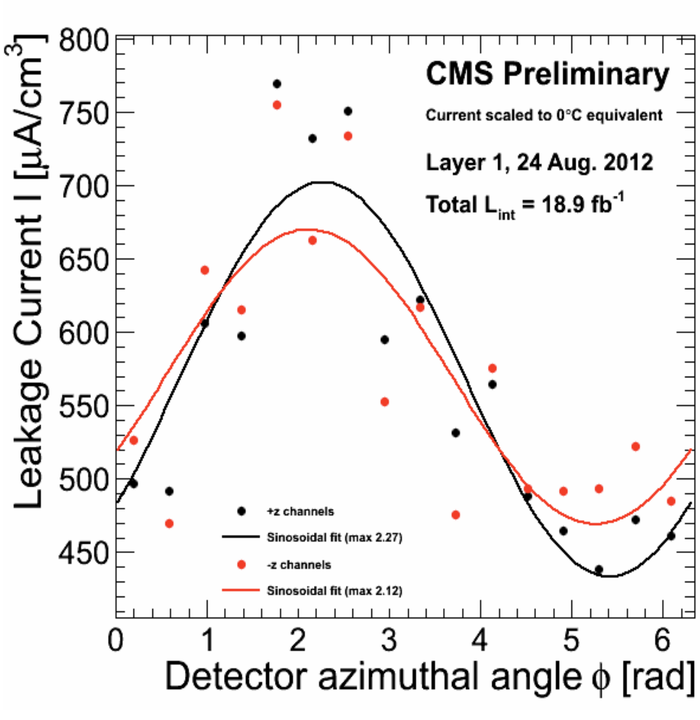
Leakage current

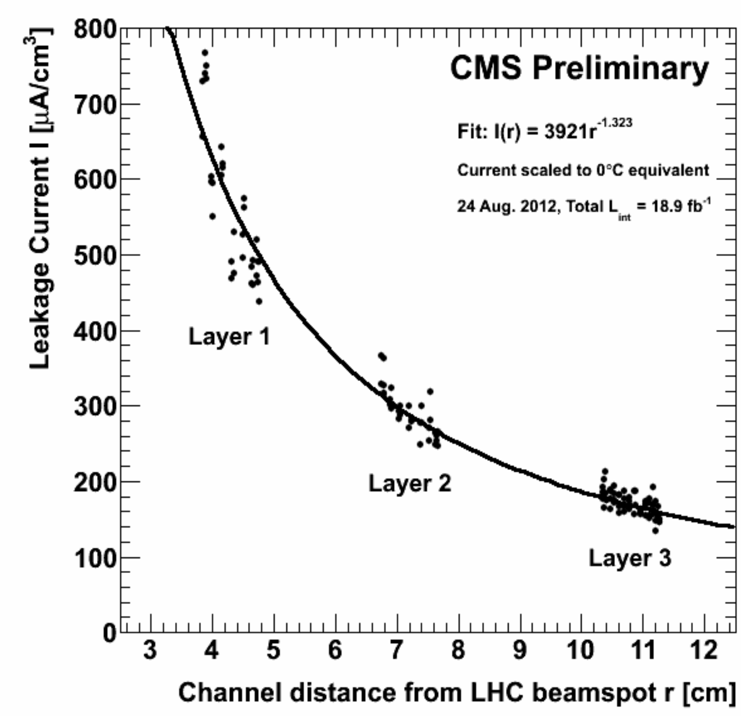
- Measured for each high-voltage channel in the barrel, normalized to volume of the silicon and adjusted to equivalent current at Cº
- Increases proportionally with irradiation – slope slows when lowering operation (coolant) temperature from 7 Cº to 0 Cº
- Reduced by annealing outside beam operation between 2011 and 2012



Leakage current

- LHC beam was off-set by a few mm leading to uneven irradiation in the azimuthal angle
- Beam offset enabled us to measure the leakage current also as function of the module radius

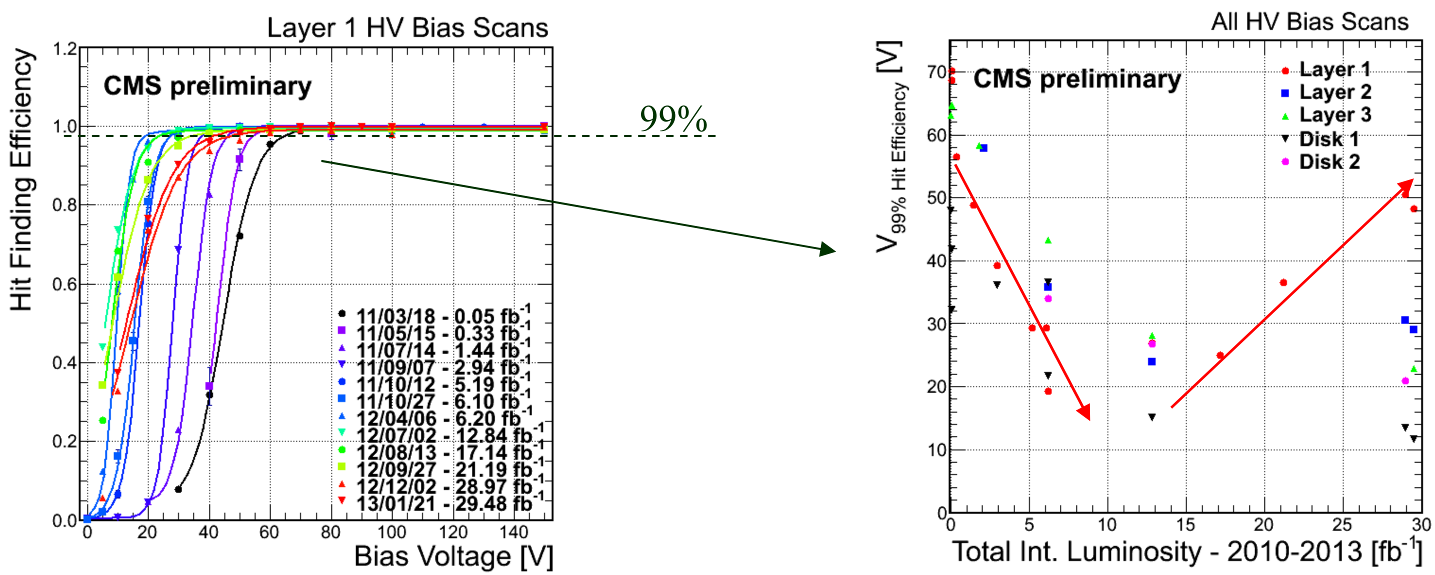




Full depletion voltage in the Pixels

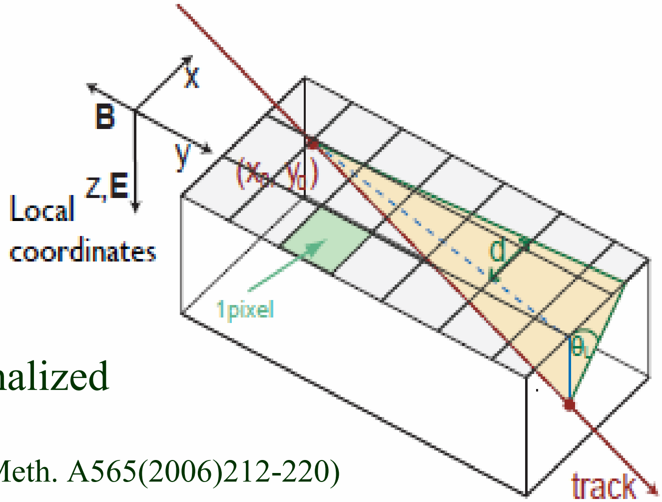
- Irradiation changes the effective doping of the sensor
  - Depletion voltage monitored regularly based on hit efficiency
  - Operational voltage is fixed at 150V (300V) in the barrel (end-cap) pixel – detector sitting on an efficiency plateau
    - No information on charge collection efficiency – measurement needs to improve
    - Consistent normalization of MPV has been difficult due to drifting thresholds and gain calibration

- Evidence for type inversion is observed in Layer 1



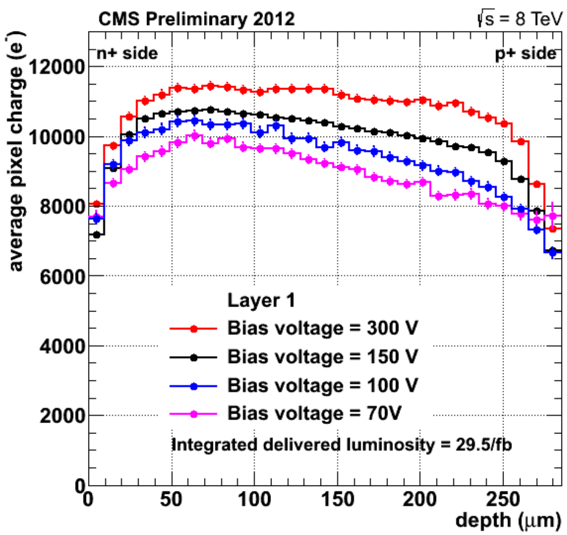
Charge collection profile

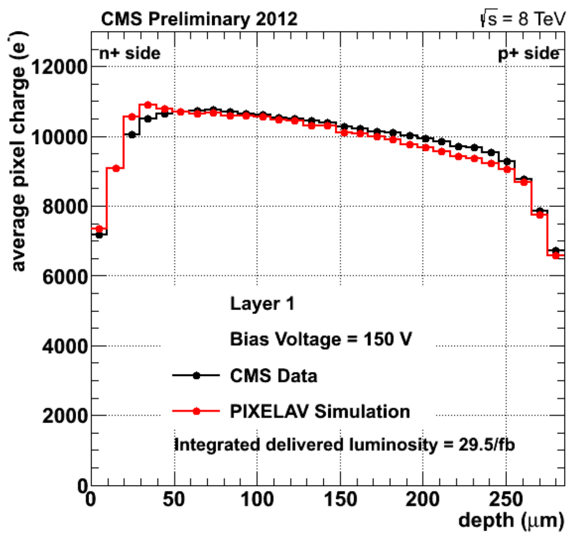
- Results of radiation damage
  - Non-uniform electric field scalps charge collection profile
  - Charge carrier trapping



- Charge collection profile implies improved efficiency at higher bias voltage, but pixel charge is not properly normalized
- Effective model is used to describe data (PIXELAV: Nucl.Instr.Meth. A565(2006)212-220)
  - Key component in cluster position measurement
  - Just being integrated into official CMS simulation

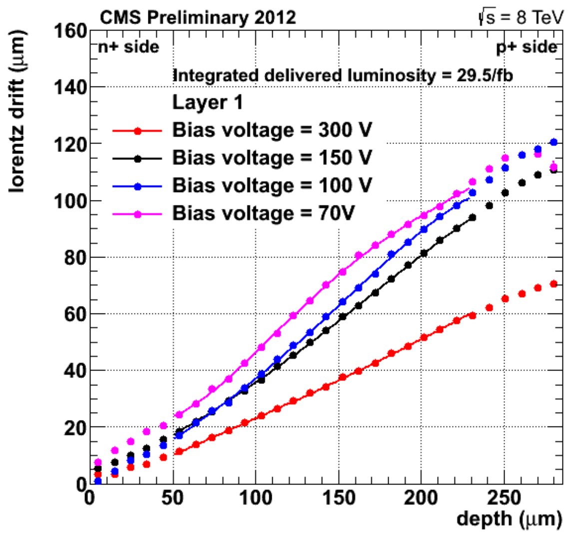
Average pixel charge in a depth „bin"



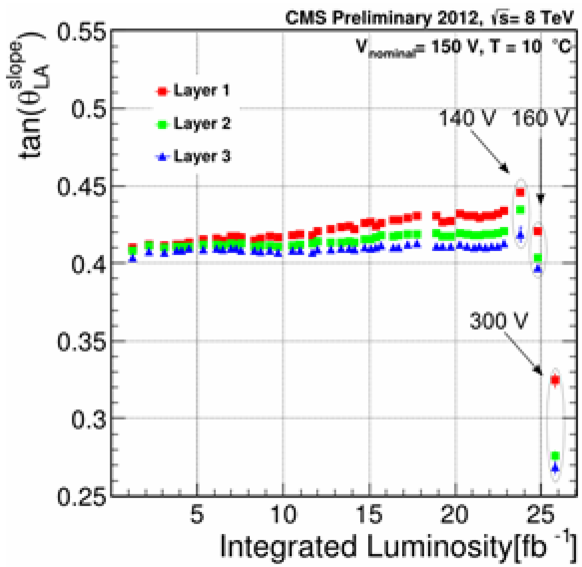


Lorentz-angle

- Lorentz-angle is measured close to mid-plane
  - Magnitude and linearity depends on bias voltage
  - Also evolves with irradiation
- Charge-sharing allows for better resolution in cluster position
  - Charge width may be estimated from the Lorentz-angle when computing cluster position



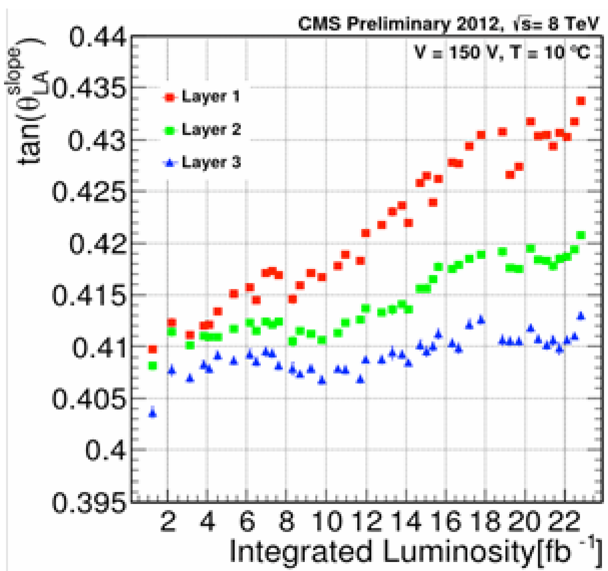
Lorentz-drift as function of depth in Layer 1



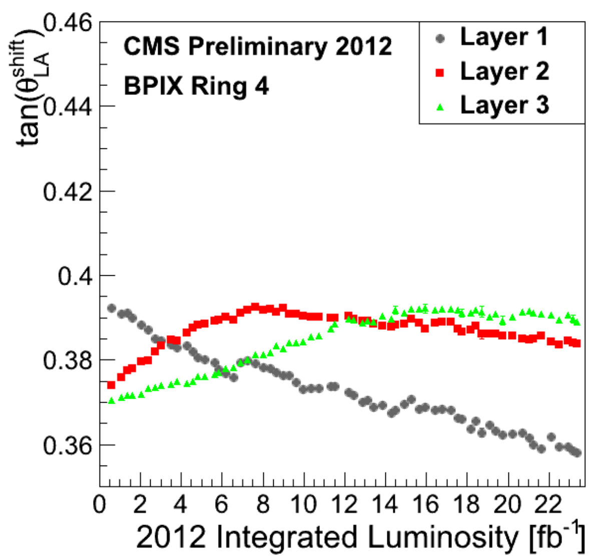
Lorentz-angle at various bias voltages

Lorentz-shift

- Single Lorentz-angle value is insufficient to describe cluster position
- A „Lorentz-shift" has been measured externally based on Tracker alignment information
  - Method compares virtual module-displacement (i.e. common shift of all cluster positions) between 0T and full magnetic fields
  - θ_{LA}^{shift} is computed such that $\Delta x = tan(\theta_{LA}^{shift}) \cdot d/2$
  - Results are confirmed by comparing drifts in inner and outward facing modules



Lorentz-angle at nominal bias voltage

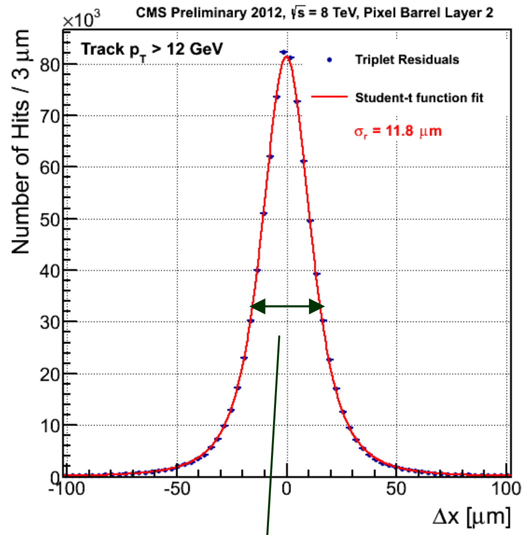


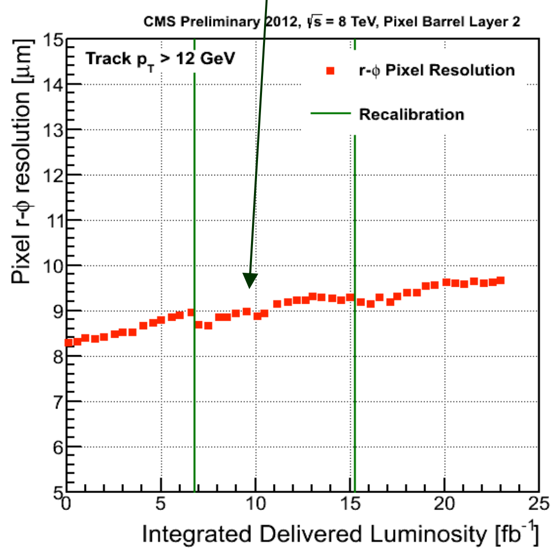
Lorentz-shift at nominal bias voltage

(sorry about the different color codes)

Detector performance: resolution

- Resolution, along with hit detection efficiency, is the most important parameter of the Tracker
  - Intrinsic resolution in the pixel is ~10 μm
- Hit position is determined by cluster charge template fitting
- Resolution depends on
  - Stability of gain calibration
  - Pixel read-out threshold
  - Precise modeling of Lorentz-angle induced charge-sharing
  - ...
- Attempts at optimizing cluster parameterization by performing a scan on Lorentz-angle did not improve the resolution...





Conclusions

- Very good performance in Run 1
- However, significant irradiation effects are just expected to appear in Run 2
- Planned improvements in detector studies/calibrations
  - More frequent and better understood gain calibrations
  - Better bias voltage characterization
  - More focus on studying the End-caps
- Developments in simulations and reconstructions
  - Understanding effects of efficiency loss due to buffer overflow in double columns
  - Better treatment of radiation induced changes in cluster properties by simulation