Overview of the CMS strip and pixel detectors

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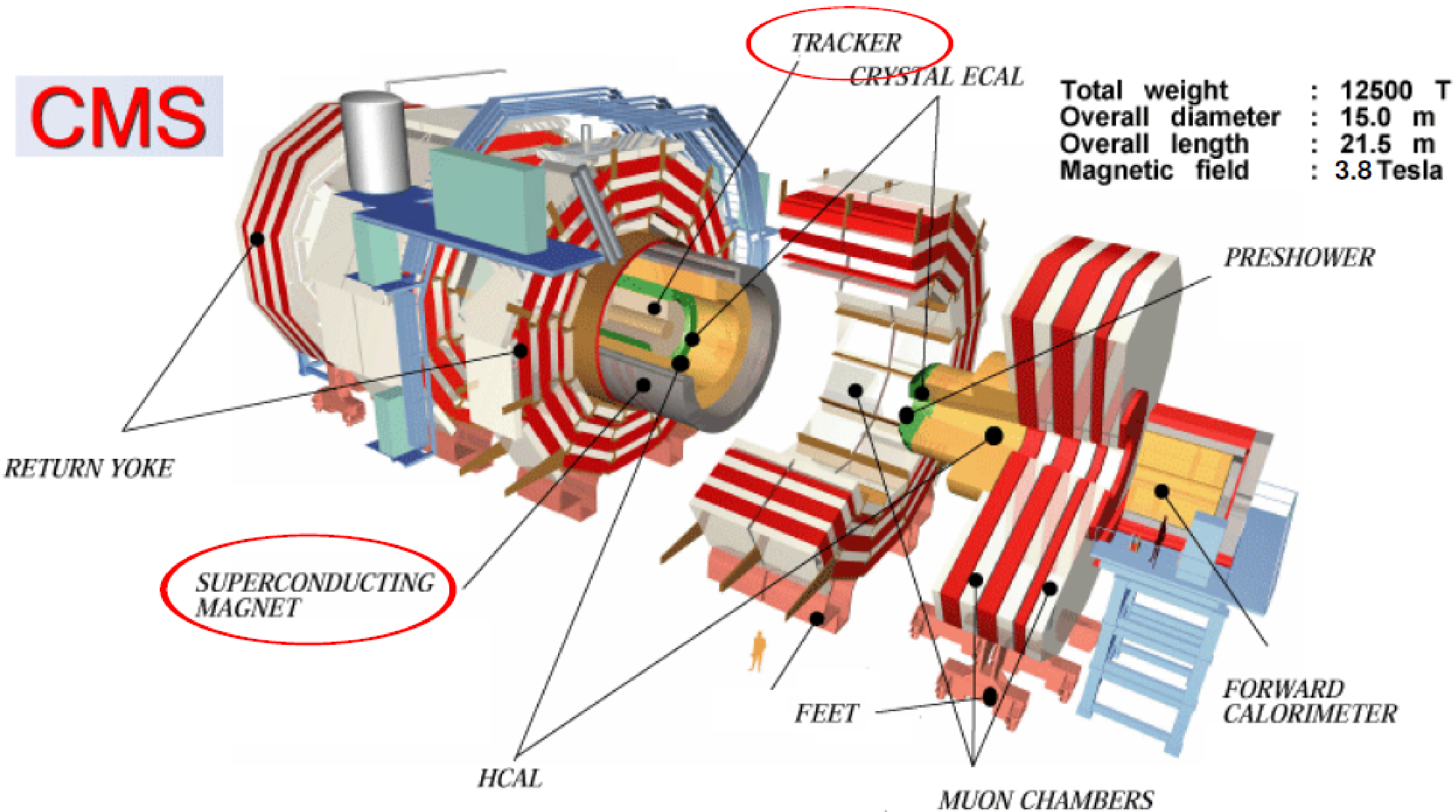
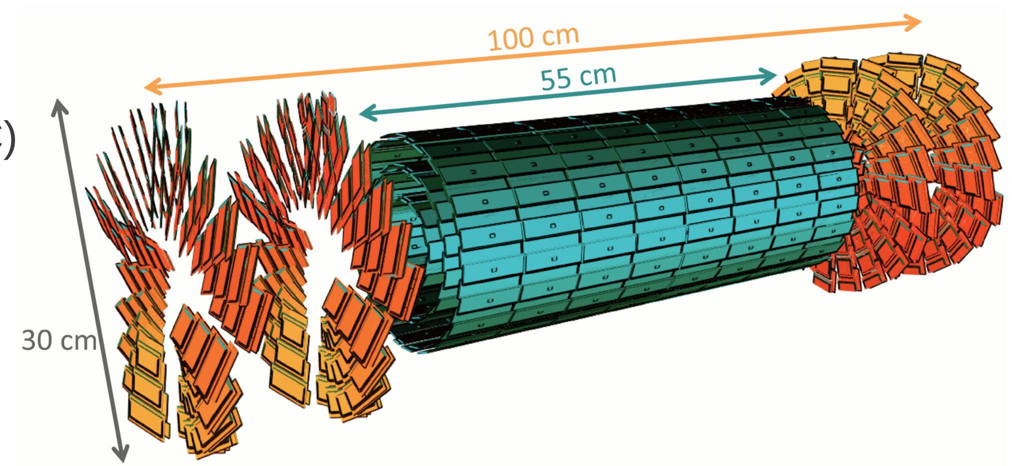
CMS Tracker Detector

- Status at the end of the data taking
- Performances and alignment
- Evolution with integrated luminosity

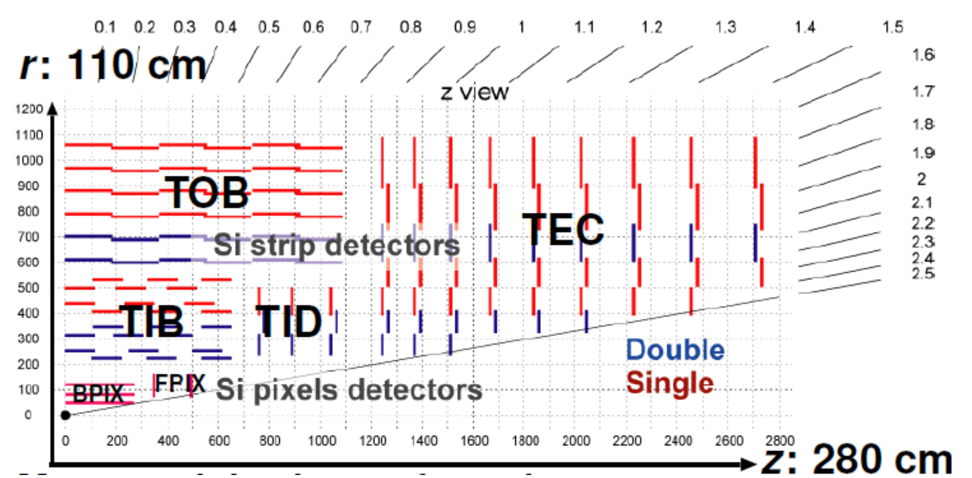


CMS Tracker Detector

- Silicon pixel + Strip detector with optical analog readout
- **Pixel** :
  - N+ in n sensors :
    - 100 µm x 150 µm
    - 52x80 pixel read by one ReadOut Chip (ROC)
  - Barrel (Bpix):
    - 3 layers (56cm long) at r= 4.3,7.2, 11.0 cm
    - → 48M pixels, 11520 ROCs, 1120 RO links
  - Endcap (FPix) :
    - 4 disks inner (outer) radius=6 (15) cm at z= ±34.5, ±46.5 cm
    - → 18M pixels, 4320 ROCs, 192 RO links



- **Strip** :
  - 9.3M strips in 15148 modules :
    - Inner: 4 layers barrel (TIB), 3 disks (TID) cap
    - Outer:6 layers barrel (TOB), 9 disks (TEC)cap
  - 200m² silicon sensor (p-in-n) :
    - Pitch from 80 to 205 µm
    - 20<r<55 cm thin (d=320 µm)
    - r>55 cm thick (d=500 µm)
  - Generally measure rΦ direction
  - Some radii ('Stereo'):
    additional 2nd modules rotated by 100 mrad
    - → measurements for η(track)

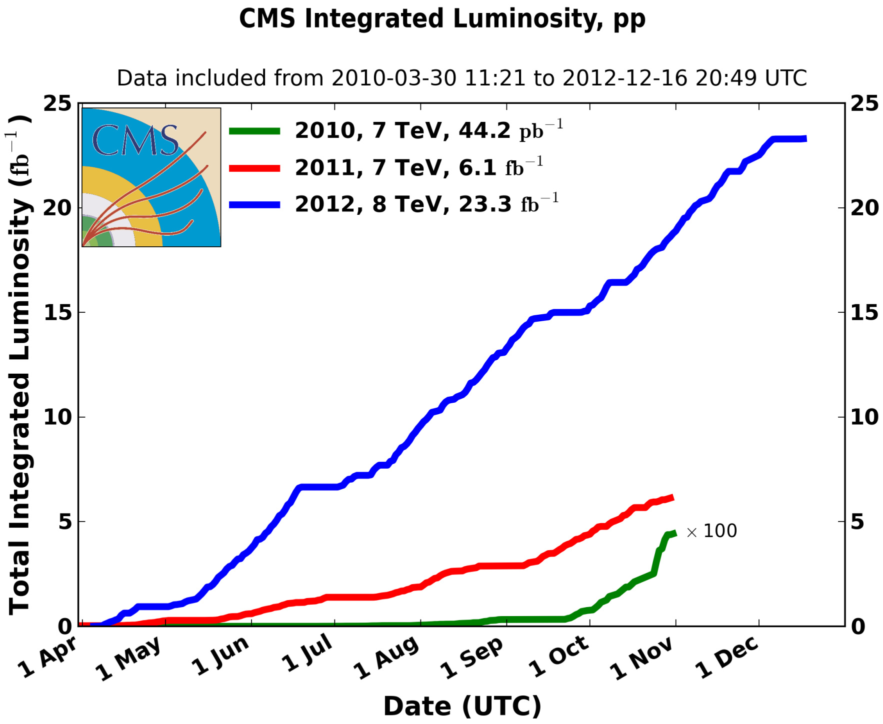


Tracker state @ end of data taking

- Luminosity :

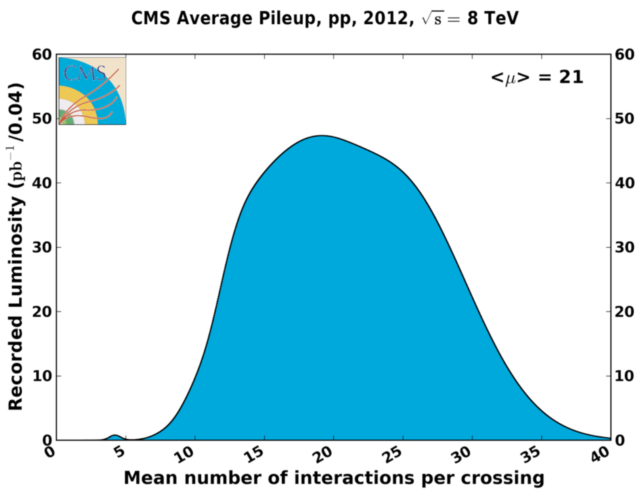
Period	√s (TeV)	Delivered Lumi (fb^{-1})	Data Taking Efficiency (%)	Validated Data (%)
2010	7	0.0442	92.2	88.6
2011	7	6.13	90.5	90.1
2012	8	23.3	93.5	90

  - 4.5 (1.7)% loss due to downtime (deadtime)
  - 77 % design inst. Luminosity reached with a 50ns bunch spacing



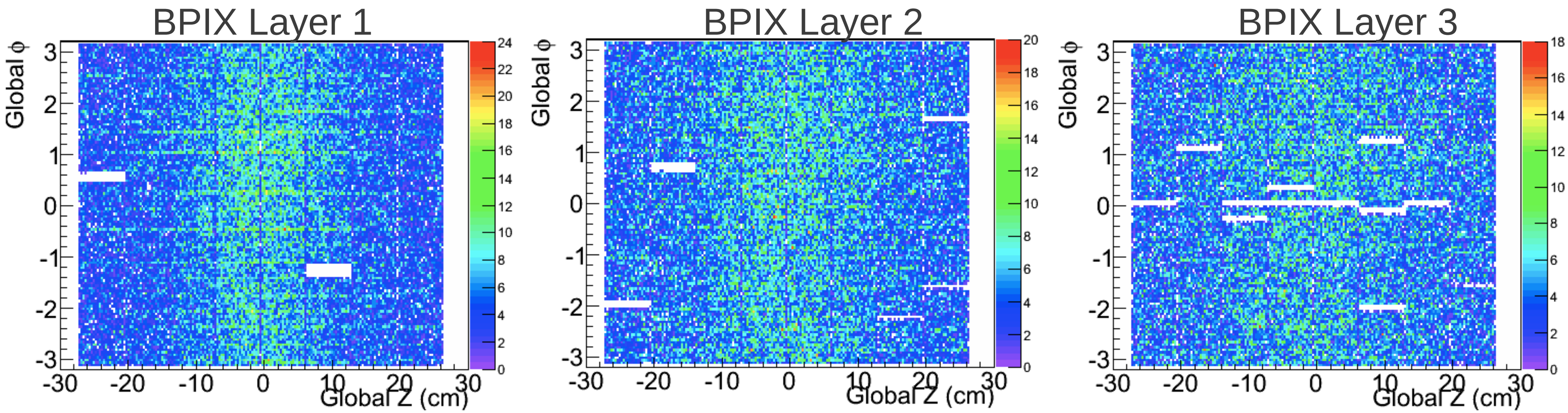
- Pile up:
  - Average in 2012: 21 interaction/bunch crossing
  - Peak PU (exept high PU runs) :

Period	Peak PU
2010	3.5
2011	18.6
2012	34.5



Pixel Status (@ end of data taking)

BPIX



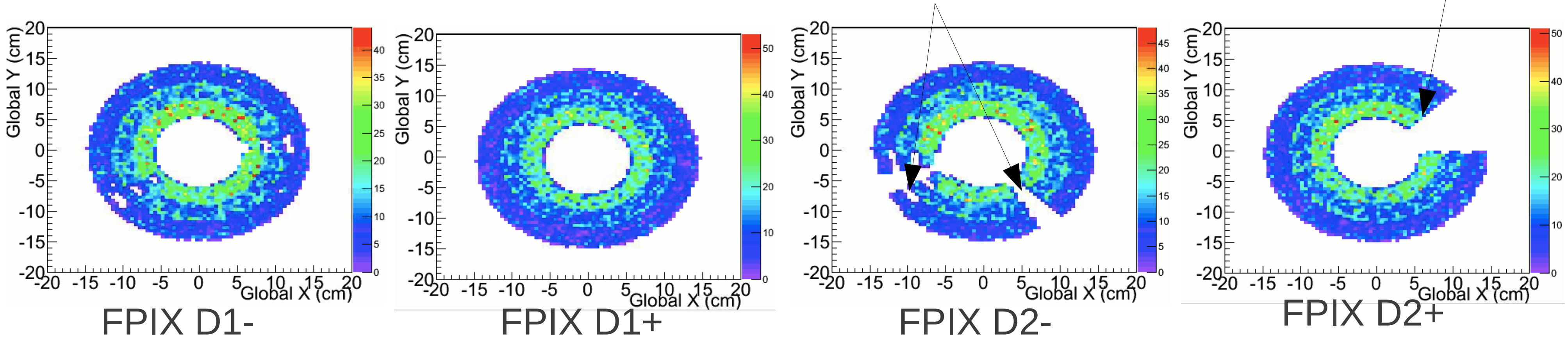
- Cluster occupancy shows the dead parts
- Channels out:
  - BPix: ~2.3%
  - FPix: ~7.2%

«Slow» channels :

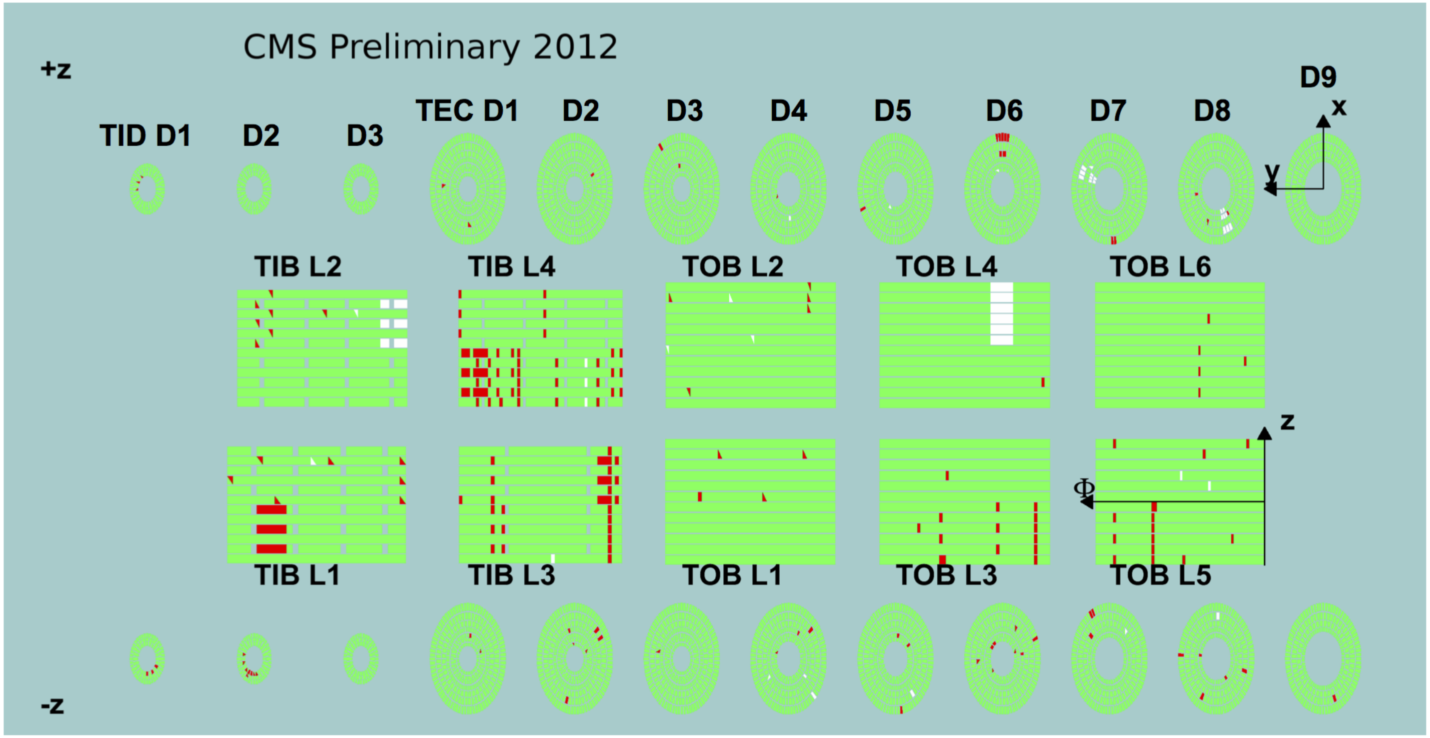
- Long rise time in analog readout
- Pixel addresses misread
- ROCs or events miscounted if headers lost

Optical readout

FPIX



Strip Status



Active, Masked, Not Commissioned

- Active fraction > 97.5%
  - No/low impact on track reconstruction as many layers
- Stable :
  - 98.5% (2008) ->97.75 % (2011)
- Can't be removed for recovery (as pixel)

Reasons for masking :

- Control ring shorts
- Control rings not functioning
- HV line shorts
- HV lines open
- Fibres, Communication and Control Units (CCU)

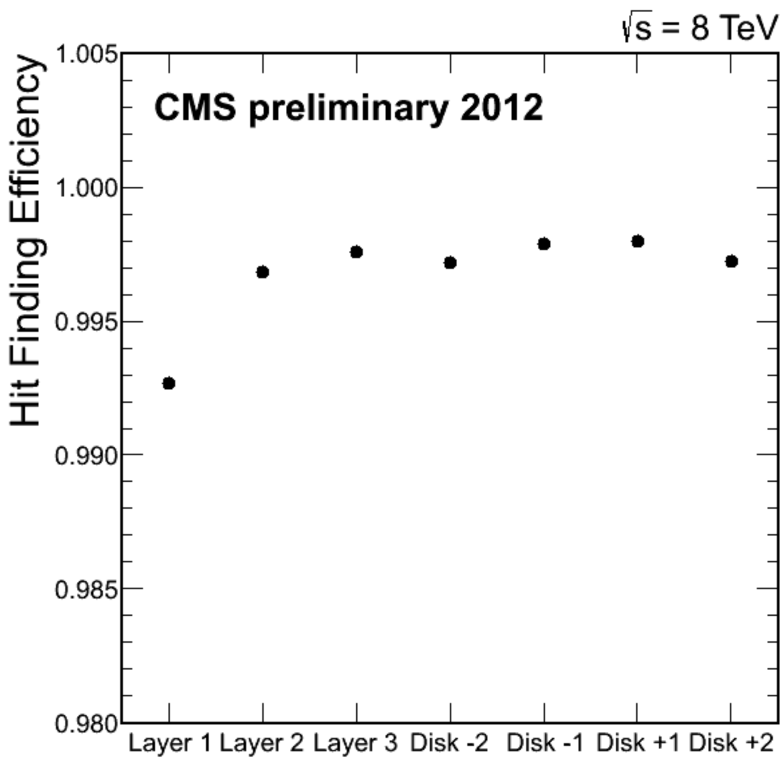
Activity on tracker during LS1

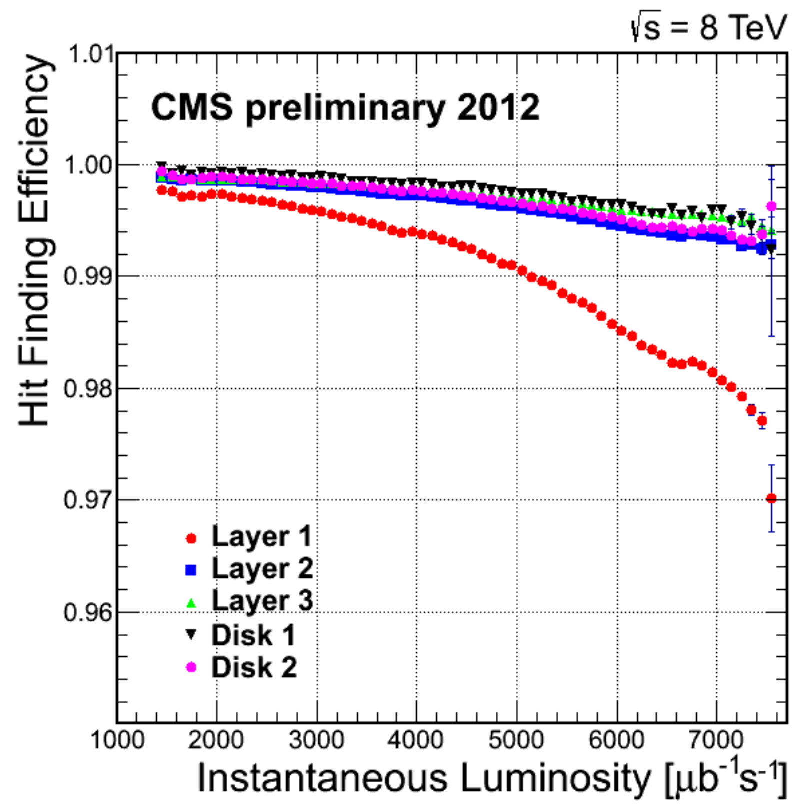
- LHC is aiming for:
  - √s=13 TeV
  - 25ns bunch spacing
  - Peak instantaneous Luminosity ~ $1.7 \times 10^{34}/cm^2/s$
- For the Pixel:
  - Extraction and storage in a clean room
  - Broken part repair:
    - FPIX basically finished (will bring FPIX to 100% minus one chip)
    - BPIX repair ongoing (will bring BPIX to 98.9%)
  - Installation of two pixel pilot blades with modules from Phase1 upgrade
  - Better center the pixel detector during insertion in 2014
  - After installation (~June 2014): extensive calibration
- For the Strip:
  - No direct access to the detector: recovery of as many channels as possible
  - Lowering of the temperature: -10°C on the sensor with -20°C coolant
    - ➔ To counteract the degradation from radiation
- Maintenance and upgrade:
  - Data Aquisition system (DAQ)
  - Detector Control System (DCS)
  - Offline tools

Tracker performances

Pixel Hit Efficiency

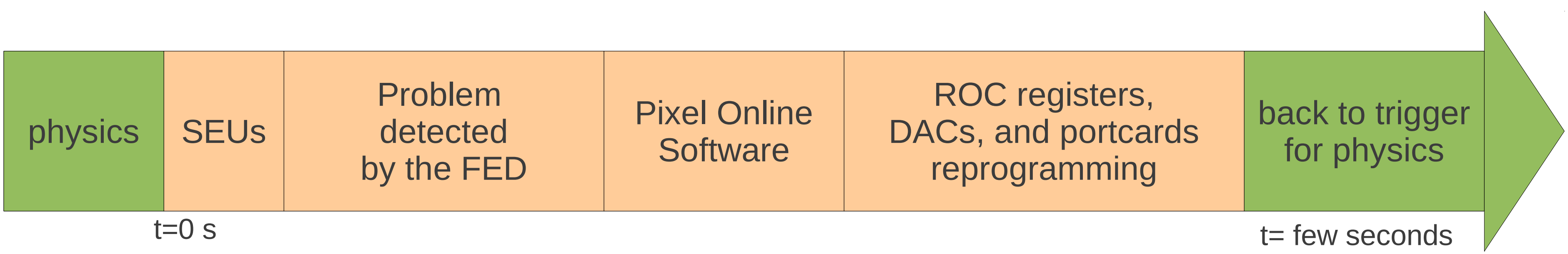
- Pixel hit efficiency in general > 99%.
- Hit efficiency depends on the instantaneous luminosity due to the occupancy
  - Unavoidable inefficiency is expected due to dynamic data losses
    - pixel-by-pixel, depends on PU, L1 rate, Inst. Lumi, orbit number
    - Consists of buffer overflow, pixel over-writes, busy pixel columns and internal resets (all within the frontend readout chip)



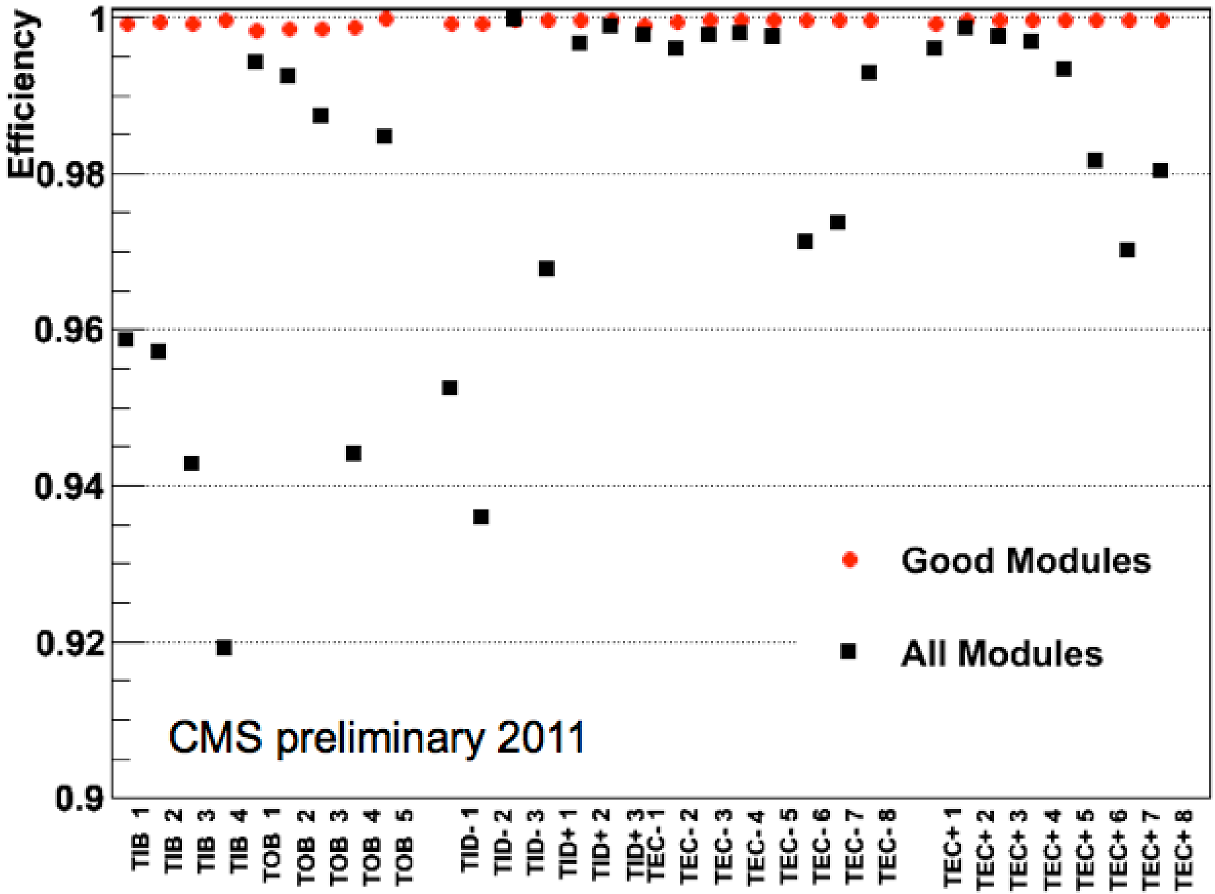


Pixel Single Event Upset (SEU)

- SEU events = bit flip in the ROC or auxiliary electronics caused by ionization
- Increase with instantaneous luminosity
- Consequences :
  - interrupt data taking
  - degradation of data quality
- Does the SEU compromise data taking ?
  - No : No action needed (concern Single Pixel and single ROC i.e. <0.1‰)
  - Yes : need to be fixed (concern auxiliary electronics i.e. ~1%)
    - → Stop the trigger and reprogram the ROC registers, DACs, and portcards
- 1 SEU (needing treatment) every ~73 pb-1 of data so ~1.5 SEUs / LHC fill



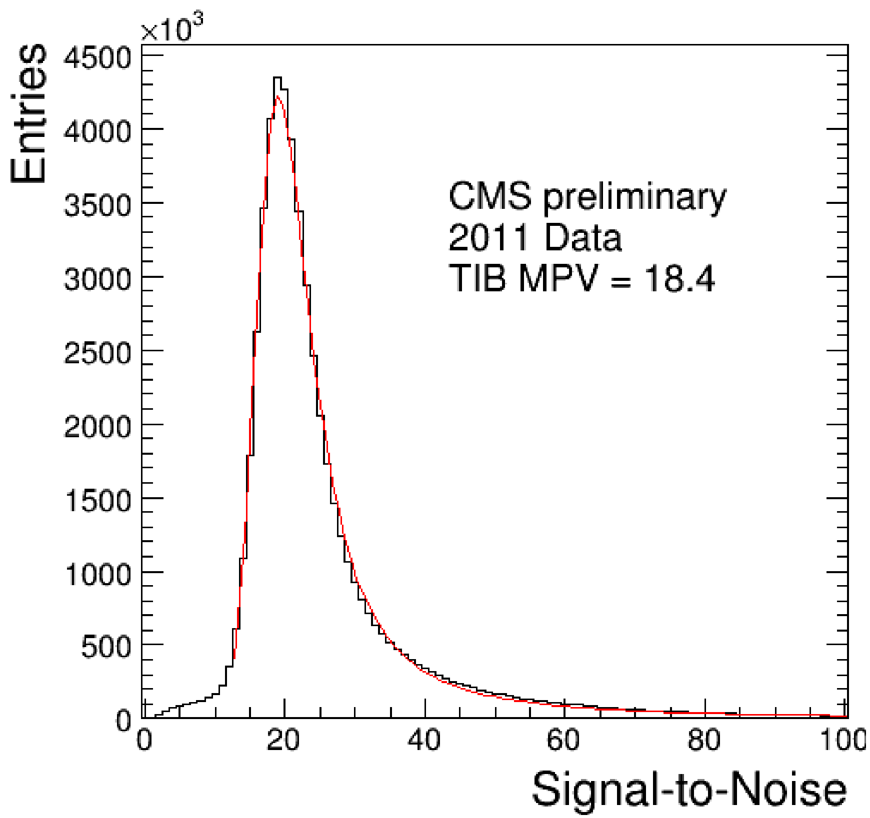
Strip Hit Efficiency

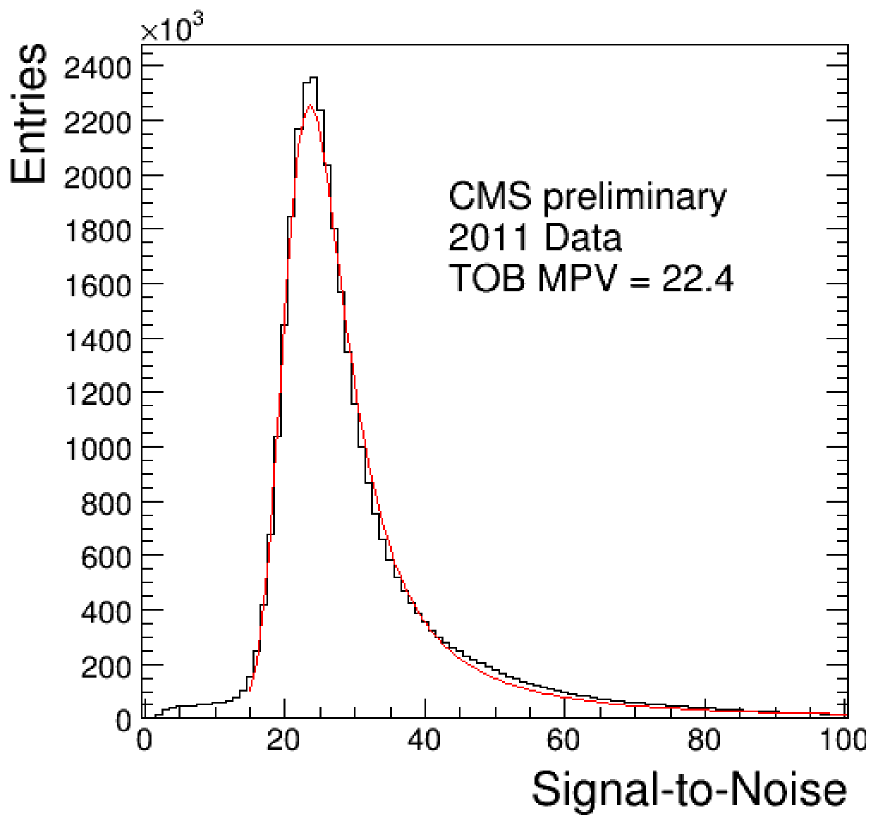


- All modules :
  - Variation down to 92 %, reflecting bad module distribution
- Good modules :
  - > **99 % efficient** → We know very well which modules are bad

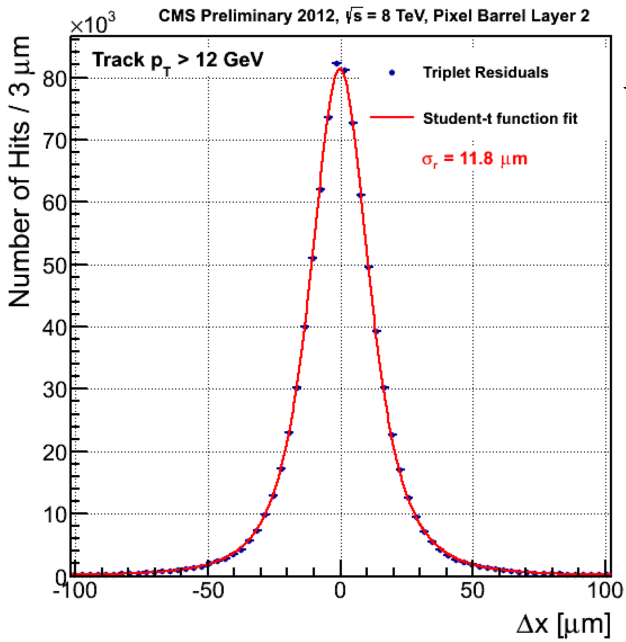
Strip Signal-to-Noise Ratio

- Clusters on track only, charge corrected for track angle.
- Distributions nicely follow Landau distributions convoluted with Gaussian resolution
- Large most probable value :
  - Thin sensor (TIB) :~18
  - Thick sensor (TOB) :~22
  - ➔ Consistent with values from irradiation campaigns prior to integration



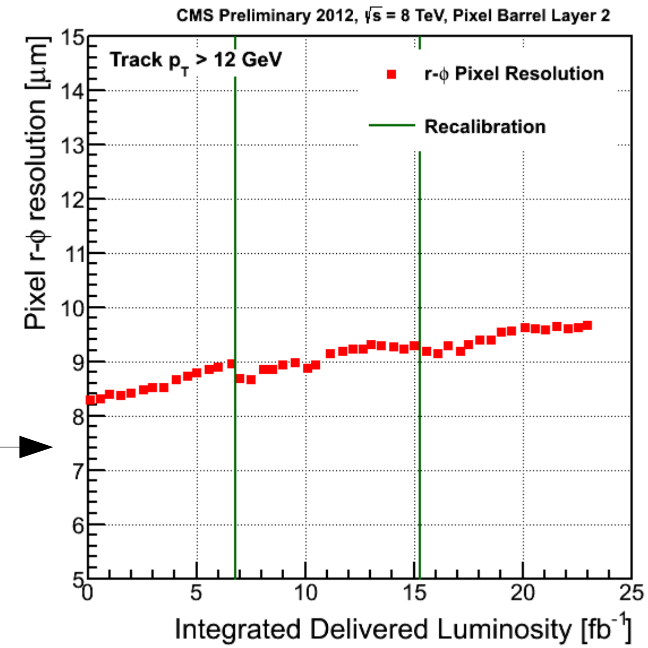


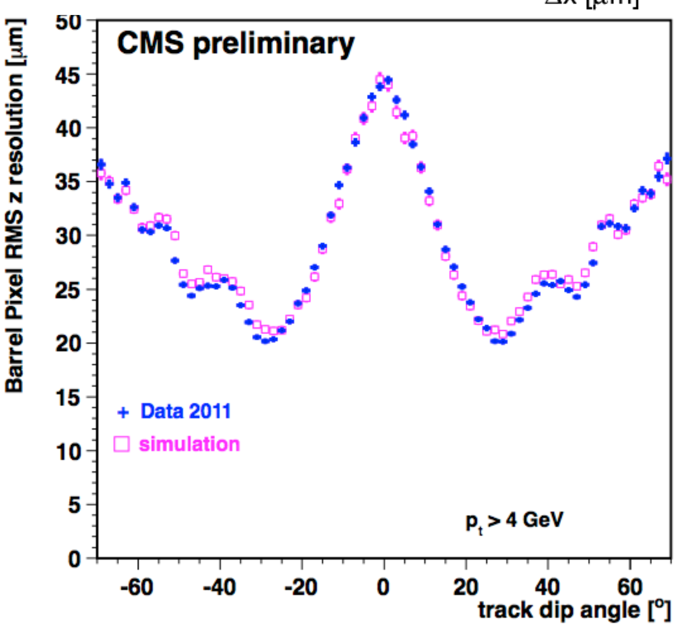
Pixel and Strip resolutions



pixel triplet resolution transverse plane

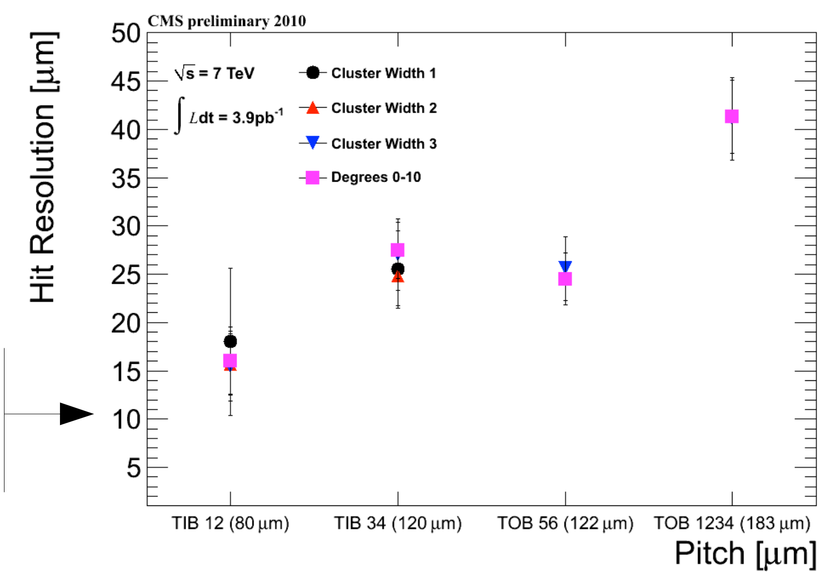
intrinsic resolution of pixel detector (barrel, layer2), from pixel triplets (2012 only)





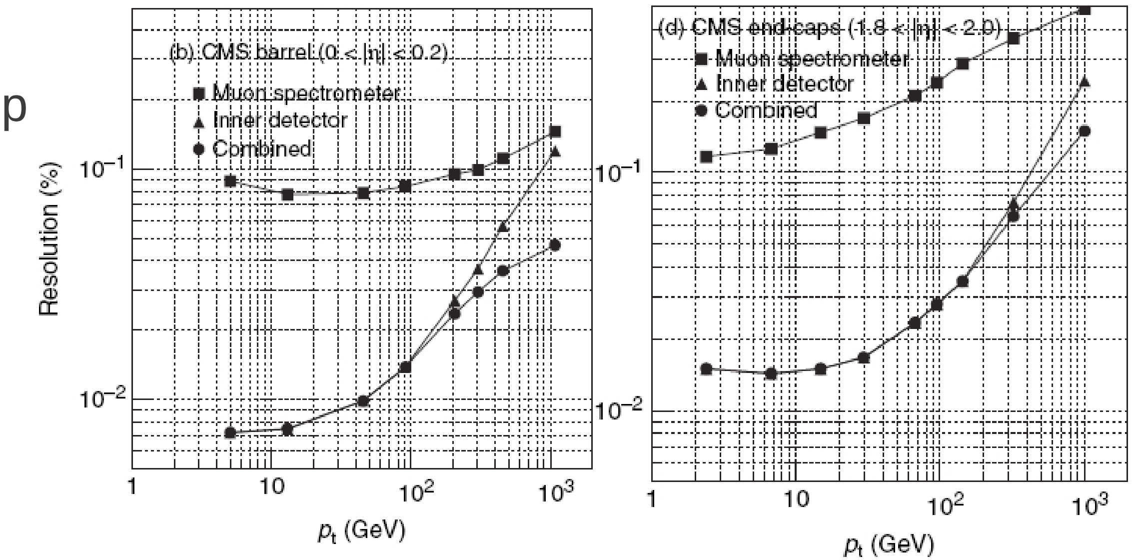
z direction resolution in barrel pixels

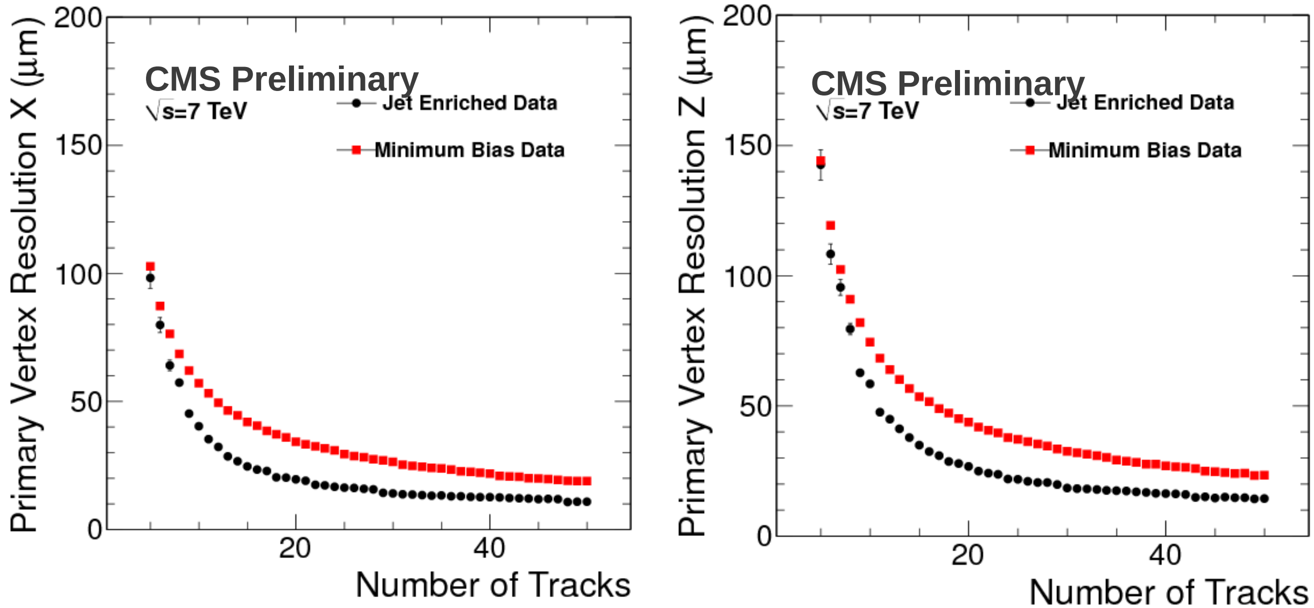
Strip Hit Resolution vs Subdetector pitch



Momentum and Primary vertex resolution

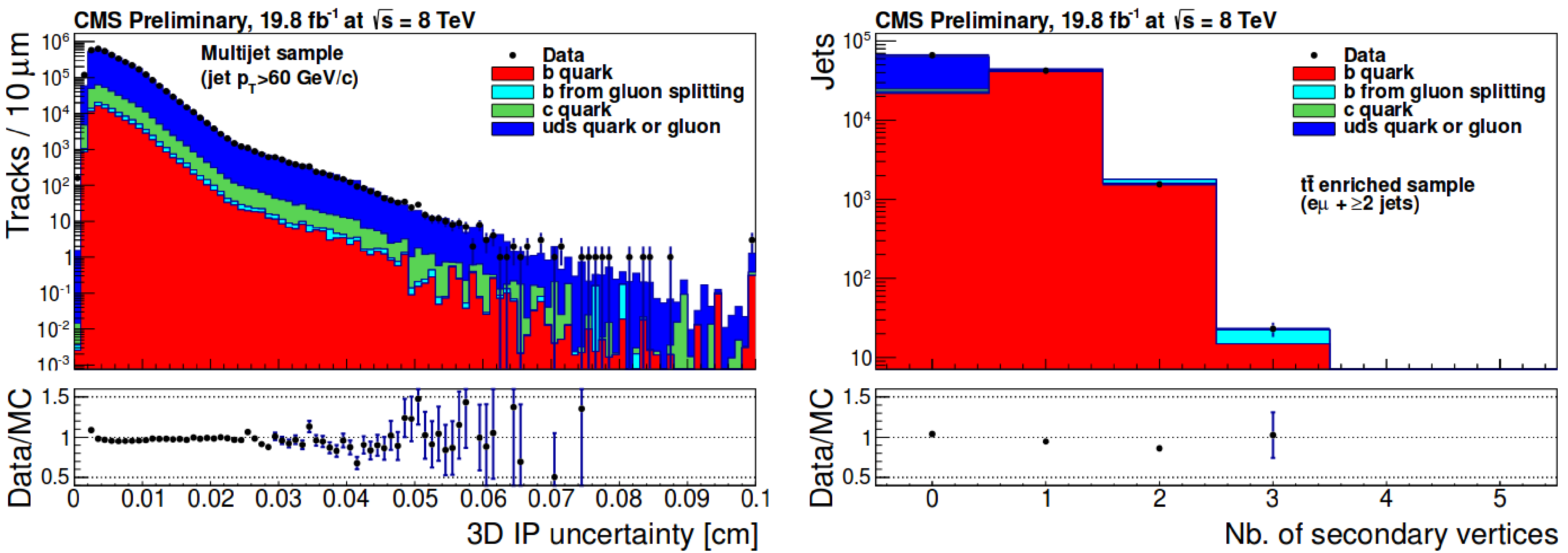
- Good hit resolution in the pixels and strip
- High hit multiplicity by tracks
  - ➔ Good Momentum resolution: $\sigma(p_t)/p_t$ = 1-2% for $p_t(\mu)$= 100 GeV/c With the tracker only
  - ➔ Combination allow to have a very good primary vertex resolution





b-tagging related variables

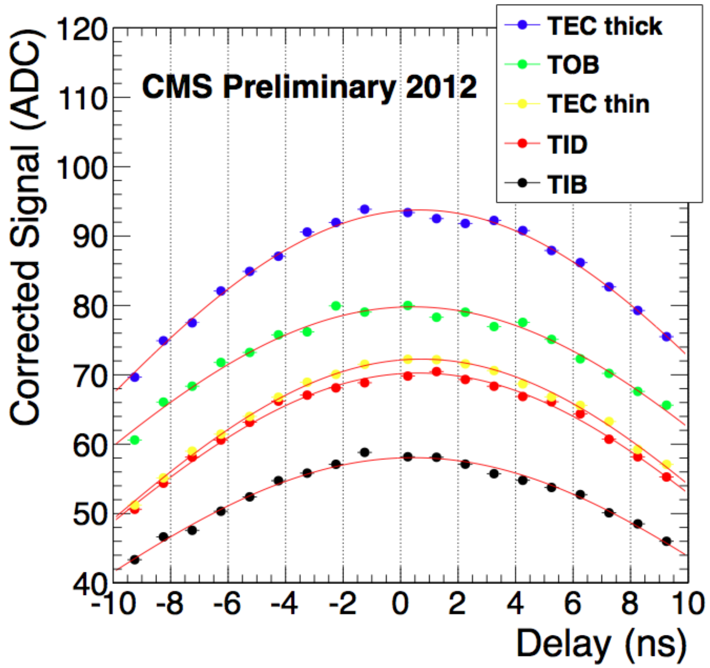
- Thanks to a very good:
  - Hit resolution performance
  - Momentum resolution
  - Vertexing resolution
  - ➔ Precises and very discriminant inputs for the b-tagging
- Excellent description by simulation

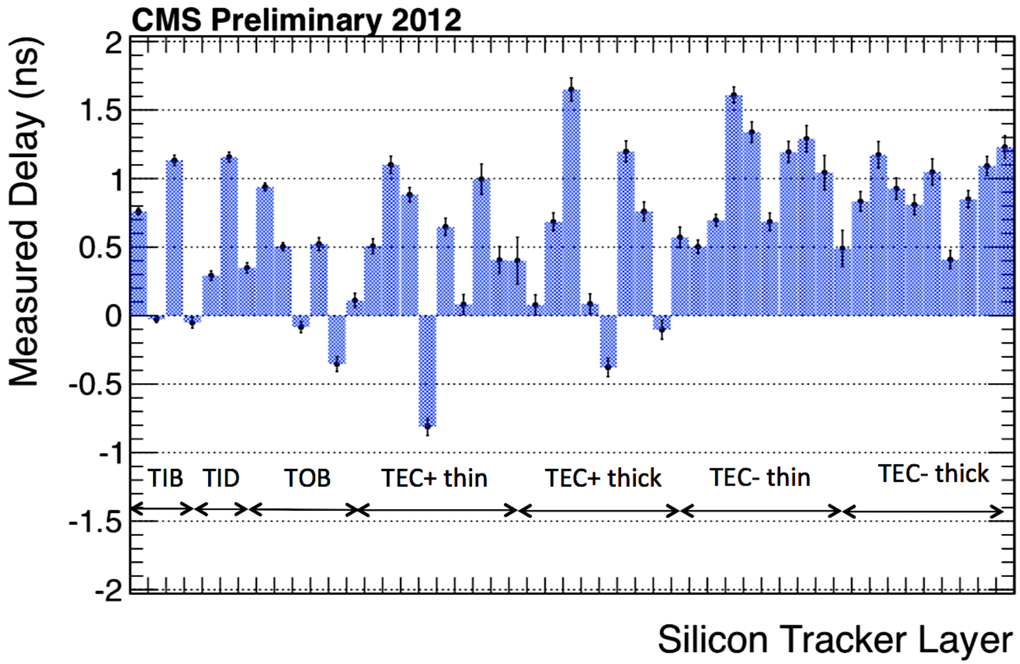


Strip Signal Time Profile

- Important for Signal-to-noise ratio if timing is off
- Efficiency suffers if far off
- Impact on occupancy due to the out-of-time pile up (OOP)
  - Minor impact at 50ns but critical at 25ns:
    - ➔ a few ns difference lead to 2→10 times more OOP

- Should be stable but can be check with a few minutes of deconvolution mode data:
  - Time delays in steps of 1.04ns (smallest possible adjustment)
  - Signal maximum must be at 0
    - Current timing is observed to be perfect and stable compared to previous years



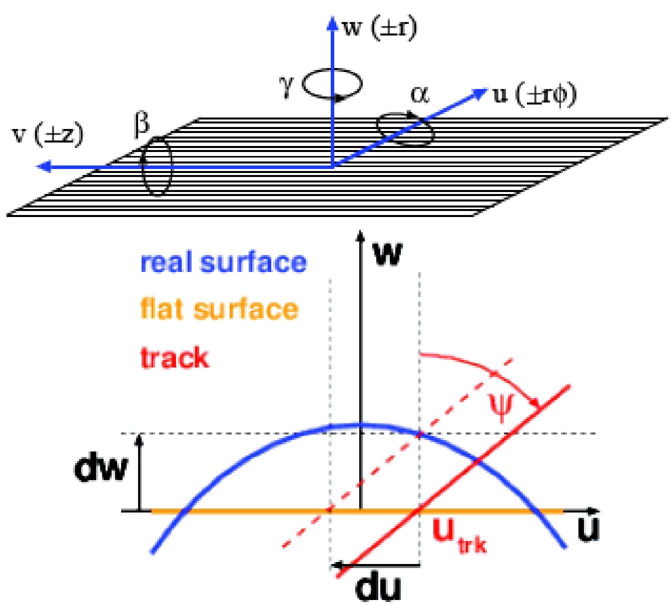


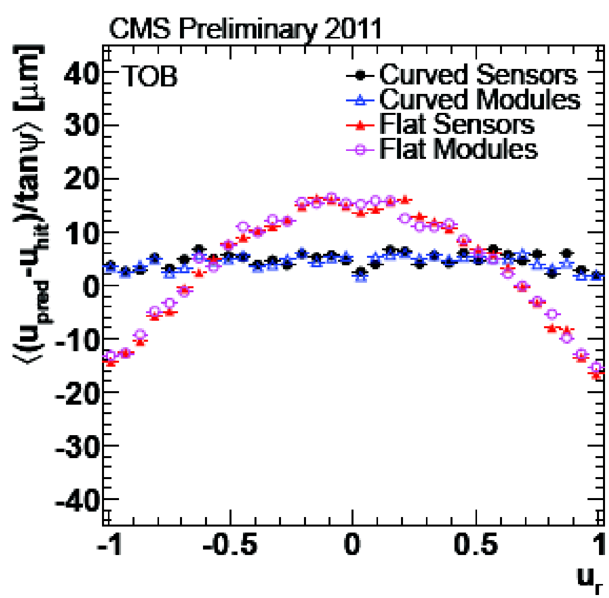
Strip Alignment : Sensors are Curved

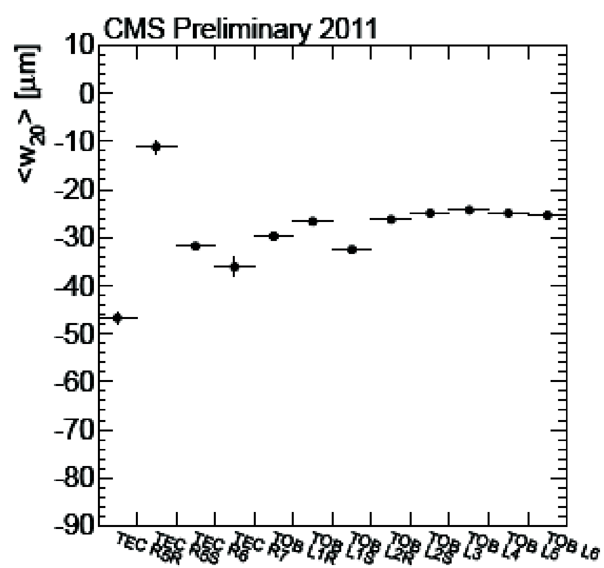
- Track-based alignment working fine (100k aligment parameters!)
  - ➔ So well mastered that we are sensitive to sensor curvature
- Single sided silicon processing
  - curved sensors (specifications: < 100 µm).
- Visible in average track angle corrected residuals:

$$\langle \Delta W \rangle = \langle (U_{trk} - U_{hit}) / \tan\psi \rangle$$

- Average amplitude in TOB: -30 µm (with relevant RMS).
- Sensor-by-sensor values determined in alignment:
  - hit position corrections let modules appear flat (as tracking expects).

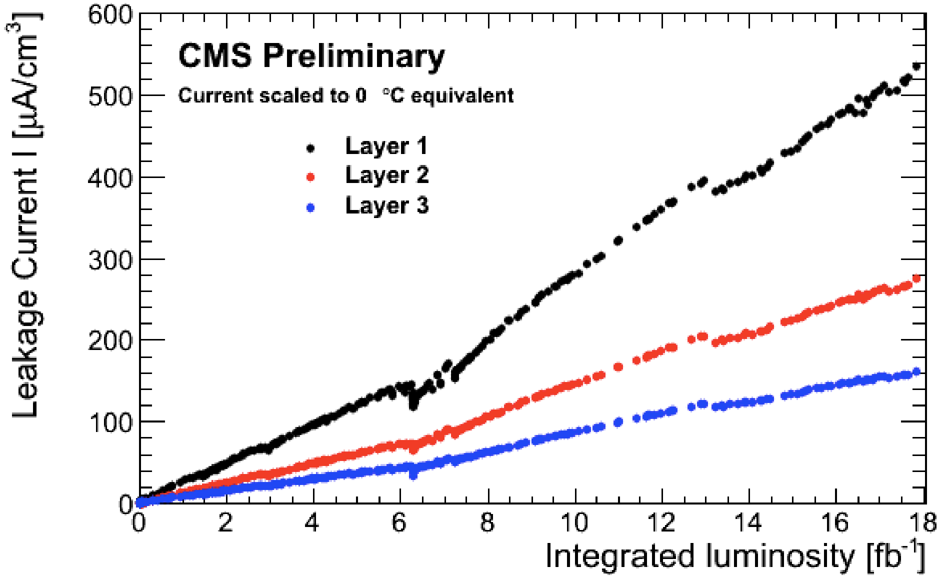


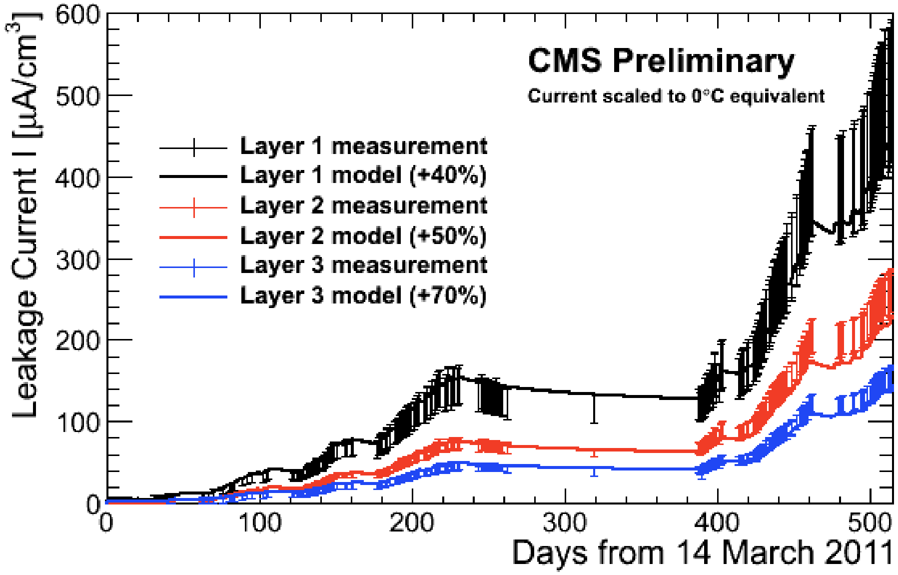




Detector evolution with integrated luminosity

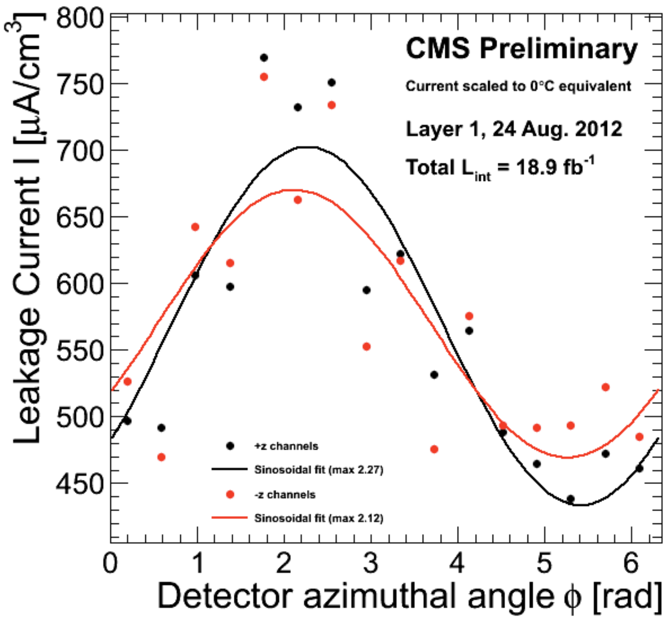
Pixel Leakage Current





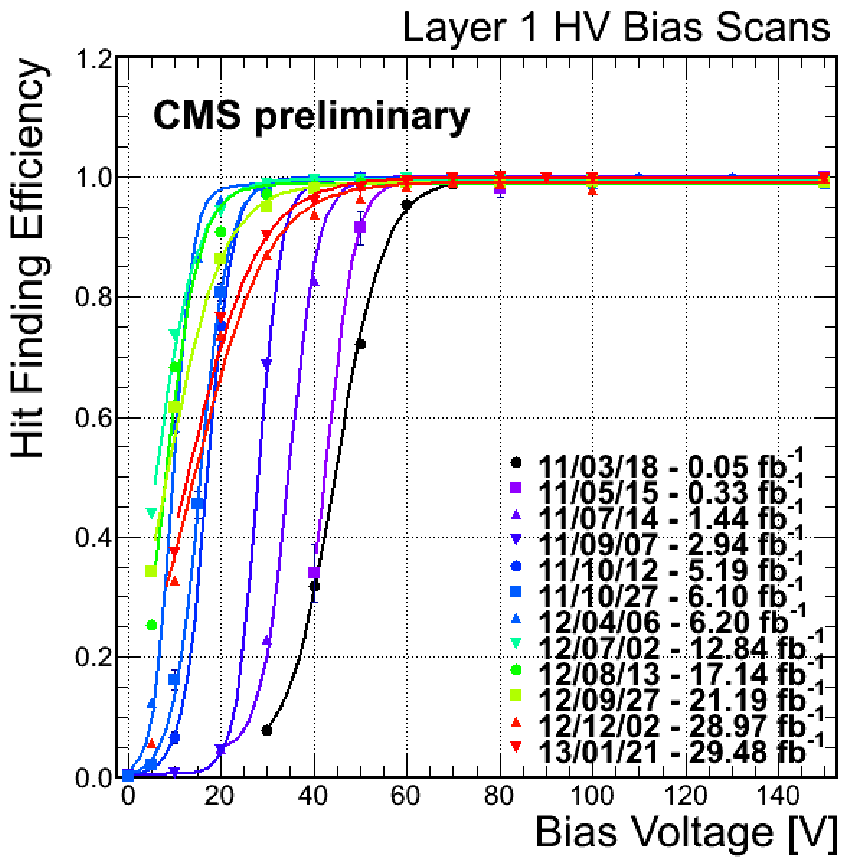
- Leakage current expected to increase :
  - linearly with fluence
  - Due to bulk silicon damage
  - Partial recovery due to annealing
- Good shape agreement with models (fluka)
- Normalization low by 40-70%

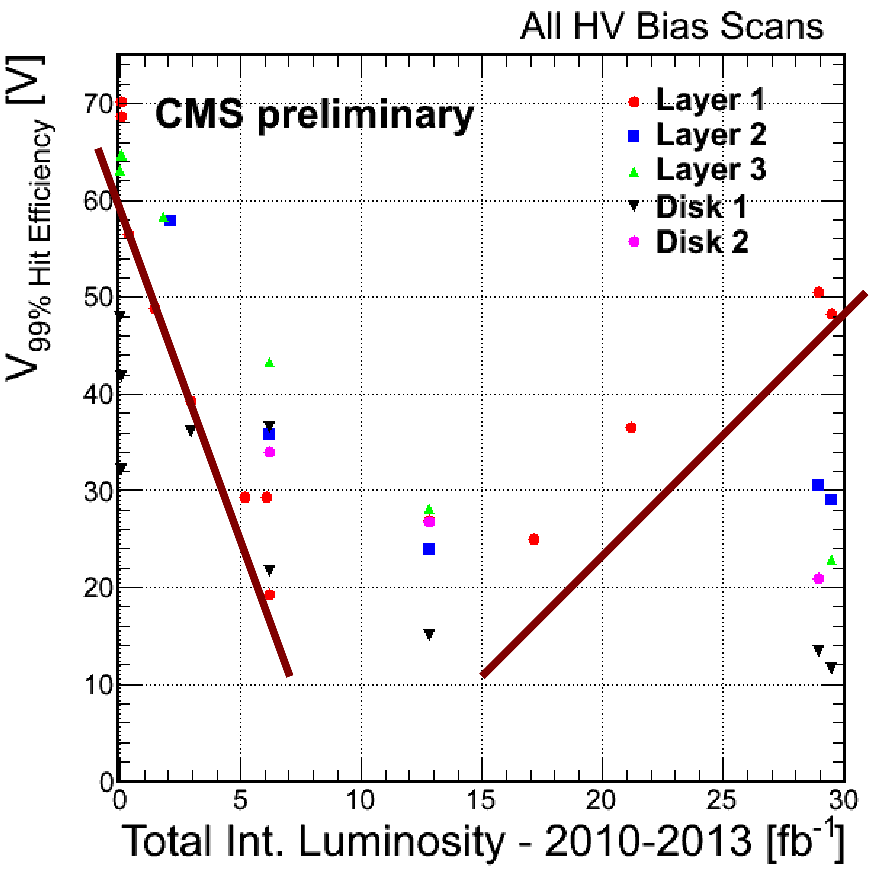
- An azimuthal dependence is observed :
  - LHC Beam Spot is not at the center of Pixel Detector
    - 30% effect on potential Layer 1 lifetime
    - Expect to be fixed after LS1 and re-centering
  - Geometric issues also impact data rates → where readout issues emerge



Pixel Bias Scan

- Regular measurements of :
  - Detection efficiency
  - Charge collection efficiency vs bias voltage

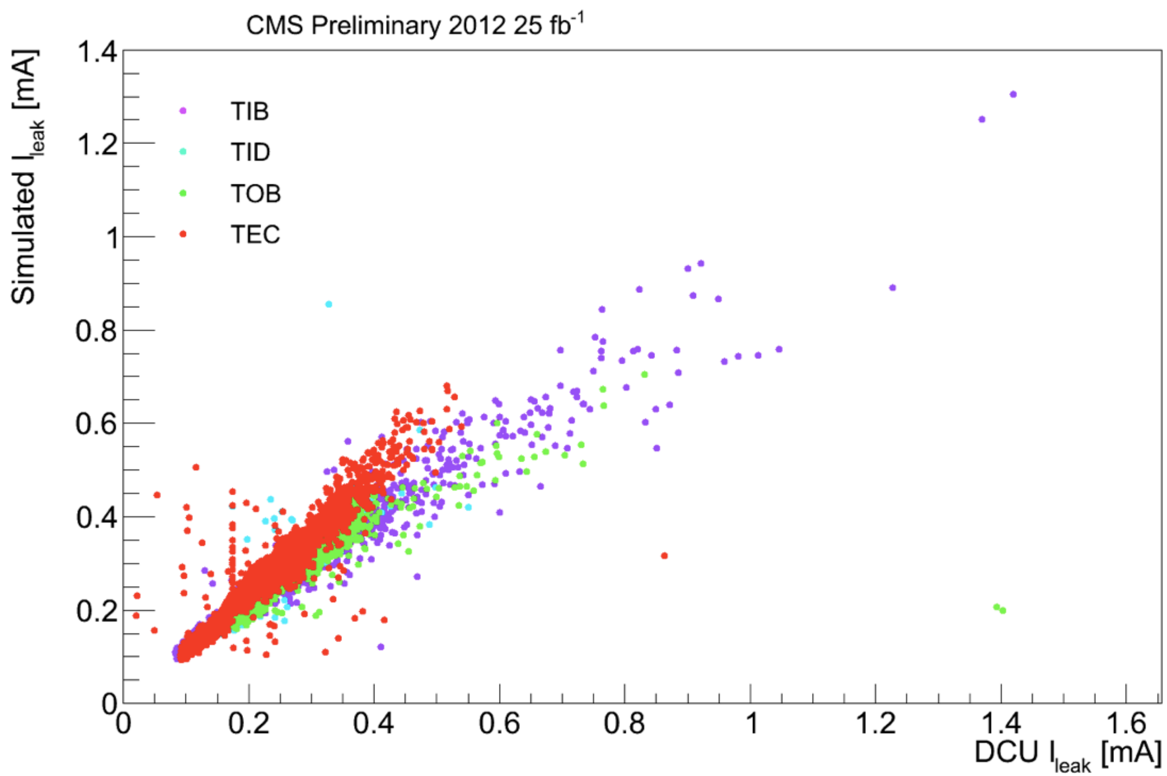




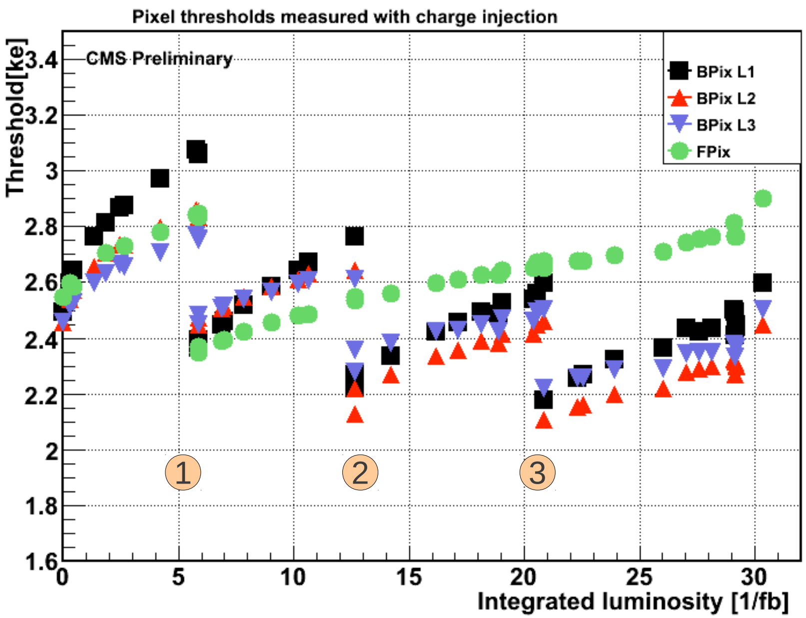
- Layer 1 and layer 2 are type **inverted**.

Strip Leakage Current

- Increase with radiation damages :
  - Give a handle to measure accumulated irradiation
- Current measured module-by-module
- Average strips measurements agree with model (fluka) within 5-20%:
  - varying over time and detector region
  - Better agreement detector regions with temperature T < 20°C (strip tracker temperature not uniform)

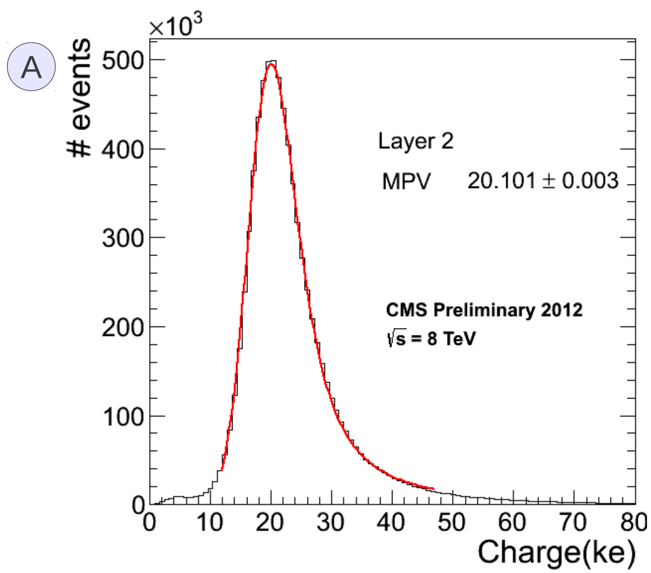


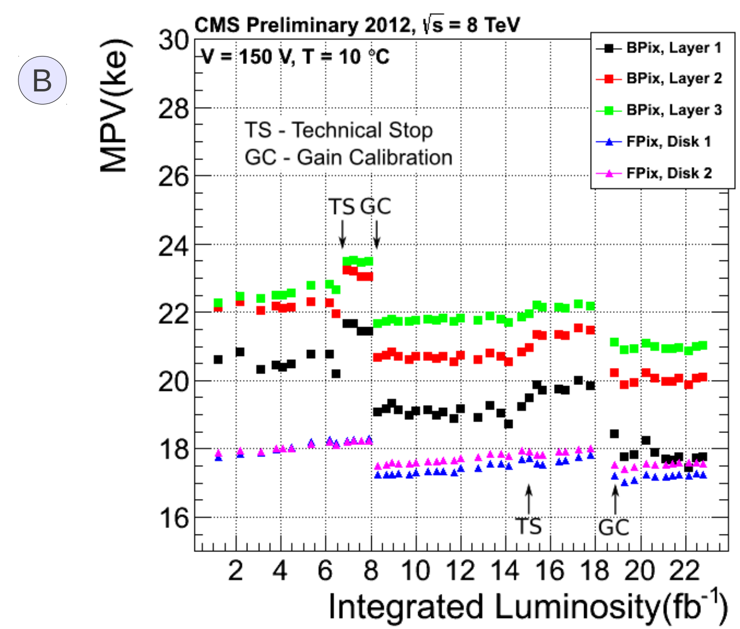
Pixel Thresholds and Cluster Charge



- Pixel Thresholds:
  - Depend on the integrated luminosity
  - optimized during technical stops
    (End of 2011 run ①,Ju. 2012 TS ②,Sept. 2012 TS ③)

- Pixel Cluster Charge:
  A) Distribution for each layer in pixel barrel
    - fitted to Landau distribution convoluted with Gaussian
  B) MPV extracted from fit and plotted vs Int. Lum.

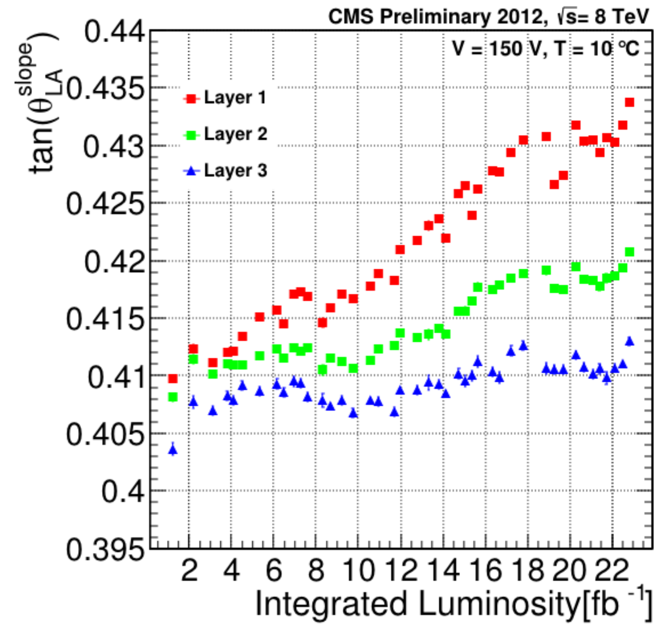


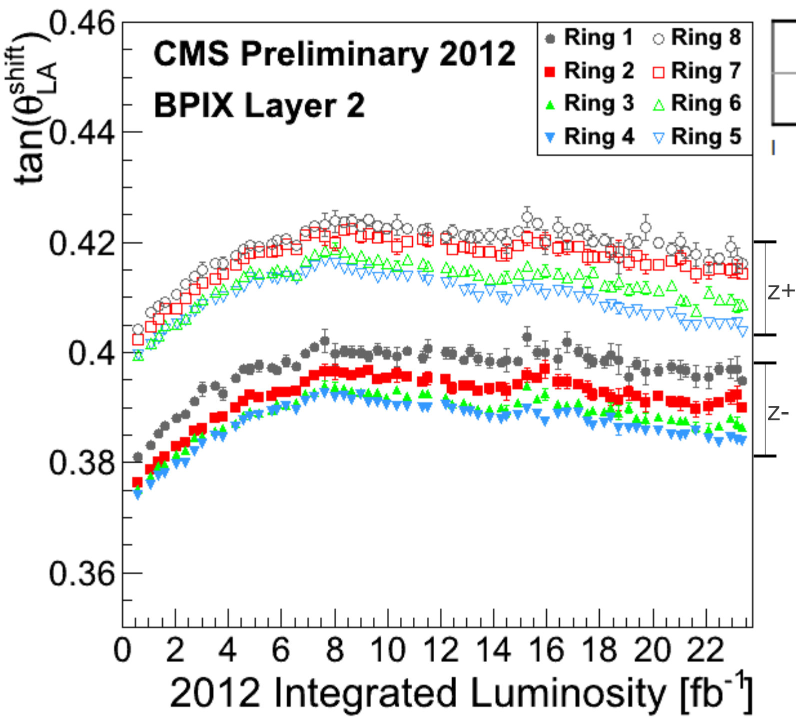


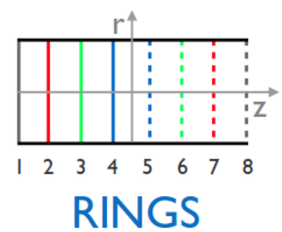
Pixel Lorentz angle

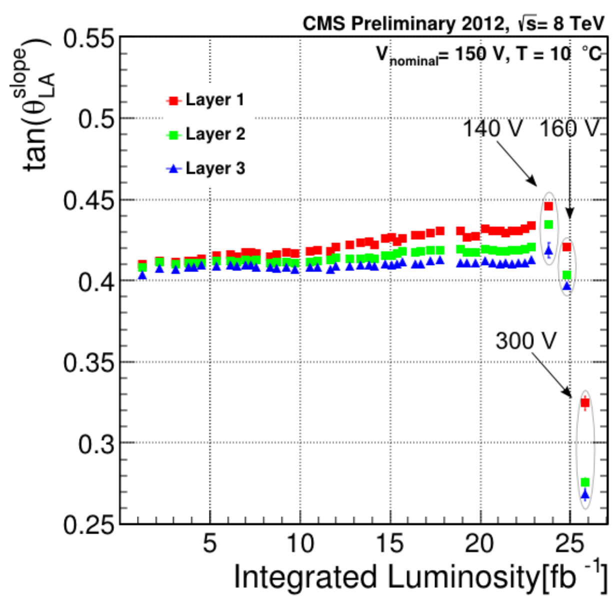
- Increase of the Lorentz angle with integrated luminosity
  - Determined using various techniques:
    - Grazing angle method
    - Alignment
    - ➔ Different impact of the irradiation on the results

- To be understood :
  Offset between z+ and z- side







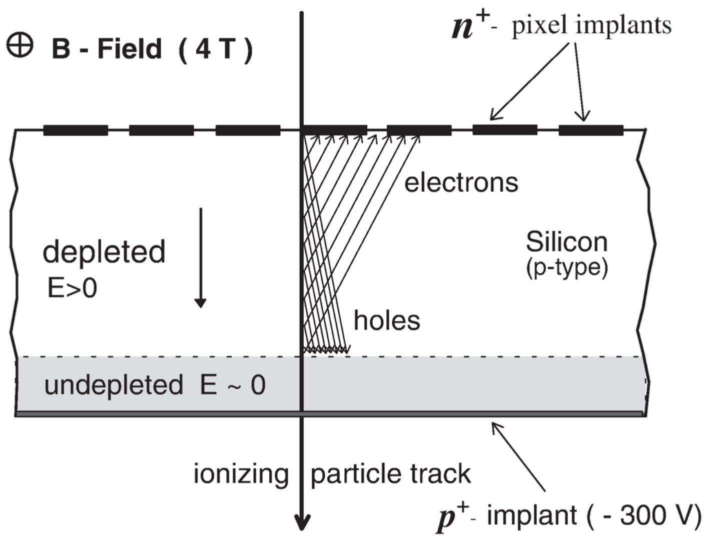


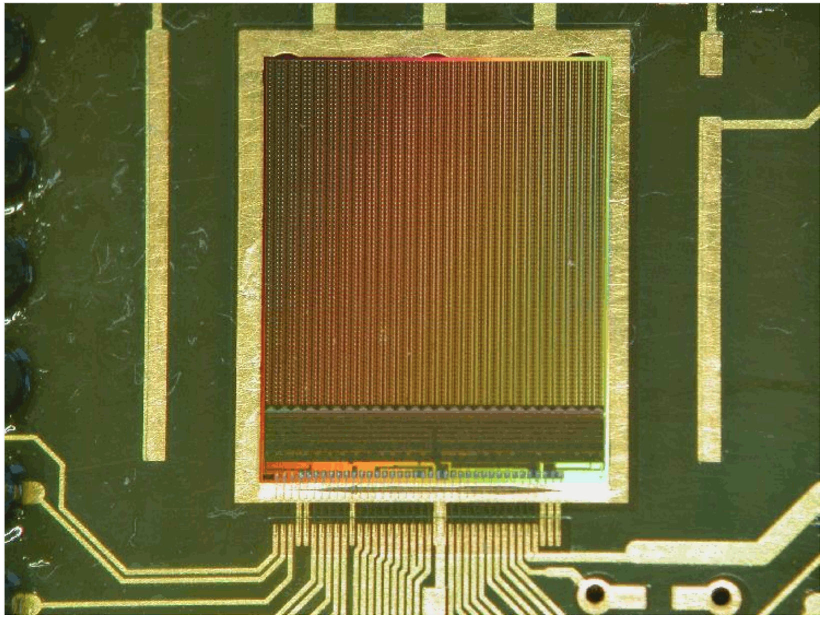
Summary

- The CMS tracker worked well during the past years of data taking
- During the data taking, some channels were lost but :
  - Mainly expected to be recovered after LS1 in the pixel
  - Not problematic in the Strip given the number of layers
- The detector has a good performance :
  - Very good signal-to-noise ratio and detection efficiency
  - In spacial, momentum and vertexing resolution
- Achieved notably because of good alignment (sensitive up to the sensor curvature) and timing
- The aging of the detector follows expectations :
  - Single event upset :
    - Rate as expected and under control
  - Irradiation :
    - Models agree in shape for both sub-detector types
      (40-70 % rescaling Pixel, 5-20 % agreement for Strip depending on the temperature)
- Maintenance work during shutdown:
  - Pixel recovery (100% in FPIX, >98% in BPIX), better centering
  - Lowering of the Strip temperature to counteract radiation effect
- We are getting ready for new adventures at higher energies ...

Backups

Pixel Modules

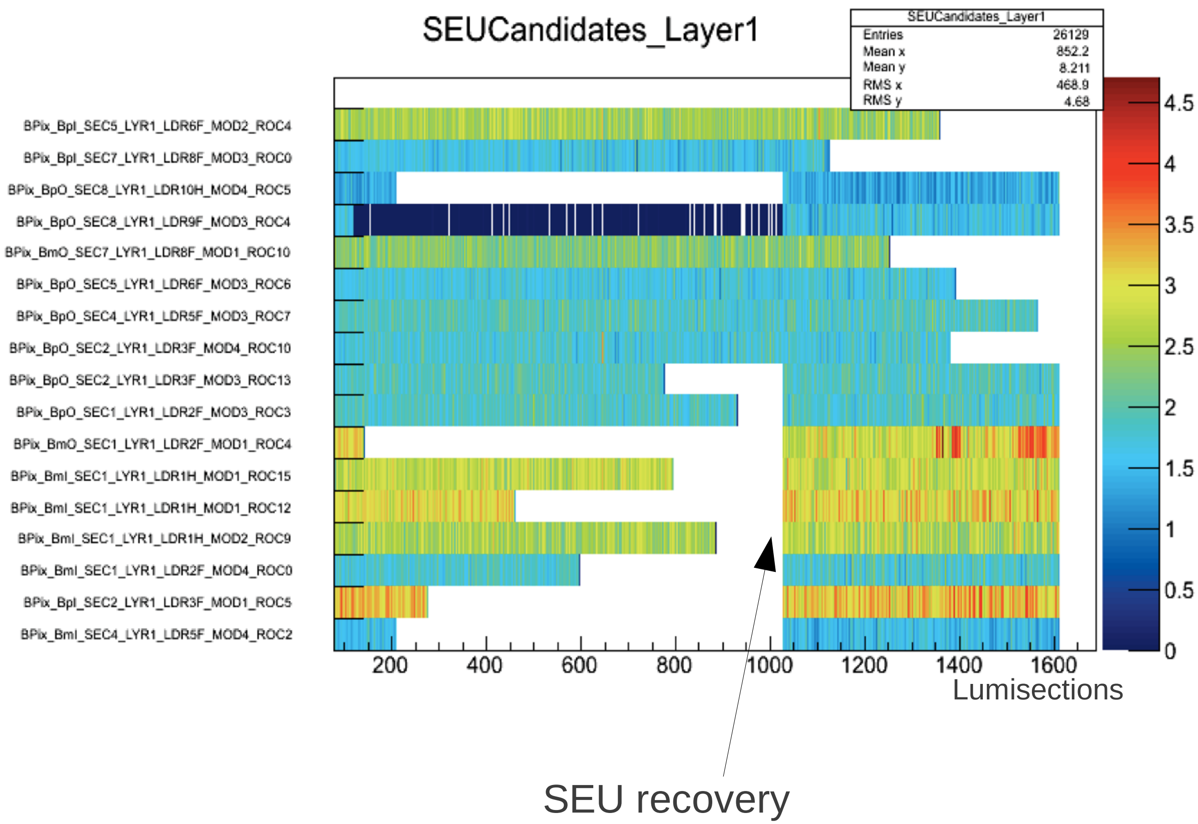


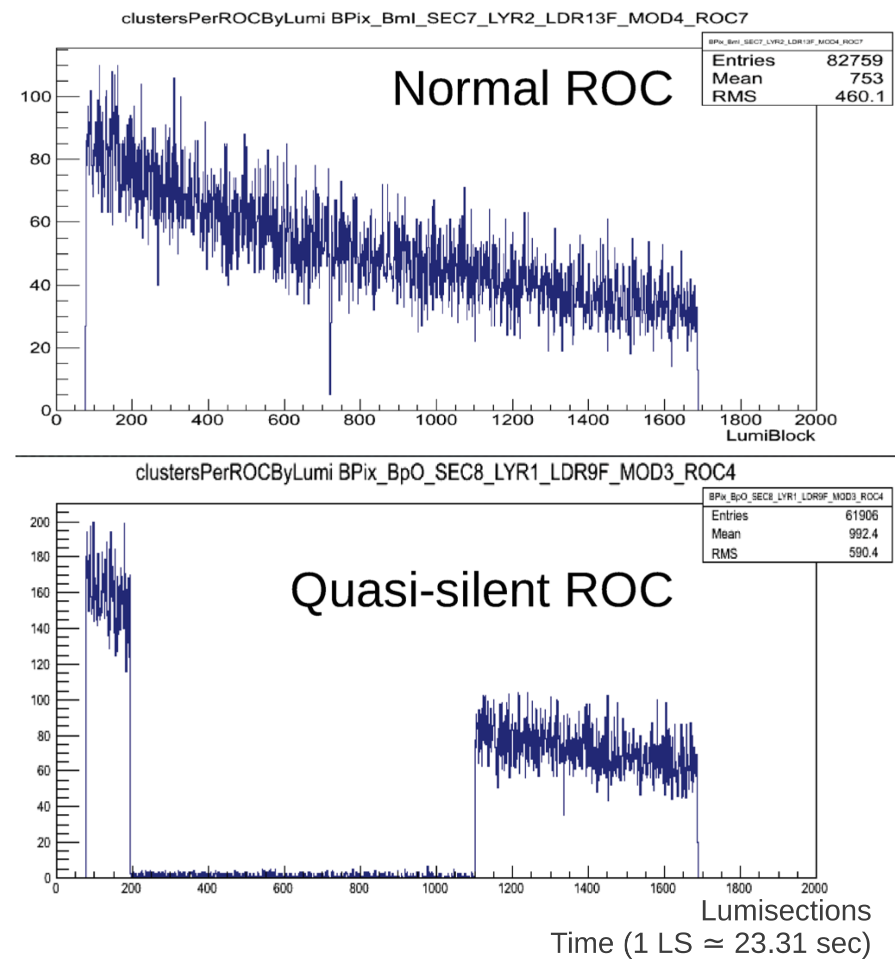


- n-in-n silicon sensor
- 52 x 80 = 4160 pixels by sensor
- Pixel size: 100µm x 150µm
- ReadOut Chip (ROC) designed by PSI and manufactured by IBM
- Automatic zero-suppression;
- 26 DACs to regulate settings, each pixel has a 4-bit DAC for fine adjustments (trimming)
- Double-column drain architecture:
  - Hits stored in a buffer until trigger confirmation
  - Single 25ns-wide bunch-crossing readout

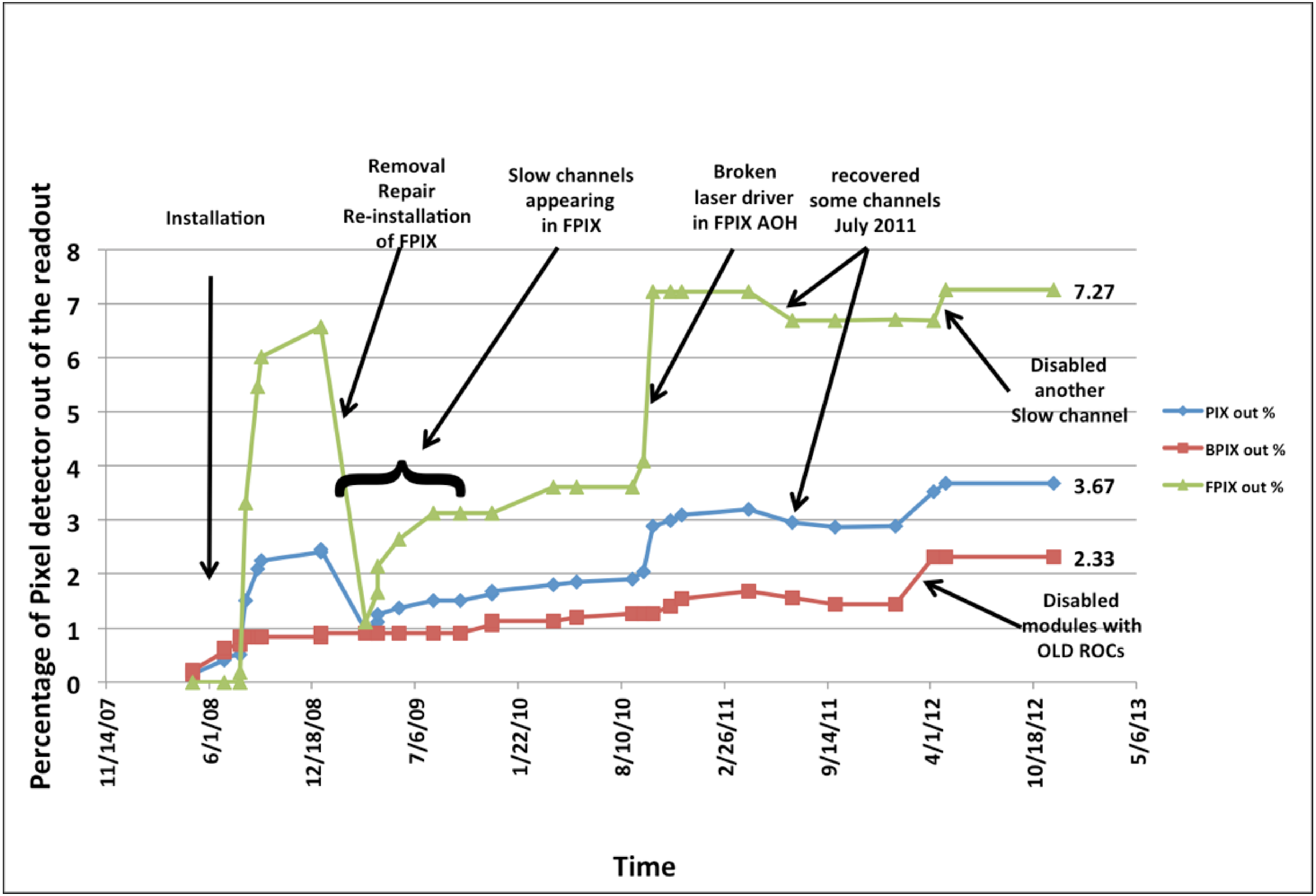
Pixel SEU detection

- Two mechanisms to detect SEU
  - monitoring the off channels
  - searching the Out of Sync (OOS) errors



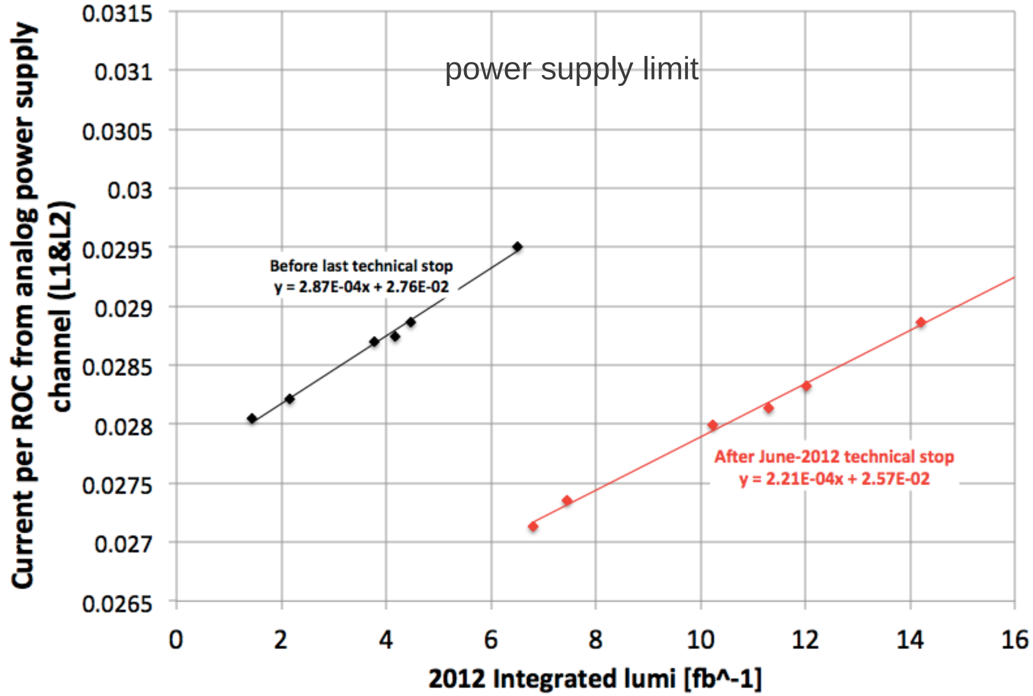


Percentage of Pixel detector out of the RO



Pixel analog current

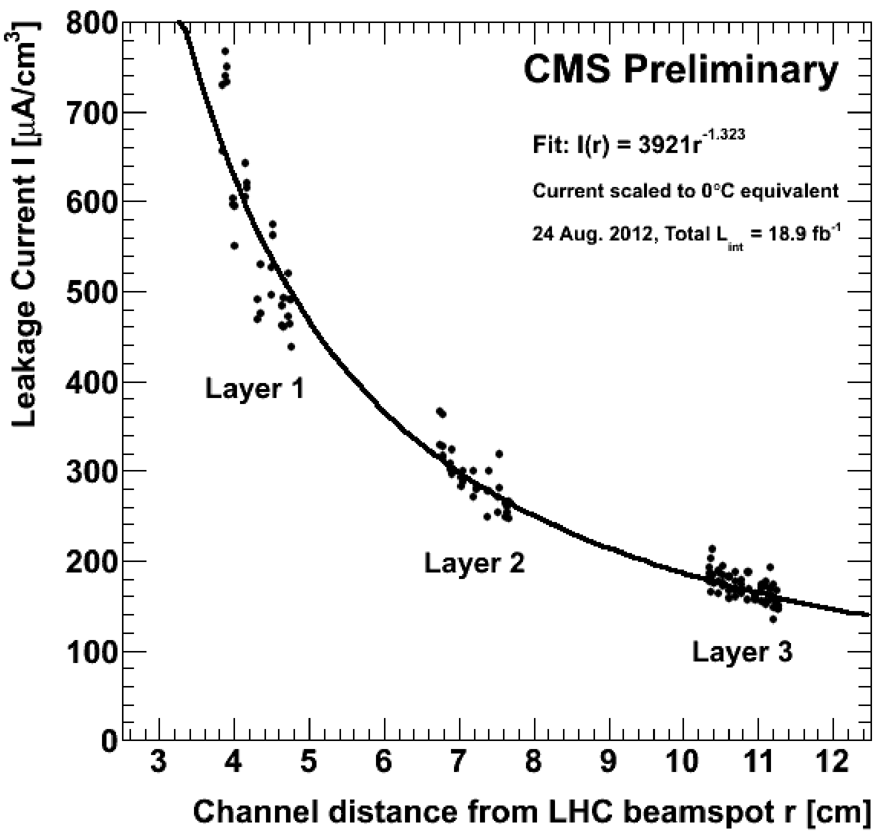
- ROC Analog circuit current increases linearly with radiation damage
  - Slower preamplifier rise time
  - Higher pixel threshold
- Biggest operational concern: power
- supply current limit per channel
  - Limit 6 A, operate ~5.5 A
- Fixed by recalibration
- Possible mechanism
  - change in DAC setting meaning
  - caused by bulk damage in diode used for reference voltage

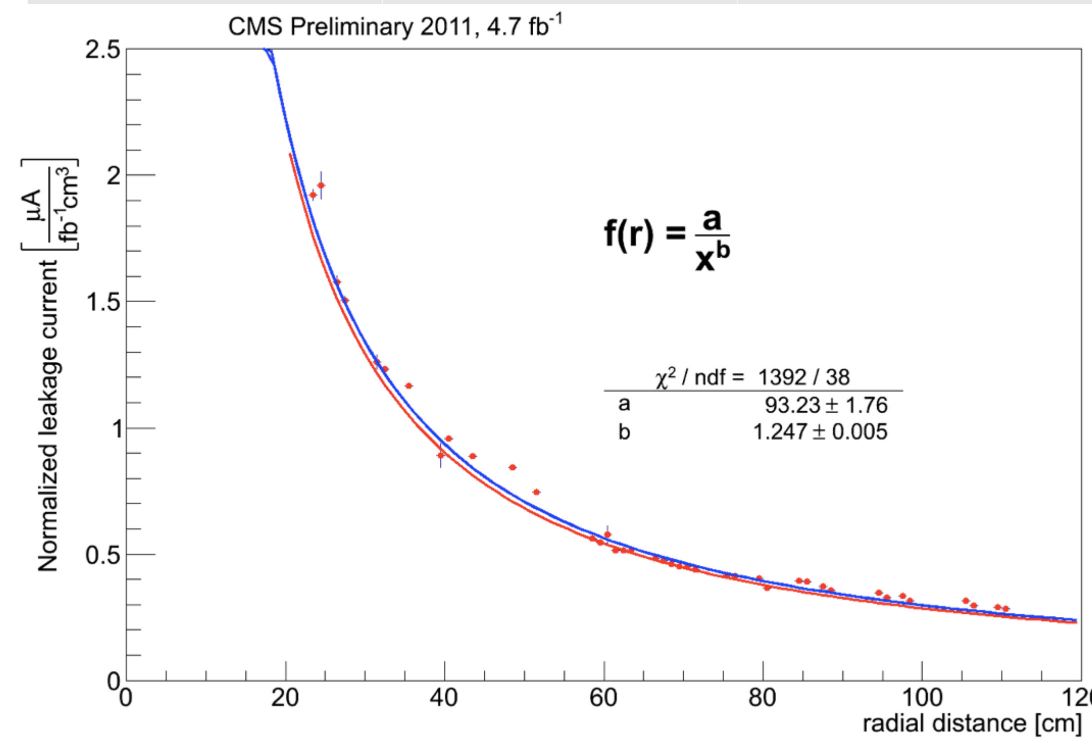


Leakage Current vs radius

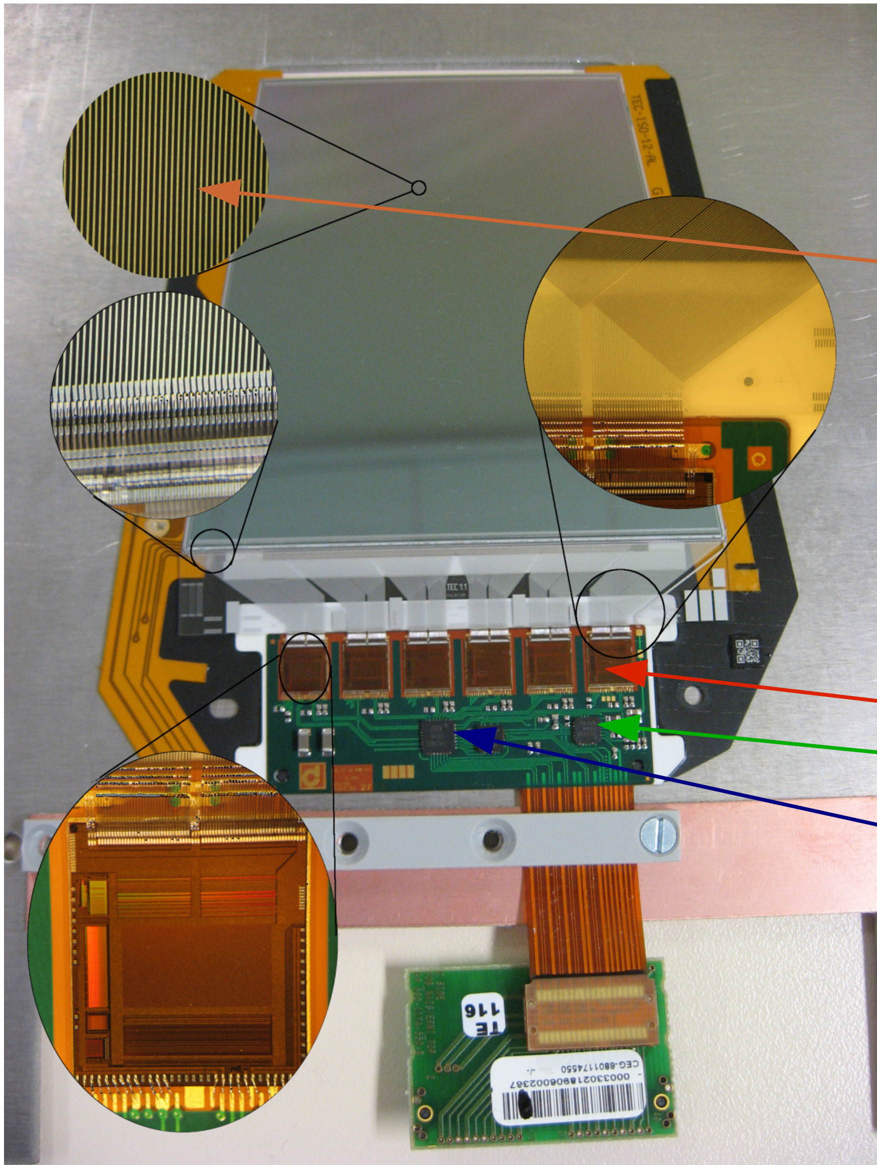
- Pixels: beam spot offset allows measurements at different radii
- Independent leakage current fits give good agreement in radial dependence
- Fitting function: a/x^b

fitted parameter	pixels (18.9 fb^{-1})	strips (4.7 fb^{-1})
a	3921 ± 5	93.23 ± 1.76
b	1.3228 ± 0.0008	1.247 ± 0.005



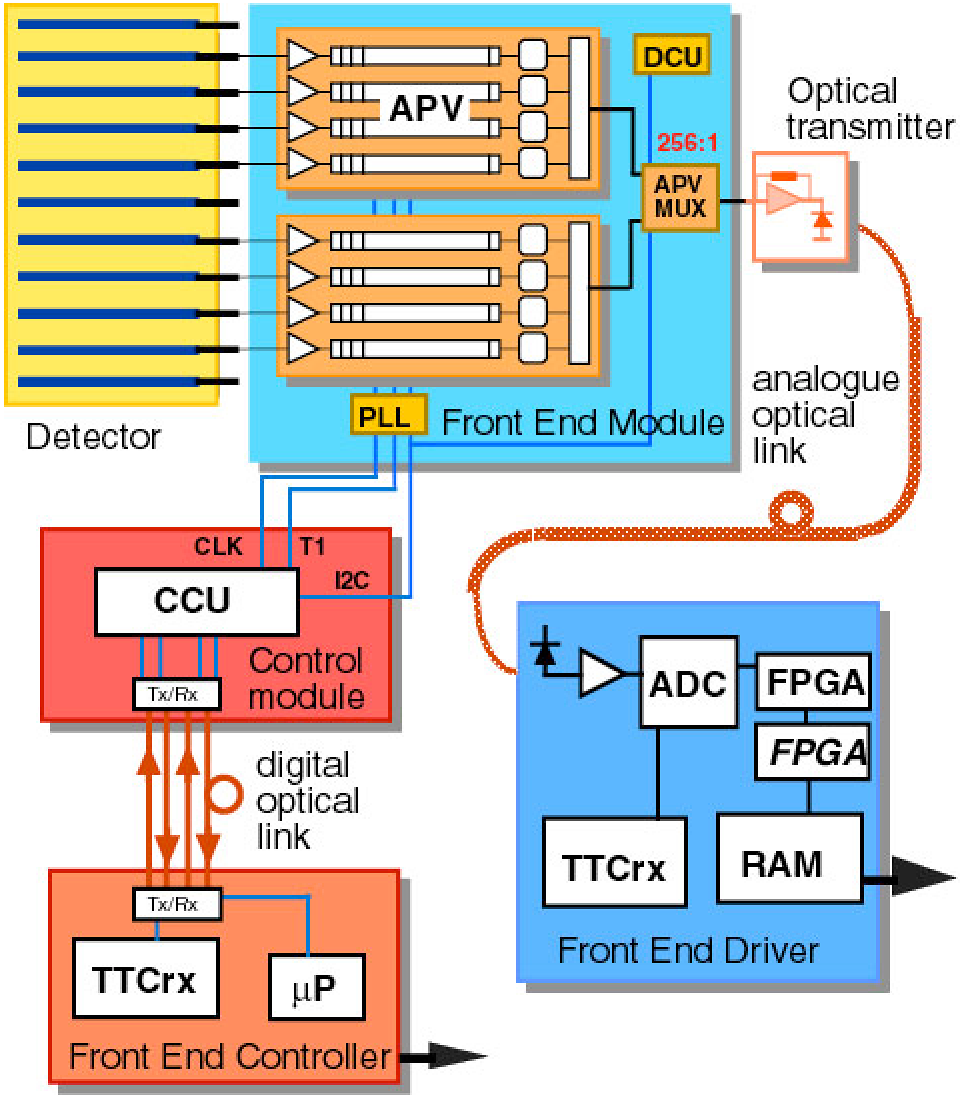


Silicon Strip Modules



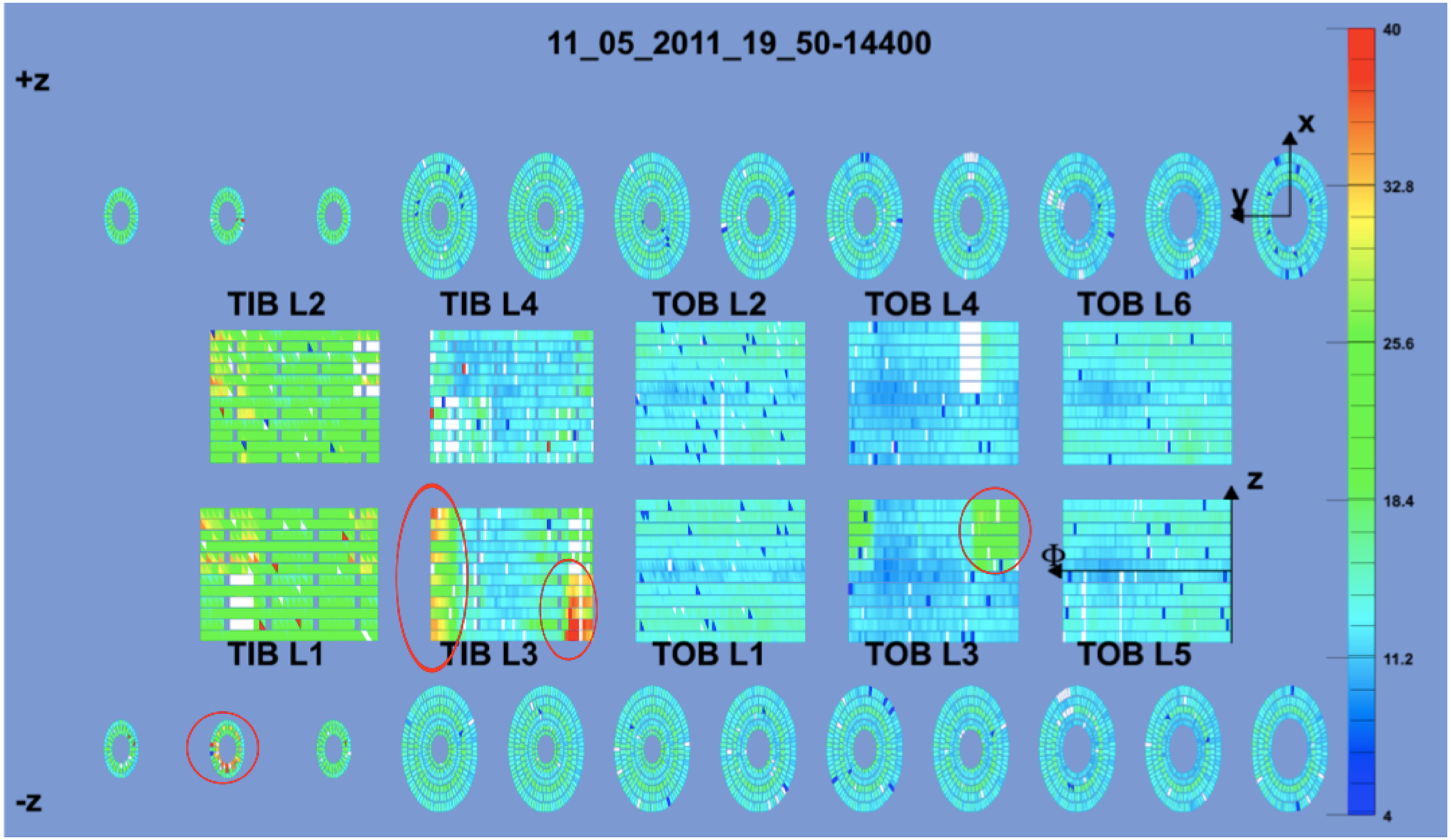
- Sensor
  - p^+ implant in n-type silicon bulk
  - 512 or 768 strips
  - strip pitch p=80-205 m.
  - w/p = 0:25 (w: p+ implant width).
  - AC-coupled readout.
- Electronics on Hybrid
  - 4 or 6 APV readout chips.
  - DCU: leakage current, temperature,.
  - Multiplexed on 2 or 3 readout lines by MUX.

Strip readout

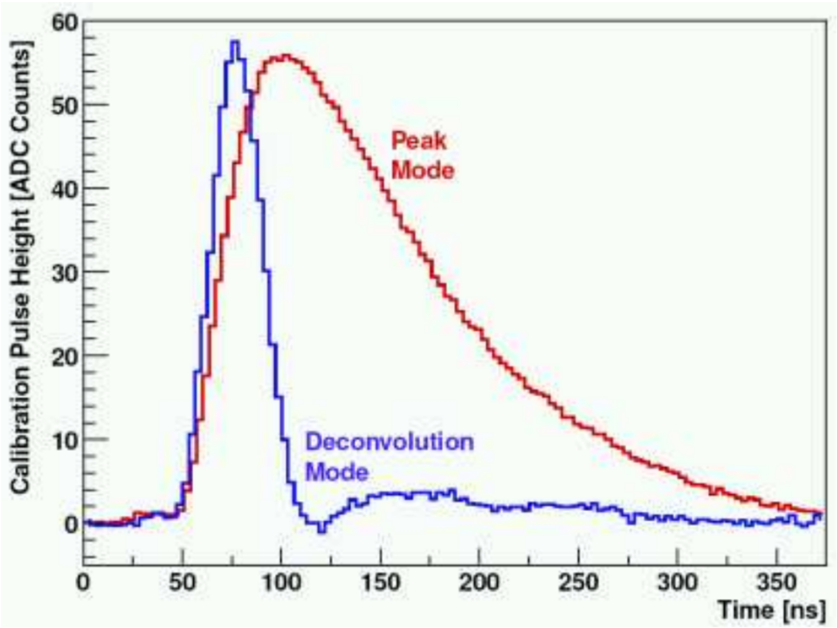


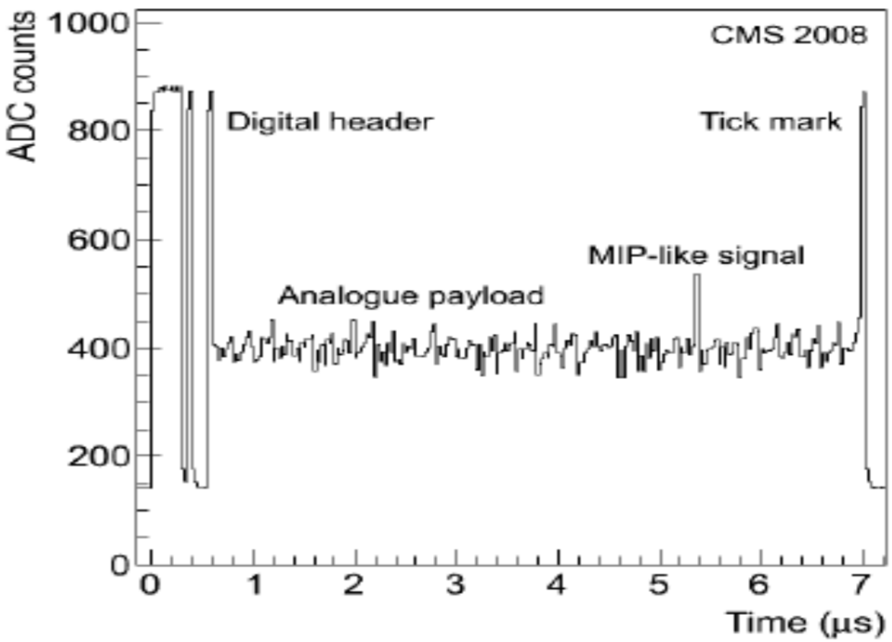
Tracker temperatures

- Pixel operates at 17˚C in 2011 and 10˚C in 2012
- Not all the strip detector regions have direct cooling



Silicon Strip Readout

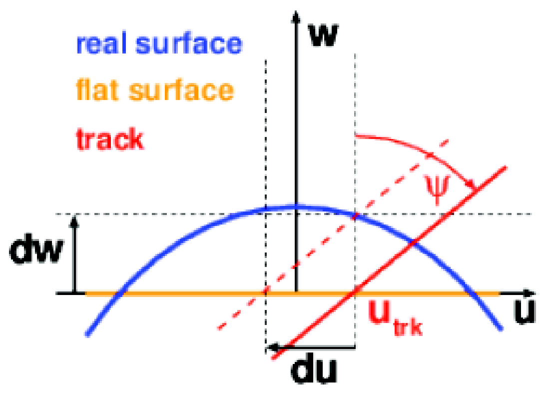


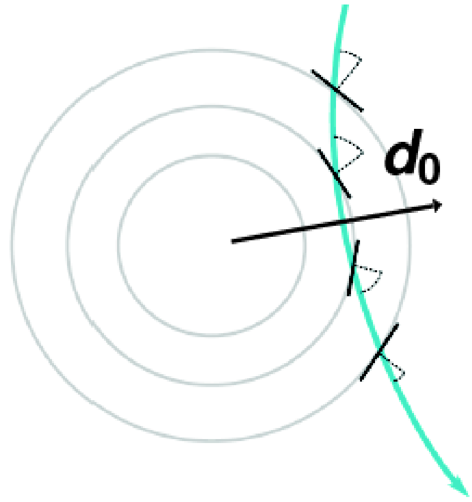


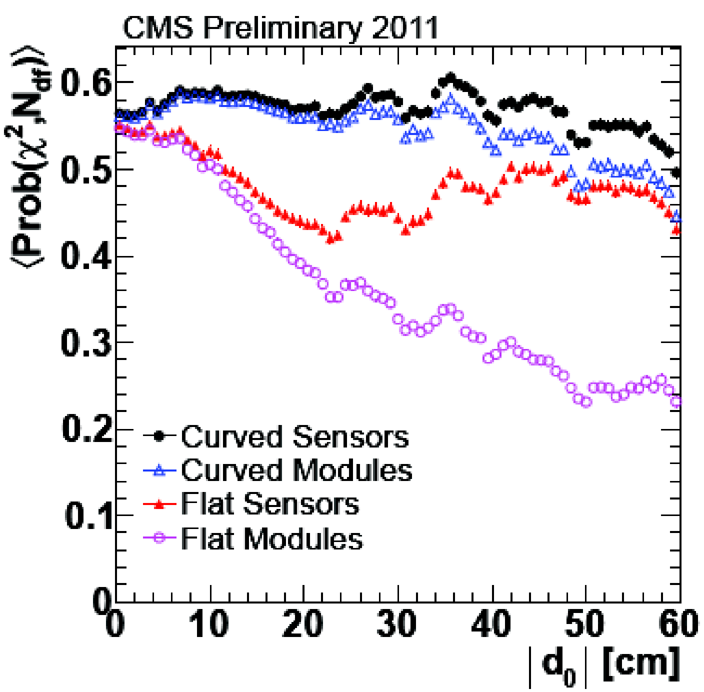
- APV Chip
  - Analog readout every 25 ns.
  - 192 cell pipeline
  - Peak mode (signal height *p*),
    - CR-RC circuit (50 ns),
    - low noise,
    - robust for time misalignment
  - Deconvolution mode,
    - signal at t is weighted mean:
      $d_t = w_3 p_{t-2} + w_2 p_{t-1} + w_1 p_t$
    - shorter signal,
    - higher noise.

- Signal Frame: 2 APVs Interleaved
  - Headers and tick marks frame
    2 x 128 analog signals
  - Send on external trigger

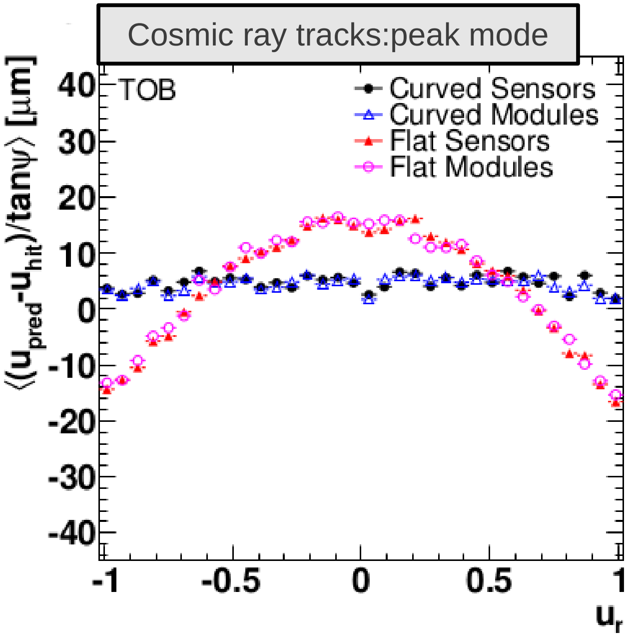
Strip Alignment : Modules with Curvatures and Kinks

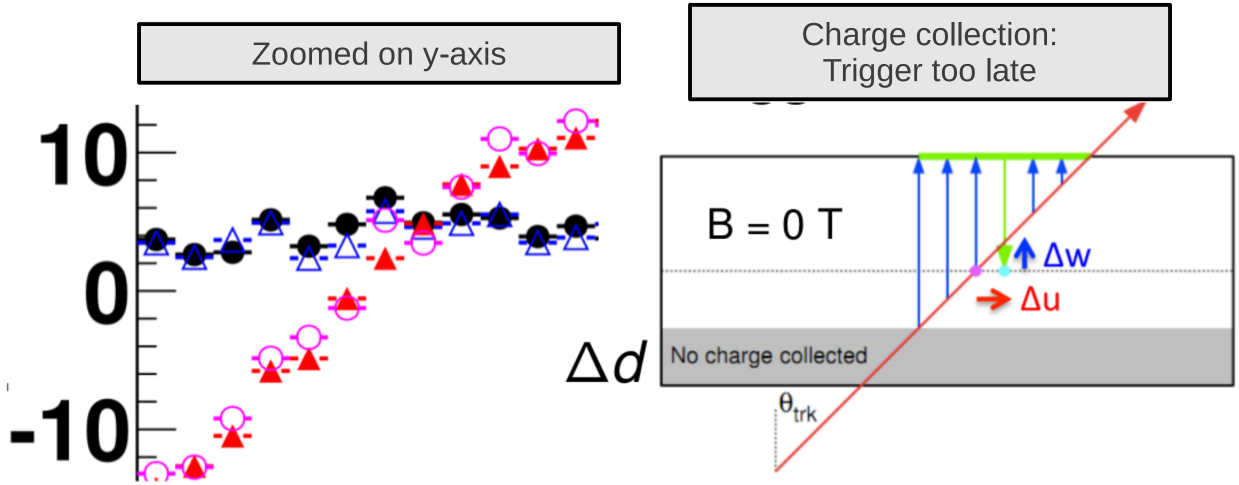






- Effect on Track Reconstruction
  - Position corrections now applied in hit reconstruction.
  - Hits of tracks with large on module surface are most affected.
  - Pixel layer 1 for forward tracks |eta| > 2 (not the topic here).
  - Cosmic ray tracks:
    - average track fit probability vs d0 now almost flat.
  - Relevance for overall tracking:
    - importance of cosmic ray tracks for alignment (weak modes).

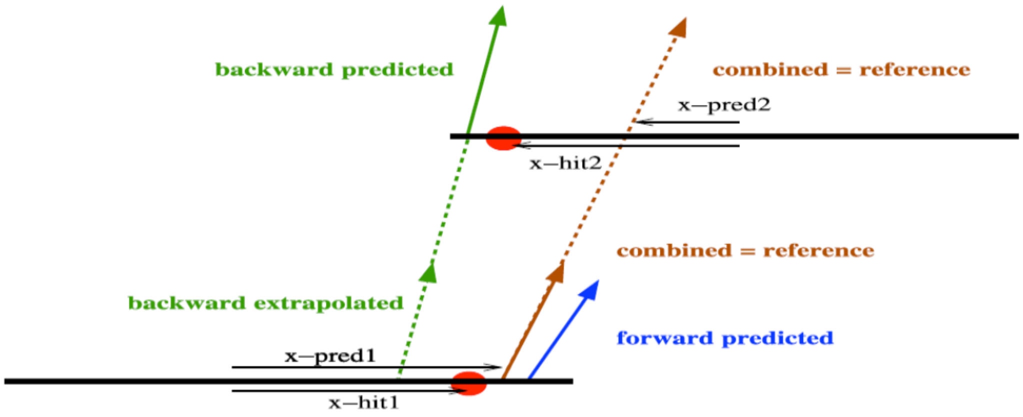


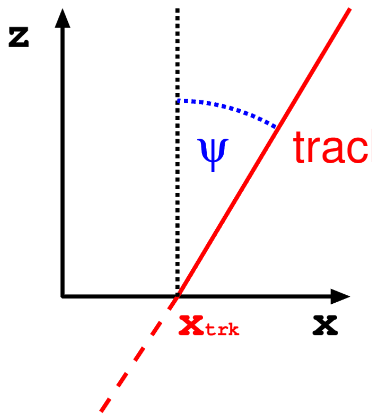


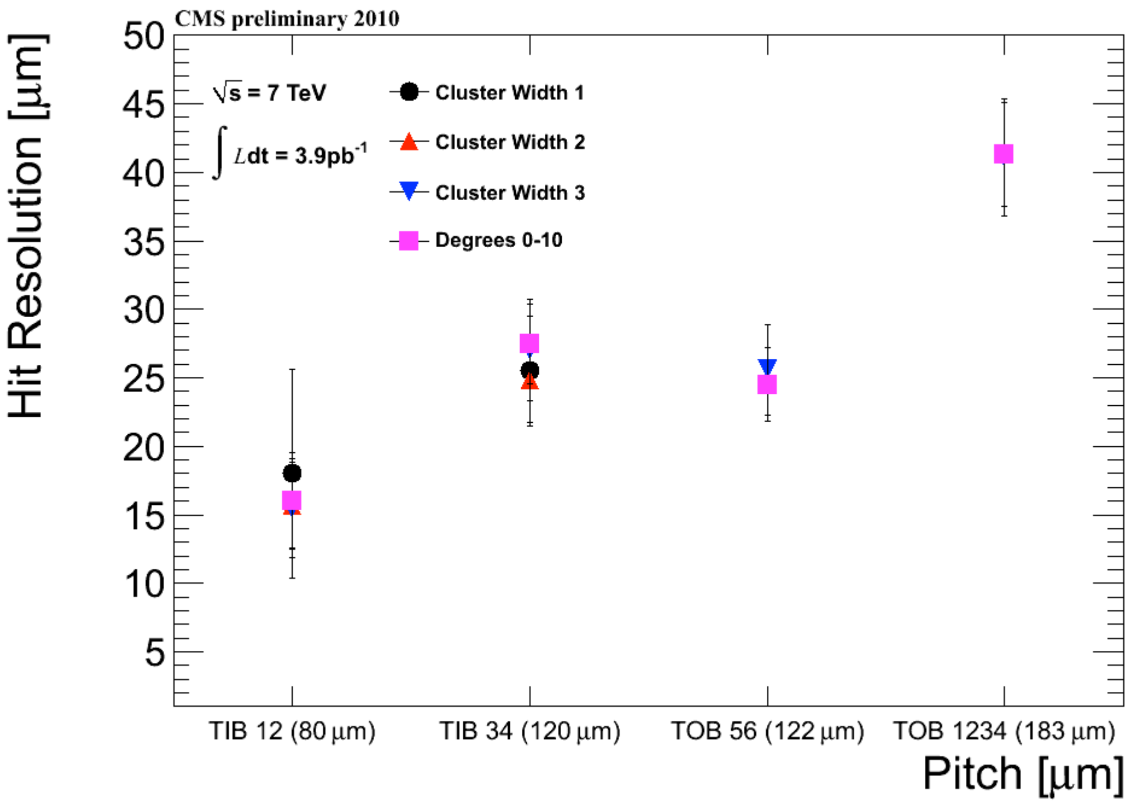
After curvature correction: ~5 μm offset in peak mode data. Why?

- If timing late: charge of sensor back-plane not collected.
  - Sensor appears thinner by Δd, mean shifted by Δw = Δd/2.
- "Back-plane" corrections for deconvolution data calibrated with 2010 data:
  Δd = 12 μm for TOB.
- Improved time alignment in 2011: 3 ± 1 ns in TOB.
- "Back-plane" correction not re-calibrated: tension peak vs deco.
- Alignment dominated by deconvolution mode data.
  - Offset remains for peak mode data.

Strip Resolution







- Using Hits in Module Overlaps
  - Track angle ψ < 10°
  - Results shown for TIB and TOB layers with pitches:
    - TIB L1+2 80 μm
    - TIB L3+4 120 μm
    - TOB L5+6 122 μm
    - TOB L1-4 183 μm
  - Values below binary resolutions.

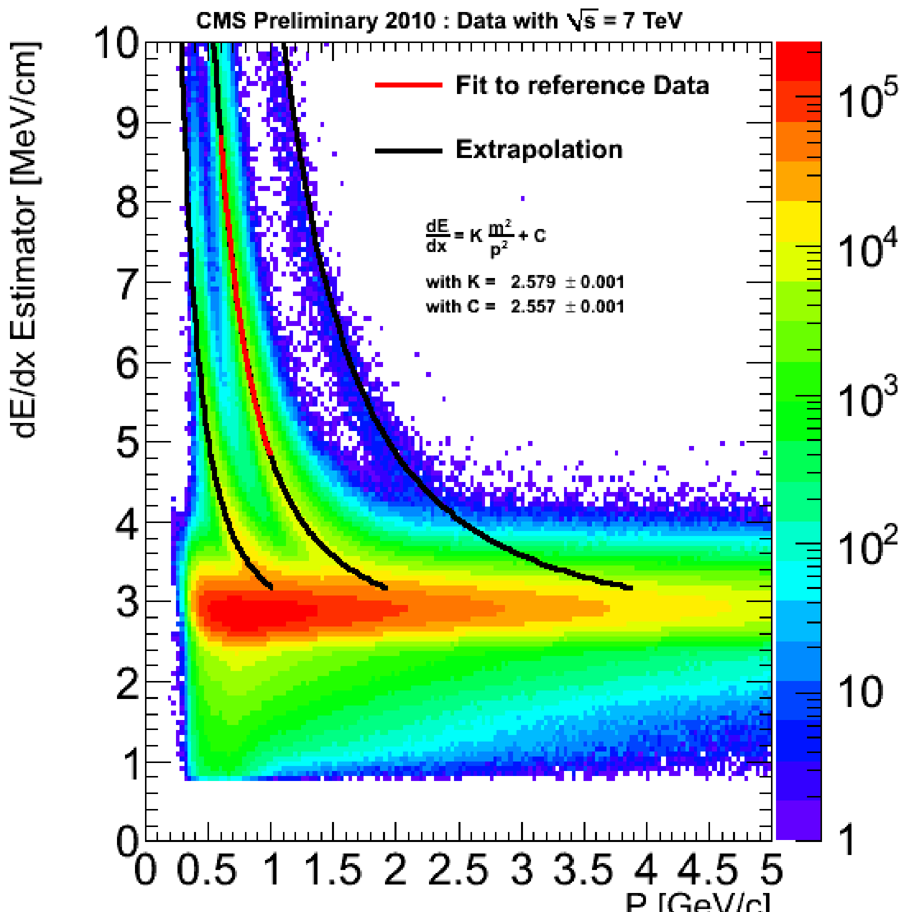
Strip dE/dx

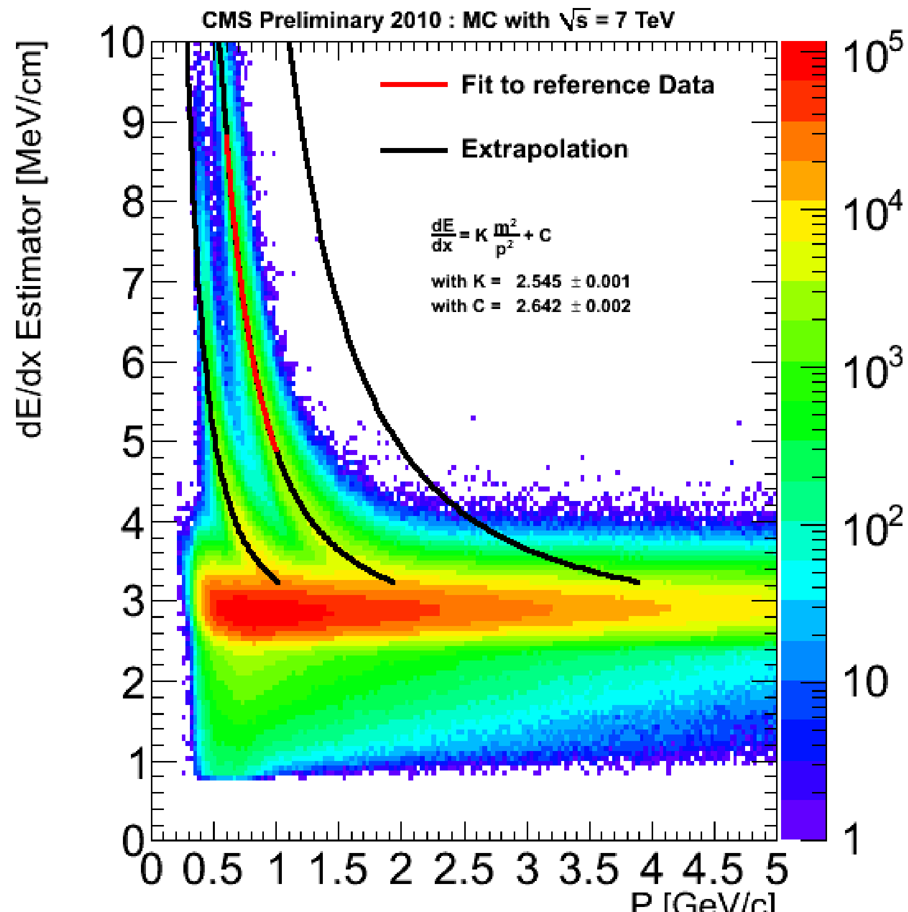
- We can determine an estimate for the most probable dE/dx value based on the measurements in the strip tracker modules traversed by a track, ie :

$$\frac{dE}{dx} = \left(\frac{1}{N} \sum_{i=1}^{N} \frac{1}{c_i^2} \right)^{-1/2}$$

Where c_i is the charge, per unit path length of silicon, of the ith hit associated to the track

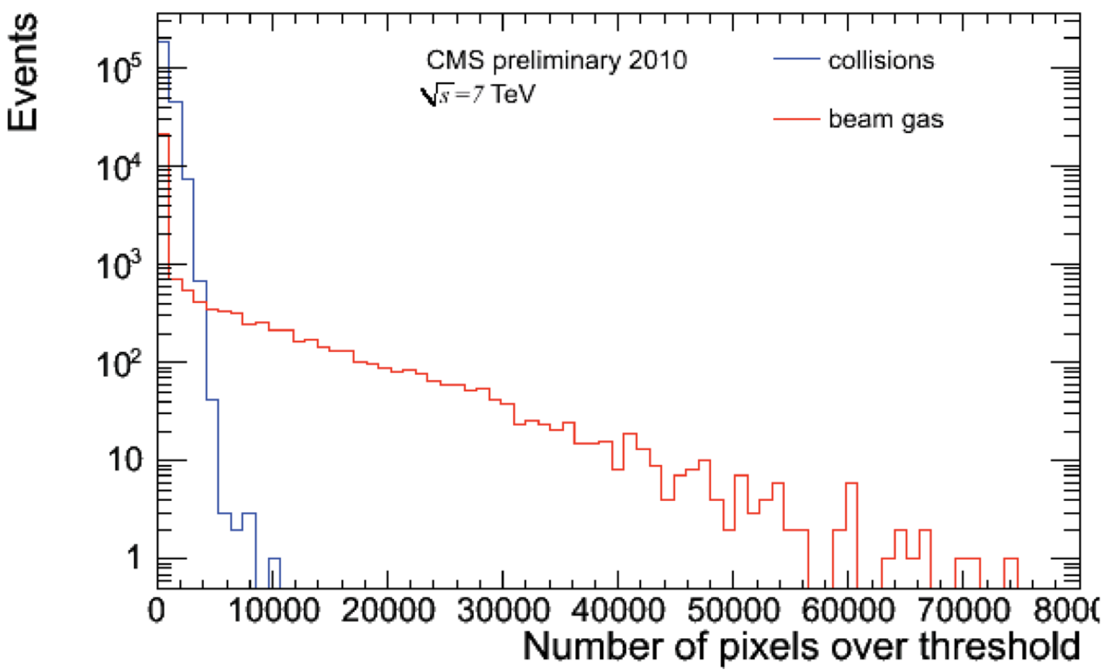
- Kaon and Proton bands are well visible in both the Data and MC.

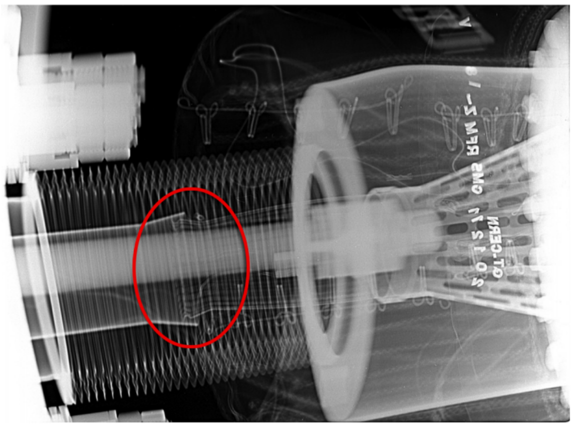




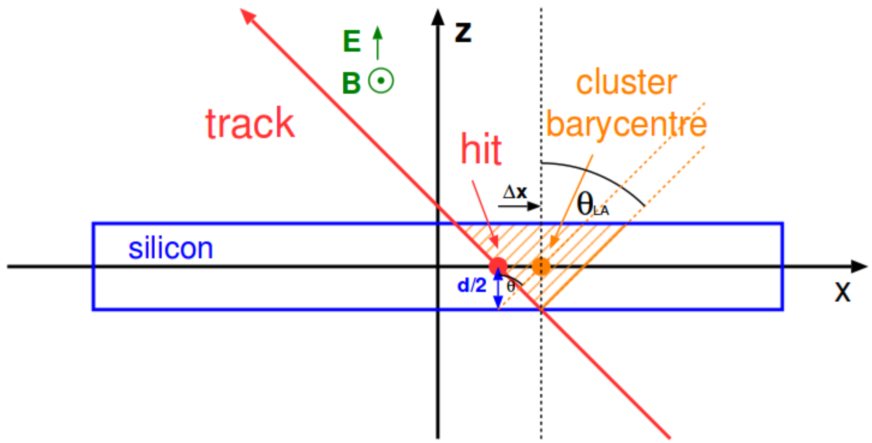
Pixel: beam gas events

- Beam-gas interactions: particles flying along z direction graze BPix modules, creating many hits
- Major issue during 2010: important source of downtime
- Solved with "busy mechanism":
  - Stop triggers until channel can catch up
  - Further optimization done on data acquisition settings and firmware to minimize dead time from mechanism
- LHC joint 18.5m from interaction point fixed during 2011-2012 shutdown
  - significant improvement





Lorentz angle determination

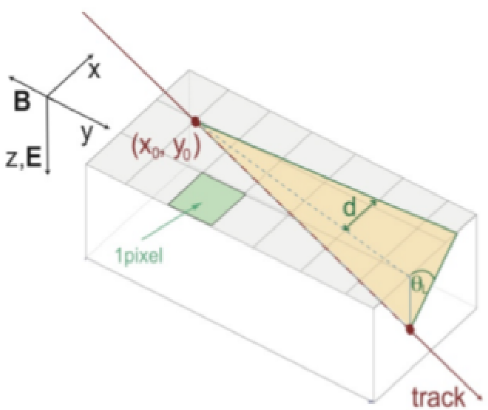


• Charge drift in B-field affects the measured hit position: $x=\tan(\theta_{LA}^{shift}).d/2$

• To correct this effect most precisely: Lorentz angle θ_{LA}^{shift} calibration integrated in MILLEPEDE II alignment procedure.
• B-on and B-off data used simultaneously in alignment to disentangle calibration and alignment effects.
• Used 60 million tracks from full 2012 data: tracks of isolated muons, Z->μμ, cosmic ray muons (B-on and B-off), low p_t, B-off, pp data from August 2012.
• Lorentz angle in pixel barrel calibrated with granularity of:
  - 24 spatial parameters (3 layers x 8 rings)
  - 65 periods in time.

LA determination: grazing angle method

- Charge carriers production depth and displacement in local x estimated from track parameters
- Using well reconstructed tracks -> path through detector well known
- Obtain the drift distance of the electrons created at certain depth
- Tracks with shallow impact (”grazing”) angle used
- Averaged over many tracks – drift distance over production depth
- Fitted over the depth of the detector excluding edges
- tan (θ_{LA}) = slope



Curvature bias investigation with $Z \rightarrow \mu\mu$ decays

- Distortions of the tracker geometry can lead to a bias in the reconstructed track curvature $\kappa\mu \pm 1/p_T$
- Investigated using the reconstructed $Z \rightarrow \mu\mu$ mass, as a function of the muon direction and separating μ+ and μ- (since curvature bias has opposite effect on their p_T)
- Invariant mass distribution is fitted to a Breit-Wigner convoluted with a Crystal ball function (i.e. taking into account the finite track resolution and the radiative tail) for the signal plus an exponential background.

 (Fit range is 75–105 GeV/c^2, Z^0 width fixed to PDG value of 2.495 GeV/c^2.)