Operation, Calibration and Performance of the CMS Silicon Tracker

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On behalf of the CMS collaboration

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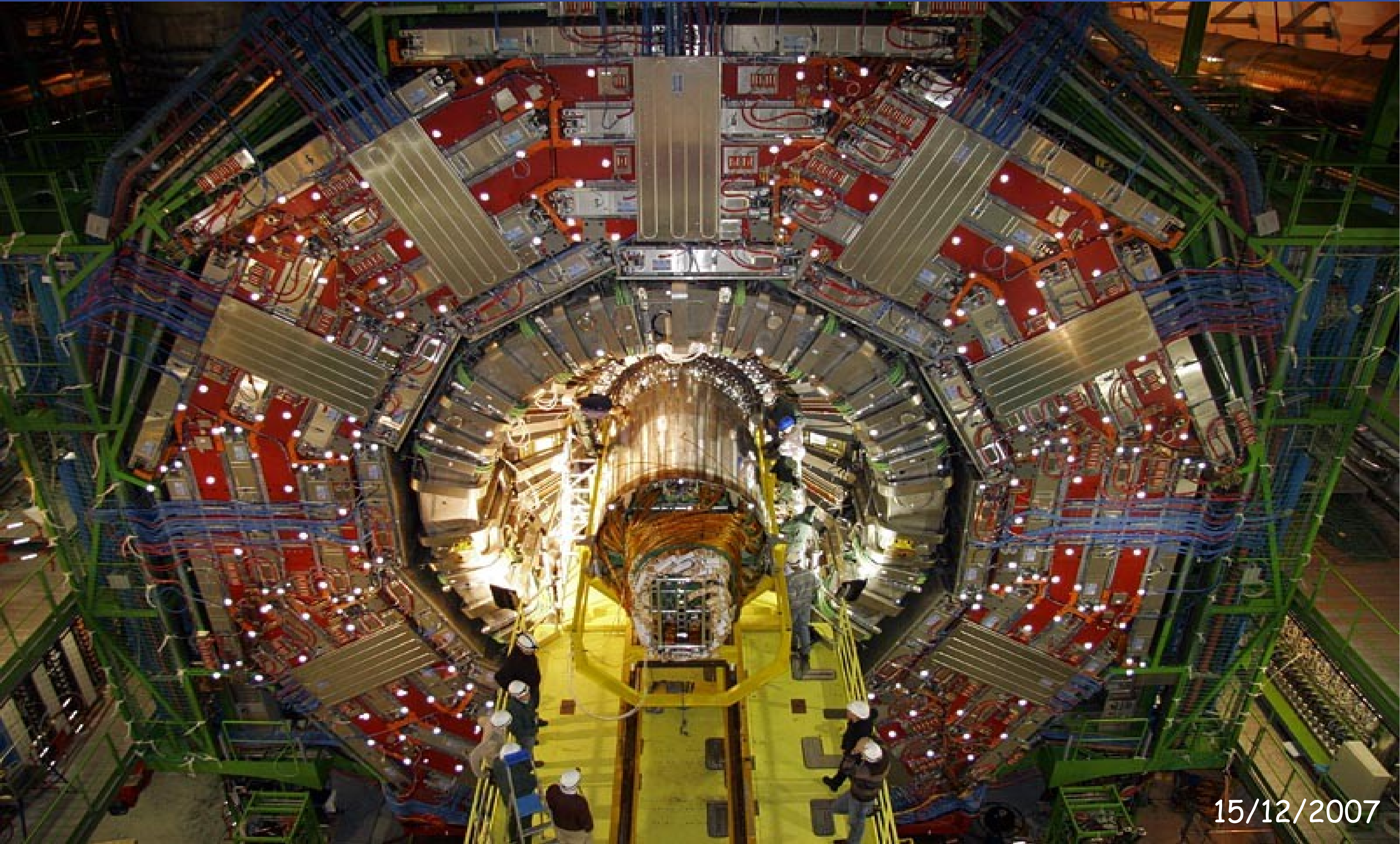
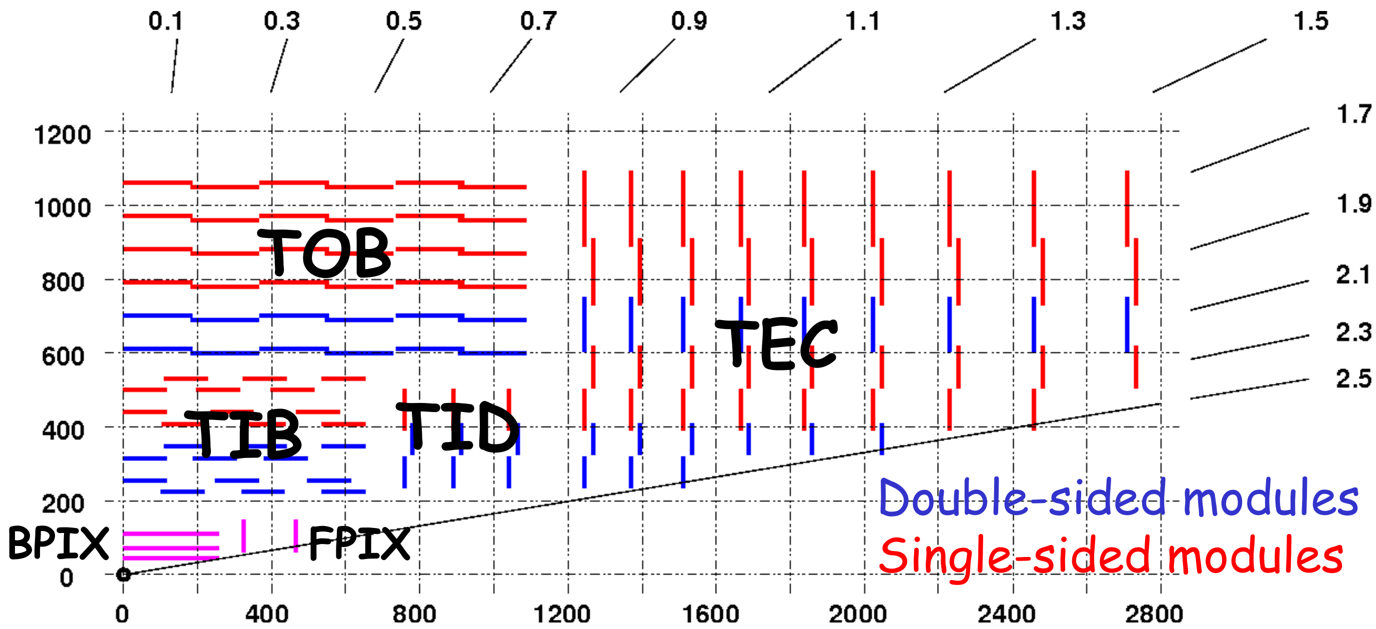
The CMS Tracker



The CMS Tracker

The largest silicon tracking detector ever built!

- must provide low occupancy for LHC high luminosity
- high-precision tracking for heavy flavour identification
- coverage up to $|\eta| < 2.5$



Strips

- 9.3M channels
- ~ 200 m^2 sensor area
- 10 barrel layers
- 9 (+3) endcap disks

Pixels

- 66M channels
- ~ 1.1 m^2 sensor area
- 3 barrel layers
- 2 endcap disks
- innermost layer at r = 4.3 cm

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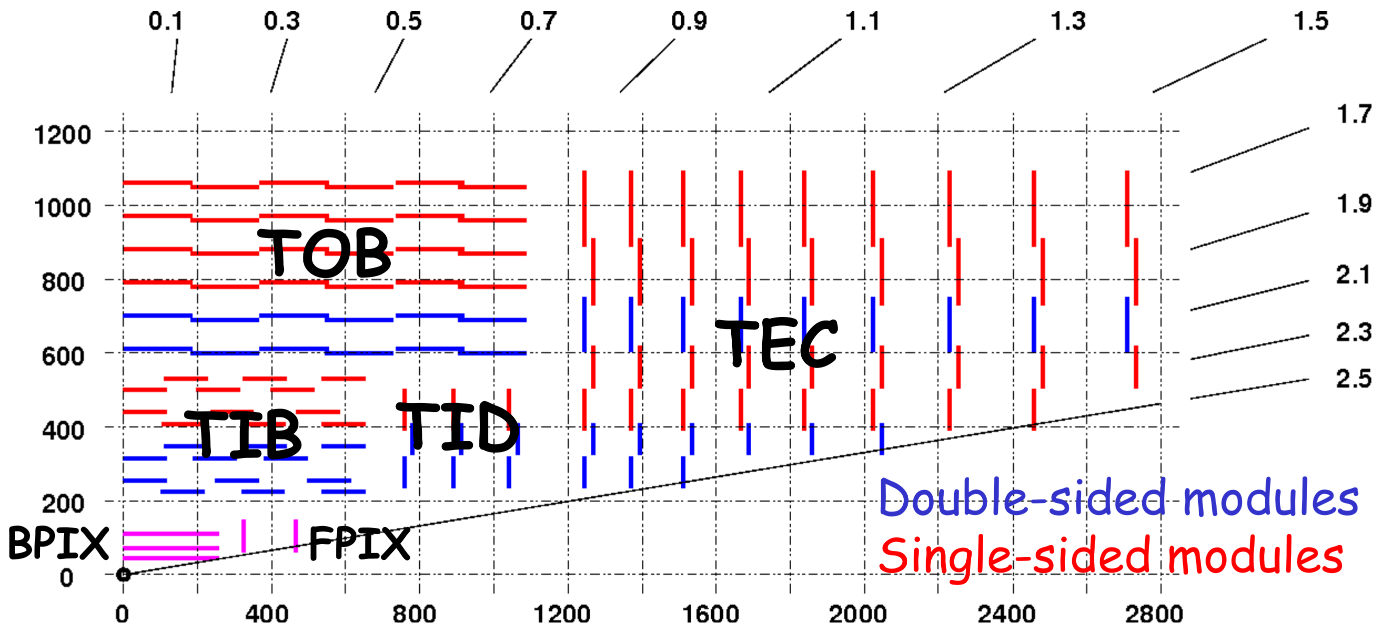

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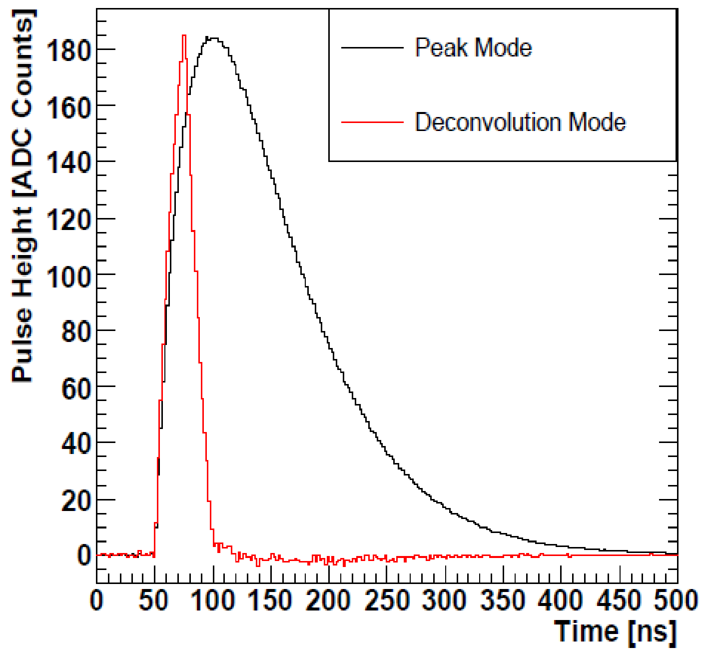
Operational fractions
strips: 98.1%
pixels: 98.3%

Strips DAQ in a nutshell

- readout chips can operate in peak and deconvolution mode
  - **peak mode** (used in 2009): 1 sample readout; robust to time misalignment; low noise
  - **deconvolution** (default): 1 readout of 3 weighted samples; indispensable for 25ns bunch spacing in LHC; needs pulse shape tuning; higher noise
- analog readout over optical links for each L1 trigger
- off-detector digitization and zero suppression



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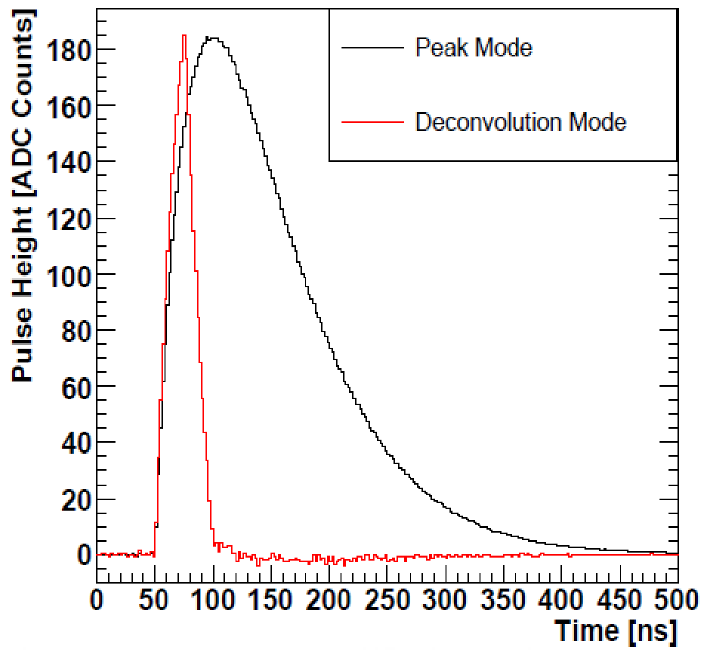
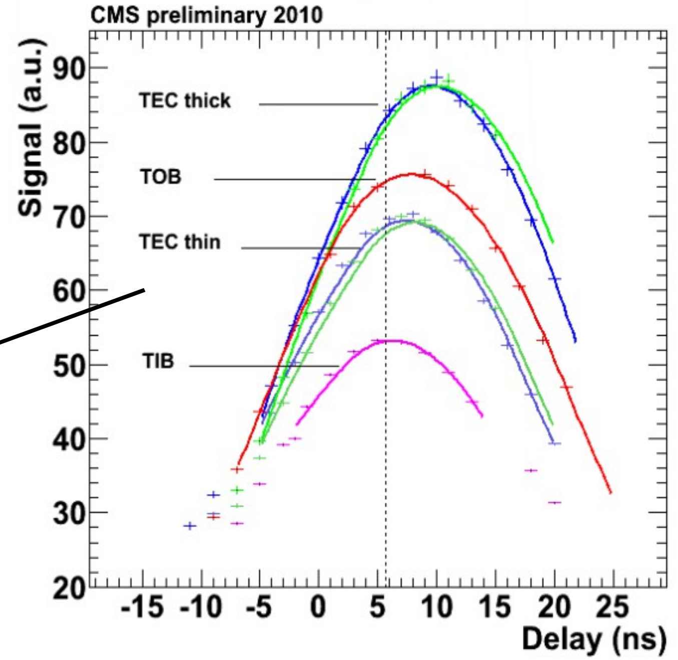


Strip commissioning

- tune lasers for optical readout links
- optimize readout chip (pulse shape, analog baseline)
- noise and pedestal measurement strip-by-strip
- synchronization on module-level
  - ➔ scanning signal peak with collisions allows to correct synchronization down to < 1ns



Pixel DAQ in a nutshell

- zero suppression in readout chip; adjustable threshold per pixel
- analog readout over optical links for each L1 trigger
- off-detector digitization

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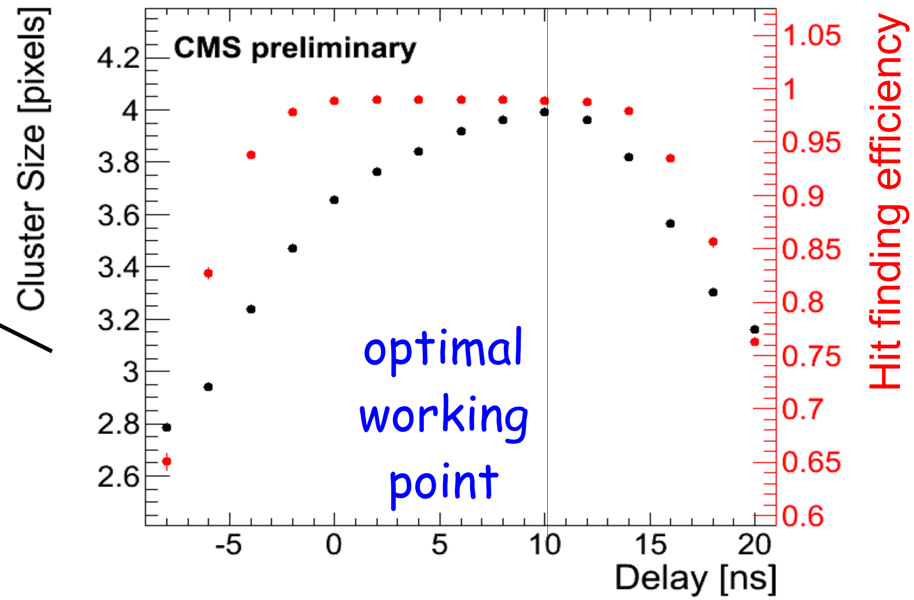
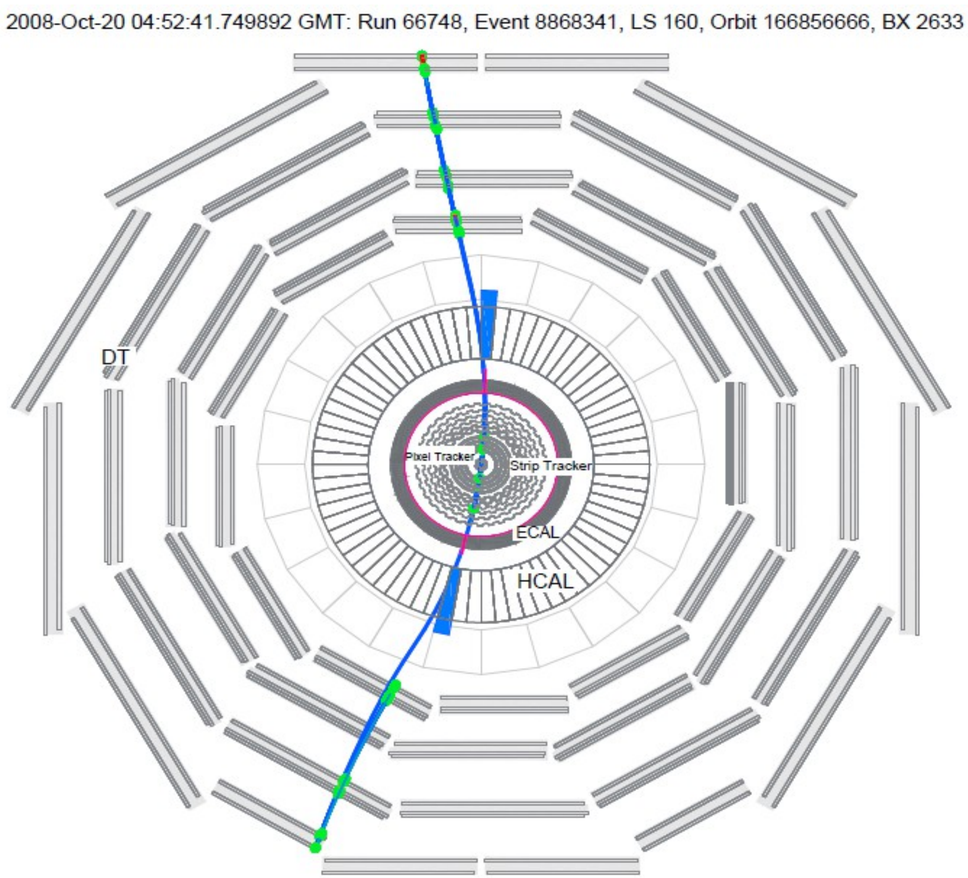
Pixel commissioning

- calibrate readout chain: timing, output
  gain, laser settings for optical readout links
- response calibration pixel-by-pixel
- zero suppression threshold optimization
- fine delay timing scan with collisions
  - maximize efficiency and cluster size



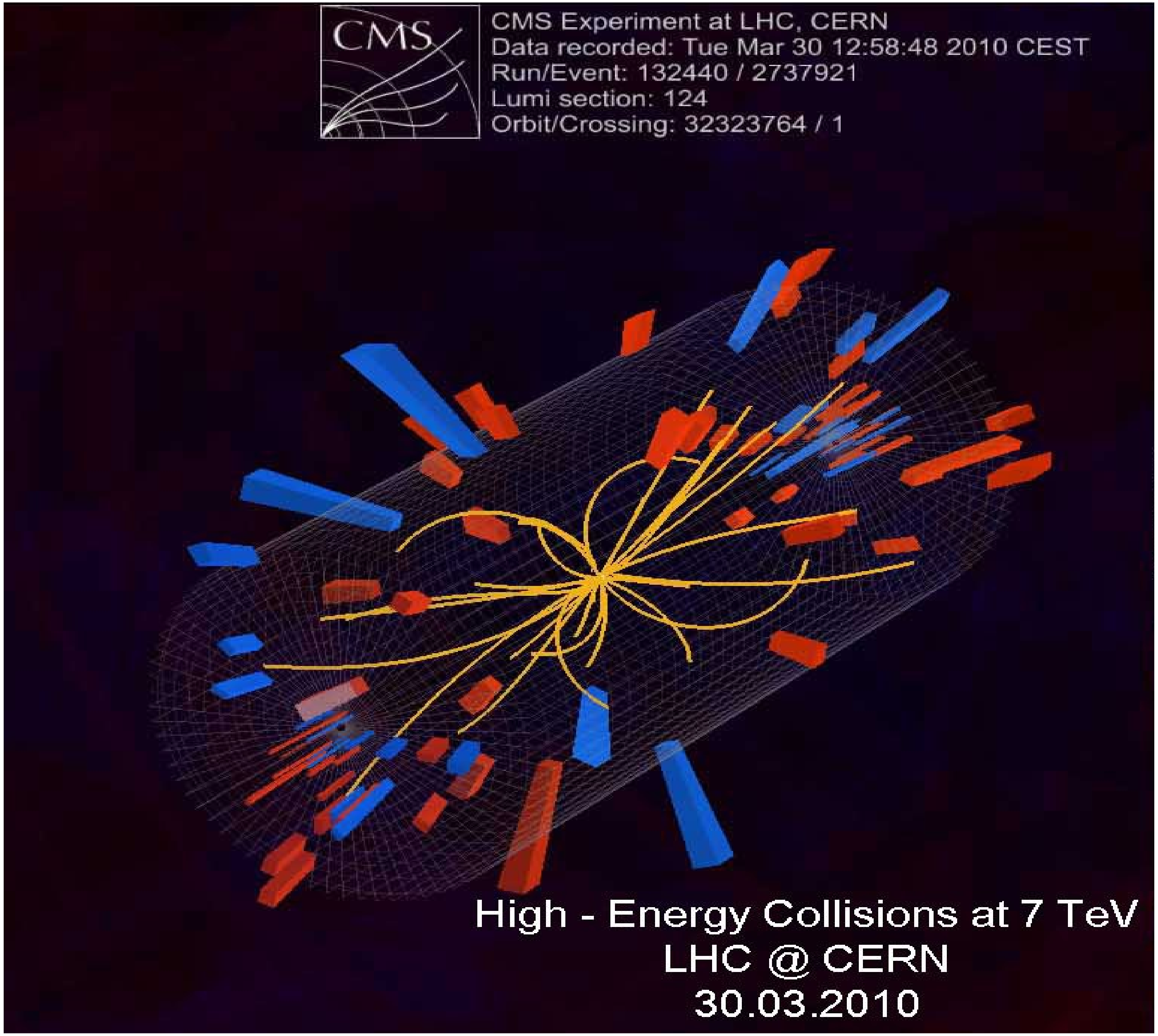
Preparing for collisions: Cosmic Run At Four Tesla

- CMS registered hundreds of millions of cosmic rays in two periods in 2008 and 2009
- these cosmics were used by the tracker for a multitude of calibrations
  - adjust detector timing
  - operate strips in deconvolution mode for extended period
  - measure hit efficiencies
  - align the tracker as good as possible with cosmics
  - measure Lorentz angle
  - test the tracking algorithms



- this allowed the tracker to be ready for collisions with a remarkably well prepared detector!

23/11/2009 – 30/3/2010: First Collisions!

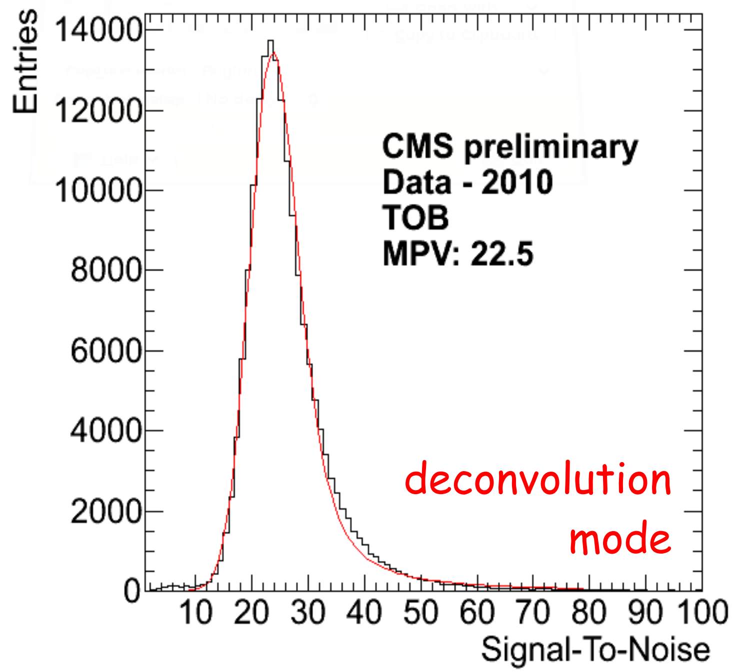


Charge Collection

Signal-to-noise ratio in strips

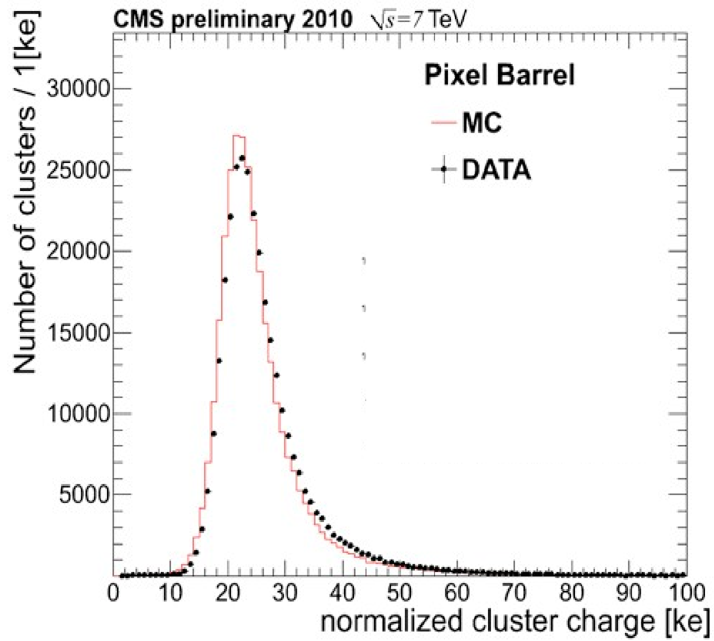
- from on-track clusters
- agrees well with expectation
  - thick sensors (outer barrel) collect more signal than thin sensors (inner barrel and disks)
  - more noise with increasing strip length
  - deconvolution readout (default) has higher noise

	TIB	TID	TOB	TEC thin	TEC thick
900GeV, peak	27.4	26.7	34.1	28.8	35.7
7TeV, deconvolution	19.4	18.5	22.5	19.2	23.7



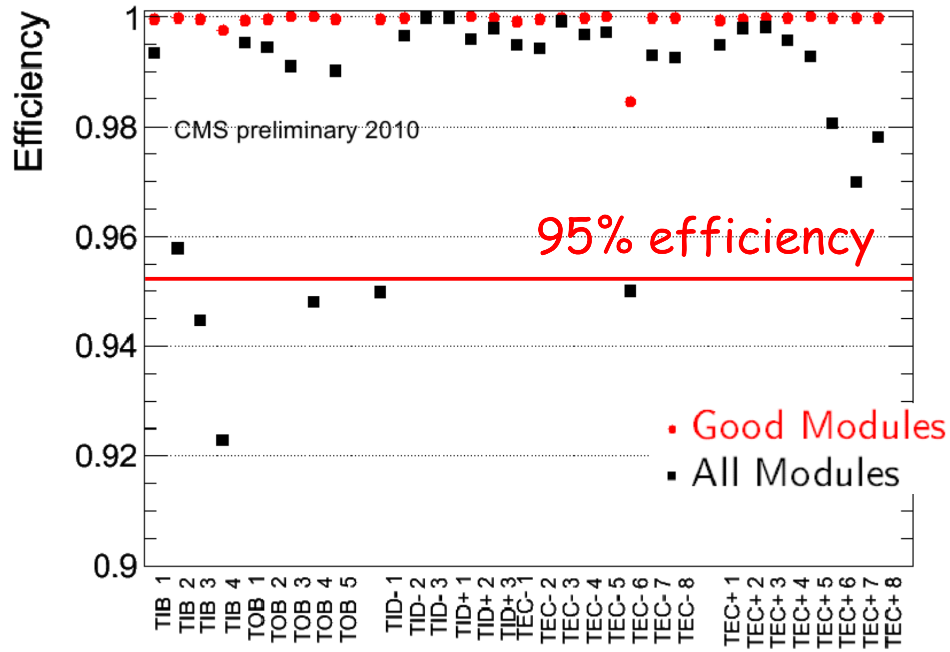
Pixel charge

- measured from hits on good tracks
- scaled by track path length and sensor thickness
- good overall data-MC agreement in both barrel and endcaps validates the readout chain calibration



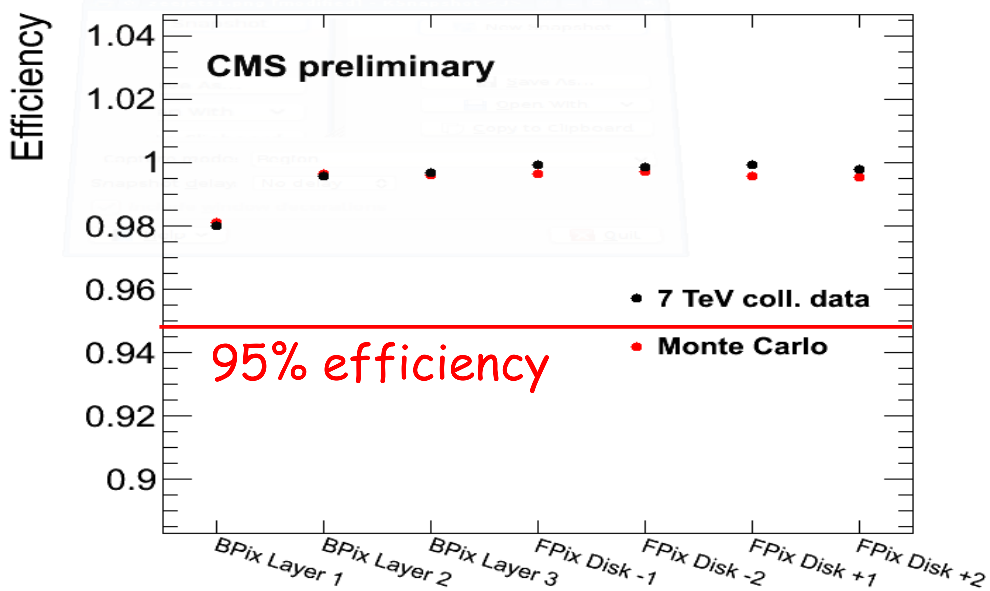
Strip hit reconstruction efficiency

- module-by-module efficiency determination
- allowed to spot and fix several issues
  - ➔ remaining inefficiencies being followed up
- very high efficiency 99.9%
  when excluding known problems



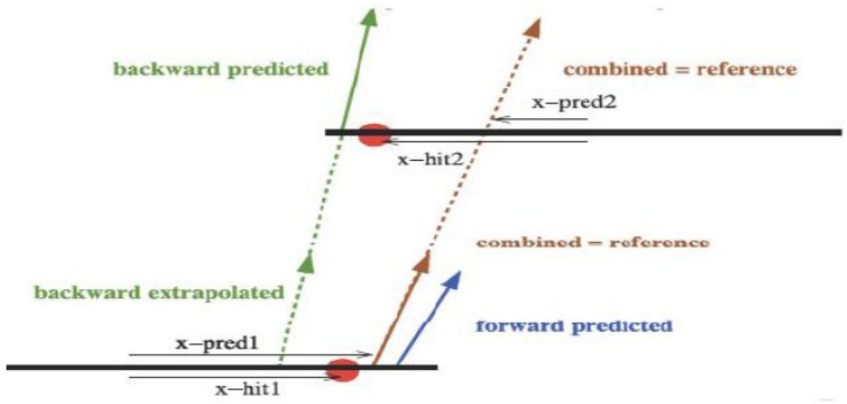
Pixel hit reconstruction efficiency

- look at hits on tracks seeded from the pixels
- very high efficiency > 99%
  - ➔ layer 1 efficiency underestimated by ~1.5% due to secondaries originating outside layer 1
  - ➔ not an inefficiency and well modeled



Strip & pixel hit resolution

- use hits in overlapping modules in barrel
- from residual of double difference of hit and track position
  - ~insensitive to misalignment
  - minimizes multiple scattering
  - as good as no effect from track extrapolation



- strips: measured in cosmics
  - agreement with simulation
  - $\sigma \sim 17$ μm in inner layers

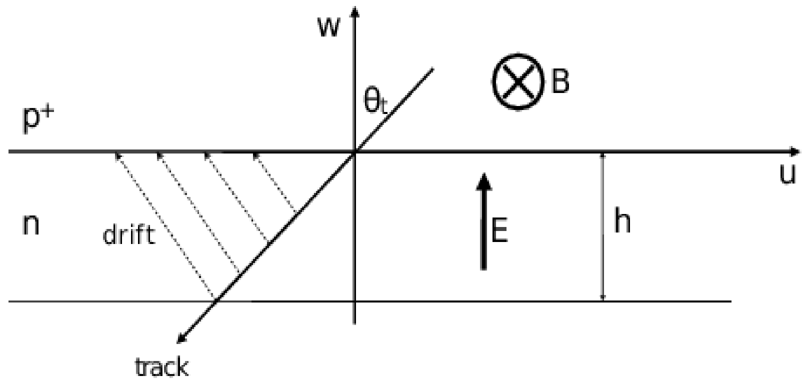
Sensor [μm]	Pitch [μm]	Resolution [μm]	Track angle $0° - 10°$
TIB 1-2	80	Measurement	17.2 ± 1.9
		MC Prediction	16.6 ± 0.5
TIB 3-4	120	Measurement	27.7 ± 3.6
		MC Prediction	26.8 ± 0.7
TOB 1-4	183	Measurement	39.6 ± 5.7
		MC Prediction	39.4 ± 1.3
TOB 5-6	122	Measurement	23.2 ± 3.6
		MC Prediction	23.8 ± 0.9

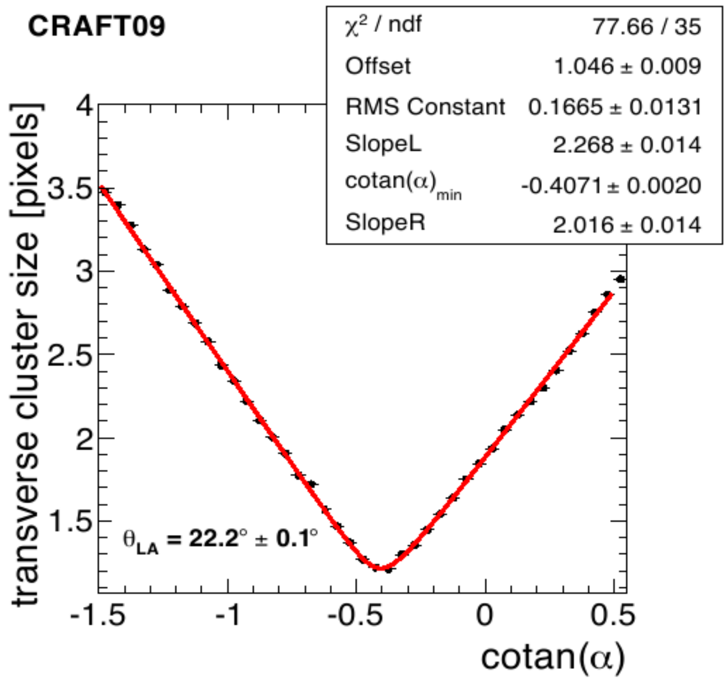
- pixels: from collisions
  - good agreement with simulation
  - $\sigma_x = 12.7 \pm 2.3$ μm (MC: 14.1 ± 0.5 μm)
  - $\sigma_y = 28.2 \pm 1.9$ μm (MC: 24.1 ± 0.5 μm)

Lorentz Angle

Lorentz Angle θ_l for pixels and strips

- Lorentz force on drifting charges
  - maximal in barrel: B perpendicular to E
  - important effect on cluster position estimates
  - direct impact on alignment
- $\tan(\theta_l)$ measured with cosmics from minimum of cluster width versus incident track angle
  - BPIX: 0.409 ± 0.001 (stat) ; MC: 0.407 ± 0.001
  - FPIX: 0.081 ± 0.005 (stat) ; MC: 0.080 ± 0.004
  - TIB: 0.07 ± 0.02 (stat)
  - TOB: 0.09 ± 0.01 (stat)
- θ_l correction for strips in deconvolution mode
  - fraction of the charge does not reach strips in time for readout
  - reconstructed hit position is biased
  - correction validated with alignment and used in reconstruction
- verification with collisions
  - same result in BPIX with cluster width method
  - cross check with new "grazing angle" method: $\tan(\theta_l)$ = 0.399 ± 0.001 (stat)

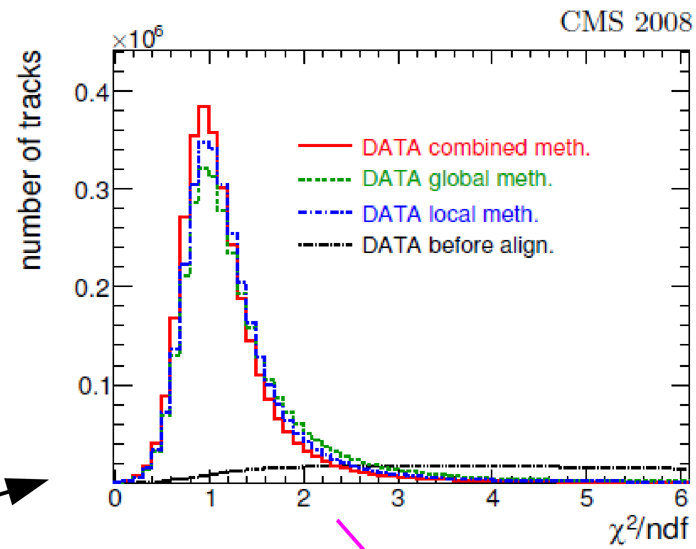




Alignment

Track-based alignment algorithms

- global method "Millipede II"
  - ➔ real module positions from residual minimization
  - ➔ matrix size reduction without loss of correlations or precision -> O(10^5) global parameters
  - ➔ only a few iterations necessary
- local method "Hit and Impact Point (HIP)"
  - ➔ local solution for each module, so no correlations
  - ➔ large number of iterations for large misalignment
- final results from running both in sequence
- first alignment campaign with cosmics
  - ➔ tracks mostly vertical, best results in barrel
  - ➔ results already close to ideal geometry
- alignment update with collisions
  - ➔ using high-quality tracks from minimum bias collisions
  - ➔ further improvement, most pronounced in forward region



input to MC

Subdetector	Data 7TeV [µm]	MC startup [µm]	MC no misal. [µm]
Pixel Barrel u	1.6	3.1	0.9
Pixel Barrel v	5.5	8.9	1.8
Pixel Forward u	5.7	10.7	2.5
Pixel Forward v	7.3	14.4	6.1
TIB	5.1	10.1	3.2
TOB	7.5	11.1	7.5
TID	4	10.4	2.4
TEC	10.1	22.1	2.9

RMS of median of residuals

Alignment outlook

- inclusion of beam halo, isolated muons, laser alignment data
- use mass constraints from resonances

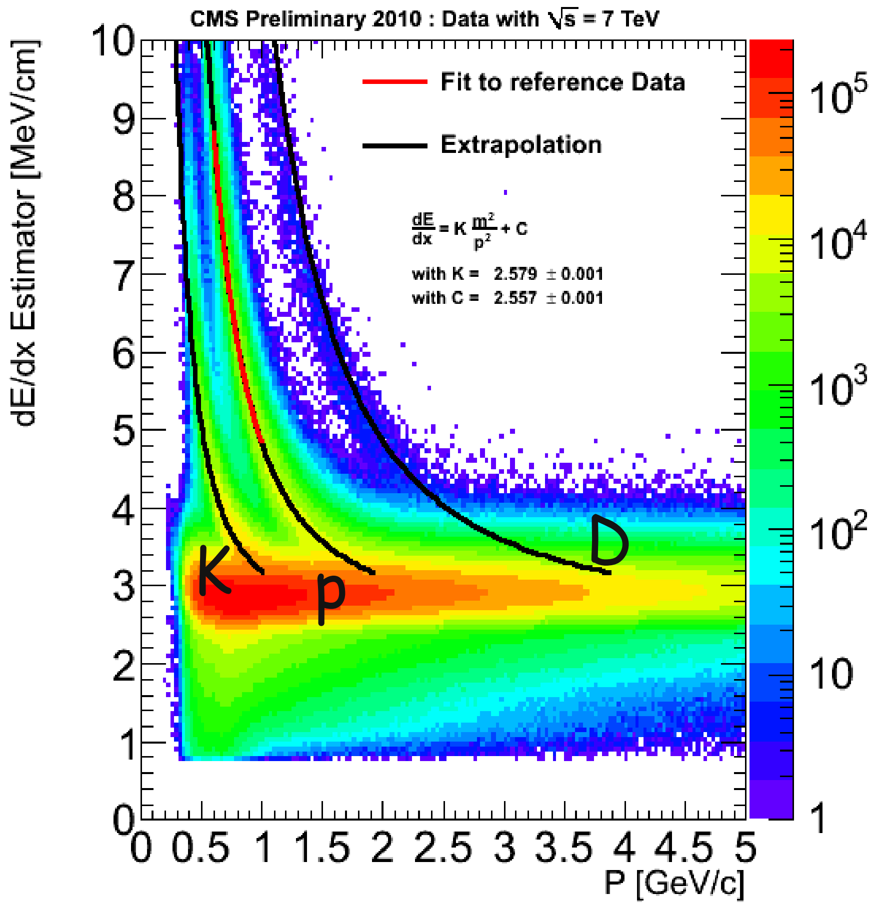
See poster by Jula Draeger

The Alignment of the CMS Silicon Tracker

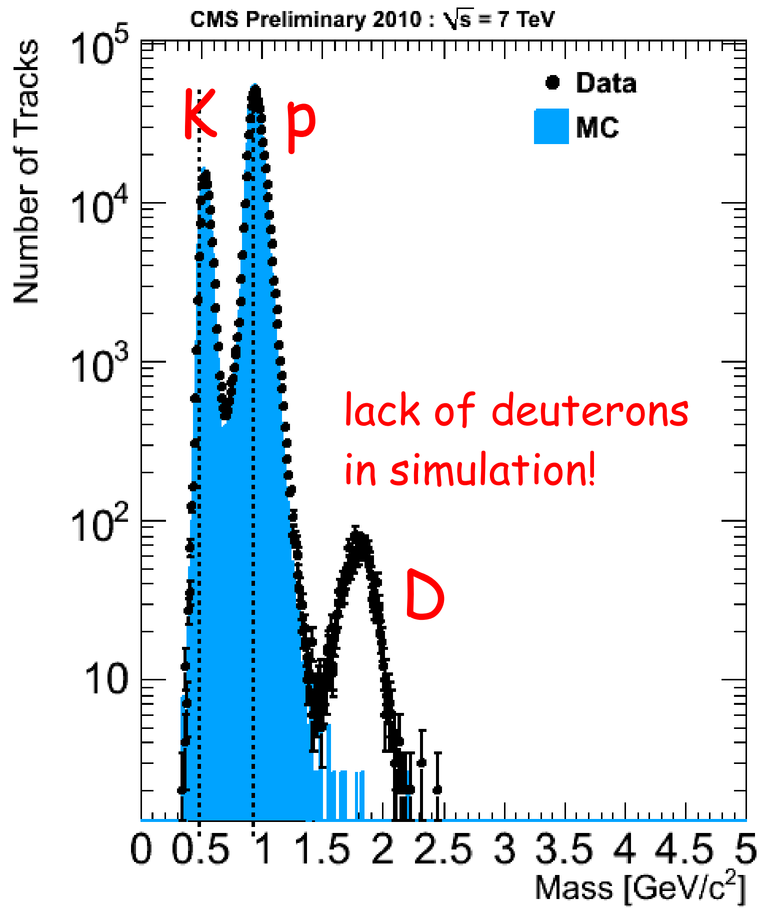
Particle identification using the strips

- all strip readout channels were calibrated to uniform energy response using particles

energy loss estimation dE/dx allows particle identification with the strip tracker



mass estimation from good tracks with dE/dx > 5MeV/cm



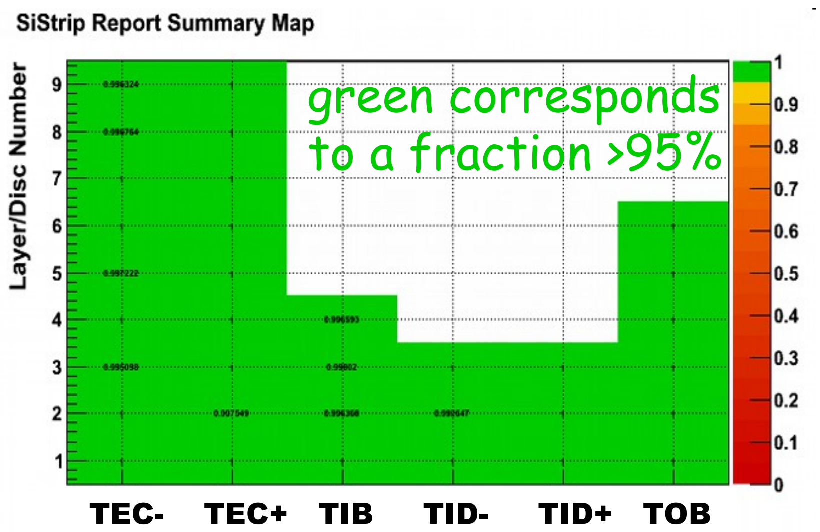
Tracker Online & Offline Operations

Prompt Calibration

- several measurements have become calibration tasks, run on data straight from CMS
  - → channel status, gain or response calibration, Lorentz angle, hit efficiency
- prompt reconstruction is delayed to be able to use these prompt calibration constants

Monitoring

- efficient recording of excellent data with the tracker possible due to fast-feedback and long-term monitoring of detector, DAQ and data quality
- essential tool: Data Quality Monitoring (DQM)
  - → monitors the detector and reconstruction performance online for prompt feedback
  - → used offline to look into details and for data certification
  - → summary histograms, automated quality tests
  - → integrates in central CMS DQM
- some new features still being developed
  - → spy channel: read out raw, unprocessed data of a subset of events during normal data taking
  - → goldmine of possibilities for monitoring and debugging



Conclusions

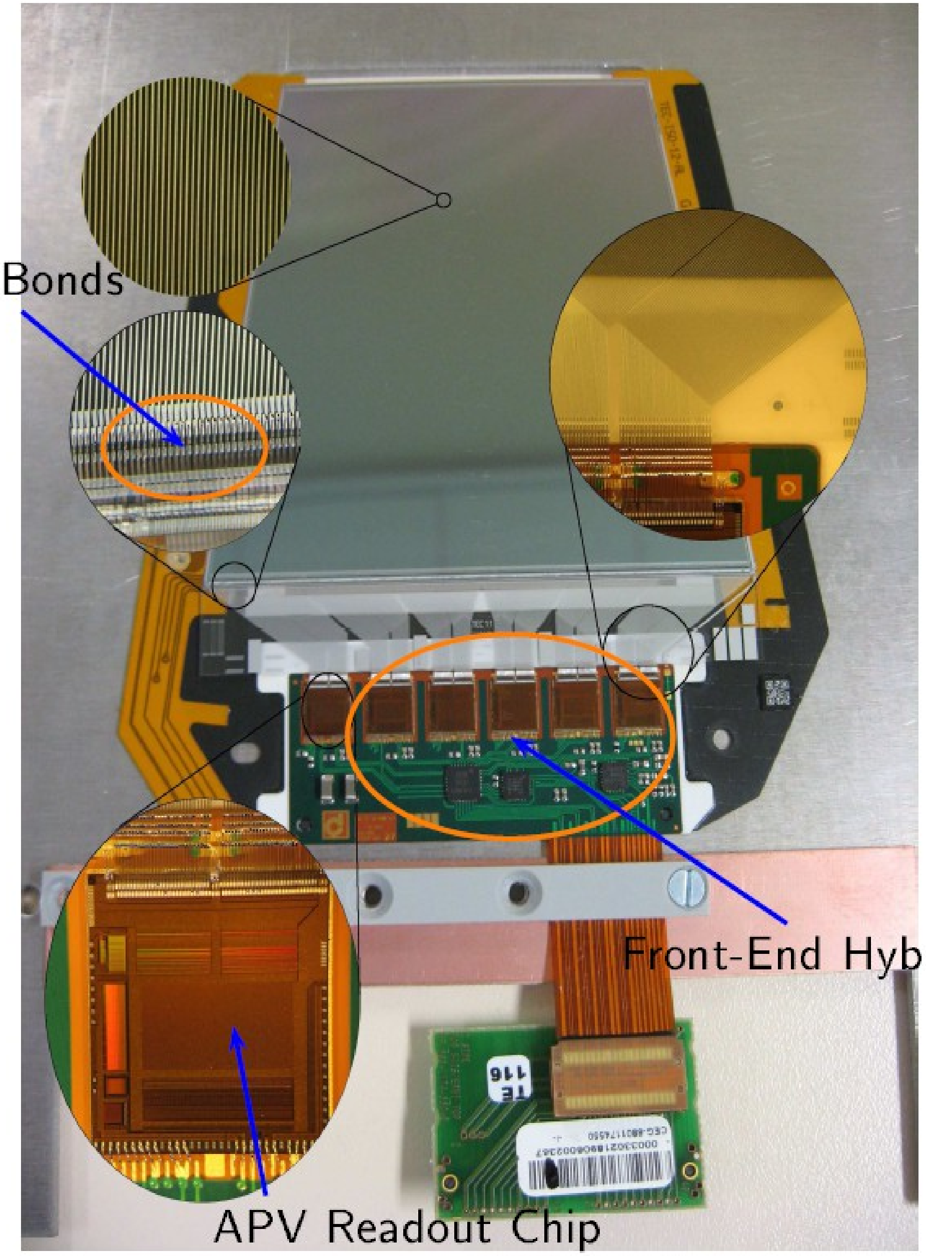
- the CMS tracker is the largest silicon tracking detector ever
  - > 98% operational detector fraction
- commissioning, calibration and alignment
  - profited fully from cosmic ray campaigns in 2008-2009
  - this lead to remarkably well understood detectors, even before the first LHC collisions
- collisions at 900GeV, 2.36TeV and 7TeV
  - collision data used to further improve calibrations and alignment routinely
  - efficient tracker operations and excellent performance confirmed

- foundations and building blocks of the CMS tracker were summarized
- but the excellence of the CMS tracker becomes really apparent in the tracking, vertexing, b-tagging and in CMS physics analyses
- highly recommended:
  - → Boris Mangano: *Performance of Track and Vertex Reconstruction and B-Tagging Studies with CMS in pp Collisions at $\sqrt{s}$ = 7 TeV*
    * in this session at 12h12
  - → Jula Draeger: *The Alignment of the CMS Silicon Tracker*
    * in the poster session
  - → and the many other CMS contributions!

References

- CMS Collaboration, *The CMS experiment at the CERN LHC*, JINST **3**:S08004, 2008
- CMS Collaboration, *Commissioning of the CMS Experiment and the Cosmic Run At Four Tesla*, JINST **5:**T03001, 2010
- CMS Collaboration, *Commissioning and Performance of the CMS Pixel Tracker with Cosmic Ray Muons*, JINST **5:**T03007, 2010
- CMS Collaboration, *Commissioning and Performance of the CMS Silicon Strip Tracker with Cosmic Ray Muons*, JINST **5:**T03008, 2010
- CMS Collaboration, *Alignment of the CMS silicon tracker during commissioning with cosmic rays*, JINST **5:**T03009, 2010
- CMS Collaboration, *CMS Tracking Performance Results from Early LHC Operation*, arXiv:1007.1988, 2010

Backup Slides



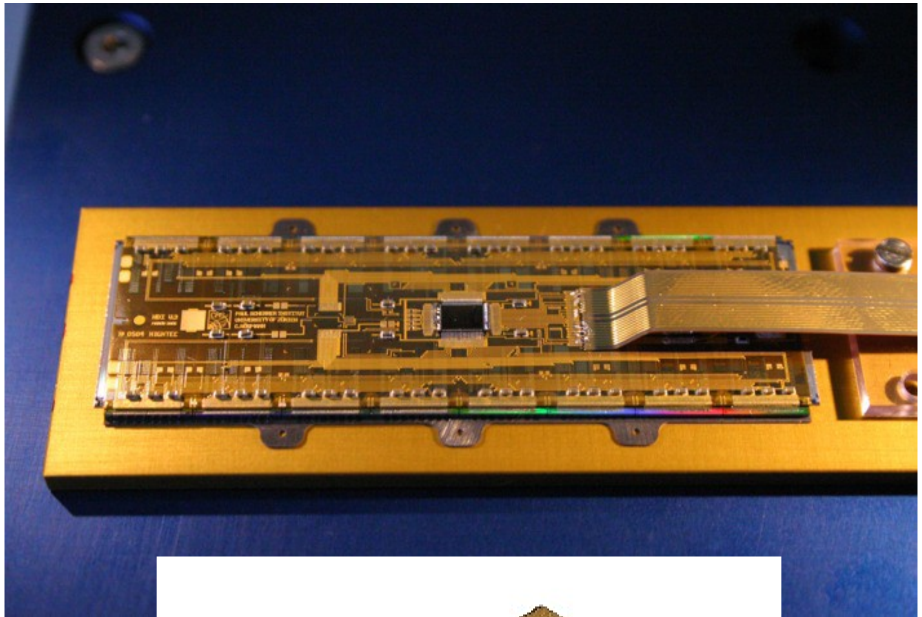
Sensors

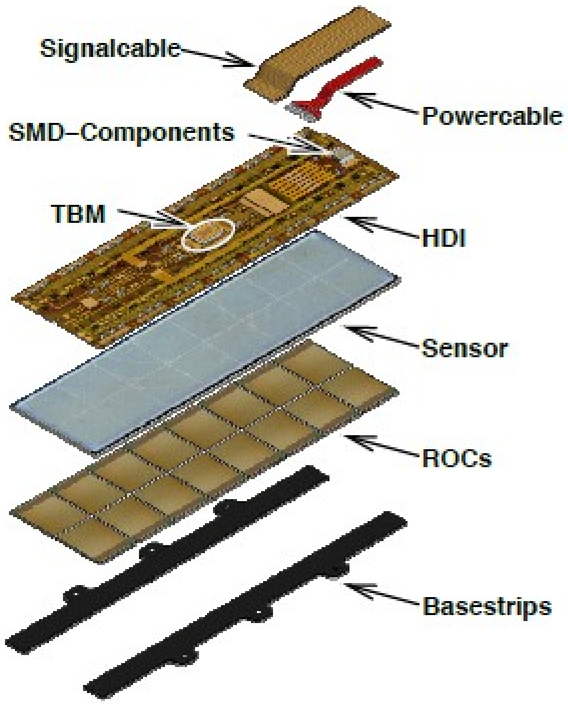
- p+ implants in n-type silicon bulk
  n+ backplane for ohmic contact
- 320um and 500um sensors
- strip pitch 83um – 205um
- *AC* coupled readout
- bias voltage: 300V

Modules

- analog readout with *APV25* chip: 128 channels x 192 cell pipeline (4.8us latency for L1 trigger) radiation tolerant 25um CMOS
- readout in peak and deconvolution modes
- data transfer via optical link

Pixel Sensors & Modules





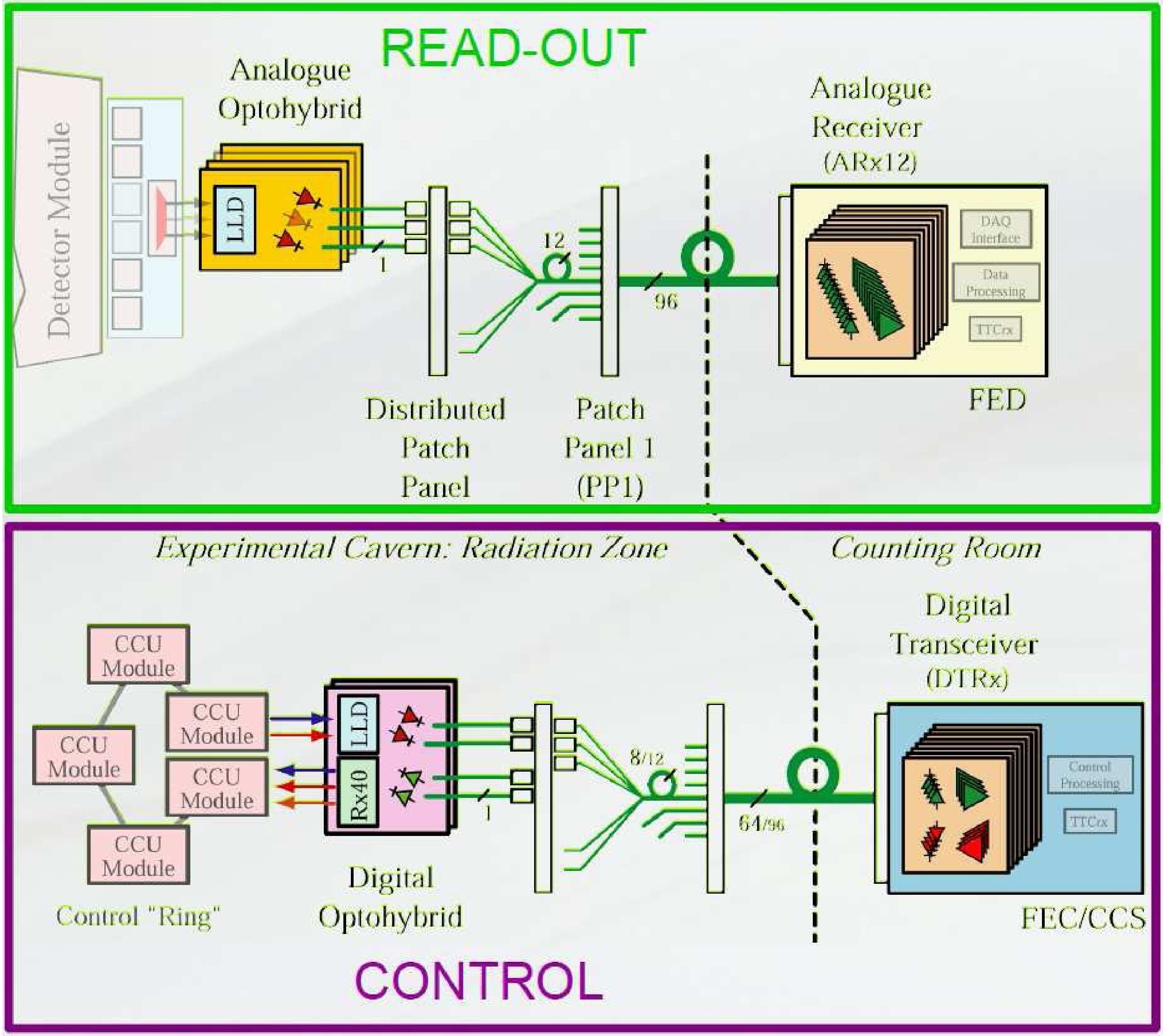
Sensors

- n-on-n silicon, thikness 285um (BPIX), 270um (FPIX)
- 150 x 100um pixels
- 4160 pixels bump-bonded to PSI46 readout chips (ROC)
- bias: 150V (BPIX), 300V (FPIX)

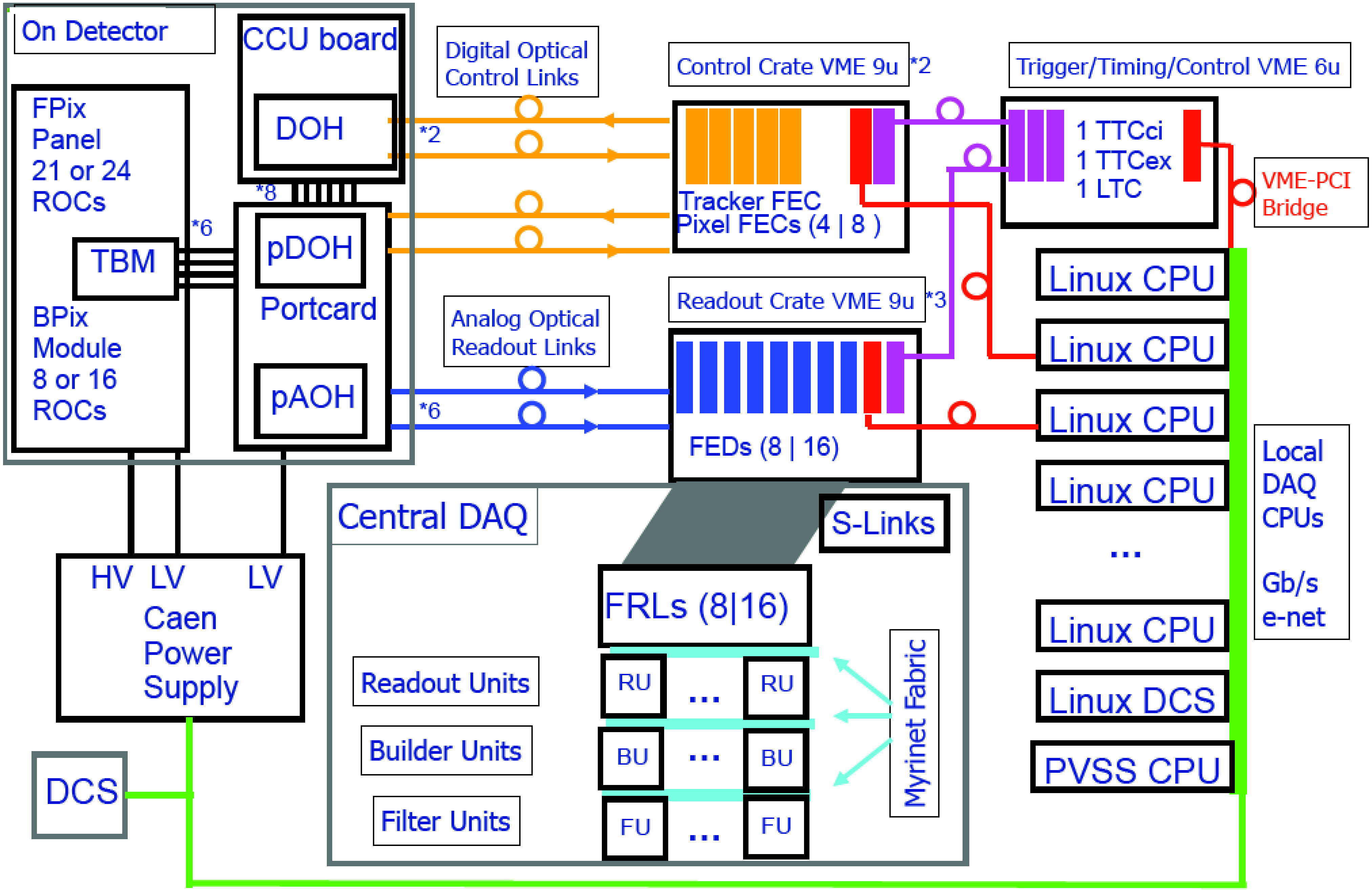
Modules

- 16 or 8 ROCs / module (barrel)
- 21 or 24 ROCs / module (endcaps)
- ROCs readout in series
- datatransfer via optical link

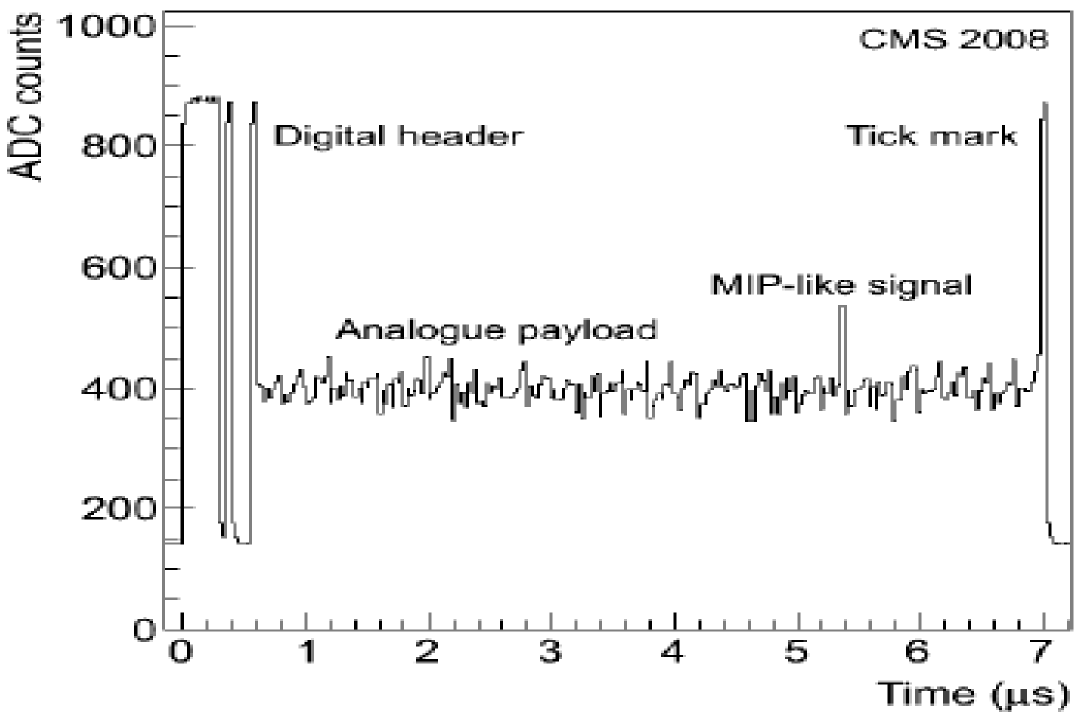
Strip DAQ System



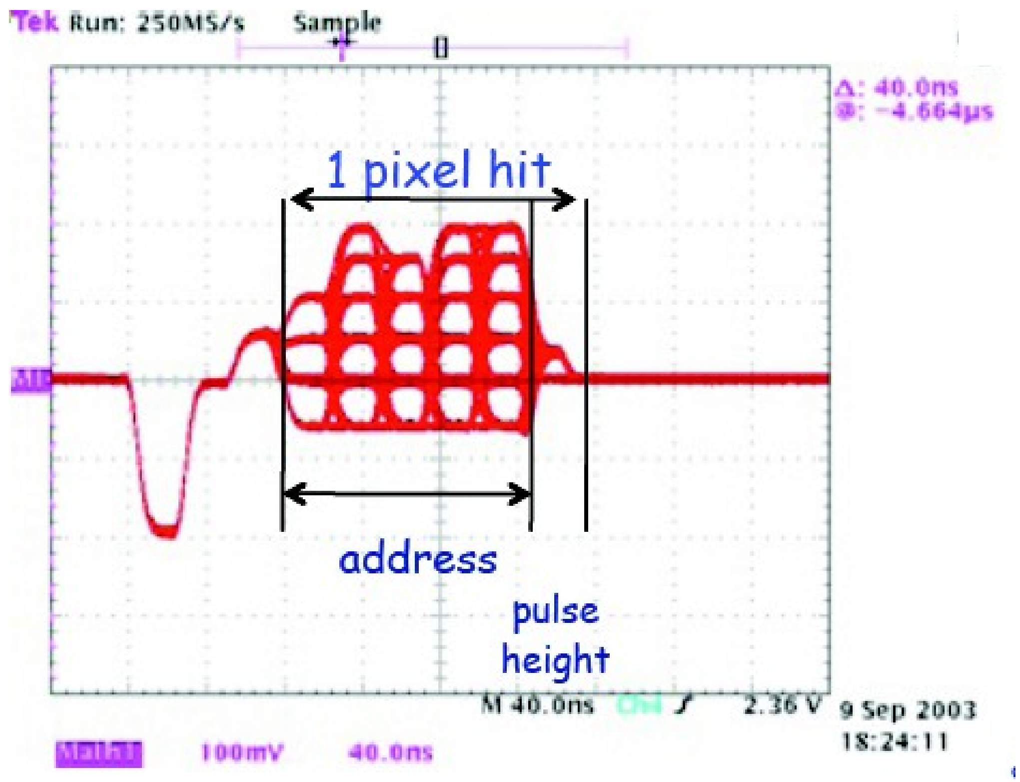
Pixel DAQ System



Data Frames



ADC counts
CMS 2008
Digital header
Tick mark
MIP-like signal
Analogue payload
Time (μs)



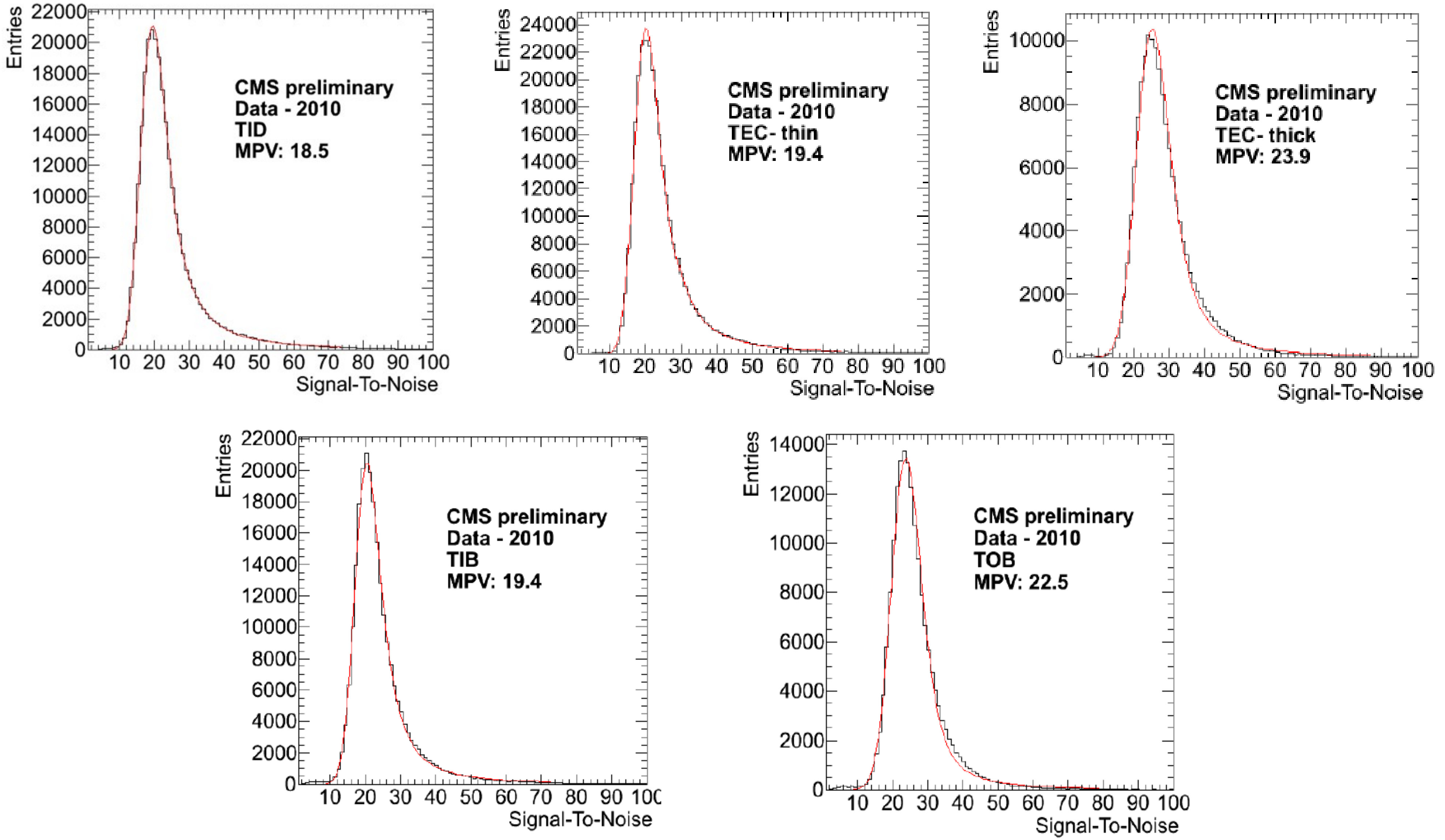
Tek Run: 250MS/s
Sample
Δ: 40.0ns
@: -4.664μs
1 pixel hit
address
pulse
height
M 40.0ns
2.36 V
9 Sep 2003
18:24:11
100mV
40.0ns

Operational Fraction Breakdown

	Operational fractions		
TIB/TID:	96.3%	BPIX:	98.9%
TOB:	98.3%	FPIX:	96.8%
TEC-:	99.1%	Total pixels:	98.3%
TEC+:	98.8%		
Total strips:	98.1%		

Strip Signal-to-Noise

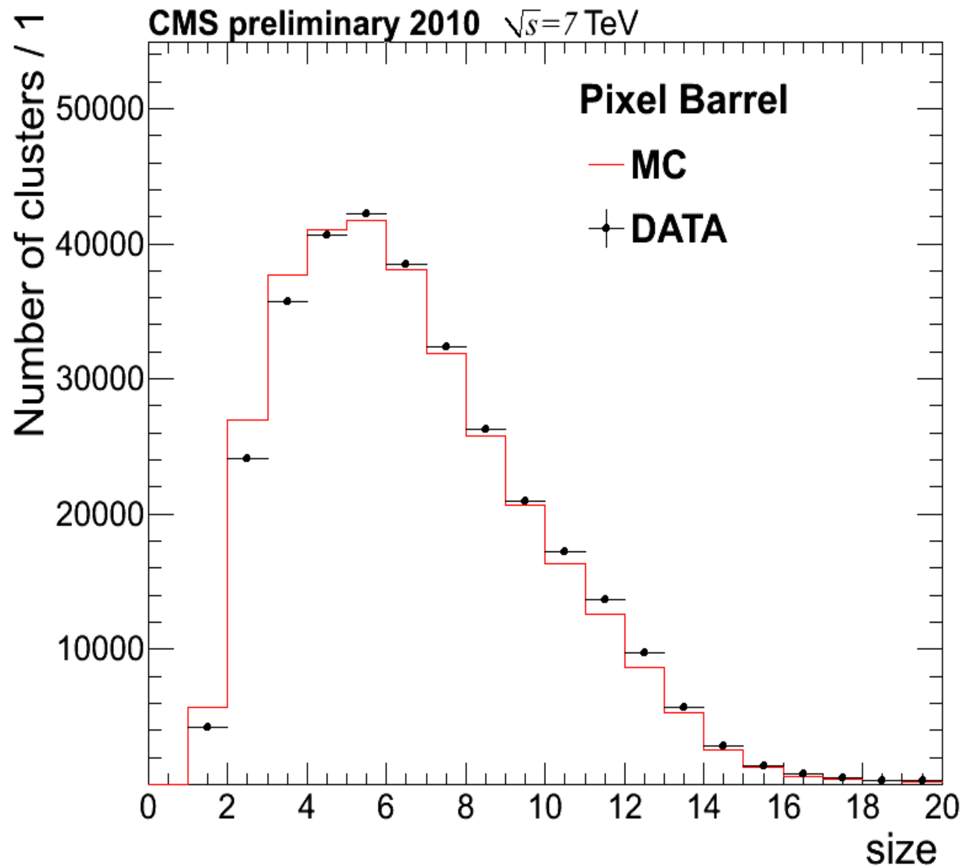
S/N for all strip partitions – 7 TeV data - deconvolution



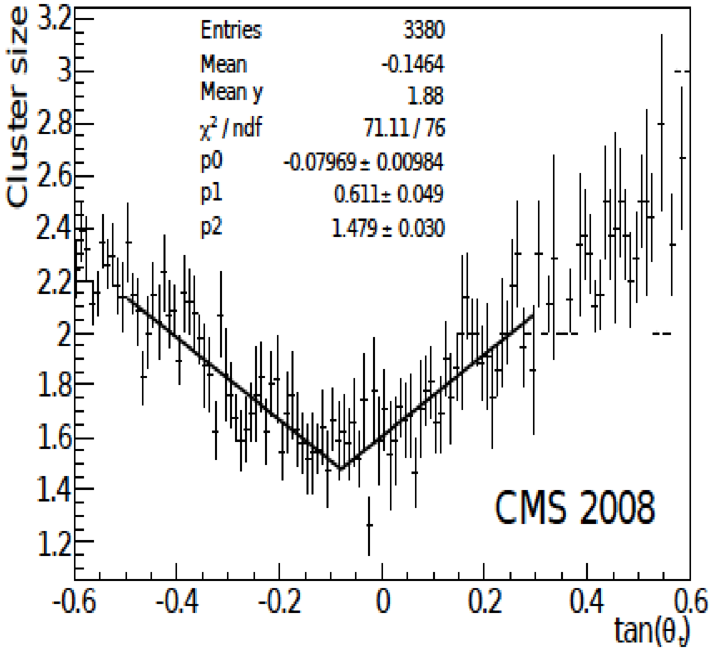
Pixel Cluster Size

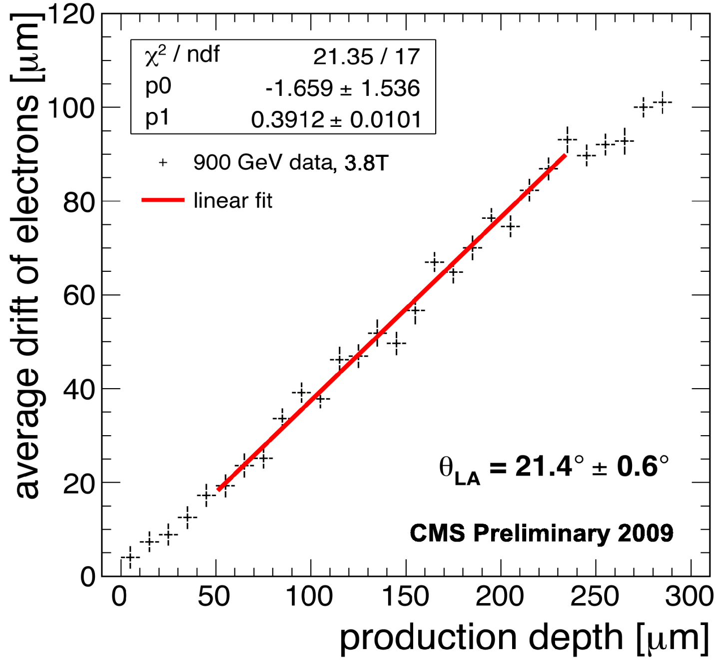
Pixel cluster size

- good overall description by simulation
- discrepancy for small cluster sizes < 4
  - ➔ being further improved



Additonal plots for Lorentz Angle measurements

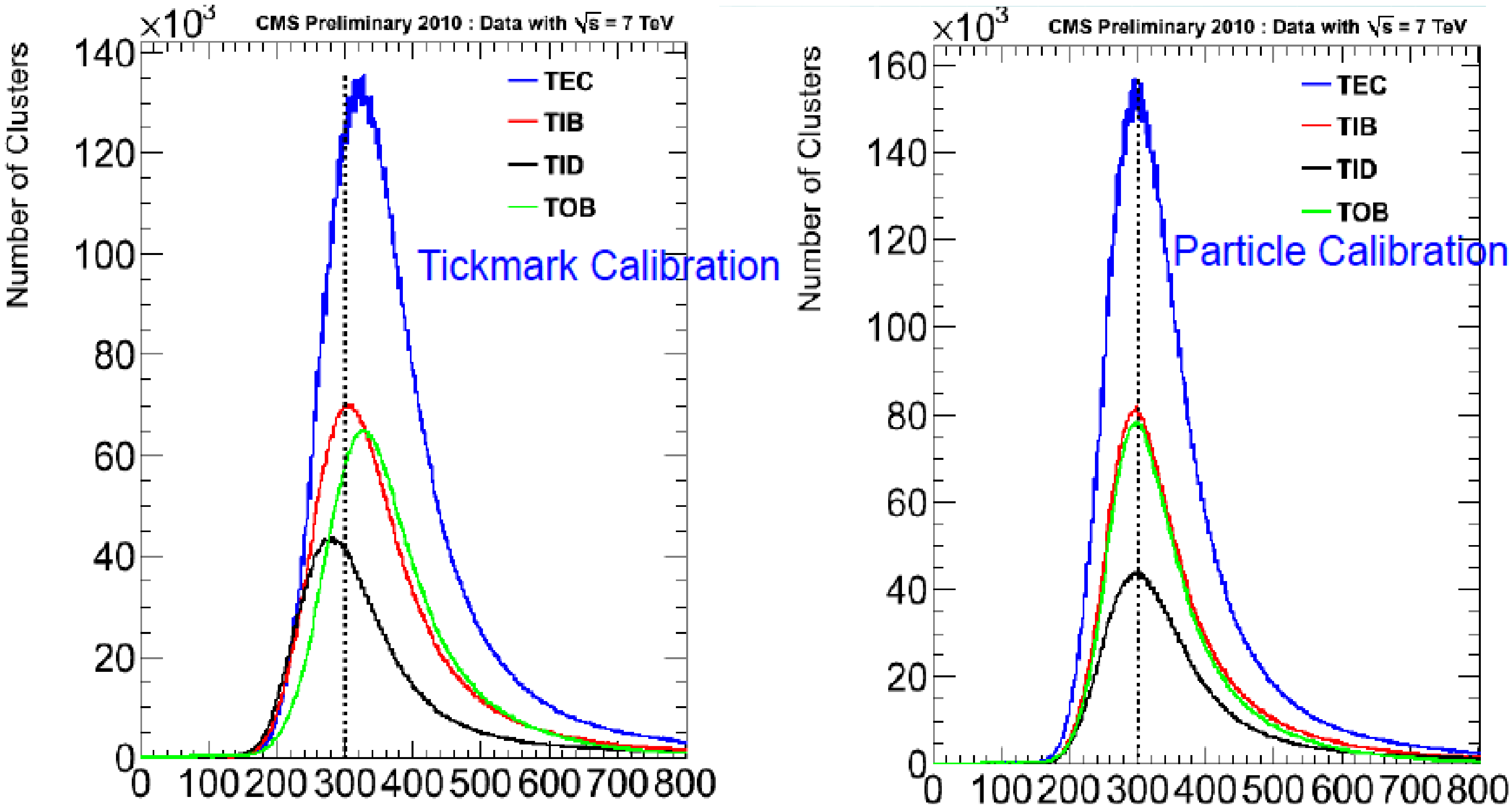




- minimal cluster size method for the strips
  - ➔ one L4 TOB module shown

- grazing angle method in BPIX
  - ➔ use tracks with shallow impact angle
  - ➔ for each pixel in cluster determine drift distance from track
  - ➔ correlate with depth
  - ➔ averaging over many tracks
  - ➔ Lorentz angle is slope of linear fit

Strips Gain Calibration



Beam Background

Beam background in pixels

- large tail observed in number of clusters in pixel detector (also to a lesser extent in strips)
- such events have large number of pixels/cluster in the barrel
  - ➔ from longitudinally grazing tracks
- beam-gas trigger veto, or cuts on cluster shape track quality and vertexing efficiently remove these background events
  - ➔ at 11kHz with nominal bunches, overlap with physics rate of ~ 0.1%
- but the large event size leads to buffer overflows in the pixel FEDs at high trigger rates
  - ➔ firmware modifications to deal with these events graciously