Offline calibration and performance of the CMS pixel detector

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on behalf of the CMS collaboration

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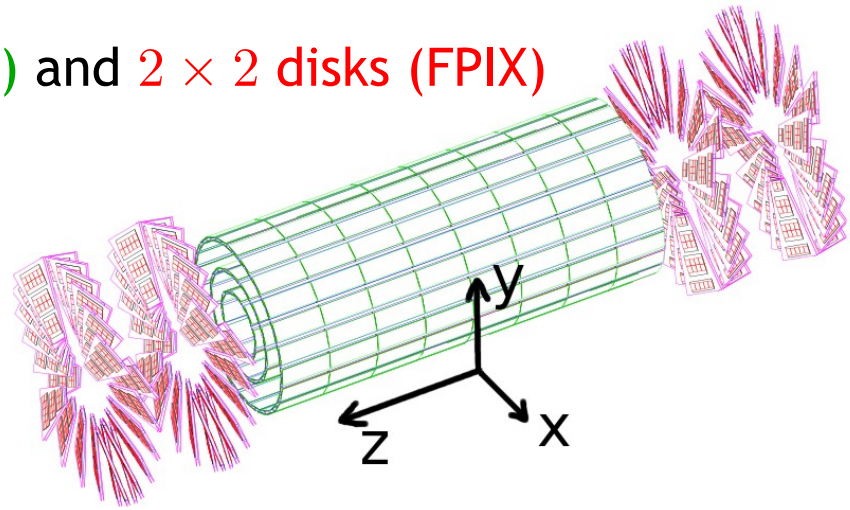
- Introduction
- Calibrations
  - ADC to charge (single pixel)
  - Lorentz Angle (cluster)
  - Timing (detector)
- Performance

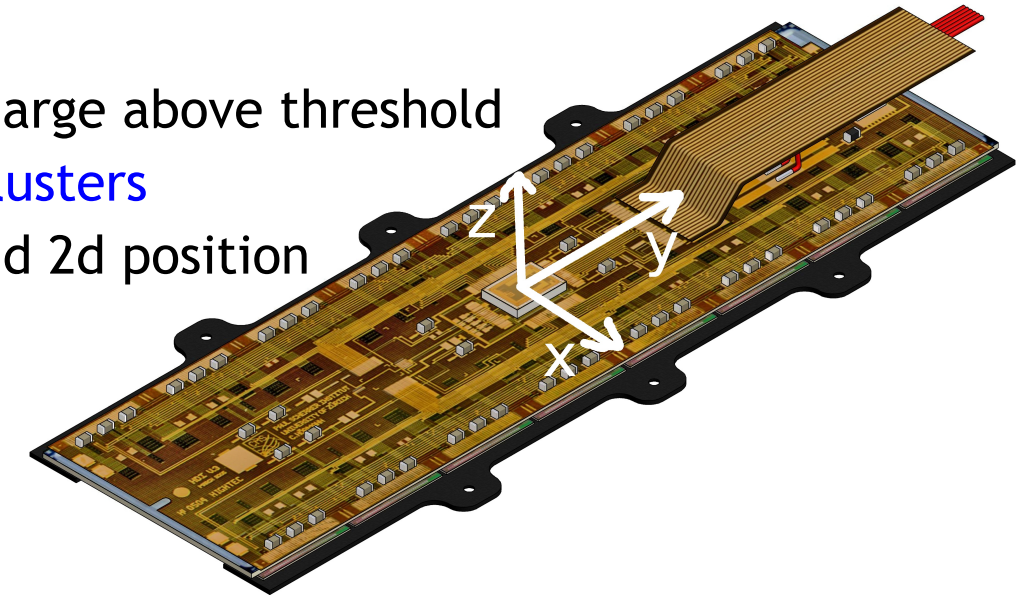
Introduction

- CMS pixel detector characteristics:
  - 66 million pixels in 3 barrel layers (BPIX) and 2×2 disks (FPIX)
  - 25 ns bunch crossing separation
  - radiation hard to $\geq 6 \times 10^{14}\, n_{eq}$



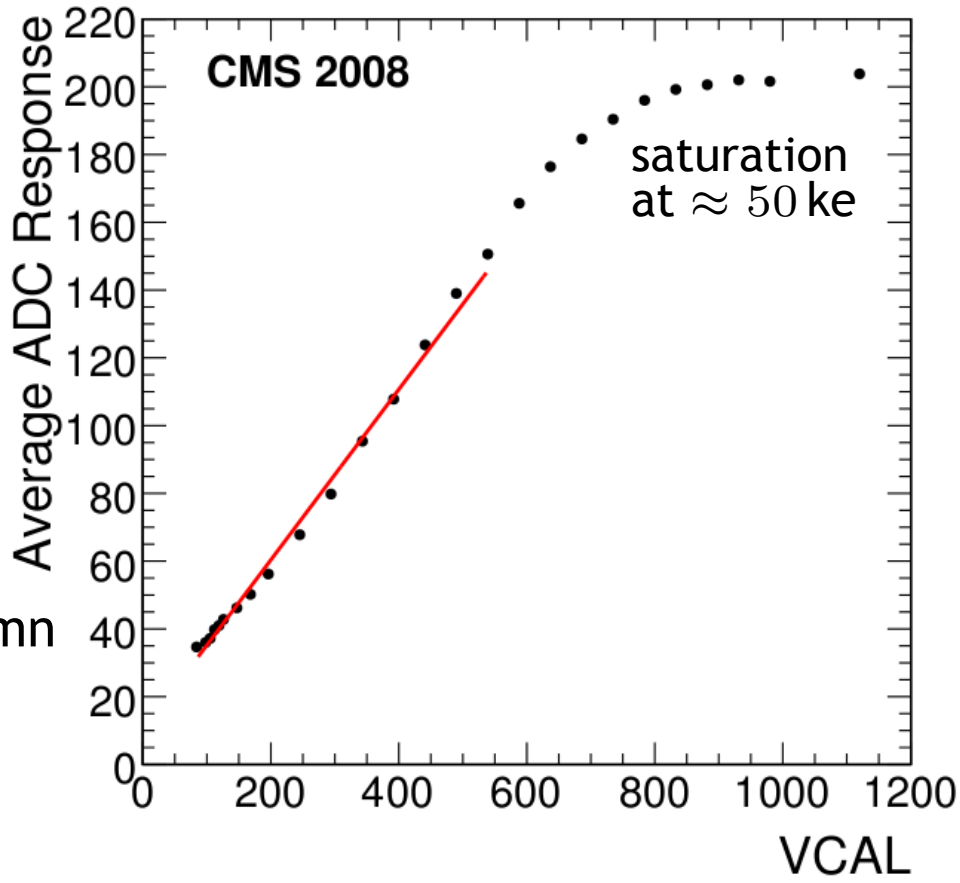
- Local coordinate system on modules
  - x along shorter pixel side (BPIX: $|\phi|$)
  - y along longer pixel side (BPIX: $|z|$)
  - z parallel to $\vec{E}$ field (BPIX: $|r|$)

- Local reconstruction
  - digis are pixels with deposited charge above threshold
  - adjacent digis are combined to clusters
  - cluster characteristics: charge and 2d position
    - generic fast algorithm
    - 'template' algorithm
      projected cluster shapes
      including radiation damage
      requires track incidence angle



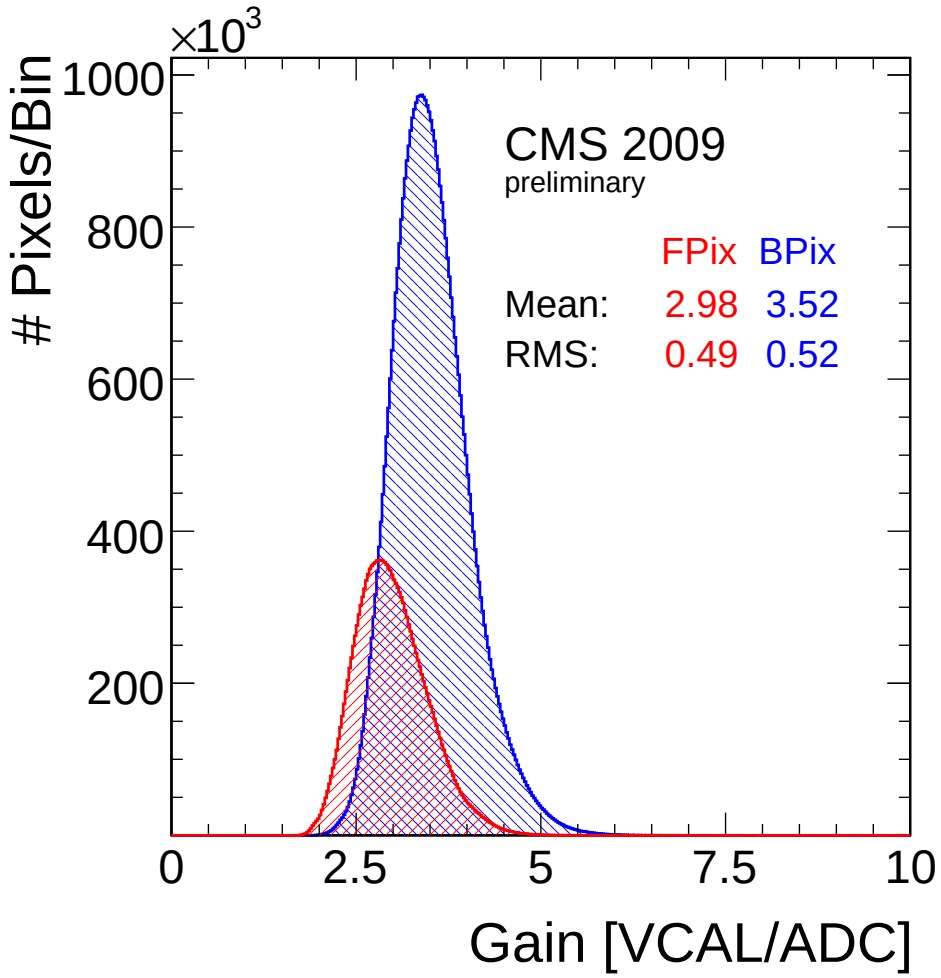
Single Pixel Calibration: ADC to Charge

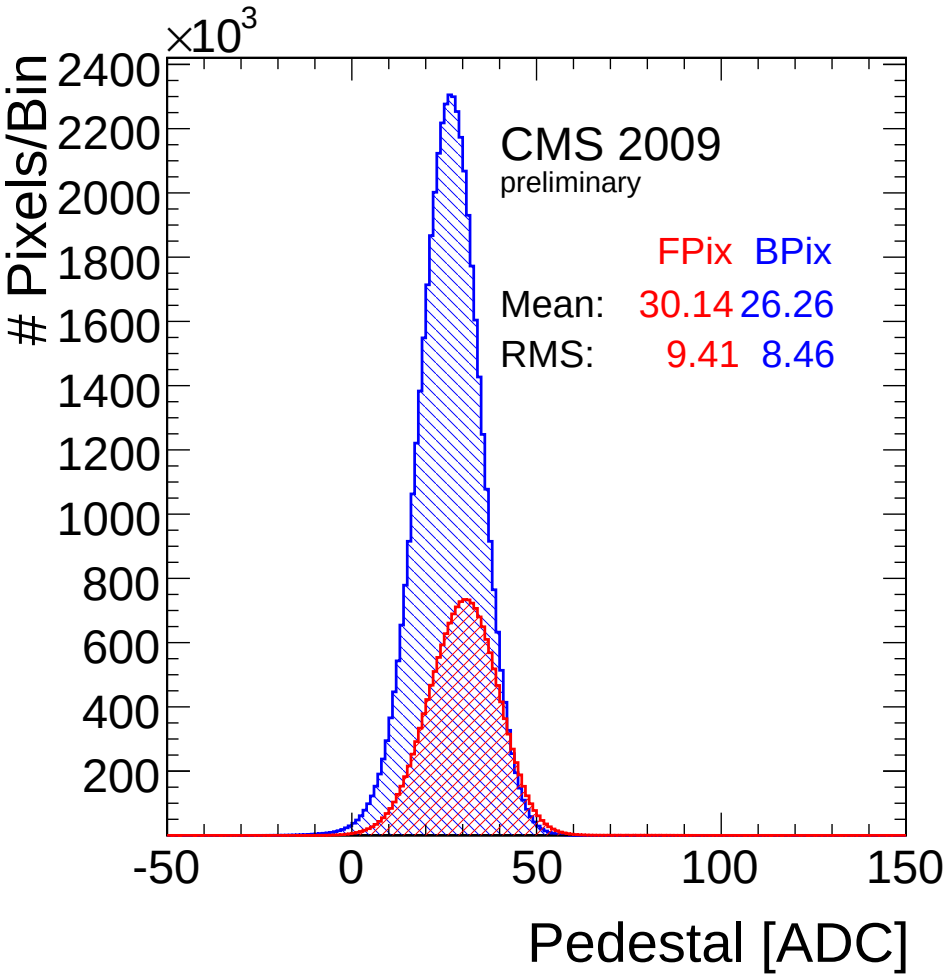
- Relate ADC readout to deposited charge
  - ▷ VCAL circuit provides charge injection capability
  - → needs to be calibrated
    ROC average known from x-ray tests: Q [e^-] = 65.5 × VCAL [DAC] - 414
  - ▷ Thresholds
    absolute: in multiple bunch crossings
    in-time: one correct bunch crossing
- offline ADC-to-charge calibration
  - ▷ fitting single pixel response
  - ▷ linear function: gain/pedestal
  - ▷ tanh function for more studies
- granularity of constants
  - ▷ HLT: averaged over ROC column
  - ▷ RECO: gain averaged over ROC column
    pedestal per pixel
  - → Calibration payload size
    HLT: 800 kB; RECO: 33 MB



Gain and Pedestals

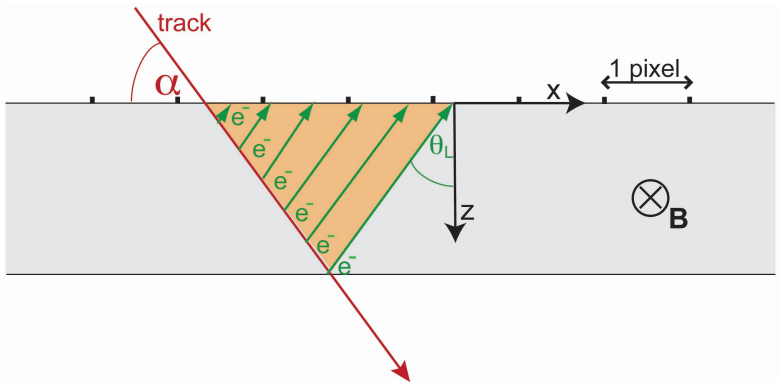
- Very stable calibration
  - about once per year; control calibration runs done more often





Cluster Calibration: Lorentz Angle

- Charge carriers moving in $\vec{E} \perp \vec{B}$ fields
  - ▷ deflection by Lorentz angle
  - ▷ Lorentz angle depends on
    bias voltage, magnetic field strength
    temperature
    radiation damage



- Lorentz deflection of charge carriers
  - ▷ cluster widening along local x (global ϕ in barrel)
  - ▷ charge sharing among pixels

$\Rightarrow$ Implications

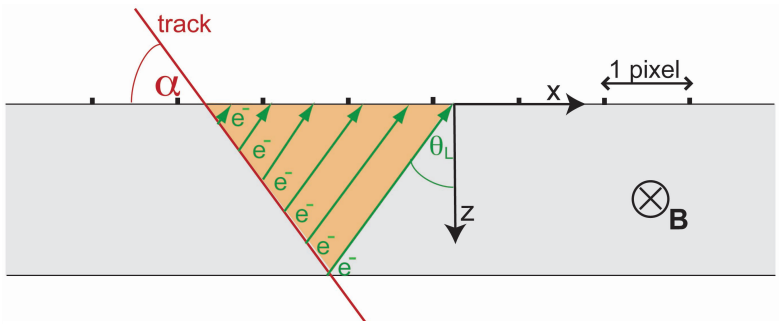
$\rightarrow$ shift in hit position
BPIX: $53\ \mu$m
FPIX: $10\ \mu$m

$\rightarrow$ improved position resolution

- Two methods to measure Lorentz angle
  1. 'minimum cluster size' method: cosmic ray muons
  2. 'grazing angle' method: collision data

1. Lorentz angle: Minimum Cluster Size

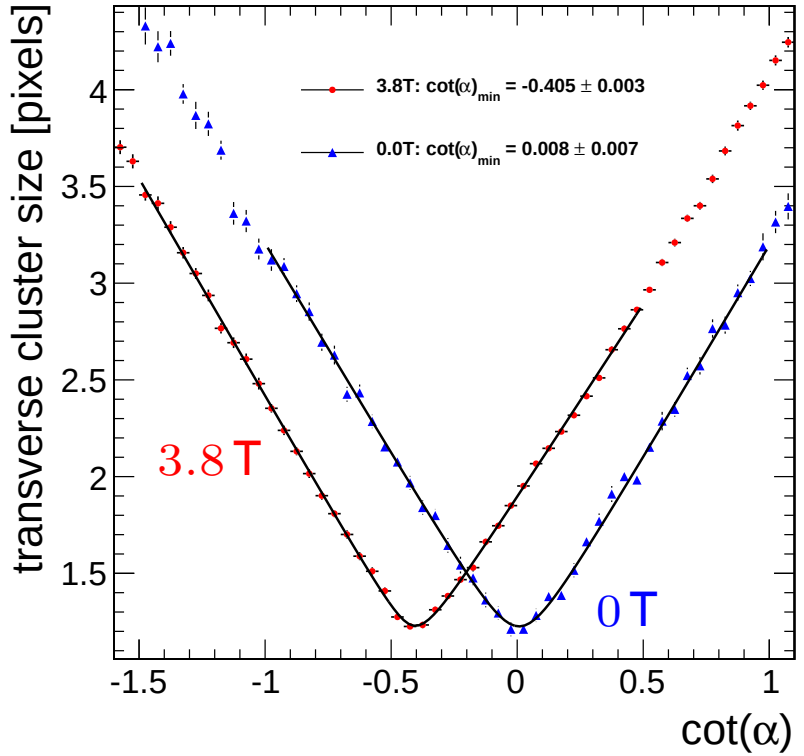
- Cluster width in (local) x depends on
  - ▷ Lorentz angle θ_L
  - ▷ particle incidence angle α
  - → minimal for $\alpha = \theta_L$
  - → $\tan\theta_L = \cot\alpha|_{\min}$



⇒ Measure cluster width vs incidence angle
  - ▷ possible with cosmic ray muons
  - ▷ in collision data only with low-$p_\perp$ tracks

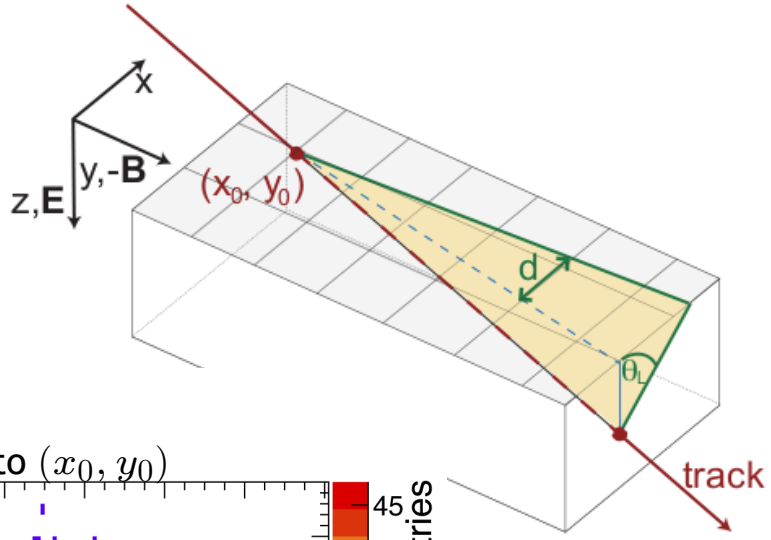
- Track selection
  - ▷ transverse momentum $p_\perp > 0.1\,\text{GeV}$
  - ▷ cluster size $N_y > 2$
  - ▷ $\chi^2/\text{dof} < 2$
  - ▷ no cluster with edge digis

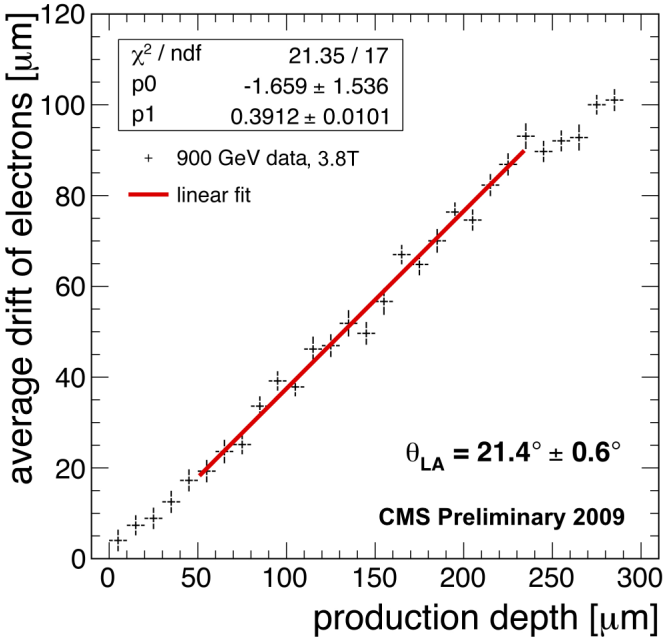
- Systematic errors of order $\pm 3\%$
  - ▷ track selection
  - ▷ fitting range

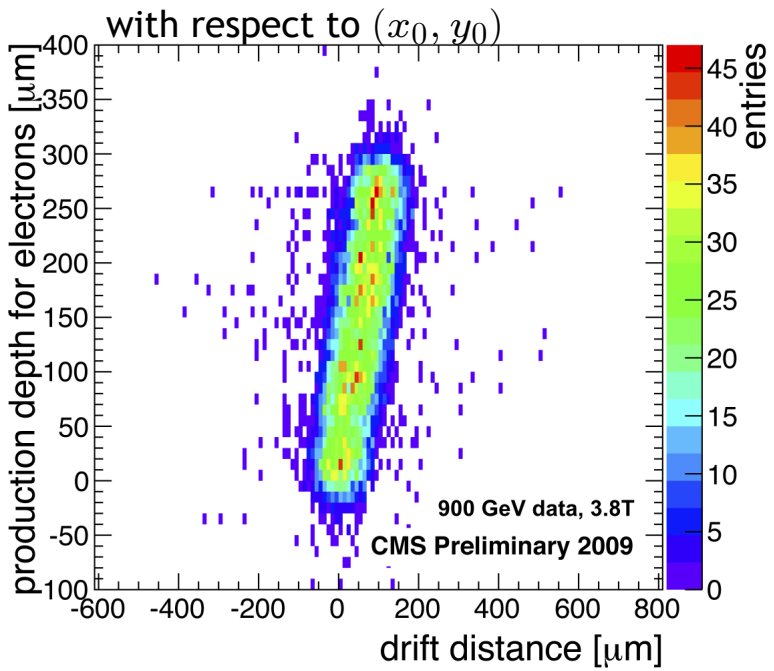


2. Lorentz angle: Grazing Angle Method

- Measure electron drift length vs production depth
  - long clusters along (local) y from shallow incidence angle tracks
  - slope corresponds to $\tan\theta_L$
- Systematic errors of order $^{+4}_{-2}\%$
  - track selection
  - fitting range







Lorentz Angle Results

- Results are consistent
  - different methods
  - with detailed simulation (PIXELAV)

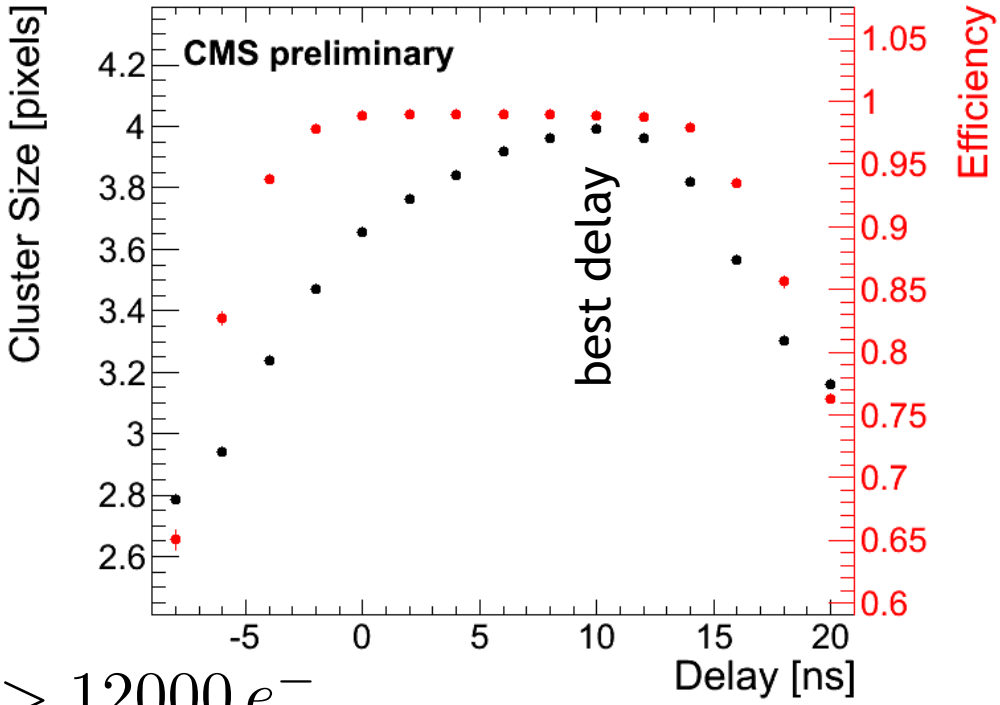
data type	method	$\tan\theta_{LA}$ (data)	$\tan\theta_{LA}$ (PIXELAV)
cosmic rays, 3.8 T	min. cluster size	0.405 ± 0.003 (stat)	0.397 ± 0.003 (stat)
900 GeV, 3.8 T	grazing angle	0.391 ± 0.010 (stat)	0.401 ± 0.001 (stat)
900 GeV, 3.8 T	min. cluster size	0.409 ± 0.002 (stat)	0.411 ± 0.005 (stat)
900 GeV, 2 T	grazing angle	0.203 ± 0.004 (stat)	0.211 ± 0.001 (stat)

Detector Calibration: Delay Scan

- Determine optimal setting of pixel detector clock vs LHC clock
  - cluster efficiency
  - cluster resolution
  - cluster charge
- Efficiency:

$$\frac{\#\text{ found clusters}}{\#\text{expected clusters}}$$

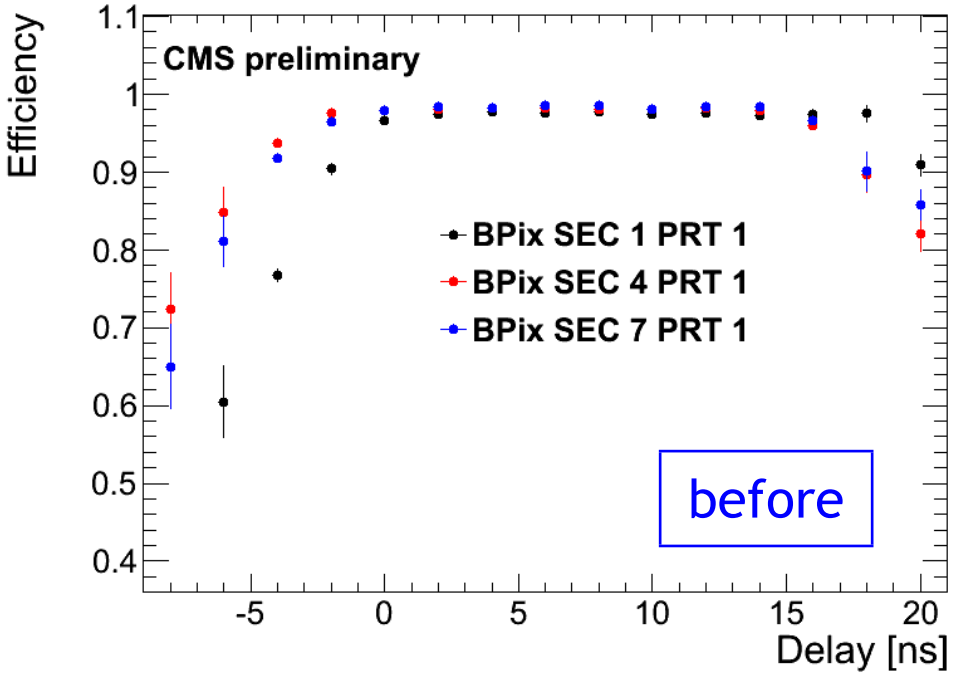
  - in fiducial region
  - in live components

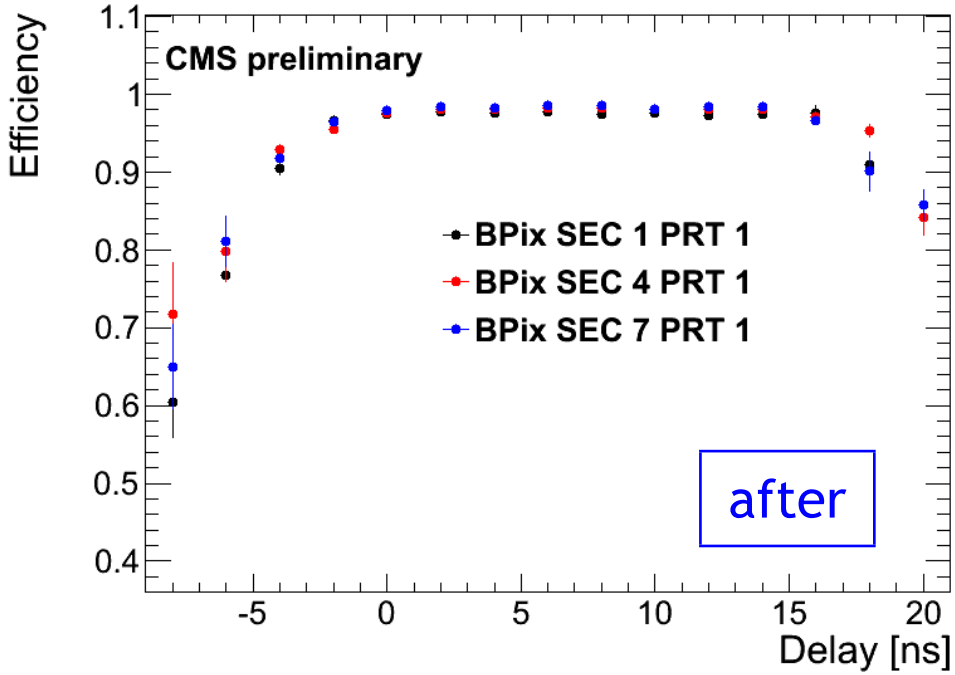


- Cluster size: clusters with $Q_{\text{tot}} > 12000\,e^-$
  - charge not corrected for track incidence angle (smaller dependence on tracking)
- Scanned pixel detector clock in steps of 2 ns
  - initially one global delay setting
  - with more statistics scanned individual port cards (sectors)

Delay Scans in Sectors

- With enough statistics, the delay settings of sectors was analyzed
  - BPIX: one sector (1/8 of a half shell) divided into L1+L2 and L3
  - FPIX: three blades (1/4 of a half disk)
- Largest corrections to a priori cable/fiber length calculations
  - BPIX: 3 ns
  - FPIX: 8 ns





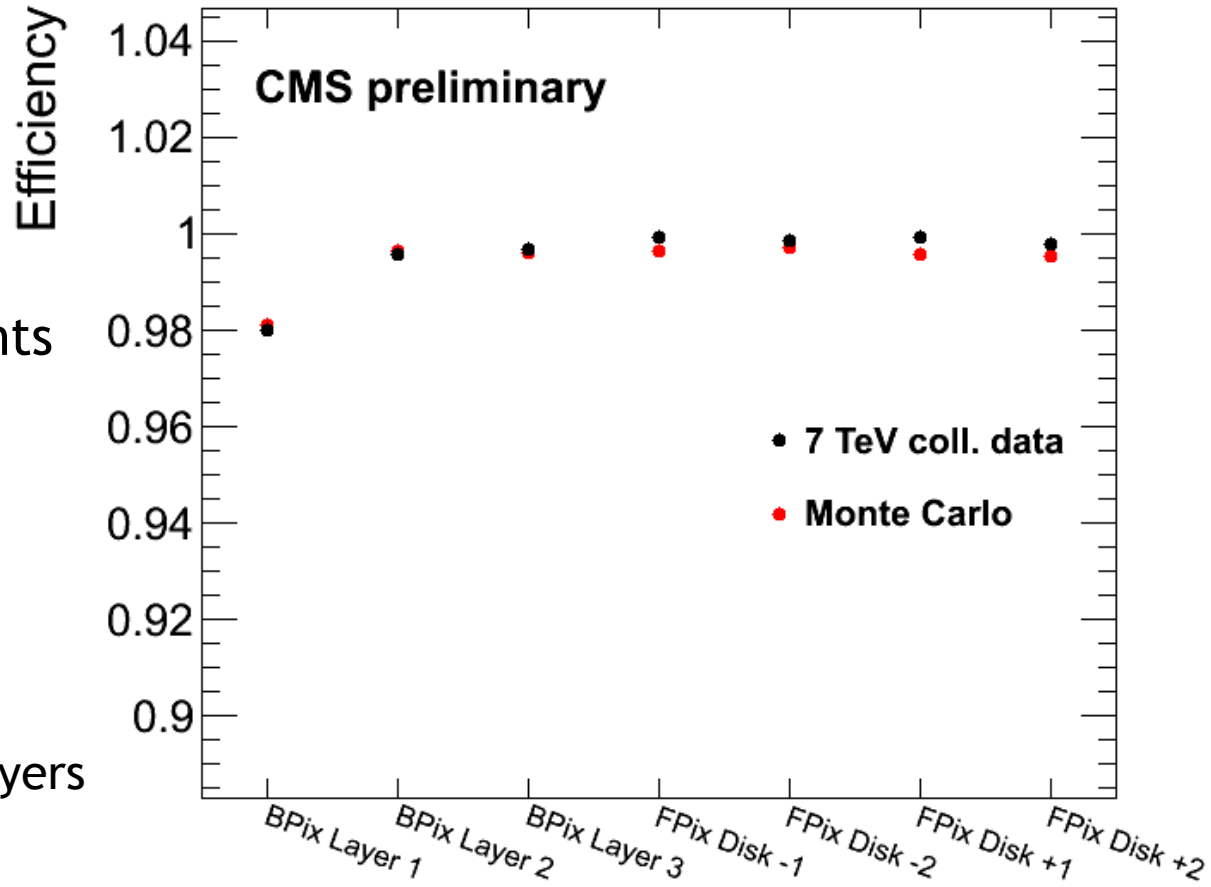
Performance: Hit Efficiency

- Efficiency:

$$\frac{\#\text{ found clusters}}{\#\text{expected clusters}}$$

  - in fiducial region
  - excluding dead components

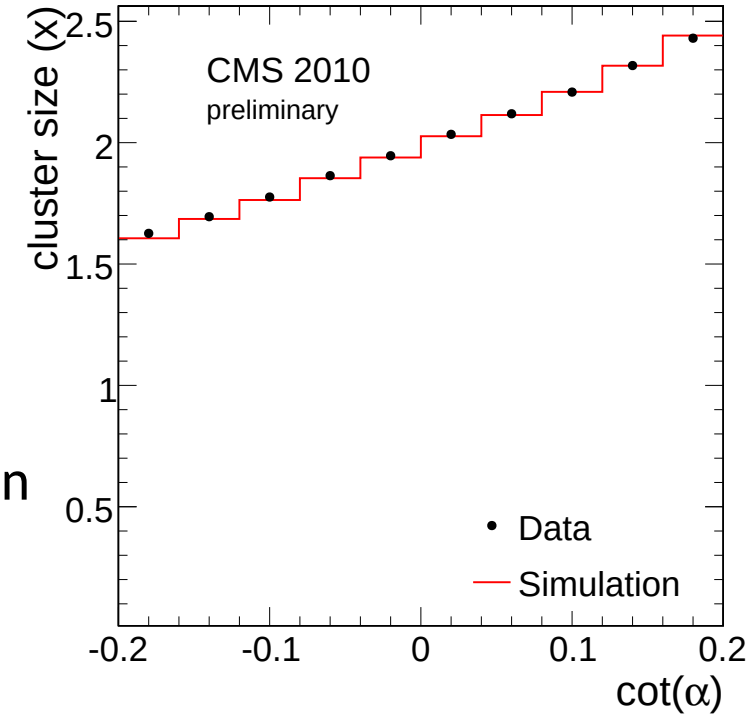
- 7 TeV collision data
  - Event selection
    ≥ 1 primary vertex
  - Track selection
    seeded with pixel clusters
    valid clusters on 'other' layers
    $p_\perp > 0.9\,\text{GeV}$
    $N_{\text{strip hits}} > 10$
    track consistent with vertex

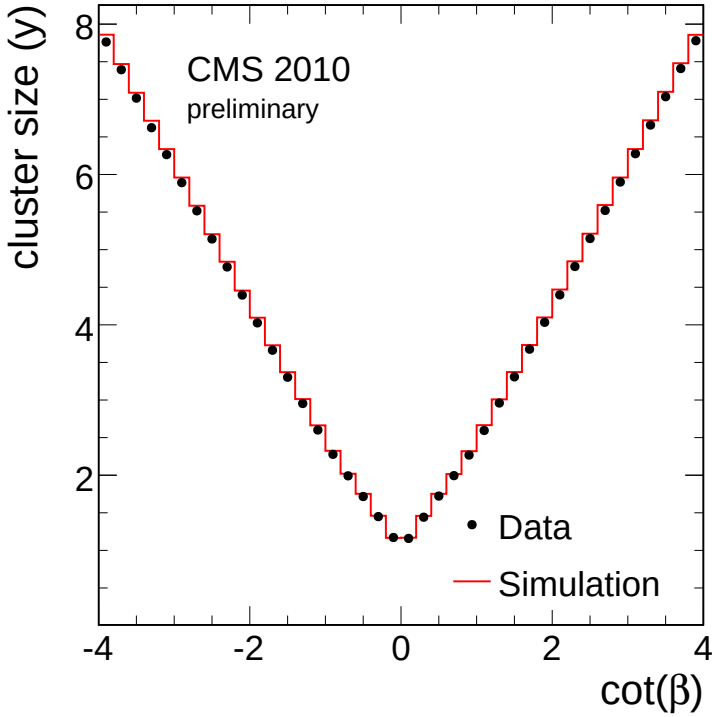


$\Rightarrow$ Cluster efficiency in entire detector $> 99\%$
  - Layer 1: underestimate by $\approx 1.5\%$ due to secondaries
    Consistent with expectation from MC simulation

Pixel Thresholds

- Threshold subtleties
  - absolute vs in-time:
    single vs multiple bunch crossing r/o
    (not possible in data taking)
  - units: VCAL or electrons
- Thresholds in electrons
  - Q_{dep} and path length: MIP in data
  - cluster size: comparison with MC simulation





- Results
  - absolute thresholds: $\langle T \rangle = 2457$
  - in-time thresholds: $\langle T \rangle \approx 3200$

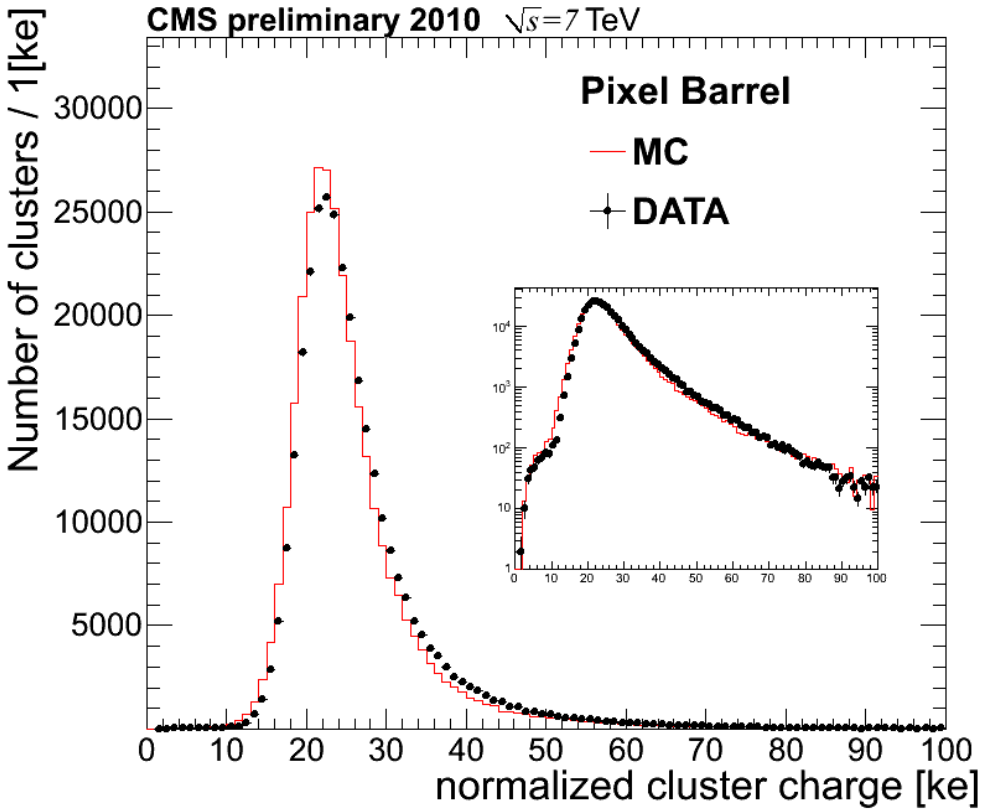
    assuming

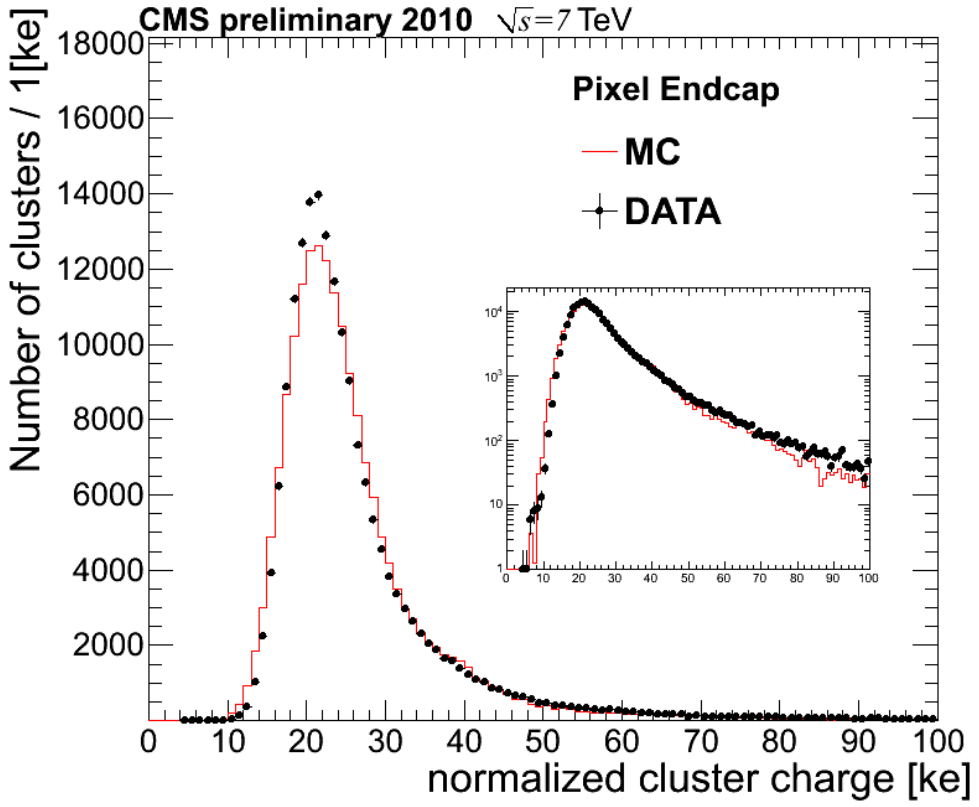
    single threshold for all pixels

    specific response model in simulation

Cluster Charge Distributions

- Detector MC simulation provides accurate description of data
  - much better than anticipated
  - mostly irrelevant for detector performance
    (MC simulation normalized to data histograms)

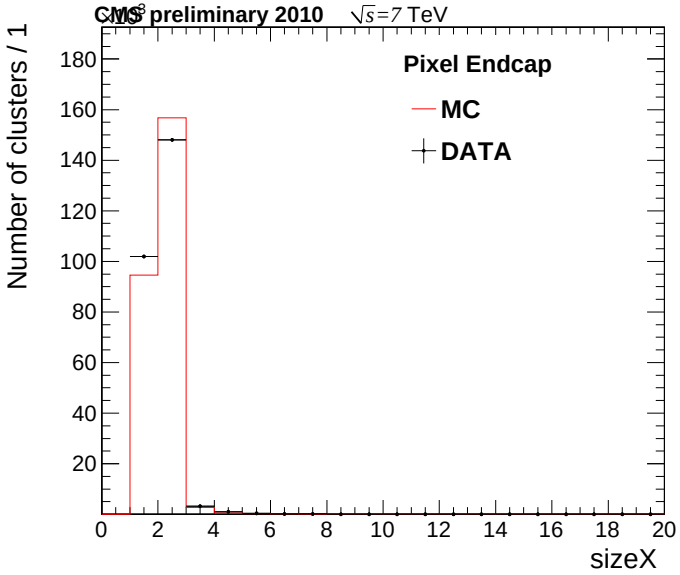


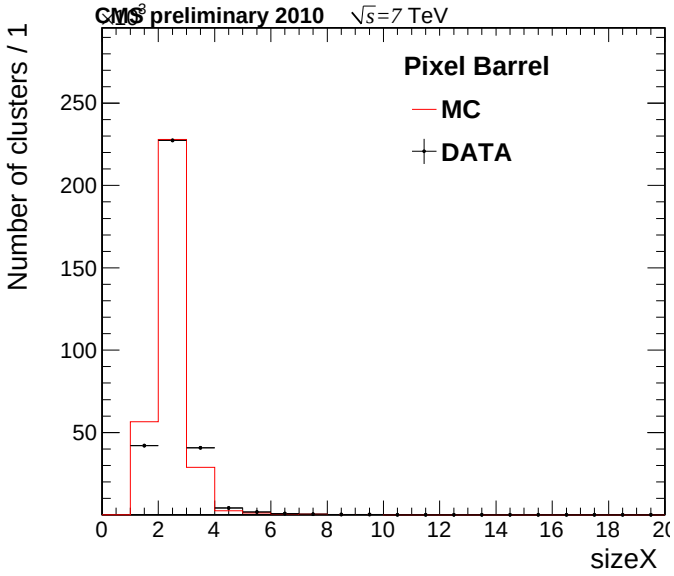


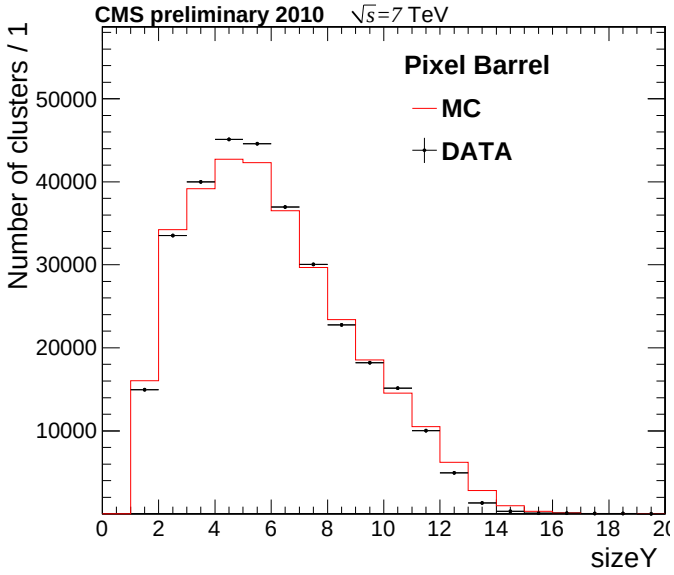
Cluster Size

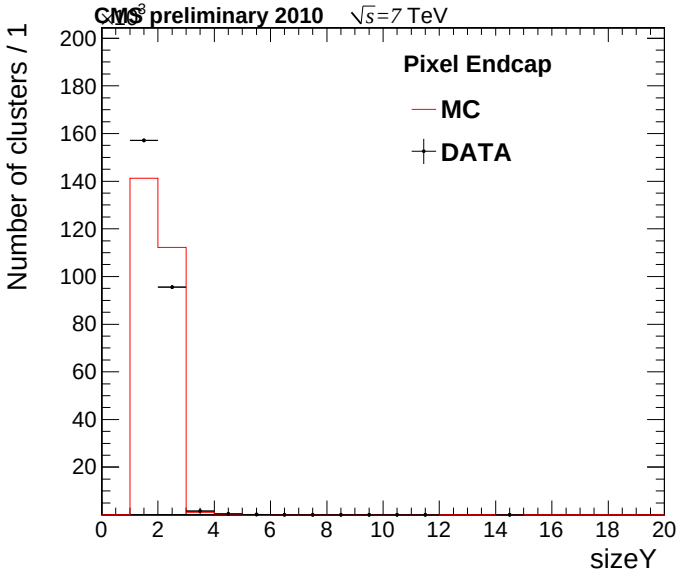
- MC simulation describes data quite well
  - cannot simultaneously described x and y
  - possibly (somewhat) different thresholds
    ROC readout mechanism affecting threshold differently in x and y
  - geometry difference between FPIX and BPIX

(MC simulation normalized to data histograms)



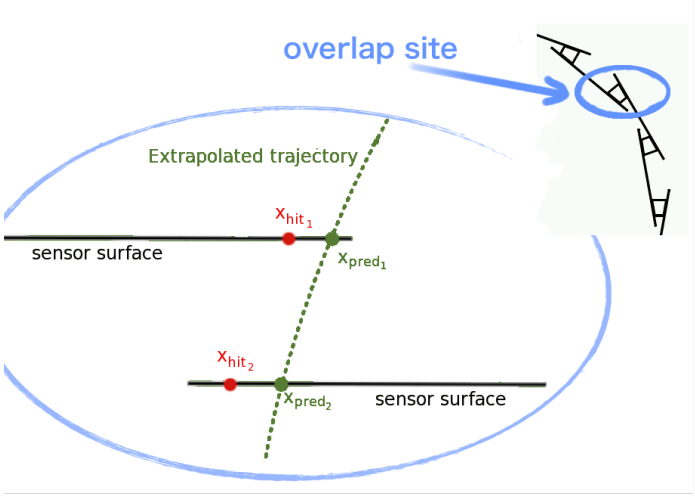


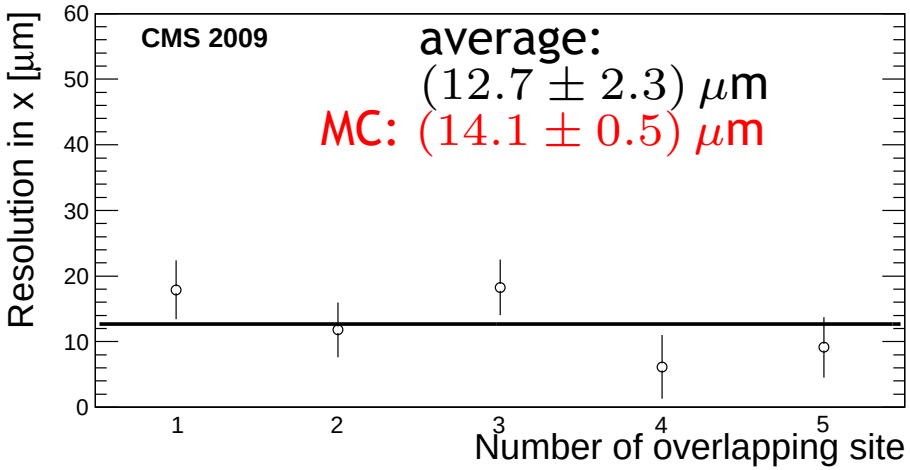


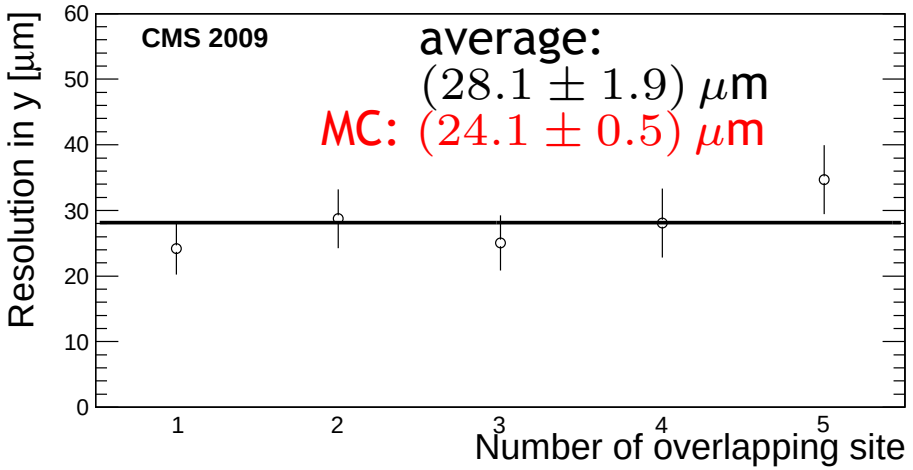


Hit Resolution

- Method: Compute double difference
  - ▷ difference of measured hit positions
  - ▷ difference of extrapolated hit positions
  - ▷ difference of the two differences
  - → reduces sensitivity to
    misalignment
    extrapolation errors







- Caveat: overlaps only at the edges of the track α-acceptance
  - ▷ cluster x sizes deviate from the optimal size (of two)
  - → the x resolutions are somewhat worse than the typical x resolution

Summary and Conclusions

- Offline calibrations
  - readout ADC to digi charge
  - Lorentz angle
  - Timing
- Performance
  - threshold ≈ 3200 electrons
  - efficiency $> 99\%$
  - resolution $\sigma_x = 13\,\mu$m
    $\sigma_y = 28\,\mu$m
- CMS pixel detector at design specifications
  - operations
  - calibrations
  - performance

$\Rightarrow$ We have an excellent detector

$\rightarrow$ looking forward to much more data