Commissioning the CMS Pixel Detector

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On behalf of the Tracker Project

APS DPF 2009

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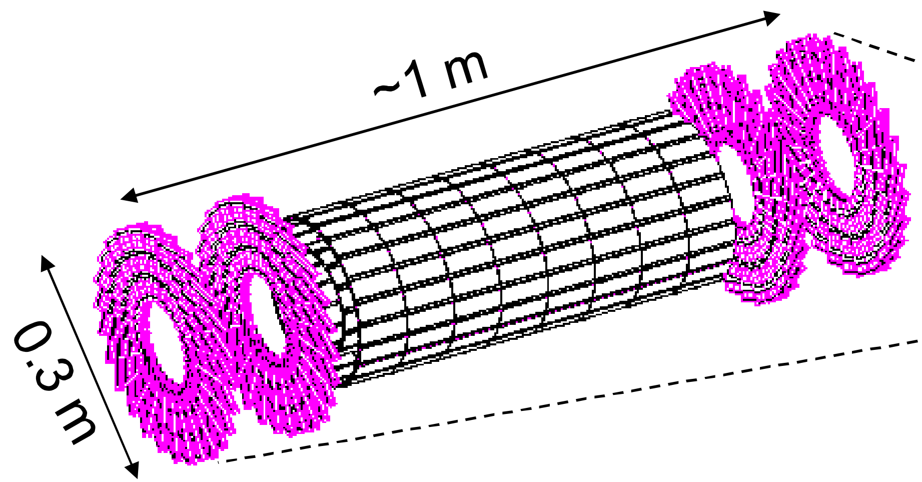
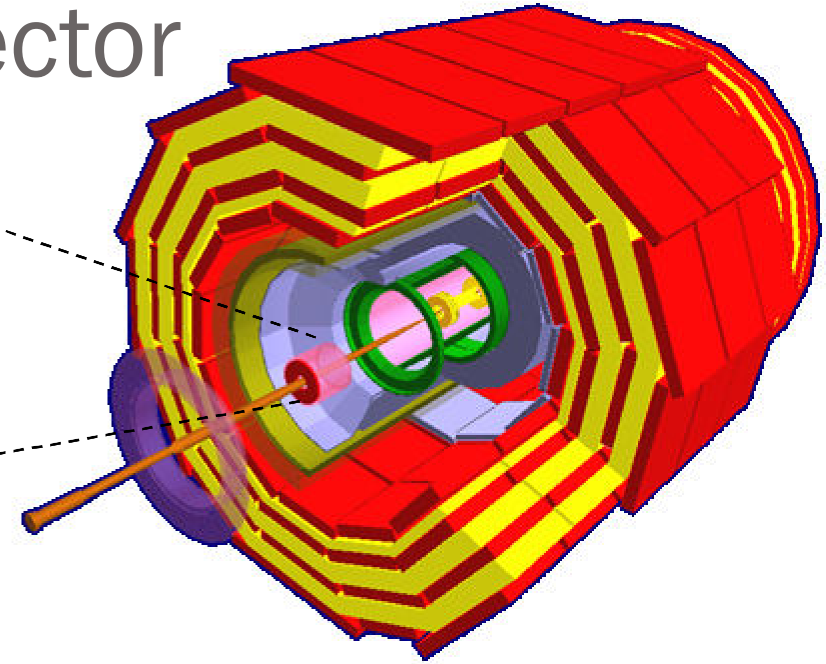
Overview

- Purpose: discuss work done commissioning CMS Pixel subdetector, including calibration and studies done using cosmic ray data
- Outline:
  - Description of Pixel
  - Online calibration
  - Description of Cosmic Run At Four Tesla (CRAFT)
  - Lorentz Angle studies
  - Pixel residuals and resolution
  - Pixel efficiency

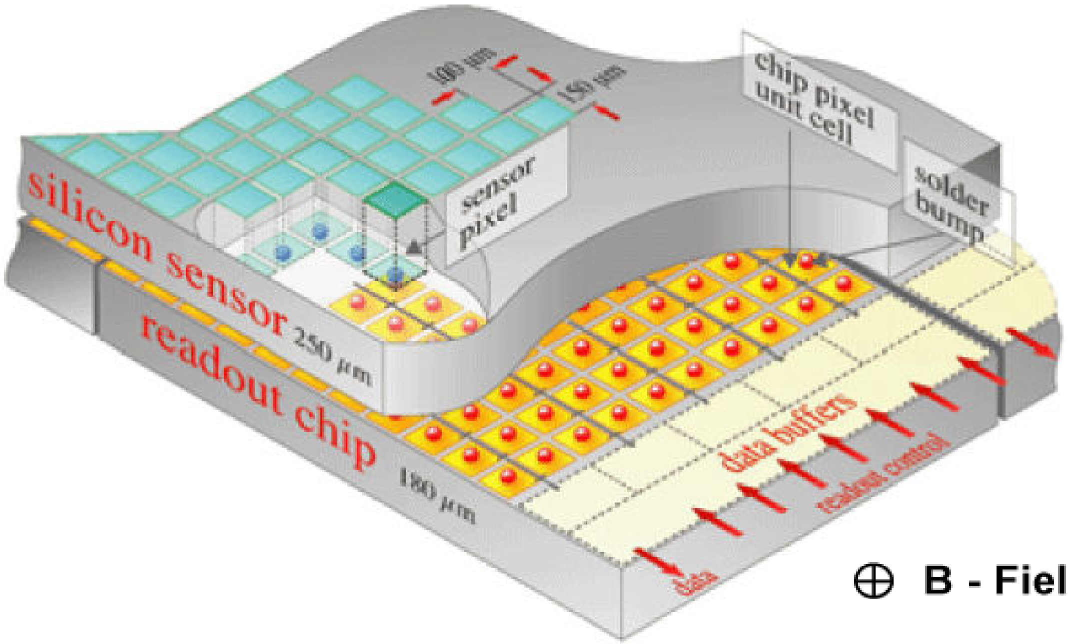
The CMS Pixel Subdetector





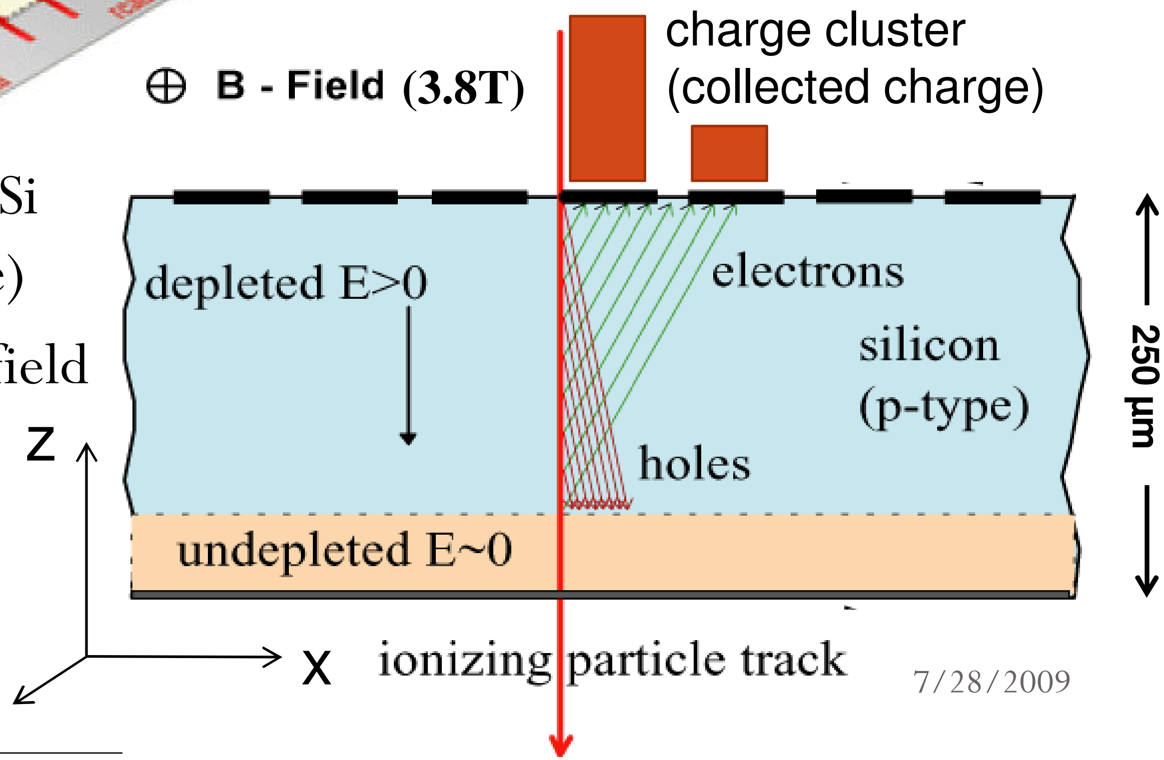
- Requirements:
  - High resolution (~12μm), granular tracker
  - Cover η range of $-2.5 \leq \eta \leq 2.5$
  - Survive radiation fluency of $5\text{x}10^{14}\ \text{cm}^{-2}\ \text{s}^{-1}$ at radius 7cm
  - Important for t, b, c quark and τ lepton identification
- Barrel Pixel Detector (BPix)
  - 3 layers at radii 4.3, 7.2, and 11.0 cm
  - 768 modules, 11520 Read-Out Chips (ROCs), ~48 million pixels
- Forward Pixel Detector (FPix)
  - 2 disks at Z= 34.5 and 46.5 cm
  - 672 modules, 4320 ROCs, ~18 million pixels

Silicon Pixel Readouts

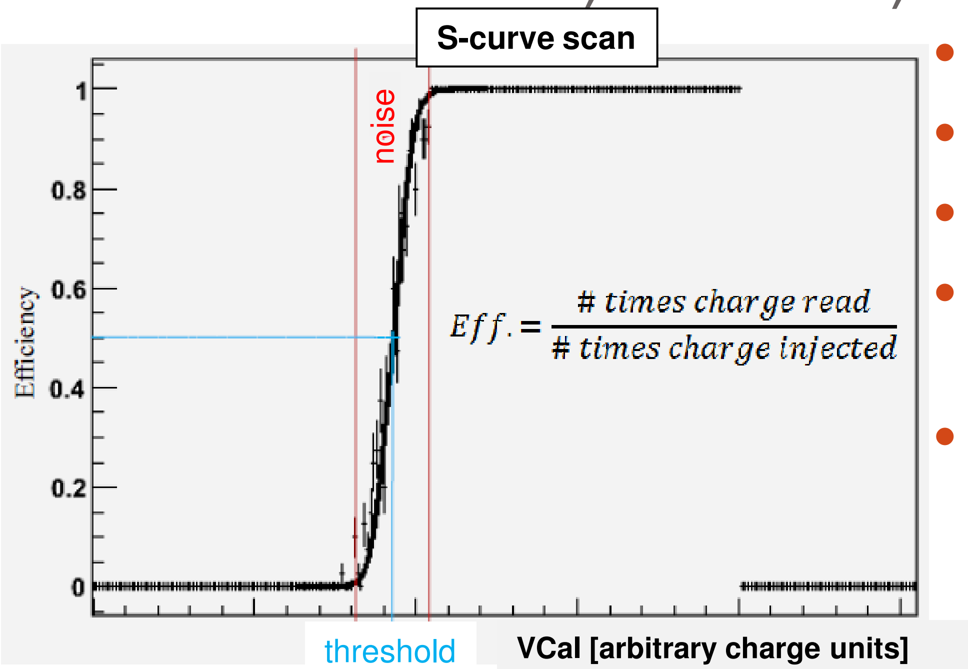


- 4160 pixels bump bonded to each ROC
- Pixel size is 100x150µm
- Automatic zero-suppression
- Programmable pixel thresholds

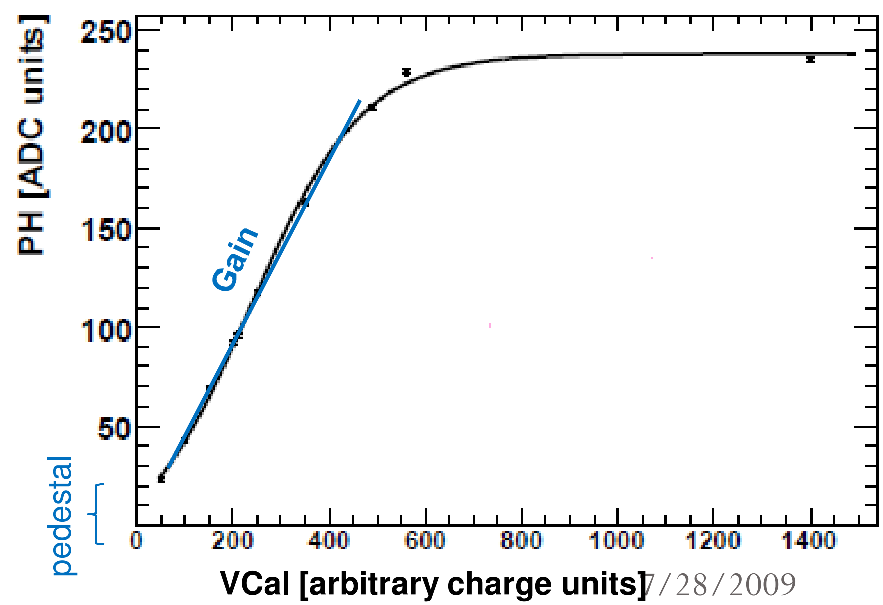
- Ionizing particle traversing Si liberates e^- (minimum 22ke)
- ~450 mV bias and 3.8T B-field lead to charge smearing, improved resolution
- Expected Lorentz Angle:
  - 24.3° BPix, 4.6° FPix



Thresholds, Noise, Gain, and Pedestal



- VCal: test charge injected by local capacitor
- Threshold: value of VCal at 50% efficiency
- Noise: width from 0-100% efficiency
- For threshold and noise, only 81 cells per ROC are measured
- VCal varies, on average: $e^- = 65.5 * VCal - 410$



- ADC charge conversion described by

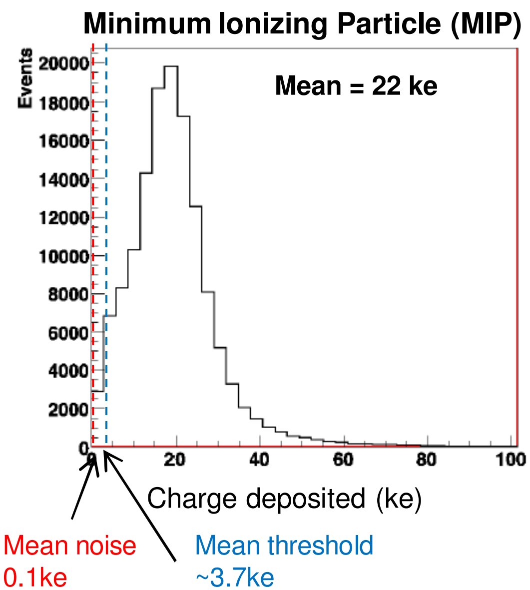
$$ADC = p_3 + p_2 * \tanh(p_0 * VCal - p_1)$$

  but linear approximation used for calibration
- Gain: mean slope of ADC/test charge
- Pedestal: ADC offset (y-intercept)
- Pedestals stored per pixel, gains stored per ROC column

Thresholds and Noise

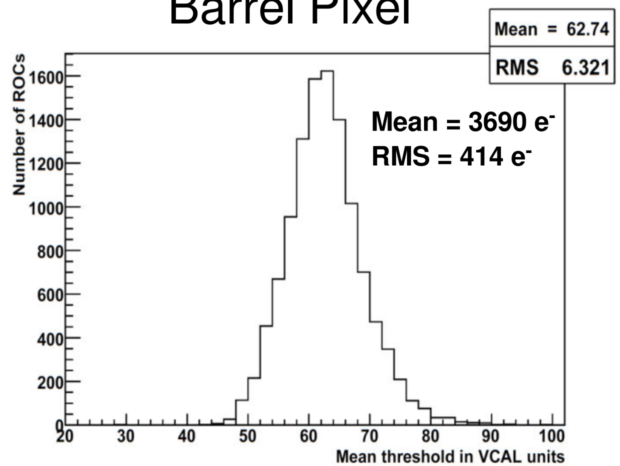
(D. Kotlinski)

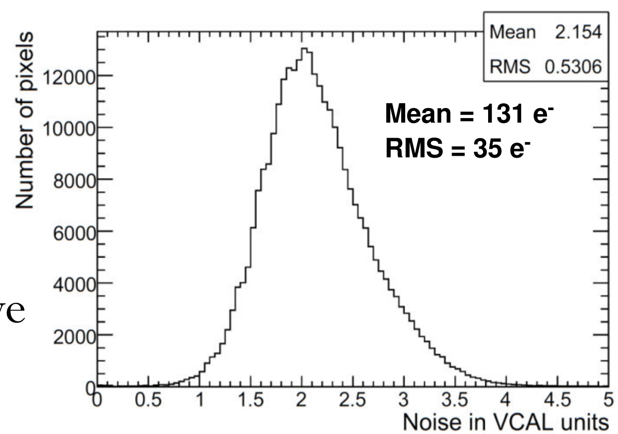
- Keep in mind scale:



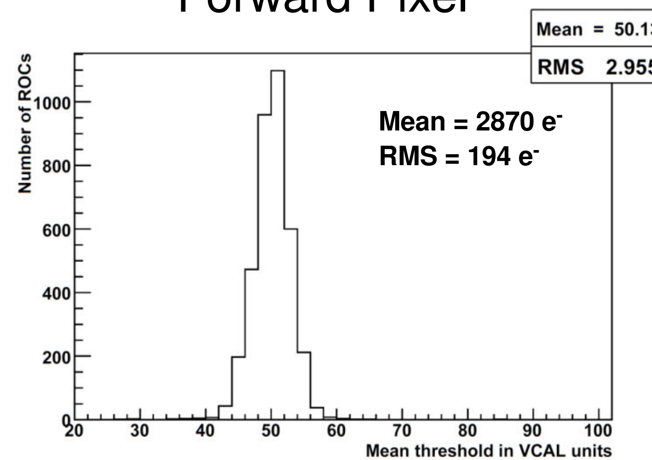
- Threshold and noise have no adverse impact on detector performance

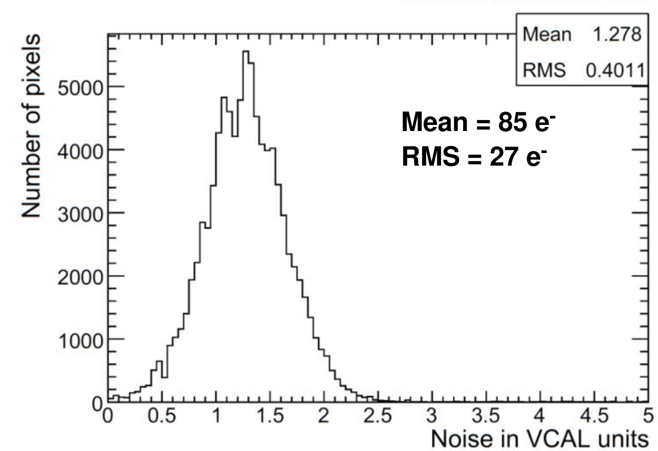
Barrel Pixel





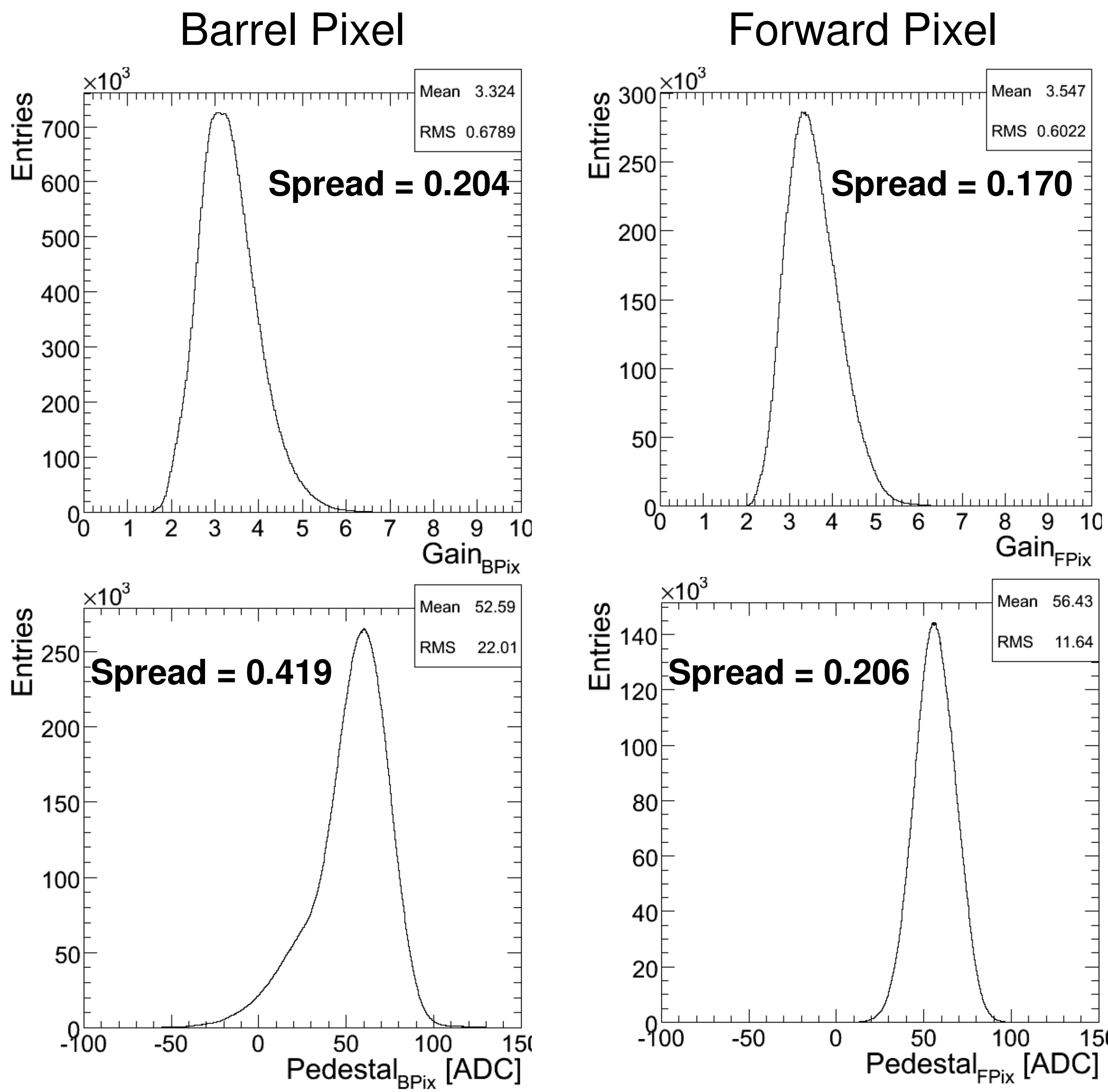
Forward Pixel





Gain Calibration

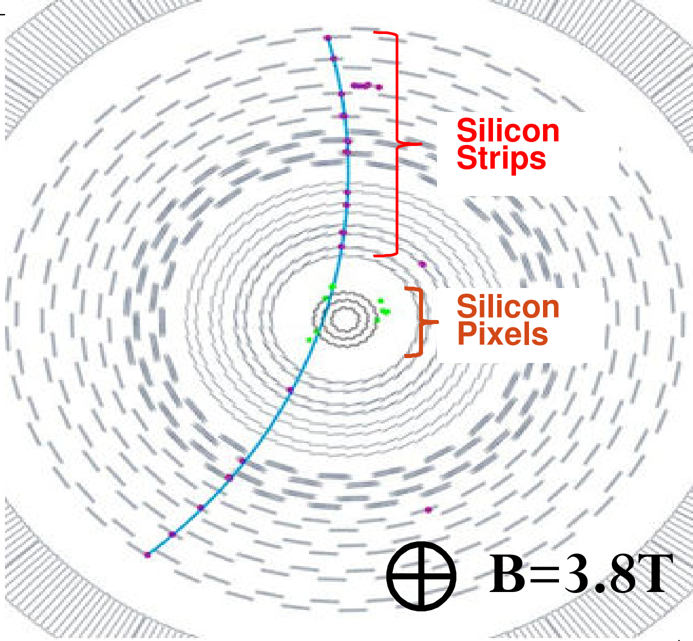
(F. Blekman, R. Rougny, B. Heyburn)

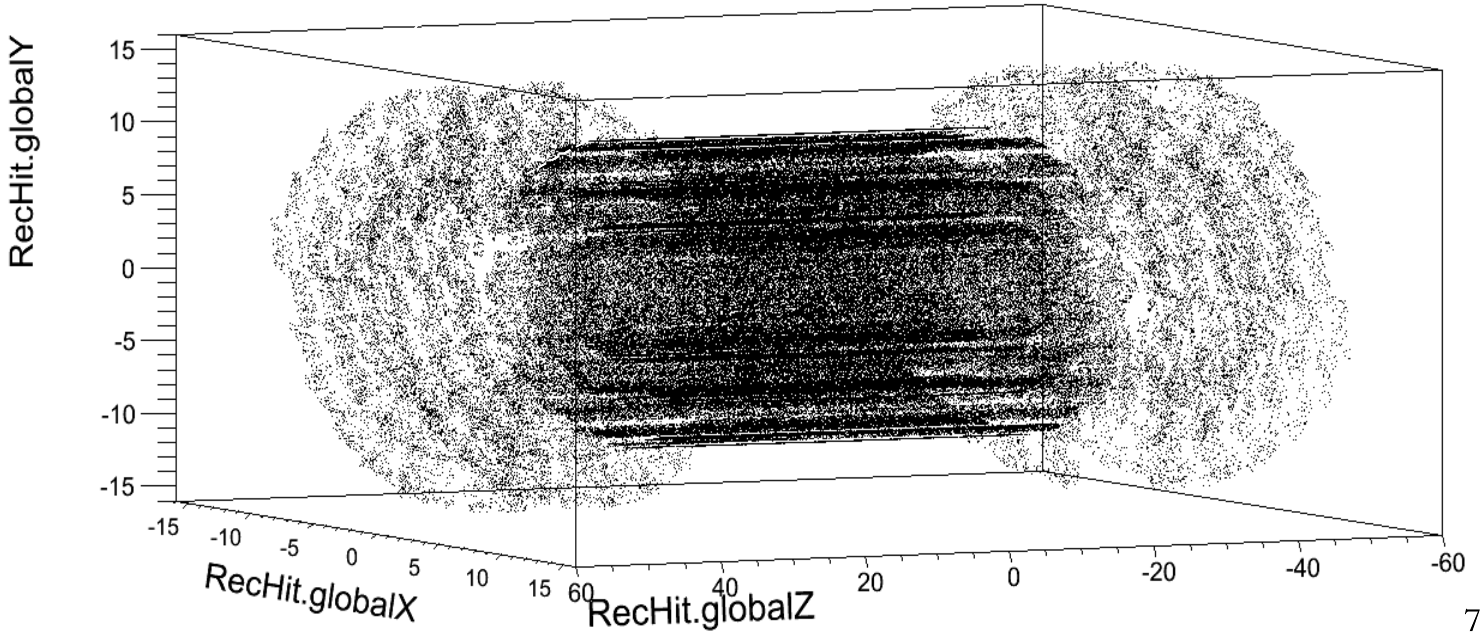


- Linear fit of ADC to VCal test charge:
  - Pedestals stored per pixel
  - Gains stored per ROC column
- These constants used in CRAFT reprocessing

Cosmic Ray Studies

- CRAFT 2008 data taking
  - Cosmic events triggered at each subdetector except Pixel
  - Cross-section (and rates) for cosmics highest for outer layers
- ~85000 tracks in Pixel
- Avg. 3.01 pixel hits/pixel track
- 256800 pixel clusters





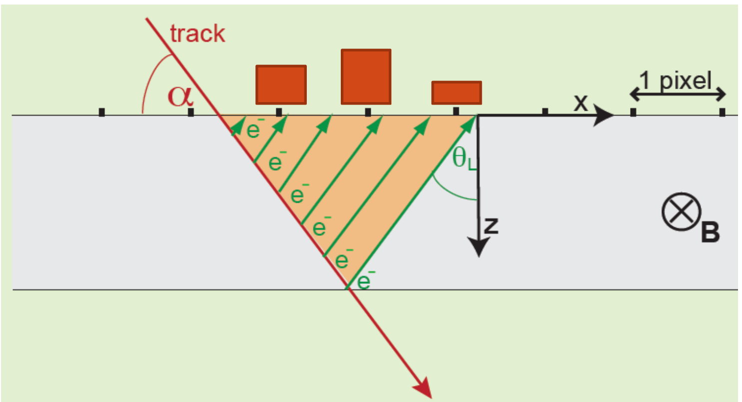
Noisy Pixels

(P. Merkel)

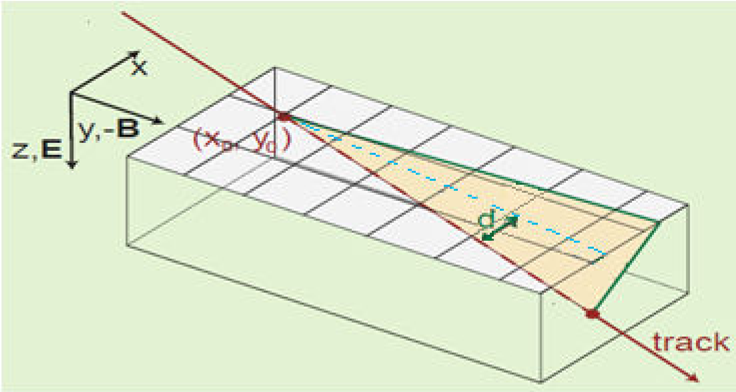
- Noisy pixels detected via the Pixel Data Quality Monitoring (DQM) package
  - Can be done real time or offline (running on reprocessed data)
  - Counts number of events in which a pixel registers a charge above threshold, and divides by the total number of events – the **"digi event rate"**
- Cutoff: digi event rate > 0.001
  - Barrel: 235 noisy pixels
    - One full column
    - Two full rows
    - 51 individual, randomly distributed pixels
  - Forward: 17 noisy pixels, all randomly distributed
- Noisy pixels masked during data taking
- Tightening cutoff to 0.0001 results in only 13 additional pixels noisy (not currently done)
- Number of noisy pixels is very small: **.00038% of total pixels**

Lorentz Angle Studies

Cluster Size Method



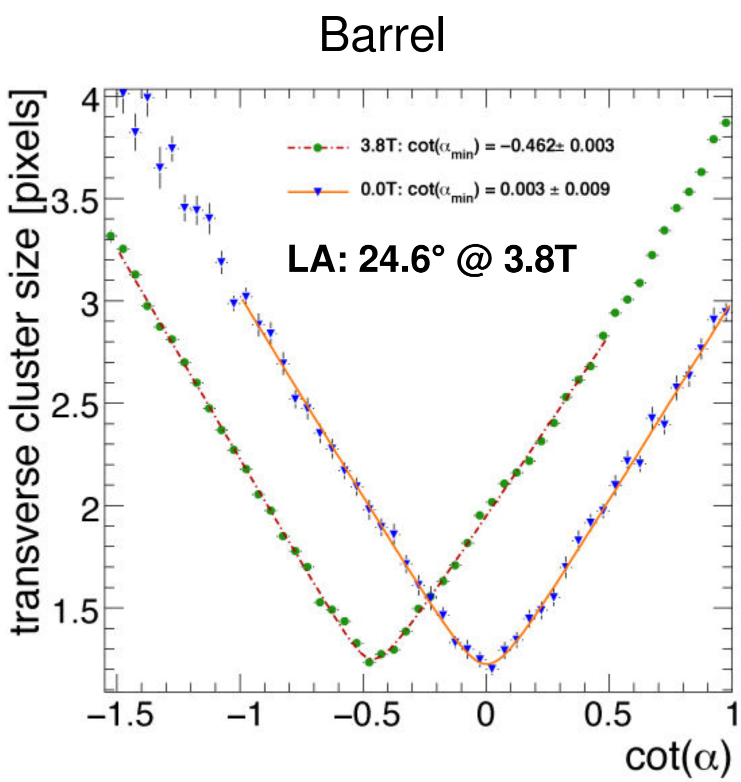
Collision Method

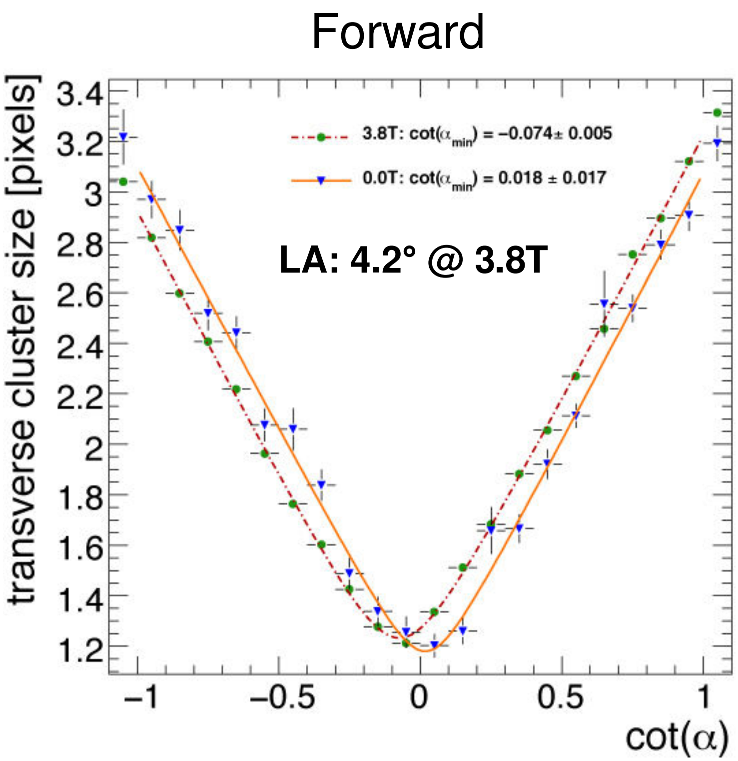


- Lorentz Drift of electrons liberated by particle tracks allows for charge smearing and better position resolution in Pixel
- Cluster Size Method attempts to measure Lorentz Angle (θ_L) based on cluster size in X and angle of track on det in XZ
  - Will not work for collisions (tracks perp. in XZ), but more suitable for cosmic rays
- Collision Method attempts to measure Lorentz Angle (θ_L) from deflection (d) b/t center-line of charge deposit and reco track
  - Relies on clusters long in local Y (direction of B-field)

Lorentz Angle Results

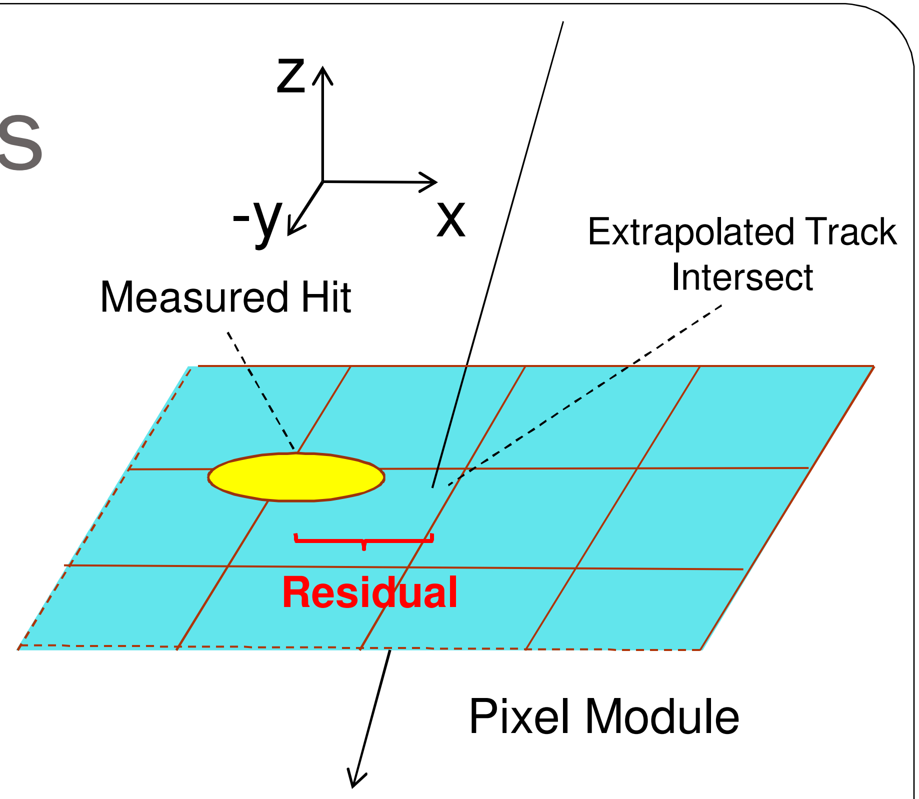
(L. Wilke, A. Kumar, M. Schwartz)





- Cosmic Data: Barrel 24.6±0.2° Forward: 4.2±0.3°
- Monte Carlo: Barrel 24.3° Forward: 4.6°

Track Fit Residuals



$$\Delta X_{resid} = X_{pred^*} - X_{meas}$$

* Predicted position determined by refitted track with hit removed

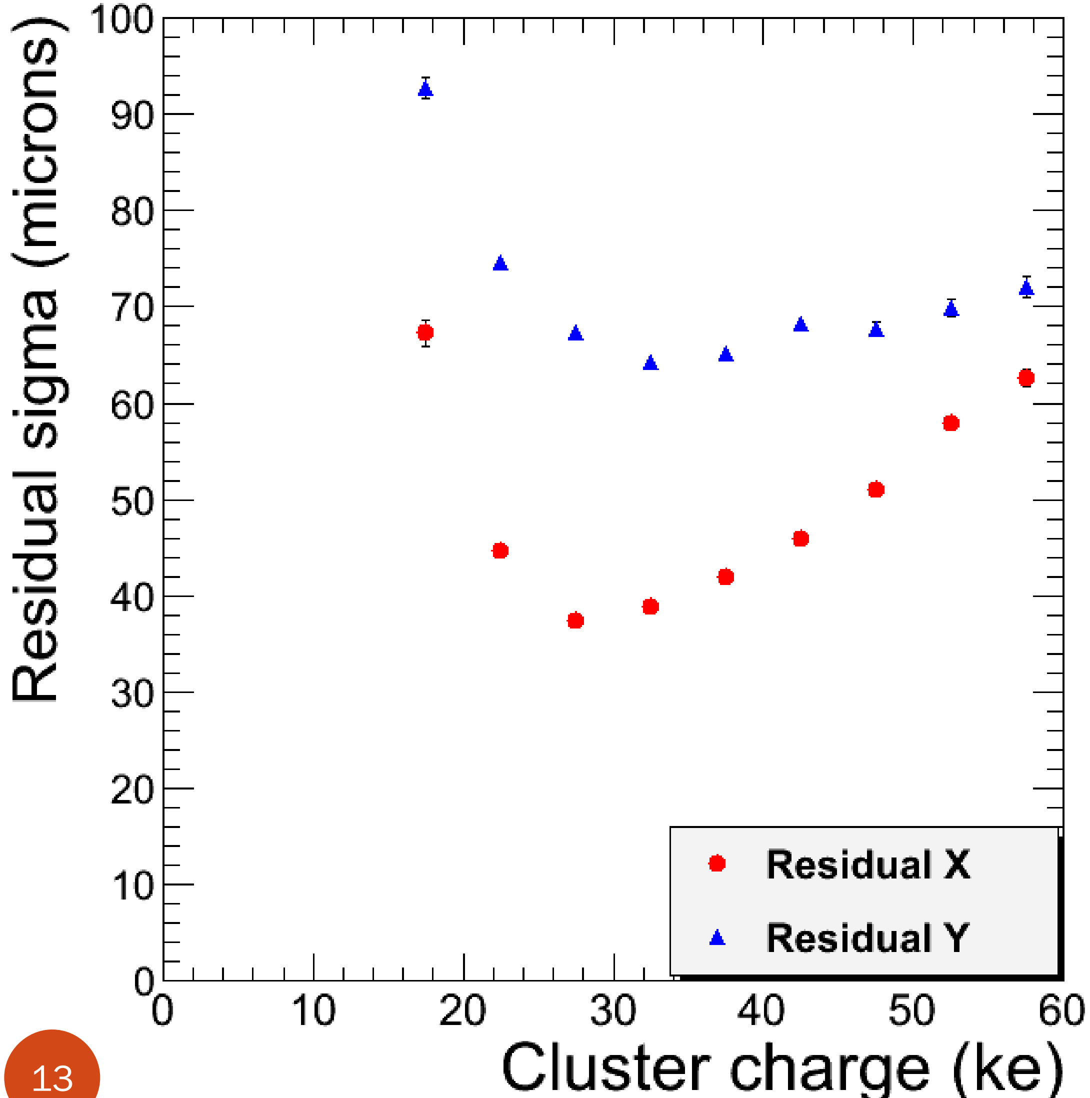
σ_{resid} of Gaussian fit is a measure of uncertainty

$$\sigma^2_{resid} = \sigma^2_{track} + \sigma^2_{align} + \sigma^2_{MS} + \sigma^2_{pixel}$$

σ_{track}	- error of track fit
σ_{align}	- alignment error per module
σ_{MS}	- error due to multiple scattering in previous layer
σ_{pixel}	- intrinsic resolution of Pixel

Residual vs Charge Deposited

(A. York)



- Cuts:
  - Track pt>10 GeV/c
  - Track angle within 30° of perpendicular to module
  - Edge hits and broken clusters removed
- MIP deposits 22 ke
- Overall residual sigmas in collision range:

  σ_x - avg: 41 µm

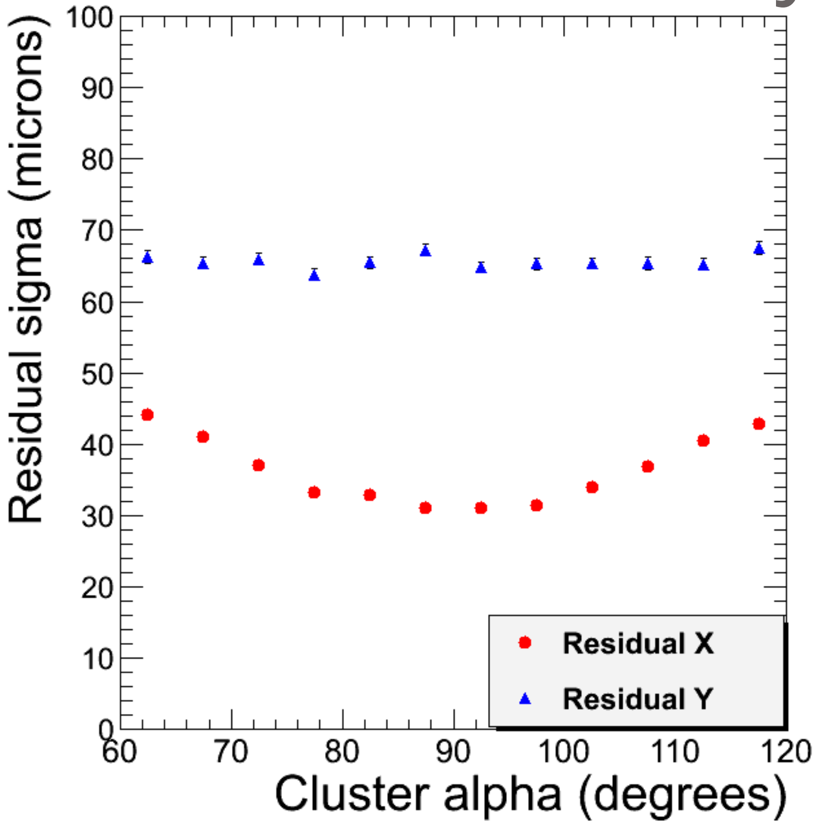
  best deposits: 37 µm

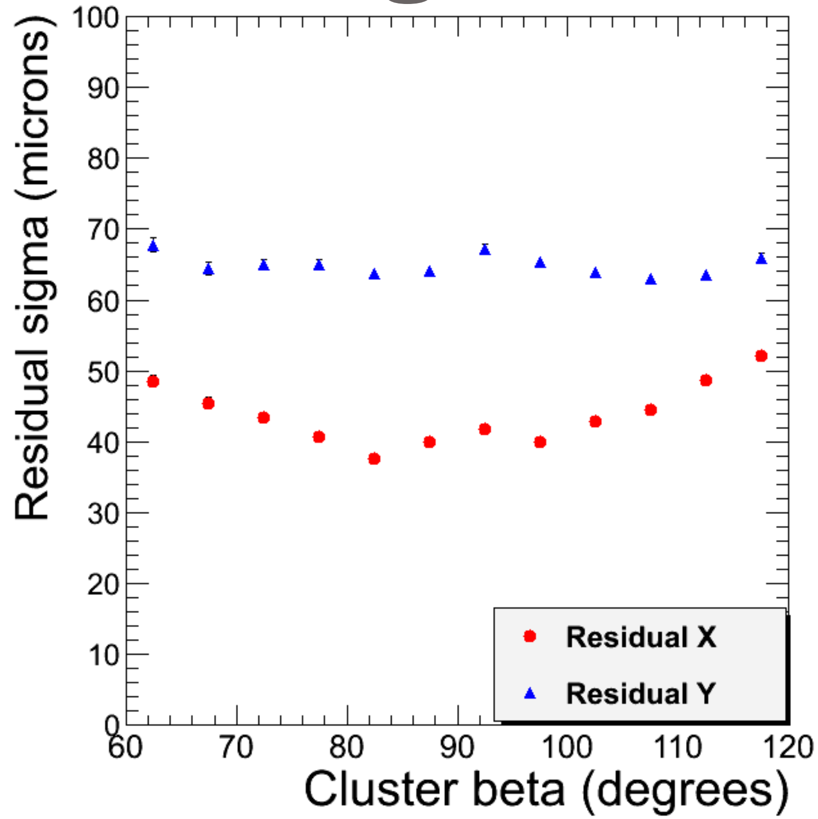
  σ_y - avg: 69 µm

  best deposits: 63 µm

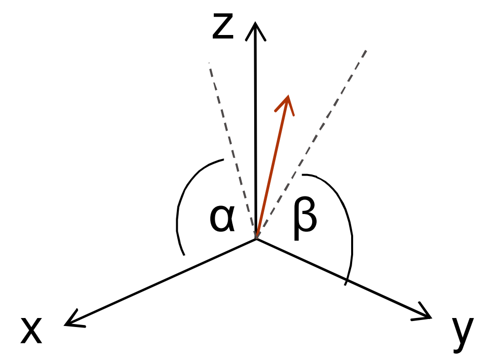
Residuals by Track Angle

(A. York)



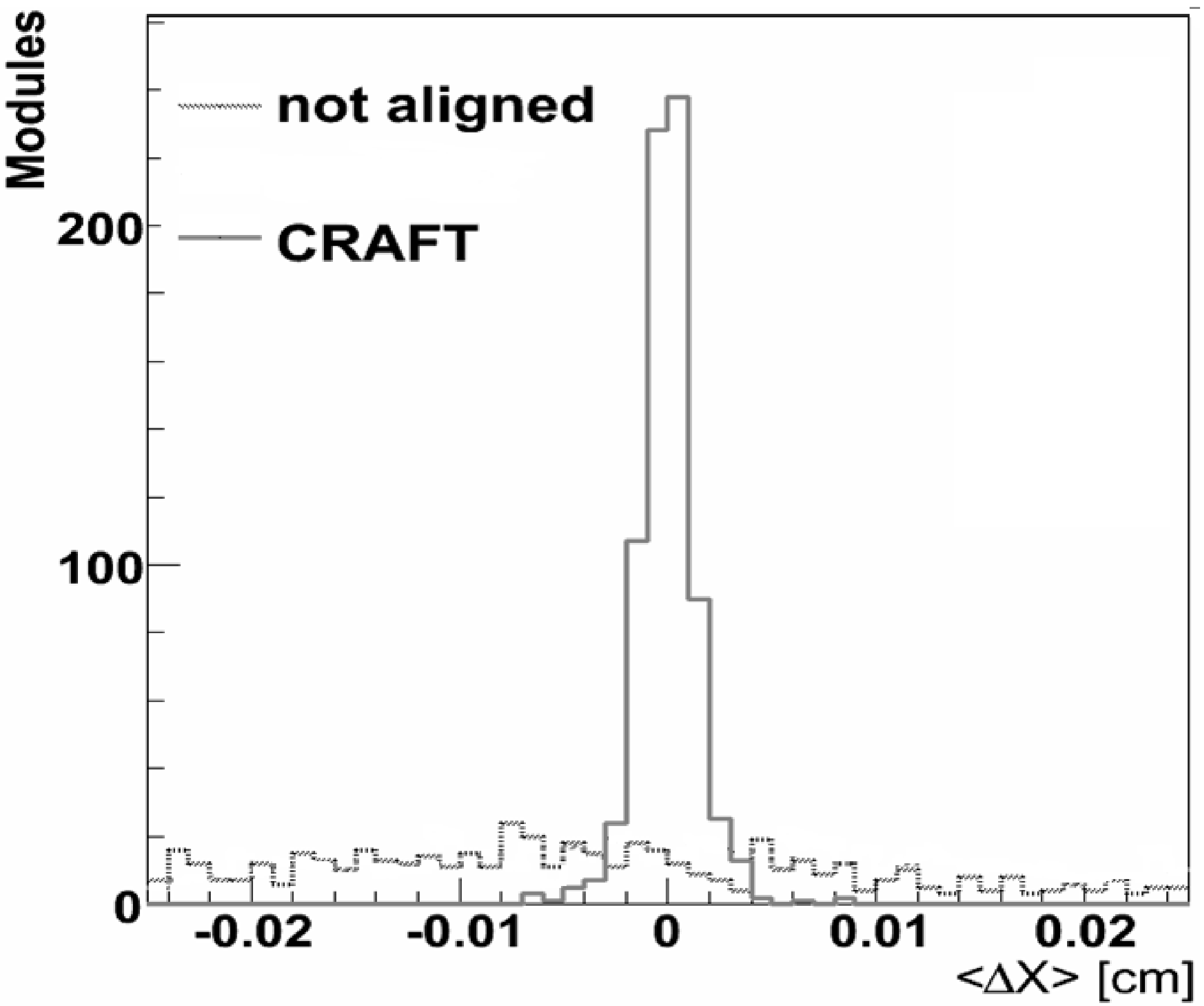


- Residual about twice as small in local X as Y due to charge sharing, best at β slightly off perpendicular
- Y-residual relatively flat, X-residual higher at extreme angles (threshold effects)



Pixel Alignment

(A. Bonato, N. Tranh)



- CRAFT provided opportunity for first Pixel alignment
- Align using residual information
- σ_{align} of 14 μm appears achievable

Pixel Resolution

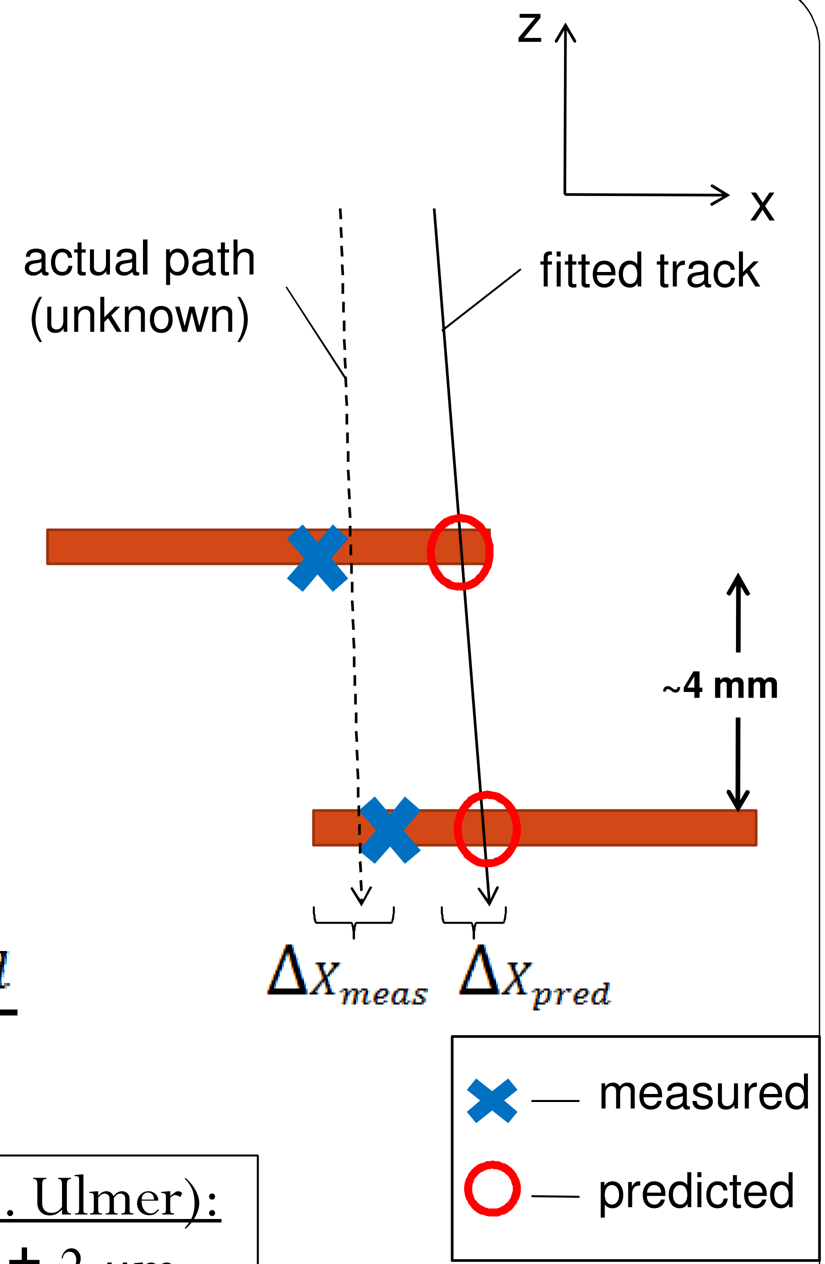
- Method:
  - Find overlap hits in same layer and refit track to exclude them
  - Define "Double Difference":

$$DD = \Delta X_{meas} - \Delta X_{pred}$$

- In principle,

$$\sigma_{DD}^2 = \sigma_{meas}^2 + \sigma_{pred}^2$$

$$\sigma_{pixel}^2 = \frac{\sigma_{meas}^2}{2} = \frac{\sigma_{DD}^2 - \sigma_{pred}^2}{2}$$



σ_{pixel} results (K. Ulmer):

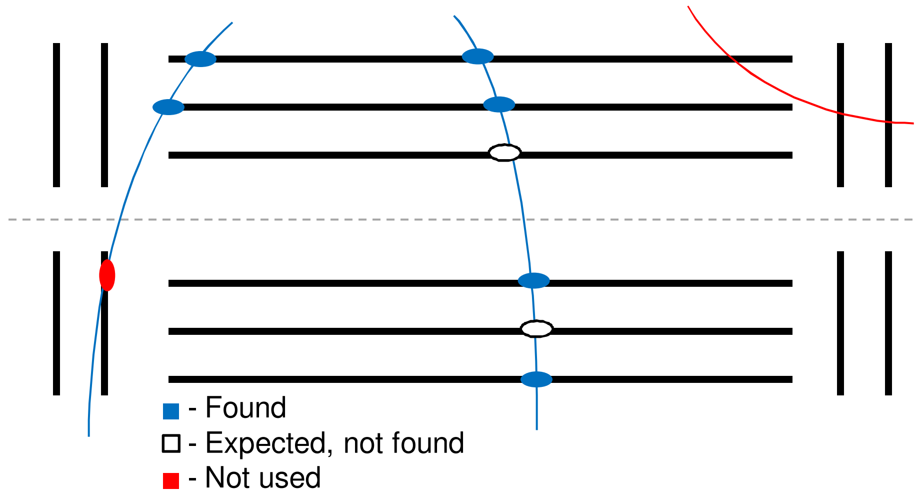
$\sigma_x = 16 \pm 2$ μm

$\sigma_y = 29 \pm 3$ μm

Pixel Hit Efficiency

(L. Mucibello, R. Rougny, N. Van Remortel)

$$Eff. = \frac{\#\ hits\ found\ on\ modules}{\#\ hits\ expected\ on\ modules}$$

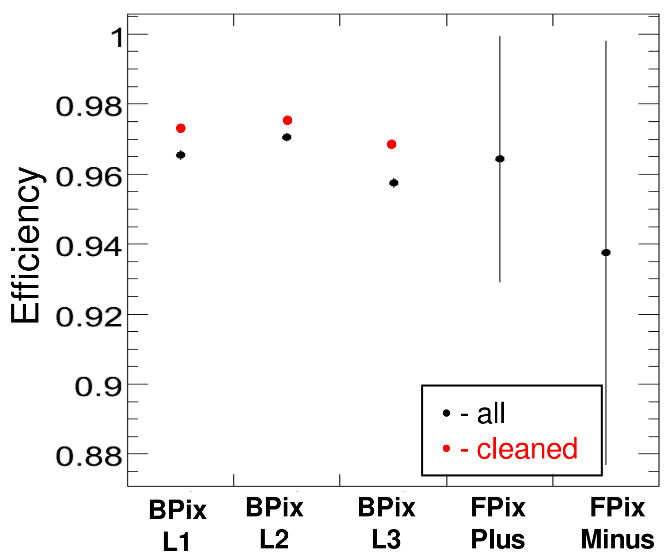


Cuts:

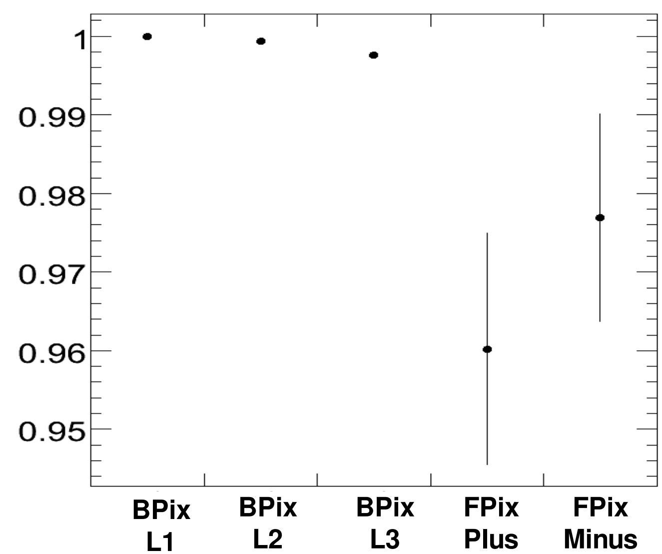
- Additional pixel hit in upper and lower Pixel regions (in global Y)
- $> \sigma_{track}$ from module edge
- pt >10 GeV/c
- 1 track/event

"cleaned" results have known problematic modules removed

CRAFT



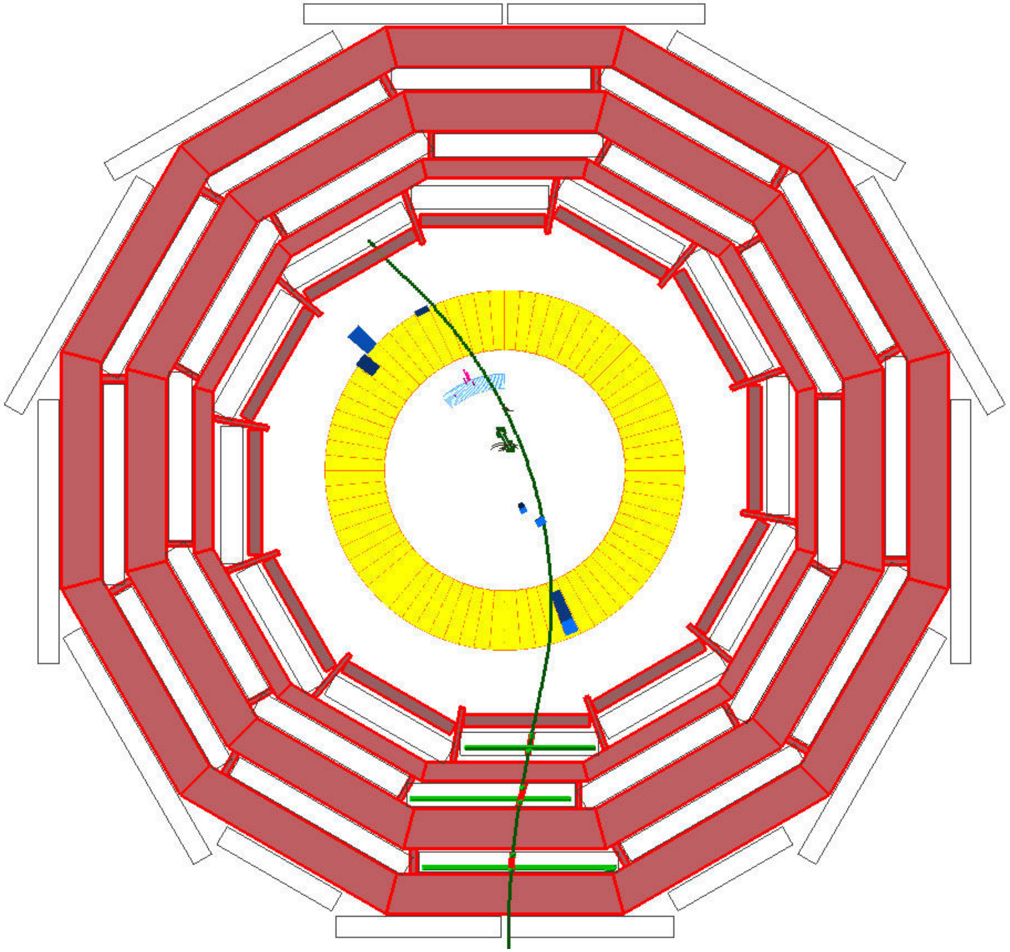
Monte Carlo



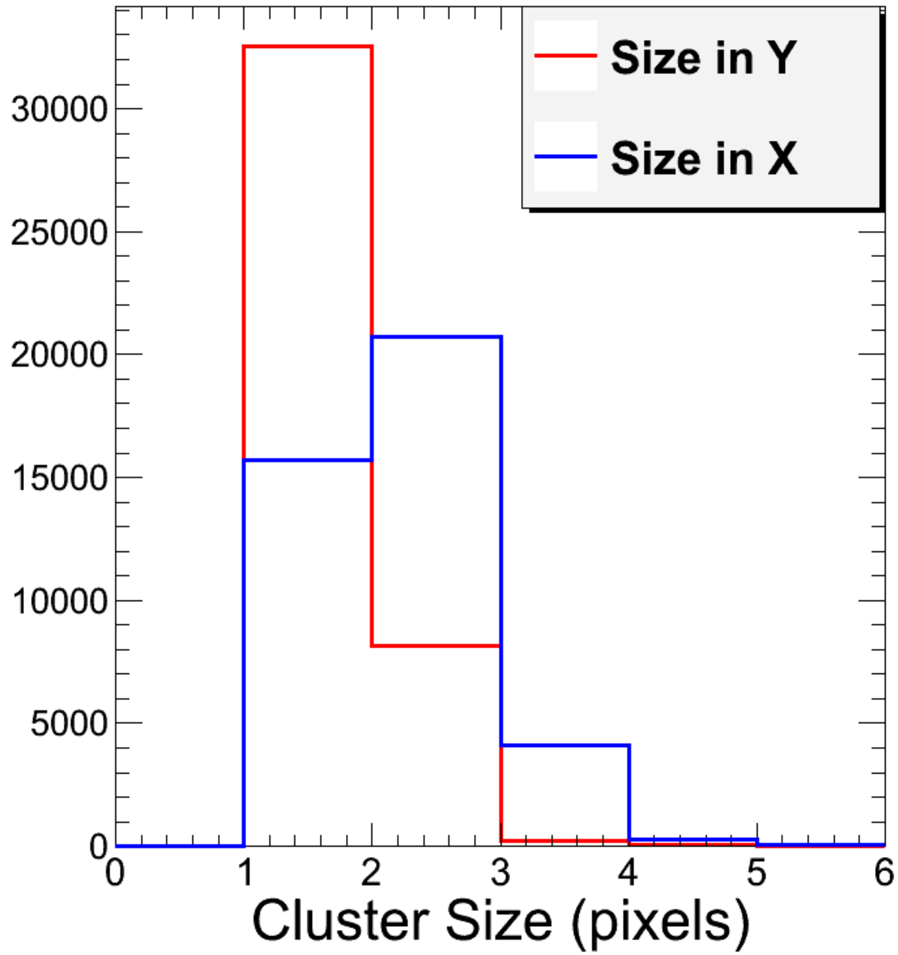
Closing Remarks

- Results of calibration (thresholds, pedestals, gain, and noise) found and used for CRAFT 2008
- Noisy pixels identified and masked (0.00038% of total)
- Lorentz Angle calculated using data (BPix: 24.6°, FPix: 4.2°)
- Pixel residual studies performed using cosmics
  - Total unbiased residuals in ~30-60 μm range
  - Alignment of 14 μm precision achievable
  - Pixel resolution found to be ~15-30 μm
- Efficiency studies find ~97% efficiency in Pixel Barrel, fixes made during downtime
- Expect additional results from CRAFT 2009 data taking

Backup



Cluster Shape

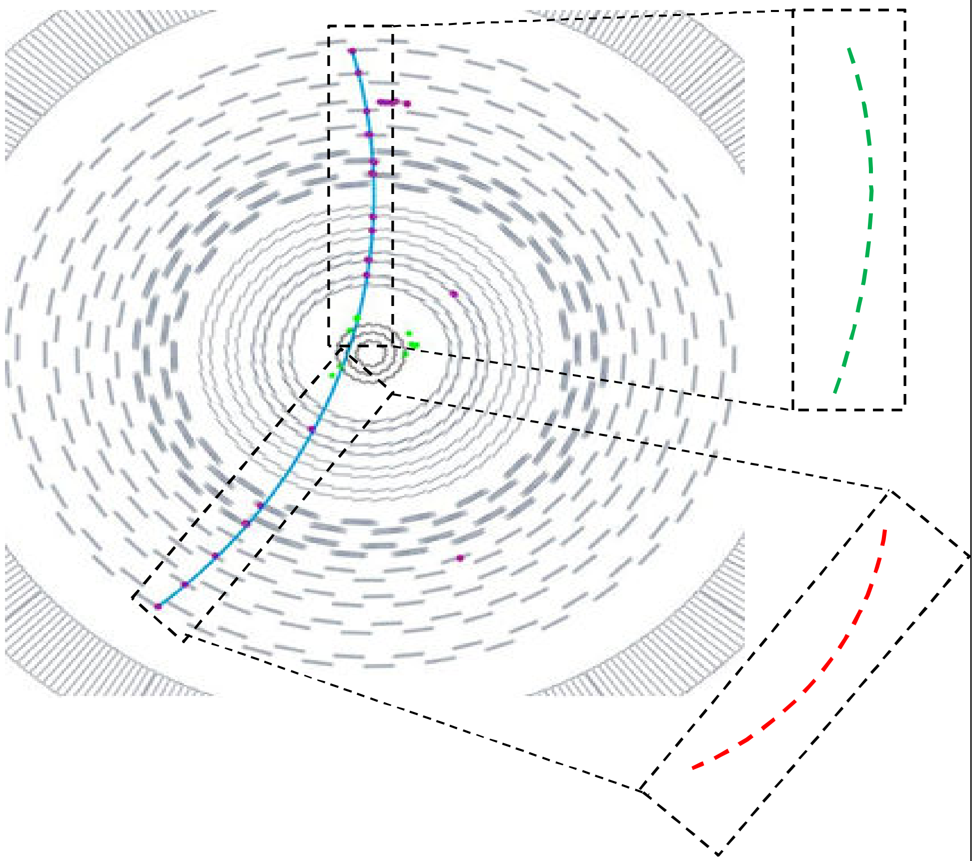


- Only considering Pixel Barrel
- Requirement for selection:
  - Track p>10 GeV/c
  - Track angle within 30° of perpendicular to module
  - Edge hits and broken clusters removed
- B-field in Y, Lorentz drift in X

Split Track Residuals

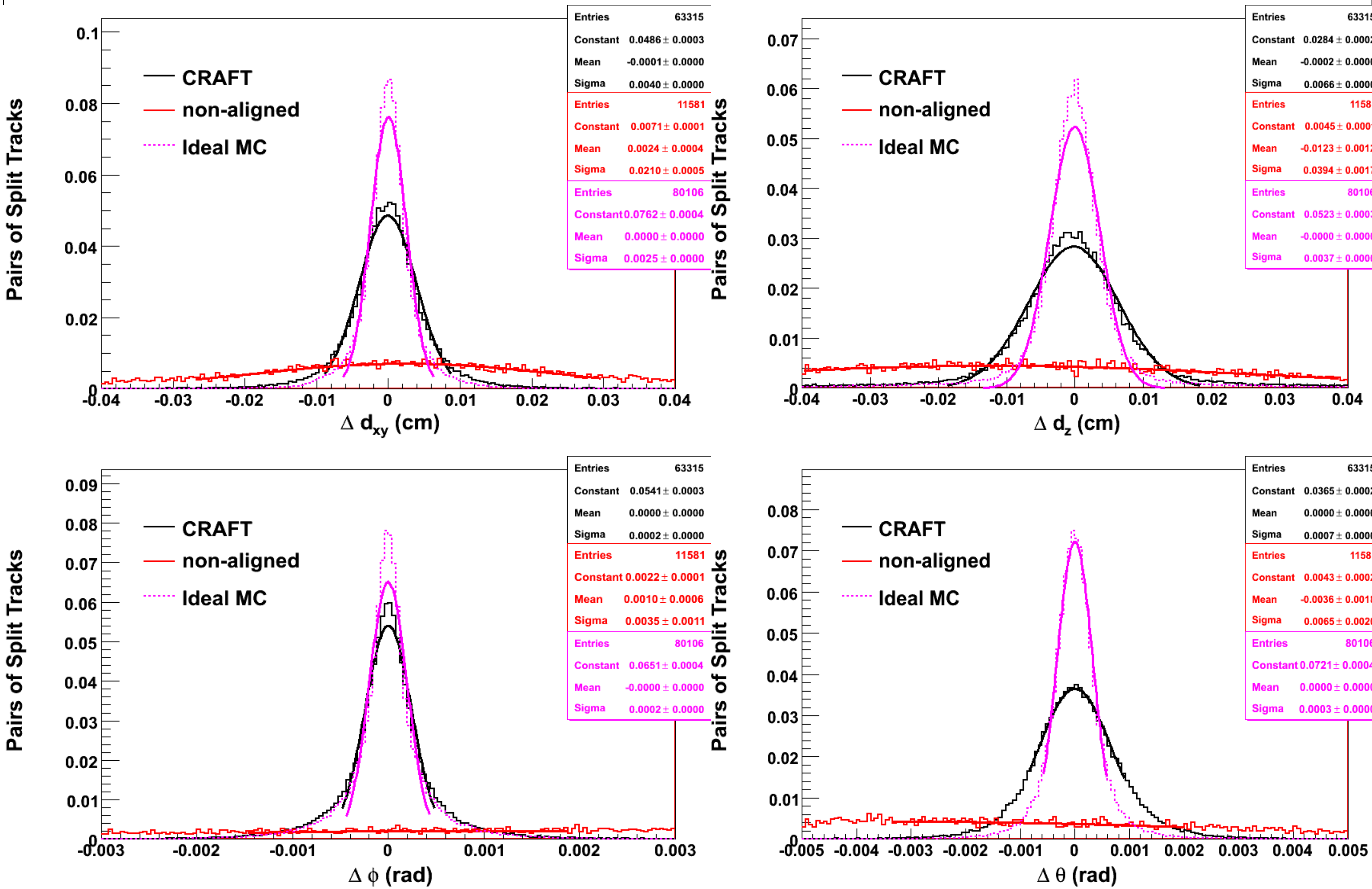
- Method:
  - Split cosmic track into two at closest approach to beamline
  - Refit each track separately
  - Compare differences in split track variables according to:

$$\delta u = \frac{(u_1 - u_2)}{\sqrt{2}}$$



- Cuts applied to tracks:
  - Split tracks have at least 6 hits
  - Original track has pt > 4 GeV, $\chi^2 < 100$, at least 10 hits (with 2 in Pixel Barrel)

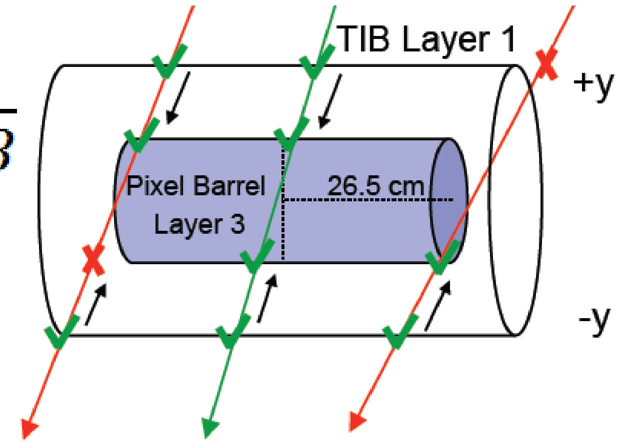
Split Track Method Results (A. Bonato, N. Trahn)



Pixel Barrel Track Efficiency

(M. Lebourgeois, B. Mangano)

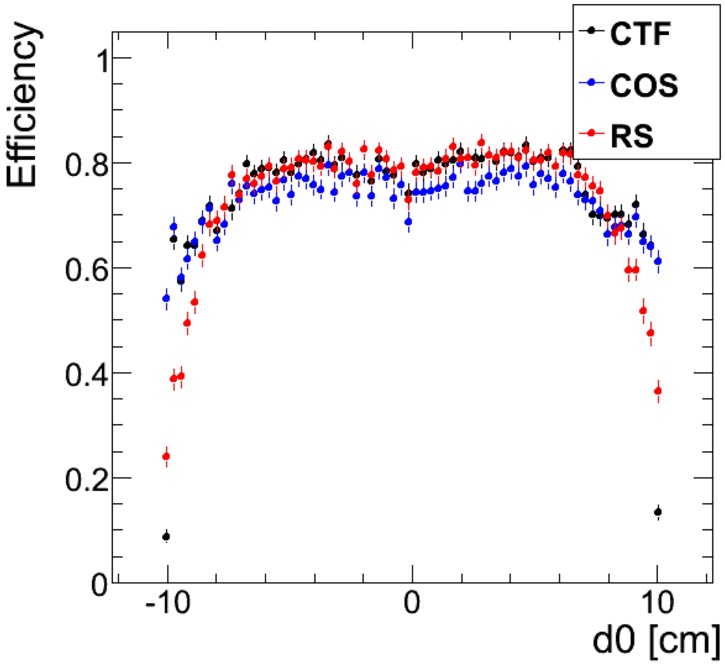
$$Eff. = \frac{tracks\ with\ \#\ hits > 1\ in\ PXB}{tracks\ propagating\ through\ PXB}$$

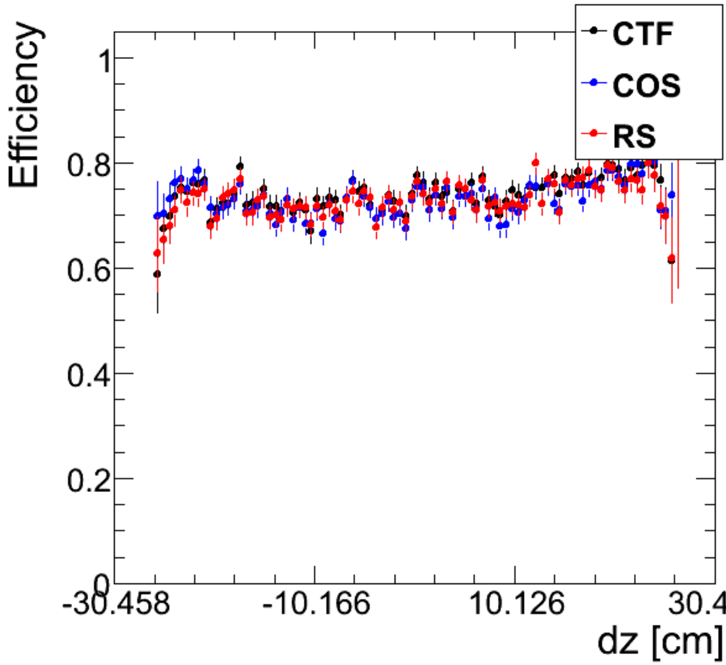


- Cuts:
  - pt > 20 GeV

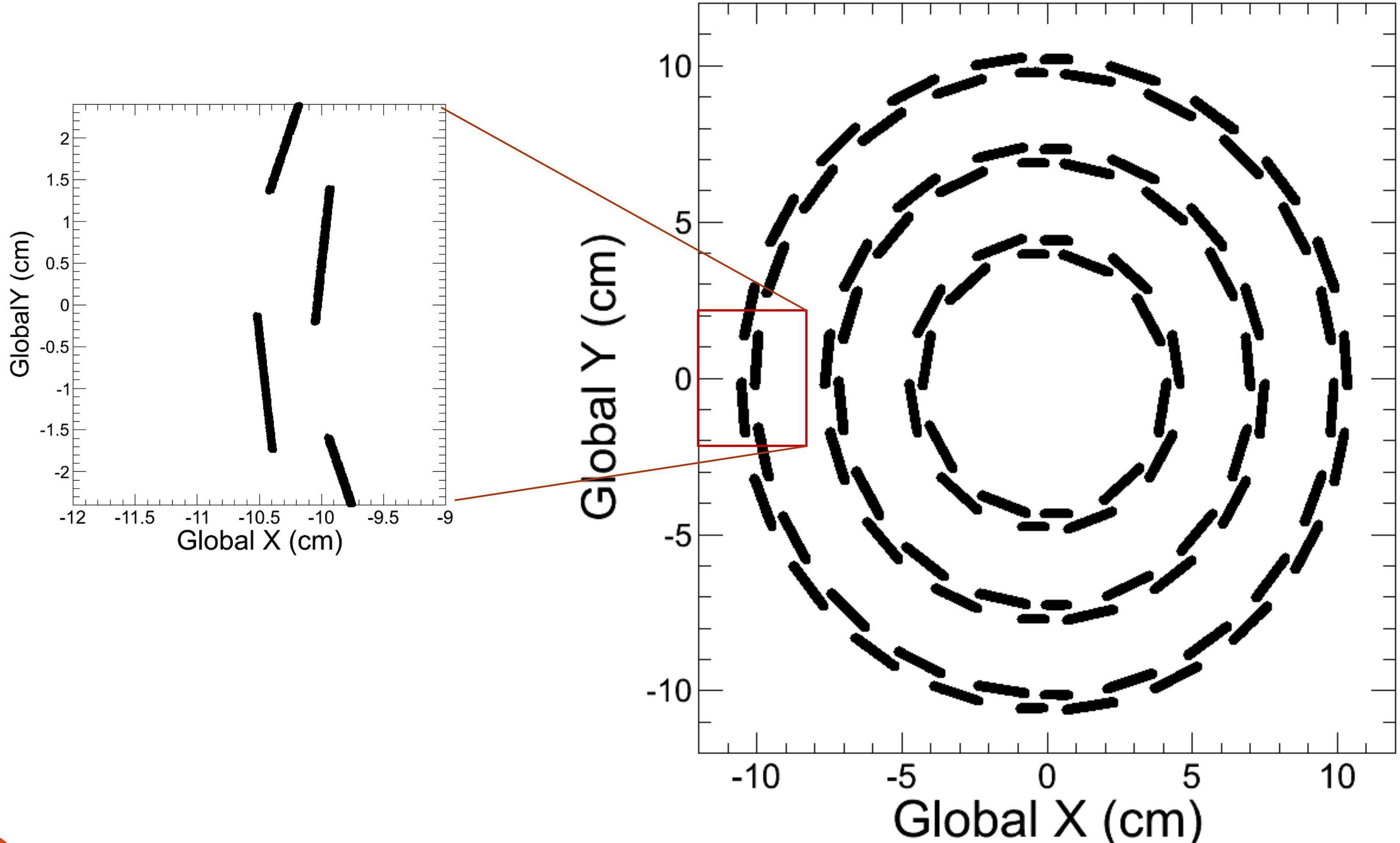
<u>Note</u>

- Matches MC results
- Eff. for RS drops at low pt
- Efficiency result of timing, track algorithm, alignment, sensor efficiency, etc.

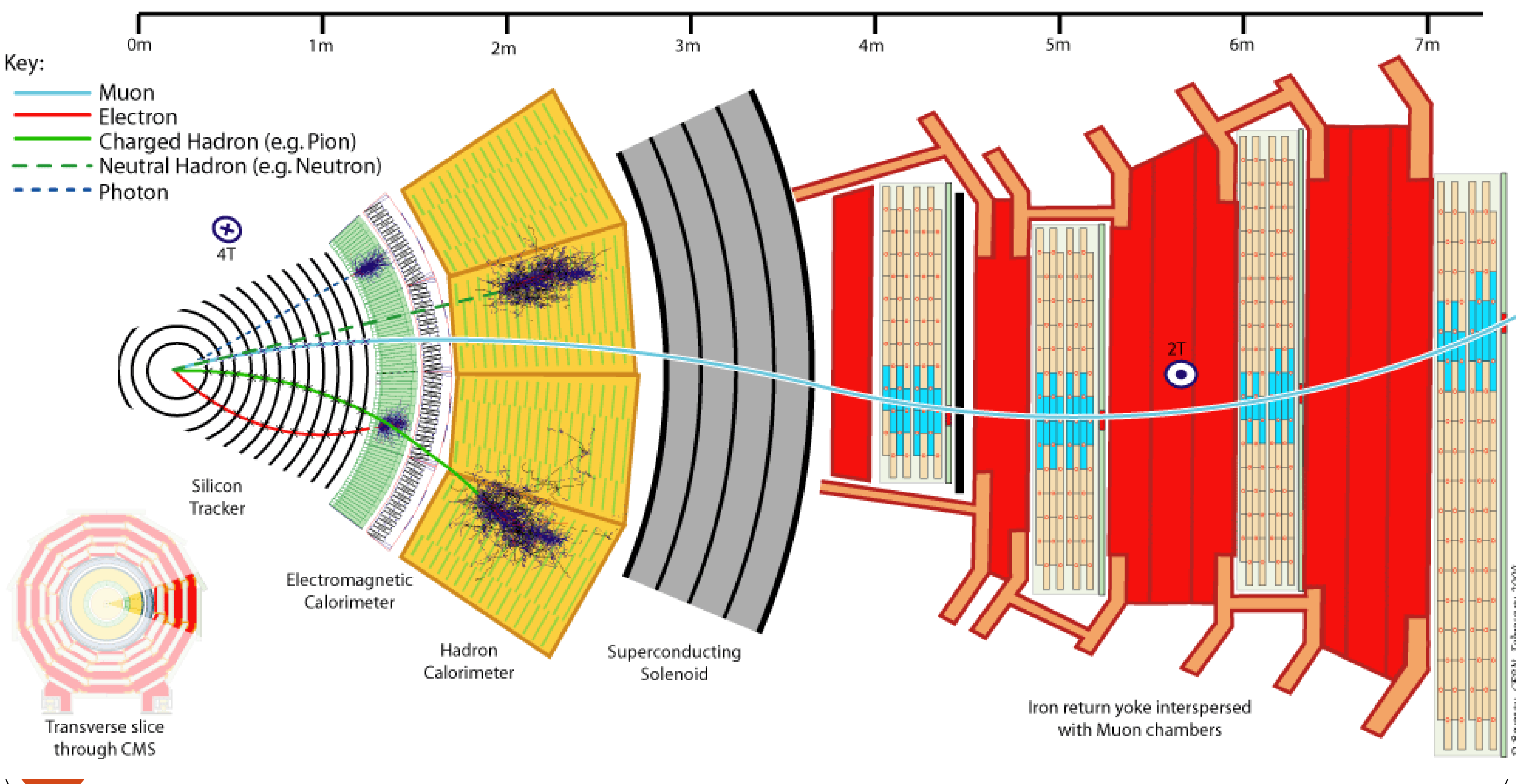




Distance between Overlap Modules

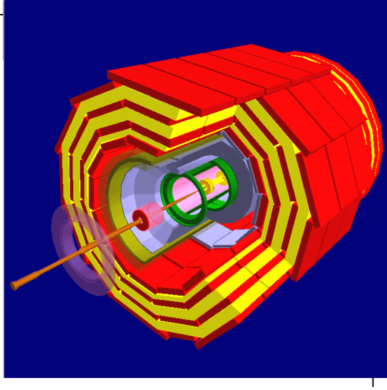


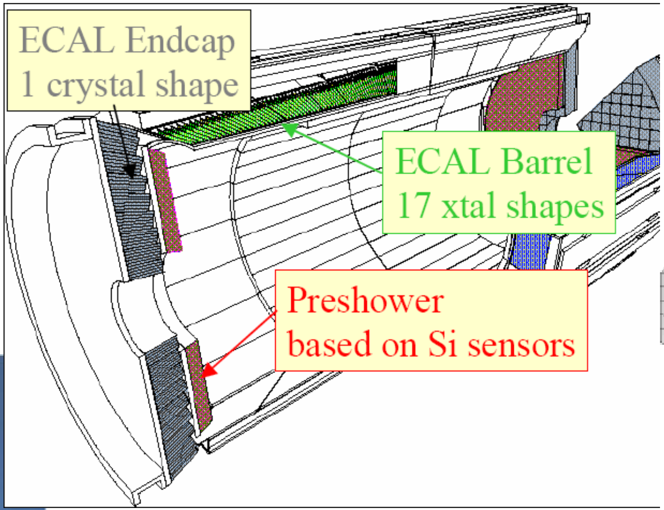
CMS Events

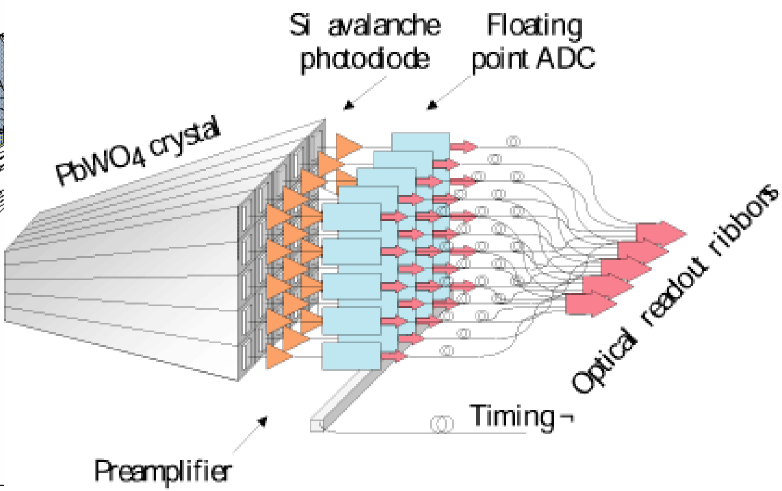


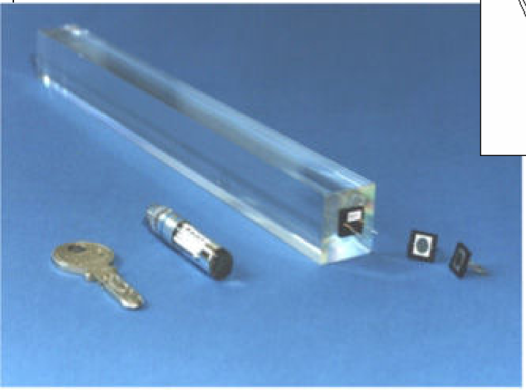
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Electromagnetic Calorimeter (ECAL)



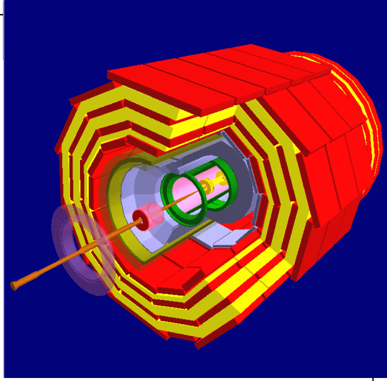


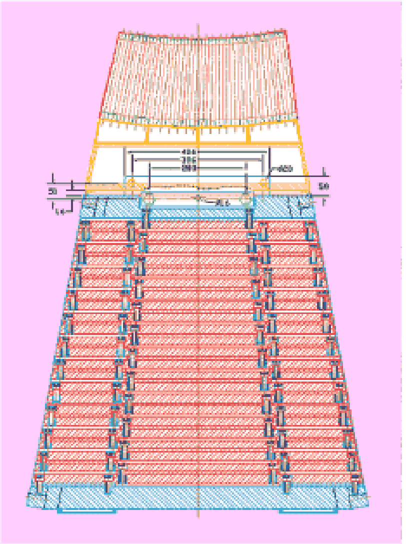


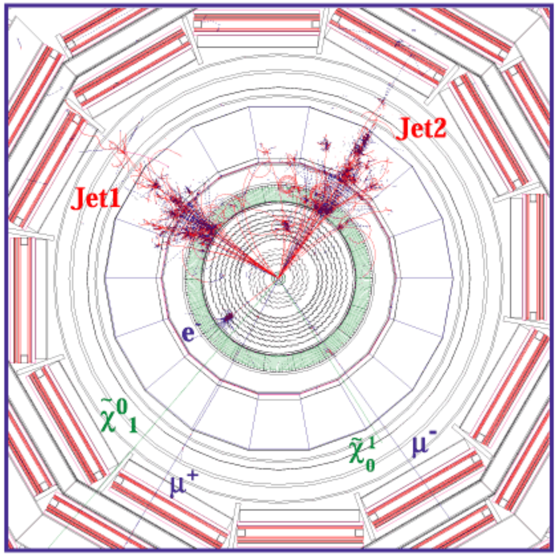


- Measures (absorbes) energy of electrons and photons
- Lead tungstate crystal chosen for high density, small Moliere radius, short radiation length
- Almost 80,000 crystals in total
- Preshower detector on endcaps assists identification

Hadron Calorimeter (HCAL)

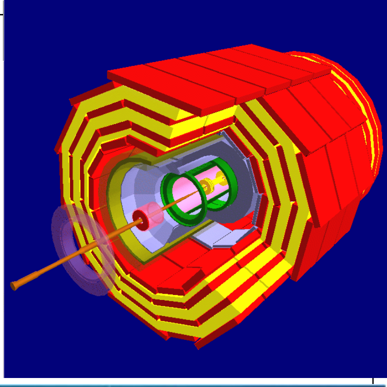


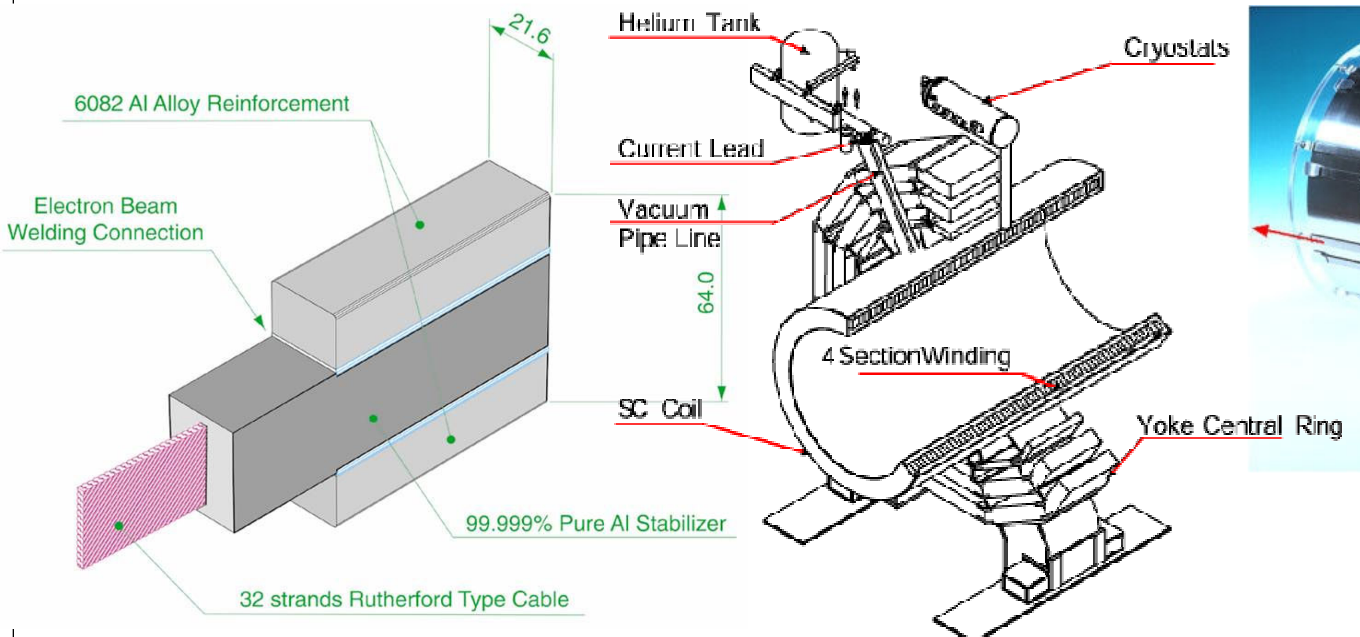


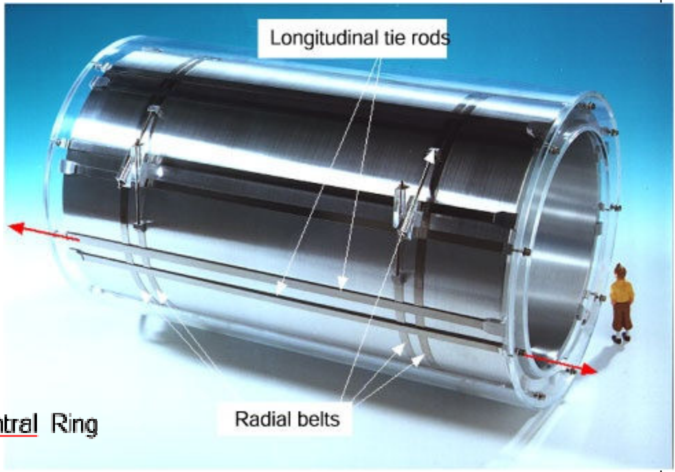


- Measures (absorbes) energy of hadrons (protons, neutrons, pions, kaons, etc)
- Made of alternating layers of brass (50 mm thick) and silicon strip scintillators (4 mm thick)
- Brass creates particle showers, Si detects products

Magnet

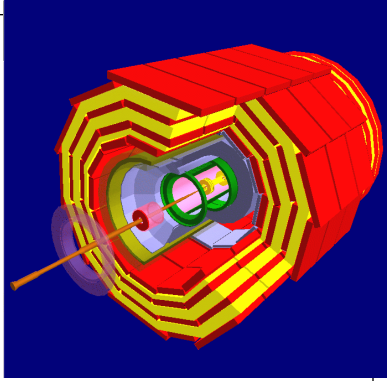


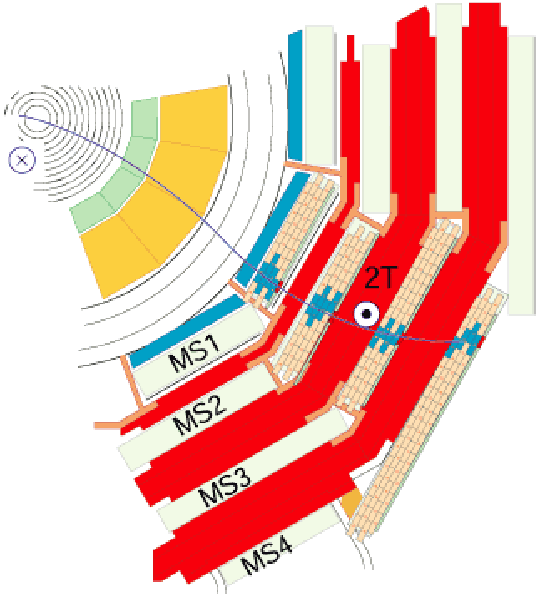


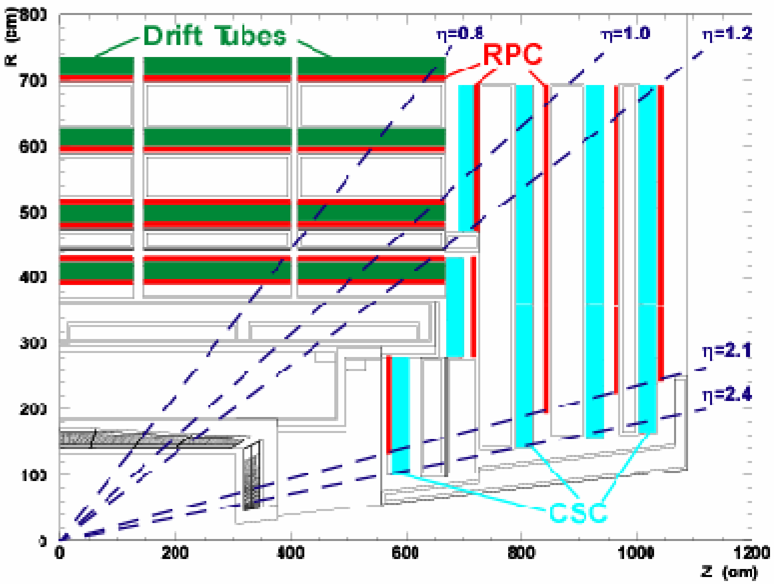


- Superconducting coil generates 4 T field inside
- Field deflects charged particles; enables charge/mass ratio calculations and improves resolution
- Coil made of niobium-titanium cable, stabilized by ultra-pure aluminum and strengthened by aluminum alloy

Muon Detectors and Iron Return Yoke







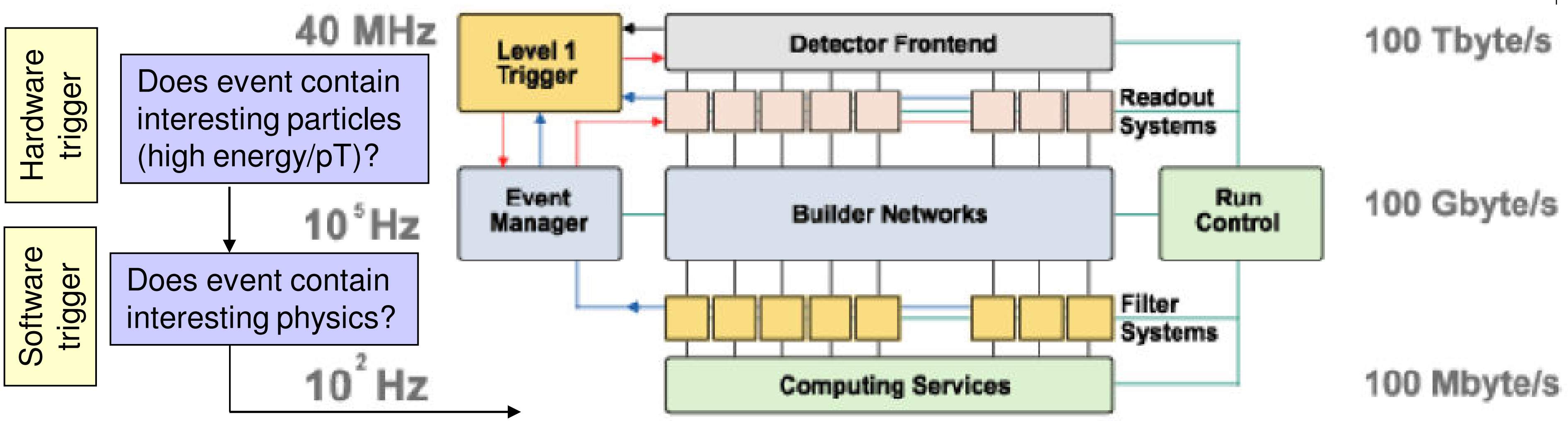
- Muon detectors interleaved with layers of iron yoke
- 3 types of detectors: Drift Tubes (DT) in central barrel, Cathode Strip Chambers (CSC) in endcaps, and Resistive Parallel plate Chambers (RPC) in both
- DT and CSC provide best spatial resolution (100 μm), RPC best time resolution (3 ns)

Muon Detectors

Detector	Drift Tubes	Cathode Strip Chambers	Resistive Plate	
Function	Tracking p_T trigger BXID	Tracking p_T trigger BXID	BXID p_T trigger Resolve tracking ambiguities	
region	0.0 - 1.3	0.9 - 2.4	0.0 - 2.1	
Stations	4	4	Barrel 6	Endcap 4
Layers	Rφ 8, Z 4	6	2	
Chambers	250	540	360	252
Channels	195000	Strips 273024 Wire groups 210816	80640	80642
Spatial resolution (σ)	per wire 250 μm Rφ (6/8 pts) 100 μm Z (3/4 pts) 150 μm	R (6 pts) 75 μm (outer CSCs) 150 μm R(6pts) $(15\text{-}50)/\sqrt{72}$ μm	Cell size	
Time resolution	5 ns	6 ns	3 ns	
Within 20 ns window	> 98% (station) no parallel B field	> 92% (station)	98%	

Trigger and Data Acquisition System (DAQ)

- ~10^{34} $n_{eq}/cm^2/s$ nominal luminosity means 20 events @ 40 MHz
- 100 Hz maximum archive rate for data farm
- Need powerful filtering mechanism



Trigger and Data Acquisition baseline structure