Performance of the CMS Pixel Detector

M. Swartz

Johns Hopkins University

CMS Pixel Detector: Design Philosophy

Facts:

- Use n-in-n sensors (collect electrons) for speed, charge coll after irrad.
- Must live in a 3.8T field
  - very large Lorentz width ~ 100μm in a 300μm thick sensor
- Optimal (analog) resolution in each projection occurs when projected cluster size is exactly two pixels
  - charge sharing allows precise interpolation of hit position
- Radiation damage will reduce sharing with time
- 0.25μm CMOS technology permits readout chip area of 15kμm^2 per cell

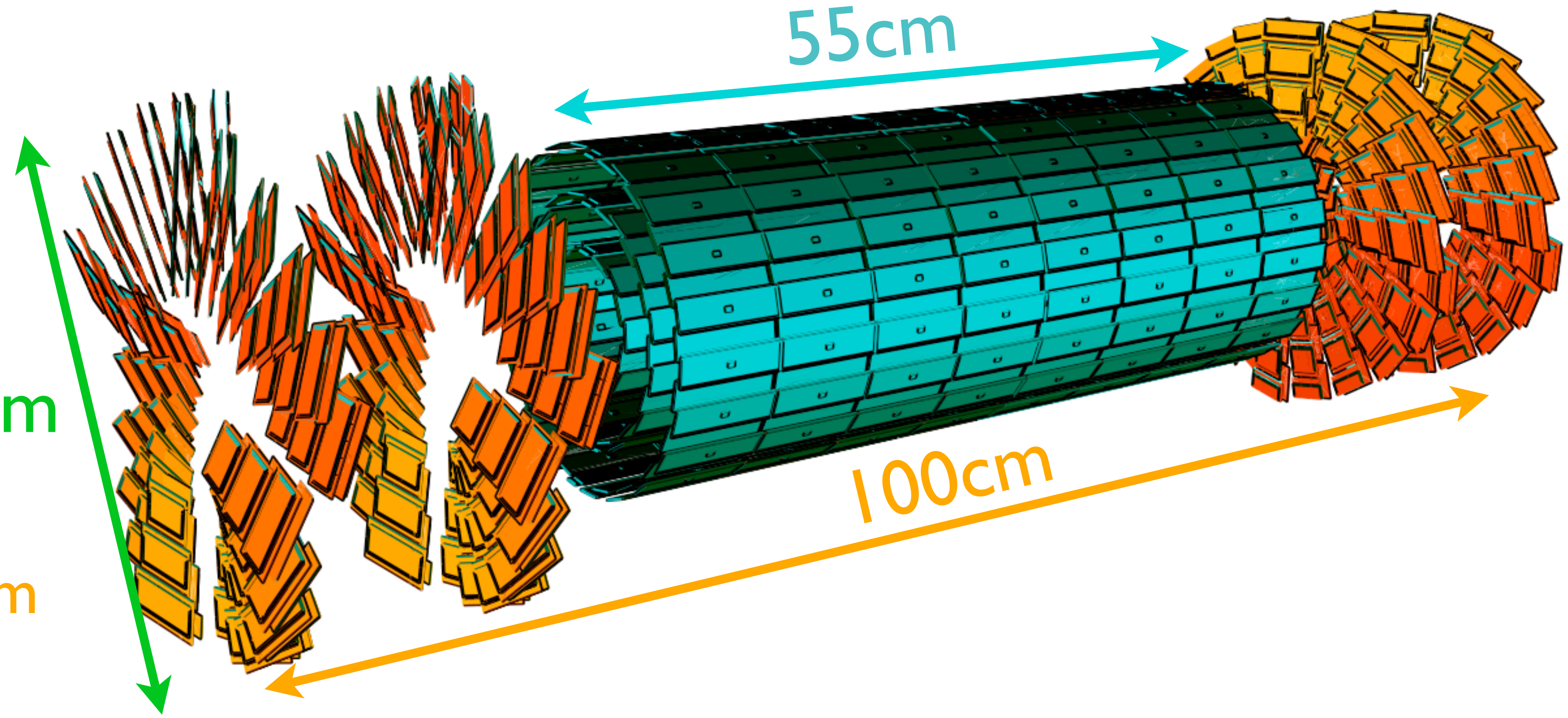
Barrel Design:

- Choose pixel size 100μm x 150μm
  - Lorentz drift along 100μm direction to maximize 2-pixel projections
  - 150μm segmentation along high-η clusters allows control of delta rays and eliminates charge saturation of preamps
- No tilting of sensor modules to reduce charge widths from Lorentz drift
  - reduces two-track resolution (develop cluster splitting to deal with high track density in high pt jets)

Forward Design: use same pixel size and readout electronics

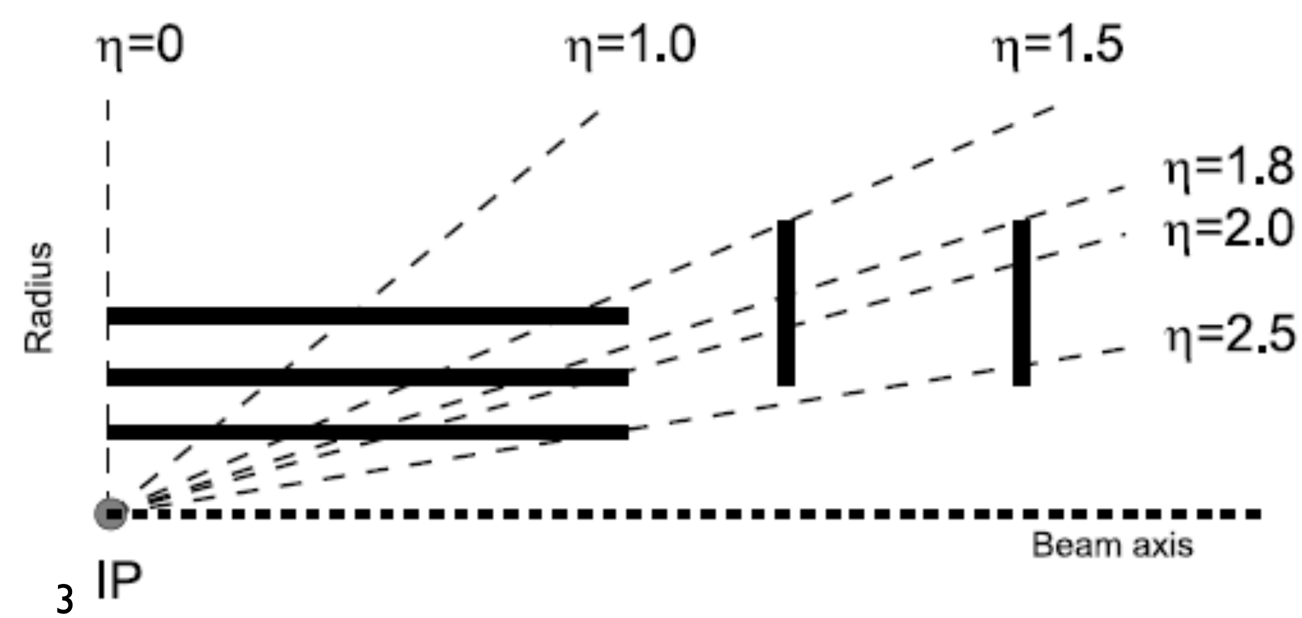
- Rotate sensors by 20 deg about radial axes to make “fan blades”
  - Lorentz drift along radial 100μm direction to increase 2-pixel projs
  - produces geometrical charge sharing in 150μm azimuthal direction

Barrel Pixels (BPix)
3 layers: r=4.3,7.2,11cm
48M pixels

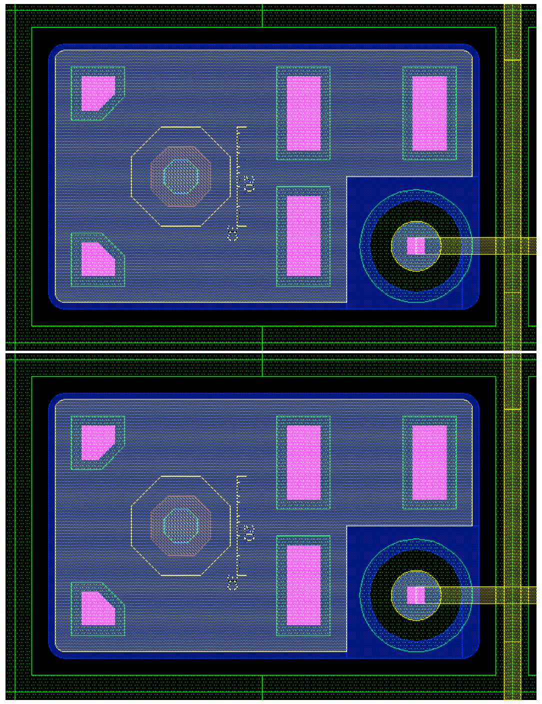


Forward Pixels (FPix)
4 disks: z=±34.5,±46.5cm
18M pixels

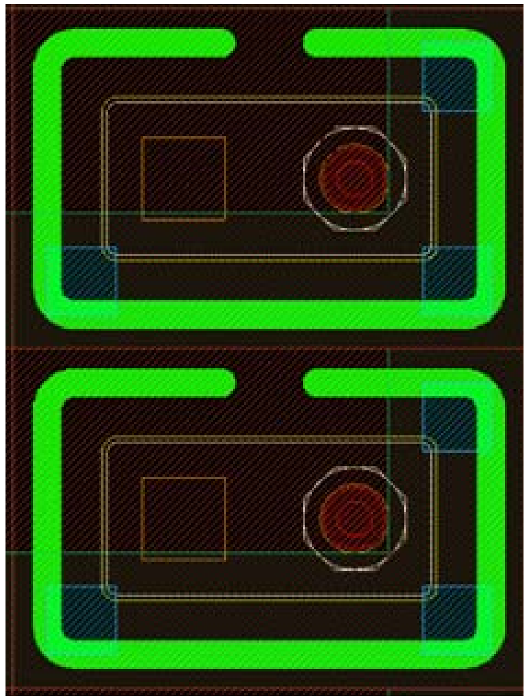
- nominal three-hit (two-hit) coverage to $|\eta|<2.1$ (2.5)



Pixel Sensors

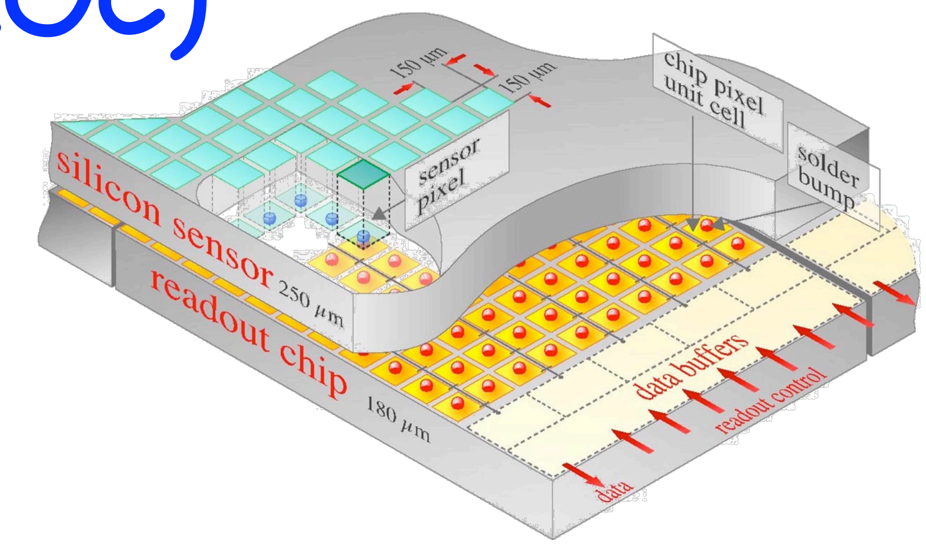


- BPix Sensor is a p-spray sensor fabricated by CiS
  - 285um DOFZ substrate
  - nominal depletion voltage: ~60V
  - operating bias: 150V
  - operating temperature: ~13C

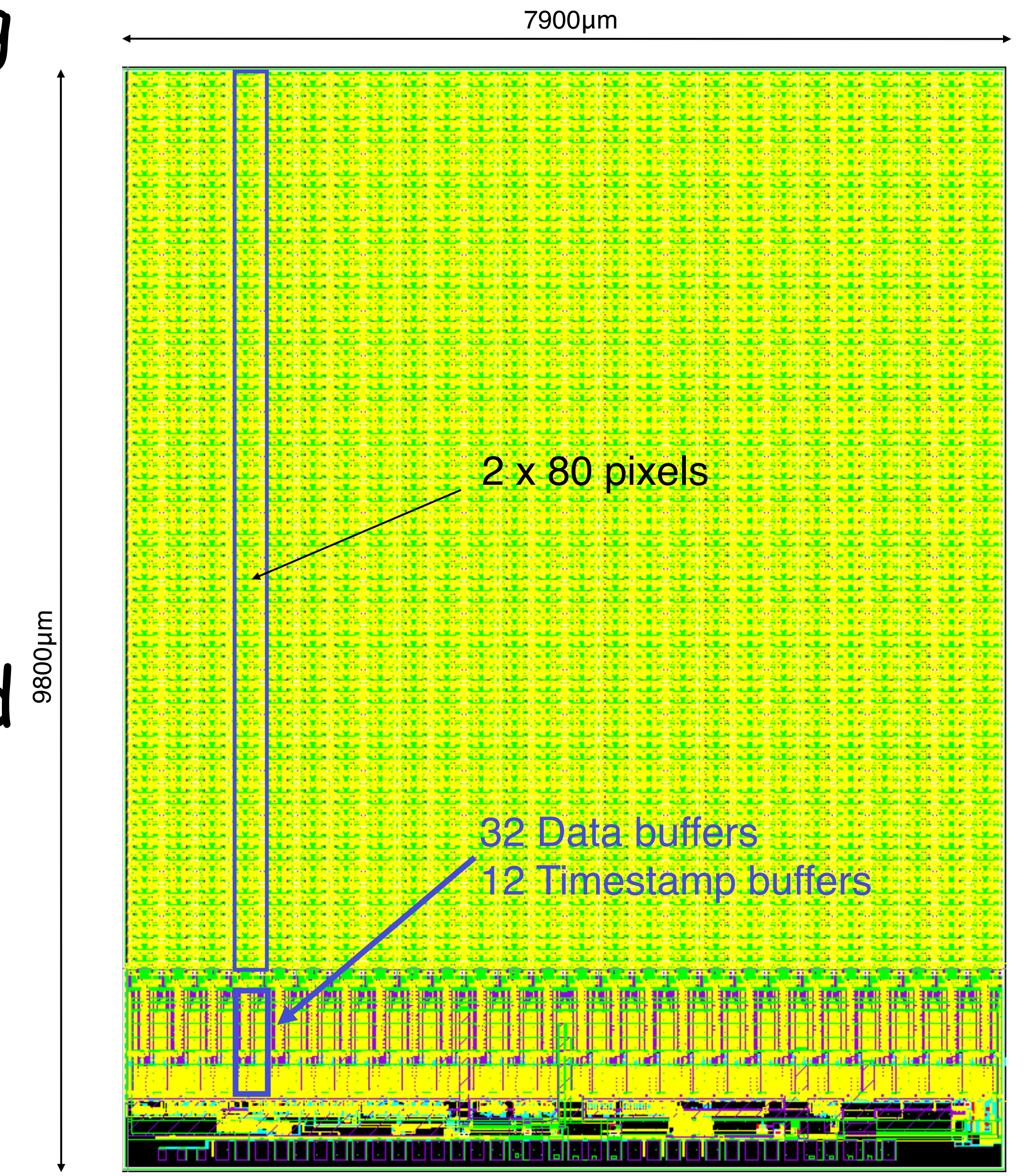


- FPix Sensor is a p-stop sensor fabricated by Sintef
  - 270um high oxygen FZ substrate
  - nominal depletion voltage: ~70V
  - operating bias: 300V
    - noisey at lower bias (surface current effect?)
  - operating temperature: ~13C
  - smaller n+ implant size increases carrier focusing
    - affects charge sharing and Lorentz calibration

Pixel Readout Chip (ROC)



- Bump bonded in tile fashion to sensors
  - thinned to 200um
  - per pixel amplification, shaping, zero supp
  - charge injection for calibration
  - pixel-by-pixel readout threshold trimming
- PSI design, fabricated by IBM
  - 0.25um process, 1.3 million transistors
- Double column drain architecture
  - 26 double columns of 160 pix (4160 pix)
  - hits buffered until trigger decision
  - designed for 25ns bunch spacing
    - preamp shaping time leads to threshold effects
- 40 MHz Analog Readout
  - supervised by Token Bit Manager
  - analog encoding of digital addresses,etc

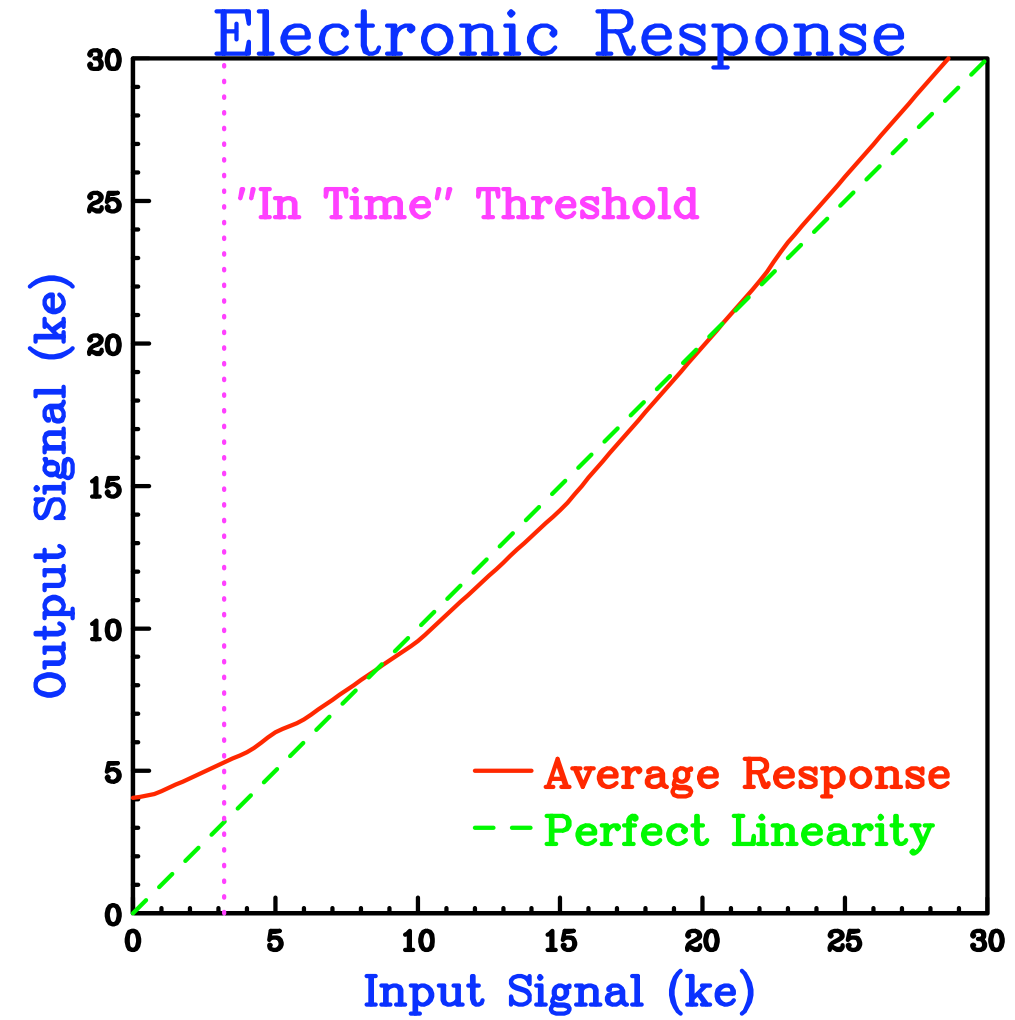


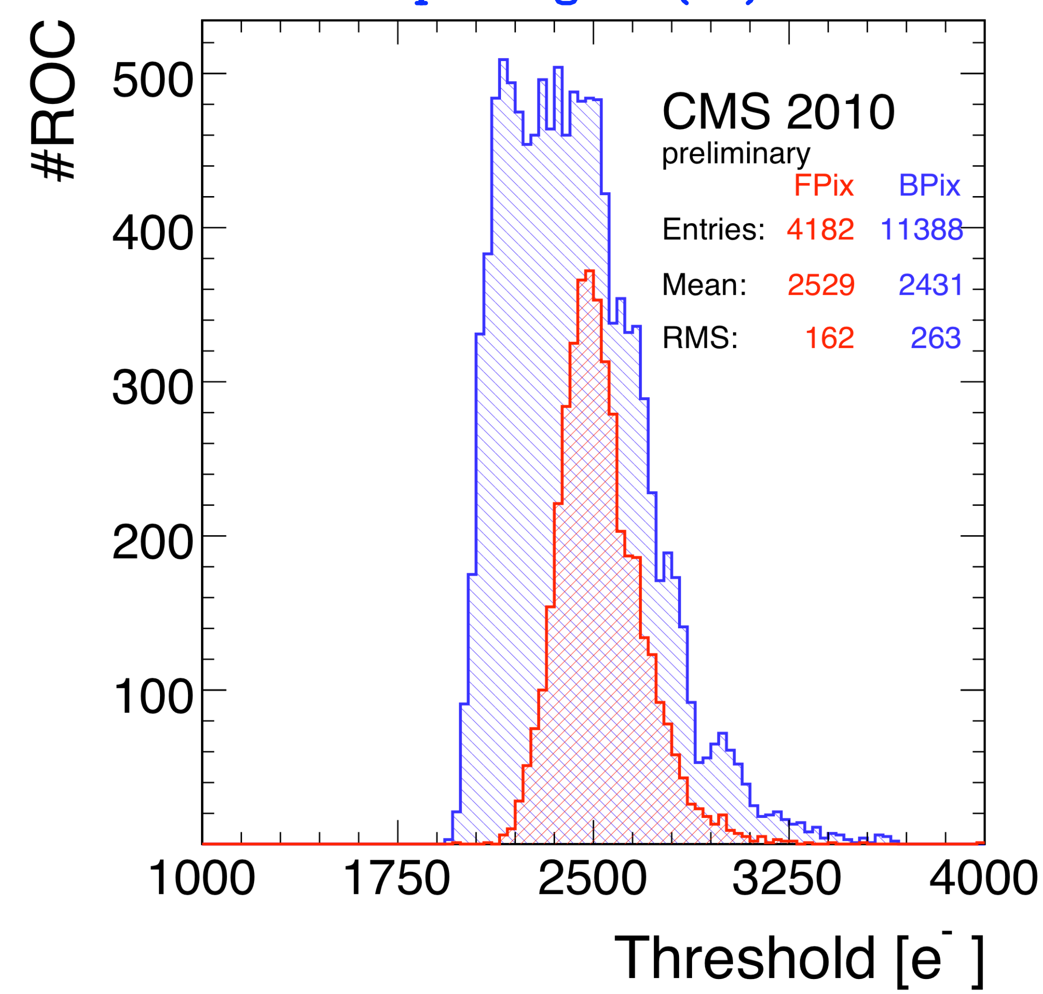
IBM_PSI46

Electronic Calibration

The charge injection feature of the ROC is used to determine/tune several quantities:

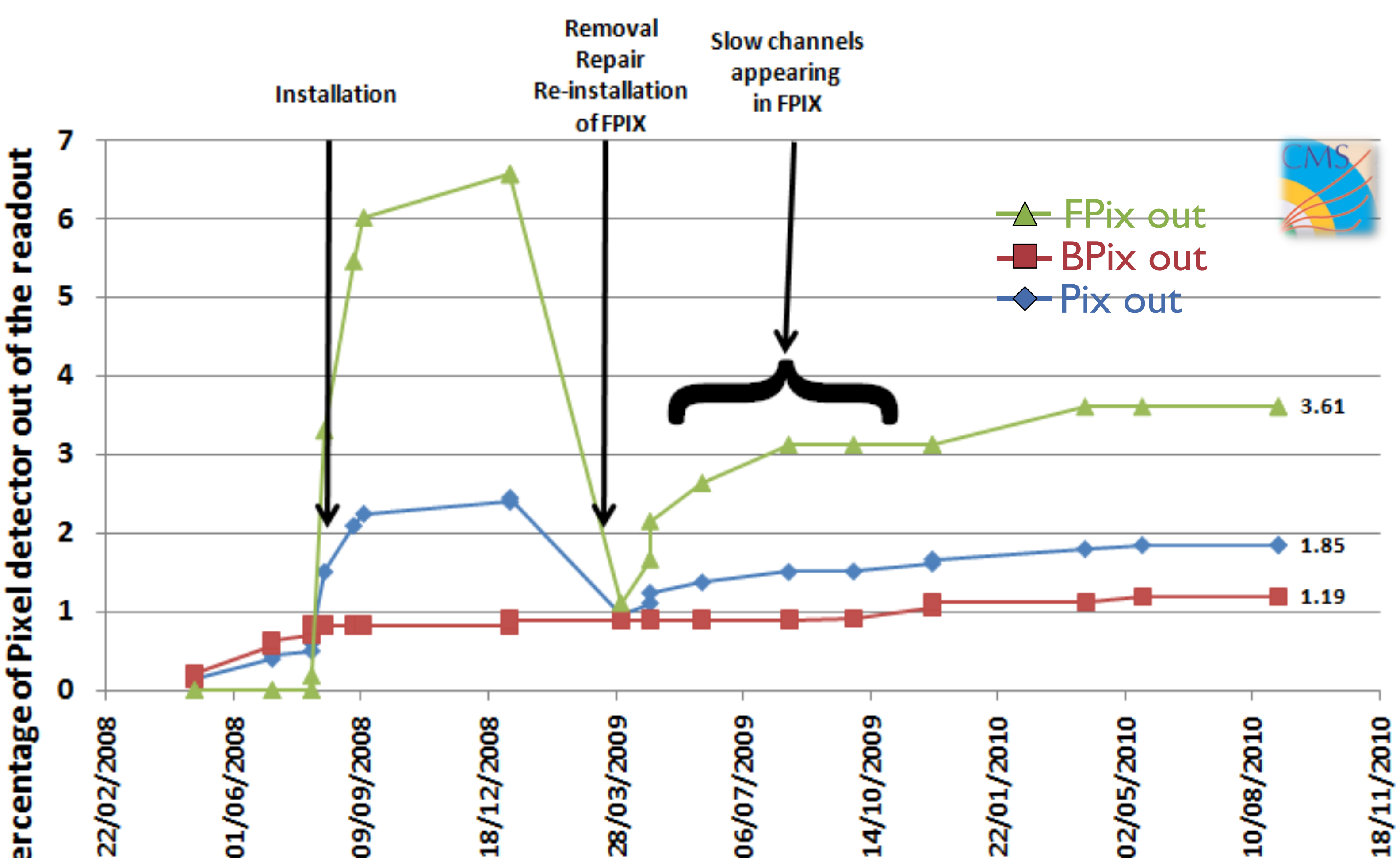
- electronic response function
  - significant non-linearity Q<5ke/Q>40ke
    - ✶ small (~10%) effect on simulated resolutions from low Q response
- gains/pedestals (~67 MB of info)
  - assumes linear response
  - store 1 pedestal for each pixel
  - store 1 gain for each column
    - ✶ adds additional "calibration" noise
- readout thresholds
  - iteratively adjusted to be about 2500e
  - smaller signals slew into the next BX and are lost
    - ✶ "in time" threshold is about 700e larger

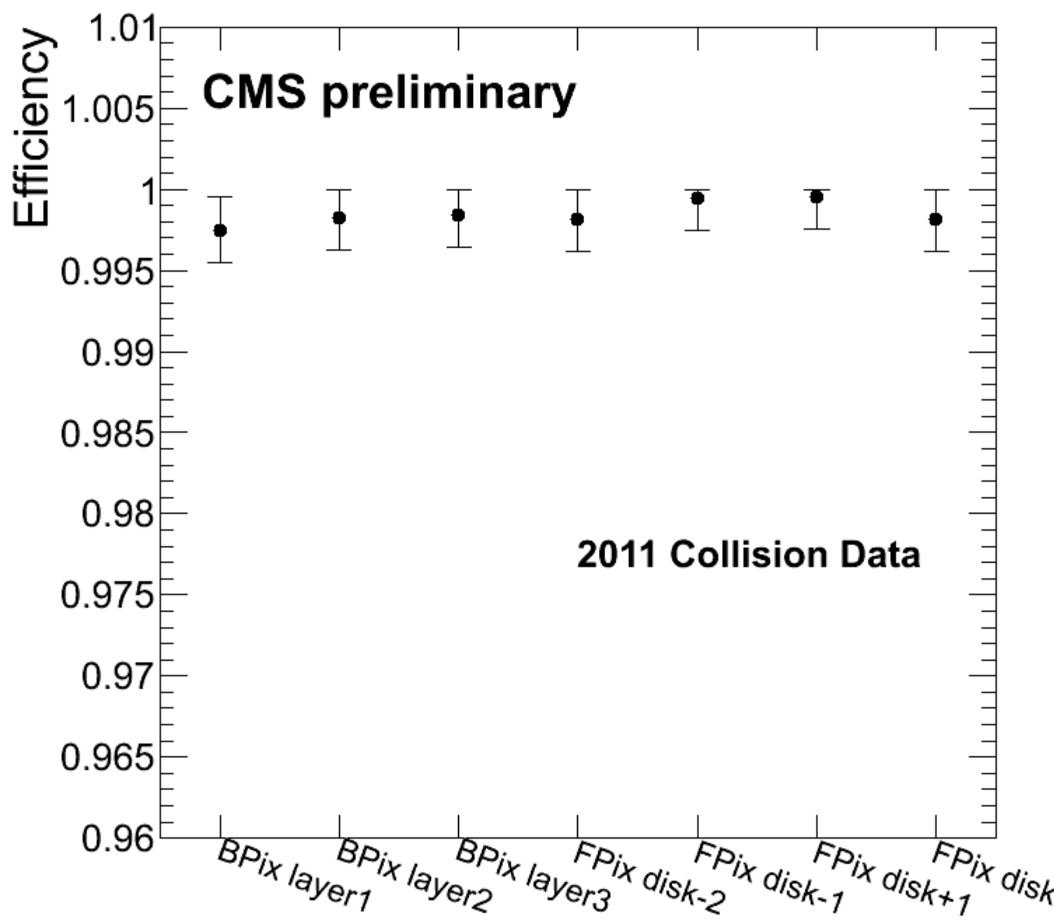




Live Fraction/Efficiencies

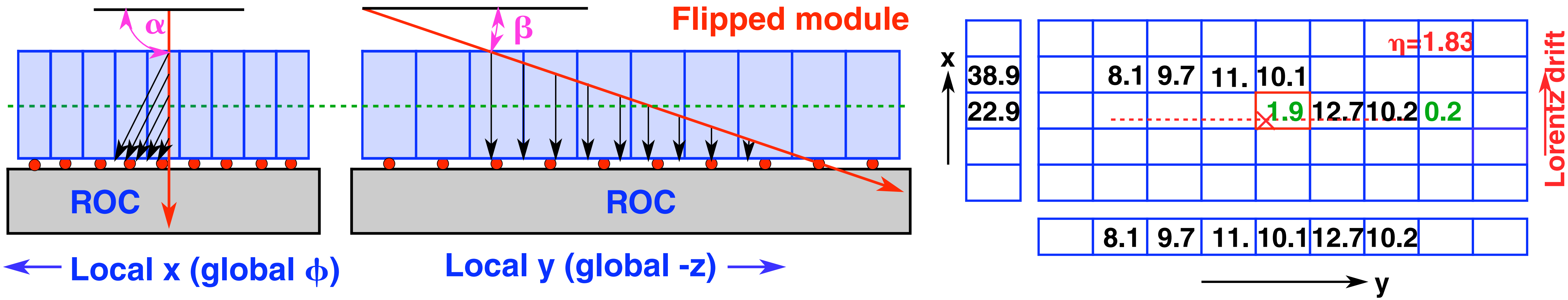
- Most of the inefficiency is due to problematic/dead channels
  - was ~2% in 2010, increased to ~3% in 2011
- Efficiencies of the live portions of the detector are above 99.5%
  - few % losses expected from finite ROC buffering at $1x10^{34}$ $cm^{-2}s^{-1}$ design luminosity. Don't expect to see more than $2x10^{33}$ $cm^{-2}s^{-1}$ this year (very non-linear in occupancy).





Hit Reconstruction

Tracks deposit distinct patterns of charge on the pixel sensors



- Hit position estimation is based on 1D projections of the 2D cluster
  - factorizes due to field configurations and cell periodicity
  - projected shapes depend upon the projected angles α and β
    - reconstruction algorithms use angle information iteratively
- Two techniques used in track reconstruction
  - "Generic" technique is η-like, uses end pixel charges of projection
    - faster, less precise algorithm used for all but last tracking pass
    - needs external Lorentz drift calibration
  - "Template" technique fits projections to simulated profiles
    - slower, more precise algorithm used for final fitting pass
    - needs full cluster shape calibration
    - generates probabilities that test the consistency of the shapes

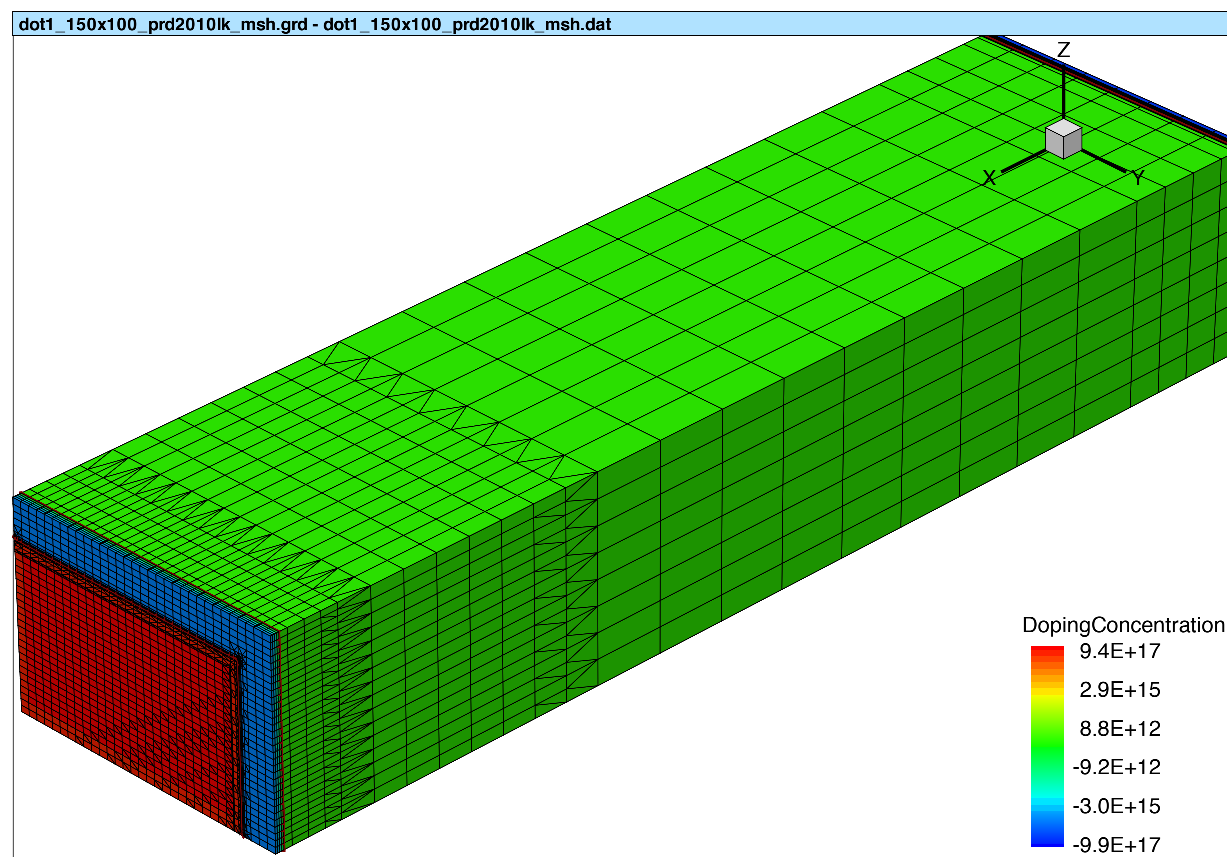
Pixelav Detailed Simulation

Created to interpret beam tests of irradiated sensors, now used to perform Lorentz calibrations and generate template profile shapes:

- Charge deposition model based on Bichsel π-Si x-sections
  - delta ray range: Continuous Slowing Down Approx + Nist Estar dedx
  - plural scattering and magnetic curvature of delta ray tracks
- Carrier transport from Runge-Kutta integration of saturated drift

$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\mu\left[q\vec{E} + \mu r_H \vec{E} \times \vec{B} + q\mu^2 r_H^2 (\vec{E} \cdot \vec{B})\vec{B}\right]}{1 + \mu^2 r_H^2 |\vec{B}|^2}$$

  - electric field map from ISE TCAD simulation of pixel cell
  - includes diffusion, trapping, and charge induction on implants
- Electronic Simulation: noise, linearity, thresholds, mis-calibration



Calibration of Reconstruction Algs

Sensor Structure, V_{bias}, T, r_H, Φ, electronic response (6 params)

→

Pixelav (detailed simulation)

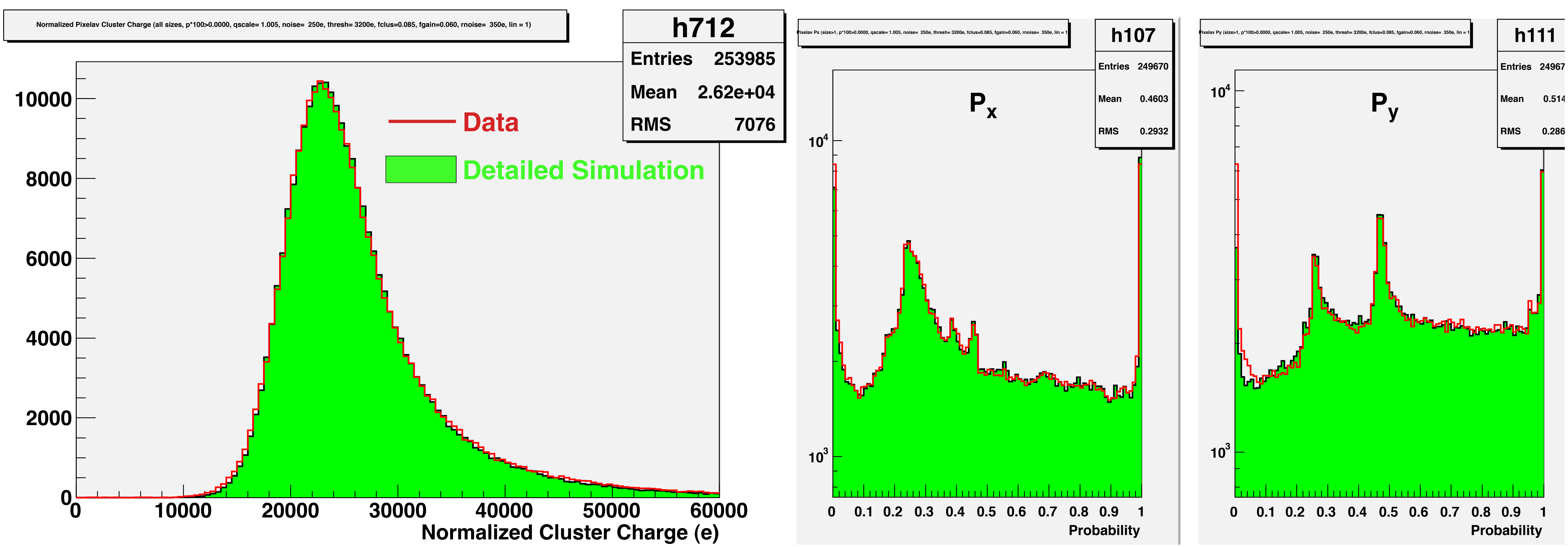
→

Simulated Data:
- charge distribution
- size distributions
- shape probabilities
- Lorentz angle cals
  - *clust size vs cot(α)
  - *grazing angle
- charge coll profiles (after rad damage)

→

Calibrations:
- Standard Reco
  - * Lorentz corrs
  - * error estimates
- Template Reco
  - *cluster shapes
  - *error estimates
  - *probability info
  - *cluster split info

Adjust these to match these to data

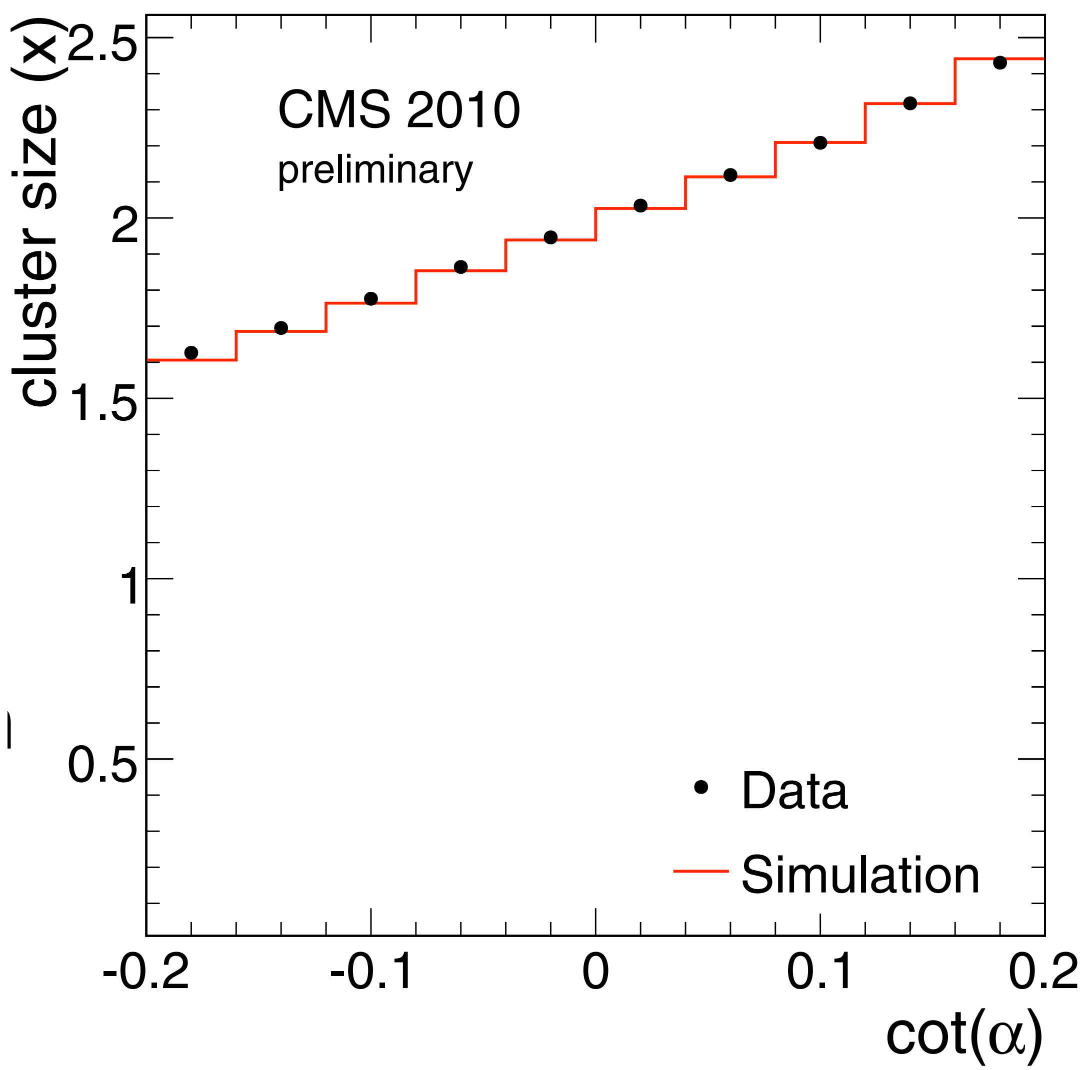


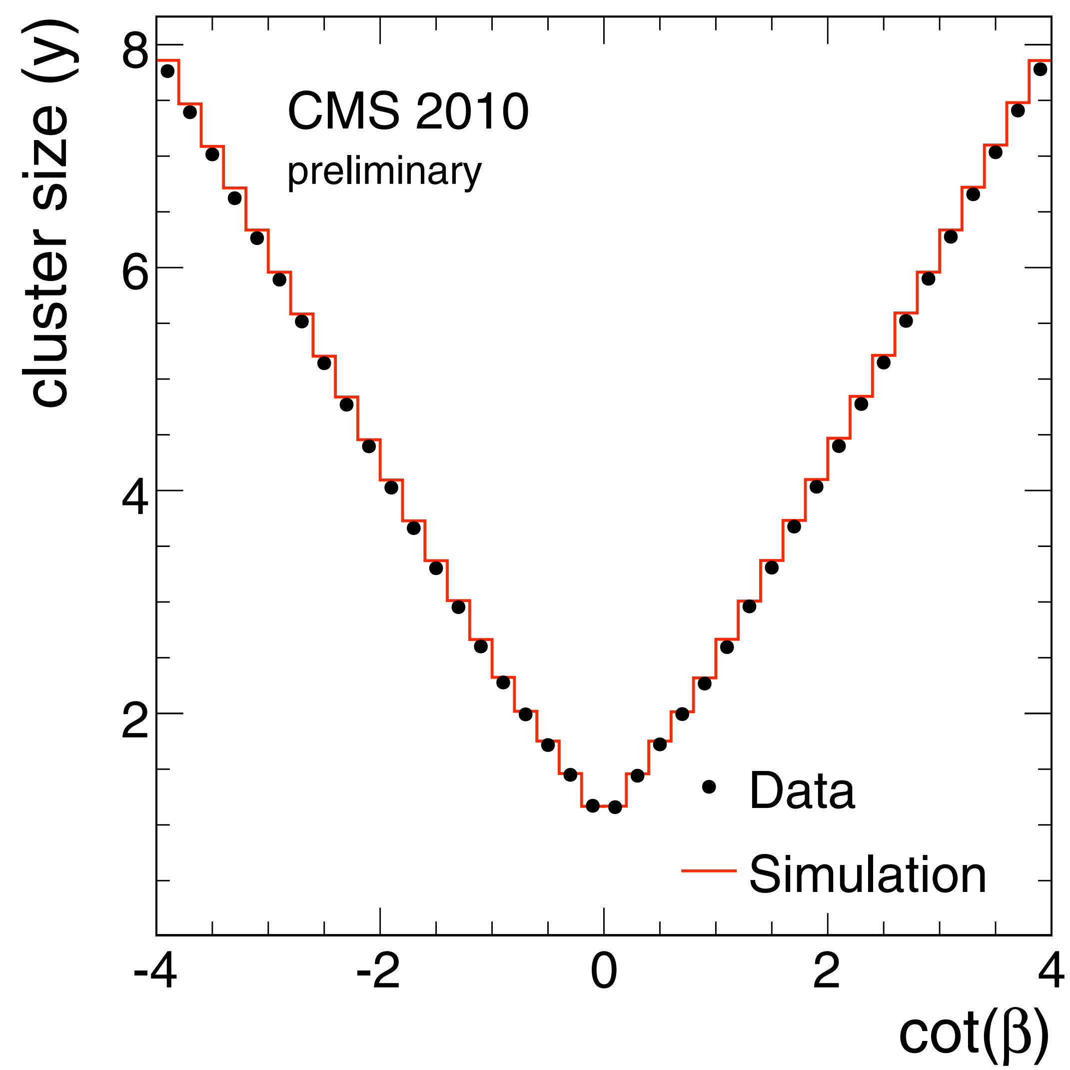
Saturday, June 11, 2011

Calibration of "In-Time" Thresholds

The average x/y cluster sizes for each bin in cot(α)/cot(β) depend upon the effective threshold.

- Simulate the same track angles, momenta as reconstructed in the data
  - charge per unit cot(α/β) is same for simulated/measured samples
- Adjust threshold to achieve best agreement
  - x-size vs cot(α) is also sensitive to the Lorentz angle (meas separately)
  - 3200e seems to work reasonably well





Lorentz Calibration

Lorentz drift follows from the saturated solution to carrier eq of motion

$$m^* \frac{d\vec{v}}{dt} = qe\vec{E} + qer_H \vec{v} \times \vec{B} - \frac{e}{\mu(E)}\vec{v} \;\rightarrow\; \vec{v} = \frac{\mu \left[q\vec{E} + \mu r_H \vec{E} \times \vec{B} + q\mu^2 r_H^2 (\vec{E} \cdot \vec{B})\vec{B} \right]}{1 + \mu^2 r_H^2 |\vec{B}|^2}$$

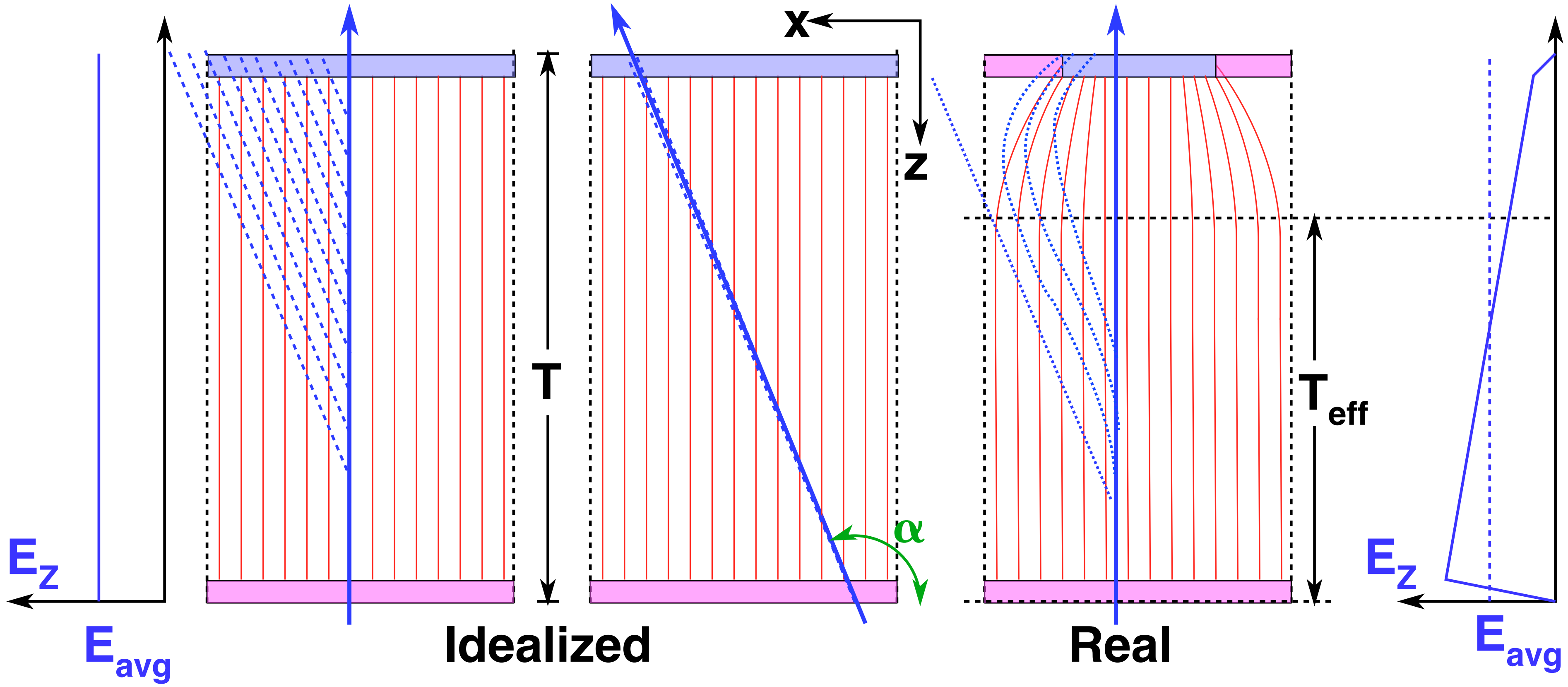
Taking z in the E direction, x in the ExB direction and q=-1, the BPix Lorentz drift direction can be described by a familiar expression,

$$\cot(\alpha_{\rm L}) = \frac{v_x}{v_z} = -r_H \mu B = -\mu_H B \quad [\mu_H \equiv r_H \mu \;\; \text{Hall Mobility}]$$

Using the same conventions, the FPix Lorentz drift dir is less familiar,

$$\cot(\alpha_{\rm L}) = \frac{v_x}{v_z} = -\frac{\mu_H B s_{20}}{1 + \mu_H^2 B^2 c_{20}^2} \qquad \cot(\beta_{\rm L}) = \frac{v_y}{v_z} = \mp \frac{\mu_H^2 B^2 c_{20} s_{20}}{1 + \mu_H^2 B^2 c_{20}^2}$$

- Skew angle [20 deg] between E and B makes 2nd-order effects
  - large B field and large electron mobility make these non-negligible
  - first-order LA is altered by ~6-7%
  - new 2nd-order drift in the B direction (reduces cluster sizes)
  - probably unique to this detector

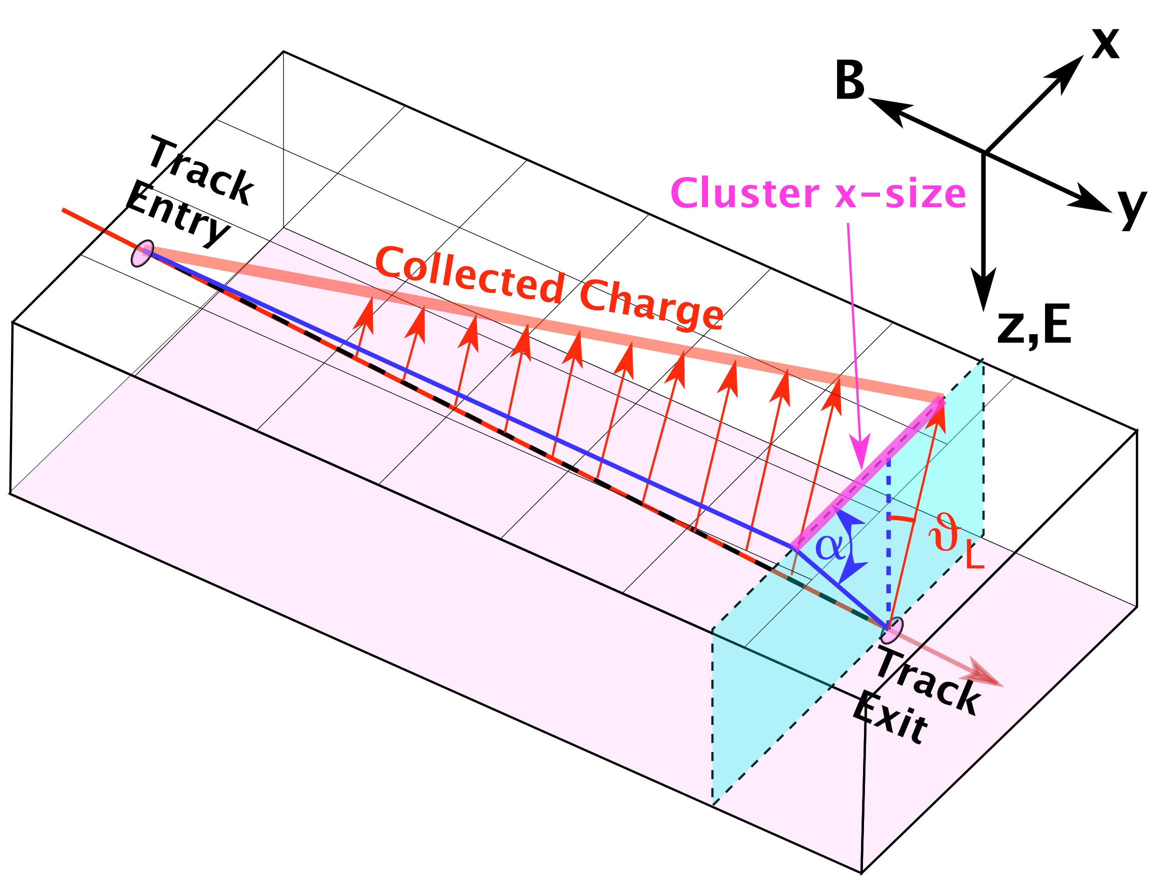


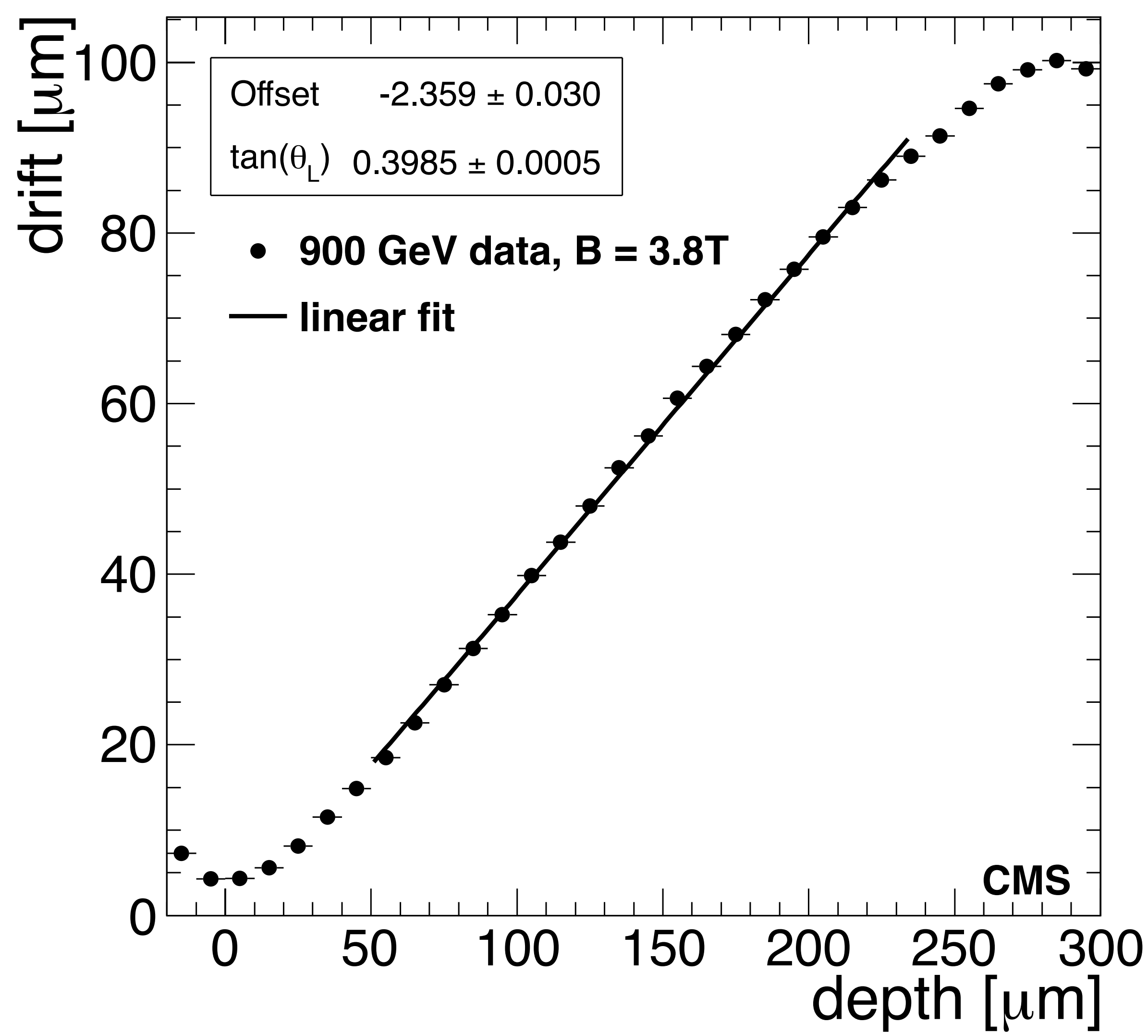
$$s_x = 1 + |T(\cot\alpha - \cot\alpha_L)|/p_x$$

- Cluster size S_x minimum at $\cot(\alpha) = \cot(\alpha_L)$
  - independent of the sensor thickness
  - measure with cosmics or low pt collision tracks for BPix
  - need cosmics to calibrate the FPix
- Ideal Lorentz bias correction: $\delta_x = T\cot(\alpha_L)/2$
  - linear in sensor thickness T
- Real sensors have implant focusing
  - effective thickness T_{eff} is less than T
  - bias correction: $\delta_x = T_{eff}\cot(\alpha_L)/2 = T\cot(\alpha_{eff})/2$
  - cluster size calibration determines α_L, need simulation for T_{eff}/α_{eff}

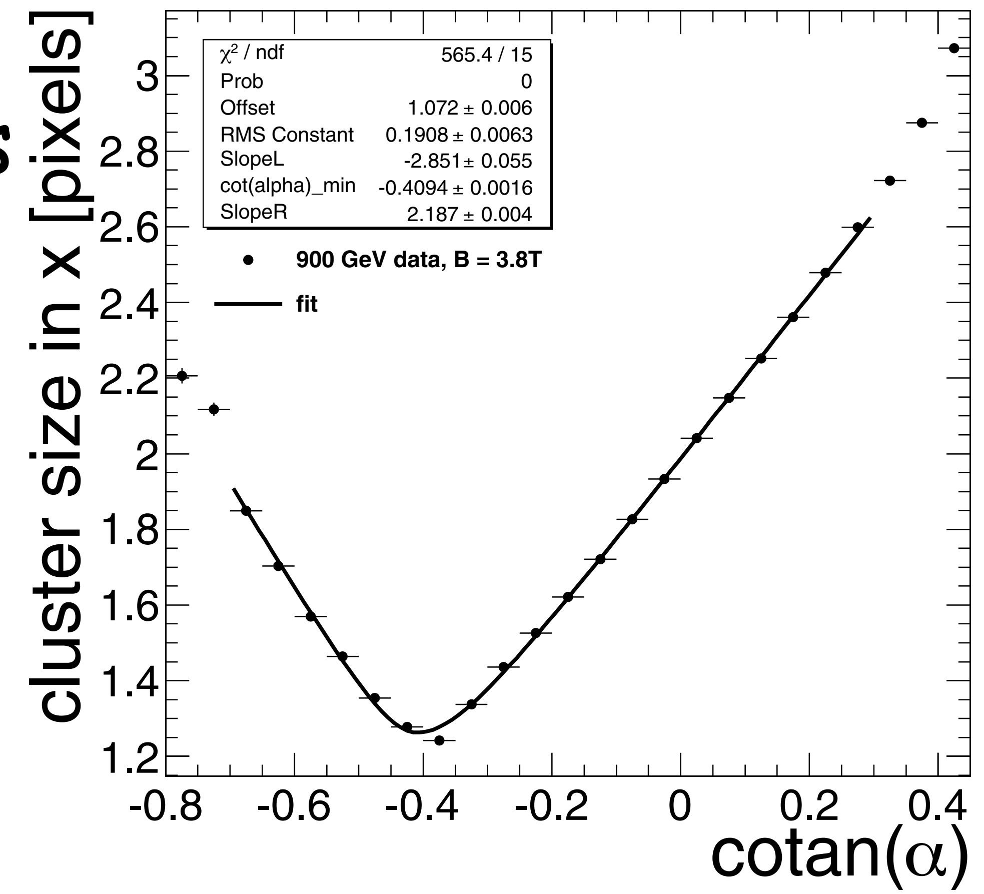
A new grazing angle technique was developed to calibrate the BPix with tracks from collisions

- Measure the x-displacement of the signal as a function of depth (distance along cluster)
  - has different, analysis-dependent systematics
  - uses high pixel segmentation (won't work for strips)
  - works with collision data (not cosmics)





- Cluster size vs cot(α) technique works with both BPix and FPix
  - BPix w/ low pt collision tracks and w/ cosmics
  - FPix with cosmics only
- Cluster sizes are sensitive to deposited charge
  - non-uniform illumination in cot(α), cot(β), p leads to sample-dependent biases
  - simulate exactly the same cot(α), cot(β), p for comparison of quantities
  - adjust r_H to get best agreement

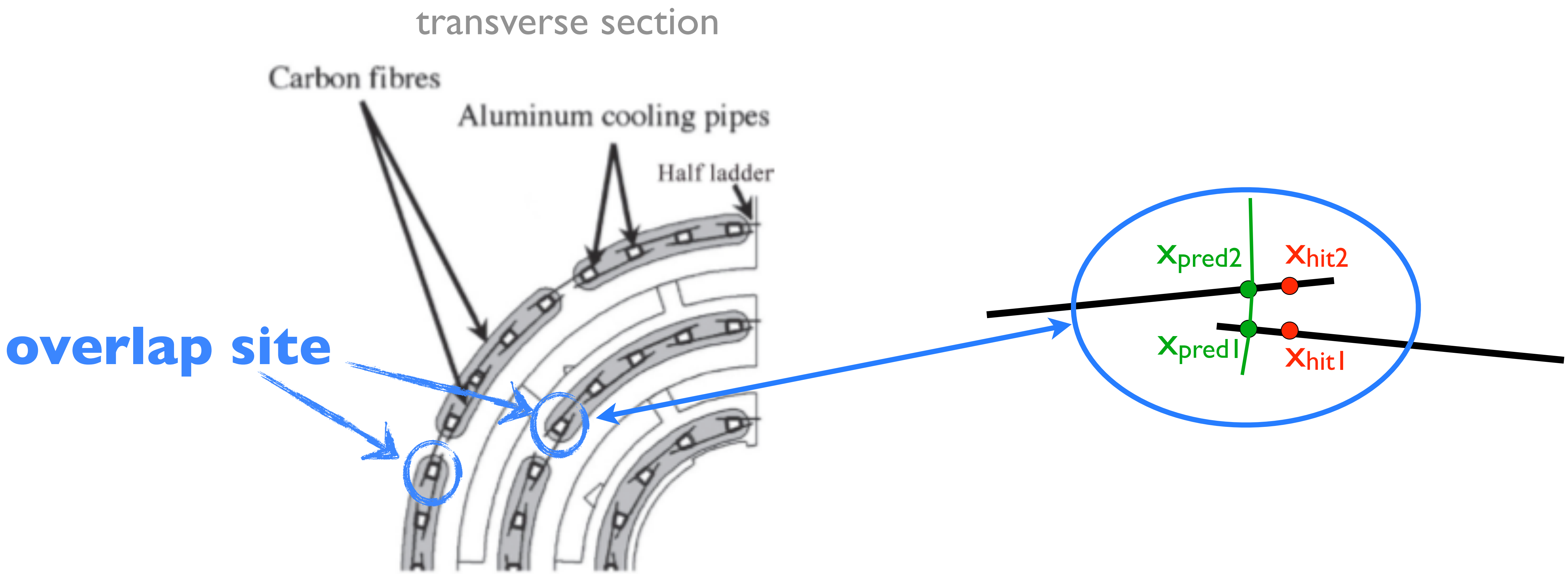


Sample	Det	Technique	Data cot(α_L)	Pixelav cot(α_L)	cot(α_{eff})	cot(β_{eff})
CRAFT 2009	BPix	Cluster Size	0.409±0.002(stat)	0.407±0.002(stat)	0.369	0.0
CRAFT 2009	FPix	Cluster Size	0.081±0.005(stat)	0.080±0.005(stat)	0.074	0.020
Collisions 2009	BPix	Grazing Angle	0.3985±0.0005(stat)	0.4006±0.0005(stat)	0.369	0.0
Collisions 2009	BPix	Cluster Size	0.4094±0.0016(stat)	0.4113±0.0048(stat)	0.369	0.0

- Excellent consistency from one tune of r_H (1.05), systematics < 2%
- Focusing effects [cot(α_{eff})] are at the ~10% level
- Grazing angle BPix calibrations in 2010, 2011 produce consistent results

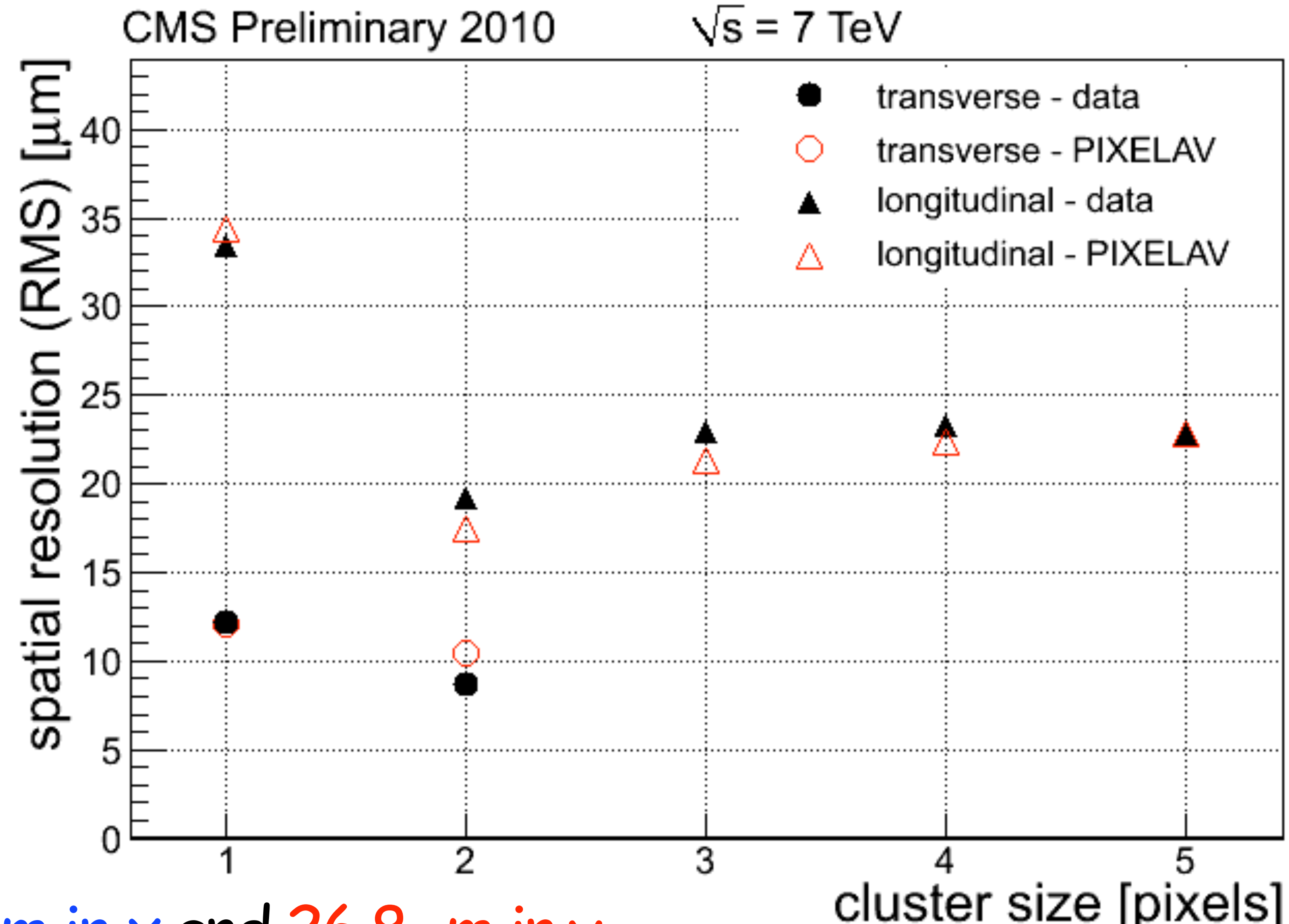
Intrinsic BPix Resolution

The instrinsic resolution of the BPix detector has been extracted from overlapping hits observed in "flipped" and "un-flipped" detector modules



- Measure distribution of $\Delta x = (x_{hit2} - x_{hit1}) - (x_{pred2} - x_{pred1})$
  - minimizes alignment effects
  - require a minimum number (30) overlaps to use an overlap site
  - calculate RMS (not Gaussian fit width) of the double difference dist
  - remove extrapolation uncertainty from the RMS
  - require both hits to have same size, divide RMS by sqrt(2)

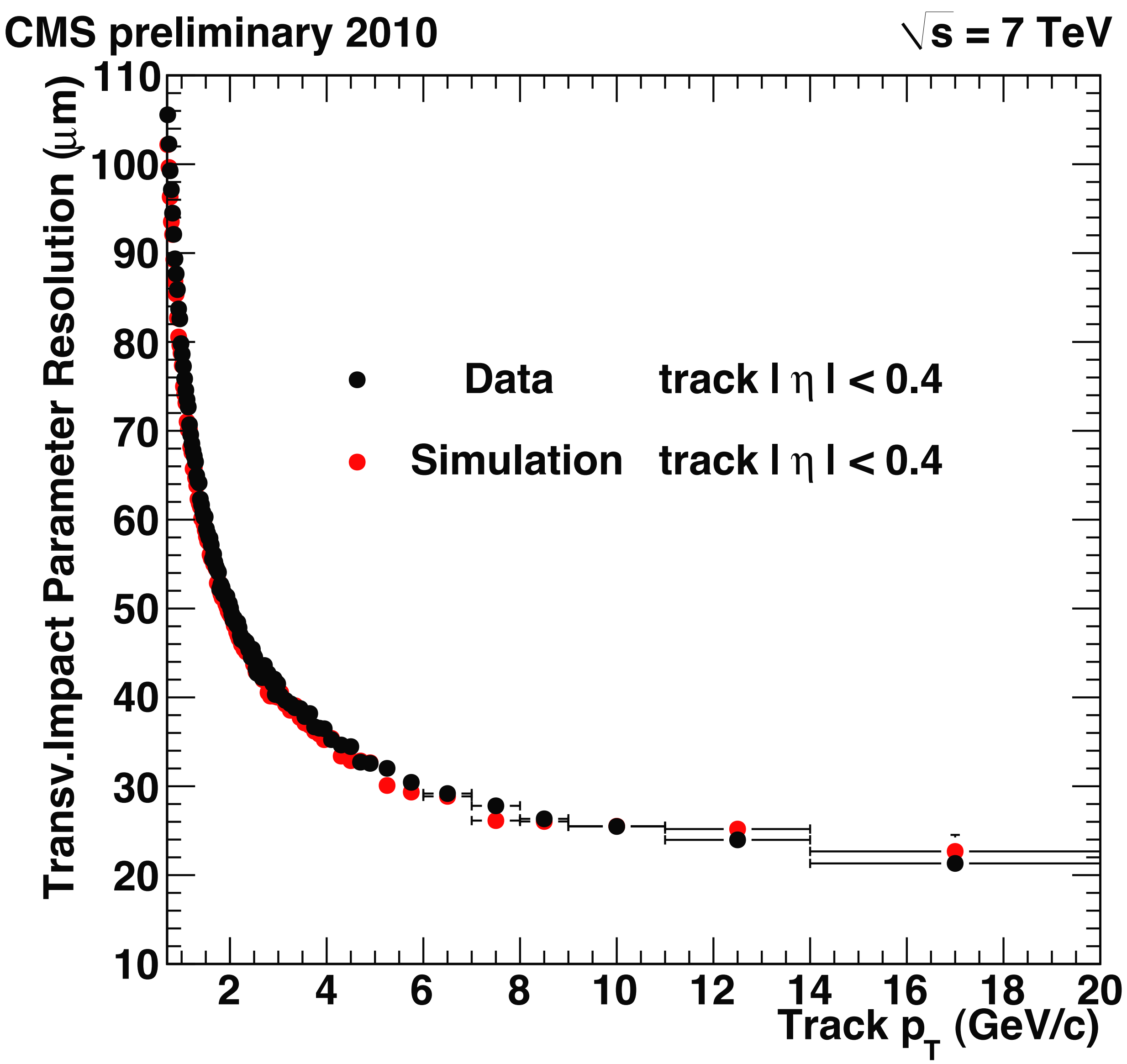
- Additional requirements:
  - good quality tracks
  - p > 5 GeV/c
  - extrapolation errors less than 10μm
  - cut to suppress module bowing effects
- Compare with Pixelav clusters generated at the same angles and p
  - resolution is sensitive to these

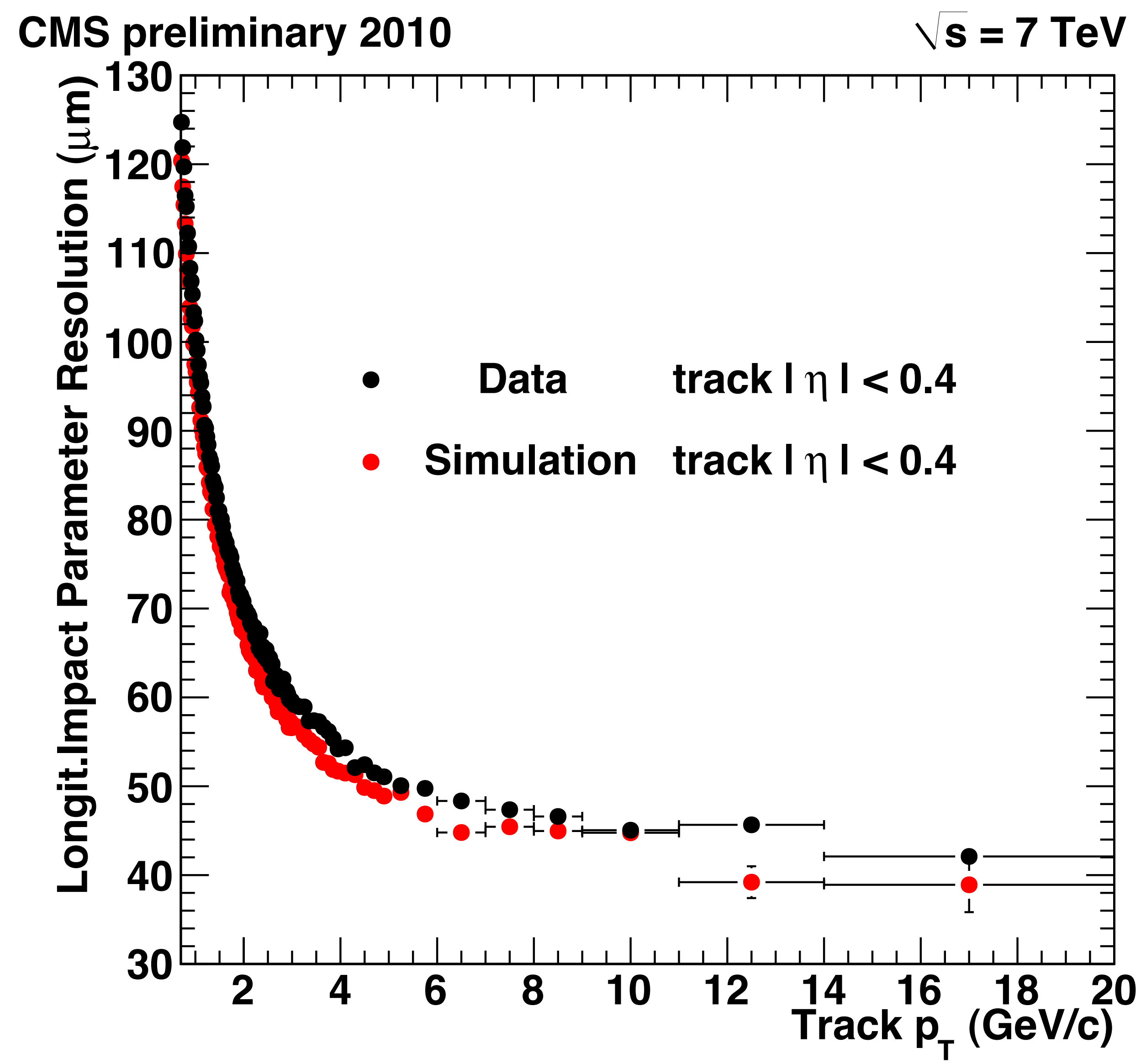


- Average resolutions: 11.2μm in x and 26.8μm in y
  - RMS (includes tails) not Gaussian fits
  - 1-pix x projections are much better than p_x/sqrt(12) [and they should be: ~(p_x-W_Lf)/sqrt(12)]
  - Pixelav accurately predicts the measured errors (good because we use them in tracking)
  - resolution expected to be dominated by high Q tails (delta rays)
    - expect many smaller charge hits to be better resolved

Performance in Tracker

The pixels dominate the position/angle measurement of tracks (4/5 track parameters). The main physics consequences follow from improved impact parameter res:





- For pt > 10 GeV/c, resolutions are 20-30μm (trans), 40-50μm (long)
  - worsens at larger η

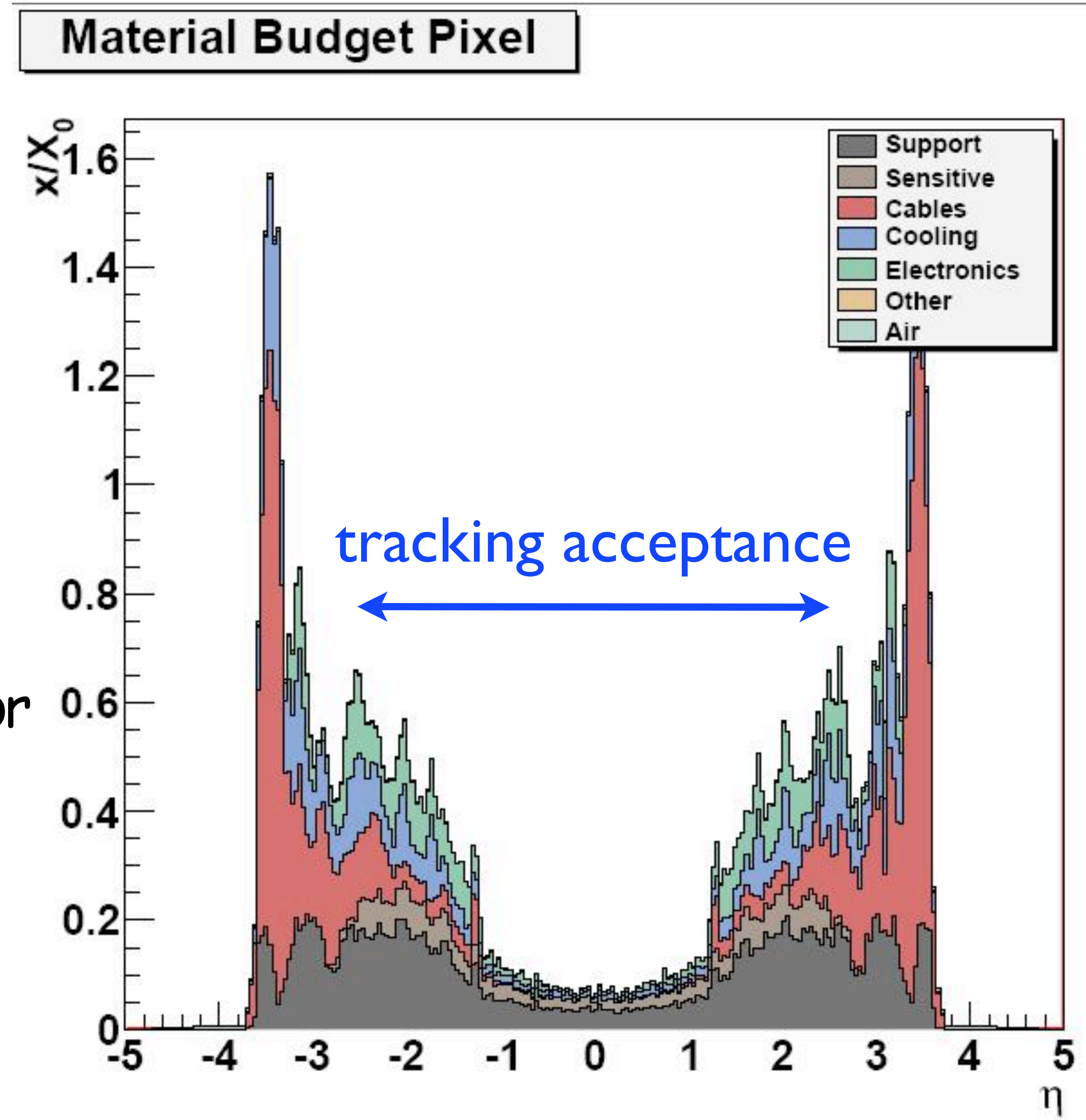
Status/Future

- Detector is performing as well as anyone could have expected
  - were some problems with readout lockup due to beam-gas tracks
  - wish TBM firmware allowed BX/BX+1 readout for 50ns LHC operation
    - ✳ would make "in-time" thresholds = set thresholds
- Studies of detector performance are continuing
  - resolution studies incorporating alignment effects are in progress
  - FPix resolution studies are underway
- Some performance improvements are expected in the coming year
  - module bowing will be included in the geometrical description
    - ✳ good alignment should improve
  - cluster splitting algorithm may improve high-pt jet reconstruction
- Cold operation to control radiation damage will begin this year
  - need to maintain low humidity
  - need several recalibrations
  - template reco designed to handle radiation-induced response changes which may become relevant before "intermediate" upgrade

Extra Slides

Material Budget

- Tracking performance is affected by the not-so-small thickness of the detector
  - thickness dominated by power, cooling, and support
    - active material is small part of the total
    - especially problematic for $1.2<|\eta|<2.5$



Simulation of LA Calibration

- generate clusters at EXACTLY the same angle pairs and momenta to simulate charge deposition and threshold effects correctly
  - make list of angle pairs (and track momenta) for simulation
  - vertical displacement of curves can be caused by incorrect thresholds