in-pixel resolution studies

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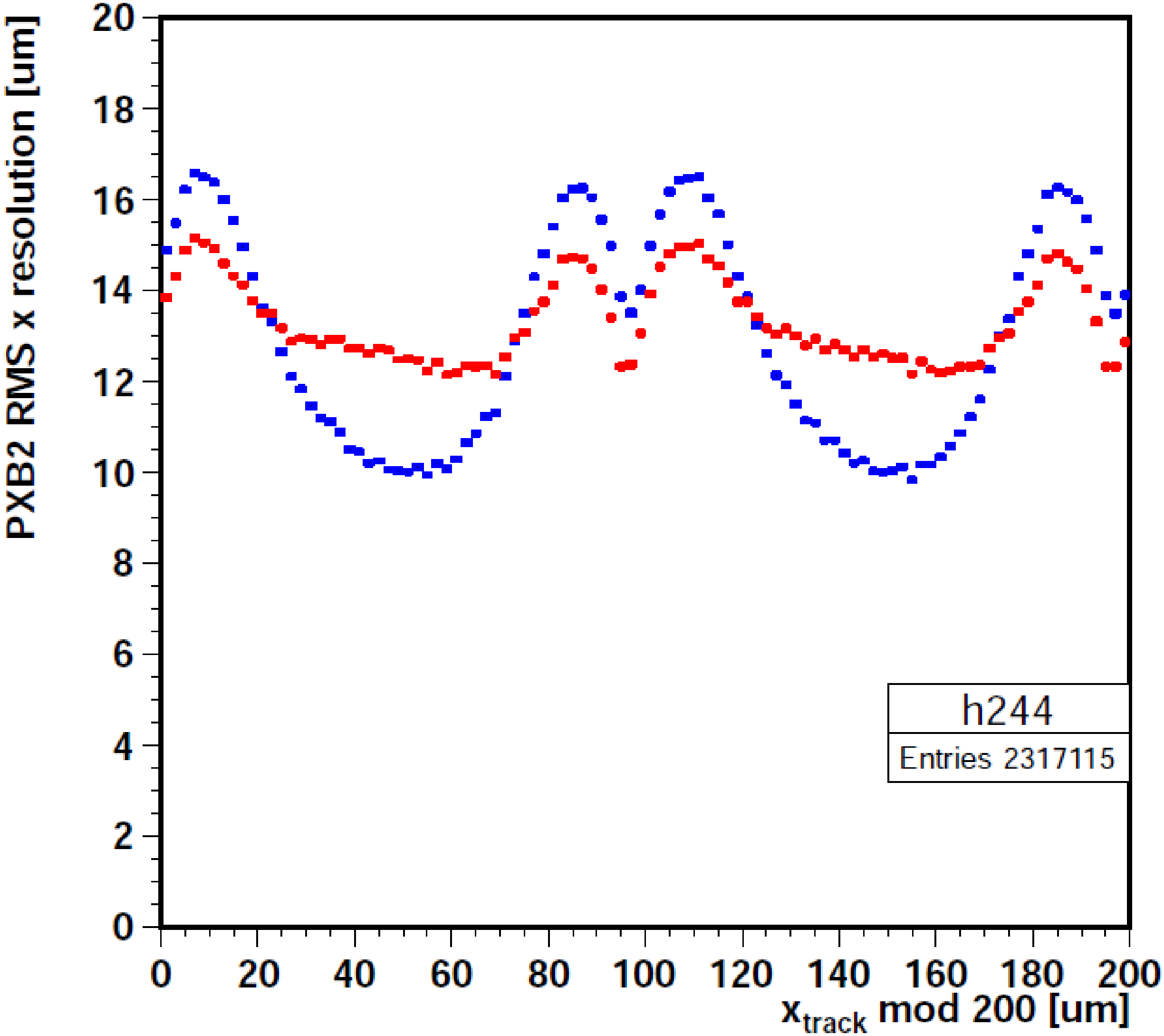
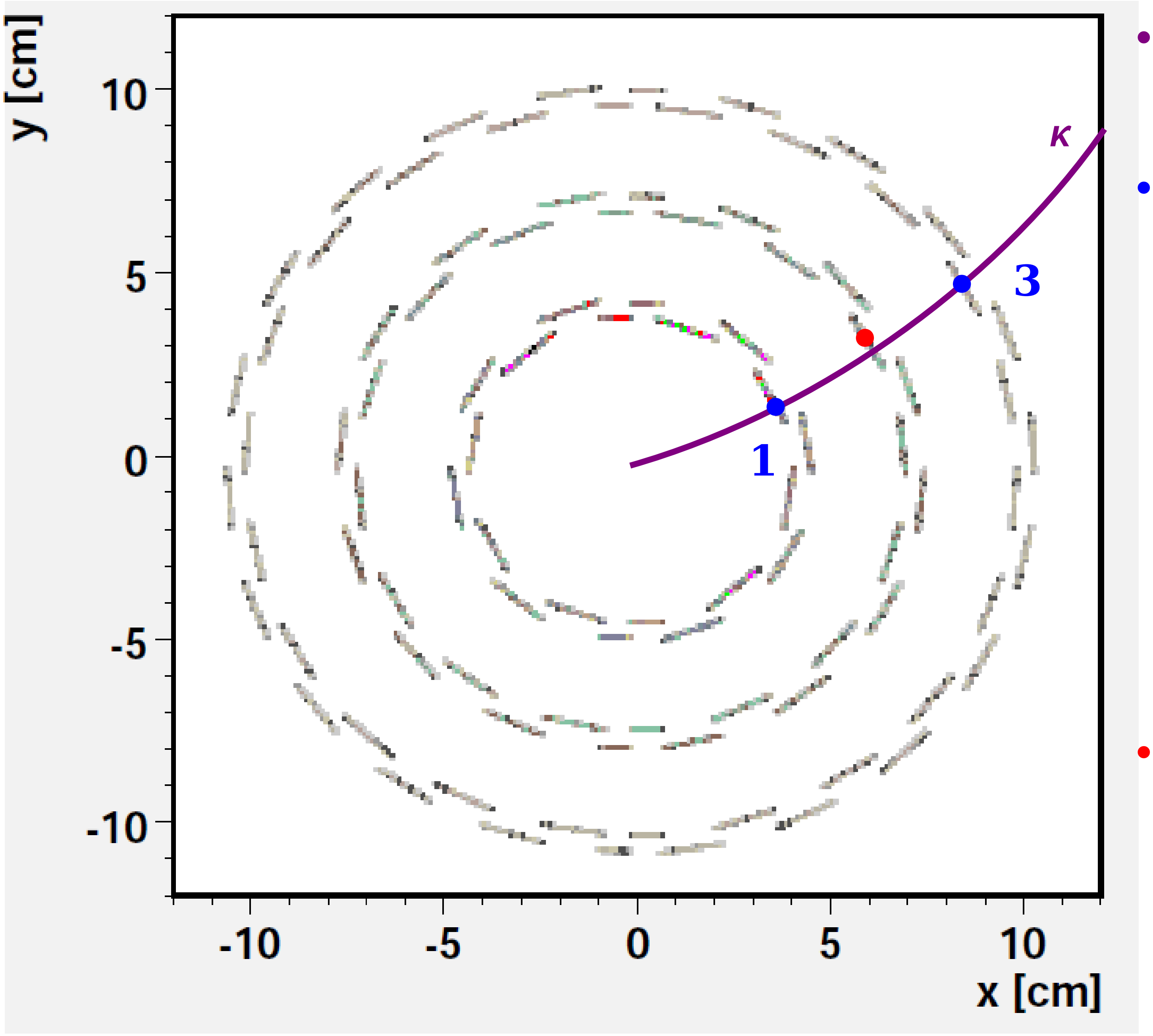
CMS Pixel DPG, 30.6.2011

updated 3.1.2012



- Pixel resolution from triplets
- Charge sharing
- Profiles within a pixel

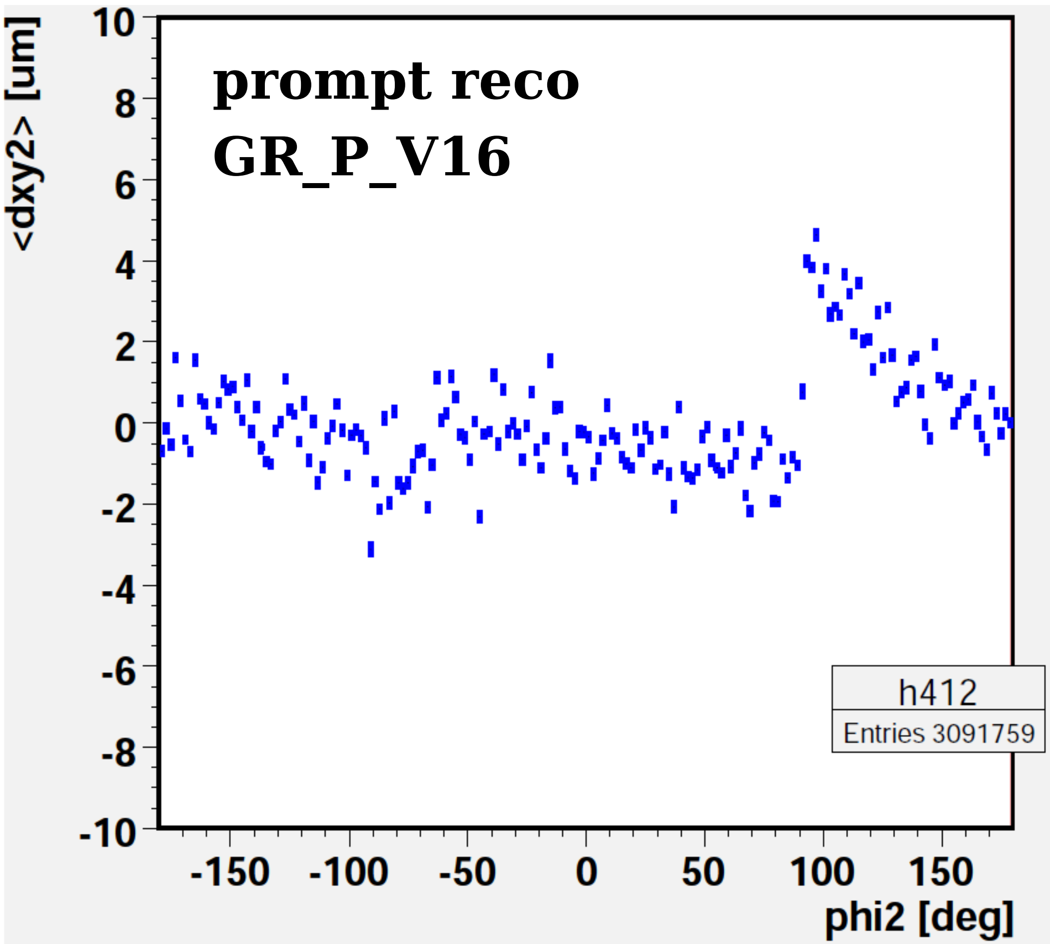
Pixel triplets

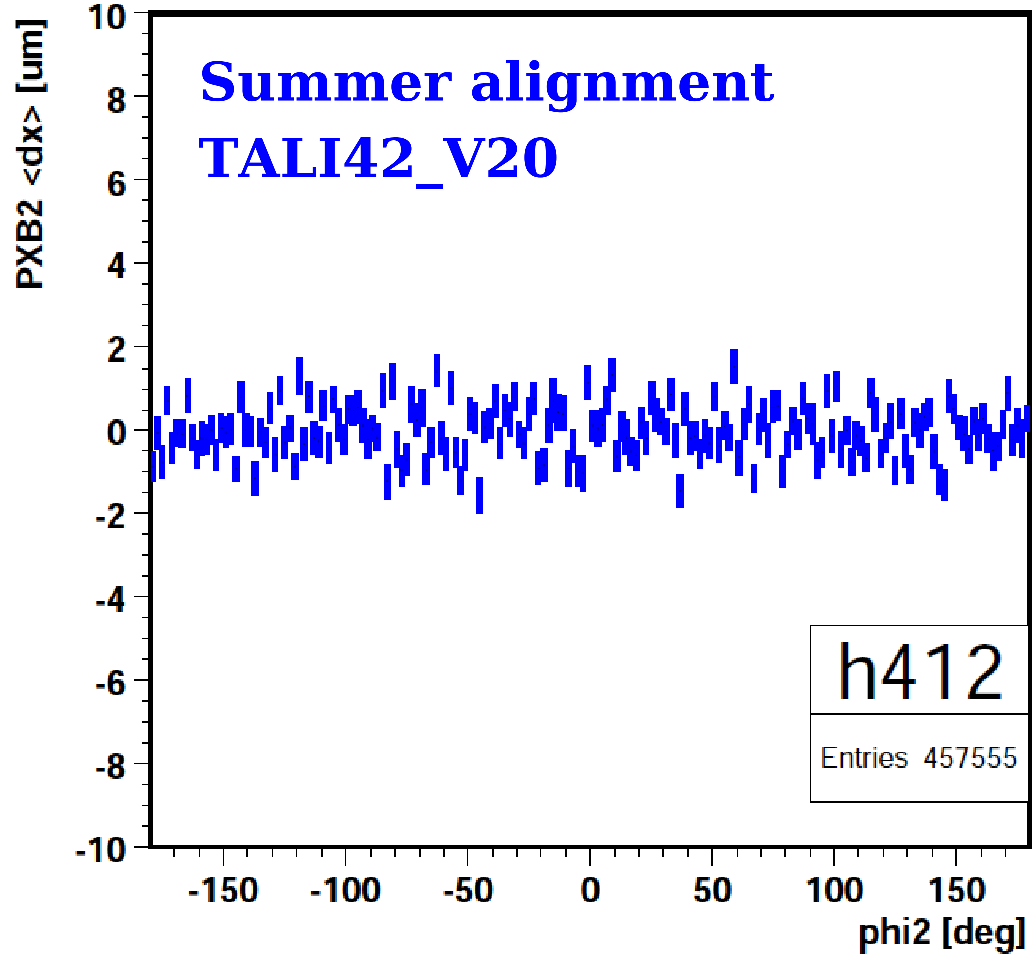


- Select tracks with hits in 3 pixel layers.
- Redefine track:
  - curvature κ from full tracker,
  - position and angles from hits 1 and 3.
  - analytic code from J. Gassner 1996 (ETH Zürich, H1).
- Interpolate to middle layer:
  - residual between track and hit.

mean residual: alignment check

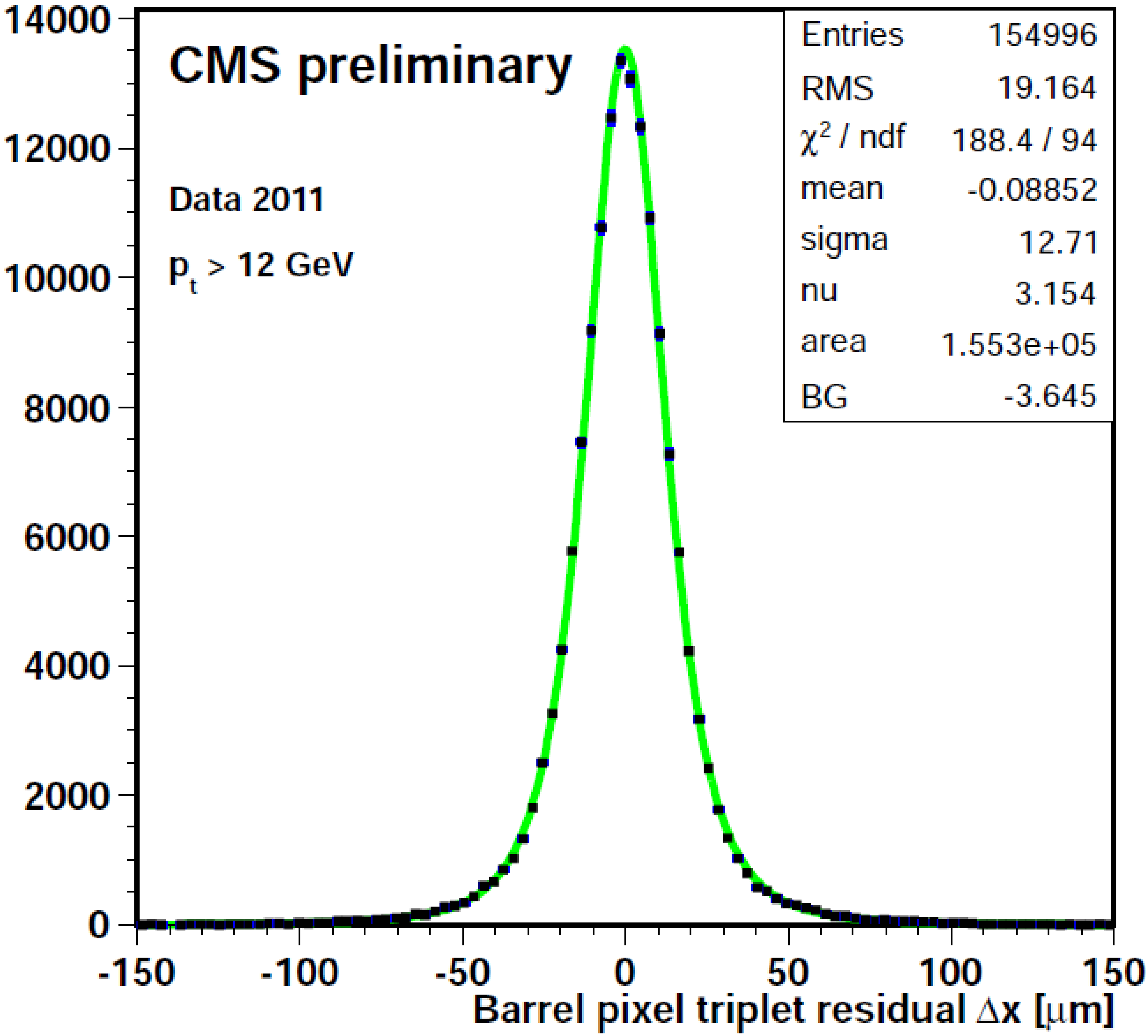
PXB2, Spring 2011 data





p_t > 4 GeV

Barrel pixel triplet rφ residuals at high p_t



- Data Mar 2011
- Width of the residual distribution at high p_t:

$$\sigma_{\boldsymbol{r}}^2 = \sigma_2^2 + (\sigma_1/2)^2 + (\sigma_3/2)^2$$

- All σ equal:

$$\sigma_r = \sqrt{3/2}\,\sigma_i$$

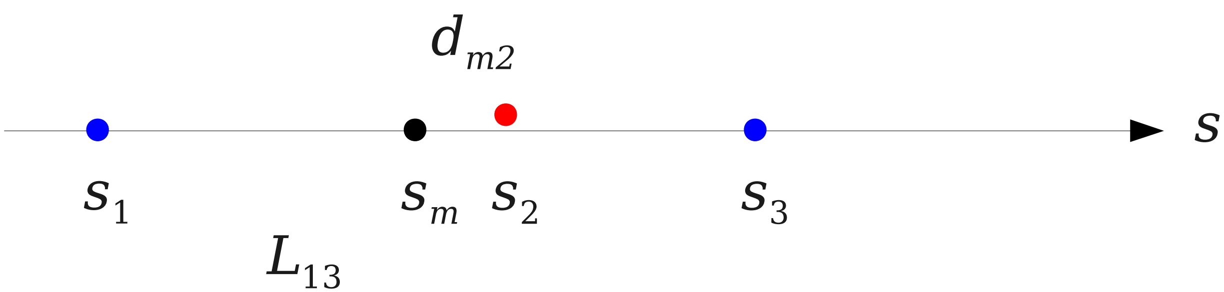
- Result:
  - σ_r = 12.7 μm,
  - σ_i = 10.4 μm.
  - with 100 μm pixel size!

triplet resolution function

Propagation of the intrinsic resolution at high p_t:

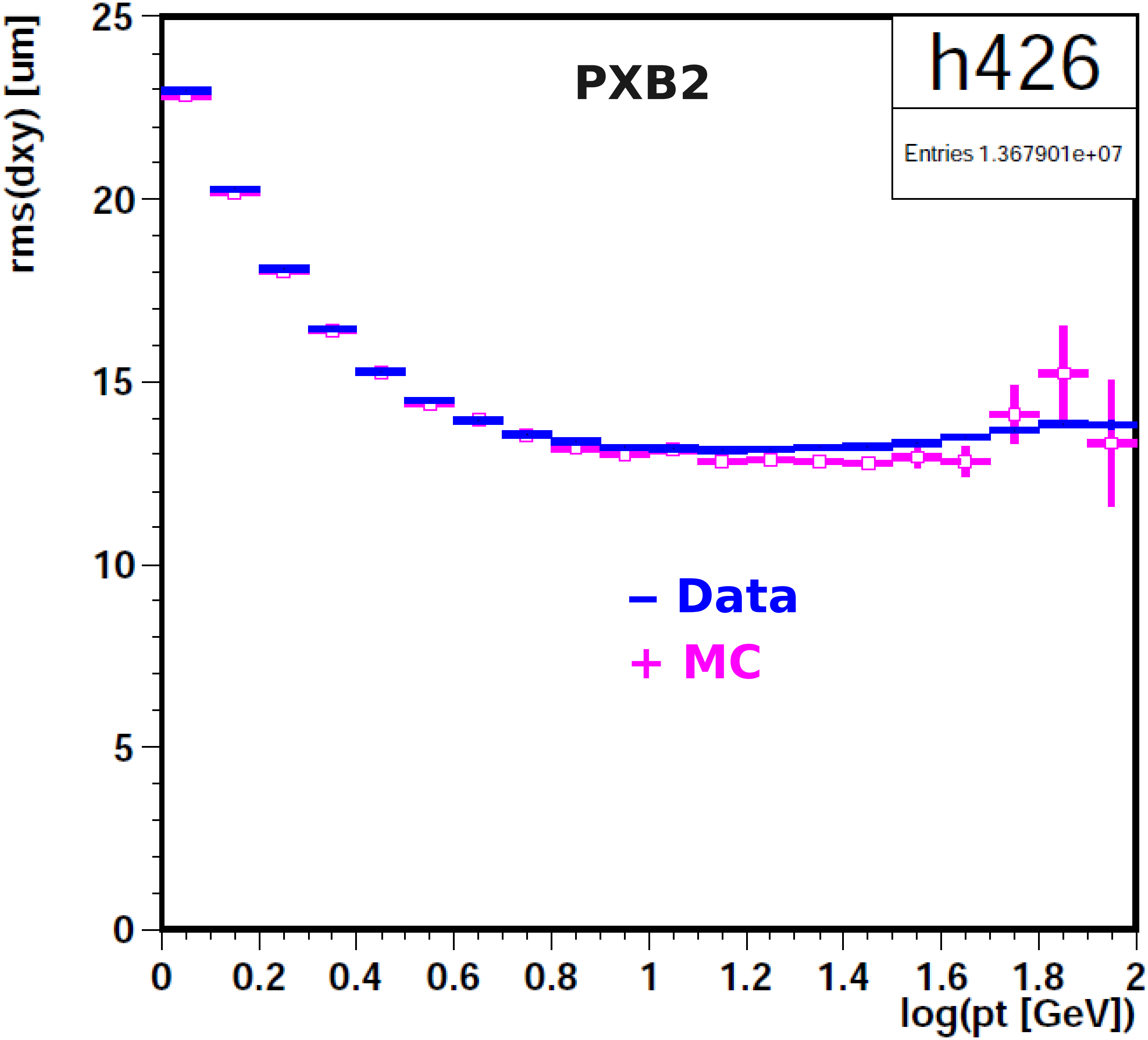
$$\sigma_r^2 = \sigma_2^2 + \frac{\sigma_1^2}{4} + \frac{\sigma_3^2}{4} + \frac{d_{m2}^2}{L_{13}^2}\left(\sigma_1^2 + \sigma_3^2\right)$$

$L_{13} = s_3 - s_1$	length of base line
$d_{m2} = s_2 - s_m$	distance of point 2 from mid point
$s_m = (s_1 + s_3)/2$	mid point
s	radial coordinate (arc length)



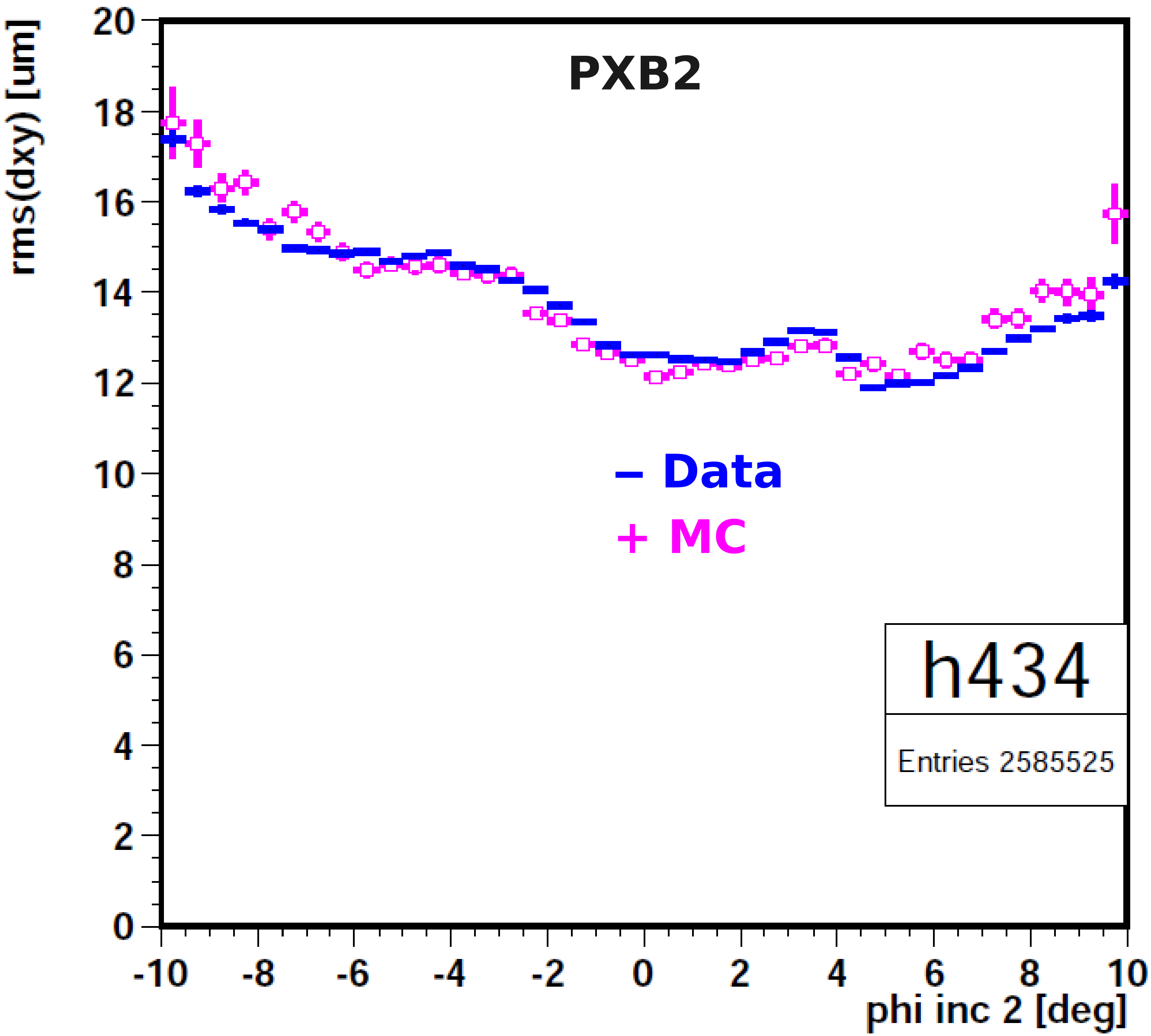
like for a straight line developed around its center, where offset and slope are uncorrelated.

p_t dependence of rφ resolution



- Width of the residual distribution is affected by multiple scattering in layers 1 and 2:
  - Need p_t > 4 GeV to observe intrinsic pixel resolution.
- Very well described by simulation.

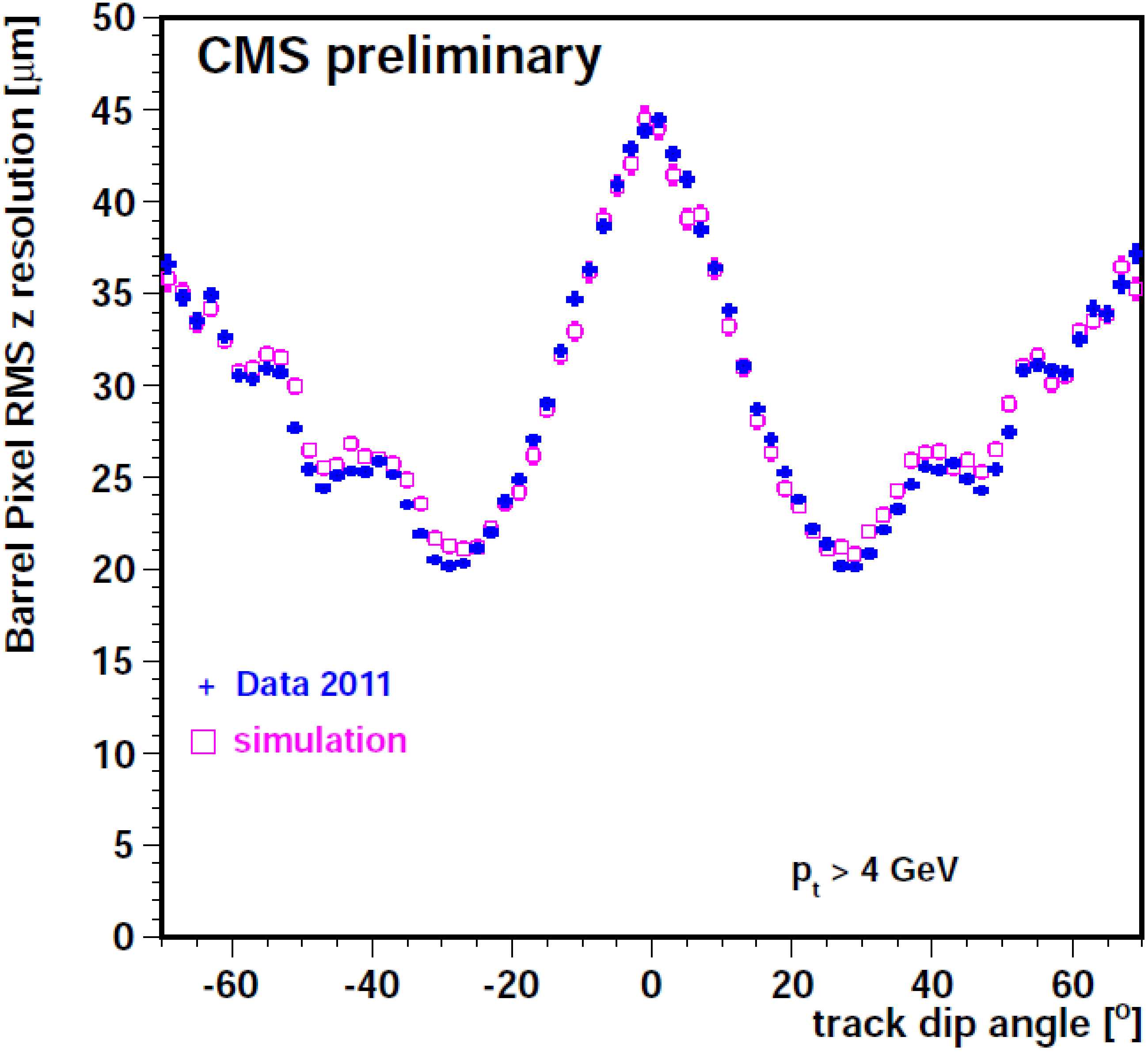
incident angle dependence of rφ resolution



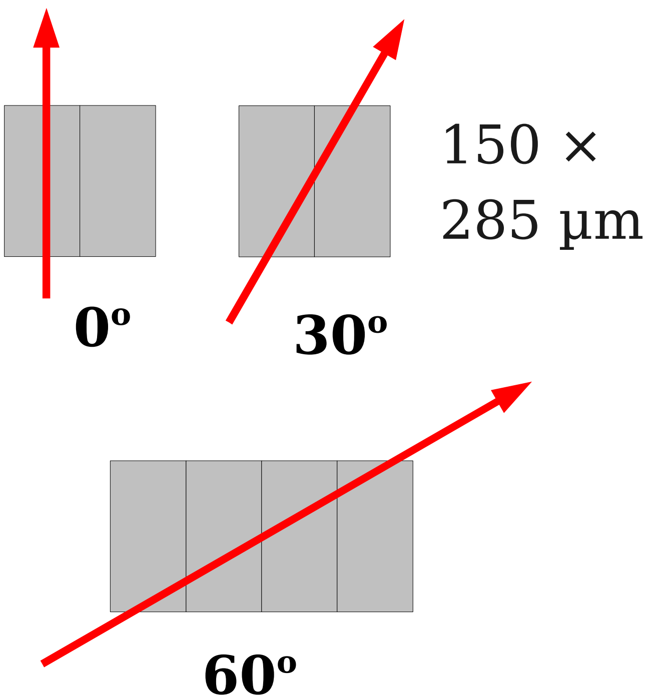
p_t > 4 GeV

- Pixel barrel layer 2 has 30 (full) modules:
  - each covers +-6° in azimuth.
  - larger angles due to curvature (lower p_t).
- Optimal rφ resolution reached for incidence between -1° and +7°.
- Quite well described by simulation.

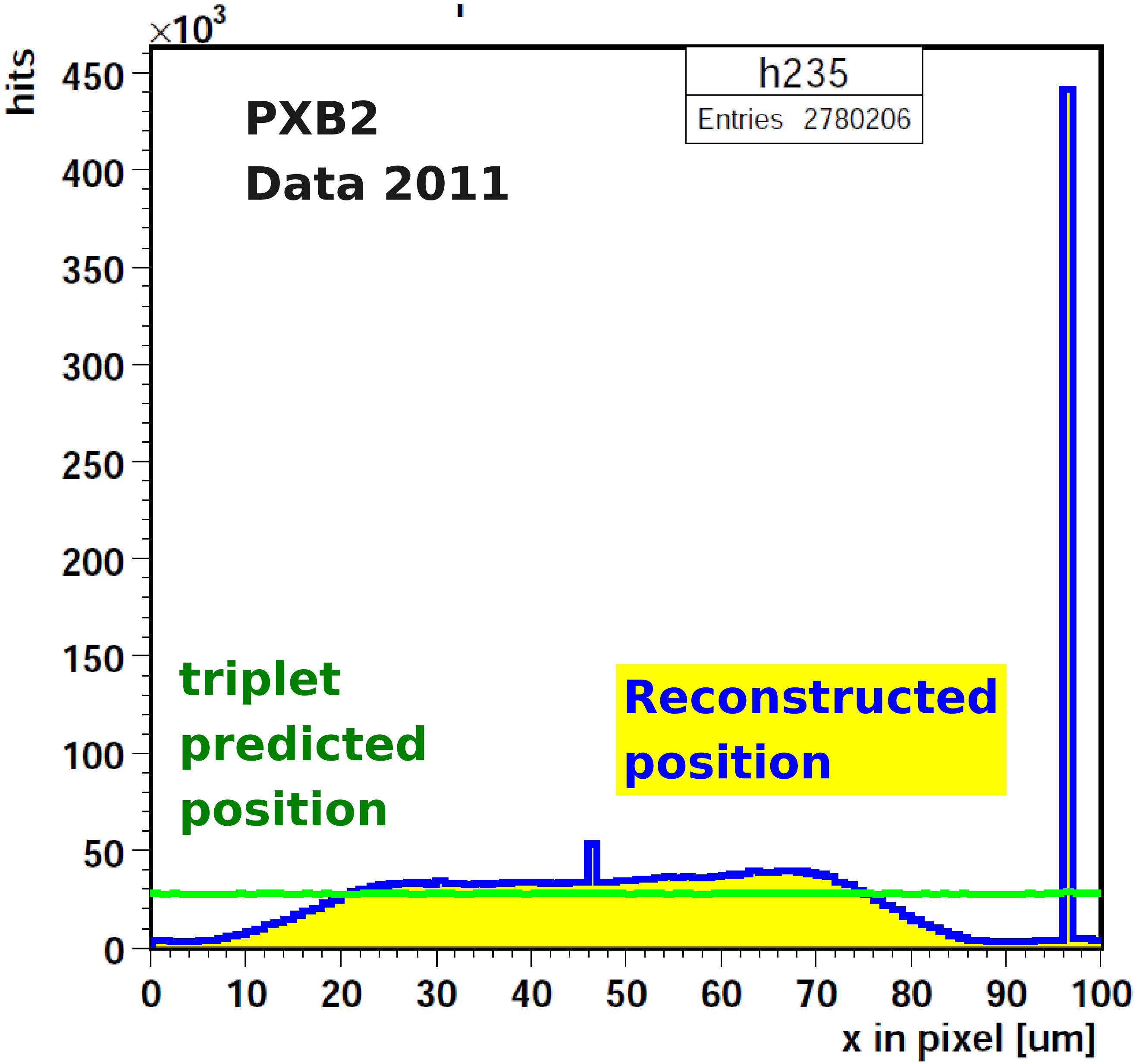
dip angle dependence of z resolution



- dip angle:
  - $\lambda = \pi/2 - \theta$.
- optimal resolution at $\lambda = \pm 30^o$:
  - sharing between neighboring pixels

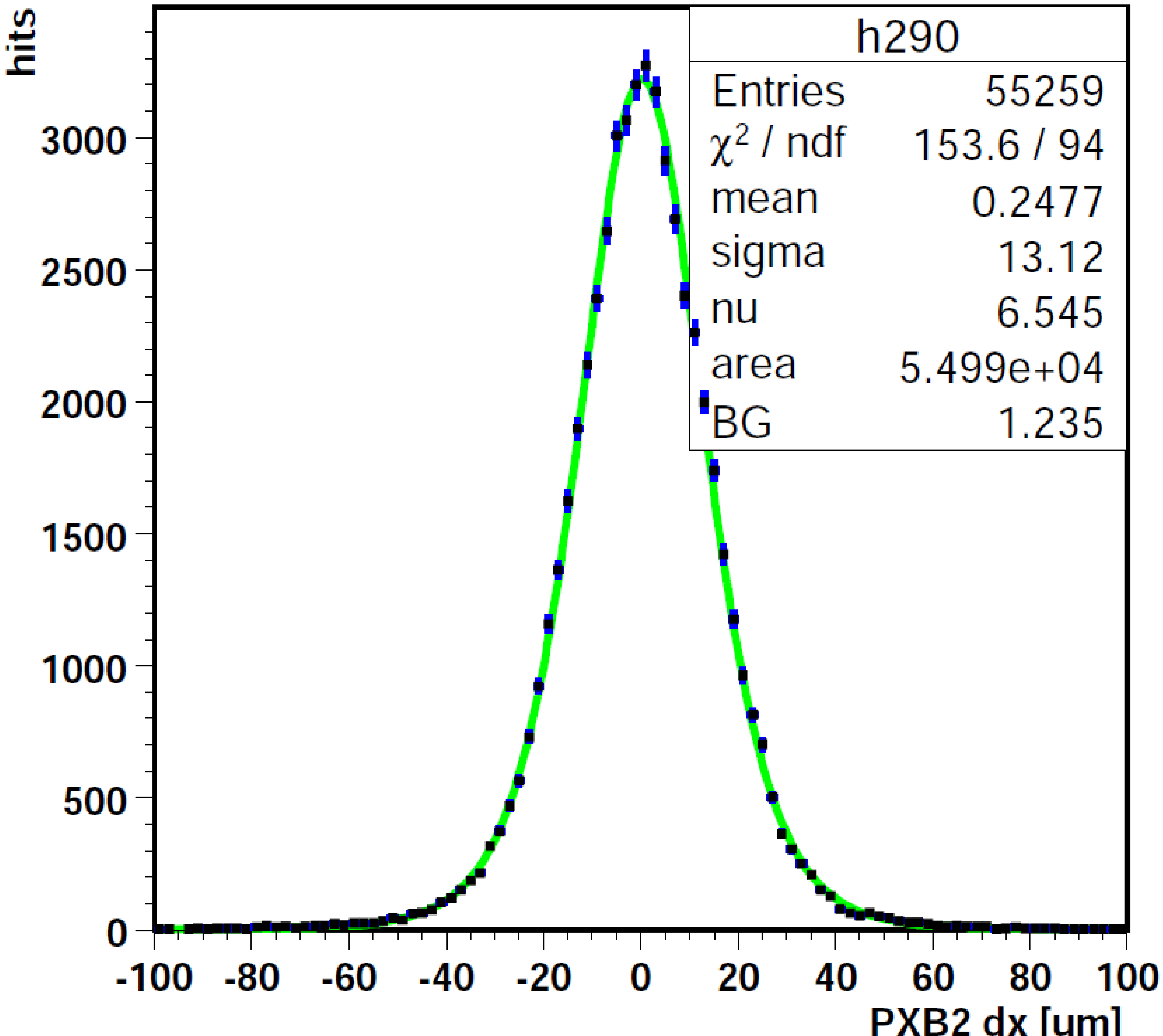


zoom into pixel



- x_{pix} = fmod(x_{loc}+0.8, 0.01).
- Predicted distribution is flat, as expected.
- Reconstructed position from Pixel-CPE-with-Templates:
  - peak at 97 from 1-row clusters,
  - peak at 46 μm?
  - almost flat between 22 and 74 μm.

triplet *x* residuals for 1-row clusters

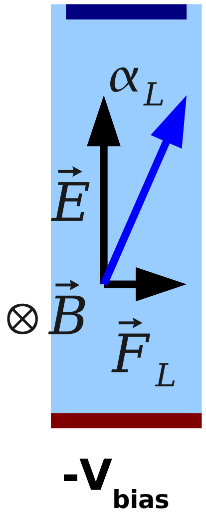


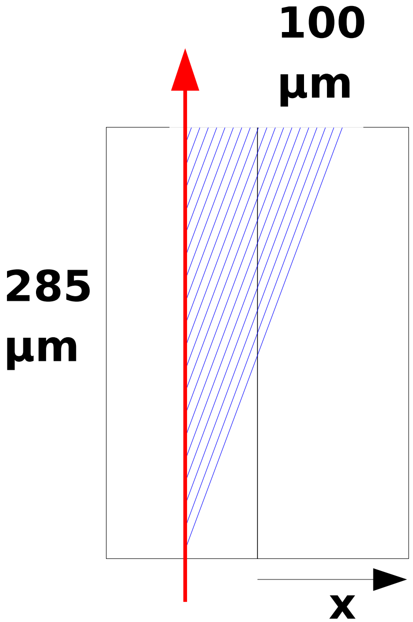
p_t > 12 GeV

1-row clusters

- Data Mar 2011
- Mean of the residual distribution is zero:
  - no bias, alignment OK.
- Width of the residual distribution at high p_t:
  - σ_r = 13 µm.
  - OK.
- Upgrade:
  - ROC with lower thresholds
  - less 1-row clusters.

Lorentz angle

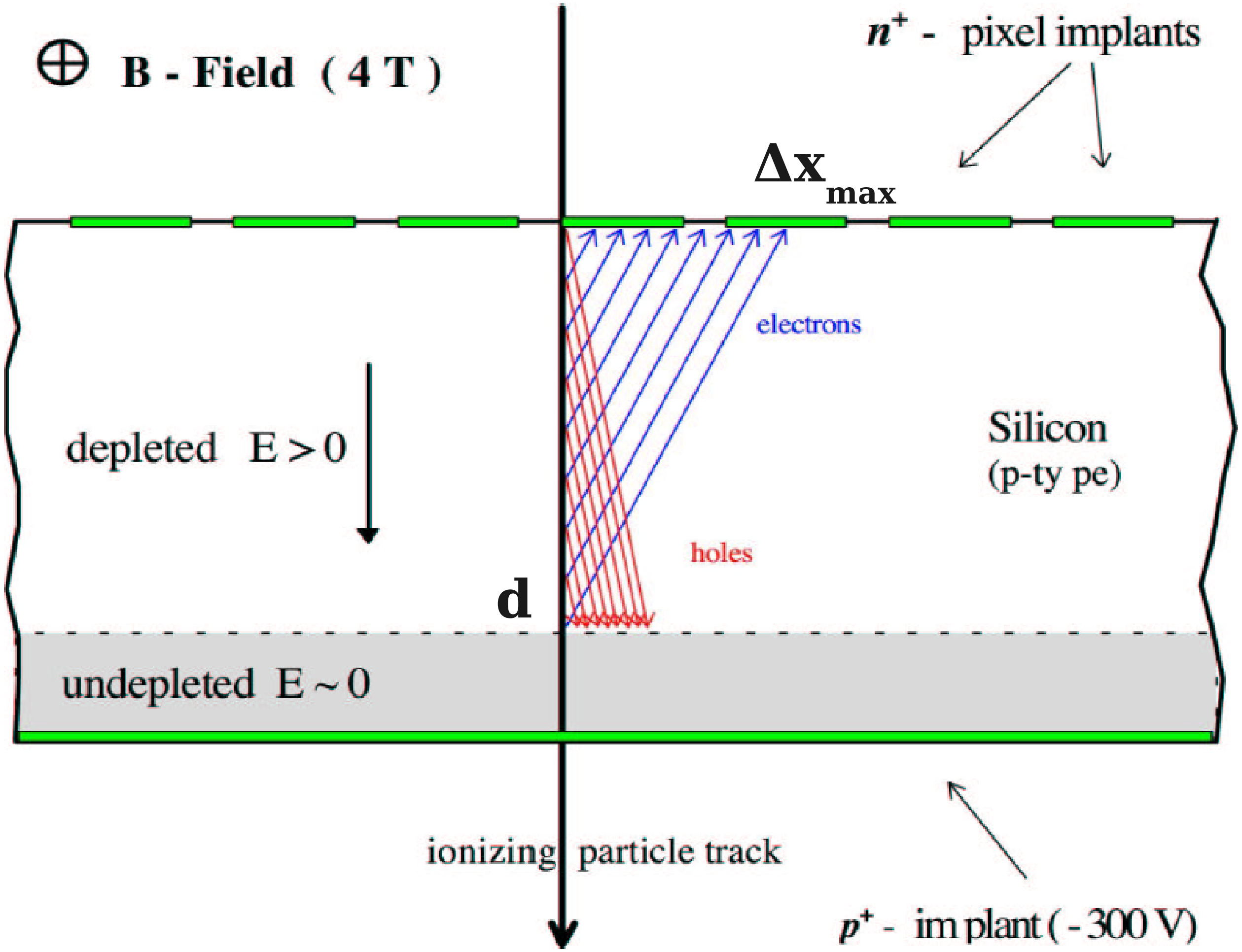




atan(100/285) = 19.3°

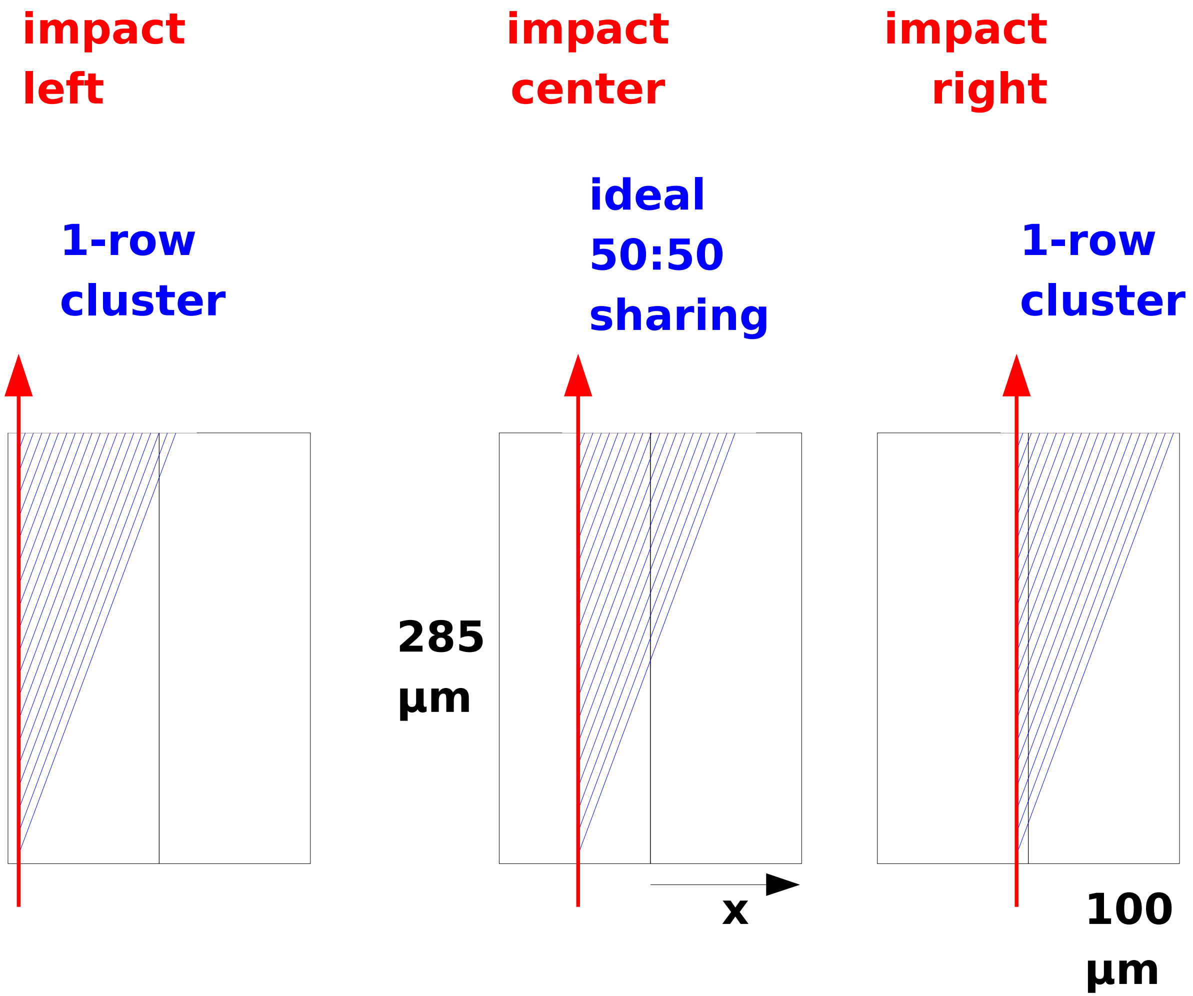
- Drift field:
  - $F = q\,E$
- Lorentz force:
  - $F_L = q\,v\,B$
- Drift velocity:
  - $v = \mu\,E$, Hall mobility μ
- Residual drift direction:
  - $\tan\alpha_L = F_L\,/\,F = \mu\,B$
- electrons in Si at 3.8 T, 0°C:
  - $\alpha_L \approx 20^o$
  - degrades with radiation

Lorentz drift



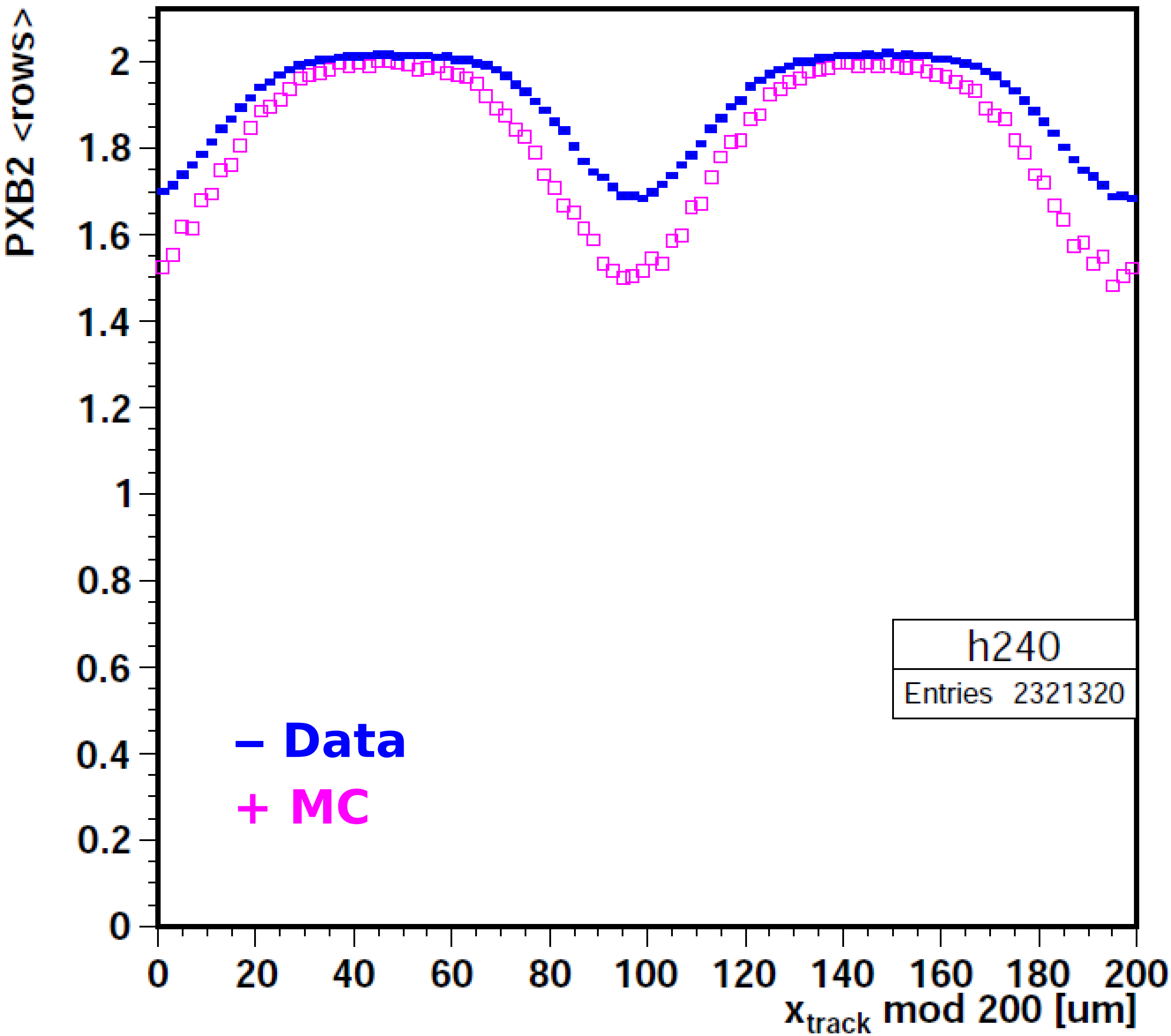
- $\tan\alpha_L = \mu B$
- electrons in Si at 3.8 T:
  - $\tan\alpha_L \approx 0.4$
- pixel sensors:
  - $d = 285\ \mu m$
  - $\Delta x_{max} = d \tan\alpha_L$
    $= 114\ \mu m$
  - $\Delta x_{mid} = 0.5\ d \tan\alpha_L$
    $= 57\ \mu m$

Cluster size vs impact point



- $\tan\alpha_L = \mu\, B$
- electrons in Si at 3.8 T:
  - $\tan\alpha_L = 0.4$
- pixel sensors:
  - d = 285 µm
  - $\Delta x_{max} = d \tan\alpha_L$
    $= 114$ µm
  - $\Delta x_{mid} = 0.5\, d \tan\alpha_L$
    $= 57$ µm

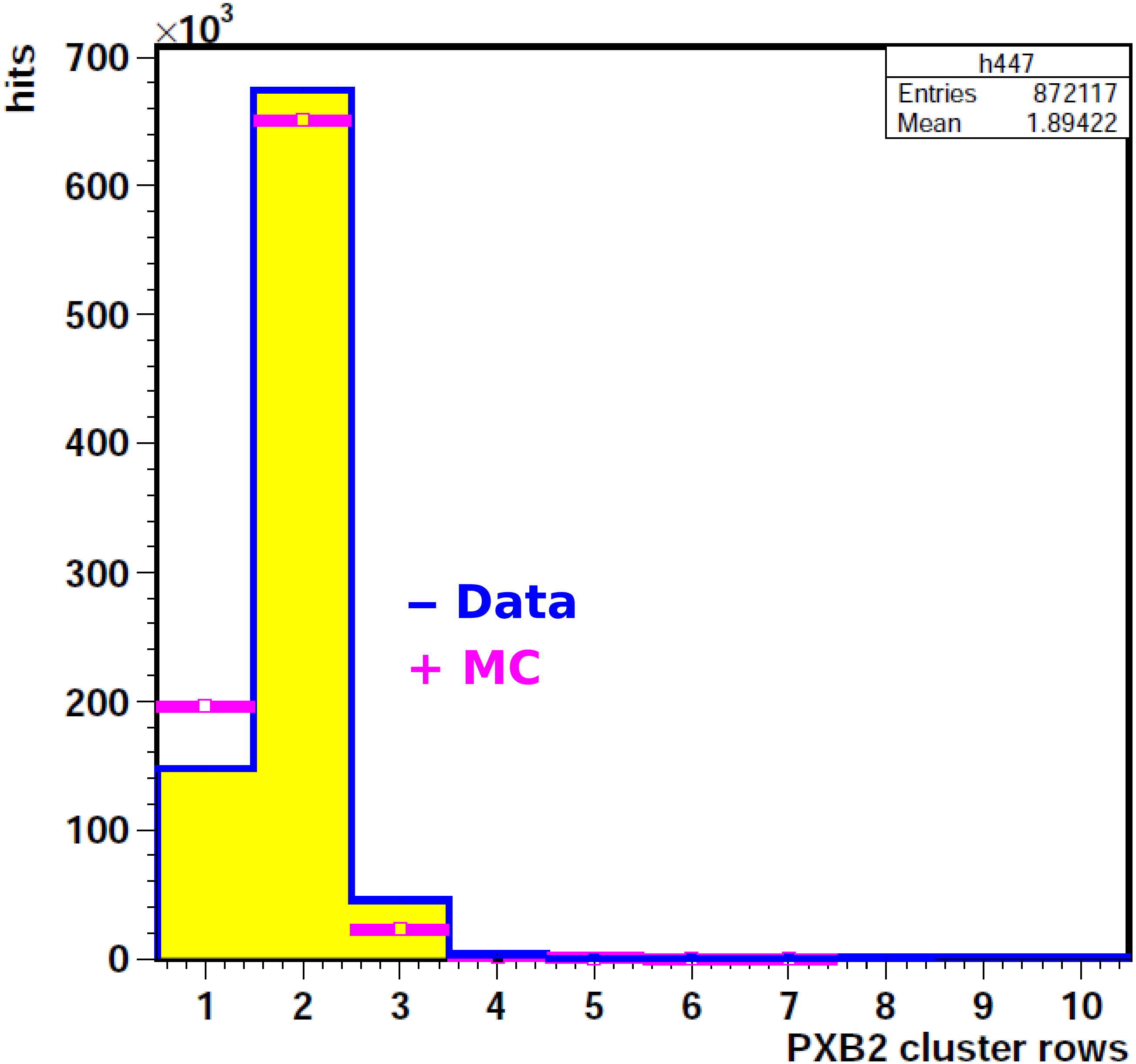
cluster size vs *x* impact point



***p_t* > 4 GeV**

- mean number of rows per cluster vs predicted *x* position mod 200 μm.
- mostly 2-pixel clusters
  - ideal Lorentz angle
- 1-row clusters contribute near pixel boundaries, as expected from geometry.
- Simulation seems to have more 1-row clusters.

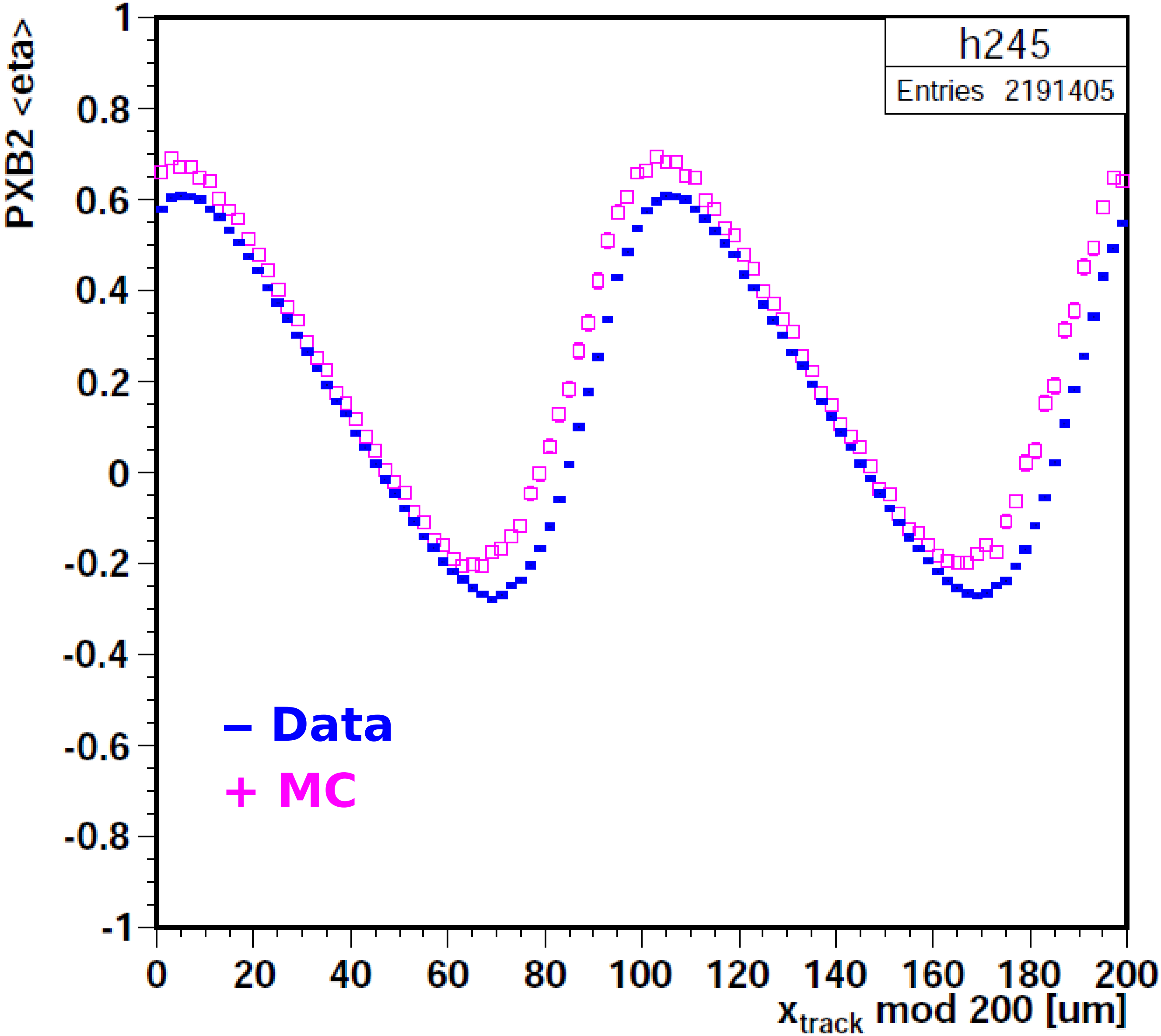
cluster size distribution



$p_t > 4$ GeV

- mean number of rows per cluster.
- Simulation has 6% more 1-row clusters, less 2- and 3-row clusters:
  - too few δ rays?
  - too few merged clusters?

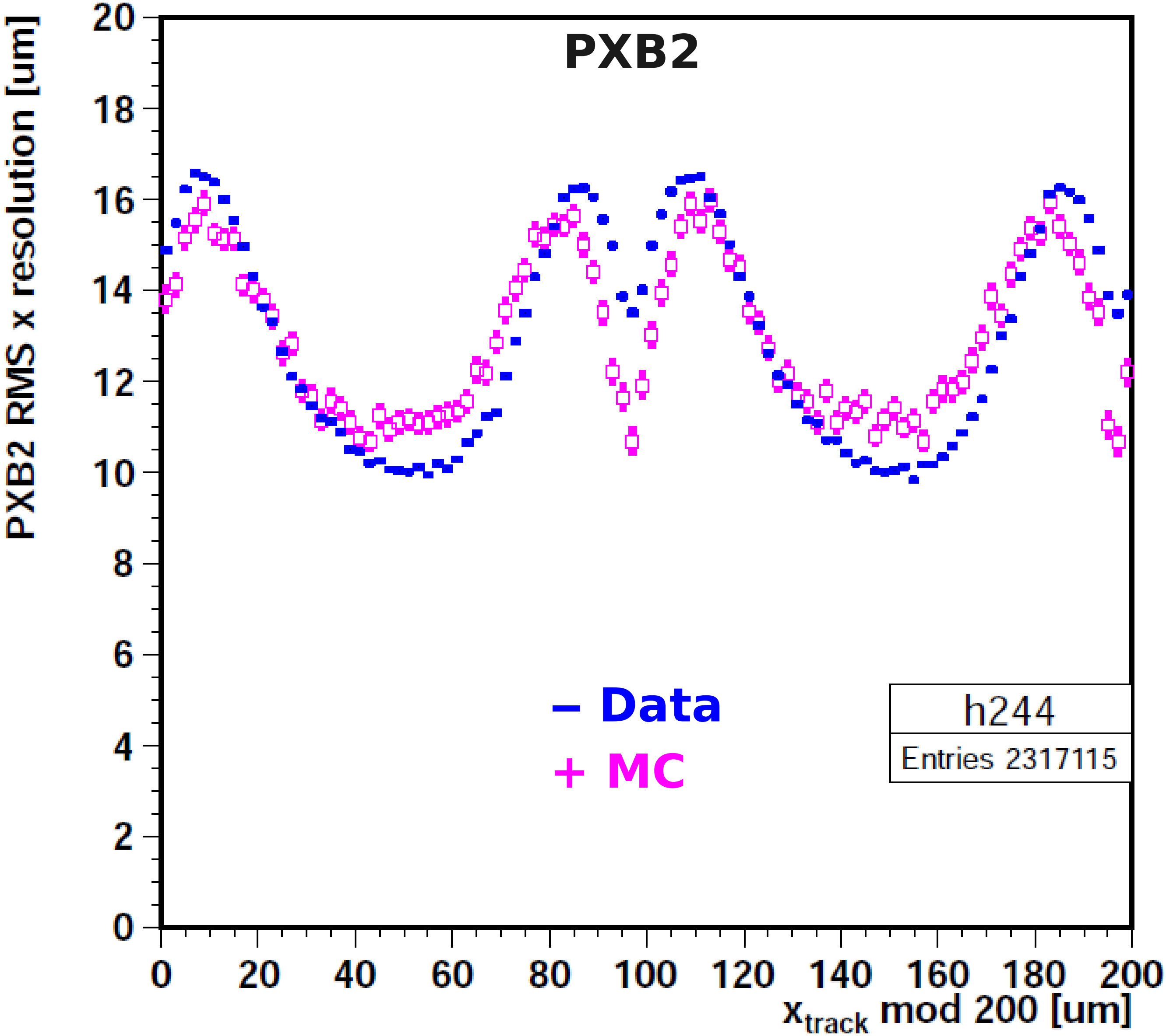
charge sharing vs *x* impact point



p_t > 4 GeV

- 1- and 2-row clusters:
  - $\eta = (Q_L - Q_R) / Q_{tot}$
- saw-tooth would be ideal,
  - smearing due to track resolution, thresholds, gain non-linearity...
- Simulation has similar shape, slightly shifted.

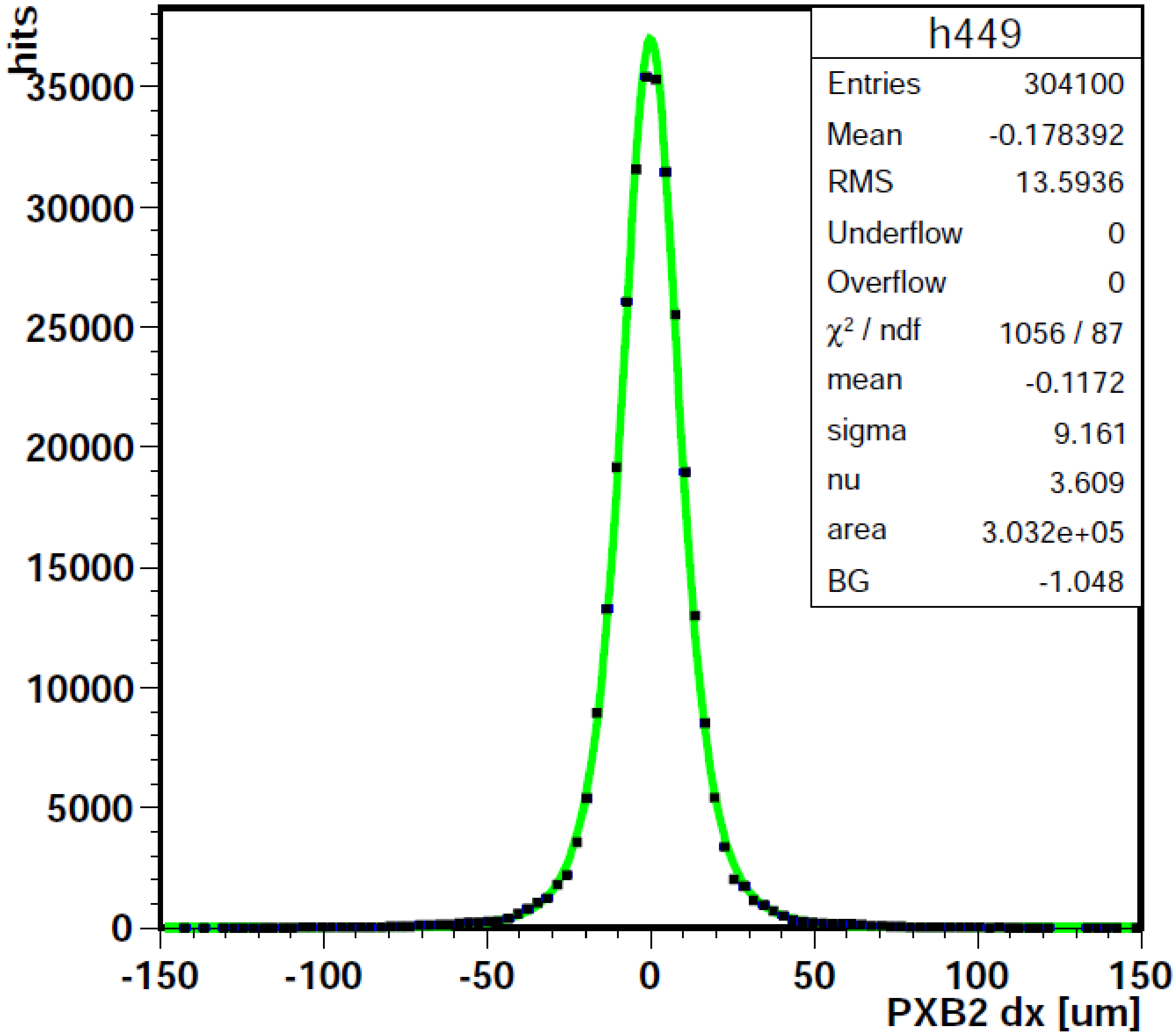
local *x* resolution in pixel



p_t > 4 GeV

- Pixel rms *x* resolution from triplets vs predicted *x* in pixel mod 200 µm.
- Strong resolution variation from 10 to 16 µm:
  - best resolution at pixel center,
  - worst resolution near pixel edges.
- Simulation is similar, a little more pronounced.

triplet *x* residuals at pixel mid



p_t > 12 GeV,

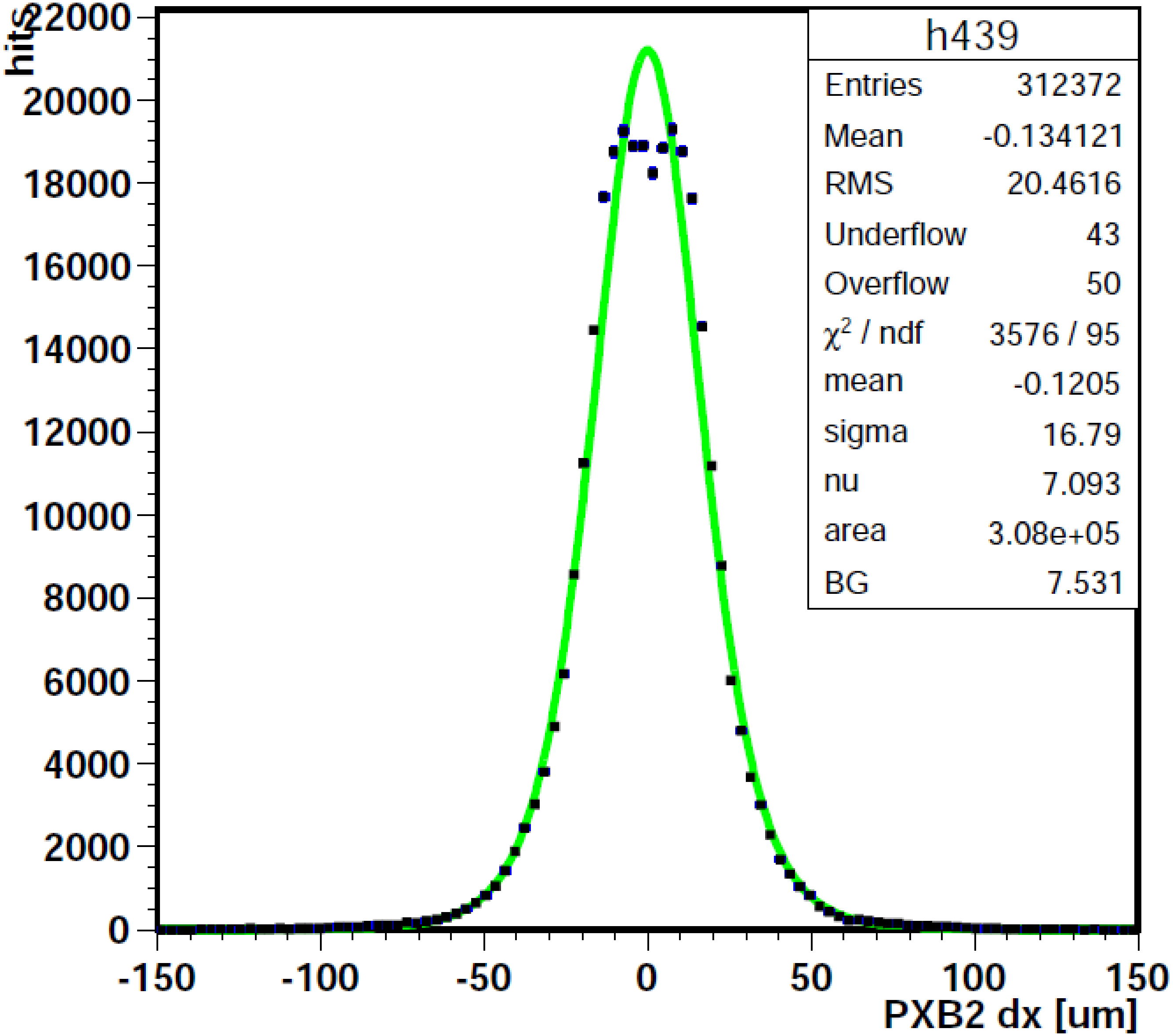
2-row clusters, 30 < x_{track} < 70 µm.

- Data Mar 2011
- Width of the residual distribution at high p_t:
- σ_r = 9.2 µm.

$$\sigma_r^2 = \sigma_2^2 + (\sigma_1/2)^2 + (\sigma_3/2)^2$$

- Other layers have average σ_i = 10.5 µm.
- Result:
  - σ_2 = 5.4 µm at pixel mid.
  - Somewhat academic: need to know that hit was in the middle.

triplet *x* residuals at pixel edge



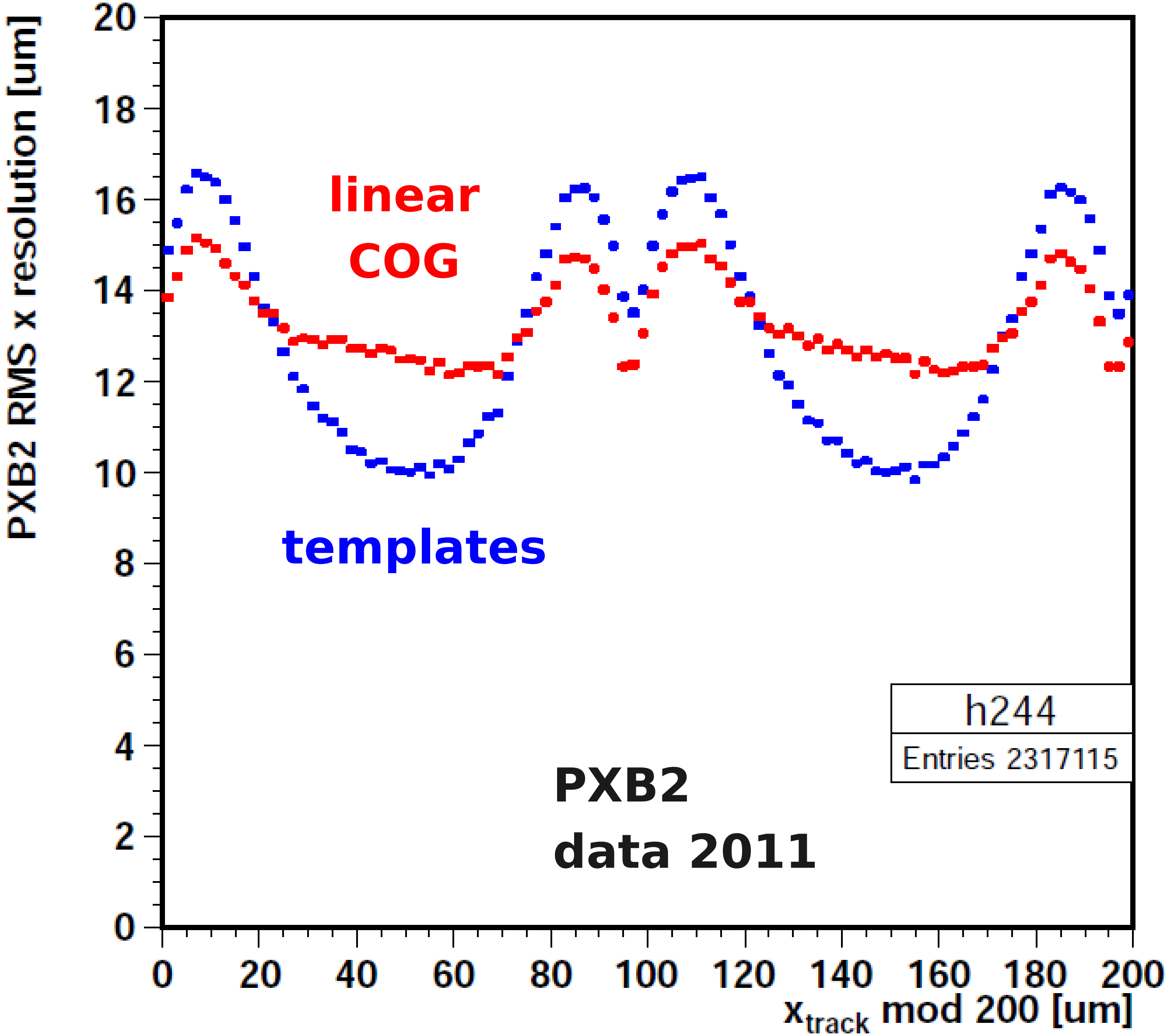
p_t > 12 GeV

x_{track} < 20 or > 80 μm.

- Data Mar 2011
- Width of the residual distribution at high p_t:
- σ_r = 16.8 μm.

  $\sigma_r^2 = \sigma_2^2 + (\sigma_1/2)^2 + (\sigma_3/2)^2$
- Other layers have average σ_i = 10.5 μm.
- Result:
  - σ_2 = 15 μm at pixel edge,
  - double peak?

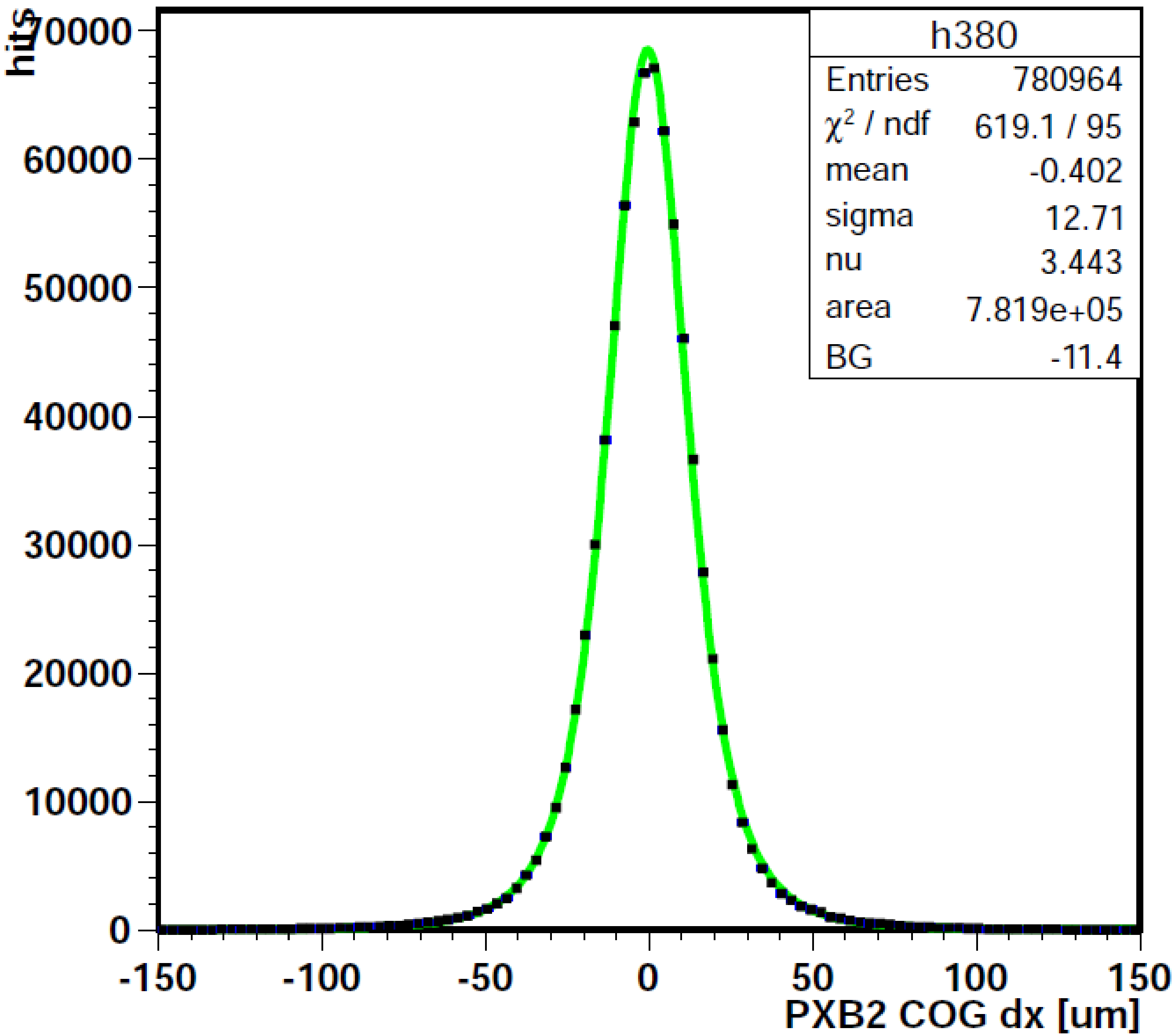
local *x* resolution in pixel



p_t > 4 GeV

- Pixel rms *x* resolution from triplets vs predicted *x* in pixel mod 200 µm.
- CMS standard templates varies from 10 to 16 um.
- Simple cluster center-of-gravity algorithm:
  - worse resolution at pixel center,
  - better resolution near pixel edges.

Pixel *x* resolution with the COG method



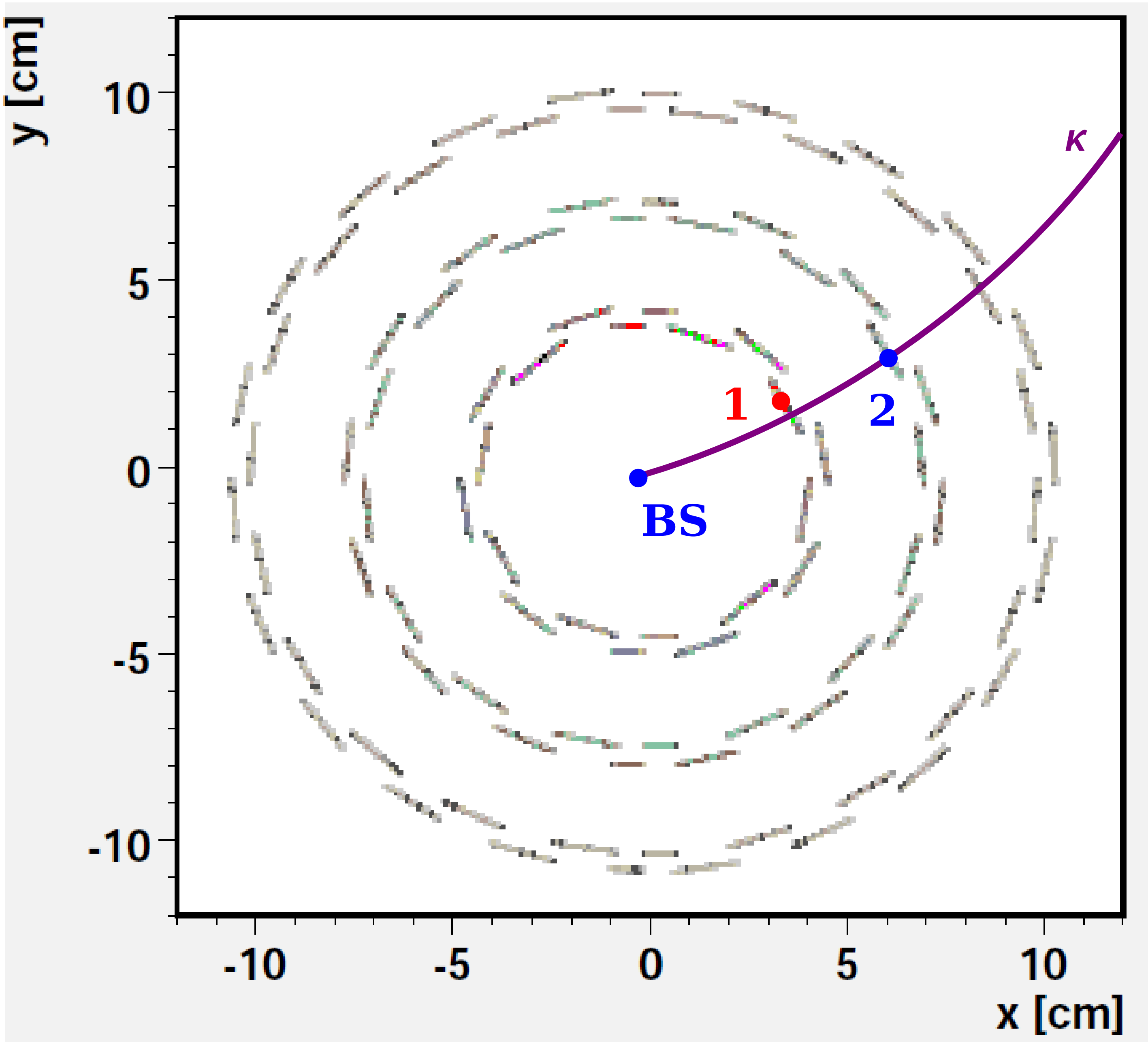
p_t > 12 GeV

- Data Mar 2011
- Width of the residual distribution at high p_t:
- σ_r = 12.7 μm.

$$\sigma_r^2 = \sigma_2^2 + (\sigma_1/2)^2 + (\sigma_3/2)^2$$

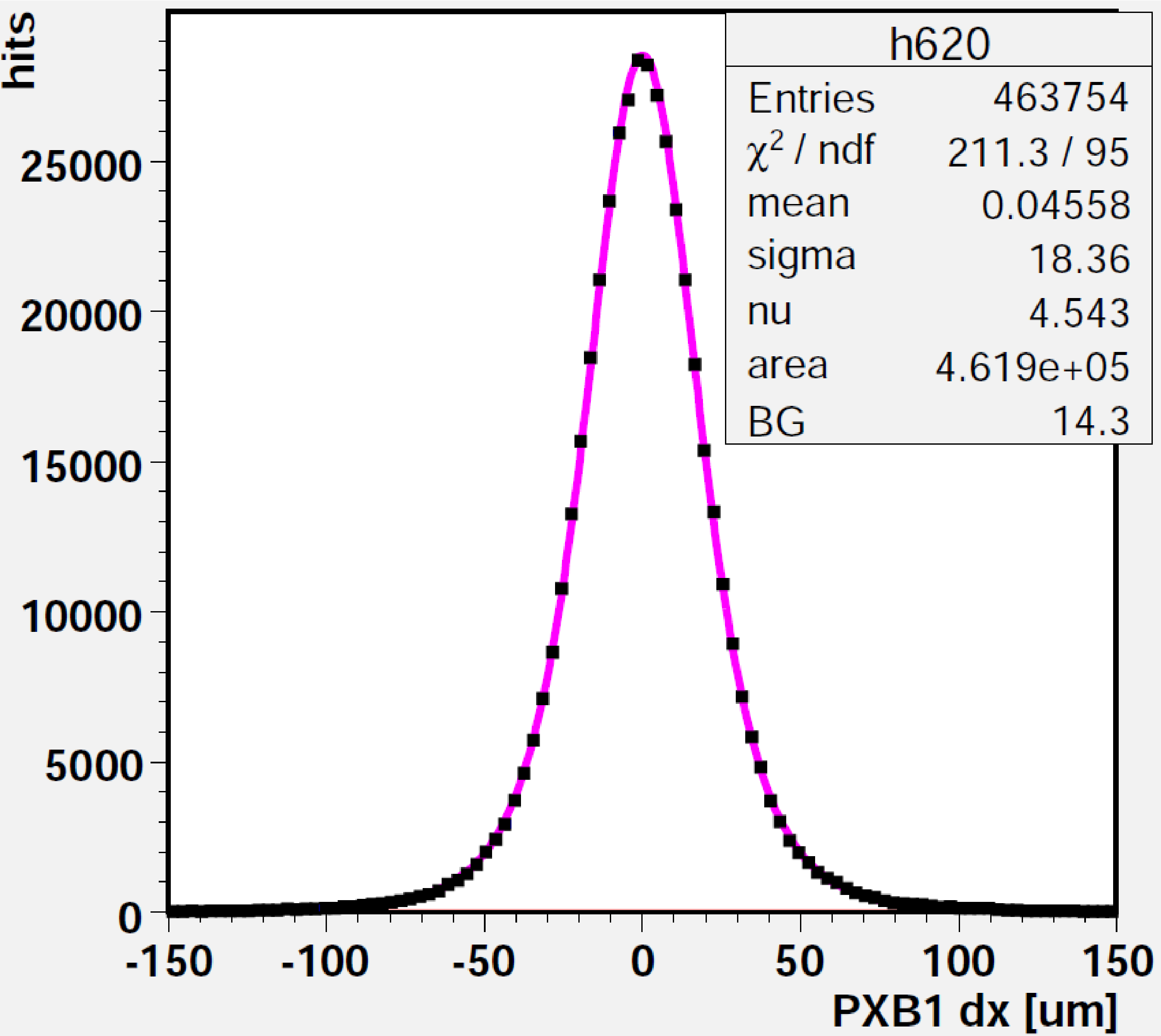
- Other layers have average σ_i = 10.4 μm.
- Result:
  - σ_2 = 10.4 μm with COG method,
  - identical to CMS template method.

layer 1 residual using the beam spot



- Select tracks with hits in 2 pixel layers.
- Use offline beam spot.
- Impact parameter: $|d'_{CA}| < 5\ \sigma$.
- Redefine track:
  - curvature κ from full tracker,
  - position and angle from beam spot and 2nd layer, in rφ.
- Interpolate to 1st layer.

Layer 1 triplet rφ residuals at high p_t



p_t > 12 GeV

- Data Mar 2011
- Width of the residual distribution at high p_t:

$$\sigma_r^2 = \sigma_1^2 + (\sigma_{BS}/2)^2 + (\sigma_2/2)^2$$

- Measured:
  - σ_r = 18.4 μm
- Assume for beam spot:
  - σ_{BS} = 27 μm
- Gives for intrinsic
  - σ_1 = 11 μm

Summary

- Triplet method for pixel hit residuals:
  - x and z resolutions across a module well described by simulation
  - x resolution varies strongly across one pixel:
  - best resolution at pixel mid (optimal charge sharing under Lorentz drift),
  - worst resolution near pixel edges (especially for 2-row clusters). Improvement possible?
  - Resolution of 10.5 µm previously observed seems to be a mixture of 5 µm at best and 15 µm at worst.
  - quite well described by simulation.
- Upgrade:
  - new ROC with lower thresholds
  - less 1-row clusters?
  - wider plateau with optimal resolution?

CMS Pixel DPG

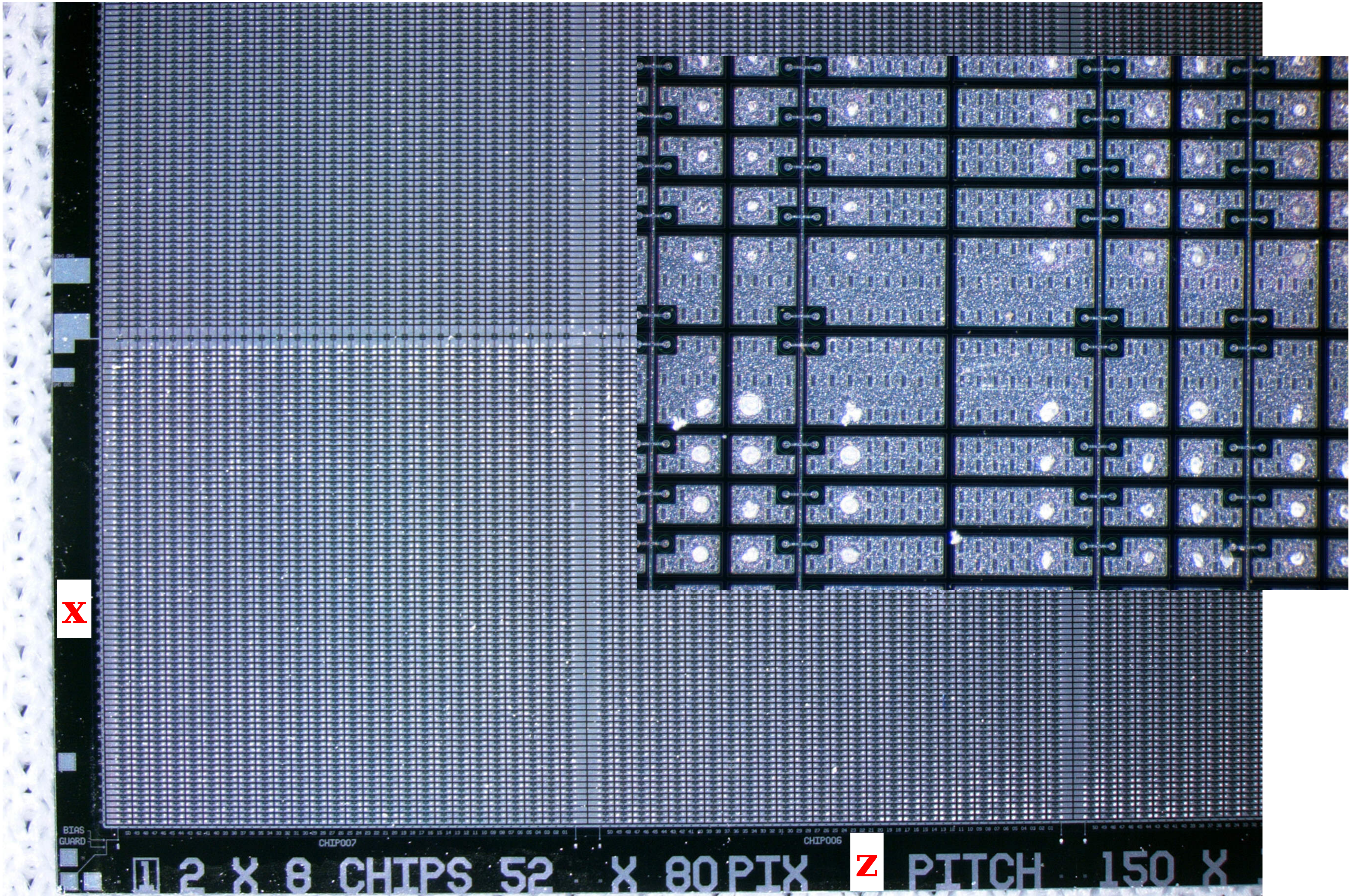
- Triplet method is established for pixel resolution studies.
  - Should be followed as function of time and radiation,
  - requires monitoring of cluster size, charge sharing, alignment, and beam spot position and size as well.
- Reporting to the Pixel Detector Performance Group:
  - meeting bi-weekly Thursdays at 14:00, convenors Urs Langenegger (PSI) and Viktor Vezpremi (Hungarian Acad. Sci.)
  - part of the Tracker DPG, convenors Petra Merkel (Purdue) and Andrea Venturi (Pisa)

  `https://indico.cern.ch/categoryDisplay.py?categId=1358`

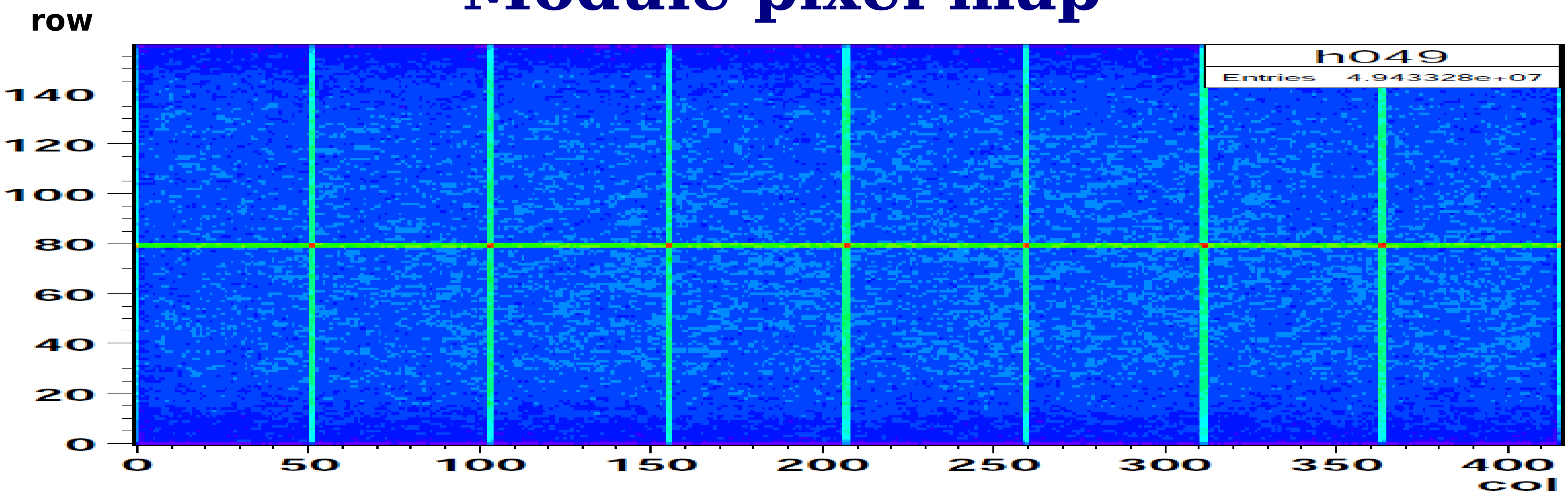
- Open tasks and credits:

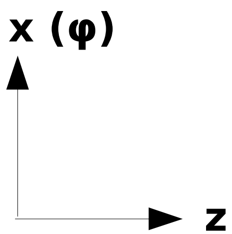
  `https://twiki.cern.ch/twiki/bin/viewauth/CMS/TrackerDPGManpowerNeeds2012`

pixel sensor: wide and long pixels

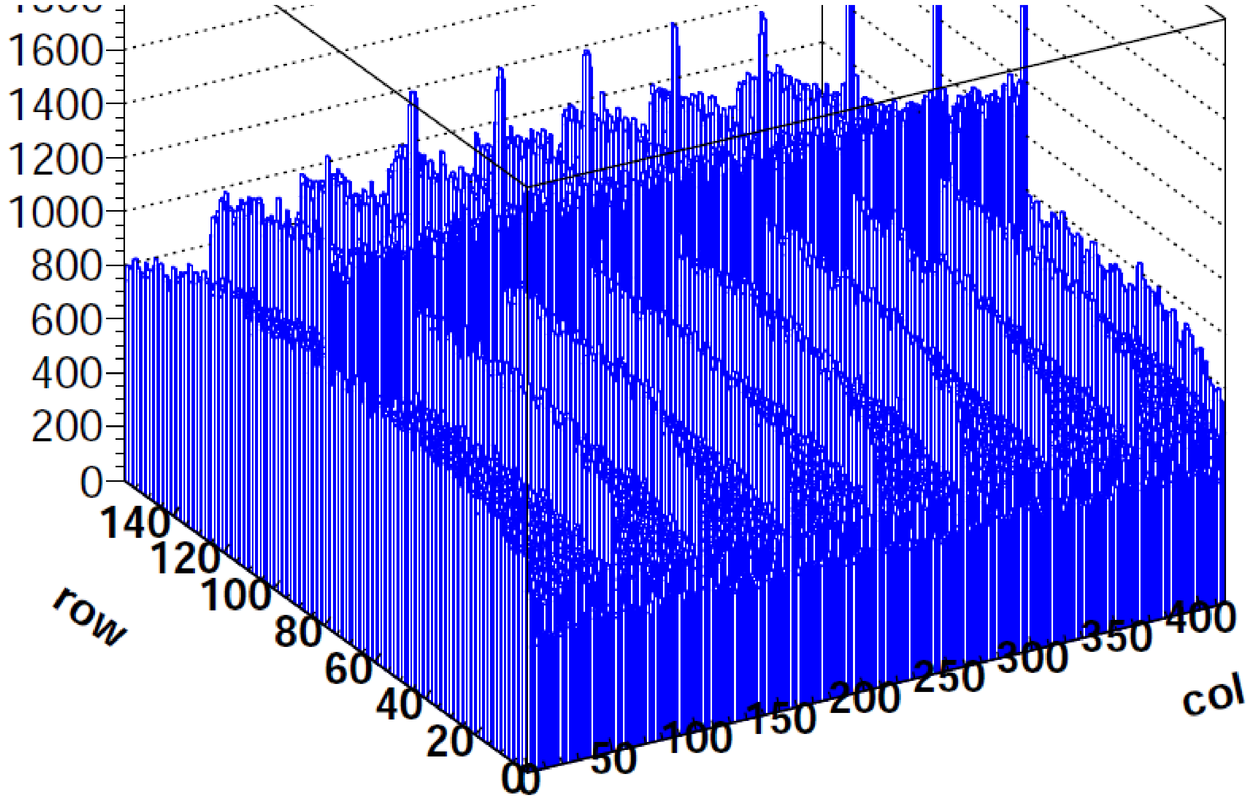


Module pixel map



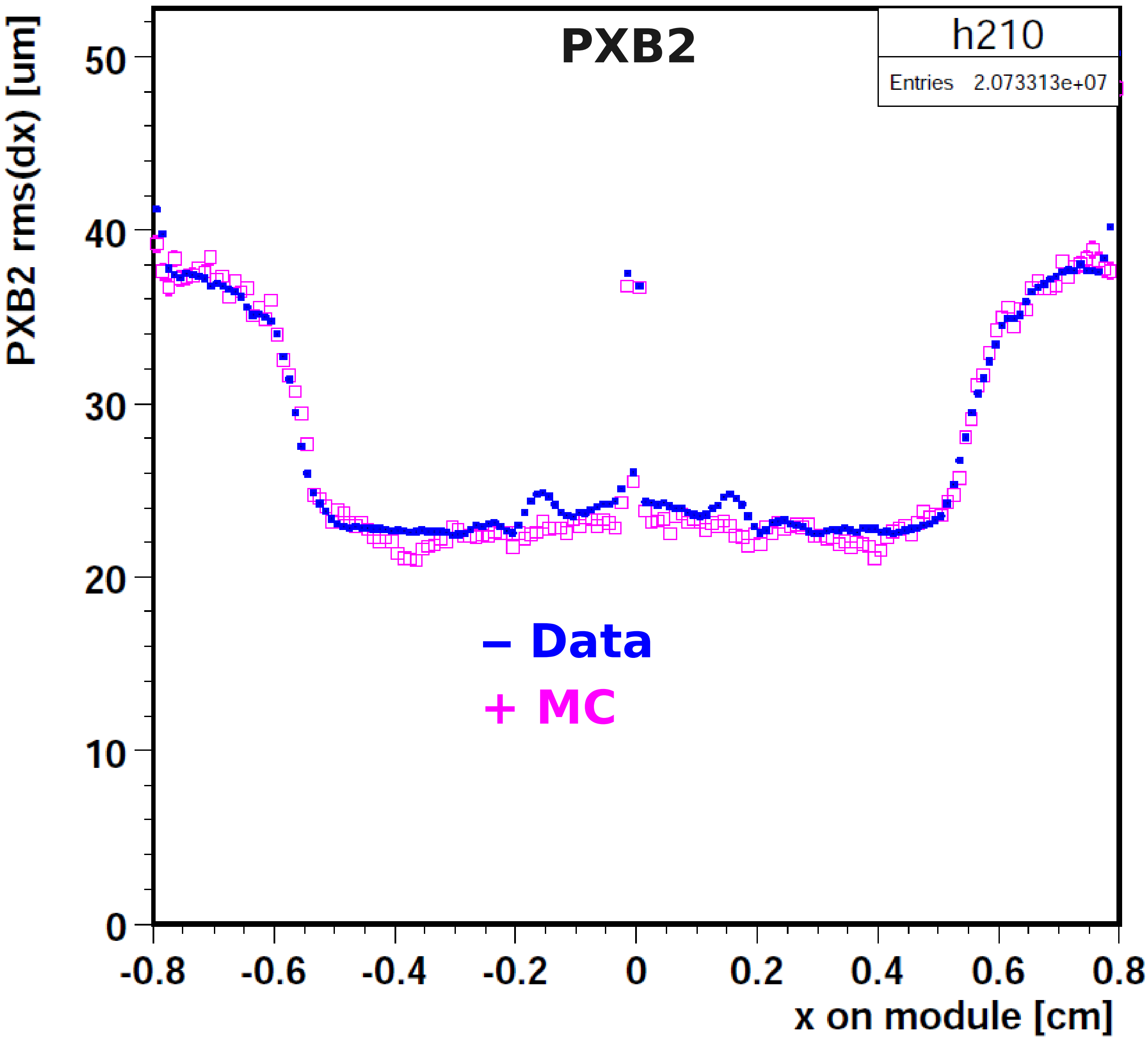


rows 79 and 80: wide pixels: 200 instead of100 µm to cover the ROC edge.



colums 51, 52: 300 µm instead 150 µm.

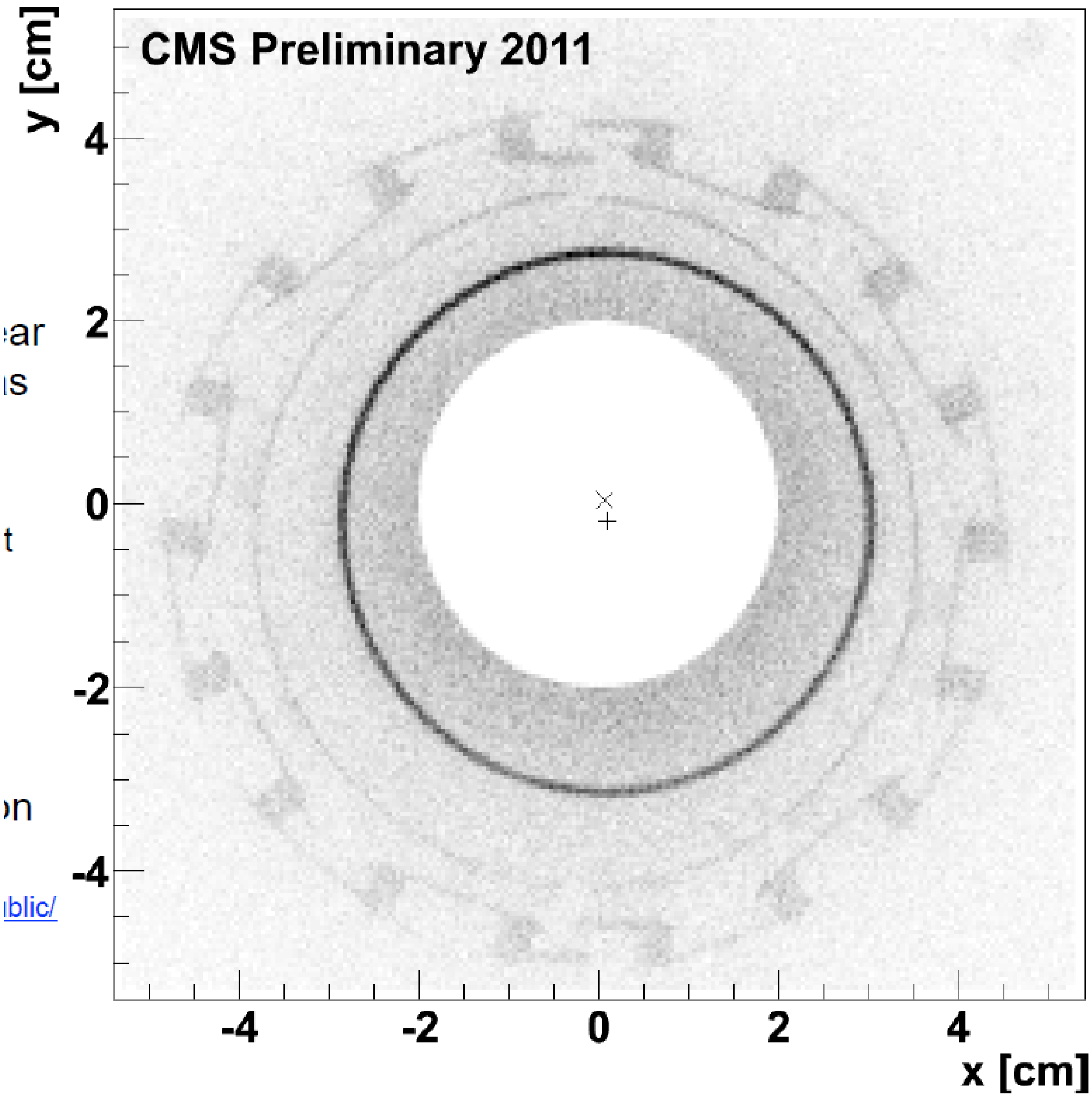
local *x* resolution at low p_t



0.8 < p_t < 1.2 GeV

- Multiple scattering dominates at low p_t.
- Flat valley:
  - only silicon at mid-module.
- Peak at center:
  - wide pixels.
- Edges:
  - SiN base strips, cooling pipes.
- Well described by simulation. No phase shift when plotted in this way.

PXB1 in nuclear interactions

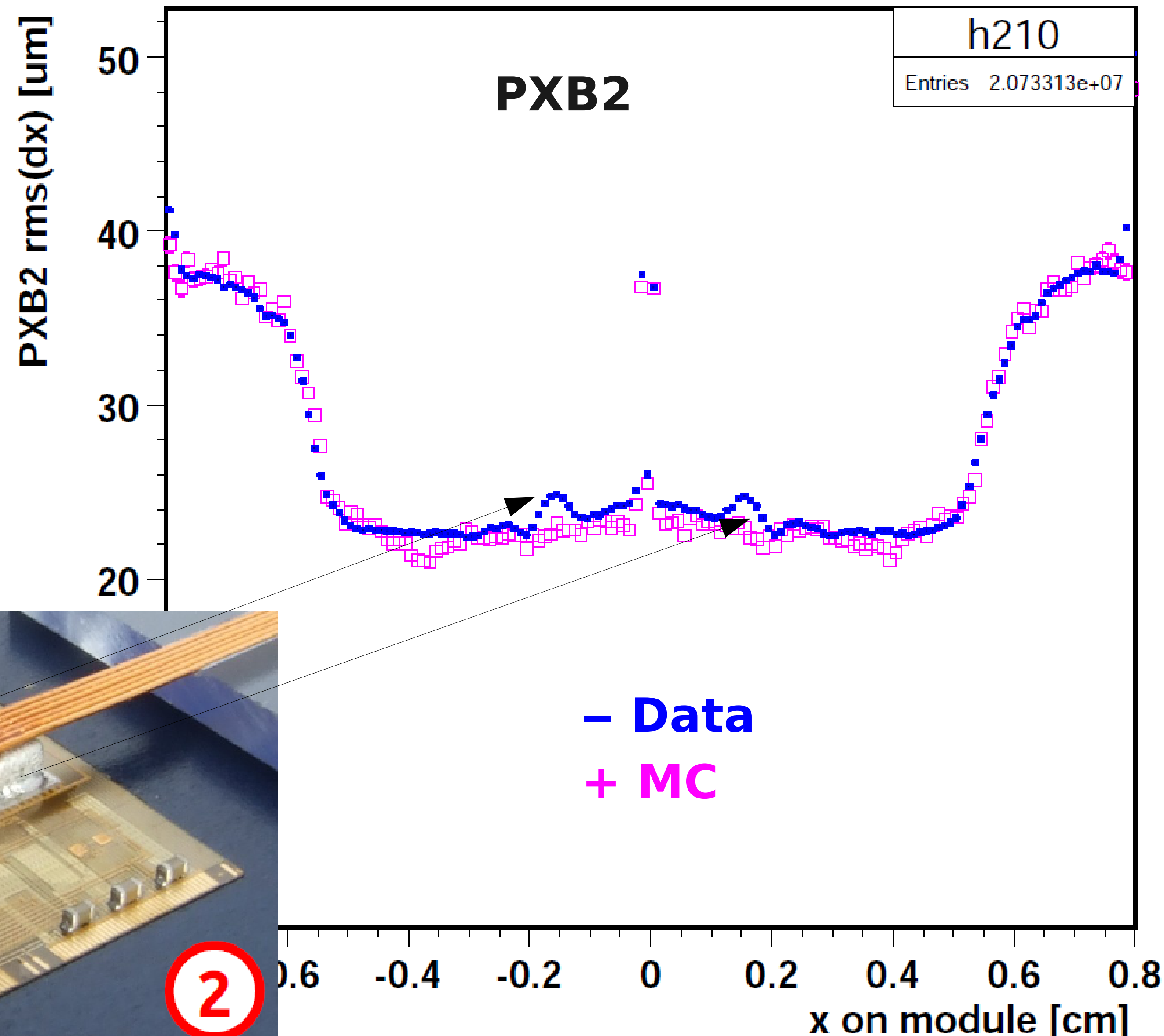


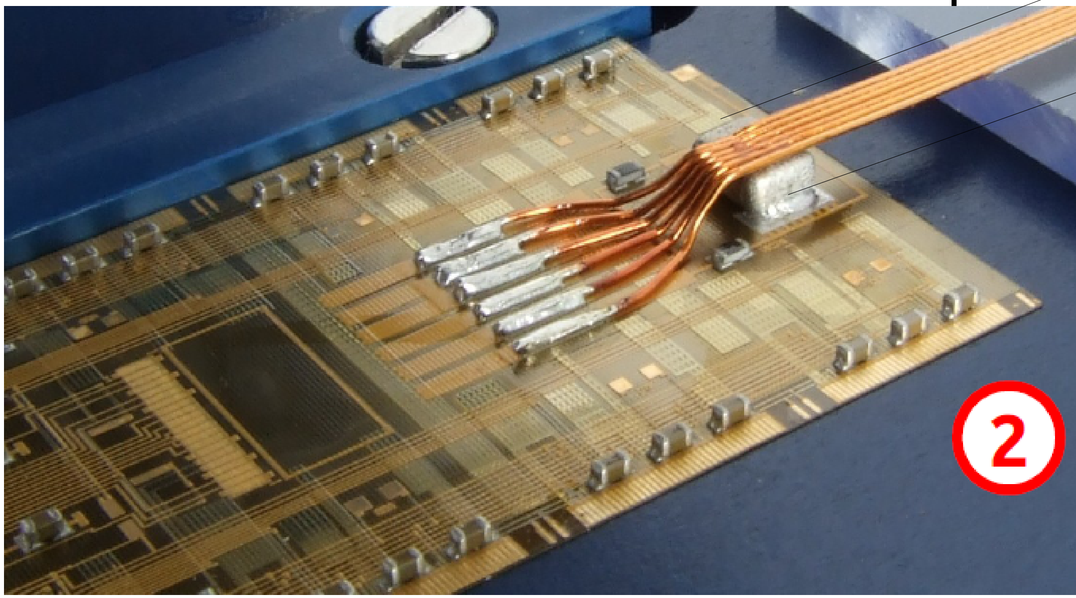
- Nuclear interaction vertices (M. Gouzevitch, G. Squazzoni).
- https://indico.cern.ch/conferenceDisplay.py?confId=123717
- First pixel barrel layer with 18 cooling pipes clearly visible.

local x resolution at low p_t

resolution humps at ±0.15 cm due to HV filter capacitor?

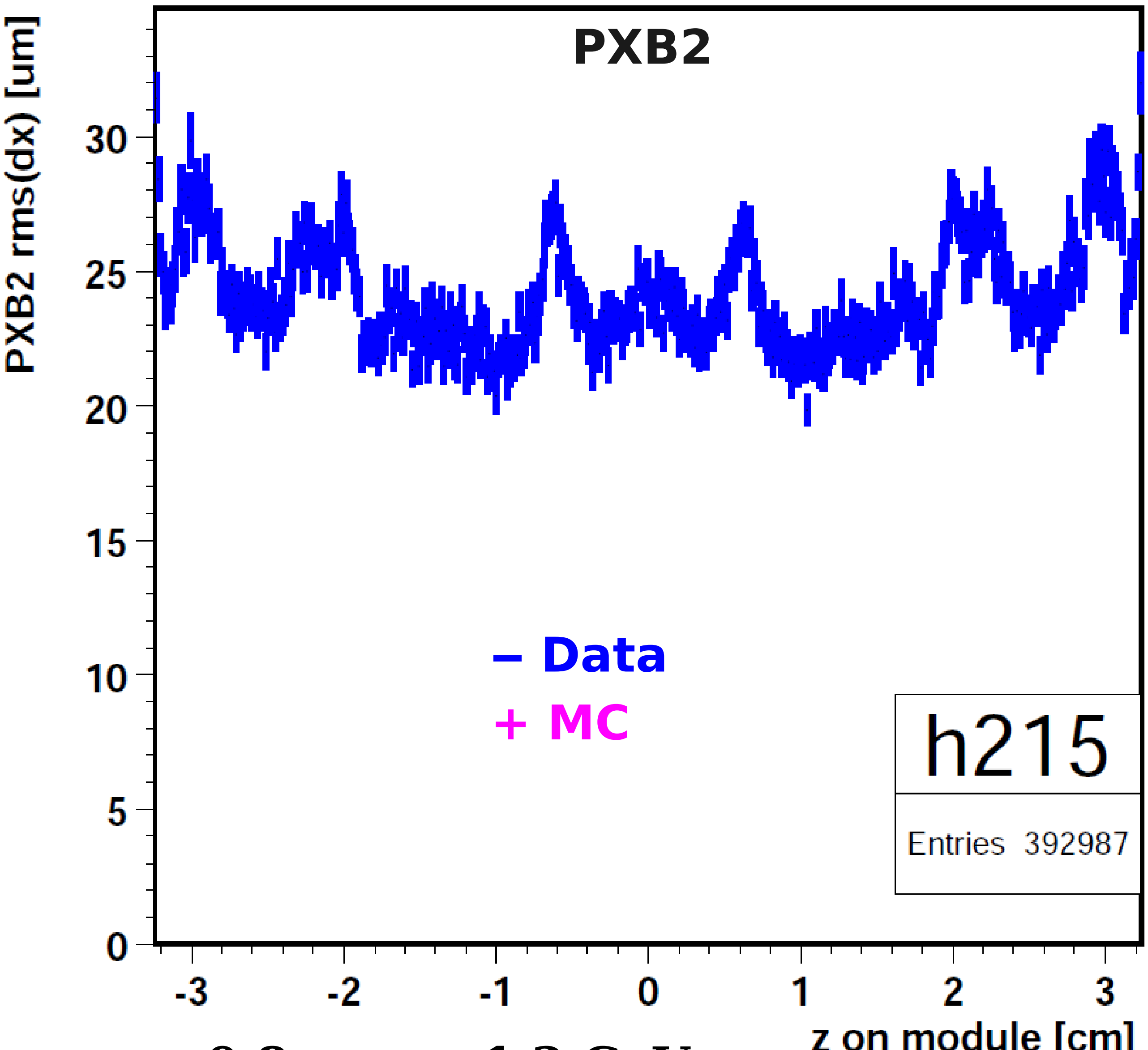
Make z profile in x-slices!

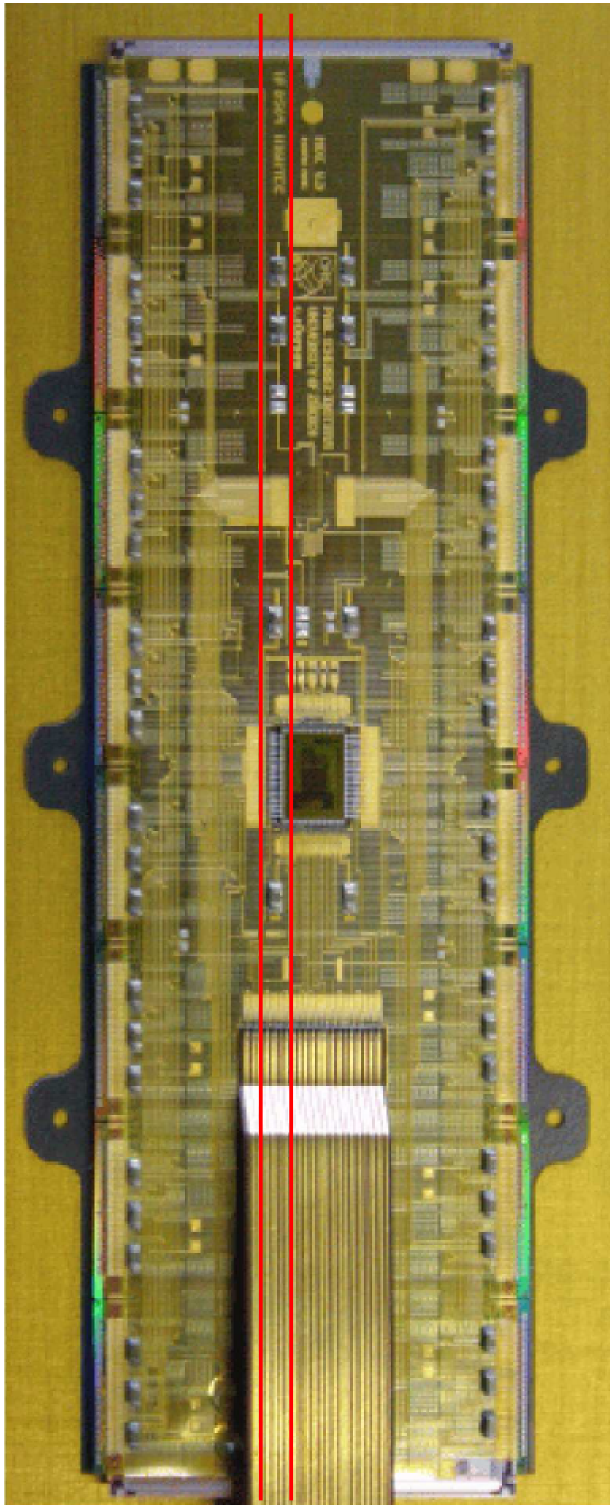




$0.8 < p_t < 1.2$ GeV

local *x* resolution at low p_t

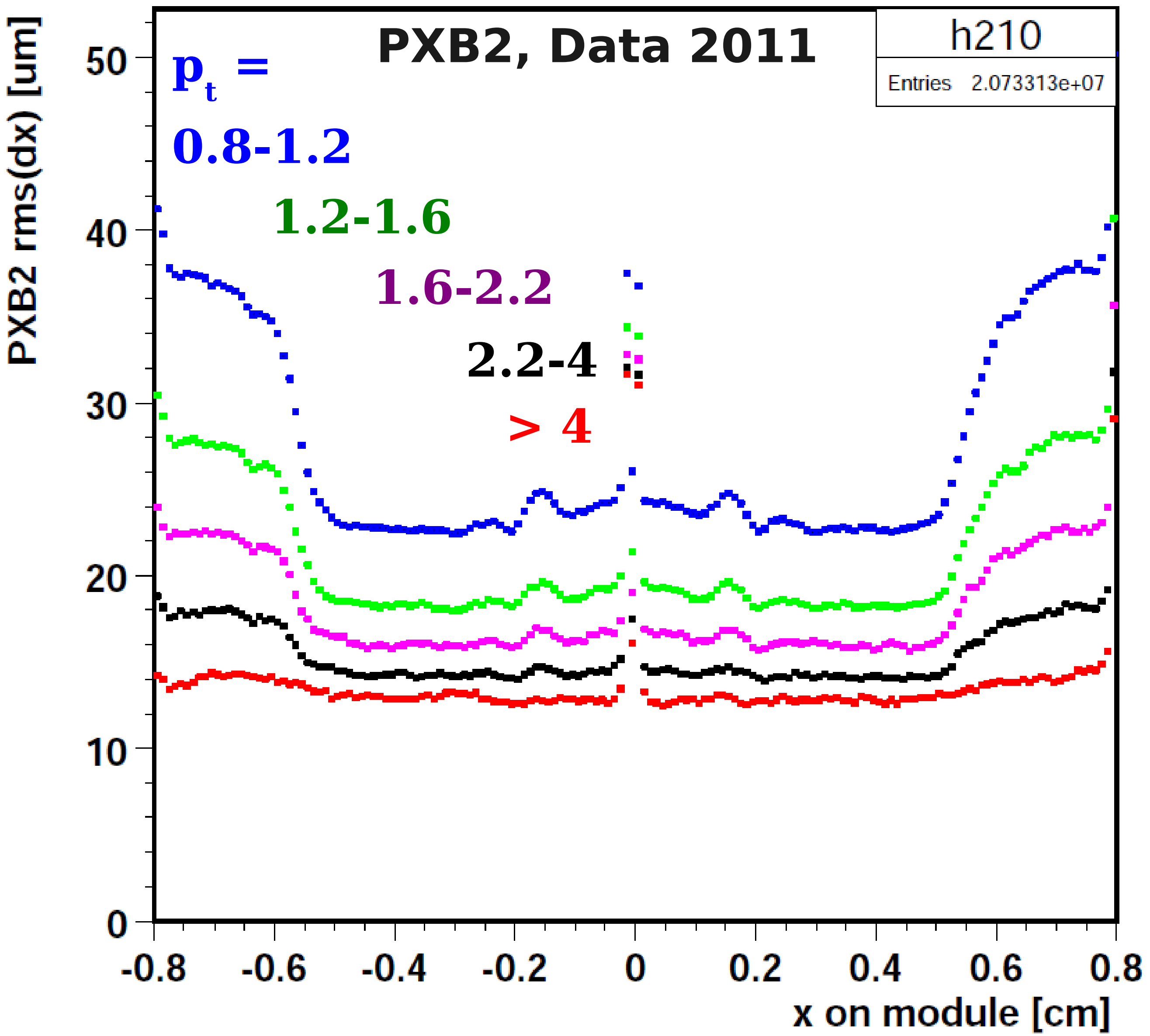




$0.8 < p_t < 1.2$ GeV

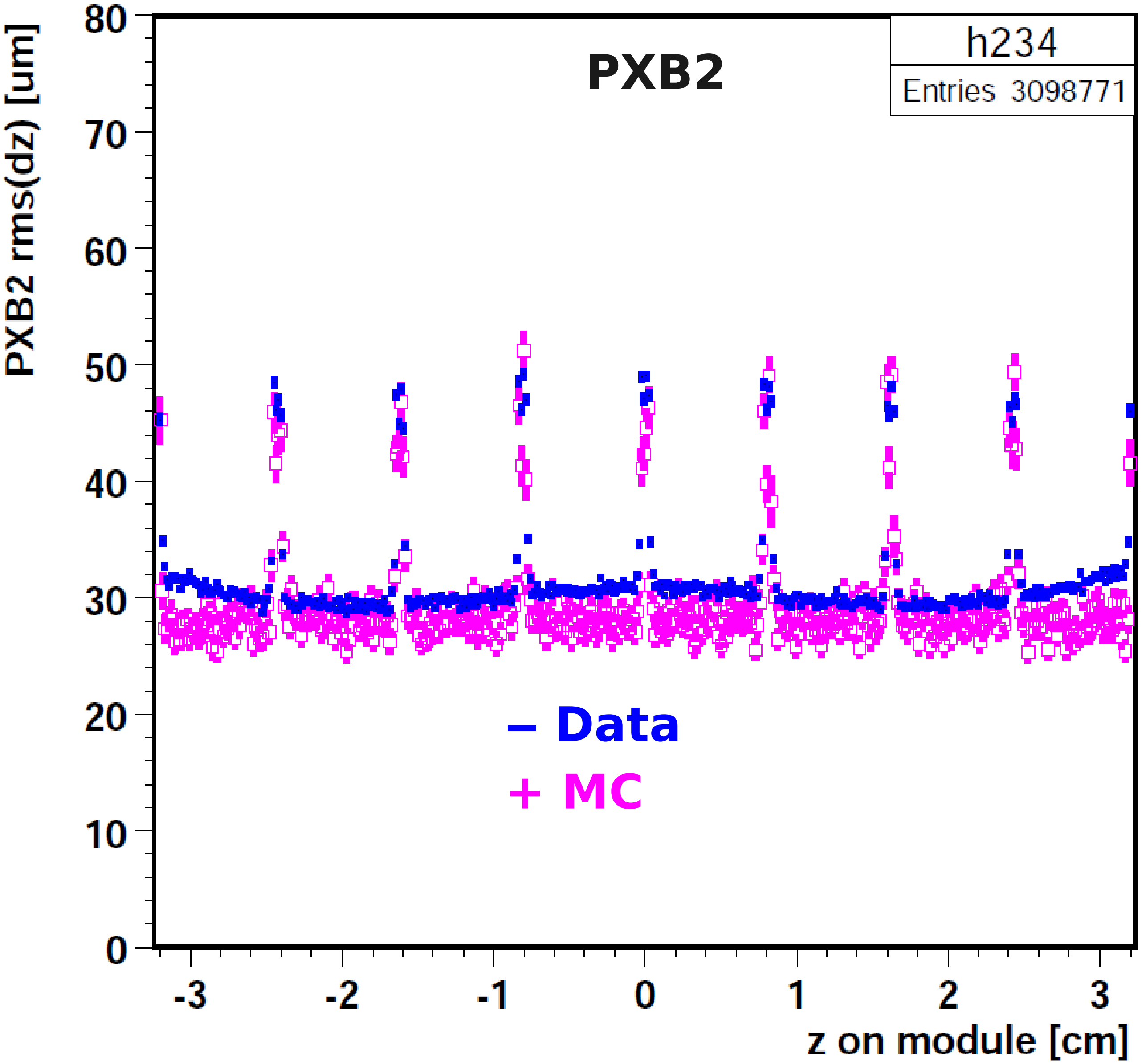
$0.1 < |x_{loc}| < 0.2$ cm

local *x* resolution vs p_t



- Need p_t > 4 to reach intrinsic resolution.

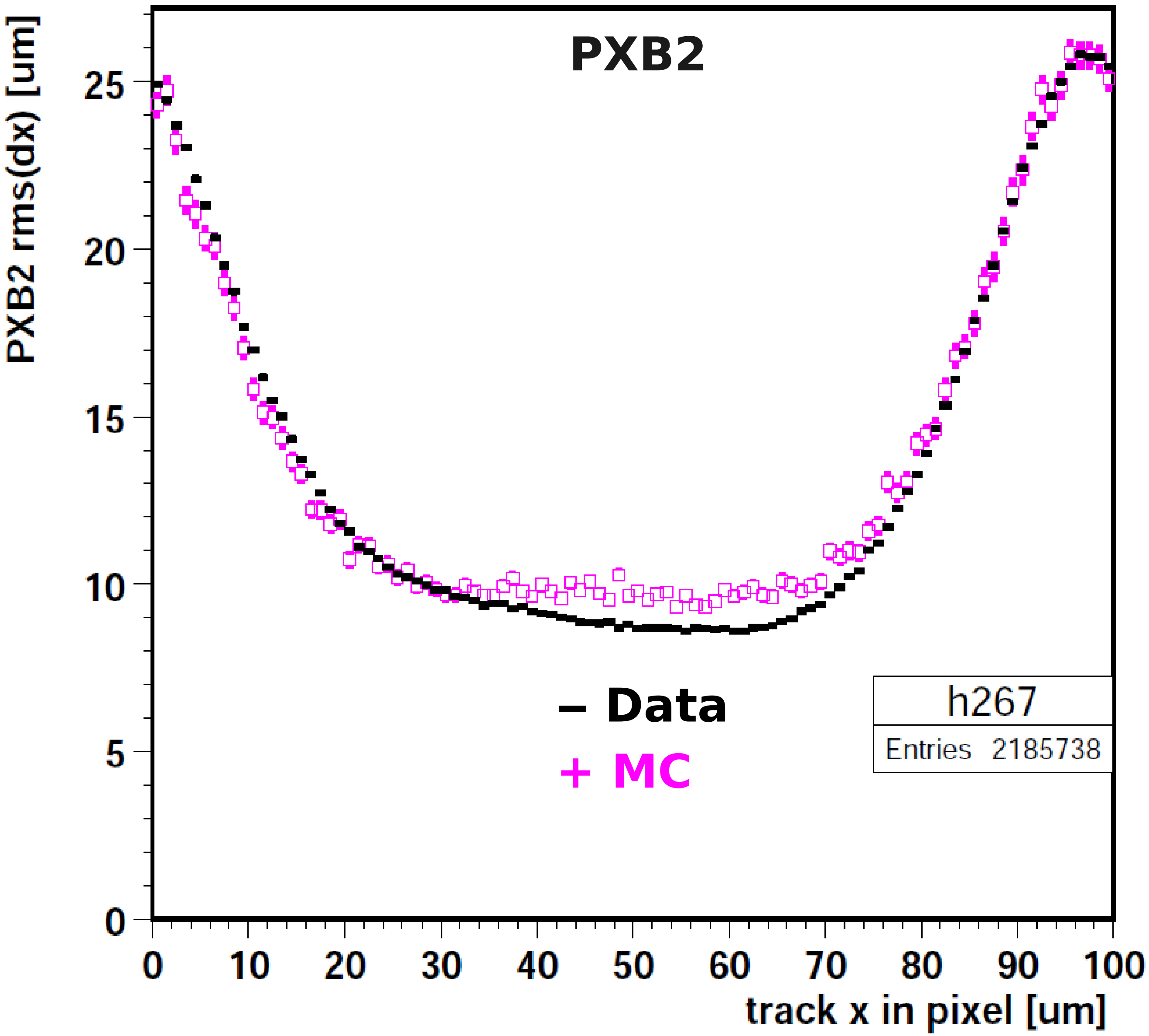
local z resolution along module



p_t > 4 GeV

- Triplet z residual rms.
- All angles, p_t > 4 GeV.
- Peaks every 0.8 cm:
  - long pixels at ROC edges.
- MC z resolution is slightly too optimistic.

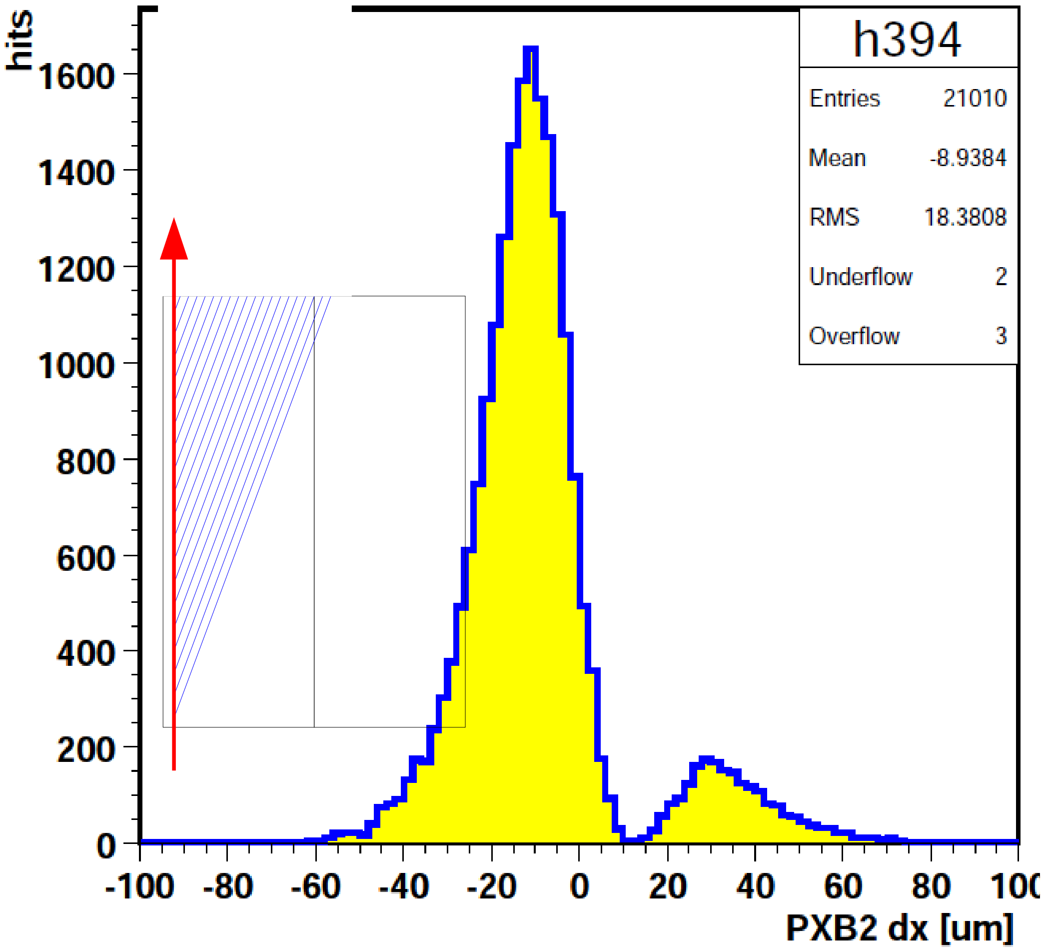
local *x* resolution in pixel

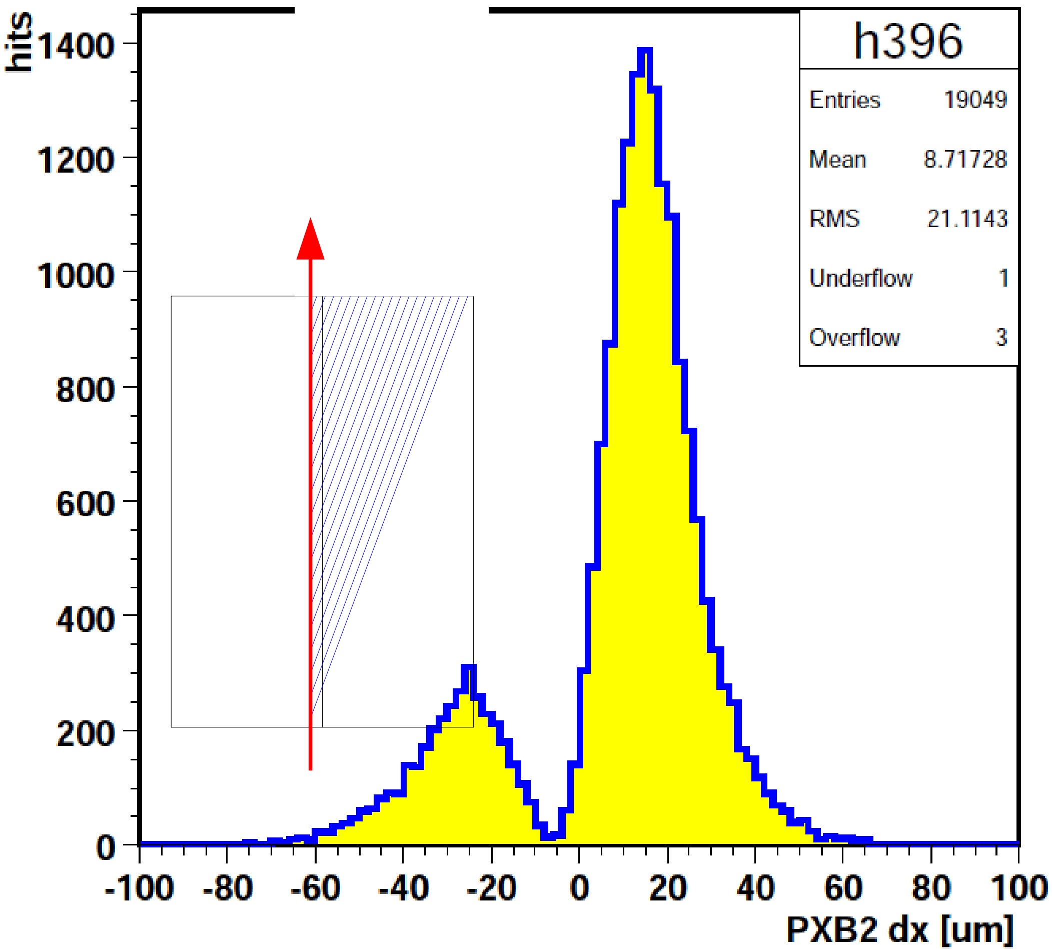


p_t > 4 GeV, 2-row clusters

- Triplet *x* rms as function of predicted *x* in pixel at high p_t.
- Strong resolution variation from 9 to 25 µm:
  - best resolution at pixel center,
  - worst resolution near pixel edges.
- Well described by the simulation.

triplet *x* residuals at pixel edge





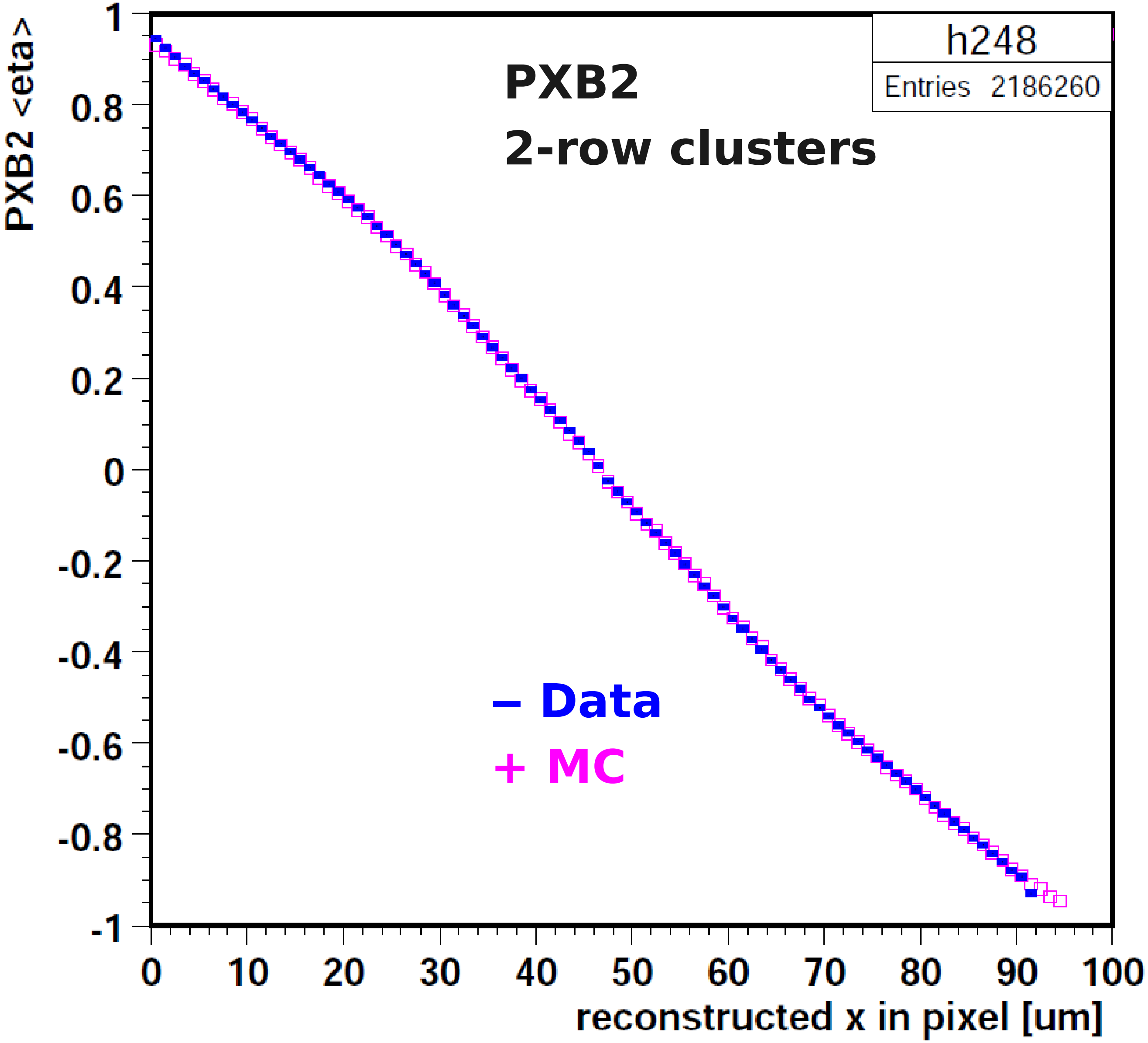
p_t > 12 GeV, 2-row cluster

x_{pix} < 20 μm, outward module

p_t > 12 GeV, 2-row cluster

x_{pix} > 80 μm, outward module

charge sharing



p_t > 4 GeV

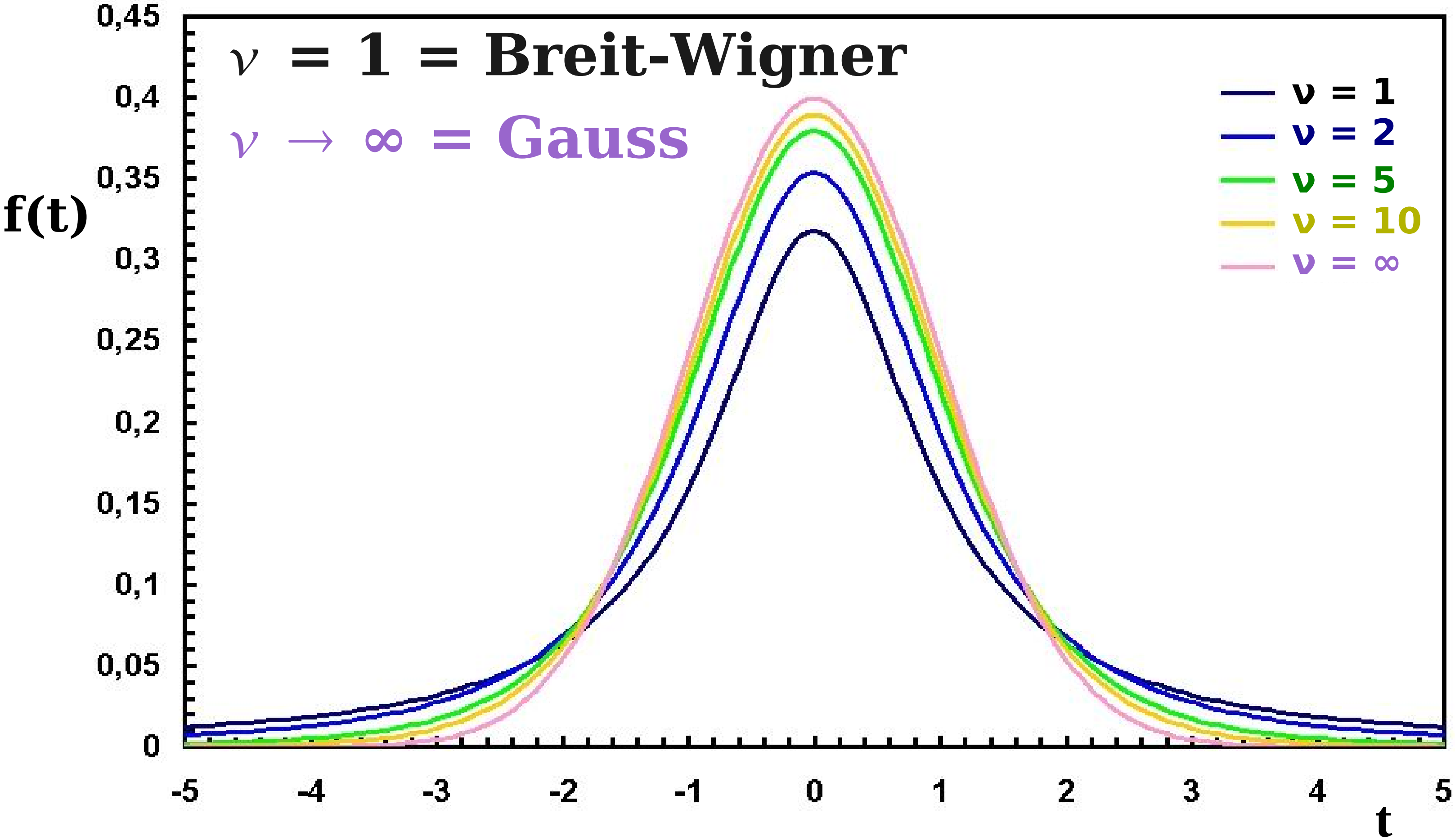
- 2-row clusters:
  - $\eta = (Q_L - Q_R) / Q_{tot}$
- almost linear:
  - uniform charge sharing due to Lorentz drift.
- x > 90 μm:
  - only 1-row clusters.
- Perfect description by MC:
  - algorithm tuned to MC.

Fitting peaks with Student's t

$t = (x - x_0)/\sigma$ = normalized residual.

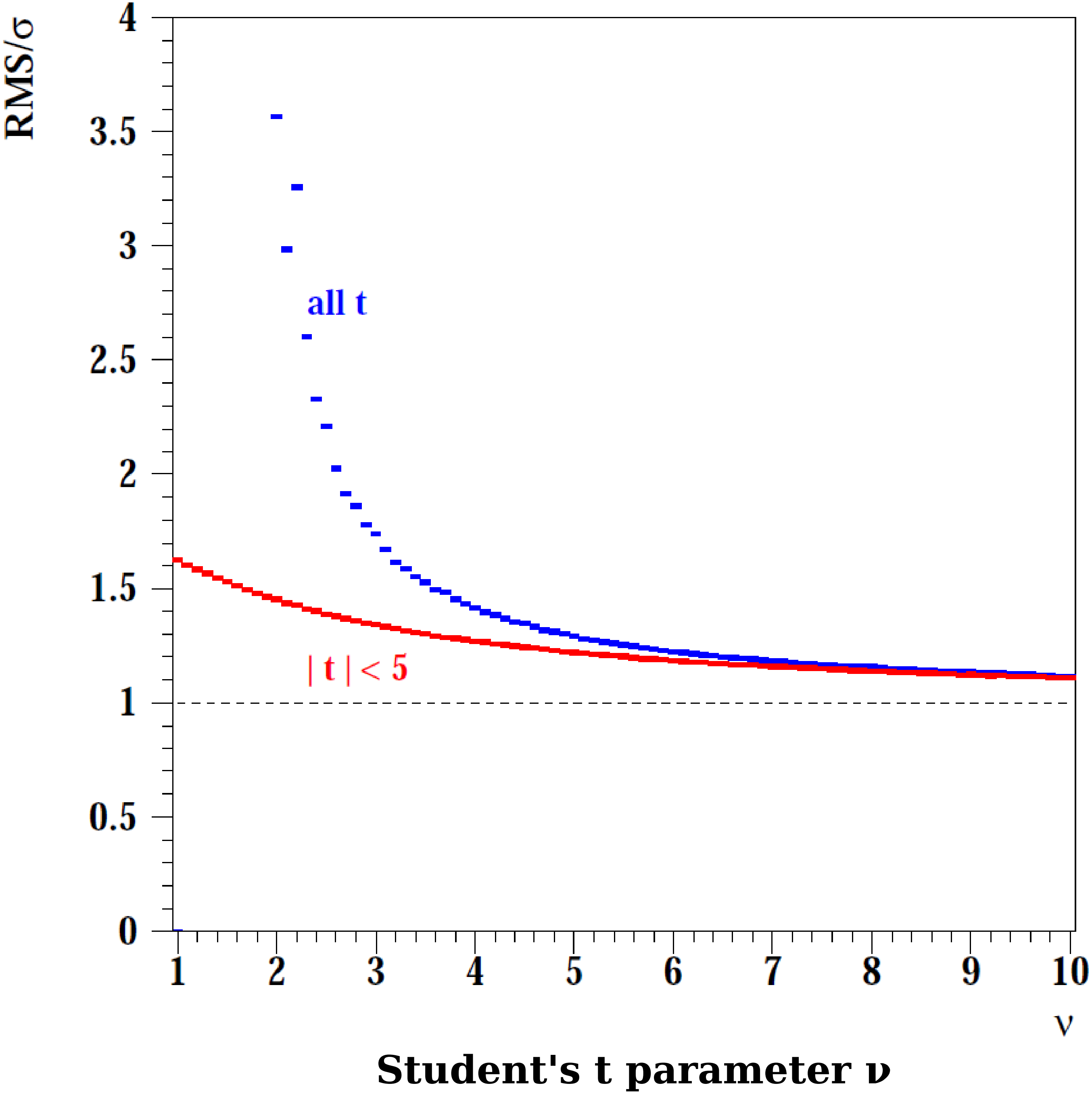
$$f(t) = \frac{\Gamma((\nu+1)/2)}{\sqrt{\nu\pi}\,\Gamma(\nu/2)}(1+t^2/\nu)^{-(\nu+1)/2}$$

f(t) is a normalized probability density.
Γ function is in PAW, ROOT.



Parameter ν interpolates between Gaussian and Breit-Wigner.

rms/σ for Student's t



- Generate random numbers according to Student's t for different ν (see W. Hoermann, Computing 81 (2007) 317).
- calculate rms:
  - for all t. (rms diverges for $\nu = 1$).
  - for | t | < 5. (rms stays below 1.62 for all $\nu \geq 1$).
- Asymptotic value (rms/σ = 1) slowly approached.