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# **CMS TRACKER ALIGNMENT RESULTS WITH COSMIC MUONS**

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*on behalf of the CMS Tracker Alignment group*

**3<sup>rd</sup> LHC Alignment Workshop, CERN**

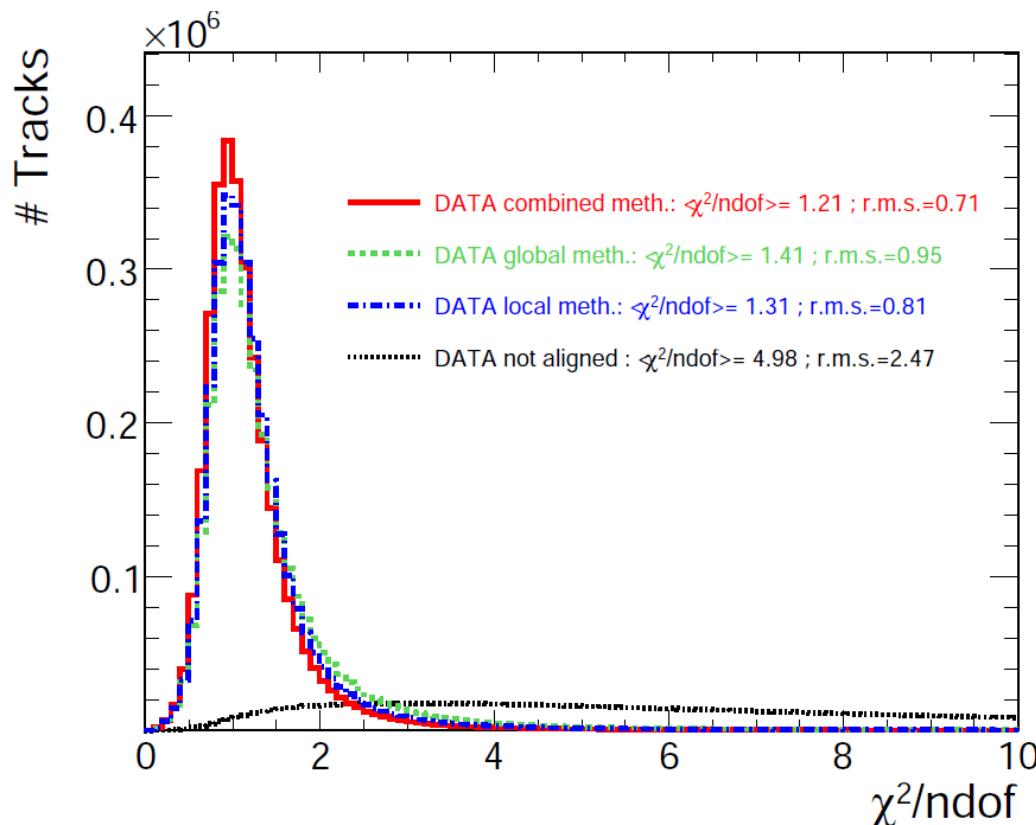
# Outline

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- Alignment procedure of the CMS Tracker described in detail in the talk by [A.Gritsan](#)
- Here we will focus on:
  - low level validation:  $\chi^2$  of the track and residuals
  - high level validation: residuals in overlapping modules and cosmic track splitting
  - checks of the geometry of CMS Tracker resulting from track-based alignment
- Results obtained with cosmic data taken in the global run of CMS in 2008 with  $B=3.8$  T and the detector in its final position (aka CRAFT) → [4 M](#) pre-selected events

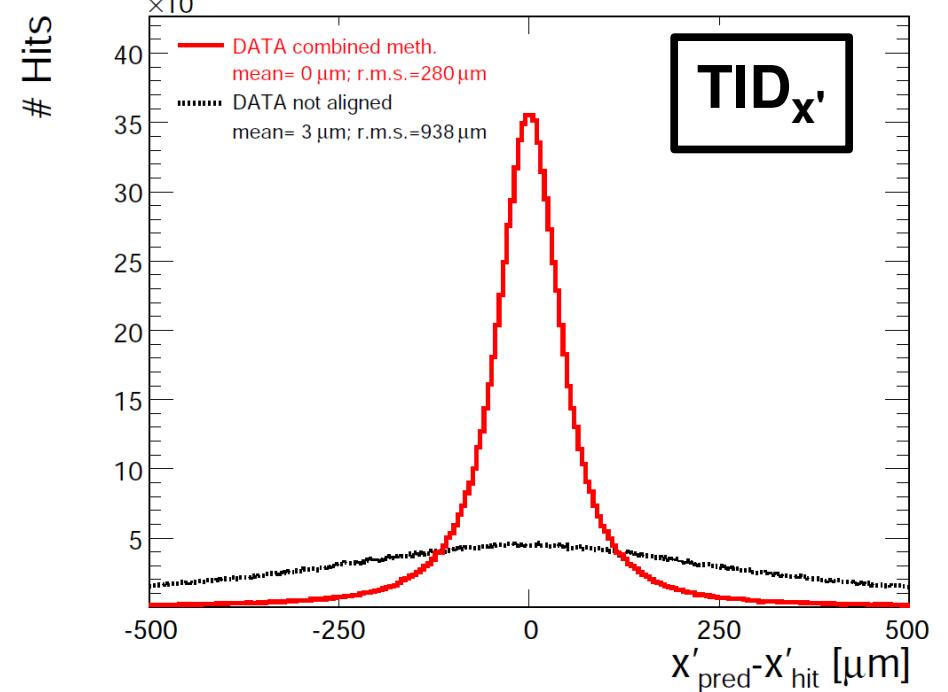
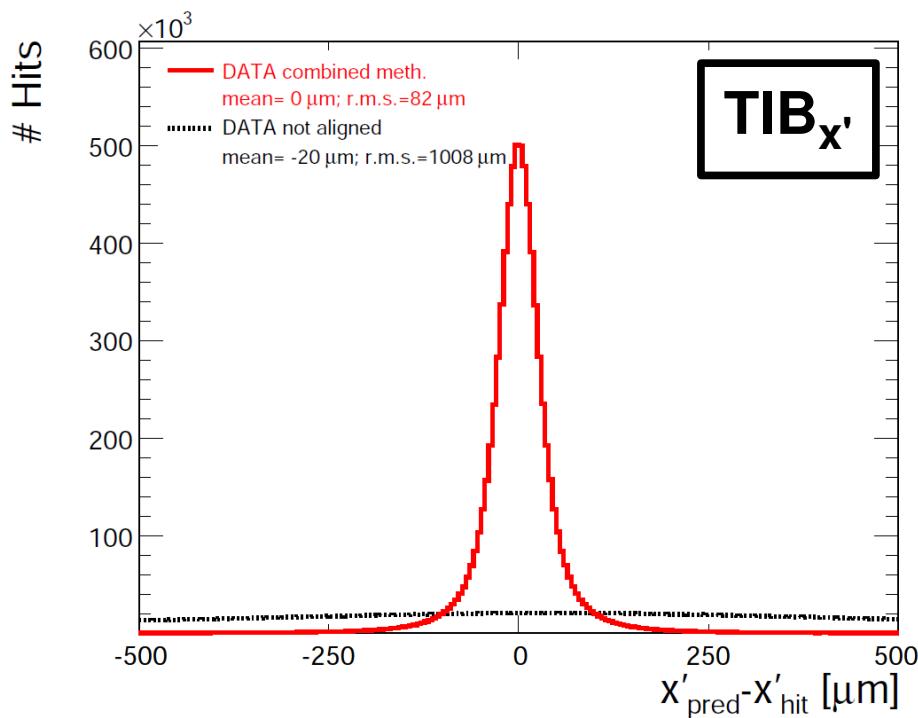
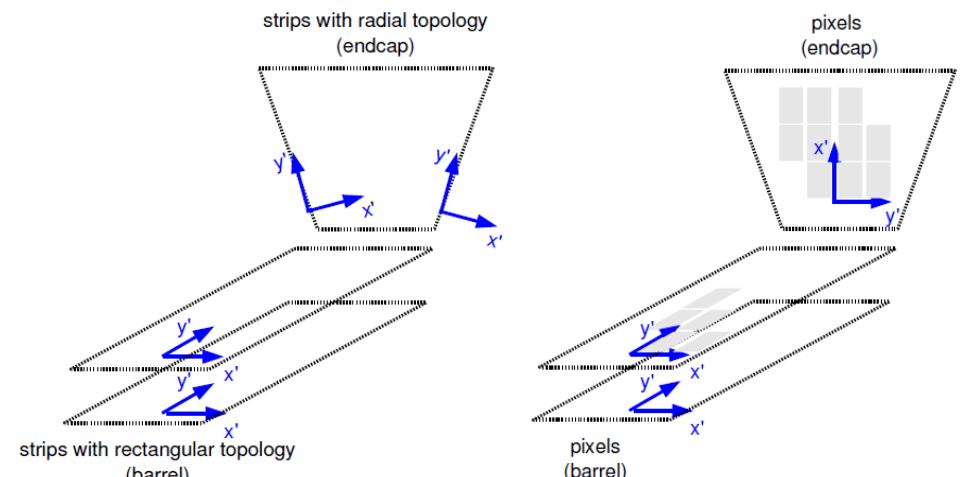
# Low level validation: track $\chi^2/\text{ndof}$

- Default validation performed every alignment cycle on the full CRAFT sample:
  - same sample used also for the alignment but statistics is critical when evaluating the performance on all the sub-detectors (only 1.5% of tracks in PXE)
  - inclusive sample of tracks:  $p>4 \text{ GeV}/c$ ,  $N_{\text{hit}} \geq 7$ ,  $N_{2\text{Dhit}} \geq 2$ ,  $(S/N)_{\text{hit}} > 14$
  - Alignment Parameter Errors properly tuned to have pulls of residuals with  $\sigma \approx 1$

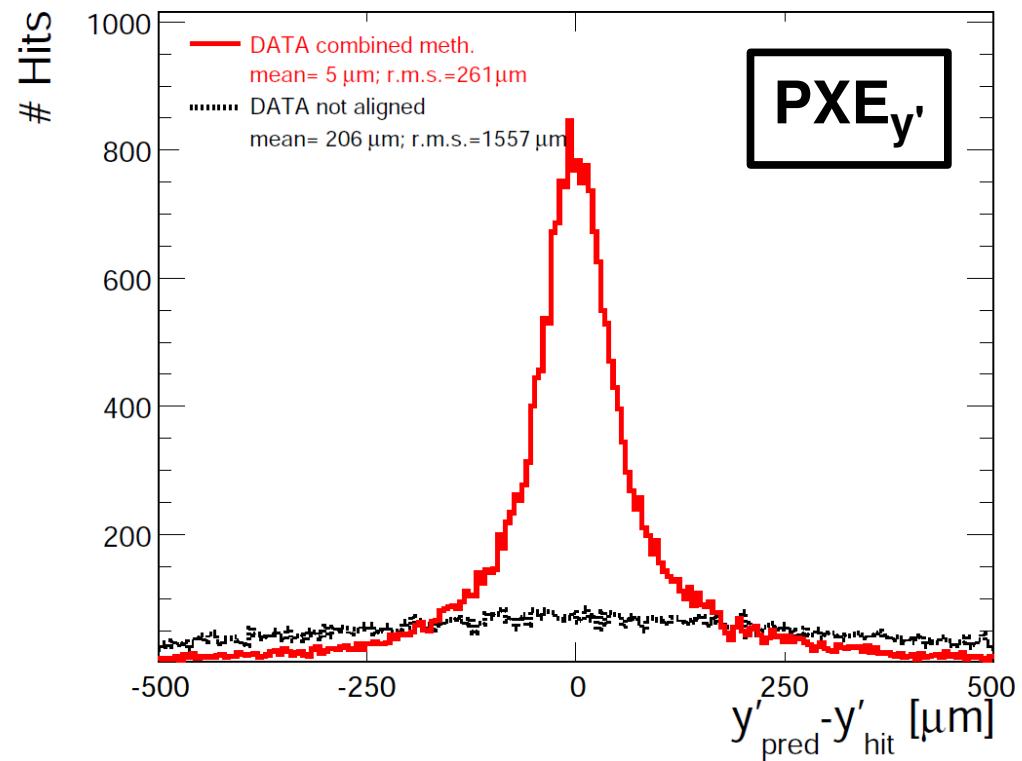
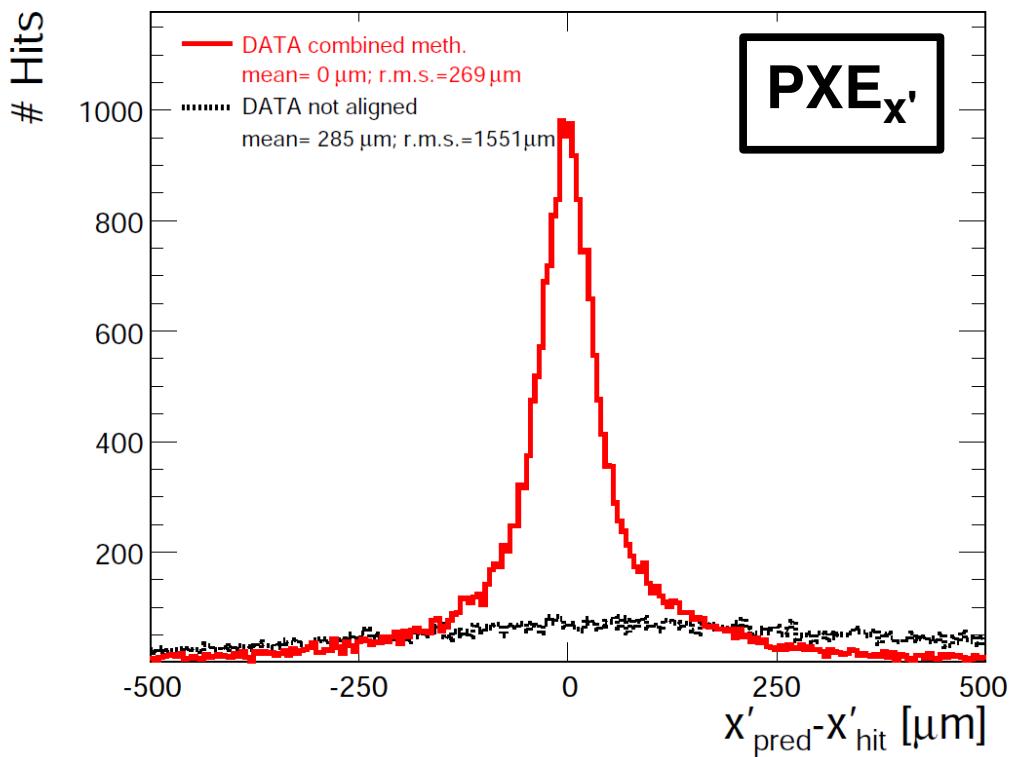


# Low level validation: unbiased residuals

- Computed at the same time as  $\chi^2/\text{ndof}$ 
  - unbiased as the hit on the module under investigation is removed from the re-fit of the track
  - shown as function of the local coordinates  $x'$  and  $y'$

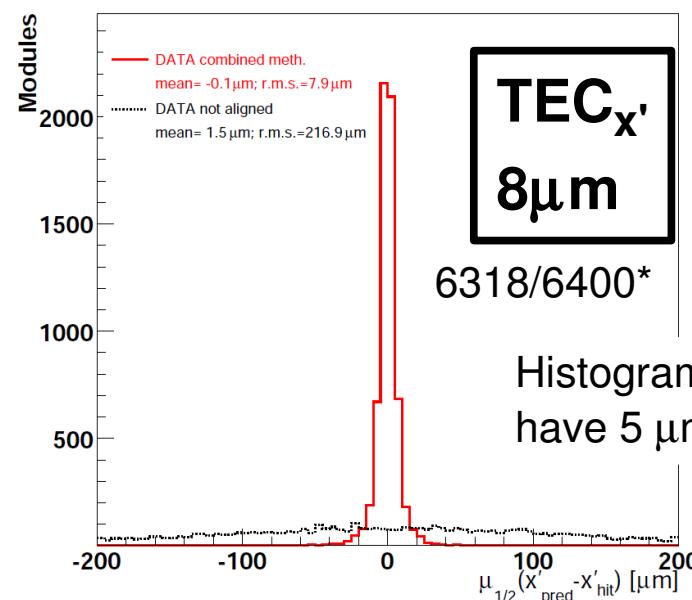
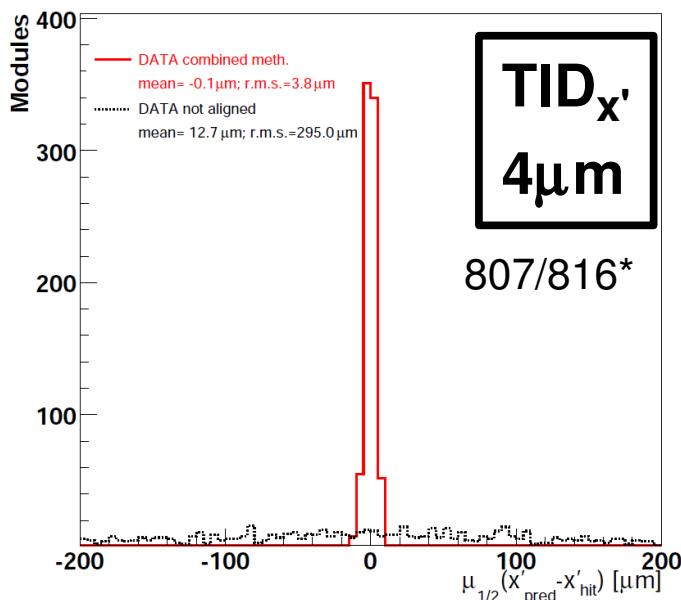
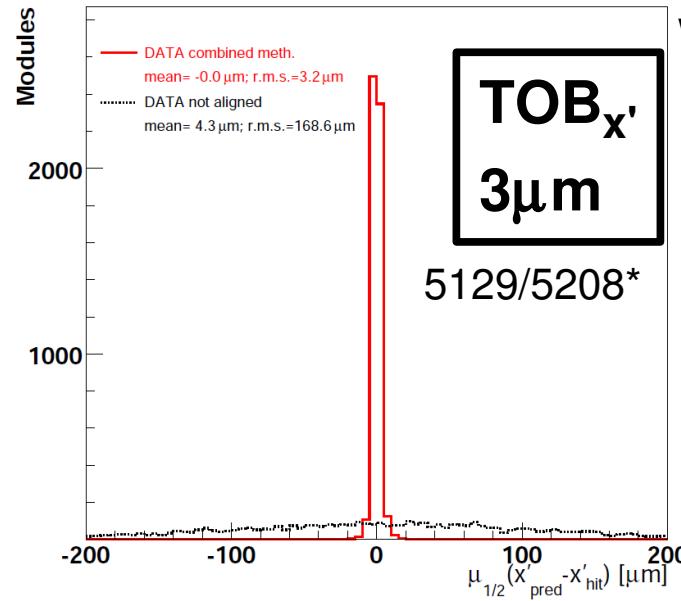
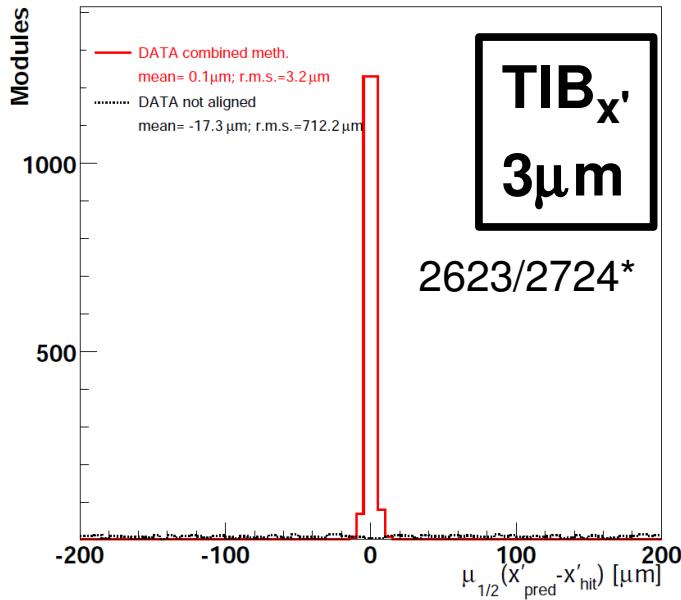


# Low level validation: unbiased residuals



- loose selection of tracks: random fluctuations (multiple scattering, track-extrapolation, hit resolution) broadening the residuals
- at zero-th order the alignment should recover the true position of modules along the measurement coordinate → check that the residuals are “centered” after the alignment
- Distribution of the Median of Residuals (DMR)  
Median: robust estimator of the position of the peak of the residuals when dealing with 16k histograms: consistency checks performed both with DATA and with MC

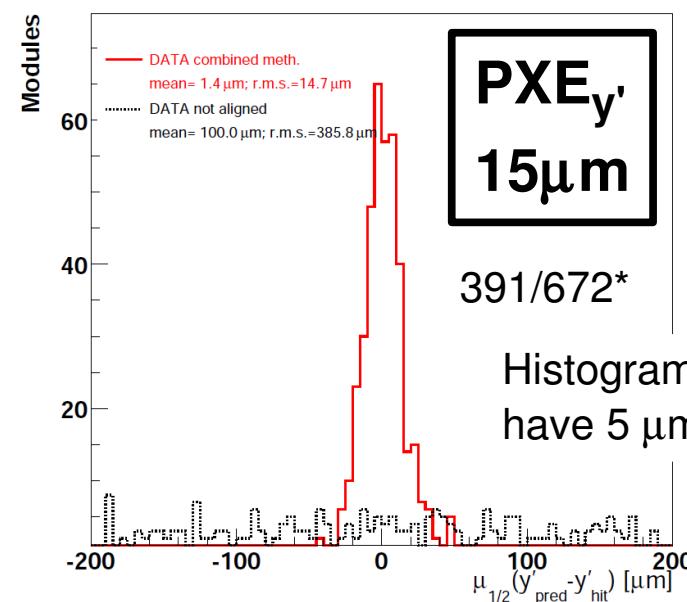
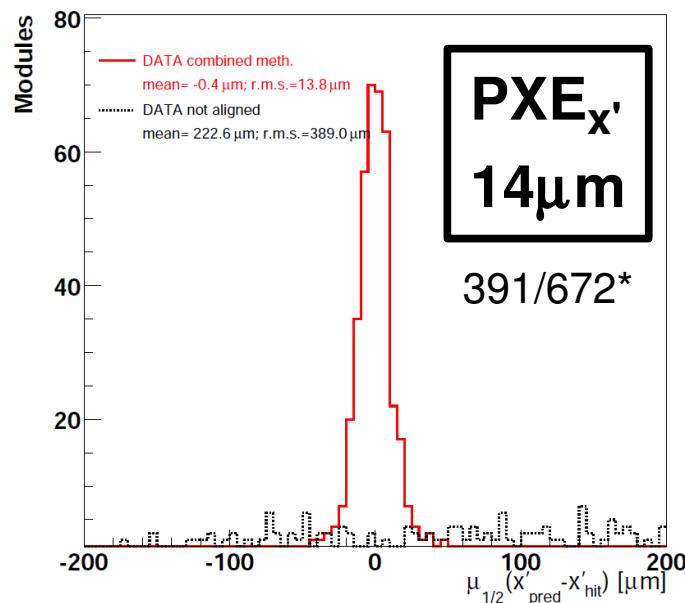
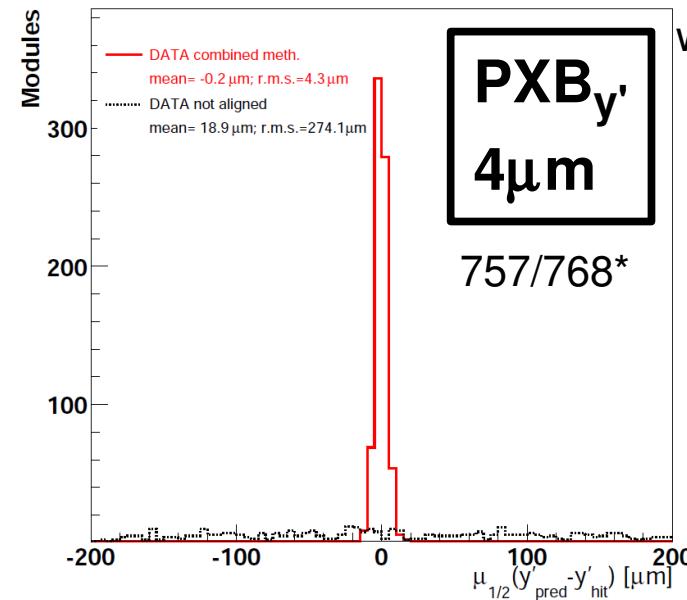
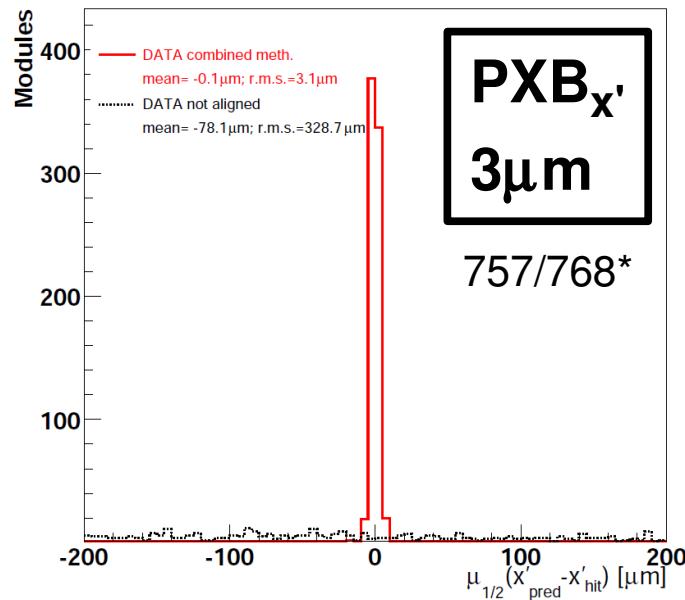
# Track DMR: strips



\*modules  
with  $N_{\text{entries}} > 30$

Histograms of residuals  
have 5 μm bin!

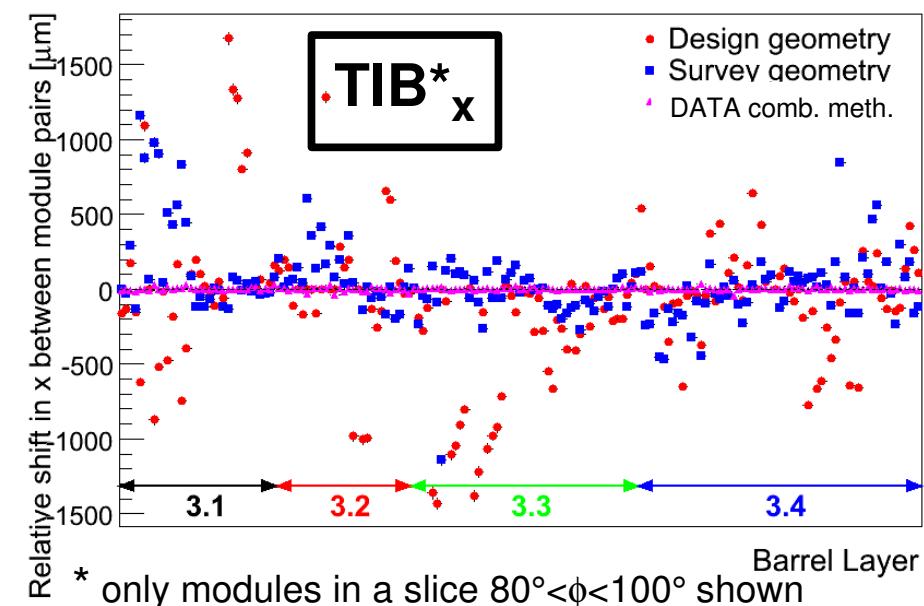
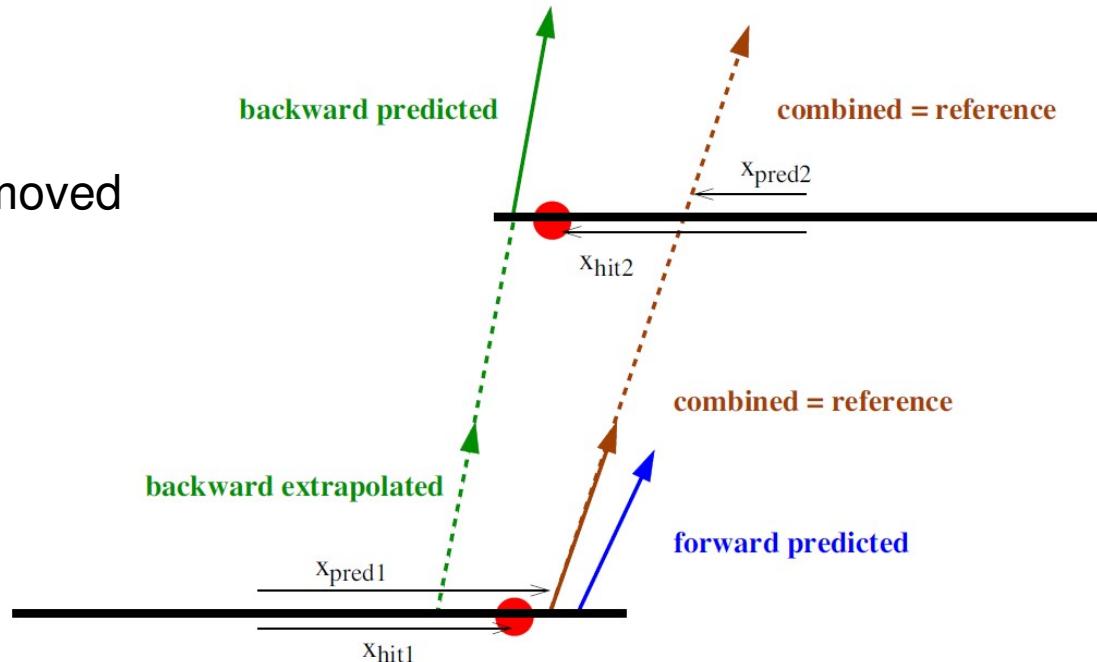
# Track DMR: pixels



\*modules  
with  $N_{\text{entries}} > 30$

# High level validation: residuals in overlapping modules

- Plot the double difference  
 $\Delta x_{\text{hit}} - \Delta x_{\text{pred}}$   
with hits in the layer under test being removed  
when computing the prediction
- Nearby modules → small effects of:
  - track extrapolation
  - crossed material
- Track selection:  $p_T > 4 \text{ GeV}/c$ ,  $\chi^2/\text{dof} < 6$   
 $N_{\text{hit}} \geq 8$ ,  $N_{2D\text{hit}} \geq 2$
- Only overlaps with  $N_{\text{entries}} \geq 100$  analyzed
- Gaussian fit to  $\Delta x_{\text{hit}} - \Delta x_{\text{pred}}$ 
  - mean → remaining shift
- Difficult to compare with DMR as the same module enters several times

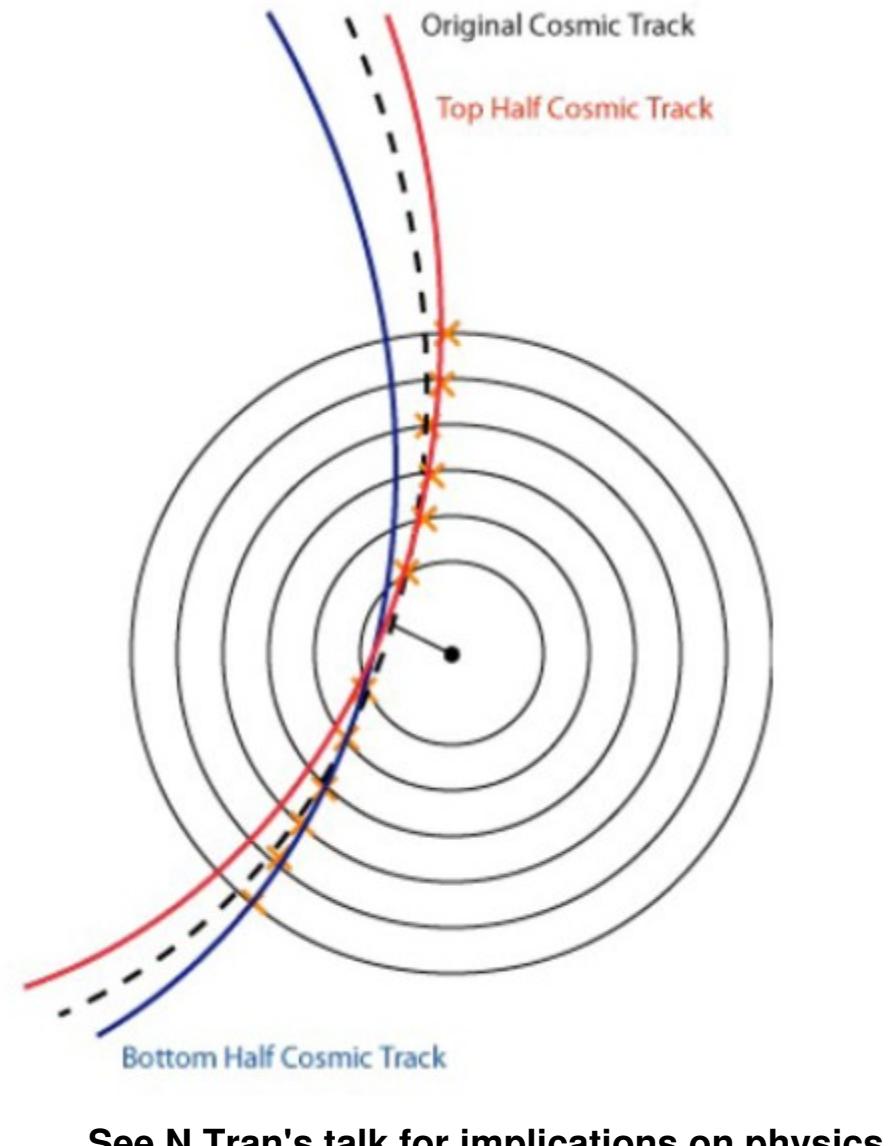


# High level validation: Cosmic Track Splitting

- Method: split cosmic tracks at the Point of Closest Approach (PCA) to the nominal beamline
- Re-fit separately top and bottom legs and compare the 5 track parameters at the PCA
- Track selection:  $p_T > 4 \text{ GeV}/c$ ,  $\chi^2/\text{dof} < 100$   
 $N_{\text{hit}} \geq 10$ ,  $N_{2D\text{hit}} \geq 2$ ,  $N_{\text{PXLhit}} \geq 2$   
PCA in the volume of the pixel  
each split track:  $N_{\text{hit}} \geq 6$

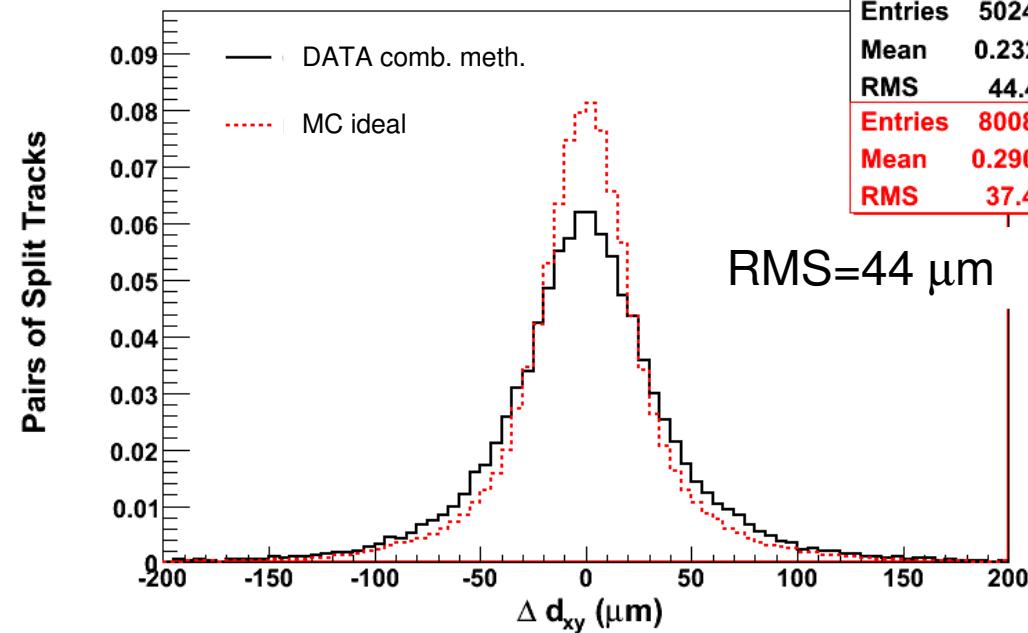
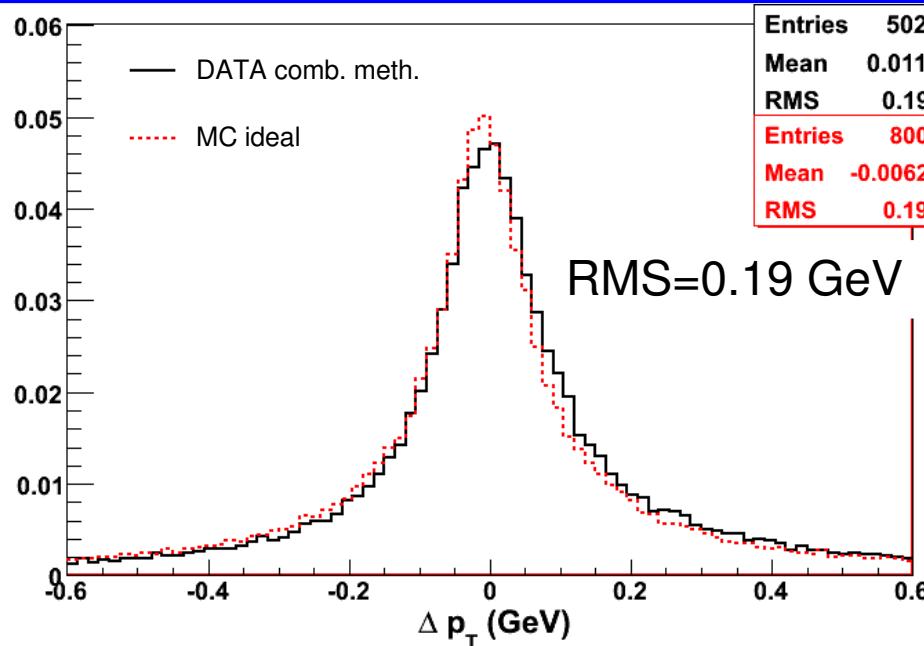
$\sim 50k$  evts selected

- In the following:
  - absolute residuals: 
$$\frac{X_{\text{top}} - X_{\text{bottom}}}{\sqrt{2}}$$
  - normalized residuals: 
$$\frac{X_{\text{top}} - X_{\text{bottom}}}{\sqrt{\sigma_{X_{\text{top}}}^2 + \sigma_{X_{\text{bottom}}}^2}}$$
  
 $x = d_{xy}, d_z, \phi, \theta, 1/p_T$



See N.Tran's talk for implications on physics

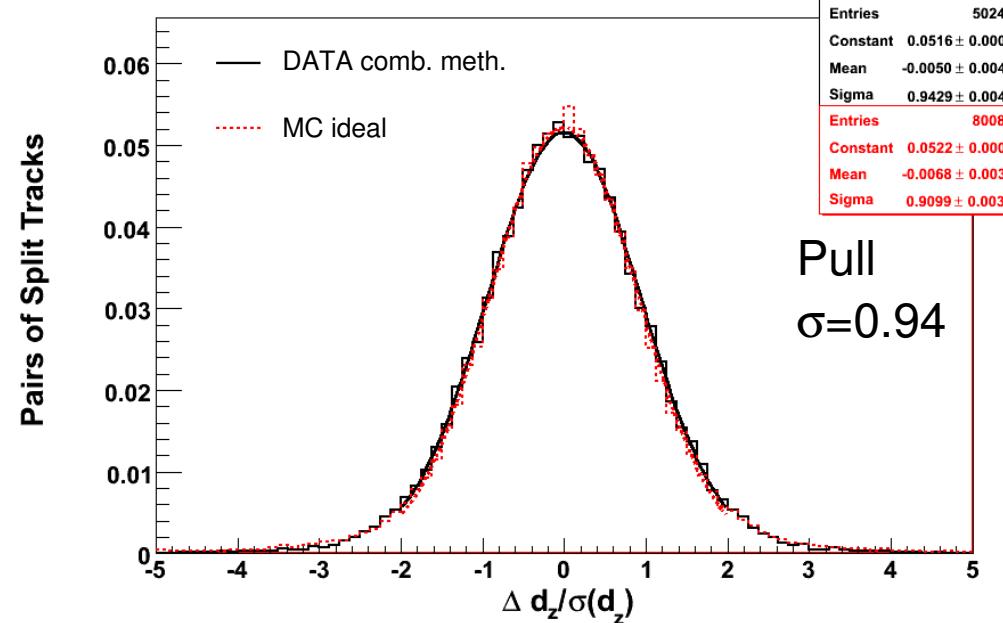
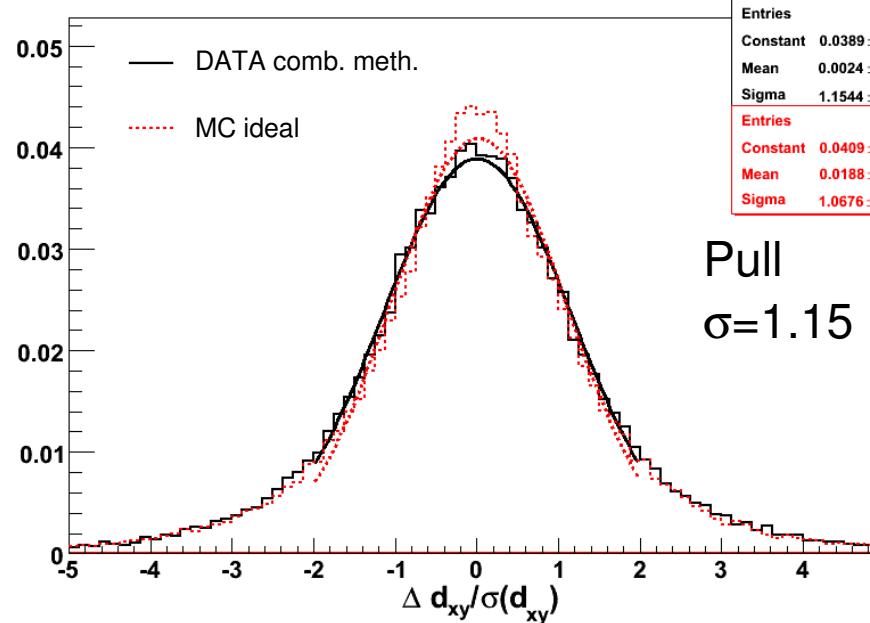
# Cosmic Track Splitting: absolute residuals



absolute residuals	DATA combined meth. r.m.s.	MC ideal r.m.s.
$\Delta p_T$ (MeV/c)	193	193
$\Delta d_{xy}$ ( $\mu\text{m}$ )	44	37
$\Delta d_z$ ( $\mu\text{m}$ )	59	47
$\Delta \phi$ ( $\mu\text{rad}$ )	425	406
$\Delta \theta$ ( $\mu\text{rad}$ )	639	511

- $p_T$  mainly sensitive to the alignment in the strips: close to the ideal performance for comics-like track topology
- $d_{xy}$  and  $d_z$  mainly sensitive to the alignment in the pixels

# Cosmic Track Splitting: normalized residuals

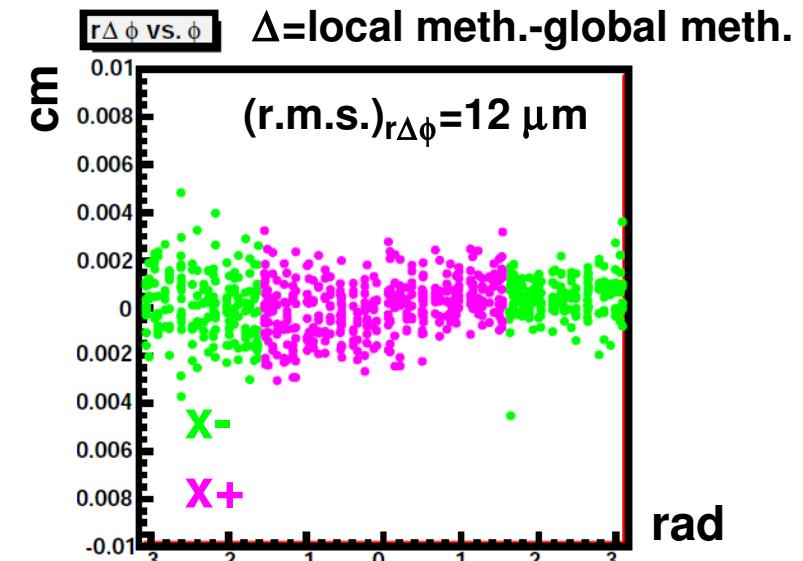


normalized residuals	DATA combined meth.	MC ideal
	$\sigma$	$\sigma$
$\Delta p_T/\sigma(p_T)$	0.99	0.95
$\Delta d_{xy}/\sigma(d_{xy})$	1.15	1.07
$\Delta d_z/\sigma(d_z)$	0.94	0.91
$\Delta \phi/\sigma(\phi)$	1.14	1.05
$\Delta \theta/\sigma(\theta)$	0.97	0.96

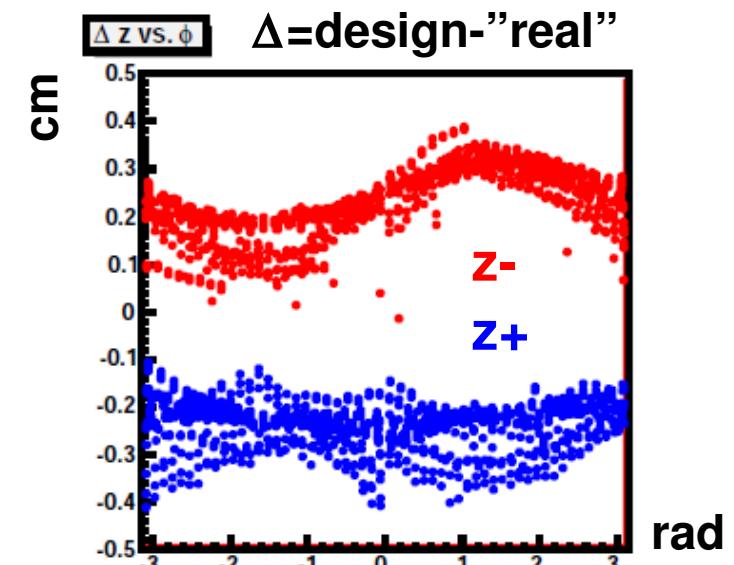
- Mainly to monitor that alignment errors assigned to different sub-detectors give a correct description of the remaining misalignment uncertainty

# Checks of the geometry

- Deformations leaving the track  $\chi^2$  unchanged not caught by low level validation ( $\chi^2$ , DMR)
- Compare geometries from two methods:
  - case study: local meth. vs global meth. geometries in PXB  
(2D measurements, small lever arm)



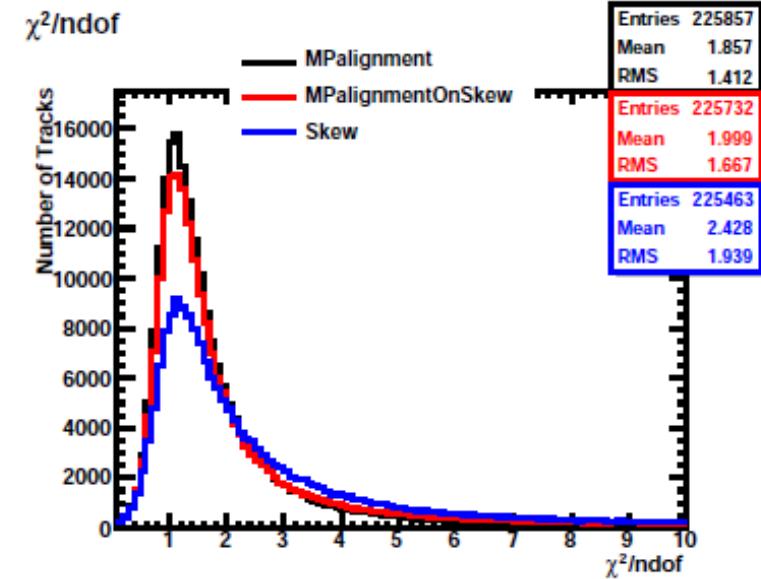
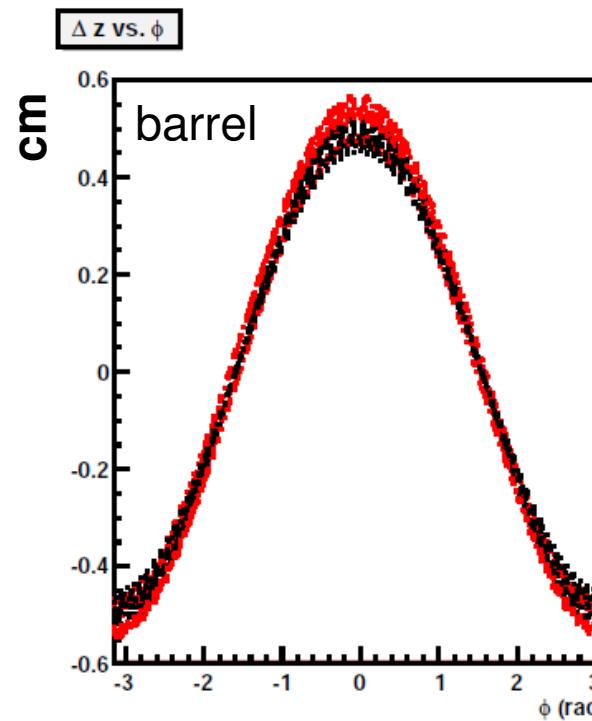
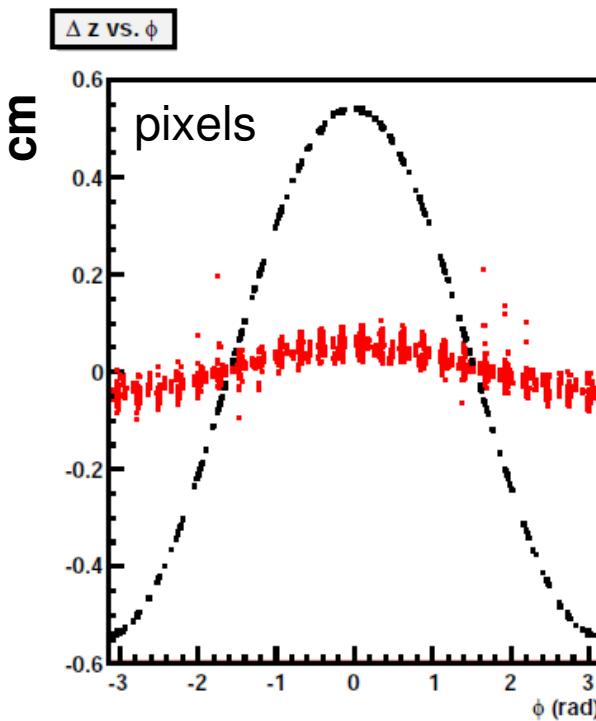
- Compare the “real” (from combined meth.) to the design geometry
  - TIB: 5 mm shift of the two HalfBarrels along z-axis (two halves shifted apart)
  - confirmed by optical survey
  - remaining scatter: indication of “skew”?



# Sensitivity to weak modes from cosmics: skew

“skew”  $\Delta z$  vs  $\phi$

- Systematic misalignment added to the geometry from the global method
- Re-align (global method) using DATA starting from the systematically misaligned geometry



- In the plots: shifts w.r.t starting alignment geometry (flat horizontal line at zero if the mode is recovered)
- Skew is not recovered in the barrel!

# Conclusions

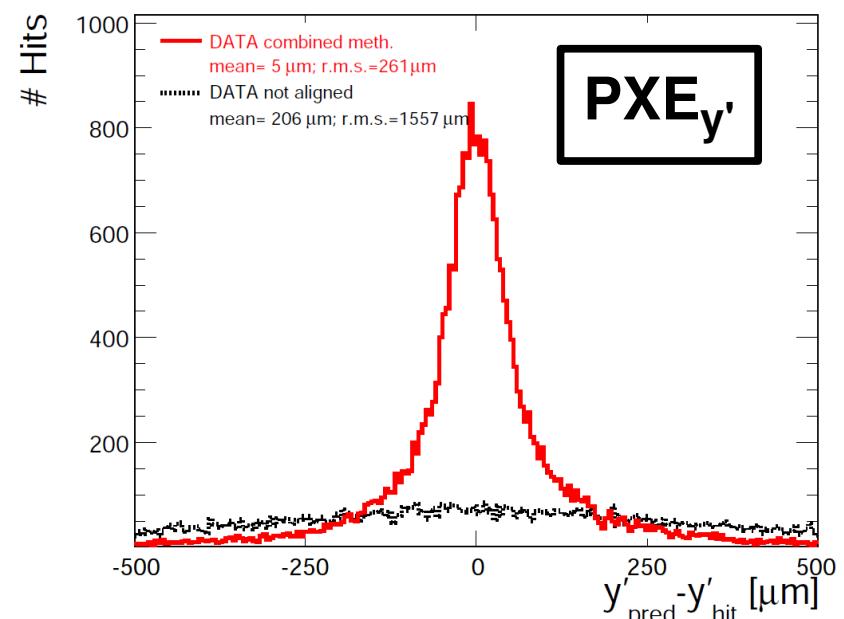
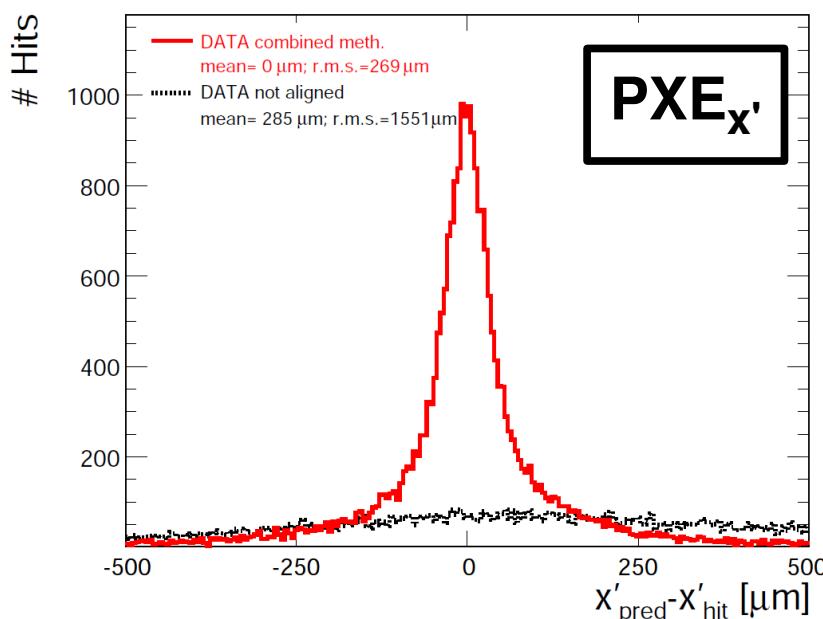
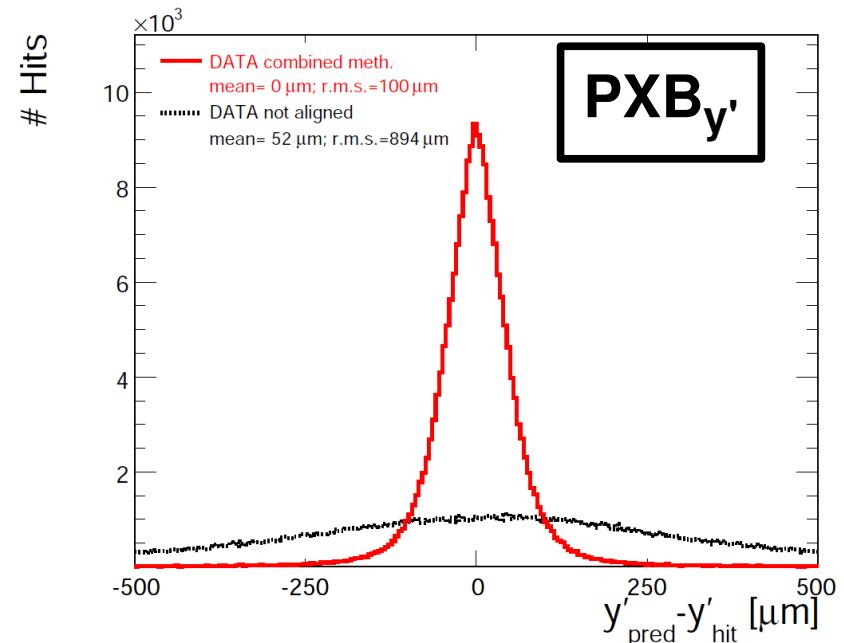
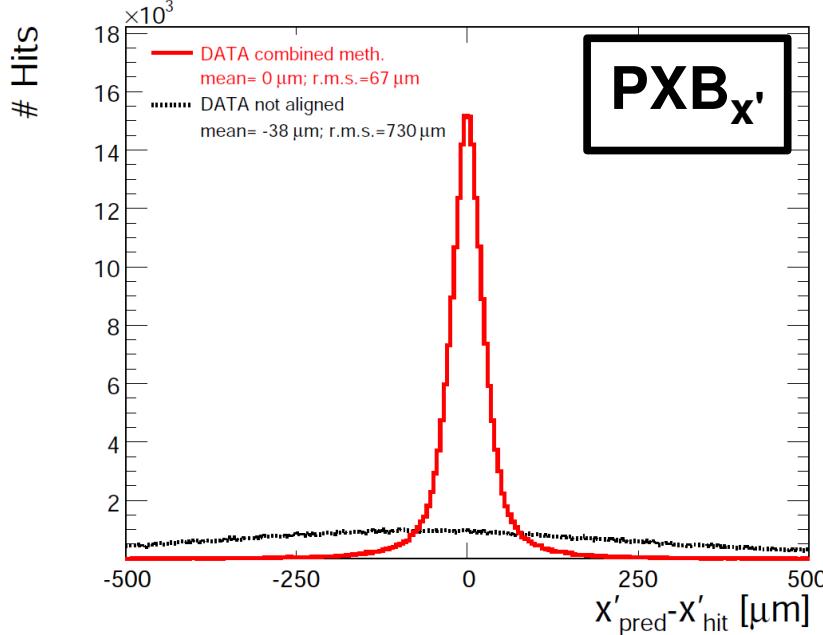
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- Alignment is the final step of a complex construction and commissioning work
- Complex alignment methodology successfully applied to data from an extended cosmics run
- Analysis of results indicates that a very encouraging alignment accuracy has been already achieved before first collisions
  - considerable improvement of the misalignment scenario expected for the CMS Tracker at the LHC startup
- Collision data essential to achieve the ultimate precision and fully address the remaining systematic uncertainties (weak modes)

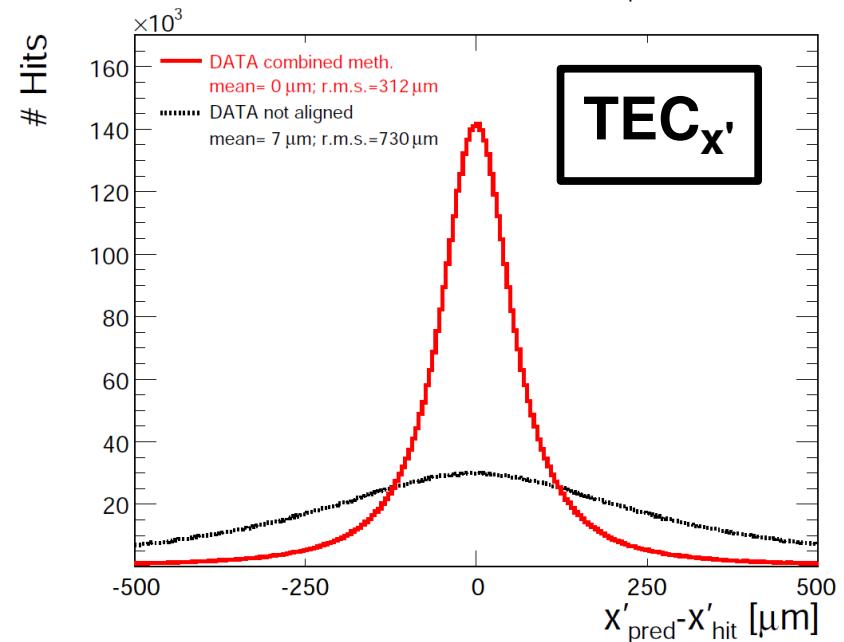
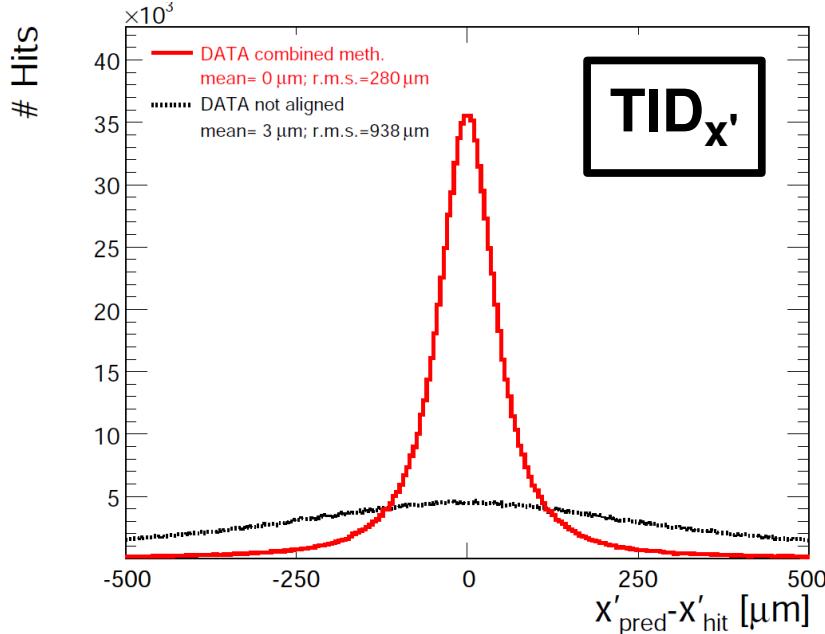
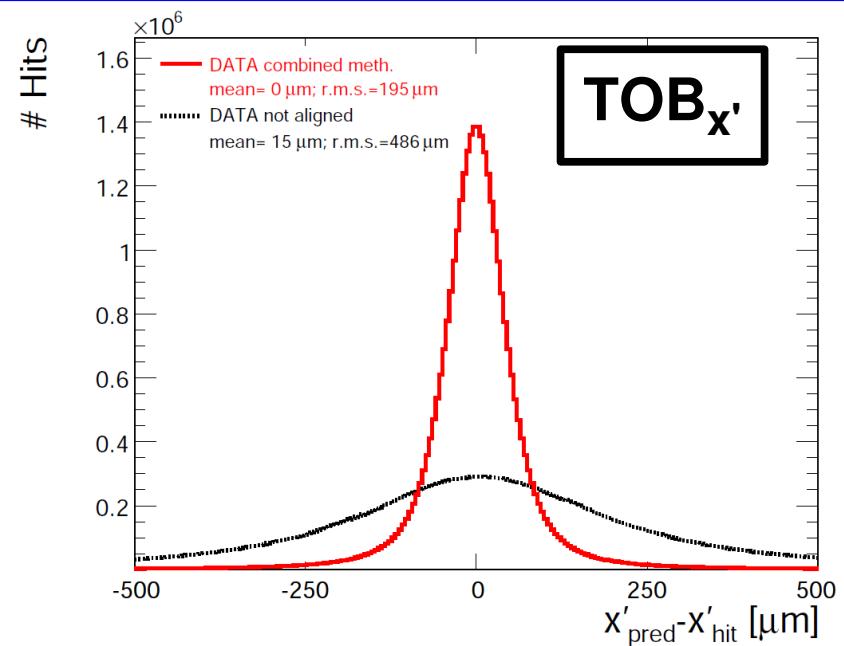
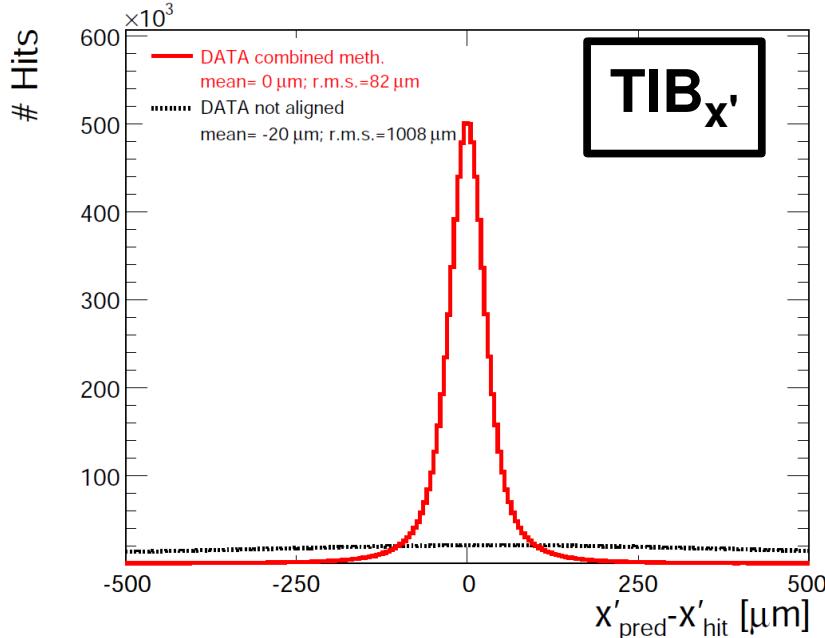
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# **EXTRA-SLIDES**

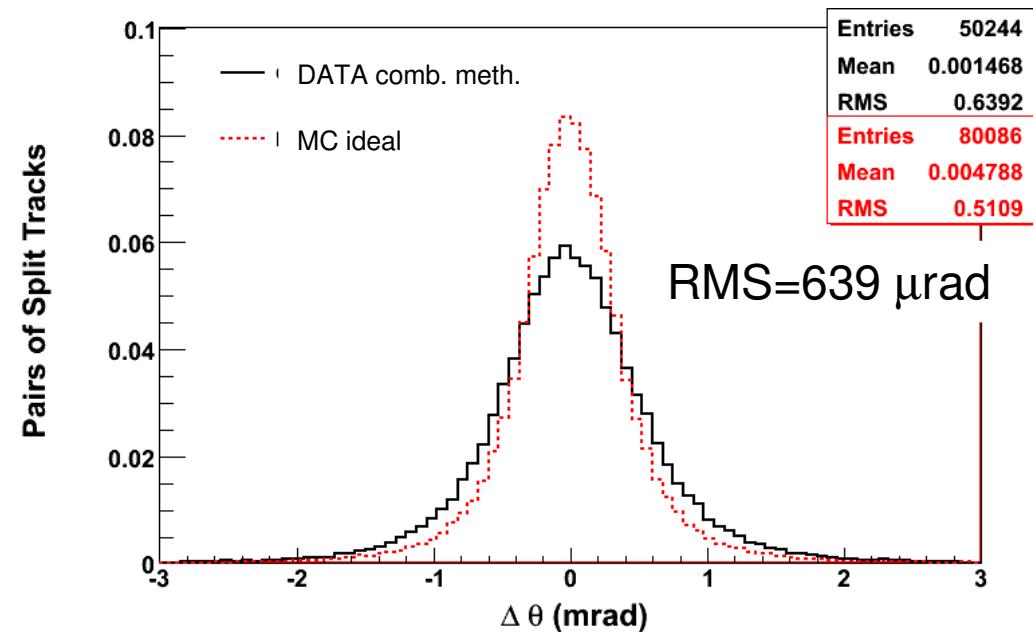
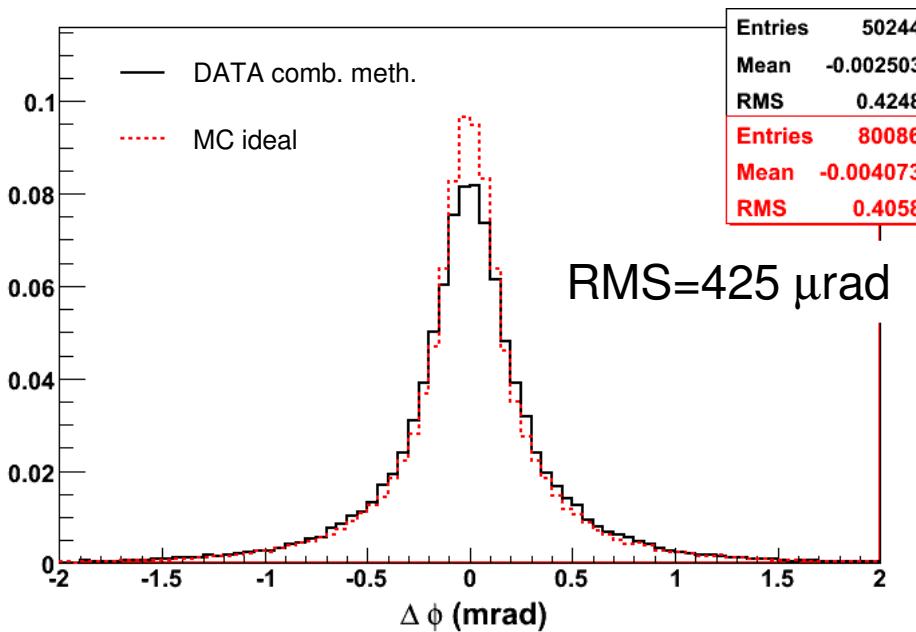
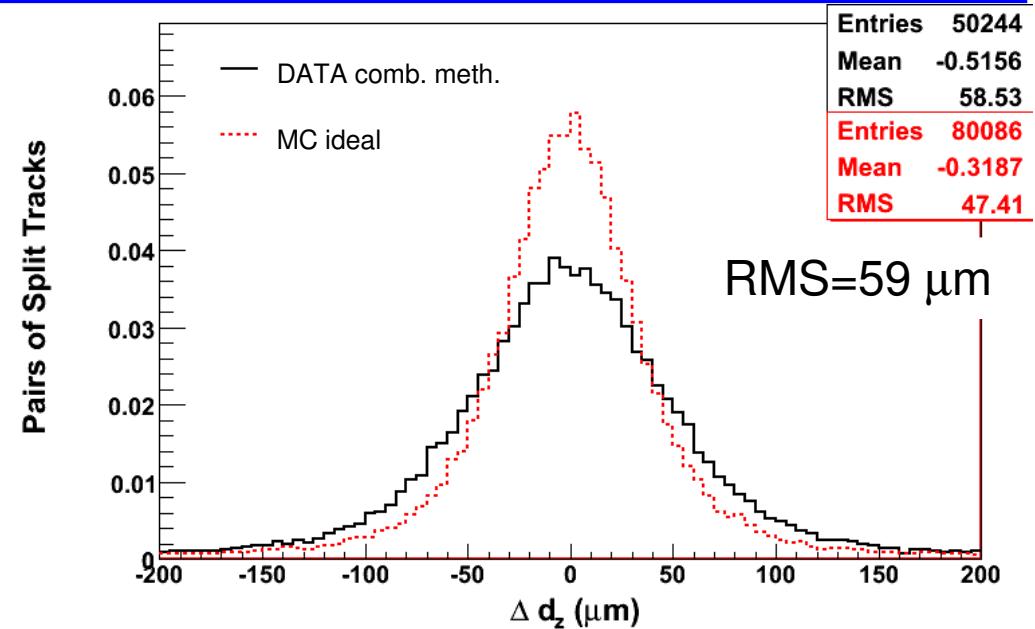
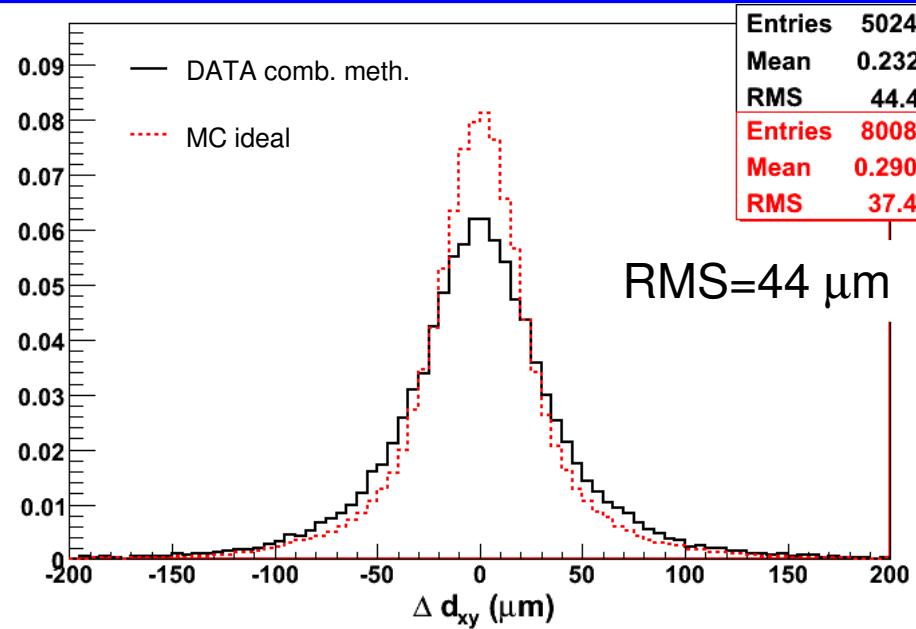
# Low level validation: unbiased residuals



# Low level validation: unbiased residuals

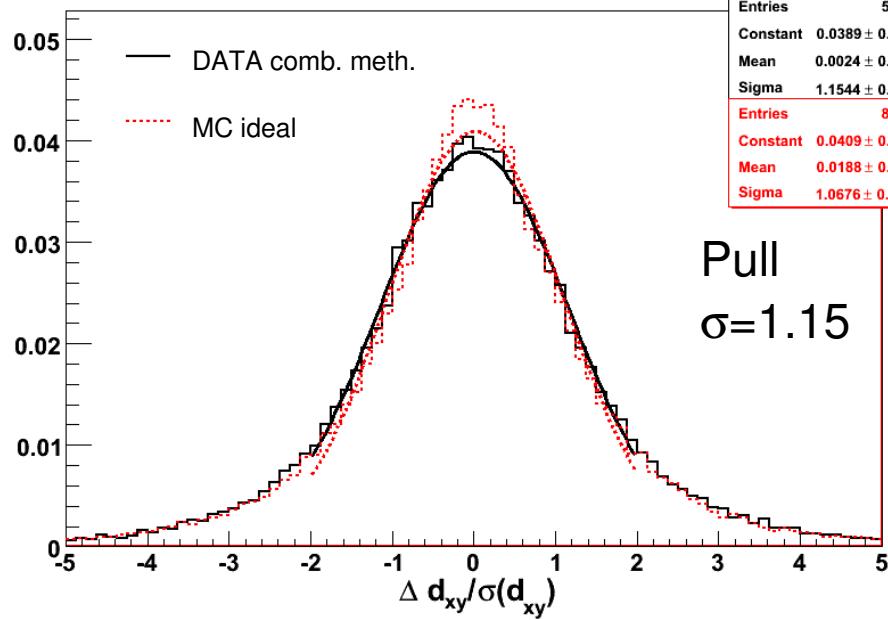


# Cosmic Track Splitting: absolute residuals

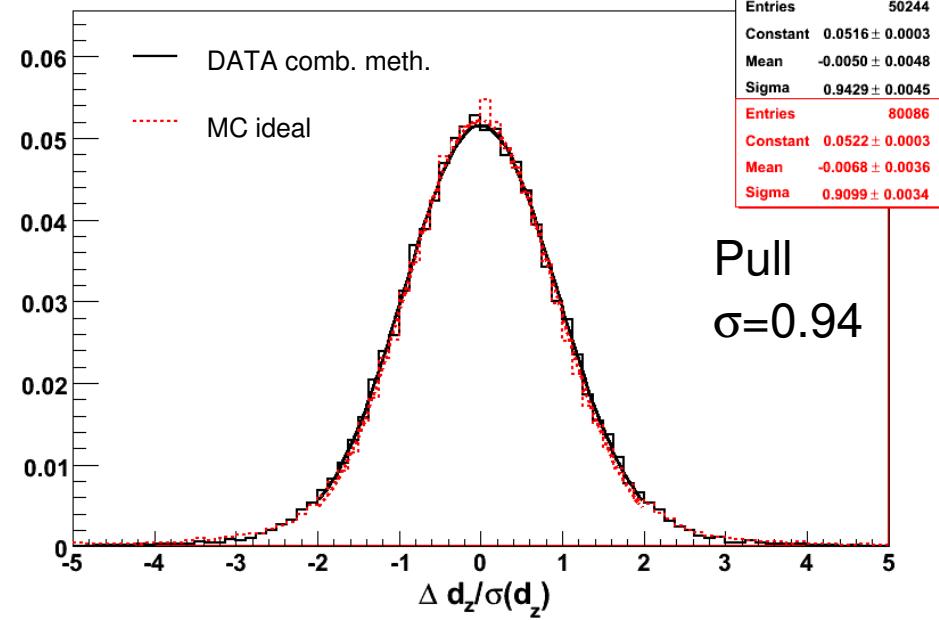


# Cosmic Track Splitting: normalized residuals

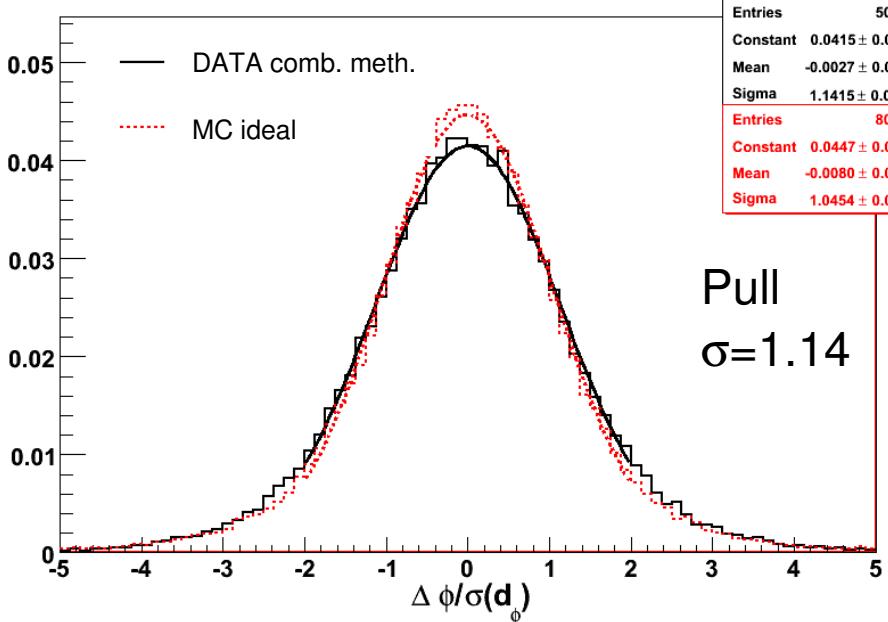
Pairs of Split Tracks



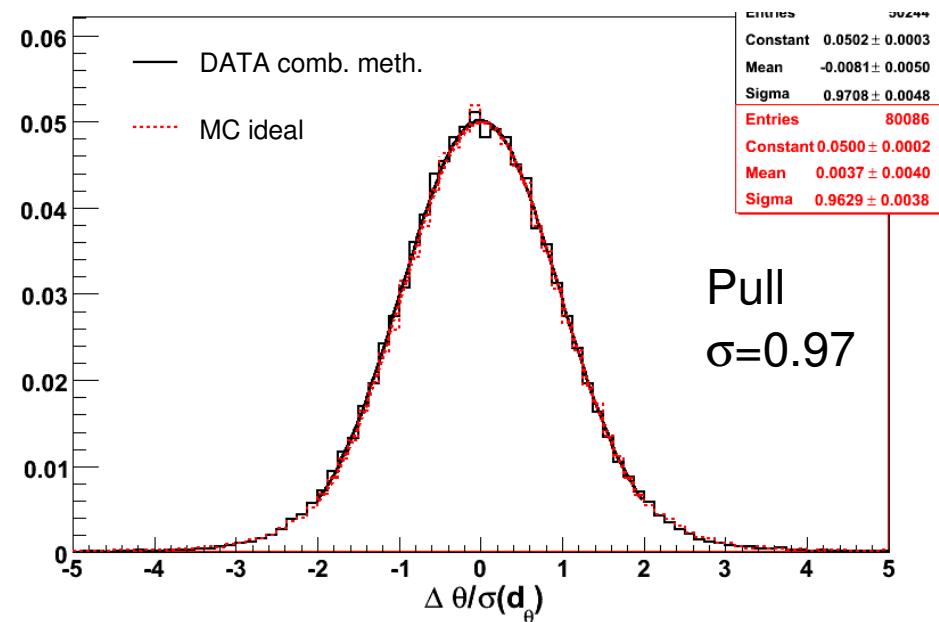
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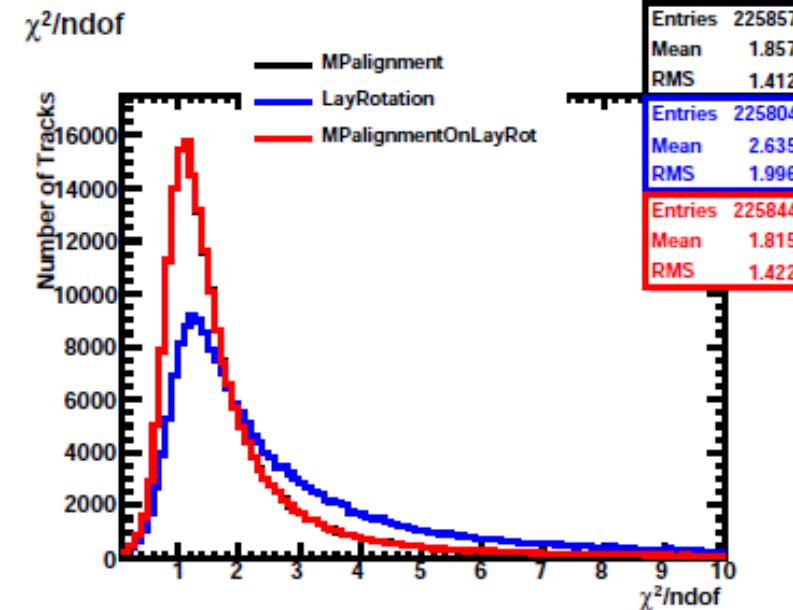
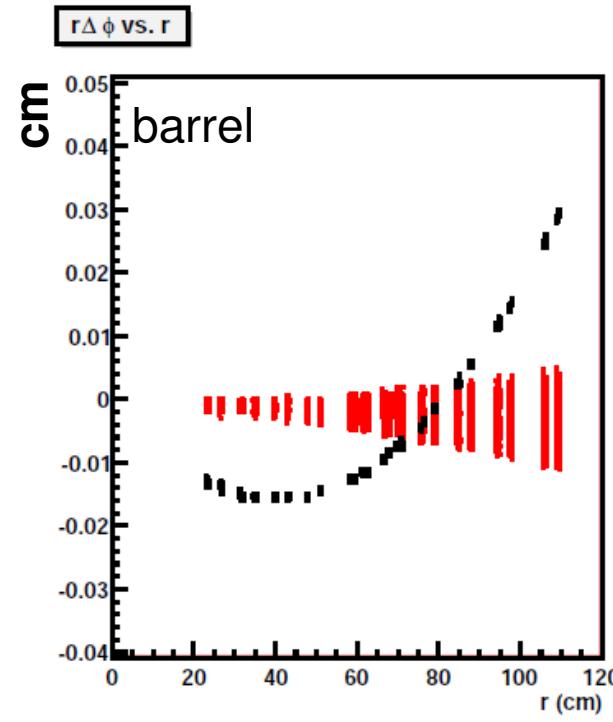
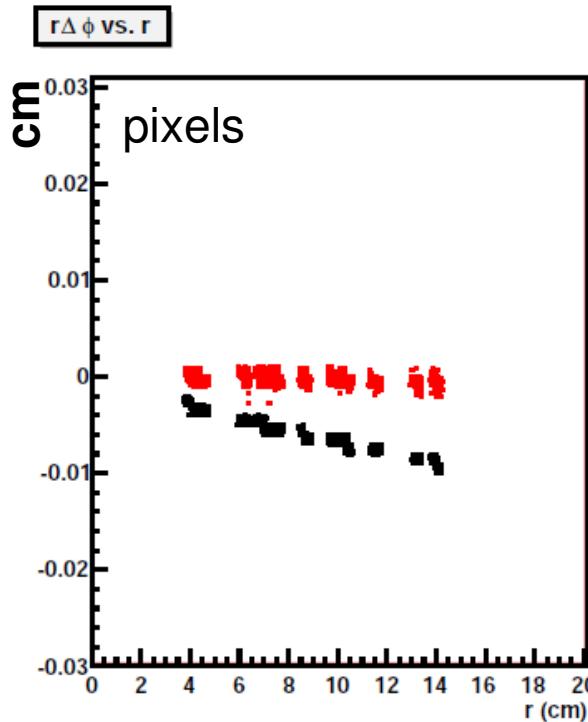
Pairs of Split Tracks



# Sensitivity to weak modes from cosmics: layer rotation

“layer rotation”  $r\Delta\phi$  vs  $r^2$

- Systematic misalignment added to the geometry from the global method
- Re-align (global method) using DATA starting from the systematically misaligned geometry

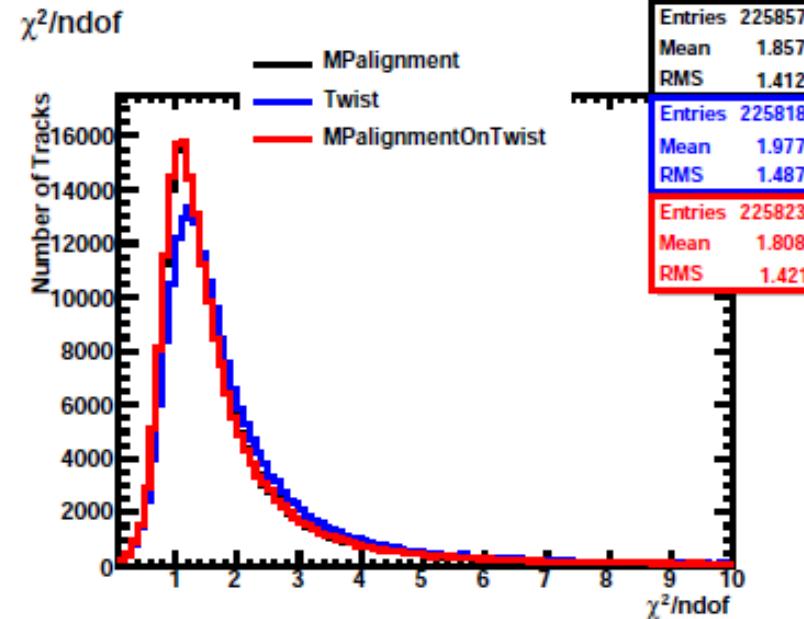
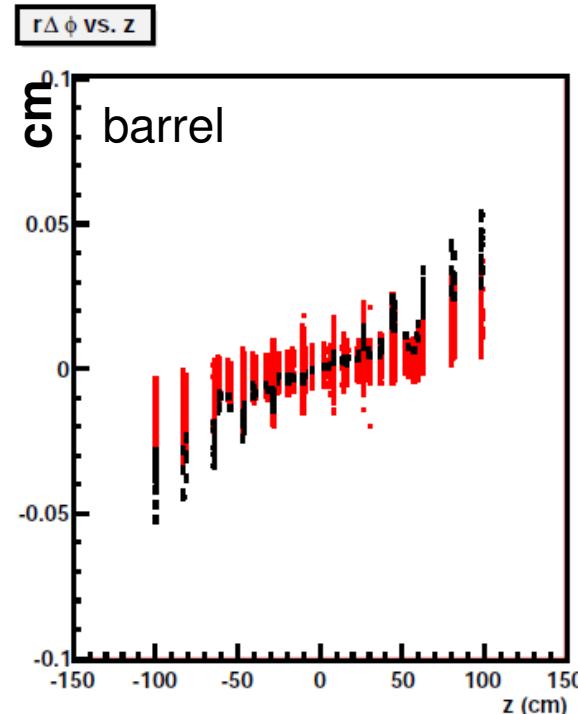
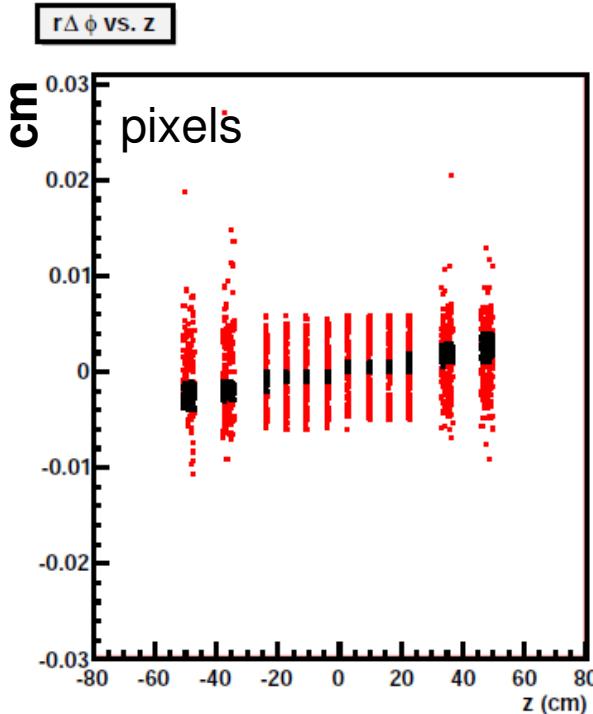


- In the plots: shifts w.r.t starting alignment geometry (flat horizontal line at zero if the mode is recovered)
- Layer rotation is recovered!

# Sensitivity to weak modes from cosmics: twist

“twist”  $r\Delta\phi$  vs z

- Systematic misalignment added to the geometry from the global method
- Re-align (global method) using DATA starting from the systematically misaligned geometry



- In the plots: shifts w.r.t starting alignment geometry (flat horizontal line at zero if the mode is recovered)
- Twist is not fully recovered! Precision on absolute module position is not represented by DMR also in  $r\phi$  coordinate