First Alignment of the CMS Tracker and Implications for the First Collision Data

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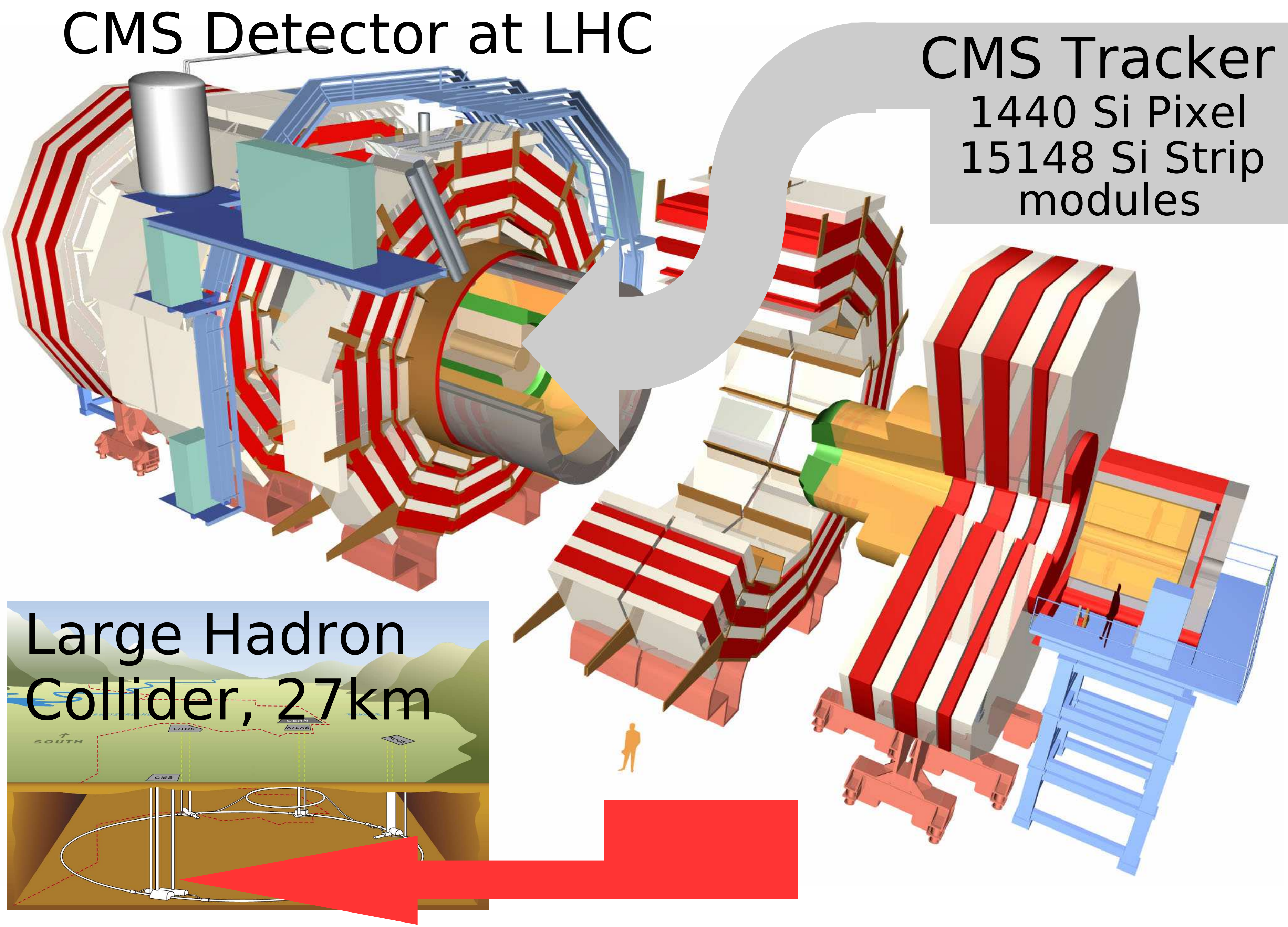
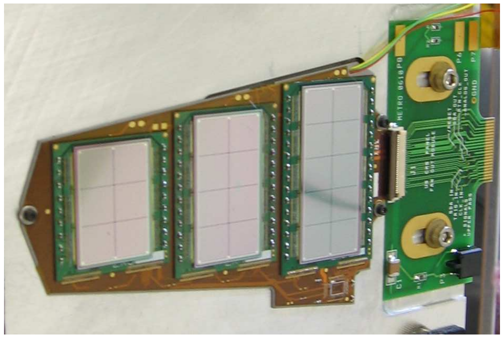
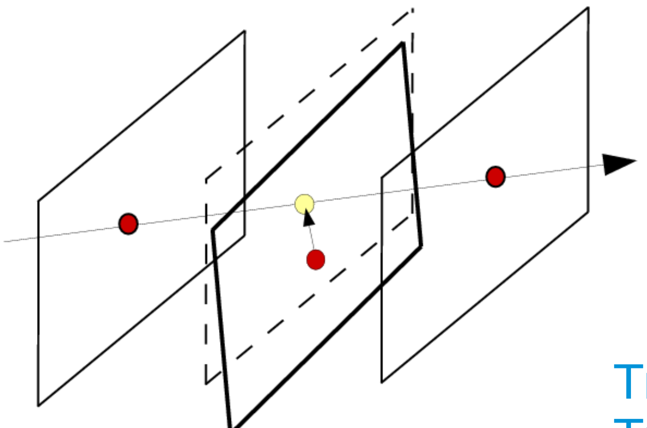
Tracker in the CMS Detector

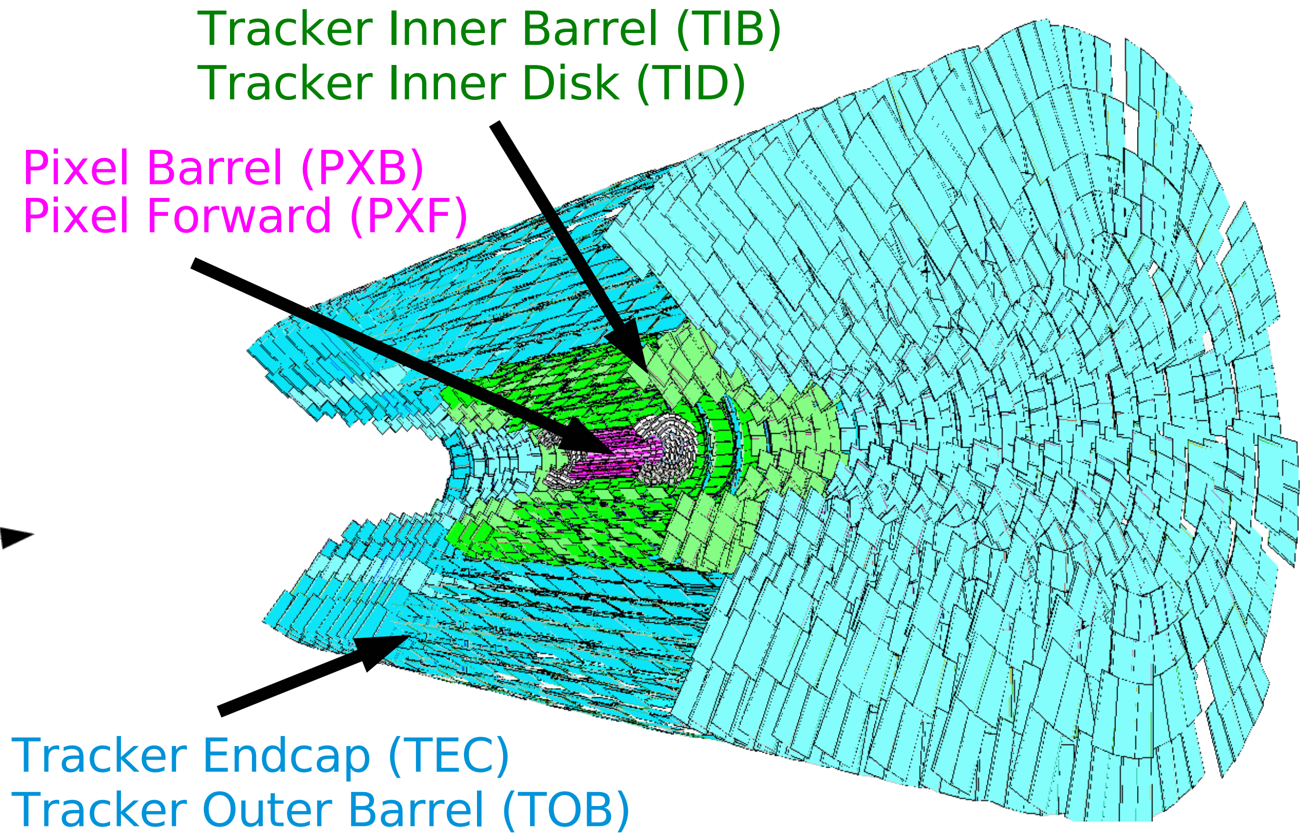


CMS Tracker Alignment Goal

- Alignment goal: nail down (few μm) all 16,588 modules ($\times$ 6 dof)





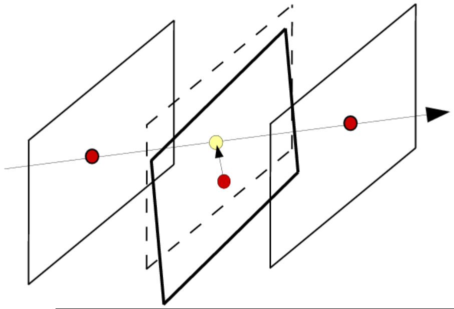


- Minimize residuals

$$\chi^2(\mathbf{p}_{\mathrm{modules}}, \mathbf{q}_{\mathrm{tracks}}) = \sum_{i=1}^{\mathrm{N}_{\mathrm{residuals}}} r_i^T \mathbf{V}_i^{-1} r_i$$

Statistical Methods in CMS Tracker Alignment

- Global method ("Millepede II") NIM A 566, 5 (2006)



$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \frac{\left(y_{ji} - f_{ji}(\mathbf{p},\mathbf{q}_j)\right)^2}{\sigma_{ji}^2} = \sum_{ji} \frac{\mathbf{r}_{ji}^2}{\sigma_{ji}^2}$$

CMS implementation

pros	module correlations included	less CPU with one or few iterations
cons	helix trajectory model used	large matrix may limit N parameters

- Local iterative method CMS-NOTE-2006/018, arXiv:0809.3823

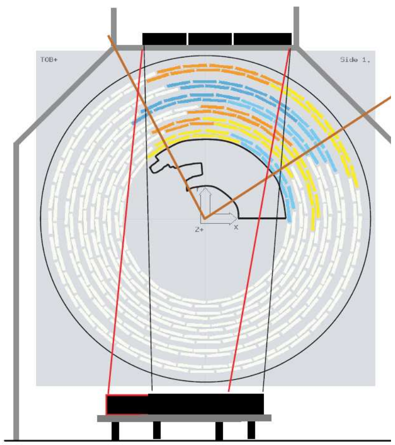
$$\chi^2_{\text{module}} = \sum_i^{\text{hits}} \mathbf{r}_i^T(\mathbf{p_m})\mathbf{V}_i^{-1}\mathbf{r}_i(\mathbf{p_m}) + \sum_j^{\text{survey}} \mathbf{r}_{*j}^T(\mathbf{p_m})\mathbf{V}_{*j}^{-1}\mathbf{r}_{*j}(\mathbf{p_m})$$

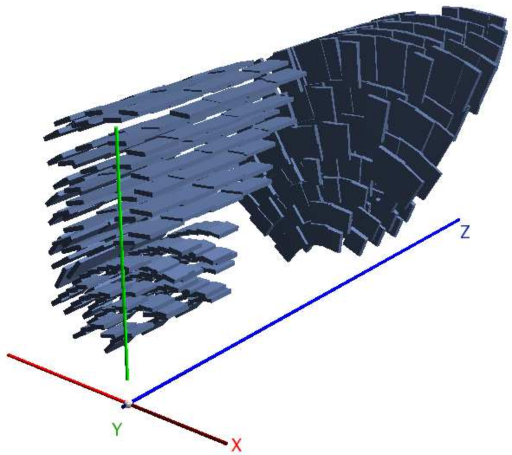
$$\Delta\mathbf{p_m} = \left[\sum_i \mathbf{J}_i^T\mathbf{V}_i^{-1}\mathbf{J}_i\right]^{-1}\left[\sum_i \mathbf{J}_i^T\mathbf{V}_i^{-1}\mathbf{r}_i\right] \quad ; \qquad \mathbf{J}_i = \partial\mathbf{r}_i/\partial\mathbf{p_m}$$

pros	full Kalman Filter track model	simple implementation, all dof
cons	ignore correlations in one iteration	large CPU with many iterations

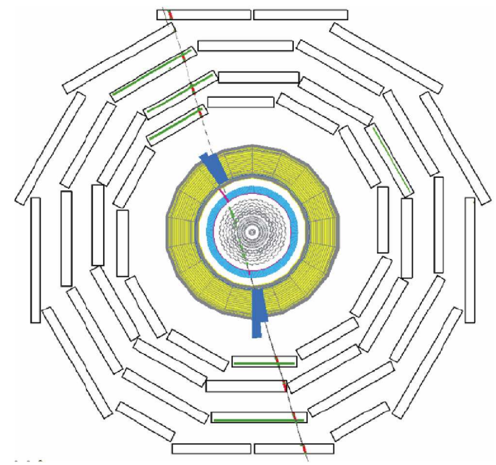
Tracker Alignment without Magnetic Field

- Partial tracker: summer 2007

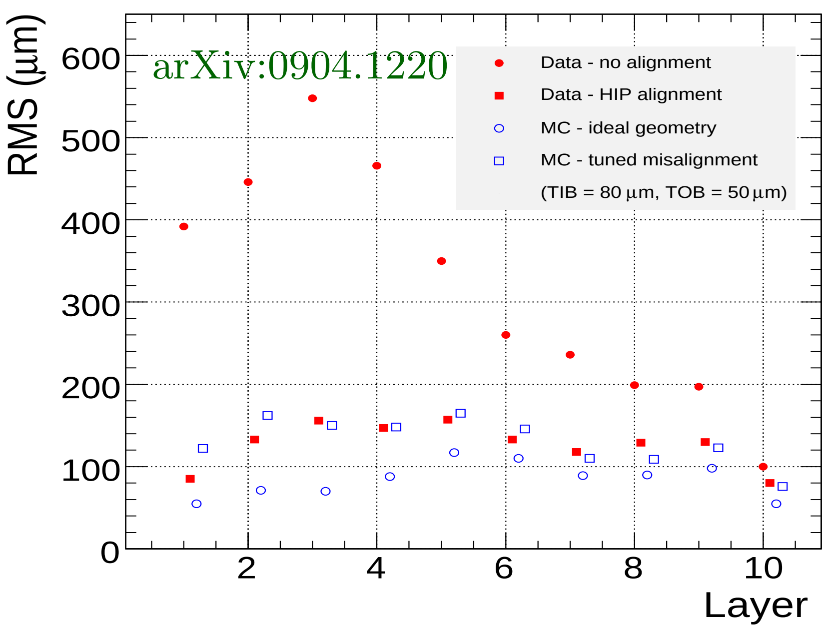




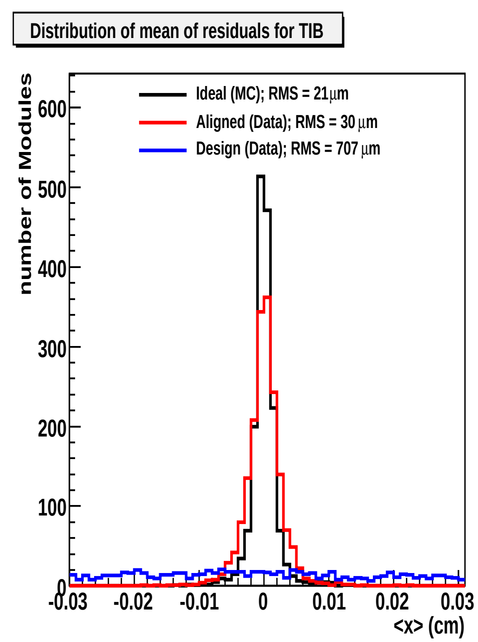
- Full tracker: summer 2008

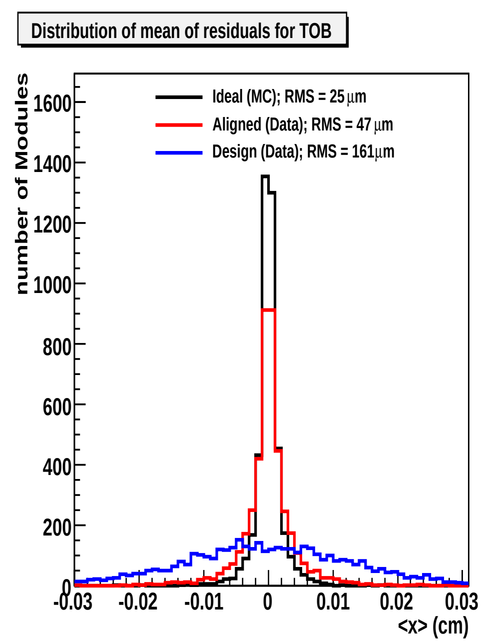


- ~50/80μm in TOB/TIB



- ~30-40μm in TOB/TIB





CMS Tracker Alignment with Magnetic Field

- Best data for alignment of CMS Tracker: fall 2008 (“CRAFT”)

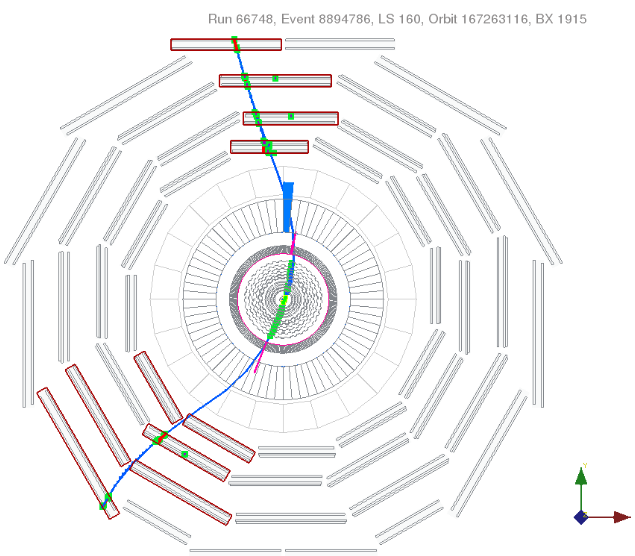
  ~ 4M cosmic tracks for Tracker alignment

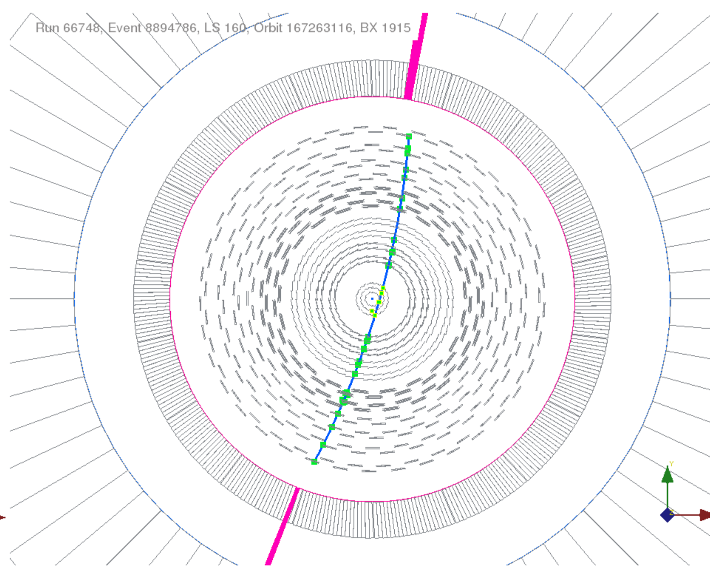
  B-field $=$ 3.8T $\Rightarrow$ account for multiple scattering track-by-track

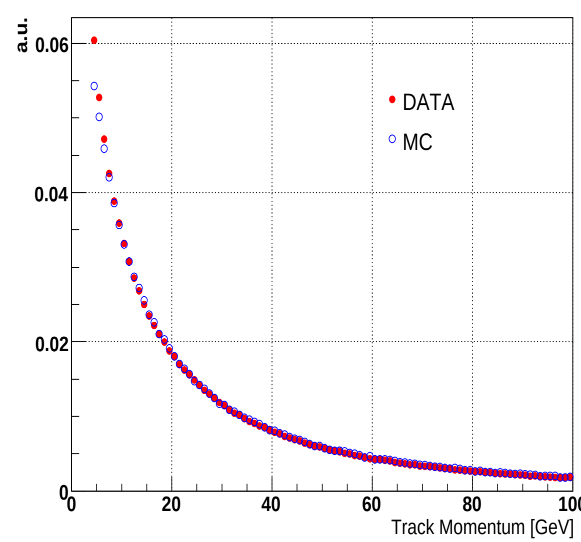
- Require good quality tracks and hits: $p > 4$ GeV$/c$

  clean hits, outlier hit rejection, χ^2 cut, min hits, 2D hits

  only $\sim$4$\%$ in Pixels

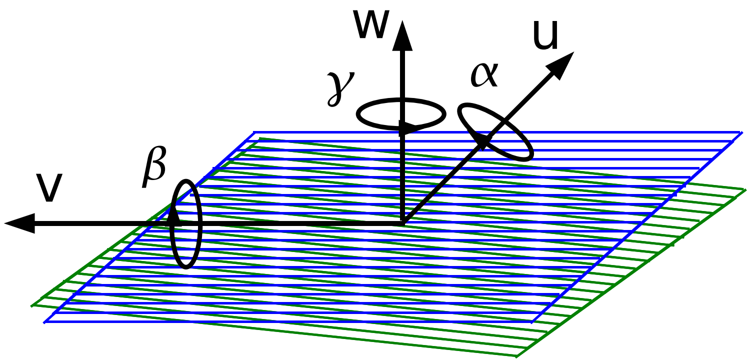


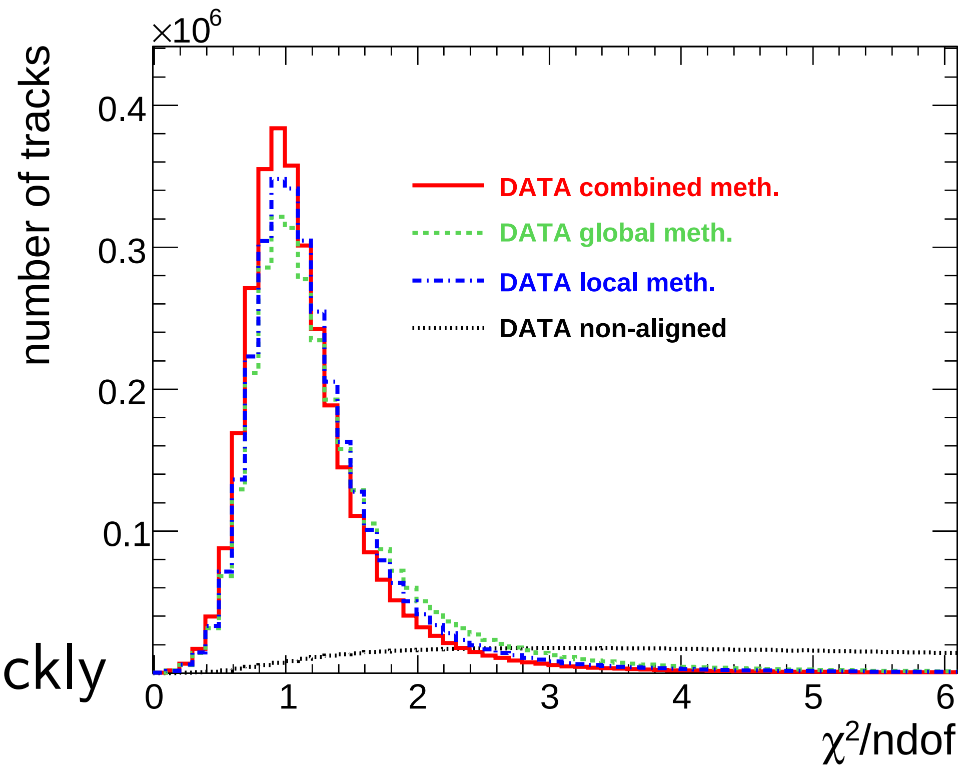




Alignment Strategy

- Multi-step approach by both algorithms to address CMS geometry:
  - large structure movement: coherent v alignment of 1D modules
  - alignment of two sides of 2D strip modules (units): u, w, γ





- Combined method

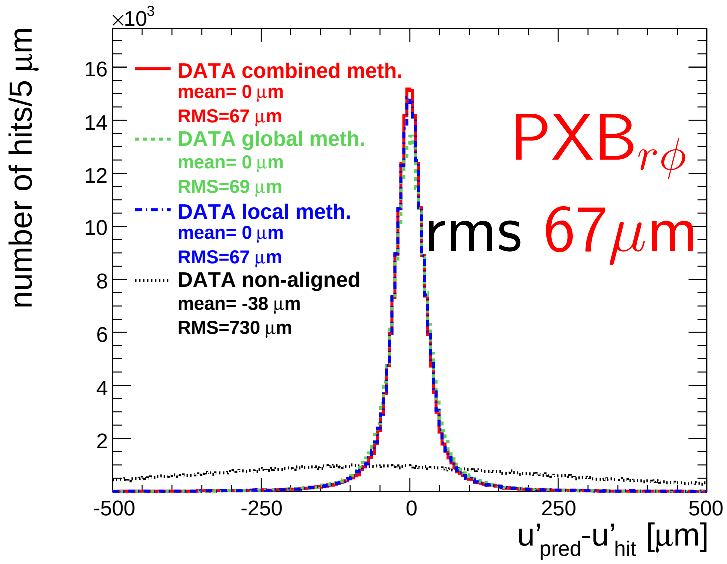
(1) run global method

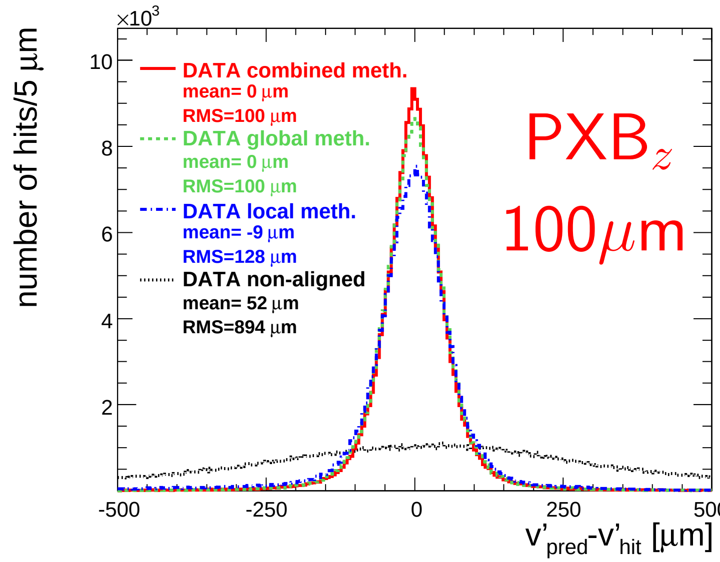
$\Rightarrow$ solve global correlations quickly

(2) run local method

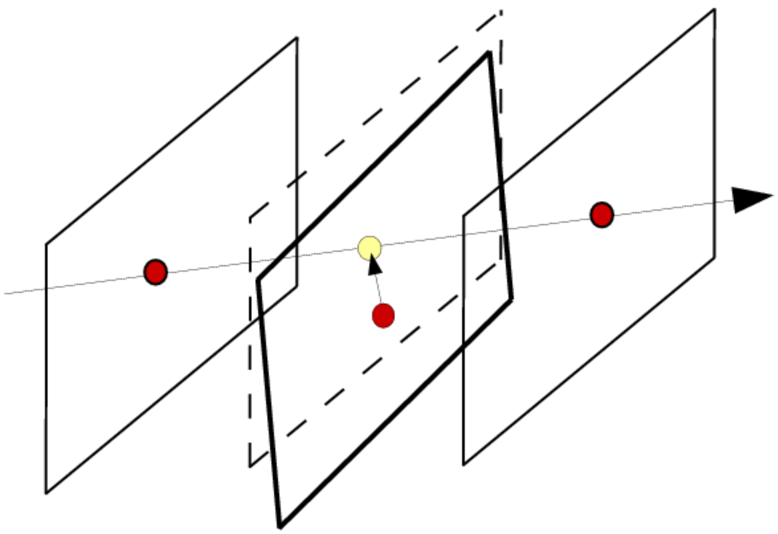
$\Rightarrow$ solve locally to match track model in all degrees-of-freedom (dof)

Example: Pixel Residuals (local, global, combined)

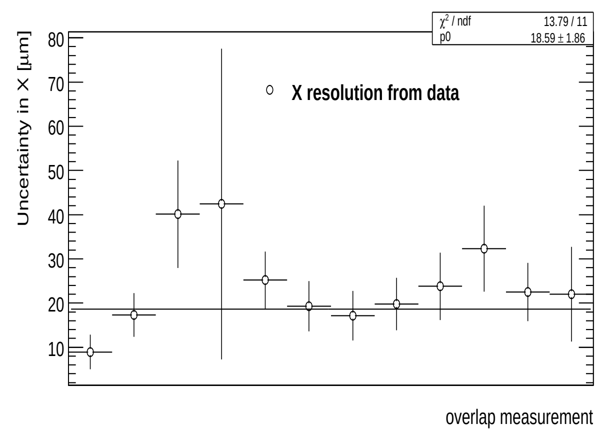




- Residuals $\Leftarrow$ multiple scattering (random) + hit errors (random) + alignment errors (systematic)



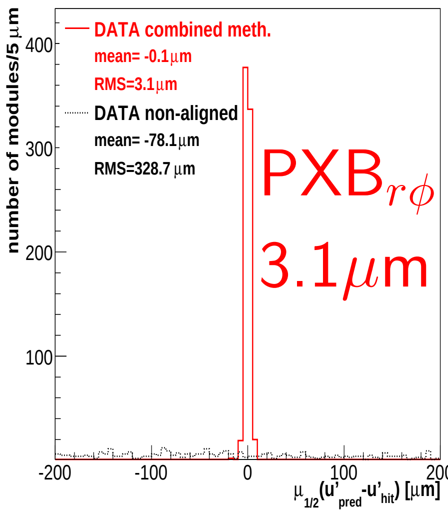
$r\phi$ pixel hit errors $\sim 19\mu m$ here

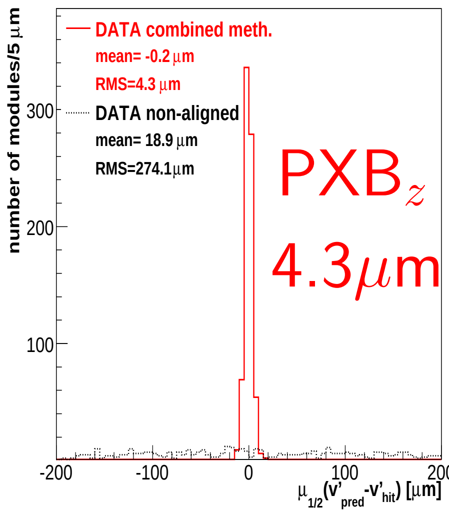


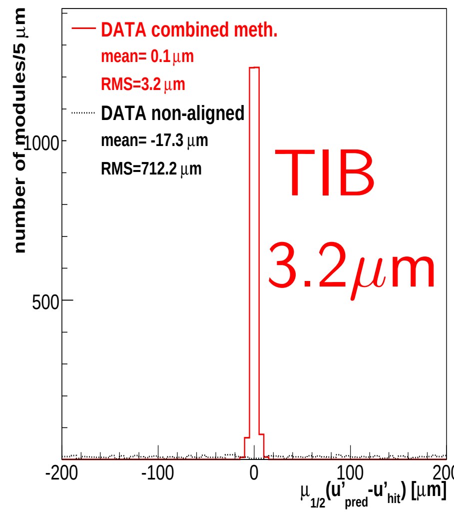
Median of the Residuals

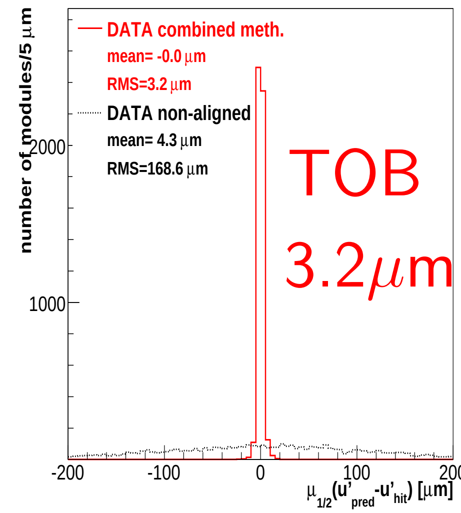
Pixel Barrel

Strip Barrel





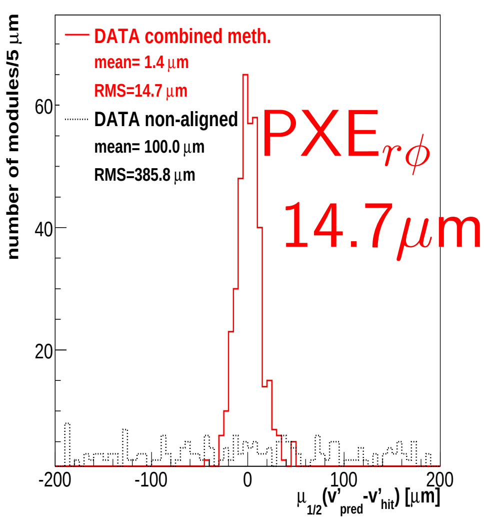


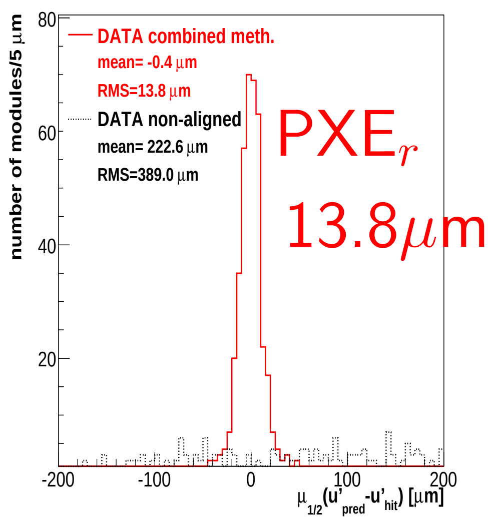


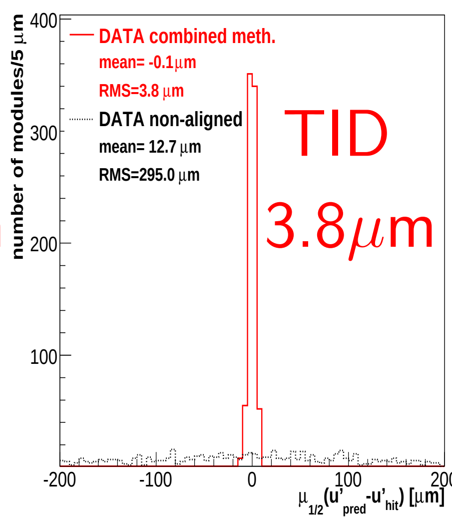
Pixel Encap

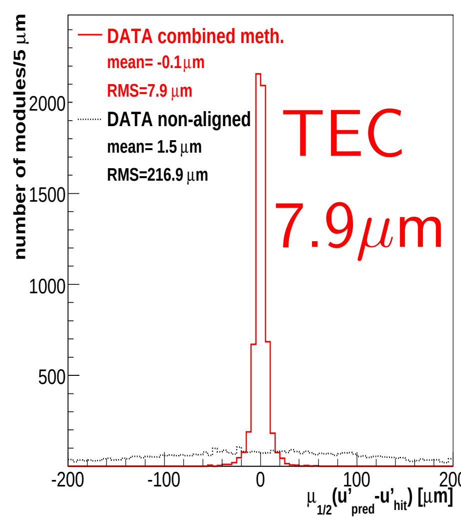
Strip Endcap

note: vertical cosmics ⇒ lower statistics in endcaps



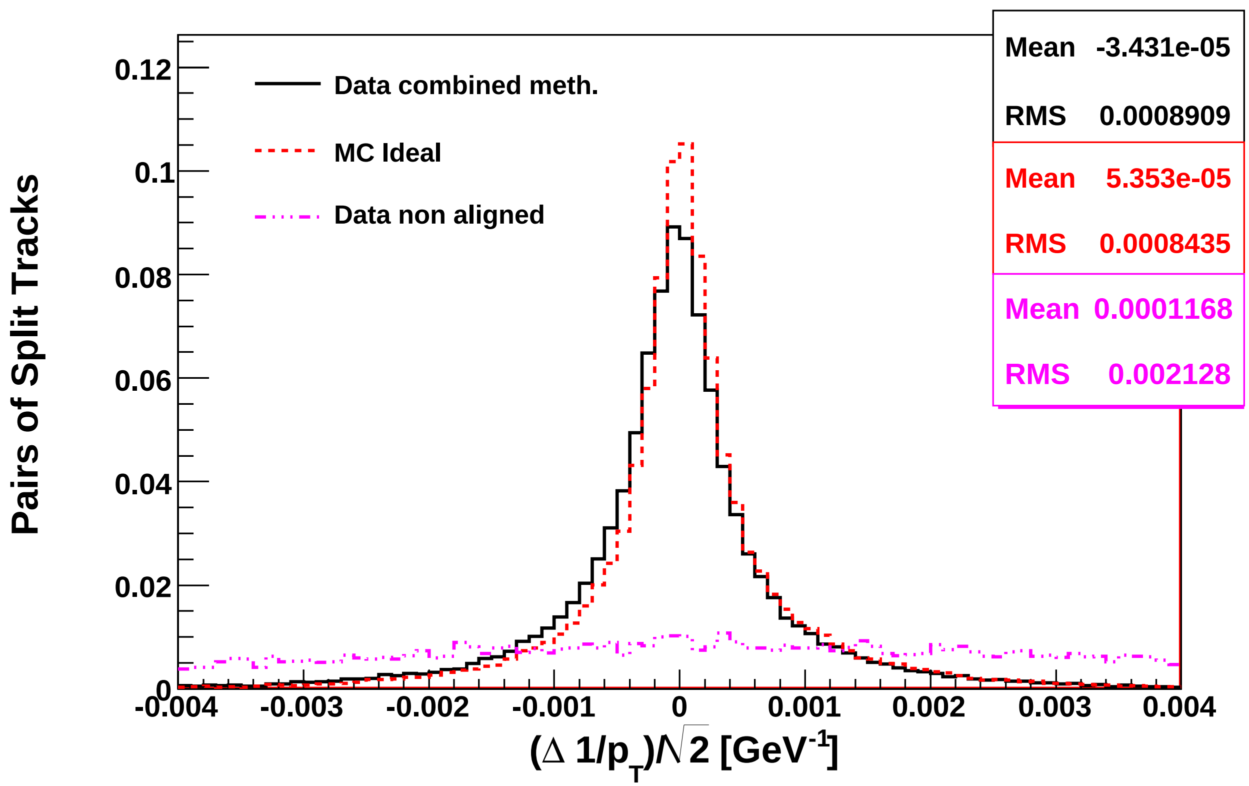


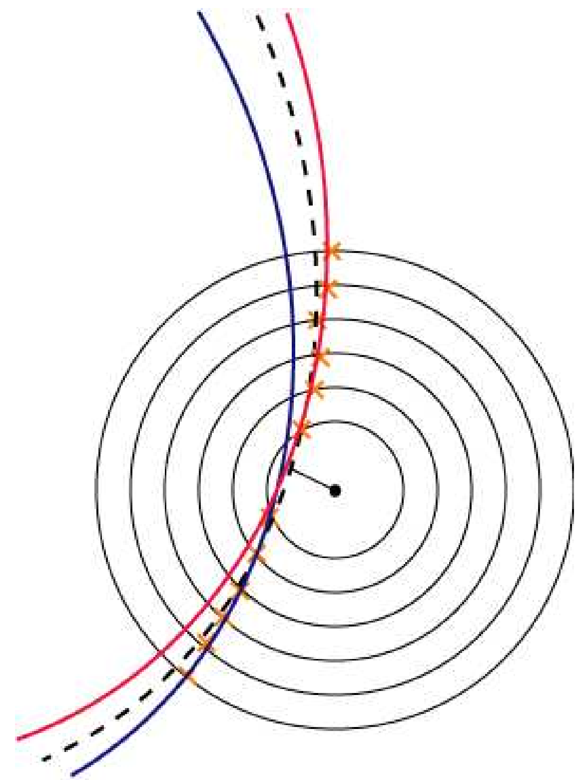




Cosmic Track Halves: Collision-like Tracks

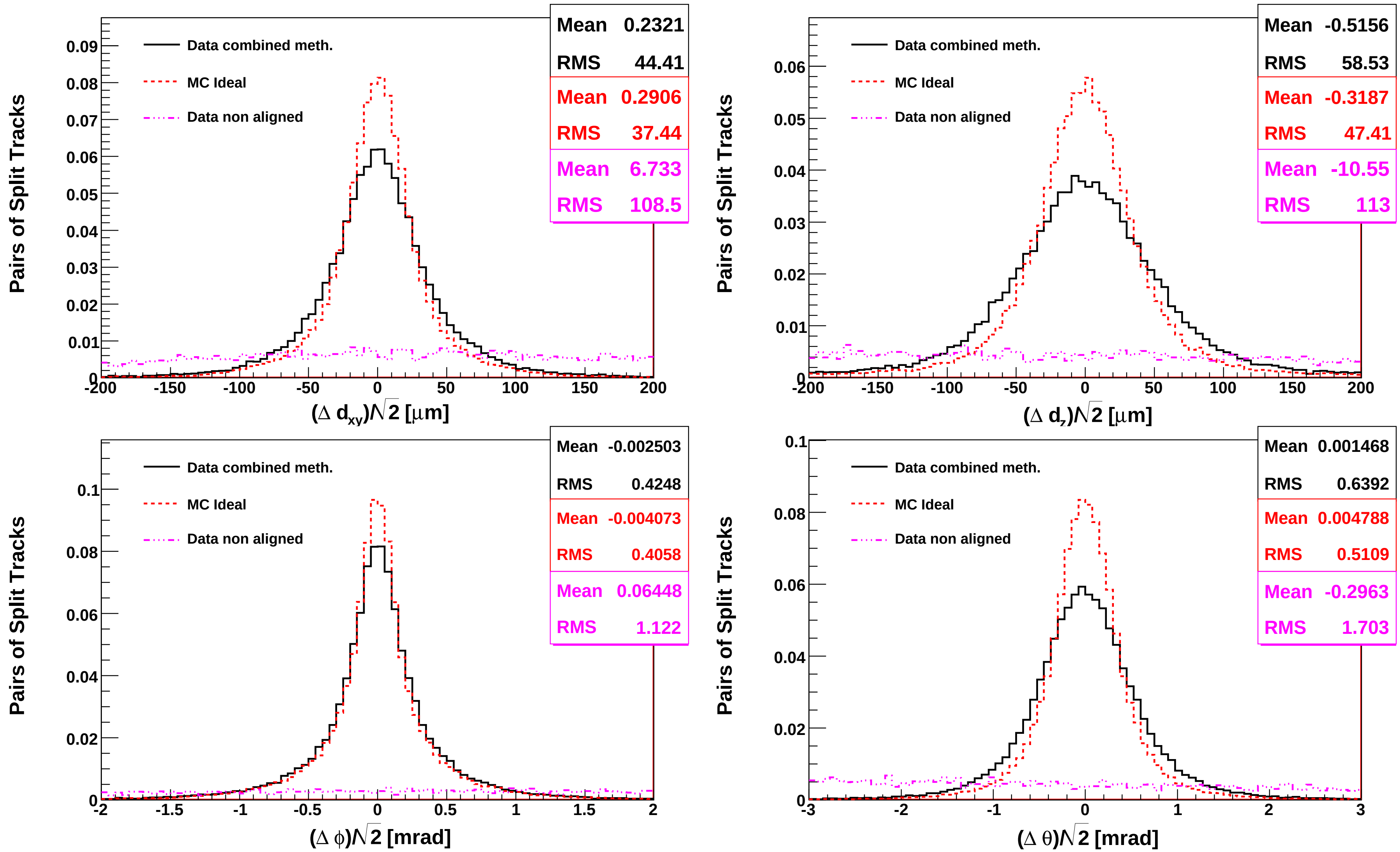
- Tracker resolution with data (require Pixel hits, near collision point)
  - compare non-aligned data $\longrightarrow$ aligned with data $\longrightarrow$ "ideal" MC
  - significant effect of alignment
  - approaching ideal in momentum precision with this track sample





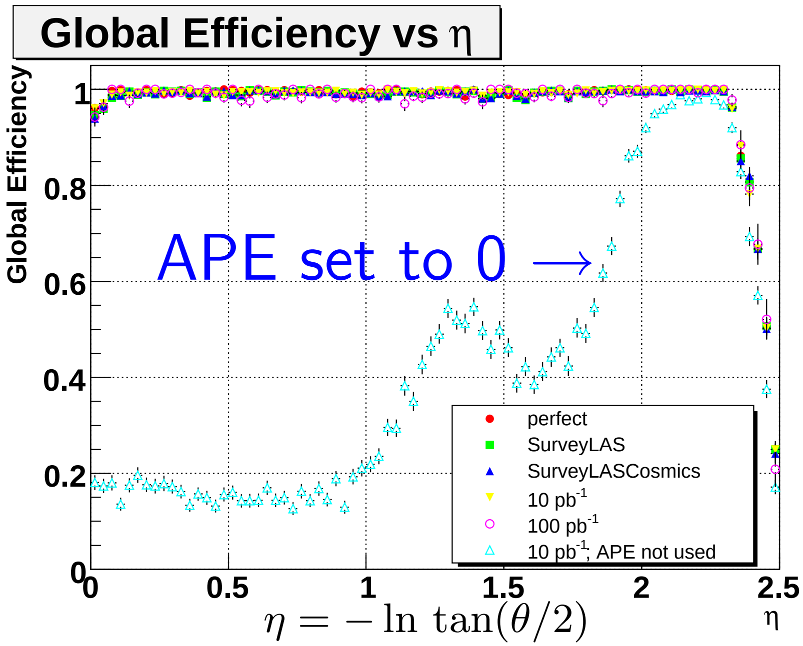
Cosmic Track Halves: Four Other Parameters

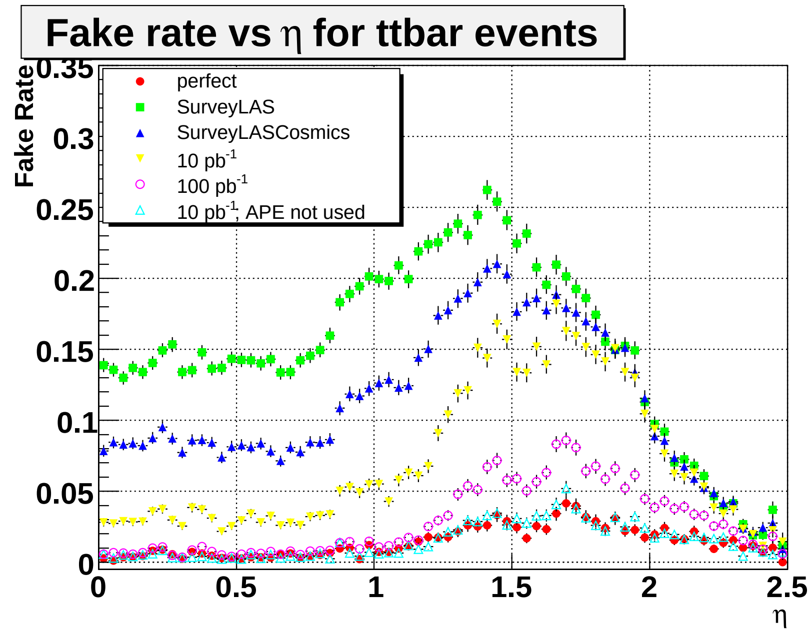
- These four parameters (d_{xy}, d_z, ϕ, θ) dominated by Pixels
  - measuring vertex and track direction, note: all p_T-dependent



Monte Carlo Studies: Misalignments

- Comprehensive hierarchical model of CMS Tracker misalignment:
  - "hardware" only "SurveyLAS"
  - "Startup-2008" before collisions "SurveyLASCosmics" (based on 2008 info)
  - "10/pb"
  - "100/pb" (roughly data expected in 2009-2010 LHC run)
  - "ideal" best possible alignment
- Track efficiency stable with proper APE (Alignment Parameter Errors)
  - but fake rate goes up with misalignment



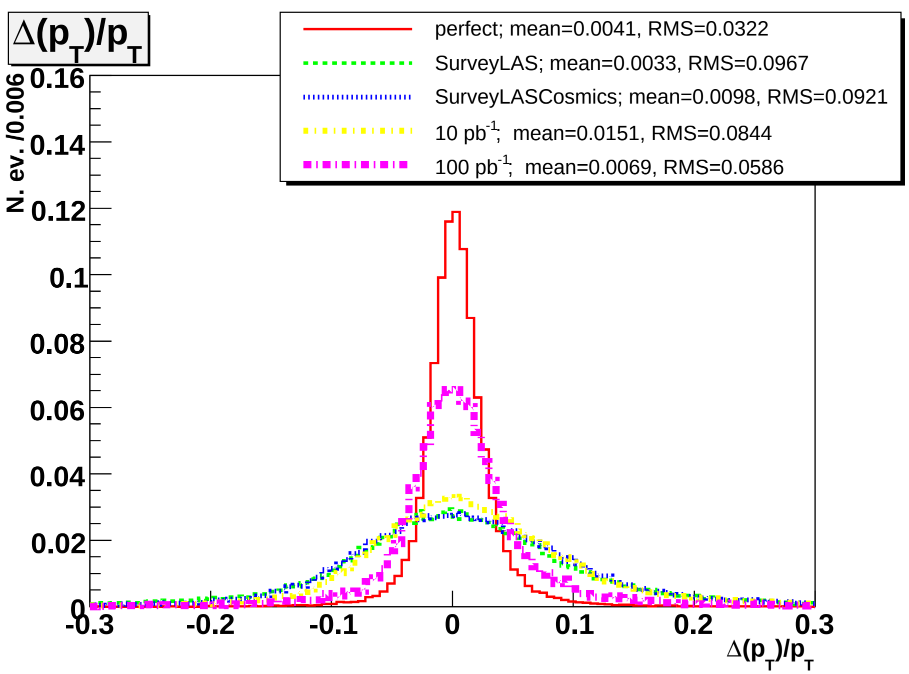


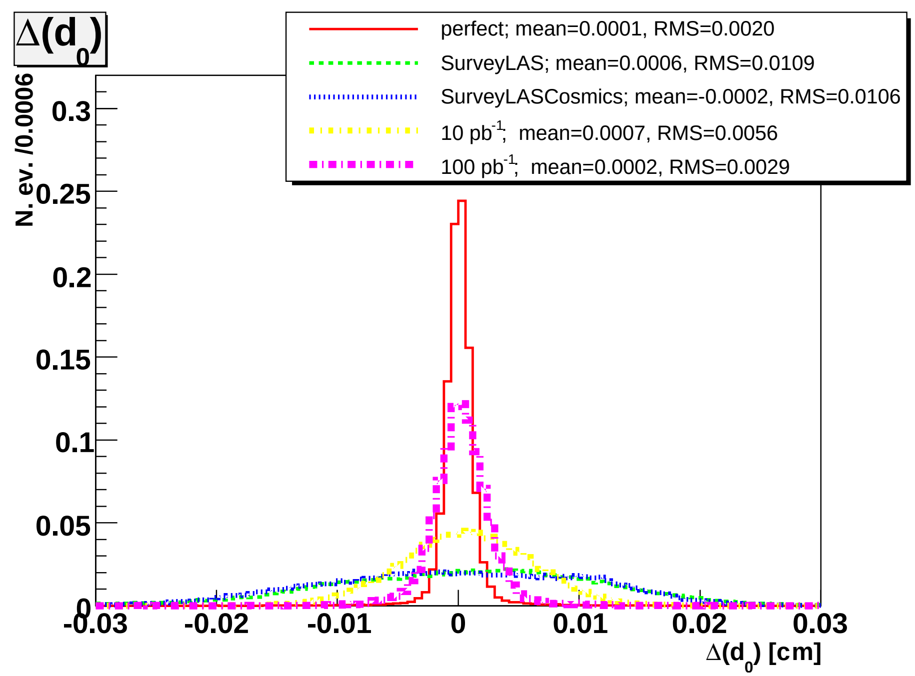
Monte Carlo Studies: Misalignments

- Compare resolution in track parameters
  - compare "Startup-2008" $\rightarrow$ "100/pb" $\rightarrow$ "ideal"
  - for 100 GeV/c track $\frac{\Delta p_T}{p_T} \sim$ 9.2% $\rightarrow$ 5.9% $\rightarrow$ 3.2%

    $\Delta(d_{xy}) \sim$ 106μm $\rightarrow$ 29μm $\rightarrow$ 20μm

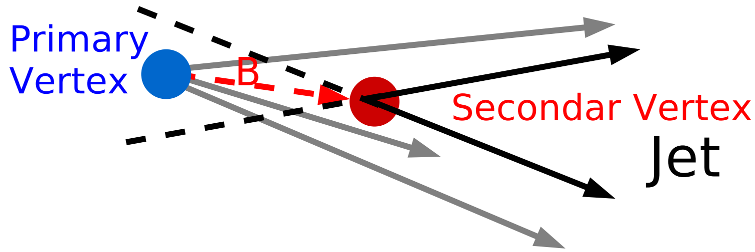
- New "Startup-2009" would be closer to "100/pb" already
  - benefit from cosmic commissioning run and analysis presented today
  - note: systematic effects not considered here

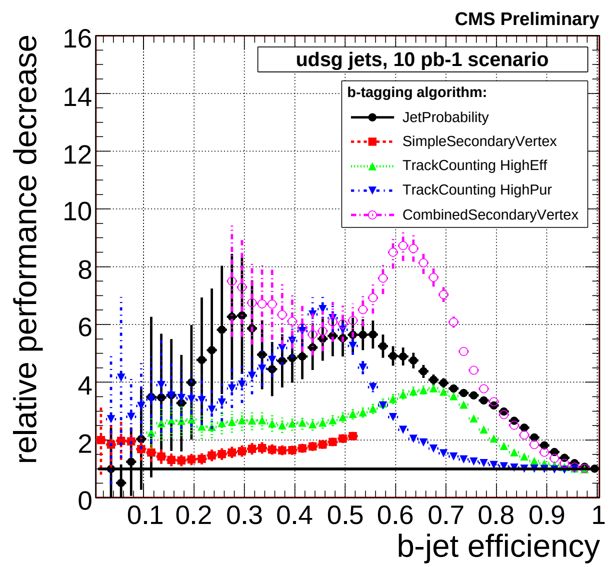




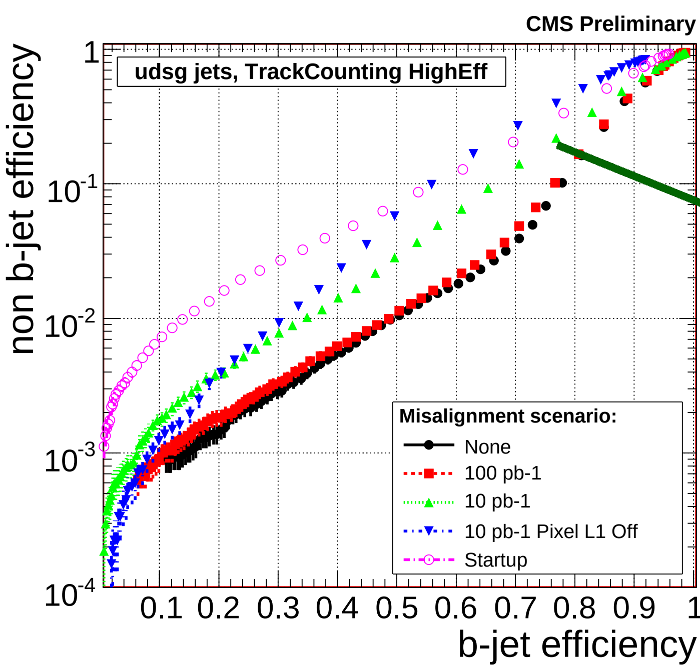
Monte Carlo Studies: b-tagging

- Many New Physics models: $t \to b$ displaced vertex ($c\tau_b \approx 450\ \mu$m)

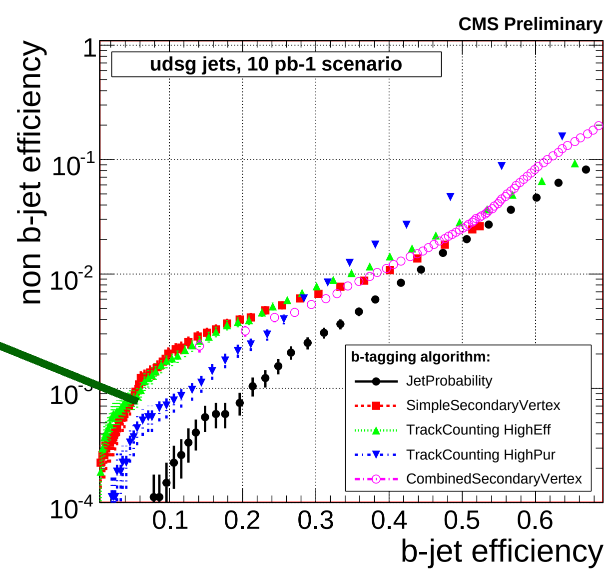




  - all b-tag alignment sensitive
    both positions and errors important
  - approaching "ideal" at "100/pb"



10/pb
TrackCounting alg.



Monte Carlo: Example of a Discovery Reach

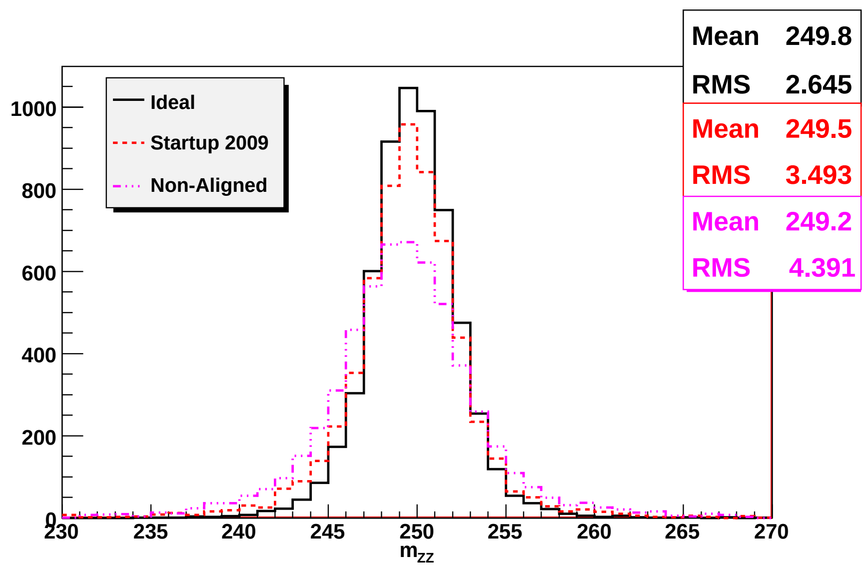
- Reconstruct narrow $X \to ZZ \to 4\mu, 4e$, or $2e2\mu$

  joint likelihood fit analysis as an example
  test 5/fb at Higgs production rate

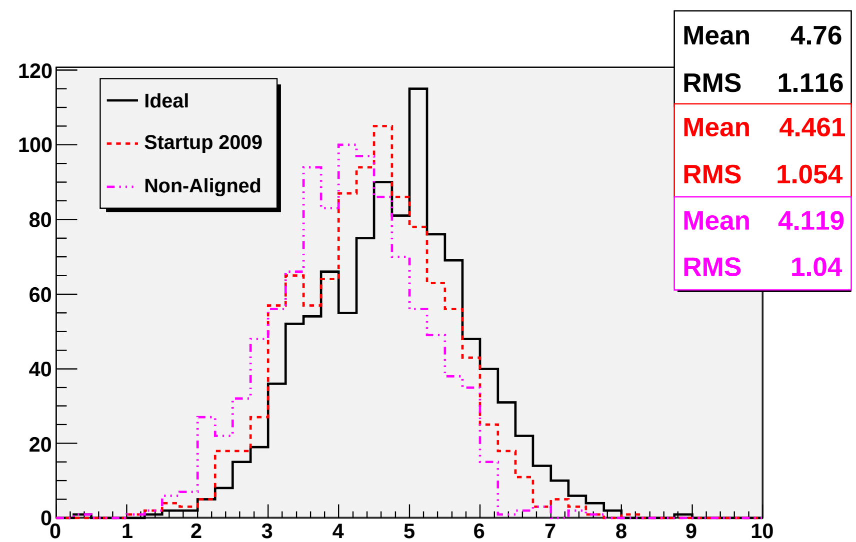
"non-aligned" $\to$ "Startup-2009" $\to$ "ideal " $\Rightarrow$ makes big difference

– m_{ZZ} width 4.4 $\to$ 3.5 $\to$ 2.6 GeV (in 4μ, but in $4e$ little effect)

– significance 4.1 $\to$ 4.5 $\to$ 4.8 σ from $\sqrt{2\ln(\mathcal{L}_{s+b}/\mathcal{L}_b)}$



$m_{4\mu}$

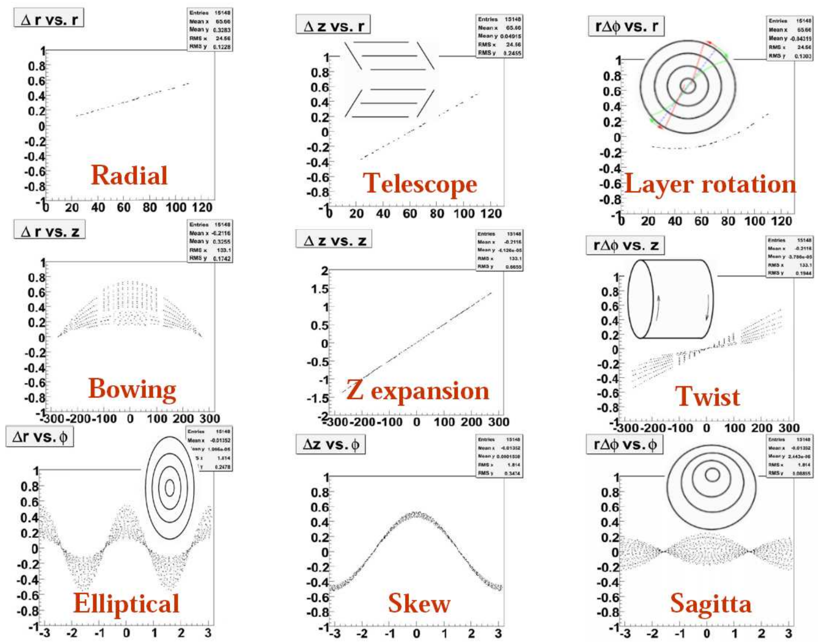


significance

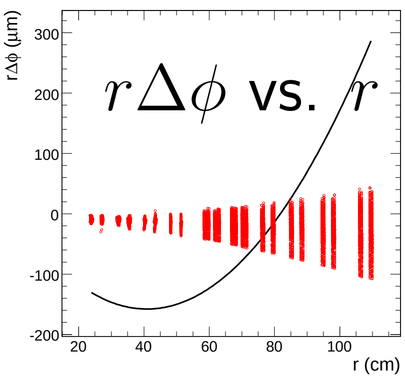
Systematic Misalignments

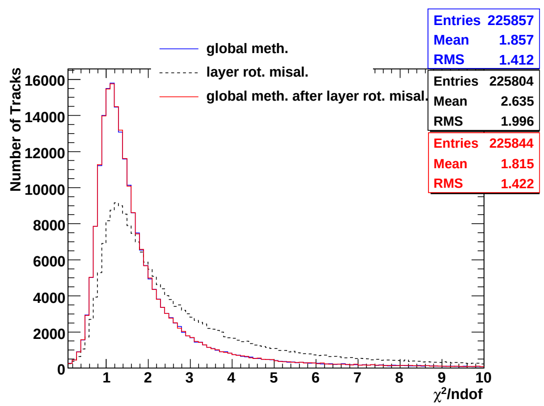
- Systematic distortions of the Tracker
  - may be χ^2 invariant
  - may introduce physics bias

  e.g. charge bias with layer rotation



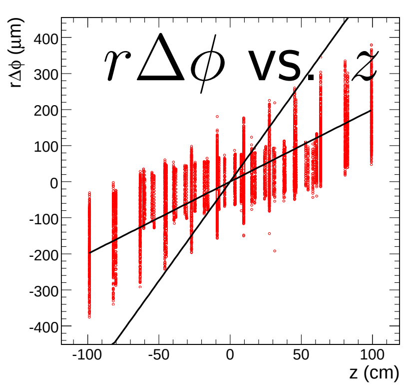
$(\Delta r,\ \Delta z,\ r\Delta\phi)$ vs. $(r,\ z,\ \phi)$

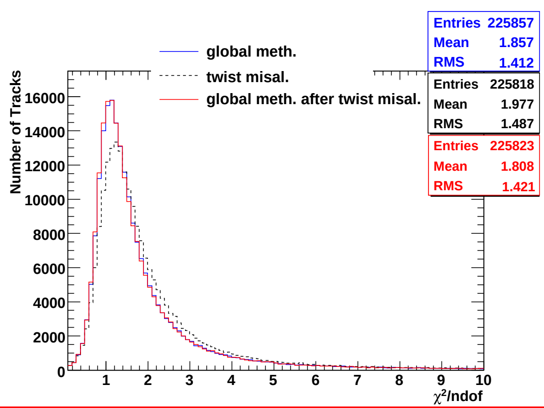




← layer rotation

recovered in alignment



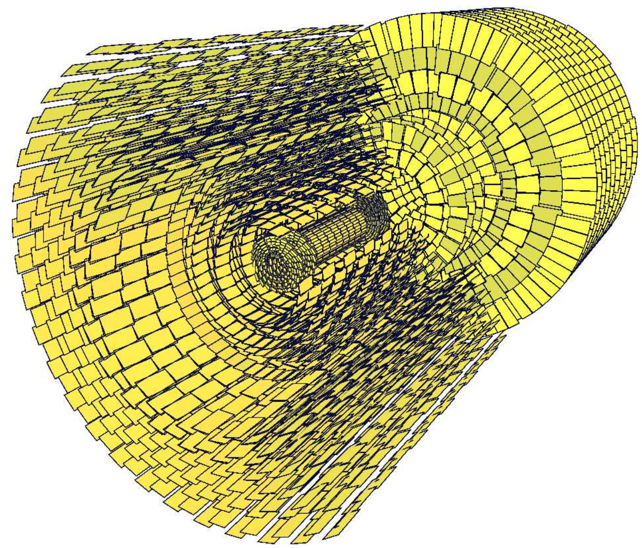


← twist and some others

harder with cosmics alone

Summary

- CMS Tracker alignment:
  - challenging task (16588 elements)
  - successful CMS run with cosmics
  - complementary statistical methods
    best combination of global & local
  - achieved local deviations as low as 3μm



- Implication for first physics
  - discovery reach sensitive to tracker alignment
    e.g. fake rate, b-tag, resonance resolution
  - performance is already ahead of expectation
  - systematic limitations with cosmics alone
    more to come from collisions