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

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OUTLINE

- Input to CMS Tracker alignment algorithms:
  - Laser Alignment System
  - optical survey
  - tracks from cosmic muon runs -> ultimate precision

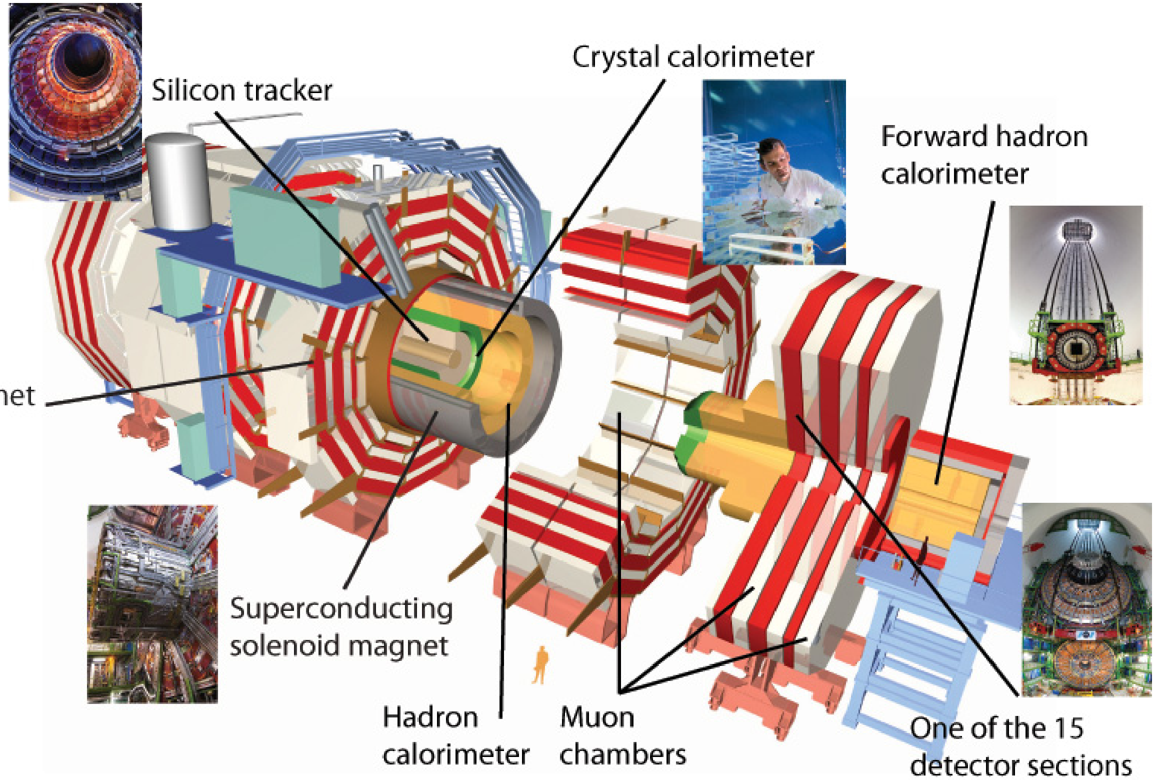
  Tracker Integration Facility (TIF) with partial Tracker in 2007
  CMS at LHC Point-5 ("CRAFT" cosmic run) with full Tracker in 2008

- Alignment results with cosmic muons and validation

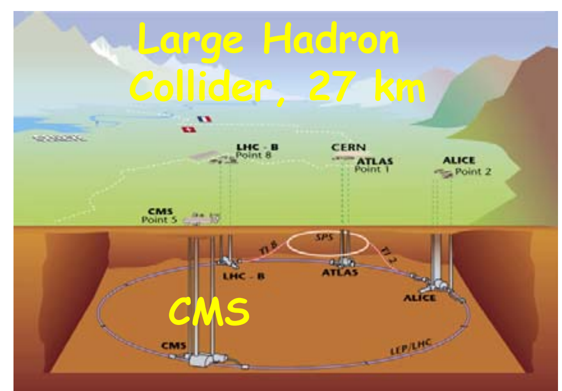
- Alignment implications for physics performance
  and some on systermatics

Alignment is a big project, but only the final step in commissioning

Tracker in the CMS detector

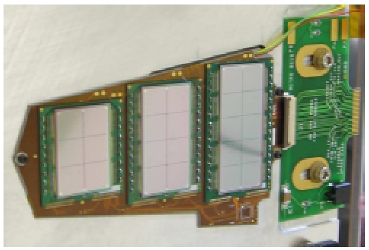


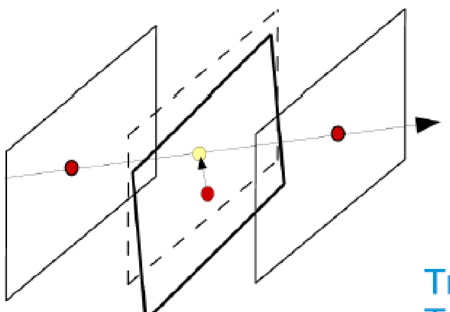
CMS Tracker
1440 Si Pixel
15148 Si Strip modules

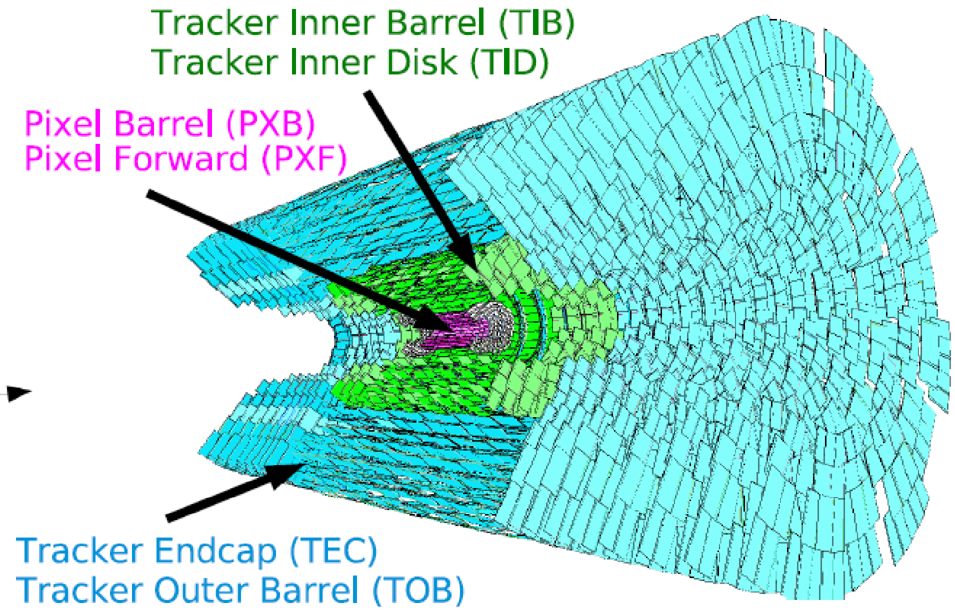


CMS Tracker Alignment Goal

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





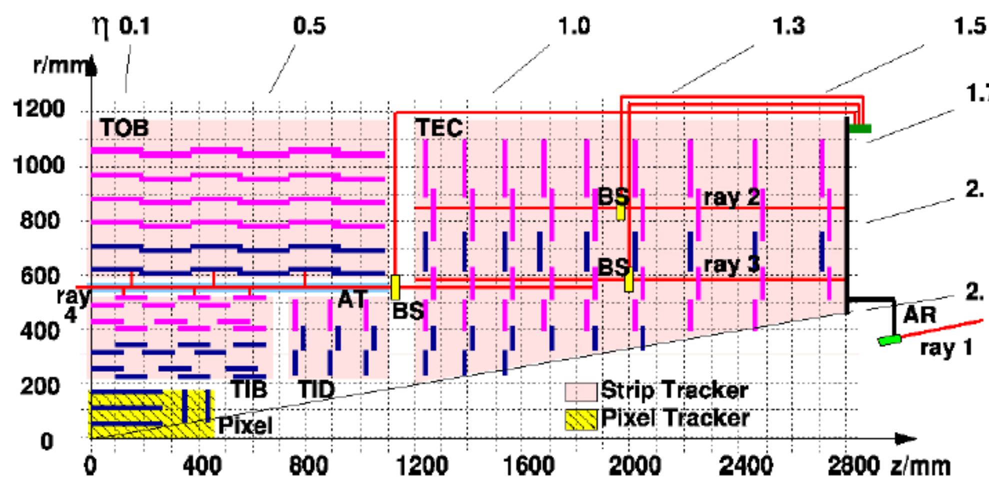


- Minimize residuals

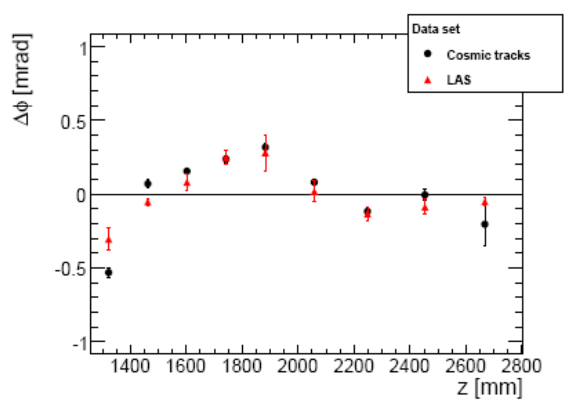
$$\chi^2(\mathbf{p}_{\text{modules}}, \mathbf{q}_{\text{tracks}}) = \sum_{i=1}^{N_{\text{residuals}}} r_i^T \mathbf{V}_i^{-1} r_i$$

Laser Alignment System (LAS)

- Goal: provide continuous position measurements of large scale structure
  - 100 μm precision standalone; 20 μm precision monitoring over time
  - Both during dedicated runs and physics data-taking
- Monitor large composite structures in TIB, TOB, TEC
- Uses laser beams to measure positions of specific sensors on particular structures
- Work ongoing to incorporate LAS measurements into track-based algorithms



- LAS vs. Track-based ϕ of TEC disks



Optical Survey of CMS Tracker

- Survey of Tracker via coordinate measurement machine, touch probe, photogrammetry, and theodolites at varying hierarchies

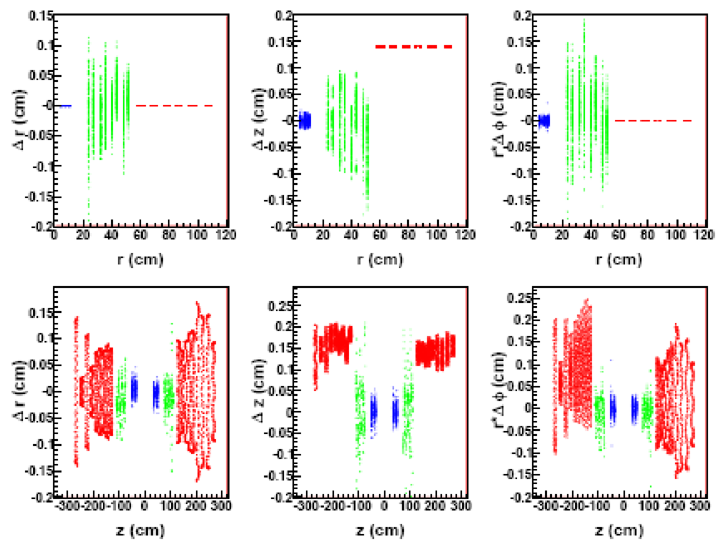
Barrels:

- PXB - modules (2D only)
- TIB - modules and up
- TOB - barrel

Endcaps:

- PXE - modules and up
- TID - modules and up
- TEC - disks and endcap

survey vs. design geometry



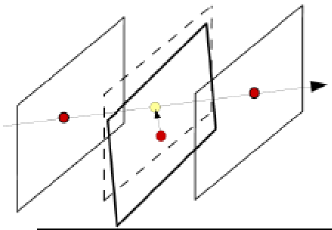
- Tracks + Survey in "local algorithm", to constrain all 6 dof:

$$\chi^2_{\mathrm{module}} = \sum_i^{\mathrm{hits}} r_i^T(\mathbf{p}_{\mathrm{m}})\mathbf{V}_i^{-1} r_i(\mathbf{p}_{\mathrm{m}}) + \sum_j^{\mathrm{survey}} r_{*j}^T(\mathbf{p}_{\mathrm{m}})\mathbf{V}_{*j}^{-1} r_{*j}(\mathbf{p}_{\mathrm{m}})$$

following BaBar implementation: NIM A 603, 467 (2009)

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 ("Hits and Impact Points")

CMS-NOTE-2006/018, NIM A 603, 467 (2009)

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

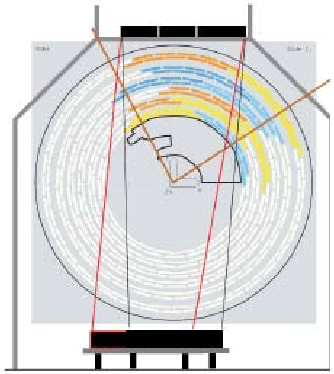
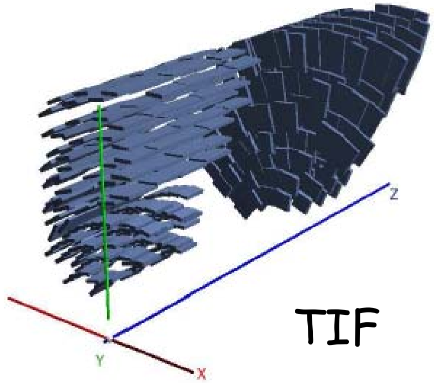
$$\Delta\mathbf{p}_{\mathrm{m}} = \left[\sum_i \mathbf{J}_i^T\mathbf{V}_i^{-1}\mathbf{J}_i\right]^{-1}\left[\sum_i \mathbf{J}_i^T\mathbf{V}_i^{-1}\mathbf{r}_i\right] \quad ; \qquad \mathbf{J}_i = \partial\mathbf{r}_i/\partial\mathbf{p}_{\mathrm{m}}$$

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

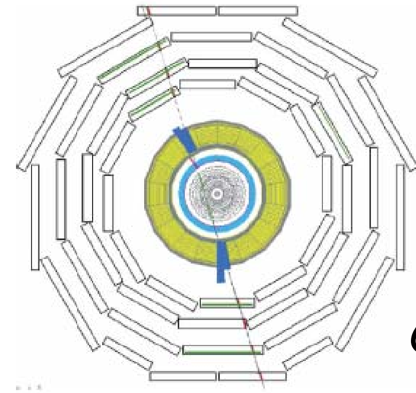
Tracker Alignment without Magnetic Field

- Partial tracker: summer 2007

Full tracker: summer 2008

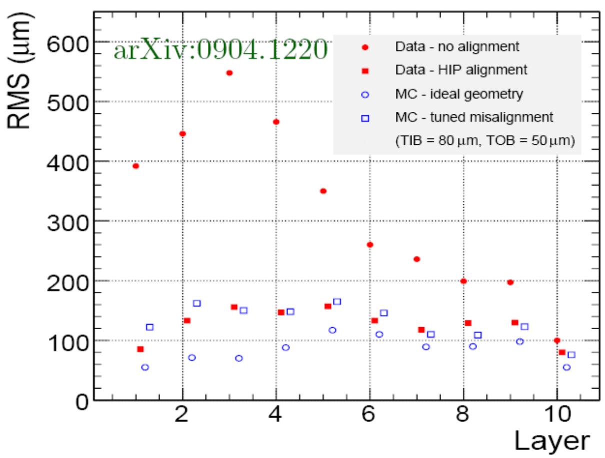
TIF

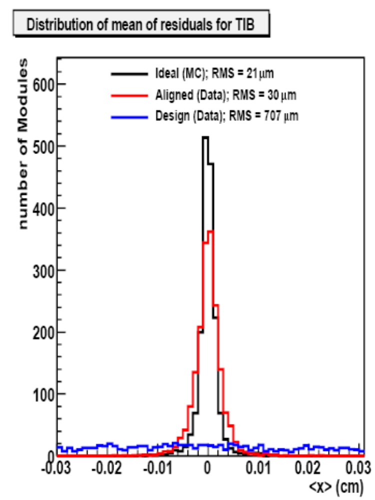


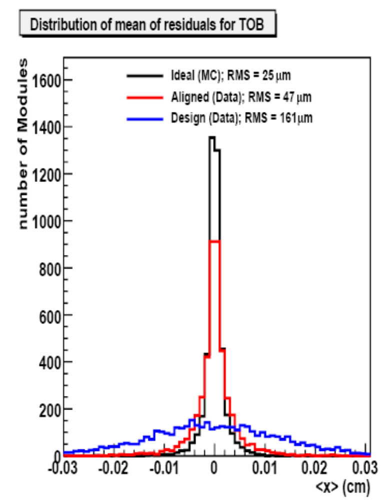
CRUZET

- ~ 50/80μm in TOB/TIB

~ 30/40μm in TOB/TIB







Tracker Alignment with Magnetic Field

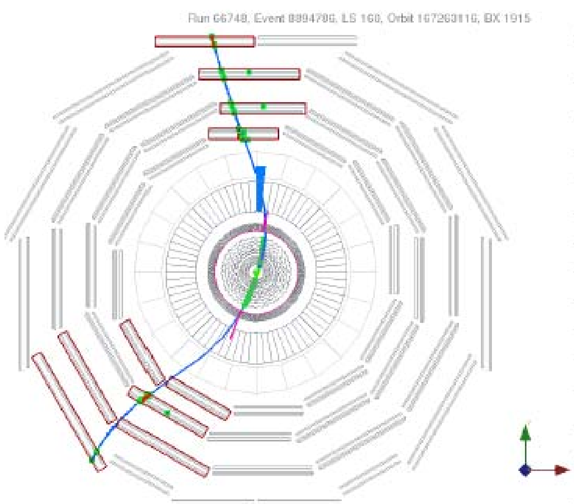
- Best data for alignment of CMS Tracker: fall 2008 ("CRAFT")

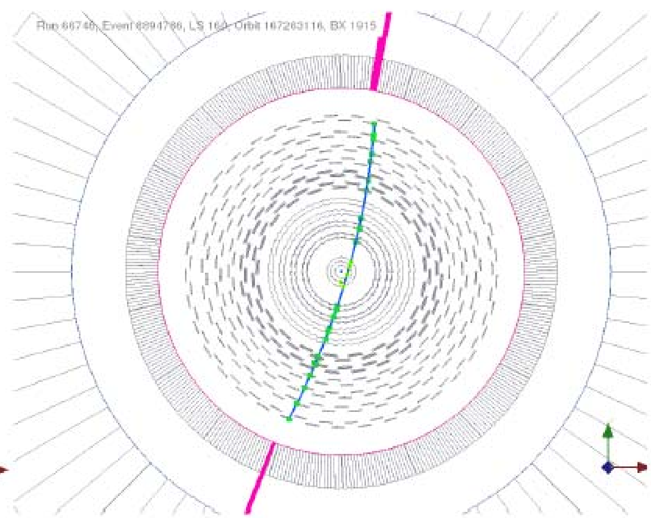
  ~ 4M cosmic tracks for Tracker alignment

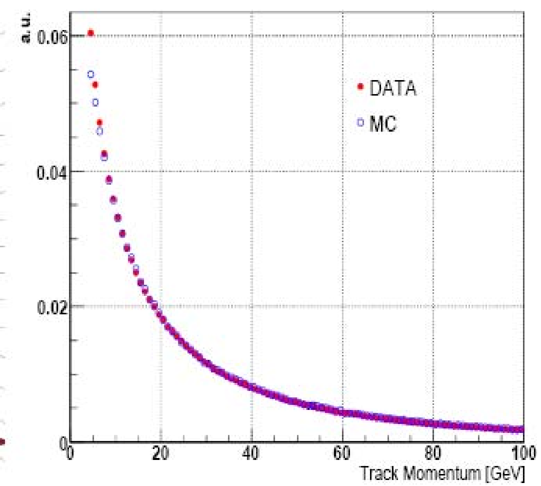
  B-field = 3.8T -> account for multiple scattering track-by-track
- Require good quality tracks and hits: p > 4 GeV/c

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

  accept all good tracks (statistics limited); only ~ 4% in pixels

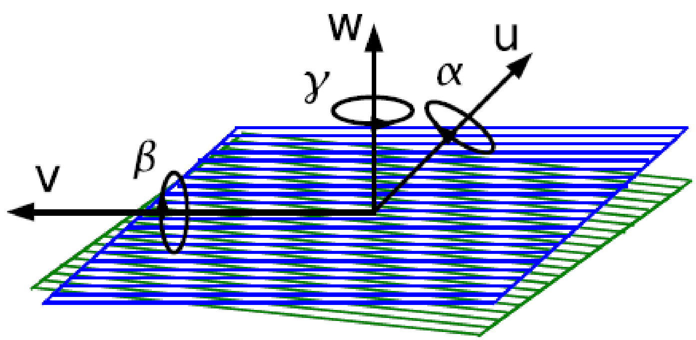


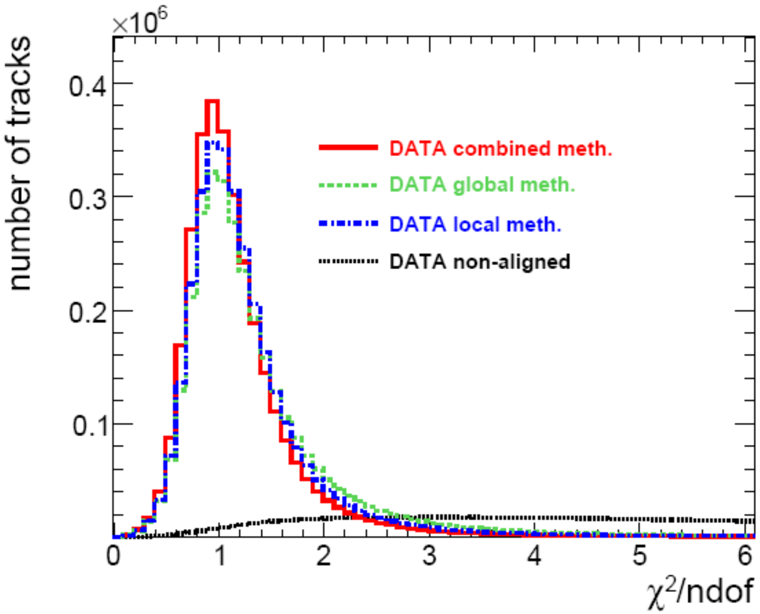




Alignment Strategy

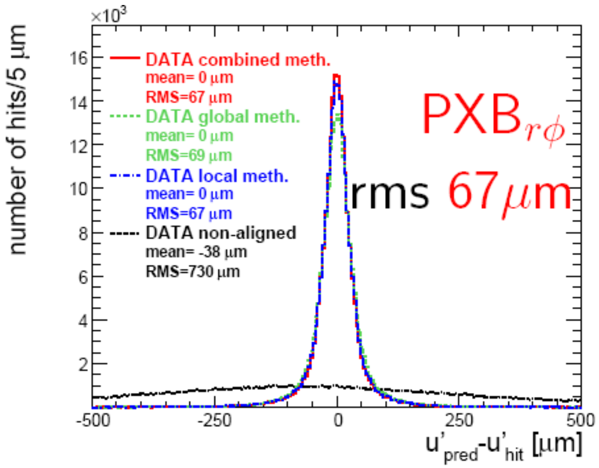
- Multi-step approach by both algorithms to address CMS geometry:
  - large structure movement: coherent v alignment of 1D modules
  - alignment of two sides of 2D strip modules (units): u, w, γ

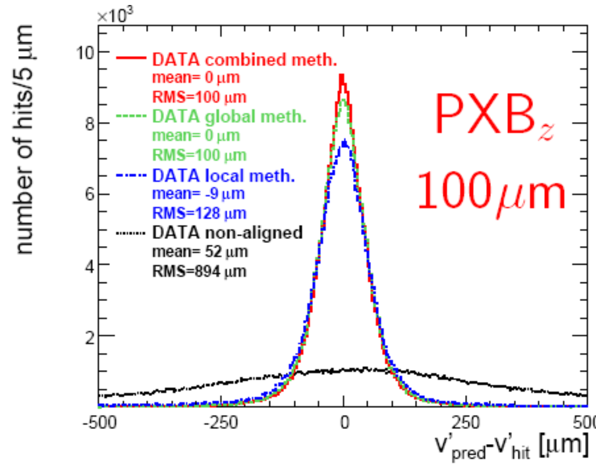




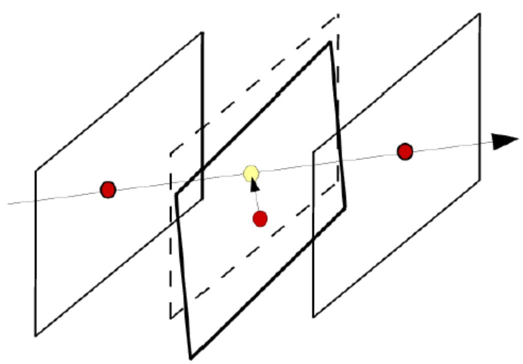
- Combined method
  (1) run global method
  -> solve good correlations quickly
  (2) run local method
  -> solve locally to match track model in all degrees-of-freedom (dof)

Example: Pixel Residuals
(local, global, combined)

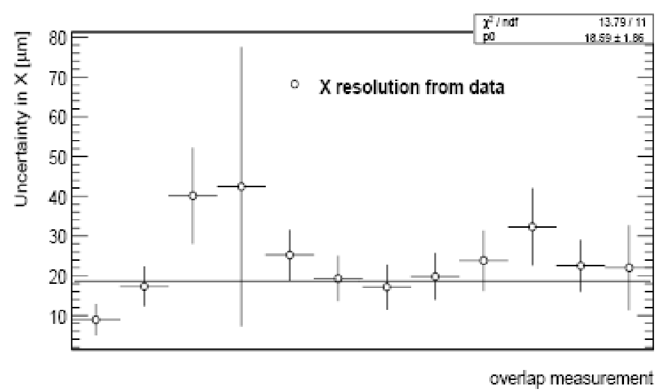




- Residuals <- multiple scattering + hit errors + alignment errors
  (random) (random) (systematic)

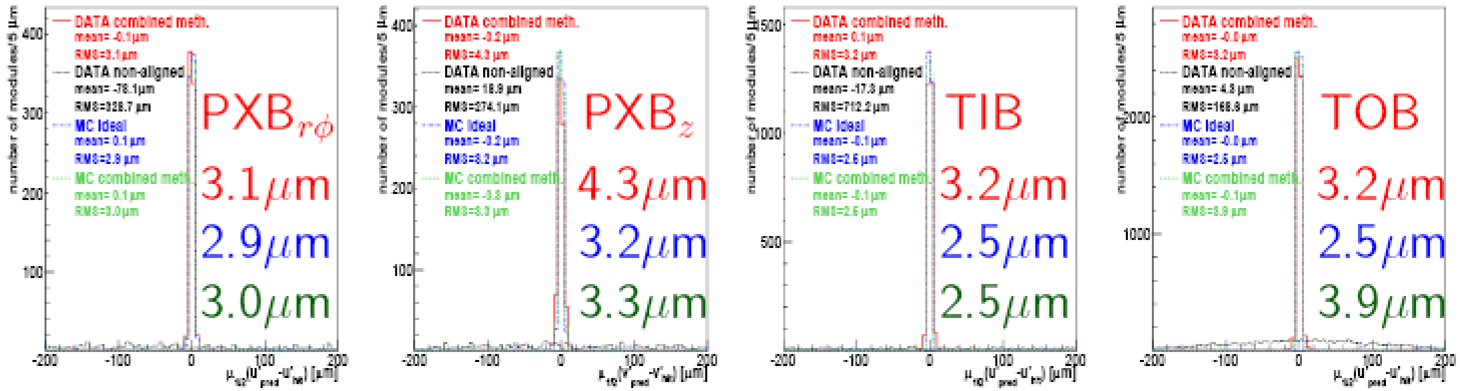


rϕ pixel hit errors ~ 19µm here

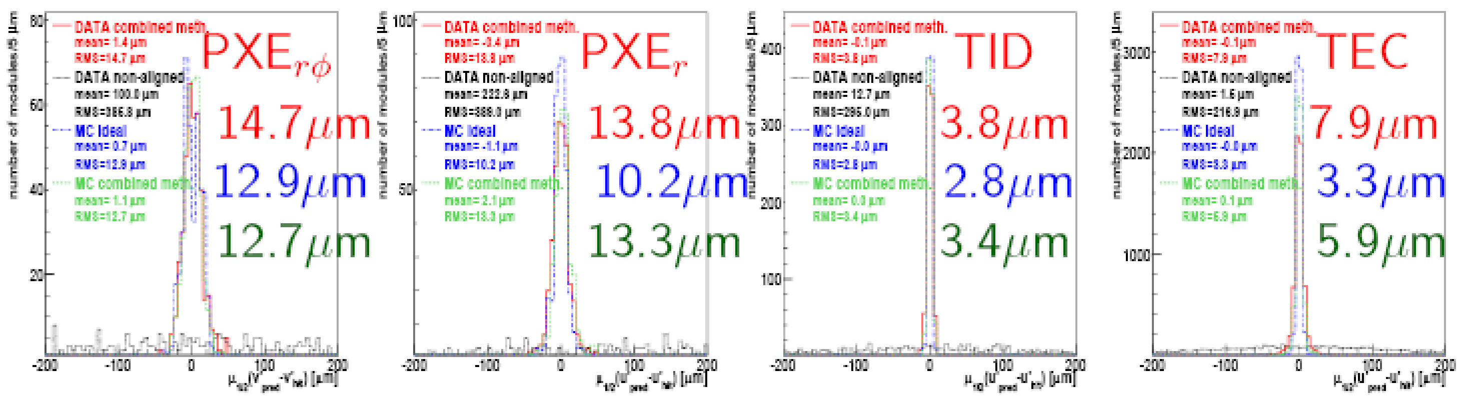


Median of the Residuals

Pixel Barrel | Strip Barrel



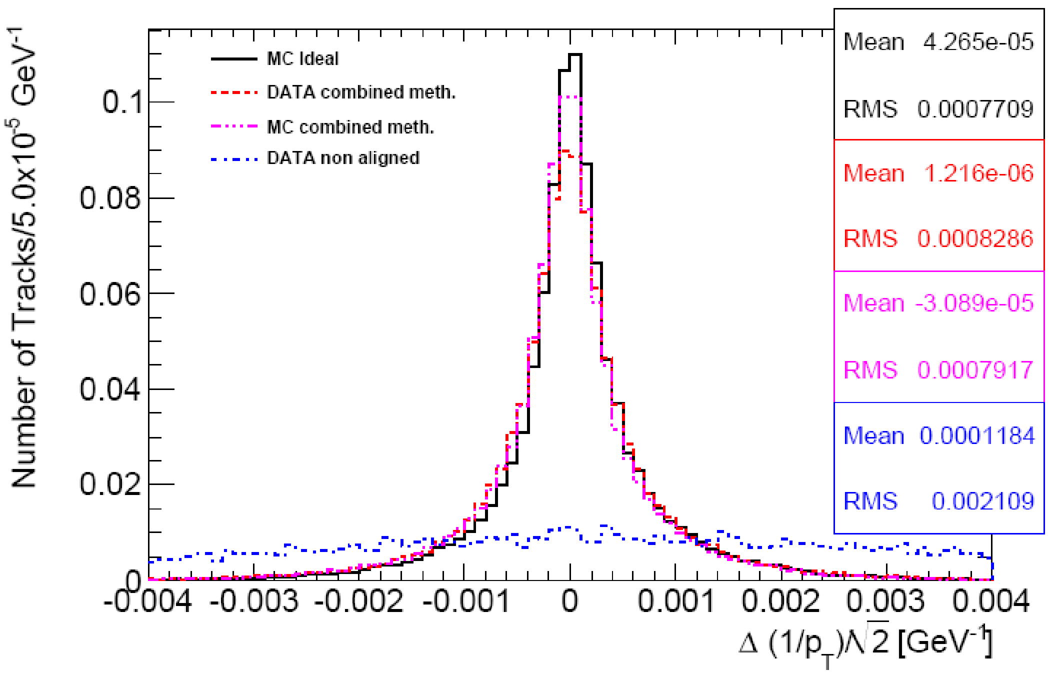
Pixel Encap | Strip Endcap

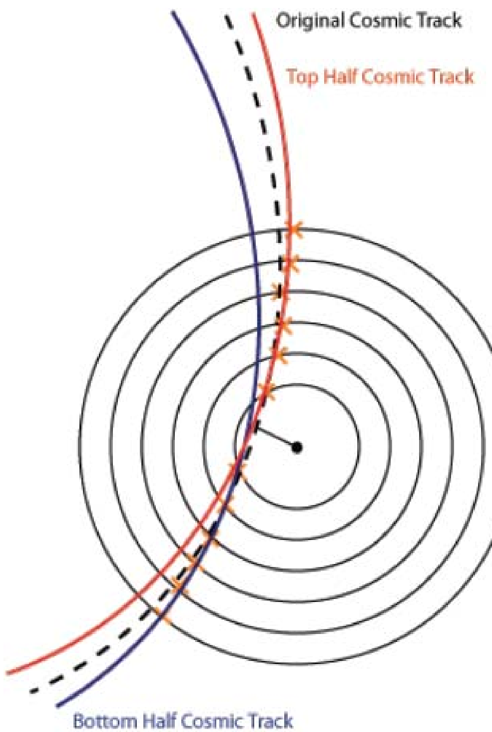


Compare aligned data to ideal MC and aligned MC

Collision-like Tracks with Cosmic

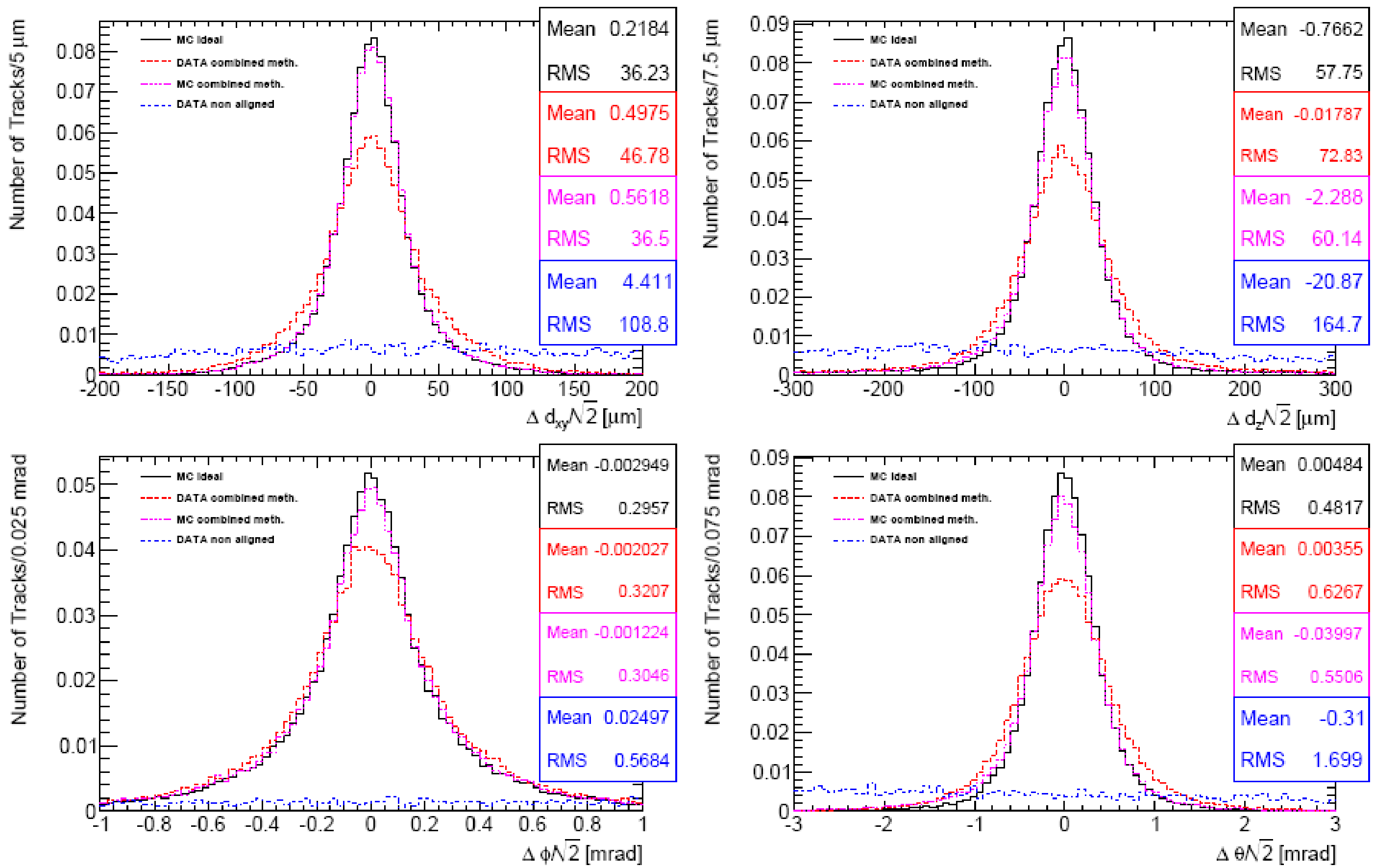
- Tracker resolution with data (require Pixel hits, near collision point)
  - compare non-aligned data -> aligned with data -> "ideal" MC
  - significant effect of alignment, also compare to aligned with MC
  - approaching ideal in momentum precision with this track sample





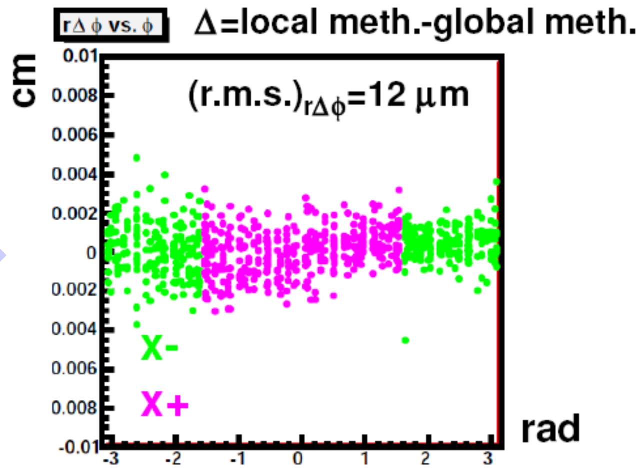
Cosmic Track Halves: four more parameters

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

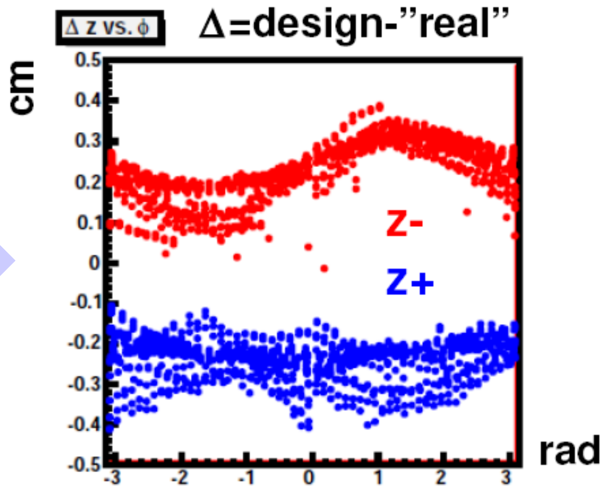


Geometry Comparison

- Compare geometries from two methods
  local vs global in PXB
  (χ^2-invariant deformations removed)
  2D measurements, small lever arm



- Compare the "real" (from combined method) to design geometry
  - TIB: 5 mm shift of the two HalfBarrels along z-axis (two halves shifted apart)
  - confirmed by optical survey



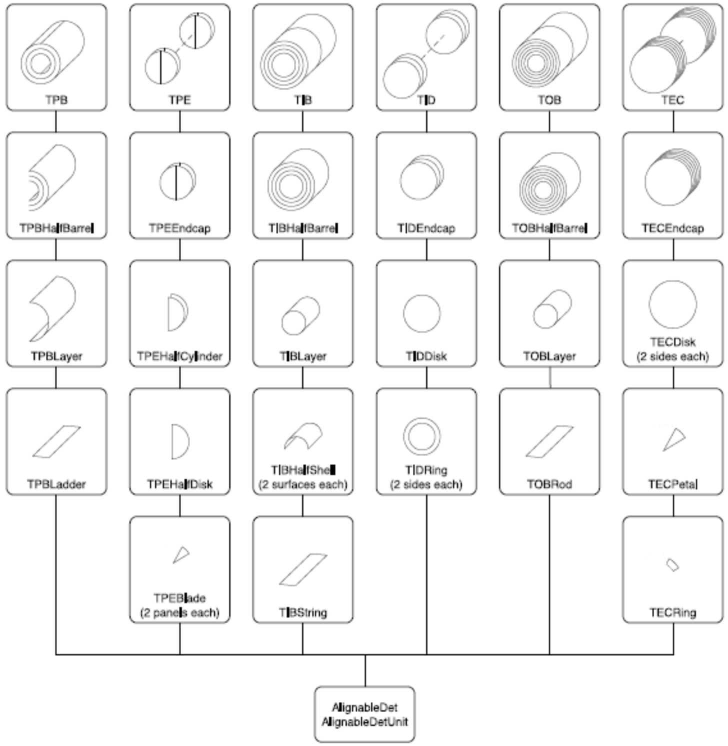
Monte Carlo Studies: Misalignments

- CMS has a very powerful, realistic misalignment model necessary for studying misalignment impact on physics analyses

- Necessary to understand assembly precision of full detector hierarchy

- Create misalignment scenarios based on expectations:
  - "hardware" only "SurveyLASOnly"
  - "Startup-2008" before collisions "SurveyLASCosmics" (based on 2008 info)
  - 10 pb^{-1}
  - 100 pb^{-1} (roughly data expected in 2009-2010 LHC run)
  - "ideal" best possible alignment

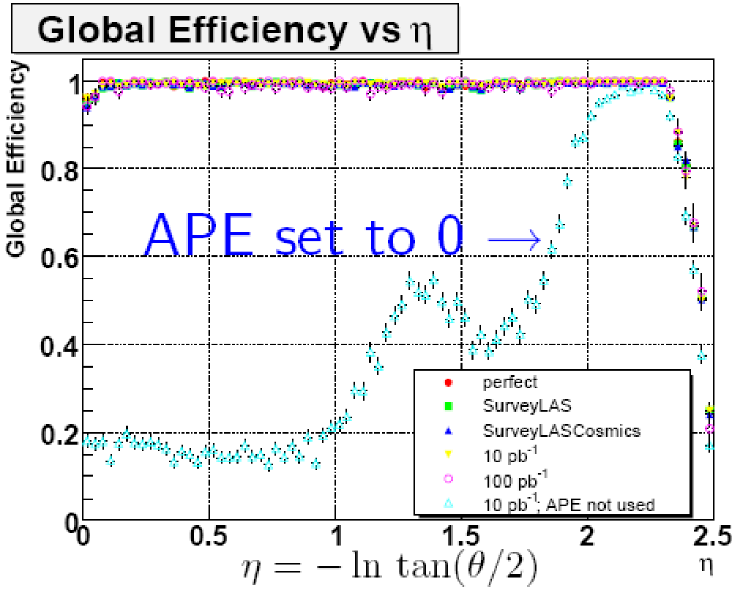
Full tracker hierarchy

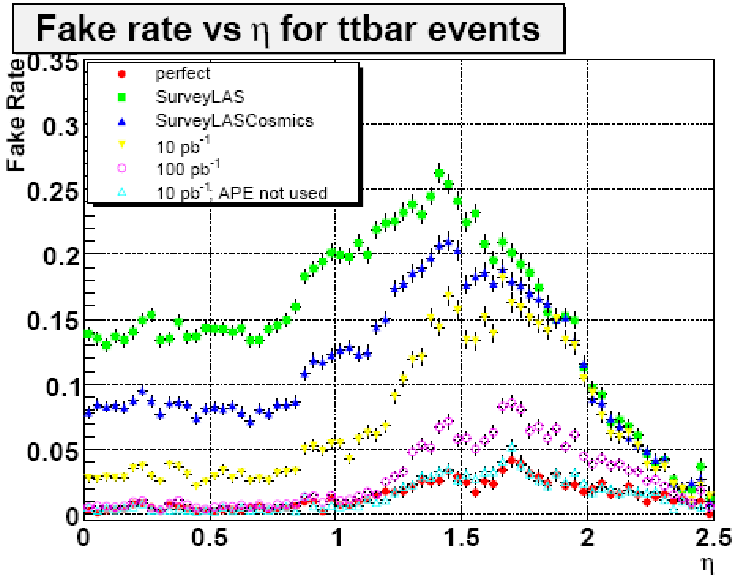


No systematic distortions studied (χ^2-invariant deformations)

Impact on Tracking

- Alignment position error (APE) added to hit/track uncertainties
- Using proper APE, full track-finding efficiency recovered
- Increasing APE to recover efficiency increases fake rate



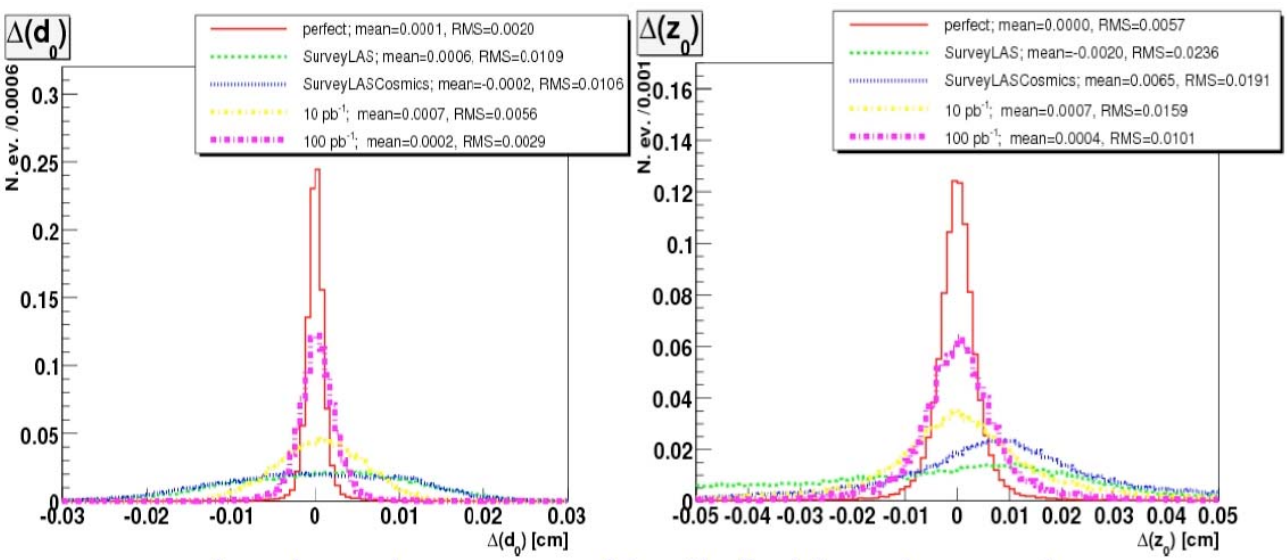


Impact on Tracking

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

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

- d_0 and z_0 highly affected by barrel pixel misalignment
  - Large barrel pixel misalignments in 'SurveyLASOnly' and 'SurveyLASCosmics'

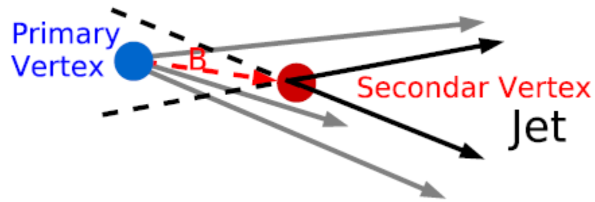


d_0 and z_0 - transverse and longitudinal impact parameters

Monte Carlo Studies: b-tagging

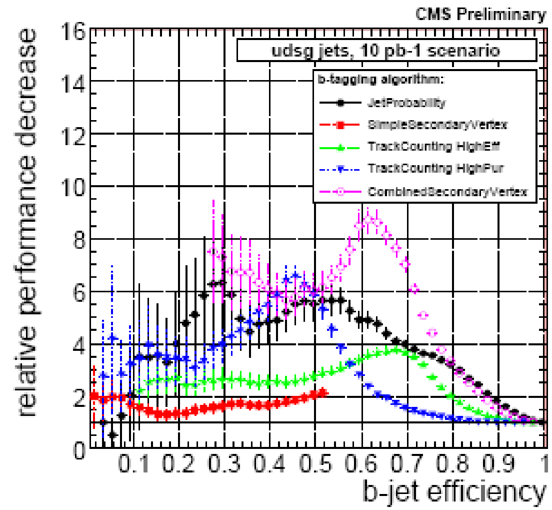
- Many New Physics models:

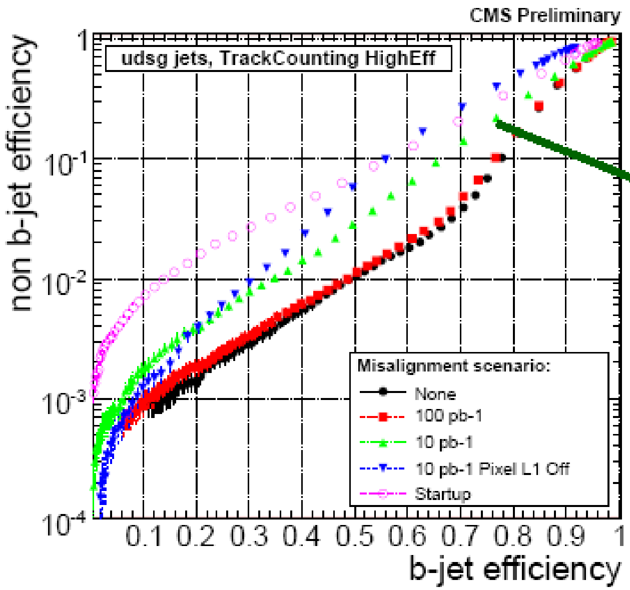
  t -> b displaced vertex ($c\tau_b \approx 450\ \mu m$)



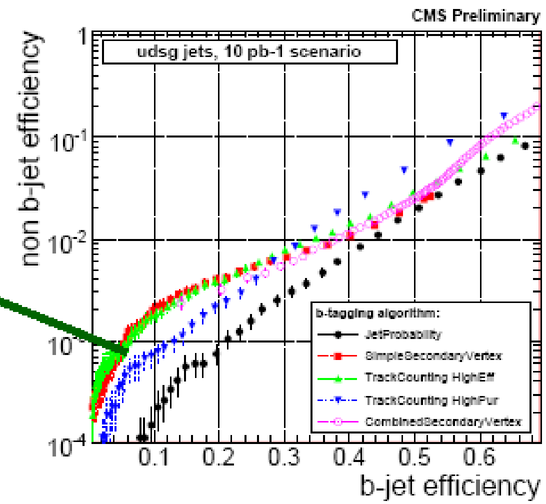
- all b-tag alignment sensitive

- approaching "ideal" at "100/pb"





10/pb
TrackCounting alg.



Monte Carlo: Example of a Discovery Reach

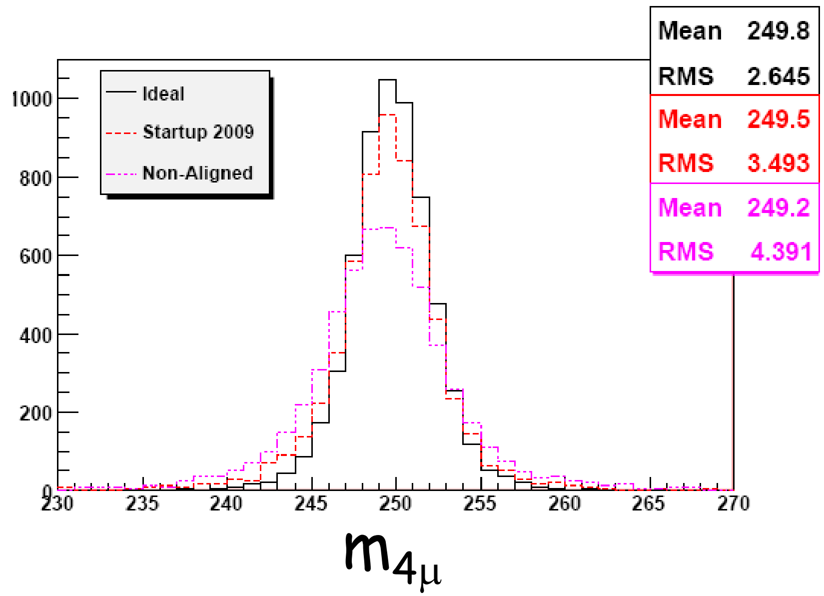
- Reconstruct narrow X -> ZZ -> 4μ, 4e, 2e2μ

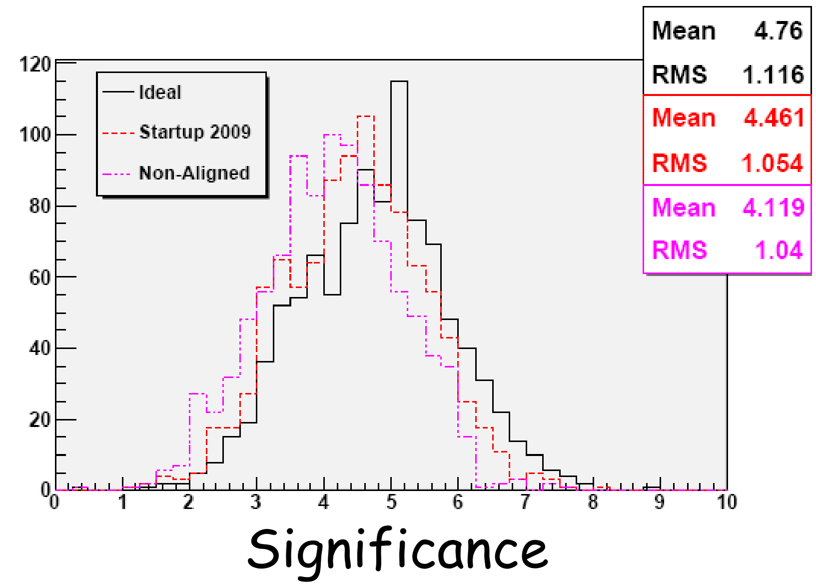
  joint likelihood fit analysis as an example

  test 5/fb at Higgs production rate

  "non-aligned" -> "startup" -> "ideal" ⇒ makes a difference for discovery

  - width 4.4 -> 3.5 -> 2.6 GeV (in 4μ, but in 4e little effect)
  - significance 4.1 -> 4.5 -> 4.8 σ from $\sqrt{2\ln(\mathcal{L}_{s+b}/\mathcal{L}_b)}$

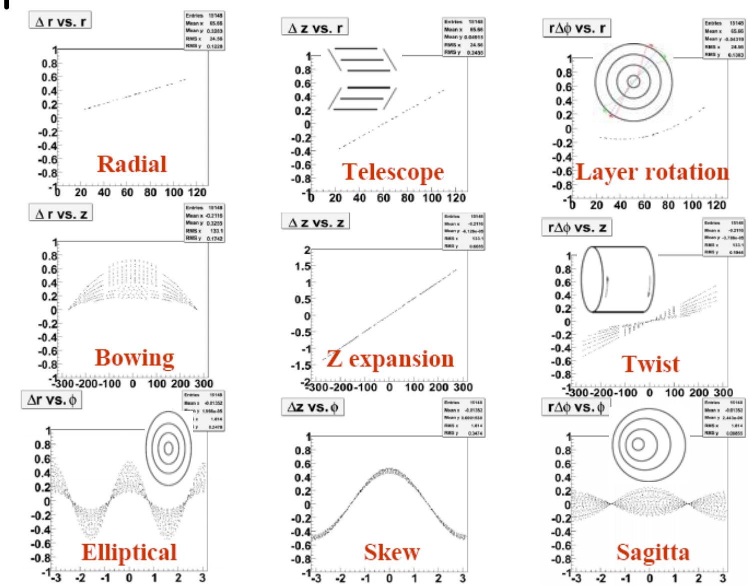




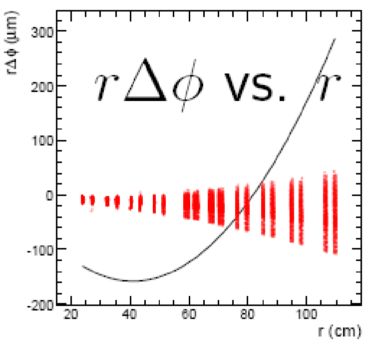
Systematic Misalignments

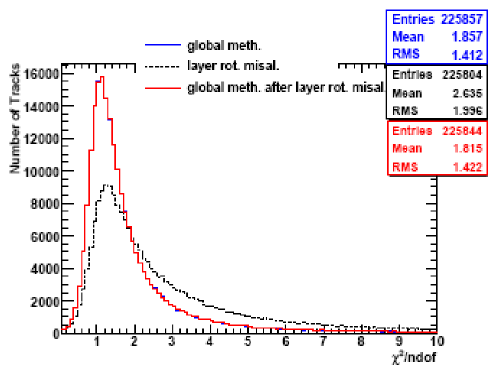
- Systematic distortions of the Tracker
  - may be χ^2 invariant
  - may introduce physics bias

  e.g. charge bias with layer rotation

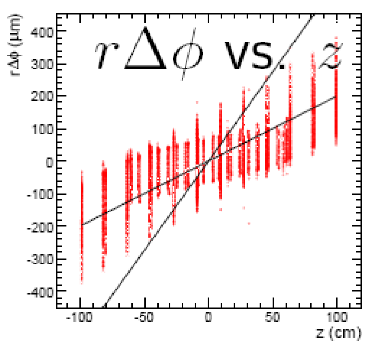


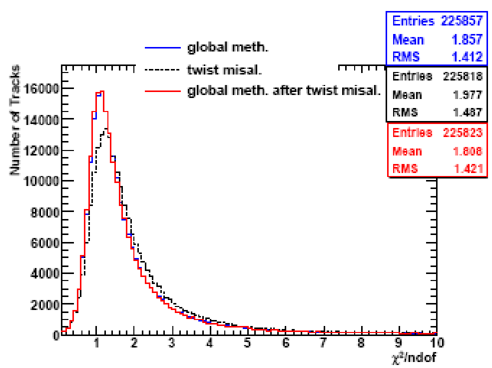
$(\Delta r,\ \Delta z,\ r\Delta\phi)$ vs. $(r,\ z,\ \phi)$





layer rotation recovered in alignment

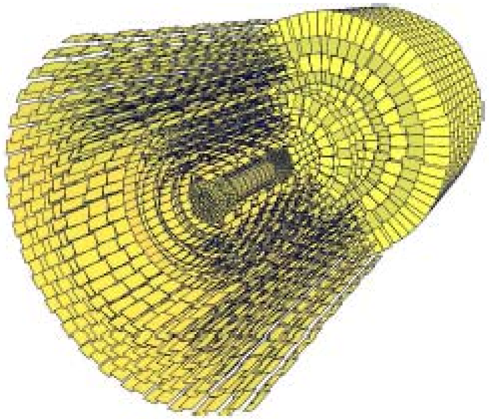




twist and some others harder with cosmics alone

Summary

- CMS Tracker alignment:
  - challenging task (16588 elements)
  - successful CMS run with cosmics
  - complementary statistical methods
    best combination of global and 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