CMS Tracker Alignment and RECO

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OUTLINE

- Input to CMS Tracker alignment algorithms:

  - Laser Alignment System
  - optical survey
  - tracks from cosmic muon runs -> ultimate precision

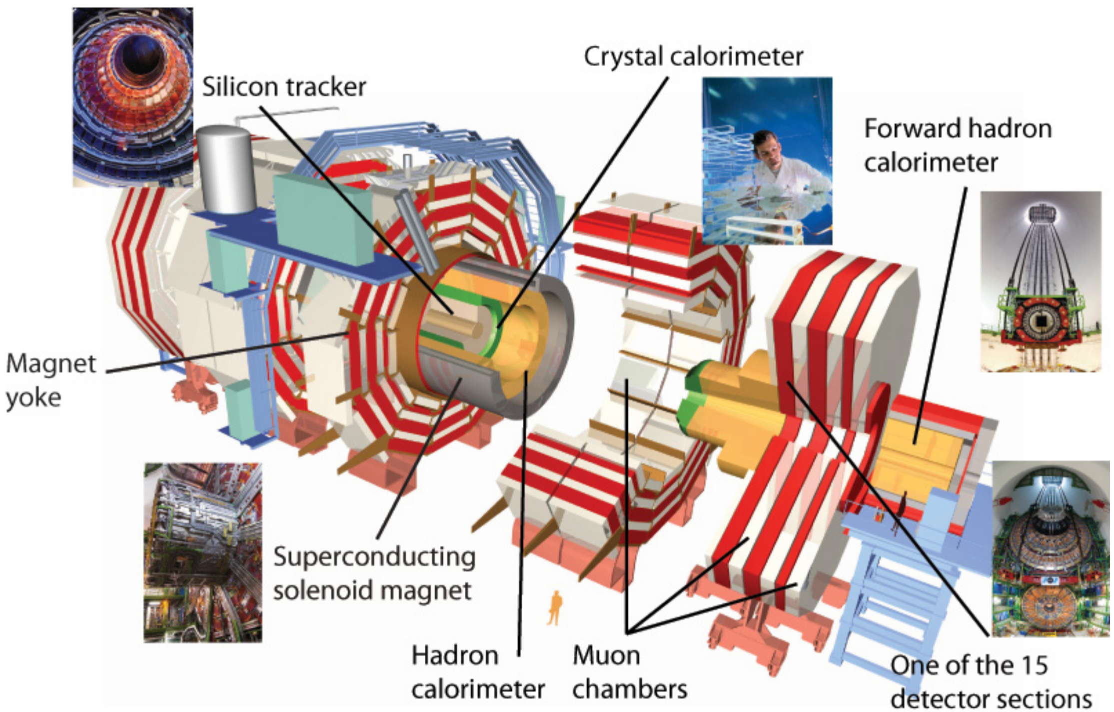
  Tracker Integration Facility (TIF) with partial Tracker in 2007
  CMS at LHC Point-5 ("CRAFT" cosmic run) with full Tracker in 2008

- Alignment results with cosmic muons and validation

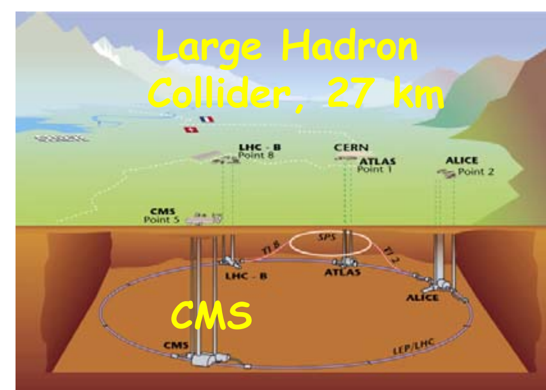
- Alignment implications for physics performance
  and some on systermatics

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

Tracker in the CMS detector

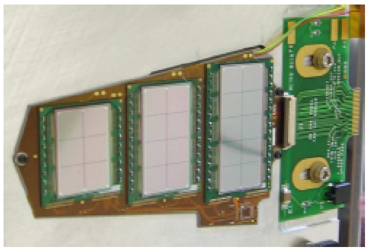


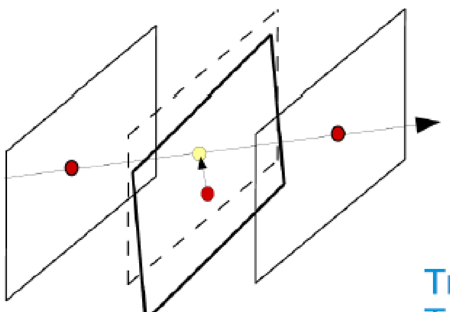
CMS Tracker
1440 Si Pixel
15148 Si Strip modules

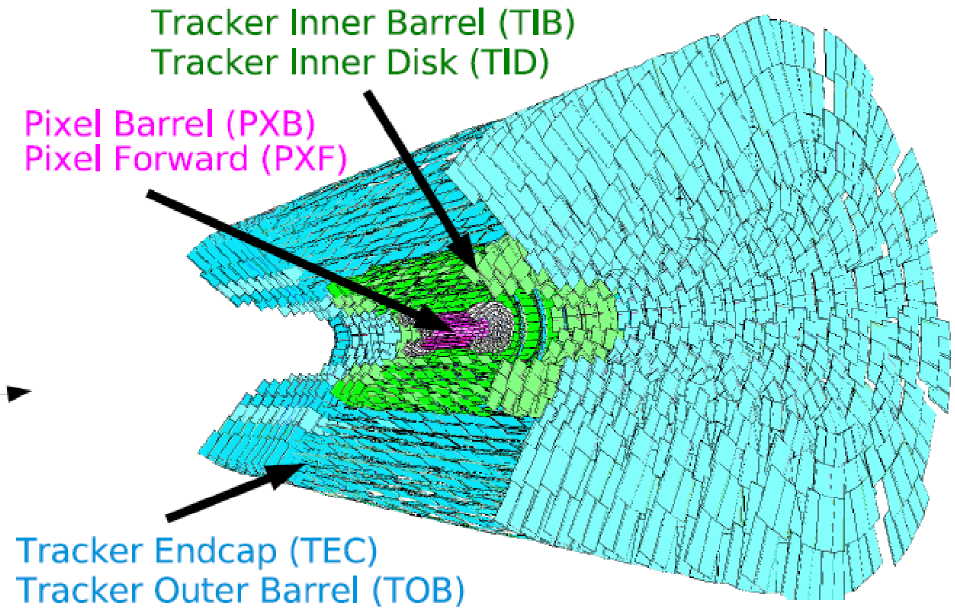


CMS Tracker Alignment Goal

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



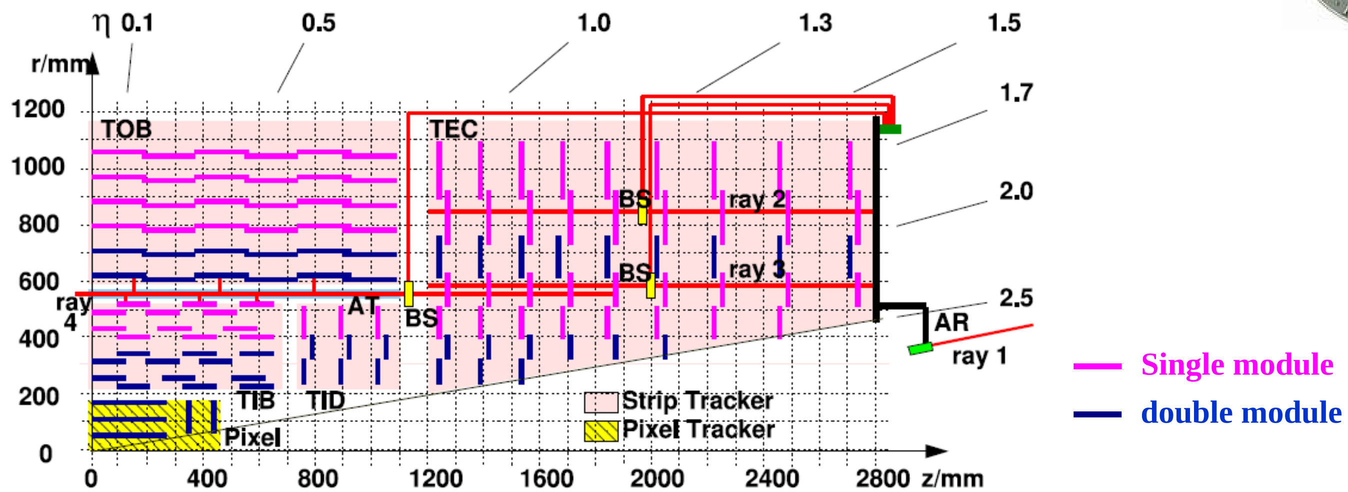


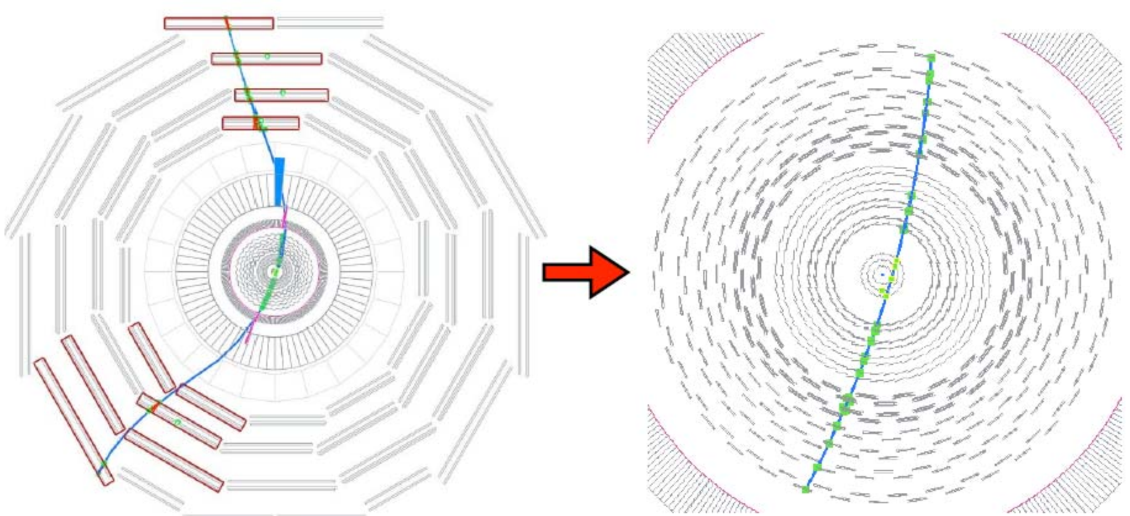


- Minimize residuals

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

Tracker Commissioning with Cosmic Rays





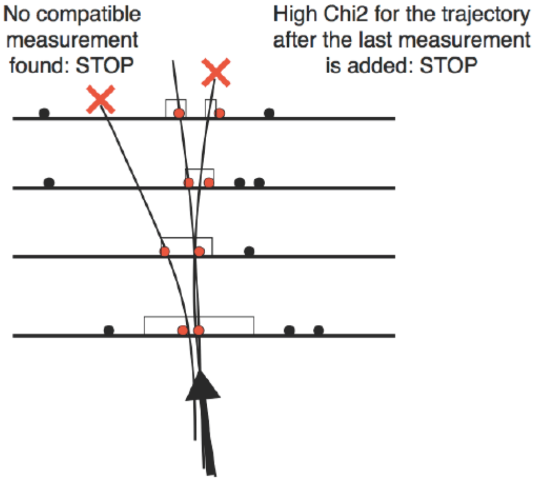
Track Reconstruction

- Charged track reconstruction includes three essential steps: seed finding, pattern recognition, and track fitting

- Three algorithms are employed on CMS:
  - Combinatorial Track Finder (CTF): default tracking algorithm for pp collisions with seeding modified for cosmic reconstruction
  - Cosmic Track Finder (CosmicTF): dedicated cosmic reconstruction algorithm
  - RoadSearch (RS): alternative algorithm for collisions, modified for cosmics

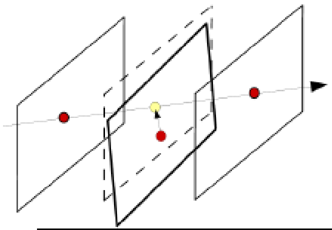
Kalman-filter approach used to build the track by extrapolating the track layer-by-layer, adding compatible hits at each layer, and updating the track parameters

Trajectory building stops when no more hits can be added or the trajectory has reached the end of the tracker



Statistical methods in CMS Tracker Alignment

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



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

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)

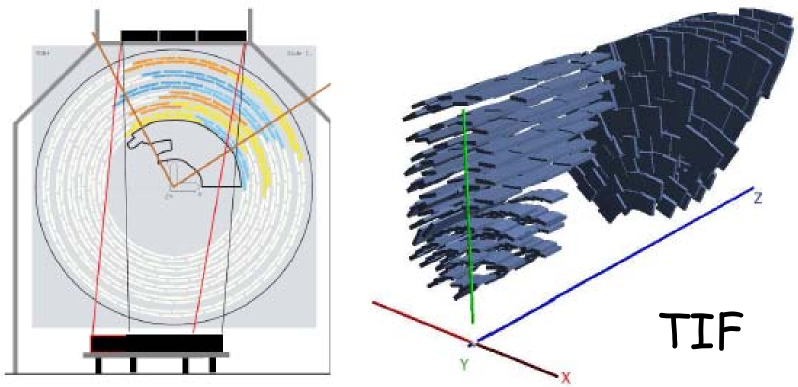
$$\chi^2_{\text{module}} = \sum_i^{\text{hits}} \mathbf{r}_i^T(\mathbf{p}_\mathrm{m})\mathbf{V}_i^{-1}\mathbf{r}_i(\mathbf{p}_\mathrm{m}) + \sum_j^{\text{survey}} \mathbf{r}_{*j}^T(\mathbf{p}_\mathrm{m})\mathbf{V}_{*j}^{-1}\mathbf{r}_{*j}(\mathbf{p}_\mathrm{m})$$

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

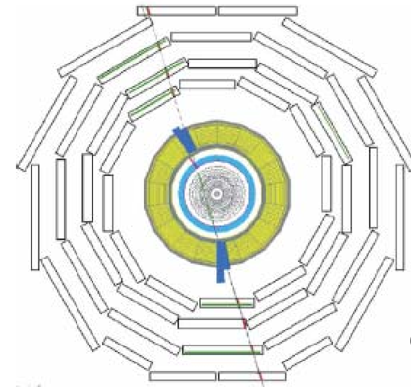
pros	full Kalman Filter track model	simple implementation, all dof
cons	ignore correlations in one iteration	large CPU with many iterations

Tracker Alignment without Magnetic Field

- Partial tracker: summer 2007 — Full tracker: summer 2008

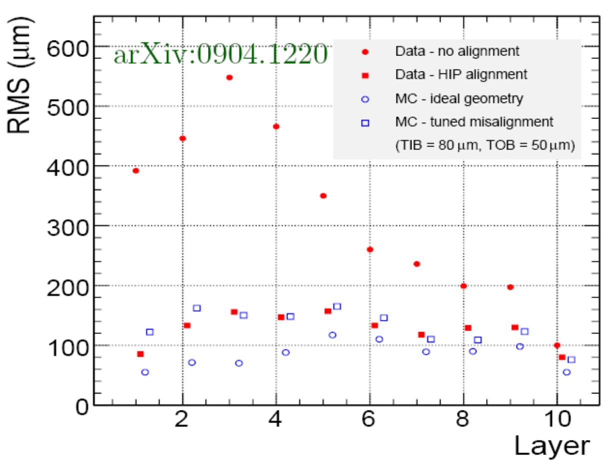


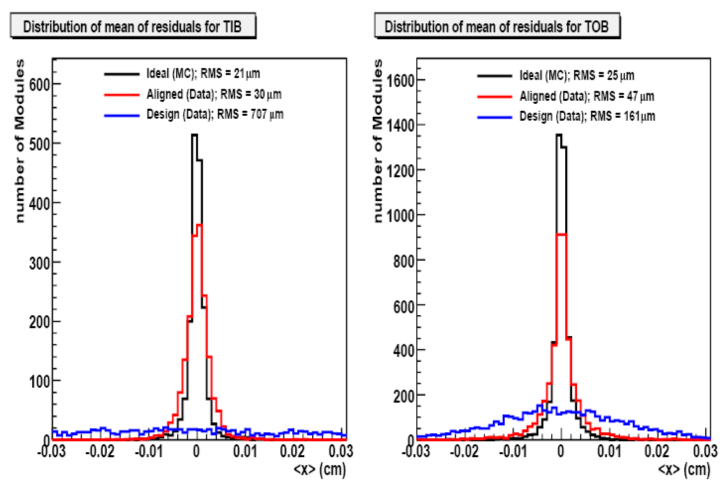
TIF



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”)

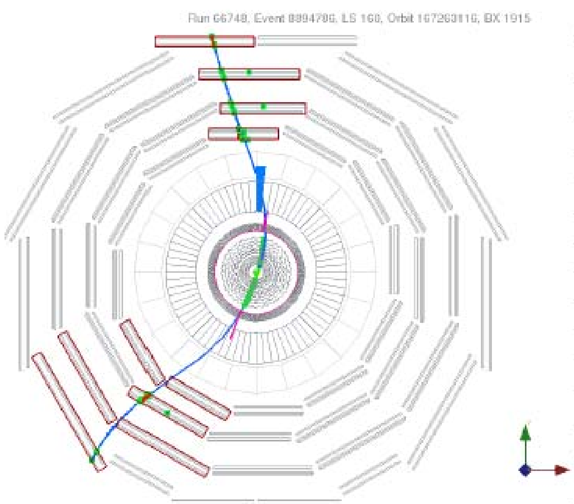
  ~ 4M cosmic tracks for Tracker alignment

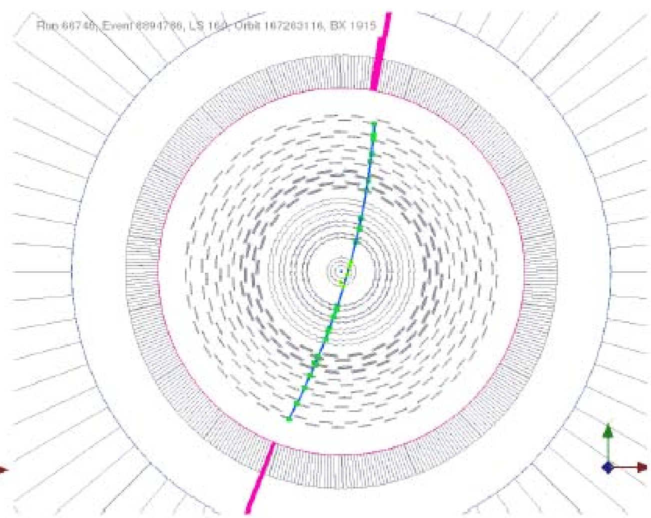
  B-field = 3.8T -> account for multiple scattering track-by-track

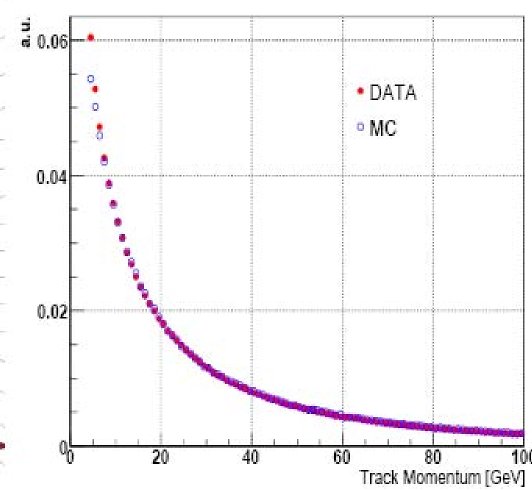
- Require good quality tracks and hits: $p > 4$ GeV/c

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

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

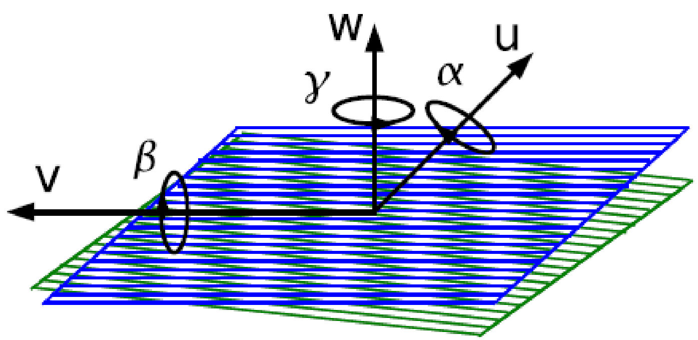


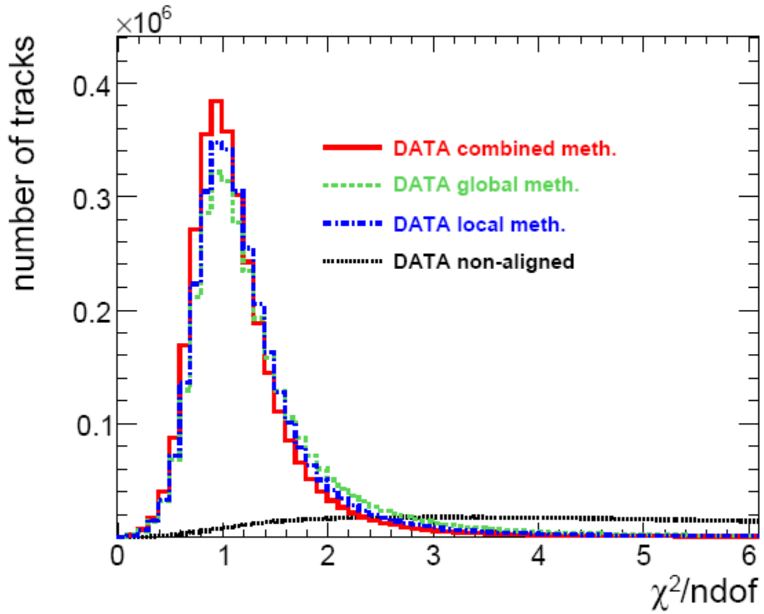




Alignment Strategy

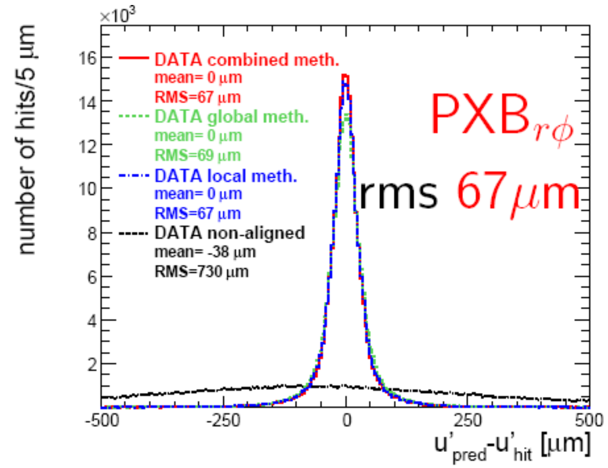
- Multi-step approach by both algorithms to address CMS geometry:
  - large structure movement: coherent v alignment of 1D modules
  - alignment of two sides of 2D strip modules (units): u, w, γ

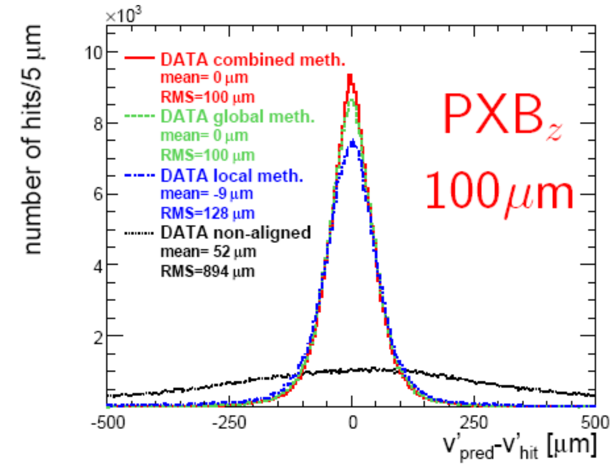




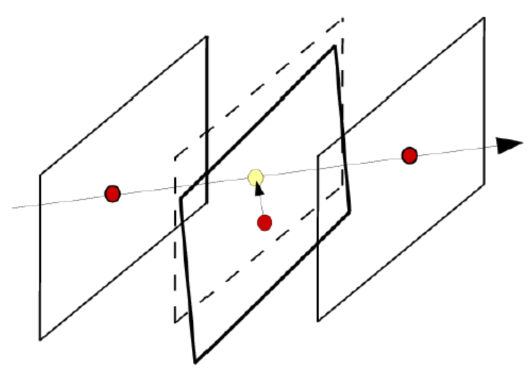
- Combined method
  (1) run global method
  -> solve good correlations quickly
  (2) run local method
  -> solve locally to match track model in all degrees-of-freedom (dof)

Example: Pixel Residuals
(local, global, combined)

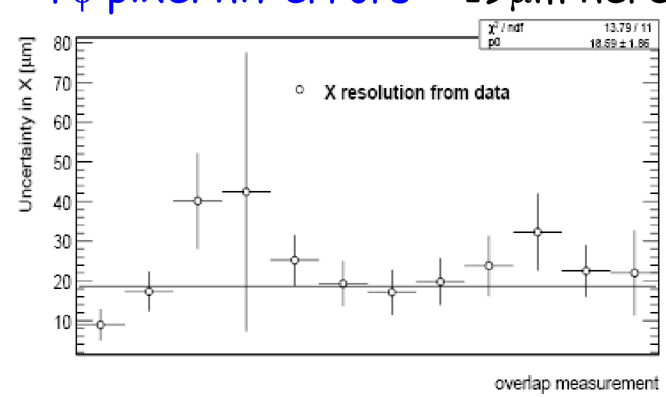




- Residuals <- multiple scattering + hit errors + alignment errors
  (random) (random) (systematic)

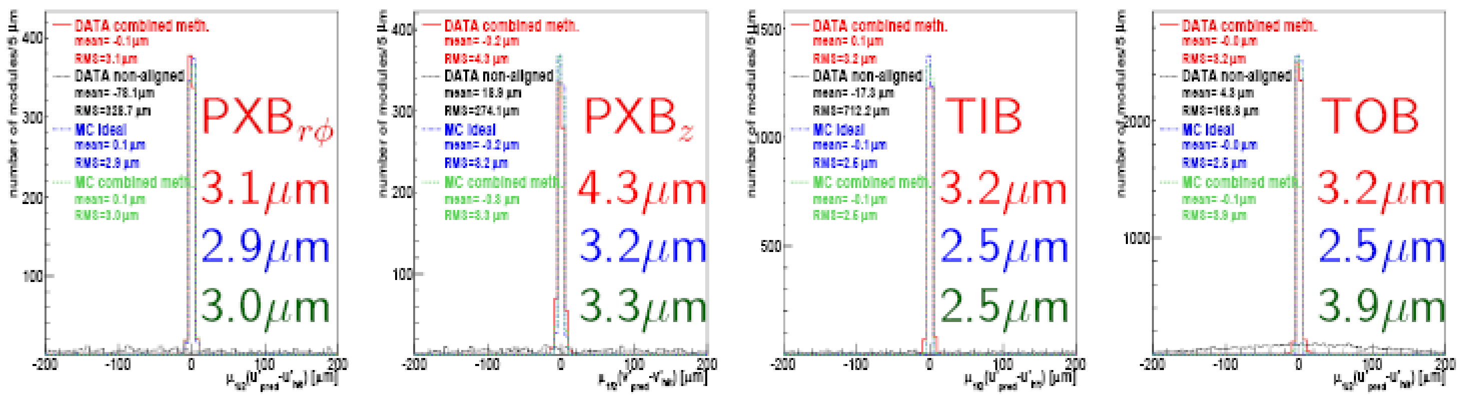


rφ pixel hit errors ~ 19µm here

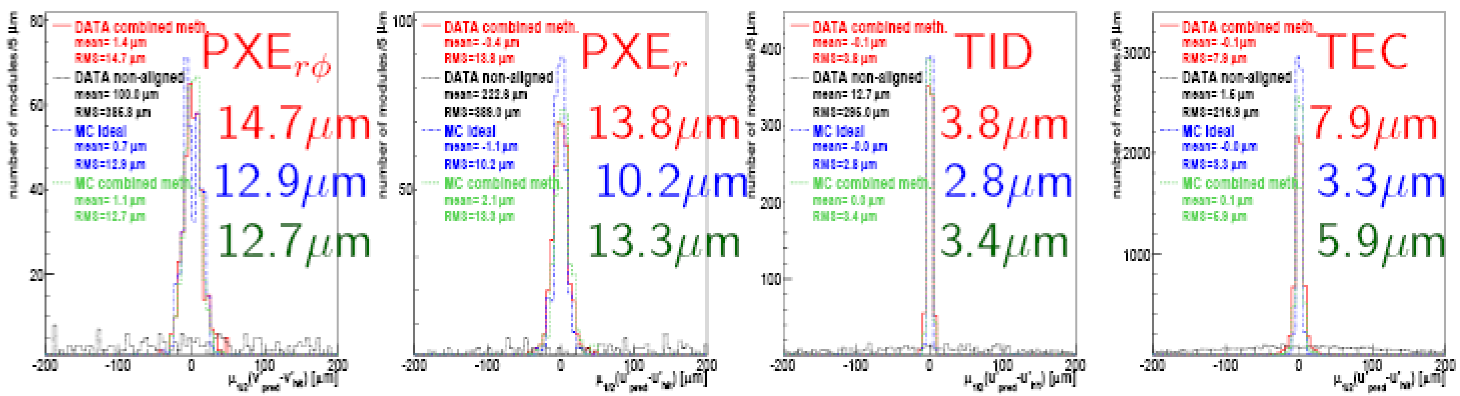


Median of the Residuals

Pixel Barrel Strip Barrel



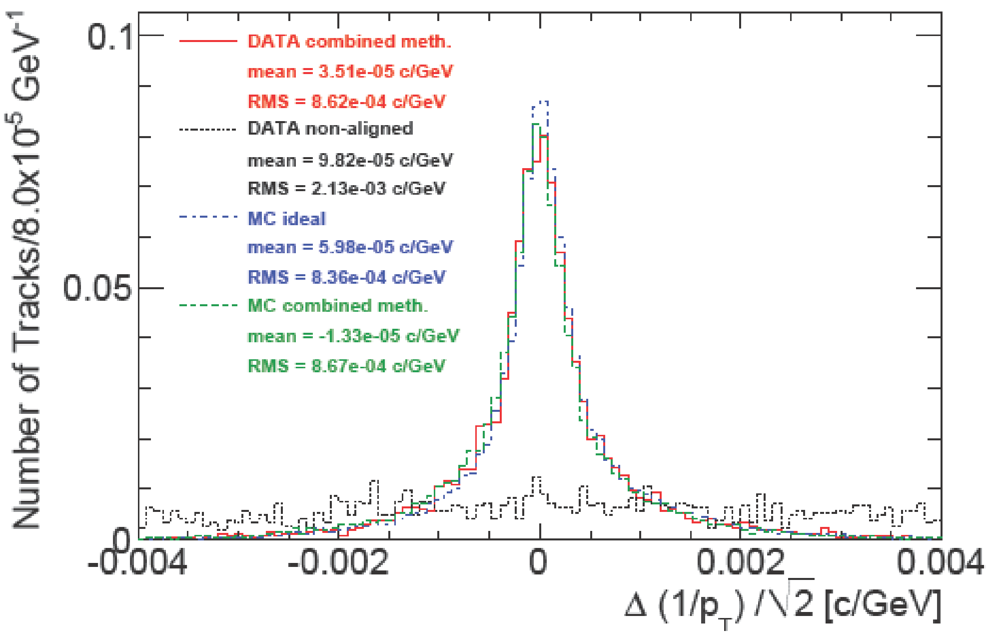
Pixel Encap Strip Endcap

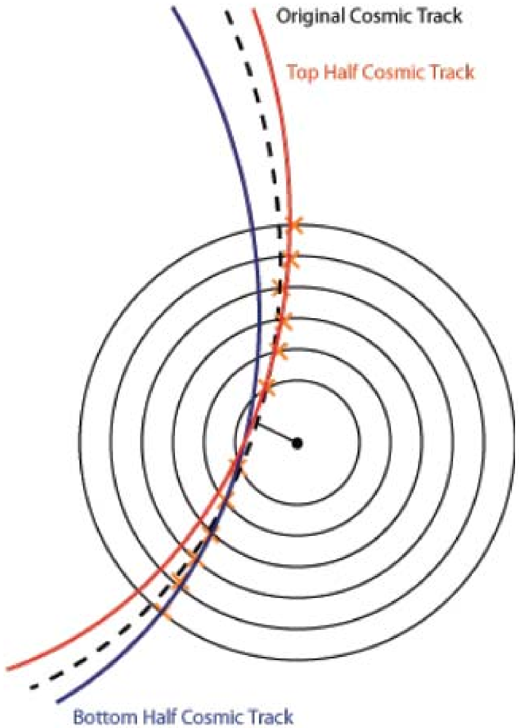


Compare aligned data to ideal MC and aligned MC

Collision-like Tracks with Cosmic

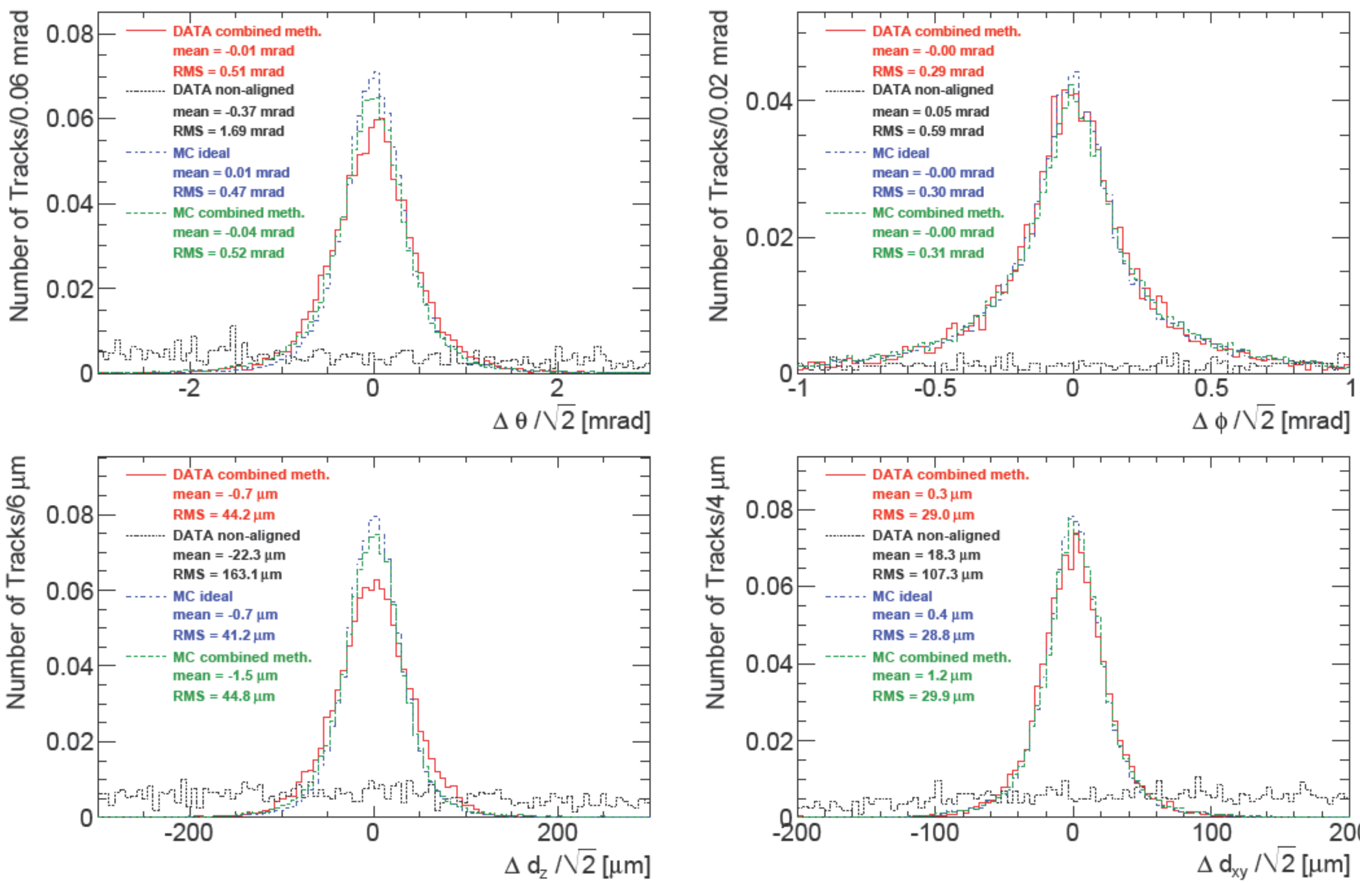
- Tracker resolution with data (require Pixel hits, near collision point)
  - compare non-aligned data -> aligned with data -> “ideal” MC
  - significant effect of alignment, also compare to aligned with MC
  - approaching ideal in momentum precision with this track sample





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



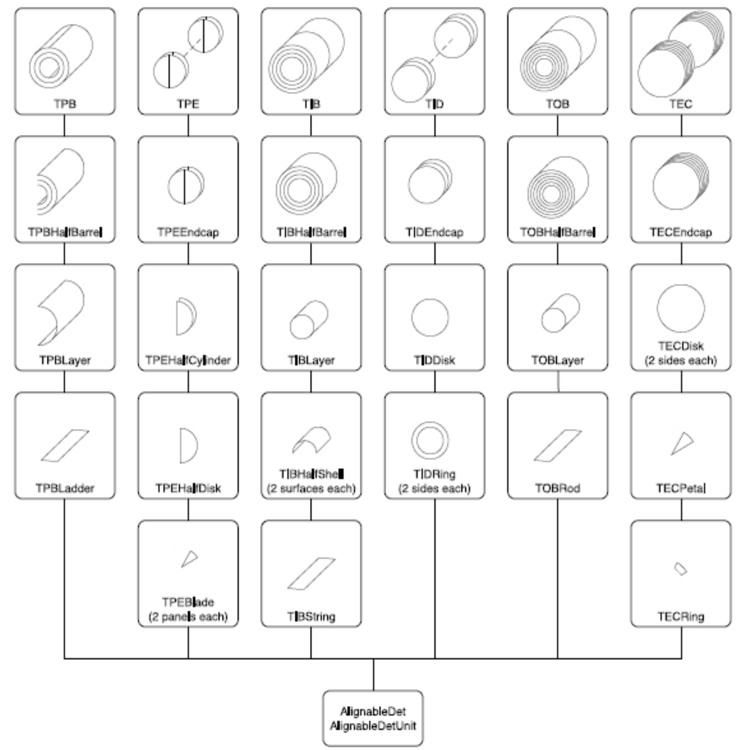
Monte Carlo Studies: Misalignments

- 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

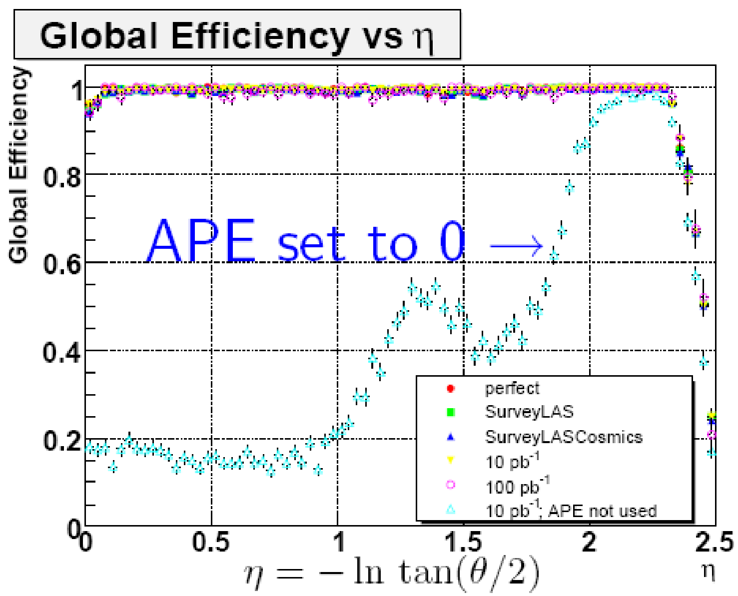
Full tracker hierarchy

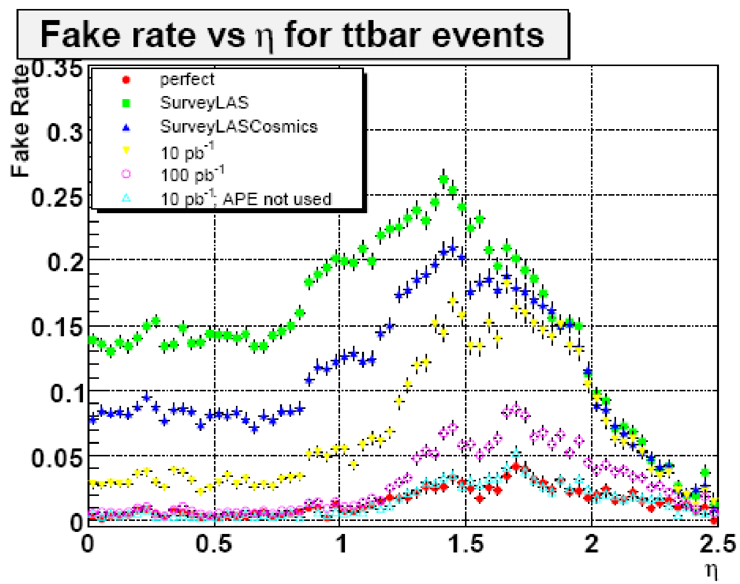


No systematic distortions studied
(χ^2-invariant deformations)

Impact on Tracking

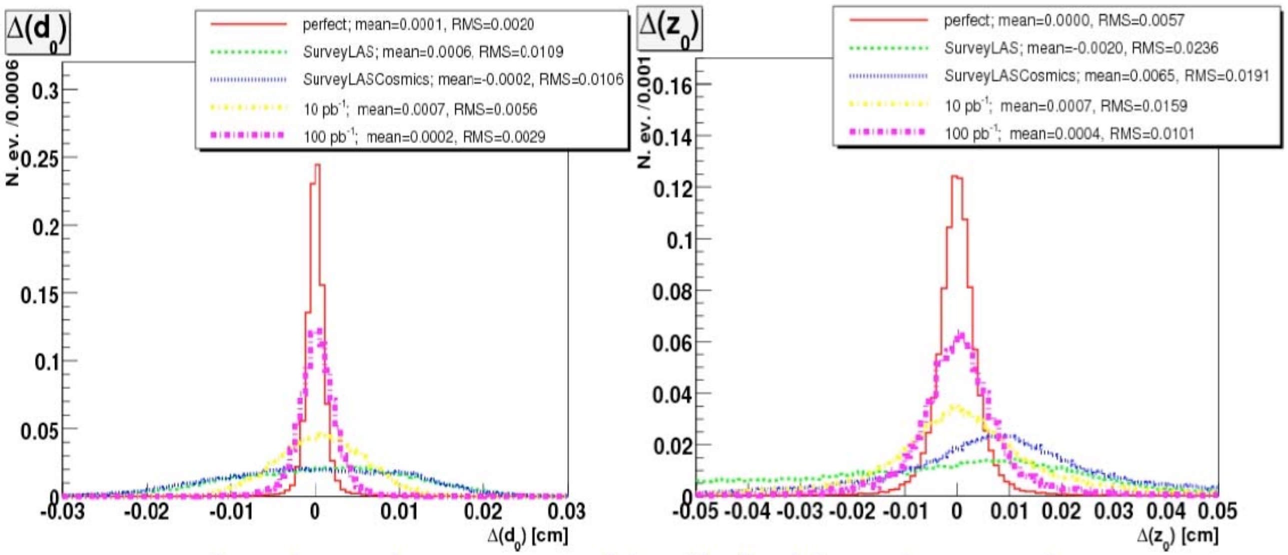
- Alignment position error (APE) added to hit/track uncertainties
- Using proper APE, full track-finding efficiency recovered
- Increasing APE to recover efficiency increases fake rate





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'

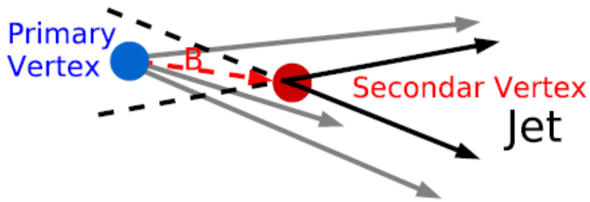


d_0 and z_0 - transverse and longitudinal impact parameters

Monte Carlo Studies: b-tagging

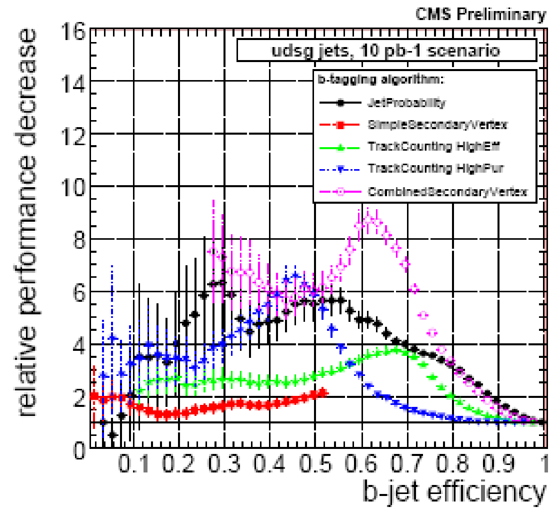
- Many New Physics models:

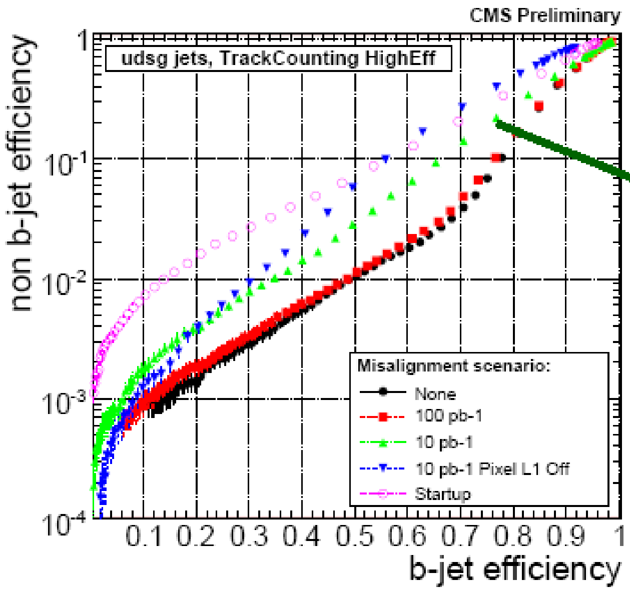
  t -> b displaced vertex ($c\tau_b \approx 450\ \mu m$)



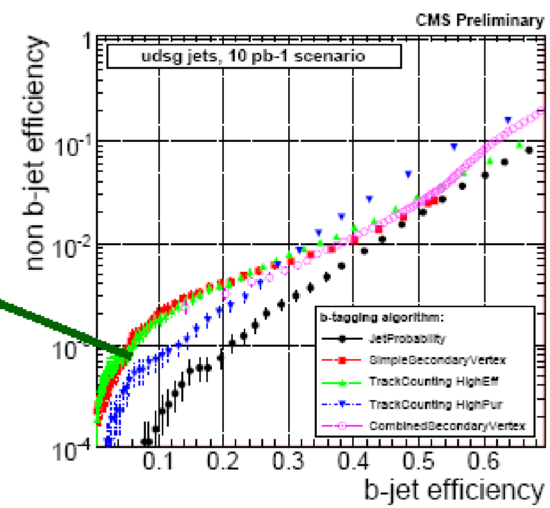
  - all b-tag alignment sensitive

  - approaching "ideal" at "100/pb"



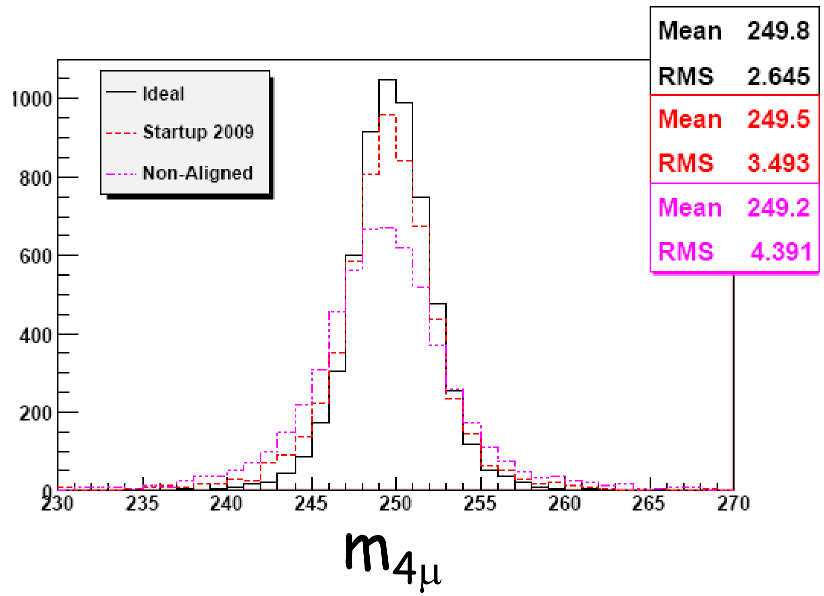


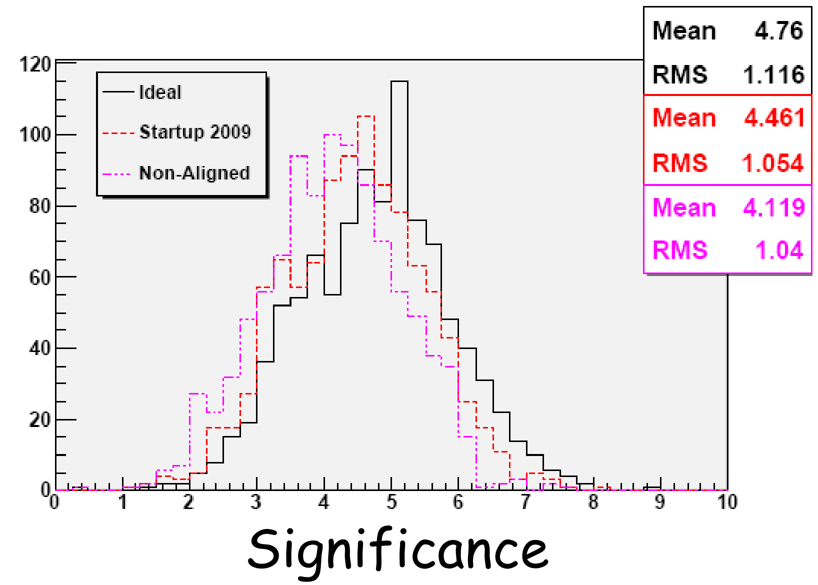
10/pb
TrackCounting alg.



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" $\Rightarrow$ 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 $\sqrt{2\ln(\mathcal{L}_{s+b}/\mathcal{L}_b)}$

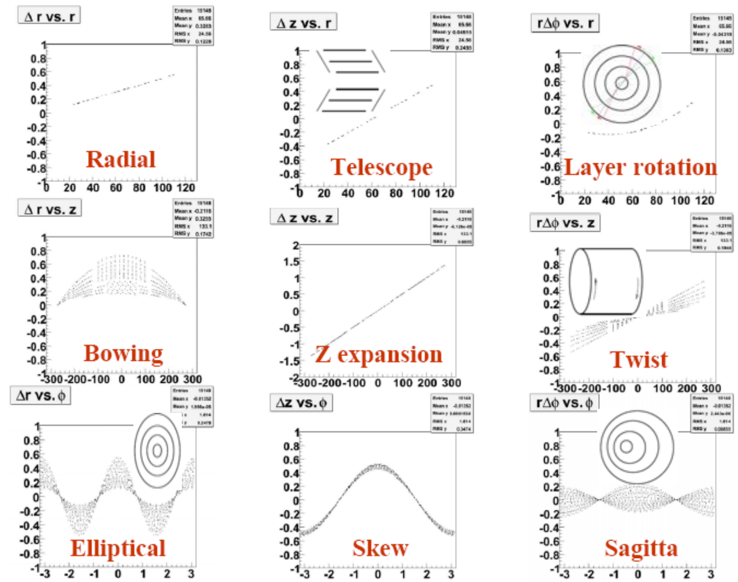




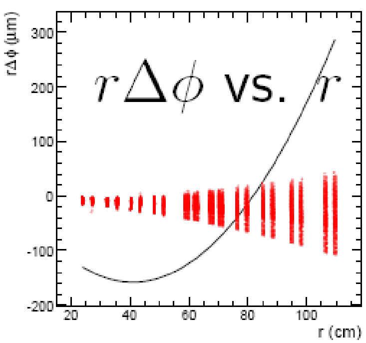
Systematic Misalignments

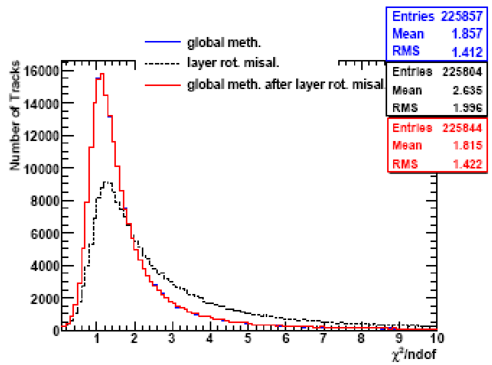
- Systematic distortions of the Tracker
  - may be χ^2 invariant
  - may introduce physics bias

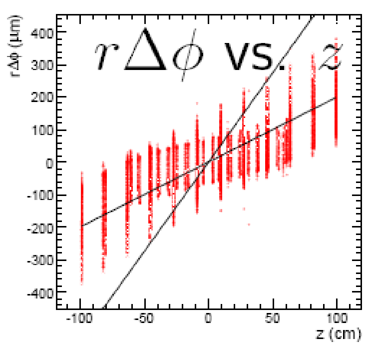
  e.g. charge bias with layer rotation

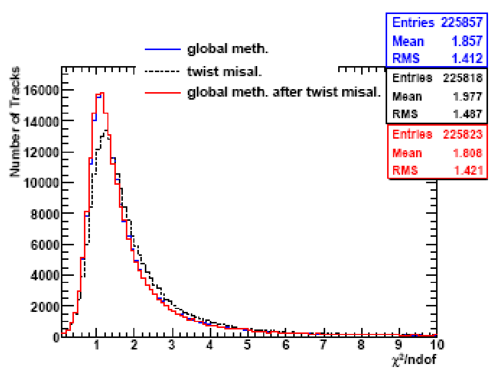


$$(\Delta r,\ \Delta z,\ r\Delta\phi)\ \text{vs.}\ (r,\ z,\ \phi)$$







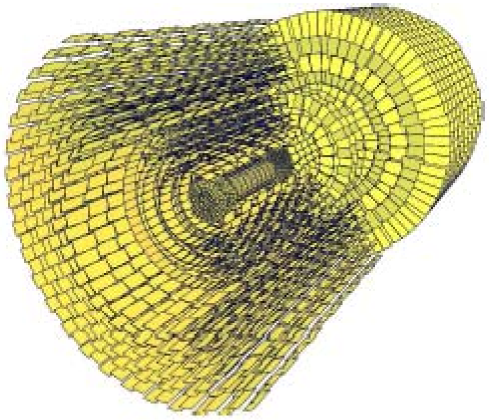


layer rotation recovered in alignment

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

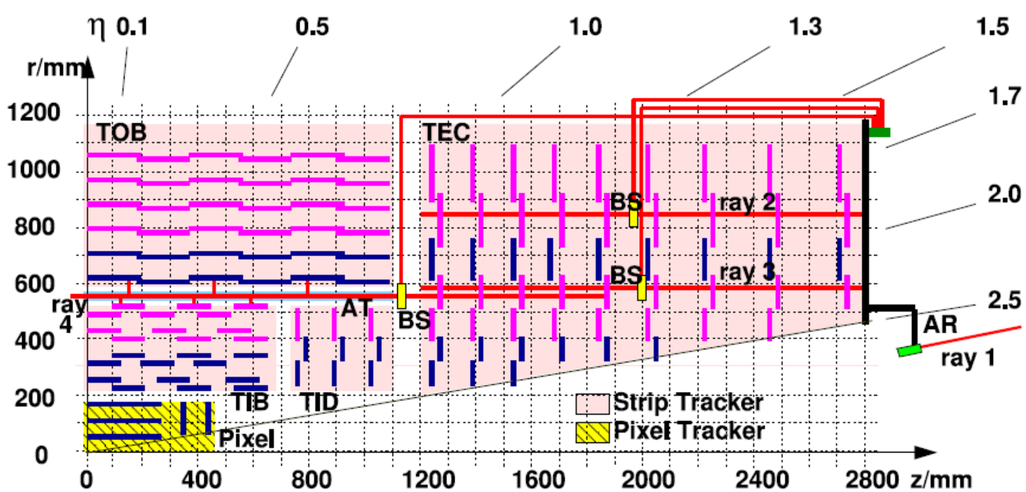


- Implication for first physics
  - discovery reach sensitive to tracker alignment
    e.g. fake rate, b-tag, resonance resolution
  - performance is already ahead of expectation
  - systematic limitations with cosmics alone
    more to come from collisions

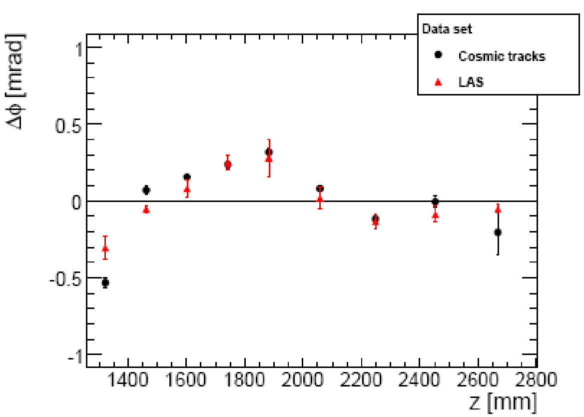
Backup Slides

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

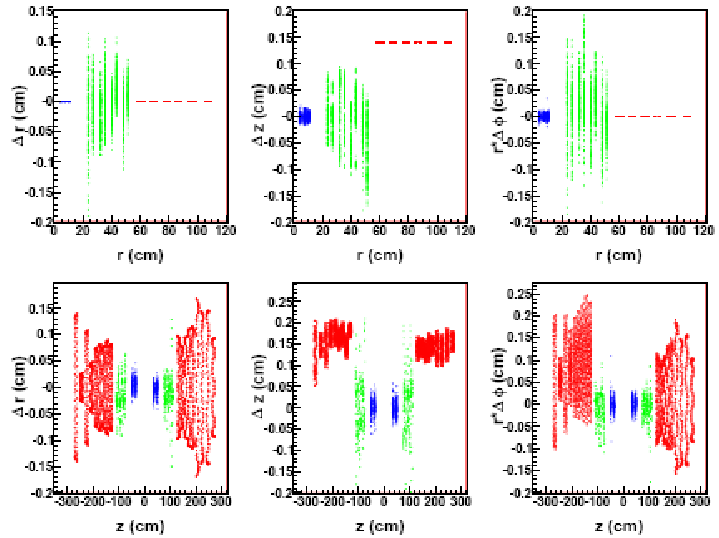
Barrels:

- 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



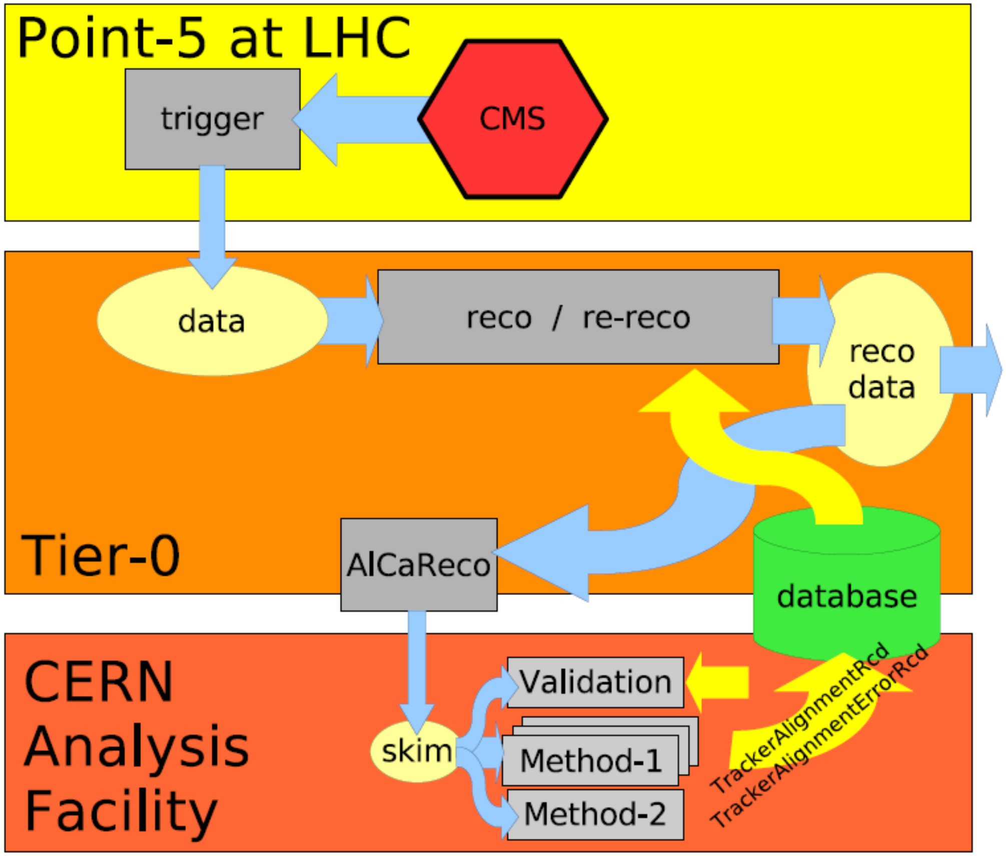
- Tracks + Survey in "local algorithm", to constrain all 6 dof:

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

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

Track Data Delivery: Alignment Workflow

- Track reco data: reduced skim "AlCaReco" for alignment
- Result: 16,588 Positions (6D) and APE (3D)



Residuals in overlapping modules

- Plot the double difference

  Δx_{hit}-Δx_{pred}
  with hits in the layer under test being removed when computing the prediction

- Nearby modules -> small effects of:

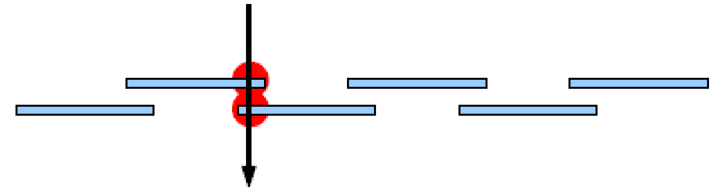
  - track extrapolation
  - crossed material

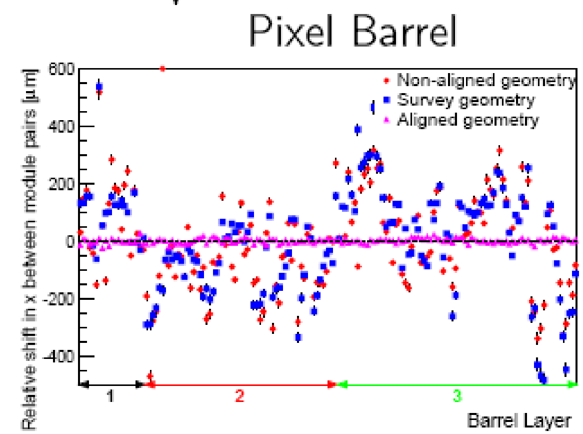
- Only overlaps with $N_{entries} \geq 100$ analyzed

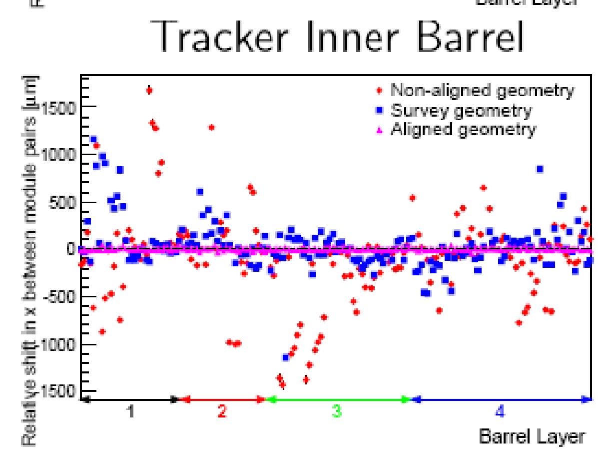
- Gaussian fit to Δx_{hit}-Δx_{pred}

  - mean -> remaining shift

- Difficult to compare with DMR as the same module enters several times

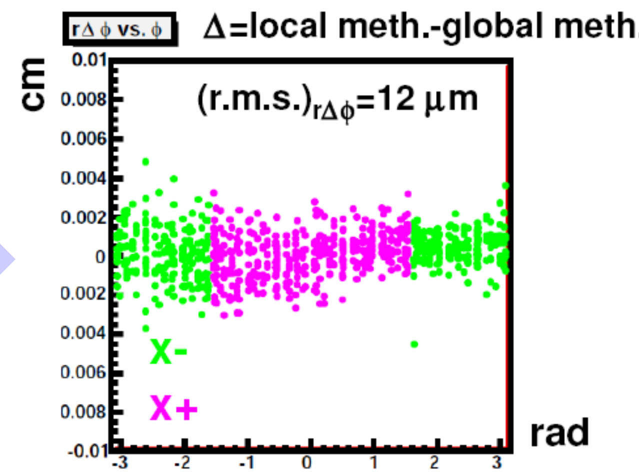






Geometry Comparison

- 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