CMS Tracker Alignment and Implications for Physics Performance

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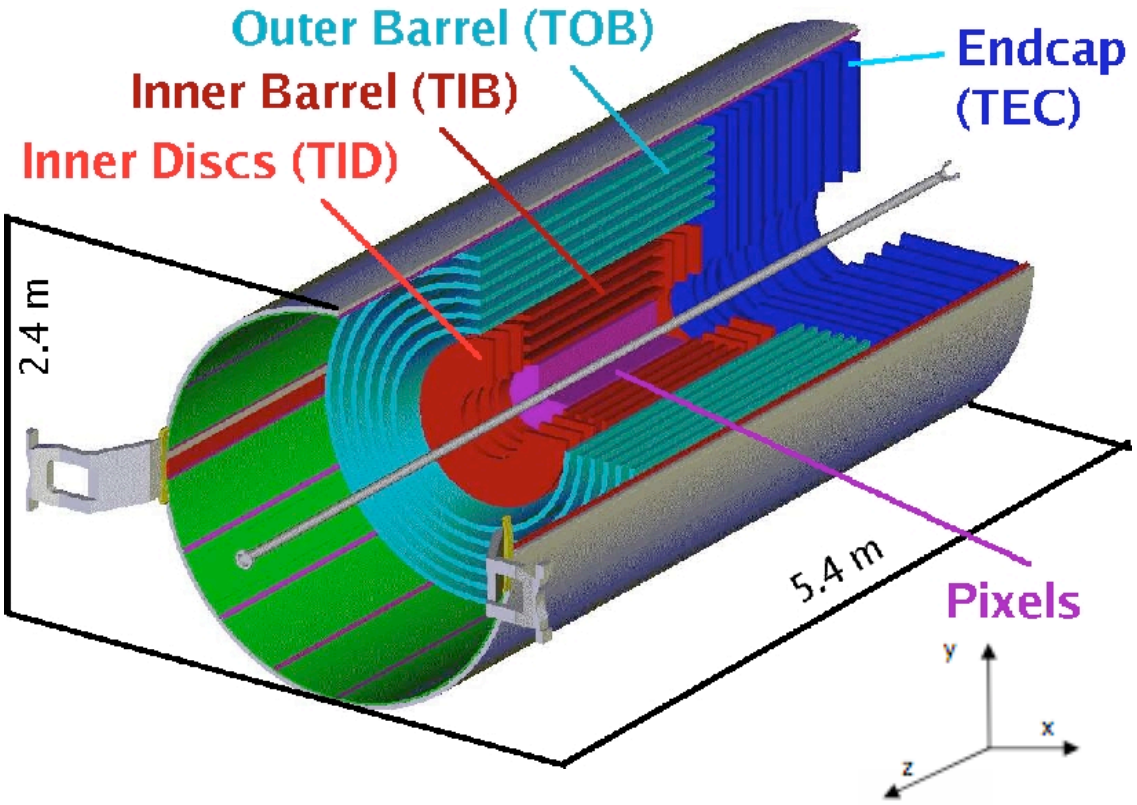
Outline

- The CMS Tracker
- Alignment Strategy
  - Track-Based Alignment
  - Survey of the Tracker
  - Laser Alignment System (LAS)
- Alignment Studies
  - Alignment at Tracker Integration Facility (TIF) with cosmic ray data
  - Alignment at CMS Cosmics Runs with cosmic rays data
  - Computing, Software, and Analysis 2008 (CSA08) exercise: MC startup studies
- Impact on Physics
  - Misalignment Studies

CMS Tracker



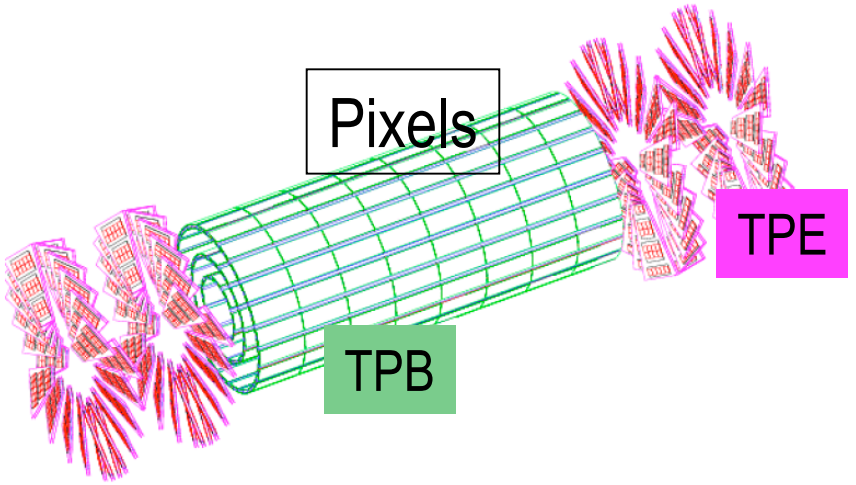
CMS All-silicon Tracker

Strips (80-205 μm pitch): 9.6M

TIB - 4 layers [2 stereo]
TID - 3 disks [2 stereo]
TOB - 6 layers [2 stereo]
TEC - 9 disks [3 stereo/3 rings per]

Pixels (100x150 μm^2): 66M

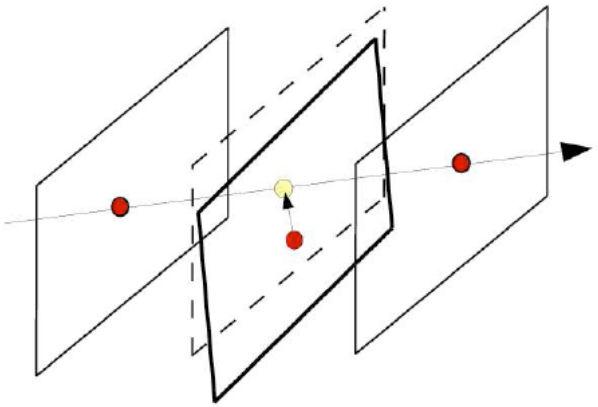
TPB - 3 layers
TPE - 2 disks



Challenge: Determine position of ~15000 silicon sensors to few micron precision!

Alignment Strategy

- Use all available data sources
  - Tracks, Laser Alignment System (LAS), Survey
- Previous experiments: to reach desired precision, track-based alignment necessary
- Challenge of alignment with tracks: Find 6 d.o.f. for ~15000 sensors; a problem with O(100k) unknowns
  - Goal to minimize a global χ^2:



$$\chi^2 = \sum_{i}^{\text{tracks}} \mathbf{r}_i^T(\mathbf{p},\mathbf{q})\mathbf{V}_i^{-1}\mathbf{r}_i(\mathbf{p},\mathbf{q})$$

r = residuals
p = position/orientation
q = track parameters
V = covariance

3 statistical methods:

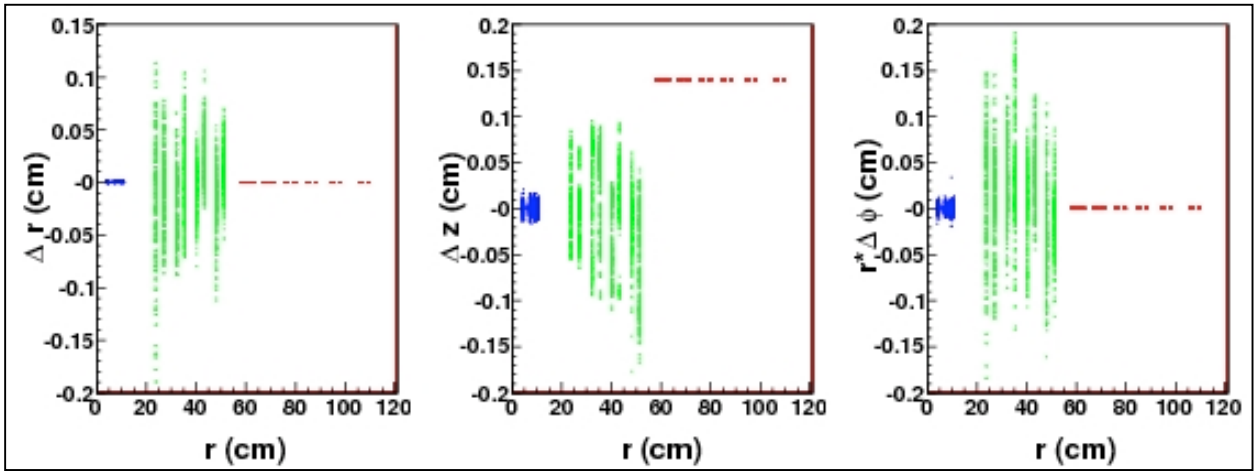
- HIP (Hits and Impact Points) - local method done iteratively
- MillePede II - global method solving with correlations
- Kalman Filter - global method updating parameters after every track

Tracker Survey

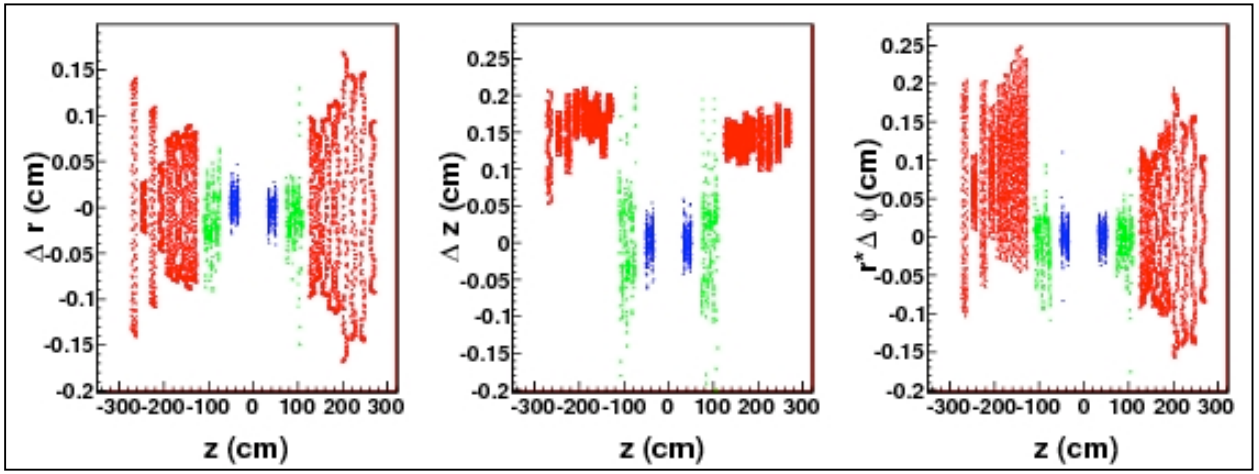
Survey of Tracker via coordinate measurement machine, touch probe, photogrammetry, and theodolites at varying hierarchies

Difference of each module's survey position in CMS Tracker w.r.t. design geometry

Barrels (TPB, TIB, TOB)



Endcaps (TPE, TID, TEC)



Levels of Survey

TPB: modules 2D

TPE: modules->disks 6D

TIB: modules/layers 6D

TID: modules/rings 6D; disks 3D

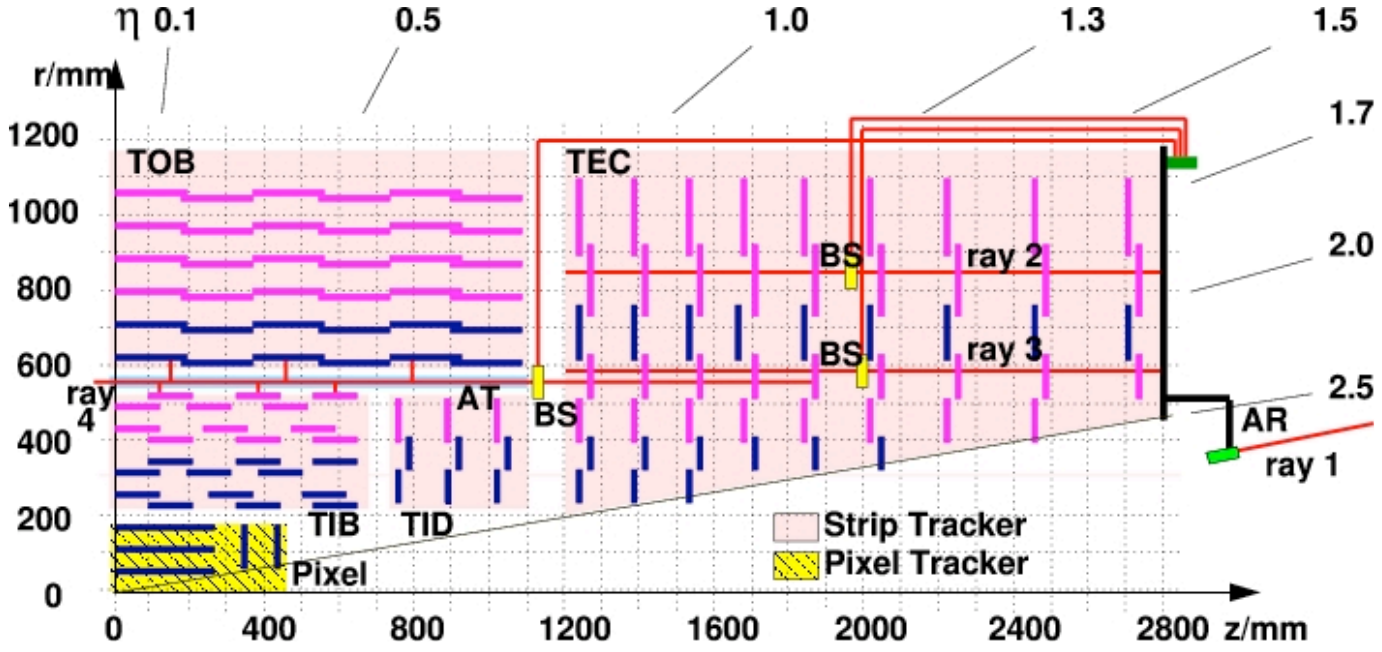
TOB: barrel only 3D

TEC: disks/endcaps only 6D

Survey info can be used as constraint in track-based alignment

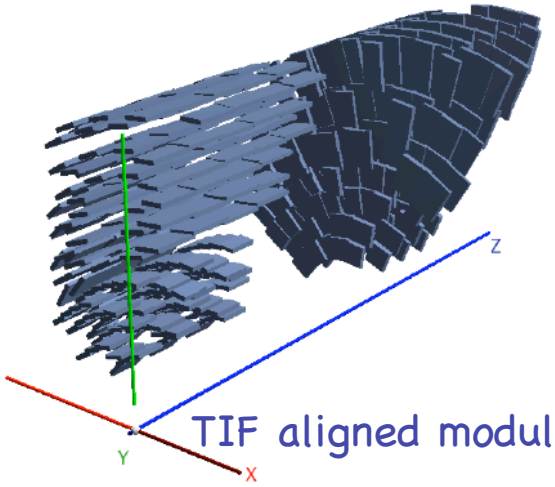
Laser Alignment System (LAS)

- Goal: provide continuous position measurements of large scale structures
  - 100 μm precision standalone; 10 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

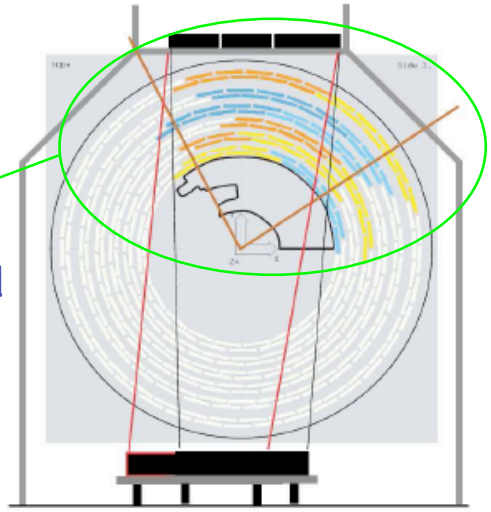


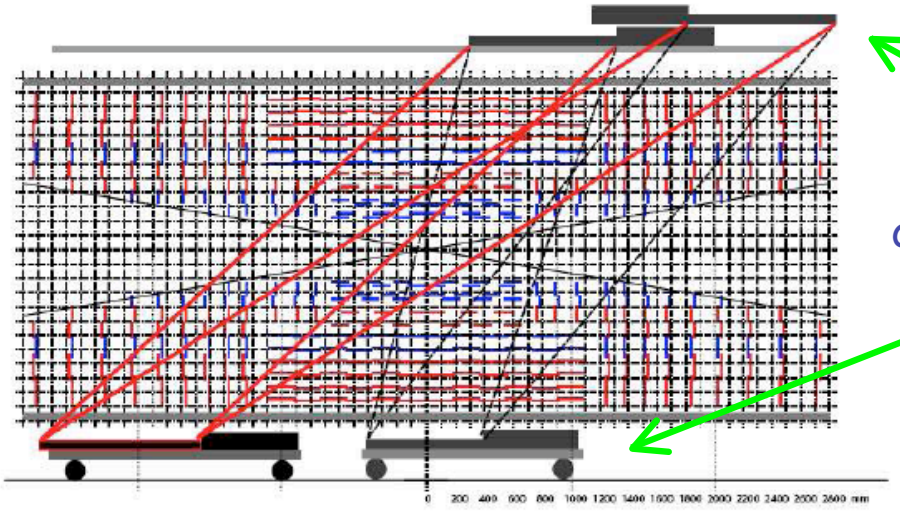
Alignment at TIF

- First attempt at (partial) CMS Tracker Alignment at Tracker Integration Facility with Strip Tracker (~15%) in spring and summer 2007
- Tracker readout test with cosmic ray data
- No magnetic field
- Incorporated data from optical survey, cosmic tracks, and LAS system
- Tested the stability of the tracker system for various stresses and temperatures
- Collected approximately 5 million events (~8% used for alignment) for TIB, TOB, TEC (inserted mid-run)

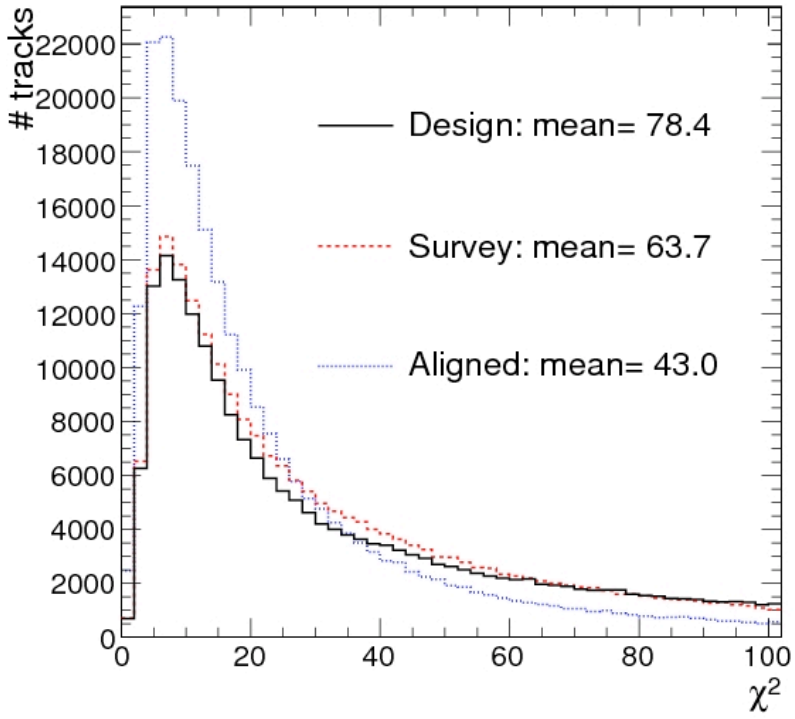


TIF aligned modules


ϕ-region powered and read-out


Trigger configurations

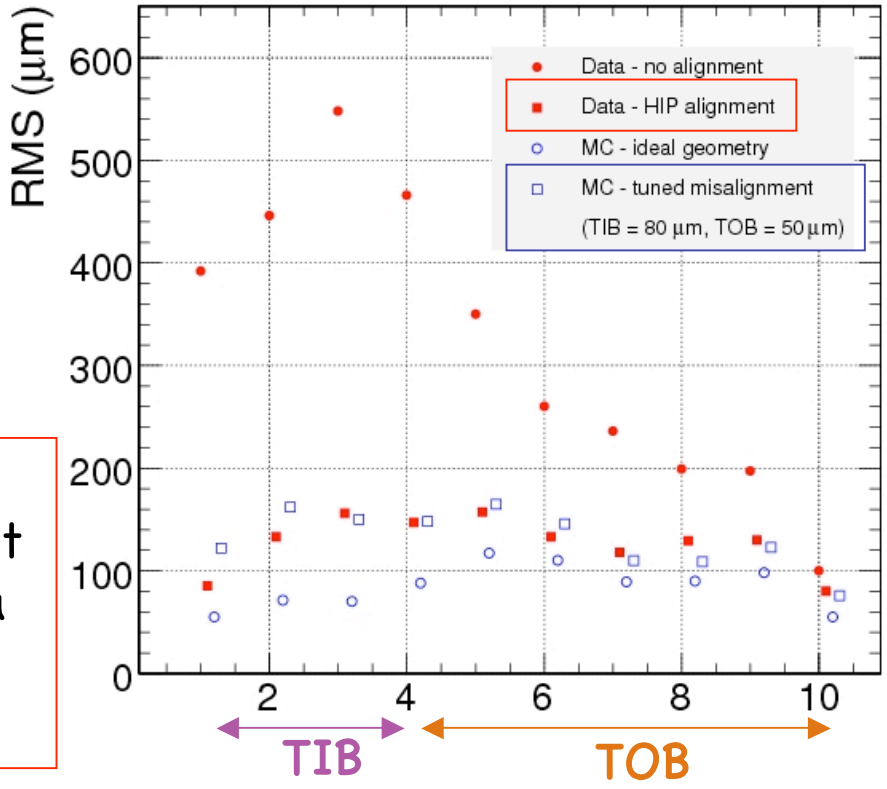
TIF Alignment: Results



- First validation of optical survey
- Testing of LAS operation; good agreement with track-based alignment
- Application of 3 track-based alignment methods showed good agreement
- Valuable experience for full CMS Tracker alignment!

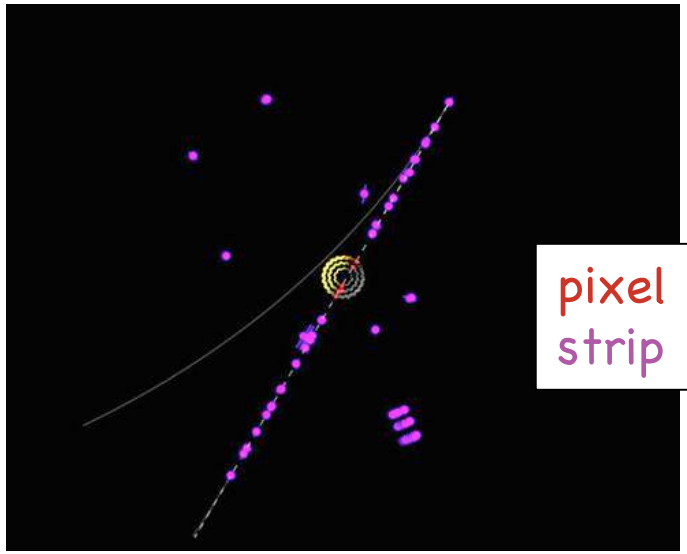
Overall track χ^2 is improved;
design -> survey & survey -> aligned

- Using MC data, perform track reconstruction over increasing misalignment
- Repeat until χ^2 and residuals match data with aligned geometry
- Misalignment of 80 (50) μm in TIB (TOB)



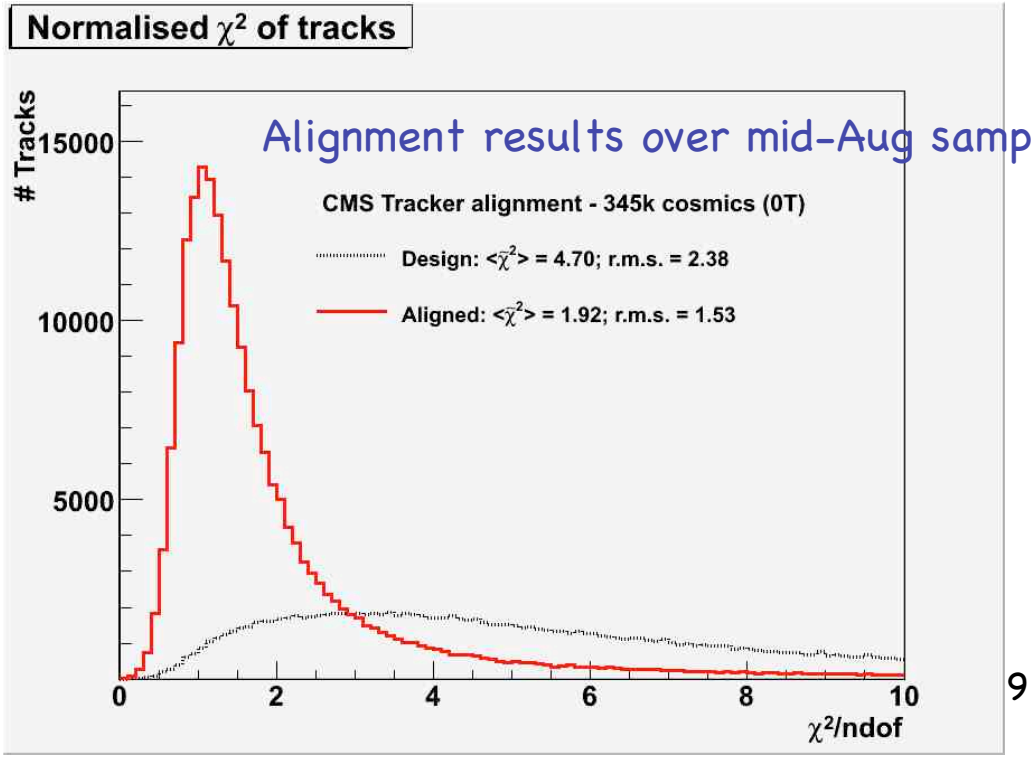
CMS Cosmic Runs at 0T

- First attempt to align almost full CMS Tracker
  - No magnetic field -> no momentum measurement
- Two event samples
  - 285k selected tracks, mid-July
  - 345k selected tracks, mid-Aug.
- Strategy
  - Aligning both with tracks and tracks plus survey



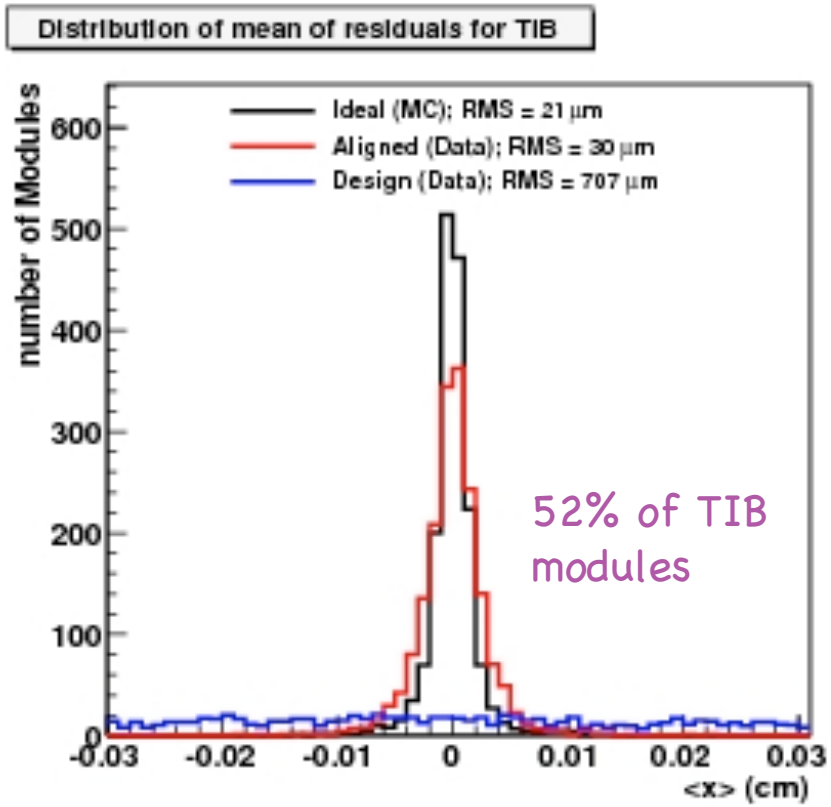
$$\chi^2 = \sum_{i}^{\text{tracks}} r_i^T(\mathbf{p},\mathbf{q}) V_i^{-1} r_i(\mathbf{p},\mathbf{q}) + \sum_{j}^{\text{survey}} r_{*j}^T(\mathbf{p}) V_{*j}^{-1} r_{*j}(\mathbf{p})$$

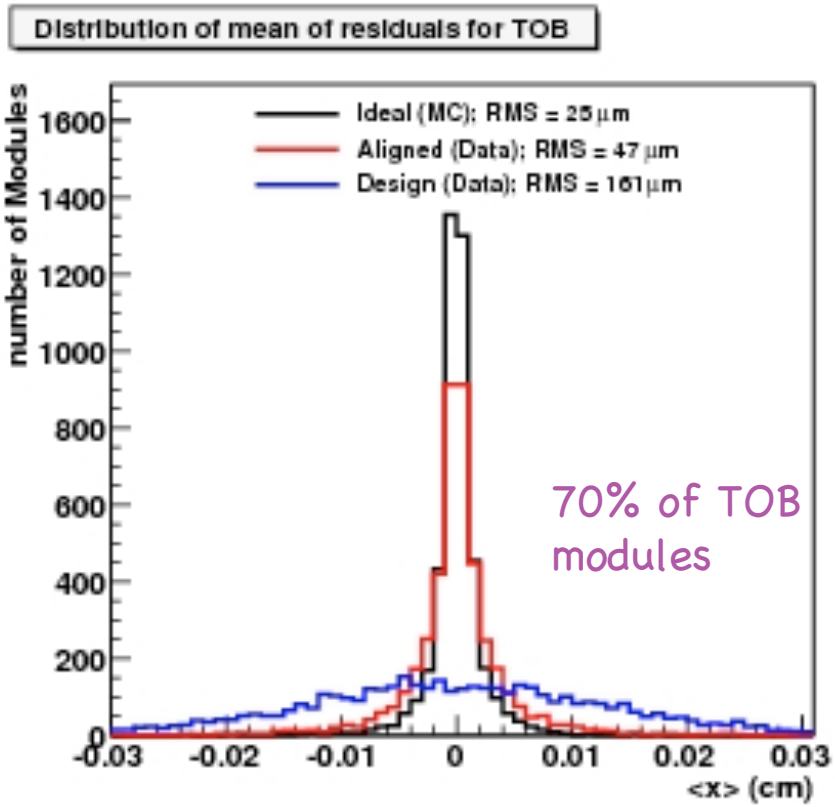
- Ran HIP and MP algorithms - similar results
- First experience with pixel detector
- Improvement of track χ^2 and residuals



Cosmics Runs Results

Residuals in local x (global r-ϕ) dominated by multiple scattering.
Instead, plot distribution of mean of residuals for modules with more than 100 hits for 3 different geometries:
-> ideal on MC, aligned on data, design on data



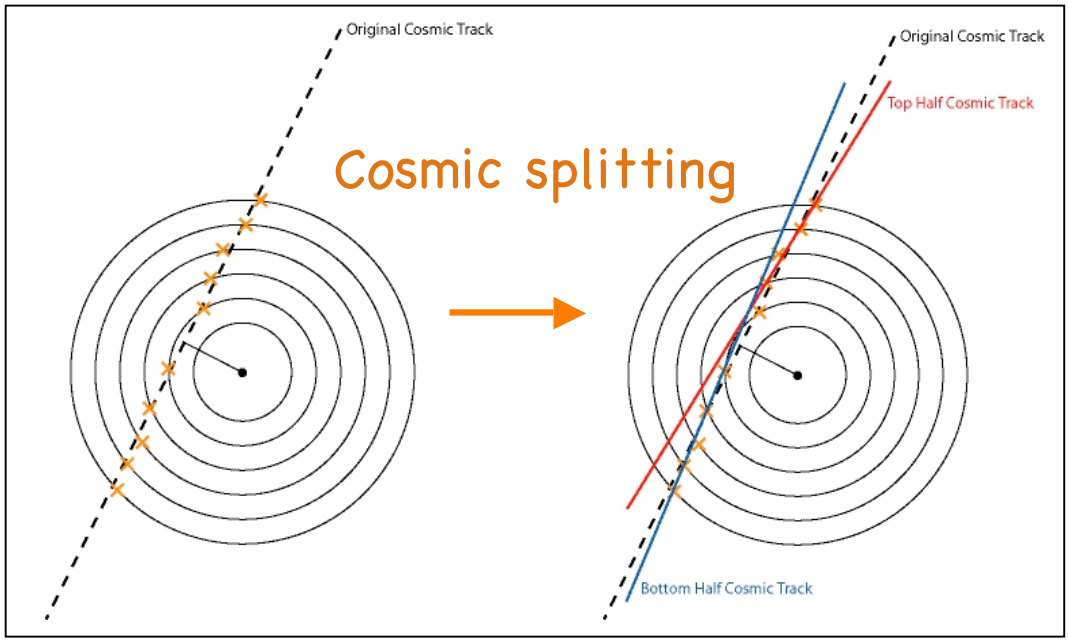


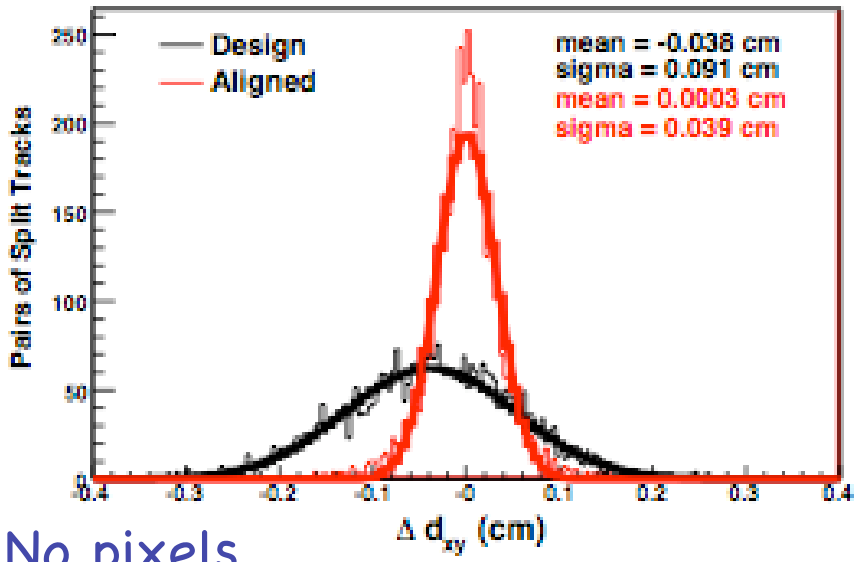
Marked improvement from design to aligned
Ideal distribution gives measure of statistical contribution

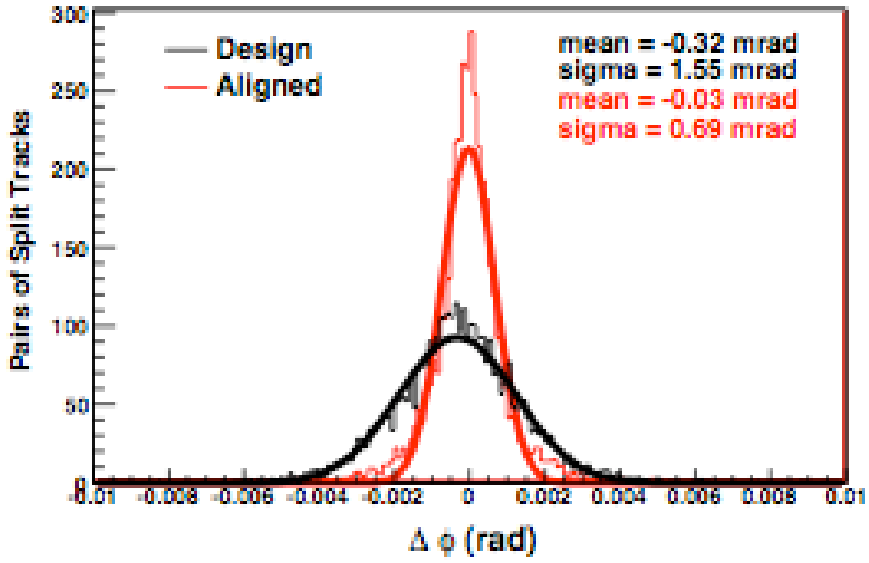
Cosmics Runs Results: Tracking

Effect of alignment on tracking:
Idea to split cosmics tracks along impact parameter and compare track parameters of top and bottom halves

Alignment shows improvement in bias and resolution of the track parameters Δd_{xy} and $\Delta\phi$ (also for Δd_z and $\Delta\theta$)







n.b. No pixels

MC Startup Studies

- CSA08 to test full scope of total alignment workflow in "real time" with MC data
  - 2 week exercise: week 1 corresponding to 1 pb^{-1} of data taking and week 2 corresponding to 10 pb^{-1}
- Initial misalignment scenario corresponding to startup based on survey, LAS, and cosmics knowledge
- Alignment constants for week 2 based on first week alignment

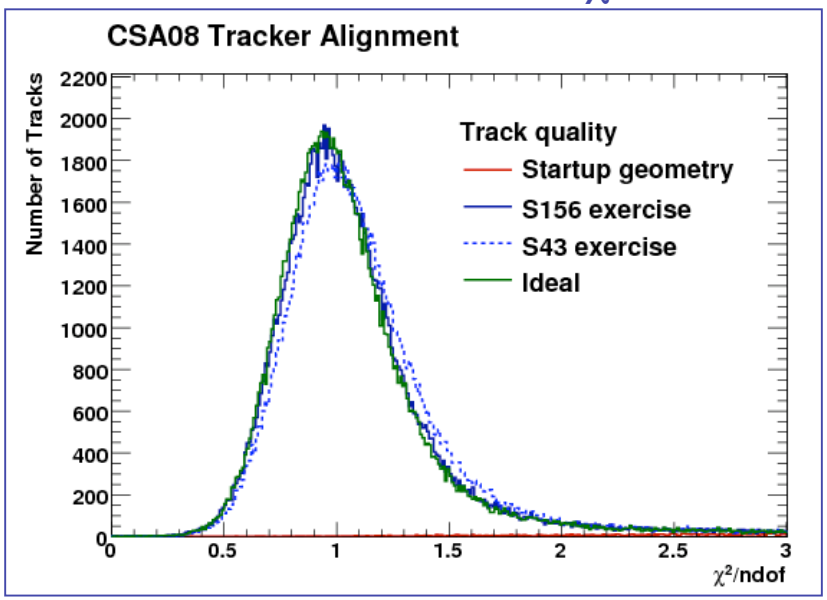
Sample	Events	Cuts/Comments
Minbias	6M, 3M	pT > 1.5 GeV
High pT Jets	150k, 150k	-
Muon pT>11	1M	-
Cosmics4T	3M	pT > 15 GeV, nHits > 18 Used x5
$Z \rightarrow \mu^+ \mu^-$	16k	Vertex/Mass constraint Used x5
$J/\psi \rightarrow \mu^+ \mu^-$	750k	-

Week 1
Week 2

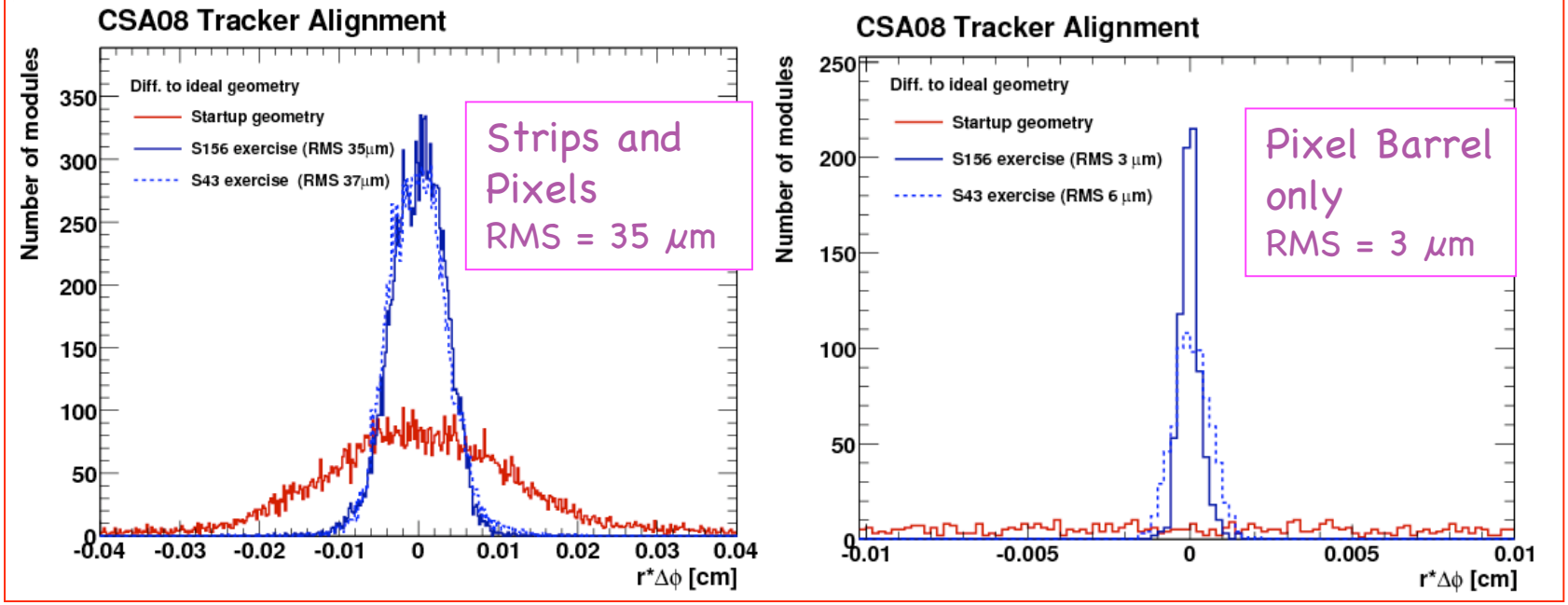
CSA08: Results

- Exercise completed successfully in time
- Data, configuration, and alignment workflow ran smoothly
- Ran all 3 algorithms; best performance by MP
- Improvement in overall $\chi 2$ and positions of sensors w.r.t. to initial misalignment
- Disclaimer: MC exercise, no χ^2-invariant deformations studied

Overall Track χ^2



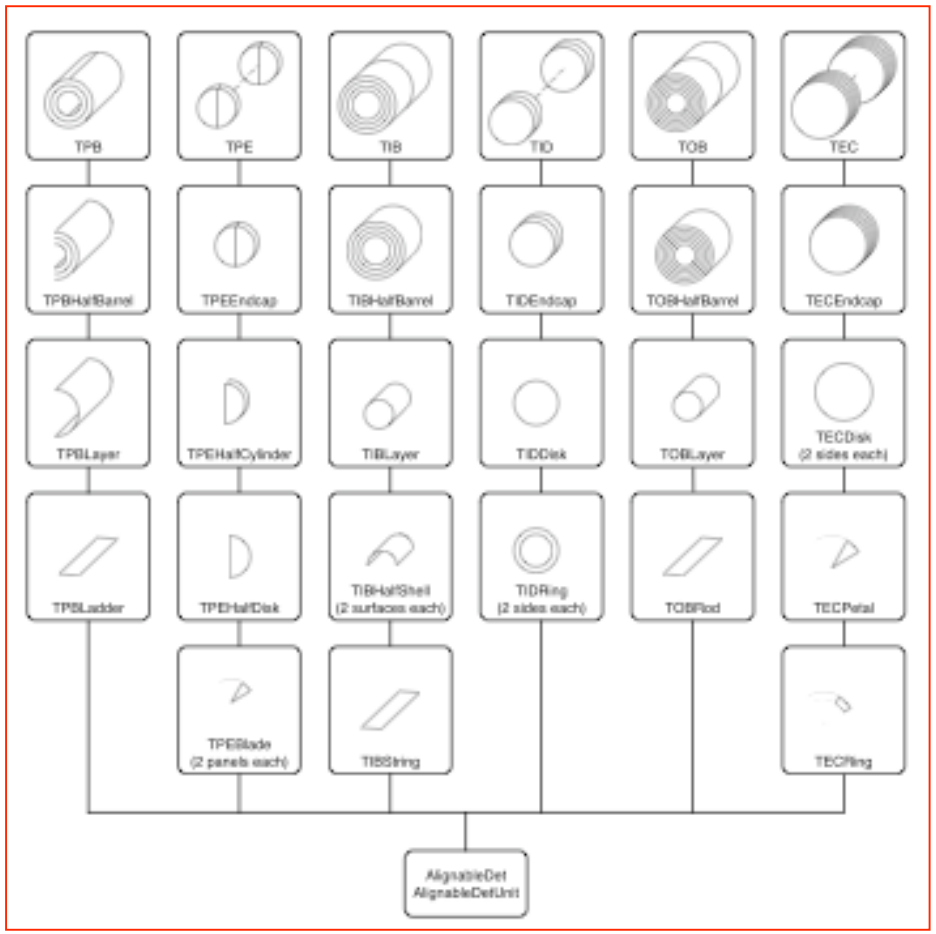
Difference between determined parameter and true parameter in most sensitive coordinate



Misalignment Studies

- A realistic misalignment model necessary for studying misalignment impact on physics analyses
- Necessary to understand assembly precision of full Tracker hierarchy
- Create misalignment scenarios:
  - SurveyLAS
  - SurveyLASCosmics
  - 10 pb^{-1}
  - 100 pb^{-1}

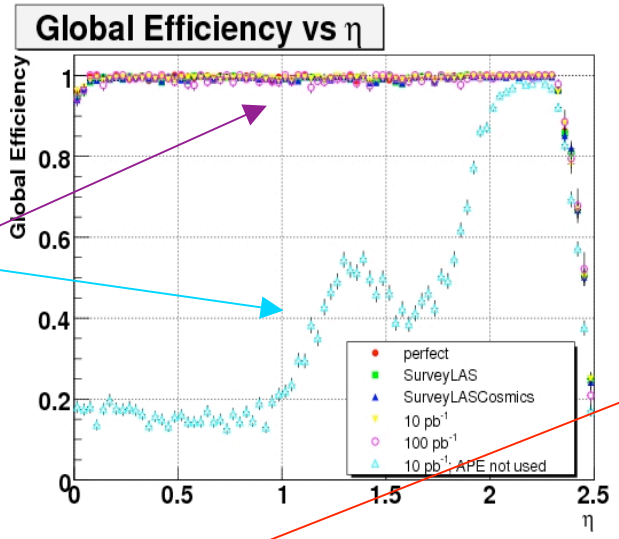
Full tracker hierarchy

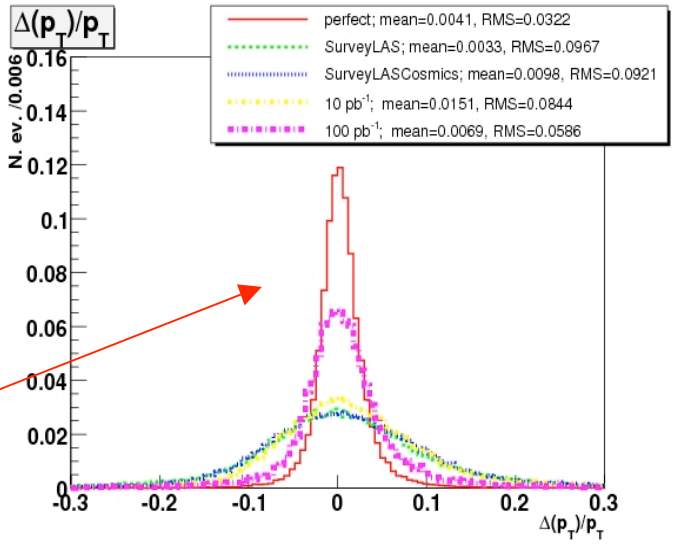


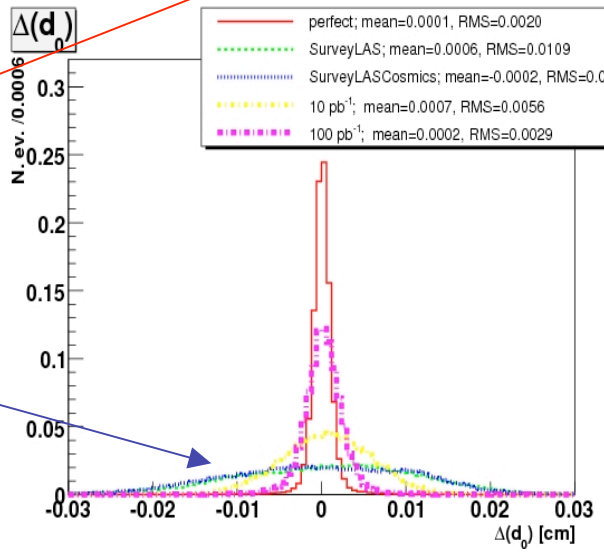
No weak modes (χ^2-invariant deformations) studied

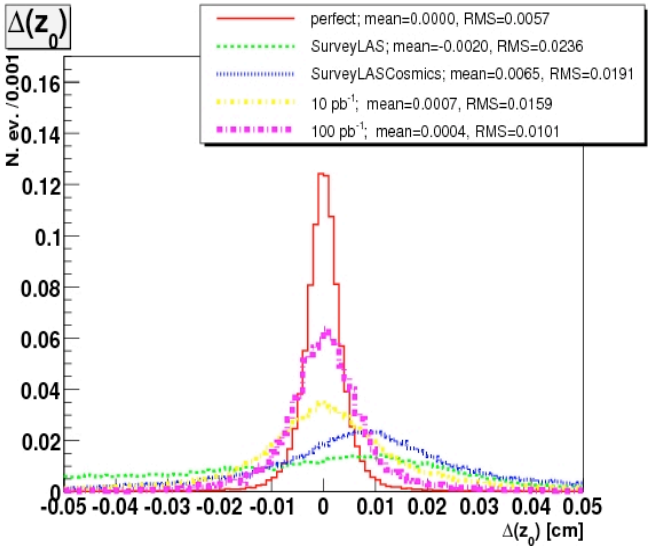
Impact On Tracking

- 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
- Benchmark using muons with pT = 100 GeV: resolution increases by ~6% from ideal to 'SurveyLASCosmics'
- d_0 and z_0 highly affected by TPB misalignment
- TPB misaligned in 'SurveyLASOnly' and 'SurveyLASCosmics'





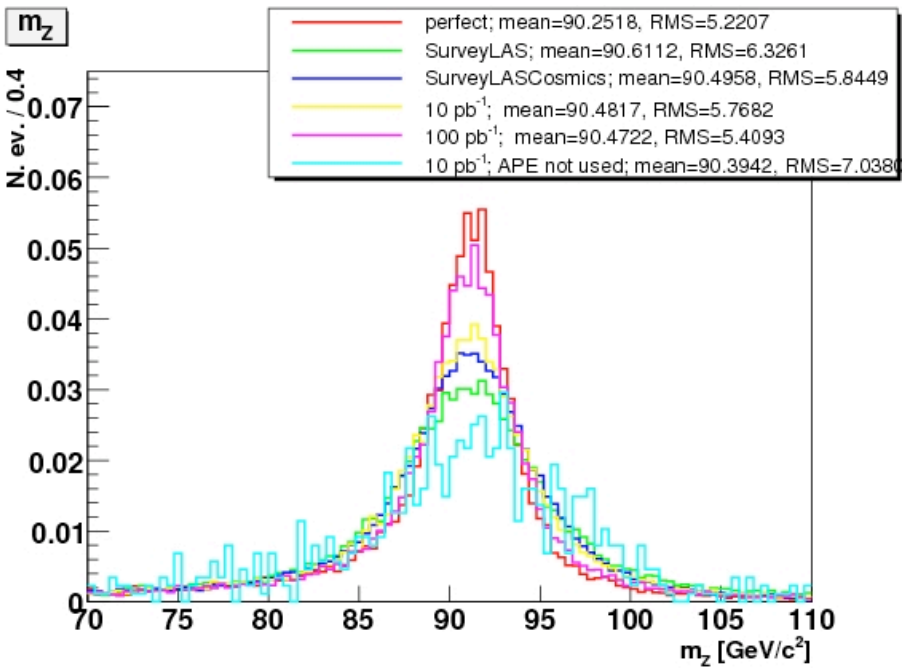


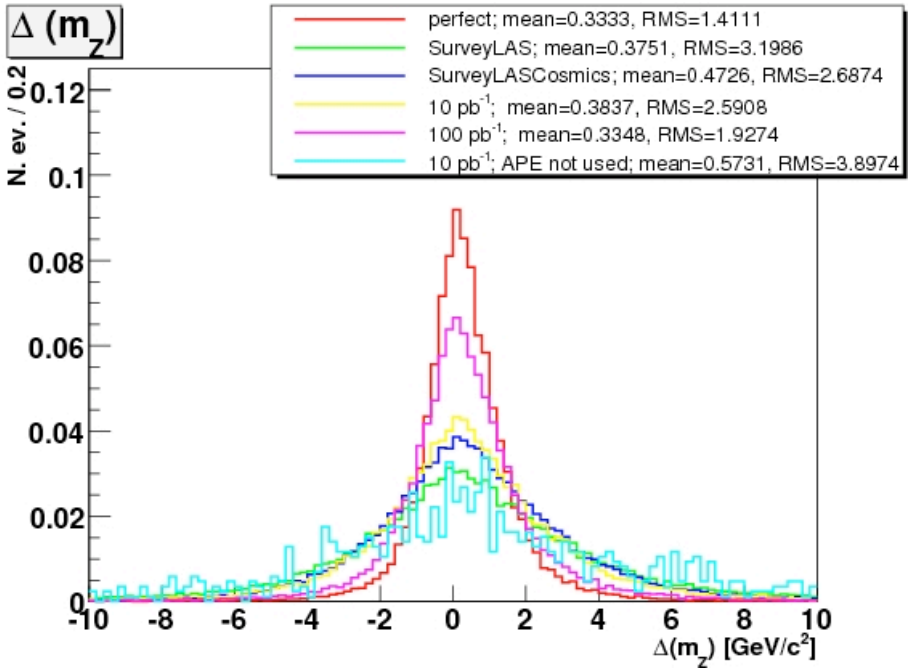


d_0 and z_0 - transverse and longitudinal impact parameters

Impact On Z -> $\mu\mu$

- Effect of misalignment on p_T resolution less for low p_T due to multiple scattering
- Di-muon invariant mass width is increased by 12% w.r.t. ideal for 'SurveyLASCosmics'
- Z mass resolution improves by 24% going from 'SurveyLAS' to '10pb^{-1}' scenarios





Summary

- CMS Tracker Alignment: challenge to align ~15000 silicon modules
- Use all available information: Survey, LAS, Tracks
- Alignment exercises with data
  - TIF: partial detector, first look at what to expect
  - Global Runs: using experience from TIF; more efficient turnaround;alignment with mostly full CMS tracker
- Alignment exercises with MC
  - CSA08: Full workflow simulation for early LHC collisions; successful alignment achieved in less than a week
- Study impact on physics using misalignment scenarios
  - Examine effect on tracking and Z -> $\mu\mu$ mass
  - Misalignment heavily affects physics performance - especially barrel pixel misalignment and APE estimation
- Recent experiences and progress encouraging in preparation for LHC startup!


CMS
Compact Muon Solenoid

Backup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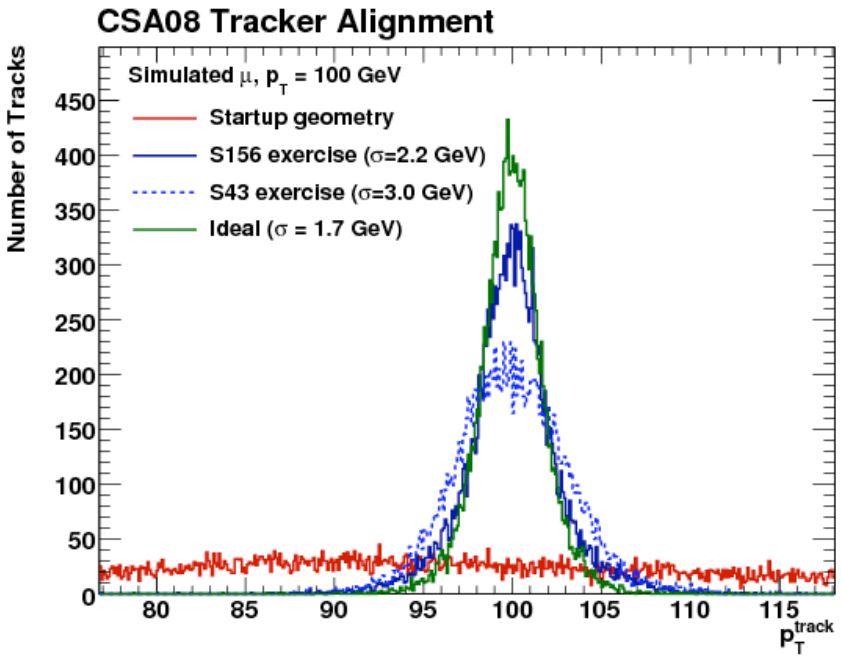
CSA08: Results

Intrinsic Subdetector Resolution:

Difference between true and aligned parameter after removing global movements from subdetector

in μm	Startup	1 pb^{-1}	10 pb^{-1}
TPB	105	6	3
TPE	120	48	48
TIB	106	30	23
TID	482	24	10
TOB	445	48	38
TEC	92	29	25



Effect of alignment on resolution:

Good improvement in the TPB (important for physics!)

Impact on p_T resolution:

Use muons with pT = 100 GeV as benchmark, resolution after alignment only 0.5% from ideal