The CMS Tracker Alignment in p-p Collisions

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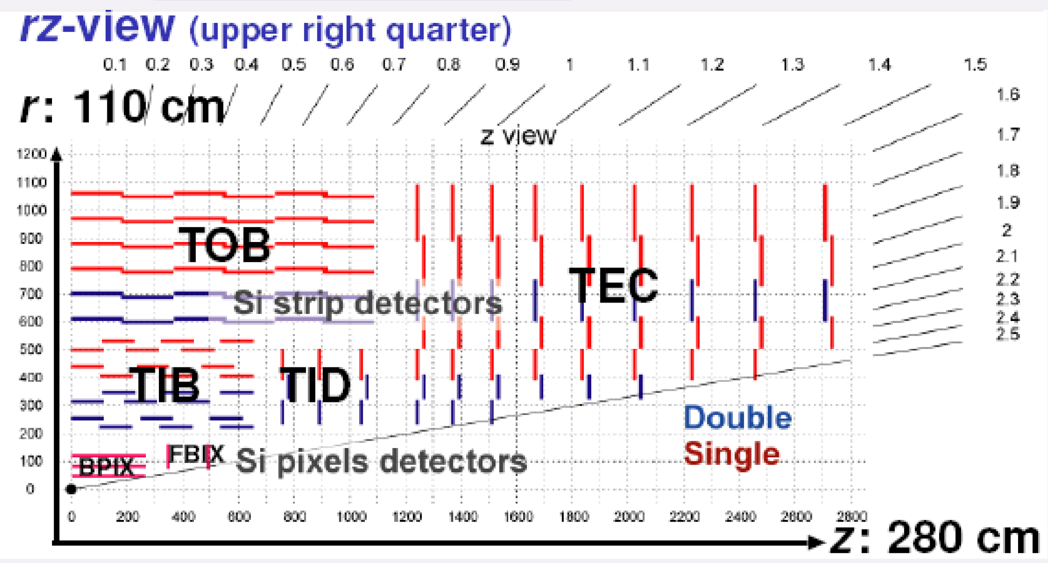
On Behalf Of The CMS Collaboration

The CMS all-silicon tracker consists of 16588 modules. Aligning these with the desired precision of a few micrometers is only feasible using track based alignment procedures. Ultimate local precision is now achieved by the determination of sensor curvatures. This faces the algorithms with about 200k parameters to be calculated simultaneously. This can be well handled using the Millepede II program interfaced with CMS software. The main remaining challenge are systematic distortions in the achieved geometry that are systematically biasing the track parameters like the track momenta. These distortions are controlled by adding further information into the alignment workflow, e.g. the mass of decaying resonances. In addition, the orientation of the tracker with respect to the magnetic field of CMS is determined with a stand-alone chi-square minimization procedure. The geometries are finally carefully validated. The monitored quantities include the basic track quantities for tracks from both collisions and cosmic muons and physics observables like resonance masses.

The CMS Tracker Alignment

The CMS Tracker



All Silicon

- 1440 Si pixel modules
- 15148 Si strip modules
  - 24244 strip sensors in total
  - Strips generally measure *r-φ* direction

Single Hit Resolution

Pixel: up to $\sigma = 9\ \mu m$

Strip: $\sigma \approx 23-60\ \mu m$

Alignment Challenge: 200k parameters (taking into account that sensors are not flat)

Track Based Alignment Using Millipede II Algorithm

Global Fit Approach

- Simultaneous fit of all parameters: shifts, track parameters etc.
- Minimise Sum of Squares of Residuals:

$$\chi^2(p,q) = \sum_j^{tracks} \sum_i^{measurements} \left(\frac{m_{ij} - f_{ij}(p,q_j)}{\sigma_{ij}} \right)^2$$

f_{ij} : the track model prediction, p : the global alignment parameter & q_j : local track parameter

- Linearise track model & minimise
  Normal Equation $C\,a = b$ with $a^T = (p,q)$, $q^T = (q_1, \ldots, q_n)$
- Local parameters appear in part of the data only
  Block structure in C, matrix algebra reduces to: $C'\,p = b'$
- C' & b' summing up contributions for all tracks
- Provides alignment solution in one step: All correlations from tracks are taken into account

Need clever algorithms for > 100 k global parameters

Experiment Independent Global Fit Tool

- Setting up & Solving Matrix Equation: $C'\,p = b'$
- Here C' is nxn matrix (n ≈ 200k, typically sparse)
- Very demanding for memory & CPU

Input From Experiment

- Linearised track fit information:
  - Residuals with uncertainties & Derivatives $\frac{\partial f}{\partial q}$ & $\frac{\partial f}{\partial p}$

Features: Computing Aspects

- Optimized for speed
  - Iterative MINRES, CPU intense parts parallelized using OpenMP
  - Local fit defects bordered band matrices (Broken Line Fit)
- Stand alone Fortran program, Reading binary input
- Optimized for memory space
  - Symmetric *C'* would need 160 GB in double precision
  - Reduction due to sparsity, Compression by bit packed addressing
  - By single precision for elements summing up from few tracks

Alignment Strategy & Results During 2011 pp Collision (1fb^{-1})

Input Data & Settings

- Loosely selected isolated muon tracks : 15 M
- Muon track pairs from Z boson decays : 375 k
- Low momentum tracks: 3 M
- Cosmic ray tracks (collected between LHC fills, during collisions & before collision data taking): 3.6 M

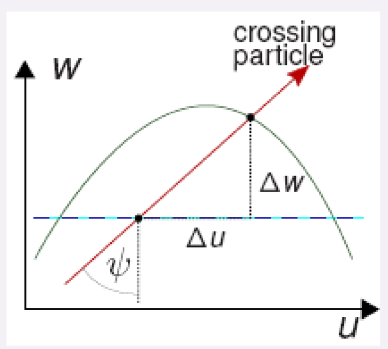
Millepede II at Work

- 246 parallel jobs ➡ ∑ 46.5 GB, read 13 times
- 22.6 M objects: MINRES iterating 4 times (tightening outlier rejection)
- 200 614 fit parameters (including 138 Lagrange multipliers)
- CPU usage 44.5 h using eight threads, Intel Xeon L5520, 2.27

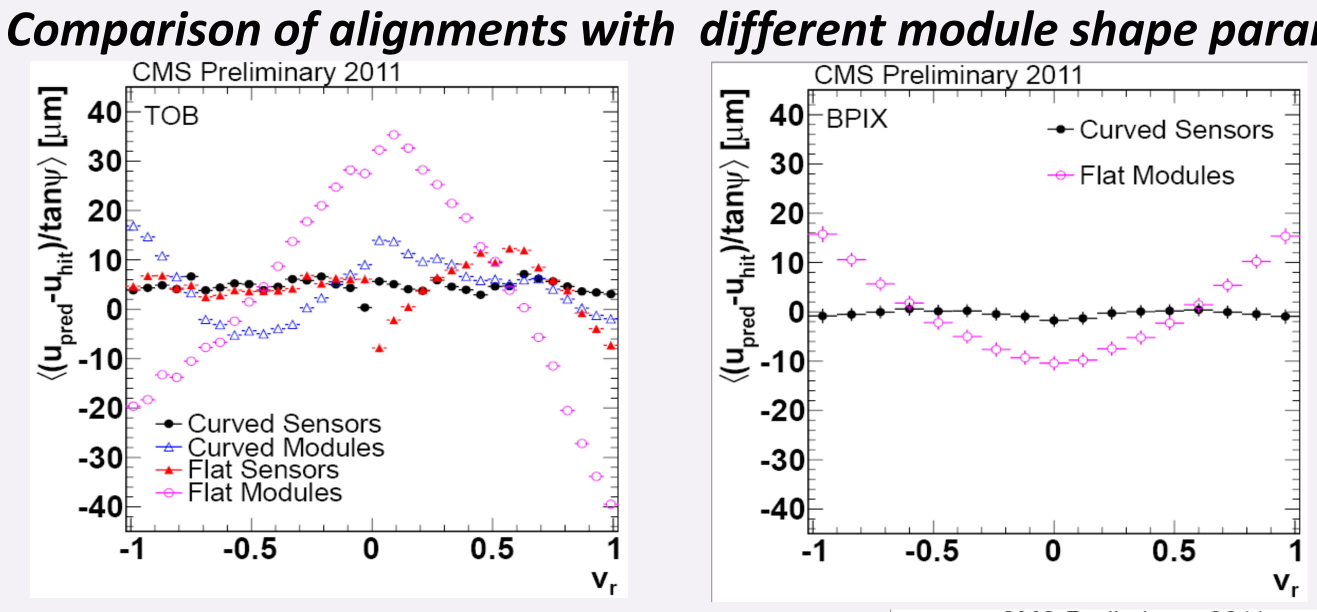
Very efficient usage of resources with fast turnaround for analysis!

Determination of Module Surface Deformation

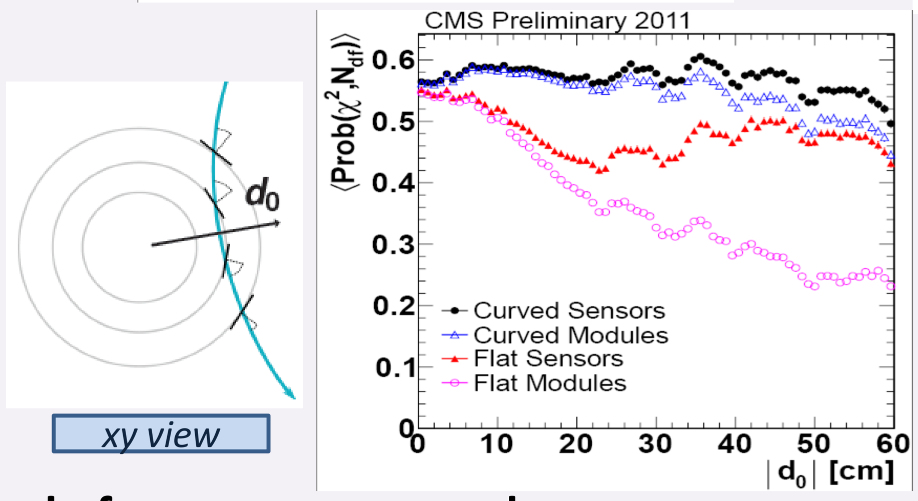
- Sensor surfaces can be bowed
- Kink within two daisy chained sensors
  - Typical kink is 2 α^δ = 1.6 mrad
  - Larger effect than sensor bow
- Alignment: Determination of "bows" & "kinks"
- Residual *du*, track slope *tan ψ* :
  - map residual perpendicular to sensor, validated by $dw = du/\tan\psi$



Comparison of alignments with different module shape parameterizations



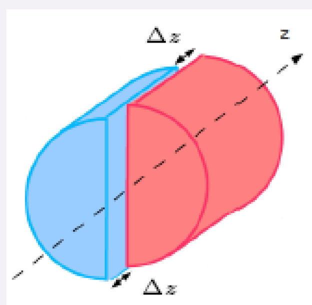
- "Curved Sensors": determination of kinks/bows
- "Curved Modules": determination of bows
- "Flat Sensors": determination of kinks
- "Flat Modules": neglecting kinks/bows

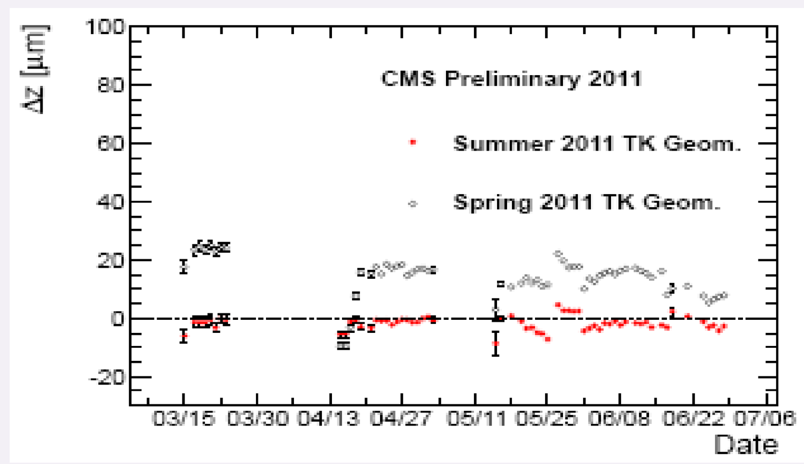


- ↑ d_o ↑ average track angle from sensor normal
- Average goodness of fit vs d_o demonstrates improvements from flat modules via flat sensors, bowed modules to bowed sensors

Sensor bow treatment improves cosmic tracking

Pixel Movements & Monitoring

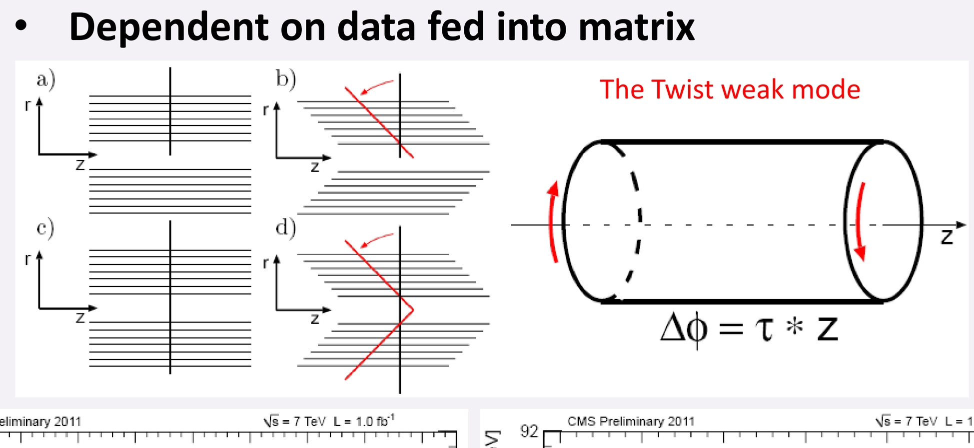


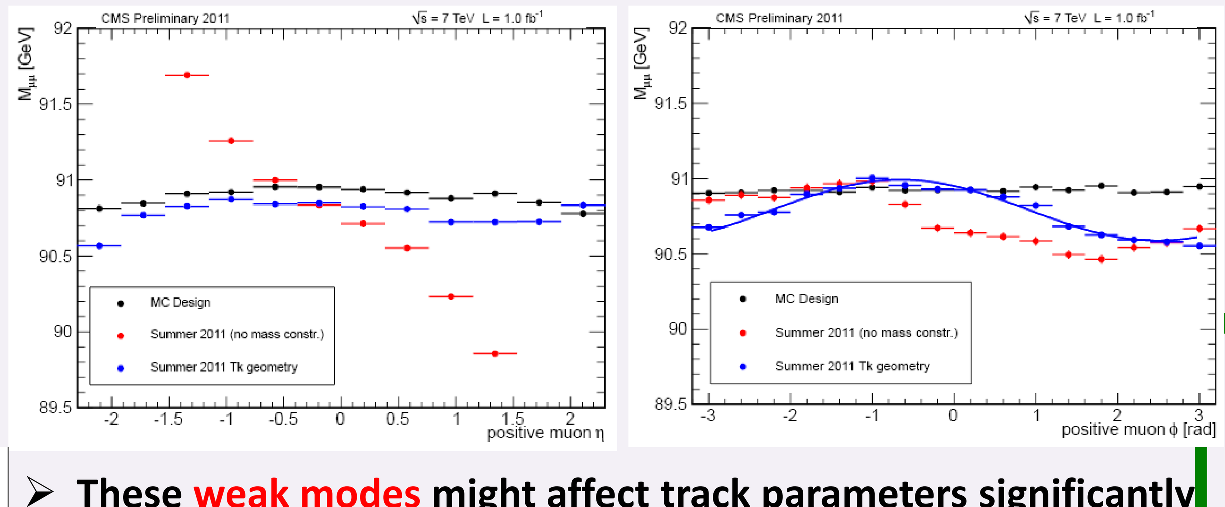


- Time dependence of pixel structure alignment
- Alignment corrects for the shifts along z of the pixel half-shells
- B-tagging insensitive to remaining 10 μm effect

The Weak Mode Issue

- Minimising residuals can be insensitive to certain global distortions
  - Potential bias on track parameters
  - Dependent on data fed into matrix

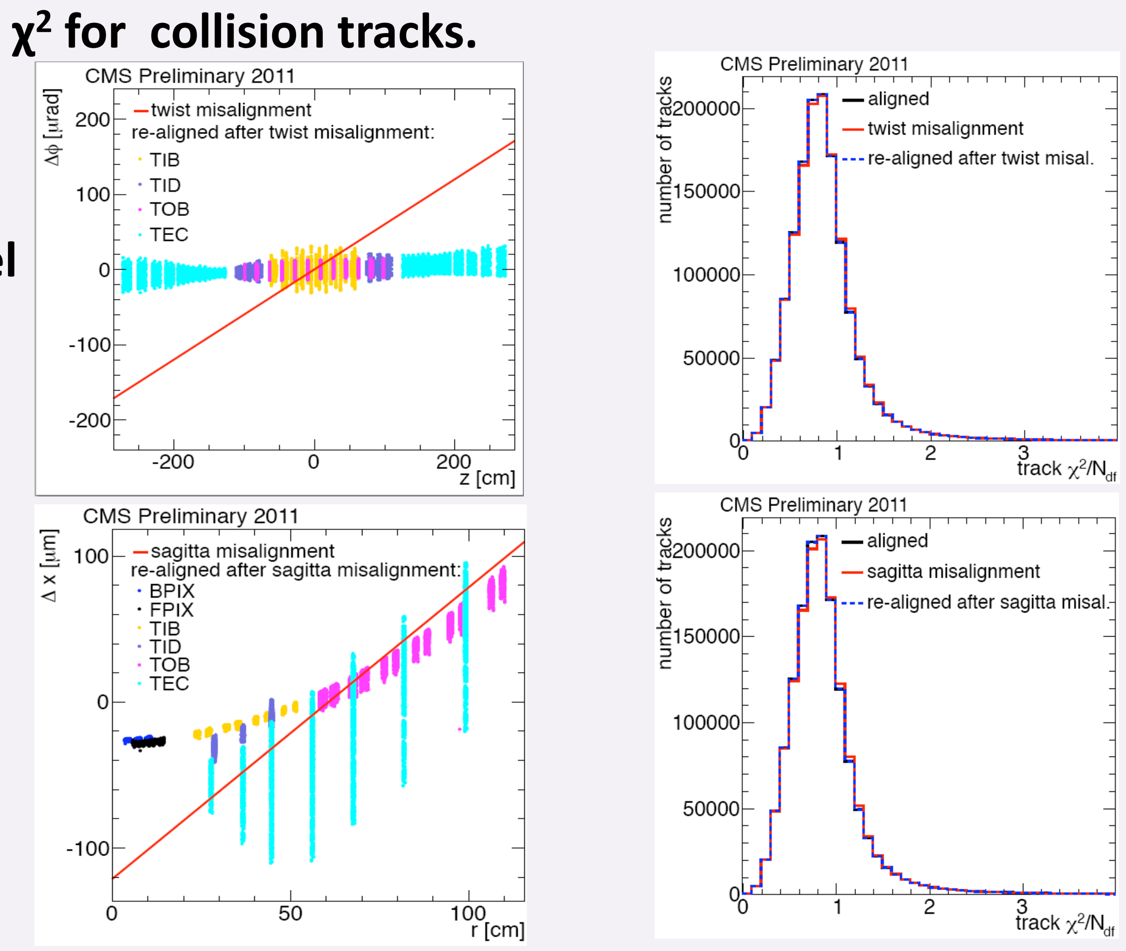




- These **weak modes** might affect track parameters significantly
  - Twist changes the track curvature of positively & negatively charged particles oppositely, biasing measured p_t
  - Bias more pronounced for larger Δη ➡ More severe for less boosted high mass resonances
- Twist cured adding external information from Z → mummu decay
- Re-parametrise muon tracks by common fit object: 9 instead of 2x5 parameters
- Add Z mass as virtual measurement in alignment contributes in removing the twist dependence

Sensitivity to Weak Modes

- Run alignment with same Summer 2011 strategy and input data on top of systematically misaligned geometry.
- Compare resulting geometry (module-by-module difference w.r.t. Summer 2011 geometry) and track χ^2 for collision tracks.



- χ^2 for collision tracks unaffected by misalignment
- Applied twist misalignment eliminated after re-alignment: usage of virtual Z0 mass measurement.
- Sagitta (Δx = c. r) misalignment not fully recovered by alignment procedure ➡ reduced bias in barrel region, still large induced scattering of modules in endcaps

Summary

- Large apparatus & finer segmentation of the CMS Si Tracker is a challenge for the alignment
- In the Summer 2011 with track based alignment 200 K parameters were determined
  - Sensor bows & kinks
  - Following time dependent movements of large pixel structures
  - Weak modes in alignment were suppressed by using cosmic tracks & by using the Z mass
- Main working horse: Millipede II interfaced with CMS software with General Broken Lines ➡ Global fit approach in < 10 h wall clock time

2011 CMS Tracker Alignment has provided desired precision for physics analysis discoveries

References:[1] CMS Detector Performance Summary DP 2012/004 ; [2] Twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK

[3] V. Blobel, 'Software alignment for tracking detectors', NIM A566 (2006) 5

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