Alignment procedures for the CMS Silicon Tracker detector during pp collisions

Roberto Castello\(^1\)
on behalf of CMS collaboration

\(^1\)Centre for Cosmology, Particle Physics and Phenomenology, Université Catholique de Louvain, Belgium

Roberto.Castello@cern.ch

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Outline

• Alignment of CMS Tracker detector
• Track based alignment: strategy in 2011 (used for Higgs searches)
• Achieved precision: from sensor deformation to the higher structures
• Control of systematic distortions
• Momentum scale using Z resonance
• Summary and prospects
Why do we need alignment?

- CMS Tracker complex system:
  - 1440 silicon pixel modules (2D measurement), 15148 silicon strip modules (r-\(\phi\) measurement)
  - 24244 sensors in total
  - \(\sigma_{hit}\): Pixels/Strips, 9\(\mu\)m/20-60 \(\mu\)m

Expected \(\sigma_{align} < 10 \mu\)m: need in situ track-based alignment

- \(\frac{\delta p_T}{p_T} = C_1 \cdot p_T \oplus C_2\)
- \(C_1\) depends on the detector geometry: \(C_1 \propto \frac{\sigma_x}{\sqrt{n \cdot B \cdot L^2}}\)
- \(\sigma_x \sim \sqrt{\sigma_{hit}^2 + \sigma_{align}^2}\)
Track based alignment

Principle

- Several parallel planes providing 1D/2D measurement: displaced module in one layer cannot be treated independently, depends on shifts in other planes
- Tracks correlate alignment parameters: global fit approach

Alignment algorithm

- Minimizing the squares of normalised residuals, summing over many tracks:

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

- \( f_{ij} \) track model prediction at the position of the measurement, depending on the alignment \( p \) and track \( q_j \) parameters, \( m_{ij} \) the measurements (hit, Multiple Scattering expectation, ...) with uncert. \( \sigma_{ij} \)
- \( \chi^2 \) minimization leads to linear equation system \( A \cdot x = b \): solved with MillePede II [1] (MP), using \( f_{ij} \) linearization.
- Improved track model (General Broken Lines) [2] [3] allowed for a rigorous treatment of MS effects: increasing \( n_{par} \) for a charged particle in a \( B \) field to \( n_{par} = 5 + 2n_{scat} \), adding two deflection angles for each thin scatterers.
Strategy for 2011 Tracker alignment

Input dataset (~ 1/\(fb\)):
- 15M loosely selected isolated muon tracks, 3M low momentum tracks, 3.6M cosmic ray tracks and 375k muon track pairs from \(Z\) decays

Strategy (MP):
- MINRES: fast solution of lin. eq. system by (iteratively) minimizing \(|A \cdot x - b|\)
- \(O(200k)\) free alignment parameters: 5(6) rigid body-like + 3 bow parameters per sensor
- Time dependent rigid body alignment for larger pixel structures (modules within constant): 9 periods
- \(Z\) mass measurement as a constraint

Computing performances of final fit:
- Total CPU 44.5 h, wall 9:50 h
- efficient and fast turnaround
Sensor deformations

- **Bows**: if flat sensors are assumed, track angle dependence on the hit residuals
- **Kinks**: in TOB/TEC, typically 1.6 mrad

\[ \Delta w = \frac{\Delta u}{\tan \psi} \]

Determination of just kinks (for TOB and TEC) or just bows (TIB, TOB, TEC, BPIX) does not fully correct the dependence: only after consideration of both the dependence is much flatter. \( u_r = 2u/L_u, L_u = \) module length \)
Pixels: local precision

- Estimated from the RMS of the Distributions of the Medians of the Residuals (DMR) for each module (# hits > 30): more robust against MS
- Refitting data/MC design/MC misalignment geometry with 1.1 M isolated muons from Z, $p_T > 40$ GeV for a relative comparison of achieved precision

CMS Preliminary 2011

- Data close to design performances, misalignment scenario well reproducing it
- Collision tracks and module surface deformation allowed to significantly improve local precision in the Pixels w.r.t cosmic rays alignment [4]
Pixels: monitoring of large structures

- Correcting vs time relative pixel half barrels displacements
- Monitoring separation along z using unbiased vertex-track residuals: 9 time intervals found

Time dependence of pixel structure alignment accounts for separation as function of time: \( b \)-tagging insensitive to remaining 10 \( \mu \)m effect
Monitoring of large structures by Laser beams

- 434 strip modules (3%) are illuminated by infrared laser beams [5]
- The stability of the Strip Tracker sub-detectors calculated w.r.t. TOB as reference: 2000 triggers every 5 minutes (sync. with bunch crossings)

- **Relative** stability observed within a run (during stable running conditions)
- **Good absolute** stability during the 2011 \( pp \) collisions (w.r.t. reference run)
- Achieved resolution: **absolute** 2-4 \( \mu m/3-9 \mu rad \), **relative** 1-3 \( \mu m/1-3 \mu rad \)
The remaining challenge: control of global distortions

The weak mode problem:

- Alignment algorithms look for the geometry minimizing global $\chi^2$
- Given a track topology, there are global movements leaving global $\chi^2$ unchanged, but track parameters do change
- Bias on the track parameters ($p_T$), affecting physics measurement

**Example of twist mode**

How to constrain?

- Different input track topology: cosmics taken with and w/o $B$ field
- Standard candles: $Z \rightarrow \mu\mu$ mass constraint
- External informations: survey, cross alignment with other detectors

**Example of telescope mode**
Weak mode sensitivity: Twist deformation

- **Procedure**: geometry (A) misaligned according to 9 cylindrical modes [6] (B), then re-alignment with same strategy and inputs (C)

- **Validation**: module-by-module difference after subtraction of global movements and rotations ($\Delta = C - A$) and $\chi^2$ from loosely selected isolated muons ($p_T > 5\text{GeV}$)

- Usage of $Z \to \mu\mu$ constraint cures Twist: great achievement compared to previous alignment geometry ($\chi^2$ unchanged with collision tracks)
Weak mode sensitivity: Sagitta-like deformation

- After re-alignment large scattering in TID and TEC, reduced in Barrel region
- However, alignment is not able to fully recover the introduced sagitta misalignment: remaining global distortion is a weak mode for the geometry
- Accounted for in physics analysis dominated by momentum scale systematics (like $\sin^2\theta_W$, $\Lambda_B$ lifetime), by evaluating the effect of applying the remaining $\Delta$ on the geometry used for the results.
Momentum scale

- $p_T$ resolution dominated by Tracker up to 200 GeV
- Twist results in curvature changes, biasing measured $p_T$ of pos. or neg. tracks oppositely $\rightarrow$ effect on $M_Z$ (red): $\partial(M_Z^2)/\partial \tau \sim (p_{\mu^-} - p_{\mu^+})$
- Adding Z mass as virtual measurement (5x2 $\rightarrow$ 9 parameters), RMS as uncertainty: keeps twist under control (blue)

- Sinusoidal modulation of $M_Z$ vs $\phi$ still visible in the geometry ($\sim$200 MeV):
  - mostly harmless, since physics integrated over $\phi$
  - hints for a strong reduction when reweighing more the $Z \rightarrow \mu\mu$ event topology in alignment procedure
Summary

- Large CMS silicon Tracker: a challenge for alignment
- Track based alignment in 2011 performed with $\sim 200k$ parameters:
  - determining sensor bows and kinks
  - following time dependent movements of large pixel structures
  - controlling weak modes changing momentum using the $Z$ mass
- Achieved local precisions in the Pixels and Strips match CMS requirements
- Remaining systematic distortions not constrained by alignment procedure are accounted in the analysis as systematics
- Studies ongoing to understand origins: hints for possible reduction

Tracker alignment keeps serving CMS physics with high precision

...contributing to the 'recent' physics discoveries.
References

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