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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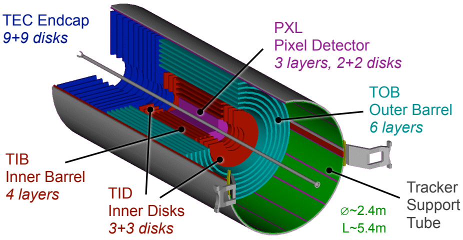
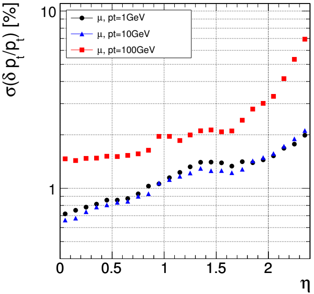
Outline

- 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-ϕ measurement)
- 24244 sensors in total
- σ_{hit}: Pixels/Strips, 9μm/20-60 μm

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

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

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:

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

- f_{ij} track model prediction at the position of the measurement, depending on the alignment $(\mathbf{p})$ and track $(\mathbf{q}_j)$ parameters, m_{ij} the measurements (hit, Multiple Scattering expectation, ...) with uncert. σ_{ij}
- χ^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.

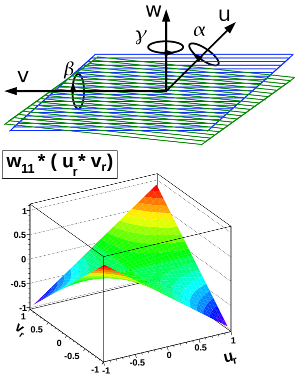
Strategy for 2011 Tracker alignment

Input dataset ($\sim 1/fb$):

- 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 $|A \cdot x - b|$
- $O(200\text{k})$ 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

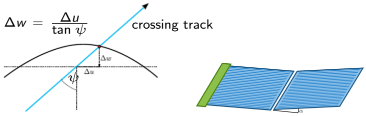


Computing performances of final fit:

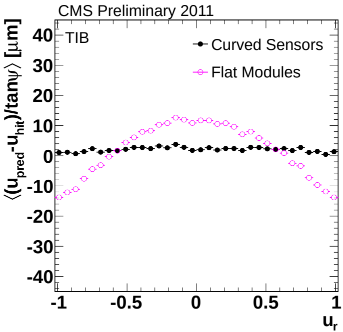
- Total CPU 44.5 h, wall 9:50 h
- efficient and fast turnaround

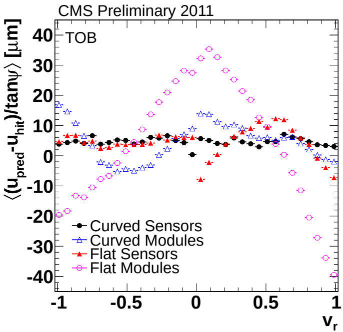
Sensor deformations

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



Visualization of bows and kinks

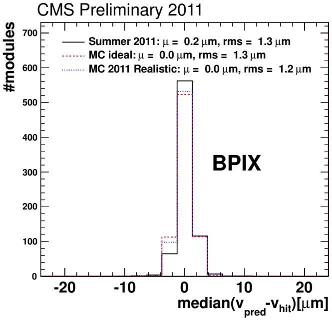


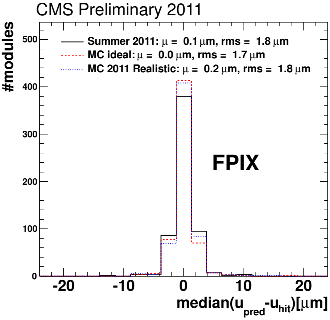


- Determination of just kinks (for TOB and TEC) or just bows (TIB, TOB, TEC, BPIX) does not fully correct the dependence: only after consideration of both the dependence is much flatter. ($u_r = 2u/L_u$, L= module length)

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

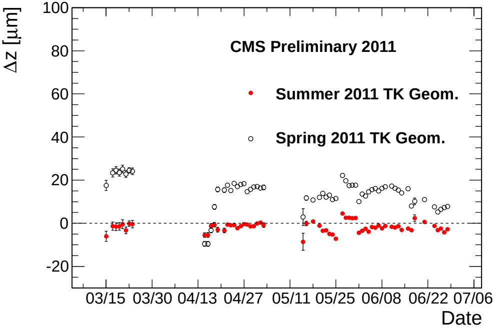


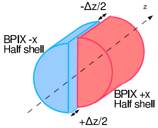


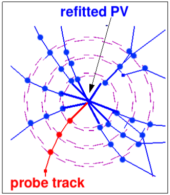
- Data close to design performances, misalignment scenario well reproducing it
- Collision tracks and module surface deformation allowed to significantly improve local precision in the Pixels w.r.t cosmic rays alignment [4]

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



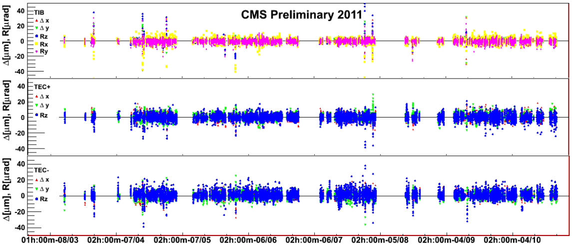




- Time dependence of pixel structure alignment accounts for separation as function of time: *b*-tagging insensitive to remaining 10 μm effect

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)

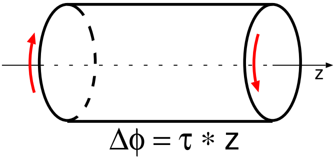


- *Relative* stability observed within a run (during stable running conditions)
- Good *absolute* stability during the 2011 *pp* collisions (w.r.t. reference run)
- Achived resolution: *absolute* 2-4 μm/3-9μrad, *relative* 1-3 μm/1-3 μrad

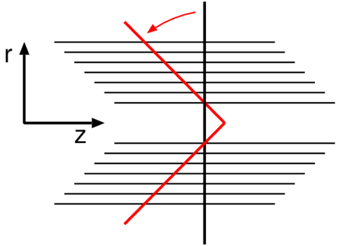
The remaining challenge: control of global distortions

The *weak* mode problem:

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



Example of twist mode



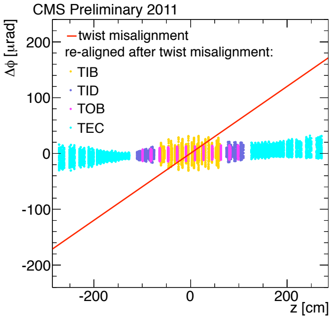
Example of *telescope* mode

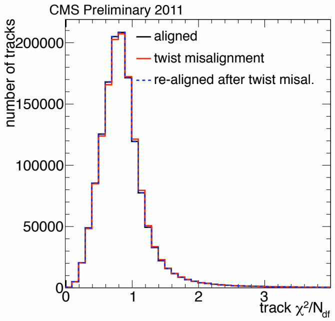
How to constrain?

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

Weak mode sensitivity: Twist deformation

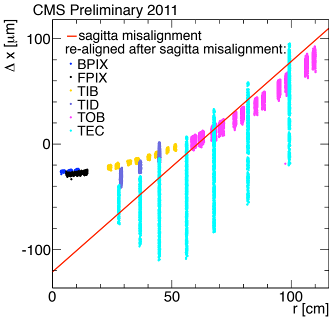
- Procedure: geometry (A) misaligned according to 9 cylindrical modes [6] (B), then re-alignment with same strategy and inputs (C)
- Validation: module-by-module difference after subtraction of global movements and rotations ($\Delta =$C-A) and χ^2 from loosely selected isolated muons ($p_T > 5$GeV)

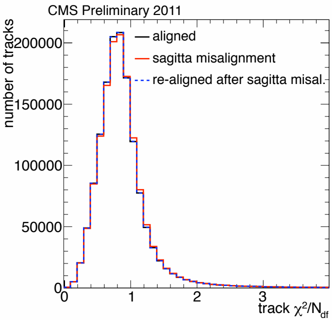




- Usage of $Z \to \mu\mu$ constraint cures Twist: great achievement compared to previous alignment geometry (χ^2 unchanged with collision tracks)

Weak mode sensitivity: Sagitta-like deformation

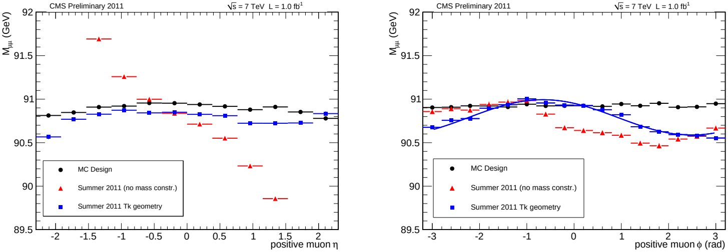




- After re-alignment large scattering in TID and TEC, reduced in Barrel region
- However, alignment is not able to fully recover the introduced sagitta misalignment: remaining global distortion is a *weak* mode for the geometry
- Accounted for in physics analysis dominated by momentum scale systematics (like $sin^2\theta_W$, Λ_B lifetime), by evaluating the effect of applying the remaining Δ 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): $\partial(M_Z^2)/\partial\tau \sim (p^z_{\mu-} - p^z_{\mu+})$
- Adding Z mass as virtual measurement (5x2 $\rightarrow$ 9 parameters), RMS as uncertainty: keeps twist under control (blue)



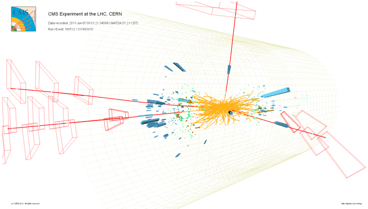
- Sinusoidal modulation of M_Z vs ϕ still visible in the geometry (~200 MeV):
  - mostly harmless, since physics integrated over ϕ
  - hints for a strong reduction when reweighing more the $Z \rightarrow \mu\mu$ event topology in alignment procedure

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.



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