Alignment procedures for the CMS silicon tracker

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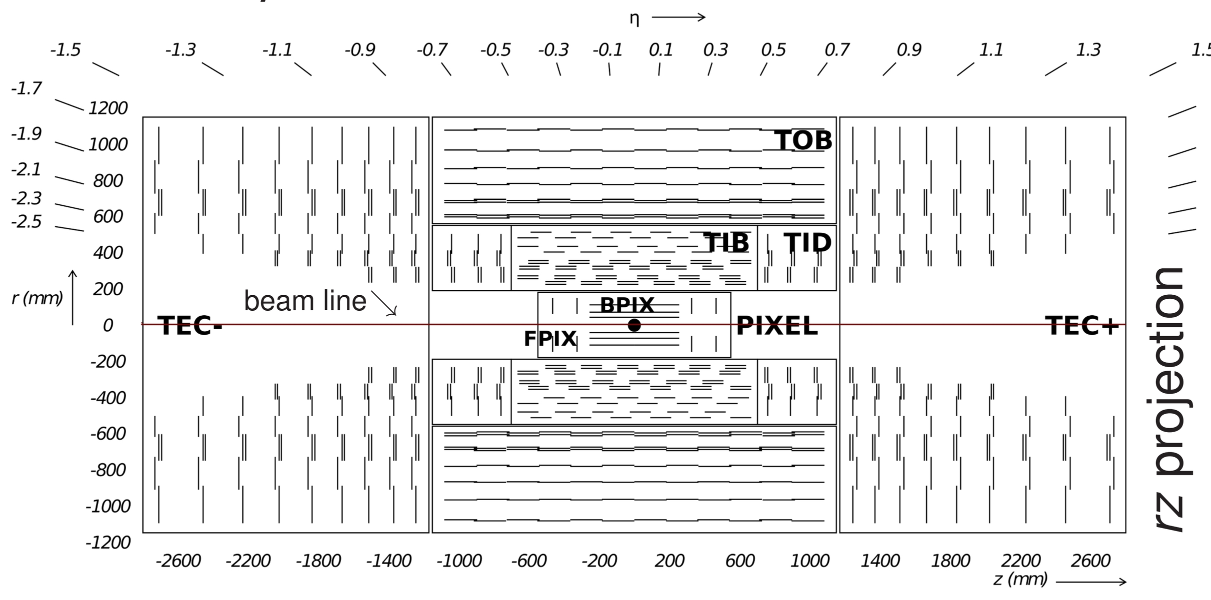
The CMS silicon tracker

The all-silicon tracker, located in the innermost part of CMS, is used to reconstruct particle trajectories and vertices. It is operated in a magnetic field of 3.8 T provided by a superconducting solenoid. The tracker is mechanically divided into several subdetectors.



The pixel detector comprises the interaction region and provides two-dimensional position measurements with a resolution of up to 9 μm. It is surrounded by the silicon strip modules providing one-dimensional measurements mainly in the transverse plane ($r\phi$). Those at outer radii consist of two daisy-chained sensors. The resolution of the strip modules is typically between 23 and 60 μm. **In total, the CMS tracker is equipped with 24244 silicon sensors**

- Analysis of physics processes requires precise knowledge of the sensor positions of the order of $< 10\ \mu$m. Therefore, at CMS sophisticated alignment algorithms are employed.

The summer 2011 tracker alignment strategy

- Misalignment generally broadens track-hit residuals.

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

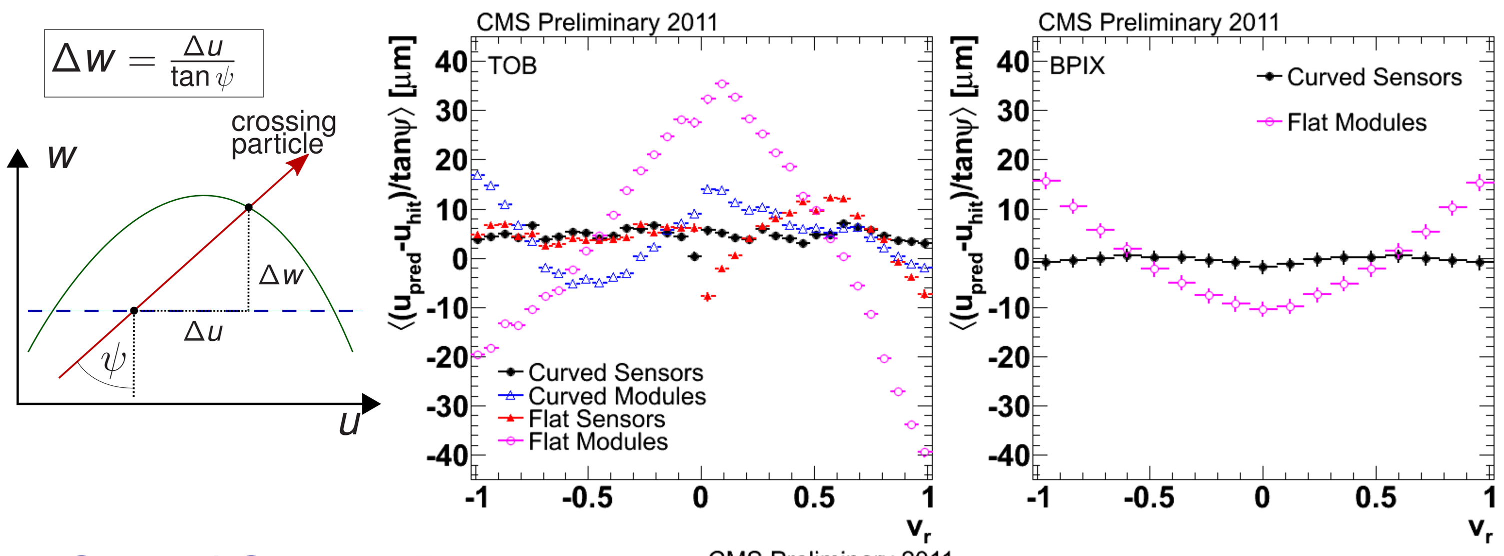
- **χ^2 minimisation using largely parallelised Millepede-II:**
  - → simultaneous linear least squares fit of all alignment parameters (**p**) accounting for their correlations due to the track parameters ($\boldsymbol{\tau}$)
- **More than 200000 alignment parameters determined:**
  - → typically 9 parameters for pixel sensors
    - 3 translations + 3 rotations + 3 parameters accounting for sensor surface deformations
  - → 8 alignment parameters for strip sensors
    - 2 translations + 3 rotations + 3 for sensor surface deformations
  - → time-dependent alignment of larger pixel structures
    - 3 translations + 3 rotations in 12 time intervals
- **Special treatment of muon tracks from $Z^0 \to \mu^+\mu^-$ decay:**
  - → replacing 2 × 5 muon track helix parameters by 9 parameters in common fit object
  - → usage of Z^0 mass as virtual measurement
- **Common fit using about 23 million tracks:**
  - 375*k* muon pairs from Z^0 boson decay
  - 15*M* tracks of loosely selected isolated muons
  - 3*M* low momentum tracks
  - 3.6*M* cosmics tracks taken between LHC fills, during collisions, and before collision data taking
- during minimisation reading 13 times 46.5 GB of compressed data
- The CPU usage on an Intel® Xeon® L5520 with 2.27 GHz was 44.5 h corresponding to 9:50 h wall clock time using in total eight threads.

Module surface deformations

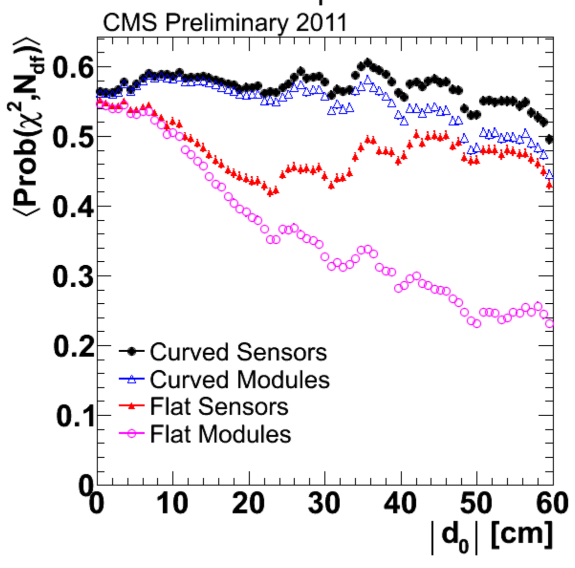
Motivation:

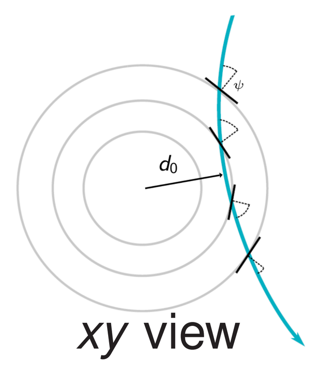
- → sensor surfaces are not flat (as assumed in track reconstruction), but bowed ⇒ "bows"
- → relative displacement between daisy-chained sensors within modules possible ⇒ "kinks"
- → Determination of "bows" and "kinks" in the alignment procedure.
- → Validated by determining average Δw residuals defined as $\langle \Delta w \rangle = \langle (u_{\text{pred}} - u_{\text{hit}}) / \tan\psi \rangle$.

Comparison of alignments with different module shape parametrisations (based on summer 2011 alignment):



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





Results/Effects:

- → For the "Flat Modules" geometry a strong track angle and position dependence on the hit residuals is observed. ⇒ Eliminated after incorporation of kinks/bows in alignment.
- → Determination of bows removes visible structure in BPIX ⇒ Particularly important for forward tracks due to their large incident angle.
- → Improved track fit probability for cosmic ray tracks when kinks and bows are taken into account. ⇒ Fully exploit complementarity of cosmics and collision tracks in alignment.

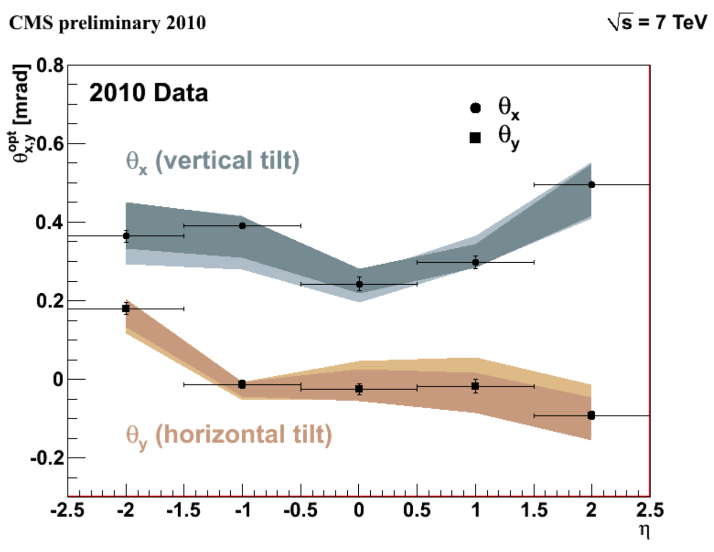
Tracker tilt angles

Utilisation of standalone approach to determine tilt angles, θ_x and θ_y, of the whole tracker with respect to the magnet field

- Scan θ_x and θ_y parameter space.

Exploiting three different track quality estimators:

1. average normalised track-χ^2: $\langle \chi^2/N_{df} \rangle$
2. average track χ^2 probability: $\langle \text{Prob}(\chi^2, \text{N}_{\text{df}}) \rangle$
3. total track χ^2: $\sum_i \chi_i^2$



Minimisation of track quality estimators:

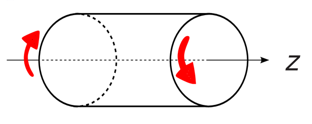
- → Vertical tilt of $0.3 \pm 0.1\,(\text{sys.})$ mrad observed.
- → Included in geometry description to reduce systematic biases in track reconstruction.

Weak mode sensitivity of 2011 alignment

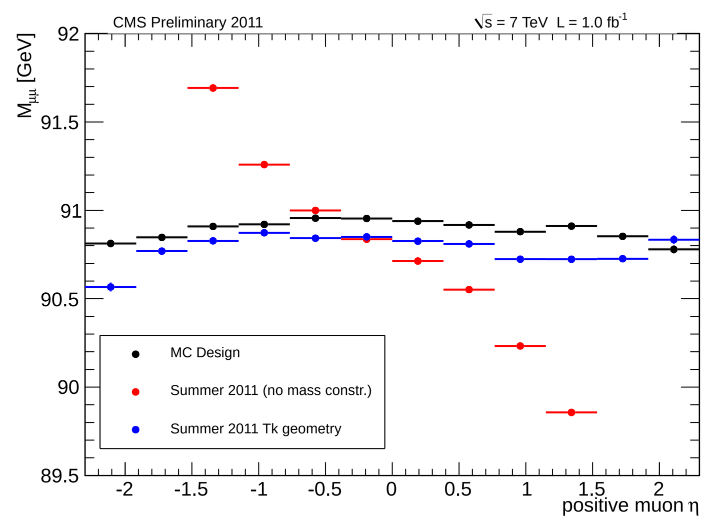
By minimising χ^2 in general not all possible distortions of the tracker can be resolved.

- → The residuals can be insensitive to certain global deformations.
- → However, these **weak modes** might affect track parameters significantly even though the χ^2 function remains unchanged.
  - Consideration of cosmic ray tracks controls several weak modes.
  - In addition include physics observables into the alignment

Effect of tracker twist deformation ($\Delta\phi = c \cdot z$):



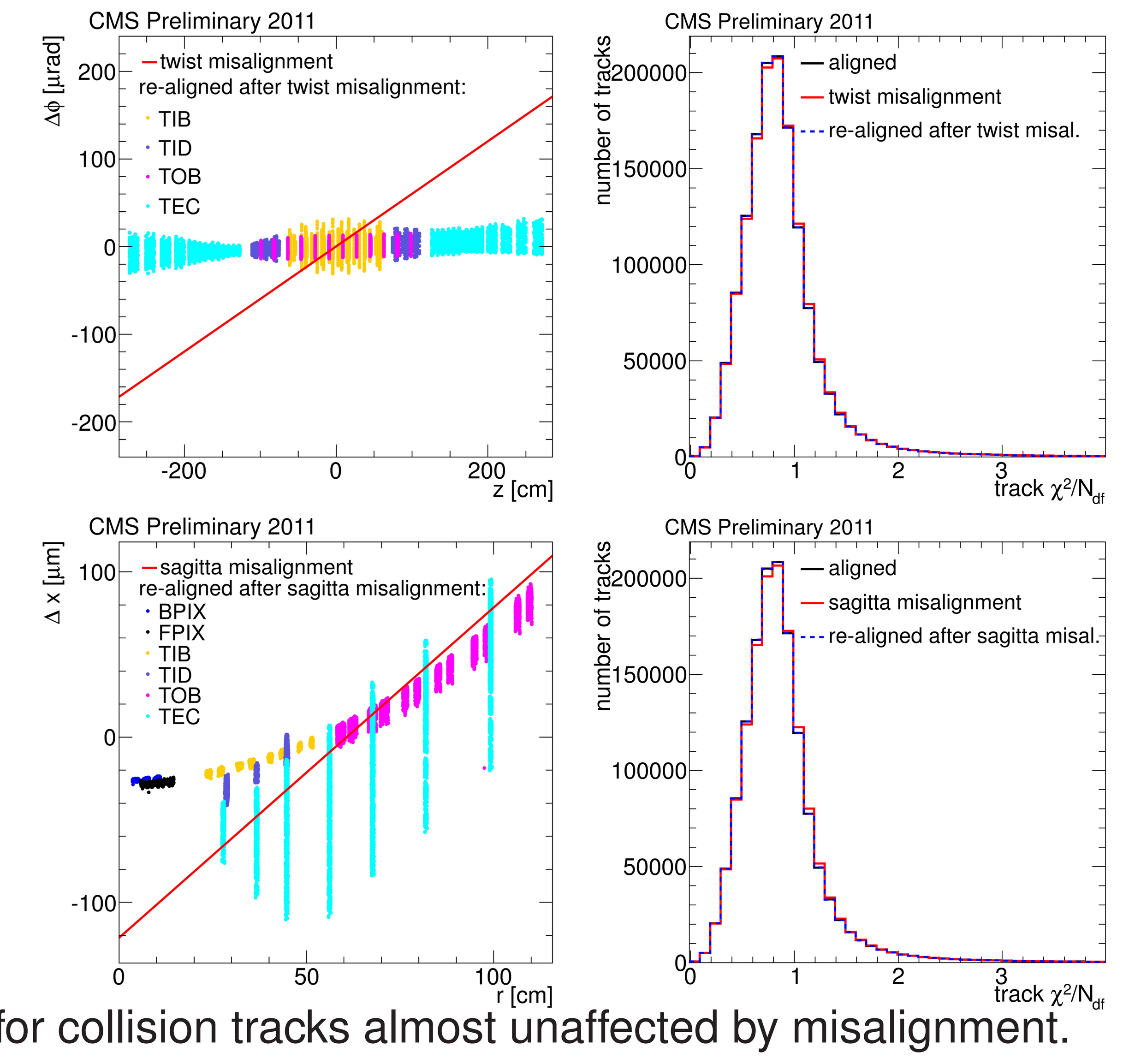
- Twist changes the track curvature of positively and negatively charged particles oppositely.
  - → Typical signature: positive muon dependence of $M_{\mu^+\mu^-}$ on η.
  - → Bias more pronounced for large $\Delta\eta$ ⇒ More severe for less boosted high-mass resonances.



- → Implementation of virtual mass measurement in alignment removes dependence.

Study sensitivity to weak modes by adding basic distortions to the summer 2011 geometry:

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



- χ^2 for collision tracks almost unaffected by misalignment.
- Applied twist misalignment eliminated after re-alignment due to usage of virtual Z^0 boson mass measurement.
- Sagitta ($\Delta x = c \cdot r$) misalignment not fully recovered by alignment procedure.⇒ reduced bias in barrel region, large induced scattering of modules in endcaps

Conclusions: In the summer 2011 alignment more than 200000 parameters were determined including parameters that take into account surface deformations of sensors. Weak modes in the alignment were suppressed by including cosmic ray tracks and by utilising the information from $Z^0 \to \mu^+\mu^-$ decays. The orientation of the tracker with respect to the magnetic field was determined and taken into account. The achievements presented here have systematically improved the CMS tracker alignment compared to previous alignment campaigns.

References:

- CMS DP-2012/004; https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK
- Millepede II: V. Blobel NIM **A566** (2006) 5