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

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

\[
\chi^2(p,q) = \sum_{ij} \left( \frac{m_{ij} - f(p,q)}{\sigma_{ij}} \right)^2
\]

- Linearise track model & minimise

\[
C = \begin{bmatrix} a \end{bmatrix} + \begin{bmatrix} b \end{bmatrix} \begin{bmatrix} p \end{bmatrix}
\]

Local parameters appear in part of the data only

**Preparation of Data**
- 246 parallel jobs (24.5 GB, 13 reads)
- Typical kink is \( \approx 1.6 \) módons

**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: \( \approx 200 \) k parameters were determined

**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 \( \mu \)m effect
- Minimising residuals can be insensitive to certain global distortions
- Potential bias on track parameters
- Dependent on data fed into matrix

**The Weak Mode Issue**
- These weak modes might affect track parameters significantly
- Twist changes the track curvature of positively & negatively charged particles oppositely, biasing measured \( \rho \)
- Bias more pronounced for larger \( \Delta \eta \)
- More severe for less boosted high mass resonances
- Twisted cabling external information from Z \( \rightarrow p \) muon decay
- Re-parametrise muon tracks by common fit object: \( 9 \) instead of \( 2 \times 5 \) parameters
- Add \( Z \) mass as virtual measurement in alignment: contributes in removing the twist dependence

### Experiment Independent Global Fit Tool
- Setting up & Solving Matrix Equation: \( C' p = b' \)
- Here \( C' \) is nnxm matrix (\( n \approx 200k \), typically sparse)
- Very demanding for memory & CPU

**Alignment Strategy & Results During 2011 pp Collision (1fb^{-1})**
- Run alignment with same Summer 2011 strategy
- Compare resulting geometry (module-by-module difference w.r.t. Summer 2011 geometry) and track \( \chi^2 \) for collision tracks.

**Alignment algorithms for > 100 k global parameters**
- Use linearised model
- Local track parameter
- Summing up contributions for all tracks

**Sensitivity to Weak Modes**
- \( \chi^2 \) for collision tracks unaffected by misalignment
- Applied twist misalignment eliminated after re-alignment: usage of virtual 20 mass measurement.
- Sagitta (\( \Delta x \approx c. \tau \) ) misalignment not fully recovered by alignment procedure reduced bias in barrel region, still large induced scattering of modules in endcaps

### References

- [CMS Detector Performance Summary DP 2012/004](http://cds.cern.ch/record/1440707)
- [Detector Performance Summary DP 2012/004](http://cds.cern.ch/record/1440707)
- [Detailed analysis of muon tracking performance with the CMS tracker, 2011](http://cds.cern.ch/record/1440707)

**Frontier Detectors For Frontier Physics, La Bidola, Italy, May 20-26, 2012**