Alignment of the CMS Silicon Tracker using Millepede II

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on behalf of the CMS collaboration

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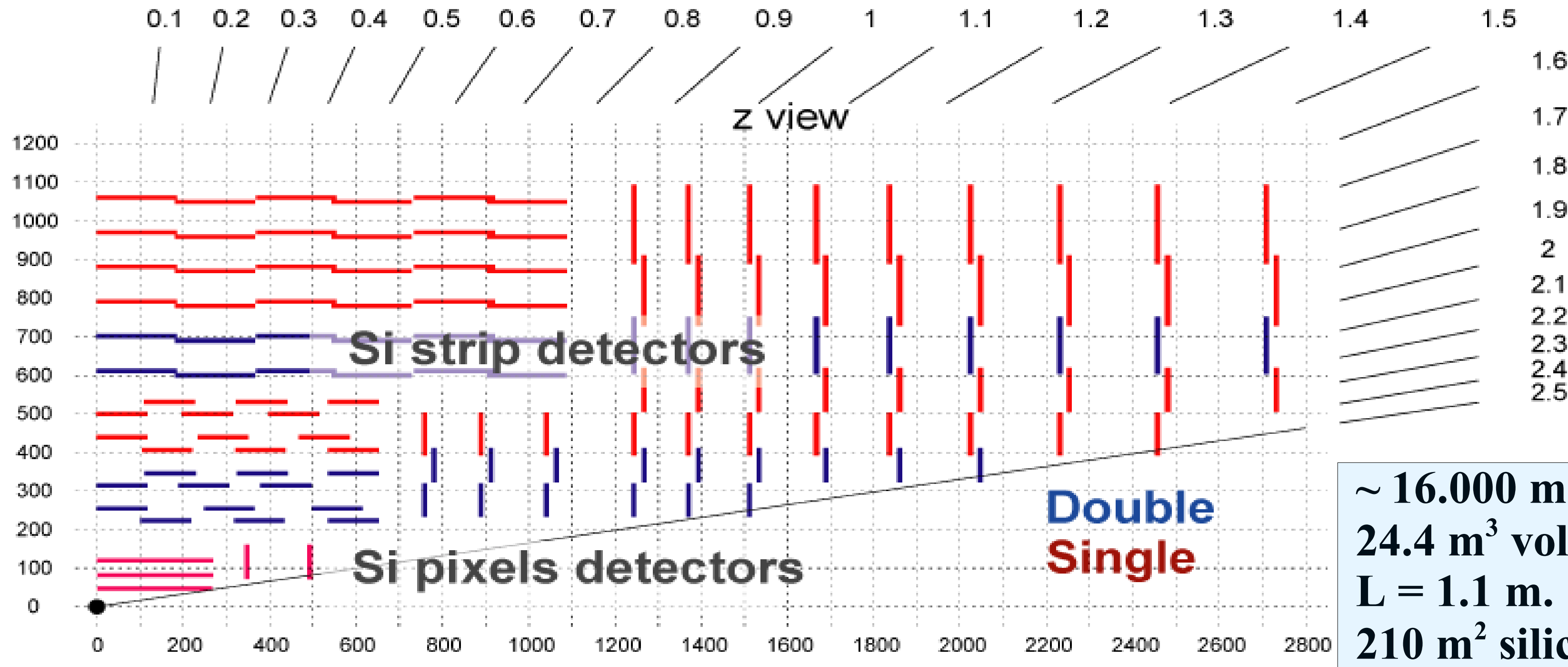
CMS Silicon Tracker



The layout of the CMS inner tracker

~ 16.000 modules.
24.4 m^3 volume.
L = 1.1 m.
210 m^2 silicon.
$|\eta| < 2.5$

The alignment task:

- About 50.000 geometry parameters need to be determined.
- Positions need to be known to the µm level.
- Modules are up to meters apart.
- LEP's golden alignment ee → µµ channel is missing.

The unique size and high resolution leads to a unique alignment challenge.

Problem of track based alignment

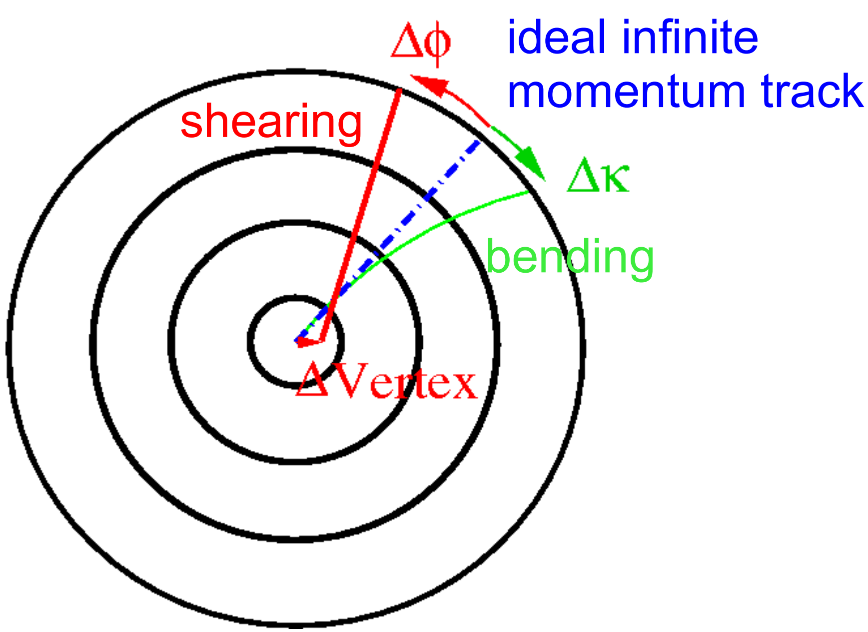
Concept: Track based alignment minimizes the average $\chi^2(\mathbf{a},\boldsymbol{\tau})$ of the track fits. (**alignment** parameters **a**, **track** parameters $\boldsymbol{\tau}$).

Problem: Some deformations of the tracker leave this χ^2 invariant.

- This is a generic problem independent of the used algorithm.
- These deformations dominate the remaining misalignment.
- They may bias track parameters.

Ideally we would have tracks with known track parameter values!

Example: Shearing and bending deformation.



More sources of information are required than single tracks from the interaction point yield!

Simultaneous Alignment Strategy

Sources of Information

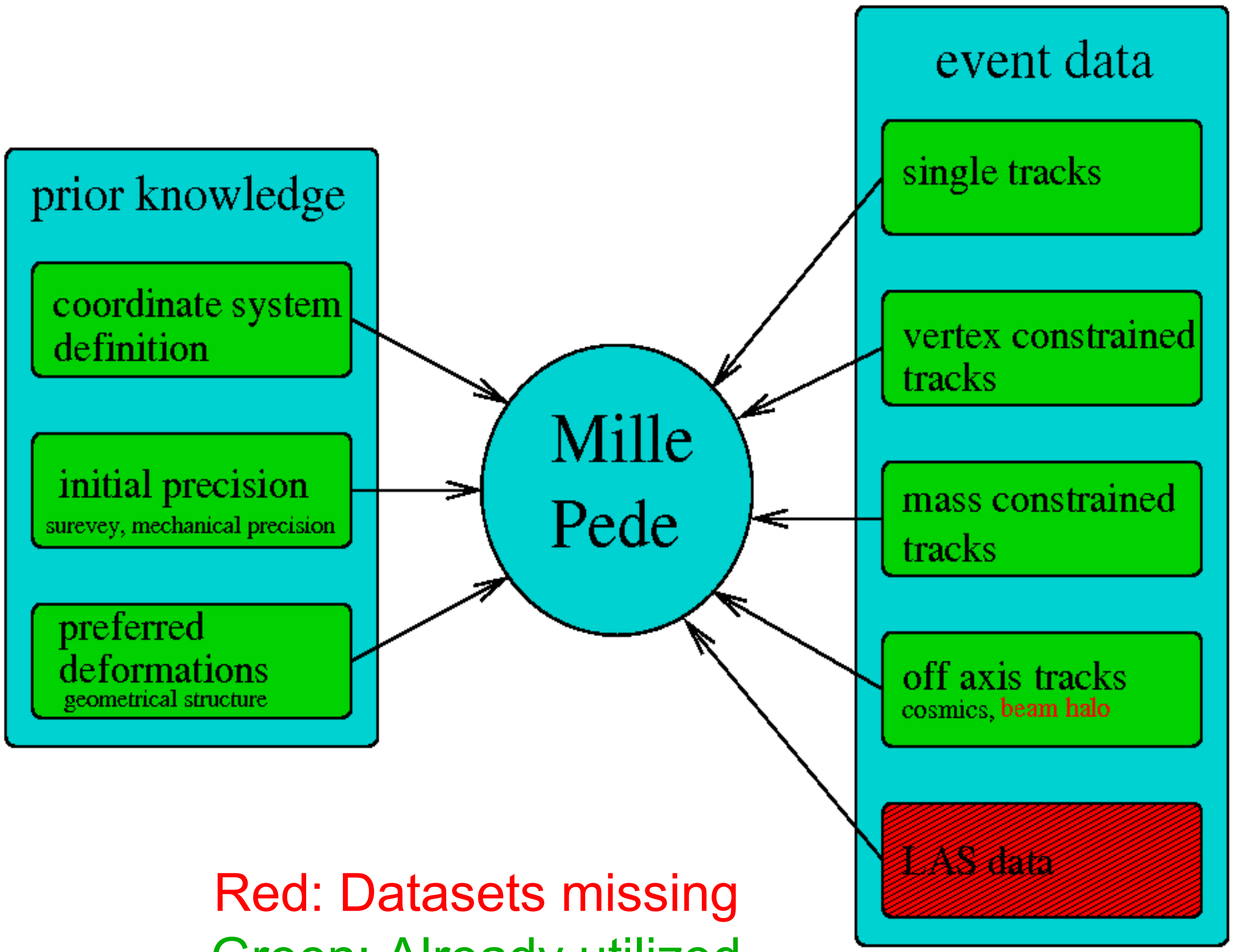
Prior knowledge:

- Known uncertainties of alignment parameters after survey measurements and mechanical mounting.
- The geometry of support structures is known.

Complementary data sets:

- Data sets like cosmic muons and beam halo muons reduce deformations.
- Constraints on the trajectory fit like mass and vertex constraint.

Schematic illustration of input to Millepede



Red: Datasets missing
Green: Already utilized

Simultaneous Alignment Strategy

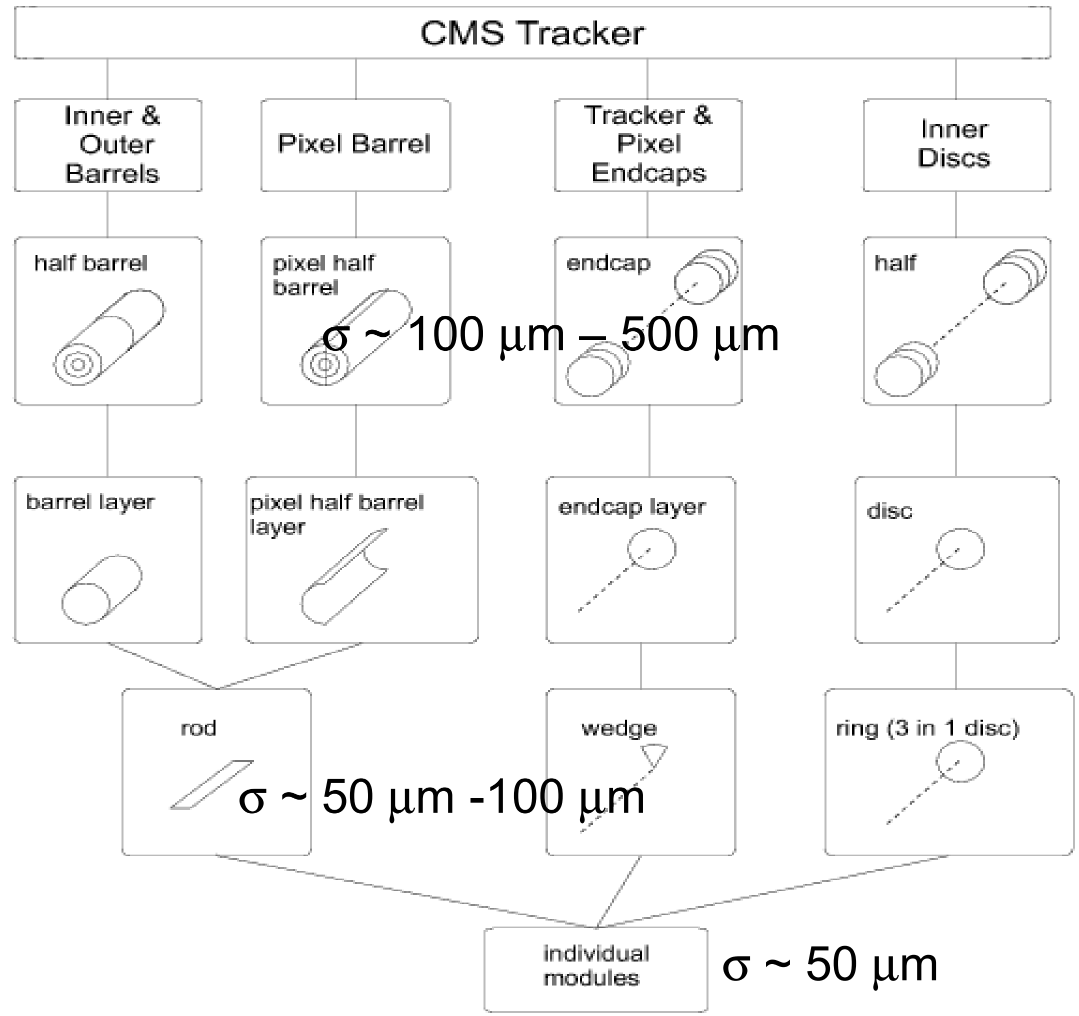
Hierarchical Structure of the Tracker

The tracker is composed of hierarchies of supporting structures.

- Modules or mounted on Rods/Petals/Ladders ...

This should be reflected in the alignment parametrization.

- Parameters for support structures are introduced.
- An equality constraints is needed for each parameter of a higher hierarchy!
- The **initial position uncertainty** of modules with respect to the next structure can be utelized.
- The initial displacement of modules is simulated in a correlated way.



Hierarchy of support structures.

Alignment Algorithm

The **average $\chi^2(a,\tau)$ of track fits** is dependent on all alignment parameters **a and** all track parameters τ.

All track and alignment parameters fitted **simultaneously** in an ideal algorithm, only alignment parameters need to be determined:

No track parameters fixed → no bias introduced!

All parameters free → **All correlations between alignment parameters taken into account!**

Constraints and uncertainties on alignment parameters need to be implemented. Preferably by standard methods (Lagrangian Multipliers and presigmas):

Prior knowledge can be implemented!

→ Is there a linear χ^2 minimization program capable to deal with millions of parameters and including standard methods for constraints?

Simultaneous Alignment Strategy

Millepede*

Linear χ^2 minimization including all track and alignment parameters:

millions of free parameters → **millions** x **millions** matrix

- Only **N** alignment parameters need to be determined
- A matrix size reduction leads to an **N**x**N** matrix.

This is the core of the Millepede algorithm.

Millepede II*

For the CMS tracker the **N**x**N** (**N** ~ 50.000) matrix is too large to be inverted.

Millepede II makes use of the sparsity of the matrix. Only **Matrix** x **vectors** operations occur.

- GMRES fast equation solver implemented in Millepede II.

This is the core of Millepede II.

*developed by V. Blobel
manual: http://www.desy.de/~blobel/mptalks.html

Full Scale Tracker Alignment Study

The **simultaneous alignment strategy** is tested for the **full strip and pixel tracker** of CMS. No reference modules are fixed.

Misalignment:

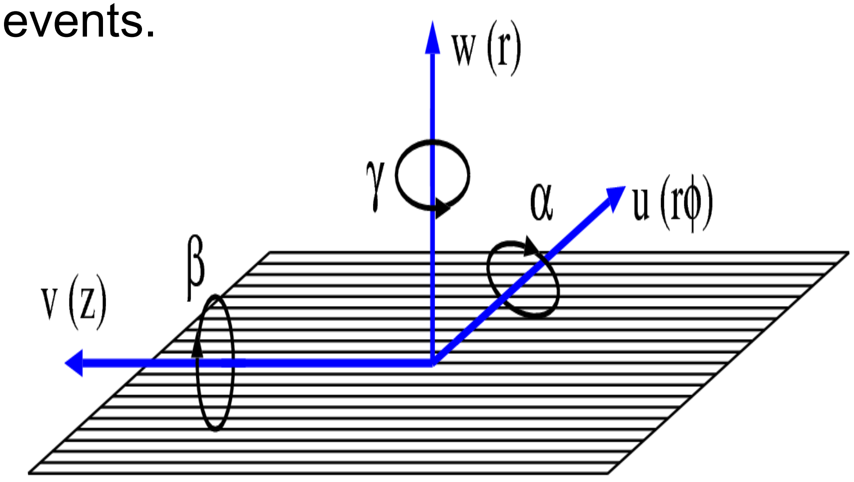
- Initial misalignment reflects starup-condition of CMS. Only pixel sensors are roughly prealigned to 15 μm precision.

Data sets:

- 0.5 M $Z^0 \rightarrow \mu\mu$ (0.5 fb^{-1}) events with mass and vertex constraint.
- 25 k cosmic μ with momentum > 50 GeV.
- Single μ of 1.5 M $Z^0 \rightarrow \mu\mu$ ~ 3 M $W \rightarrow \mu\nu$ (0.5 fb^{-1}) events.

Alignment parameters:

- All silicon modules (pixel+strip).
- 3 (2 for 1D) translation and the rotation around normal of sensor.

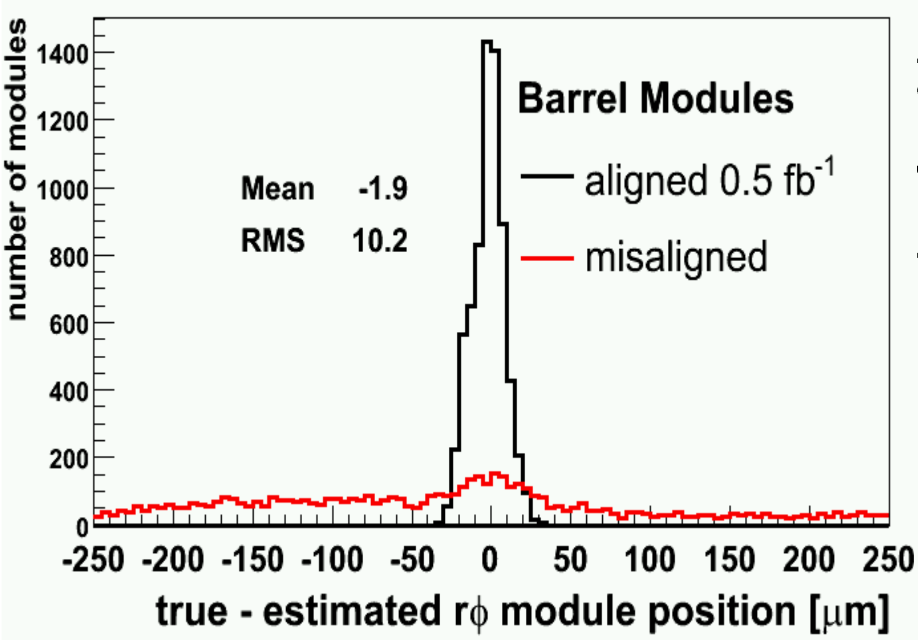


Coordinate Definition:

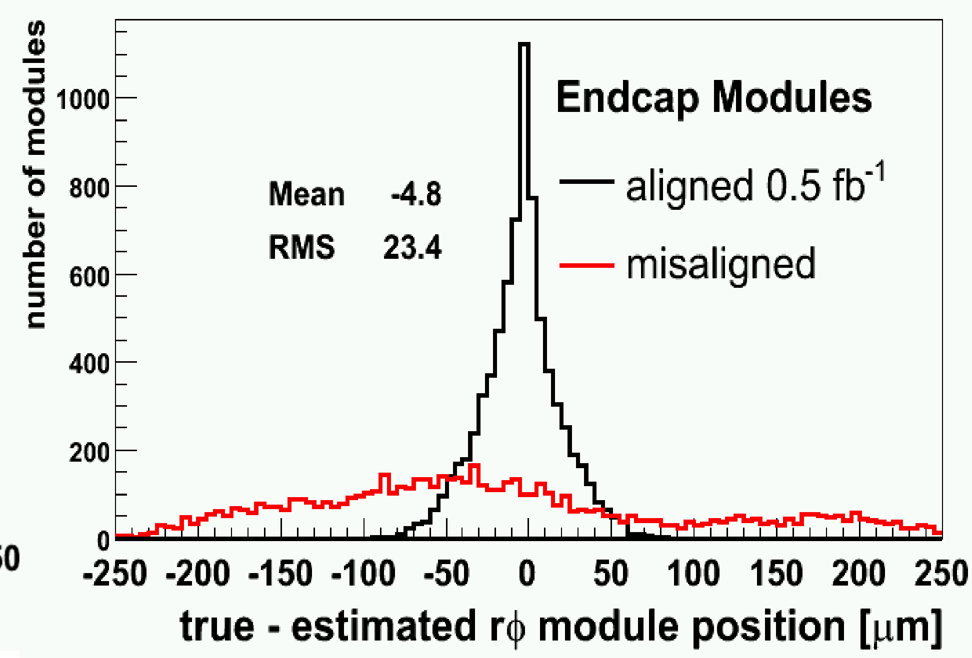
- Center of the pixel barrel sensors.
- Rotation of pixel barrel fixed.

Alignment Results: Position Residuals in rϕ

PB,TIB,TOB



PE,TID,TEC



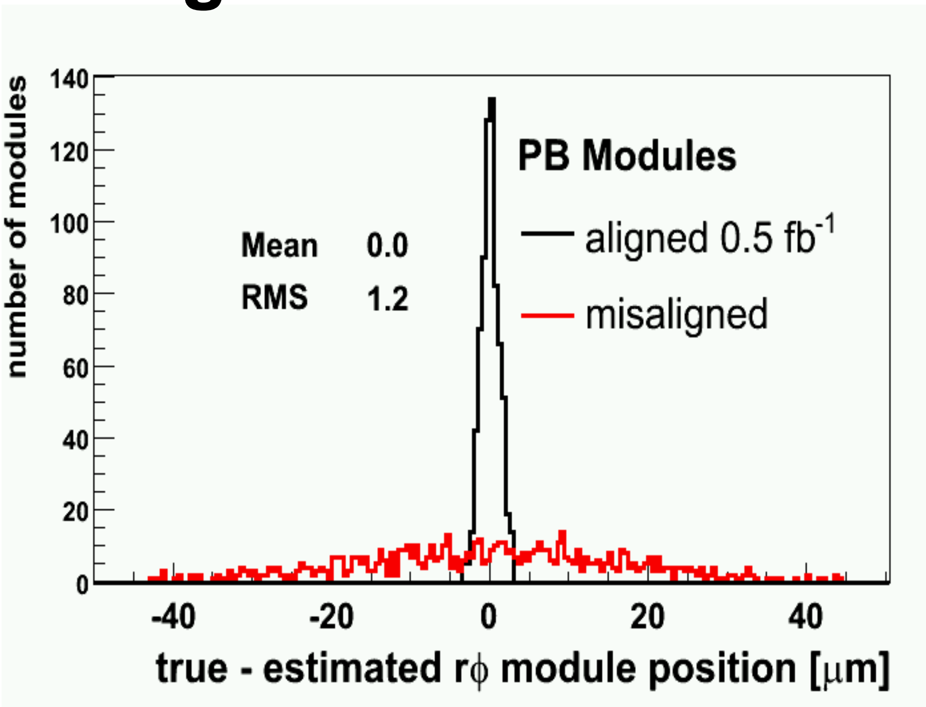
Barrel Modules RMS = 10 μm

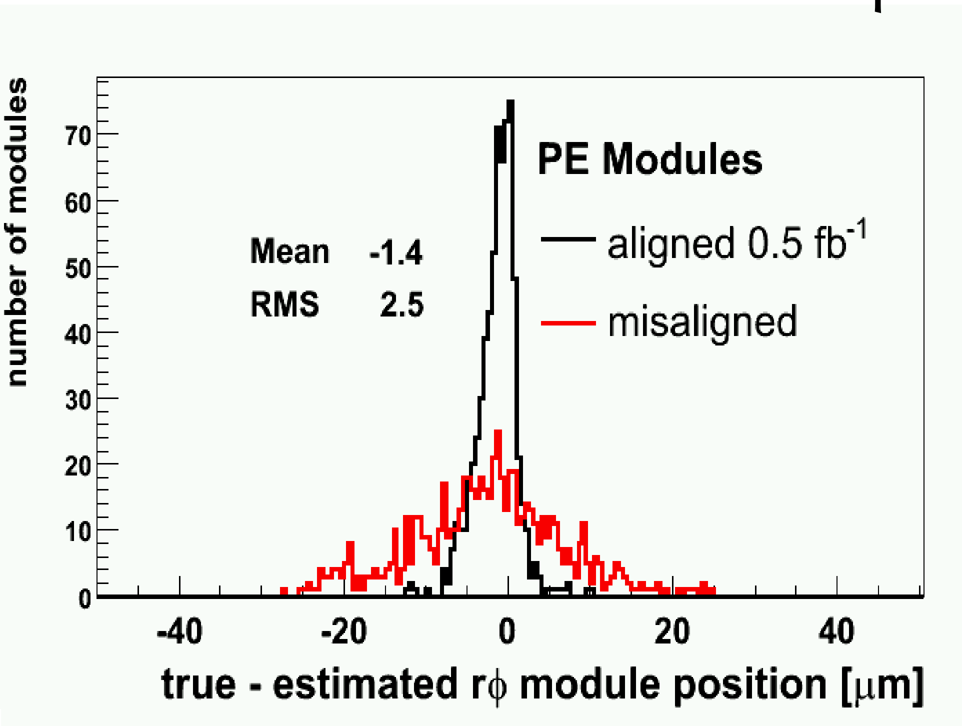
Barrel alignment precision significantly better than in the Physics TDR long term scenario.

Endcap Modules RMS = 23 μm

The mean is better than the long term scenario. The RMS is similar.

Alignment Results: Pixel Position Residuals in rϕ

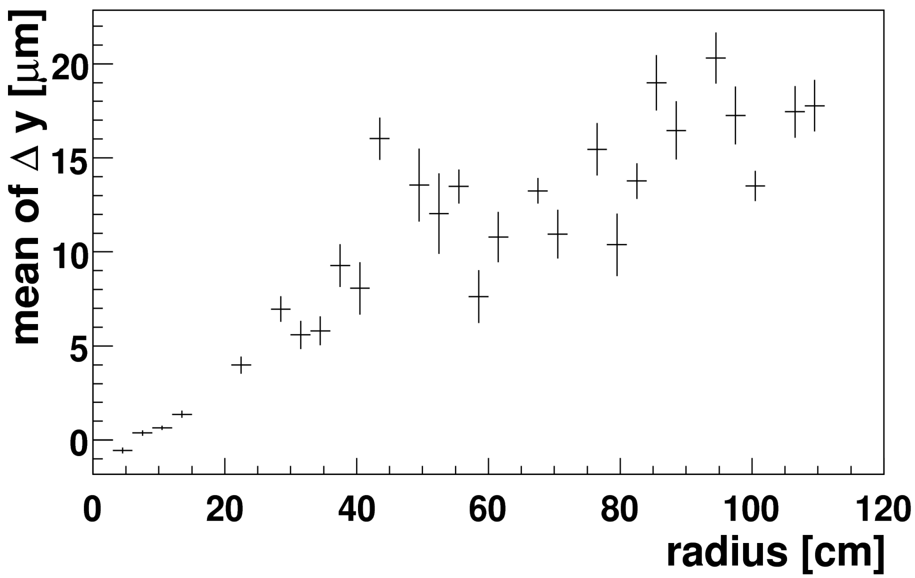




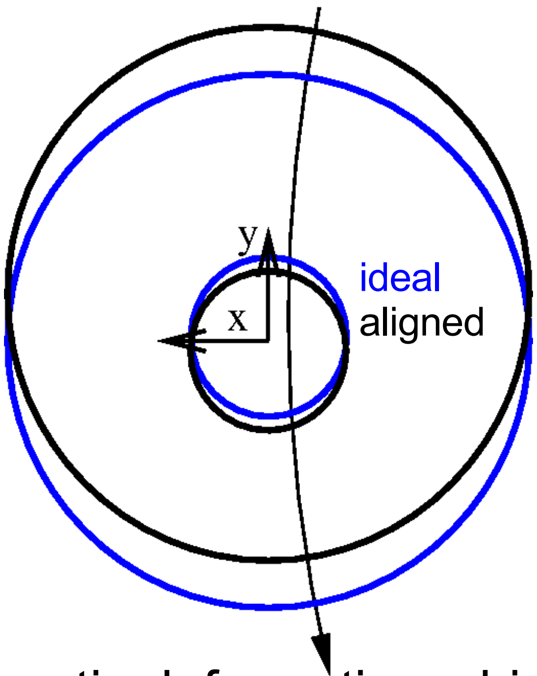
Pixel barrel RMS = 1 μm **Pixel endcap RMS = 2.5 μm**

- Pixel aligned to a precision < module resolution.
- No significant effect on vertex reconstruction would be expected.

Small Remaining Misalignment Effects



Mean displacement in global y for all modules. A linear increase with the radius is visible: A typical sign of the r-rϕ mode 1.

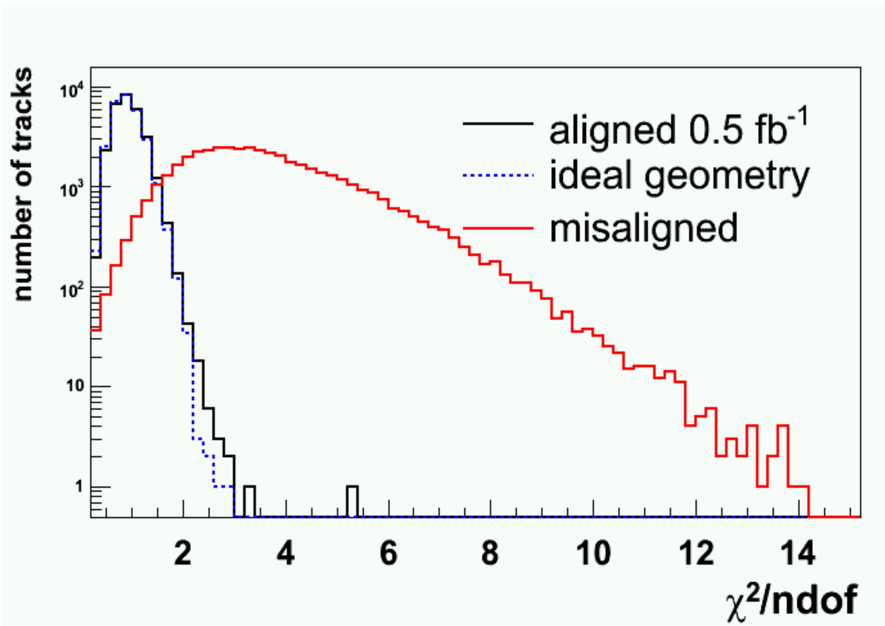


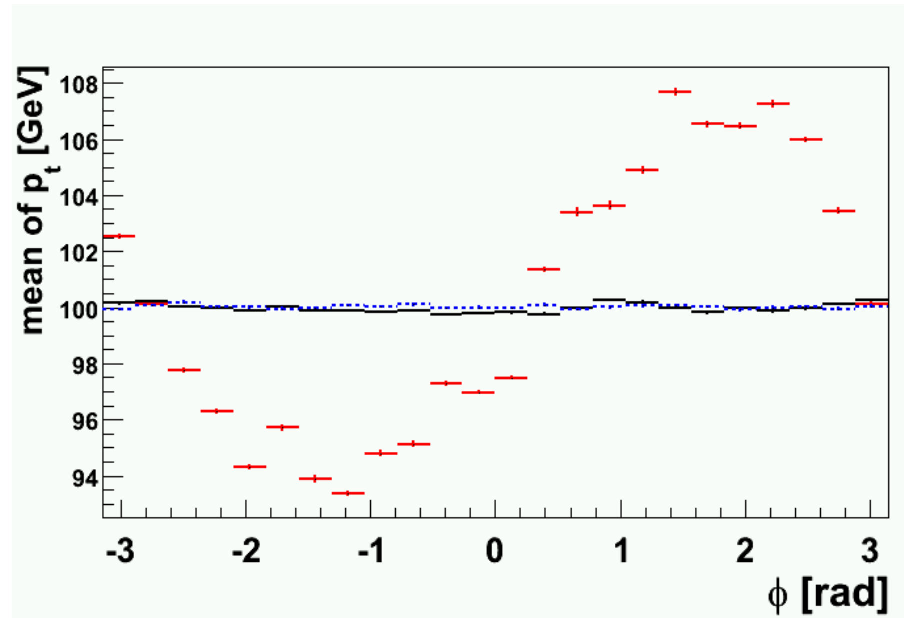
Schematic deformation which is not well determined. The black arrow indicates a typical cosmic muon track.

Small deformation remains and is the dominating source of the remaining misalignment

Control Plots

50.000 μ^+ tracks* with 100 GeV transverse momentum from vertex (0,0,0) used.





χ^2/ndof of track fits

- Pattern recognition would work properly.
- **χ^2/ndof minimized successfully**

Reconstructed p_t as function of ϕ

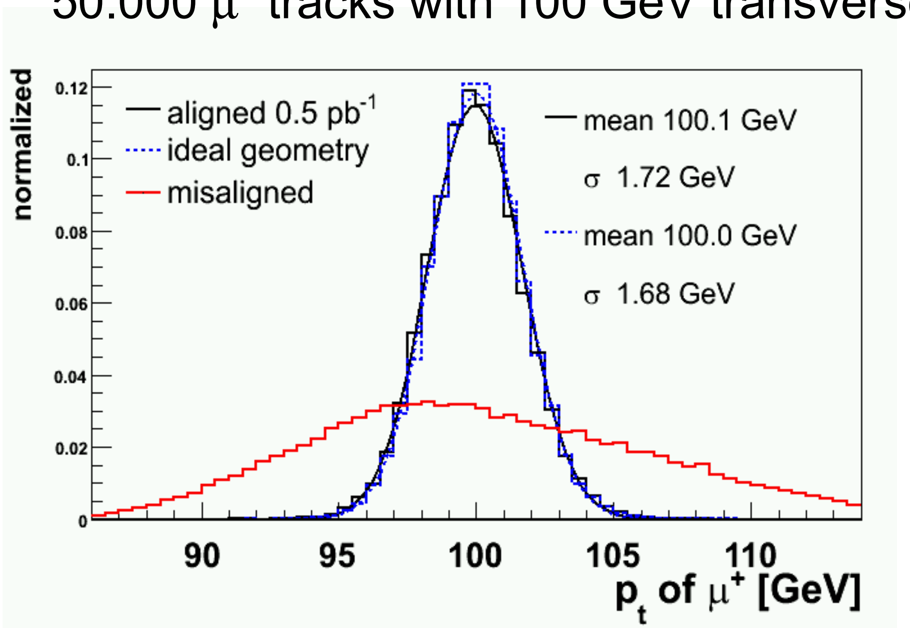
- Initially p_t bias of a few %.
- p_t bias of ~ 0.1 % after alignment.

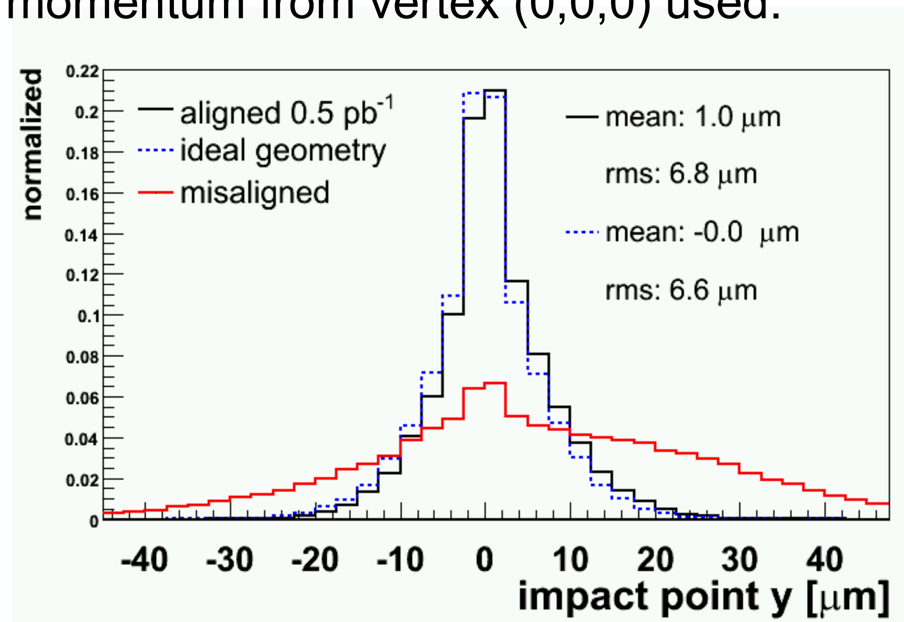
*Tracks from a particle gun without material interaction simulation.

Full Scale CMS Tracker Study

Resolution and Bias

50.000 μ^+ tracks with 100 GeV transverse momentum from vertex (0,0,0) used.





0.1% bias in p_t remains

Vertex shifted by 1 μm

- Vertex and p_t resolution would decrease only minimally.
- The effect on physics would be small.

Proof of principle for simultaneous alignment strategy!

Computing Requirements

The GMRES option with preconditioning with the band-Chauleky method was used:

- Matrix Density :15%.
- CPU time solving matrix equation: 10 min.
- Iterations for outlier rejection: 5.
- Matrix building: ~ 50 min.

Memory: 2GB
CPU time total: 1:40

- Hamburg resources: 64 Bit, 8 GB Memory.
- Still space for complementary datasets and more alignment parameters.

CPU and Memory needs modest!
Fast turnaround time!

Conclusion

Summary of alignment strategy:

- Complementary datasets to reduce deformations.
- Implementation of prior knowledge
- Simultaneous approach.
- Inclusion of all correlations between alignment parameters.

First successful test of a full alignment procedure for the CMS tracker!

Computing requirements are modest (2 GB, <2h)!

Outlook:

- Real data will lead to further challenges!
- A tested framework for alignment ready for real data alignment.
- Additional datasets will allow to give more emphasis on event data.

Proof of Principle shown!

Markus Stoye's Phd thesis with all the details: http://documents.cern.ch/cgi-bin/setlink?base=preprint&categ=cern&id=cern-thesis-2007-049

References

CMS studies and short algorithm description:

"Calibration and alignment of the CMS silicon tracker", PhD thesis **Markus Stoye**, Hamburg CERN-THESIS-2007-049 or DESY-THESIS-2007-0026:

http://documents.cern.ch/cgi-bin/setlink?base=preprint&categ=cern&id=cern-thesis-2007-049

Detailed algorithm description of Millepede II:

Millepede II manual draft, **Volker Blobel**:

http://www.desy.de/~blobel/mptalks.html