Track based Alignment of the CMS Tracker

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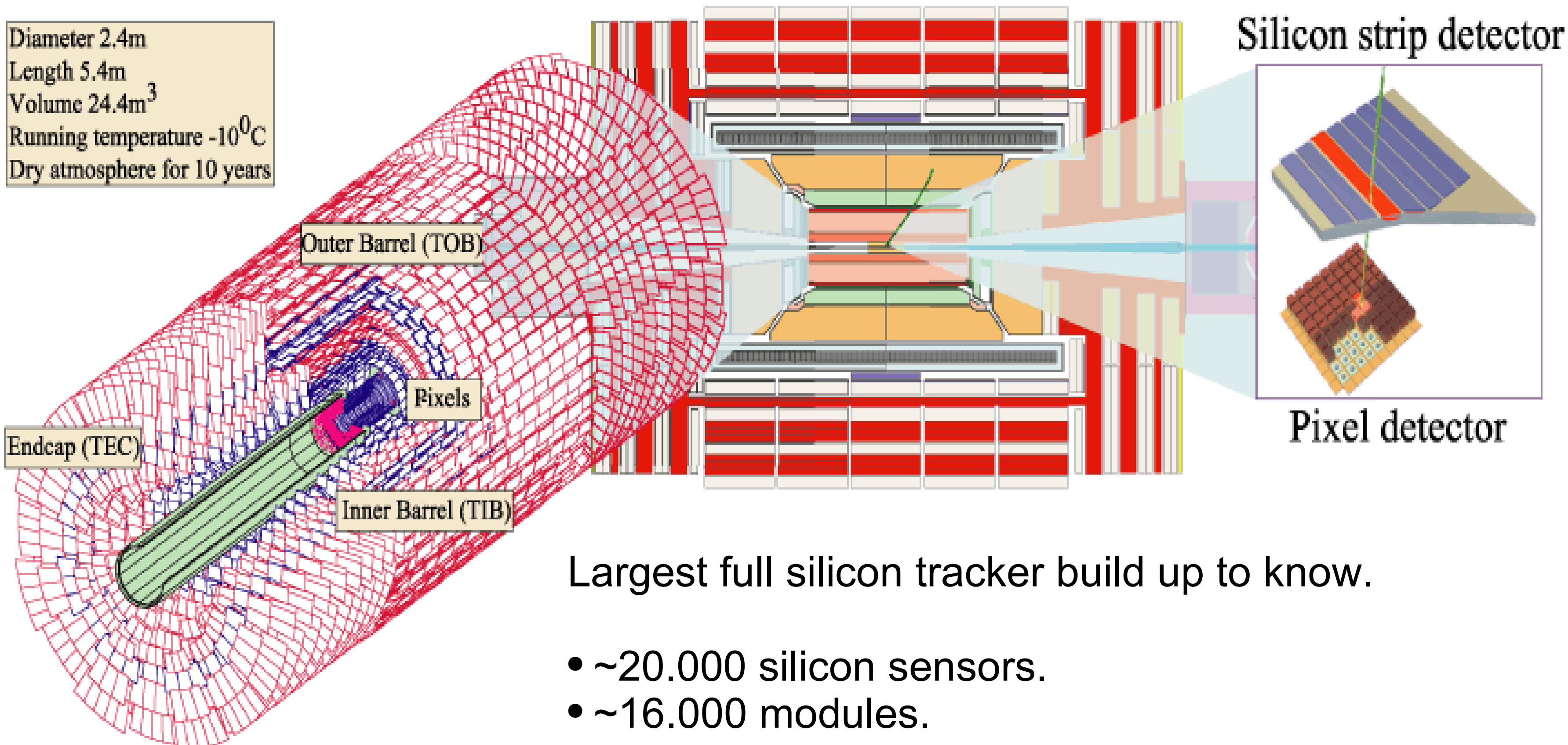
The CMS Tracker



Largest full silicon tracker build up to know.

- ~20.000 silicon sensors.
- ~16.000 modules.
- Sensor resolution 10-40 µm.
- $\Delta p_t/p_t$ at 1 TeV = 4.5%

The aim of alignment is to reduce effects due to module position uncertainties to a negligible amount.

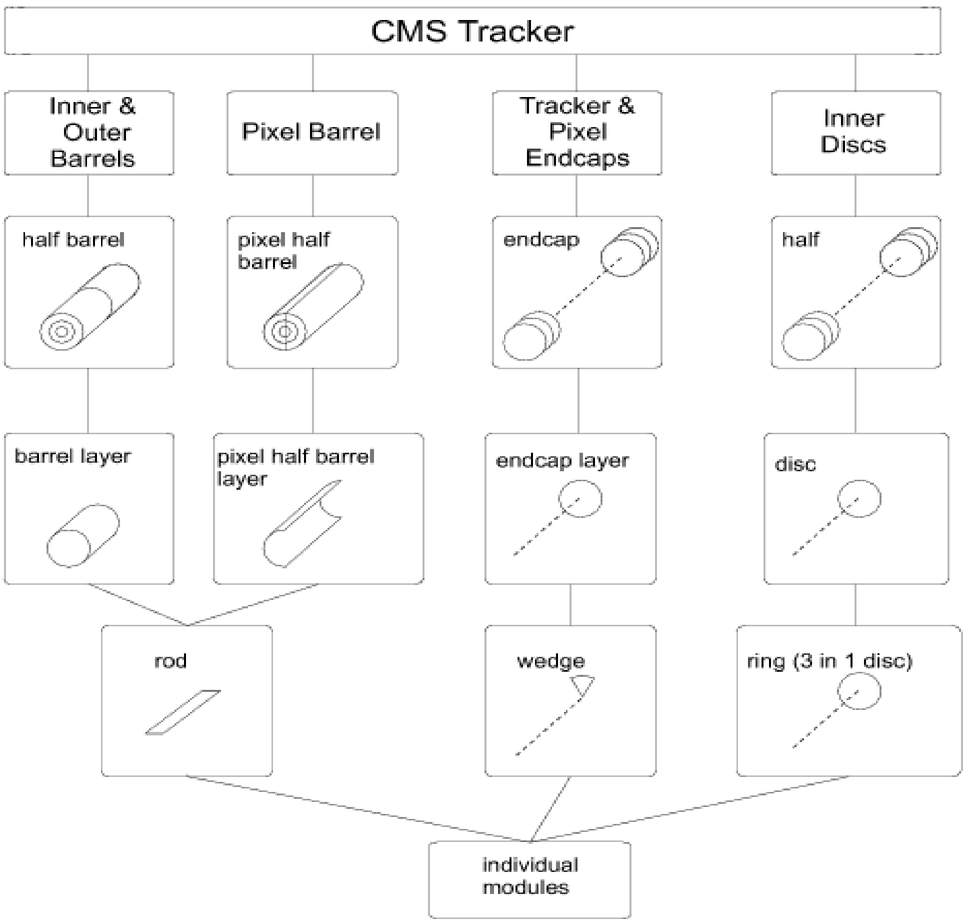
First Step: Misalignment Simulation

Two default scenarios for the Tracker have been defined.

First data scenario:
- Survey and mechanical precision.
- Laser alignment
- Misalignment of tracker modules 100µm – 500µm.
- First pixel barrel pre-alignment ~ 15µm.

Long term scenario:
- Luminosity > 1 fb^{-1}
- PTDR educated guess of alignment knowledge.

An alignment **milestone**: Establish alignment procedure and precisions for < 1 fb^{-1}.

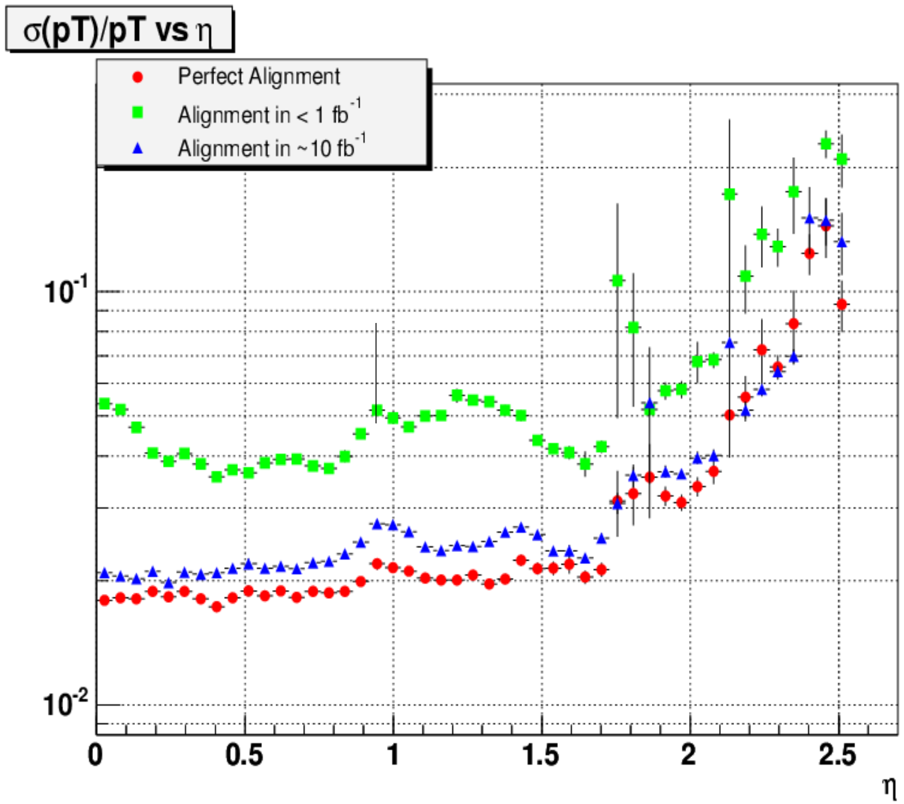


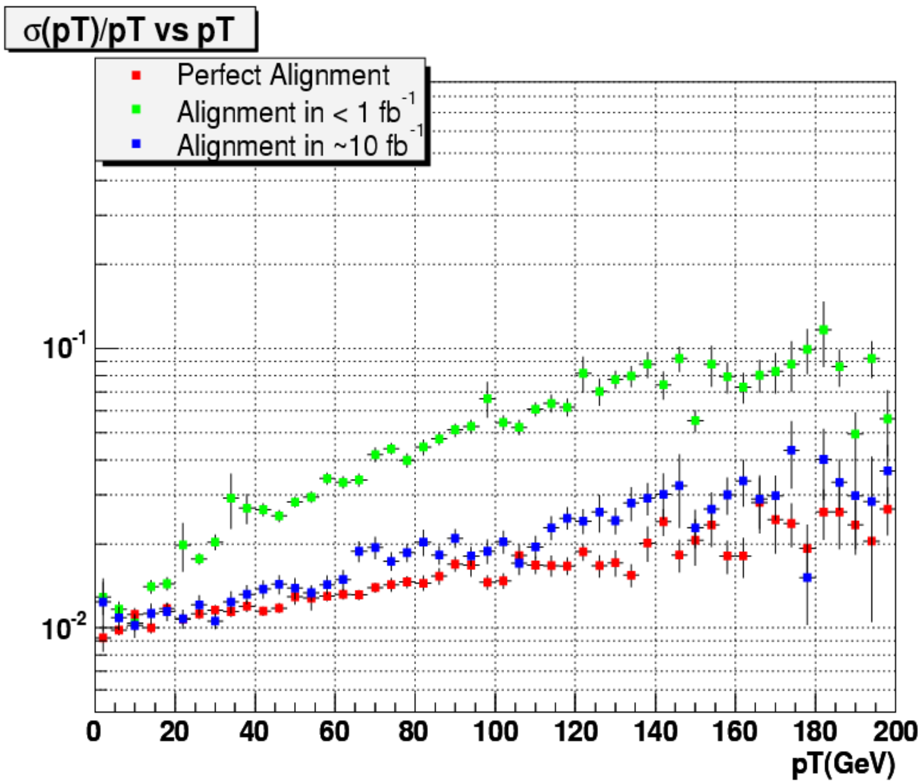
The correlated nature of misalignment is taken into account in the misalignment simulation!

Impact of Misalignment

Studies of the impact of misalignment have been done (CMS-Notes):

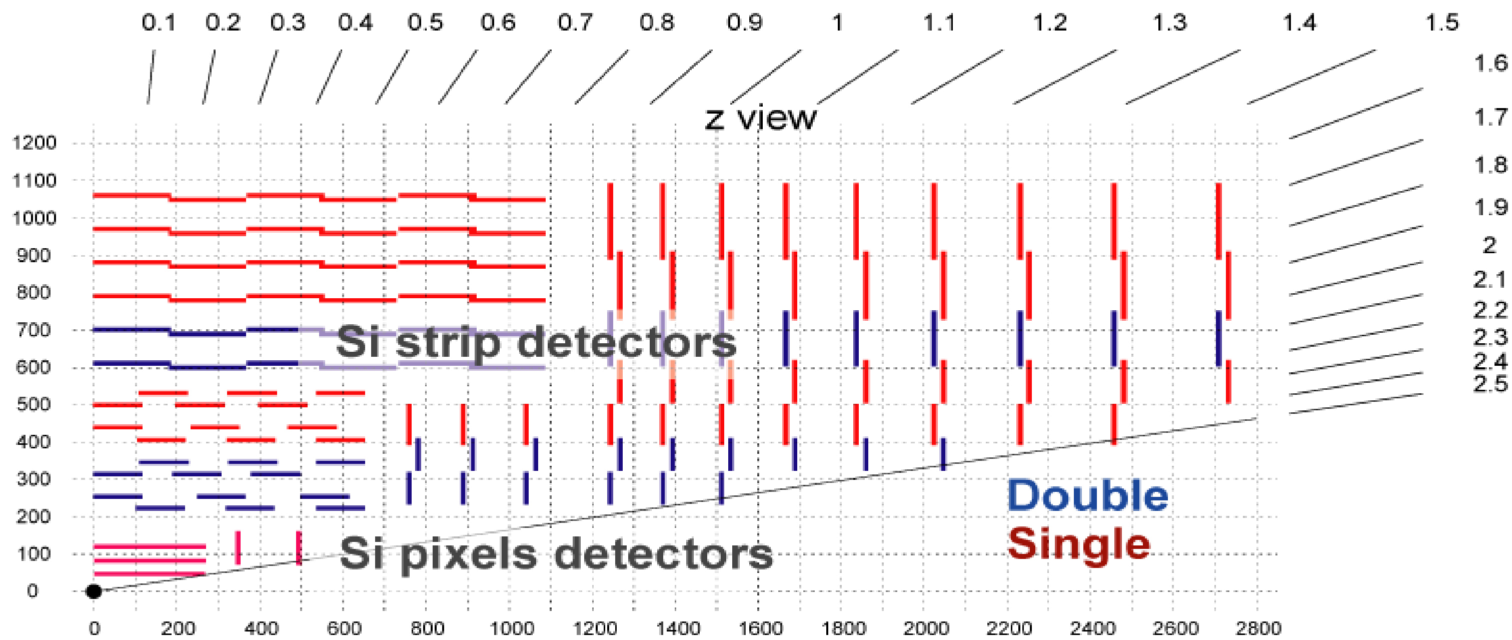
Studies are based on first data and long term scenarios!





The impact of alignment on the reconstruction is large.

The CMS Tracker Alignment Challenge



The layout of the CMS inner tracker

The unique size of the CMS Tracker leads to a unique alignment challenge.

- ~ 50k alignment parameters (3 for 1D, 4 for 2D modules).
- Total size ~24.4 m^3.
- High resolution $\rightarrow$ high alignment precision demands.
- Golden channel ee$\rightarrow\mu\mu$ missing.

Previous strategies and algorithms cannot be easily adopted.

Track Based Alignment at CMS

Concept: Track based alignment minimizes the average χ^2 of the track fits.

Currently three different approaches are followed in CMS:

Iterative:
HIP, simular algotithms successfully used at BARBAR ...

http://cms.cern.ch/iCMS/jsp/openfile.jsp?type=NOTE&year=2006&files=NOTE2006_018.pdf

Sequential:
Kalman Filter, new.

http://cms.cern.ch/iCMS/jsp/openfile.jsp?type=NOTE&year=2006&files=NOTE2006_022.pdf

Non iterativ:
Millepede (II), succesfully used in H1, Zeus ...

http://cms.cern.ch/iCMS/jsp/openfile.jsp?type=NOTE&year=2006&files=NOTE2006_011.pdf

This talk focuses on Millepede II!

Millepede Algorithm

The **average χ^2 of track fits** is dependent on **all alignment parameters and all track parameters**.

All track and alignment parameters are free parameters in the Millepede algorithm, only alignment parameters are determined:

No track parameters fixed -> no bias introduced!

All parameters free -> **All correlations between alignment parameters taken into account!**

Equality constraints, uncertainties on alignment parameters, and survey measurements are implemented by standard methods (Lagrangian Multipliers, additional measurements):

Prior knowledge is implemented!

Alignment procedure in a single pass (linearizations effects small):

Fast Turn around time!

Millepede Algorithm

The minimization translates to a matrix equation:

$$\mathbf{Ca=b}$$

where C is a nxn matrix, n the dimension of alignment parameter vector **a**.

Several approaches can be used to solve this equation:

Diagonalization:

+ All correlations.
+ Diagnostics: Eigenvectors with small eigenvalues have few impact on minimization problem
- CPU time ~ n^3, memory ~ n^2: limited number of parameters!

Inversion:

+ All correlations.
+ Covariance matrix available.
- CPU time ~ n^3, memory ~ n^2: limited number of parameters!

Fast Matrix Equation Solvers

GMRES (only matrix • vector operations needed):

+ All correlations.
+ Fast and small memory demands.
- Matrix should be sparse.

Varible Band Cholesky (variable band -> Lagrangian Multiplyer included!):

+ Fast and small memory even with full matrix.
- Matrix elements are ignored: iterations.

HIP (block diagonal: subset of VBC):

Studies of different algorithms with one tool. (Lagrangian Multiplyer included!)

Limited Memory (BFGS: matrix not stored):

+ All correlations.
+ Small memory and CPU demands.
+ Matrix can be full!
- Not appliciple for semidefinit matrices (NO Lagrangian Multipliers!).

BFGS currently under invenstigation by V. Blobel

Generic Problem of Alignment

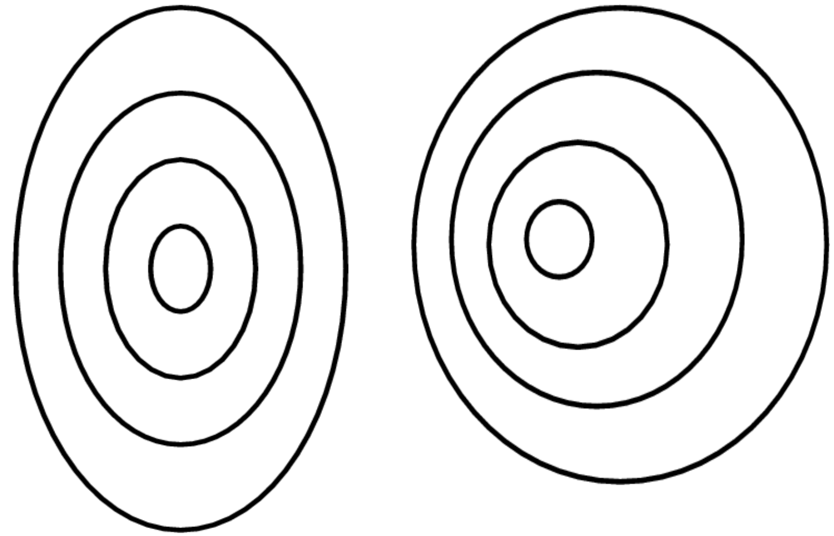
A minimal χ^2 is not equivalent to the correct geometry!

Some Deformations leave the average χ^2 invariant, but **bias** track parameters!

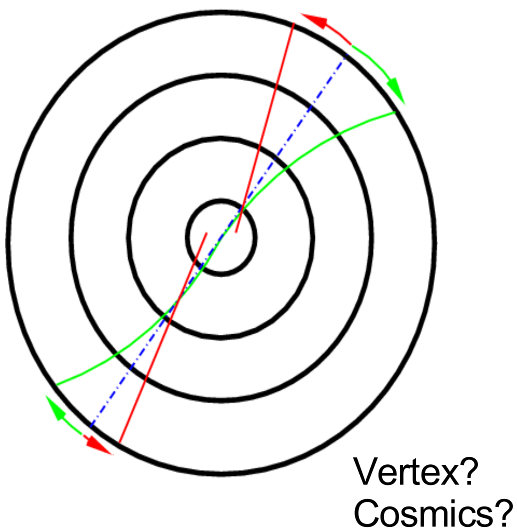
The plots illustrate the basic deformations:

R-rϕ oscillations

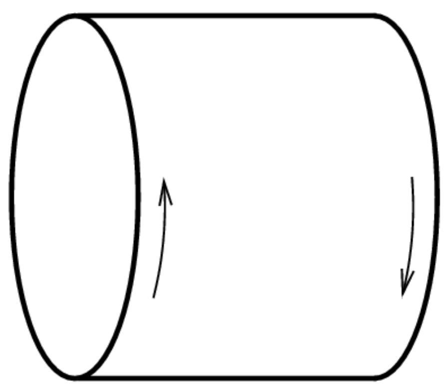
Mode 2: Mode 1:



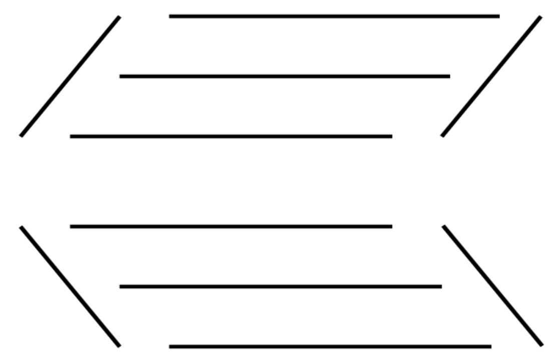
Shearing & bending:



Twist:



Z shearing:



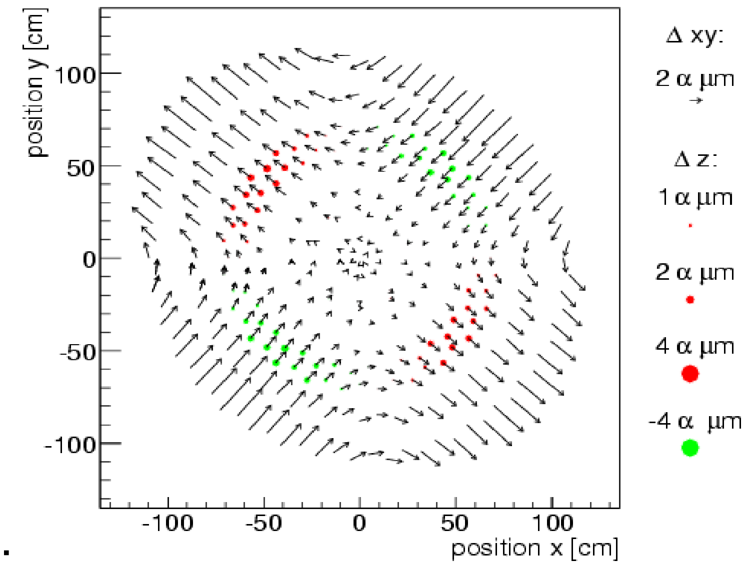
Generic Problem of Alignment

Diagnostic:

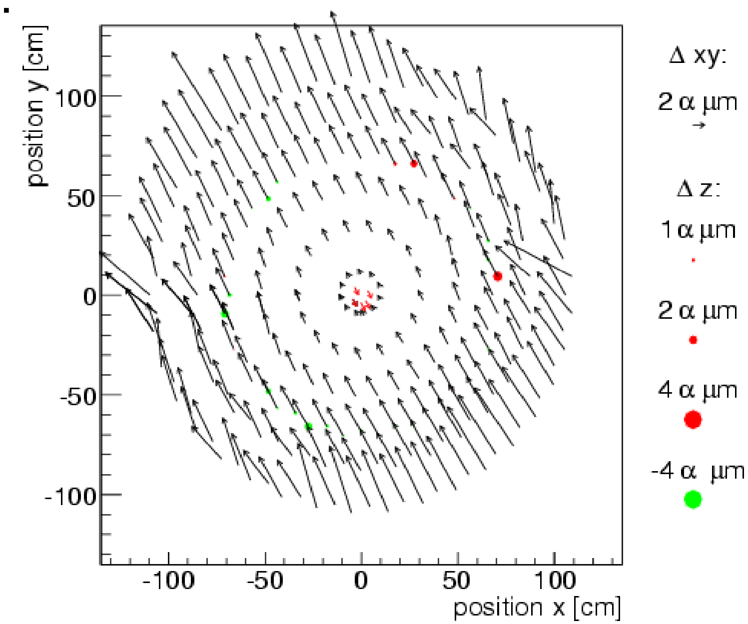
- Millepede with diagonalization method.
- The eigenvectors of the matrix with the smallest eigenvalues have least impact on χ^2.
- Deformations can be visualized.

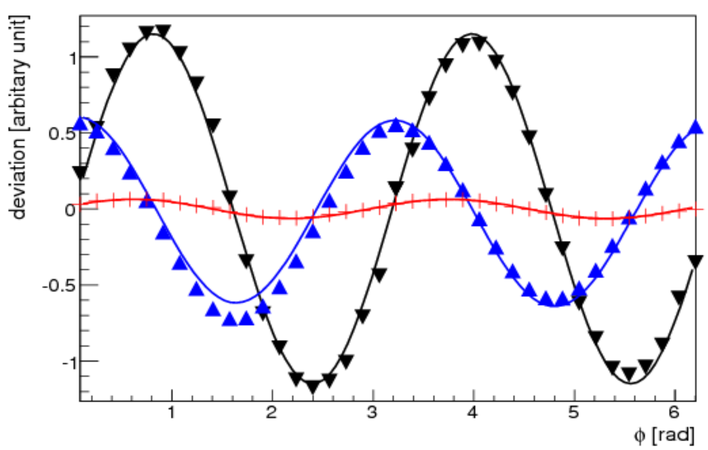
R-rϕ oscillations:

Mode 2:



Mode 1:





Fit of r-rϕ oscillation to displacements obtained eigenvector with small eigenvalue.

More Sources of Information

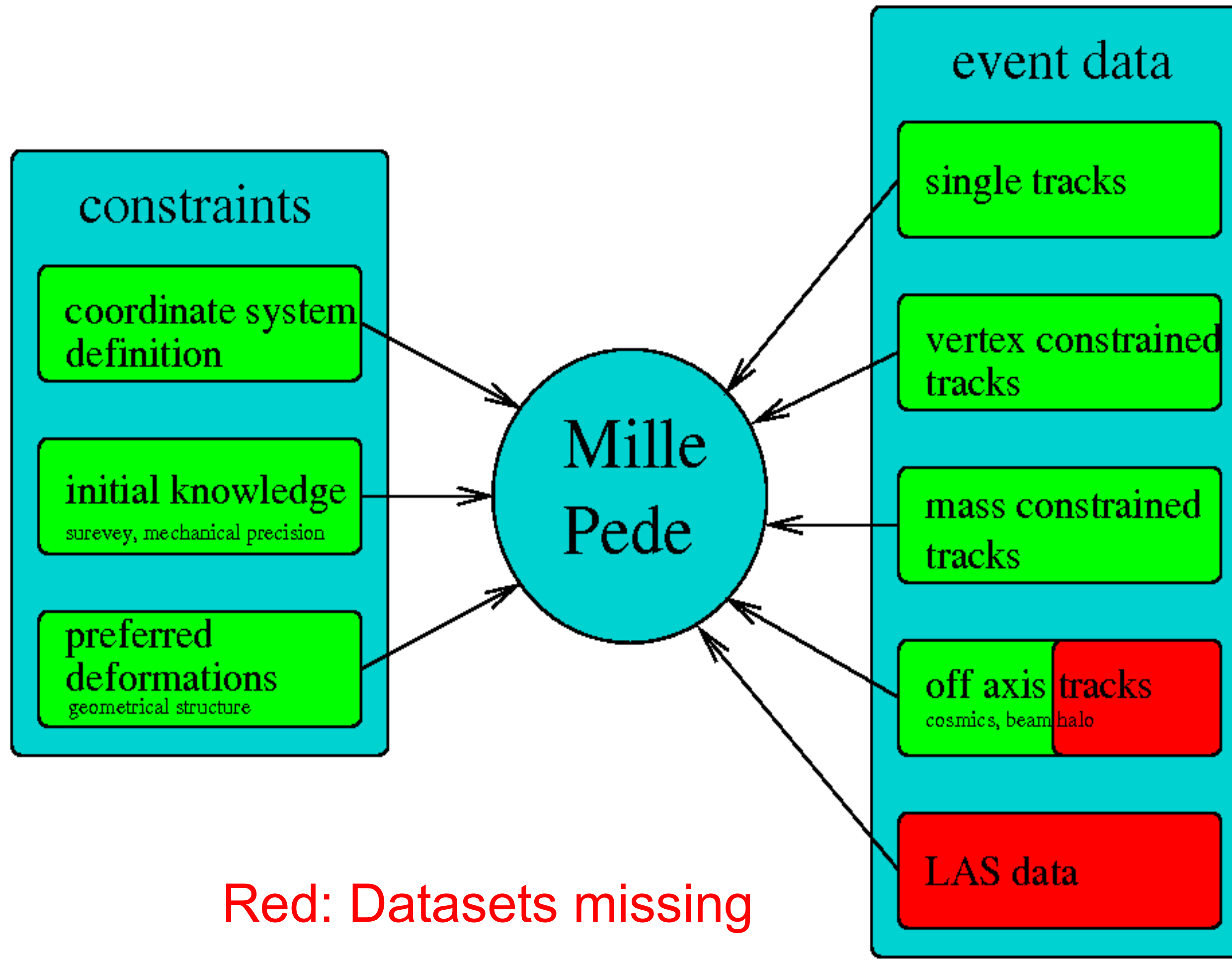
Schematic illustration of input to Millepede

Prior Knowledge:

- Uncertainties of alignment parameters can be estimated from survey measurements and mechanical mounting precision.
- The geometrical of supporting structures is known.

Complementary data sets:

- Data sets like cosmics and beam halo muons constrain deformations.
- Constraints on the trajectory fit like mass and vertex constraint.
- **ee->μμ for you!?**



Red: Datasets missing

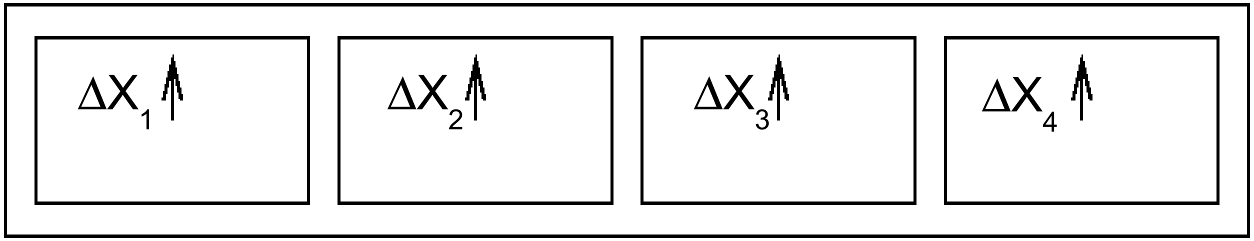
Green: Already utilized

Implementing Initial Knowledge

Relative Alignment Parametrization:

Alignment parameters are defined with respect to the next supporting structure:

Example:
New parameter X_C
Constraint $\Sigma\Delta xi=0$



The full mechanical hierarchy of supporting structures is mirrored in the alignment parametrization:

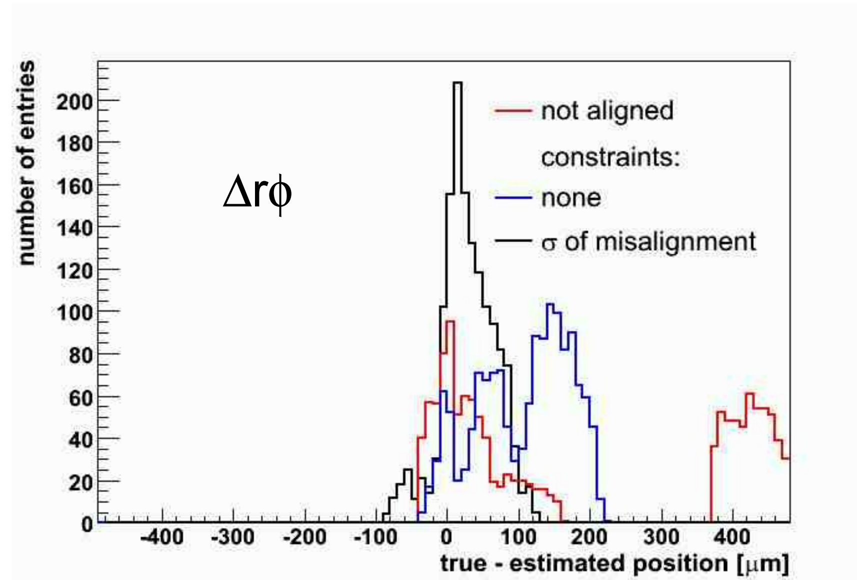
- Initial module alignment parameters uncertainties represent their position uncertainty with respect to the supporting structure (small uncertainties).
- Allows to apply initial knowledge as it is typically known.
- Allows to **simultaneously** align hierarchies.

All hierarchies, Tracker and Pixel aligned simultaneously!
Non iterative!

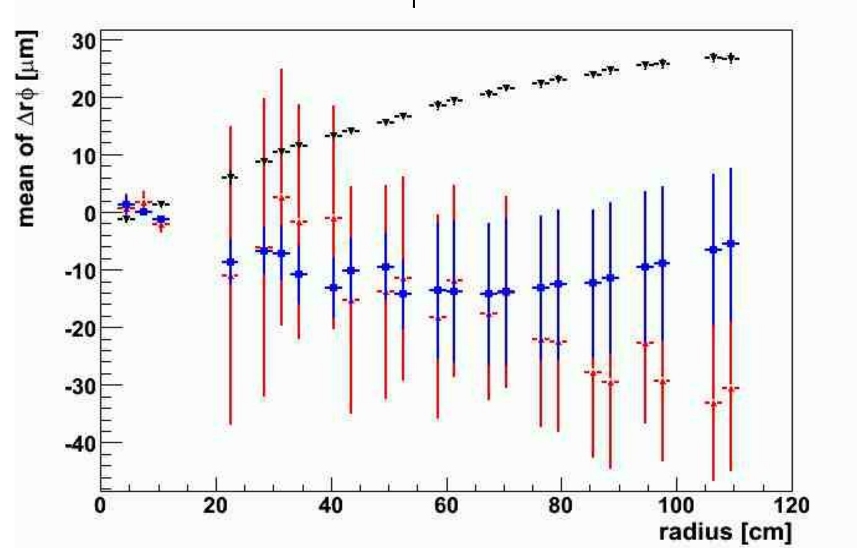
Impact of Constraints (Initial Knowledge)

The impact of the initial knowledge has been studied in a simplified tracker barrel scenario using only single muon tracks. (Millepede II with constraints was not available at that point of time.)

The plots show the position errors with constraints black, without, and the initial errors.



Mean $\Delta r\phi$ vs radius:



The results improved a lot!

Initial knowledge of positioning uncertainties is of vital importance for CMS tracker alignment!

Applying the Strategy to the Full Tracker

Misalignment:

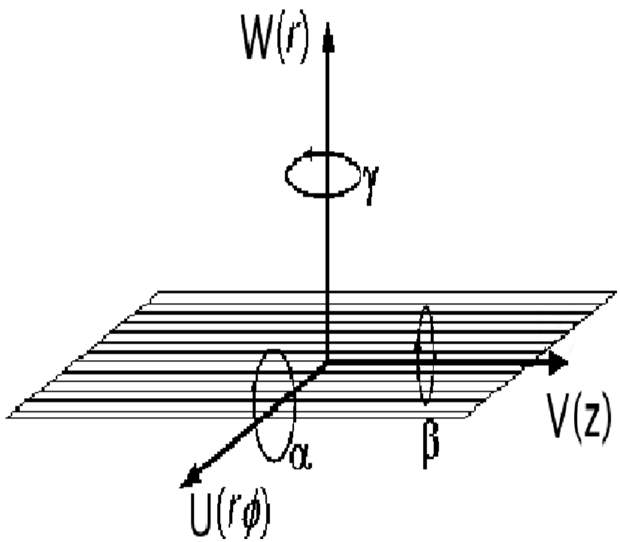
Default first data scenario.

Data sets:

- 0.5 mio. $Z^0 \to \mu\mu$ (0.5 fb^{-1}) with mass and vertex constraint
- Full reconstruction and pileup.
- 25 k cosmics with momentum > 50 GeV
- Single muons of 1.5 mio. $Z^0 \to \mu\mu$ ~ 3 mio $W \to \mu\nu$ (0.5 fb^{-1}) events

Alignment:

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



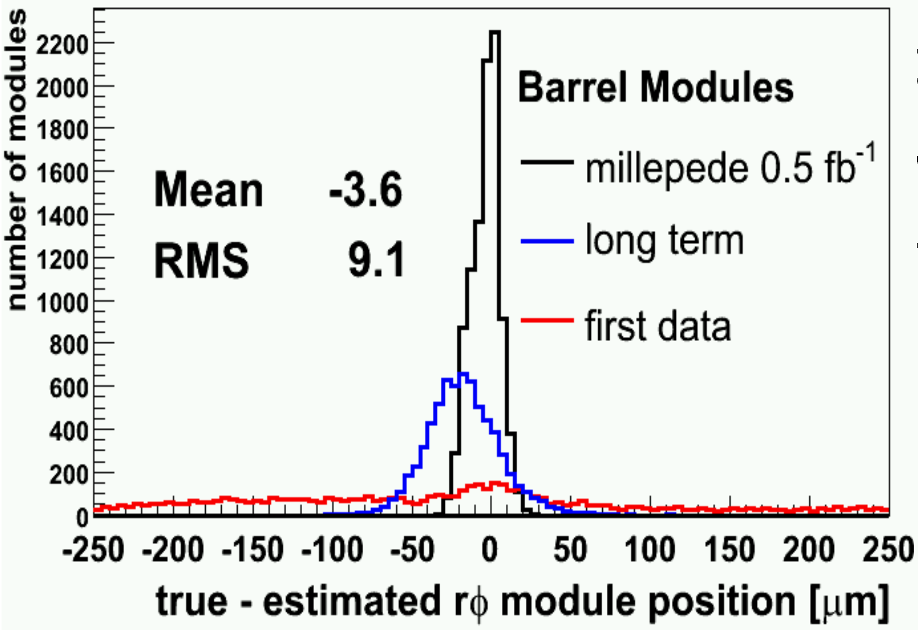
Coordinate Definition:

- Center of the pixel barrel sensors.

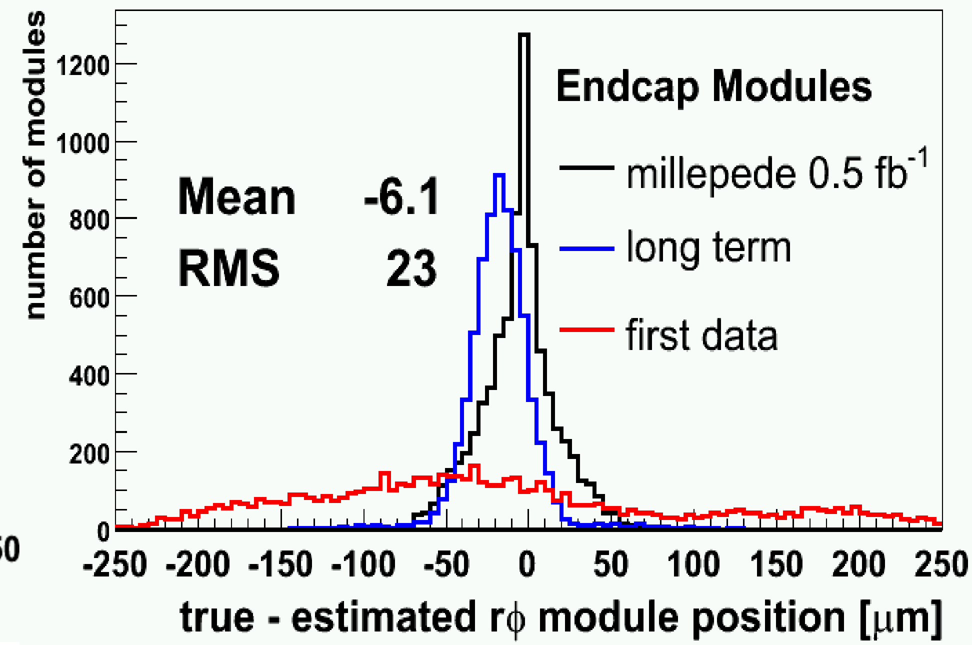
Results: Misalignment in rϕ

Cosmic s and single muons of 2 mio. Z^0 events used.

PB,TIB,TOB



PE,TID,TEC



Barrel Modules RMS = 9 μm

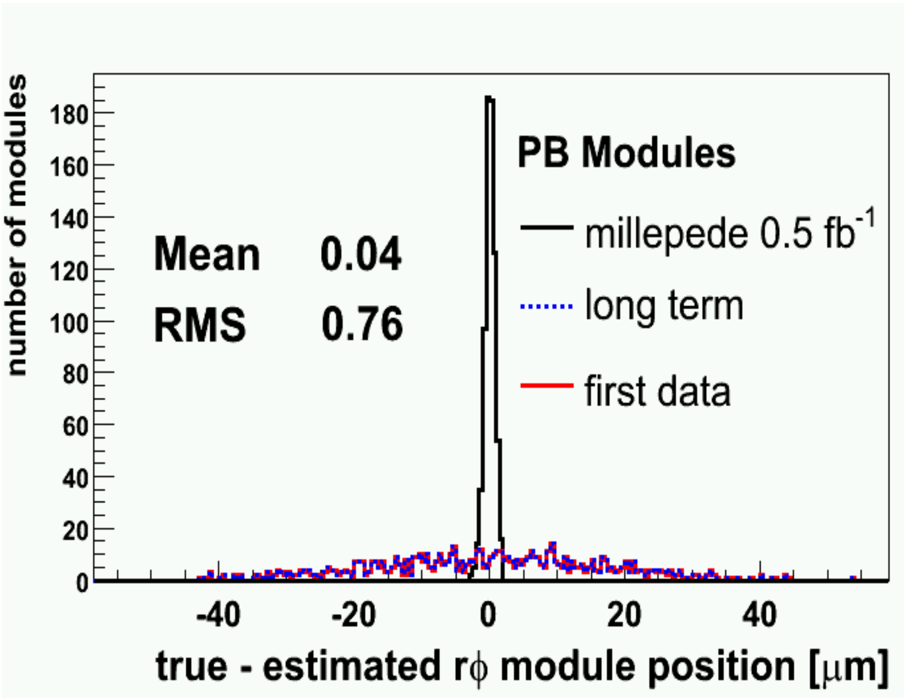
Endcap Modules RMS = 22 μm

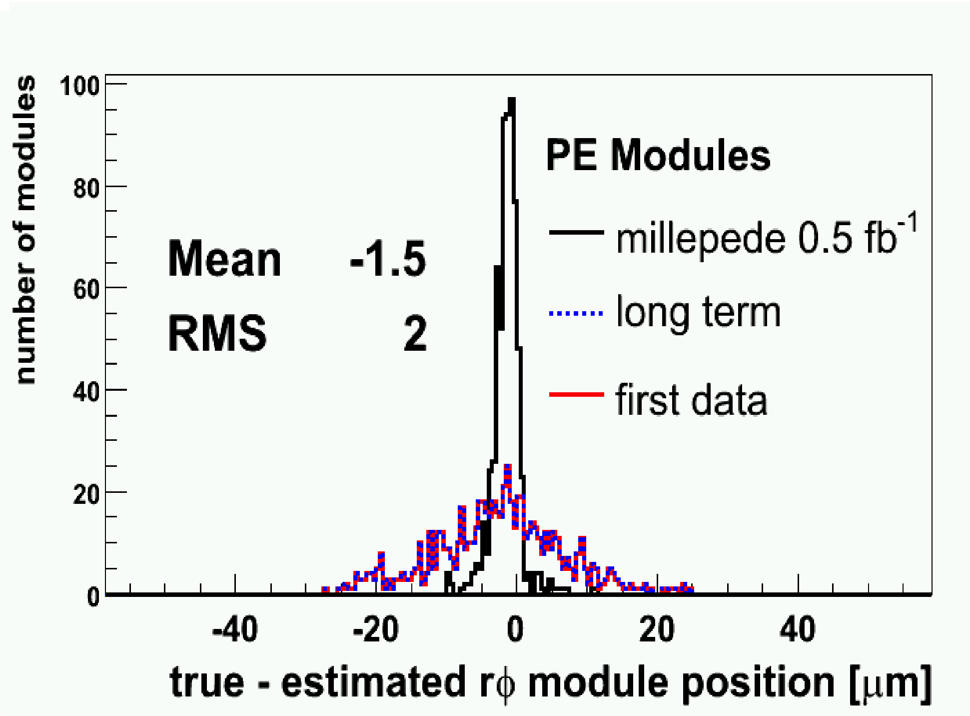
Barrel alignment (strip+pixel) significantly better than in the long term scenario.

The mean is better than the longterm scenario! The RMS is similar.

Milestone reached!

Results: Pixel Misalignment in rϕ





Pixel barrel RMS < 1 μm

Pixel barrel alignment an **order of magnitude** better than in the long term scenario.

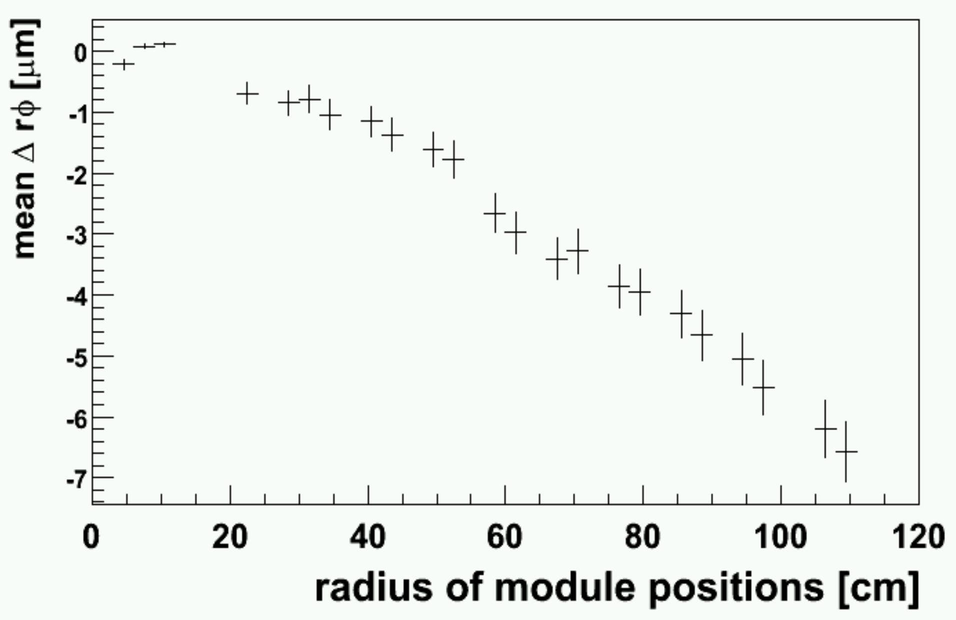
Pixel endcap RMS = 2 μm

Better than long term scenario. Further studies needed.

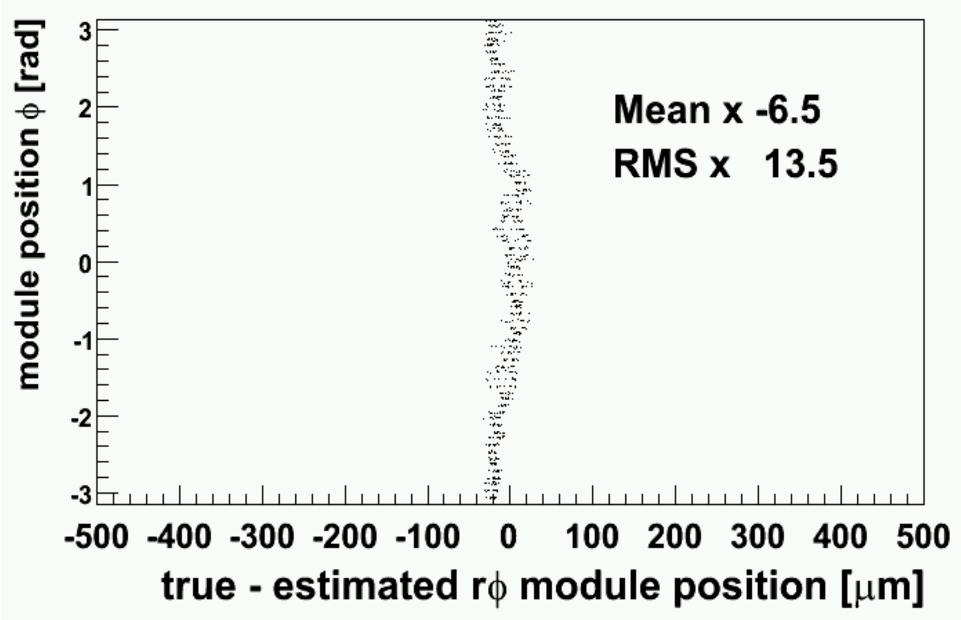
Pixel aligned to μm precision!

Results: Remaining Misalignment in rϕ

Mean Δrϕ of barrel modules vs radius:



ϕ of last barrel layer modules vs Δrϕ

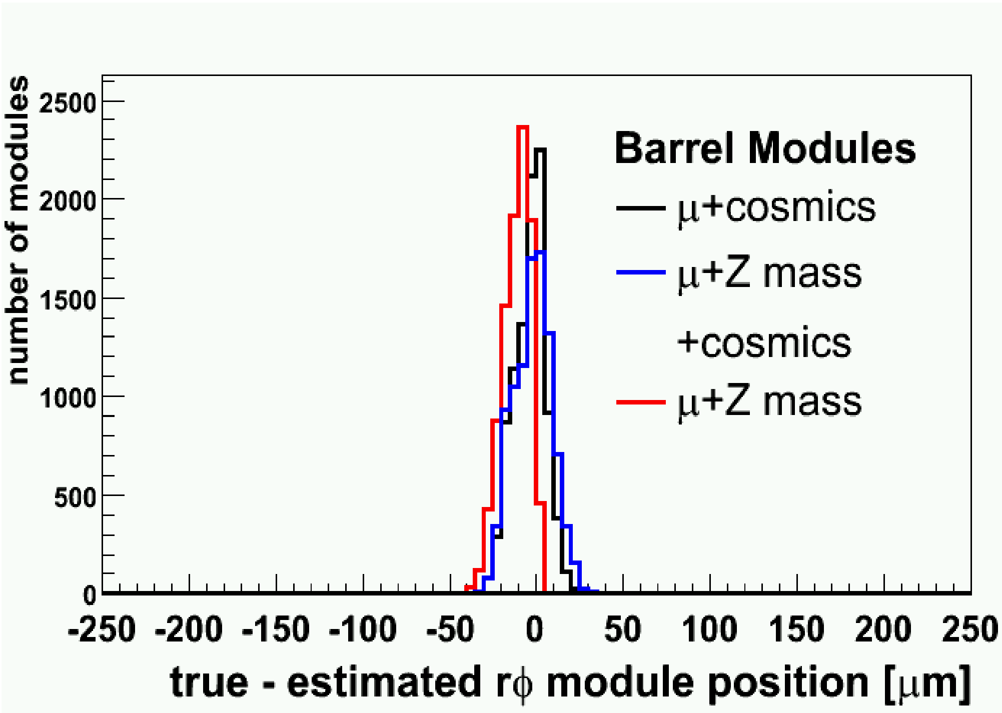


Remaining misalignment is dominated by global deformations:

- Bias in ϕ the order of μrad.
- Bias in Pt in the order of few 10MeV at ~50 GeV.

More cosmics, mass constrained track, beam halo ... will help!

Results: Different Datasets



Data	Mean [μm]	RMS [μm]
μ + Z mass	-11.2	7.9
μ + cosmics	-3.6	9.1*
μ + Z mass + cosmics	-2	10.8*

* to be studied

The complementary datasets reduce global correlations:

- Mean displacements are reduced!

Exotic data sets like cosmics need special care:

- Hit reconstruction and hit error estimation for tracks with large inclination angles.
- Linearization effects for Z mass constraint.
- LAS and beam still halo missing!

Complementary data are of vital importance to alignment!

Results: Computing Requirements

Millepede II developed by V. Blobel

Memory requirements:

More complementary datasets lead to fuller matrices:

•Sparse Matrix Memory ≈ 12.5 GB x density.
•Full Matrix ≈ 8.3 GB memory

CPU Requirements:

Fuller matrices increase CPU time if sparse matrix algorithms are used (GMRES).

Computing needs of the study:

- Data: cosmics, 500k mass constrained tracks, and single tracks
- Density 15%.
- CPU solving matrix equation: 10 min

Note: For outlier rejection 5 internal iteration in Millepede have been done!

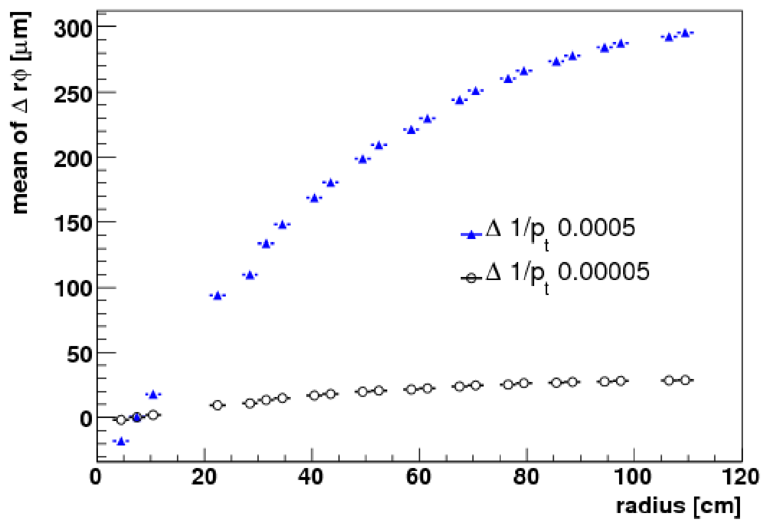
Memory: 2GB
CPU time total: 1:40

Hamburg resources: 64 Bit, 8GB

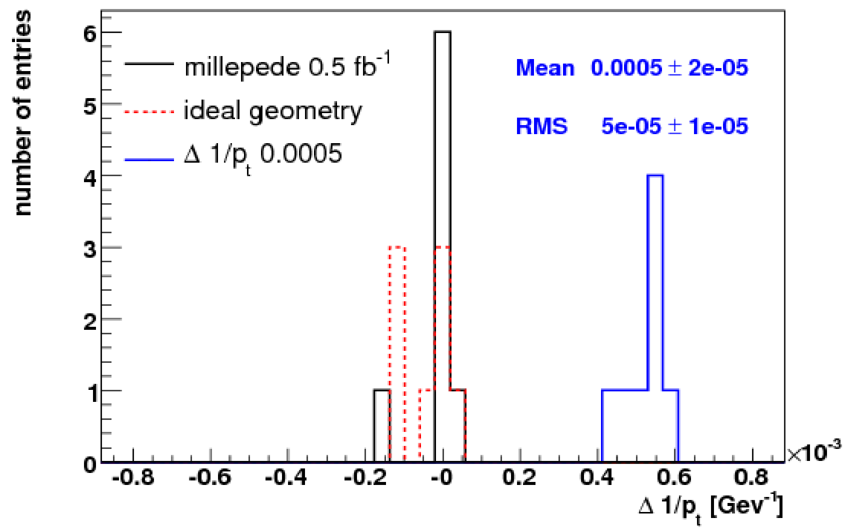
CPU and Memory needs modest!
Fast turnaround time!

Outlook: Expected Symmetries

The symmetry between the $1/P_t$ distribution for $\mu+$ and $\mu+$ from the $Z^0 \rightarrow \mu\mu$ events distorted by bending deformation.



Bending produced on purpose via Millepede.



Symmetry fit for different etaphi bins. 500k $Z^0 \rightarrow \mu\mu$ events used.

- The produced bending deformation was found by a symmetry fit.
- The uncertainty of the fit is still large
- More statistics needed

Promising approach for alignment.

Conclusion

Outlook:

Further global alignment studies needed:

• Positive: More datasets and symmetry constraints.
• Negative: Time dependent movements, uncertainty of magnetic field, outliers in displacements, wrong uncertainty estimations, material budget uncertainties ...

Alignment with real data:

•Tracker test facility “25% test” alignment.

Conclusion:

A proof of concept for a global alignment strategy has been shown.

The available datasets and the prior uncertainty knowledge are the key ingredients for alignment.

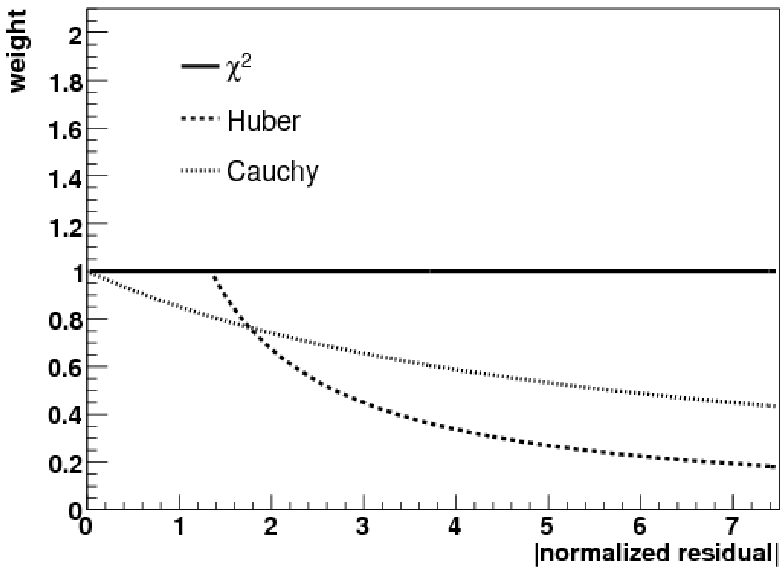
Millepede II is a working package for large χ^2 minimization problems!

Outlier Rejection (robust fitting)

Rejecting tracks:

- Millepede refits (in the course of the matrix size reduction) the track parameters → χ^2/ndof cut on the track fit can be applied.
- First is large due to misalignment.

In each iteration the cut can be thighed, since the sensor position estimates improve.



Reweighing hits (M-estimates):

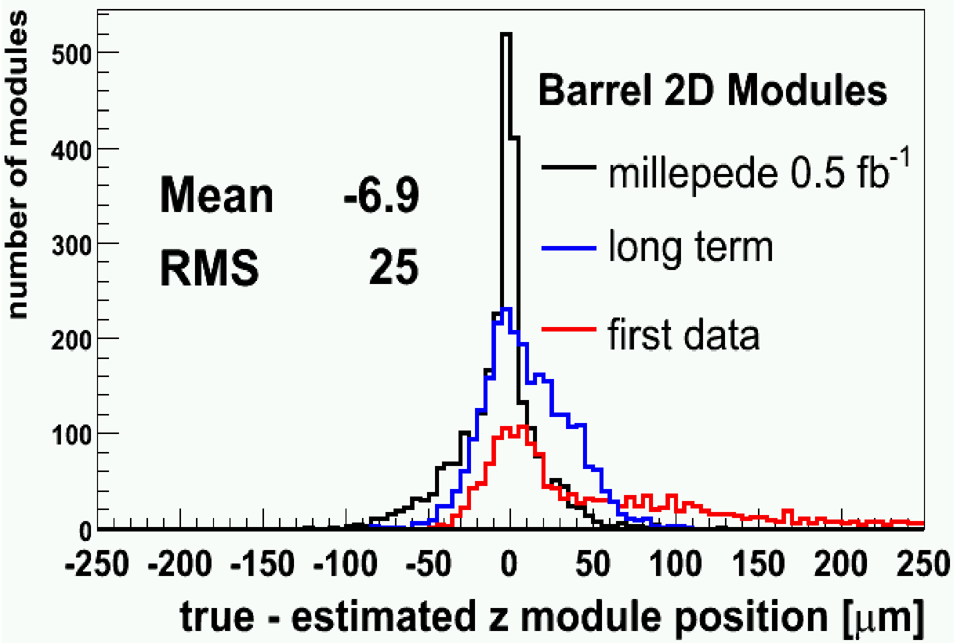
- Individual hits are re weighted in dependence of the normalized residual value.
- For weight is always = 1 for min(χ^2).
- If average hit weight for track is < 80%, the track is rejected.

For both outlier rejection methods 5 internal iteration were used.

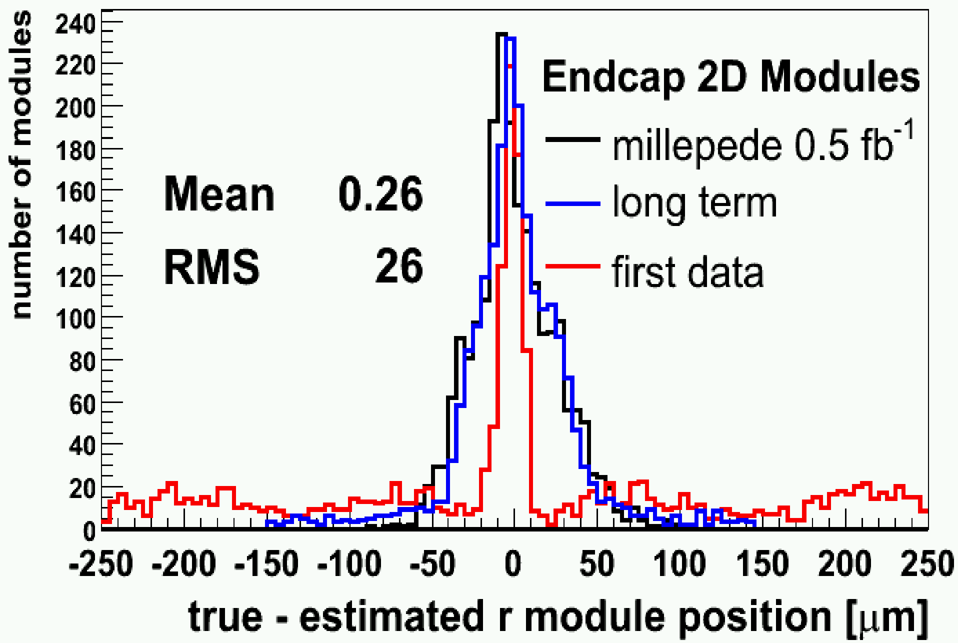
	None	Reject	Reweight
Barrel $\Delta r\phi$ mean[μm]:	1.9	-1.1	-1.9
Barrel $\Delta r\phi$ rms [μm]:	17.9	9.6	10.3
Endcap $\Delta r\phi$ mean [μm]:	-3.1	-7.1	-4.7
Endcap $\Delta r\phi$ rms [μm]:	31.5	23.6	23.2

Results: Misalignment in z and r

PB,TIB,TOB Δz:



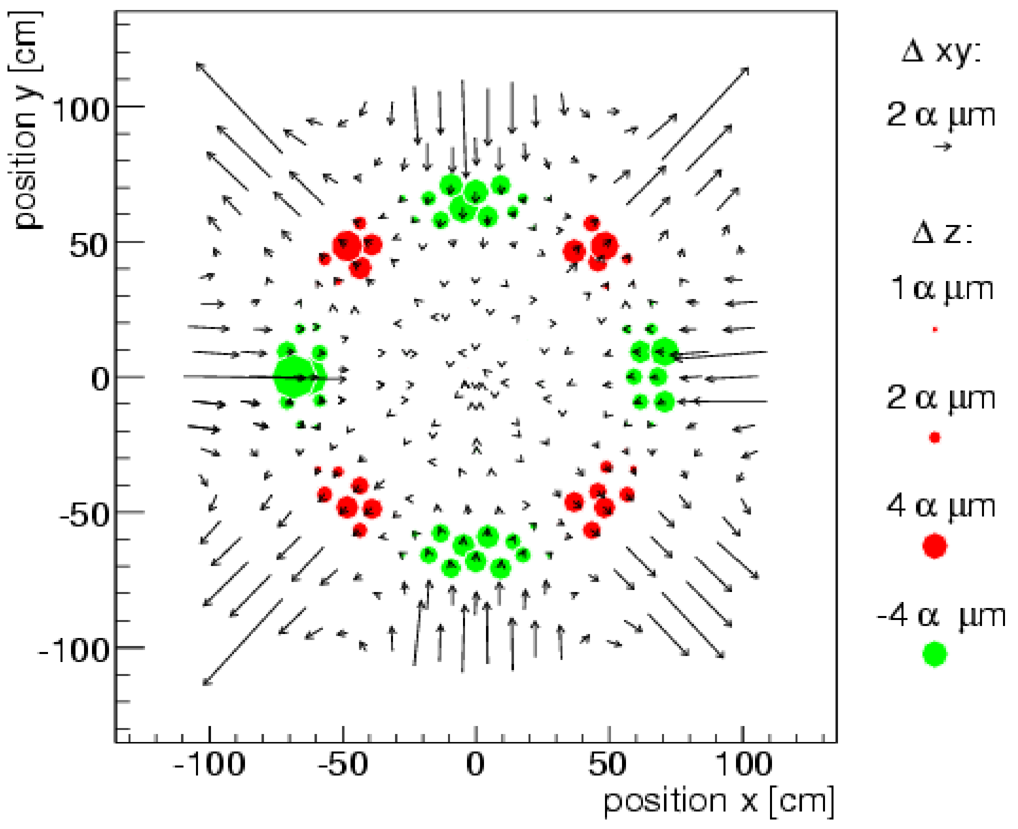
PE,TID,TEC Δr:



- **Remaining misalignment << resolution.**
- Also the second sensitive coordinates (barrel z, endcap r) similar or better aligned than in the long term scenario.

Promising results for all alignment parameters.

Mode 4:


position y [cm]
100
50
0
-50
-100
-100
-50
0
50
100
position x [cm]
Δ xy:
2 α μm
Δ z:
1 α μm
2 α μm
4 α μm
-4 α μm