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CMS
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Universität Hamburg

Application of Millepede II to CMS Tracker Alignment

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II. LHC Detector Alignment Workshop 25.6.07

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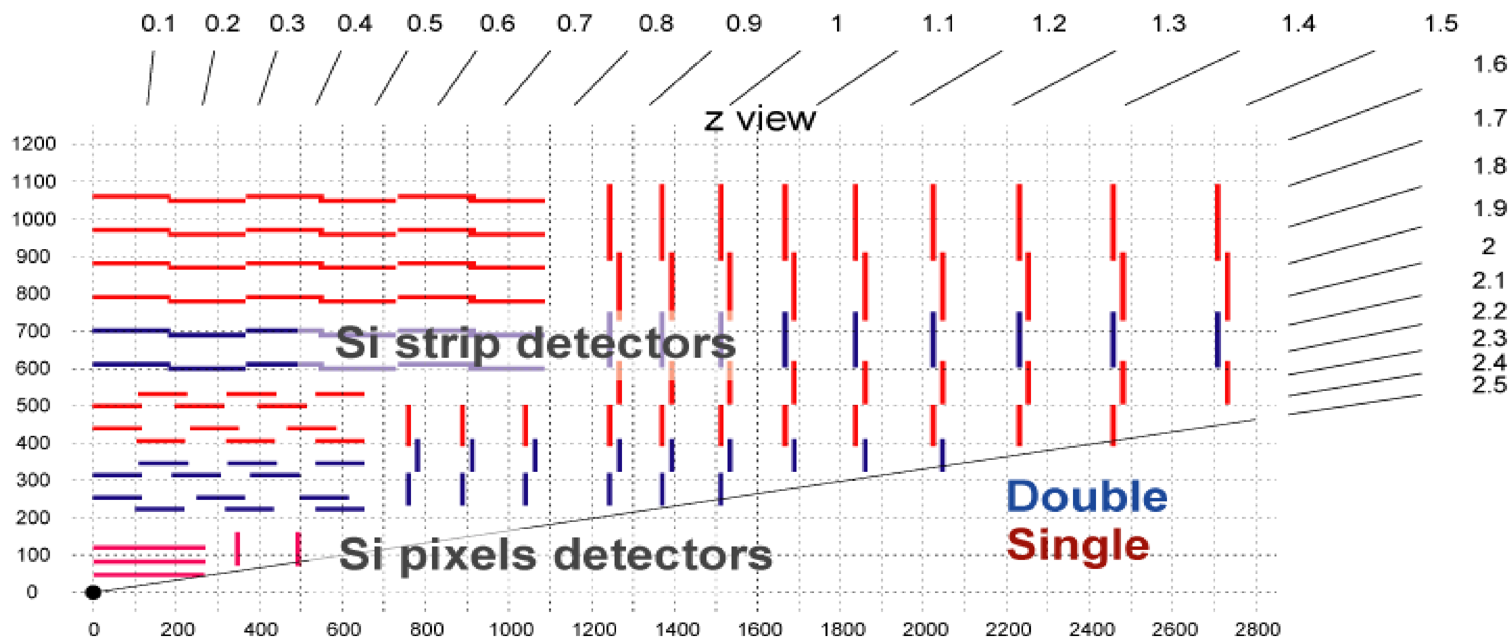
Alignment Challenge



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 ~18 m^3.
- High resolution $\rightarrow$ high alignment precision demands.
- LEP's golden alignment channel $ee \rightarrow \mu\mu$ missing.

Previous strategies and algorithms cannot be easily adopted.

2. Introduction

Track based alignment

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

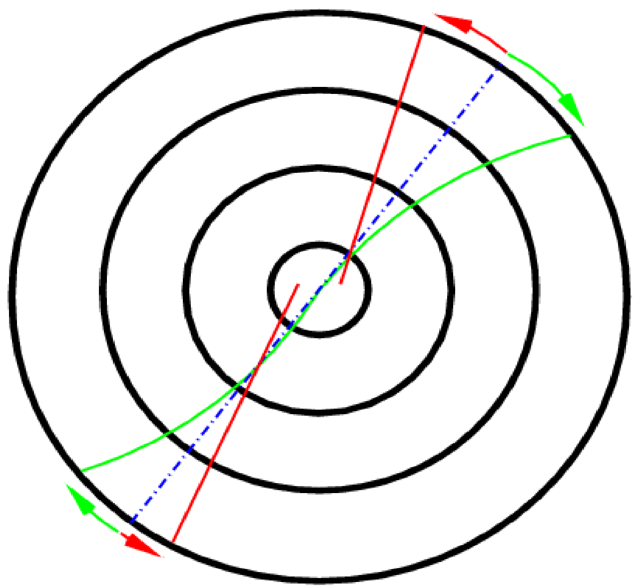
Problem: Some deformations of the tracker leave this χ^2 invariant.

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

More sources of information required than only χ^2 of track fits!

Illustration of a χ^2 invariant deformation

Shearing and bending:

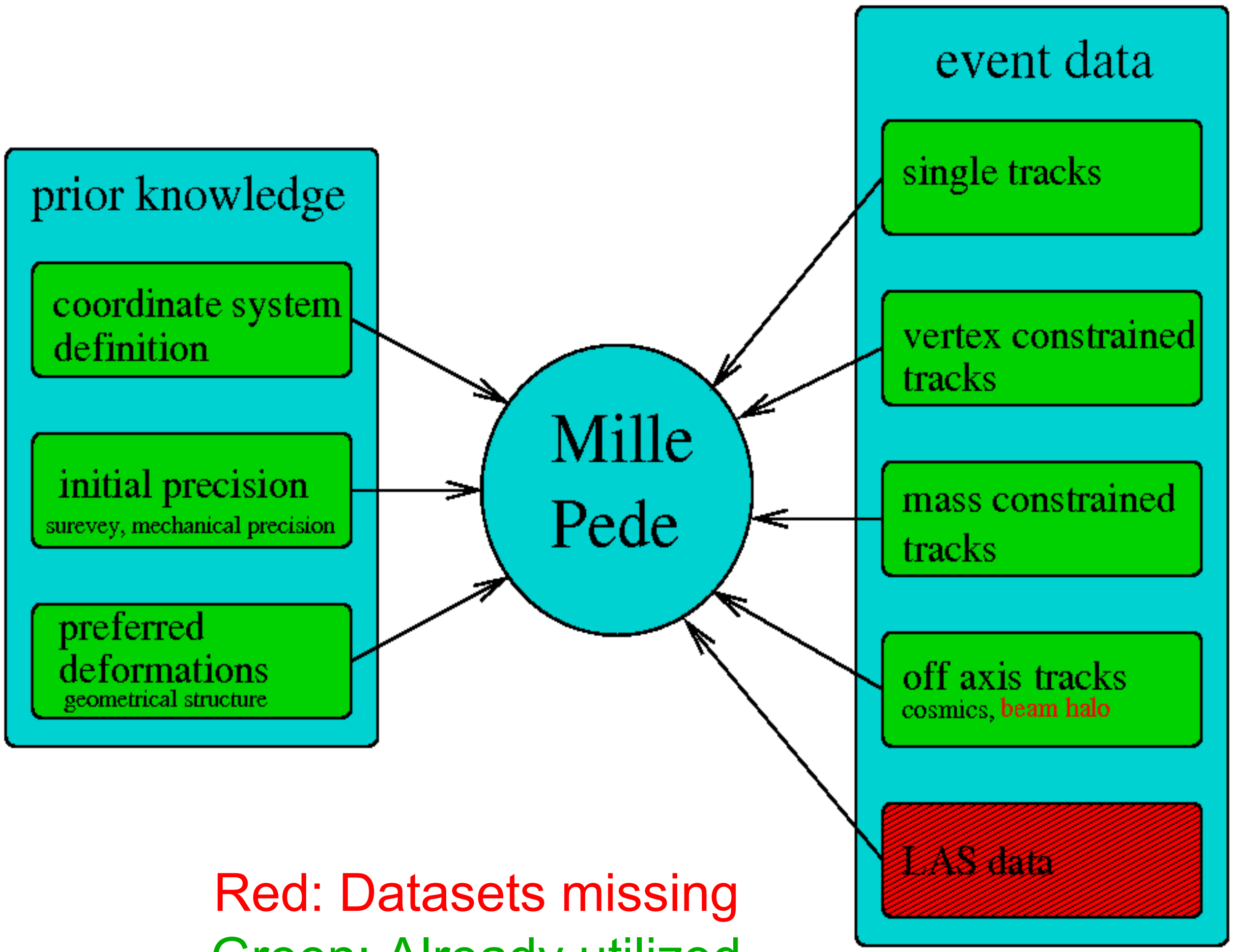


Bias of P_t measurement!

2. Simultaneous Alignment Strategy

Sources of Information

Schematic illustration of input to Millepede



Red: Datasets missing
Green: Already utilized

Prior knowledge:

- Known uncertainties of alignment parameters after survey measurements and mechanical mounting.
- The geometry 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

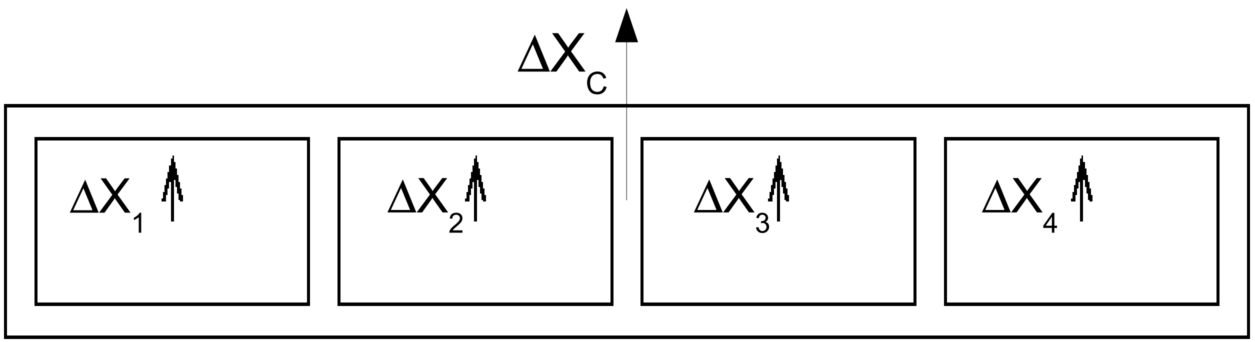
2. Simultaneous Alignment Strategy

Survey Measurements and Mounting Precision

Relative Alignment Parametrization:

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

Example:
New parameter ΔX_C
Constraint $\Sigma \Delta x_i = 0$



- Allows to apply initial knowledge as it is typically known.
- Allows to simultaneously align hierarchies (modules, rod, layer, barrel).

Survey Measurements:

Example: $\Delta x_1 + \Delta x_2 = 10\ \mu m \pm 5\ \mu m$

- Survey measurements can also be directly implemented as measurement.
- No dataset available yet → not used yet.

2. Simultaneous Alignment Strategy

Simultaneous Approach

Using all information simultaneously leads to **optimal** results in **one go**.

- Alignment and track parameters fitted simultaneously.
- Hierarchies aligned simultaneously.
- Pixel and strip tracker aligned simultaneously.
- All complementary data used in one go.

Only outlier rejection and non linearities (small for alignment) require iterations.

3. 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:

- Default first data scenario of CMS.

Data sets:

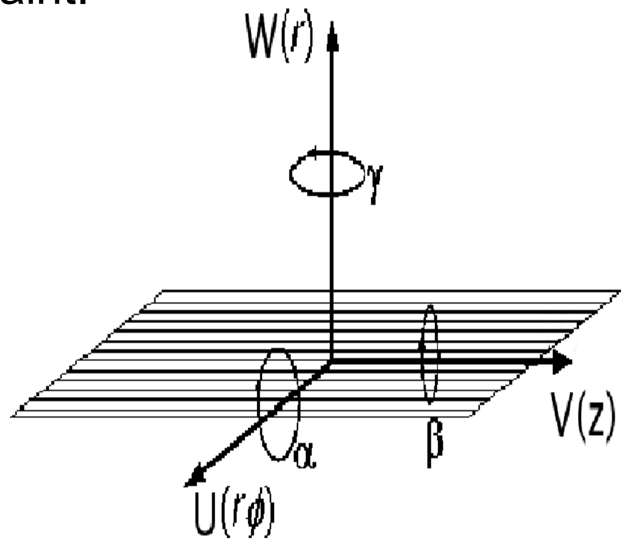
- 0.5 M $Z^0 \rightarrow \mu\mu$ (0.5 fb^{-1}) events with mass and vertex constraint.
- 25 k cosmic μ with momentum > 50 GeV.
- Single μ of 1.5 M $Z^0 \rightarrow \mu\mu$ ~ 3 M $W \rightarrow \mu\nu$ (0.5 fb^{-1}) events.

Alignment:

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

Coordinate Definition:

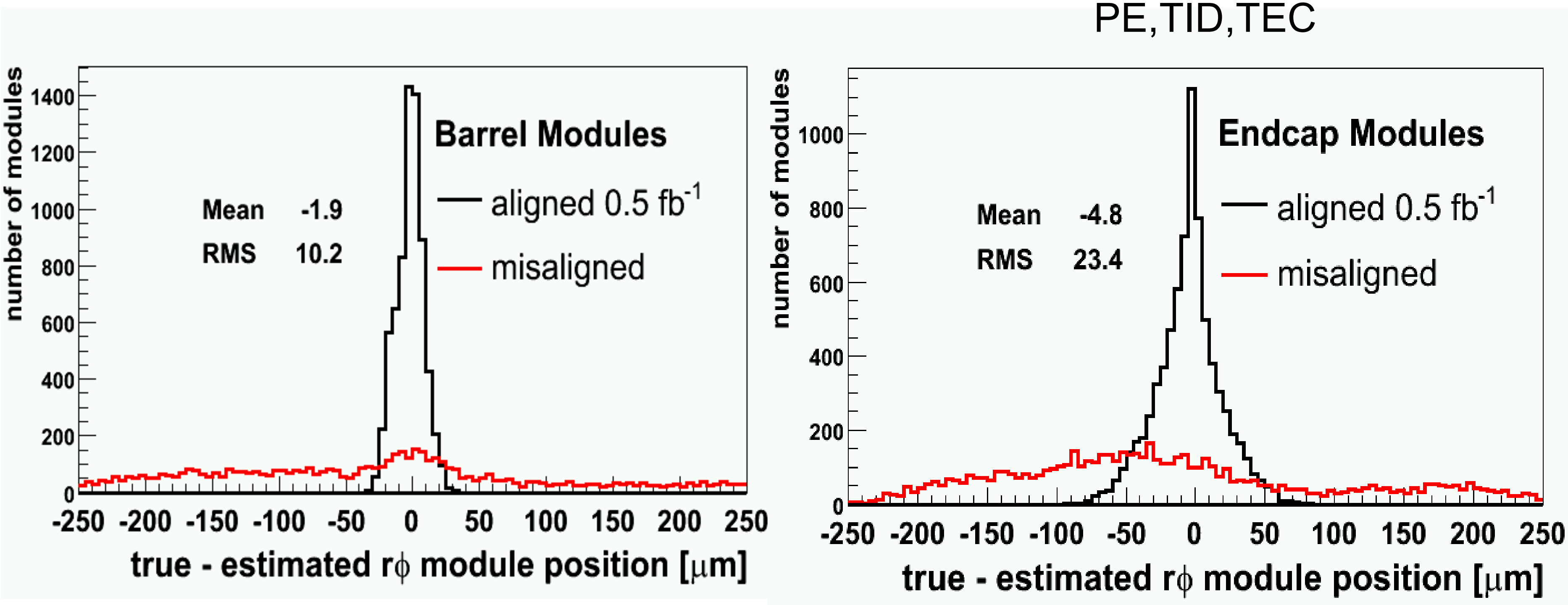
- Center of the pixel barrel sensors.
- Rotation of pixel barrel fixed.



3. Full Scale CMS Tracker Study

Resulting Position Residuals in rϕ

PE,TID,TEC



Barrel Modules RMS = 10 μm

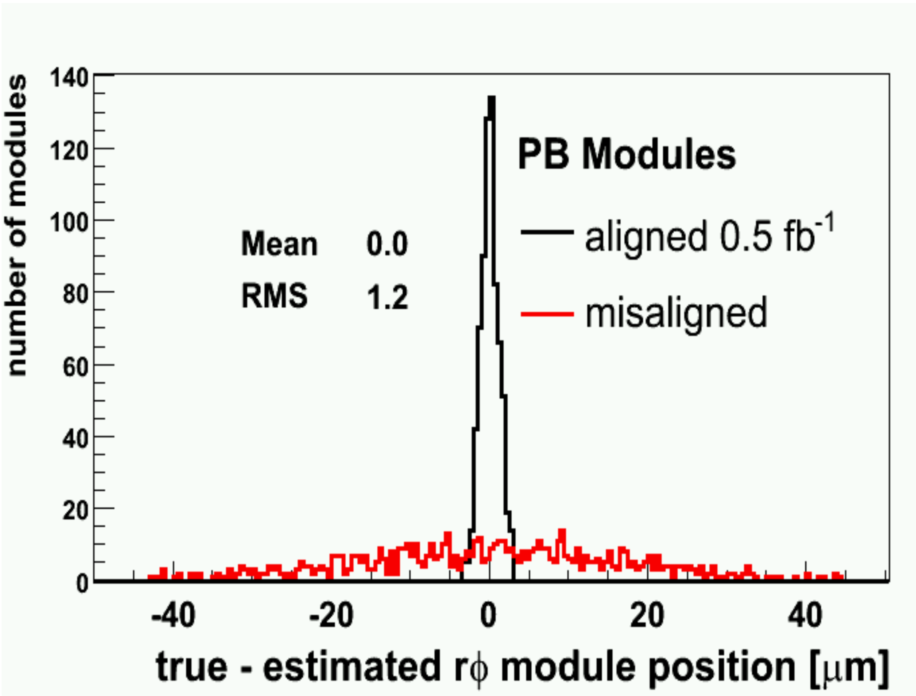
Endcap Modules RMS = 23 μm

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

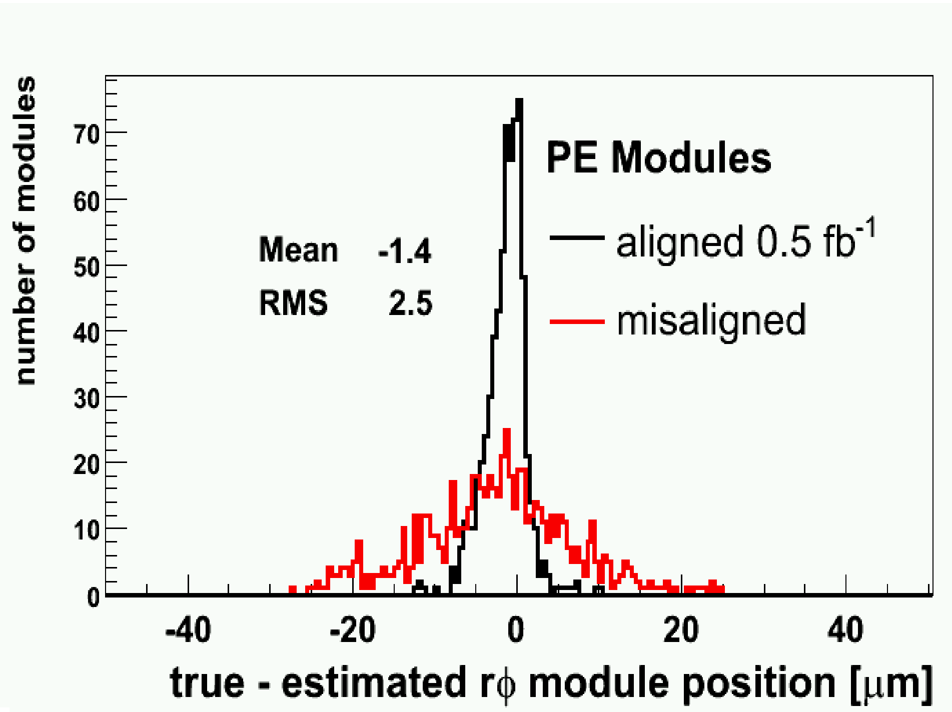
The mean is better than the long term scenario! The RMS is similar.

3. Full Scale CMS Tracker Study

Resulting Pixel Position Residuals



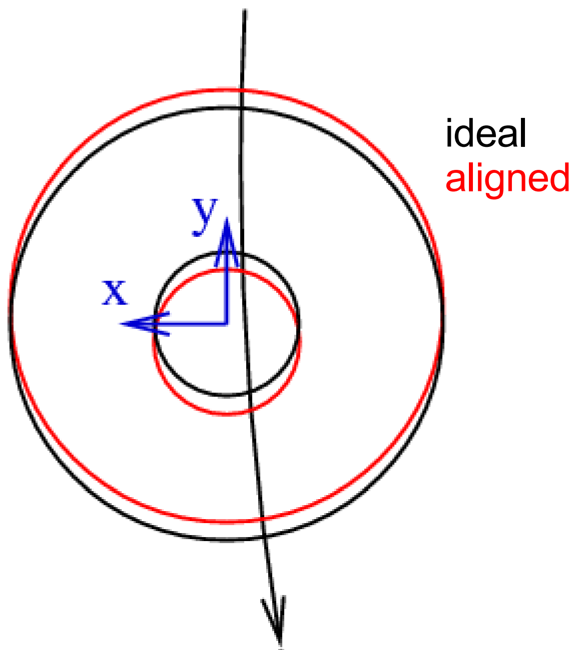
Pixel barrel RMS = 1 μm

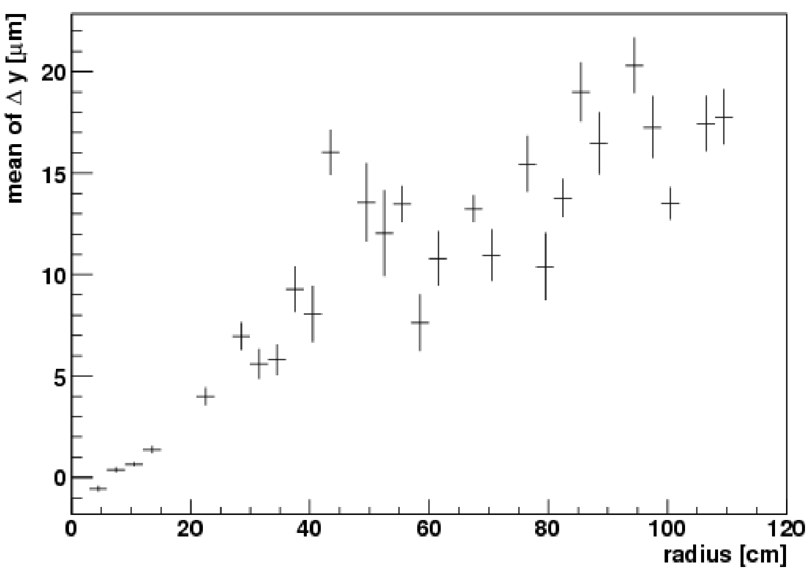


Pixel endcap RMS = 2.5 μm

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

Small Remaining Misalignment Effects





Schematic illustration of a r-rϕ mode 1, which is not well determined. The black arrow indicates a typical cosmic muon track.

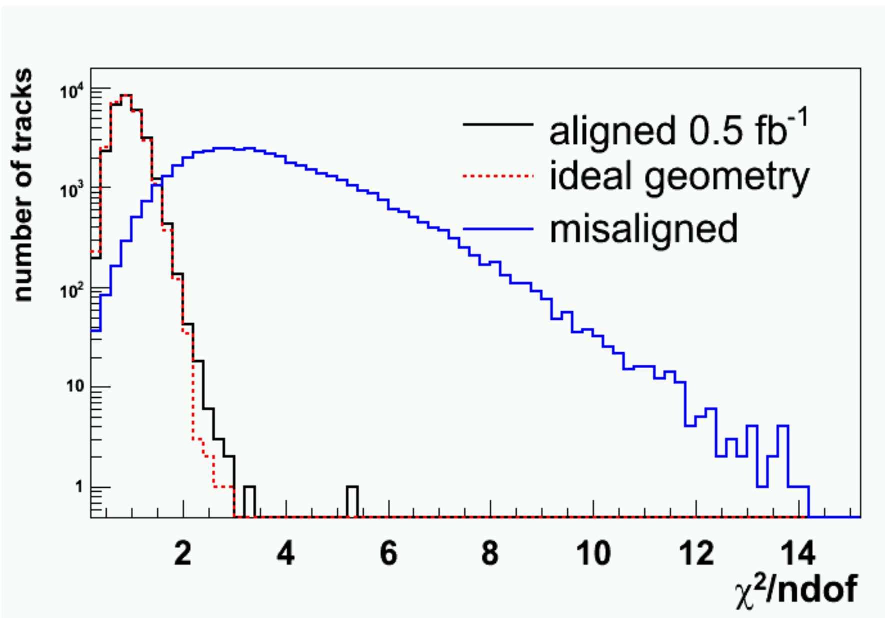
Mean displacement in global Y for all modules. A linear increase with the radius is visible: A typical sign of the r-rϕ mode 1.

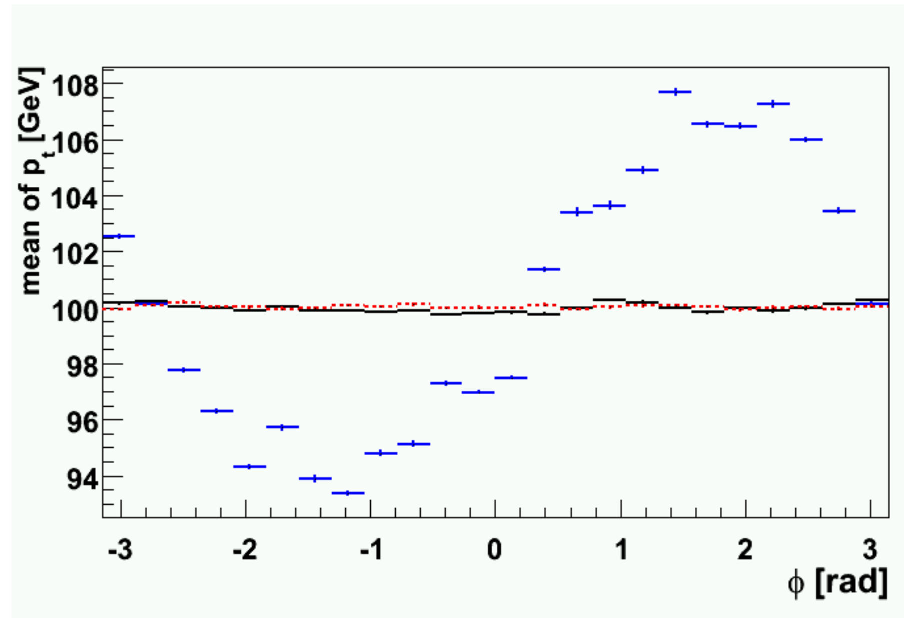
An r-rϕ of mode 1 remains and is the dominating source of the remaining misalignment

3. Full Scale CMS Tracker Study

Control Plots

50.000 μ^+ tracks* 100 GeV transverse momentum tracks 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

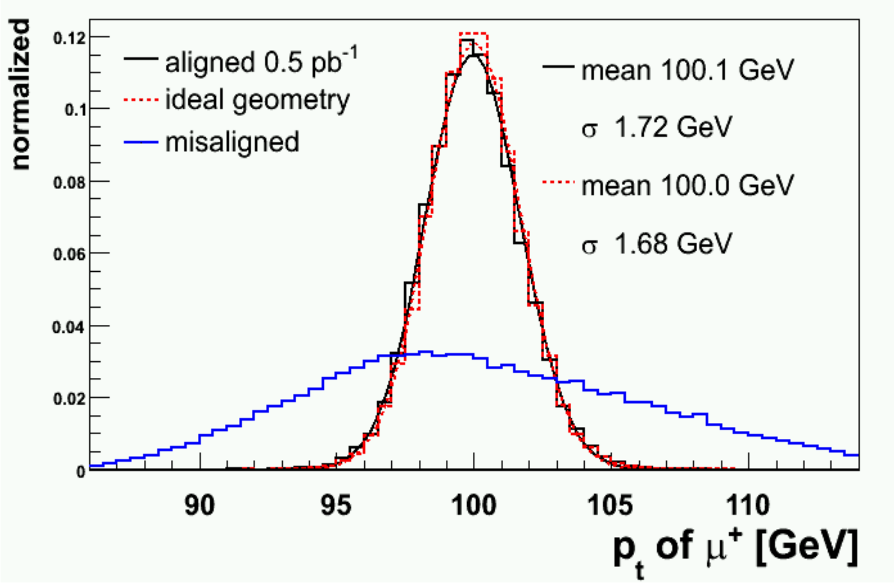
- Initially P_t bias of a few %.
- P_t bias of ~ 0.1 % after alignment.

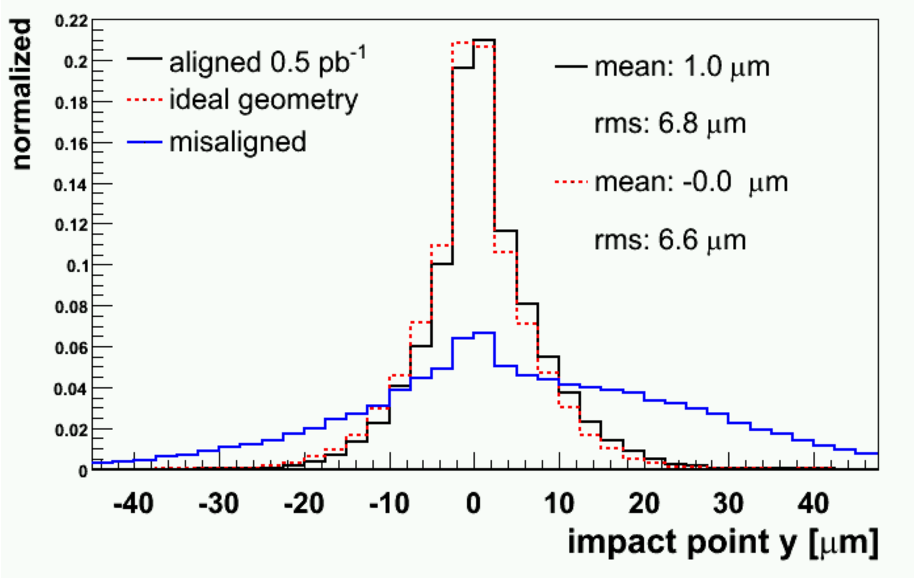
*Note: tracks from a gun without material interaction simulation.

3. Full Scale CMS Tracker Study

Resolution and bias

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





0.1% bias in P_t remains

Vertex shifted by 1 μm

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

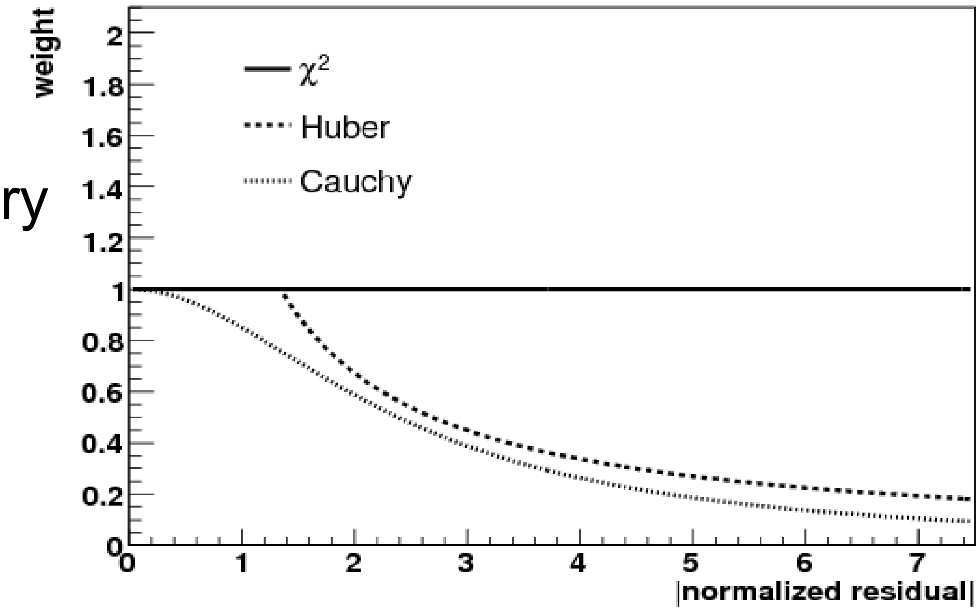
Proof of principle for simultaneous alignment strategy!

3. Full Scale CMS Tracker Study

Outlier Rejection

MPII internal Iterations are necessary for outlier rejection

- Reweighting (M-estimate): 2 x Huber then Cauchy.
- χ^2/ndof cut for tracks: tightened each iterations.



method iterations		none 1	reweighting 5	χ^2 cut 5	reweighting 10
barrel rϕ [μm]	mean	1.9	-1.9	1.1	-4.3
	rms	17.9	10.3	9.6	8.4
barrel z [μm]	mean	-10.9	-5.9	-7.0	-3.3
	rms	33.7	23.9	23.6	20.9
barrel r [μm]	mean	-0.8	-1.0	-0.9	-1.0
	rms	32.7	23.2	22.8	20.5
endcaps rϕ [μm]	mean	-3.1	-4.7	-1.3	-6.9
	rms	31.47	23.4	23.0	19.9
endcaps r [μm]	mean	1.7	1.9	1.6	1.9
	rms	35.9	27.0	26.3	23.7
endcaps z [μm]	mean	-6.0	0.3	-0.2	2.1
	rms	44.9	42.9	42.7	40.6

Results with different methods similar.

Outlier rejection is mandatory, even with simulated data!

Computing Requirements

Memory requirements:

More complementary datasets lead to denser matrices:

• Sparse Matrix Memory ≈ 12.5 GB x 15% = 2 GB.
• Full Matrix ≈ 8.3 GB memory

CPU Requirements:

Denser matrices increase CPU time if sparse matrix algorithms are used (GMRES + preconditioning).

Computing needs of the study:

• Data: cosmics, 500k mass constrained tracks, and 3 million single IP tracks.
• Density 15%.
• CPU time 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, 8 GB Memory

CPU and Memory needs modest!
Fast turnaround time!

4. MPII as Diagnostic Tool

Identification of χ^2 Invariant Deformations

The diagonalization method can be used to visualize χ^2 invariant deformations.

- The diagonalization method of MPII is limited to ~10.000 parameters.
- Eigenvectors with 0 as eigenvalue (or very small) represent χ^2 invariant Deformations.
- Apply Eigenvectors to geometry for **visualization**.

Diagnostic for Simplified CMS Tracker

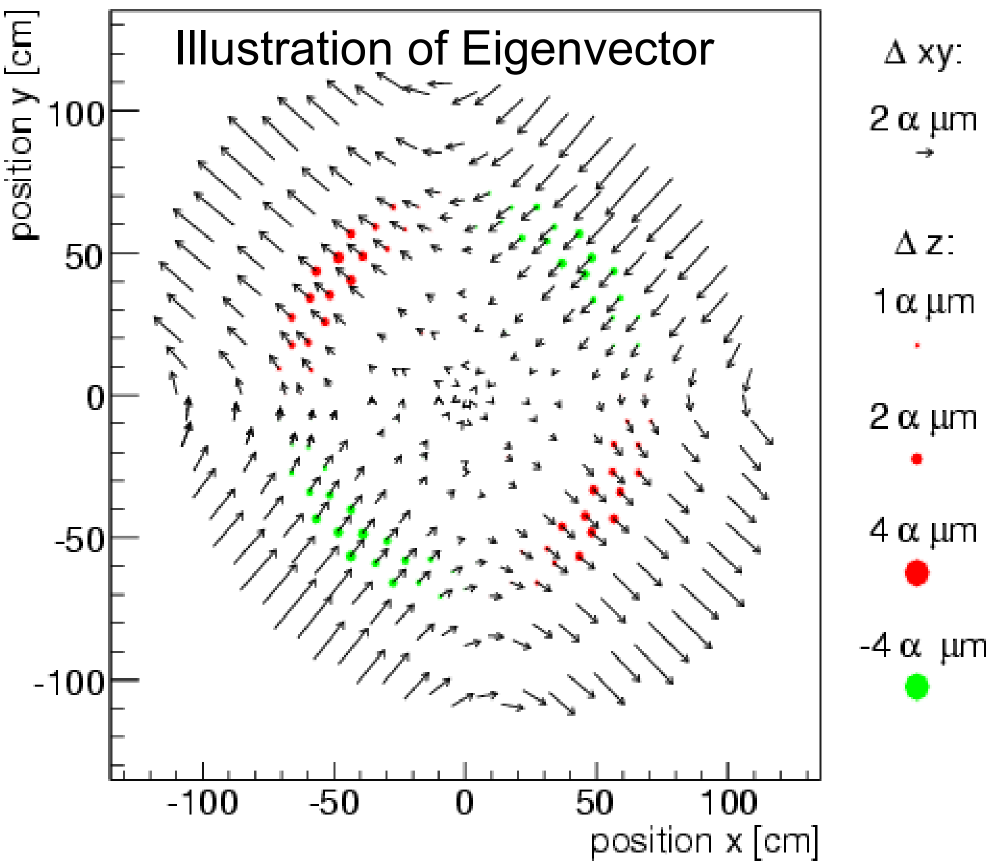
- **No cosmics, vertex constraint and initial knowledge used.**
- **Only single μ of 1 M $Z^0 \rightarrow \mu\mu$.**
- Simplified Geometry (rods, ladders of barrel).

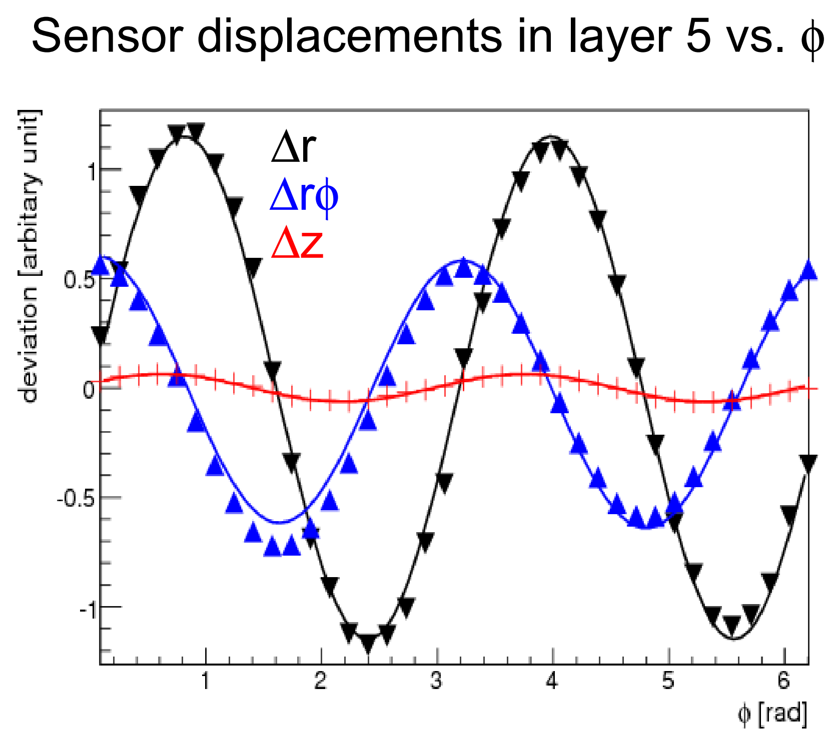
Note: ATLAS global χ^2approach equivalent to Millepede, except for “very fast” diagonalization procedure.

4. MPII: As Diagnostic Tool

Example of an Eigenvector

r-rϕ oscillation (mode 2) found to be χ^2 invariant deformation.





- Note: This is not the remaining misalignment of a study!
- Identifcation of potentially difficult deformations!

5. Possible Extensions

Symmetry Corrections

Certain symmetries can be expected to be maintained such as:

- Same $|\kappa|$ distributions for μ^+ and μ^- from Z^0 decay.
- Average P_t value independent of ϕ.
- ...

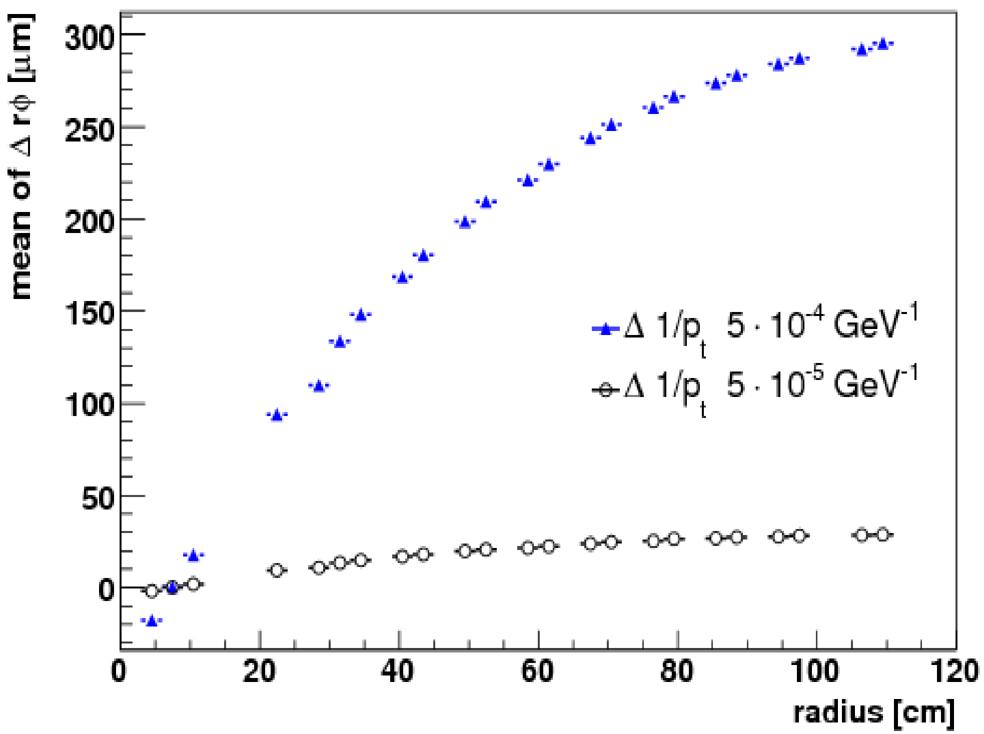
This is an interesting input to alignment.

MPII now:

1. Asymmetries would need to be found.
2. Geometry with track parameter corrections could be enforced.

→ Iterative process.

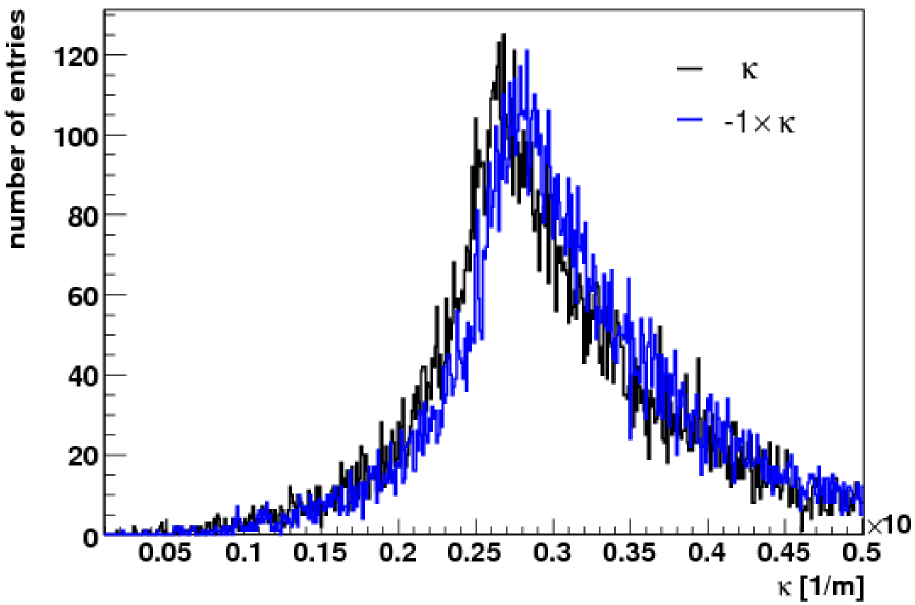
Technical test: Resulting geometry with enforced signed **curvature measurement bias**.



5. Possible Extensions

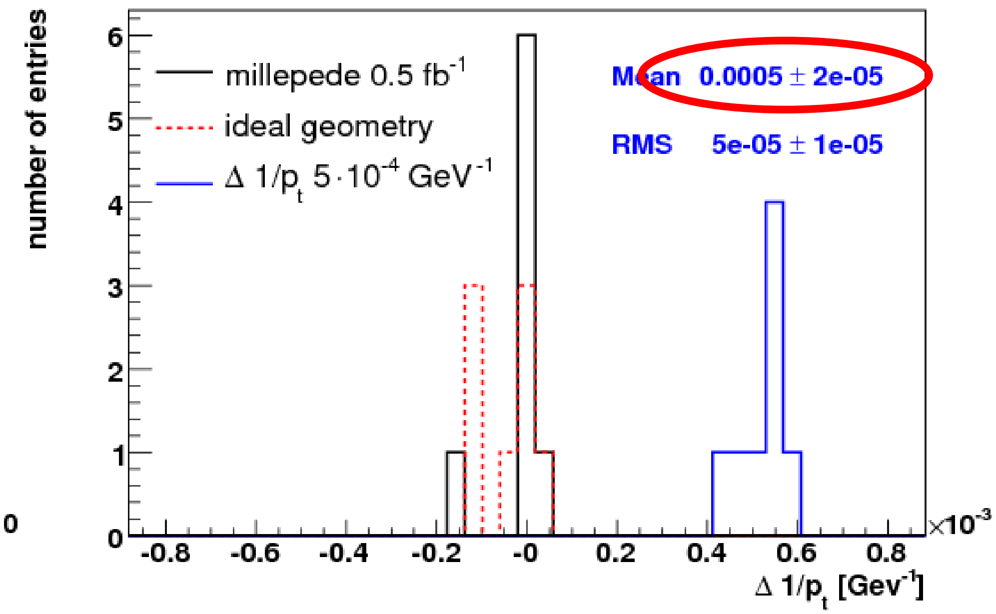
Finding Asymmetries

$|\kappa|$ distributions for μ^+ and μ^- in a ϕ bin for enforced $\Delta 1/P_t$ 5 10^{-4} GeV^{-1} geometry:



- Large asymmetries visible.
- Limited Statistics in a ϕ bin.

Fit of $\Delta 1/P_t$ for 8 different ϕ bins:



- $\Delta 1/P_t$ of 5 10^{-4} GeV^{-1} found in fit.
- Large uncertainty of fit.

Possible MPII Extension:

- Track parameters can be given to MPII (in current version).
- Asymmetry “fit” in MPII as extra term in minimization (not yet).

Tracker Alignment

Simultaneous alignment strategy developed and tested:

- Align the full strip and pixel tracker simultaneously!
- Complementary data sets.
- Utilizing initial knowledge.
- Incorporate all correlations between alignment parameters.

First time full tracker alignment procedure tested in CMS!

Millepede II

- Interfaces all sorts of information.
- Useful diagnostic tool.
- Outlier rejection included.
- Modest computing requirements.

Millepede II tested in large scale alignment procedure!

6. Summary

Outlook

Improvements:

New datasets:

- Beam Halo, Laser Alignment trajectories, ...

Symmetry Corrections:

- κ symmetry, ...

$\longrightarrow$ More emphasis on event data and less on prior knowledge.

Challenges:

- Including twists, bowings, more rotations, ...
- Unexpected Deformations.
- Thermal movements.
- Outliers in survey data.
- Magnetic field uncertainties.
- Material budged uncertainties.
- ...

Proof of principle with Millepede II shown, but still much work ahead.

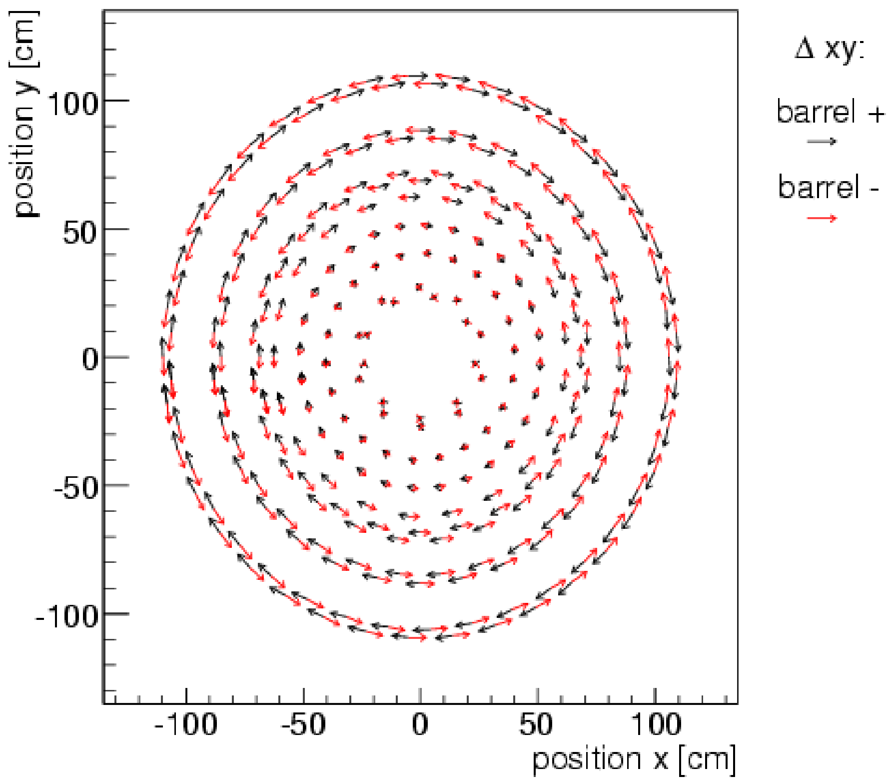
References

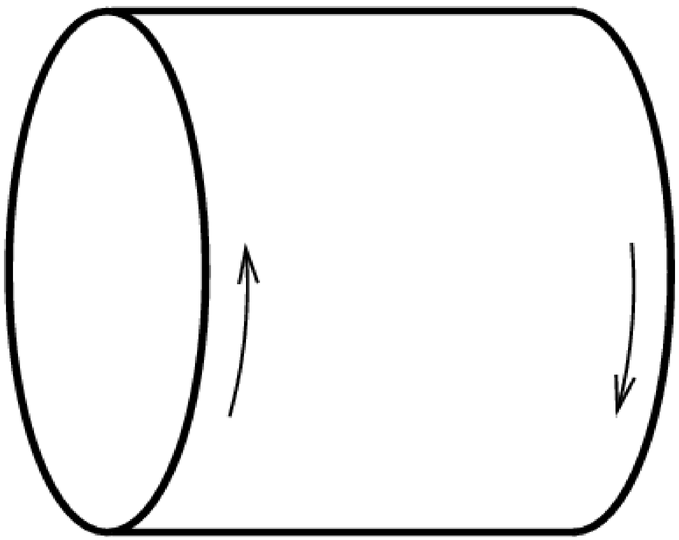
This and further studies:
"Calibration and Alignment of the CMS Tracker," M. Stoye, PhD Thesis **Draft**. Availible at: http://www.desy.de/~mstoye

Discription of Millepede II:
"Millepede II Manual **Draft**," V. Blobel, available at: http://www.desy.de/~blobel

4. MPII: As Diagnostic Tool

Examples of χ^2 invariant deformations: Twist





- Note: Many of these deformations are suppressed by the complementary data as shown in **Full Scale Study**.