$\sum \chi^2$ Invariant Deformations and Constraints

Gero Flucke, Peter Schleper, Georg Steinbrück, **Markus Stoye**
in collaboration with Volker Blobel
University of Hamburg

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Content:

$\sum \chi^2$ Invariant Deformations

- Classification of $\sum \chi^2$ Invariant Deformations.
- Identifying $\sum \chi^2$ Invariant Deformations via Diagonalization.
- Fitting of Deformations to Classifications.

Impact of Constraints

- Applying Initial Knowledge.
- Simultaneous Alignment of Different Tracker Components.
- Preferring Plausible (Rigid Body Like) Solutions.
- Results Summary

Summary and Outlook

- Summary
- Next Talk Outline

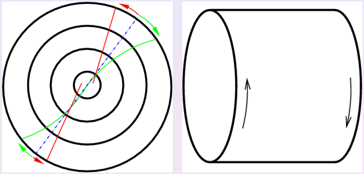
Classification of $\sum \chi^2$ Invariant Deformations

Some deformations remain undefined in a $\sum \chi^2$ minimization.

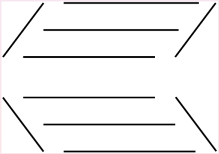
Shearing and bending

- Shearing: changing the ϕ and η measurements.
- Bending: changing the κ measurement.
- Change of bending and shearing amplitude along z. (twist)

a) shearing and bending in rϕ, twist:



b) shearing in z:

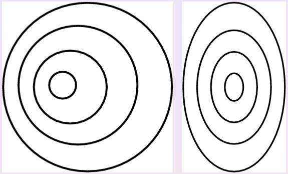


Expansion and shrinking

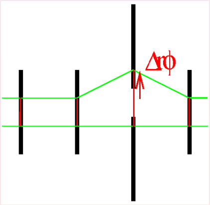
- An overall expansion increases the $\sum \chi^2$, since the size of the sensors is fixed.
- The distance between neighboring sensors in $r\phi$ is well defined (b).

$\Rightarrow$ Only oscillation between expansion and shrinking occur (a).

a) r-rϕ mode 1 and mode 2:



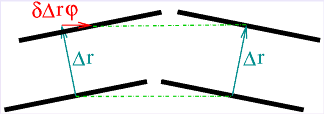
b) Δrϕ fixed by known strip pitch:



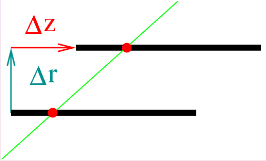
r-rϕ Oscillations

- $\delta \Delta r\phi \sim \Delta r$ to keep the rϕ distance between neighboring sensors constant. (a)
  $\Rightarrow$ Harmonic r-rϕ Oscillation!
- Δz is $\sim$ to Δr (b, vertex tracks).
  $\Rightarrow$ Δz couples to oscillation!

a)



b)



The nth r-rϕ mode can be described as follows:

$$\Delta r(\phi) \sim \cos(n\phi + \alpha) \quad \Delta r\phi(\phi) \sim \sin(n\phi + \alpha) \quad \Delta z(\phi) \sim \cos(n\phi + \alpha)$$

$\sum \chi^2$ Invariant Eigenvectors

An linear equation system needs to be solved to minimize the $\sum \chi^2$. The eigenvectors with the smallest eigenvalues have the least impact on the $\sum \chi^2$.

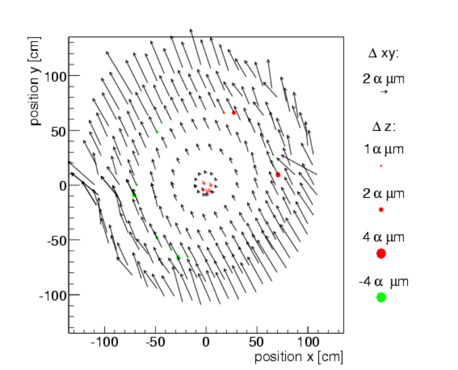
The scenario used for diagonalization:

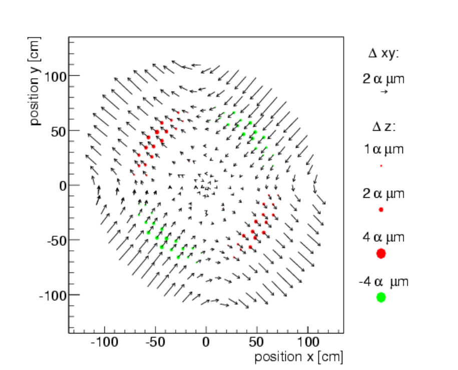
- Single muons of 1 mio Z$\rightarrow \mu\mu$.
- All rods and ladders of tracker barrels.
- $u, v(2D), w, \gamma$ are the parameters per rod or ladder.

The $\sum \chi^2$ invariant eigenvectors are applied to the geometry and illustrated in the following.

$\Rightarrow$ $\sum \chi^2$ invariant eigenvectors systematically studied and compared to classification.

Identifying Deformations via Diagonalization

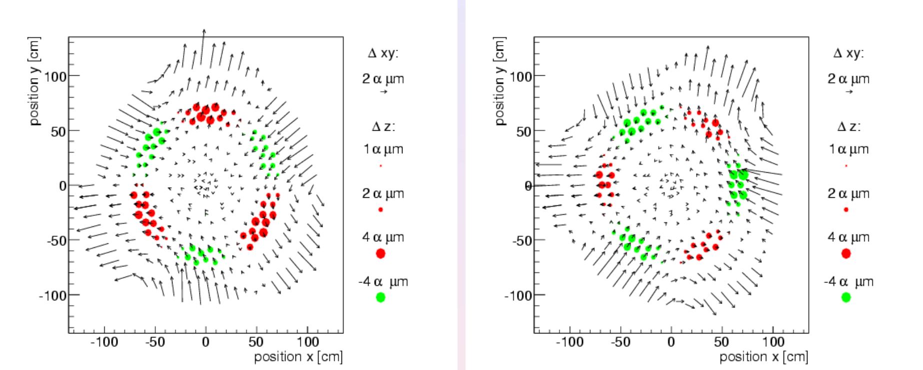




Left: First r-rϕ oscillation, Right: second r-rϕ*oscillation*

$\Rightarrow$ r-rϕ oscillation clearly visible!

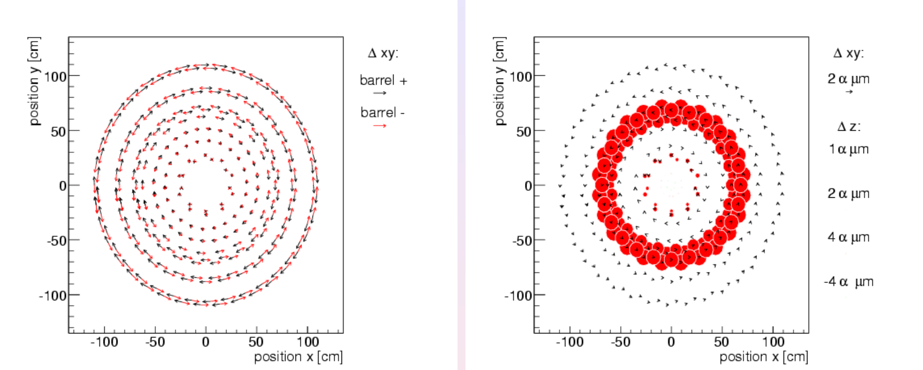
Identifying Deformations via Diagonalization



Left: Third r-rϕ oscillation, Right: Third r-rϕ*oscillation* (phase shifted 90°).

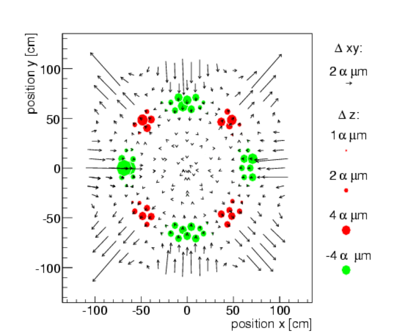
$\Rightarrow$ Each mode occurs twice with a phase shift of $\alpha = 90°$!

Identifying Deformations via Diagonalization



Left: Twist (red: barrel-,black: barrel +), Right: z shearing.

⇒ The twist and z shearing clearly visible!

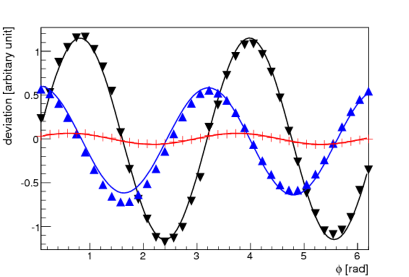


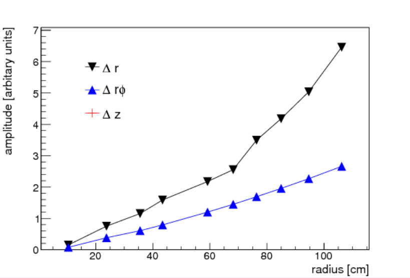
Forth mode of r-rϕ oscillation.

The 10 deformations with least impact on $\sum \chi^2$ have been studied.

$\Rightarrow$ The deformations were covered by the classification scheme!

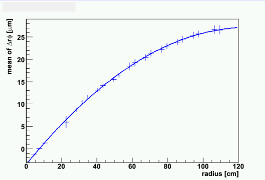
r-rϕ Oscillations



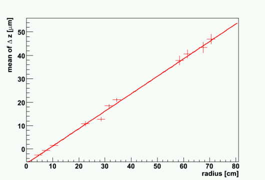


Left: Fit of deformation from eigenvector (5*th* layer) to second mode.
Right: Amplitude of oscillation versus radius of layer.

$\Rightarrow$ Deformation is clearly a harmonic oscillations!



Mean $\Delta r\phi(r)$ fitted to polynom of 2^{nd} order.



Mean $\Delta z(r)$ fitted to polynom of 1^{st} order.

Shearing and bending

Shearing and bending is fitted via polynoms to remaining misalignment (next sec.)

- Shearing well described by polynom of 1^{st} order.
- Bending well described by adding a quadratic term.

$\Rightarrow$ Deformation fit well into shearing, bending and r-rϕ oscillation scheme!

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Relative Parametrization

Via constraints relative alignment parameters can be introduced:

- Rod position and orientation w.r.t. half barrel (or layer).
- Layer position and orientation w.r.t. half barrel.
- half barrel and orientation w.r.t. pixel.

$\Rightarrow$ Allows to correctly apply initial knowledge.

$\Rightarrow$ No iterations between hierarchies necessary.

Coordinate system definition:

- $\sum$ pixel half barrel movements and rotations $= 0$.

$\Rightarrow$ No external reference system used!

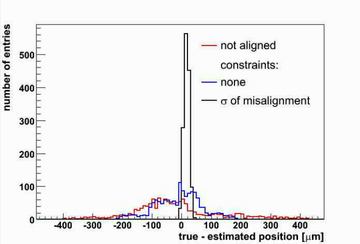
Studies of Impact of Initial Knowledge

Studies were performed in the following scenario:

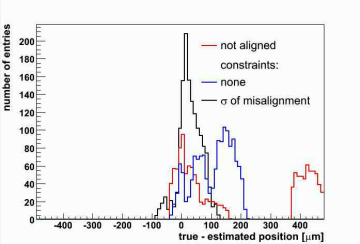
- *First data scenario* misalignment up to rod and ladder level.
- All rods, ladders, half barrels aligned.
- $u, v(2D), w, \gamma$ are the parameters per alignable.
- Single muons of 2 mio. Z$\rightarrow \mu\mu$ events.
- Initial relative alignment parameter uncertainties as given by misalignment.
- If γ was not misaligned, an uncertainty of 10 μrad was assumed.
- Coordinate system defined via constraints.

$\Rightarrow$ Similar scenario as in CMS NOTE 2006/11, but without fixing any rods or ladders!

Residuals of Global Rod Positions



Residuals of Rod Positions in $r\phi$.

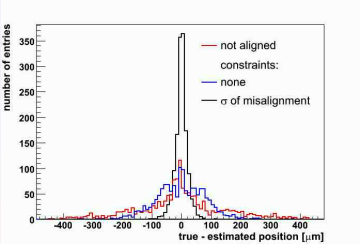


Residuals of Rod Positions in z.

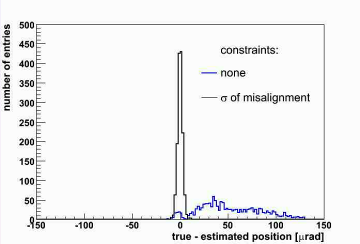
The RMS of the $r\phi$ residuals decreases from 77 μm without initial knowledge (blue) to 9 μm with initial knowledge (black).

$\Rightarrow$ The residuals improve significantly!

Residuals of Global Rod Positions



Residuals of Rod Positions in r.



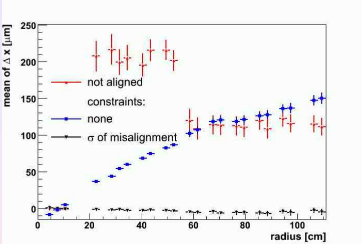
Residuals of Rod Rotation γ.

The RMS of the r residuals decreases from 80 μm without initial knowledge (blue) to 21 μm with initial knowledge (black).

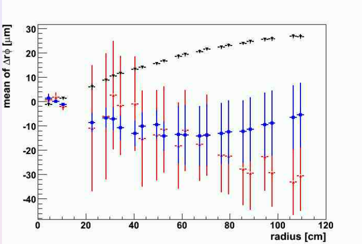
$\Rightarrow$ The residuals improve significantly!

Applying Initial Knowledge

Remaining Deformations



Mean Δx(r).

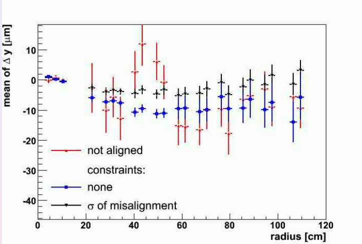


Mean $\Delta r\phi(r)$.

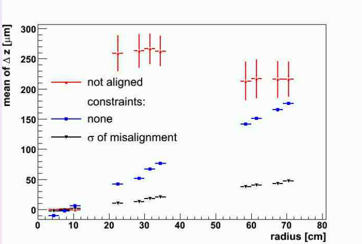
Bias due to initial correlated misalignment clearly visible. Applying initial knowledge improves the alignment, but some systematic deformations remain.

$\Rightarrow$ Initial knowledge reduces bias.

Remaining Deformations



Mean Δy(r).

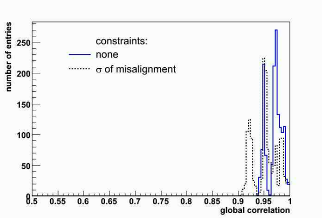


Mean Δz(r).

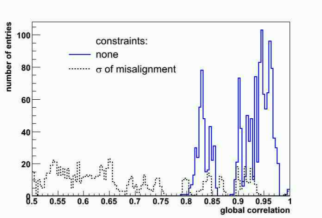
Δz(r) is still biased, even if initial knowledge applied.

$\Rightarrow$ Some deformation remain even if initial knowledge applied.

Global Correlations (Monitoring via MP output)



Global Correlation of u.

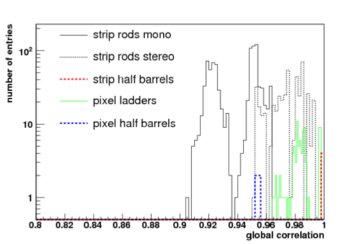


Global correlations of γ

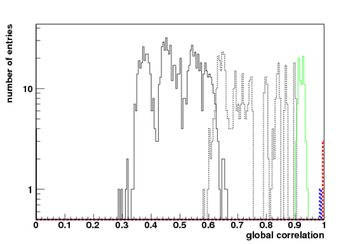
$\Rightarrow$ Improvement, but still large correlations remain (up to 0.9998)!

Global correlations are an useful tool to monitor alignment quality without knowledge of the misalignment.

Upper Limit of Global Correlations



Global Correlation of u



Global correlations of γ

Global correlations of different alignment parameter types. Initial knowledge was applied. Strip half barrels have highest correlations!

$\Rightarrow$ Global correlation of strip half barrels give upper limit of correlations!

Reminder: Fast linear equation solvers require extra effort to calculate global correlation!

Adding More Tracker Components

So far a strategy with simultaneous alignment was used:

- Pixel and Barrel aligned simultaneously!

Following this strategy TEC, TID and TPE are added to the scenario:

- The TID, TPE and a TEC layer per TEC have been added.
- Misaligned with the *first data taking* scenario up to sensor level!
- Aligned to the wedge Petal level.
- u, v, w, γ for each alignable.
- Scenario is denoted by $+$EC in legends.

$\Rightarrow$ The completely different geometry of the endcaps should constrain deformations!

Selecting Plausible Deformations

It can be chosen if internal deformation (bending, shearing ...) of a higher structures are preferred or if translations and rotations of a higher structures are preferred.

- Reducing the uncertainty of alignment parameters w.r.t. higher structure reduces the internal deformations of the higher structure.

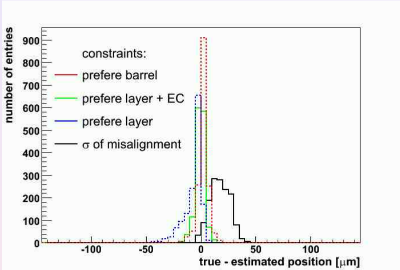
Two scenarios have been studied:

- preferring half barrel rigid body parameters.
- preferring layer rigid body parameters.

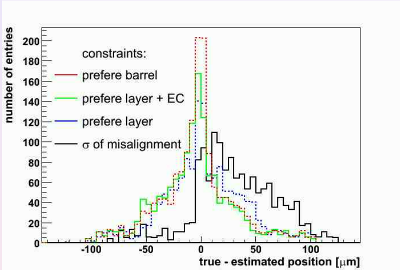
Technically the rod parameters have been reduced by a factor of 10. The remaining rod uncertainty of 10-20 μm is still in the order of a single hit measurement.

Note: Also other deformations (eg. twist, shearing) could be introduced as preferred deformations.

Residuals of Global Rod Positions



Residuals of Rod Positions in $r\phi$.

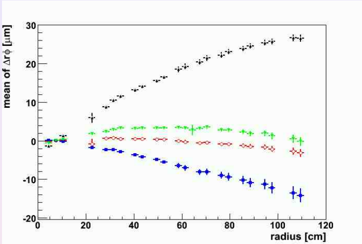


Residuals of Rod Positions in z.

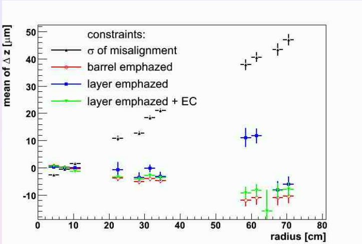
Barrel r.b.p. preferred: $r\phi$ residuals RMS $= 4.9\ \mu$m, Mean $= 0.5\ \mu$m.

$\Rightarrow$ Default misalignment scenario aligned successfully to rod level!

Remaining Deformations



Mean $\Delta r\phi(r)$.



Mean $\Delta z\phi(r)$.

All deformations are suppressed if barrel r.b.p. are preferred. Layer r.b.p. still allow shearing and bending, but no higher mode r-rϕ oscillations and twist.

$\Rightarrow$ Adding endcaps helps significantly to reduce deformations!

Summary Table of Position uncertainties

The table summarizes the results shown in the previous plots.

	Not Al.	None	Mis. σ	pr. layer	+ EC	pr. bar.
RMS u [μm]	149.8	77.5	9.1	8.47	4.66	4.90
Mean u [μm]	-15.3	-10.0	17.2	-6.70	2.17	-0.58
RMS v [μm]	200.9	64.7	37.6	35.8	33.8	35.2
Mean v [μm]	198.4	106.8	30.2	2.50	-2.7	-4.9
RMS w [μm]	144.1	80.3	20.6	13.6	22.3	23.
Mean w [μm]	-1.0	-2.2	-0.7	-1.62	-0.31	-1.1
RMS γ [μrad]	0.00	30.2	2.5	-	-	0.3
Mean γ [μrad]	0.00	50.3	0.1	-	-	-0.0

Table: Remaining position uncertainties for different scenarios.

$\Rightarrow$ Using constraints improves the alignment.

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Summary and Conclusion

Studies of critical deformations of the tracker:

- $\sum \chi^2$ invariant deformation classified.
- Classification confirmed via fits to determined $\sum \chi^2$ invariant Deformation.

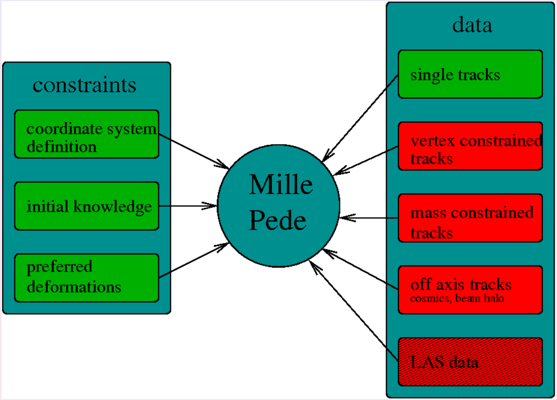
Studies of the impact of constraints:

- Applying initial knowledge helps a lot.
- Aligning different tracker components simultaneously: The different geometric properties of the structures reduce the probability of remaining deformation!
- A plausible (rigid body like movements preferred) solution of $\sum \chi^2$ minimum can be chosen: The results improve.

$\Rightarrow$ Constraints are an effective tool for alignment.

Summary and Conclusion

Green: used in study Red: not used in study.



⇒ The *fist data misalignment scenario* can be aligned standalone to rod level with single tracks and constraints to a precision $O(10)$ smaller than the intrinsic resolution of sensors!

BackUp: Outline of Next Presentation

This Presentation:

Results were presented utilizing constraints and single muon tracks. Constraints will be most important in the beginning.

$\Rightarrow$ This is a valid strategy for the starup phase.

Next Presentation

If more data is collected the alignment is less dependent on initial uncertainties and preferred solutions. Cosmics, Z^0 with mass and vertex constrains can be used suppress deformations. A new high pt cosmic muon dataset (25k) has been produced.

Content:

- Impact of Z^0 with mass ans vertex constrains
- Impact of cosmic muons.

$\Rightarrow$ The result is a strategy for the longterm alignment.

BackUp: Table of Initial Knowledge

Type	u μm	v μm	w μm	γ μrad
TOB Half Barrels	105	105	500	90
TIB Half Barrels	67	67	500	59
TPB Half Barrels	13	13	13	10
TOB Rods†	100	100	100	10^{*}
TIB Rods†	200	200	200	10^{*}
TPB Ladders†	5	5	5	10^{*}

Table: Initial Uncertainties of alignment parameters corresponding to the *first data rod level* misalignment scenario except for the uncertainties labeled with *, which are not misaligned. Uncertainties in rows labeled with † are reduced by a factor of 10 in the barrel dominated scenario.