Tracker Alignment Strategy in CMS
and Experience with Cosmic Ray Data

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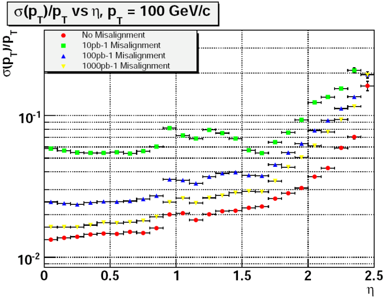
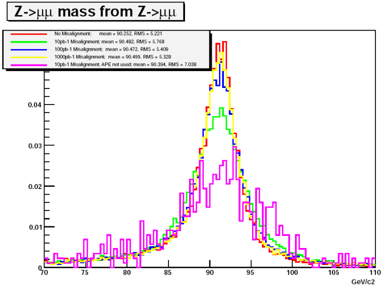
Misalignment Effects and Outline

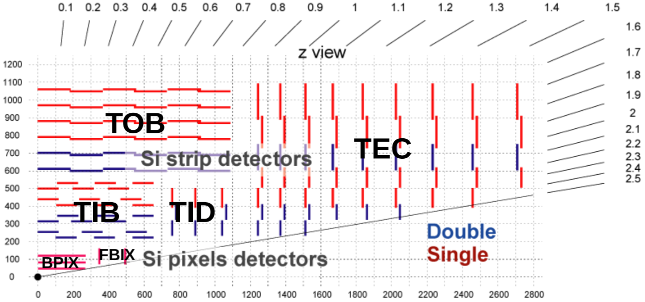




- The CMS Alignment Challenge
- The Strategy:
    - From Assembly. . .
    - . . . via Survey and Laser System Measurements
    - . . . to Track Based Alignment
    - . . . and their Combination
- Monitoring
- First Experience with Cosmic Ray Data

The CMS Tracker: All Silicon

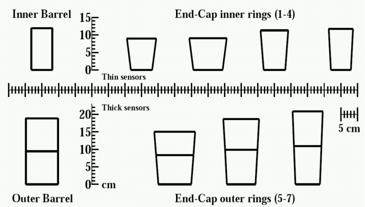
rz-view (upper right quarter)



Sensor thickness

- $r < 11$ cm: 285/270 μm (Pixel)
- $r < 55$ cm: 320 μm (Strip)
- $r > 55$ cm: 500 μm (Strip)

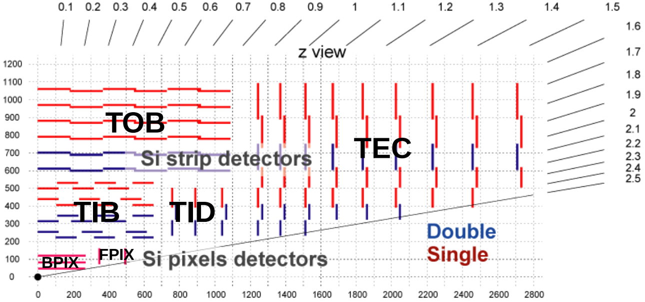
Many sensor shapes in Endcaps:



- Pixel size: $100 \times 150\ \mu m^2$
- Strip pitch: $80 - 205\ \mu m$
- Strips parallel to
  - z: rectangular sensors
  - r: wedge shaped sensors
- “2D” strip: $\angle(\text{sensors}) = 100\ \mu rad$

CMS Tracker Alignment Challenge

rz-view (upper right quarter)



Distances

- $r = 110\ cm$
- $|z| < 275\ cm$

$\Rightarrow$ More than 5 m apart!

Parameters: up to $\approx$ 100 000

- 15148 silicon strip modules: $\sigma \approx 23 - 60\ \mu m\ (r\phi)$
- 1440 silicon pixel modules: $\sigma \approx 9 \times 10 - 35\ \mu m\ (r\phi \times z)$

  $\Rightarrow 16588 \times 6 = 99528$ rigid body parameters
- some insensitive, e.g. global z of “1D” barrel strips
- modules of “2D” strip layers treated as one

Alignment Strategy in Time

1. High Mounting Precision
2. Survey Measurements
3. Laser Alignment System
4. Track Based Alignment
5. Online Monitoring

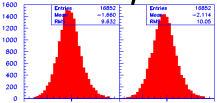
Assembly Precision and Hierarchy

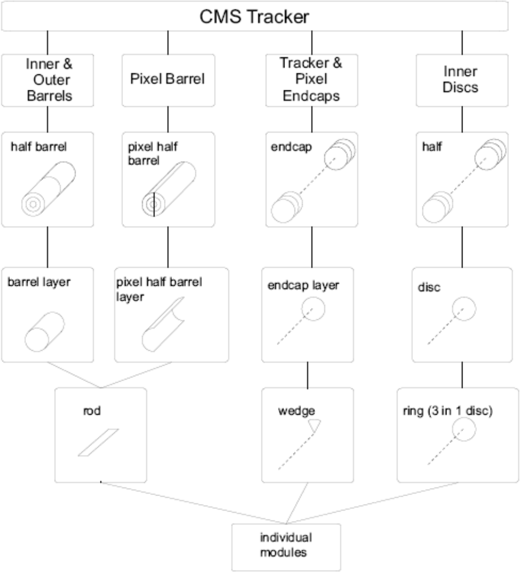
Estimated RMS in μm

TIB		TEC	
Sensor		Sensor	
	10		10
Module		Module	
	180		20
Shell		Petal	
	450		70
Cylinder		Disc	
	750		150
Tube		TEC	
			600
		Tube	

Sensor vs module:

$$\sigma = 10\ \mu m$$



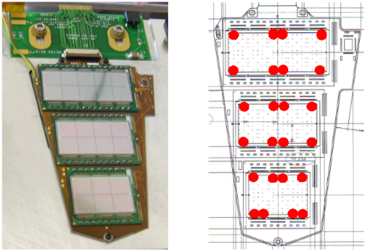


⇒ placement uncertainties increasing for larger structures

Survey Measurements

TIB+ layer 3: CMM

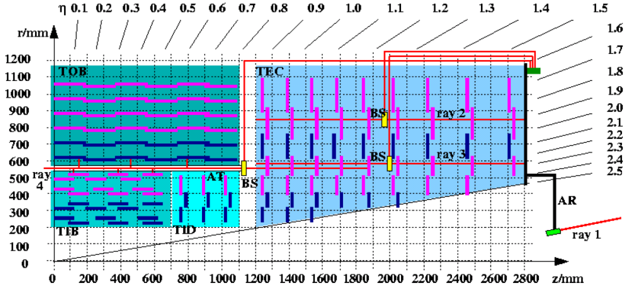
Forward Pixel Blade: Fiducial points



Photogrammetry, CMM

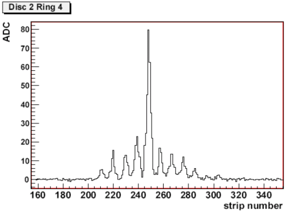
- Different subdetectors measured in different depth.
- Outer Strip (TOB and TEC):
  - large structures like Half Barrel or Endcaps measured
- Inner Strip (TIB and TID):
  - $\approx$ 2000 points per layer/disc
  - down to module level
- Forward pixel:
  - Very detailed: Many fiducial points per sensor
- Pixel Barrel
  - Partial survey planned (e.g. 1st/3rd layer)

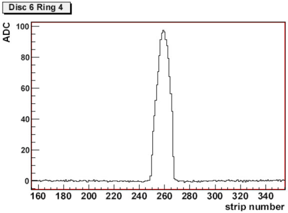
Laser Alignment System



Infrared laser

- 2x8 beams through each TEC
- 8 beams connecting TIB, TOB, TEC
- measured with tracking sensors.

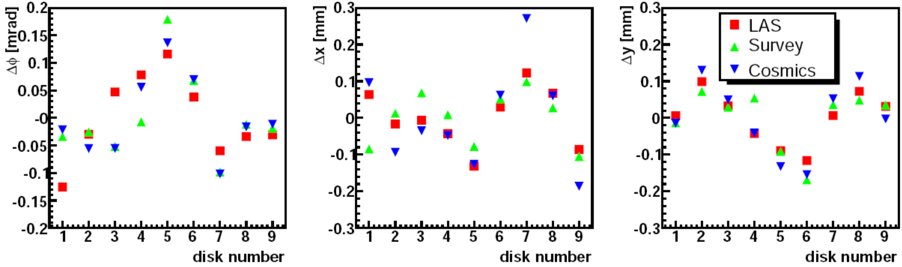


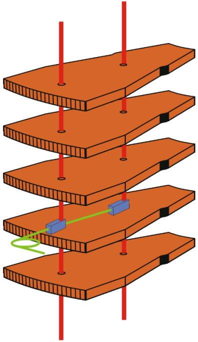


Beam:

- Intensity varied.
- $\mathcal{O}(100)$ events to increase S/N.
- Profile depends on N(sensors) crossed.

Laser Alignment System in TEC Integration





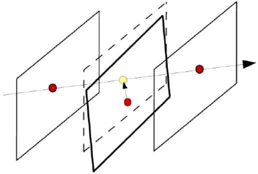
- Laser system, photogrammetry and track based alignment with cosmics.
- Global degrees of freedom fixed (shift, rotation, torsion, shear).
- Small disc misplacement and rotations.

⇒ High mounting precision confirmed!

- Agreement within 60 μm (x/y) an 80 μrad (ϕ).

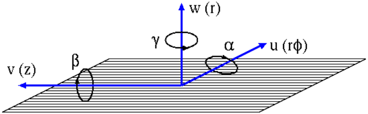
⇒ Upper limit on precision of methods.

Track Based Alignment (TBA)



Common principles

- Minimisation of χ^2 of track hit residuals.
- $\leq$ 6 rigid body parameters.



Algorithms

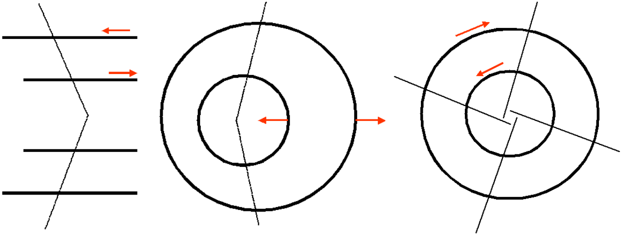
- Three algorithms in CMS:
  - **HIP:** module-wise (“local”), **iterative**
  - **Kalman:** extending track fit with alignment parameters, **sequential**
  - **Millepede II:** “global” minimisation of alignment and track, **single step** (besides outlier rejection)
- Able to deal with higher level objects, following mechanical structures.
  - ⇒ adjustable to available statistics
- CPU/memory under control. (⇒)

The Challenge: Distortions

Minimising residuals can be insensitive to certain global distortions.

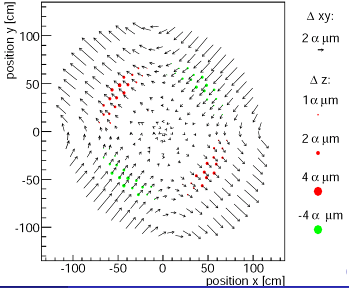
Insensitive means:

- Cannot be resolved.
- May appear in solution.

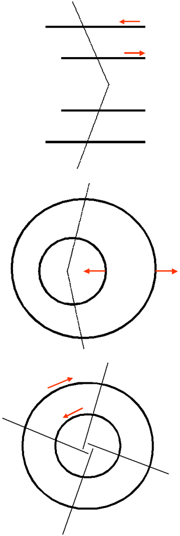


- Intrinsic to problem, independent of method.
- Resisting high statistics.
- Biases measurements.
- Dependent on data sets:
  - ⇒ need more than just tracks from interaction point

CMS Barrel: low Eigenvalue
(μ from $Z \rightarrow \mu\mu$)



Useful Data



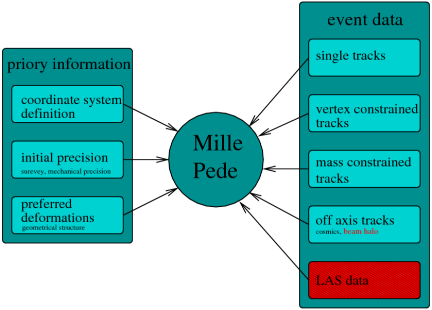
- μ tracks from $Z \to \mu^+\mu^-$ and $W \to \mu\nu$
  - abundant at high luminosity
  - low multiple scattering
- cosmic ray μ
  - relate opposite detector parts with common curvature
  - with $\boldsymbol{B} = 0$ even straight line (but moving detector?)
- beam halo μ
  - similar to cosmics for endcaps
- mass constrained $Z \to \mu^+\mu^-$ and $J/\Psi \to \mu^+\mu^-$
  - common vertex prevents $\Delta\phi(r)$
  - mass sets momentum scale (weakly. . .)
- minimum bias tracks
  - abundant in the beginning
  - high sensitivity to $r\phi$ rotation
- minimum bias tracks with primary vertex constraint
  - sensitive to shifts of opposite detector parts
  - at low luminosity well defined primary vertex
- “tracks” from laser system
  - straight lines in endcaps (known momentum)

Tracker Alignment with Millepede II

Millepede II

(by V. Blobel)

- Simultaneous fit of track and alignment parameters.
  $\Rightarrow$ $\boldsymbol{C} \cdot a = b$ with $\boldsymbol{C}$ $n \times n$ matrix for n alignment parameters
- Outlier rejection/down weighting.
- Constraints, e.g. to fix global d.o.f. (via Lagrangian multipliers).
- Fast methods for solving matrix equation (up to 100 000 parameters).
- Sparse matrix storage.
- Damping weakly of d.o.f. by χ^2-penalties ($\sim$ regularisation in unfolding).



priory information

coordinate system definition

initial precision

surevey, mechanical precision

preferred deformations

geometrical structure

Mille Pede

event data

single tracks

vertex constrained tracks

mass constrained tracks

off axis tracks

cosmics, beam halo

LAS data

Strategy

Simultaneous use of:

- Complementary data sets.
- Mass and vertex constraints.
- Knowledge of assembly/survey precision.
- Support structure hierarchy.

Full Scale Tracker Alignment Study (MC)

Millepede II: Scenario

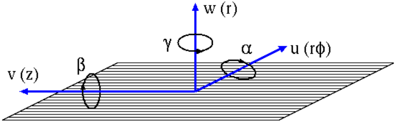
- Start up misalignment (pixel roughly pre-aligned to 15 μm).
- Data sets:
  - single μ tracks $\Leftrightarrow W \rightarrow \mu\nu$ of $L = 0.5\ fb^{-1}$
  - $Z \rightarrow \mu\mu$ with mass/vertex constraint $\Leftrightarrow L = 0.5\ fb^{-1}$
  - 25 k cosmic with $p > 50$ GeV $\Leftrightarrow \mathcal{O}$(3 weeks).

Parameters

- Shifts: 3(2) for 2D(1D) modules.
- Rotation: around sensor normal.

$\Rightarrow$ $\approx$ 45 000 degrees of freedom.

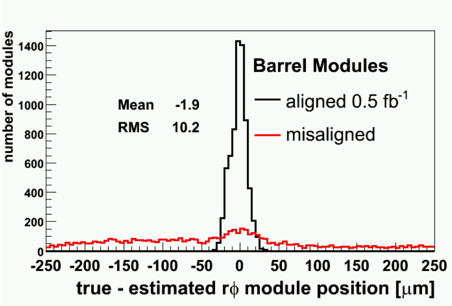
- Coordinate system defined by Pixel barrel.
- χ^2-penalties for module movements/rotations ("prior knowledge")

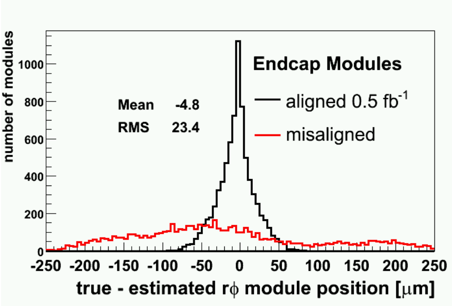


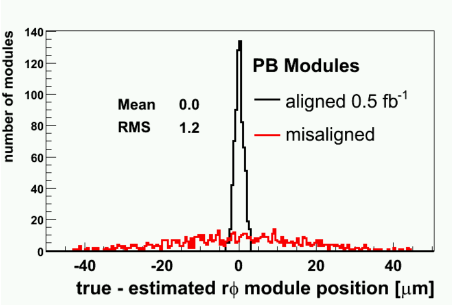
Modest Requirements

- $<$ 2 h CPU on 64bit PC
- $\approx$ 2 GB memory
- Plus parallel data acquisition.

Full Scale Tracker Alignment Study





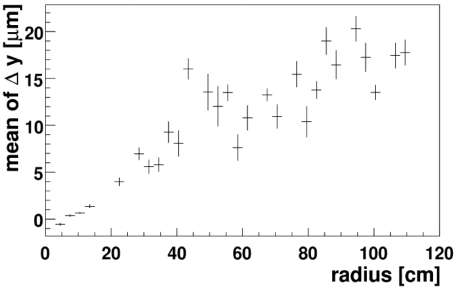


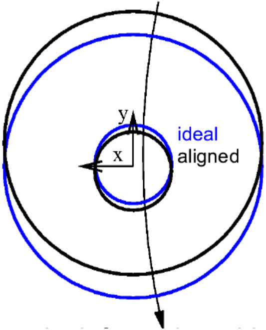
Sensitive Module Direction

Excellent precision:

- Barrel with $\sigma_{r\phi} = 10\ \mu m$:
  - aligned below resolution
  - especially in pixel
- Endcaps slightly worse:
  - miss cosmics

Small Remaining Misalignment: Distortion





- Systematic module misplacement: $\langle \Delta y \rangle \propto r$
- Equivalent in x fixed by cosmics penetrating full tracker from top.

⇒ Small deformations remain:
Dominant source of misalignment.

- But bias small: per mille on p_t of 100 GeV.

Combination of Survey and Track Based Alignment

Desirable

- Survey connects other module positions.

⇒ Can fix weak modes of TBA.

- Stabilises when low hit statistics.
- Trap: Uncertainty smaller than time stability?

⇒ Incorporate in sophisticated error analysis.

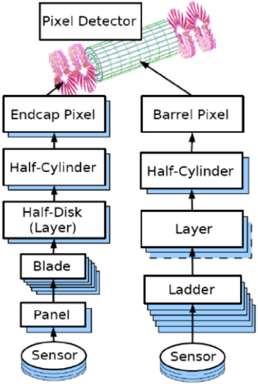
HIP Approach: Survey Residuals

- Minimise simultaneously: $\chi^2 = \chi^2_{track} + \chi^2_{survey}$
- χ^2_{survey} based on
  - fiducial points
  - hierarchical error

Millepede Approach

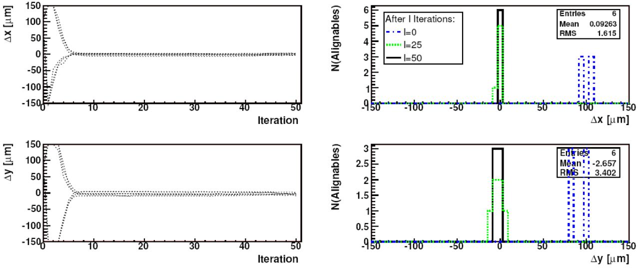
- Directly include survey measurements.
- Alternative: Use error as 'prior knowledge'.

Hierarchical errors:



⇒ Under development.

Pixel Monitoring with Minimum Bias Tracks



Pixel Barrel

- Not in Laser system.
- High Level Trigger needs it.

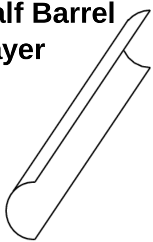
⇒ Fast feedback from TBA!

Feasibility Study (MC)

- Aligned tracker (not perfect).
- Large correlated shifts/rot. of 6 half barrel layers.
- Minimum bias tracks from $\approx$ 1 h (nominal $\mathcal{L}$).
- Vertex constraint.
- HIP algorithm with 50 iterations:

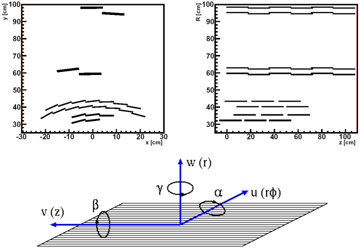
⇒ Recovering: x/y-position to $\mathcal{O}(10)$ μm
angles to $\mathcal{O}(100)$ μrad

Half Barrel Layer

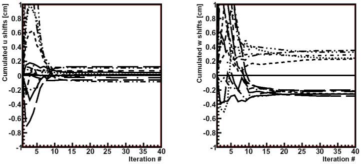


Experience with Cosmic Ray Data: MTCC

Custom Tracker Structure



TIB: convergence



⇒ First real data, lesson: Geometry description *can* be quite far off.

CMS Magnet Test Cosmic Challenge

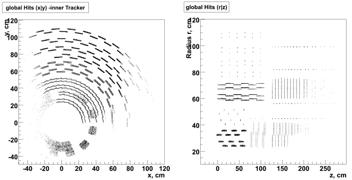
- Part of CMS operated on surface.
  - $\sim$1% of tracker channels
- Data with $B = 0..4$ T.
  - Use $B = 0$ T: statistics, straight line
- Start from surveyed module positions.
- iterative HIP algorithm on “rods” (= 3 or 6 modules):
  1. align TOB, TIB fixed: local *u*, γ
  2. vice versa: local *u*, *w*, γ
  3. cross check TOB with fixed TIB

  - decreasing Alignment Pos. Error until iteration 10

	#tracks	$\langle\chi^2\rangle$	$\langle N_{hit}\rangle$	res. TIB L3
Before	1460	20.1	3.3	416 μm
After	4956	6.0	4.3	125 μm

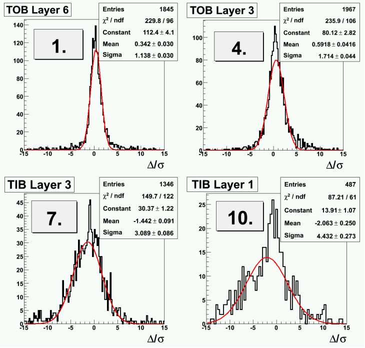
Experience with Cosmic Ray Data: TIF

Hit maps XY and RZ:



Increasing residuals:

multiple scattering



Tracker Integration Facility

- 12.5% of strip stracker read out.
- Different scintillator positions for triggering cosmics.
- Temperature: $+15 \rightarrow -15^\circ$ C
  - also fraction of laser system tested
- Special challenges:
  - Partial tracker:
    - $\Rightarrow$ missing symmetries, hit statistics
  - Low momenta:
    - $\Rightarrow$ large multiple scattering
  - No B-field to measure p.
  - Large range of $\angle$(track,$\vec{n}$(sens.)).

No Results Yet:

Work ongoing with high priority!

Detailed Alignment Strategy of CMS

1. Confirmed precise assembly
2. Many detailed survey measurements
3. Laser system proven to work well
4. Track Based Alignment (TBA)
   - full scale alignment successfully tested - and fast
   - complementary data sets essential:
     1. Cosmic Muons
     2. Beam Halo Muons
     3. minimum bias tracks, $J/\Psi \rightarrow \mu\mu$
     4. Muons from Z^0, $W^\pm$
     5. $Z \rightarrow \mu\mu$ with vertex and mass constraint
5. Combination of Survey, Laser System and TBA

Summary

- Confirmed precise assembly
- Many detailed survey measurements
- Laser system proven to work well
- Track Based Alignment (TBA)

- Combination of Survey, Laser System and TBA
- Monitoring with time:
  - TIB, TOB, TEC connected via laser system
  - fast turn around of TBA in pixel
- Real data experience currently gained with cosmics.

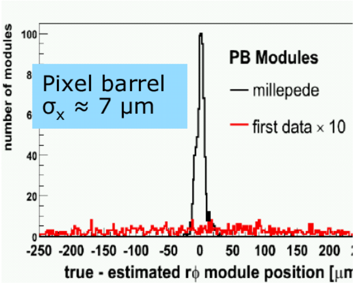
The Right Balance:

- Optimal results.
- Be in time for first physics.

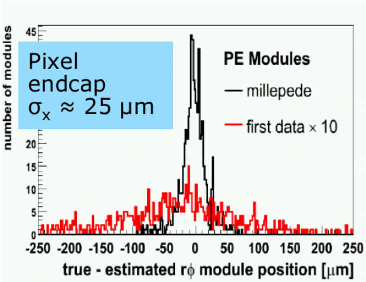
⇒ **Confident to increase precision with time according to physics needs.**

Backup

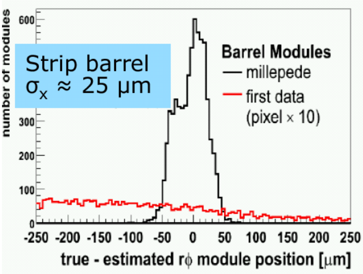
Millepede: Worsely Pre-Aligned Pixel



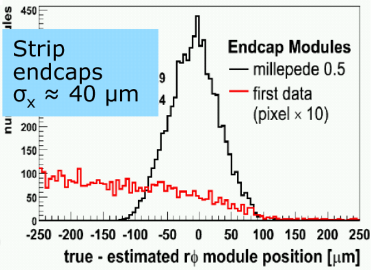
Pixel barrel
$\sigma_x \approx 7\ \mu m$



Pixel
endcap
$\sigma_x \approx 25\ \mu m$

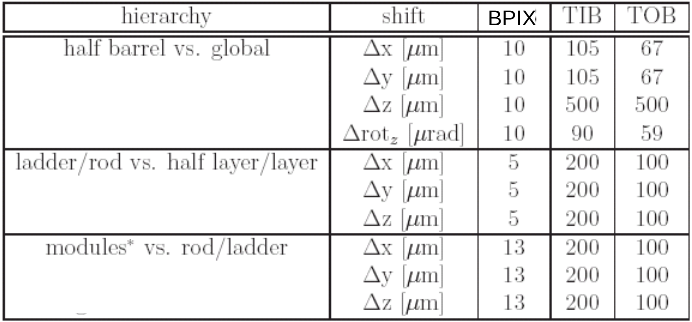


Strip barrel
$\sigma_x \approx 25\ \mu m$



Strip
endcaps
$\sigma_x \approx 40\ \mu m$

Millepede: Assumed Starting Uncertainties



hierarchy	shift	BPIX	TIB	TOB
half barrel vs. global	Δx [μm]	10	105	67
	Δy [μm]	10	105	67
	Δz [μm]	10	500	500
	Δrot$_z$ [μrad]	10	90	59
ladder/rod vs. half layer/layer	Δx [μm]	5	200	100
	Δy [μm]	5	200	100
	Δz [μm]	5	200	100
modules* vs. rod/ladder	Δx [μm]	13	200	100
	Δy [μm]	13	200	100
	Δz [μm]	13	200	100

- similar sizes in endcap like detectors
- pixel pre-aligned with minimum bias tracks
- for misalignment: hierarchically applied

Millepede Principle: Global Least Squares Fit

Normal Equations

$$\sum_j \frac{1}{\sigma_j}(\boldsymbol{d}_j \cdot \boldsymbol{d}_j^T)\cdot \boldsymbol{a} = \sum_j \frac{1}{\sigma_j} m_j \boldsymbol{d}_j$$

$\boldsymbol{d}_j$: “globale”/“local”derivatives of track j

- $\boldsymbol{a} = (\boldsymbol{a}^{global}, \boldsymbol{a}_1^{local}, \ldots, \boldsymbol{a}_n^{local})^T$
  - alignment (“global”) parameters
  - track parameters (“local”) of all n tracks

- $\boldsymbol{d}_j = (\boldsymbol{d}_{j,global}, \underbrace{\boldsymbol{d}_{j,local}^1}_{=\mathbf{0}}, \ldots, \underbrace{\boldsymbol{d}_{j,local}^j}_{\neq \mathbf{0}}, \ldots, \underbrace{\boldsymbol{d}_{j,local}^n}_{=\mathbf{0}})^T$

$$\left(\begin{array}{c||c|c|c} \sum_k \boldsymbol{C}_k^{\mathrm{global}} & \cdots & \boldsymbol{H}_k^{\mathrm{global\text{-}local}} & \cdots \\ \hline\hline \vdots & \ddots & 0 & 0 \\ \hline (\boldsymbol{H}_k^{\mathrm{global\text{-}local}})^T & 0 & \boldsymbol{C}_k^{\mathrm{local}} & 0 \\ \hline \vdots & 0 & 0 & \ddots \end{array}\right) \times \left(\begin{array}{c} \boldsymbol{a}^{\mathrm{global}} \\ \hline\hline \vdots \\ \hline \boldsymbol{a}_k^{\mathrm{local}} \\ \hline \vdots \end{array}\right) = \left(\begin{array}{c} \sum_k \boldsymbol{b}_k^{\mathrm{global}} \\ \hline\hline \vdots \\ \hline \boldsymbol{b}_k^{\mathrm{local}} \\ \hline \vdots \end{array}\right)$$

Millepede Principle: Matrix Reduction

- We are not interested in full $\boldsymbol{a} = (\boldsymbol{a}^{global}, \boldsymbol{a}_1^{local}, \ldots, \boldsymbol{a}_n^{local})^T$:
  $\Rightarrow$ We want $\boldsymbol{a}^{global}$ only!
- Matrix algebra (inversion by partitioning) helps:

Reduced Matrix

$$\boldsymbol{C}'\boldsymbol{a}^{global} = \boldsymbol{b}'$$

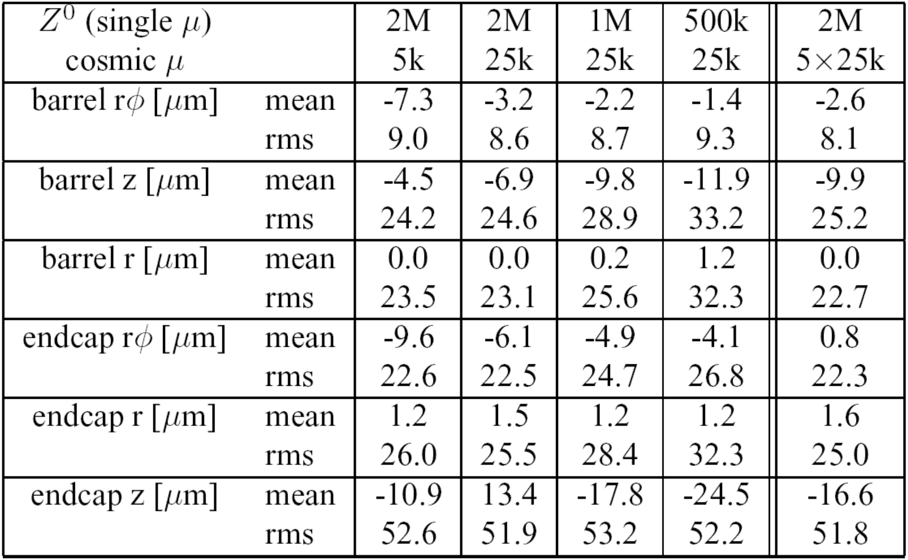
$$\boldsymbol{C}' = \sum_k \boldsymbol{C}_k^{global} - \sum_k \left(\boldsymbol{H}_k (\boldsymbol{C}_k^{local})^{-1} \boldsymbol{H}_k^T \right)$$

$$\boldsymbol{b}' = \sum_k \boldsymbol{b}_k^{global} - \sum_k \boldsymbol{H}_k \underbrace{(\boldsymbol{C}_k^{local})^{-1} \boldsymbol{a}_k^{local}}_{\text{local solution}}$$

- Sums built while running over tracks k.
- $\boldsymbol{C}'$ is “small” $n \times n$ matrix for n global (alignment) parameters.

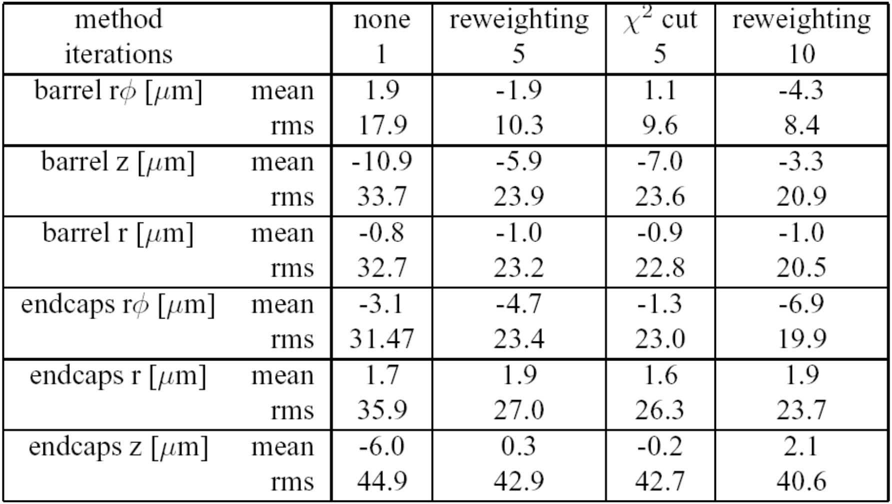
Millepede: Statistics

Use of just single μ and cosmics:
$\Rightarrow$ Cosmics statistics more relevant!



Z^0 (single μ) cosmic μ		2M 5k	2M 25k	1M 25k	500k 25k	2M 5×25k
barrel rϕ [μm]	mean	-7.3	-3.2	-2.2	-1.4	-2.6
	rms	9.0	8.6	8.7	9.3	8.1
barrel z [μm]	mean	-4.5	-6.9	-9.8	-11.9	-9.9
	rms	24.2	24.6	28.9	33.2	25.2
barrel r [μm]	mean	0.0	0.0	0.2	1.2	0.0
	rms	23.5	23.1	25.6	32.3	22.7
endcap rϕ [μm]	mean	-9.6	-6.1	-4.9	-4.1	0.8
	rms	22.6	22.5	24.7	26.8	22.3
endcap r [μm]	mean	1.2	1.5	1.2	1.2	1.6
	rms	26.0	25.5	28.4	32.3	25.0
endcap z [μm]	mean	-10.9	13.4	-17.8	-24.5	-16.6
	rms	52.6	51.9	53.2	52.2	51.8

Millepede: Outlier Rejection



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

$\Rightarrow$ **Outlier recjection improves substantially!**