First CMS Alignment Geometry: Survey Data and Their Implementation

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FOR

CMS Tracker and Muon Alignment Groups

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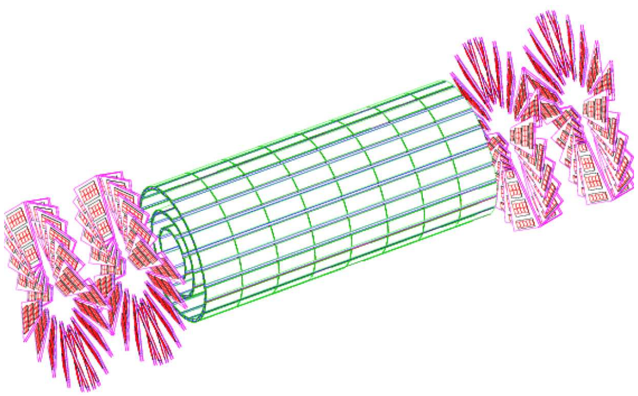
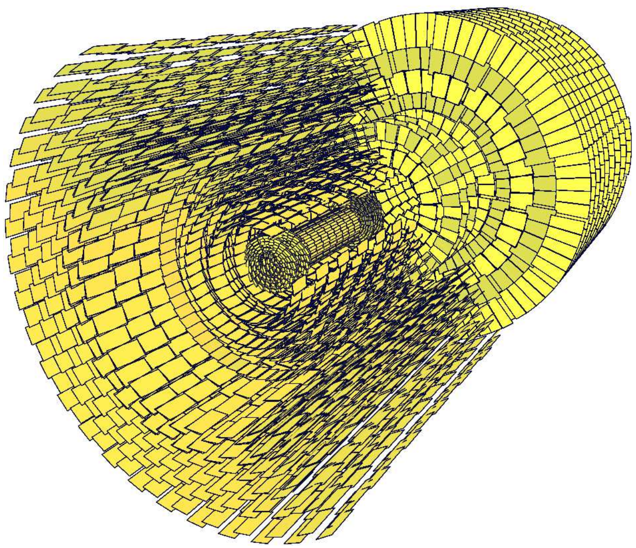
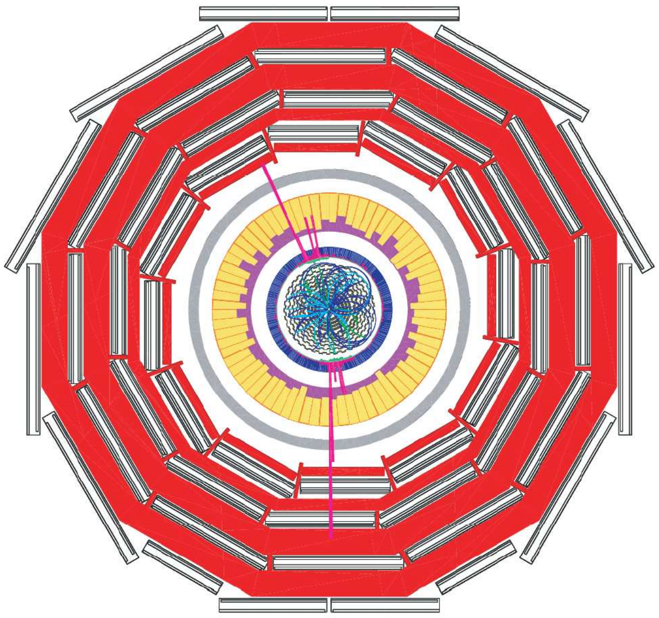
CMS Geometry: Pixel, Strip, Muon

- Complex CMS tracking geometry:

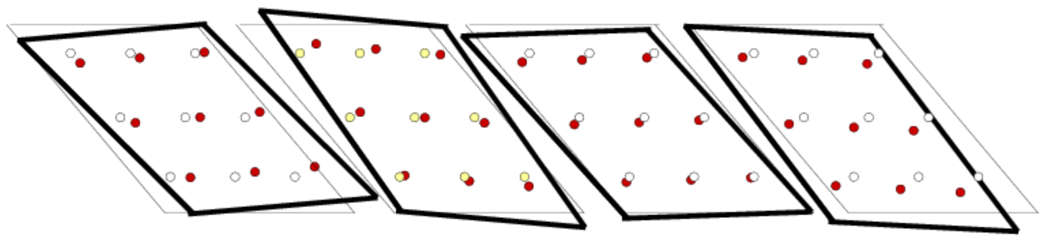
Pixel	Strip	Muon
1440 sensors	$>$15k sensors	718 chambers

- First data: “optical” survey

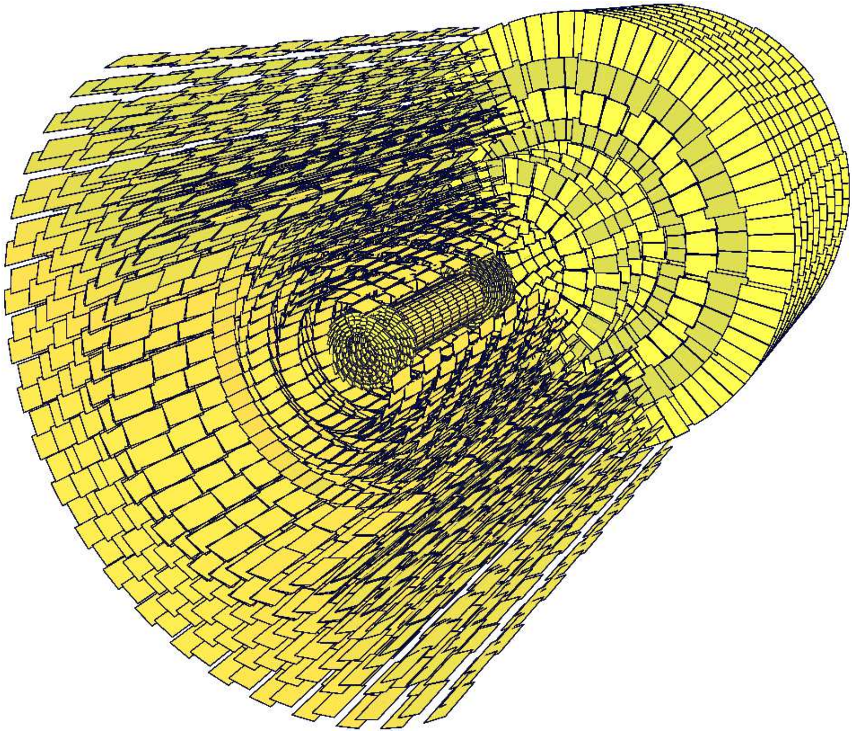
Outline

- First CMS alignment geometry: "optical" survey data
  - (1) pixel (barrel/forward)
  - (2) strip (barrel/endcap)
  - (3) muon (barrel/endcap)



- Survey implementation in alignment (with tracks)
  - (4) general idea
  - (5) algorithm-specific implementations
    (e.g. HIP, Millepede, Kalman)

Why We Need Survey



- Complexity of alignment with tracks:

  ~20k sensors on CMS

  poor degrees of freedom

  systematic deformations

  low statistics (initially)

- Survey in alignment:

  starting point (but not only)

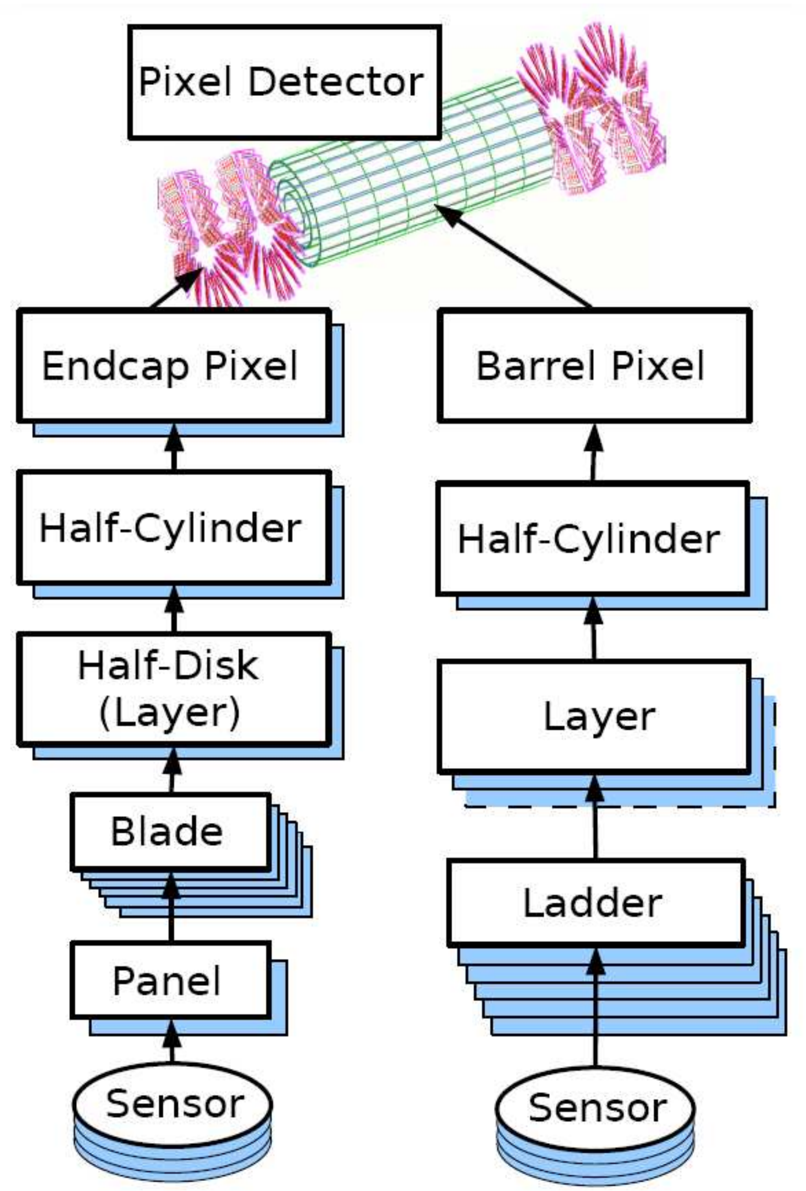
  default solution if join with tracks (avoid divergence)

  constrain poorly known (χ^2-invariant) degrees of freedom

  tracks win naturally (transition with statistics)

  the only constraint for "dead" units or strip sides

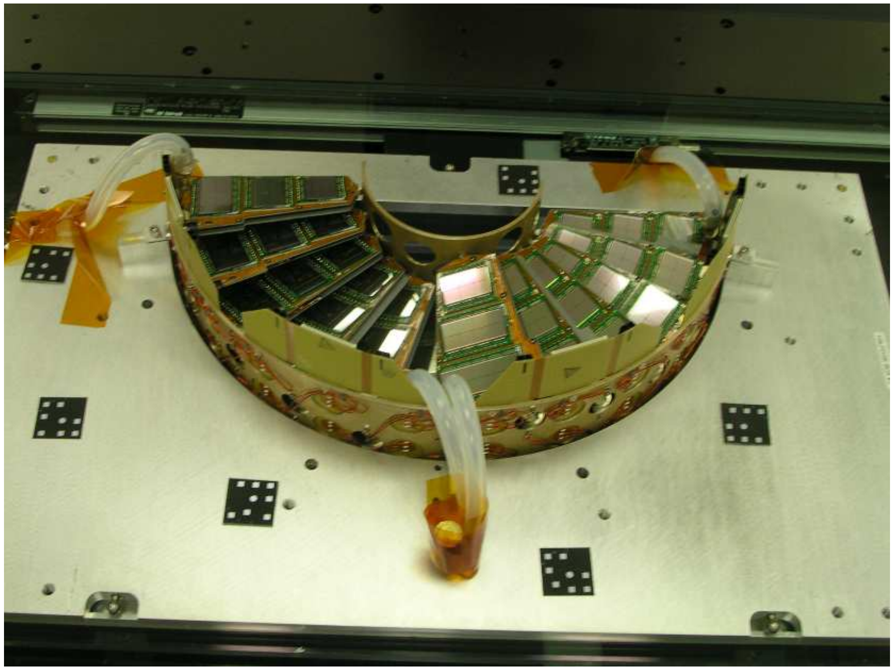
(1) CMS Pixel Detector

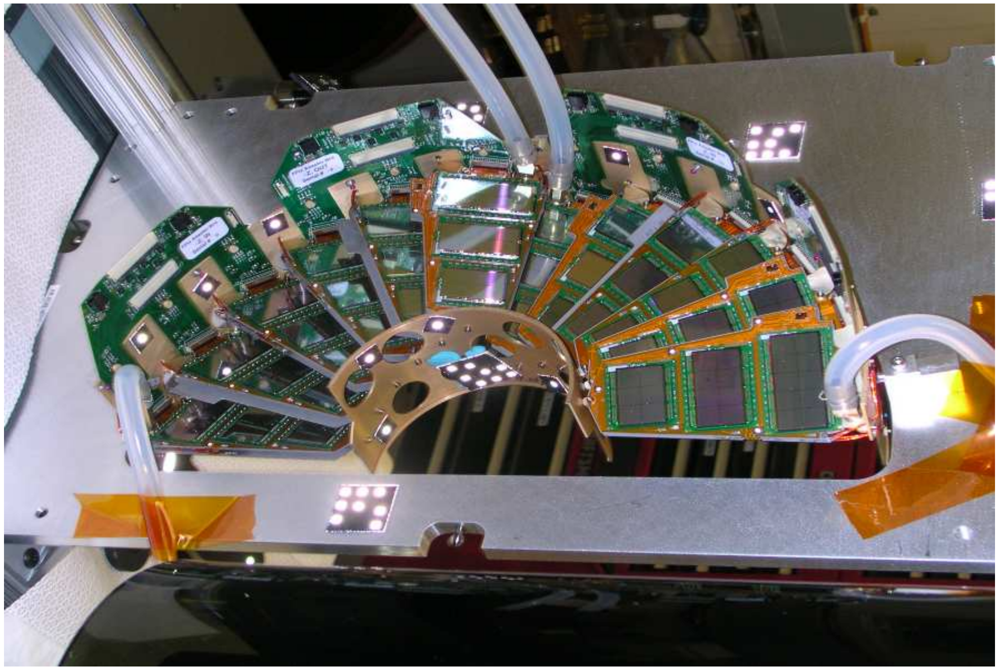


- Hierarchical structures:
  - construction
  - survey
  - movement after assembly
- Forward pixel (endcap):
  - full "optical" survey
- Barrel pixel:
  - survey planned (layer 1&3)
  - finite element analysis

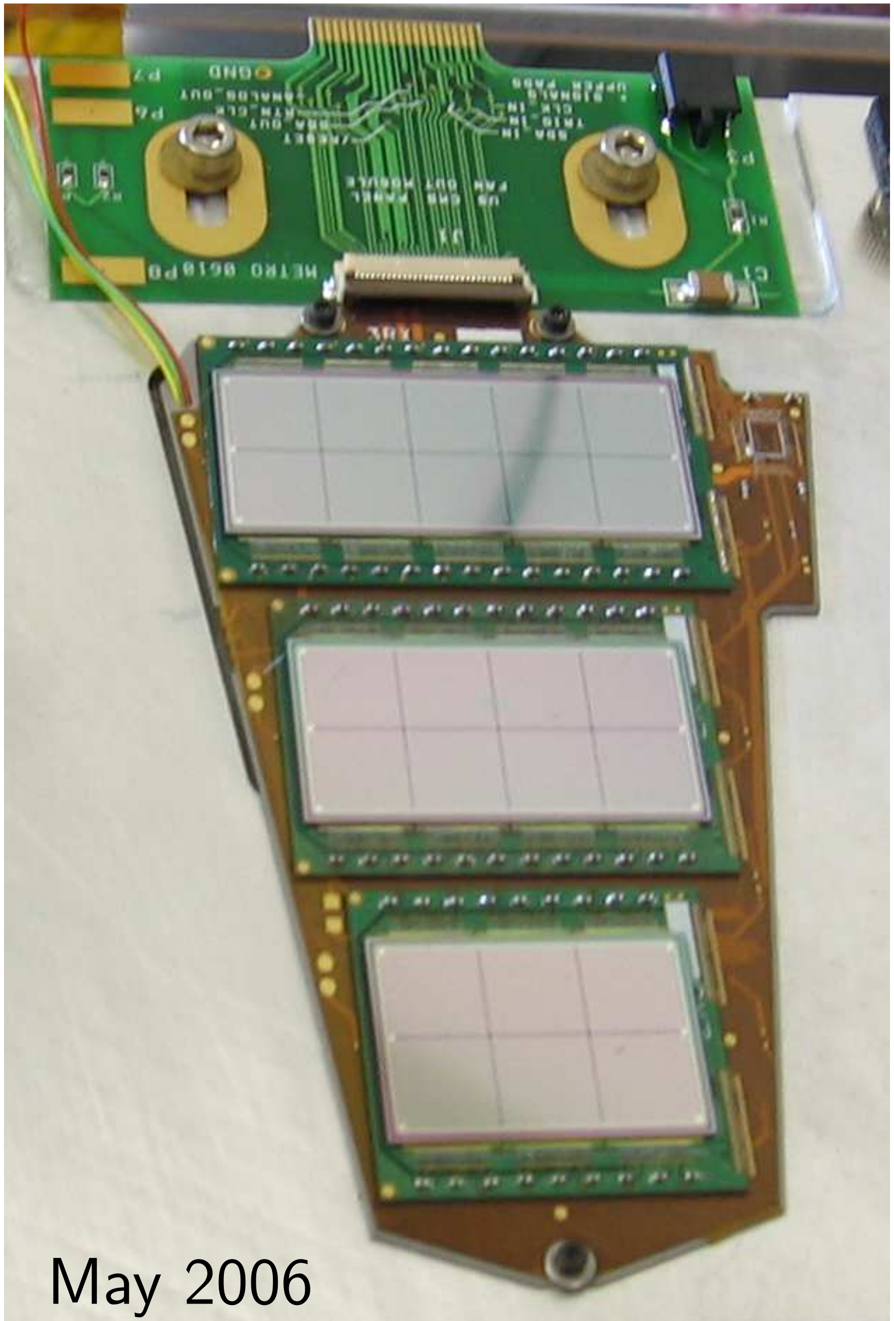
CMS Pixel Survey Data

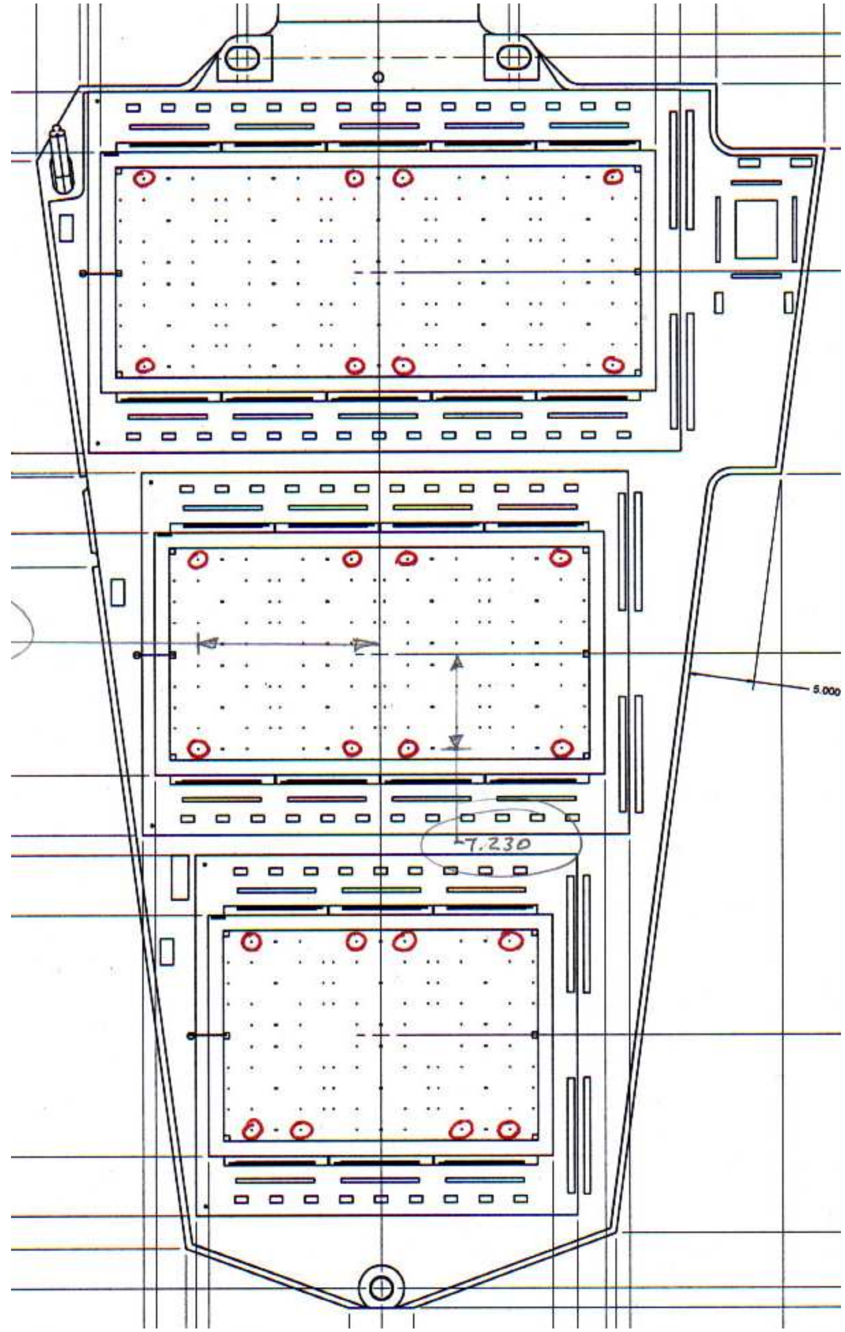
- Different methods:
  - fiducial points on sensors - optical CMM (coord. measuring machine)
  - ball target - touch probe
  - photo targets - photogrammetry with triangulation
- Example: forward pixel survey



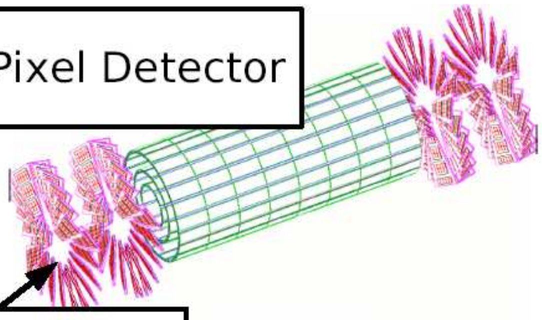


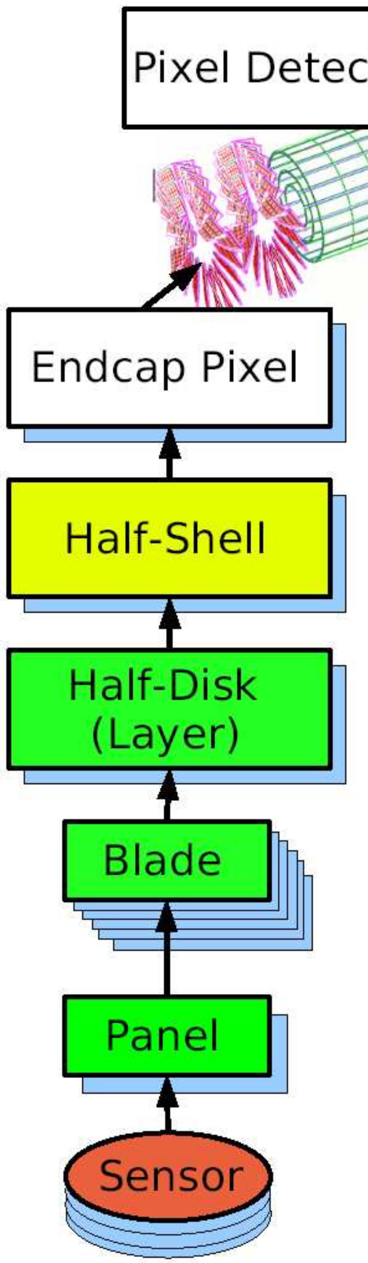
Fiducial Points





CMS FPixel Detector Survey



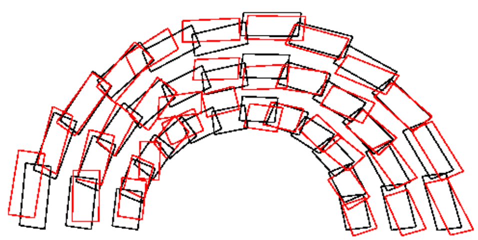


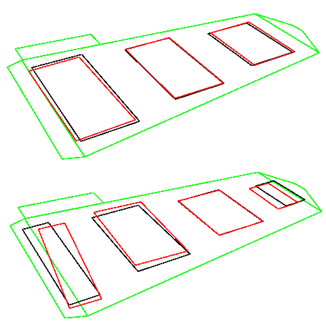
- Survey goal:

  (1) sensor positions/orientation

  (2) hierarchical errors

  from survey and time-dependence





- Typical errors:

  $(\mathbf{\Delta}\vec{\mathbf{R}}, \mathbf{\Delta}\vec{\mathbf{\Omega}})_{\mathrm{halfcylinder}}$ ($\sigma > 50\mu$m)

  $(\mathbf{\Delta}\vec{\mathbf{R}}, \mathbf{\Delta}\vec{\mathbf{\Omega}})_{\mathrm{halfdisk}}$ ($\sigma > 10\mu$m)

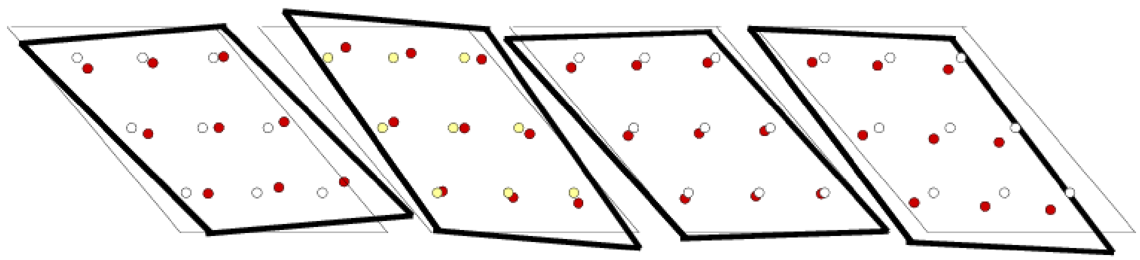
  $(\mathbf{\Delta}\vec{\mathbf{R}}, \mathbf{\Delta}\vec{\mathbf{\Omega}})_{\mathrm{blade}}$ ($\sigma \sim 10\mu$m)

  $(\mathbf{\Delta}\vec{\mathbf{R}}, \mathbf{\Delta}\vec{\mathbf{\Omega}})_{\mathrm{panel}}$ ($\sigma \sim 10\mu$m)

  $(\mathbf{\Delta}\vec{\mathbf{R}}, \mathbf{\Delta}\vec{\mathbf{\Omega}})_{\mathrm{sensor}}$ ($\sigma \sim$ few μm)

Analysis of Optical Survey Data

- Analysis idea:
  - minimize χ^2 to match fiducial points
  - obtain shift/rotation of sub-structure $(\Delta\vec{R}, \Delta\vec{\Omega})$



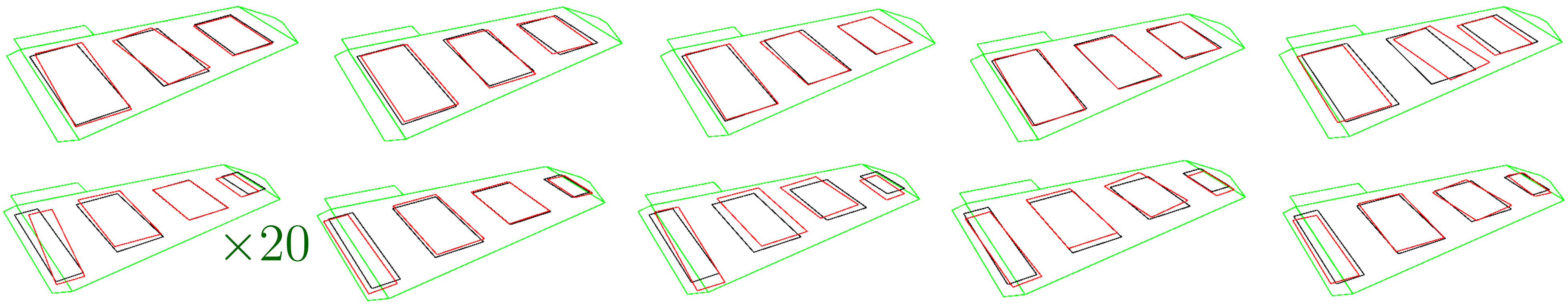
- Different implementations, e.g. analytical solution:

$$R_k = \left(\sum_{j,i\neq I}^{n\times N} m_{ij} \cdot d\vec{r}_{ij}\right)_k \Big/ \left(\sum_{j,i\neq I}^{n\times N} m_{ij}\right)$$

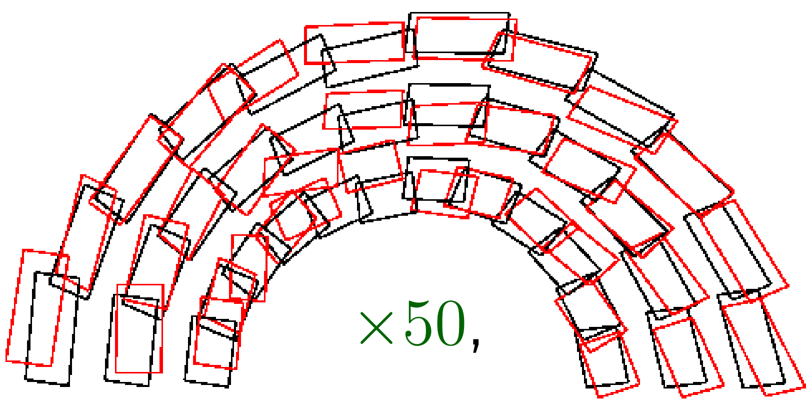
$$\sum_{k=1}^{3} \Omega_k \sum_{j,i\neq I}^{n\times N} m_{ij}\left(\delta_{kl}(\vec{r}_{ij})^2 - (\vec{r}_{ij})_k(\vec{r}_{ij})_l\right) = \sum_{j,i\neq I}^{n\times N} m_{ij}(\vec{r}_{ij} \times d\vec{r}_{ij})_l$$

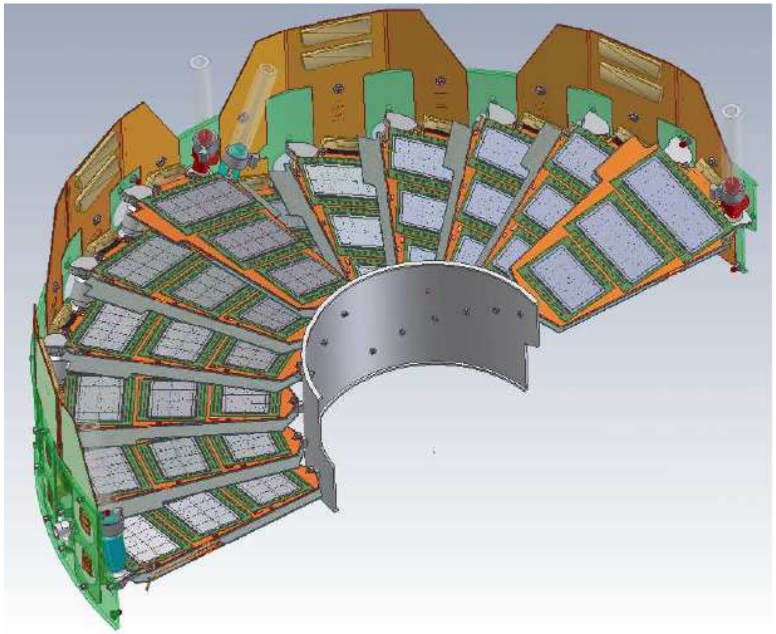
CMS Forward Pixel Detector

- Few typical panels: $\Delta R \sim 50 - 100\mu$m, $\sigma_R \sim 1 - 2\mu$m (consistency)

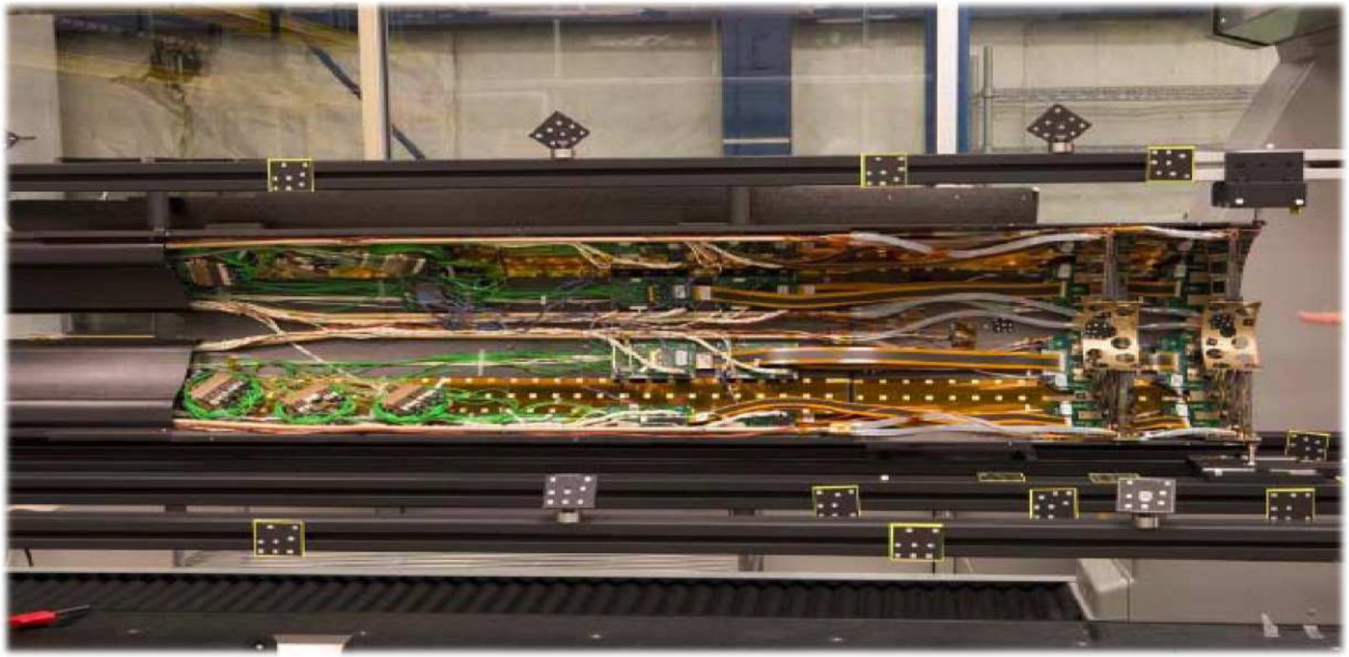


- Pixel sensors are flat to $1 - 2\mu$m





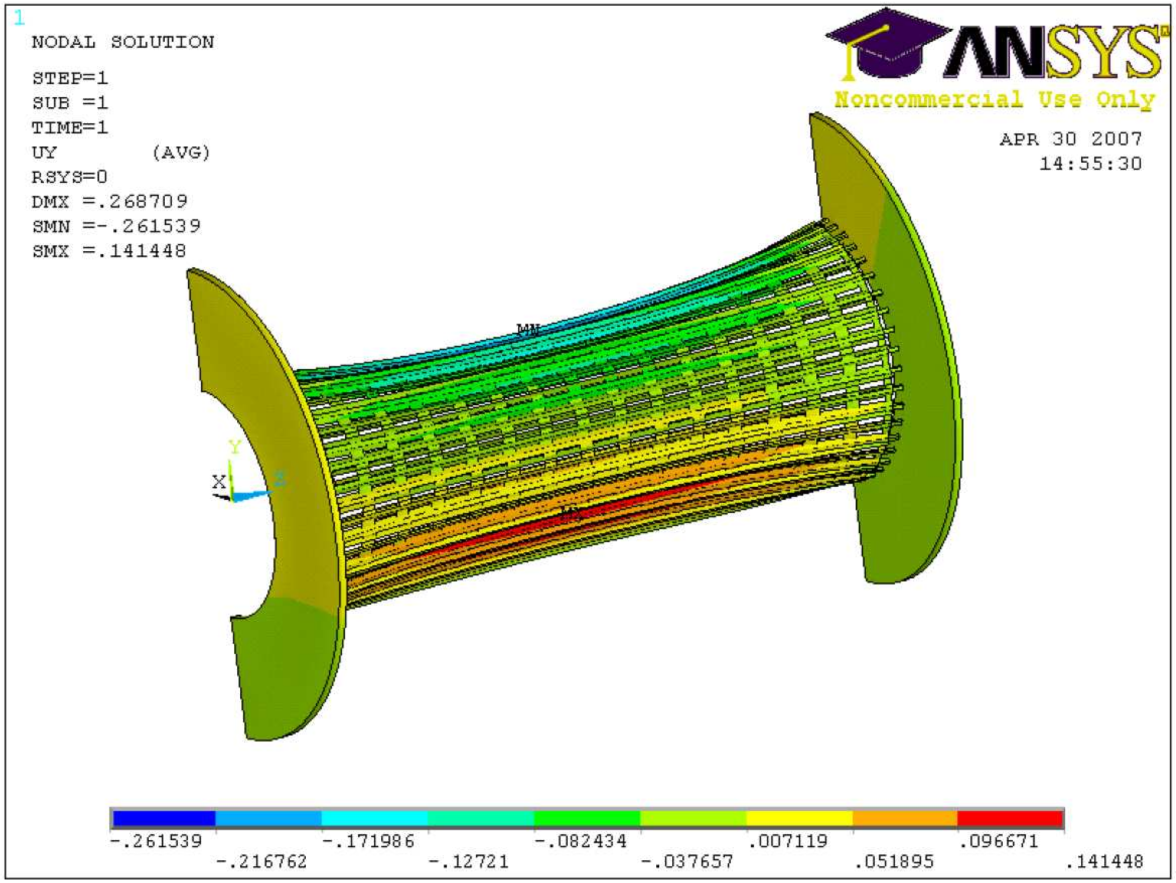
Larger Structures in Survey



- Higher-level structures: photogrammetry (survey with pictures)
  - errors 15–50μm, they also move more with time
- Account for time-dependence:
  - correct for temperature deformations (calculation and/or test-stand)
  - finite element analysis started for Barrel Pixel
  - inflate errors of survey (more for certain degrees of freedom)

Finite Element Analysis of CMS Pixel

- FEA barrel pixel L3: $+20°\text{C} \rightarrow -10°\text{C}$,
  - radial movement $\sim 260\mu\text{m}$ at z=0 ($150\mu\text{m}$ in L1)
  - end flange very stiff

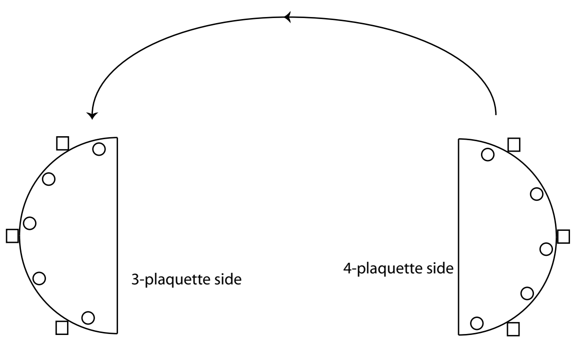


- Forward pixel
  - test stand $\sim 50\mu\text{m}$ movement with $\Delta t \sim -30°\text{C}$

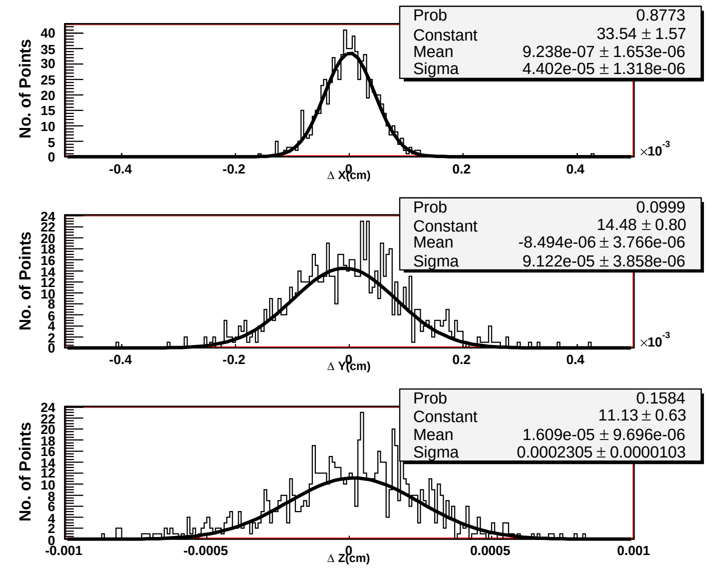
- However: 2008-2009 pixel running at $+20°\text{C}$

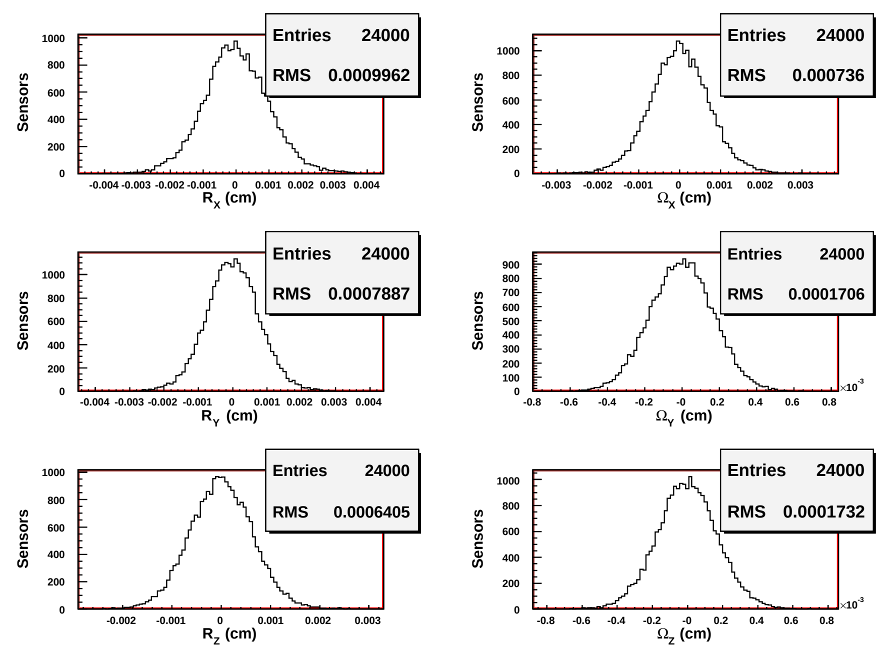
Error Analysis

- Fiducial CMM point errors:
  - from redundant measurements 1μm in plane, 3μm out
  - 5μm sensor systematic shifts
- Hierarchical errors:
  - toy Monte Carlo $\Rightarrow$ var$(\vec{R}, \vec{\Omega})$



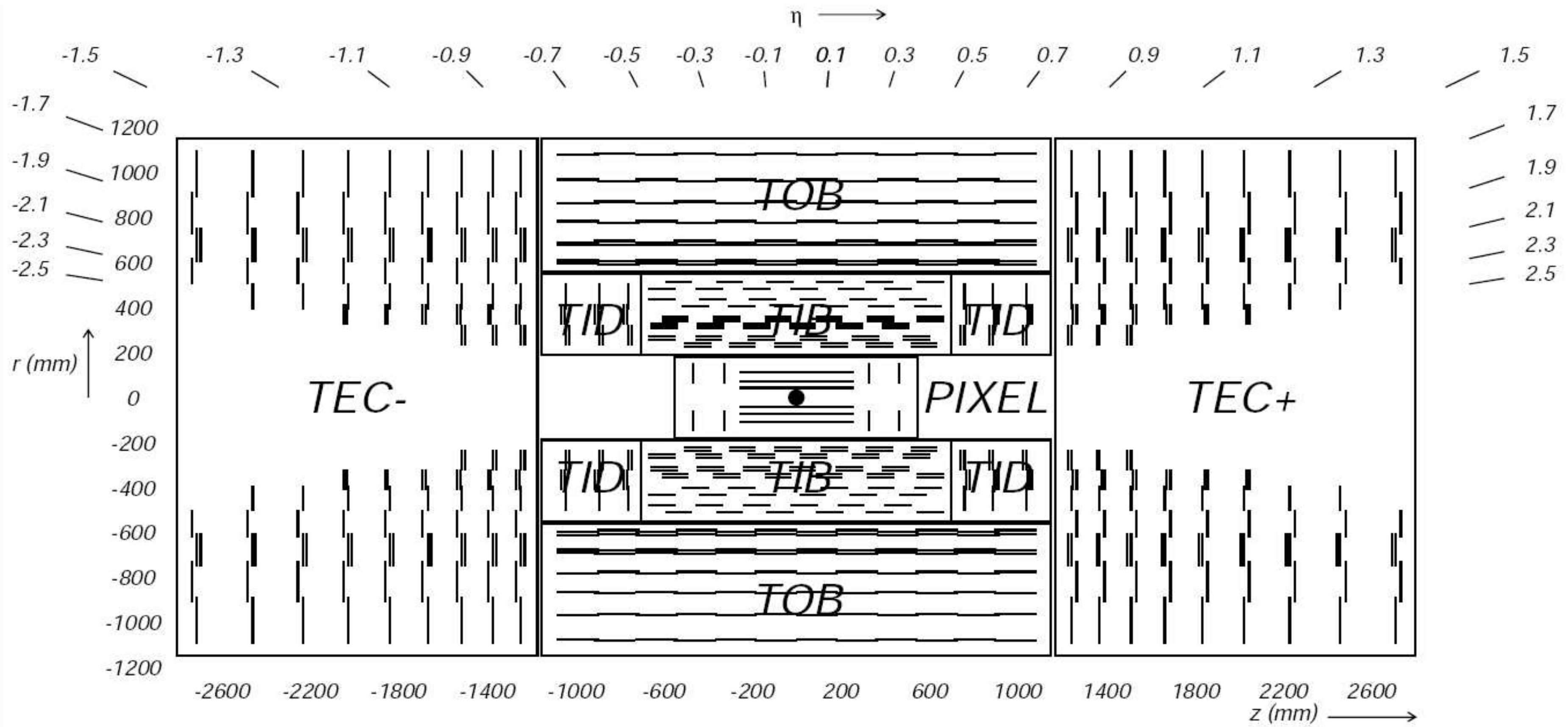
- Time-dependence in real data:
  - inflate certain errors
  - compare survey/track residuals





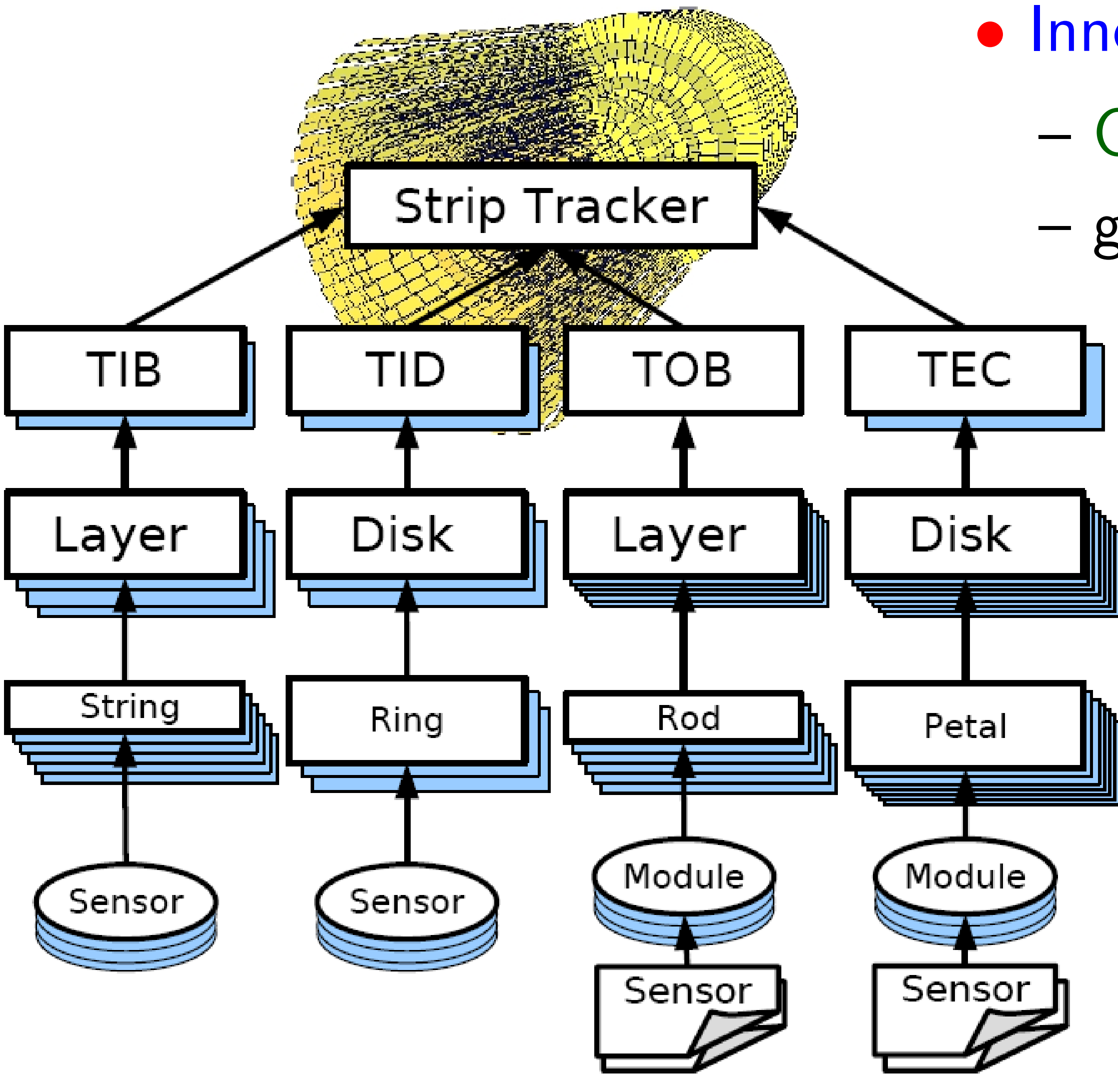
(2) CMS Tracker

- Full CMS tracker geometry:

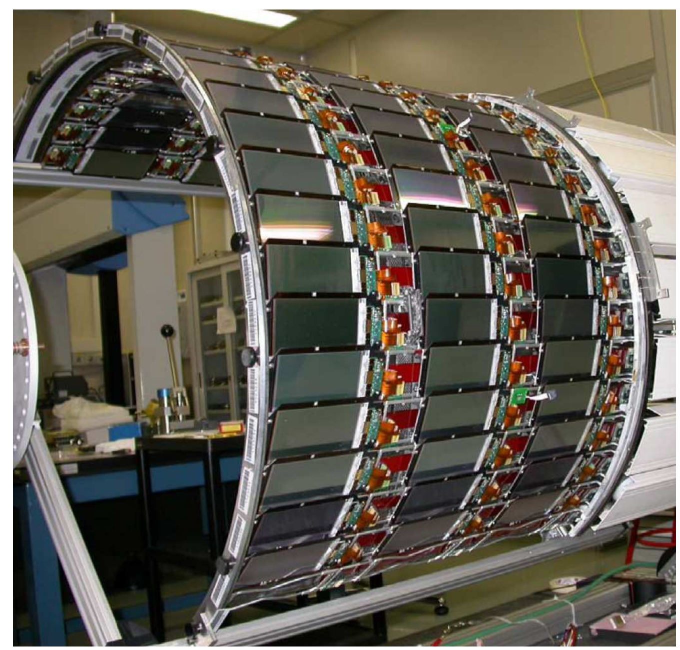


- Strip Tracker:
  - Inner Barrel (TIB) and Inner Disk (TID)
  - Outer Barrel (TOB) and EndCap (TEC)

CMS Strip Detector

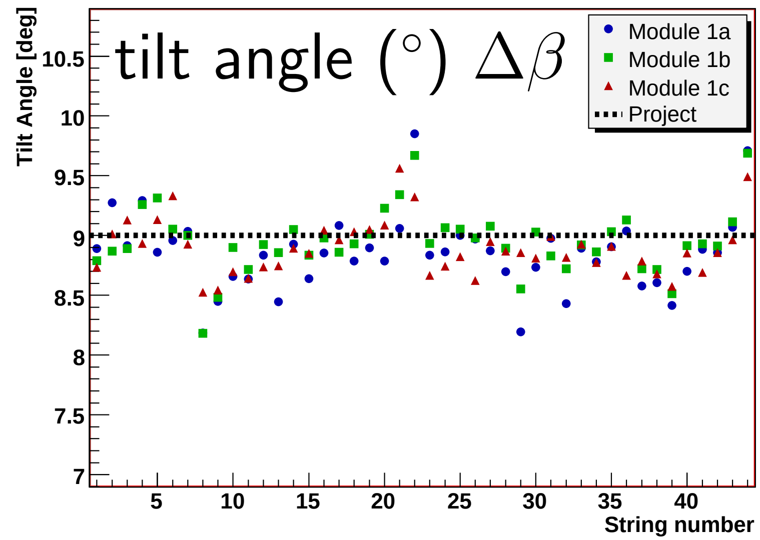


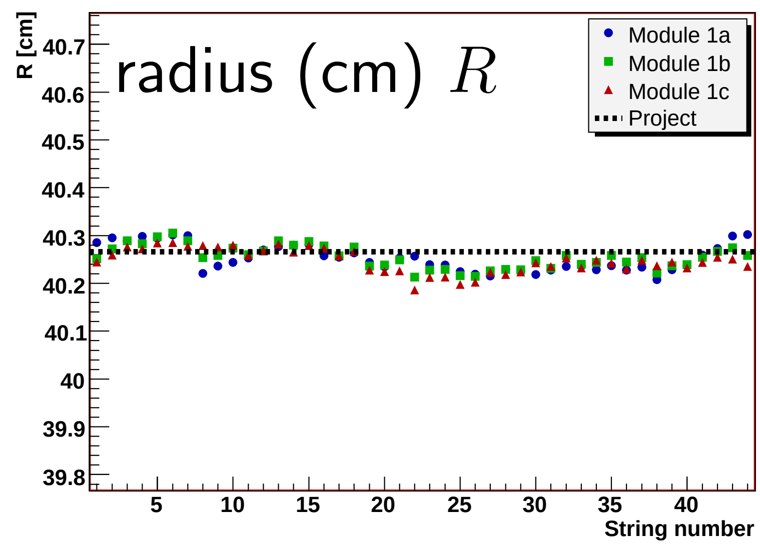
- Inner Barrel and Disk:
  - CMM survey through layer
  - global photogrammetry
- Outer Barrel and EndCap:
  - sample CMM survey
  - photogramm. wheel/disks



Strip Survey: Inner Barrel (TIB) & Disk (TID)

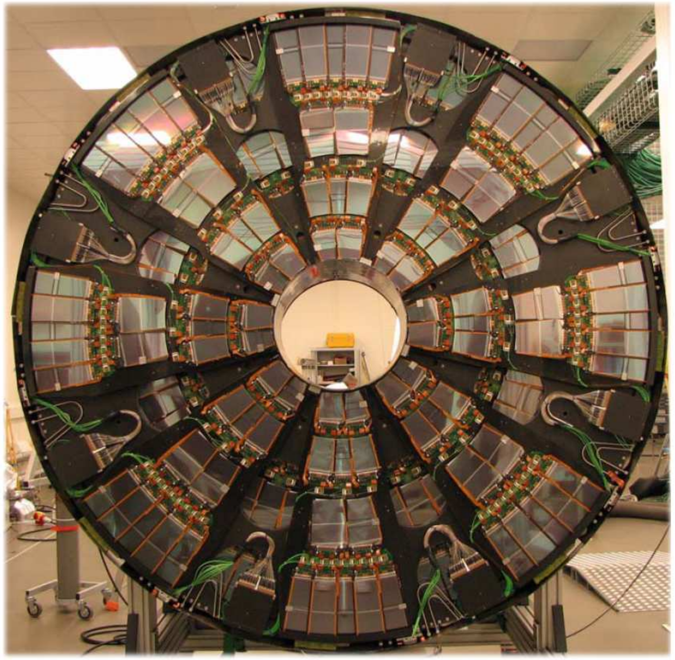
- Full CMM survey:
  - sensor planarity $\sim 100\mu m$
  - error analysis to be finalized

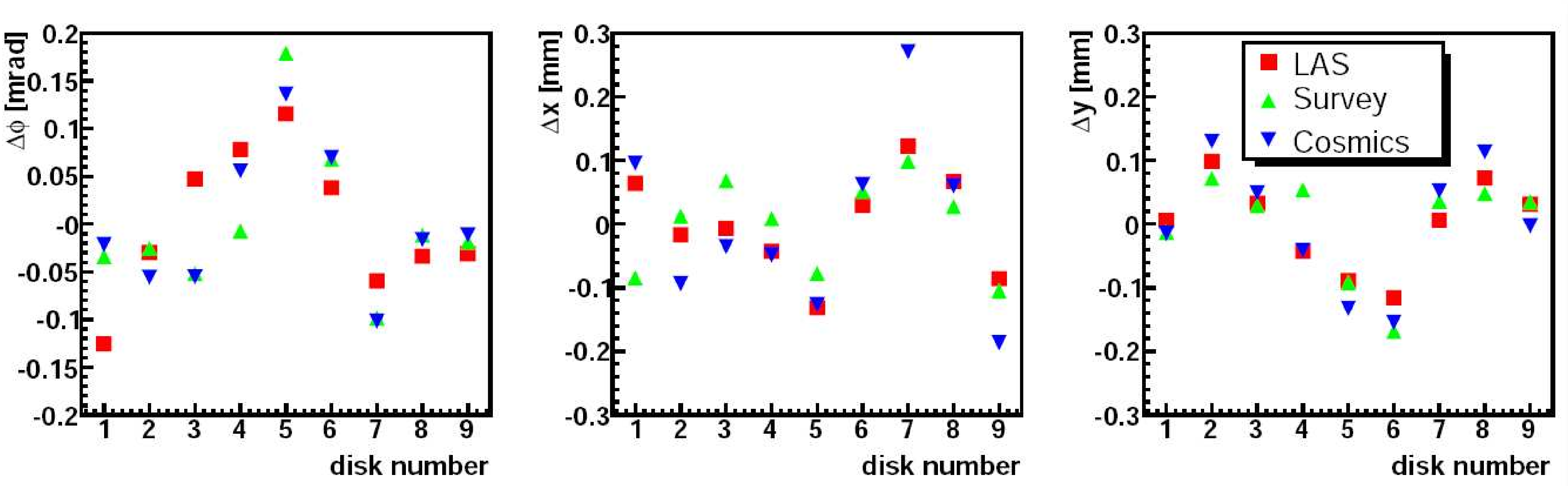




Strip Survey: Tracker EndCap (TEC)

- Only disk position with photogrammetry
  - consistent with cosmics/laser
  - to be merged in one alignment (see later)
- Sample CMM survey of petals/disks
  - quality and assembly precision control

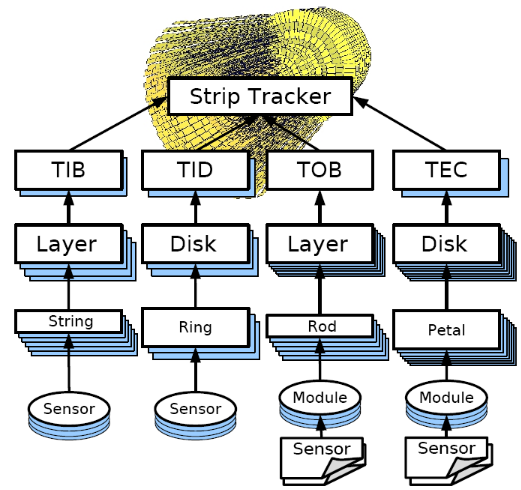




Errors in Strip Survey and Assembly

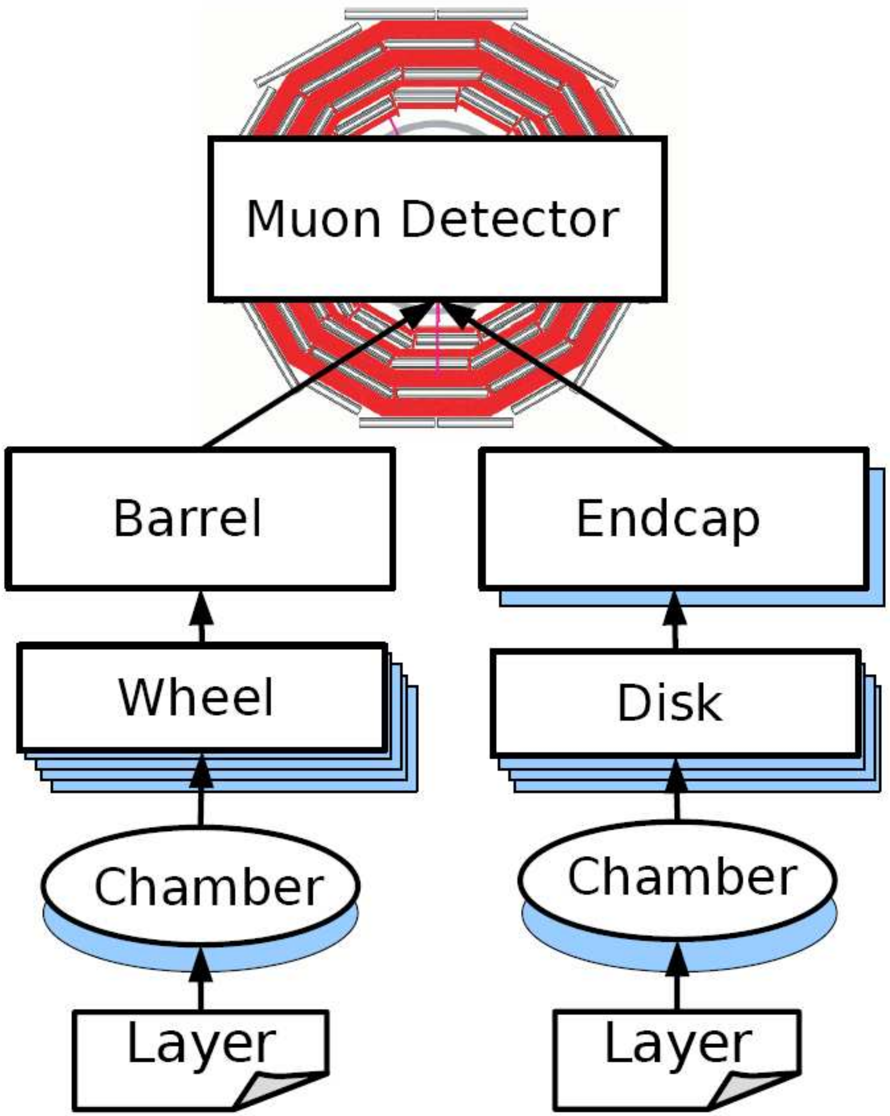
- Assembly precision (μm):

Inner Barrel		Inner Disk		Outer Barrel		EndCap	
Sensor		Sensor		Sensor		Sensor	
	10		10		10		10
Module		Module		Module		Module	
	180		54		30		20
Shell		Ring		Rod		Petal	
	450		185		200		70
Cylinder		Disc		Wheel		Disc	
	750		350		140 $(r\phi)$ 500 (z)		150
Tube		Cylinder		Tube		TEC	
			450		1000		600
		Tube		CMS		Tube	



- TOB and TEC module assembly precision sampled with CMM survey
- Survey precision of TIB/TID modules to be finalized

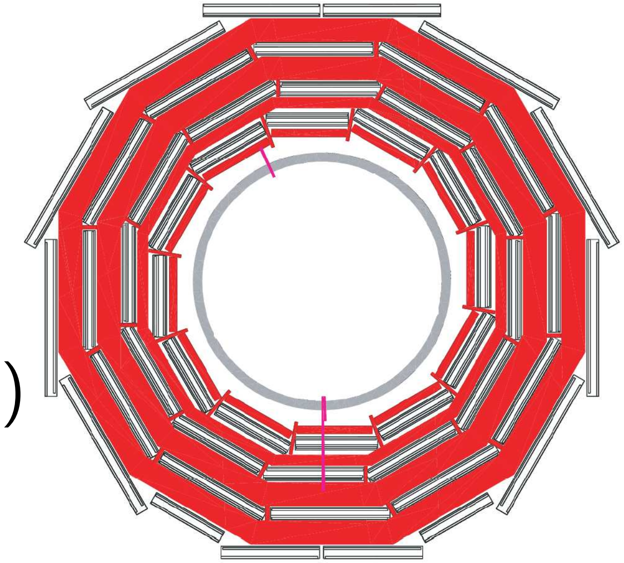
(3) Muon Detector

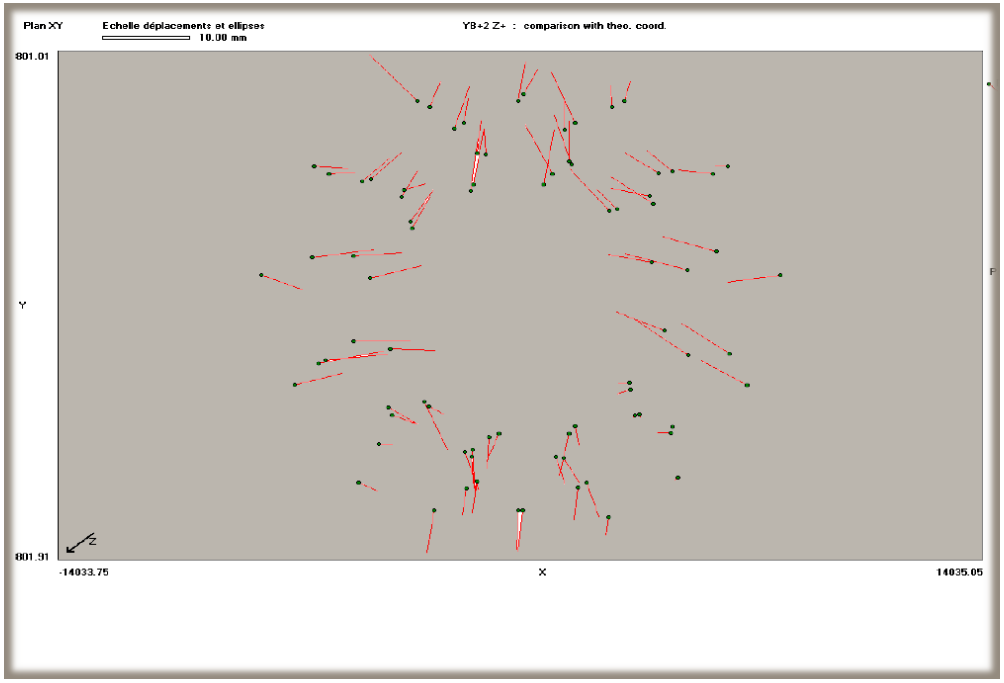


- Barrel muon:
  - Drift Tube chambers (DT)
  - 250 chambers
- Endcap muon:
  - Cathode Strip Chambers (CSC)
  - 2×236 chambers
- Survey: photogrammetry
- Internal structure of chambers:
  - survey + tracks

Muon Barrel Survey

- Geometry: 5 wheels, 4 layers, 12 sectors
- Survey: photogrammetry
  - chambers in a wheel (survey of corners)
  - wheel relative to central wheel (x, y, and α_z)
- Precision: $\sim$200μm, 0.1mrad (chambers)

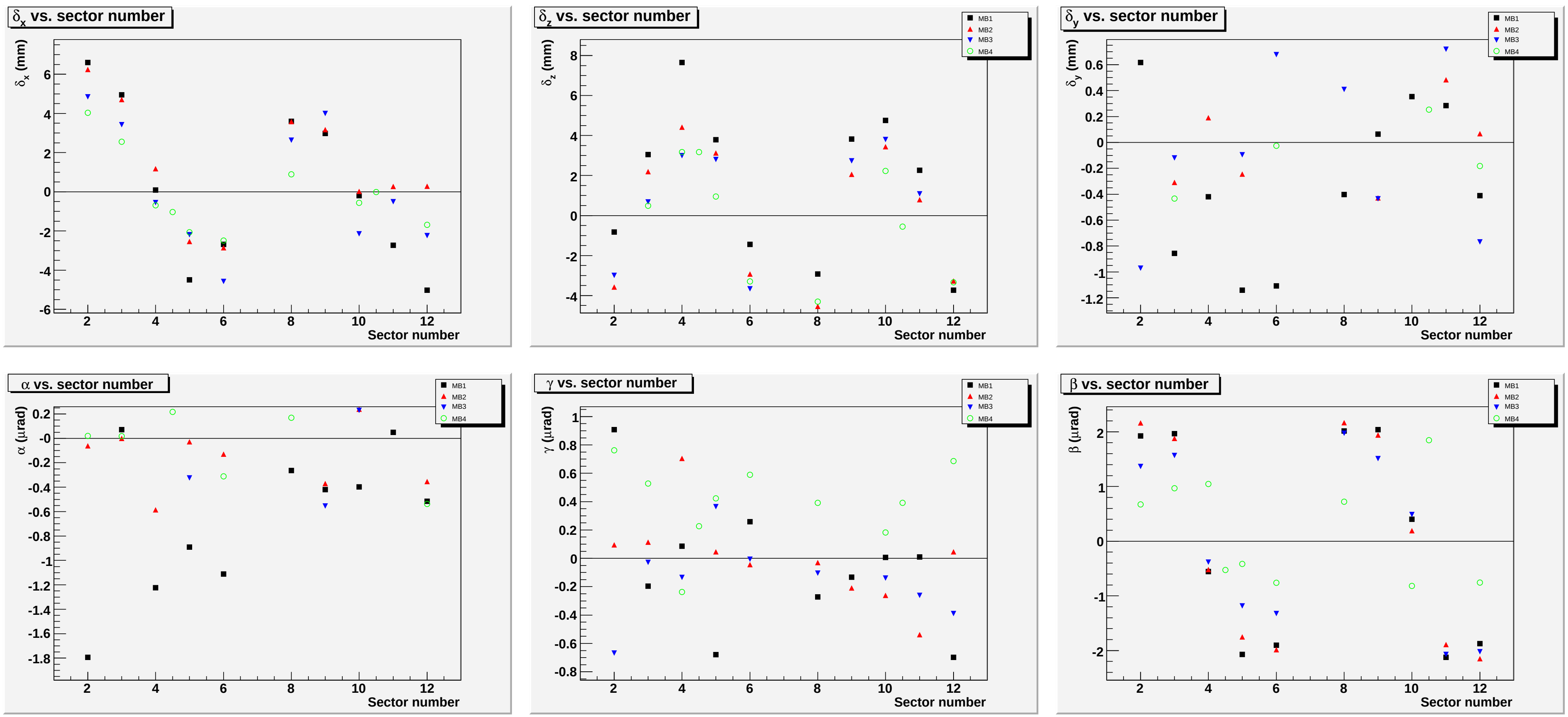




Muon Barrel Survey

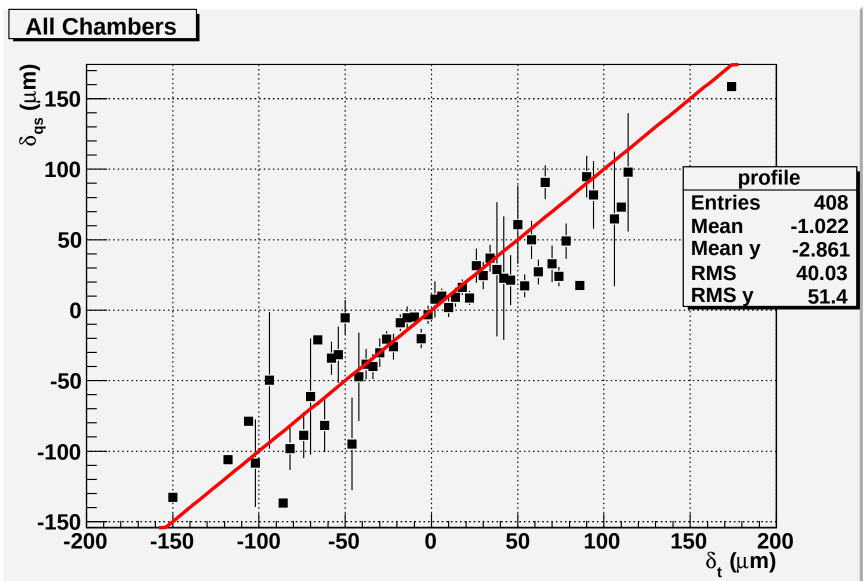
- Main effect: gravity sag
  - example: chambers in a wheel (+1) vs. ϕ

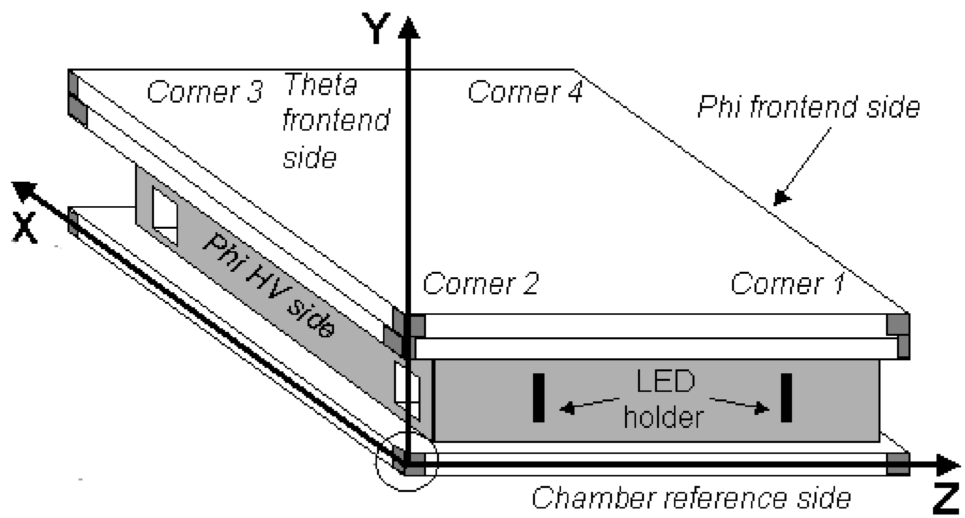
ΔX ΔY ΔZ



Muon Chamber Structure

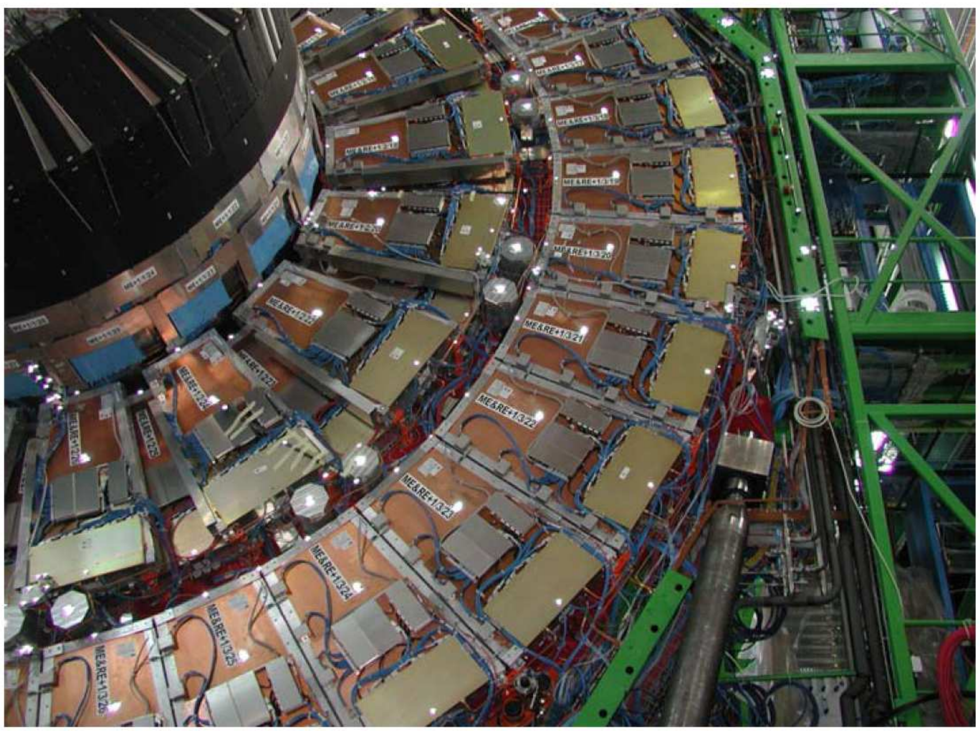
- Muon chambers provide track direction, not only "hit"
- DT chamber structure (align only once):
  - survey Super-Layer displacements
  - survey Layers within Super-Layer
  - cosmic track alignment: good agreement (e.g. ΔX below)

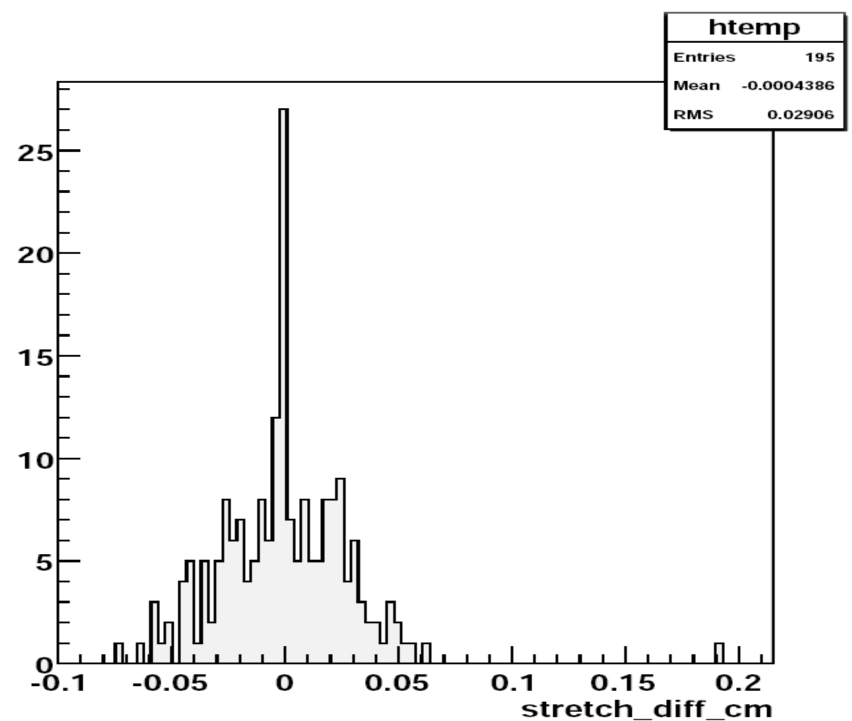




Muon Endcap Survey

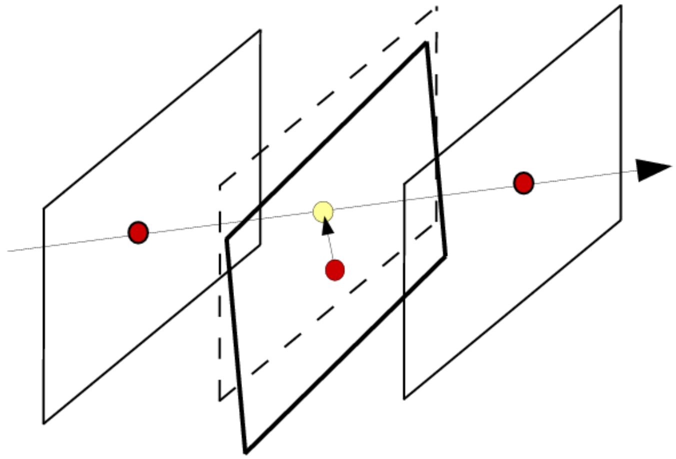
- Geometry: 4 disks, 2 rings with 36 or 18 chambers
- Survey photogrammetry
  - disk in endcap
  - chambers in a disk (2 pins only)
- Analysis in progress
  - errors ~300μm

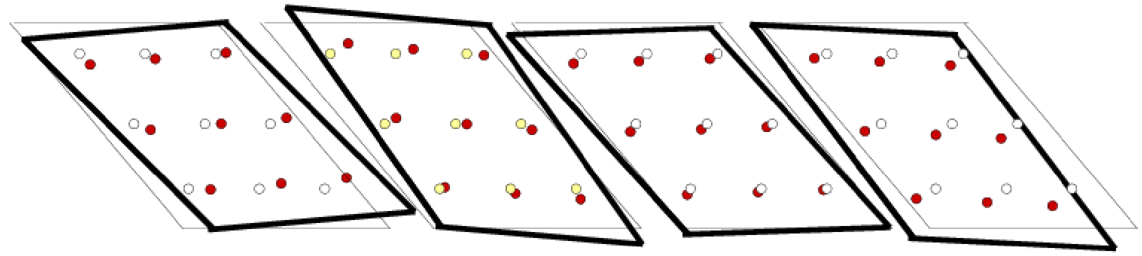




(4) Survey in Alignment: Analogy with Tracks

Tracks ← "orthogonal" → Survey





(1) loop over N	hits	structures
(2) find residuals ϵ	track	survey
(3) estimate errors $\mathbf{V}$	tracking	survey/mechanics

- Minimize residuals:

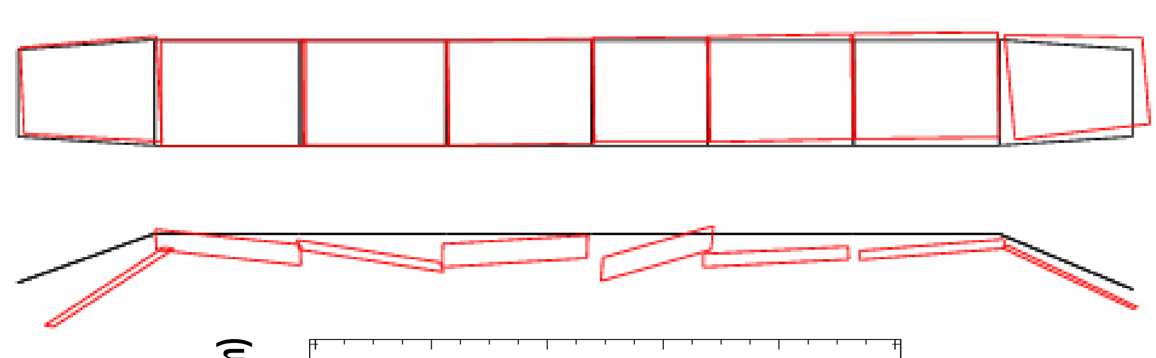
$$\chi^2(\mathbf{R},\boldsymbol{\Omega}) = \sum_{i=1}^{N} \epsilon_i^T \mathbf{V}_i^{-1} \epsilon_i$$

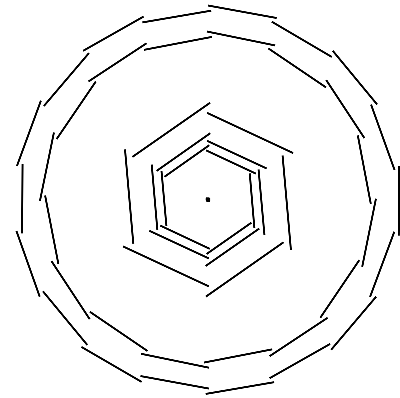
residual ϵ function of sensor position parameters $(\mathbf{R},\boldsymbol{\Omega})$, to be found

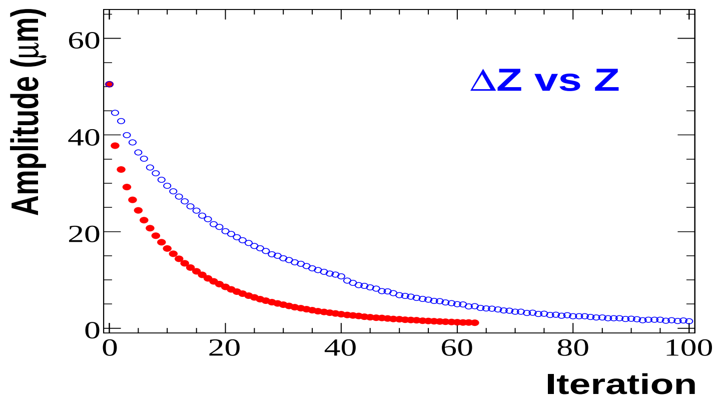
Some Prior Experience

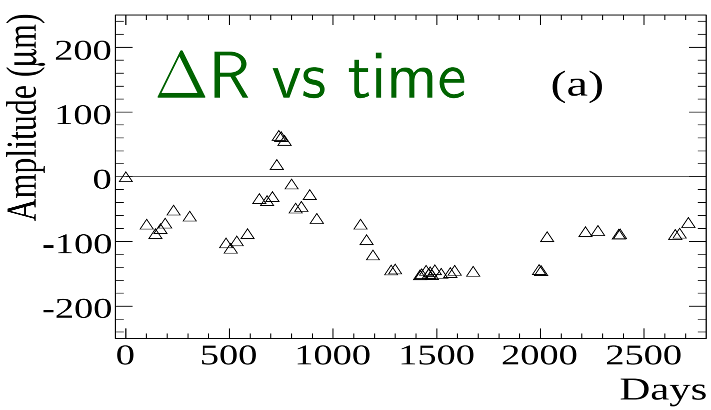
- Survey Constraint on *BaBar* proved to be useful (2000-2007):

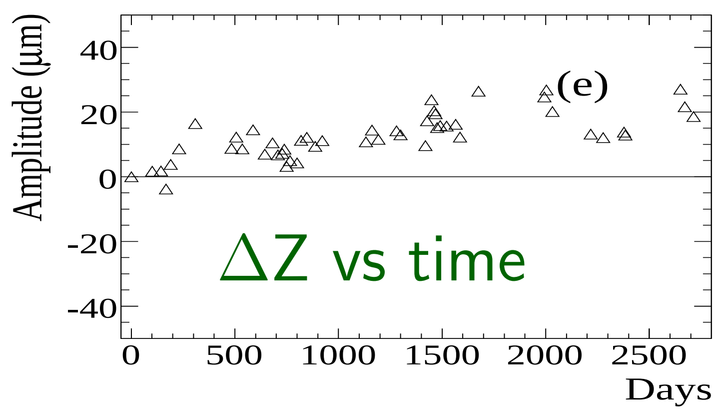
(×50)











Survey Measurement in Alignment

- Input survey of hierarchical structures:

$$\chi^2(\underbrace{\mathbf{R},\mathbf{\Omega}}_{\mathbf{p}}) = \sum_{i=1}^{\mathrm{N_{hits}}} \epsilon_i^T \mathbf{V}_i^{-1} \epsilon_i + \sum_{j=1}^{\mathrm{N_{str.}}} \epsilon_{j,\mathrm{survey}}^T \mathbf{V}_{j,\mathrm{survey}}^{-1} \epsilon_{j,\mathrm{survey}}$$

- Solution: (e.g. 6×6 matrix) (e.g. 6×1 vector)

$$\delta\mathbf{p} = \left[\sum_i^{\mathrm{hits}} \mathbf{J}_i^T \mathbf{V}_i^{-1} \mathbf{J}_i + \sum_j^{\mathrm{survey}} \mathbf{J}_{*j}^T \mathbf{V}_{*j}^{-1} \mathbf{J}_{*j}\right]^{-1} \left[\sum_i^{\mathrm{hits}} \mathbf{J}_i^T \mathbf{V}_i^{-1} \epsilon_i + \sum_j^{\mathrm{survey}} \mathbf{J}_{*j}^T \mathbf{V}_{*j}^{-1} \epsilon_{*j}\right]$$

Survey residual $\epsilon_{*j} = (\mathbf{\Delta R}_j, \mathbf{\Delta\Omega}_j) \Rightarrow \mathbf{J}_* = \partial\epsilon_*/\partial(\mathbf{p}) = \partial\epsilon_*/\partial(\mathbf{R},\mathbf{\Omega}) = \mathbf{I}$

Weighted average w/o tracks and for diagonal $\mathbf{V}_*^{-1} = 1/\sigma_{\mathrm{x}}^2 ...$:

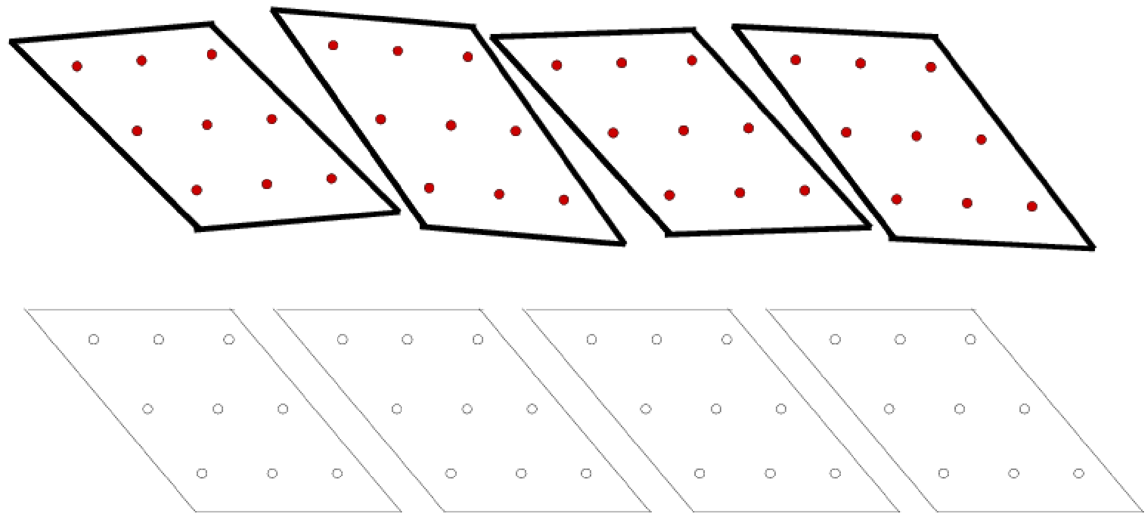
$$\delta\mathrm{x} = \left[\sum_j^{\mathrm{survey}} \left(\frac{1}{\sigma_{\mathrm{x}_j}^2}\right)\right]^{-1} \left[\sum_j^{\mathrm{survey}} \left(\frac{\Delta\mathrm{x}_j}{\sigma_{\mathrm{x}_j}^2}\right)\right]$$

Survey Residuals

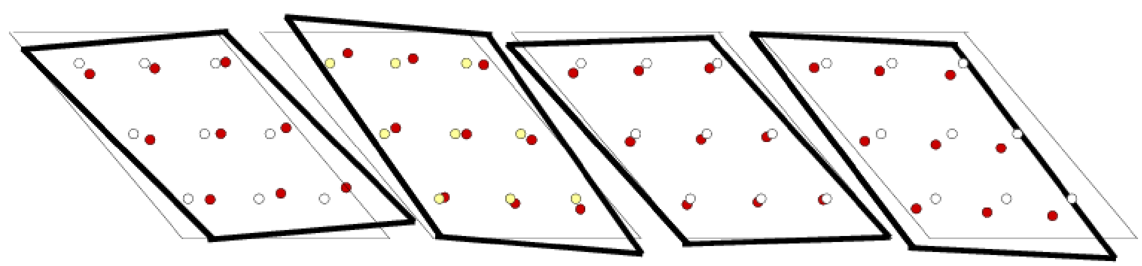
- We have "current" and "reference" sensor positions:

"current"
reco geometry

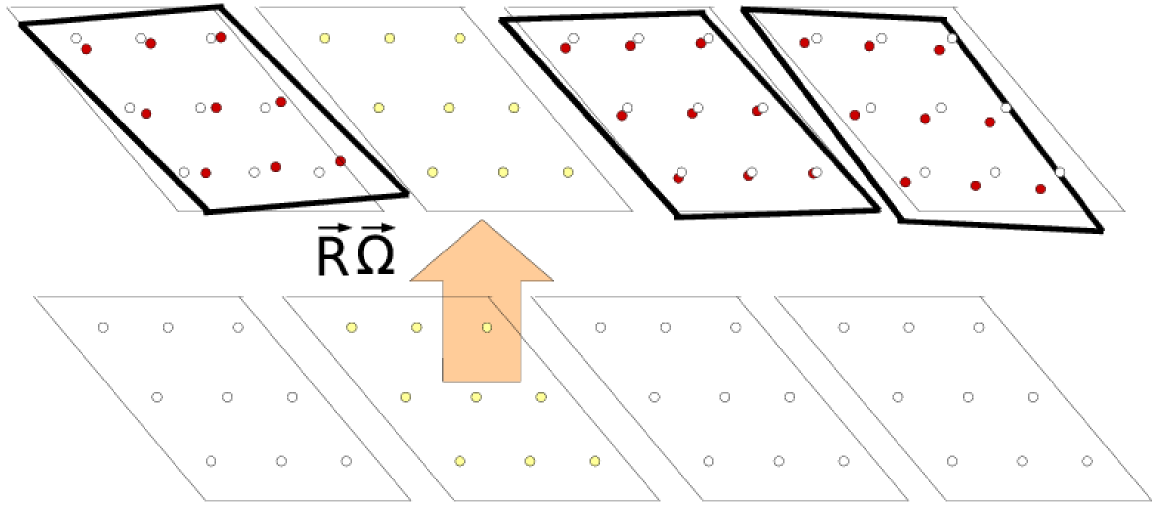
"reference"
survey geometry



- First bring to common system of coordinates ("current"):



Survey Residual: Rigid Body Motion



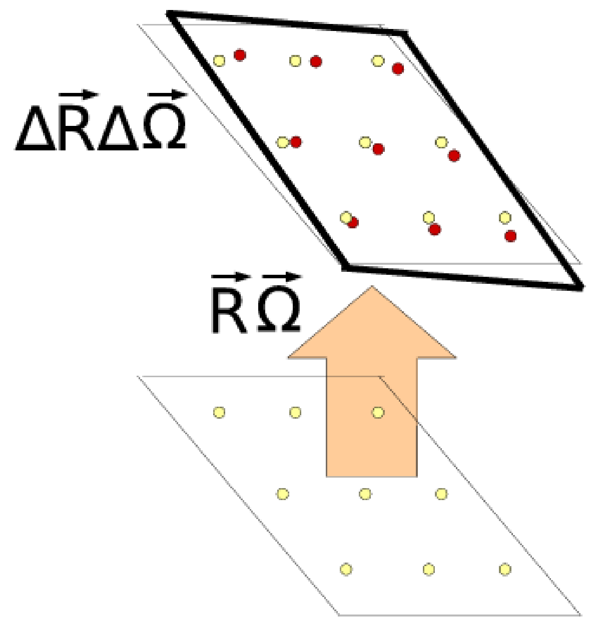
- Rigid body motion:

  minimize shift χ^2

  ("unbiased" $i \neq I$)

$$R_k = \Big(\sum_{j,i\neq I}^{n\times N} m_{ij} \cdot d\vec{r}_{ij}\Big)_k \Big/ \Big(\sum_{j,i\neq I}^{n\times N} m_{ij}\Big)$$

$$\sum_{k=1}^{3} \Omega_k \sum_{j,i\neq I}^{n\times N} m_{ij}\left(\delta_{kl}(\vec{r}_{ij})^2 - (\vec{r}_{ij})_k(\vec{r}_{ij})_l\right) = \sum_{j,i\neq I}^{n\times N} m_{ij}(\vec{r}_{ij} \times d\vec{r}_{ij})_l$$



- Residual: $\epsilon_* = (\mathbf{\Delta\vec{R}}, \mathbf{\Delta\vec{\Omega}})$

  remaining transformation

  again minimize shift χ^2, but $i = I$

- Covariance: $\mathbf{V}$

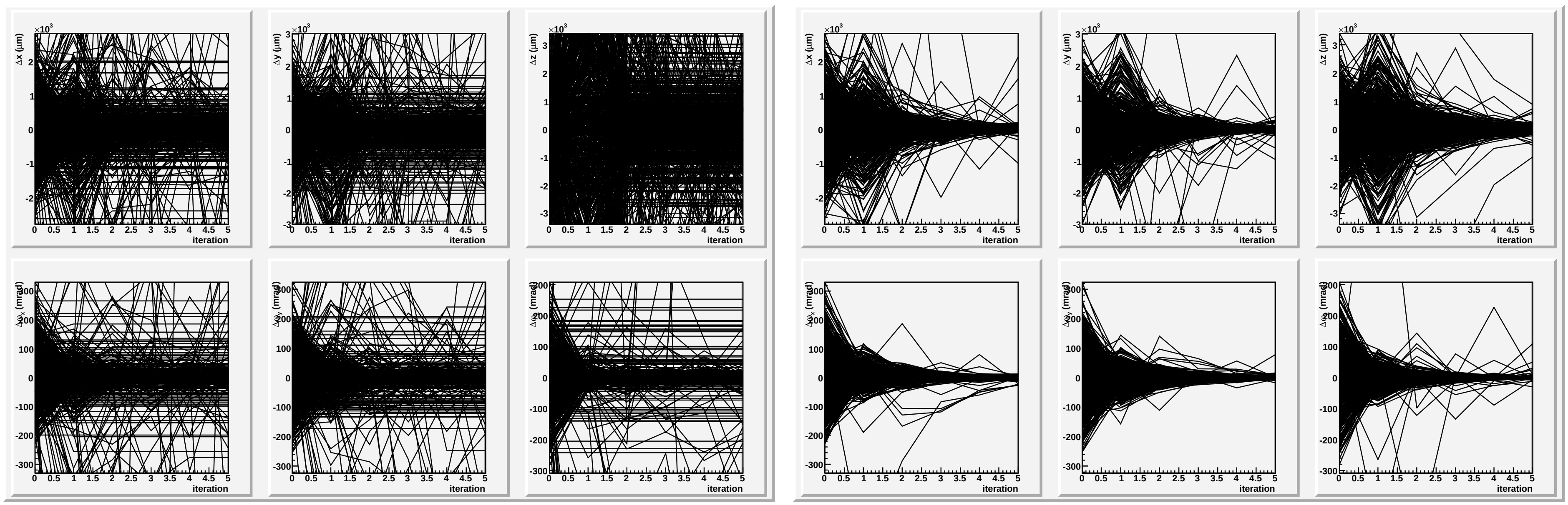
  from survey and mechanics analysis

(5) Example: Local χ^2 Iterative Method (HIP)

- Example with CMS Pixel Detector
  - small number of tracks 50k
  - iterate to solve correlations

Tracks only — Tracks + Survey

x y z — x y z



α β γ — α β γ

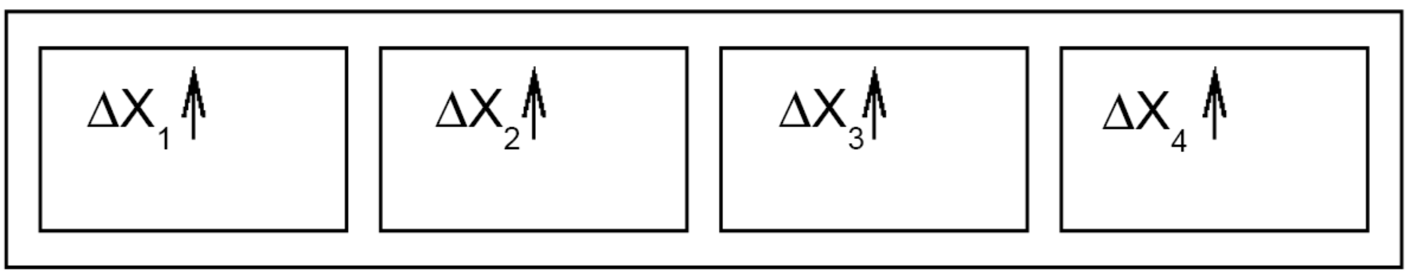
Example: MillePede Method

- Survey and mounting precision constraint:
  - improved starting values
  - large deviations from start positions suppressed: χ^2 penalties $+1/\sigma^2$ to diagonal $\Rightarrow$ increase eigenvalues, avoid numerical problems (constraint would be lost with many iterations)

- Survey measurements:

$\sum c_i p_i = m \pm \sigma_m$

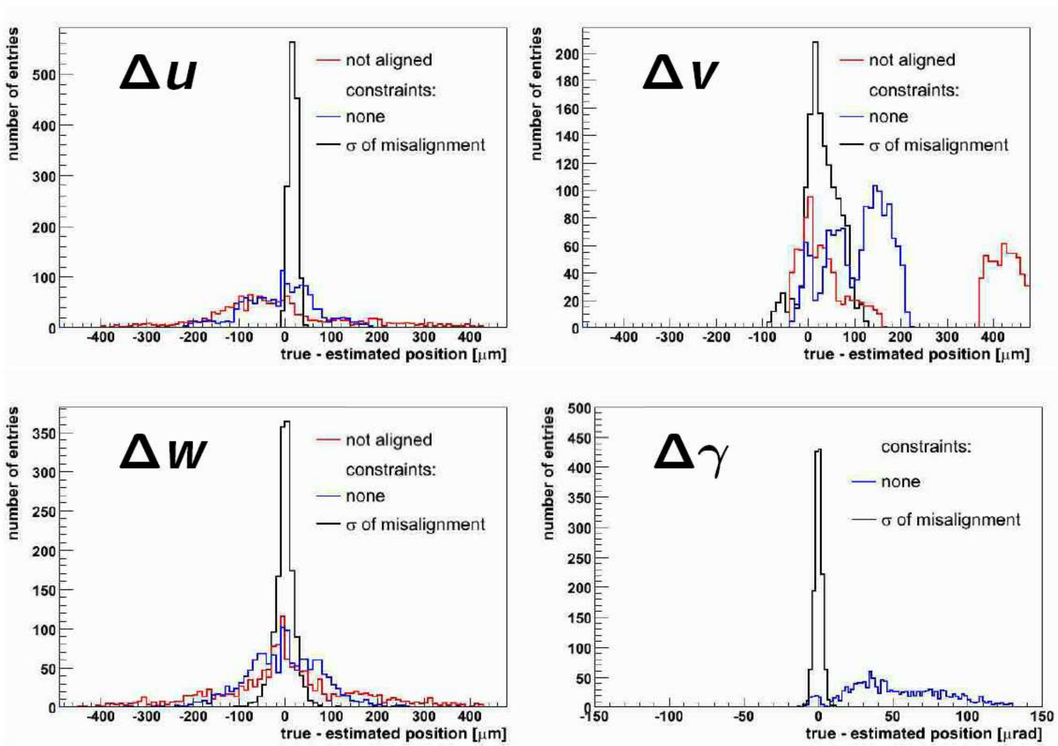
e.g. constrain linear combination of parameters $\sum \Delta X_i = 0$



  - new feature in MillePede, being tested

MillePede Example; Kalman Method

- Example with constraint (χ^2 penalties):
  - tracks from ~ 2 fb^{-1} (2 million $Z \to \mu^+\mu^-$)
  - significant improvement with constraint

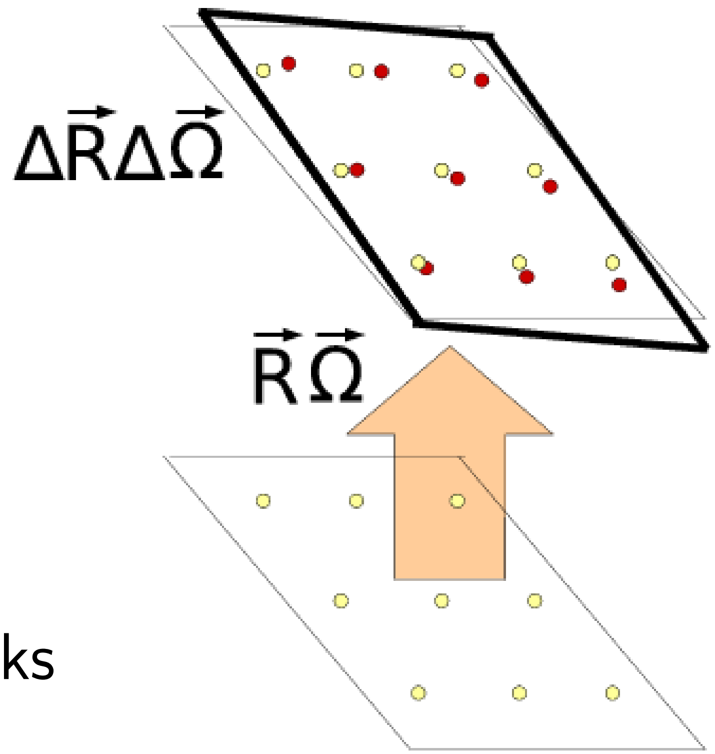


- Kalman Filter: started to implement survey residuals s_i

  align. parameters for alignable i: $\hat{d}_i = d_i + D_i(D_i + S_i)^{-1}(s_i - d_i)$

Summary of CMS Survey Geometry

- Survey of most CMS tracking systems:
  - pixel Si detectors
  - strip Si detectors
  - muon system



- Usage of survey:
  - quality control
  - geometry at start-up
  - constraint or measurement with tracks
- Importance in software alignment:
  - reduction of degrees of freedom, better convergence
  - constraint of χ^2-invariant distortions