CSIC

IFIC - Instituto de Física Corpuscular

Track-based alignment of the ATLAS Inner Detector

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On behalf of the ATLAS Inner Detector Alignment group

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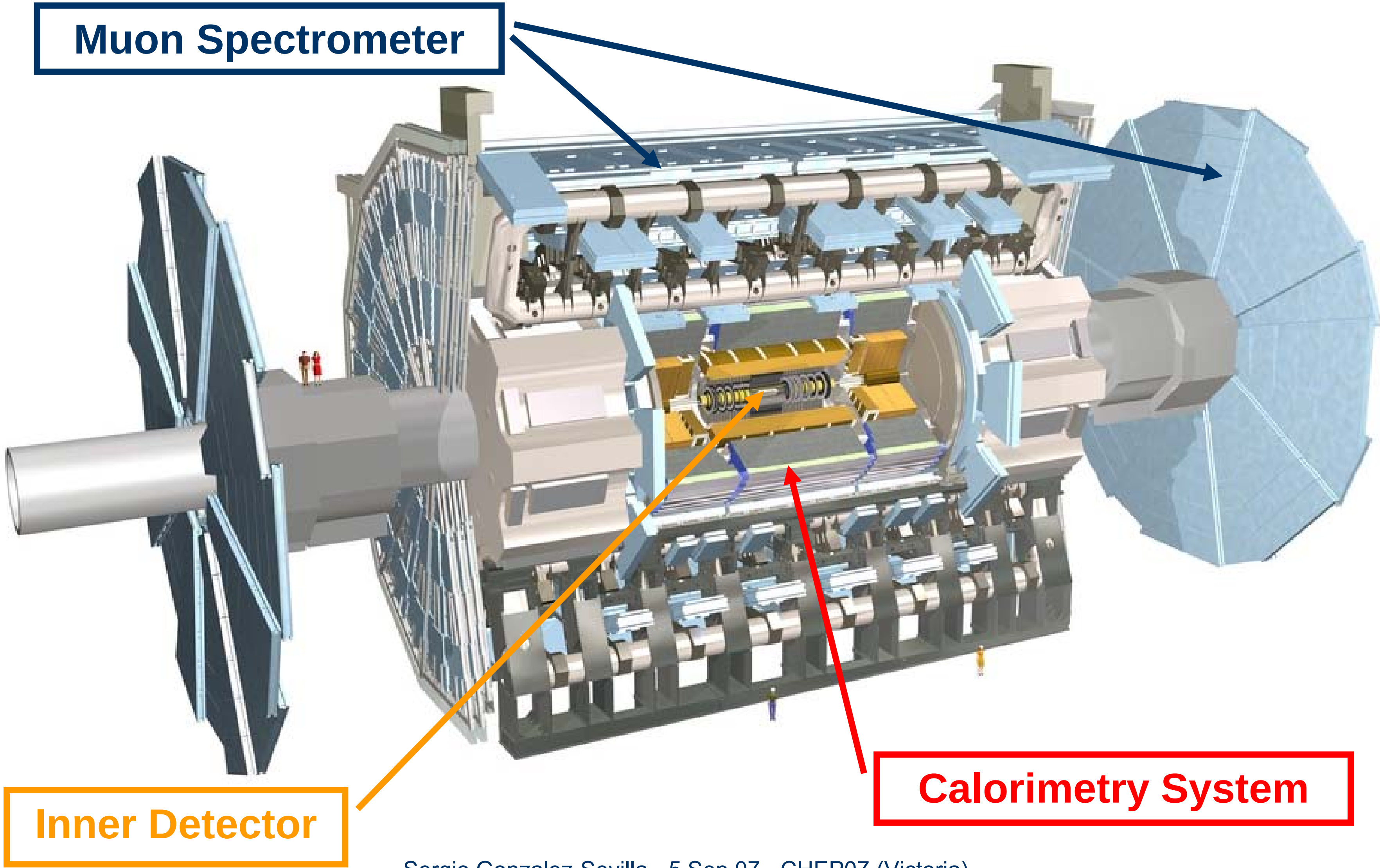
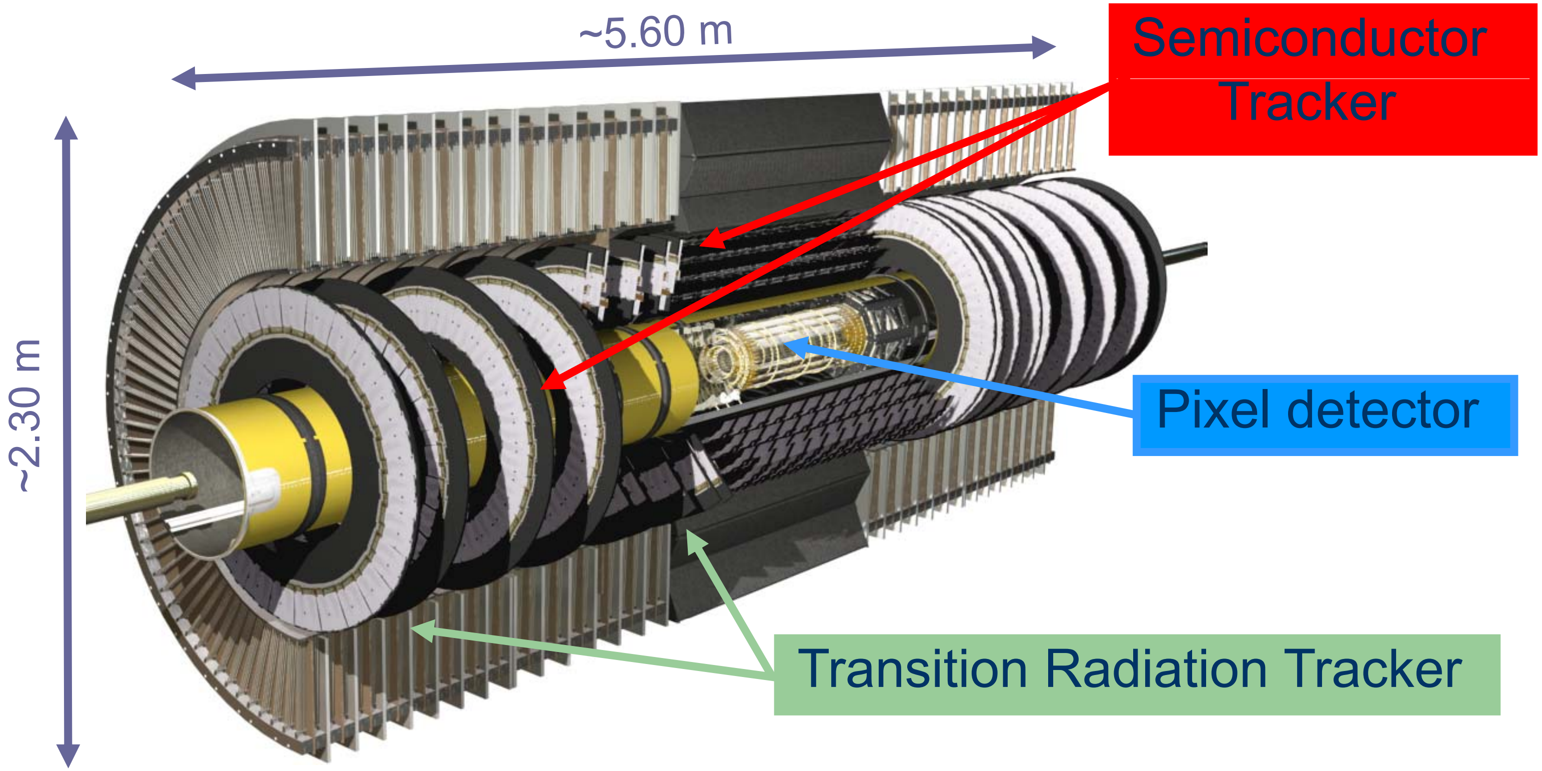
CHEP'07 VICTORIA, BC

The ATLAS experiment



ATLAS Inner Detector



Subsystem	Pixel	SCT	TRT
Technology	Silicon pixels	Silicon microstrips	Gaseous drift-tubes
Intrinsic resolution	~14 μm (rφ) ~115 μm (z)	~23 μm (rφ)	~170 μm (rφ)

Inner Detector alignment requirements

- Physics motivations of the Inner Detector alignment requirements:
  - track parameters resolutions degraded < 20% by misalignments
  - systematic error M(W) < 15 MeV/c^2
  - b-tagging, secondary vertices, etc…

$\Rightarrow$ alignment controlled to O(10) μm or better

- Initial knowledge of the detector and hardware-based alignment:
  - Mounting and Survey measurements:
    - assembly measurements during detectors production
    - survey in assembly area and pit (eg: photogrammetric measurements $\Rightarrow$ elliptical shapes in SCT barrels)
    - precisions: O(100) μm
  - Frequency Scanning Interferometry (FSI):
    - continous monitoring during ATLAS data-taking
    - deformations in shapes of mechanical structures (environmental cond.)
    - precisions: O(10) μm (3D points)
- Ultimate precisions reached with track-based alignment algorithms
- Challenge: 6 degrees of freedom (*dofs*) / module $\Rightarrow$ <u>entire system is ~36k dofs !</u>

Alignment approaches (1/2)

- Several approaches to silicon (Pixel and SCT) and TRT alignment:
  - relative alignment of the TRT wrt silicon by track extrapolation
  - implementation of combined alignment silicon+TRT (momentum constraint)

- Algorithms implementations in the ATLAS software framework (Athena):
  - Robust:
    - centre residuals and overlap residuals
    - 2-3 *dofs*, many iterations
    - alignment corrections computed without minimizations
  - Global χ^2:
    - in-plane residuals
    - 6 *dofs*, few iterations
    - large linear system (35k x 35k)
    - correlations accounted though internal track refit
  - Local χ^2:
    - distance of closest approach
    - 6 *dofs*, many iterations
    - 6x6 matrices (module level)
    - correlations through iterating
  - TRTAlignAlg:
    - local and global approaches
    - calibrations required (TRT drift-time relations)

Minimization of χ^2:

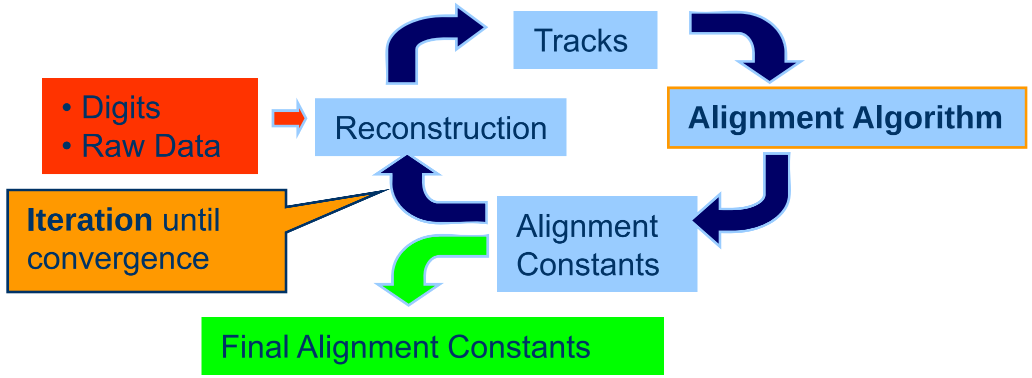
$$\chi^2 = \sum_{tracks} r^T V^{-1} r$$

(inverse) covariance matrix

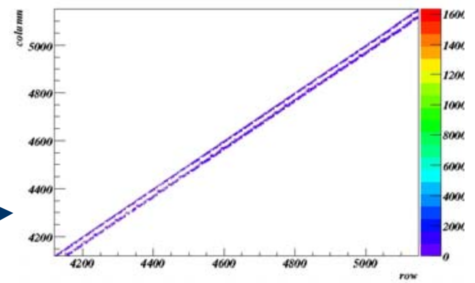
residuals

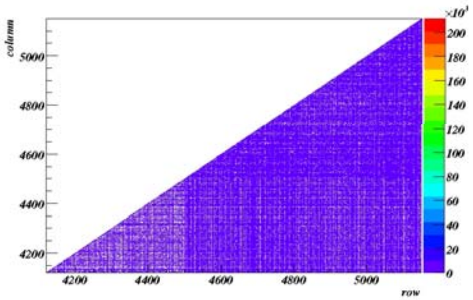
Alignment approaches (2/2)

- Iterative algorithms:
  - integration into the ATLAS offline software chain
  - alternate computation of alignment corrections and track fitting



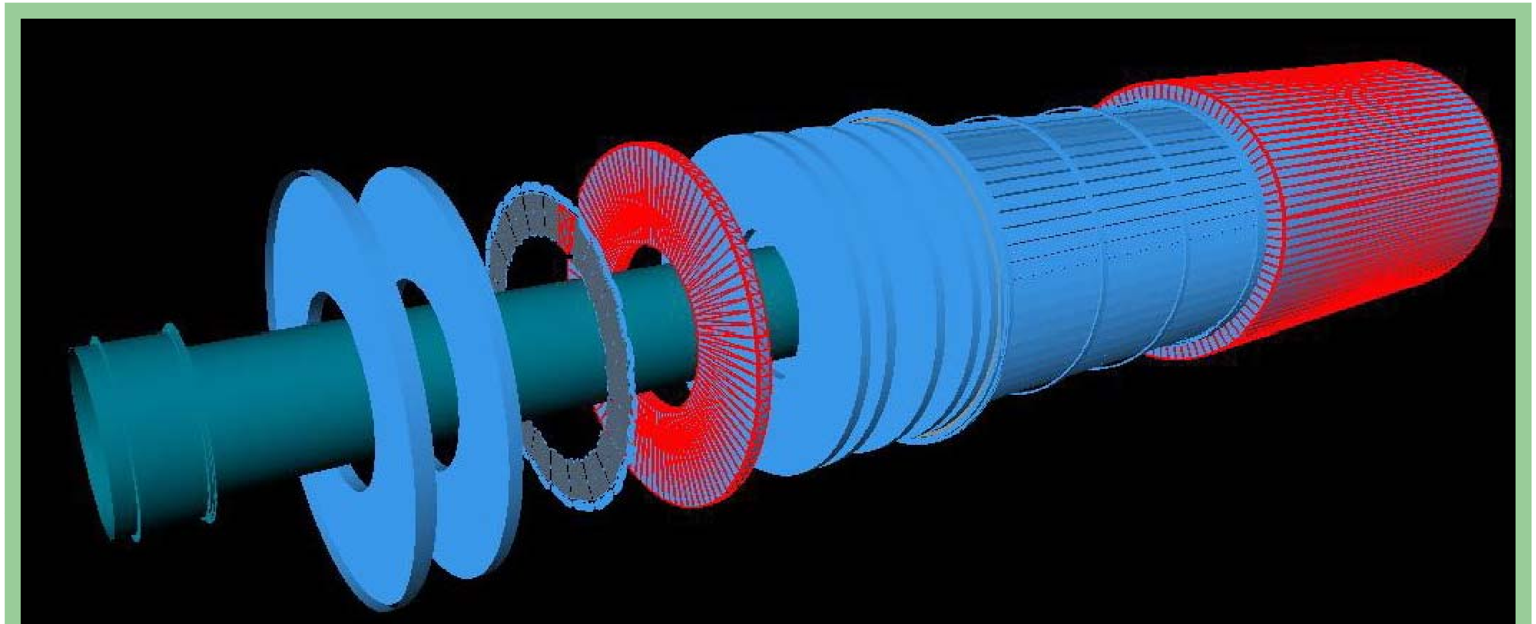
- Solving a large system of linear equations:
  - limiting factors: **size**, **precision** and **execution time**
  - fast methods:
    - **sparse matrices**
    - MA27 ⇒ less than 10 mins for 35k in a single CPU)
  - 64-bits parallel processing:
    - **dense matrices** (*e.g.* vertex constraint)
    - ScalaPack ⇒ 10 mins. for full Pixel system (12.5k) on 16 nodes (diagonalisation)





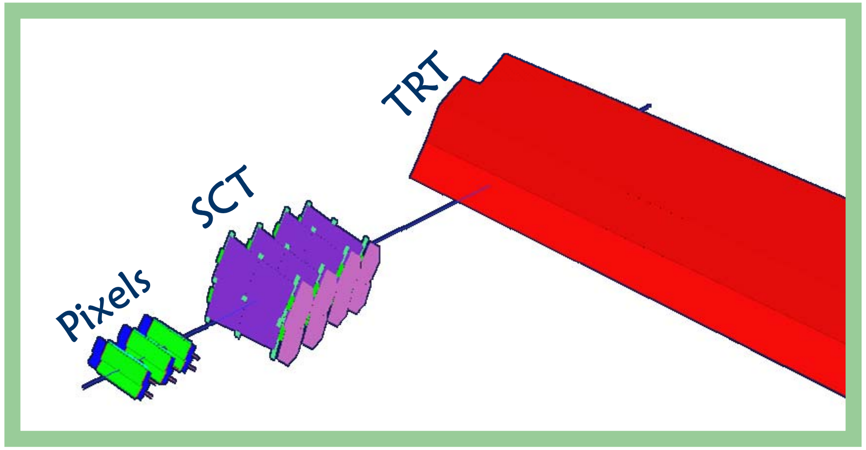
Alignment infrastructure

- Detector description in terms of geometrical primitives (GeoModel)
- Logical volumes grouped in hierarchical nodes
- Alignment infrastructure based on alignable nodes
- Three different levels:
  - **level 1:** entire subdetectors (whole Pixel, SCT & TRT barrel and end-caps)
  - **level 2:** silicon layers & disks, TRT modules
  - **level 3:** silicon modules (individual straw displacements foreseen)



Algorithms validation : CTB

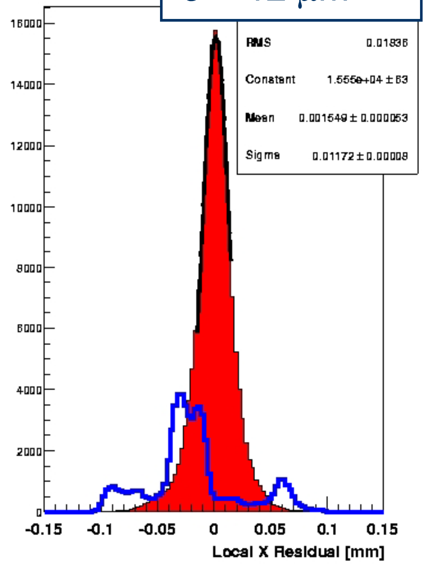
- Combined Testbeam (2004)
- ATLAS barrel slice ⇒ detectors from all different ATLAS subsystems
- Data-taking program:
  - e, π, μ, γ ; 2 up to 180 GeV/c
  - without and with B-field (1.4 T)
- ~20M validated events for the ID



Robust alignment

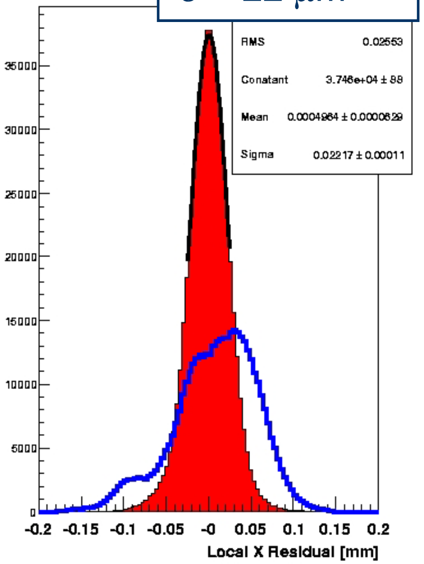
Pixel

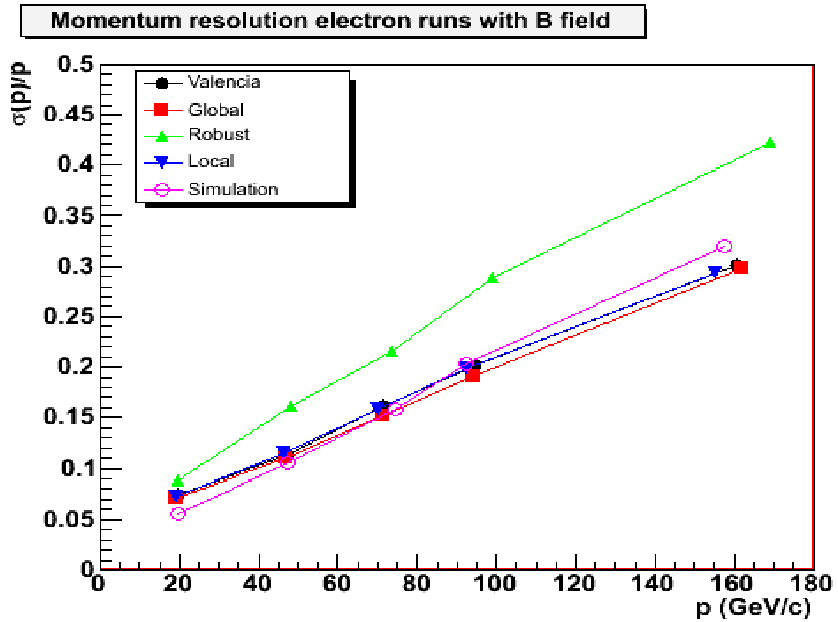
μ = 1 μm
σ = 12 μm



SCT

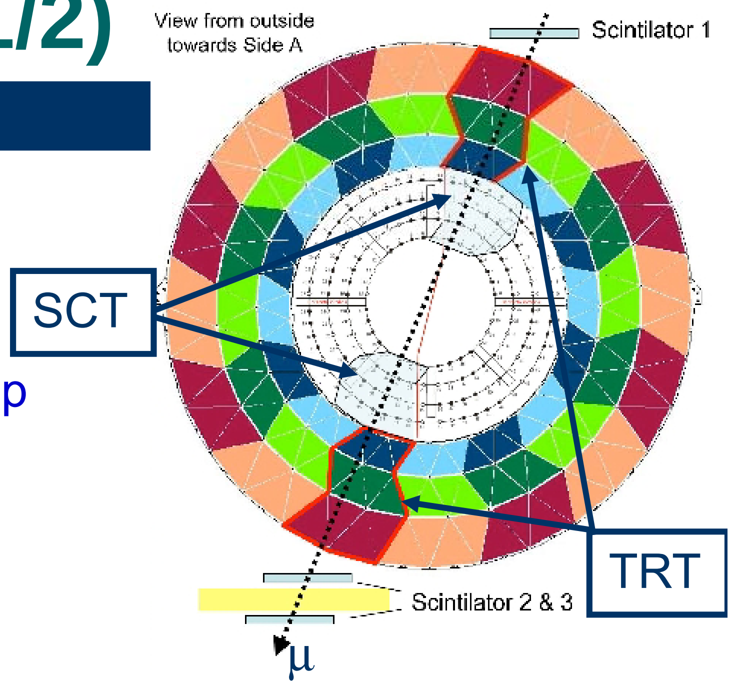
μ = 0.5 μm
σ = 22 μm

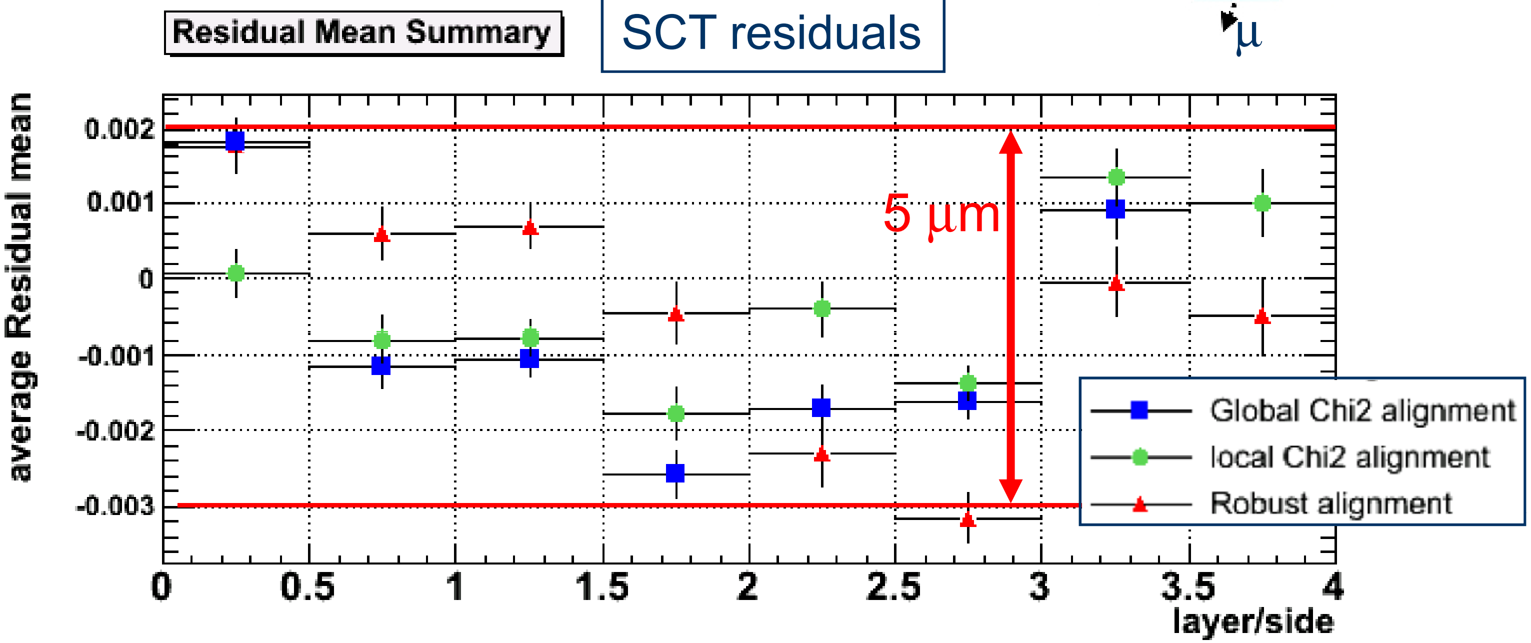




SR1 Cosmics (1/2)

- Combined SCT+TRT cosmic runs in SR1 surface assembly area (2006)
- Scintillators trigger, no B-field ⇒ MCS @ low p
- Barrel sectors: 22% SCT, 13% TRT
- ~400k events recorded

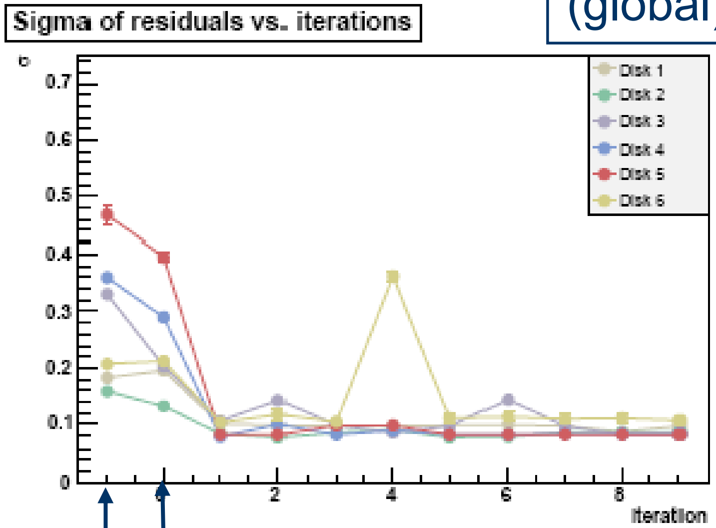




SR1 Cosmics (2/2)

SCT EC disk alignment

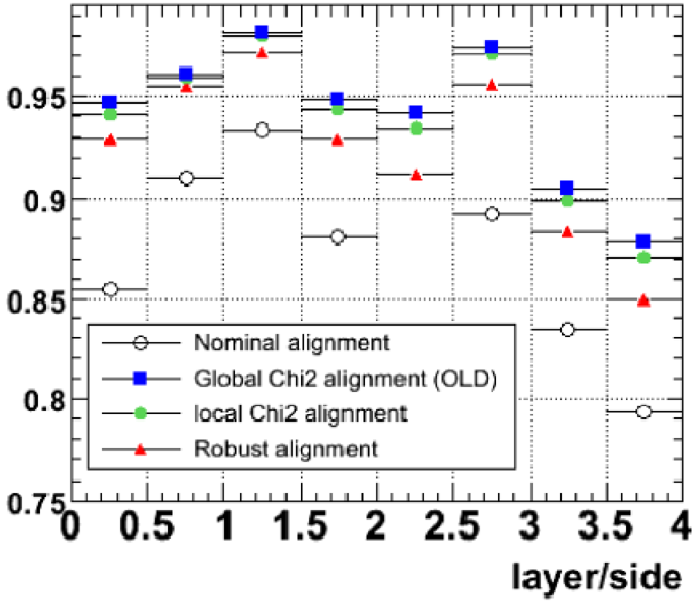
TRTAlignAlg (global)



nominal positions

usage of survey information

- Alignment improves SCT hit efficiency !

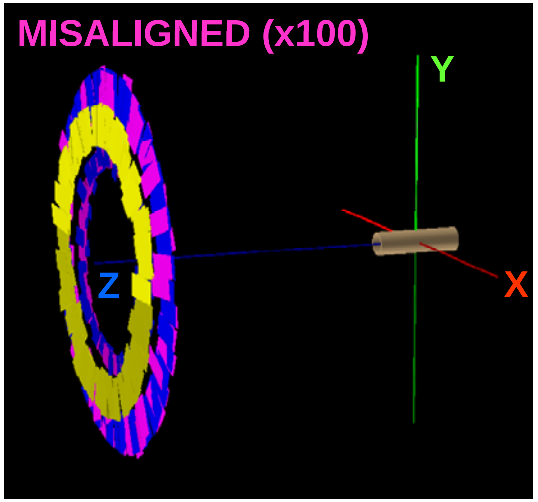


CSC and CDC

- *Computing System Commissioning* (CSC) and *Calibration Data Challenge* (CDC)
- Simulation of calibration and physics samples
- Testing the ATLAS software chain (computing model)
  - calibration and alignment procedures

- Realistic detector description:
  - misalignments at all levels (translations+rotations)
  - shifted and rotated magnetic field
  - extra-material

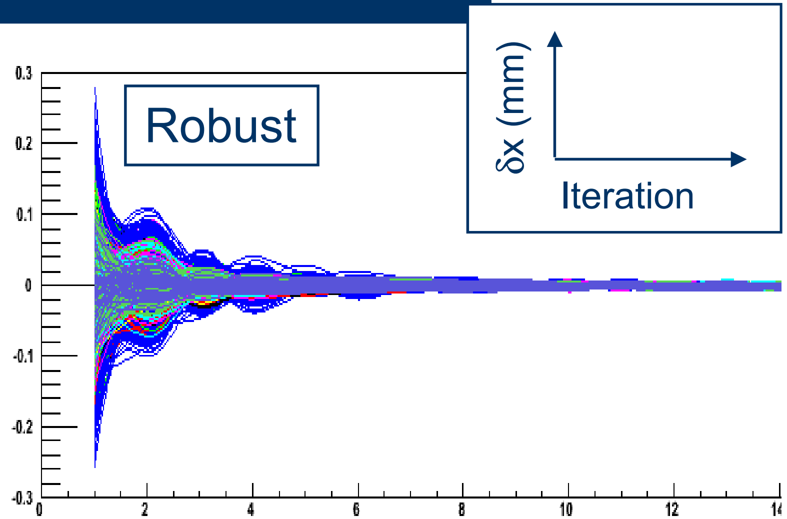
	Translations	Rotations
Level 1	O(1 mm)	O(0.1 mrad)
Level 2	O(100 μm)	O(1 mrad)
Level 3	O(100 μm)	O(1 mrad)

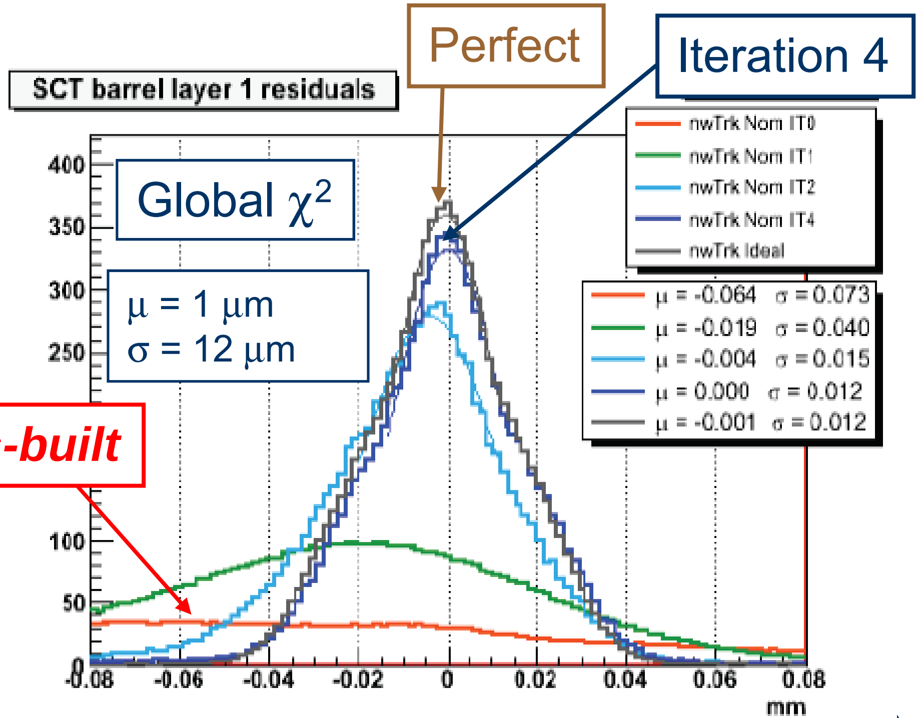


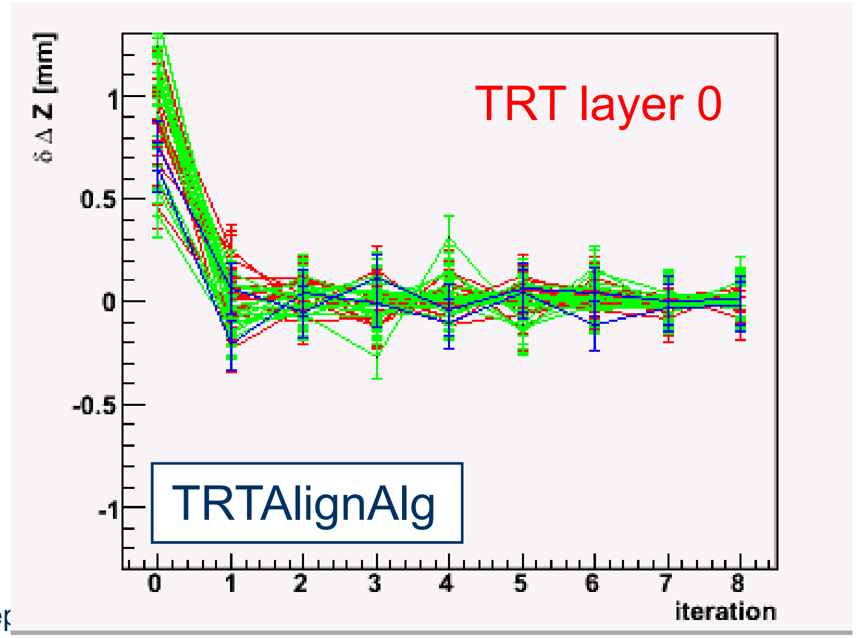
Convergence and residuals with CSC

- Multimuon sample:
  - 10 muons/event
  - σ_{xy} = 15 µm ; σ_z = 56 mm
  - Momentum spectrum : [2; 50] GeV/c

- Algorithms converging, residuals ok



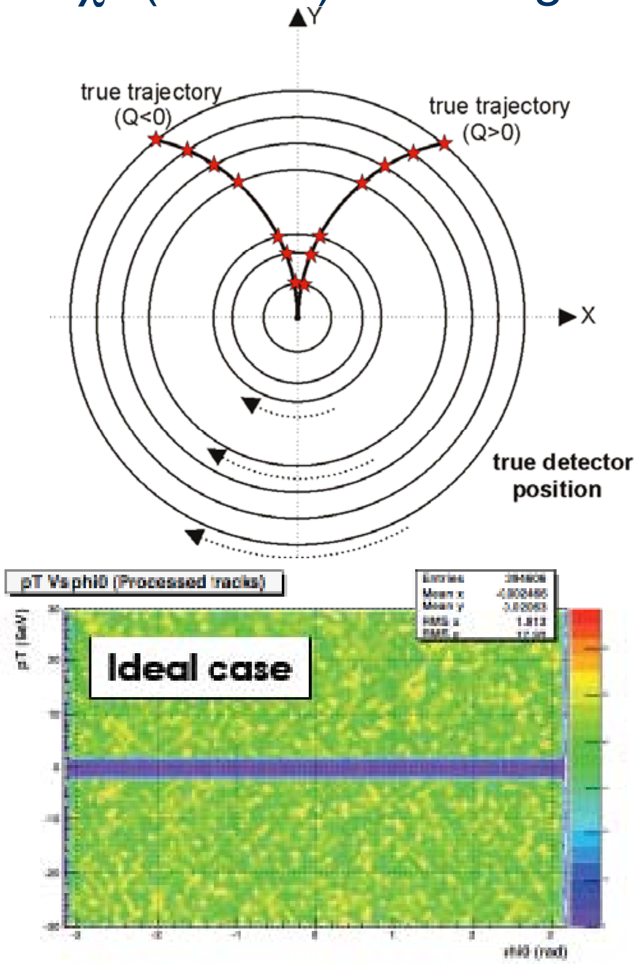


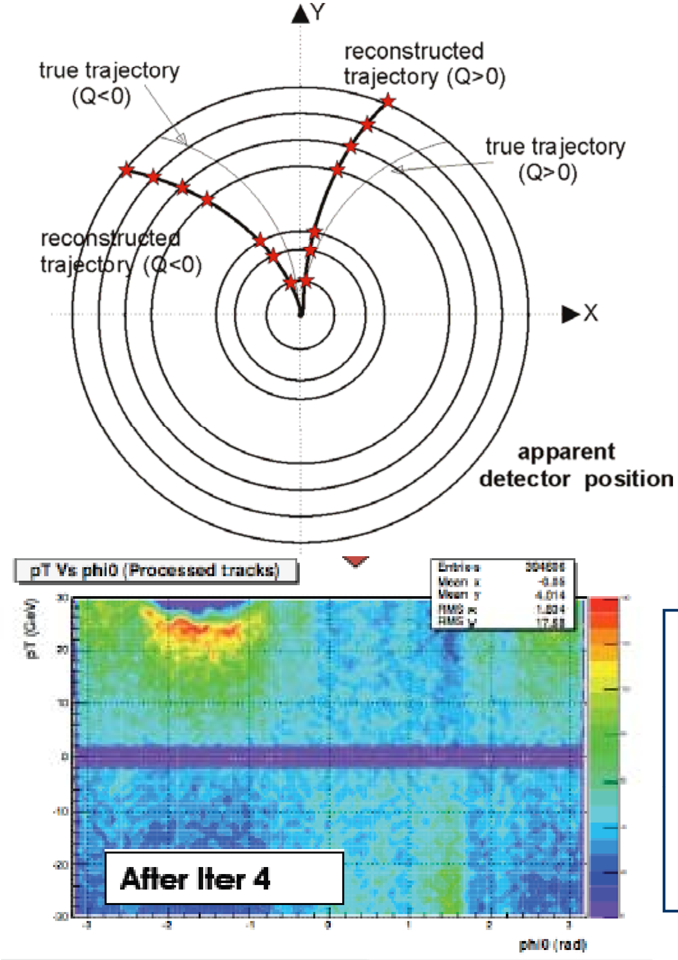


Global deformations and weak modes

- Sagitta distortions (weak modes)
- Bias in track parameters $\Rightarrow$ but helical path mantained !
- tracks χ^2 (almost) blind to global deformations

Momentum asymmetry

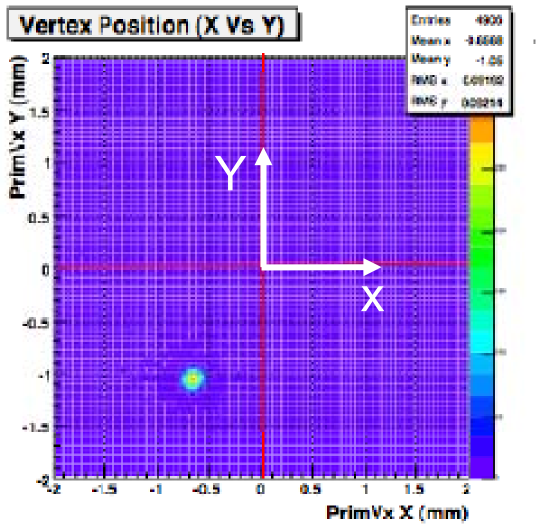


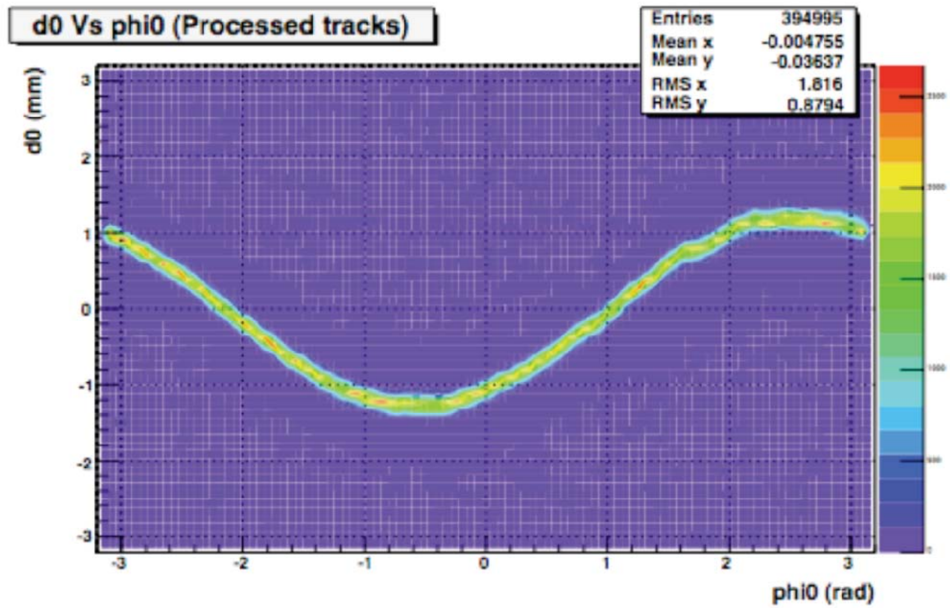


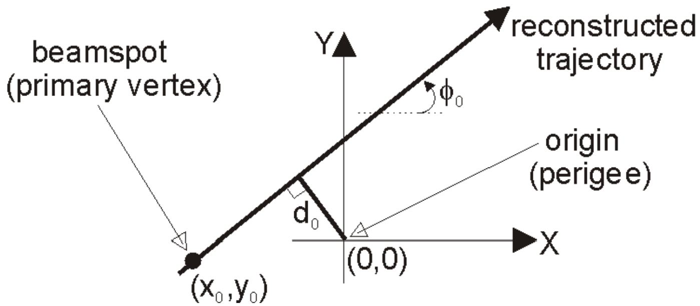
Global χ^2 (level 3 alignment)

Beamspot offset and d_0 vs ϕ_0

- Effect of global distortions: beamspot offset (primary vertex displaced)
- (transverse impact parameter) ⇔ (azimuthal angle) dependence





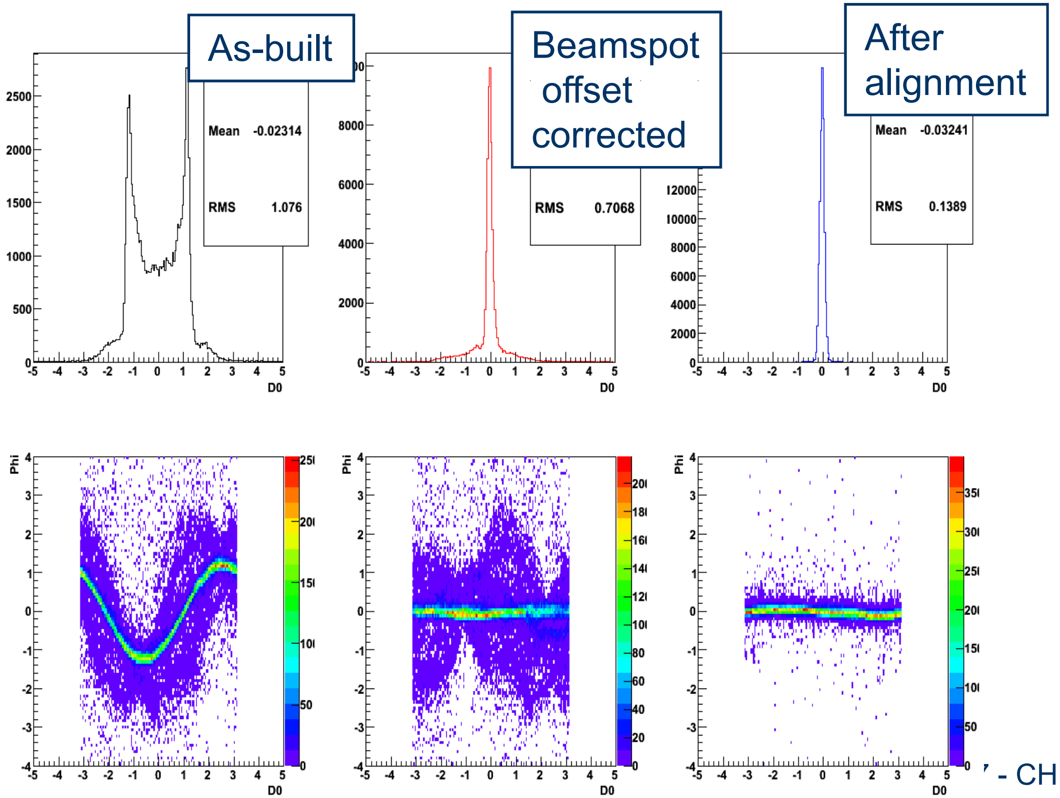


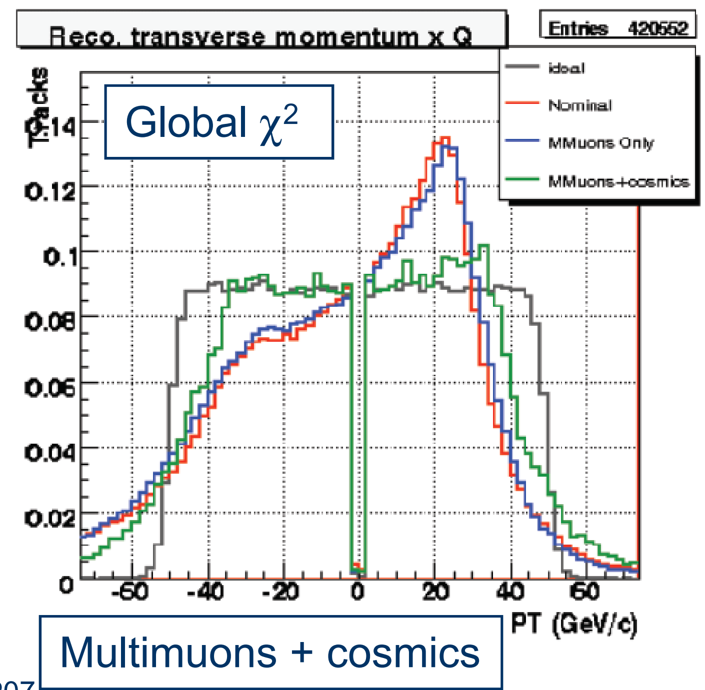
$$d_0 = -x_0 \sin\phi_0 + y_0 \cos\phi_0$$

Fit (d_0 vs ϕ_0)	CSC Pixel Level 1
x_0 = (-0.655 ± 0.005) mm	T_X = 0.600 mm
y_0 = (-1.045 ± 0.004) mm	T_Y = 1.050 mm

Removing global distortions

- Make use of all available information:
  - redundant measurements:
    - momentum measurement in the Muon Spectrometer
    - E/p relation from Calorimeters
  - external constraints (survey, FSI, common vertex, mass constraint, etc.)
  - different event topologies (cosmics, beam halo, etc.)





Summary

• Track-based alignment is required to help reaching the optimal performance of the experiment

• Different alignment algorithms implemented under the ATLAS software framework (Athena)

• Validation performed with simulation and CTB and Cosmics real data

• CSC and CDC Challenges with a realistic detector description

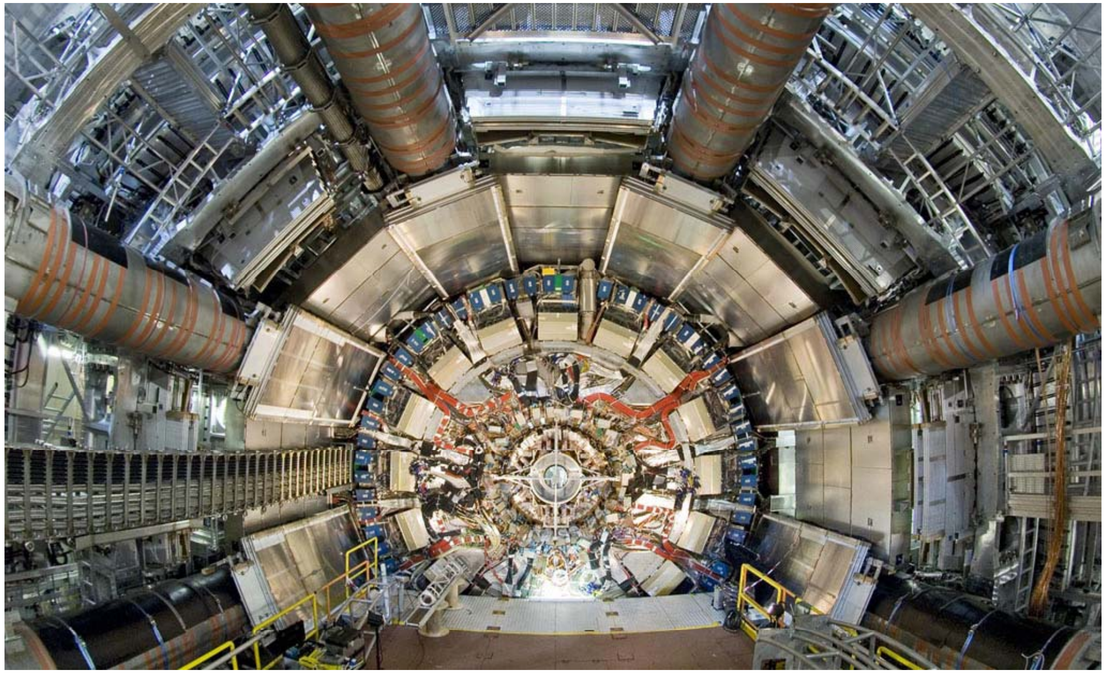
• Biases in track parameters from sagitta distortions
  • control and minimize their effects
  • importance of higher levels macro-structures alignment

Many thanks to the whole ATLAS Inner Detector alignment community !!

BACKUP

Status of the ID installation

- **All Inner Detector systems** (Barrel, EC-A and C) **already installed !!**
- Installation and commissioning of services



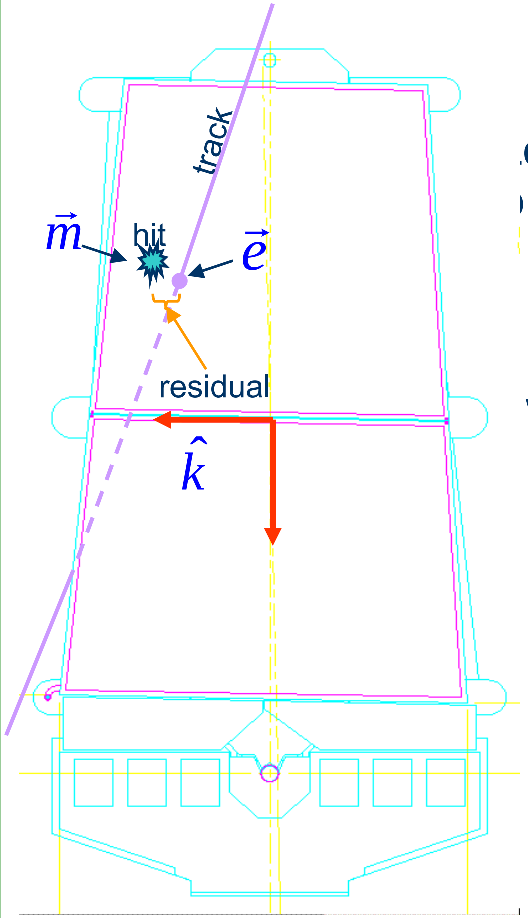
ID EC-A (May 2007)

- Survey of the detectors positioning on surface and down in the pit
- Shifts O(mm) between subsystems:
  - ID aligned <1 mm to the solenoid B-field axis
  - EC's shifts ~3 mm in z (thermal enclosures constraints)

Pawel Bruckman

The Global χ^2 approach

The method consists of minimizing the giant χ^2 resulting from a simultaneous fit of all particle trajectories and alignment parameters:



$$\chi^2 = \sum_{tracks} r^T V^{-1} r \quad \text{where} \quad r \equiv (\vec{e}(\pi, a) - \vec{m}).\hat{k}$$

Intrinsic measurement error + MCS

et us consequently use the linear expansion (we assume all second rder derivatives are negligible). The track fit is solved by:

$$\pi = \pi_0 + \delta\pi = \pi_0 - \left(\frac{\partial e^T}{\partial \pi_0} V^{-1} \frac{\partial e}{\partial \pi_0} \right)^{-1} \frac{\partial e^T}{\partial \pi_0} V^{-1} r(\pi_0, a)$$

while the alignment parameters are given by:

$$\frac{d\chi^2}{da} = 0 \quad \Longrightarrow \quad \sum_{tracks} \frac{dr^T}{da} V^{-1} r = 0$$

Key relation!

$$\frac{dr}{da} = \frac{\partial r}{\partial a} + \frac{\partial r}{\partial \pi} \frac{d\pi}{da}$$

$$\delta a = - \underbrace{\left(\sum_{tracks} \frac{\partial r^T}{\partial a_0} W \frac{\partial r}{\partial a_0} \right)}_{\mathcal{M}}{}^{-1} \underbrace{\sum_{tracks} \frac{\partial r^T}{\partial a_0} W r(\pi_0, a_0)}_{\mathcal{V}}$$

$$W \equiv V^{-1} \hat{W} \equiv V^{-1} - V^{-1} E (E^T V^{-1} E)^{-1} E^T V^{-1} \qquad \mathrm{E} \equiv \frac{\partial e}{\partial \pi_0}$$

Roland Härtel
Tobias Götffert

The Local χ^2 approach

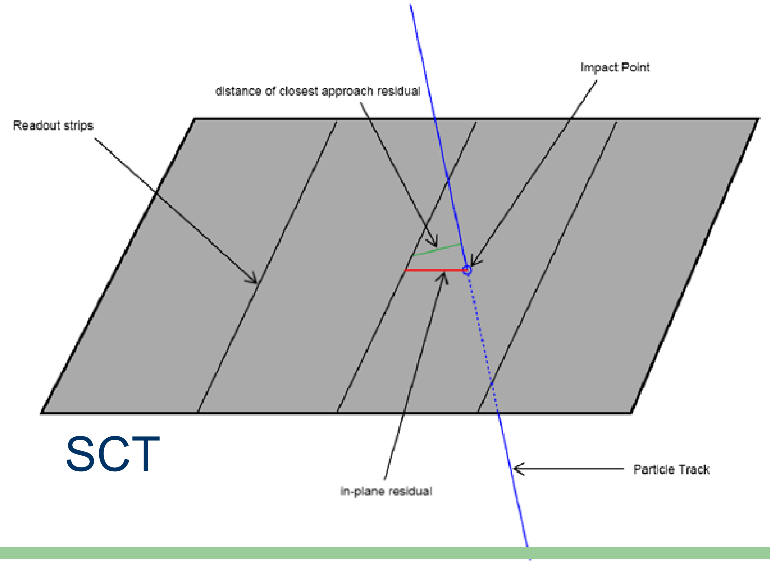
• Reduce the 36k x 36 system by looking ar 6x6 block matrices at the diagonal of the full size matrix:

$$\Delta\vec{a}_k = -\left(\sum_{tracks}\frac{1}{\sigma_{i\,k}^2}\left(\frac{\partial r_{i\,k}(\vec{a}_k)}{d\vec{a}_{k\,0}}\right)\left(\frac{\partial r_{i\,k}(\vec{a}_k)}{d\vec{a}_{k\,0}}\right)^T\right)^{-1}\cdot\left(\sum_{tracks}\frac{1}{\sigma_{i\,k}^2}\left(\frac{\partial r_{i\,k}(\vec{a}_k)}{d\vec{a}_{k\,0}}\right)r_{i\,k}(\vec{a}_{k\,0})\right)$$

• Asumptions:
  - unbiased track parameters
  - no correlations between modules
  - diagonal covariance matrix (no MCS)

• The missing correlations are restored implicitely by iterating

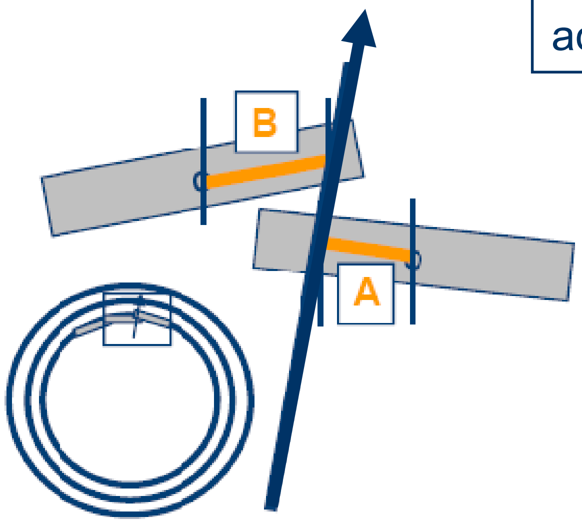
Distance of Closest Approach (DOCA) residuals



Florian Heinemann

The Robust approach

- Use overlap residuals for determining relative module to module misalignments
- Measure rϕ and z overlap residuals for each two overlaps
- Support-structures relative alignment
- Mean of overlap residual ≈ relative misalignment



- **Residual** A,B : hit – track
- **Overlap residuals**: A - B

sum over neighbours, take correlations into account

correct for changes in radius

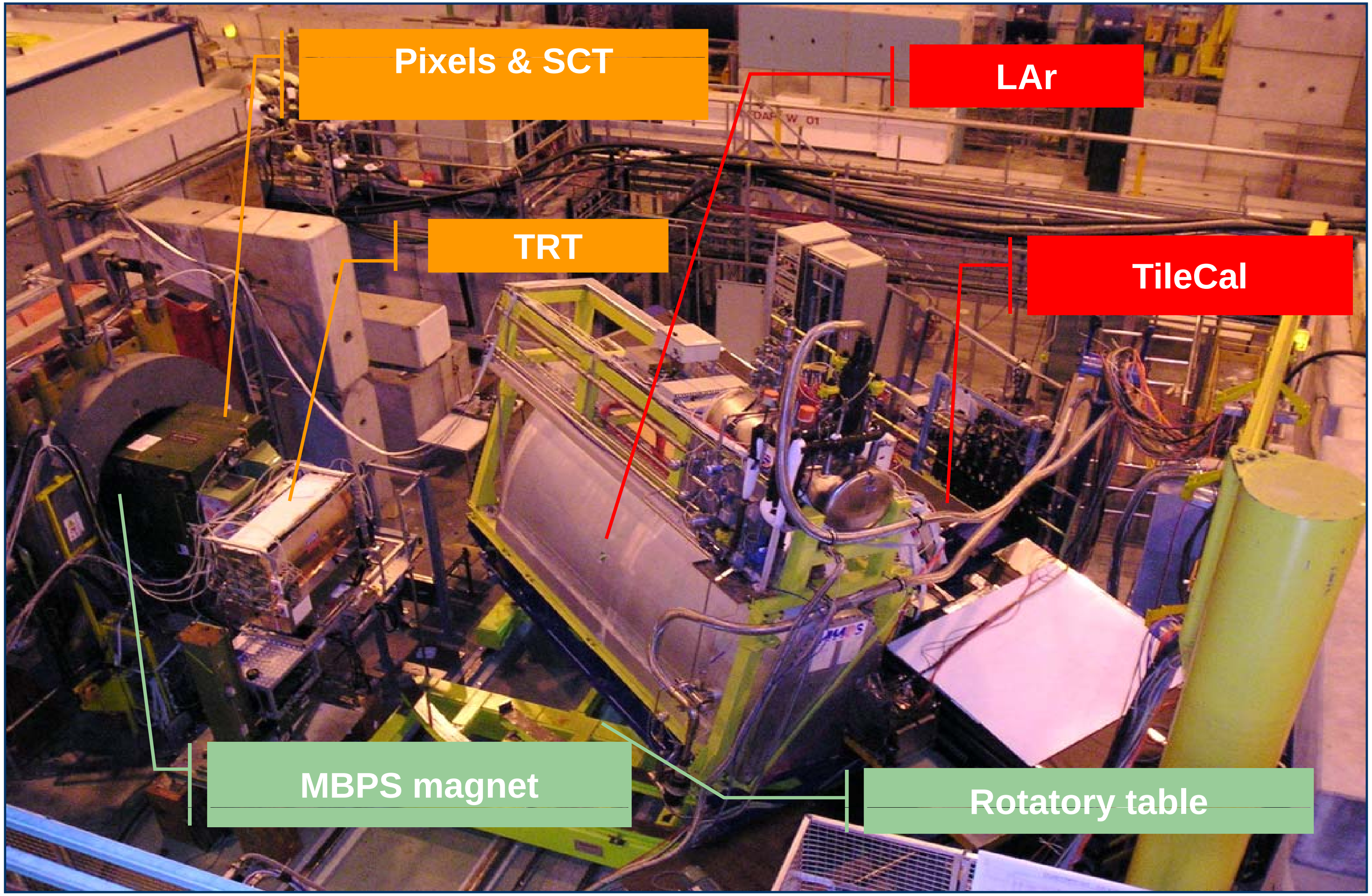
$$Shifts_{x/y} = -\frac{\sum \frac{S_j}{\delta S_j^2}}{\sum \frac{1}{\delta S_j^2}}$$

$$S_1 = \bar{r};\ S_2 = o\bar{r}_\phi;\ S_3 = o\bar{r}_z$$

$$Shifts_z = -\frac{\sum o\bar{r}_\phi}{2\pi}$$

sum over all modules in a ring

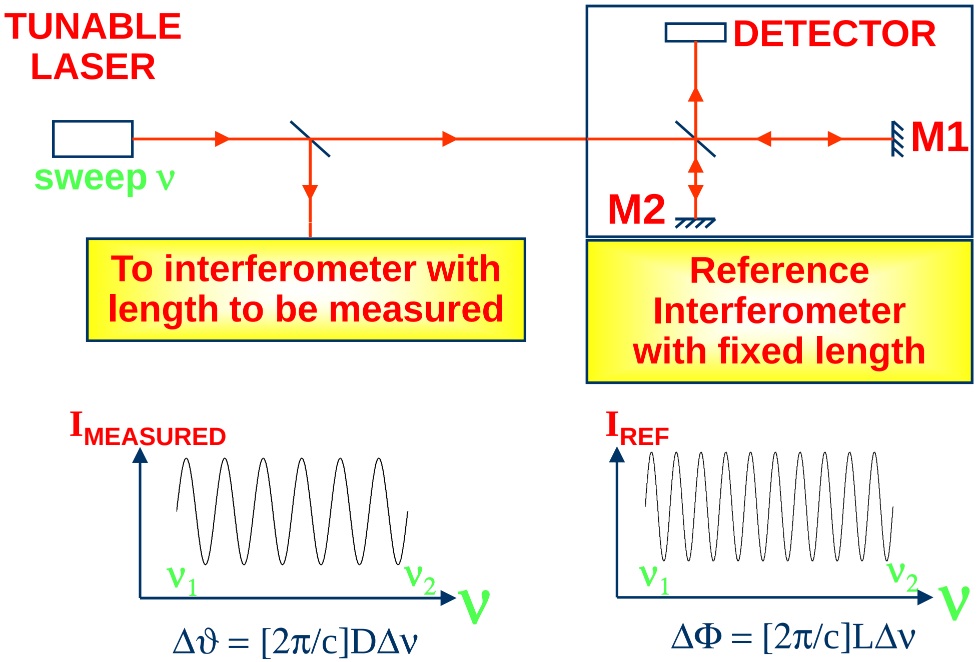
ATLAS Combined TestBeam 2004

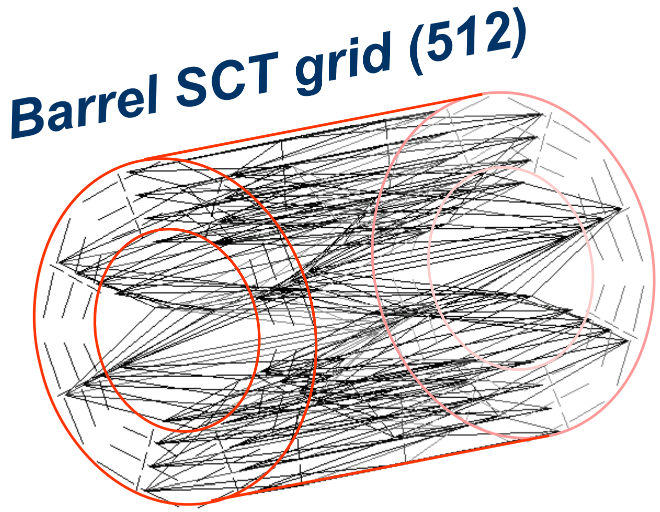


Stephen Gibson

Frequency Scanning Interferometry

- Frequency Scanning Interferometry (FSI)
  - a geodetic grid of length measurements between nodes attached to the SCT support structure
  - all 842 grid line lengths are measured simultaneously using FSI to a precision < 1 mm
  - repeat every ten minutes to measure time varying distortions

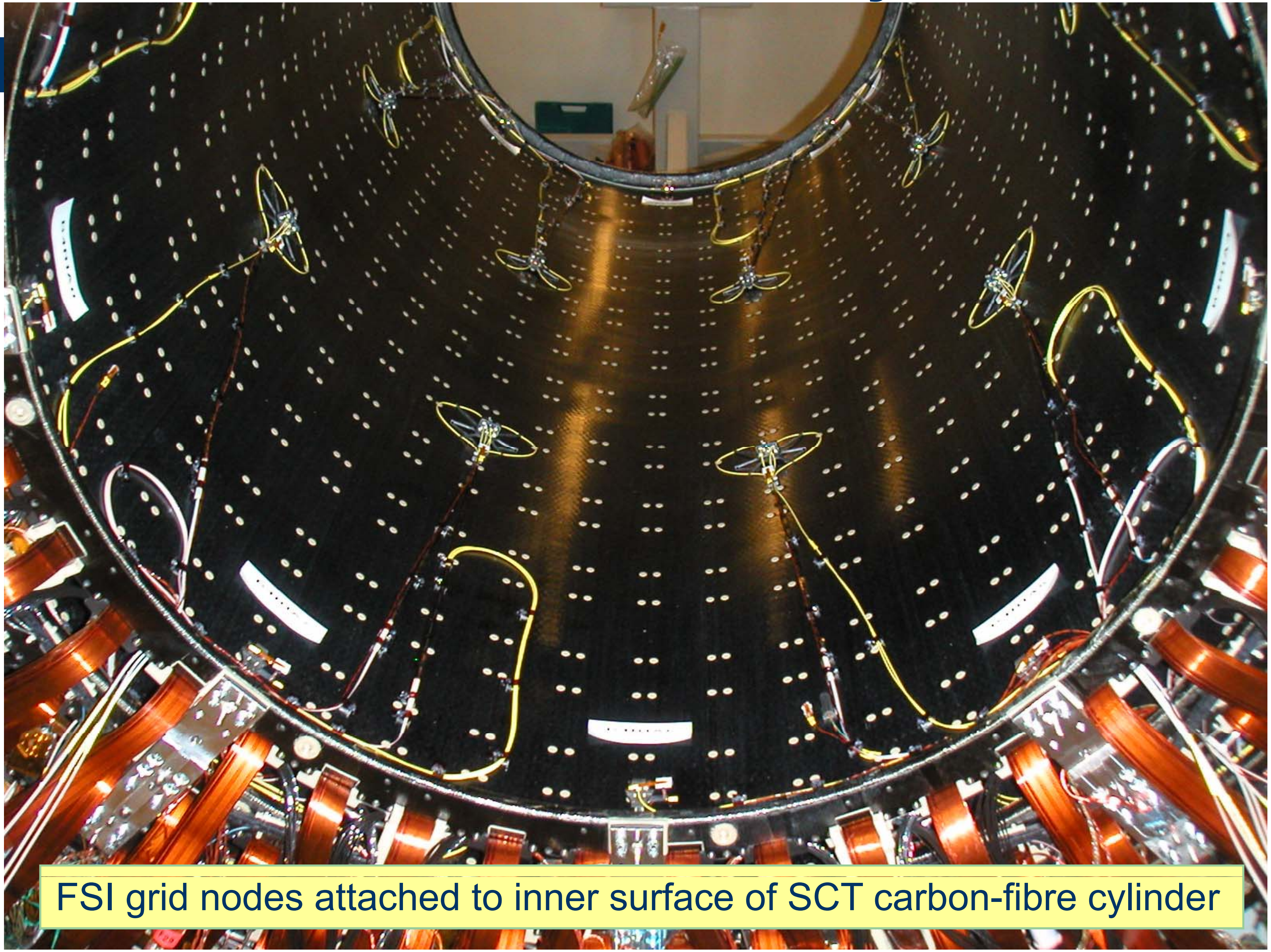




Ratio of phase change = Ratio of lengths

Stephen Gibson

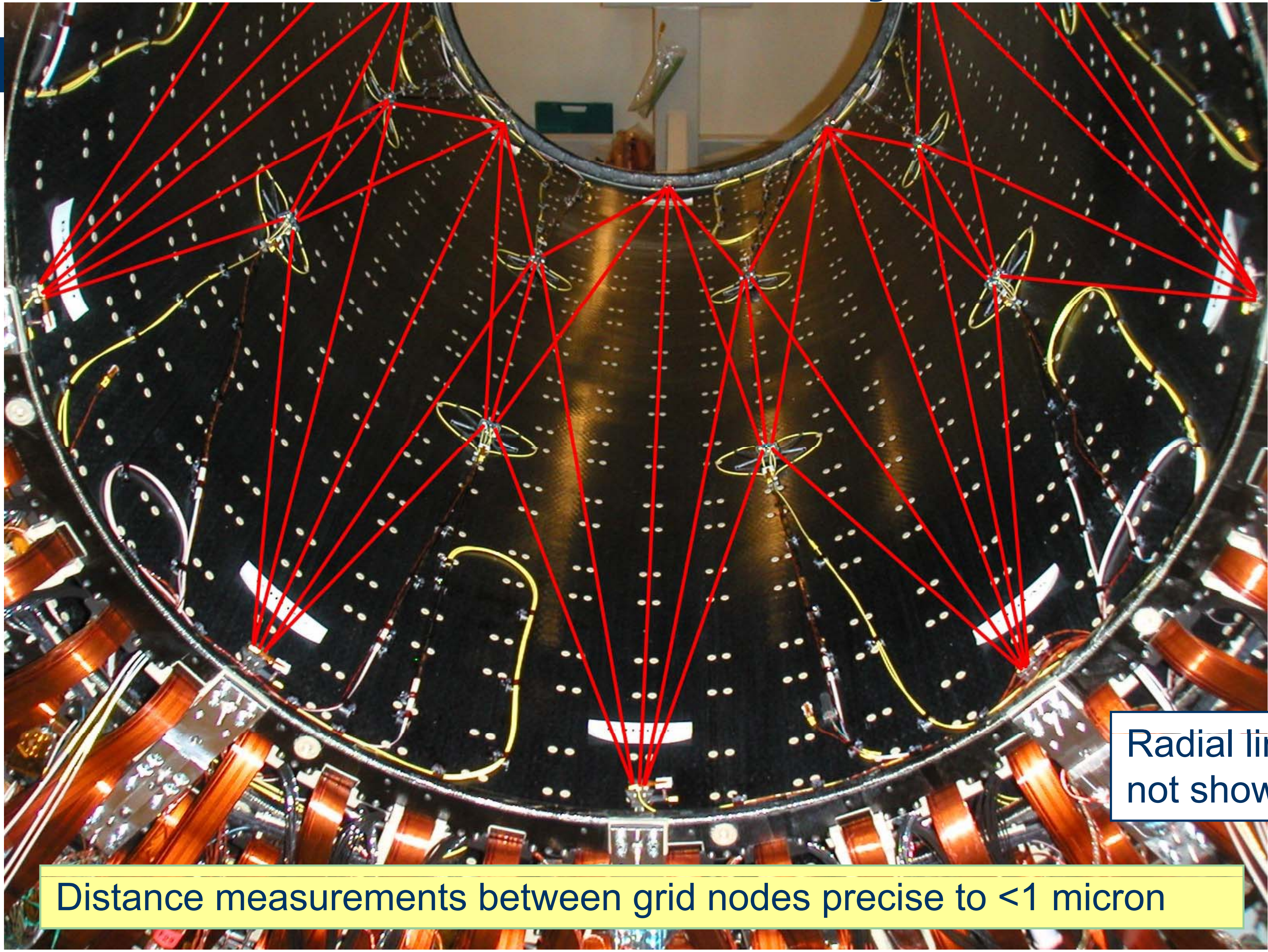
On-detector FSI System



FSI grid nodes attached to inner surface of SCT carbon-fibre cylinder

Stephen Gibson

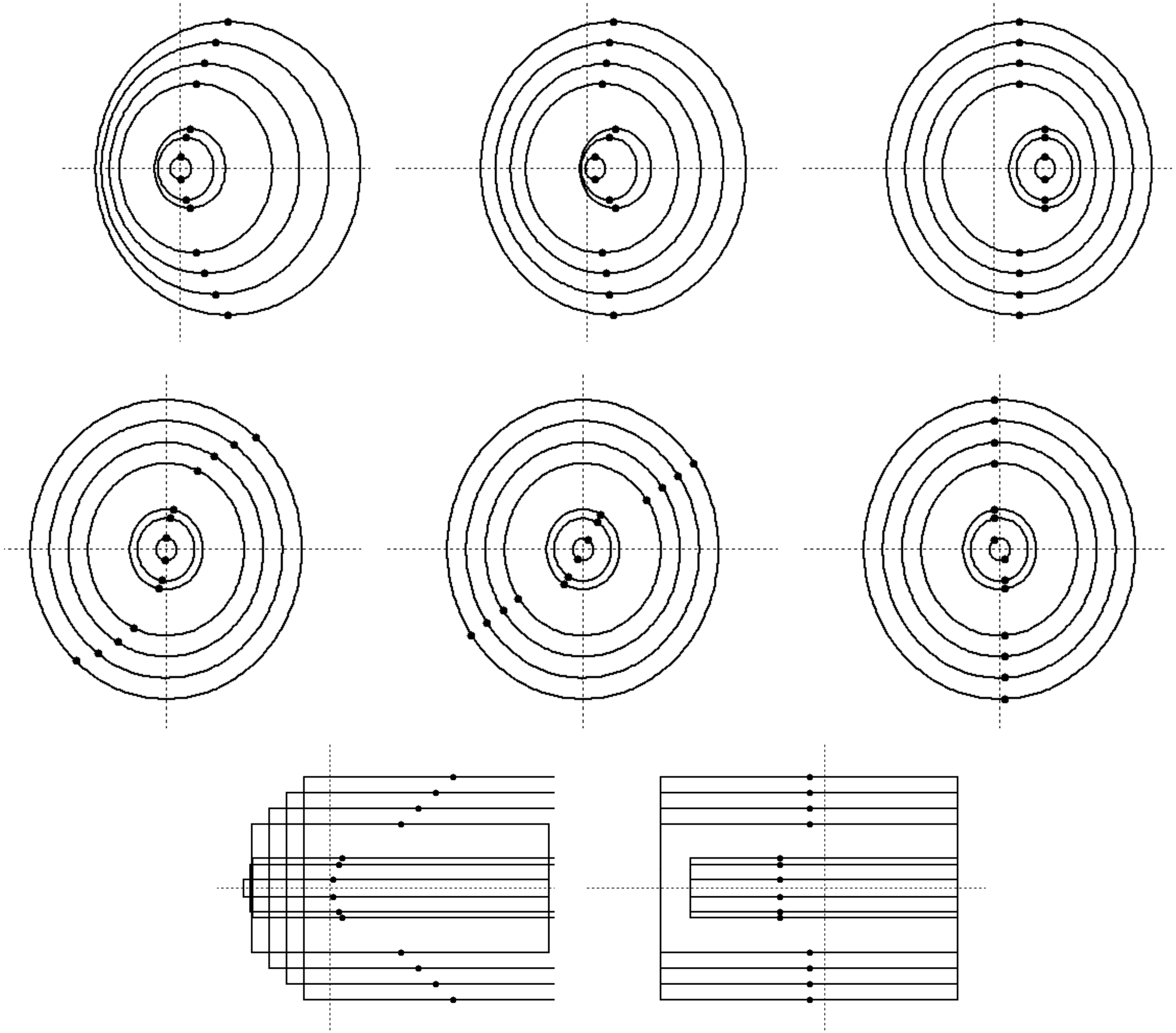
On-detector FSI System



Radial lines not shown

Distance measurements between grid nodes precise to <1 micron

Sagitta distortions



Bias on the transverse impact parameter