ATLAS Experiment Silicon Detector Alignment

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Inner Detector Collaboration

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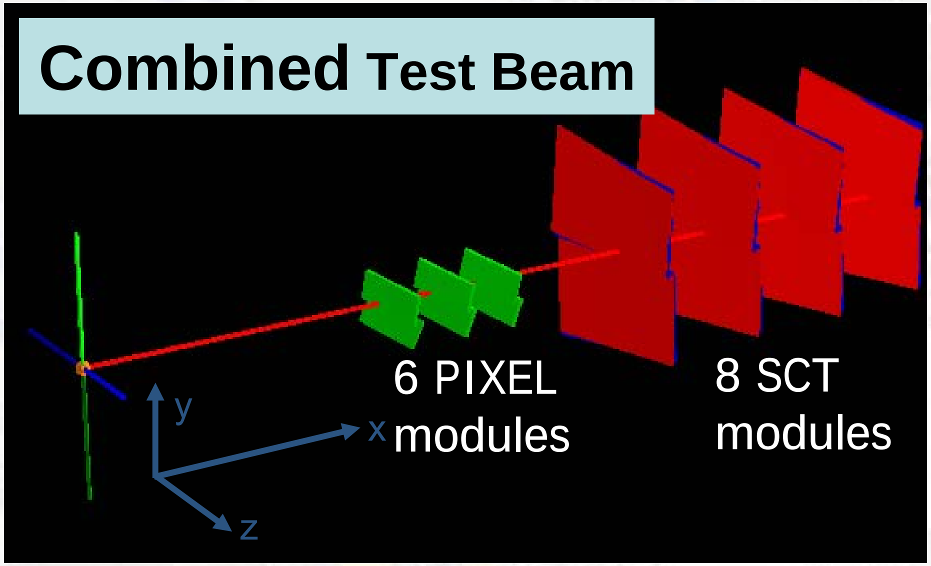
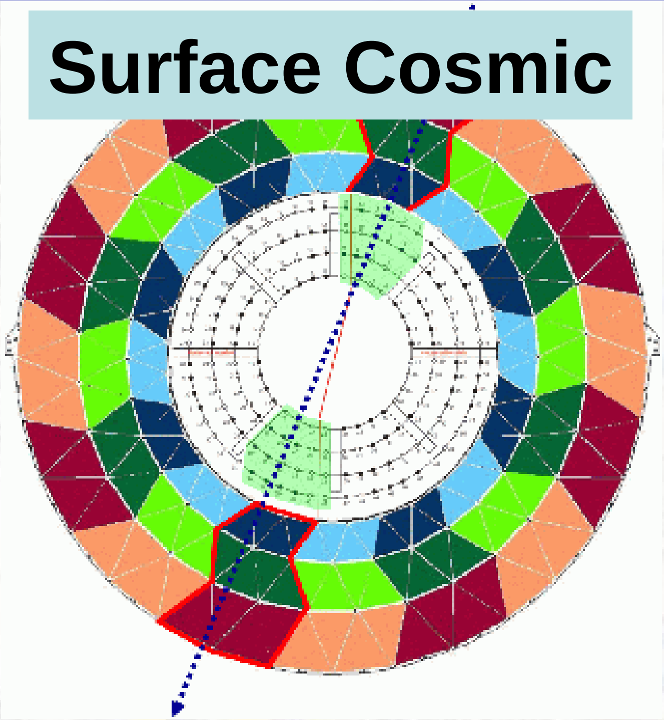
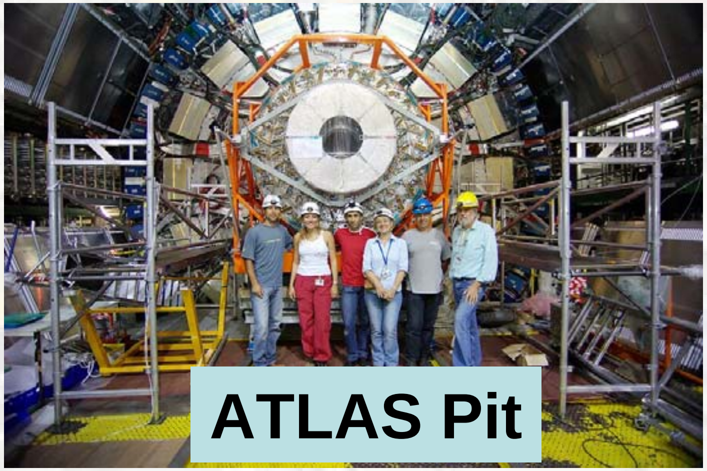
The Prelude

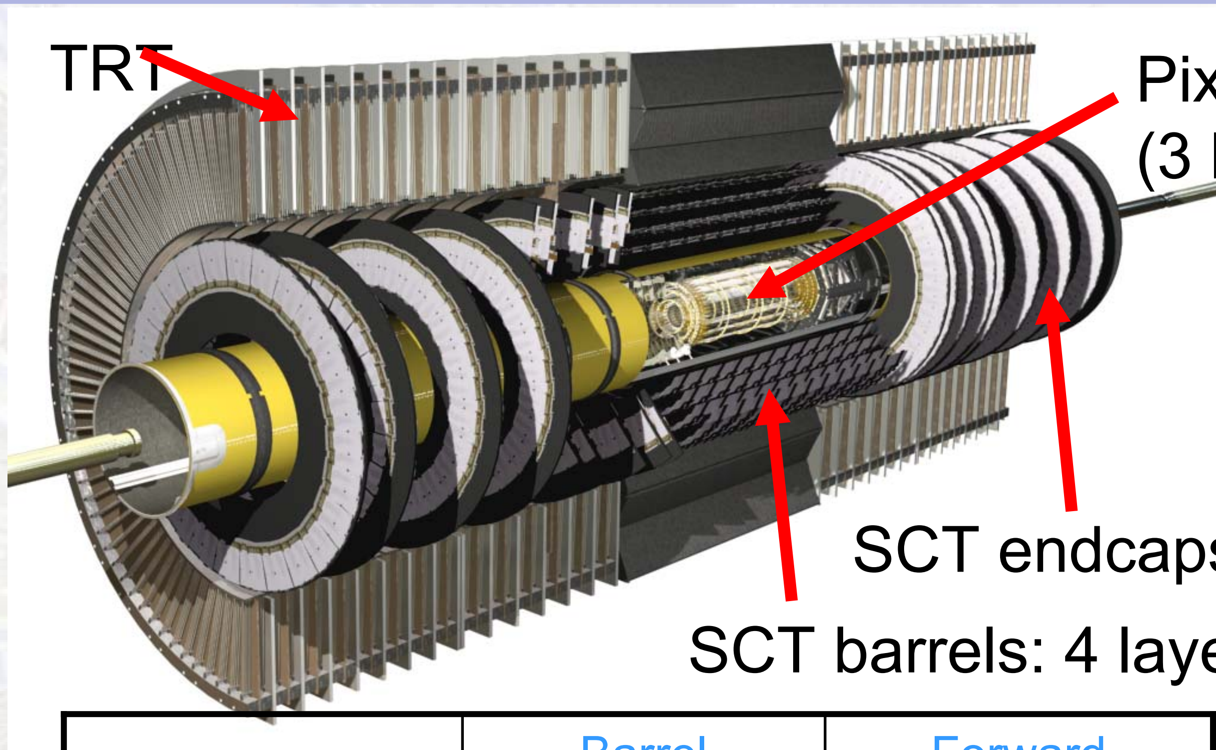




- All results are preliminary.
- There will be a bias will towards cosmic results and global χ^2 algorithm.
- For Silicon hardware, installation and performance, see talks by ***Sergio Gonzalez Sevilla***, ***Harald Fox***, ***Andreas Korn*** *and* ***Wolfgang Liebig***.

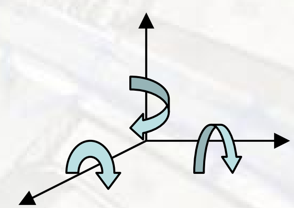


The Challenge: Atlas Silicon is BIG!



	Barrel		Forward	
Detector	PIX	SCT	PIX	SCT
# of layers/disks	3	4	2x3	2x9
# of modules	1456	2112	2x144	2x988
sub Total	3568		2264	
Total	5832			

6 DoF/module:
3 translations
& 3 rotations



In total we have to deal with **34,992** DoF's!

The Strategy: Various Approaches

Prerequisite: need to cope with demands of ATLAS physics requirements

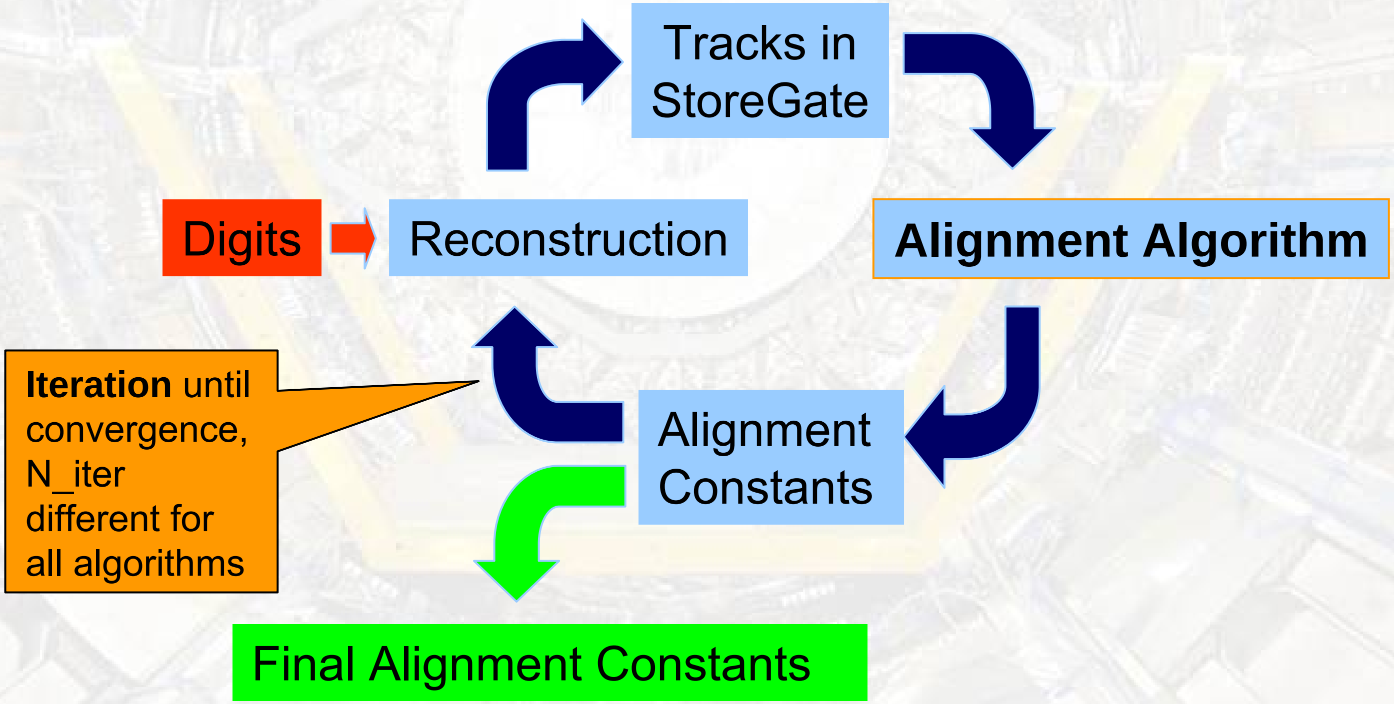
- Intrinsic alignment of Silicon
  - Offline (tracks), online (FrequencyScanningInterferometry), survey
- Si+TRT (helps sagitta, etc.)

Methods: all rely on track residual information

- Global χ^2:
  - minimization of χ^2 fit to track and alignment parameters
  - 6 DoF, correlations managed, small number of iterations
  - Inherent challenge of large matrix handling and solving
- Local χ^2 :
  - similar to global χ^2 , but inversion of 6x6 matrix/module
  - 6 DoF, no inter-module or MCS correlations (diagonal covariance matrix)
  - large number of iterations
- Robust Alignment:
  - use weighted residuals, z & rϕ overlap residuals of neighbouring modules
  - 2-3 DoF, many iterations, no minimization
- Valencia Alignment (used mainly for CTB):
  - Numerical χ^2 minimization
  - 6 DoF, many iterations

Algorithms' Functionalities

- All algorithms implemented within ATLAS framework and able to use common tools
- Functionalities to add constraints from physics & external data
  - survey constraints for global and local χ^2 algorithms implemented
  - vertex constraint for global χ^2 implemented, local χ^2 in progress
  - mass and online alignment constraints for global χ^2 algorithm tested standalone

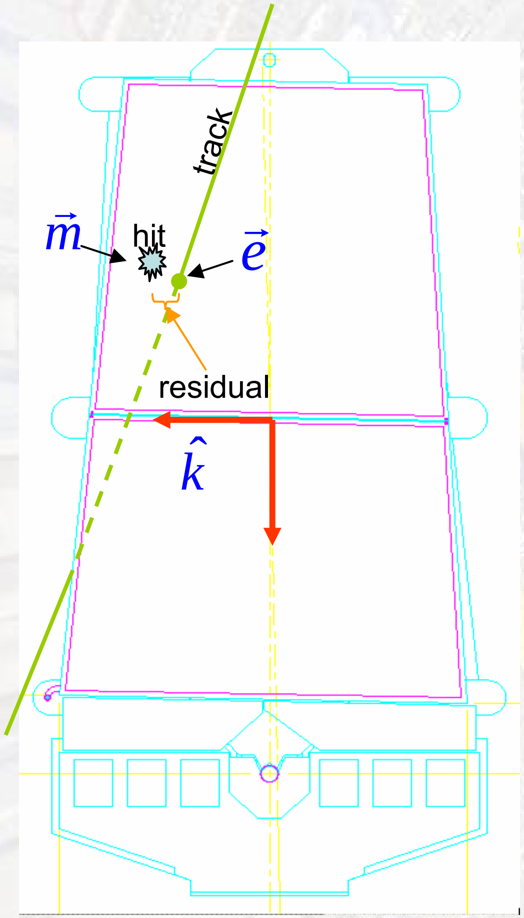


Global χ^2 Approach

Method consists of minimizing a 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



Use the linear expansion (assume all second order derivatives negligible). Track fit is solved by:

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

alignment parameters are given by:

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

Key relation!

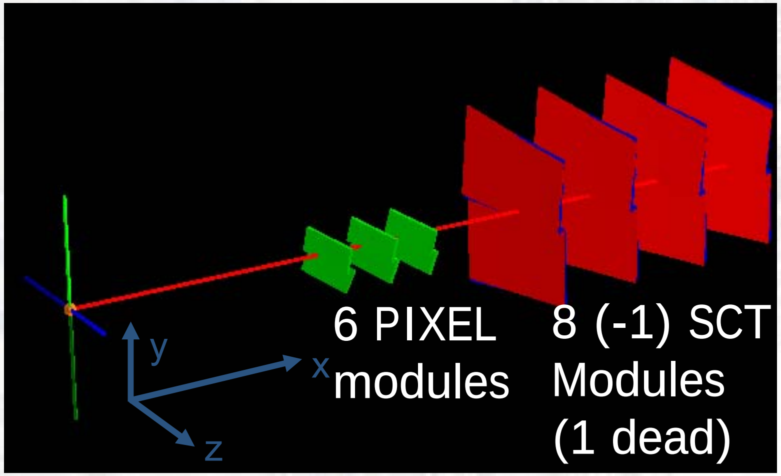
$$\frac{dr}{da} = \frac{\partial r}{\partial a} + \frac{\partial r}{\partial \pi}\frac{d\pi}{da}$$

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

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

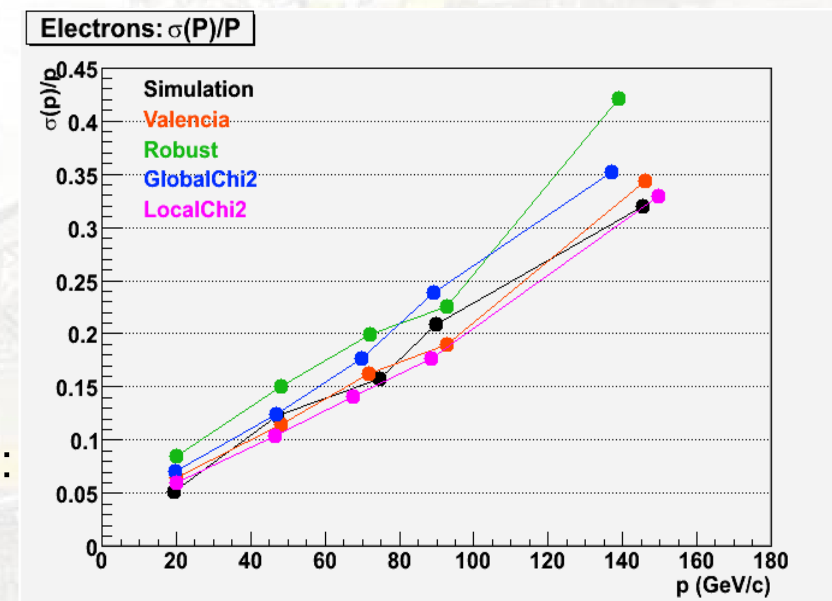
Equivalent to Millepede approach from V. Blobel

Combined Test Beam (2004)



- First real data from Inner Detector!
- Large statistics of e^+/e^- and π (2-180 GeV) ($O(10^5)$ tracks/module/E),
- Magnetic field on/off runs.
- Limited layout (systematic effects in modes)
- A good start to test algorithms for more realistic upcoming data!

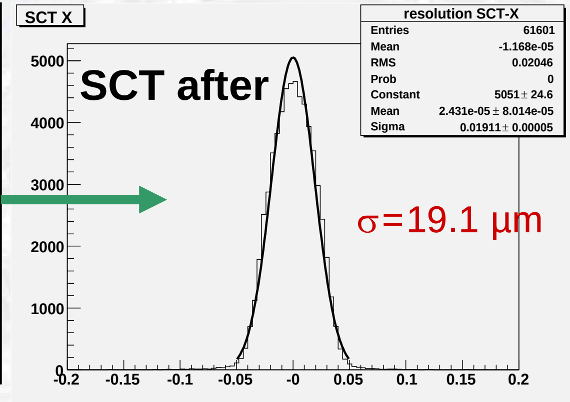
- Algorithms improve residuals and quality of track parameters.
- Algorithms use different approaches in extracting alignment constants: various DoF, (un/)biased residuals, ...
- Consistent results with slight differences (likely to be attributed to global Xformations).
- Ongoing efforts to combine/compare results: reached a level with CTB data sensitive to effects at a few microns!



CTB: Performances

Global χ^2 :

- 3DoF on detector plane (T_X,T_Y,R_Z)
- w/ and wo/ anchorage, fast convergence
- overall Pix residual sigma ~10.7μm, SCT ~ 19.1μm



Valencia χ^2 :

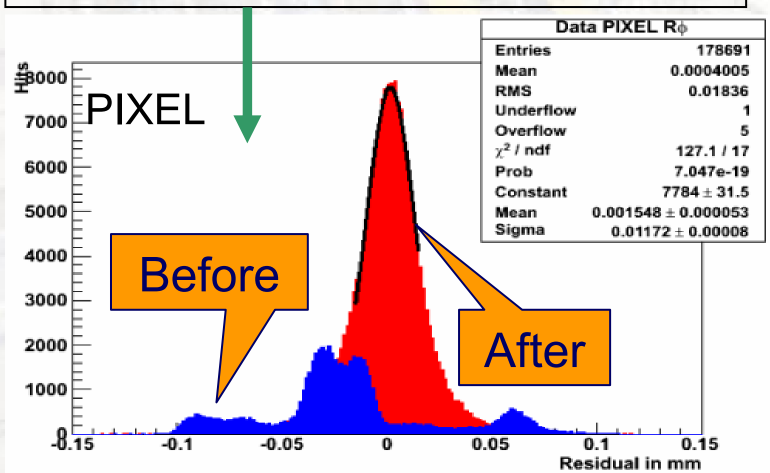
- align pixel first, then SCT, then all
- first pixel nearest beam as anchor
- many iterations

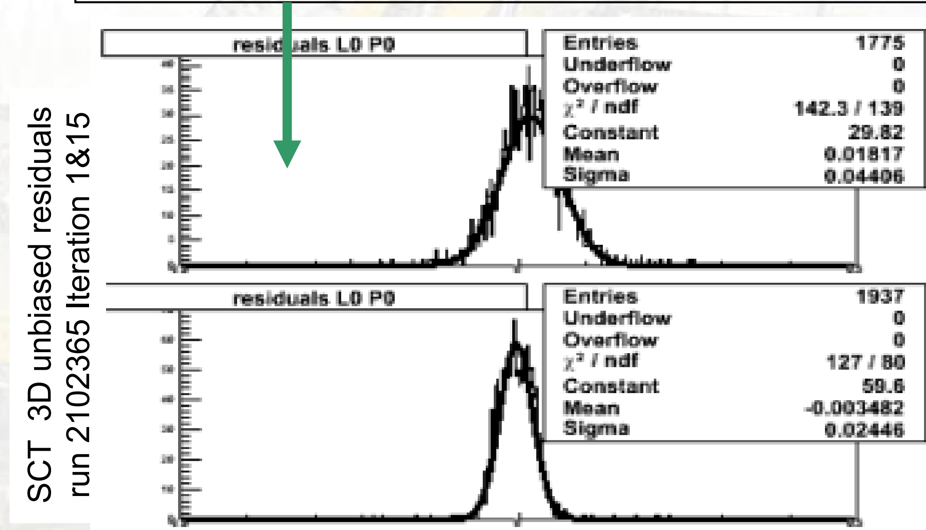
Robust:

- only detector plane alignment (X,Y)
- after alignment, pixel residual O(10μm), SCT residual O(20μm)

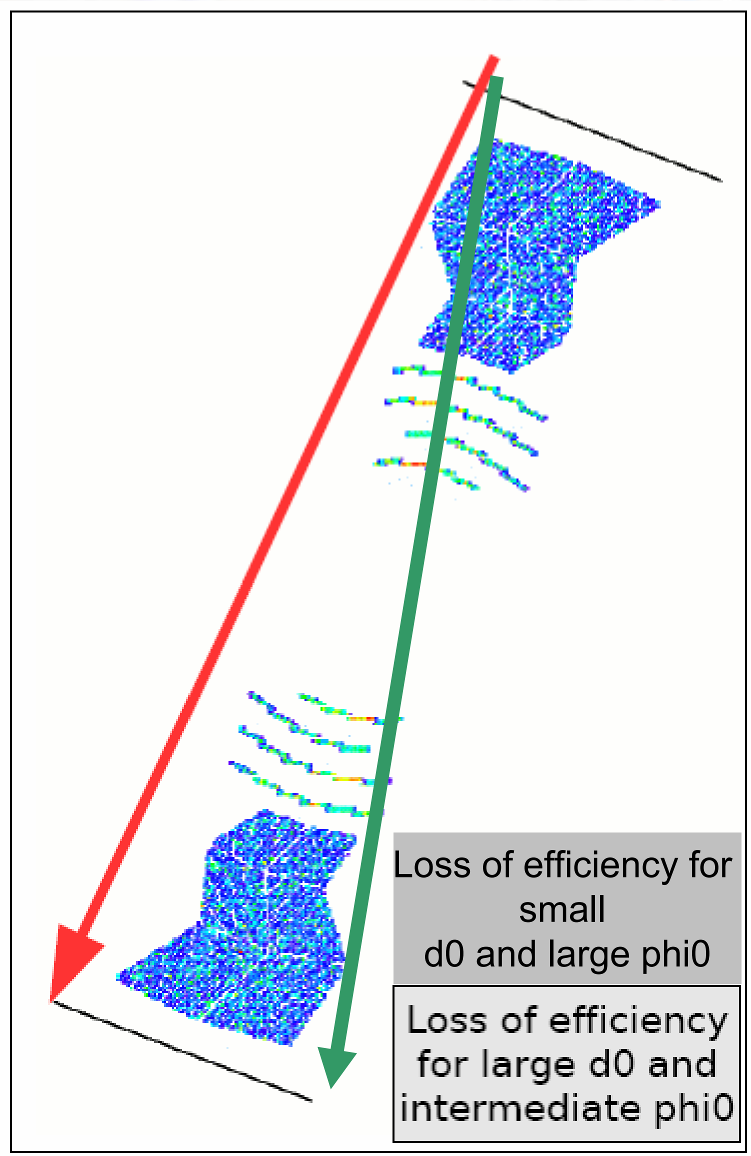
Local χ^2 :

- after alignment, pixel residual O(10μm), SCT residual O(25μm)

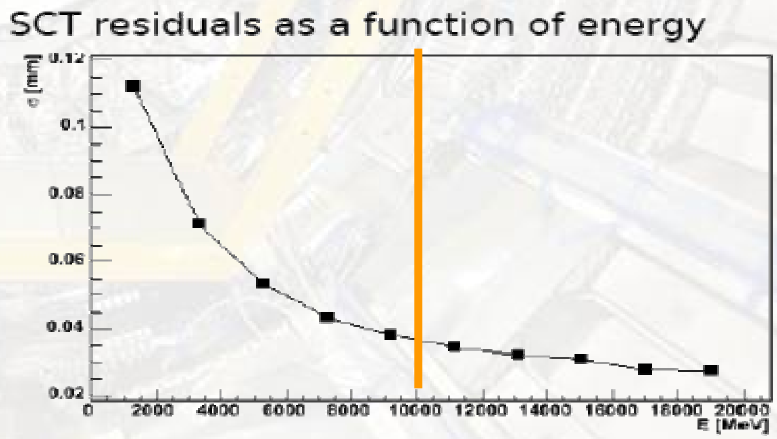




ID Cosmic Run (2006)



- Data-taking at surface (SR1) in spring 2006: ~400k events recorded!
- 22% of SCT Barrel: 467 instrumented modules
- 13% of TRT Barrel
- 3 (or 2) Scintillators to trigger 144cmx40cmx2.5cm
- Trigger allows ~ 0.3-0.4GeV cutoff for alignment studies
- No B-field! No momentum! MSC important ~<10 GeV, need to deal with large residuals



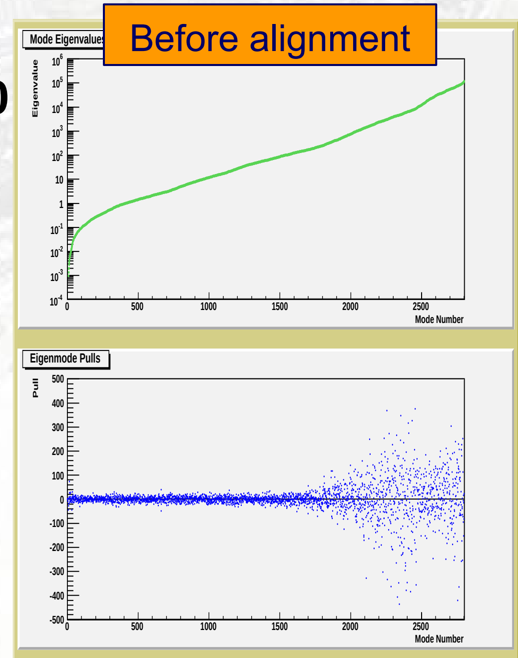
SR1 Cosmics: Global χ^2 - real data

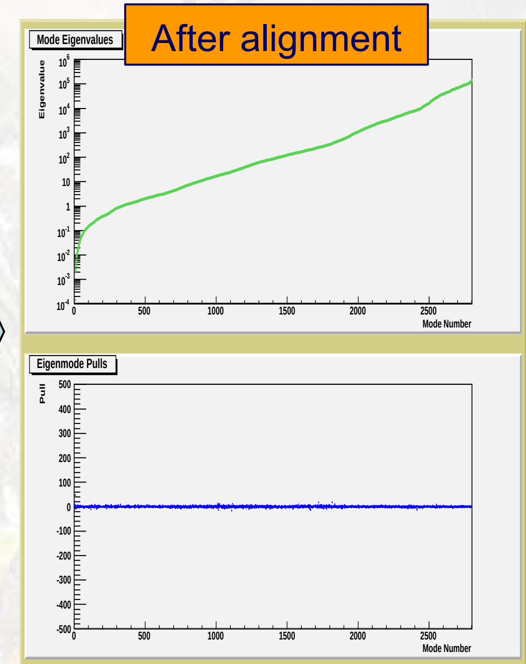
2808 DoF's, ~250k tracks

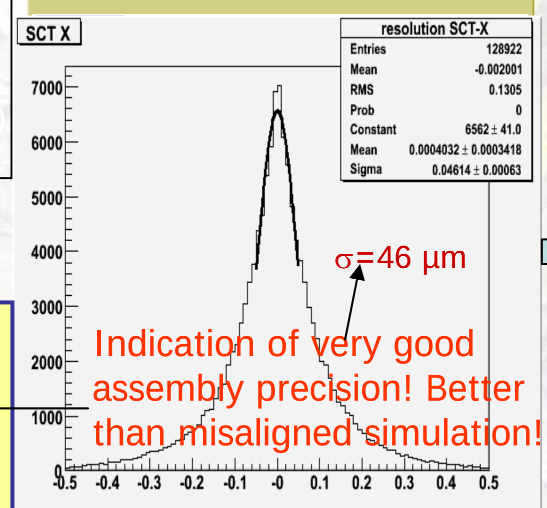
Corrections due to modes >1500

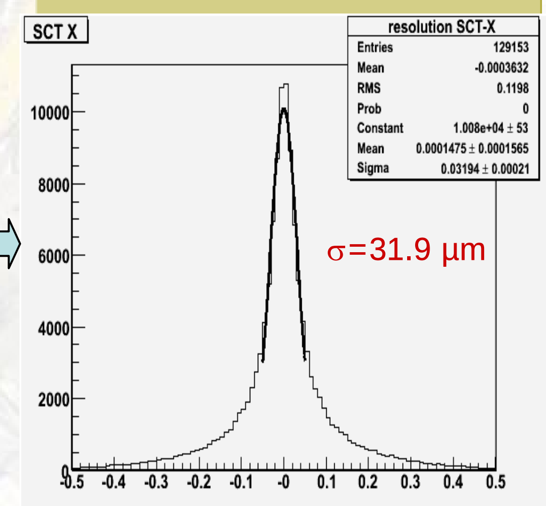
first iteration

Corrections x100







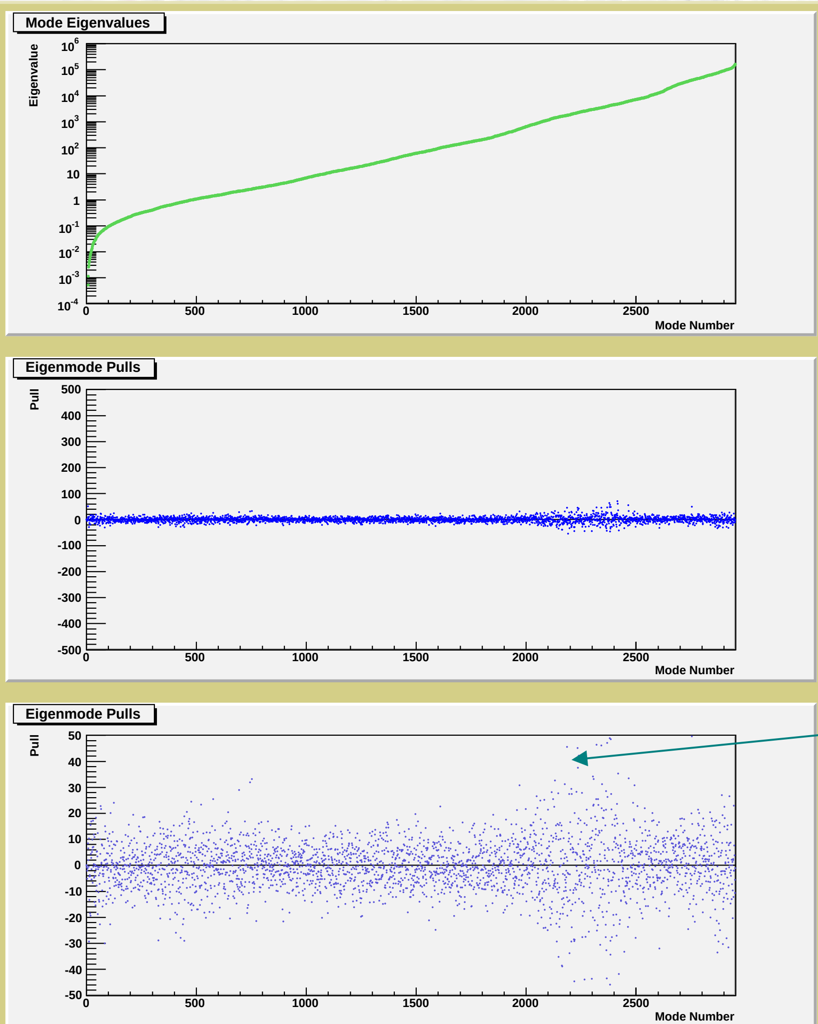


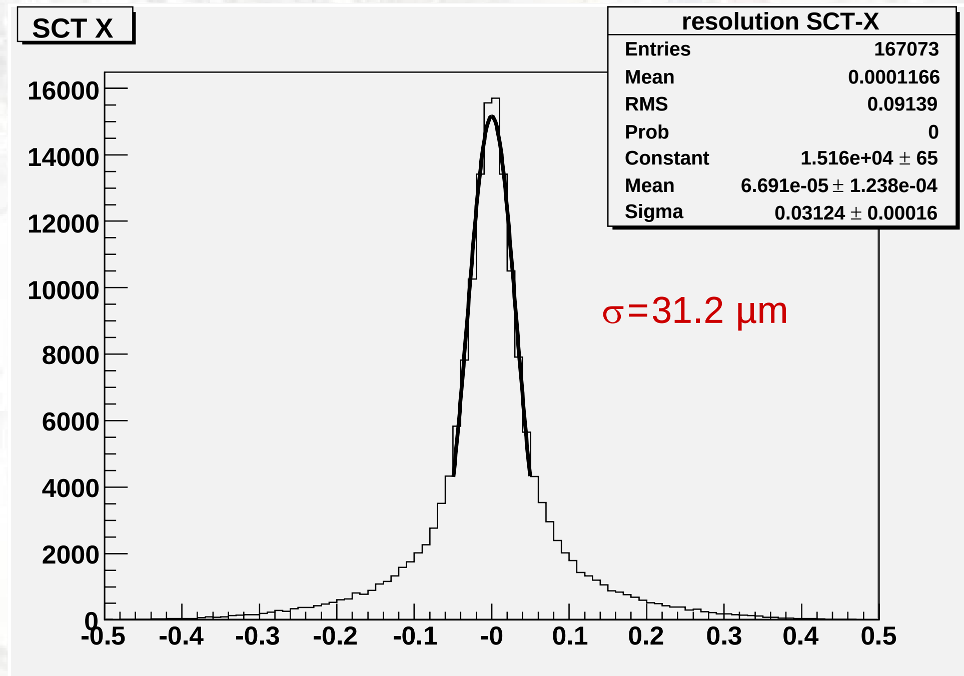
Alignment corrections for rigid barrels

	TX [mm]	TY [mm]	TZ [mm]	RX [mrad]	RY [mrad]	RZ [mrad]
Barrel3	-0.0044	-0.0162	-0.0169	0.0685	-0.0185	0.0503
Barrel4	0.0061	0.0329	-0.0462	-0.0678	0.0258	0.0527
Barrel5	0.0109	-0.0005	0.0865	0.0318	-0.0134	-0.0947
Barrel6	-0.0126	-0.0162	-0.0234	-0.0200	0.0073	-0.0083

SR1 Cosmics: Global χ^2 - simulated data

Perfectly aligned detector, but still minor bugs in detector descriptions





Traces of systematics???

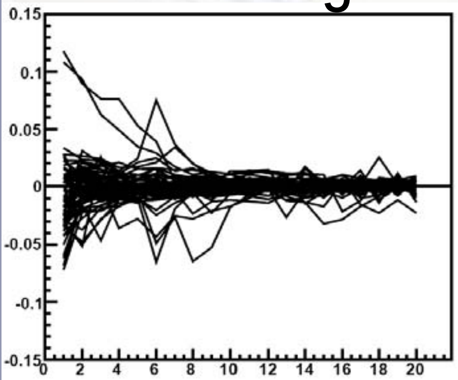
Caution:

Alignment is ultimately sensitive to own bugs and features but also to slightest upstream imperfections.

Sometimes hard to tell apart!

SR1 Cosmics: Local χ^2

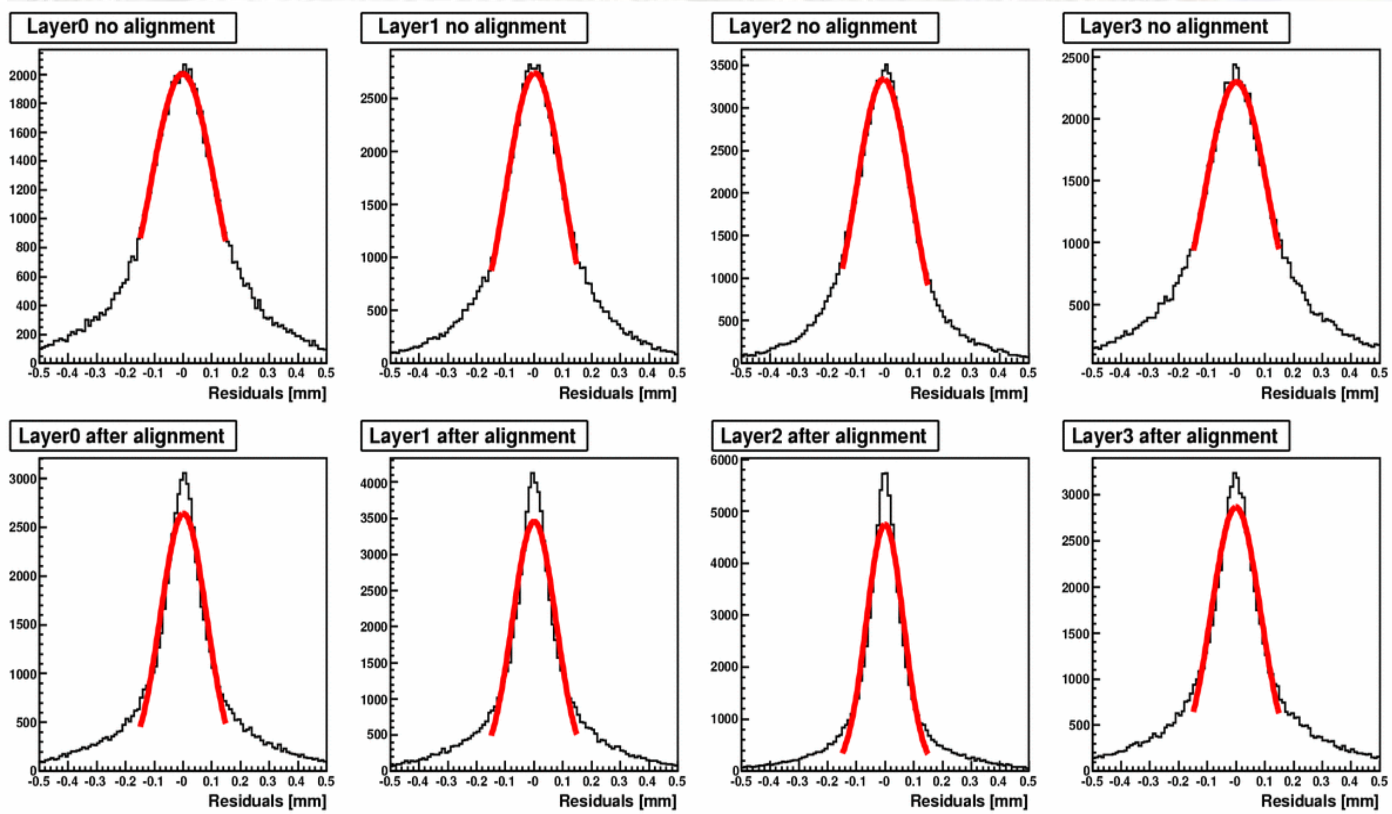
- Alignment of SCT barrel cosmic test setup with 36k tracks.



Flow of alignment parameter a_x for all modules of barrel layer 2 through iterations

BEFORE

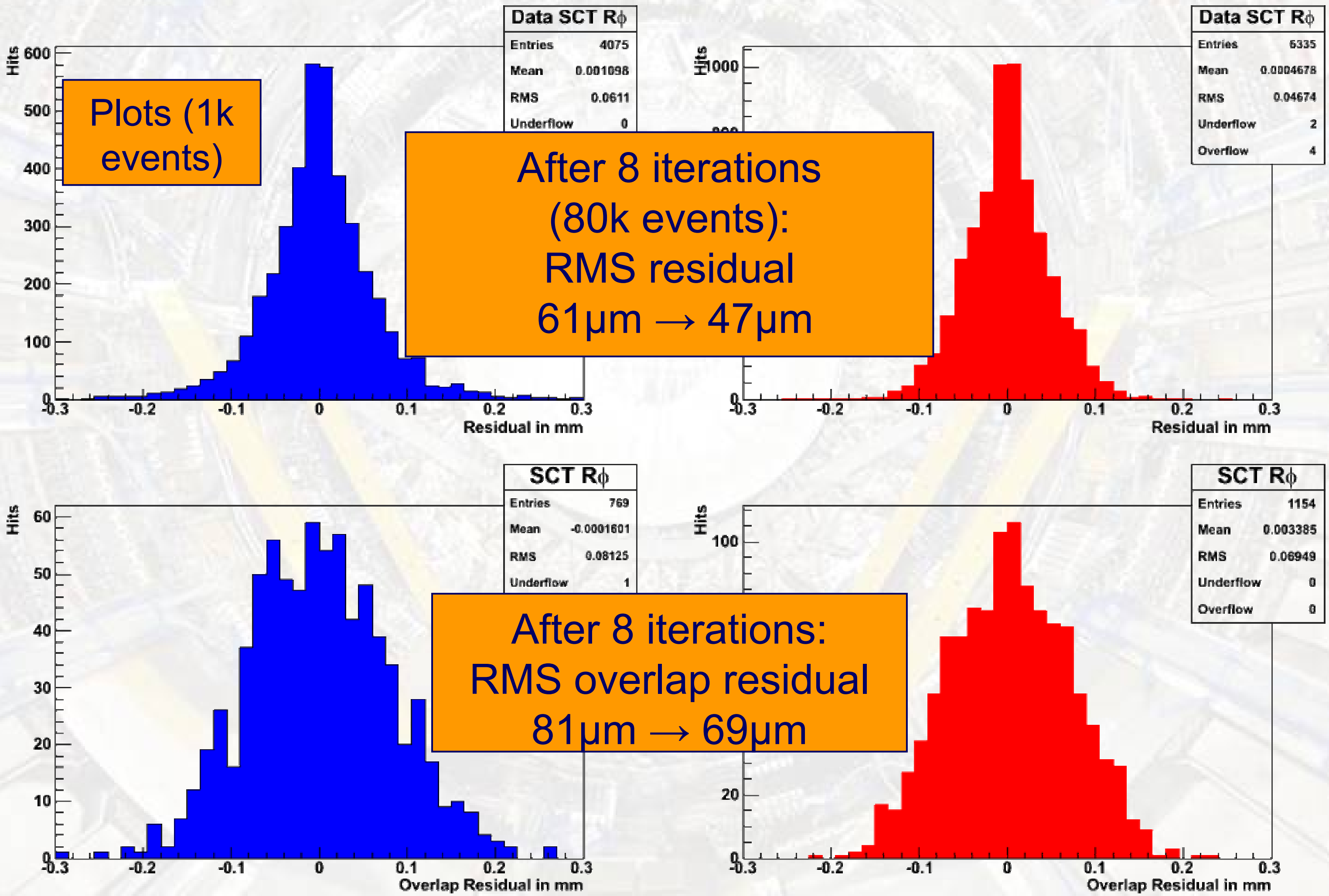
AFTER



unbiased: σ=113.8 -> 80.0 σ=99.5 -> 75.5 σ=96.1 -> 64.7 σ=111.2 -> 85.7

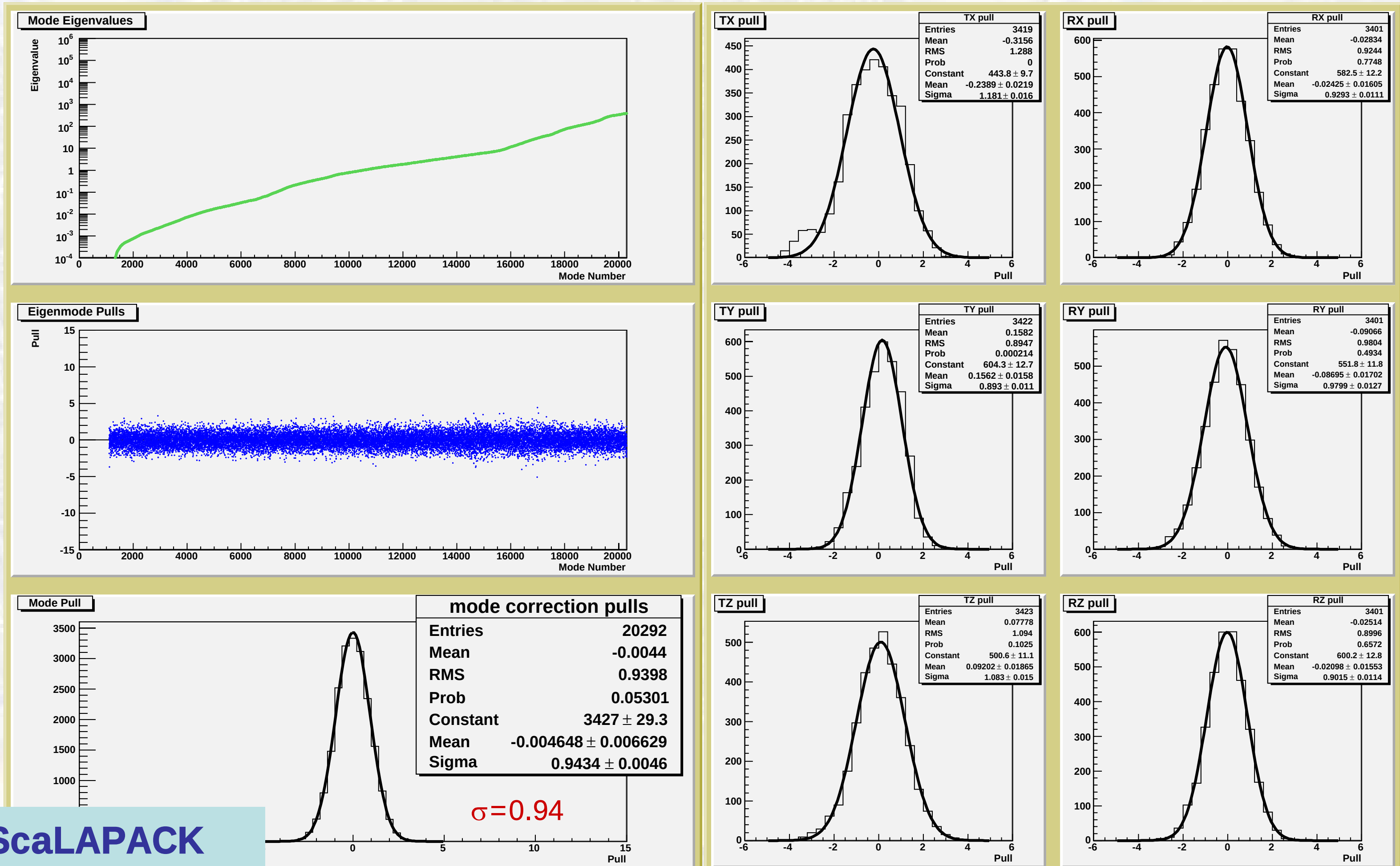
SR1 Cosmics: Robust Alignment

- Method works on the cosmic setup, ongoing studies with refitted tracks.



Nominal Detector Simulation: Global χ^2

- **Full barrel (21408 DoF's), ~800k muon tracks**



pdsyevd of **ScaLAPACK**
on a||-cluster AMD Opteron.
N=21k system diagonalised
in ~1h (16 CPU)!

Pulls in diagonal base

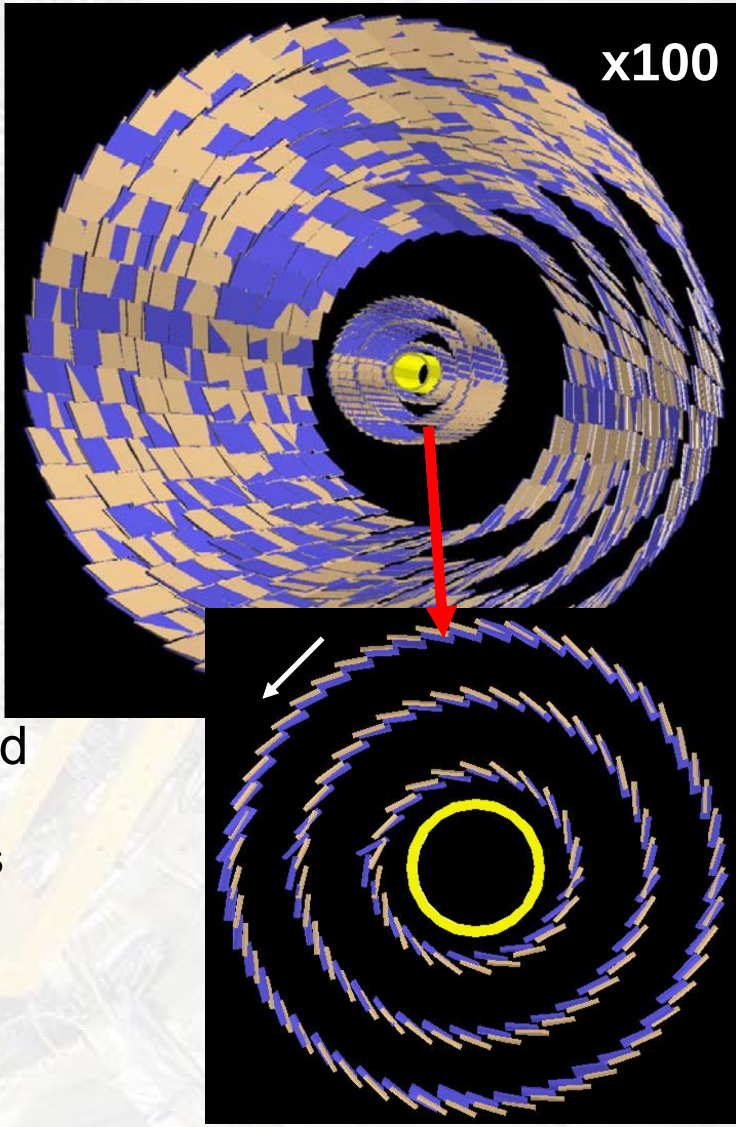
Pulls of alignment corrections

Correction pulls of ~unit width and centred at zero

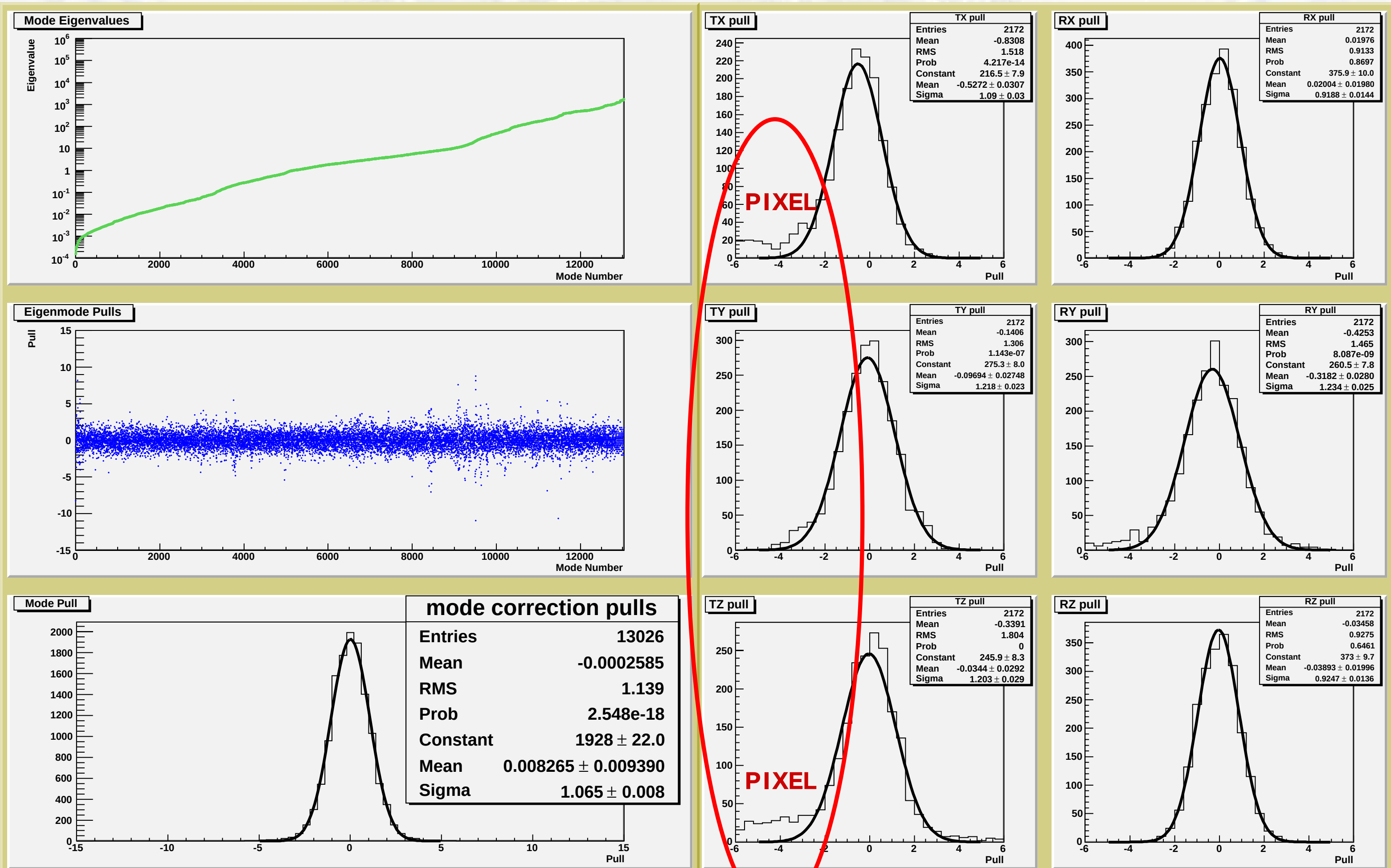
Nominal Detector Simulation: Global χ^2

- ~8M μ tracks in $|\eta|<2.7$) from ATLAS Computing Challenge sample. Largest sample looked at currently!
- Align 2172 barrel silicon modules in $|\eta|<1$ (13032 DoF)
- Solution using ScaLAPACK on an AMD Opteron ||-cluster (< ½ hour).
- Systematic effects in pixels - not visible in earlier studies:

  statistics washed out or something new?
- Disappear after cut on low freq. modes (global effect)
- Special misalignments can also be introduced in 3 levels:
  - modules, layers&disks, Silicon ID subsystems
  - Data analysis of this is ongoing..



Nominal Detector Simulation: Global χ^2



Pulls in diagonal base

Pulls of alignment corrections
Typical errors < 10µm

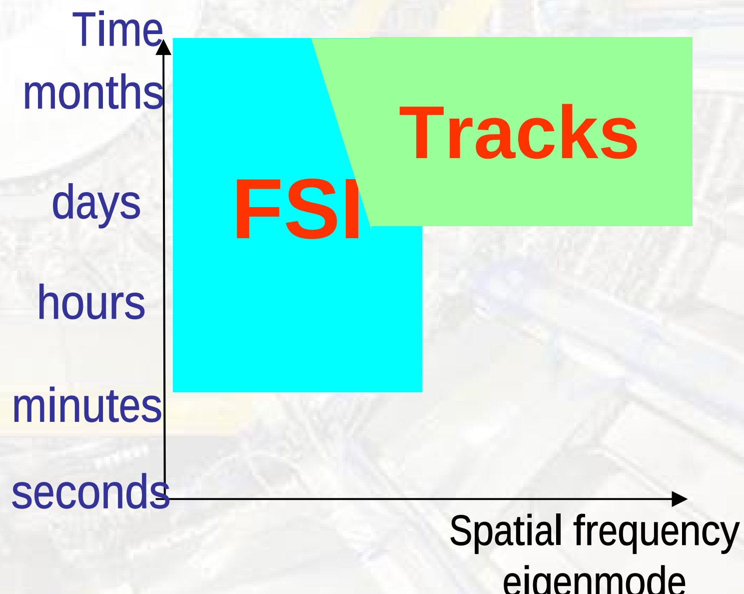
Including Online Alignment: FSI

- Frequency Scanning Interferometry: On-detector geodetic grid of 842 simultaneous length measurements (precision <1μm) between nodes on SCT support structure.
- Grid shape changes determined to < 10μm in 3D.
- Time + spatial frequency sensitivity of FSI complements track based alignment:
  - Track alignment average over ~24hrs+.
    high spatial frequency eigenmodes, “long” timescales.
  - FSI timescale (~10mins)
    low spatial frequency distortion eigenmodes.
- First principles studied, implementation work to be performed!

Barrel SCT

80+(3x[80+16])+(2x72)=512

End-cap SCT 165x2=330



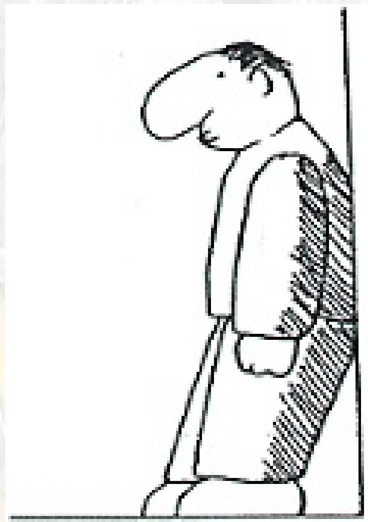
Summary & Conclusions

- Various algorithms are adapted to optimally align ATLAS ID.
- Algorithms have proved proof of principles.
- Codes are being continuously improved and heavily tested.
- We have been looking at real data already!
- SR1 data taking showed SCT barrel to be built very well!
- CTB efforts are almost finalized.
- Cosmic alignment progressing rapidly.
- On our way to understand and tackle many systematic issues, both in real data and simulation, upstream and downstream of alignment algorithms…
- Pixels and endcaps are getting ready for cosmics.
- FSI is getting ready for monitoring during pixel insertion in pit.

Stay Tuned!

We are…

- The Silicon alignment team
  - Pawel Bruckman, Stephen Gibson, Tobias Golling, Carlos Escobar, Richard Hawkings, Roland Heartel, Florian Heinemann, Adlene Hicheur (ex), MKU, Stefan Kluth, Salva Marti Garcia, Carmen Garcia, Bjarte Mohn, Ola K. Oye, Sergio Gonzalez Sevilla, Jochen Schiek.
- And
  - The hardware and DAQ teams of all setups
  - Reconstruction groups
  - CERN crew for installation and survey data
- More information:
  - *https://uimon.cern.ch/twiki/bin/view/Atlas/InDetAlignment*



BACKUP

Si modules

CTB+SR1 Details

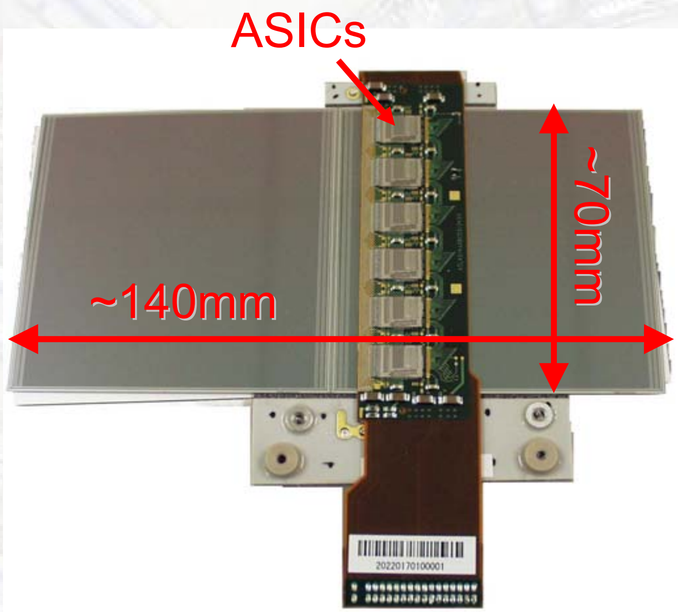
Global chi2 details

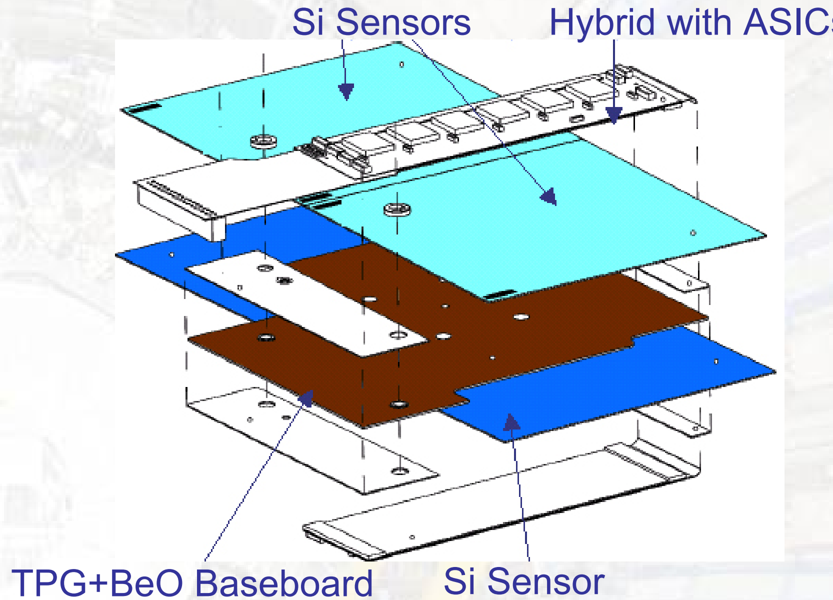
Robust align. details

FSI Details

Survey Data

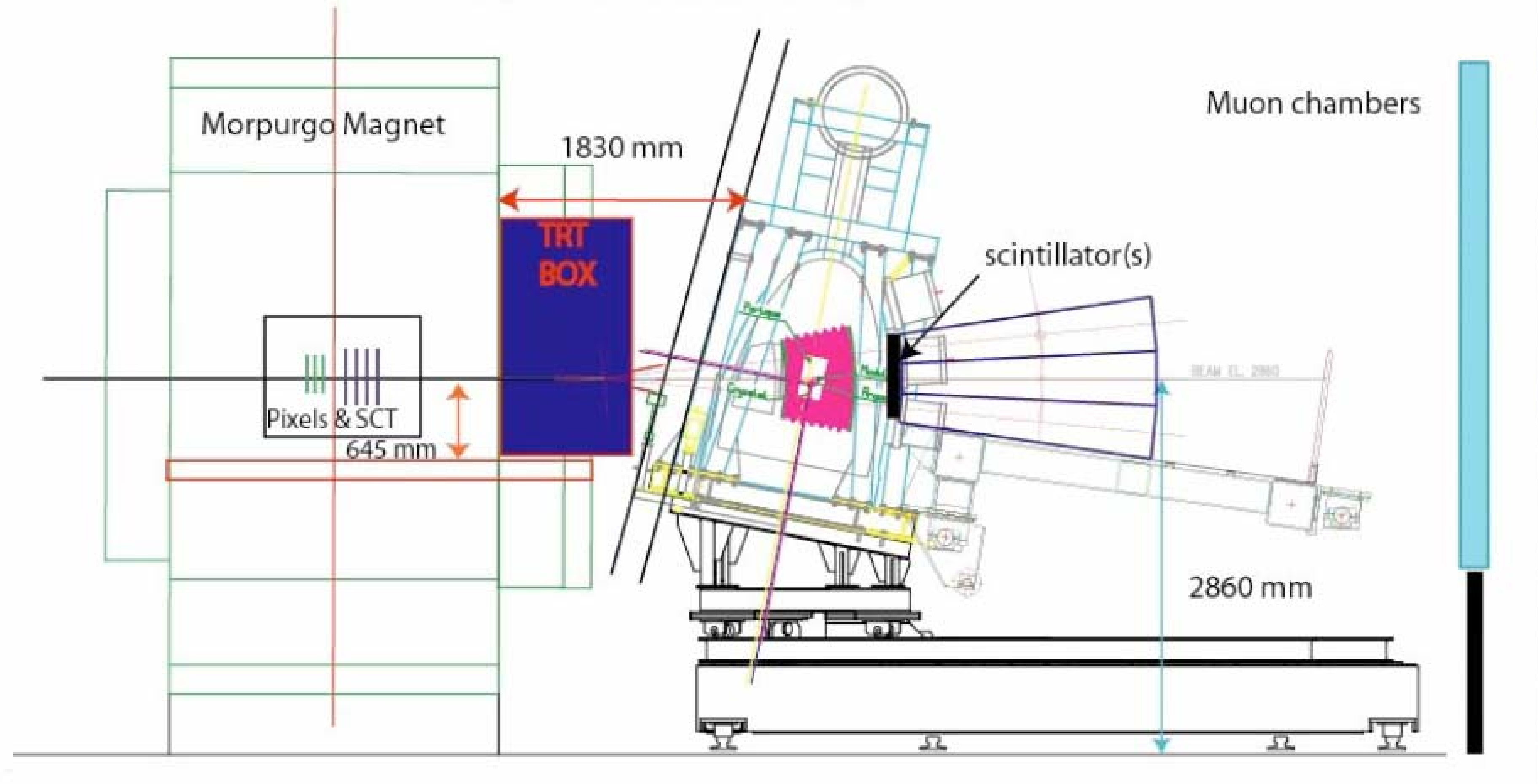
Building blocks of SCT



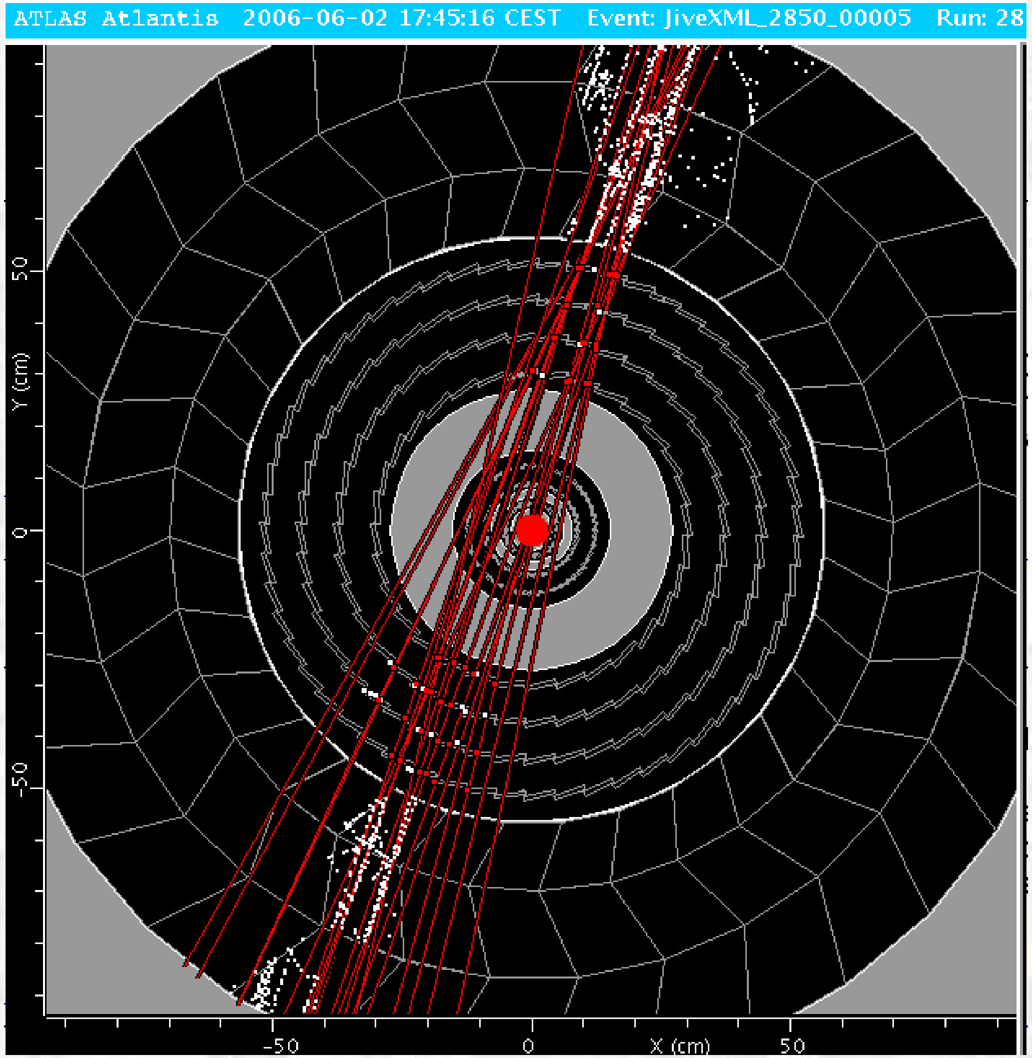


- **PIXel detectors provide real 2-D readout**
  - **size 50×400 μm resulting in 14×115 μm resolution.**
- **SCT modules are double-sided strip detectors with 1-D RO/side (768 instrumented strips).**
  - **Sensitive strips have pitch of 80 μm giving 23 μm resolution.**
  - **Stereo-angle of 40 mrad gives 580 μm resolution in rz direction.**
- **Si tracker chips do binary RO.**
- **SCT end-cap modules are different in shape: wedged structure**

CTB Setup


Morpurgo Magnet
1830 mm
TRT
BOX
Pixels & SCT
645 mm
scintillator(s)
Muon chambers
2860 mm

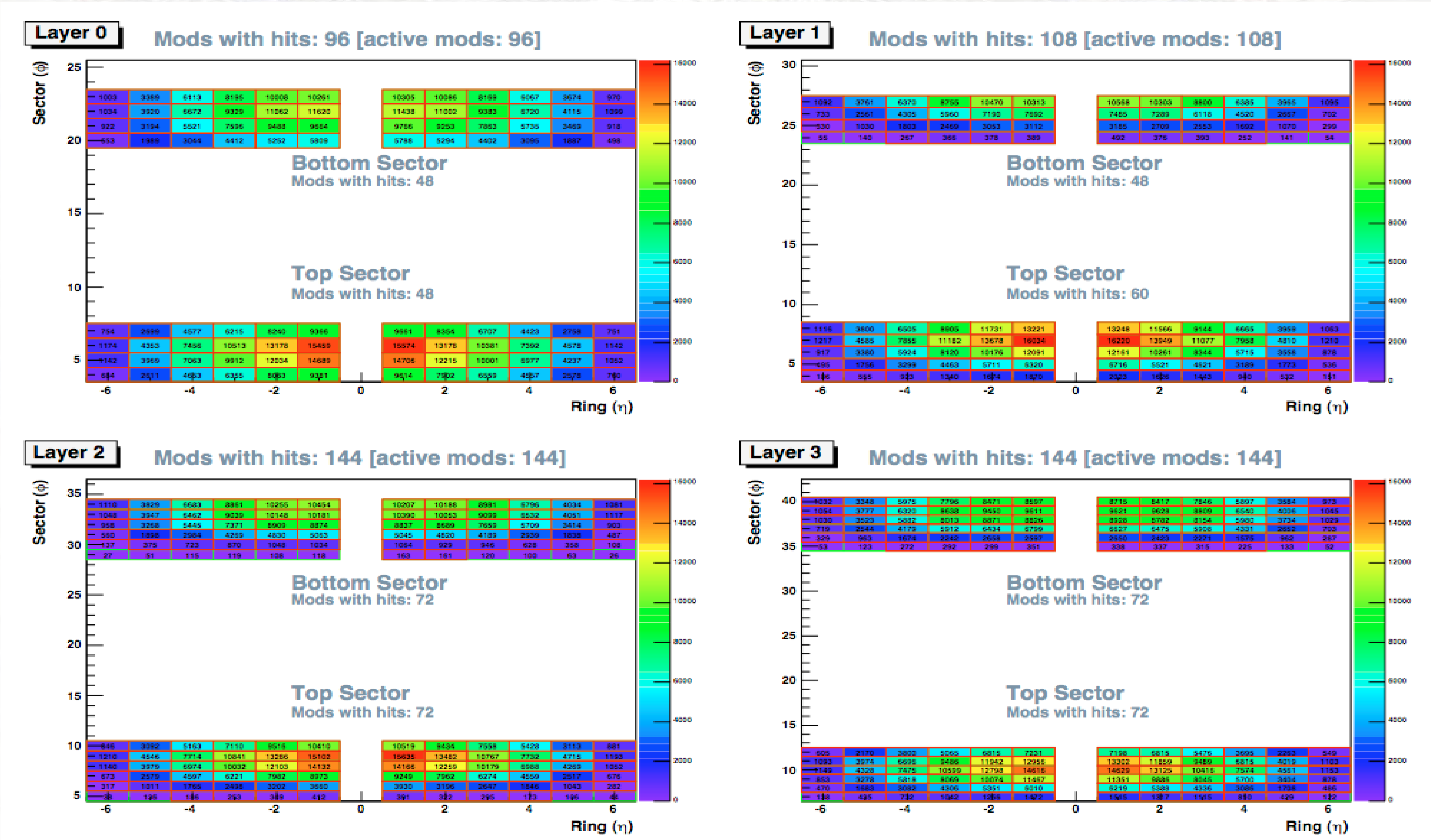
SR1 Cosmics: Readout



- SCT inserted into the TRT on17/02/2006
- Physics mode data coming in end of april until june 2006.
- SCT read 3 time bins (75nsec) and accept any hit in these three time bins
- TRT: read every 3.125nsec and 24 time bins (75 nsec).
- Trigger time res ~0.5ns

SR1 Cosmics : Hitmap

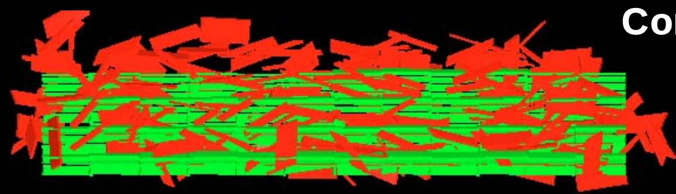
From simulation



SR1 Cosmics: Global χ^2 - real data

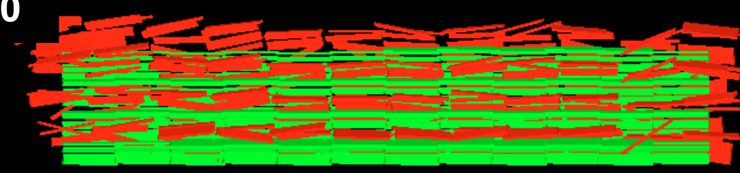
systematic effects visible when only 6 modes removed

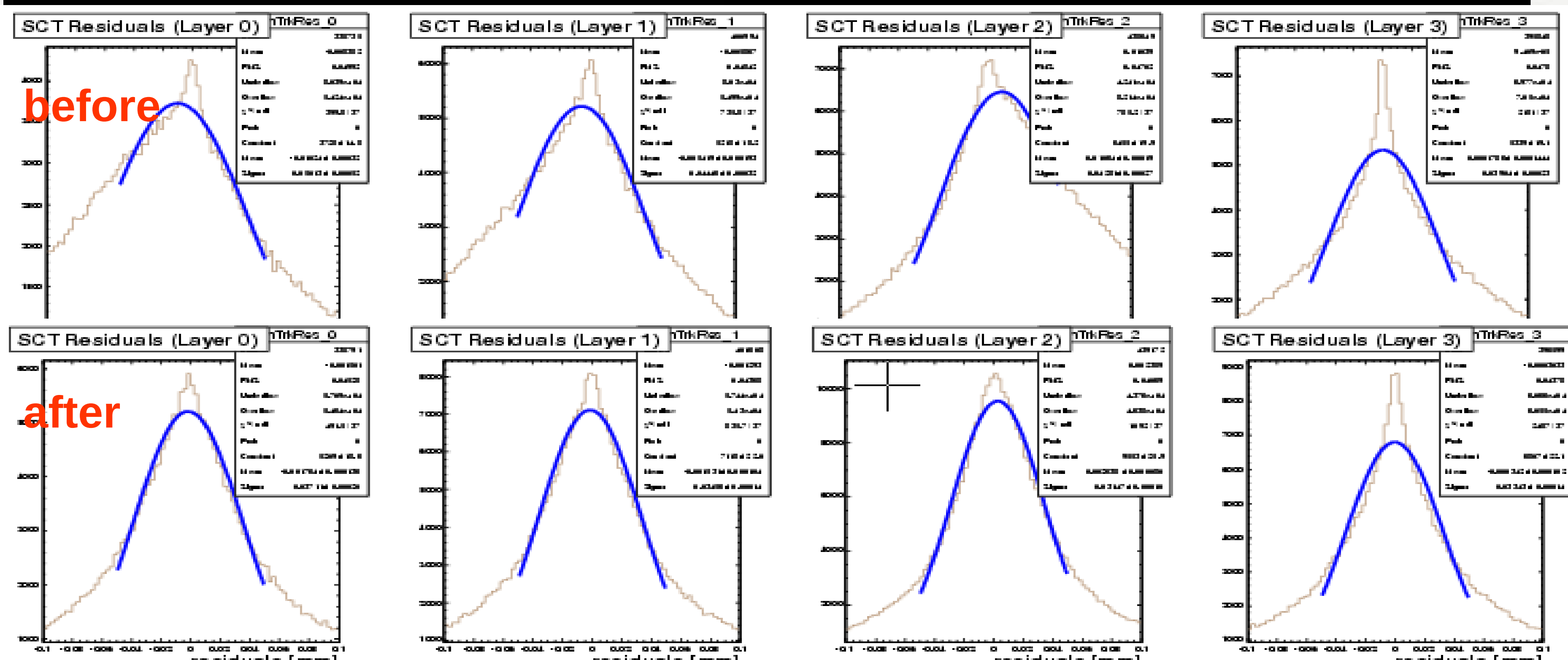
First iteration



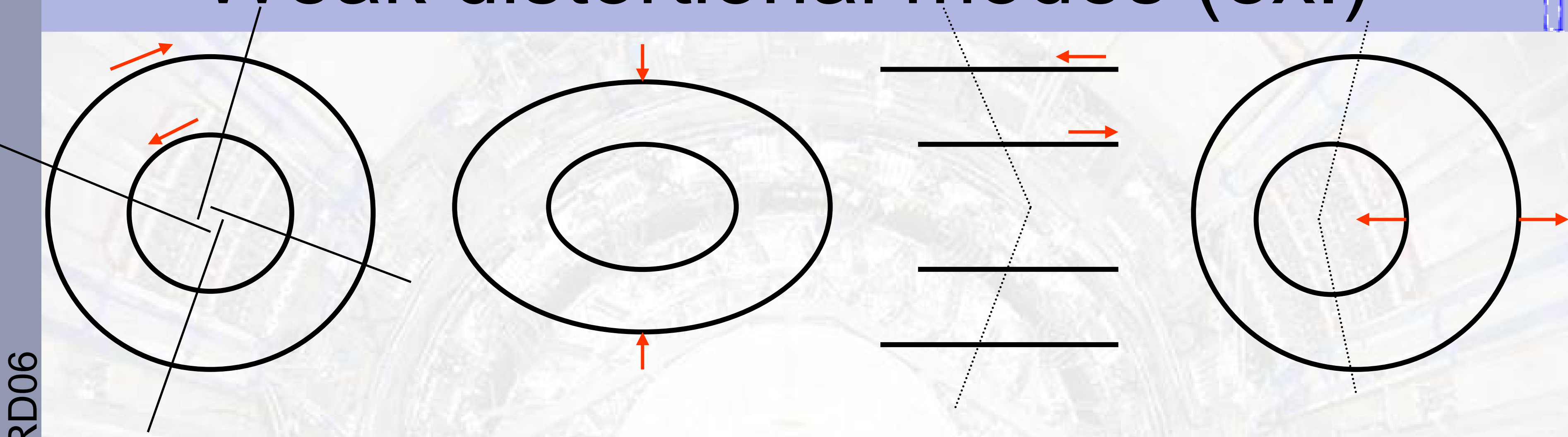
Correction x100

Third iteration (not final)





Weak distortional modes (ex.)



"clocking"
$\delta\phi = \lambda + \beta / R$
(VTX constraint)

radial distortions
(various)

"telescope"
$\delta z \sim R$

ϕ dependent sagitta
$\delta X = a + bR + cR^2$

We need extra handles in order to tackle these. Candidates:

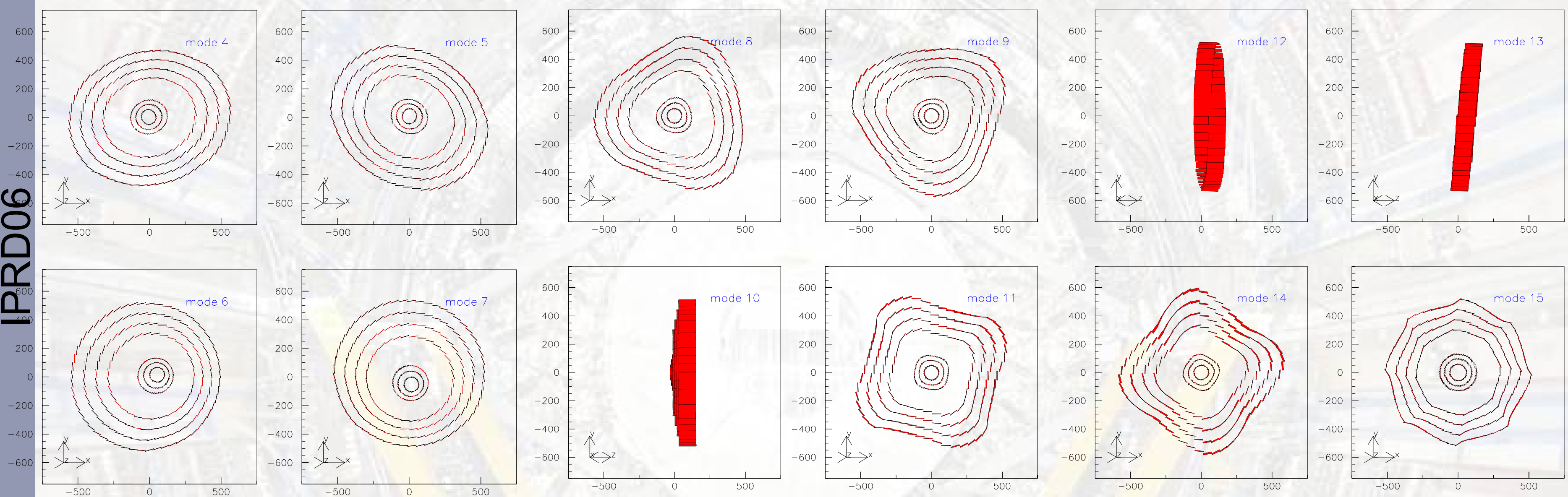
- Requirement of a common vertex for a group of tracks (VTX constraint),
- Constraints on track parameters or vertex position (external tracking (TRT, Muons?), calorimetery, resonant mass, etc.)
- Cosmic events,
- External constraints on alignment parameters (hardware systems, mechanical constraints, etc).

η dependent sagitta
"Global twist"
$\delta\phi = \kappa R \cot(\theta)$

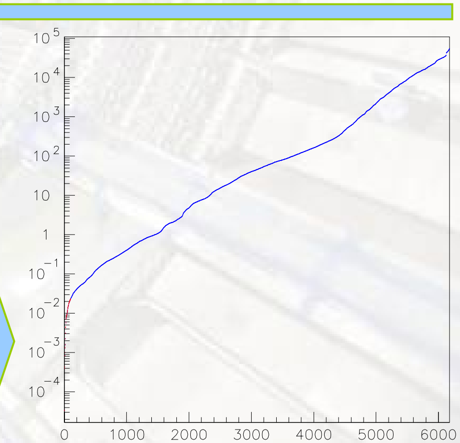
Global chi2: more on modes

Example "lowest modes" in PIX+SCT

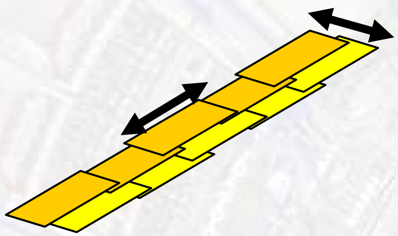
Global Freedom have been ignored (only one Z slice shown)



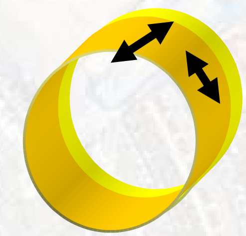
- The above "weak modes" contribute to the lowest part of the eigen-spectrum. Consequently they dominate the overall error on the alignment parameters.
- More importantly, these deformations lead directly to biases on physics (systematic effects).



Robust Alignment: Constants



Sum over neighbours, take correlations into account

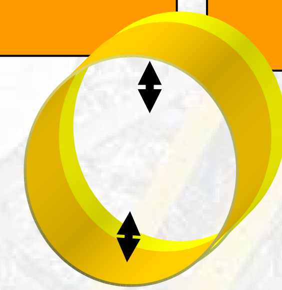


$$a = -\frac{\sum a_i/\sigma_i^2}{\sum 1/\sigma_i^2}, \quad \mathrm{a = x, y; i = mean\ residual, mean\ Z\ overlap\ residual, mean\ R}\varphi\ \mathrm{overlap\ residual}$$

Sum over all modules in a ring

Correct for change in radius

$$z = -\frac{\sum \mathrm{mean\ R}\varphi\ \mathrm{overlap\ residual}}{2\pi}$$



For a perfect detector:

$$\mathrm{Shift} \sim \frac{1}{\sqrt{\sum 1/\sigma_i^2}} \sim \frac{20\mu\mathrm{m\ (high\ energy)\ or\ 100}\mu\mathrm{m\ (cosmics)}}{\sqrt{\mathrm{Hits/module}}}$$

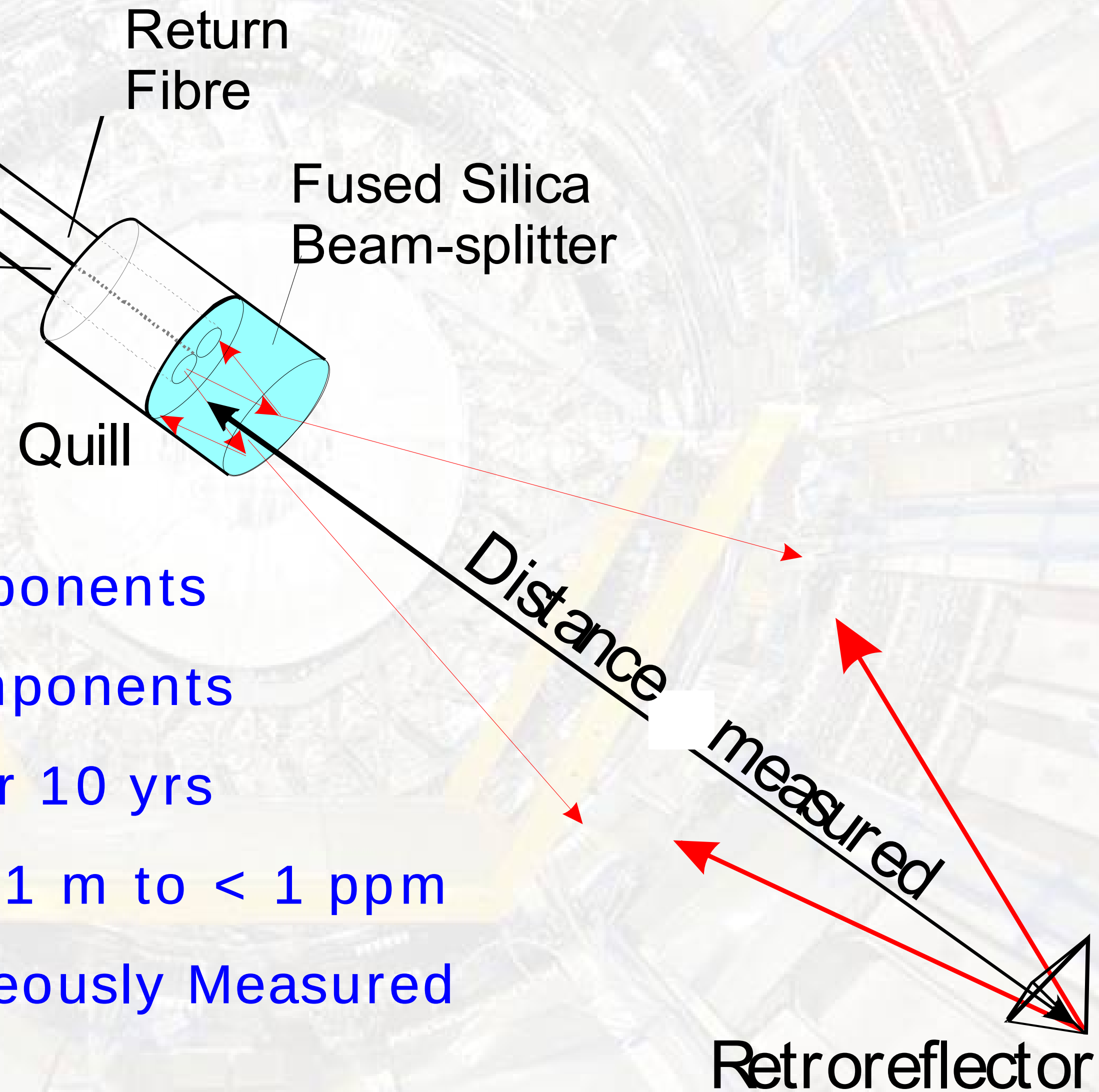
Solving the Full System

- Global χ^2 formalism requires solving and handling large-size matrices.
- Limiting factors:
  - **Size:** Solving full ID needs 9.8GB. By default, Atlas software infrastructure allows only 2GB of memory/job on 32-bit machines.
  - **Precision:** Conventional 32-bit libraries not fully adequate for full size solution. Alignment matrices can have large condition numbers (compete with machine precision).
  - **Execution time:** Single-CPU machines with unoptimized libraries can take hours to solve large-size problems.
- Currently using 64-bit //-computing: a huge improvement!
  - Solving full pixel (2112 modules, 12.5k DoF) on 16 nodes takes 10mins compared with 7hrs on Intel P4
  - And solving full system was not even possible until last year!
- Work ongoing on other methods for further improvement:
  - Various investigations on iterative methods
  - Plan to implement one such method (MA27) in athena
  - Plan to port code on 64-bit to do processing+solving all at once.

Online Alignment: FSI

ATLAS FSI System

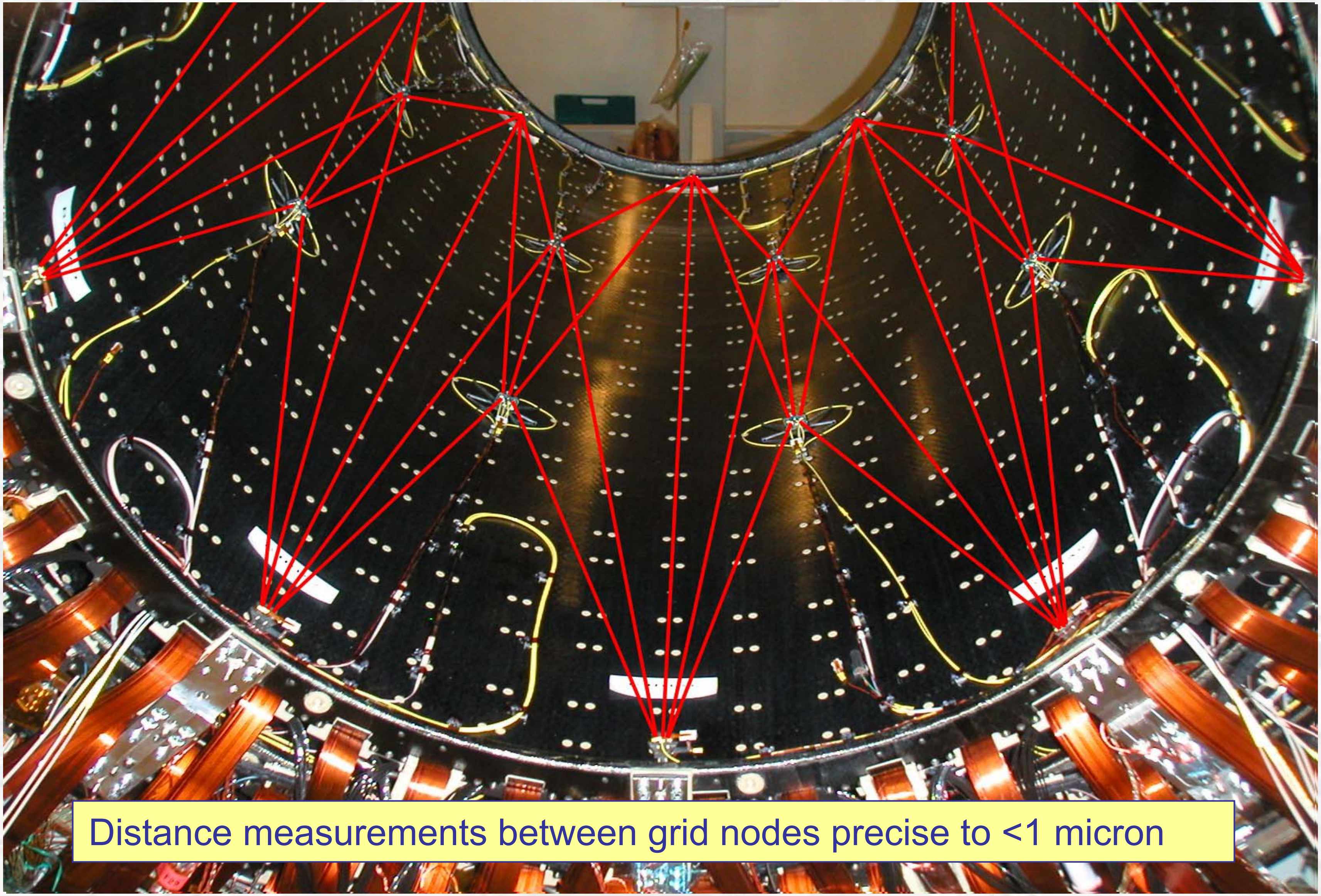
Grid Line Interferometer Design



Design Requirements

- Minimal mass components
- Radiation hard components
- No maintenance for 10 yrs
- Remotely Measure 1 m to < 1 ppm
- 800 GLIs Simultaneously Measured

On-detector FSI System



Distance measurements between grid nodes precise to <1 micron

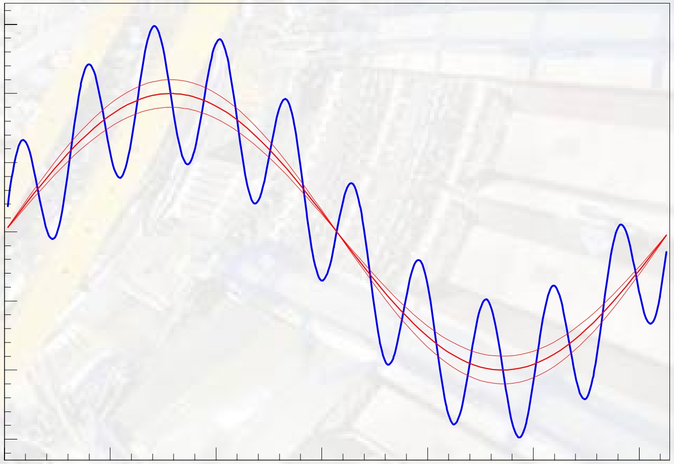
FSI + Track Alignment

- How to include time dependency?
  1. FSI provides low spatial frequency module corrections at time t_i , $t_0<t_i<t_1$
  2. Track recorded at time t_i is reconstructed using FSI module correction at time t_i .
  3. Global (or robust) Chi sq uses FSI corrected tracks to construct chi sq and minimises to solve for high spatial frequency modes, averaged over $t_0<t_i<t_1$, low frequency modes frozen.
  4. Subsequent reconstruction of track at time t_j uses average alignment from global (or robust) chi sq + time dependent FSI module correction, t_j, $t_0<t_j<t_1$

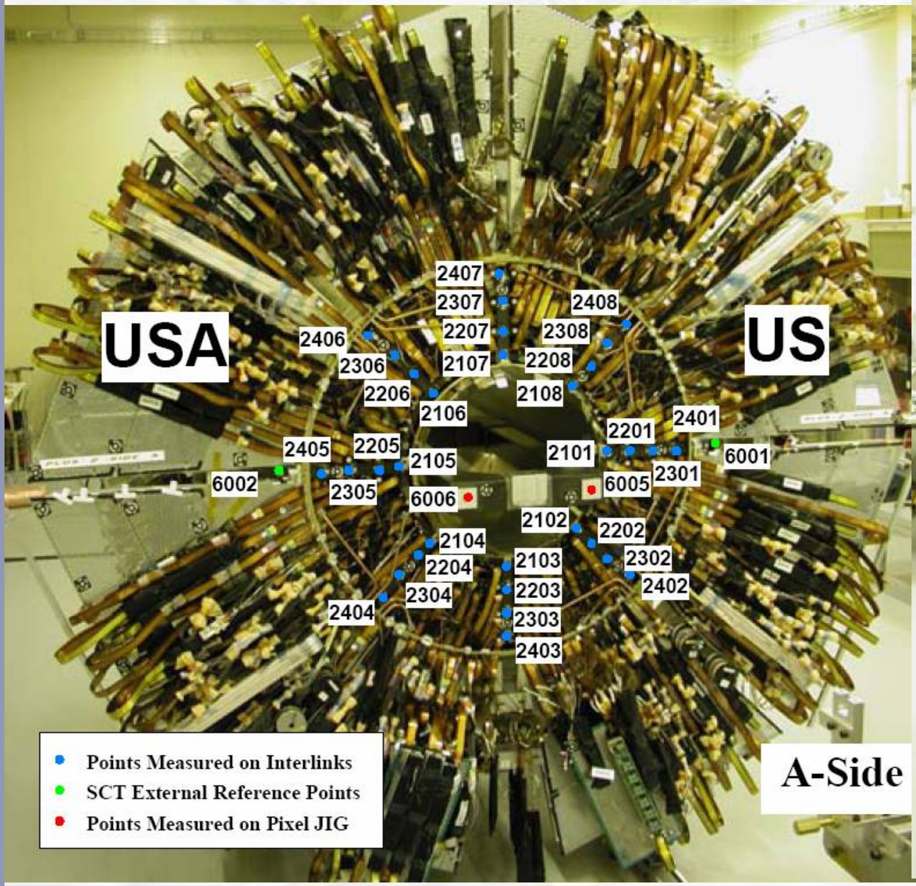
Global Chi2 can add extra terms to the weight matrix and the big vector of the final system of equations to incorpoarate external FSI constraint

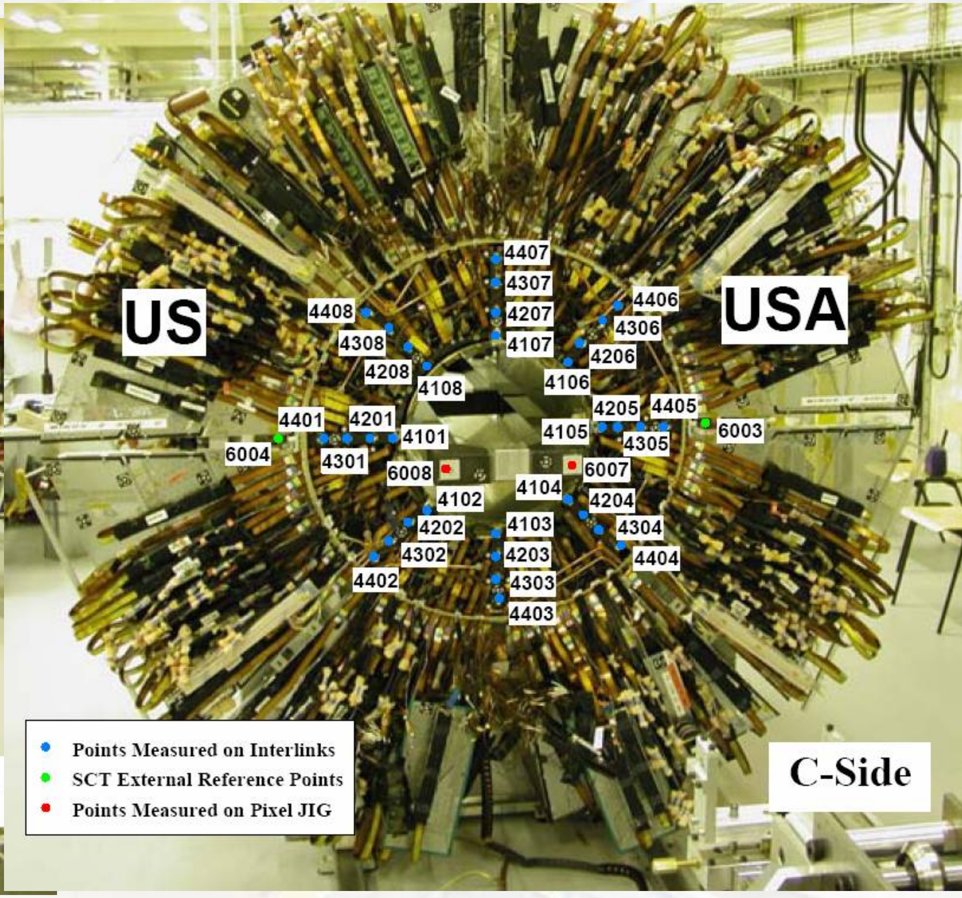
$$M += \frac{1}{{\sigma_k}^2}(\hat{F}^k \hat{F}^{kT})$$

$$V += -\frac{1}{{\sigma_k}^2} A^k F^k$$



SR1 SCT+TRT Photogrammetry

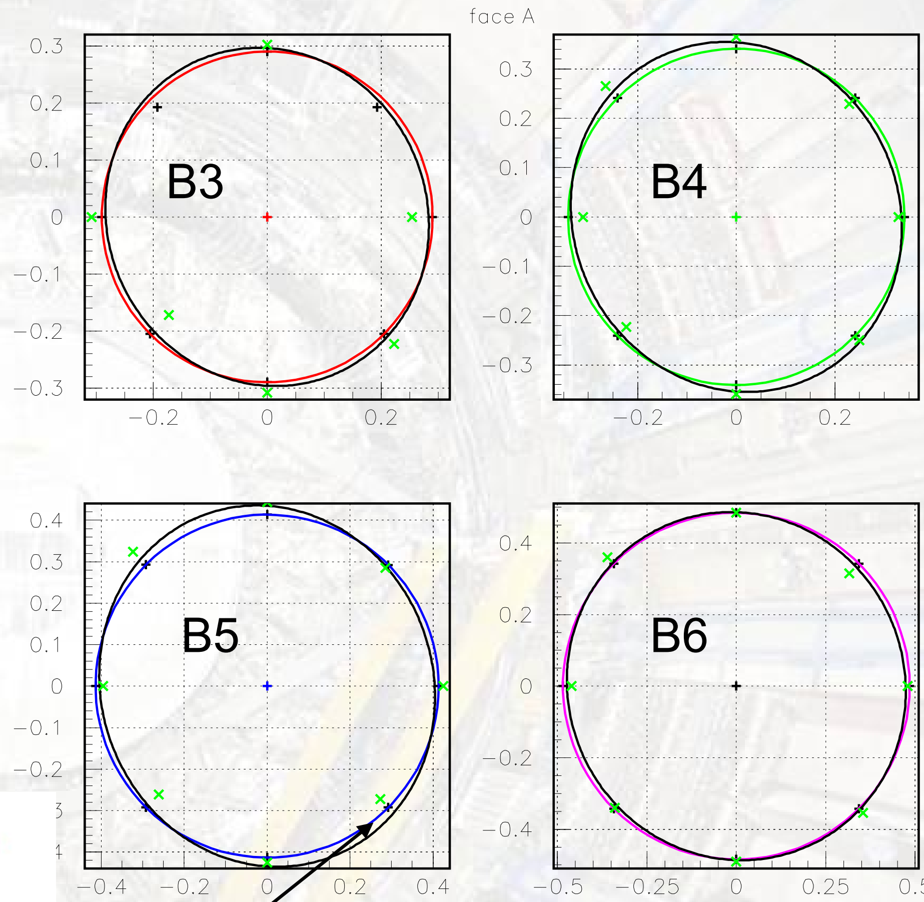




- **SCT Barrel photogrammetry survey was completed early this year.**
- **SCT-TRT relative position survey also performed.**

Photogrammetry: Deformations

- Measurements performed before and after insertion into TRT. Detailed measurements exist only before the insertion O(20µm) in XY.
- After insertion only coordinate system transfer was measured.
- The individual cylinder interlink data showed deformations consistent with tilted ellipses.
- Face A and face C appear to be rotated in opposite directions, hinting at twists of the complete barrel. Deformations are order of 100 µm.



Circles (colored) are fits, black curves are guidelines for ellipses using the scaled up differences of data points (col) to the circles