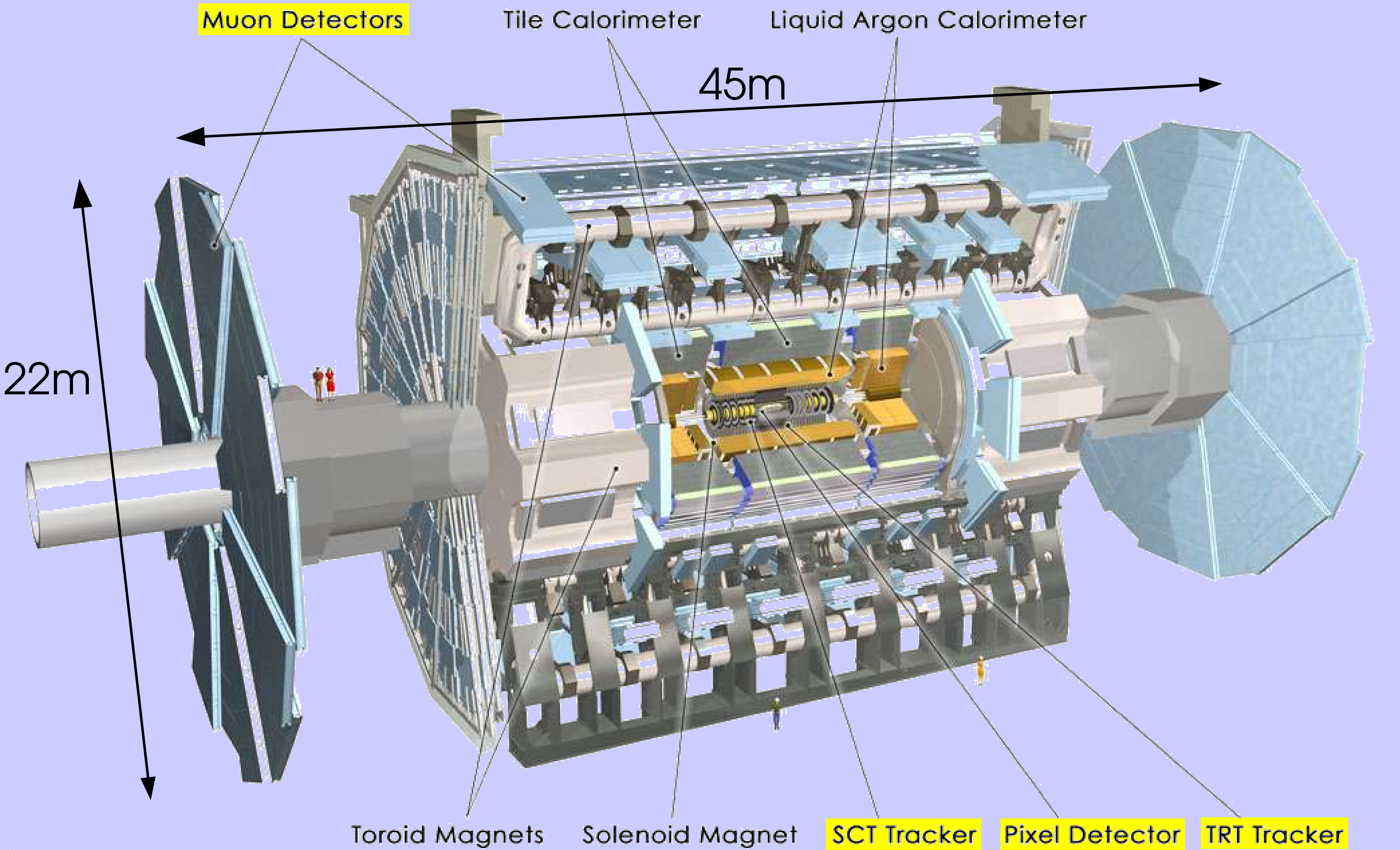
ATLAS Alignment Strategy

Strategy

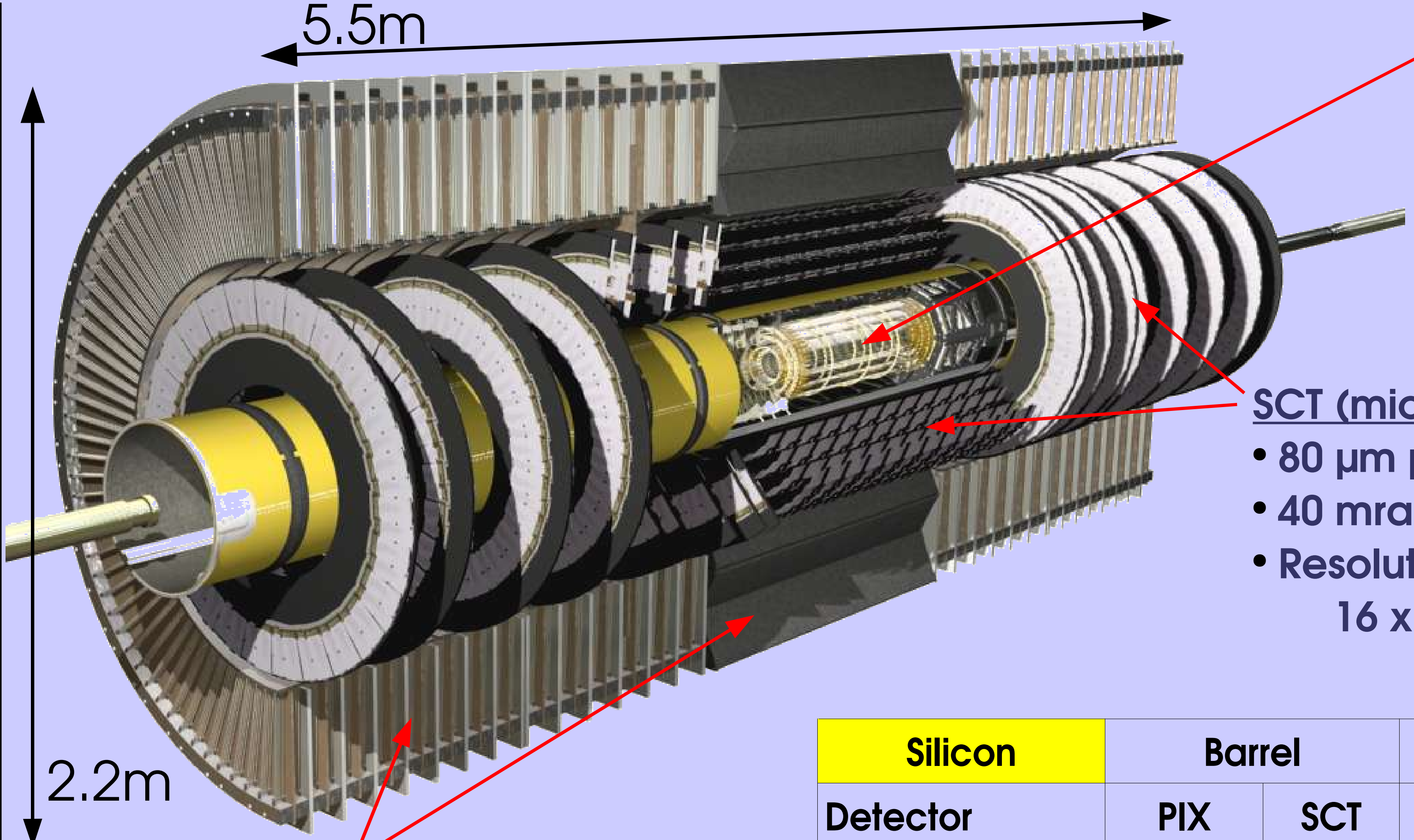
Data Challenge

MC Simulation Challenge

The ATLAS Experiment



The Inner Detector



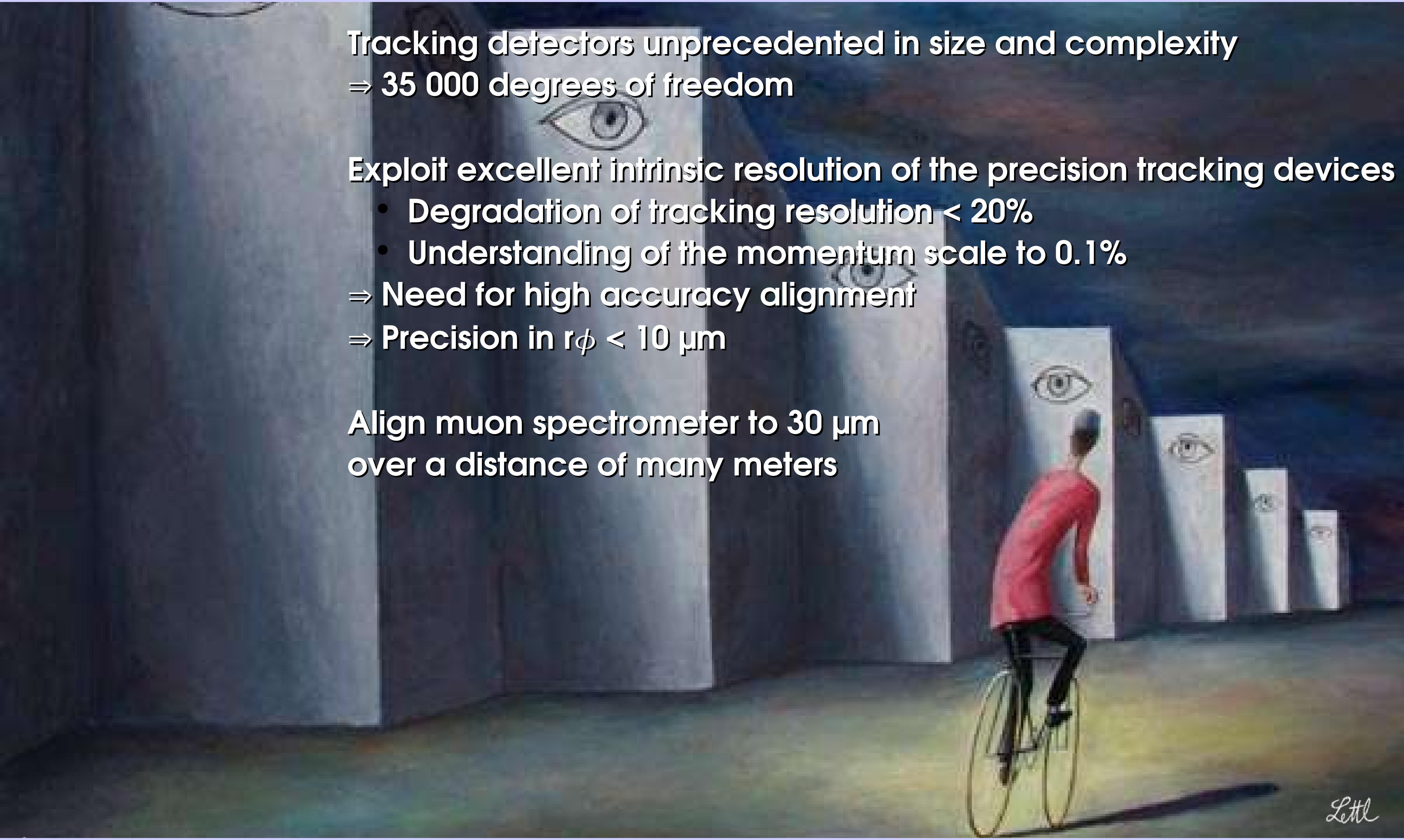
Pixels:
- 5 cm from beam
- 50 x 400 µm
- Resolution: 12 x 100 µm

SCT (microstrips):
- 80 µm pitch
- 40 mrad stereo angle
- Resolution: 16 x 580 µm

TRT (straw tracker):
- 96 barrel modules
- 28 end-cap disks
- Resolution: 170 µm

Silicon	Barrel		End-cap	
Detector	PIX	SCT	PIX	SCT
#layers/disks	3	4	2x3	2x9
#modules	1456	2112	288	1976
Total #modules	5832			

The Challenge



Tracking detectors unprecedented in size and complexity
⇒ 35 000 degrees of freedom

Exploit excellent intrinsic resolution of the precision tracking devices
- Degradation of tracking resolution < 20%
- Understanding of the momentum scale to 0.1%

⇒ Need for high accuracy alignment
⇒ Precision in $r\phi < 10\ \mu m$

Align muon spectrometer to 30 μm
over a distance of many meters

Line of Attack

Detector design:
- Material, resolution, redundancy, **stability**
- Optimize overlap, layer coverage,...

Construction:
- Measure & **survey** at all stages of assembly if possible

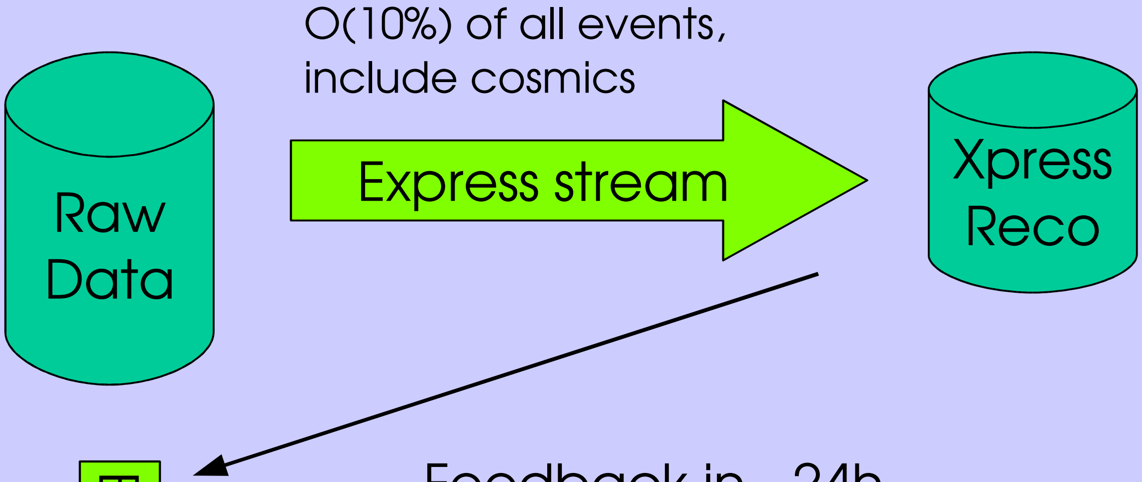
Operation:
- Dedicated data processing & **storage for alignment**

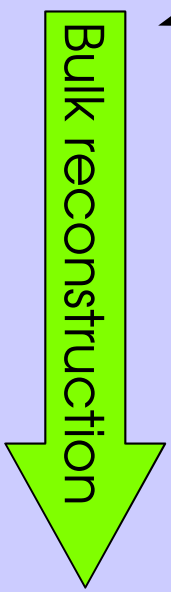
The actual alignment: **Track-based** at the core, **hardware alignment**, represent **true DOFs**, manpower vs software diversity, provide early (prelim.) alignment

Control systematic biases & "weak modes": Combine **complementary/external constraints**, relate modules across detector using **different track topologies**

Validation: Realistic **deformation scenarios** in simulation, exercise on real data (**cosmics**), **alignment monitoring**, **be prepared for the unexpected!**

Alignment Infrastructure





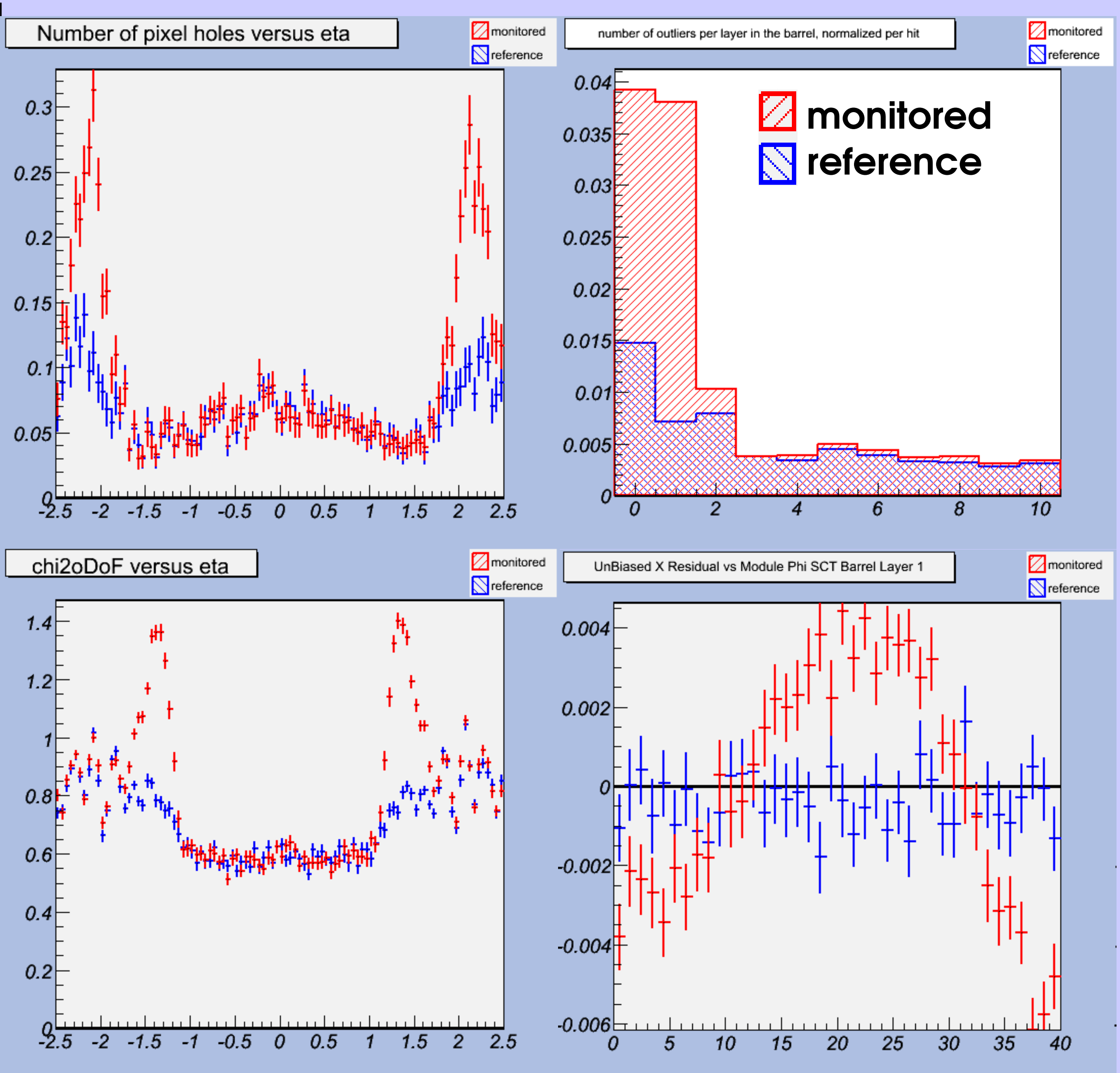
<u>Feedback in ~24h</u>

- Calibration
- Alignment
- <u>Validation:</u> DQ monitoring
  - ➔ Alignment monitoring
- Rapid alert

<u>Alignment database structure reflects underlying hardware:</u>

- Level 1 – subdetectors (few DOF's)
- Level 2 – layers (~100 DOFs)
- Level 3 – modules (35k DOFs)
- Level 4 – module non-planarities

Alignment Monitoring



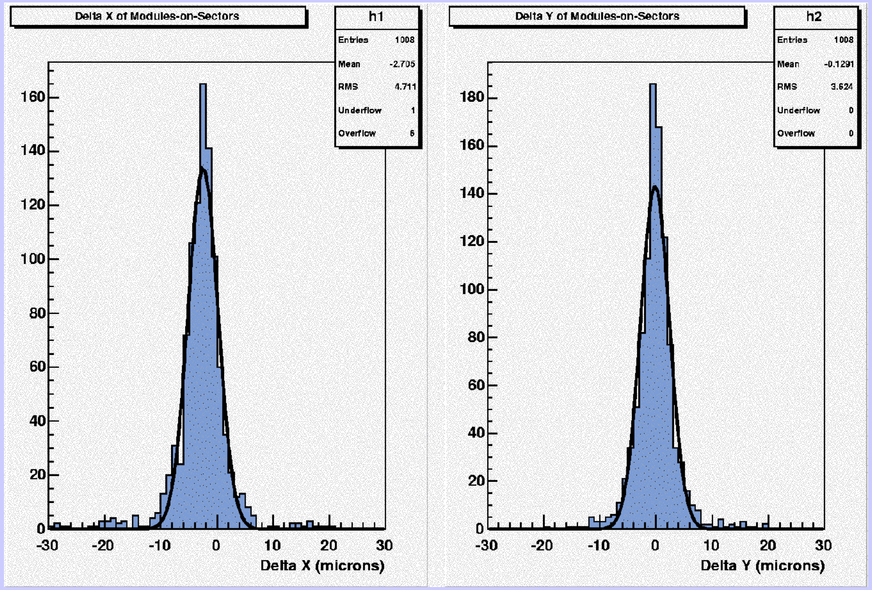
- Assess alignment quality
- Assess need for re-alignment
- Study systematic deformations

<u>Monitor:</u>

- Hit efficiency
- Generic track distributions
- Residuals
- Resonances, long lived particles
- Electrons
- Muons in muon spectrometer
- Cosmics
- Reconstructed beamline
- ...

Automatically evaluate agreement with reference (mean, width, KS,...)

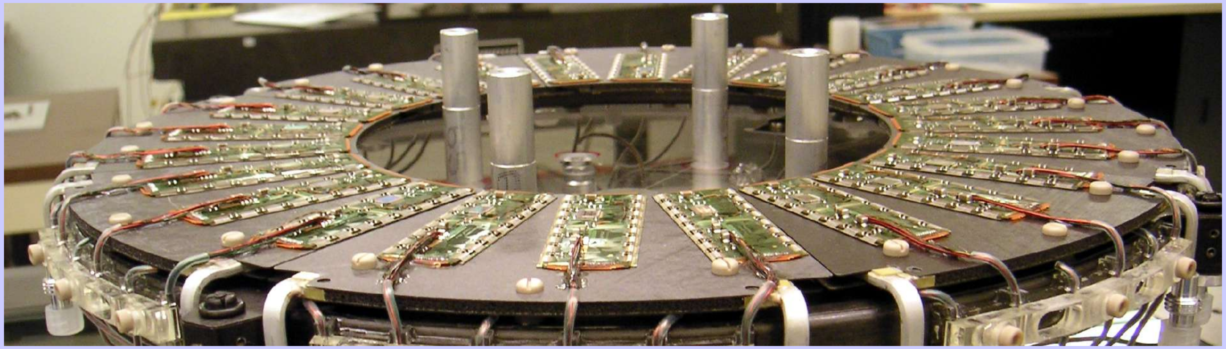
Start from the Survey – 3 Examples



1) Survey of Pixel modules on sector (very stable!):

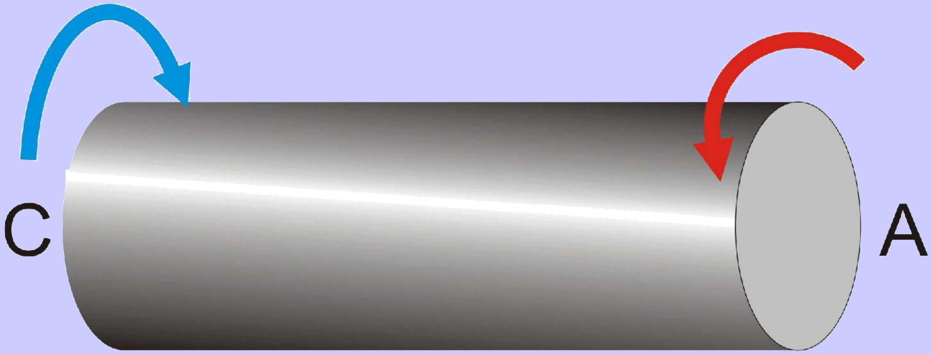
- **Measurement precision (optical) ~ 1 micron**
- **Positioning precision < 3 microns**

⇒ **Constrain nearby modules on rigid body in alignment**



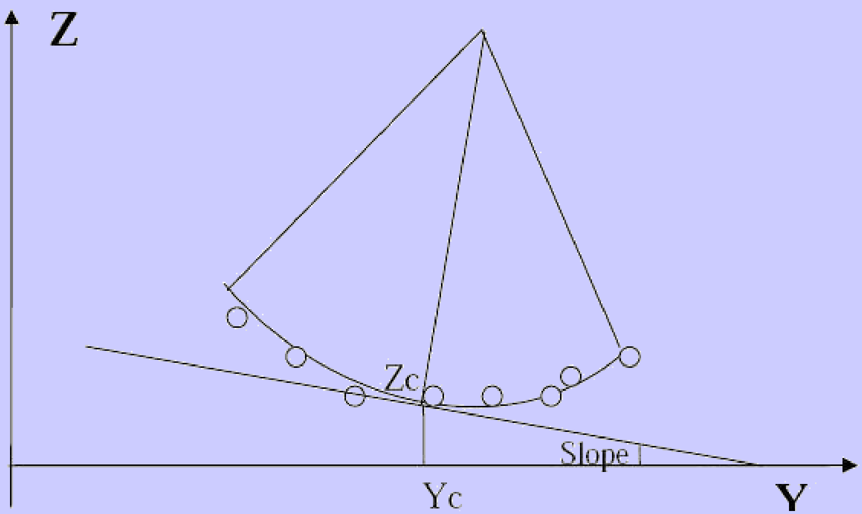
2) Photogrammetry of SCT barrels:

- **Ellipse shape** (3-point mount scenario)
- **Twist**

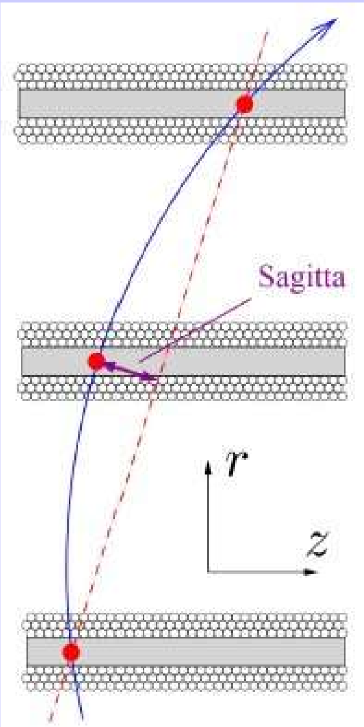


3) Pixel module out-of-plane distortions:

Correct for bow in reconstruction



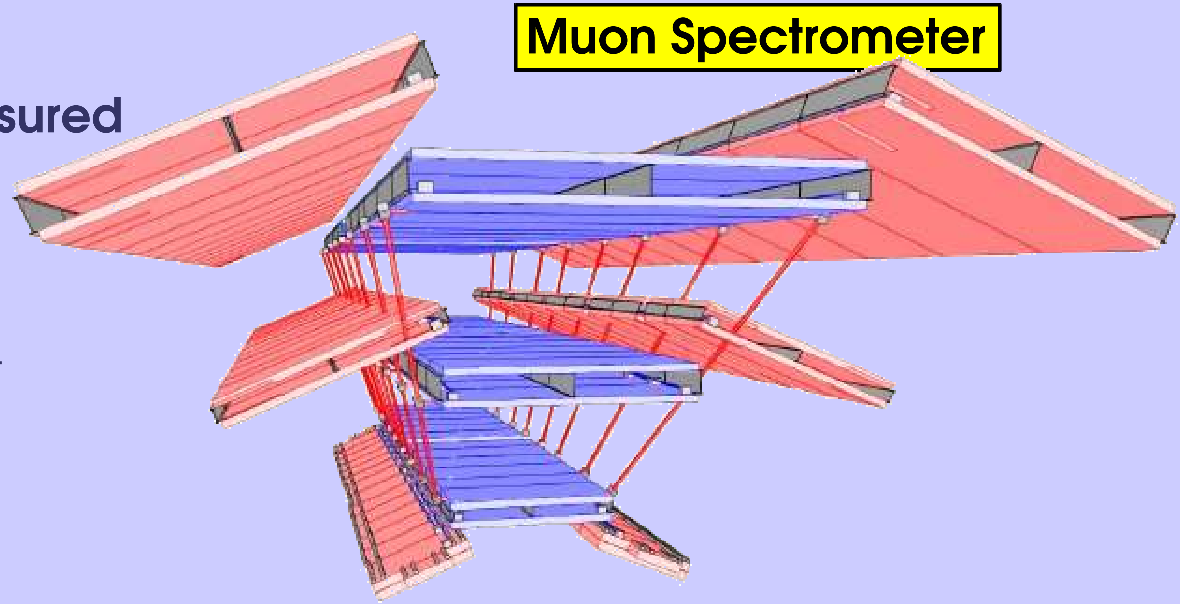
Hardware-based Alignment

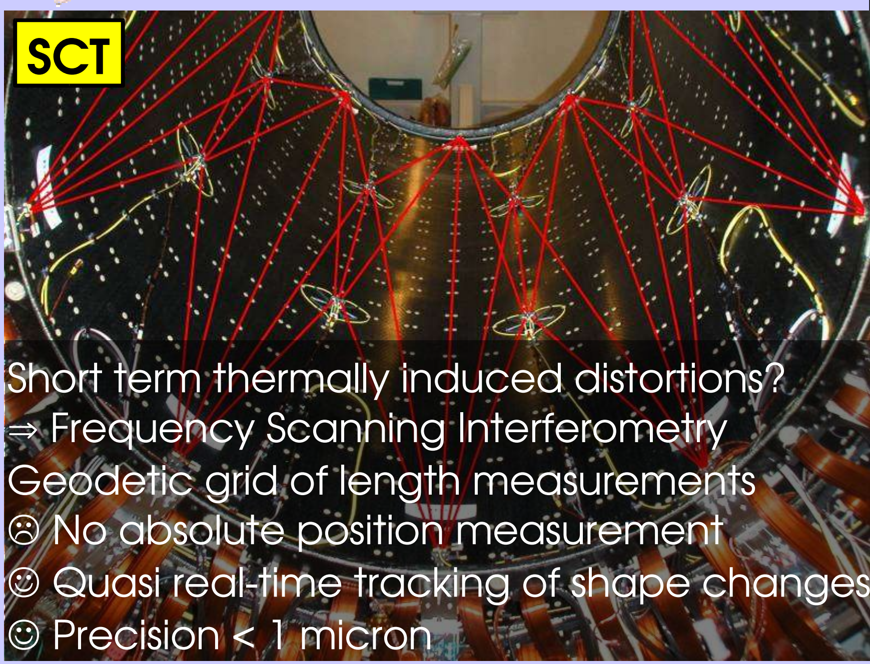


Goal for 1 TeV muon:
sagitta of 500 µm measured with 50 µm accuracy

Sense wire placement:
20 µm precision

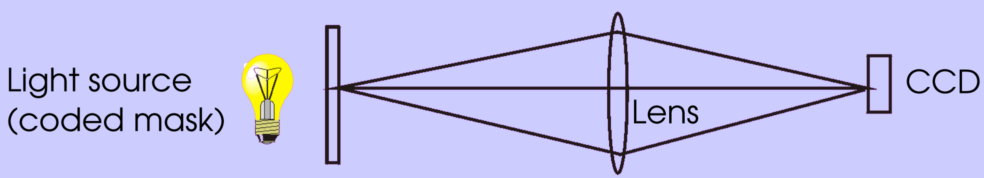
Single muon chamber spatial resolution: 40 µm
⇒ alignment accuracy: 30 µm





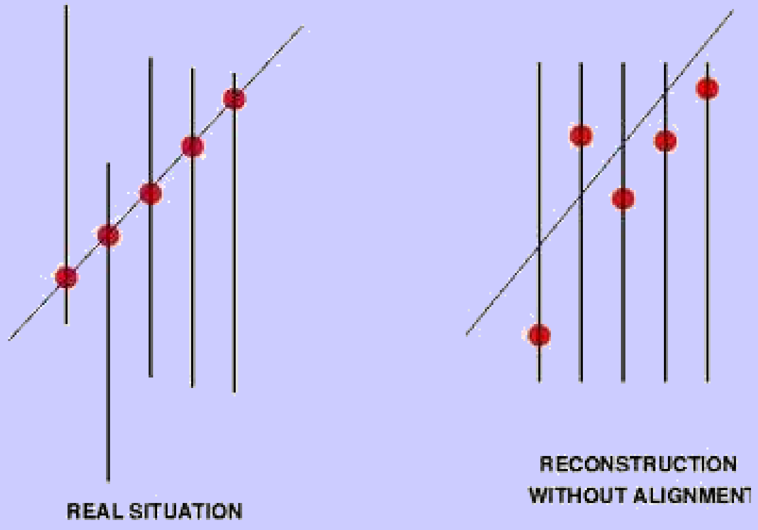
Short term thermally induced distortions?
⇒ Frequency Scanning Interferometry
Geodetic grid of length measurements
☹ No absolute position measurement
☺ Quasi real-time tracking of shape changes
☺ Precision < 1 micron

Optical alignment system fully operation @ design resolution (first results for endcap): RASNIKs & BCAMs



Complemented by track-based alignment:
Overlaping chambers

Track-based Alignment



Deduce alignment corrections from track fit quality

<u>Necessary criterion:</u>
Minimize residuals (distance from track to hit)
(χ^2 minimization)

Covariance matrix V

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

Vector of hit residuals r(a,π)

- a: alignment parameters
- π: track parameters

<u>2 alignment scenarios:</u>

Level 1 → Level 2 → Level 3

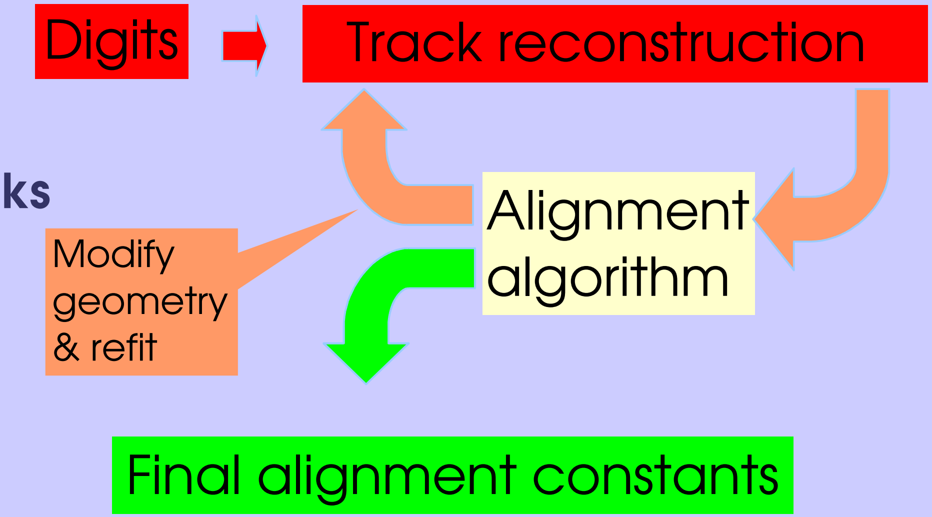
Level 2 → Level 1 → Level 3

Per sub-detector

3 Different Approaches

The Conservative: Local χ^2 Alignment Algorithm

- ✓ Simplify r(a,π) = r(a), V replaced by its diagonal
  ⇒ System of equations breaks down to 6 × 6 blocks
- ✗ Iterative to make up for neglected correlations



The Robust Alignment Algorithm

Add module overlaps in rϕ and z

- ✓ Less affected by misalignment in other layers
- ✓ Less sensitive to multiple Coulomb scattering
- ✓ Ring closure as additional constraint
- ✗ Small size of overlap

The Cutting-Edge: Global χ^2 Alignment Algorithm

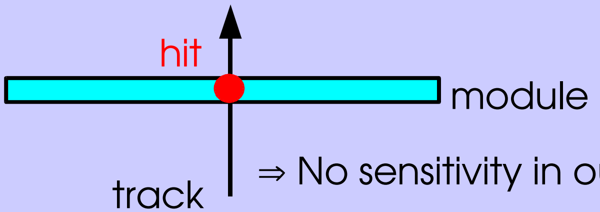
- ✓ Accounting for all correlations
- ✗ Requires inversion of a symmetric 35k × 35k matrix
- ✗ Numerical challenge: Memory, precision, CPU time

⇒ All 3 algorithms give comparable results

"Weak Modes"

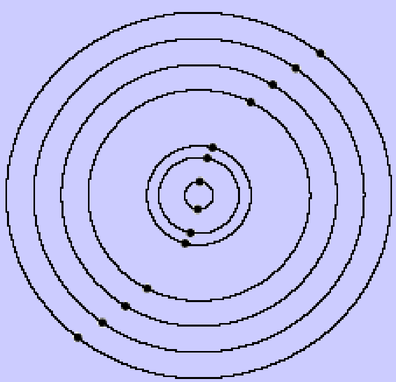
Minimizing residuals is necessary but not sufficient
Weak modes: systematic deformatins, track χ^2 ~ unchanged, track parameters biased
⇔ tracks are fitted to WRONG helices

Example 1:



⇒ No sensitivity in out-of-plane direction

Example 2:
Barrels rotated about symmetry axis ~ radius
⇒ p_T bias (charge dependent)



Example 3: "Telescope mode"
Barrels translated along beam ~ radius
⇒ η, z_0 bias

⇒ Residuals alone not good enough!
- **Physics quantities, e.g. mass, vertex constraint**
- **Different event topologies: Off-axis cosmics, beam halo**
- **Redundancy (TRT, muon spectrometer, EM calorimeter)**
- **Survey**

The MC Simulation Challenge

- Test alignment strategy before data is available

- Simulate a typical as-built detector geometry in GEANT
  - ➔ inspired by survey data, assembly & installation precisions
  - ➔ also simulate typical weak modes

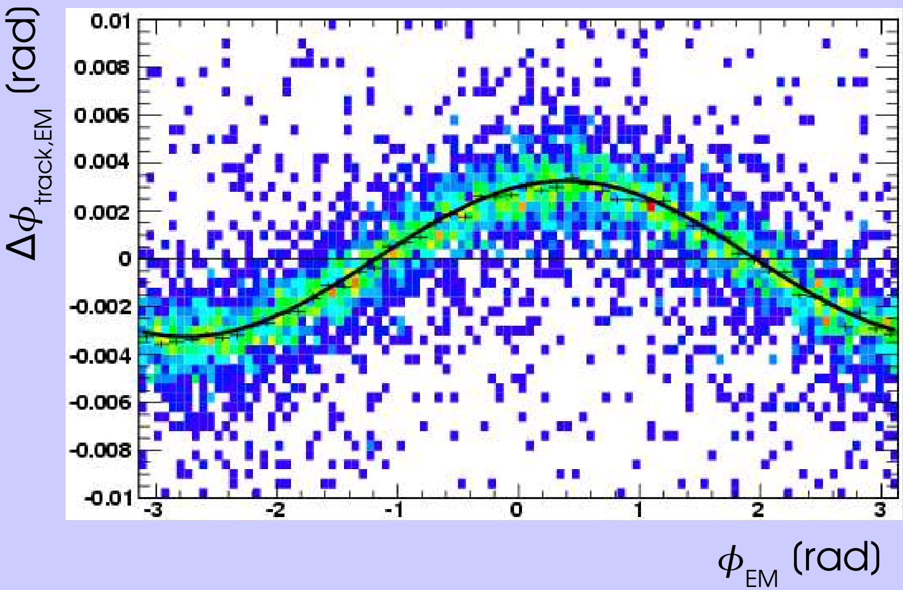
	Translations	Rotations
Level 1	O(1-3 mm)	O(1 mrad)
Level 2	O(100 μm)	
Level 3	O(10-100 μm)	

⇒ Large scale data simulation (time consuming)

<u>In addition:</u>
Dedicated study of characteristic and realistic weak modes
by implementing misalignment in the reconstruction (time efficient)

⇒ Look at one example of additional information beyond residuals

Validation with EM Calorimeter

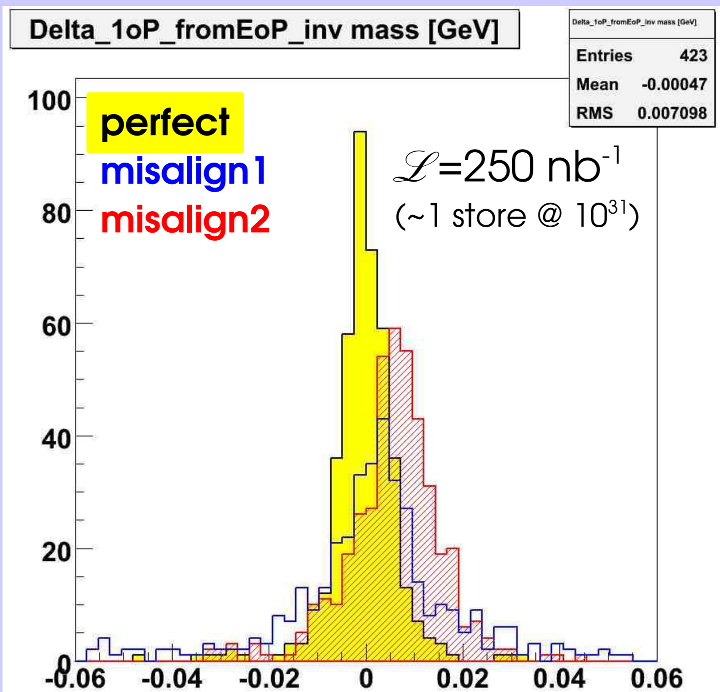


EM spatial resolution @ η = 0:

σ_ϕ (E=50GeV) = 0.85 mrad

σ_ϕ (E=20GeV) = 1.3 mrad

Use mainly W's and Z's



Z→ee events:

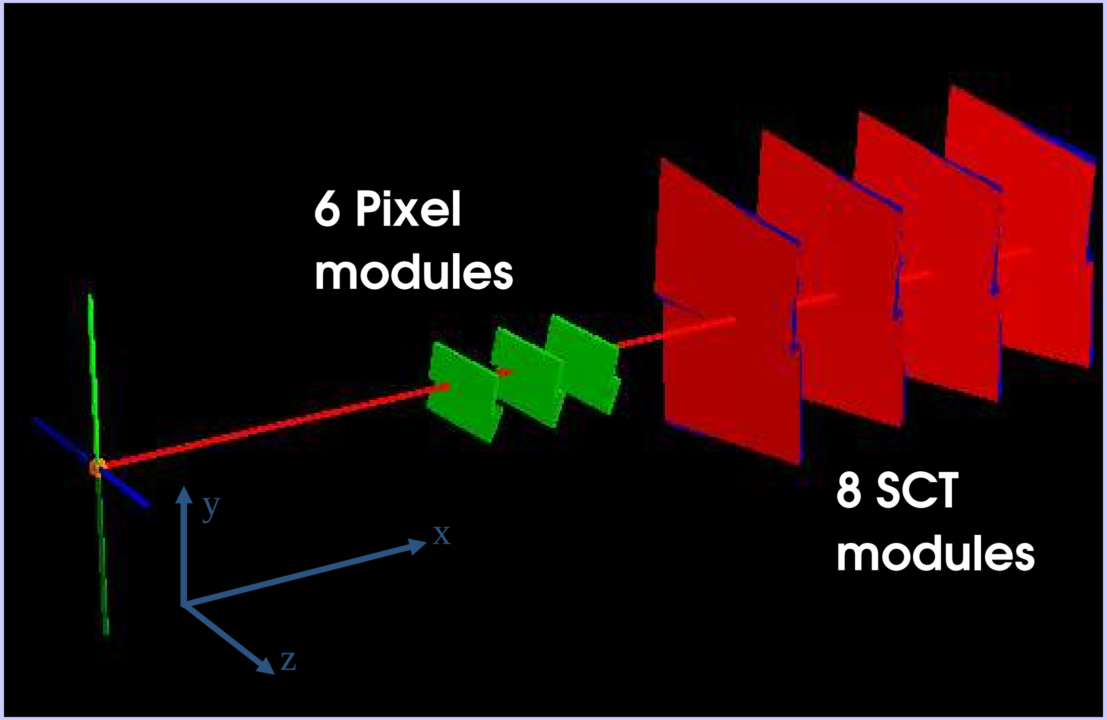
⇨ does not require absolute calorimeter calibration

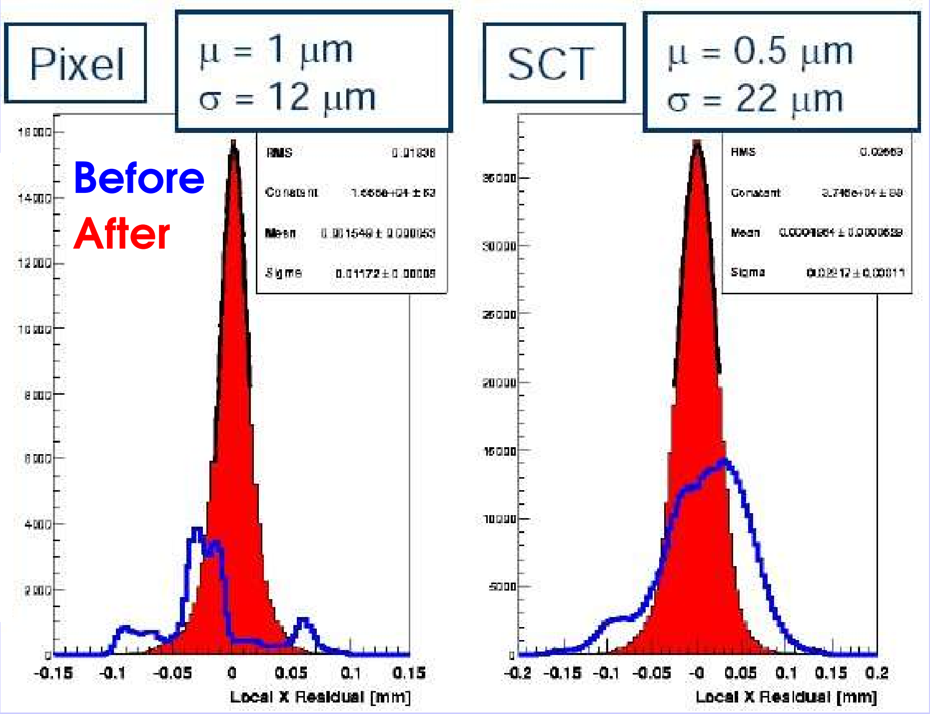
Charge asym. = $\Delta\frac{1}{p} = \frac{E/p_+ + E/p_-}{E_+ + E_-}$.

Combined Test Beam Data (CTB)

<u>CTB 2004:</u>

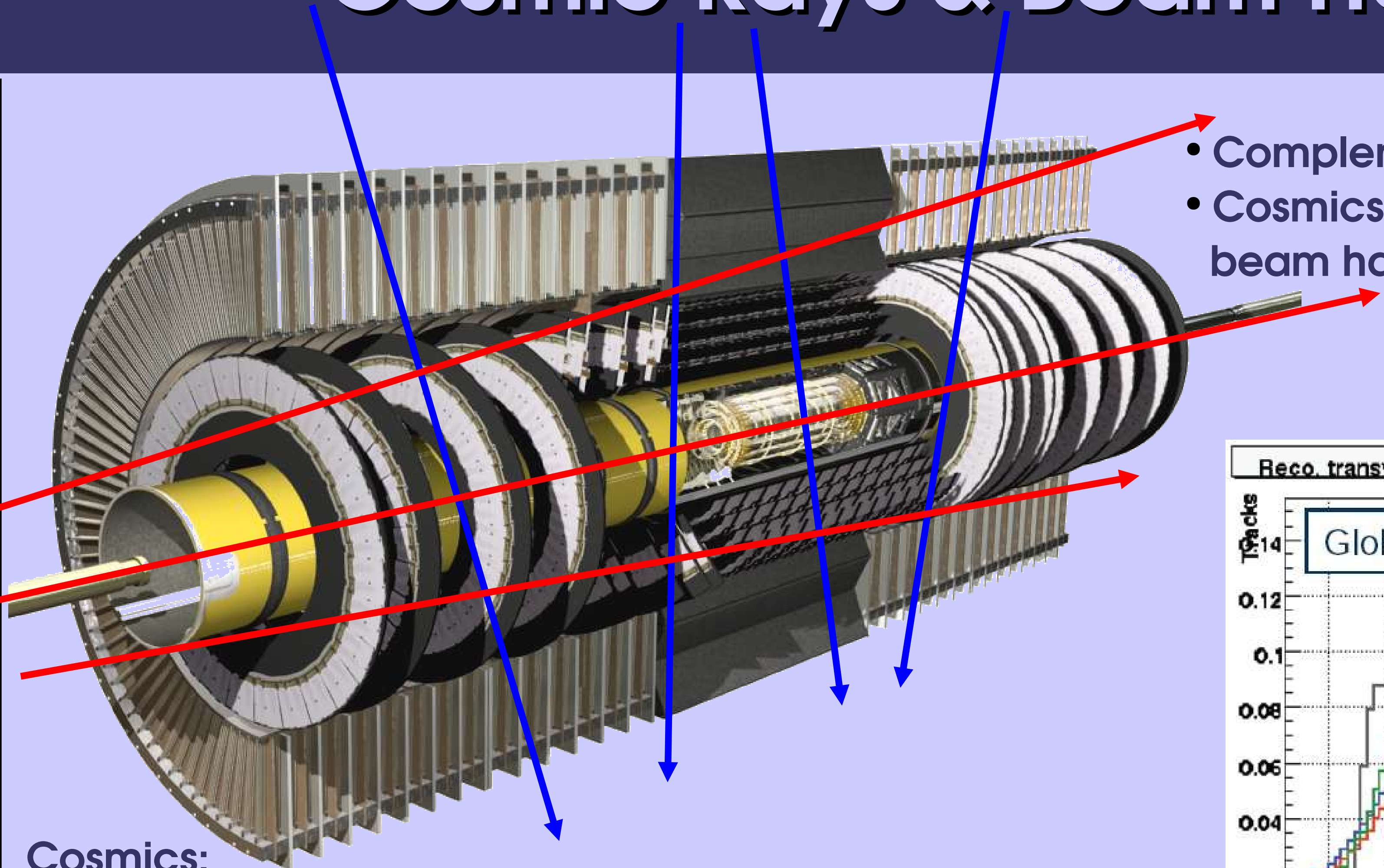
- First ever “ATLAS data” from subsystems combined
- Large statistics (~20M tracks) at different beam momenta (2-180 GeV)
- e^+, e^- and π, with and without magnetic field
- <u>Challenge for alignment:</u> small setup, collimated beam through narrow tower of modules
  ⇒ Certain DOFs unconstrained



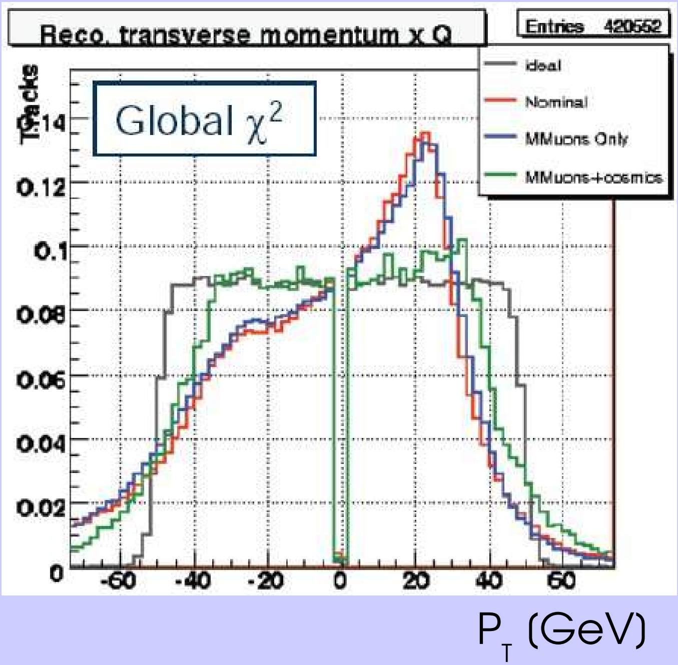


Followed by 6 TRT modules

Cosmic Rays & Beam Halo



- Complementary (in angle)
- Cosmics good for barrel, beam halo good for end-caps



<u>Cosmics:</u>

- ✓ High momentum (> 2 GeV), optionally no B-field
- ✓ constrains p_T-biasing modes
- ✓ Relate top to bottom hemisphere ⇒ constrains telescope mode
- ✓ Off-axis ⇒ constrains twist, elliptical distortions
- ✗ Low rate (MC simulation: 0.5 Hz through Pixel barrel), non-uniform illumination

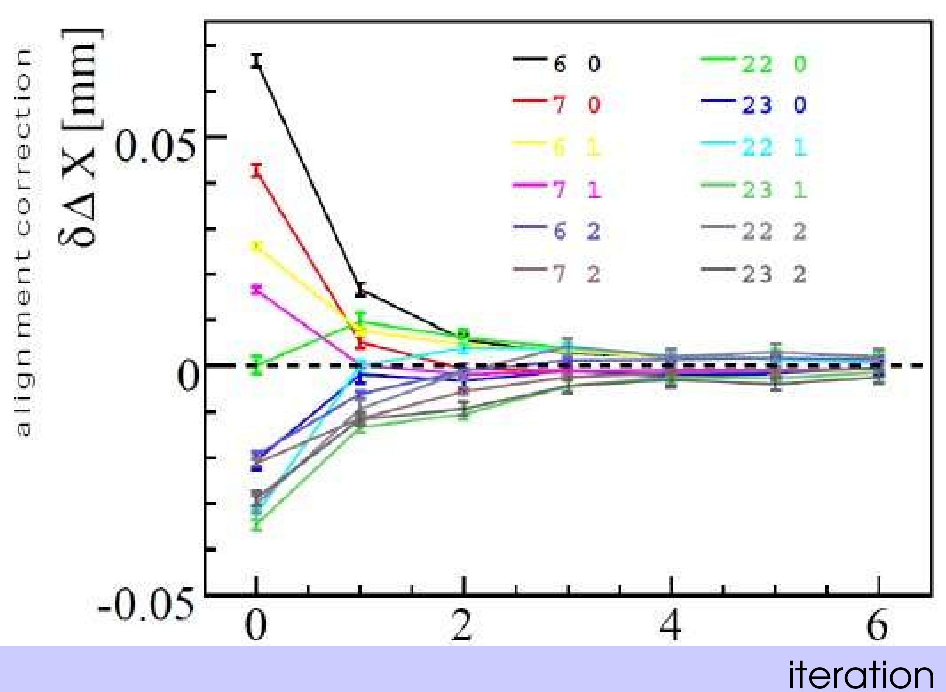
SCT/TRT Cosmics – Data on Surface

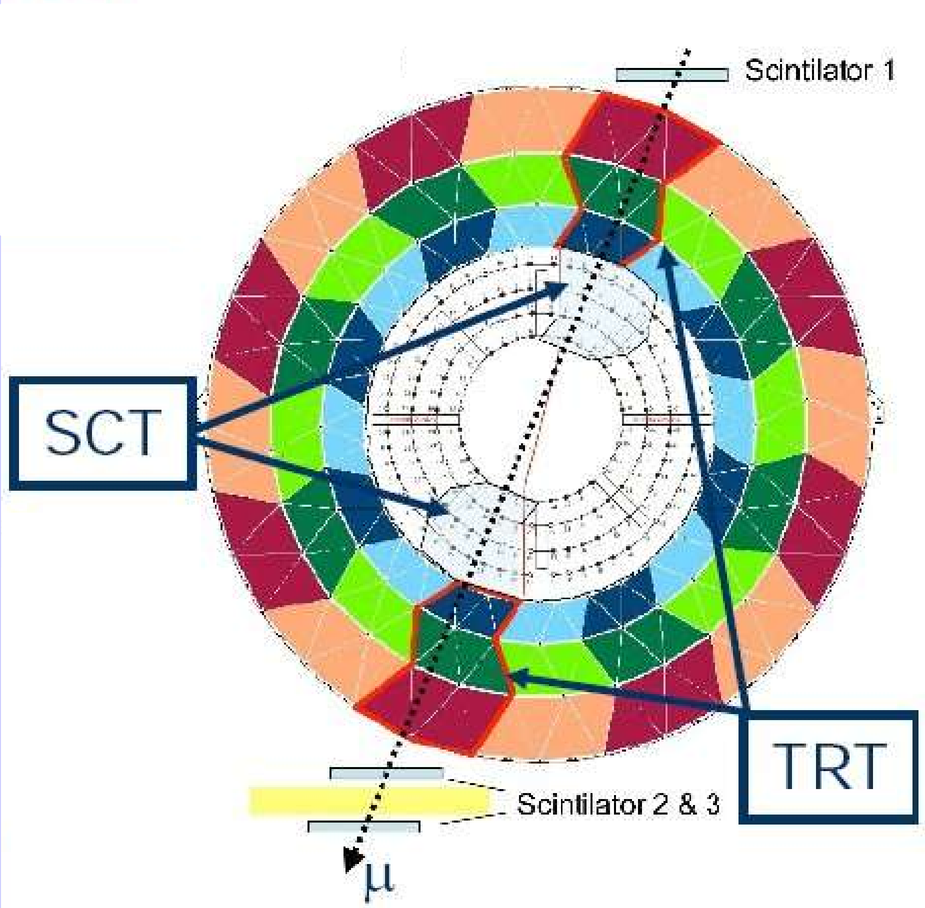
<u>2006 combined SCT & TRT barrel cosmic run:</u>

- 22% SCT, 13% TRT barrel
- No B-field
- ~400k events

- Scintillator trigger
  - ➔ Require coincidence

TRT barrel, Local χ^2: the algorithm converges



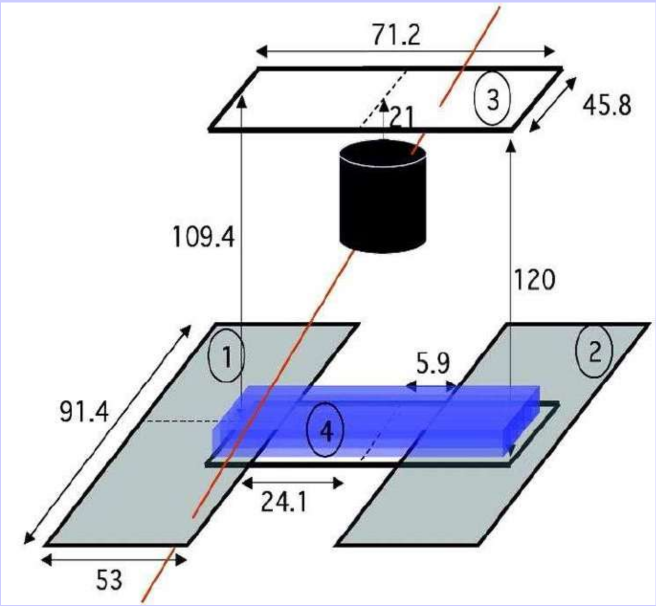


<u>SCT & TRT endcap cosmic run:</u>

Validation of survey data:

- Usage of SCT survey information improves residuals by 10-20%

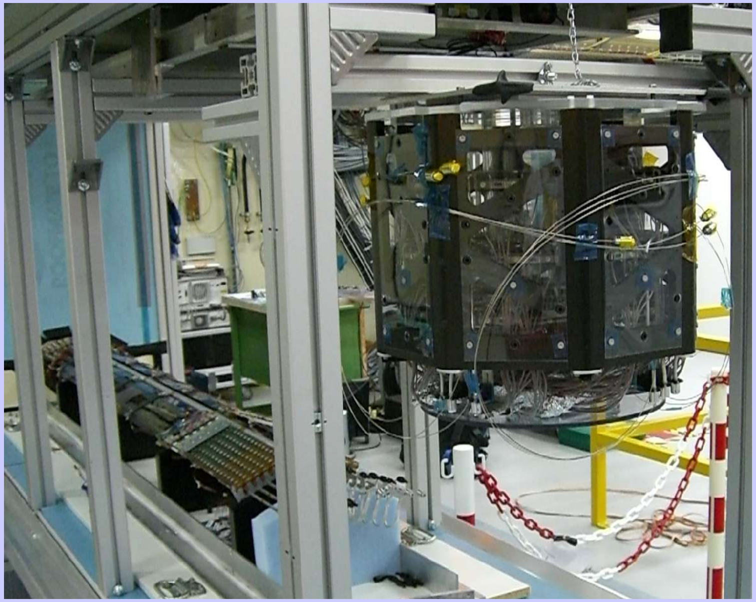
Pixel Cosmics – Data on Surface

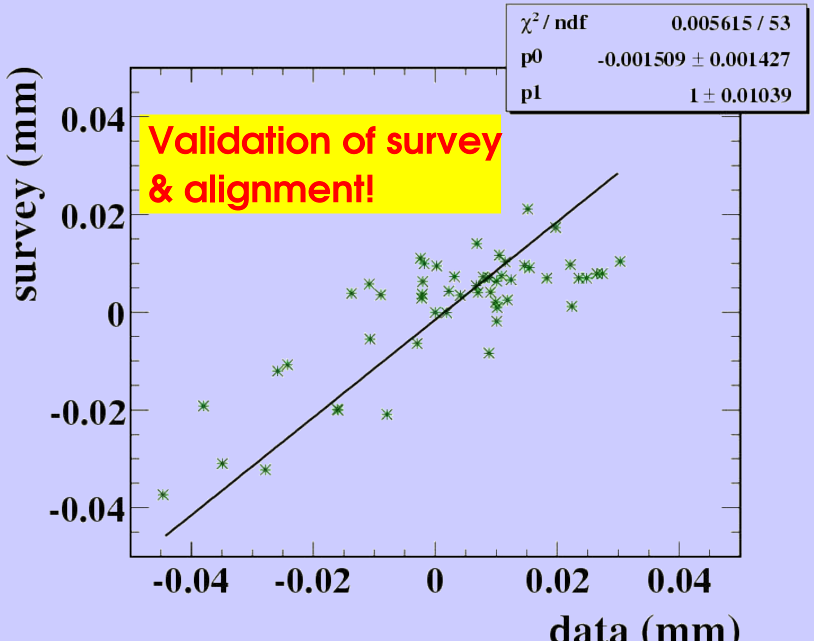


End of 2006:

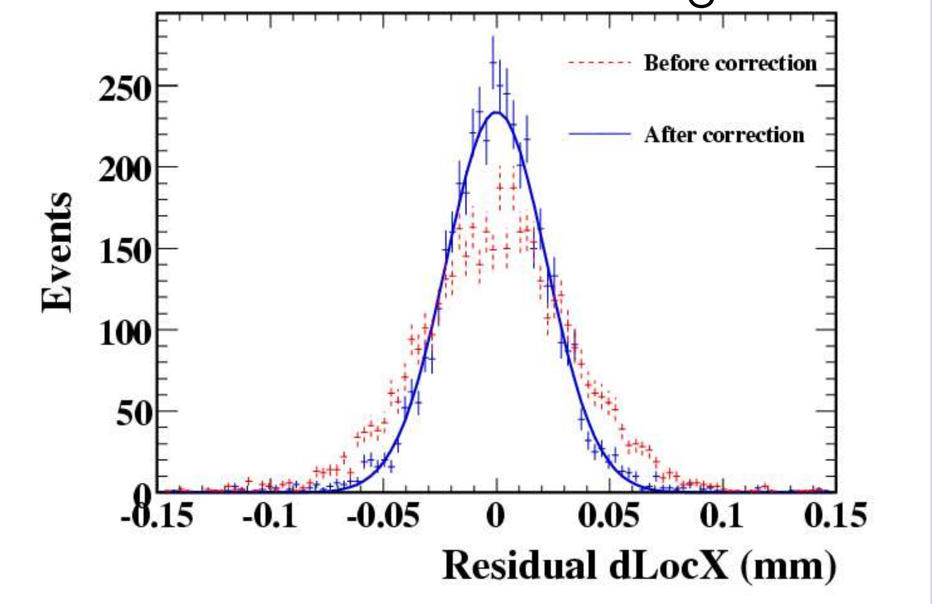
- Whole Pixel EC (10%)
- Turned by 90°
  - → Maximize acceptance
- No B-field
- Scintillator trigger
  - → Require coincidence

- Overlap alignment vs. survey data



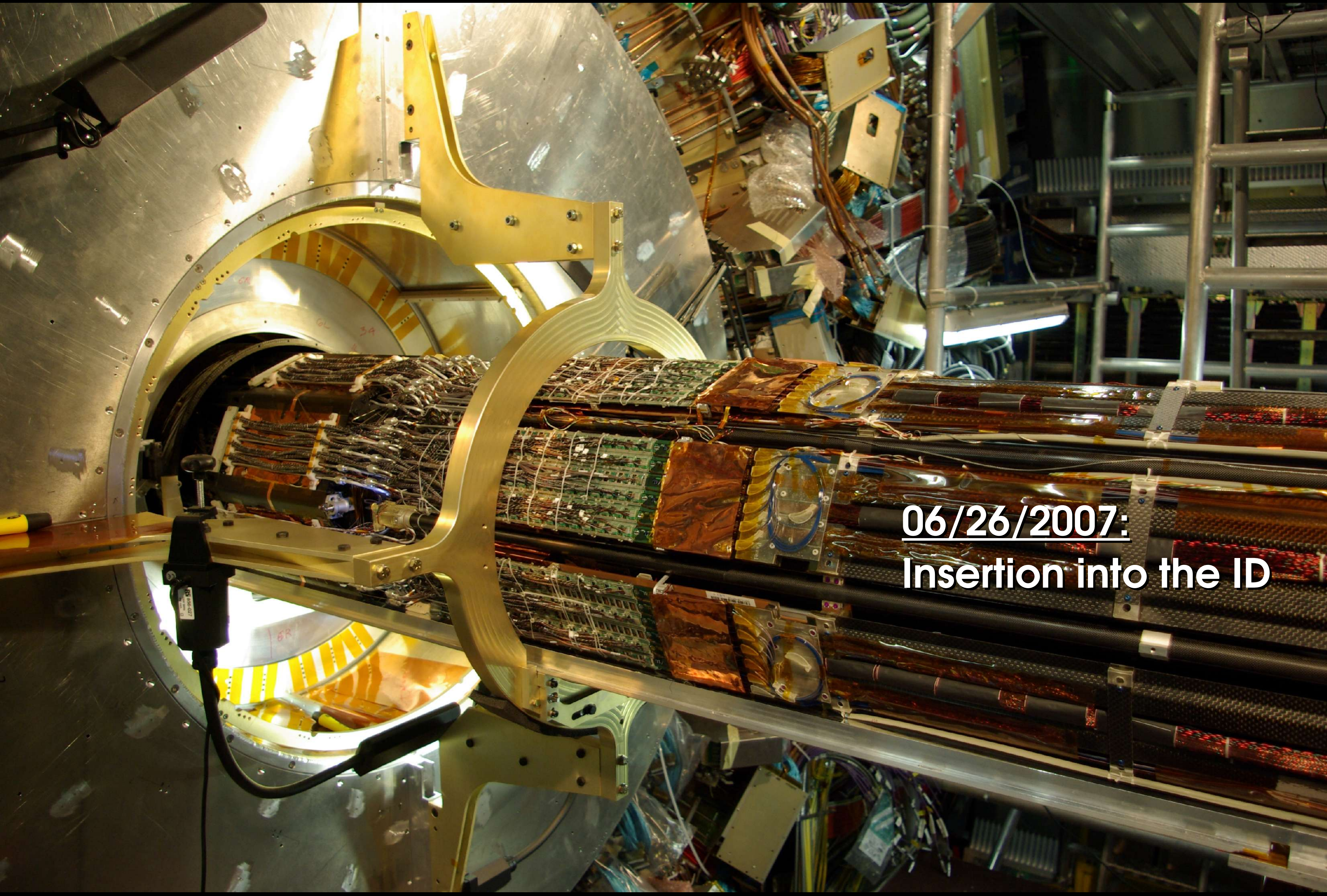


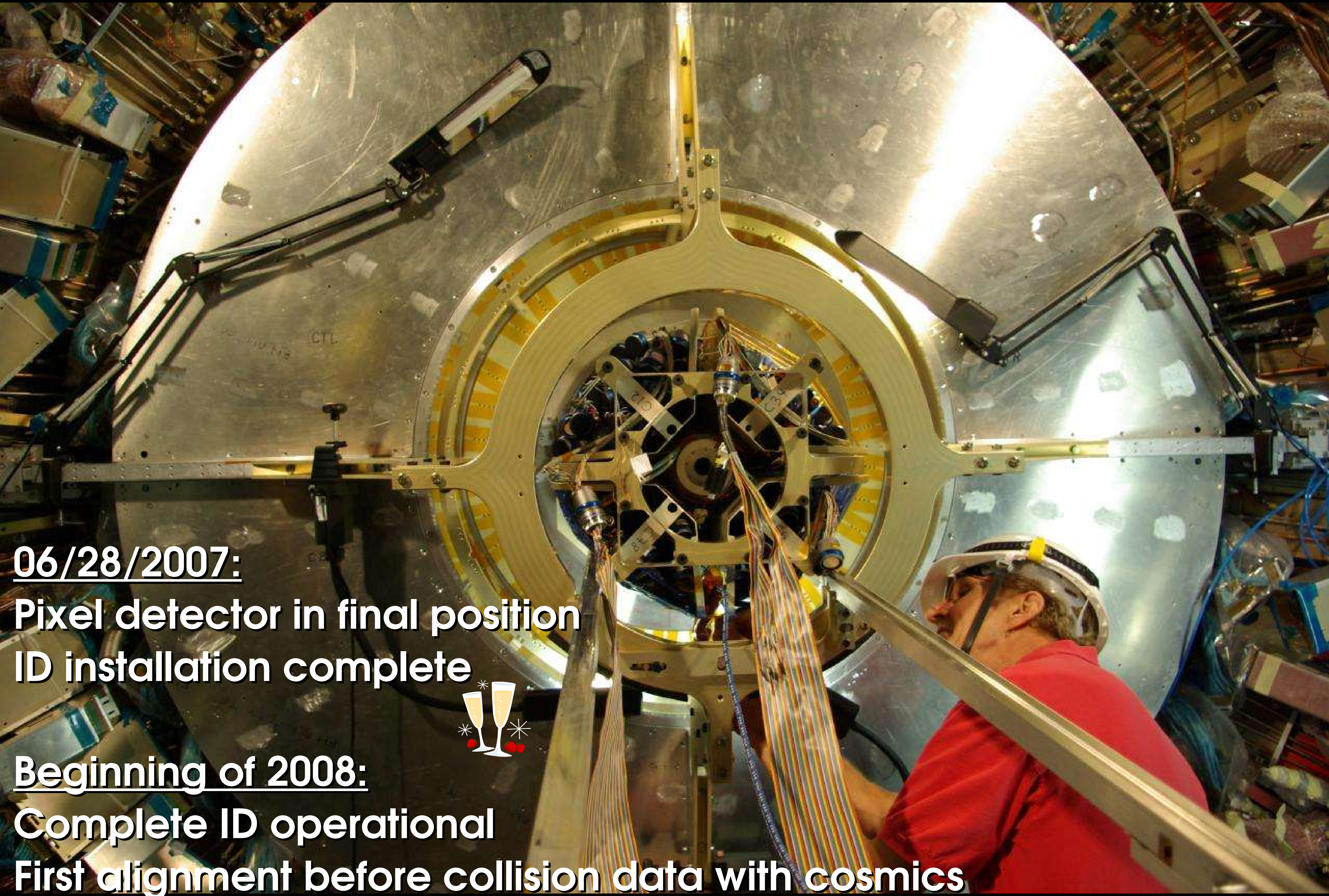
Residuals before and after alignment:



06/25/2007:

The Pixel detector goes 100 meters down into the pit


06/26/2007:
Insertion into the ID



06/28/2007:

Pixel detector in final position

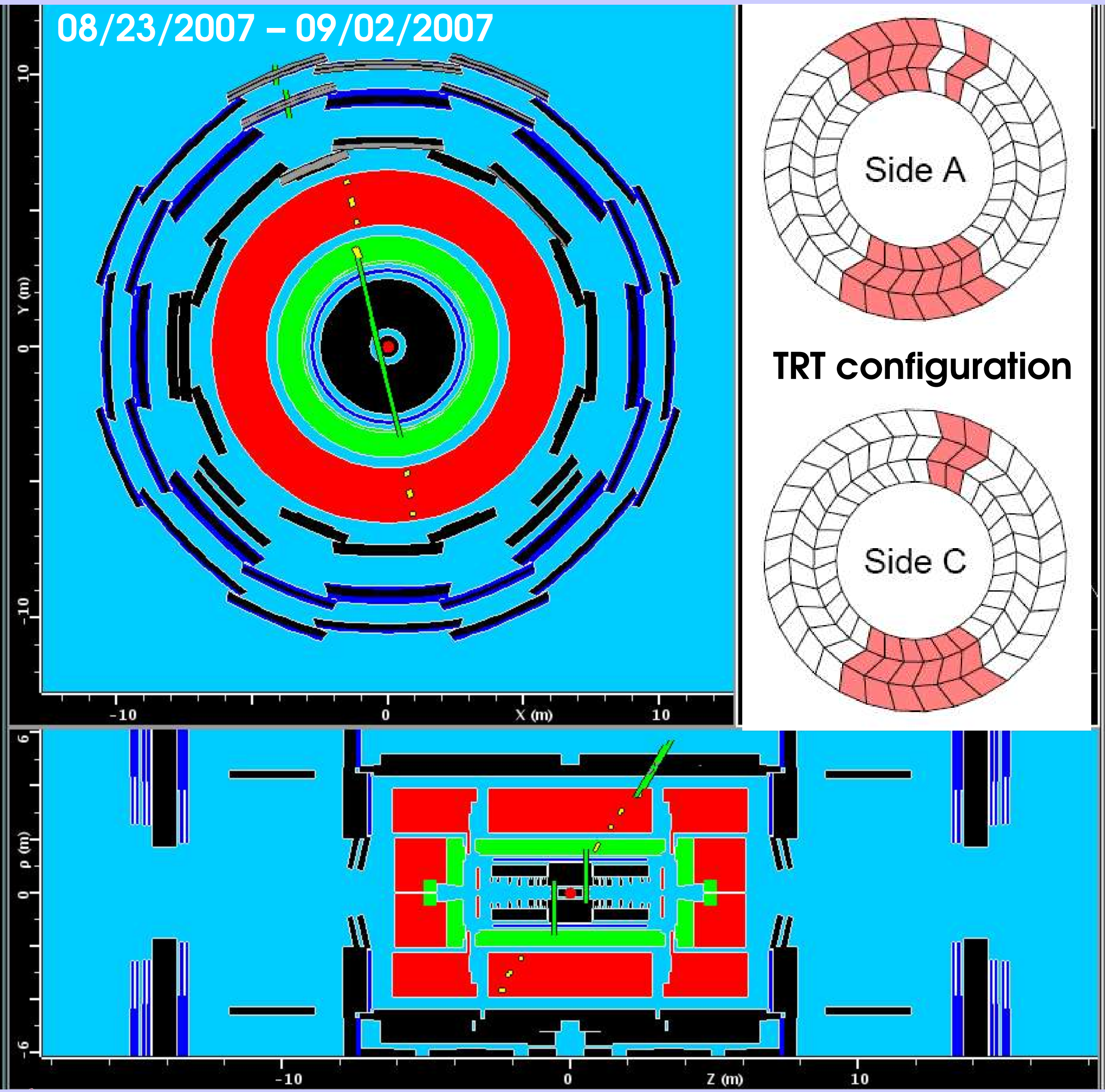
ID installation complete

Beginning of 2008:

Complete ID operational

First alignment before collision data with cosmics

Cosmics now – Data in the Pit



<u>ATLAS Milestone No. 4:</u>

- Cosmics data taking
- Commissioning

<u>Including:</u>

→ Muon system
→ TileCal
→ TRT
⇒ 20 Hz to tape

<u>>20k TRT tracks reconstructed:</u>

- TRT calibration & alignment ongoing

Conclusion & Outlook

We are aware of the challenge!

⇒ Complex but doable alignment strategy:

Data challenge:

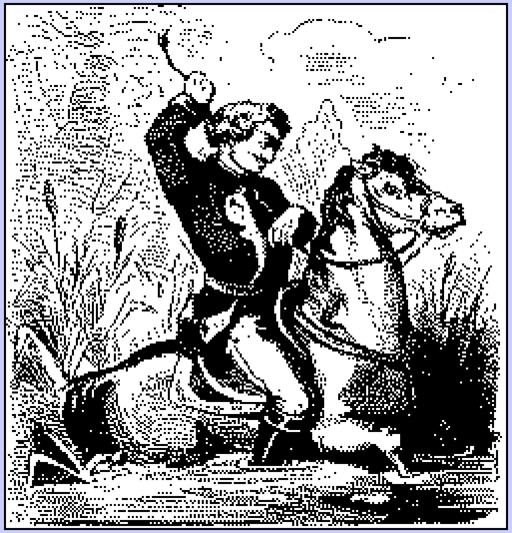
- Alignment algorithms exercised on real data
- Validation of alignment results with survey data

MC simulation challenge:

- Validate alignment strategy with MC simulation
- Weak modes are hard to control

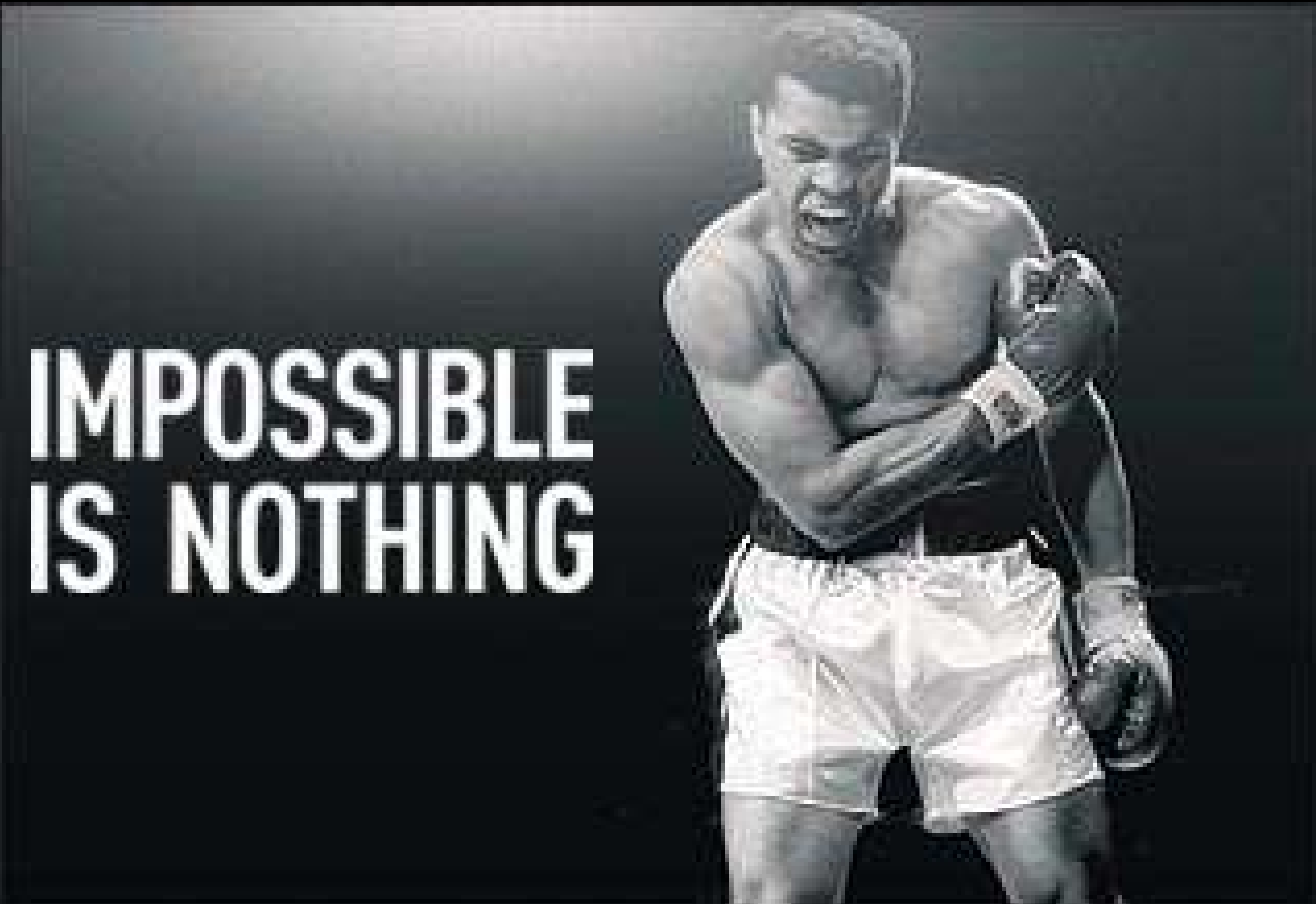
⇒ Bootstrap / additional information

Beware the Münchhausen catch!



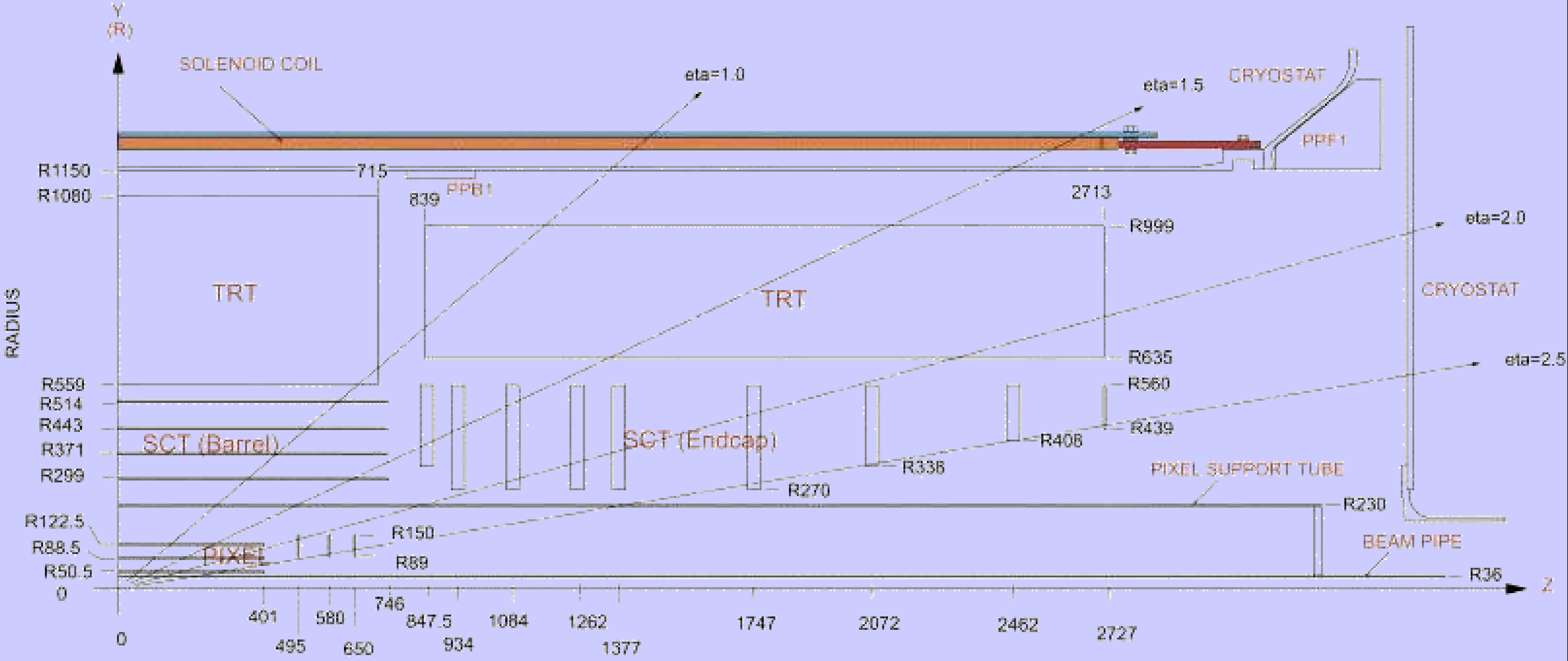
First look at cosmics:

- Helps to constrain weak modes
- First alignment with cosmics beginning of 2008

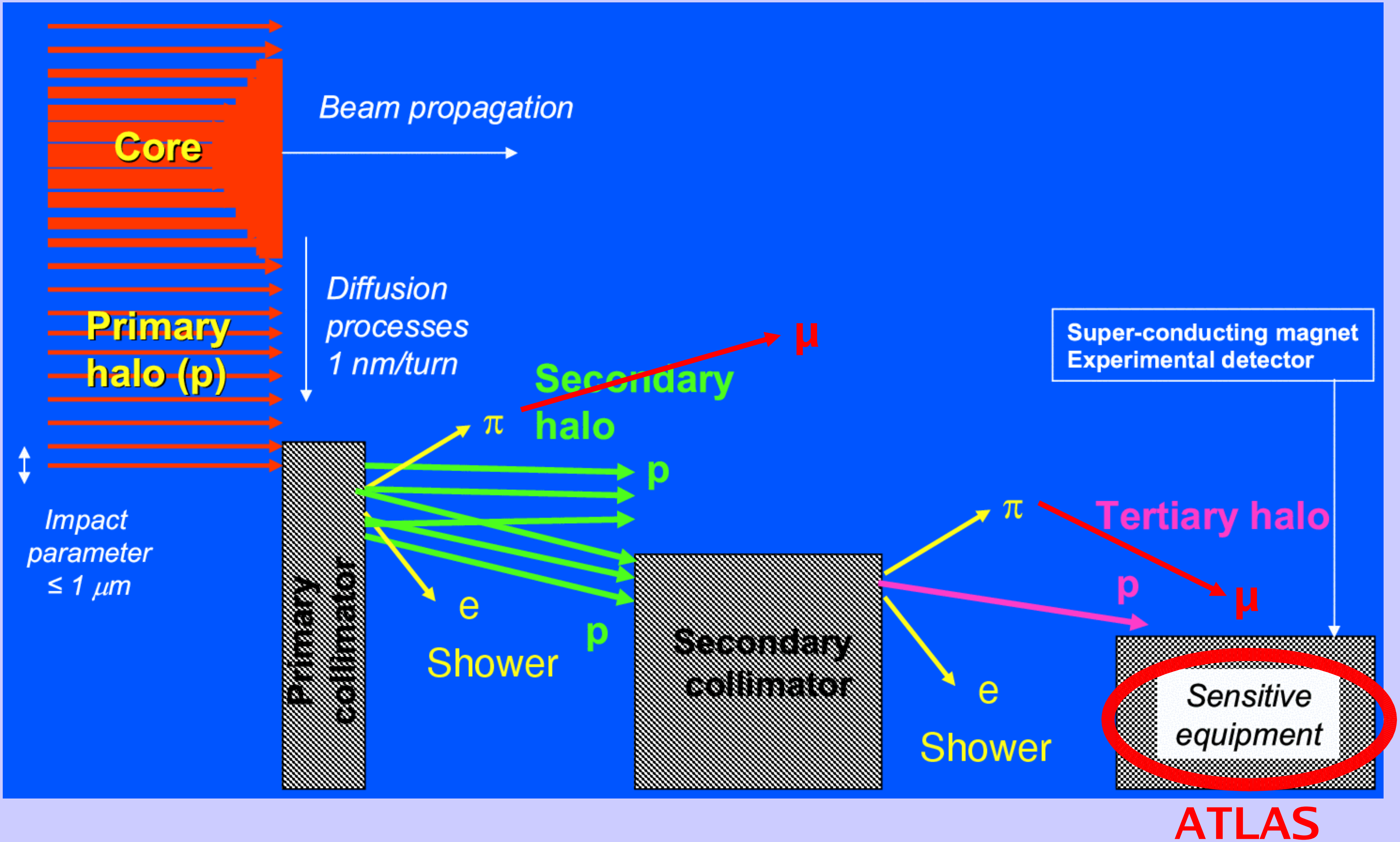

IMPOSSIBLE
IS NOTHING

Backup

The Inner Detector



Beam Halo



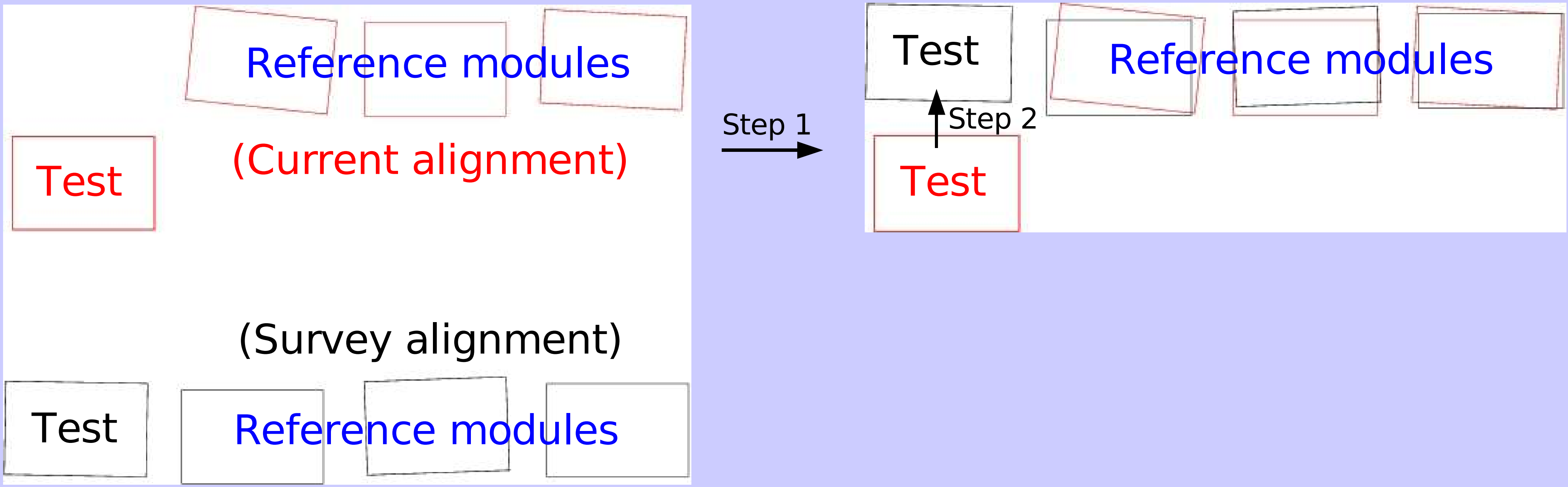
Core
Beam propagation
Primary halo (p)
Diffusion processes 1 nm/turn
Impact parameter ≤ 1 μm
Primary collimator
π
μ
Secondary halo
p
e
Shower
p
Secondary collimator
π
Tertiary halo
p
μ
e
Shower
Super-conducting magnet
Experimental detector
Sensitive equipment
ATLAS

Survey Constraints

- Survey data describes test module's position wrt reference modules
- Survey contains no information on modules' absolute positions

Step 1:
- Find global transformation of reference modules from survey alignment to current alignment
- Exclude the "test module" ⇒ this is equivalent to an unbiased residual where you exclude the hit on the "test layer"

Step 2:
The alignment correction is now given by:
the transformation of the test module from the current position to the predicted position from the survey



Solving Large Systems of Equations

Performance for the Pixel system (12.5k DOFs):

Hardware	Technique	Time
Single CPU	Diagonalisation	6 hours
64 bit cluster w/ 16 AMD Opteron 248 2.2 GHz	Diagonalisation	10 minutes
Single Intel Xeon 3 GHz processor	Sparse matrix (MA27)	15 seconds

All have similar and adequate accuracy

Sparse matrix techniques:

- No real matrix inversion
- Just the solution
- No additional information (eigenvalues, eigenvectors, errors, etc.)
- Fast ⇒ less than 10 min for 35k in a single CPU

FSI – Frequency Scanning Interferometry

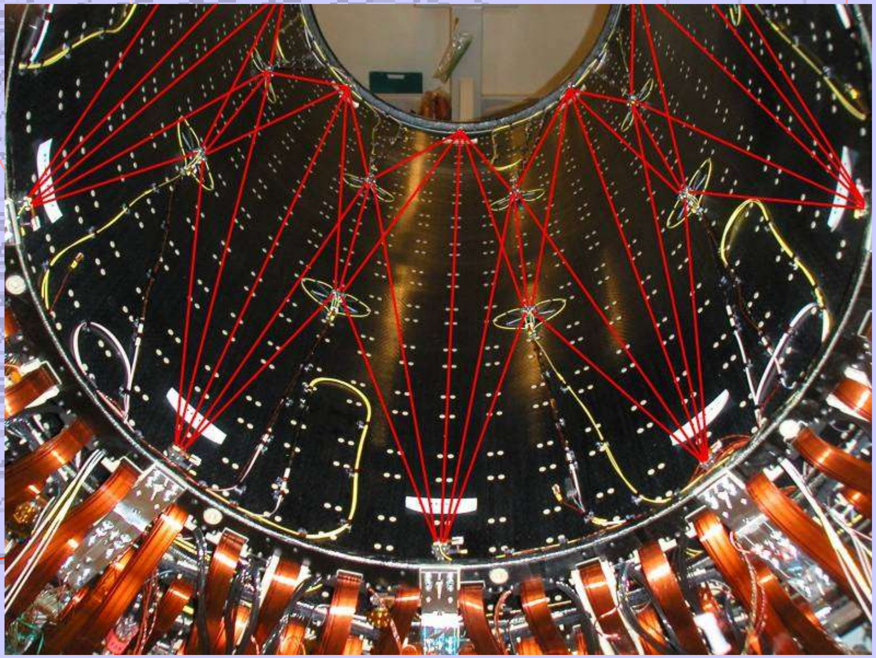
Question: **Short term thermally induced distortions?**

- Temperature stability in the pit?
- Mechanical coupling of sensors to cooling pipes & power cables

Answer: **FSI**

- **Geodetic grid of length measurements** between nodes attached to SCT support structure
- Measure 842 grid lines simulataneously
- Repeat every 10 minutes to measure time variation
- Precision < 1 micron

- **No absolute position measurement!**



Benefits:

- **Quasi real-time tracking of shape changes**
- Define periods of detector stability for alignment
- Need to model correlation between:
  FSI measurement – module position

Can We Even Improve?

Of course, one always can!

Data model support for alignment:
Event, trigger selection
Minimize statistical correlation between modules by prescaling hits on tracks

- Provide estimate of uncertainty for each alignment set

Longer timescale:
Estimate material description, thermal effects, B-field, vibrations, location of charge deposition in silicon,...

- Periodicity of alignment procedure – FSI

- Use even more complementary constraints: control systematics, cover all DOFs

Be really prepared for the unexpected!