Alignment of the ATLAS Inner Detector Tracking System with Cosmic Ray Data

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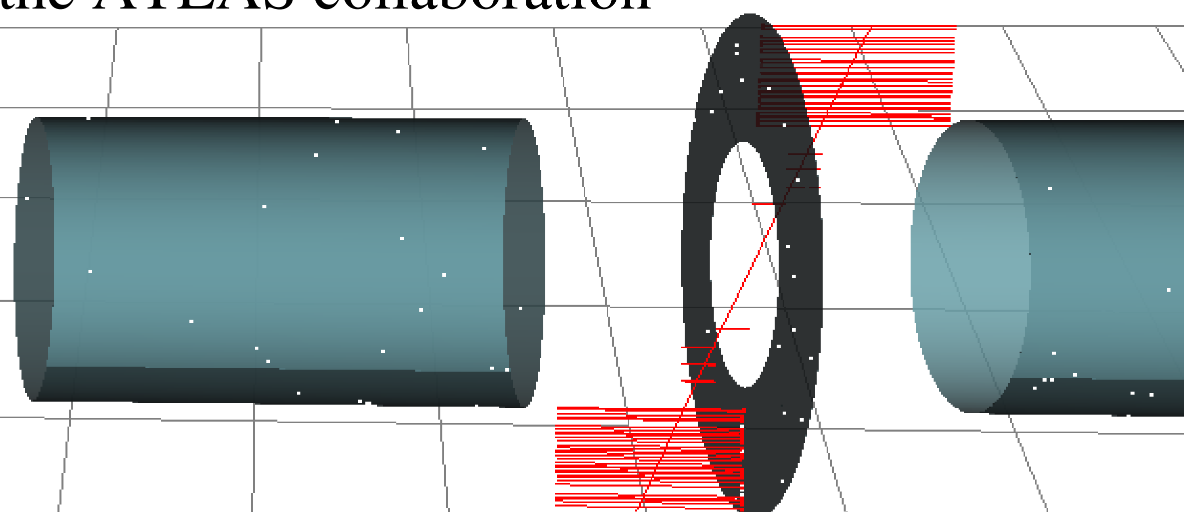
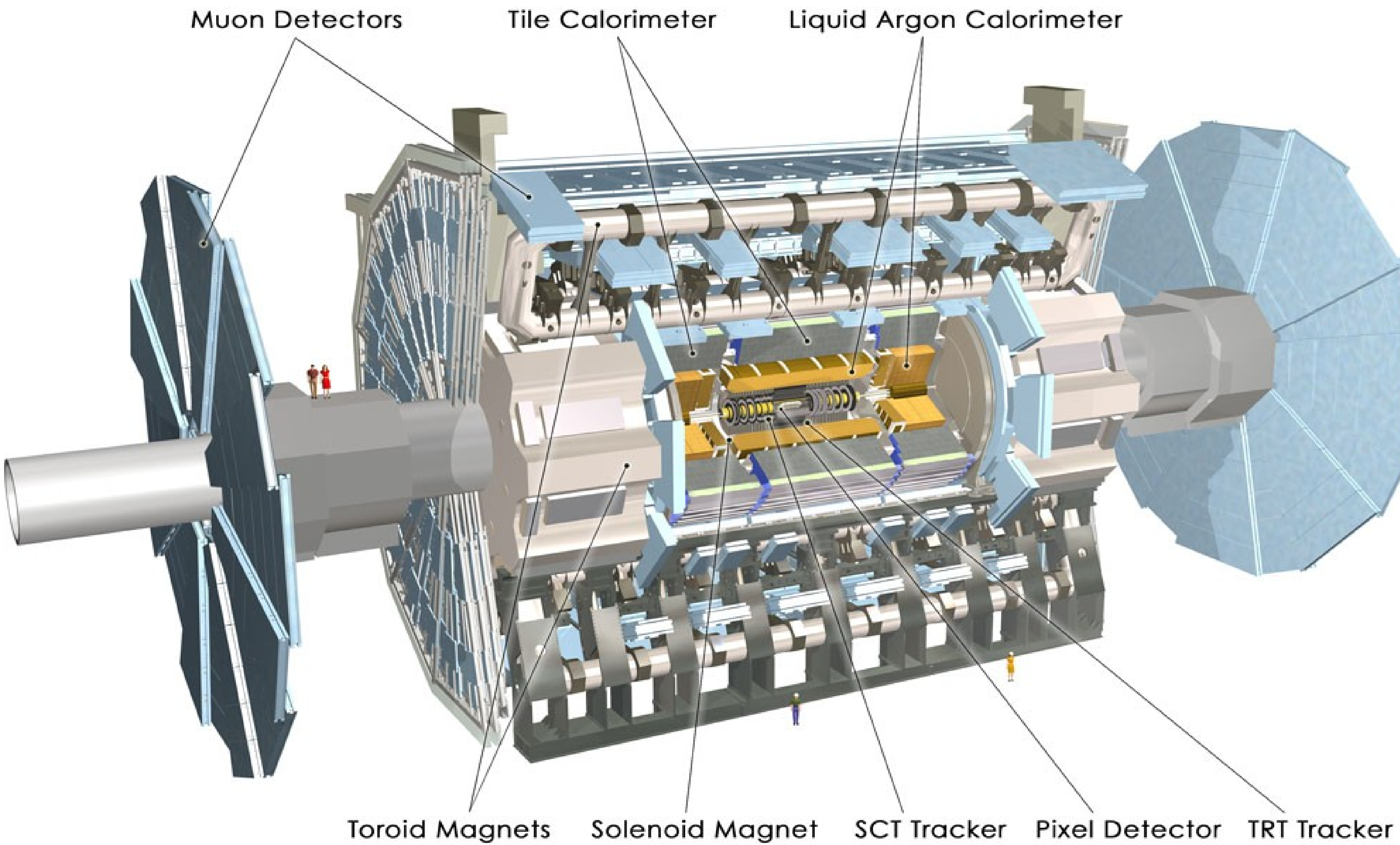
on behalf of the ATLAS collaboration



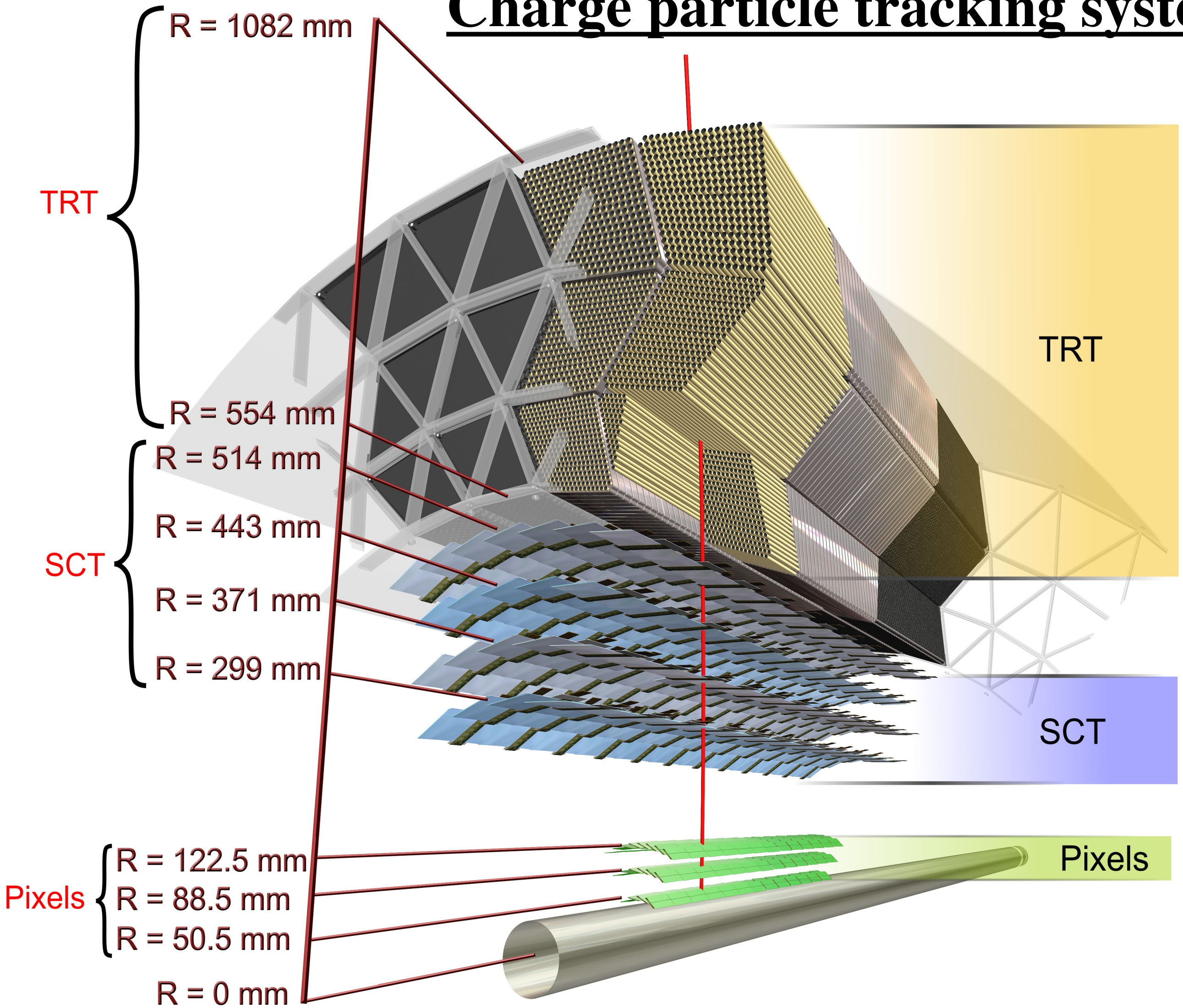
<u>Outline</u>:

- Introduction
- Track Based Alignment
- Results

The ATLAS Detector



The ATLAS Inner Detector



Charge particle tracking system built on two technologies

Drift tubes:

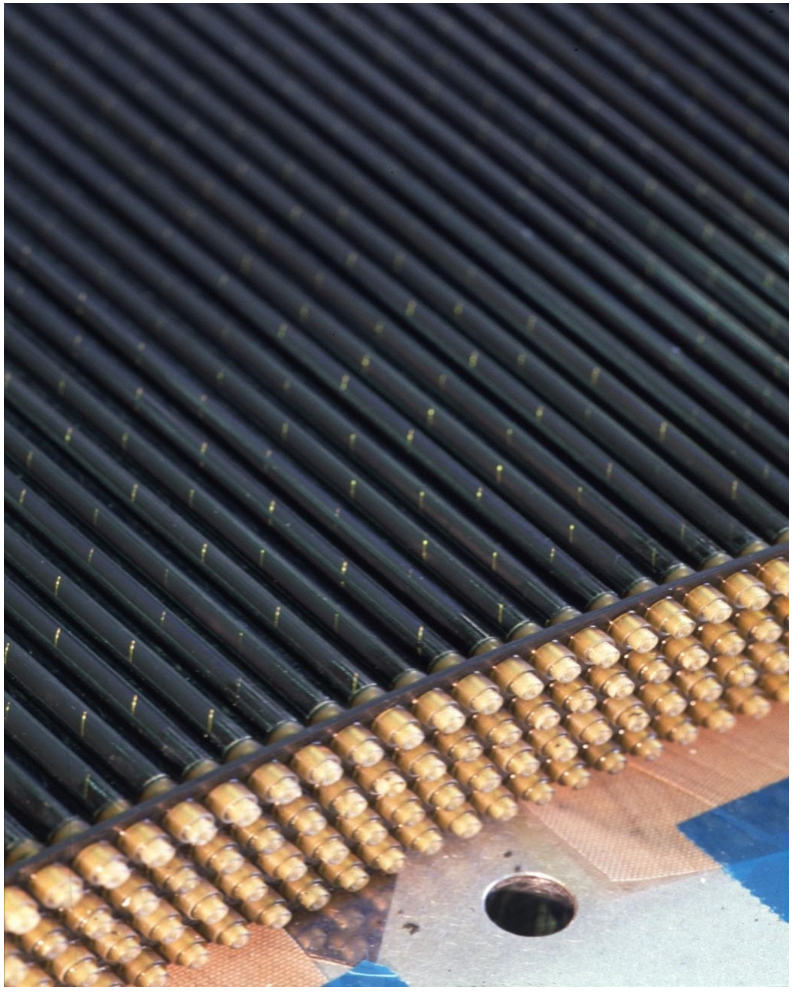
~300,000 straw tubes
resolution 130 μm (Rϕ)
$Xe\text{-}CO_2\text{-}O_2$
30 hits per track

Silicon:

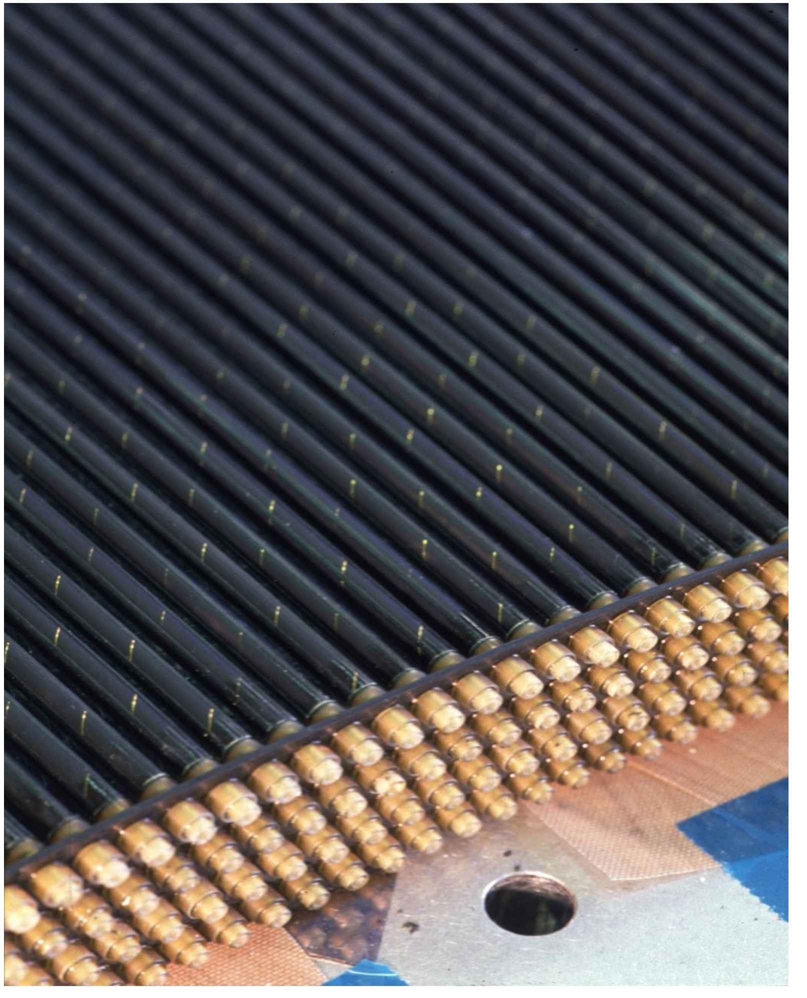
~ 6M Si strips
resolution: 17 μm (Rϕ)
580 μm (Z)
4 barrel layers / 2 x 9 endcap disks

~ 80M Si pixels
resolution: 10 μm (Rϕ)
115 μm (Z)
3 barrel layers/ 2 x 3 endcap disks

Construction highly modular



Construction highly modular



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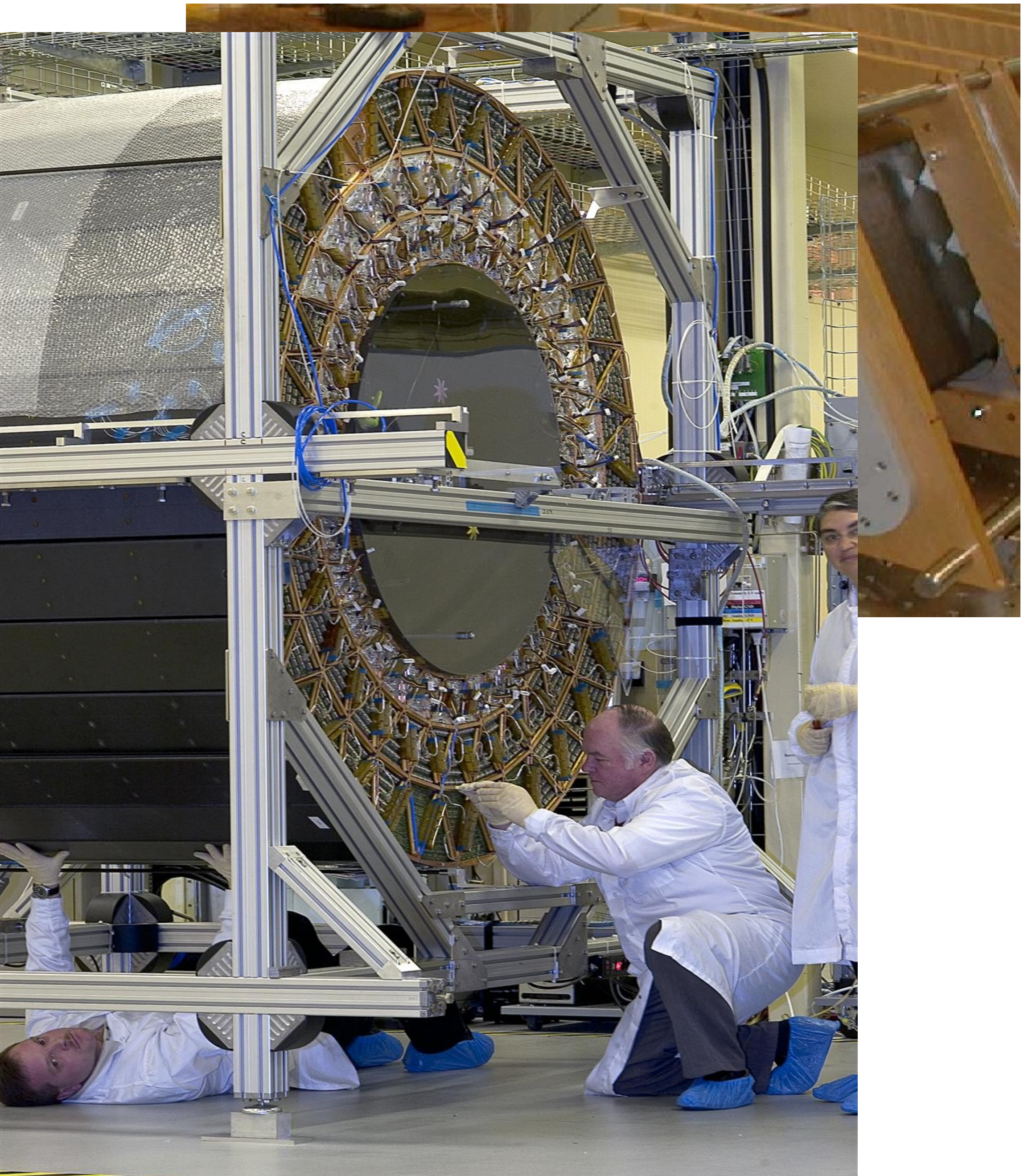

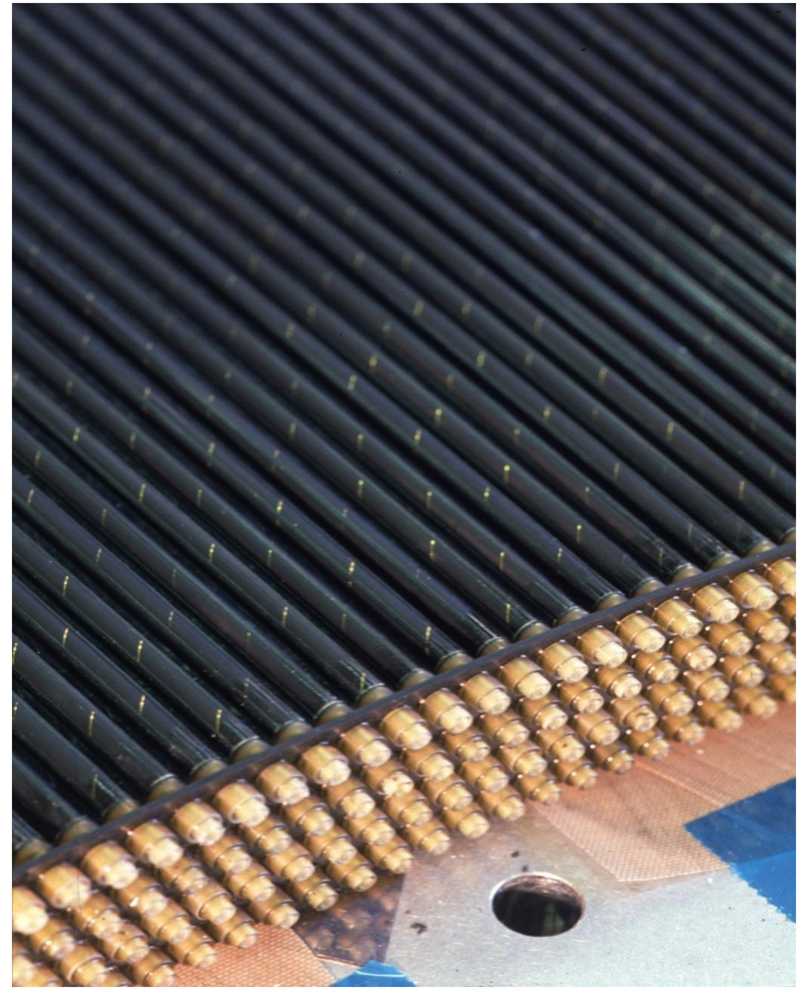

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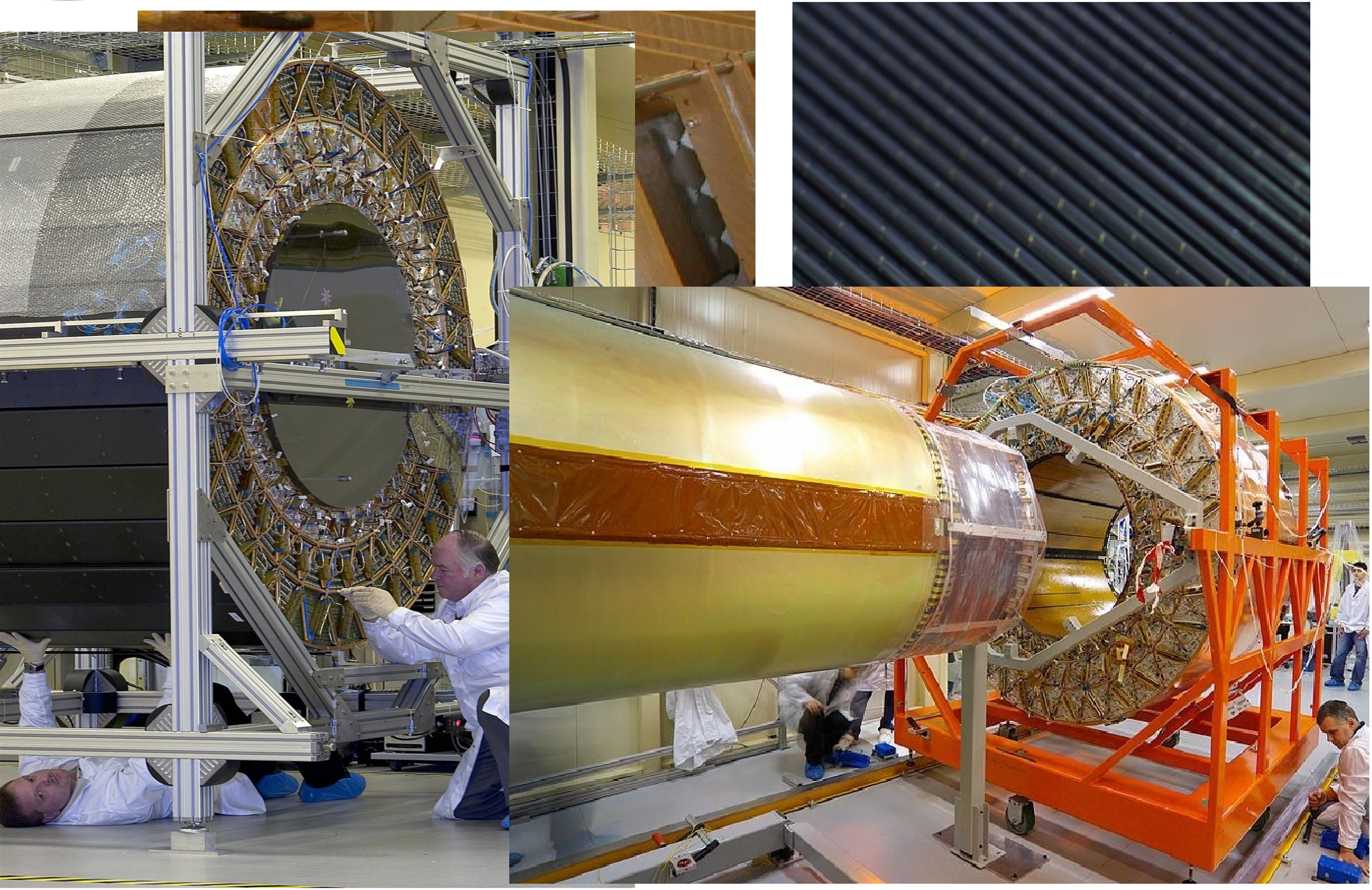

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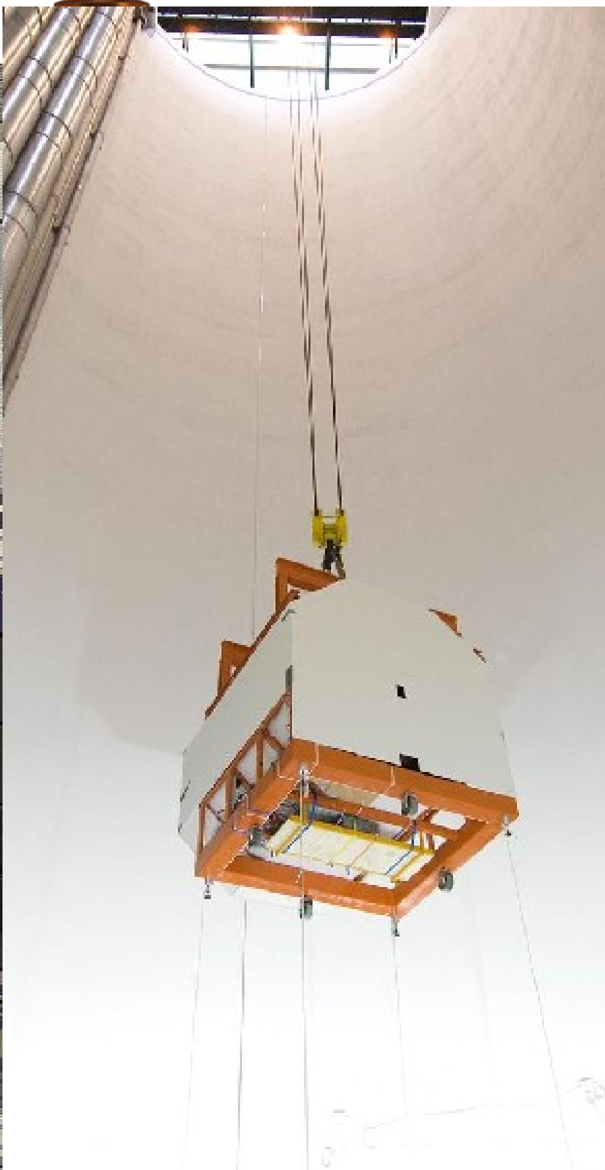
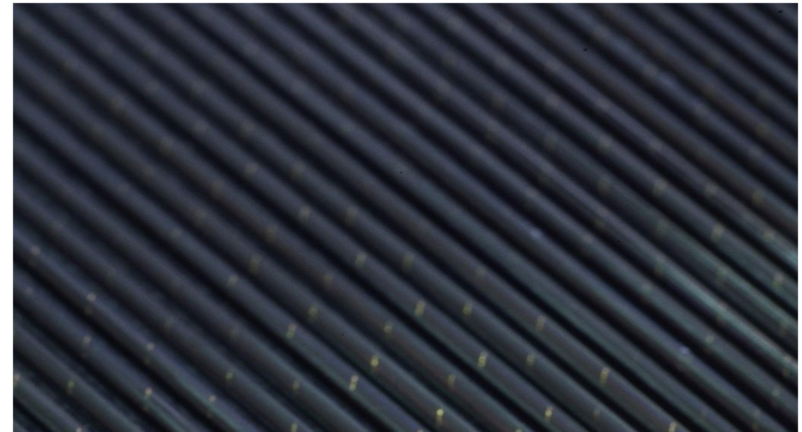
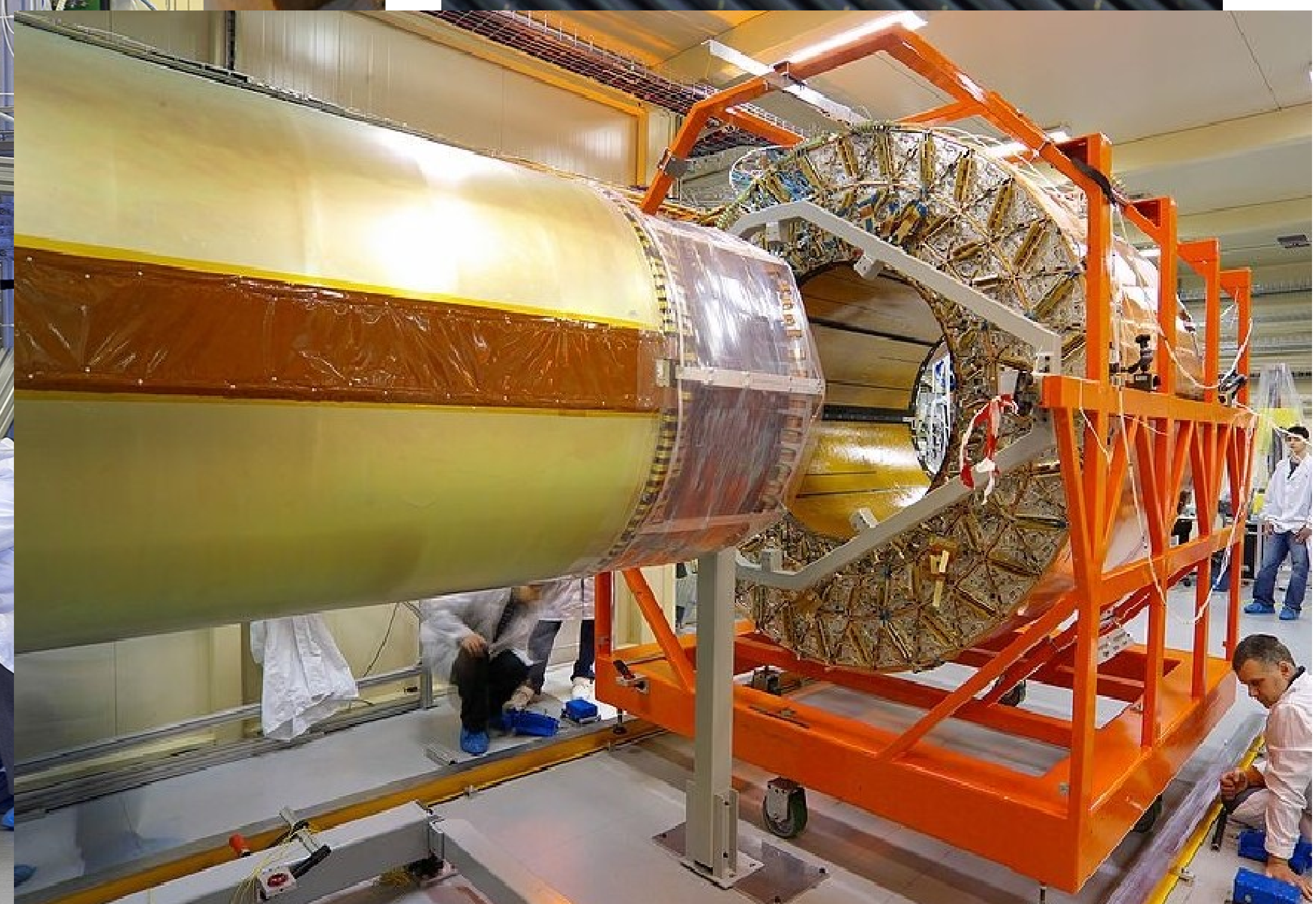
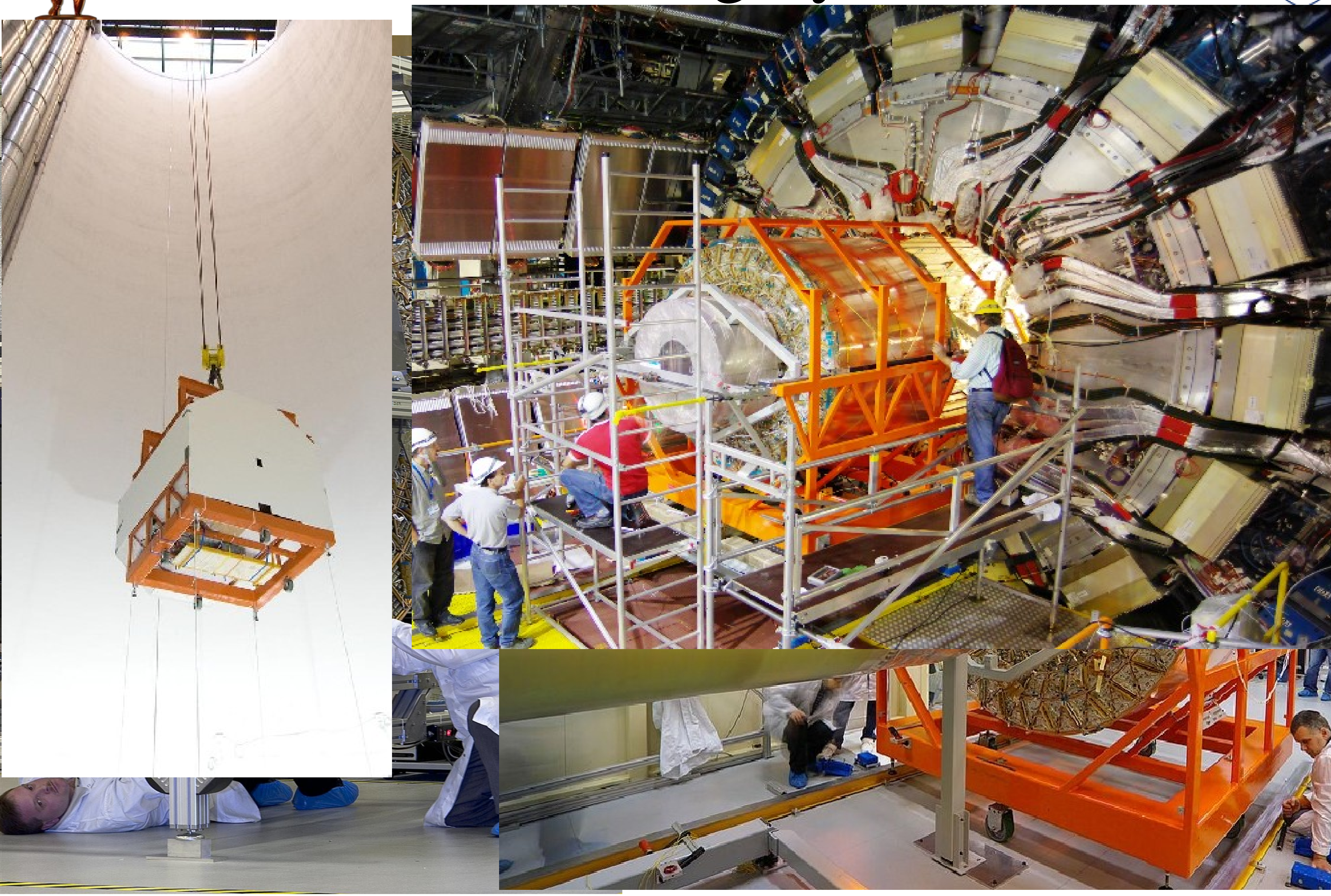




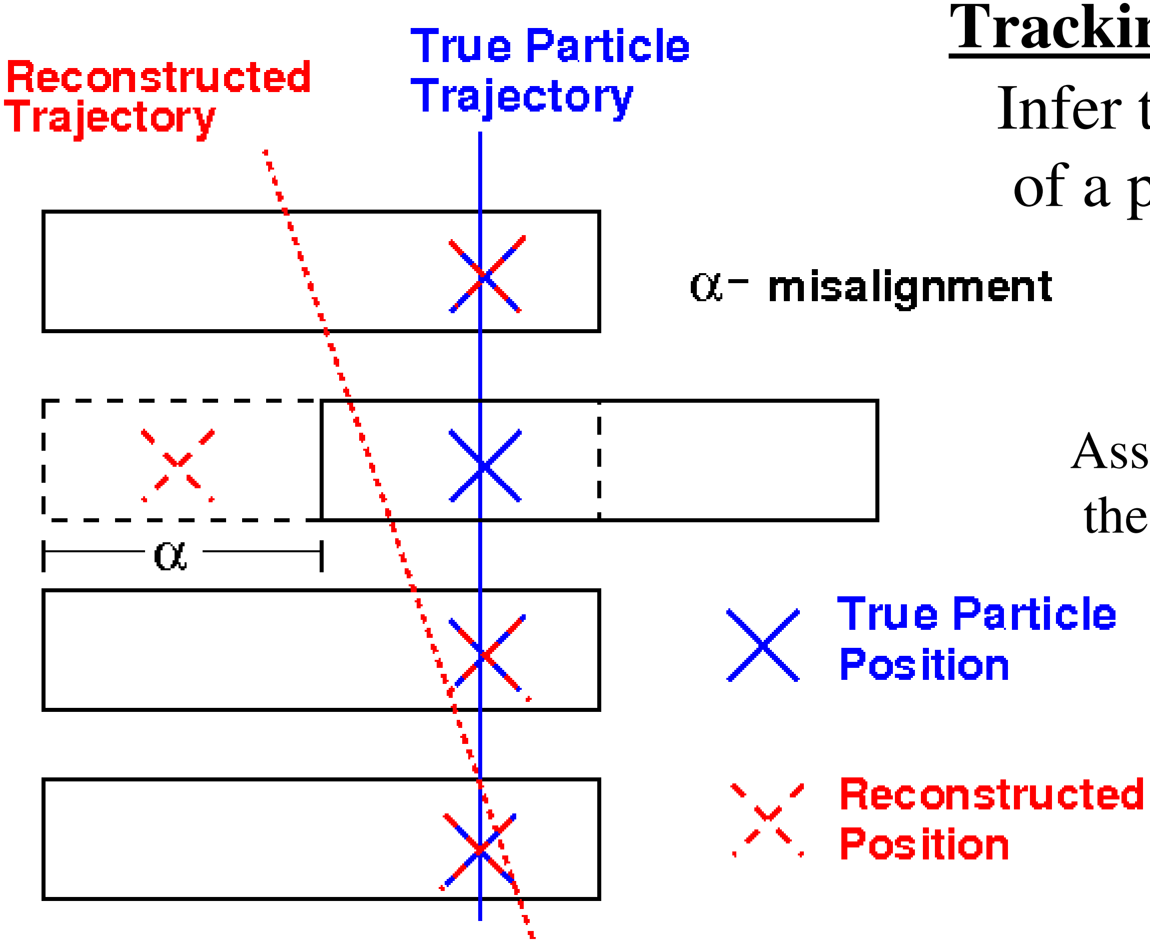


Construction highly modular



What is alignment ?

Detector positions used in reconstruction algorithms do not correspond to the actual relative positions of the installed detector.



<u>Tracking Goal</u>

Infer the position, direction, momentum of a particle given hits associated to it

Local Measurements
+
Assumptions about the relative location of the elements making these measurements

<u>Why is Alignment needed?</u>

The initial assumptions wrong

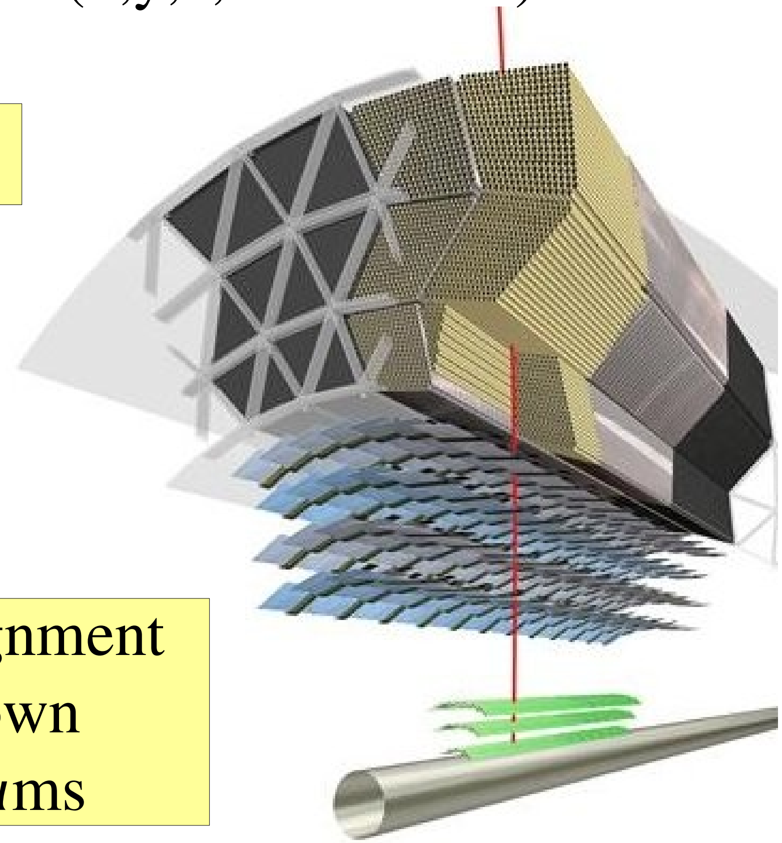
Alignment in ATLAS

Each module is positioned w/ 6 degrees of freedom (x,y,z, 3 rotations):

Si : 1744 pixel modules, 4088 SCT modules

TRT: 176 modules

~ 35,000 parameters!



Different scales of mis-alignments:

<u>Relative Sub-detector</u> (Si / TRT , Barrel, Endcap)

- Largest impact on physics

<u>Internal Sub-detector</u>

- Requires more statistics,
- Needed for ultimate precision

Requires alignment to be known order 10 μms

<u>Alignment Objective</u>

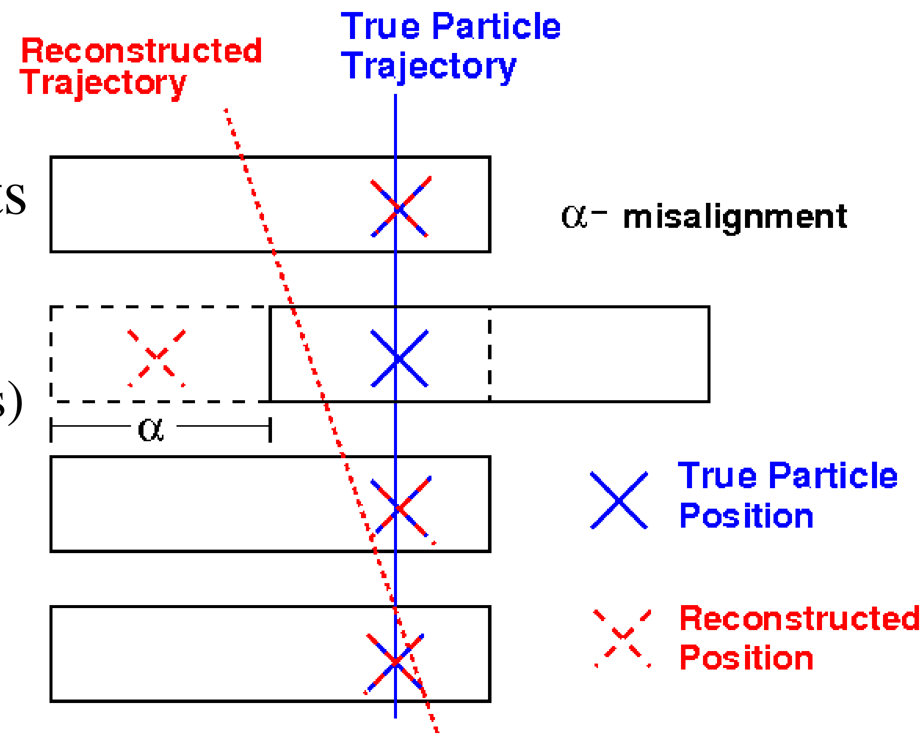
Determine relative position of in-situ detectors with the precision that alignment uncertainties contribute to less than 20% of the track parameter resolution for muons with $p_T = 100$ GeV.

* precision physics requires the alignment to be known to O(microns) longer term goal

Track Based Alignment

<u>Introspective</u>

Use fact that detector misalignments affect track parameter to measure the misalignments



Define a statistic sensitive to mis-alignments

(ie: local measurements & our offline assumptions)

$$\chi^2 = \sum_{\text{hits i}} \left(\frac{m_i - r_i(\alpha)}{\sigma_i} \right)^2$$

<u>Key properties of χ^2 function</u>

- its an explicit function of the alignment parameters (α)
- it has a minimum at the true values of the alignment parameters

Means we can calculate $\frac{d\chi^2}{d\alpha}$

True alignment gives $\frac{d\chi^2}{d\alpha} = 0$

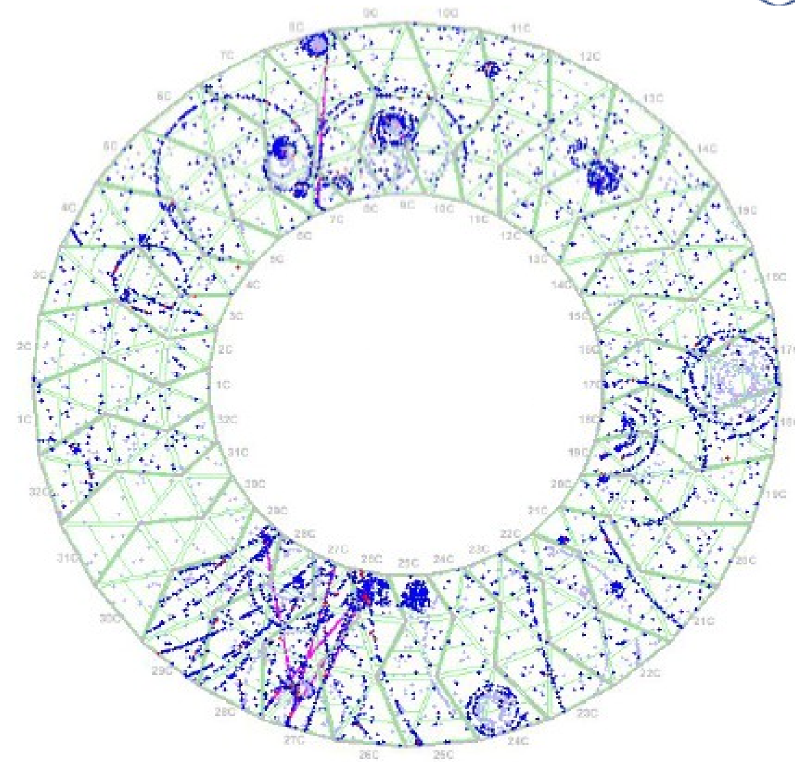
"Personally, I liked the university. They gave us money and facilities, we didn't have to produce anything. You've never been out of college. You don't know what it's like out there. I've worked in the private sector. They expect results."

- Dr. Ray Stanz

And now, some results.

Cosmic Ray Data

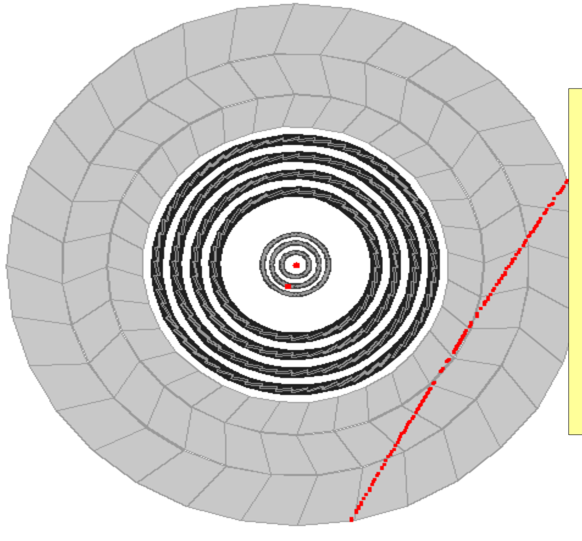
-Data taking period fall 2008.
-Over 7 million tracks reconstructed in ID
- First data available for the alignment.



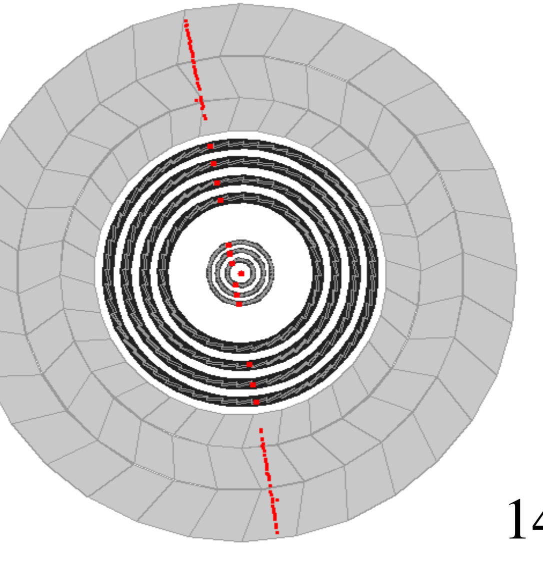
<u>Alignment has been performed:</u>

between ID subsystems

internally with in barrel modules

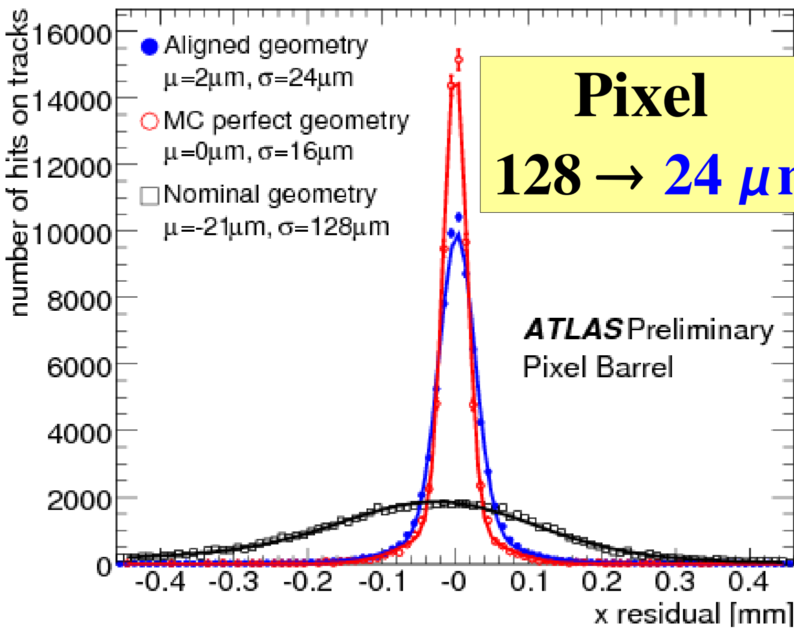


Topology of cosmic ray tracks provides alignment algorithms with a unique way of seeing the detector

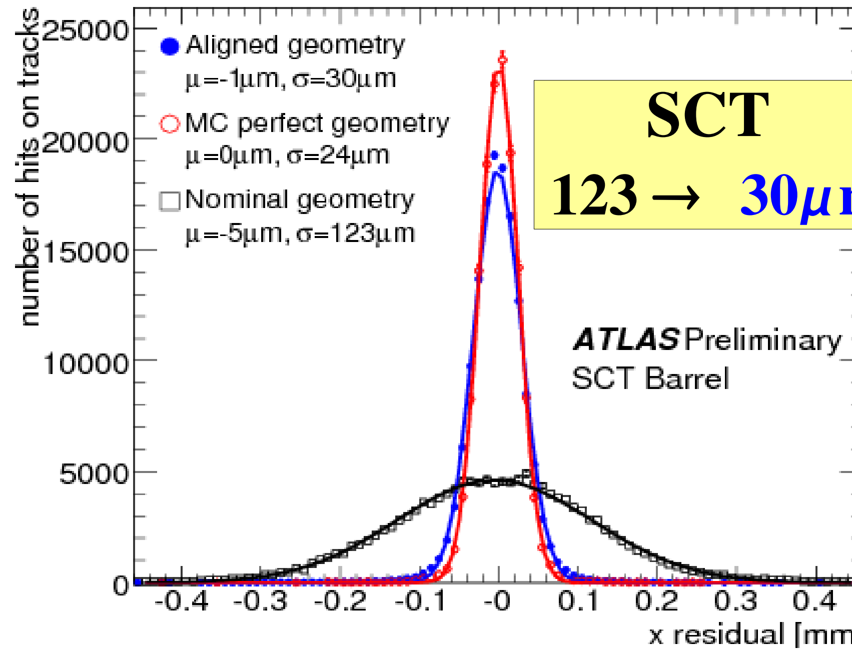


Residuals **Before** / **After** Alignment

(Difference in measured position and prediction based on track fit)



Pixel
128 → 24 μm



SCT
123 → 30μm

<u>Tracks shown required</u>

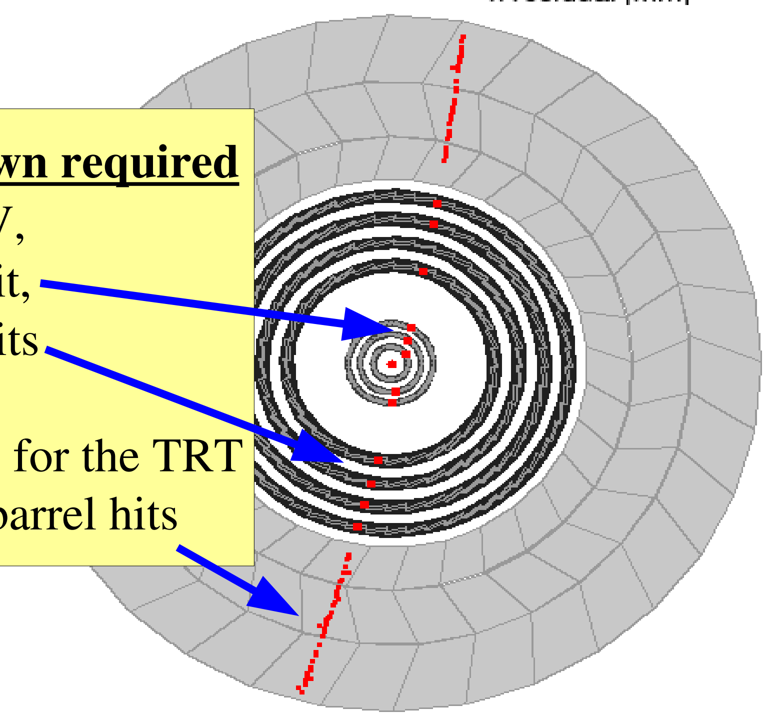
pT > 2 GeV,

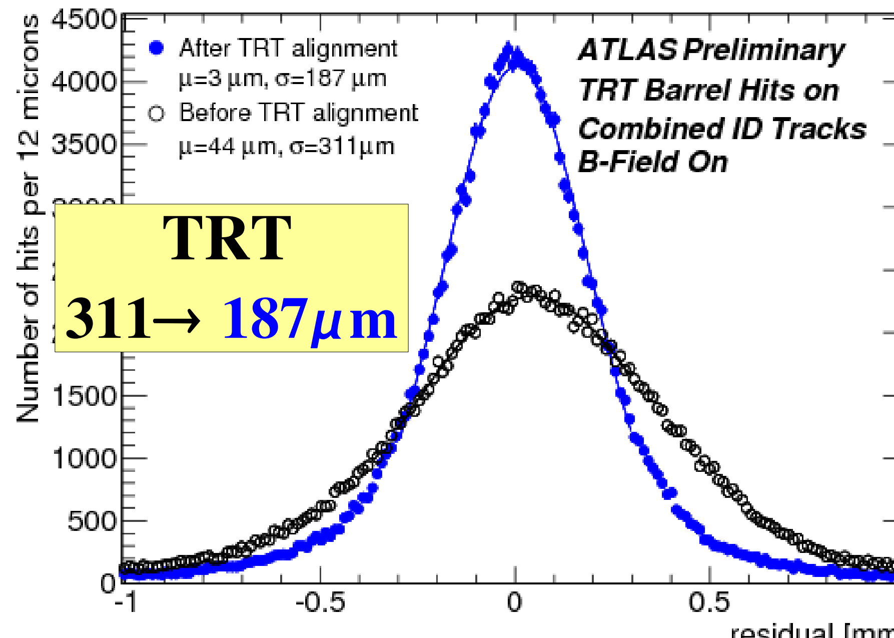
> 1 Pixel hit,

> 8 SCT hits

Additionally for the TRT

> 45 TRT barrel hits

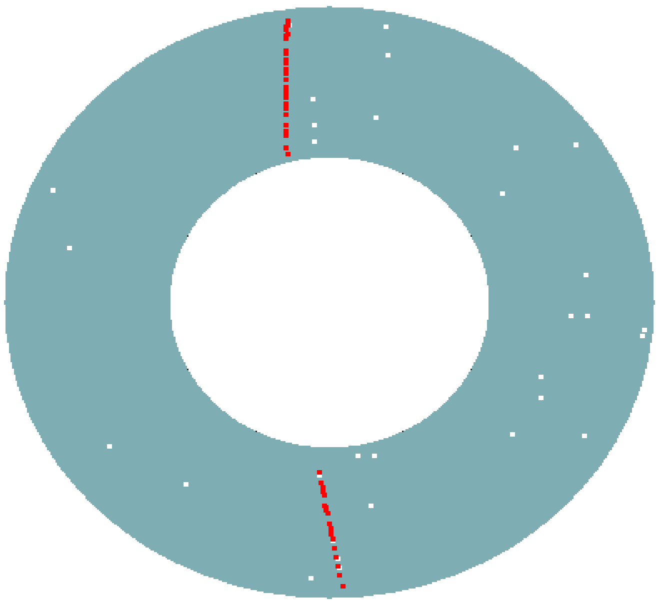




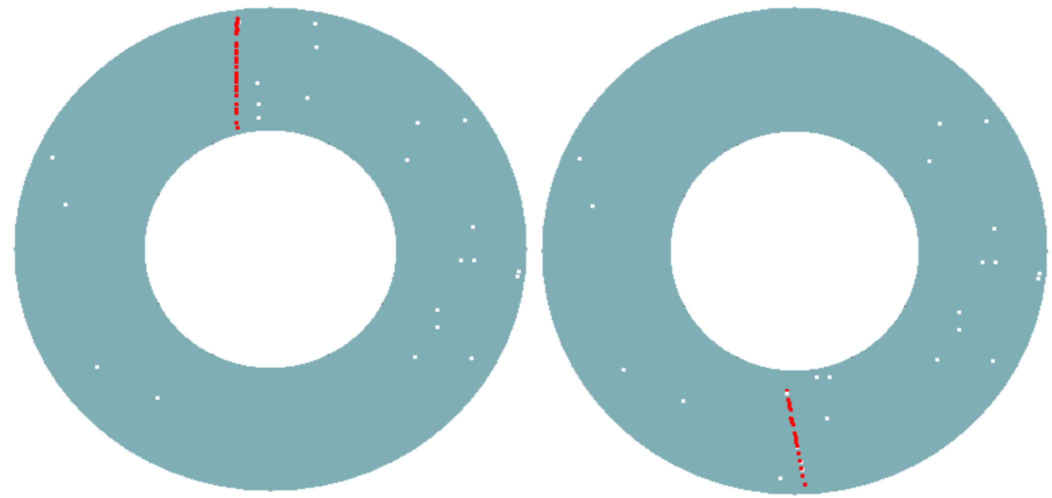
TRT
311→ 187μm

Validating alignment with data

Cosmic rays come from above traverse entire ID



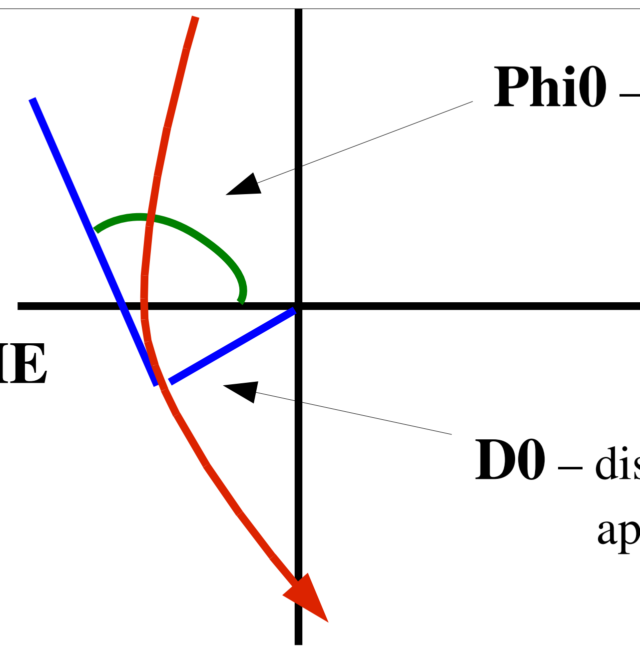
Can be split in half treated as separate particles



- Same particle.

- Track parameters describing the two reconstructed tracks should be the **SAME**

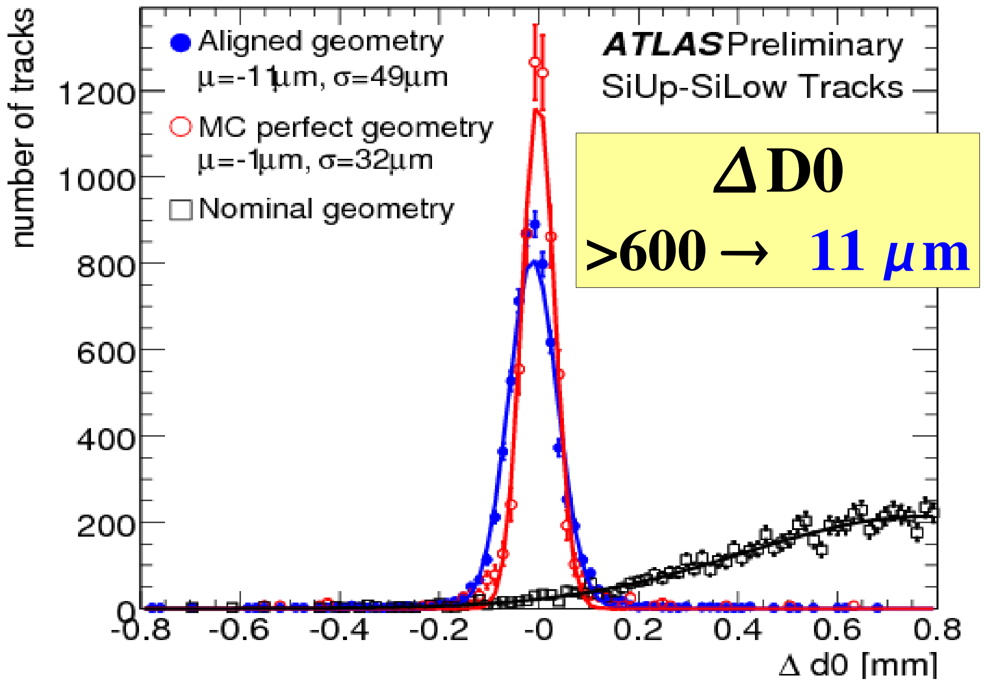
- Detector mis-alignment will lead to discrepancies

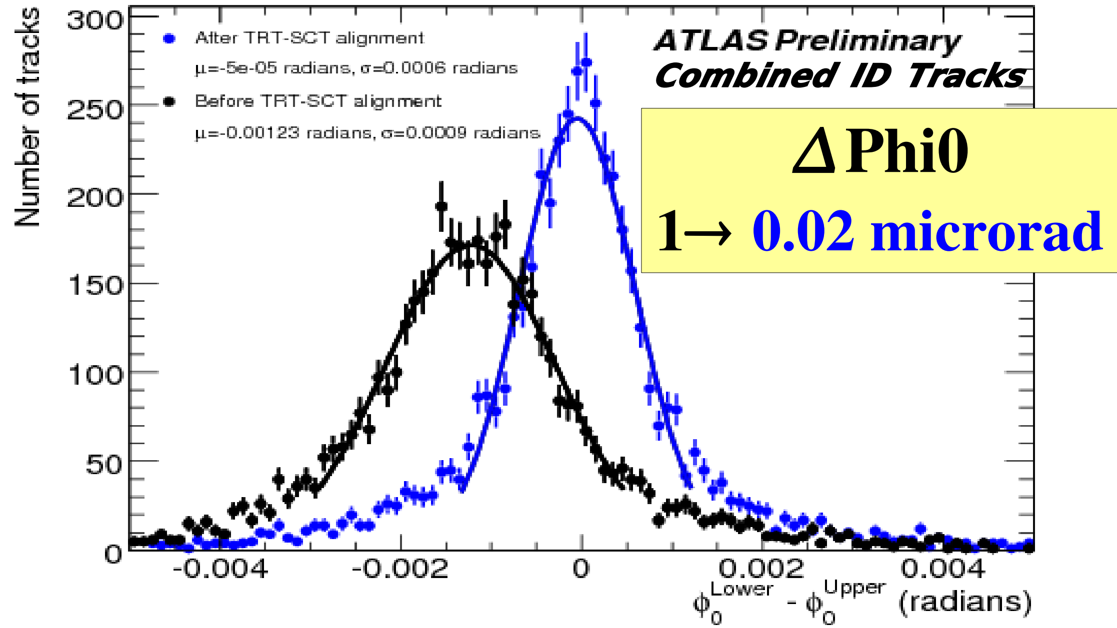


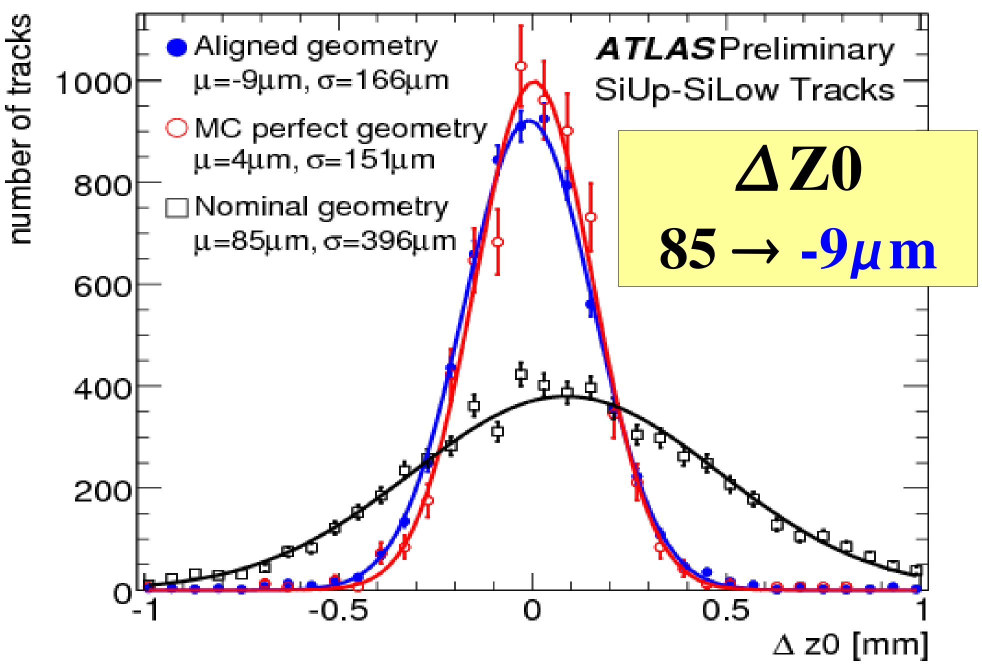
Phi0 – azimuthal direction at point of closest approach to origin

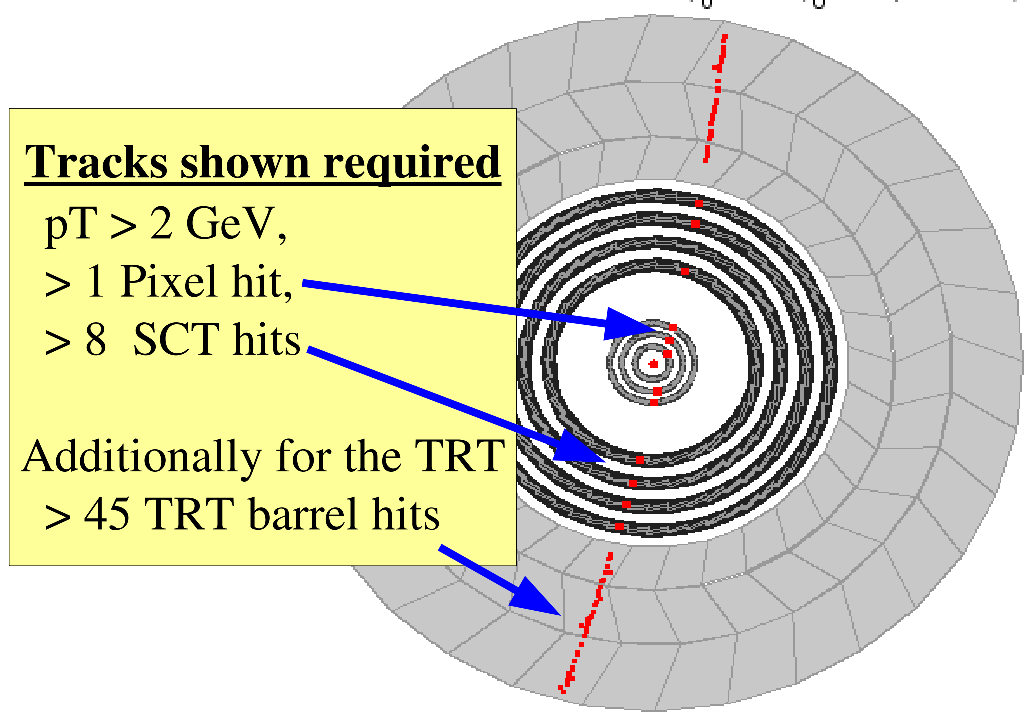
D0 – distance of closest approach to origin

Track Parameters **Before** /**After** Alignment









Conclusions

- **Overall scope and ultimate precision of ATLAS Inner Detector poses a challenging problem in terms of understanding the detector.**
  Measure rotations, displacements, and distortions of over 5,000 detector elements covering volume of m^3 to 10s of microns

- **Cosmic-ray data provided huge improvements over nominal geometry and will continue to guide the way to the ultimate alignment**

- **Detector alignment procedure has been tested and validated on data from cosmic muons and is ready for collisions.**

Bonus.

Solutions to the Alignment Problem

Assembly / Survey Measurements
- External measurements of as-built detector
- after/during installation

Frequency Scanning Interferometry
- laser interference monitors differences in detector positions in real time

Track Based Alignment Algorithms
- Global χ^2
- Local χ^2
- Robust Alignment
- External constraints
  - introduction of vertex, pT, survey, e/p constraints to formalism of Global χ^2 and Local χ^2 methods

Each of these methods have been employed in solving the ATLAS ID Alignment problem to varying degrees

Will only concentrate on track based methods in the following

Track Based Alignment

Solution:

Need:

$$\frac{d\chi^2}{d\alpha} = 0$$

Approximate:

$$\frac{d\chi^2(\alpha)}{d\alpha} \approx \frac{d\chi^2(\alpha_0)}{d\alpha} + \left.\frac{d^2\chi^2}{d\alpha^2}\right|_{\alpha_0} (\alpha - \alpha_0)$$

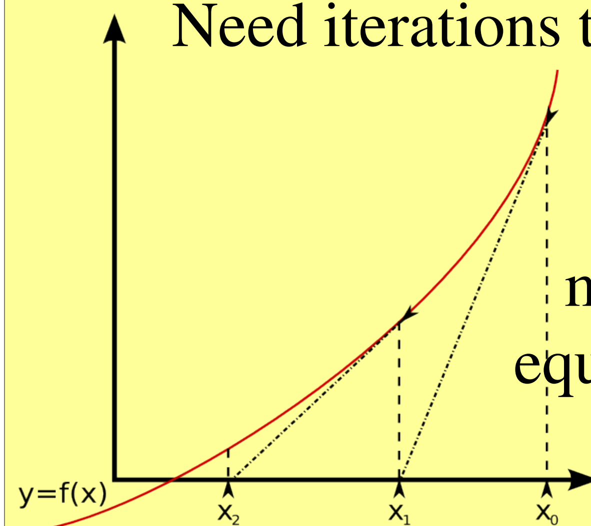
α_0 - current alignment positions

Solution:

$$\Delta\alpha \equiv \alpha - \alpha_0 = -\left(\left.\frac{d^2\chi^2}{d\alpha^2}\right|_{\alpha_0}\right)^{-1} \frac{d\chi^2(\alpha_0)}{d\alpha}$$

N x N matrix
with N ~ 35K
Inversion non-trivial

In general highly non-linear
Need iterations to solve.



moral equivalent

Global Vs Local

- Described Global χ^2 method.
- Local χ^2 method exactly the same except:

$$\left(\left.\frac{d^2\chi^2}{d\alpha^2}\right|_{\alpha_0}\right) \longrightarrow \begin{pmatrix} \frac{d\chi^2}{d\alpha_1 d\alpha_1} & \cdots & \frac{d\chi^2}{d\alpha_1 d\alpha_j} & 0 & 0 & 0 & \\ \vdots & \ddots & \vdots & 0 & 0 & 0 & \cdots \\ \frac{d\chi^2}{d\alpha_i d\alpha_1} & \cdots & \frac{d\chi^2}{d\alpha_i d\alpha_j} & 0 & 0 & 0 & \\ 0 & 0 & 0 & \frac{d\chi^2}{d\beta_1 d\beta_1} & \cdots & \frac{d\chi^2}{d\beta_1 d\beta_j} & \\ 0 & 0 & 0 & \vdots & \ddots & \vdots & \\ 0 & 0 & 0 & \frac{d\chi^2}{d\beta_i d\beta_1} & \cdots & \frac{d\chi^2}{d\beta_i d\beta_j} & \\ & \vdots & & & & & \ddots \end{pmatrix}$$

Pros:
- Invert smaller matrices

Cons:
- Iterations needed to handle module correlations
- Explicit information loss
- More susceptible to weak modes

α_i β_i alignment parameters for physically distinct align-able modules

Dealing with $\left(\frac{d^2\chi^2}{d\alpha^2}\bigg|_{\alpha_0} \right)^{-1}$

- Diagonalization:

Most CPU intensive

Provides alignment parameter errors

Removal of "weak modes"

Done w/ N ~ 1000

$$\left(\frac{d^2\chi^2}{d\alpha^2}\bigg|_{\alpha_0} \right) = UDU^T$$

U – eigenvectors D - $\begin{pmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_n \end{pmatrix}$

$$C(\alpha) = UD^{-1}U^T$$

CLHEP, LAPACK

- Full inversion:

Still CPU intensive

Provides alignment parameter errors

- Fast Solver Techniques

Exploits unique properties of derivative matrix (sparseness, symmetry)

Iterative method, minimizes distance to solution

No errors provided

Dealing with $\left(\frac{d^2\chi^2}{d\alpha^2}\bigg|_{\alpha_0}\right)^{-1}$

- Diagonalization:

Most CPU intensive

Provides alignment parameter errors

Removal of “weak modes”

- Full inversion:

Still CPU intensive

Provides alignment parameter errors

- Fast Solver Techniques

Exploits unique properties of derivative matrix (sparseness, symmetry)

Iterative method, minimizes distance to solution

No errors provided

Done w/ N > 10,000K

Minimize the distance defined as:

$$d = \left|\frac{d^2\chi^2}{d\alpha^2}\Delta\alpha + \frac{d\chi^2}{d\alpha}\right|$$

MA27 Fortran routine from HSL

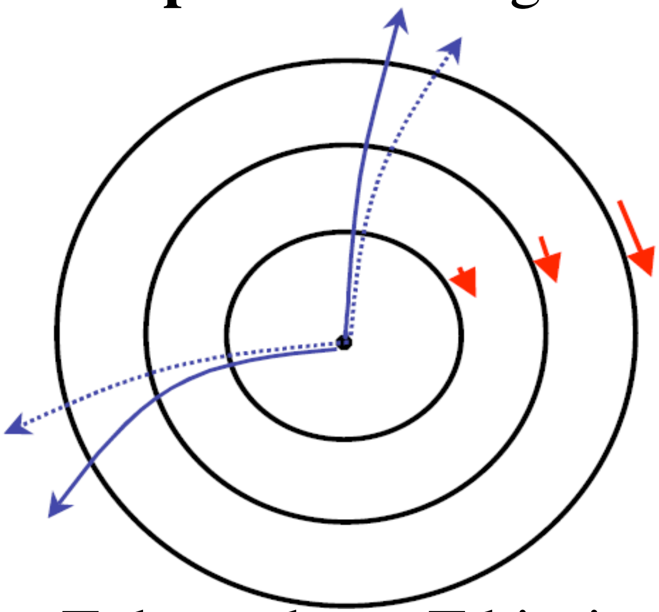
Weak Modes

Weak Modes: Detector deformations which have little if any impact on χ^2

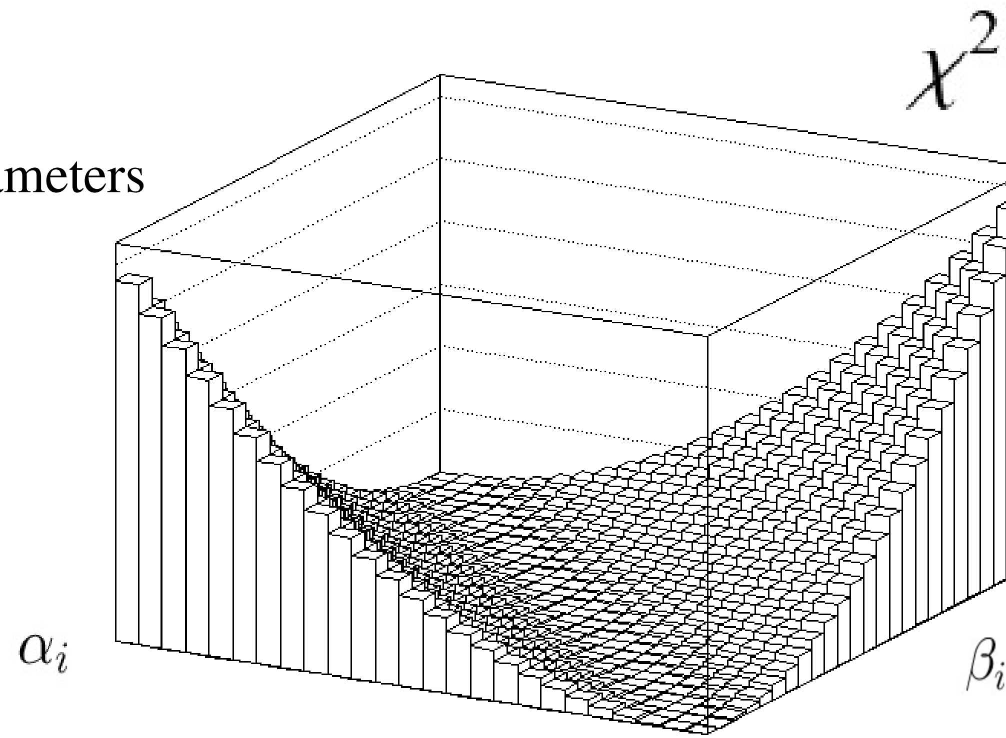
- inherently problematic for any method based only on χ^2
  - $\frac{d\chi^2}{d\alpha} = 0$ Solution is blind to multiple minima / clases of minima

- physically important:
  keep χ^2 unchanged by biasing track parameters

Example: "Clocking Effect"



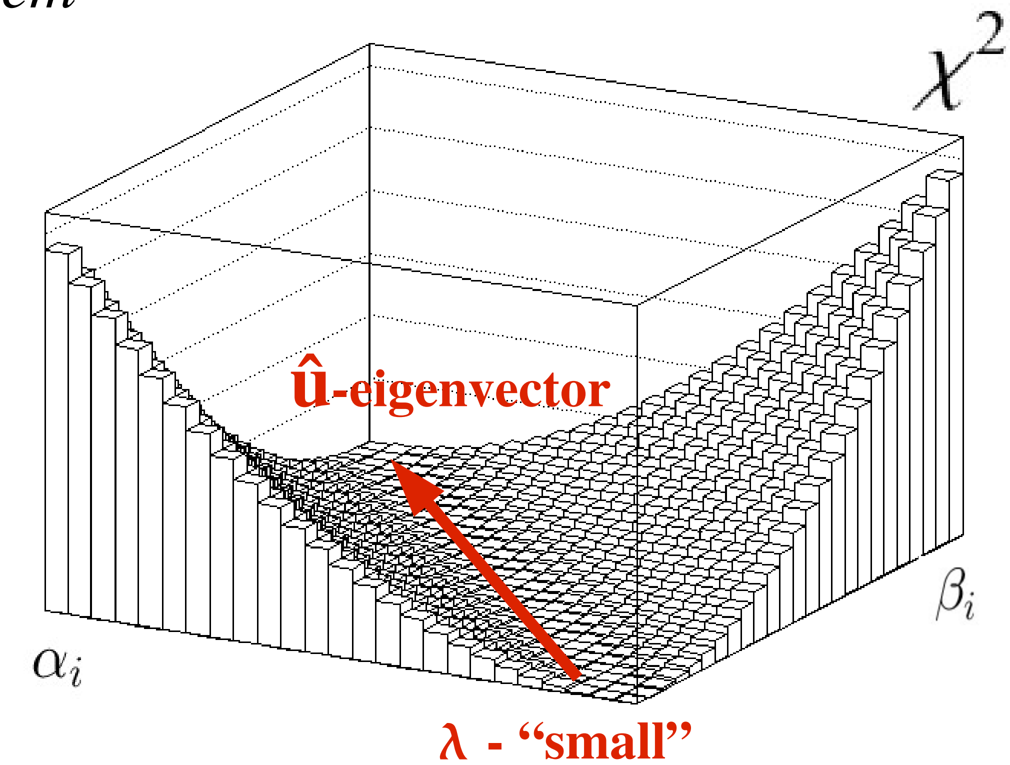
pT dependent pT biasing



Whole class of systematic distortions which plague detectors with cylindrical symmetry

Dealing with Weak Modes

Weak Modes: *The real alignment problem*



Detecting weak modes:

- Diagonalization provides means of diagnosis

$$C(\alpha) = UD^{-1}U^T$$

Removing weak modes:

- Explicitly remove modes below threshold
  - used to remove global movements,
  - can be dangerous / threshold arbitrary
- Enhancing definition of χ^2
  - add terms to χ^2 which depend on track parameters (eg: pT constraint, e/p)
- Event topology
  - χ^2 landscape highly dependent on event properties.
  - different events = different weak mode (a good thing!)
  - cosmic rays/beam halo, long lived decays.

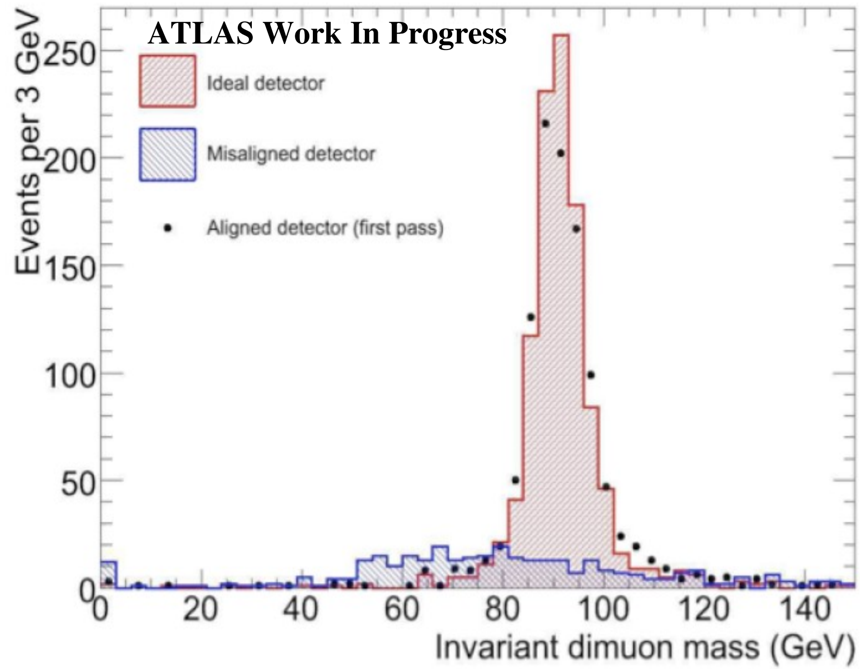
Full Scale Test Alignment Procedure

Large sample of events simulated with realistically misaligned geometry

GOAL:

- Exercise alignment algorithms, test technical infrastructure
- Provided alignment constants to the wider physics community

Type of Mis-Alignment	Magnitude of Mis-Alignment	Number Tracks Needed
Relative subsystem (Barrel / Endcap)	O(mm) translation O(mrad) rotation	20K
Si Layers/Wheels	O(100 μm) translation O(0.1 mrad) rotation	500K 50K(cosmic)
TRT Modules/Wheels	O(100s μm) translation O(0.1 mrad) rotation	20K
Si Modules	O(< 100 μm) translation O(< 0.1 mrad) rotation	1M



Muon pair mass resolution using tracks in reconstructed in the Inner Detector

Big Success:

Both in terms of validating the alignment procedures and in understanding problems likely to arise.

Alignment Levels

Silicon Alignment Levels					
Geometry Level	Structures (DoFs)	Pixel	Pixel Structures (DoFs)	SCT	SCT Structures (DoFs)
1	4 (24)	complete pixel detector	1 (6)	1 barrel + 2 endcaps	3 (18)
1.5	7 (42)	2 barrel half-shells + 2 endcaps	4 (24)	1 barrel + 2 endcaps	3 (18)
1.6	11 (66)	3*2 barrel half-shells + 2 endcaps	8 (48)	1 barrel + 2 endcaps	3 (18)
2	31 (186)	3 barrel layers + 2*3 endcap discs	9 (54)	4 barrel layers + 2*9 discs	22 (132)
2.1	- (-)	-	- (-)	-	- (-)
2.3	- (-)	-	- (-)	-	- (-)
2.5	- (-)	-	- (-)	-	- (-)
3	5832 (34992)	1456 barrel + 2*144 endcap	1744 (10464)	2112 barrel + 2*988 endcap	4088 (24528)

TRT Alignment Levels			
Geometry Level	TRT	TRT DoFs	comments
1	1 barrel + 2 endcaps	17	no alignment correction around the global Z-coordinate in the barrel
2	32*3 barrel modules+ 40*2 endcap wheels	(32x3) x 5 Dof + (40x2) x 6 Dof = 960	

More Weak Modes