Alignment of the ATLAS Inner Detector Tracking System

John Alison

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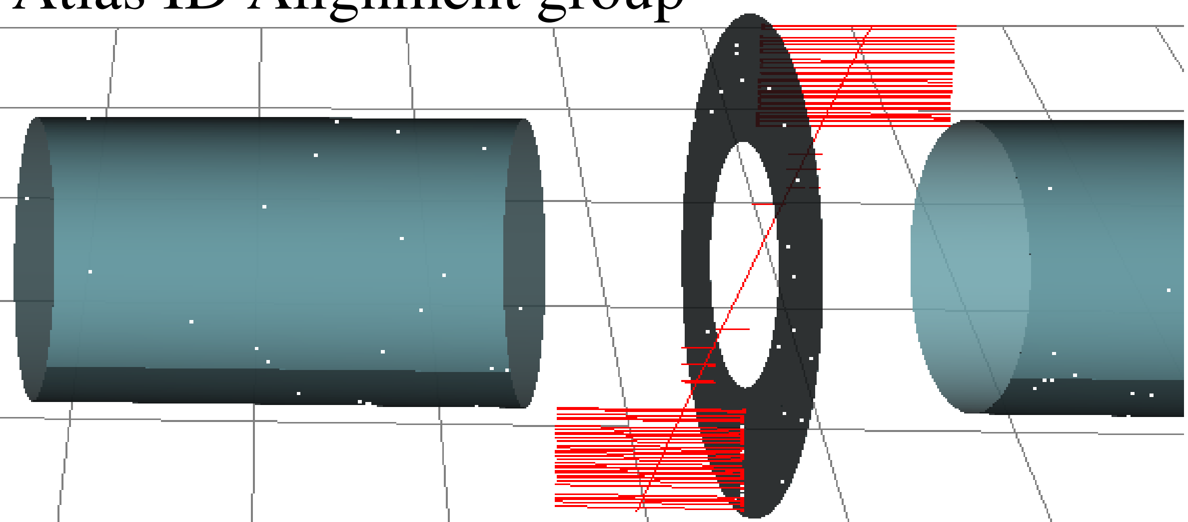
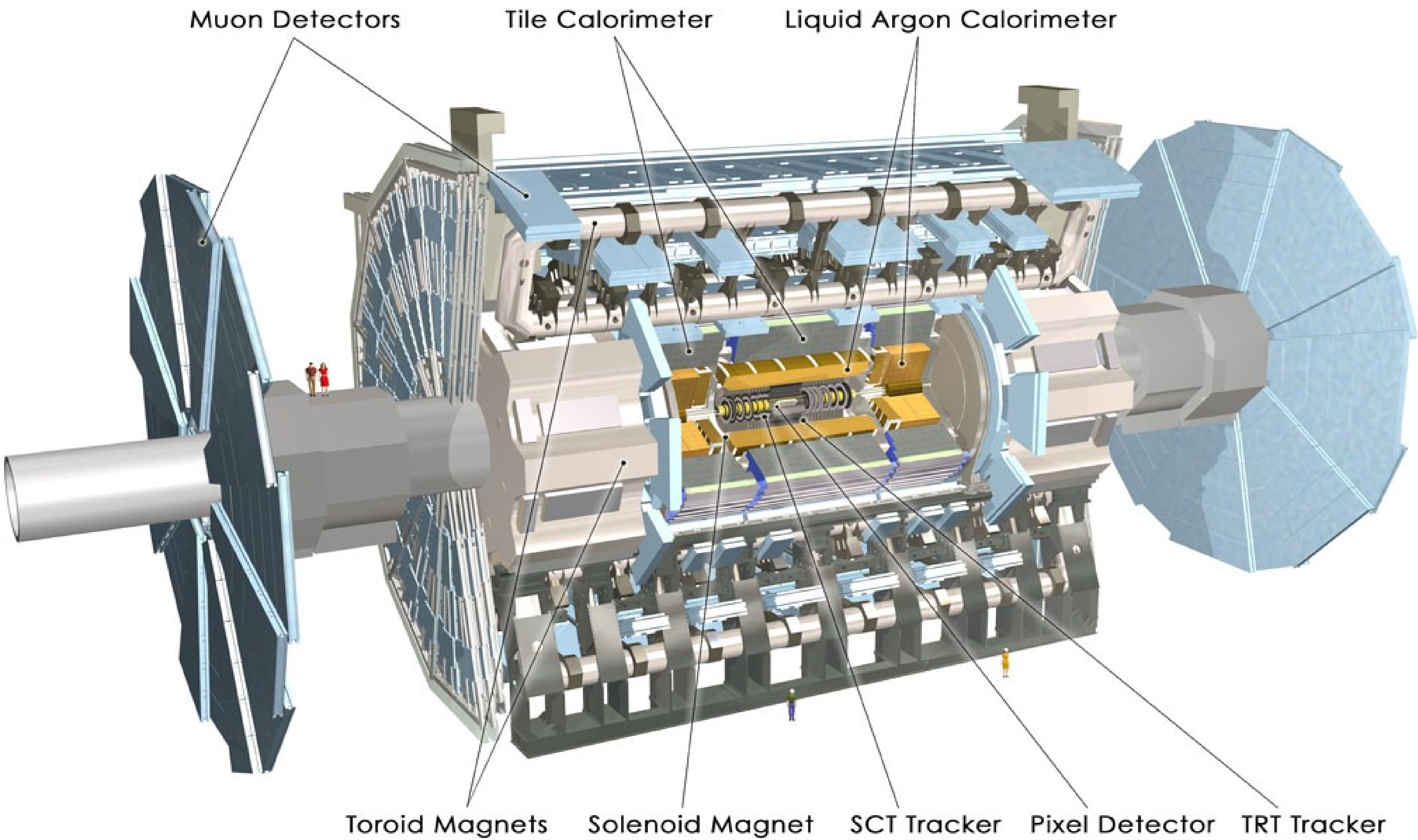
on behalf of the Atlas ID Alignment group

<u>Outline</u>:

- Introduction
- Alignment Problem
- Possible Solutions
- Track Based Alignment
- Results



The ATLAS Detector



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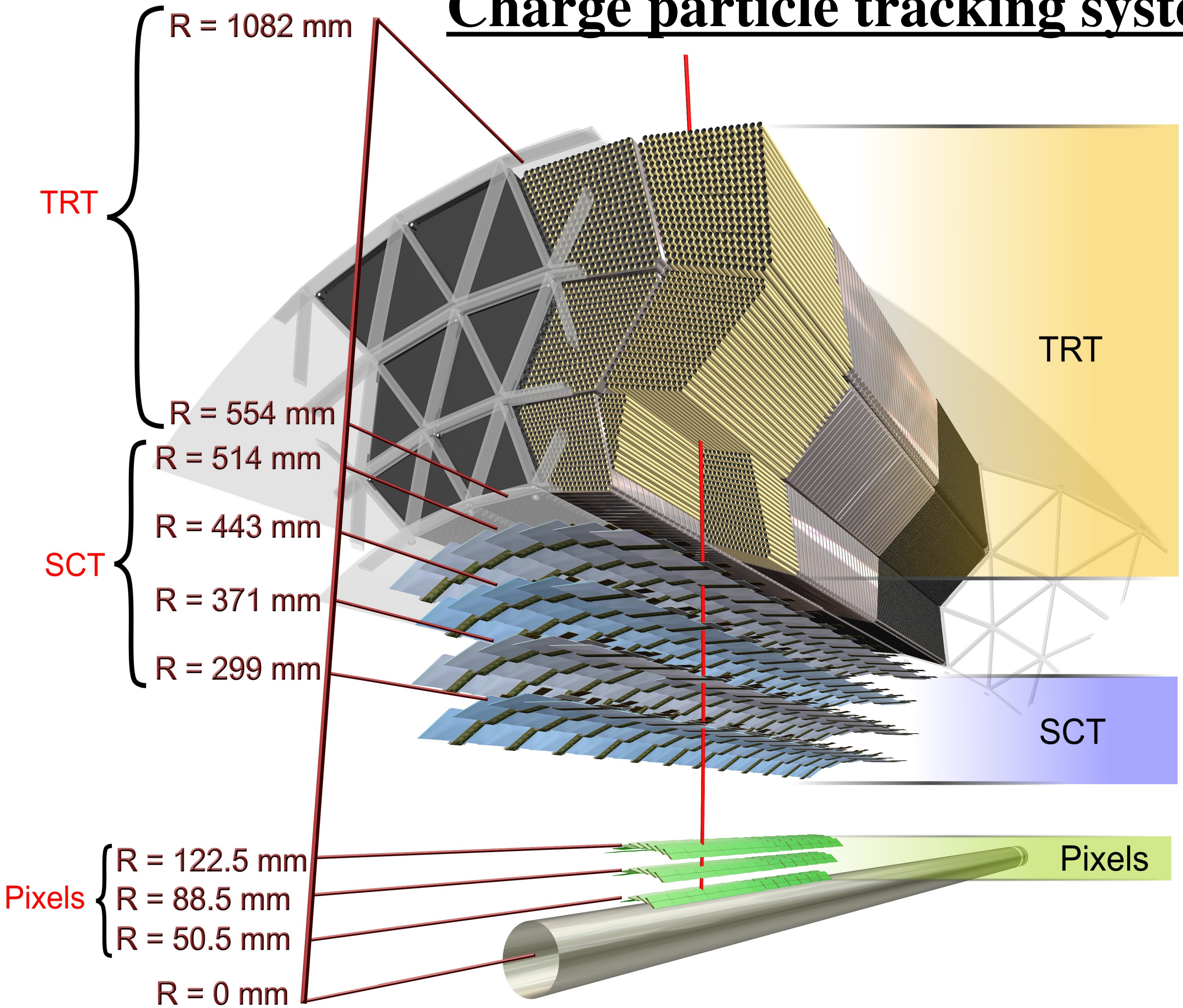


Charge particle tracking system built on two technologies

Drift tubes:

~300,000 straw tubes
resolution 130 μm (Rϕ)
$XeCO_2O_2$
36 hits per track

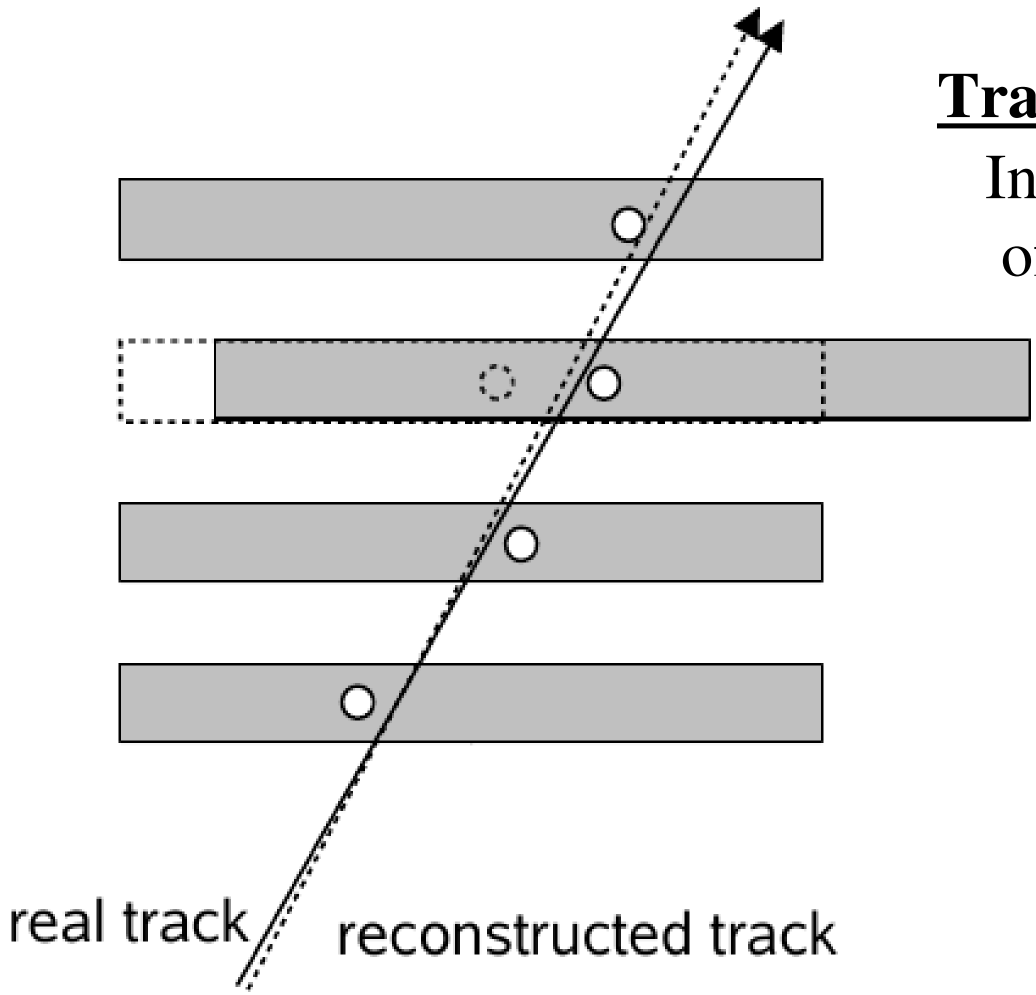
Silicon:

~ 3M Si strips
resolution: 23 μm (Rϕ)
580 μm (Z)
4 -9 hits per track

~ 80M Si pixels
resolution: 14 μm (Rϕ)
115 μm (Z)
3 hits per track

Why is alignment a problem?

Detector positions used in offline 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

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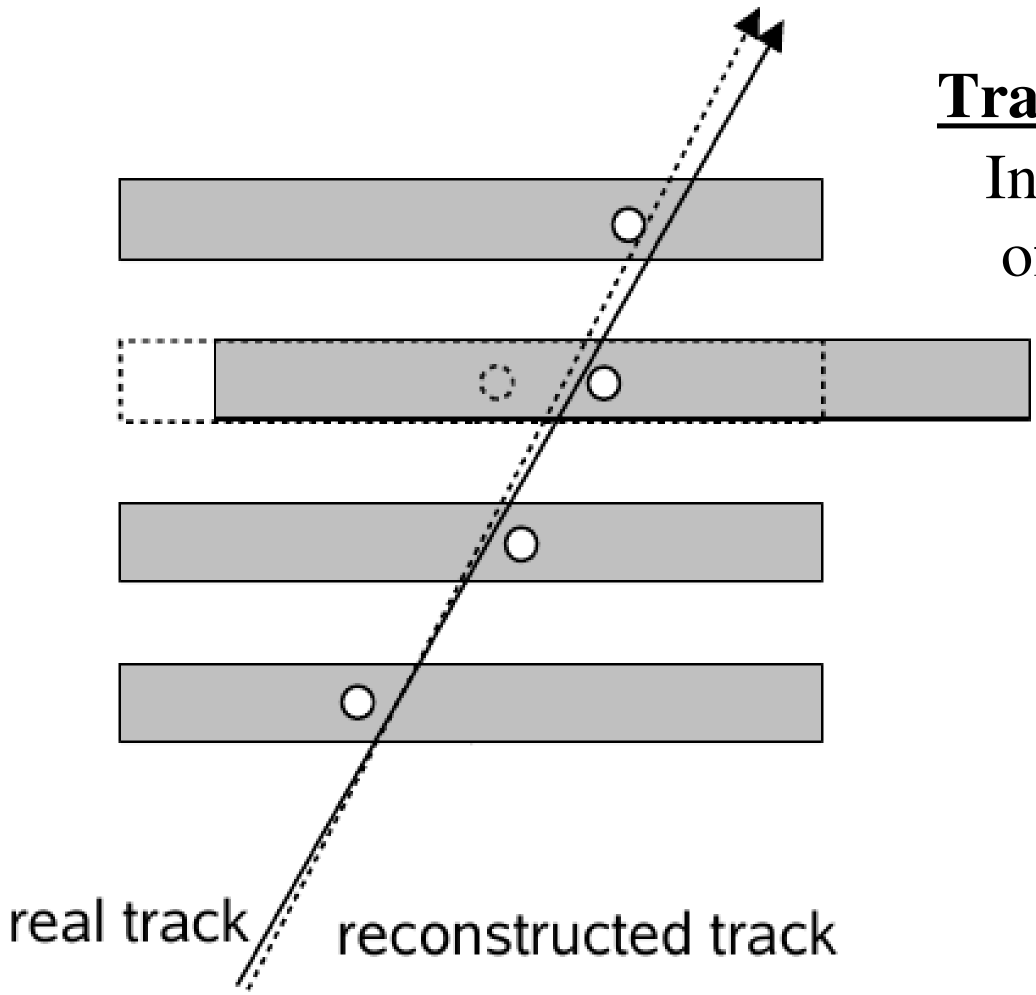

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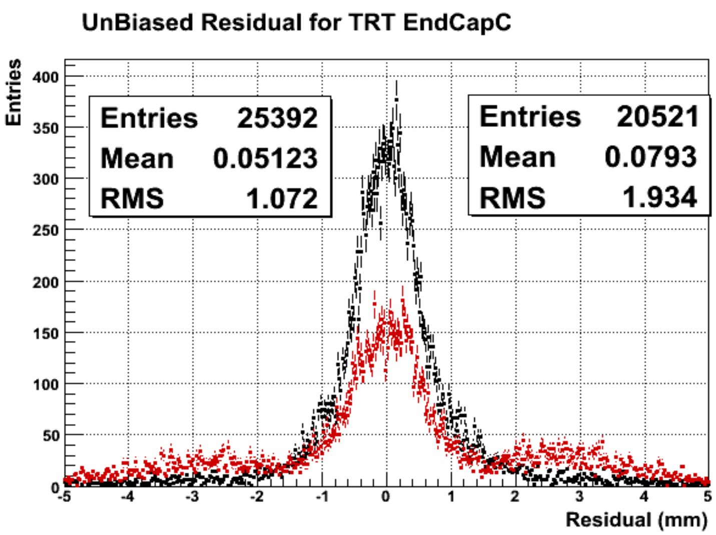
<u>Alignment Problem:</u>
The initial assumptions wrong

Why is alignment a problem?

<u>Misalignments</u>:
- Will degrade quality (potentially bias) measurements made.
- Can lead to ineffective/wrong physical conclusions.

Example:

Spatial Misalignments



misaligned aligned

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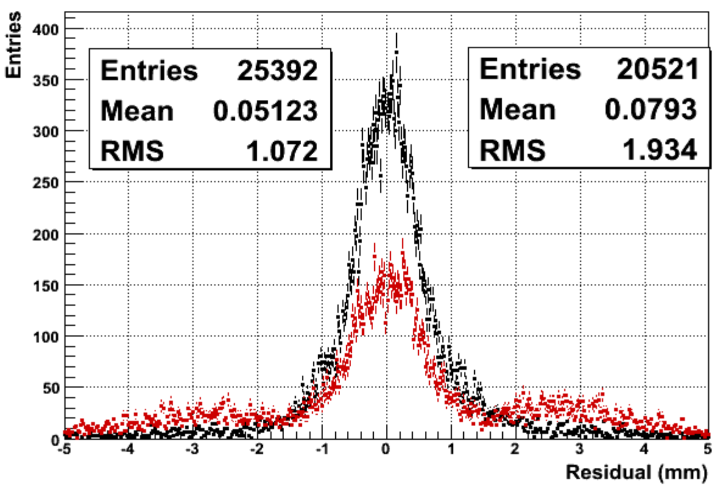

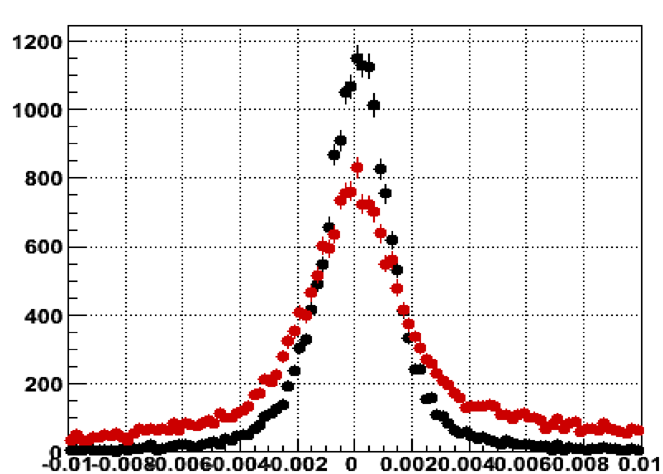

misaligned aligned misaligned aligned

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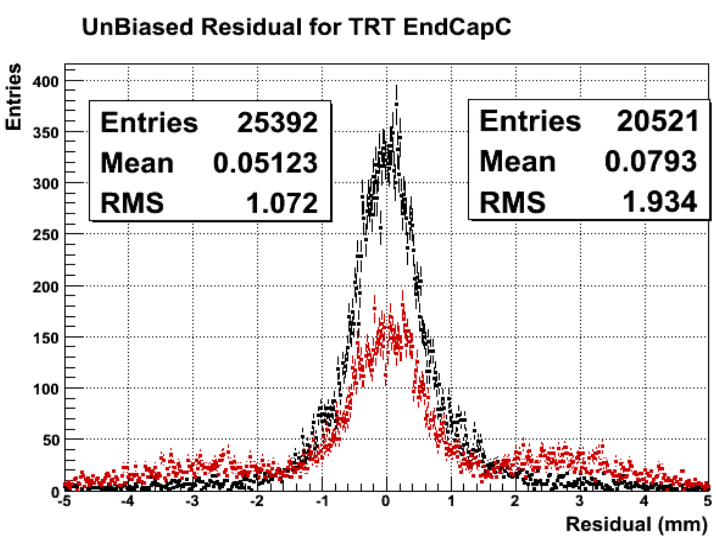

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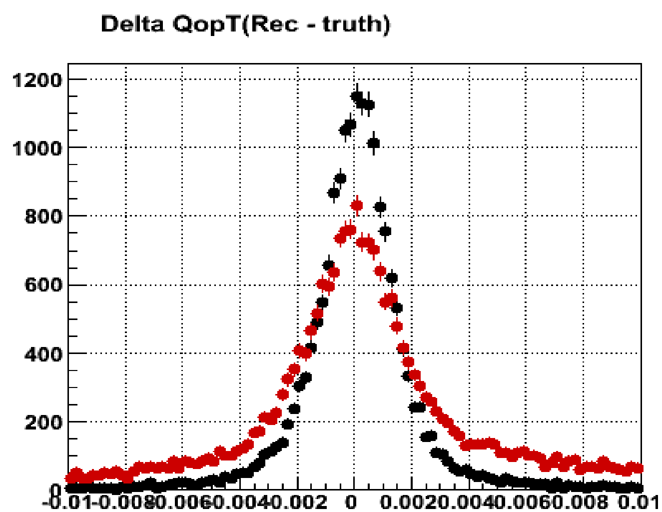

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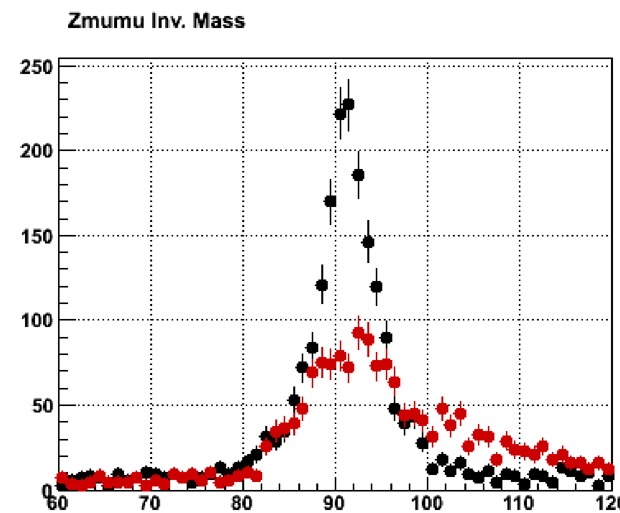

misaligned aligned

The Alignment Problem in ATLAS

Large number of degrees of freedom:

Si : 1744 align-able pixel modules, 4088 align-able SCT modules

TRT: 176 align-able modules

Different scales of mis-alignments:

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

- Largest impact on physics (Pattern Rec. / Triggering)

Internal Sub-detector

- Requires more statistics, More sensitive possible bias

Our Alignment Objective - measure relative position of in-situ detectors well enough to:

- allow for efficient track reconstruction
- minimize degradation to track parameter resolution to < 20%

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Requires that the Alignment is known to the order of 10s of μms

Solutions to the Alignment Problem

Assembly / Survey Measurements

- External measurements of as-built detector
- after/during installation

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

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Will only concentrate on track based methods in the following

Track Based Alignment

Introspective

- Use fact that detector misalignments affect track parameters to determine the misalignments

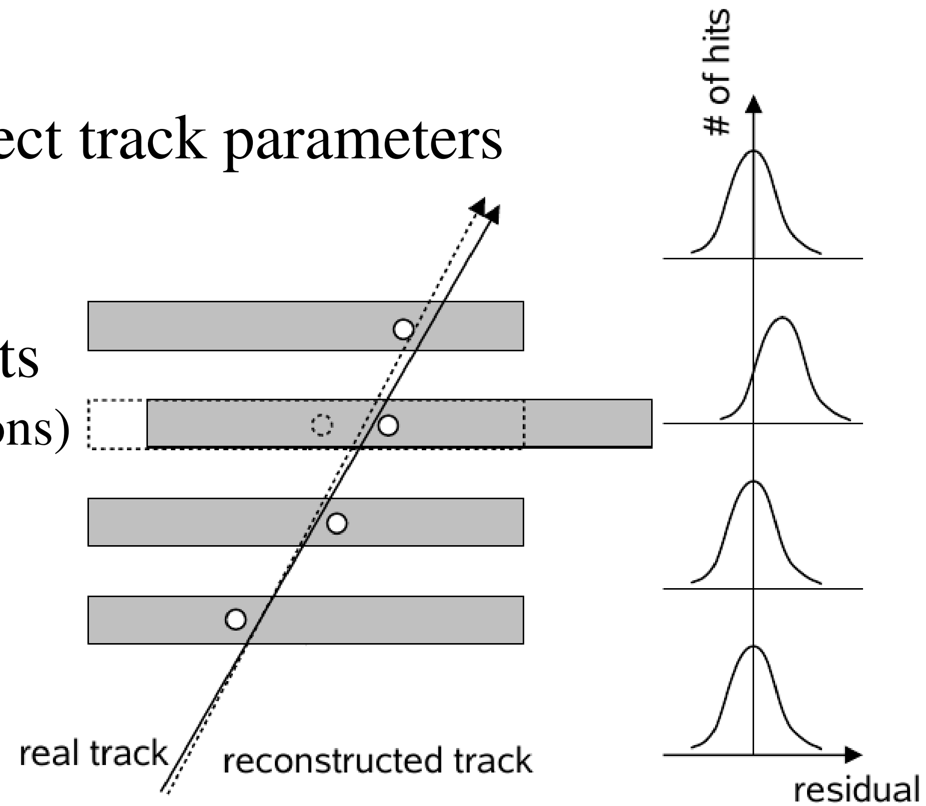
Define a statistic sensitive to mis-alignments

(ie: local measurements & our offline assumptions)

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

Key properties of χ^2 function

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



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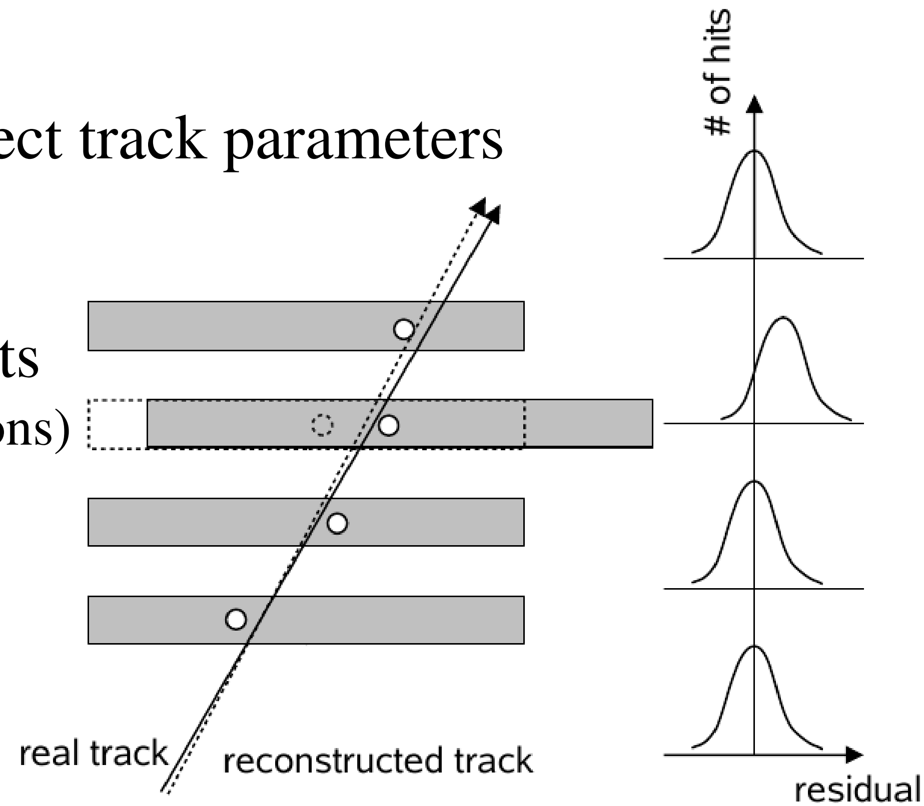

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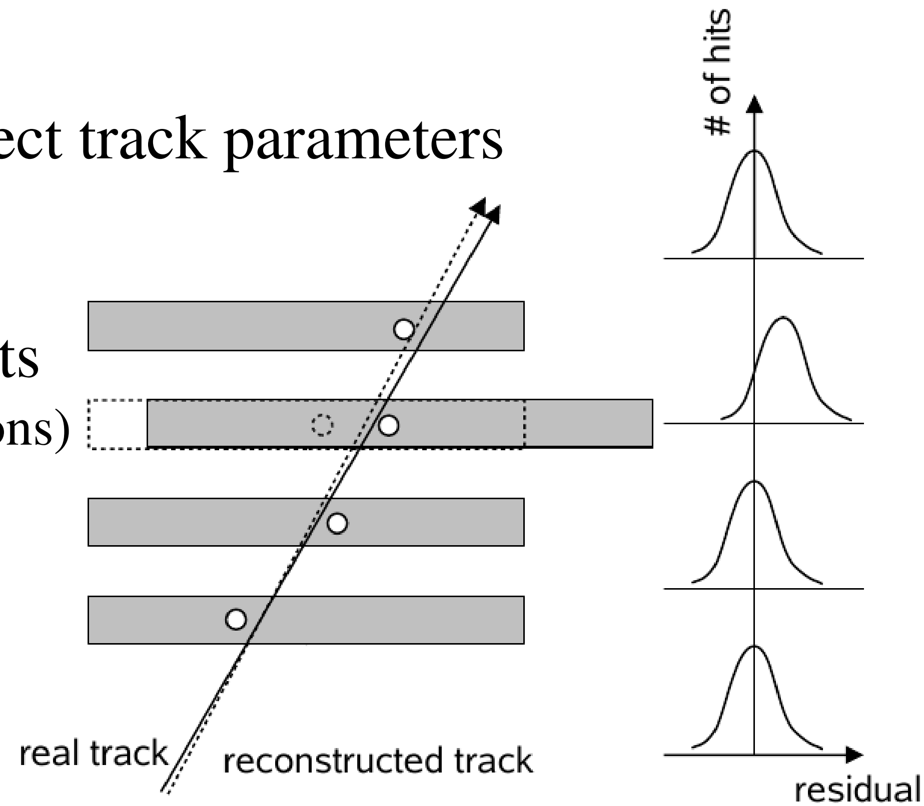

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Means $\frac{d\chi^2}{d\alpha} = 0$ gives true alignment

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:

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

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

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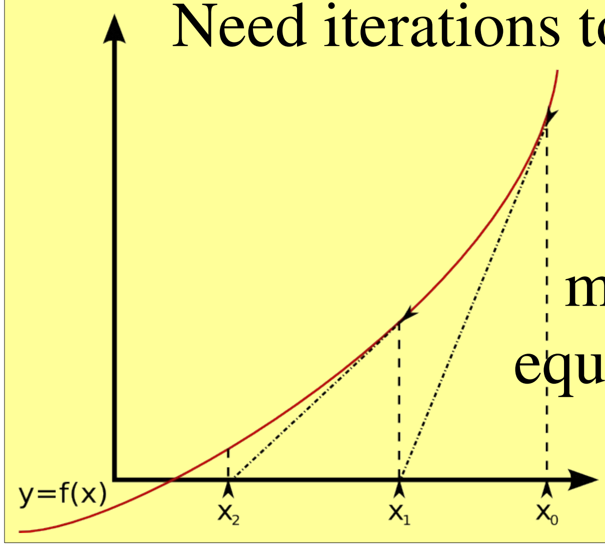
In general highly non-linear
Need iterations to solve.



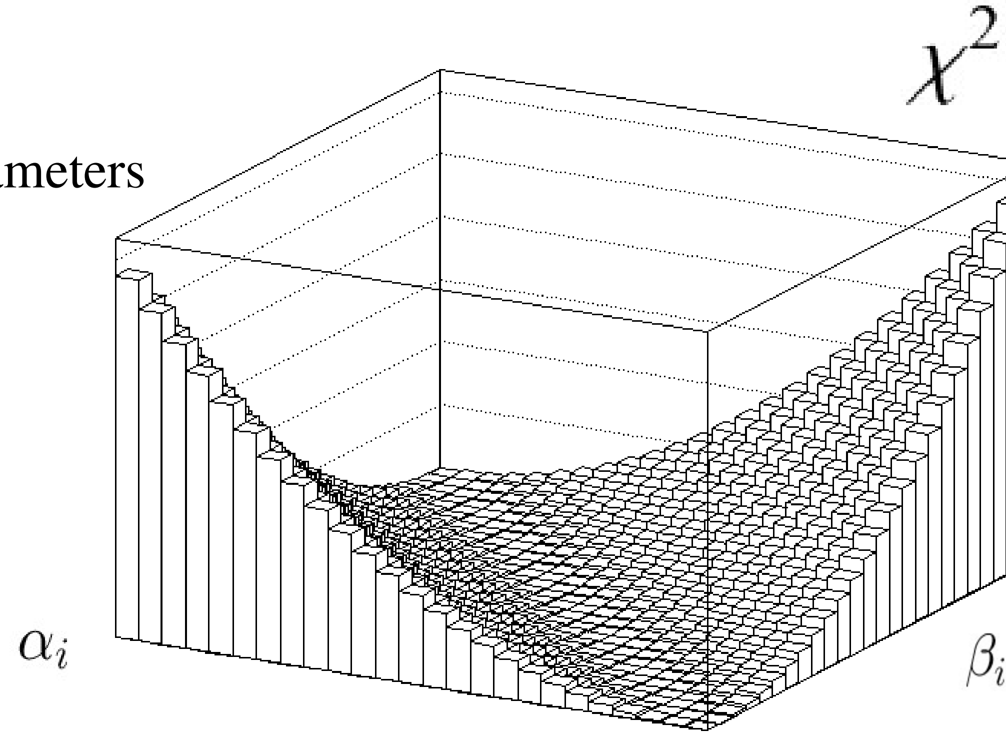
moral
equivalent

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



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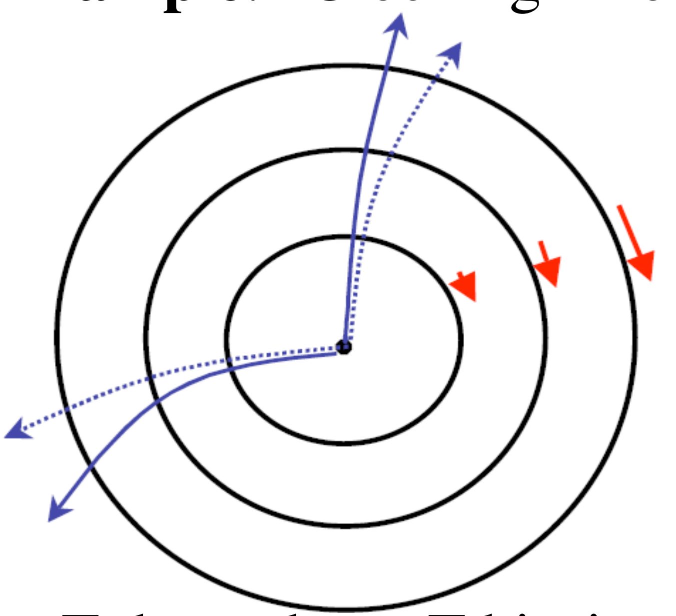
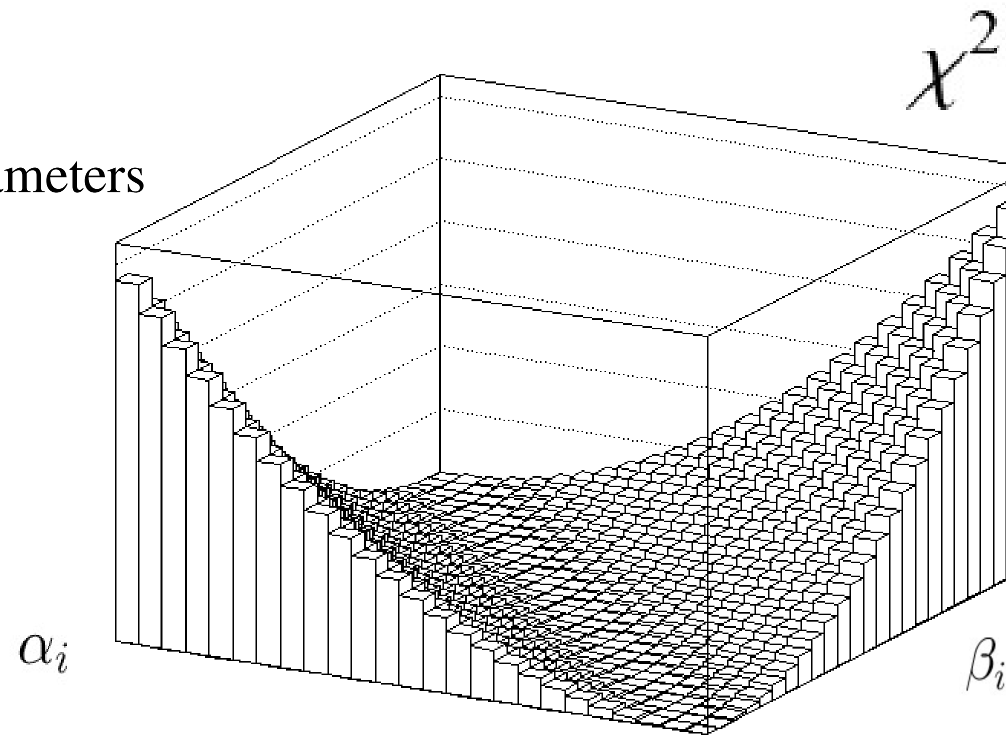
Example: "Clocking Effect"



pT dependent pT biasing



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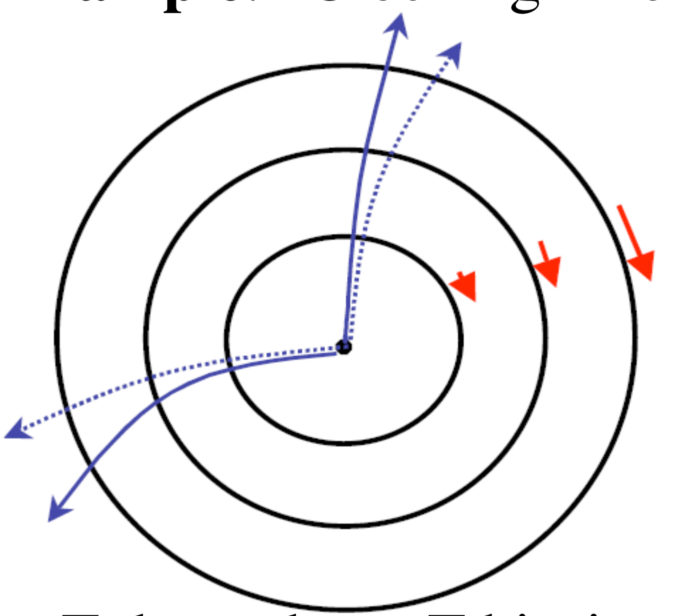

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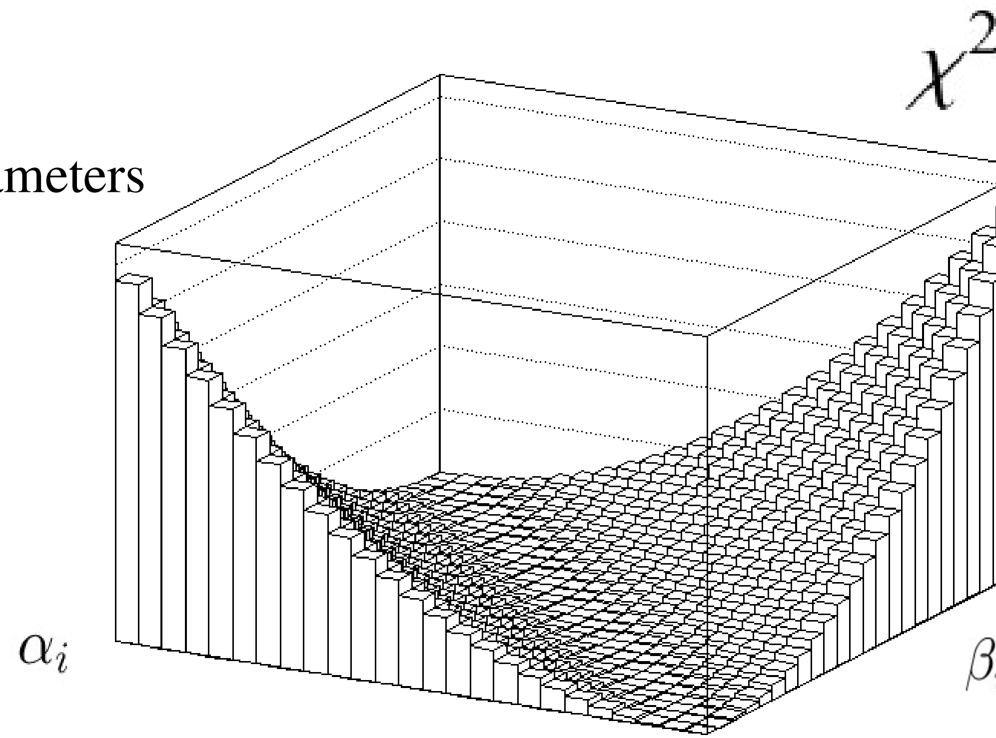

Whole class of systematic distortions which plague detectors with cylindrical symmetry

Global Vs Local

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

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

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

- **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

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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

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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

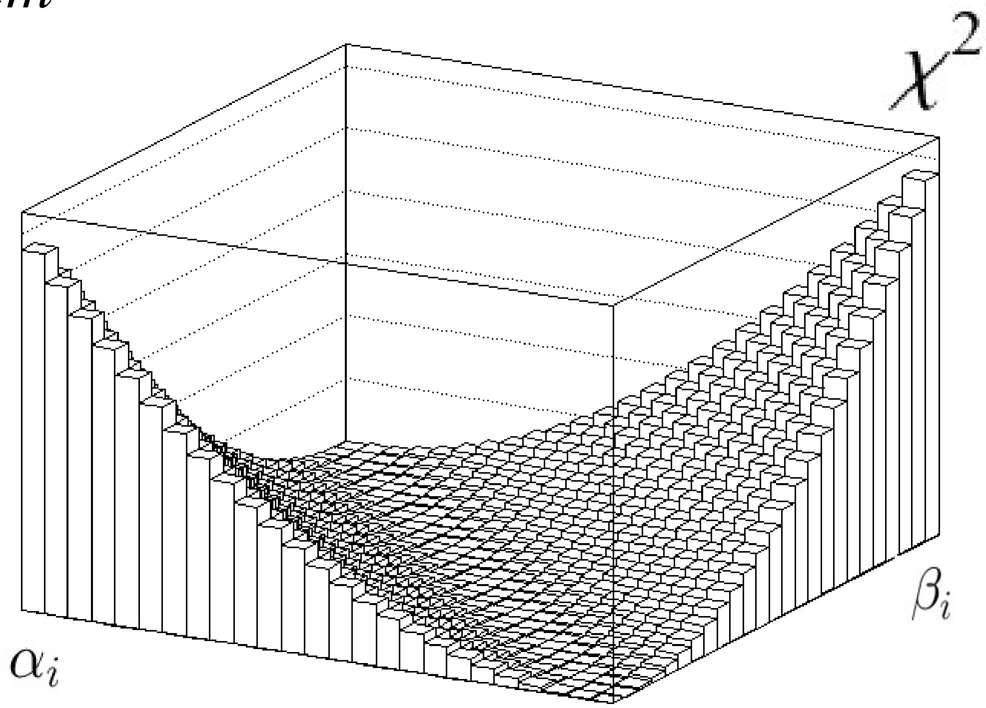
Dealing with Weak Modes

Weak Modes: *The real alignment problem*

Detecting weak modes:

- Diagonalization provides means of diagnosis

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



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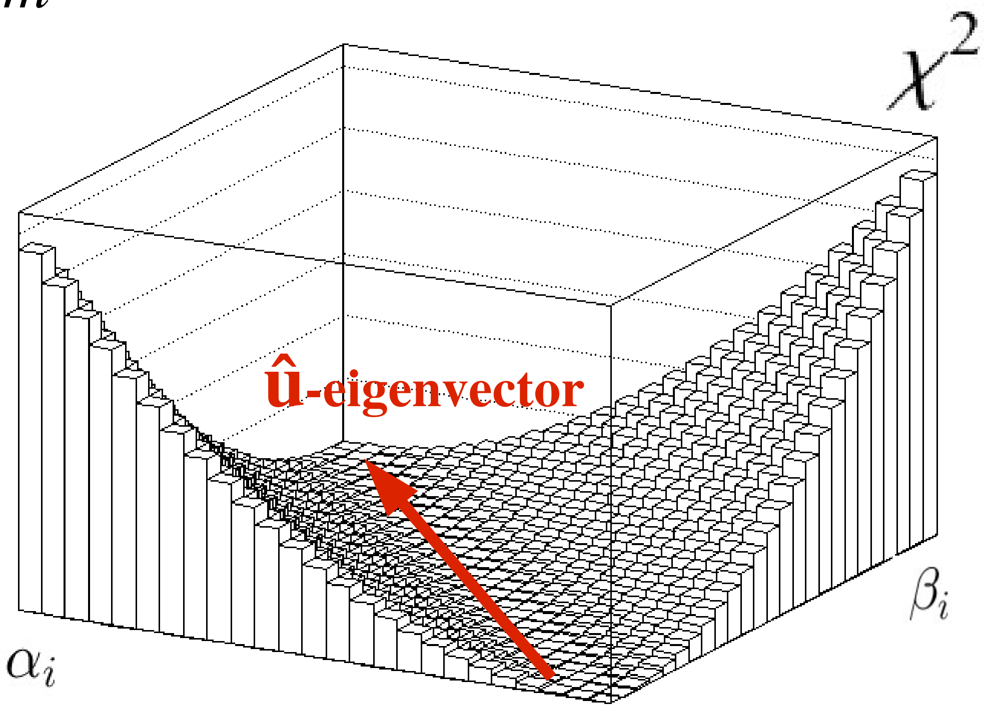

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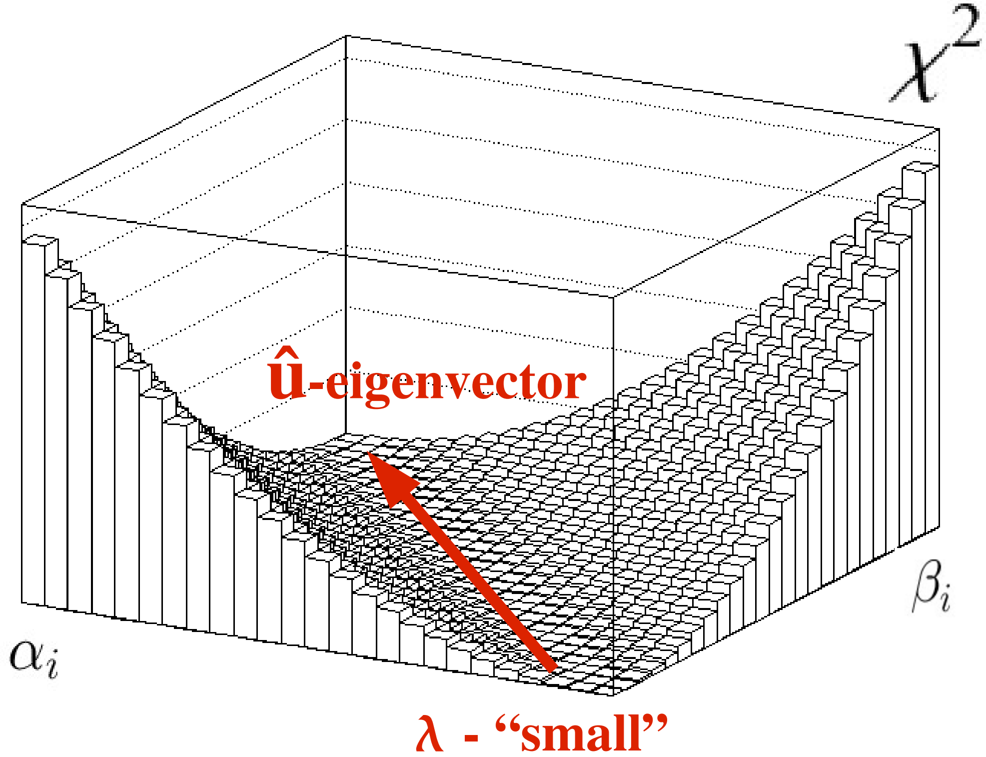

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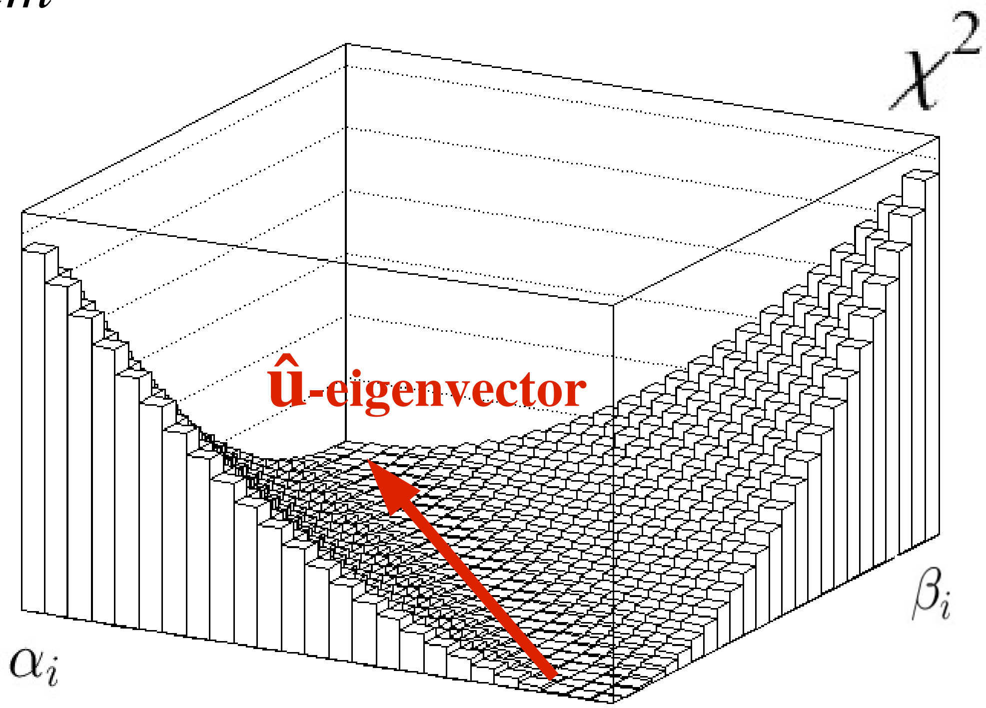

Detecting weak modes:

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

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.

"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.

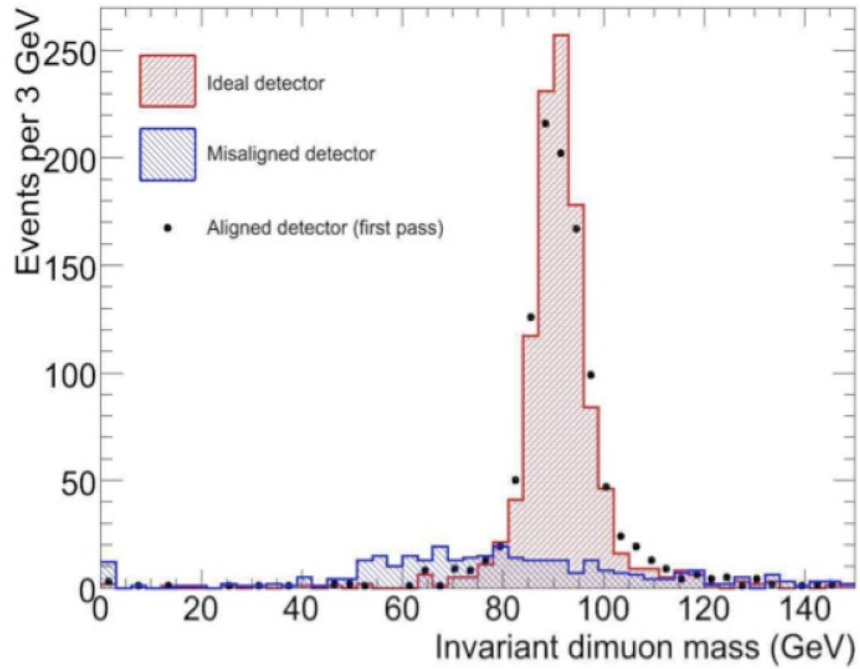
Full Scale Test Alignment Procedure

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

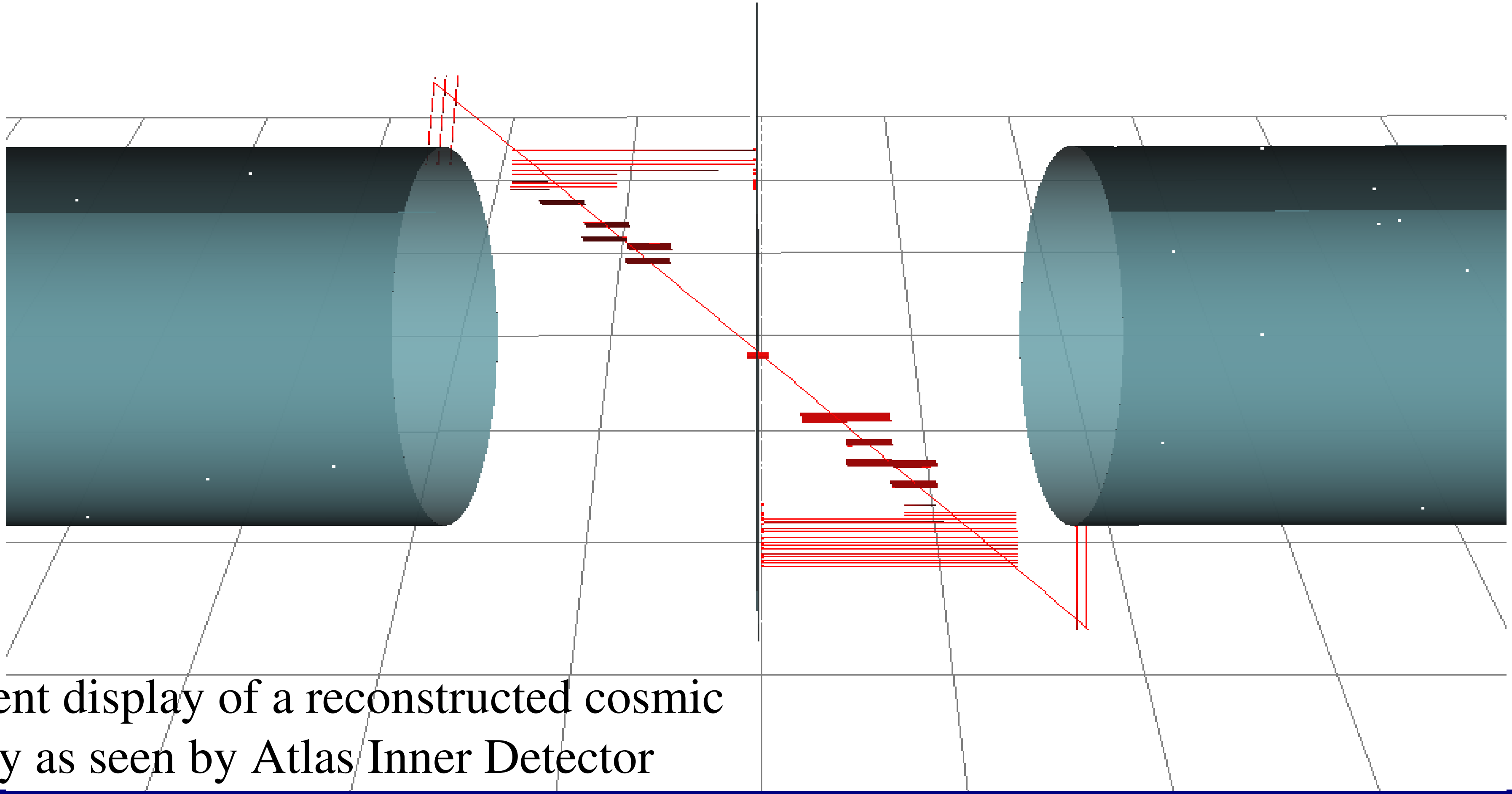
Big Success:

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

Cosmic Data

- ATLAS had dedicated cosmic data taking period (late summer early fall)
- Recorded over 2 million tracks reconstructed in Inner Detector

(both with and with out magnetic field)

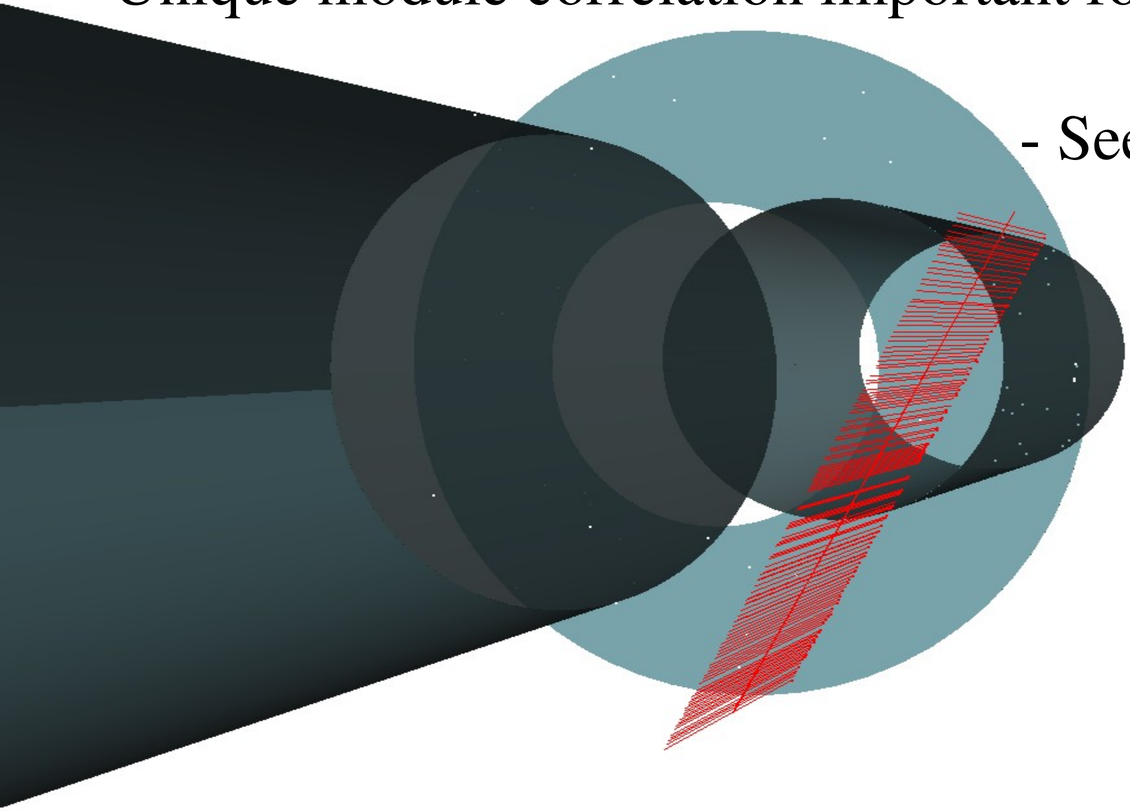


Event display of a reconstructed cosmic ray as seen by Atlas Inner Detector

Cosmic Data

Extremely Important for Alignment Algorithms

- First data available alignment.
- Remove large subsystem misalignments
  (eliminate potential problems for pattern rec and trigger before first collisions)
- Unique module correlation important for eliminating weak modes



- Seen in simulation needed for ultimate alignment precision

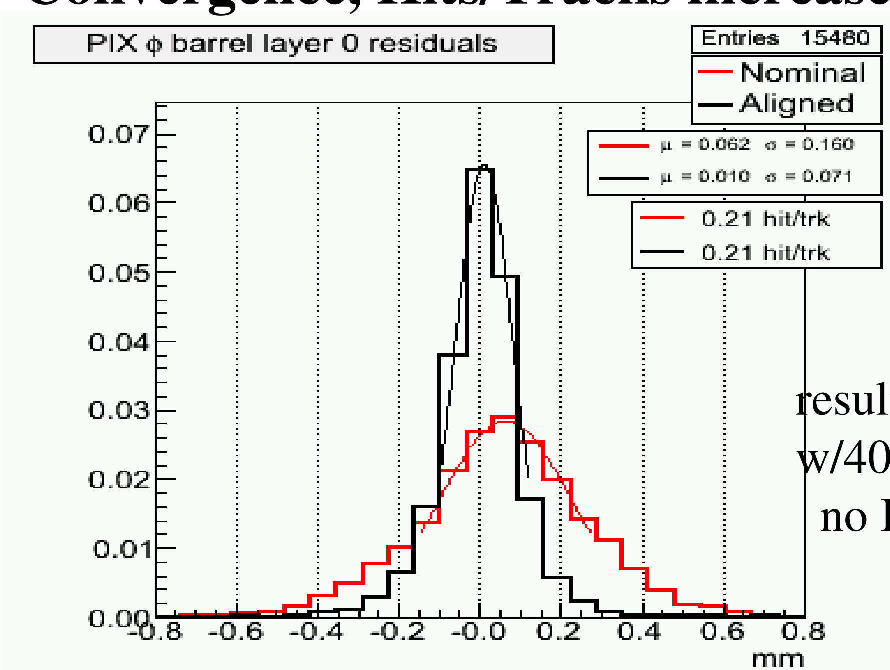
Studies of B-Field on Vs off
-measure robustness of alignment
-provide insight into weak modes

Cosmic Data

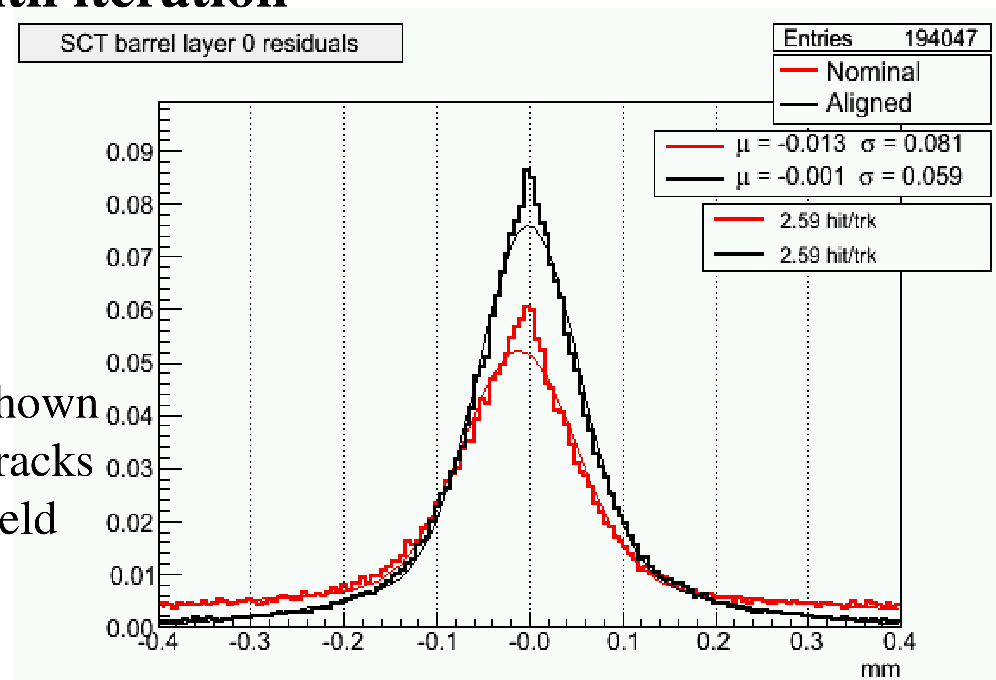
Si alignment from Cosmics

- **First ever alignment of Pixels + SCT with real data.**
- **All within 6 days of the first cosmic the data being taken:**
  - multiple sets of independent alignment constants were produced
  - results validated (shown consistent)
  - constants for "first" collisions blessed
- **Convergence, Hits/Tracks increase with iteration**

- Pixels aligned to SCT
- Alignment Barrel Si layers



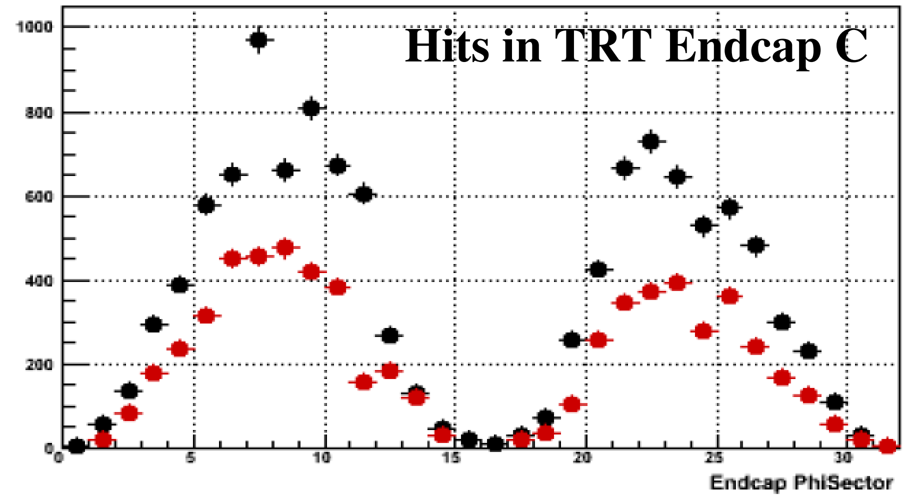
results shown
w/40K tracks
no B-field



Cosmic Data

TRT Alignment from Cosmics

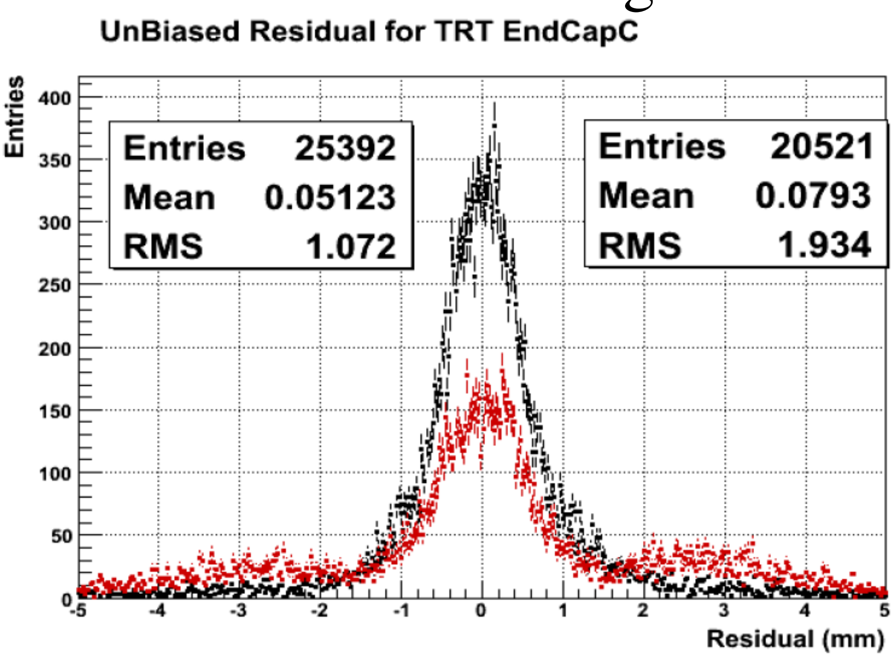
- TRT Barrel and both Endcaps aligned wrt the Si detectors
- Saw convergence with Hits/Tracks increasing w/iteration

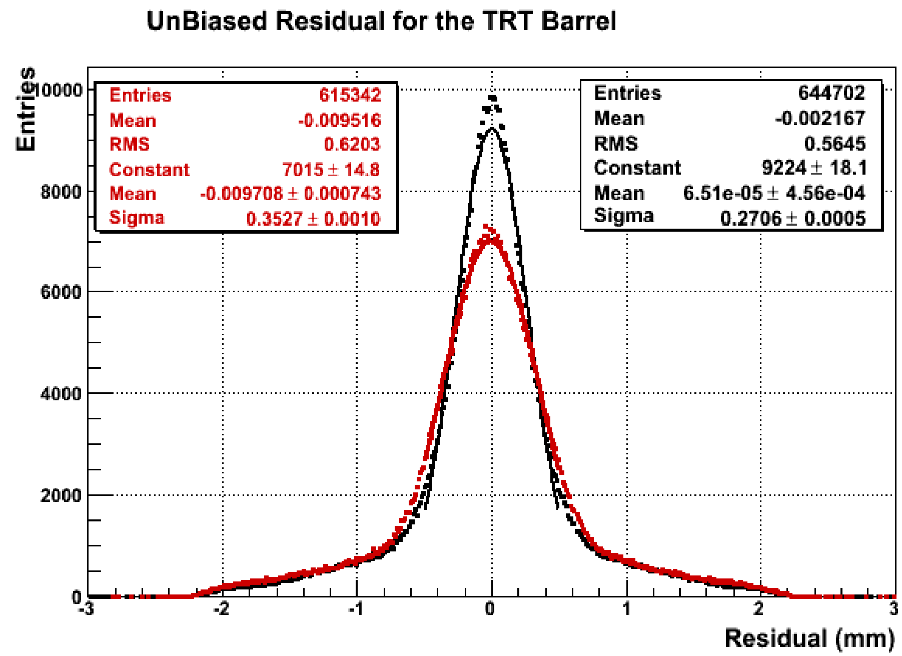


TRT Barrel Alignment

x (μm)	y (μm)	rotx (mrad)	roy (mrad)	rotz (mrad)
-142(3)	-196(9)	-0.32(1)	0.391(4)	-0.963(3)

Before After TRT Alignment





Conclusions

- Overall scale and ultimate precision of ATLAS Inner Detector poses a challenging problem in terms of understanding the detector.
- Alignment crucial to reach full physics potential / detector performance
- Track based method provides means of addressing alignment problem
- Implemented in ATLAS framework
- Thorough and Stringent tests of software allowed for capitalization on early cosmic data.
- Cosmics have and continue to provide a starting point and guide the way to the ultimate alignment
- Poised meeting the alignment challenge at first collisions

Bonus.

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	

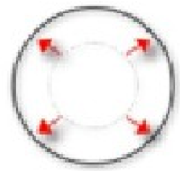
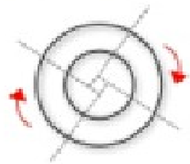
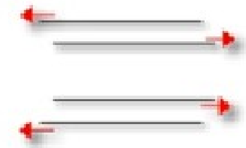
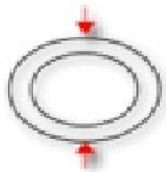
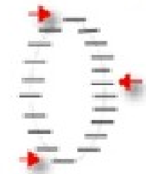
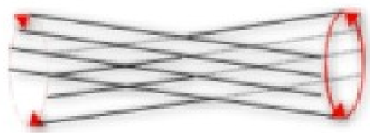
Alineator

Computing Cluster at Valencia, running SCALAPACK

Unofficial successful tests w/ ~32k DoF

Description	Vtx constr	Align Level	Modules	Dofs	Matrix size	System	Solving time	Sample
Single PC (CPU Pentium IV Dual Core 3 GHz, Memory 3 GB)								
Double Cone	yes	2	7	42	-	single PC	0.01 min	CSC Multimuons
SR1	no	3	468	2808	31 MB	single PC	5 min	CSC Multimuons
Cone	no	3	1030	6180	146 MB	single PC	33 min	CSC Multimuons
Cone	yes	3	1030	6180	146 MB	single PC	33 min	CSC Multimuons
Double Cone	no	3	2328	13968	745 MB	single PC	-	CSC Multimuons
Double Cone	yes	3	2328	13968	745 MB	single PC	5 hr 59 min	CSC Multimuons
Silicon Barrel	-	3	3568	21408	1.8 GB	single PC	imposible	CSC Multimuons
Full System	-	3	5832	34992	4.6 GB	single PC	imposible	CSC Multimuons
Alineator I (CPU: 2 AMD 64bit Opteron Dual Core 2,6 GHz + Memory: 32 GB)								
SR1	no	3	468	2808	31 MB	Alineator	4 min	CSC Multimuons
Cone	no	3	1030	6180	146 MB	Alineator	19 min	CSC Multimuons
Cone	yes	3	1030	6180	146 MB	Alineator	20 min	CSC Multimuons
Double Cone	no	3	2328	13968	745 MB	Alineator	53 min	CSC Multimuons
Double Cone	yes	3	2328	13968	745 MB	Alineator	55 min	CSC Multimuons
Silicon Barrel	no	3	3568	21408	1.8 GB	Alineator	2 hr 38 min	CSC Multimuons
Silicon Barrel	yes	3	3568	21408	1.8 GB	Alineator	-	CSC Multimuons
Full System	yes	3	5832	34992	4.6 GB	Alineator	-	CSC Multimuons

More Weak Modes

	ΔR	Δφ	ΔZ
R	**Radial Expansion** (distance scale) 	**Curl** (Charge asymmetry) 	**Telescope** (COM boost) 
φ	**Elliptical** (vertex mass) 	**Clamshell** (vertex displacement) 	**Skew** (COM energy) 
Z	**Bowing** (COM energy) 	**Twist** (CP violation) 	**Z expansion** (distance scale)