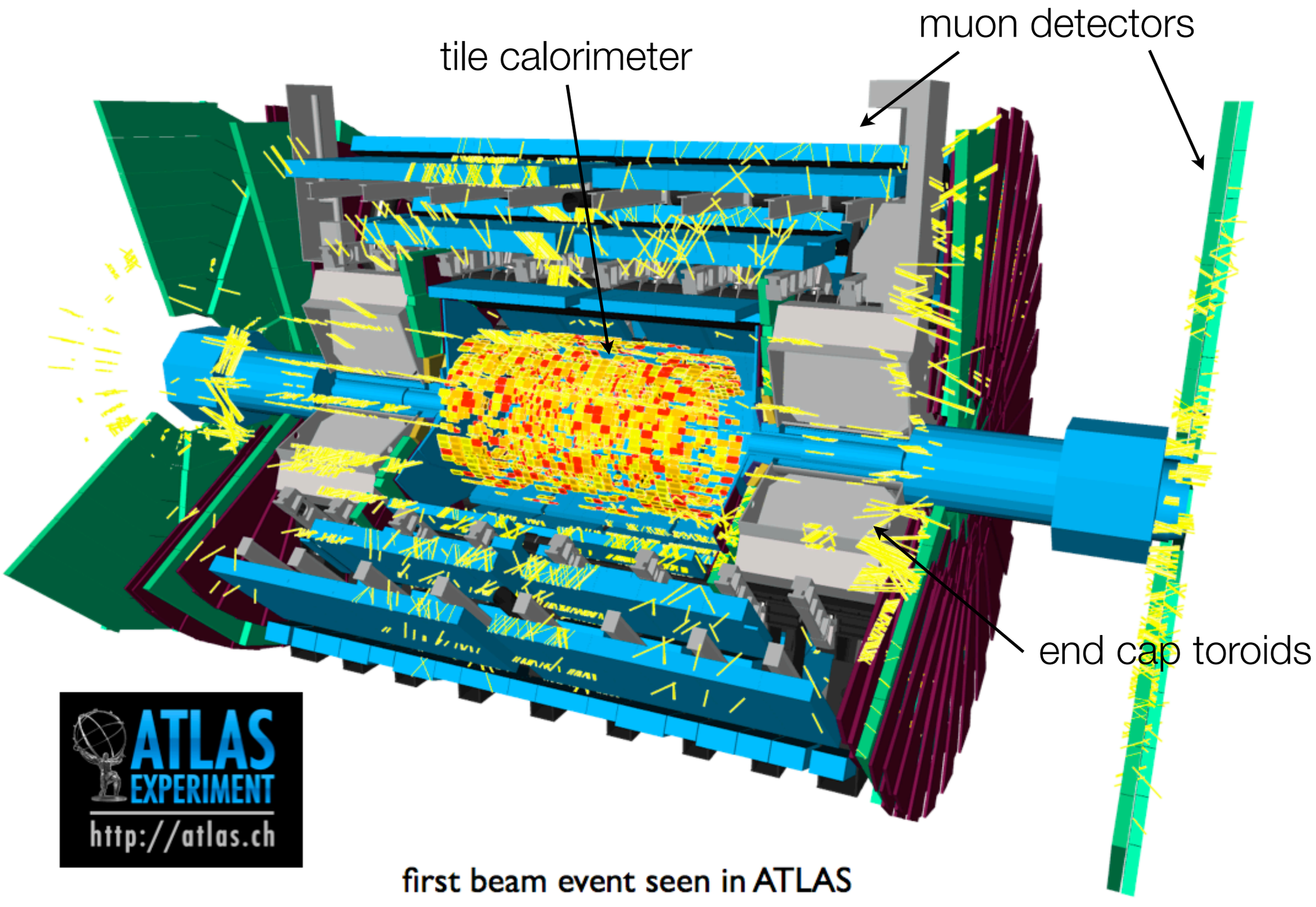
Alignment of the ATLAS Inner Detector

Heather M. Gray[1,2] on behalf of the ATLAS ID Alignment Group
[1] California Institute of Technology
[2] Columbia University

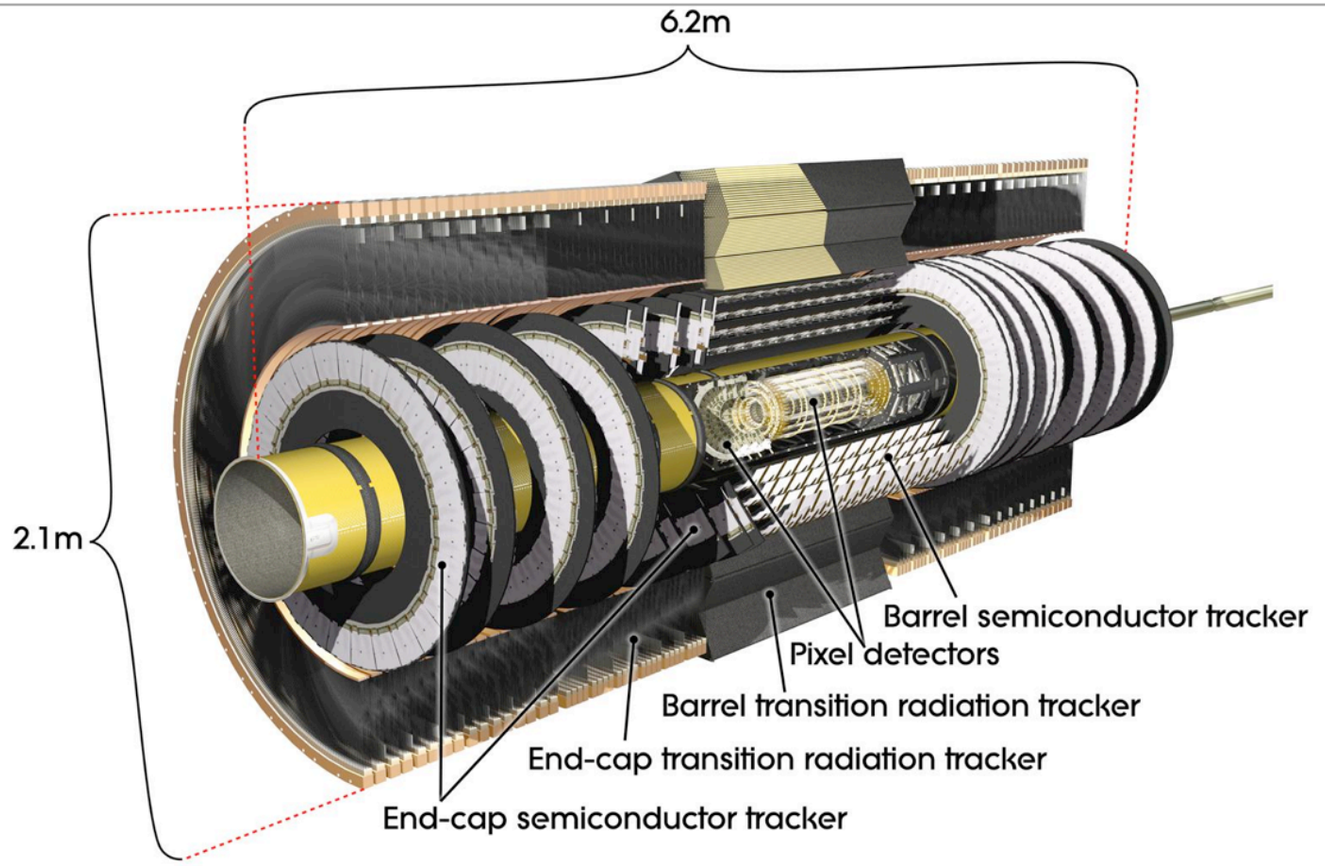
The ATLAS Experiment



first beam event seen in ATLAS

The Inner Detector

- Efficient track reconstruction
- Precise momentum measurements
- Vertex Detection
  - b-tagging



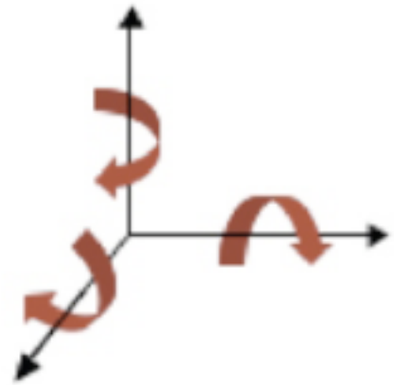
	Pixel		SCT		TRT	
Technology	silicon pixel		silicon strips		gas drift tubes	
Resolution	14 μm (rϕ) 115 μm (z)		23 μm (rϕ)		140 μm	
# Layer/Disks	3	6	4	18	3	28
# Modules	1744		4088		992	

5832

The Alignment Challenge

- 5832 x 6 d.o.f. per module = **35010** degrees of freedom in the silicon detectors!

- Requirements for physics: muon momentum scale and b-tagging
  - Degradation of tracking resolution < 20%
  - Understand momentum scale to 0.1%
- Need alignment O(10 μm)



3 translational d.of.

3 rotational d.o.f.

- After construction the precision ranges from O(1 mm) between sub-detectors to a few microns in the Pixel ECs
  - requires sophisticated alignment techniques

How to achieve alignment

Detector Design
Material, Redundancy, Stability

Construction
Survey

Operation
Data processing
Calculation of alignment constants

Alignment Algorithms
Track-based hardware alignment

Control of Systematic Deformations

Validation and Monitoring
Data (including cosmics)
Realistic misalignment in MC
Alignment Monitoring

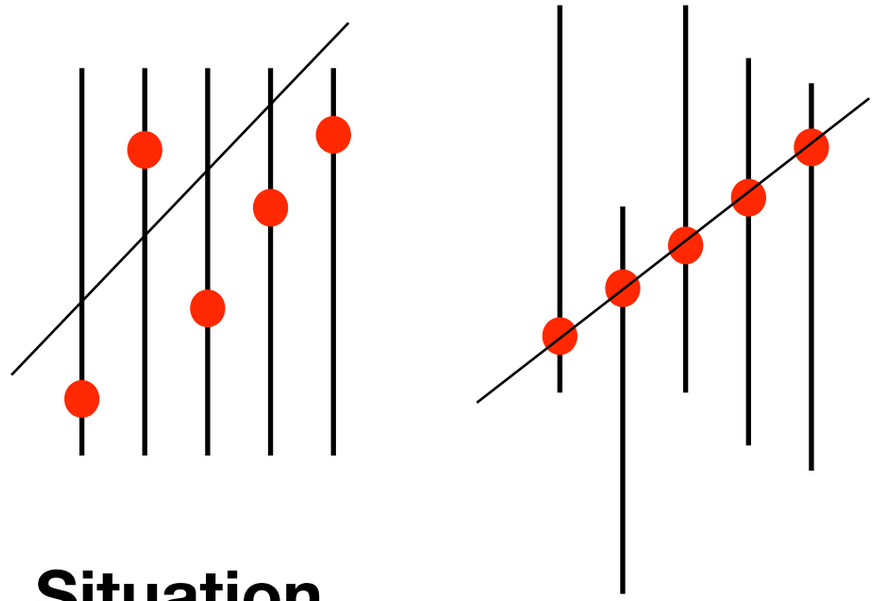
Track Based Alignment

- Calculate alignment corrections from track fit quality
  - minimise distance from track to hit (residual) using X^2 minimisation

covariance matrix (V)

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

- vector residuals r=r(π,a)
- π: track parameters
- a: alignment parameters



Situation without Alignment

Real Situation

- Three levels of alignment
  - **Level 1**: entire subdetectors
  - **Level 2**: layers & disks
  - **Level 3**: modules (SCT and Pixel)

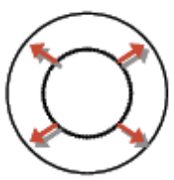
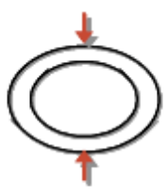
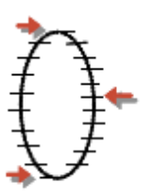
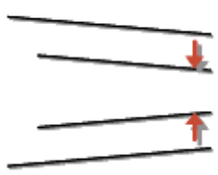
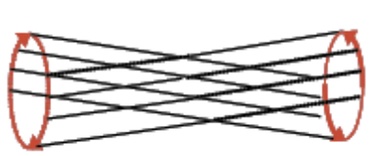
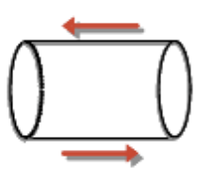
Approaches to track-based Alignment

- **Global X^2 Alignment Algorithm**
  - Account for all correlations
  - Invert a 35k x 35k matrix -> numerical challenge
- **Local X^2 Alignment Algorithm**
  - Reduce 35k x 35k matrix to 6x6 diagonal blocks
  - Iterate to include neglected correlations
- **The Robust Alignment Algorithm**
  - Add module overlaps in rΦ and z
  - Less sensitive to misalignment in other layers and multiple scattering
  - Only small overlap

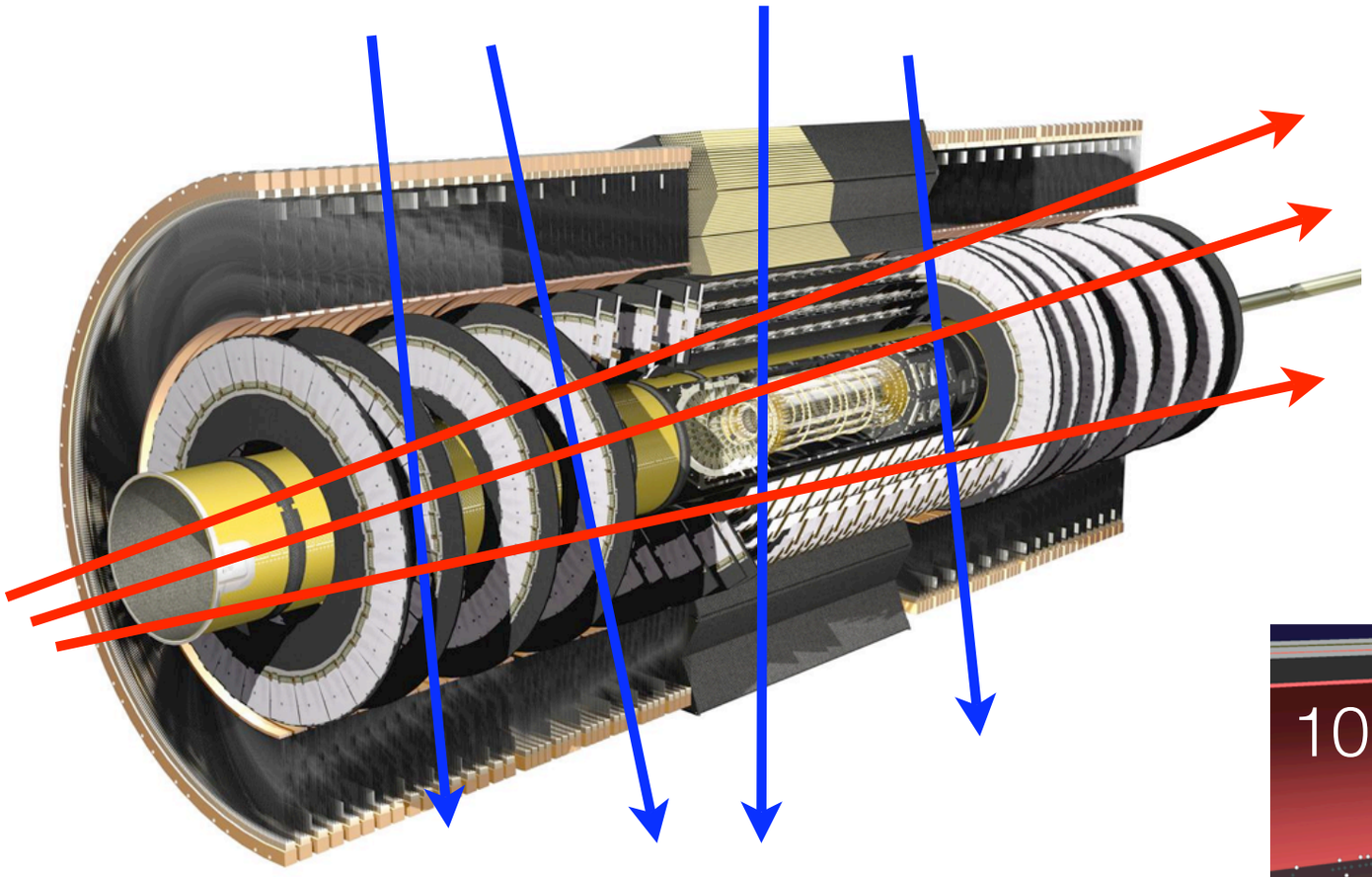
Comparable results from all 3 algorithms

“Weak modes”

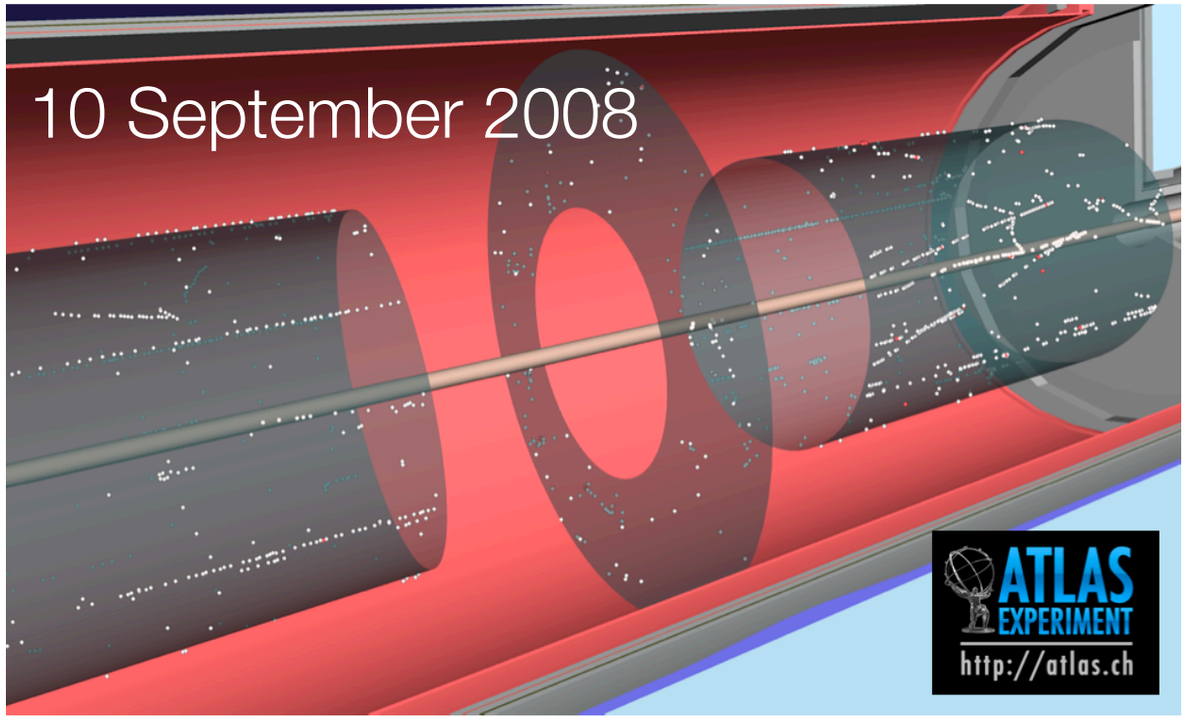
- Residual minimisation is necessary but not sufficient
- Weak modes are systematics distortions which leave the track X^2 unchanged
- Use track parameters or vertex positions, cosmic rays, beam halo/beam gas, external constraints

	ΔR	Δϕ	ΔZ
R	**Radial Expansion** 	**Curl** 	**Telescope** 
ϕ	**Elliptical** 	**Clamshell** 	**Skew** 
Z	**Conical Warping** 	**Twist** 	**Z expansion** 

Cosmics and Beam Halo



- Complementary measurements
  - cosmics are good for the barrel
  - beam halo is good for the end caps

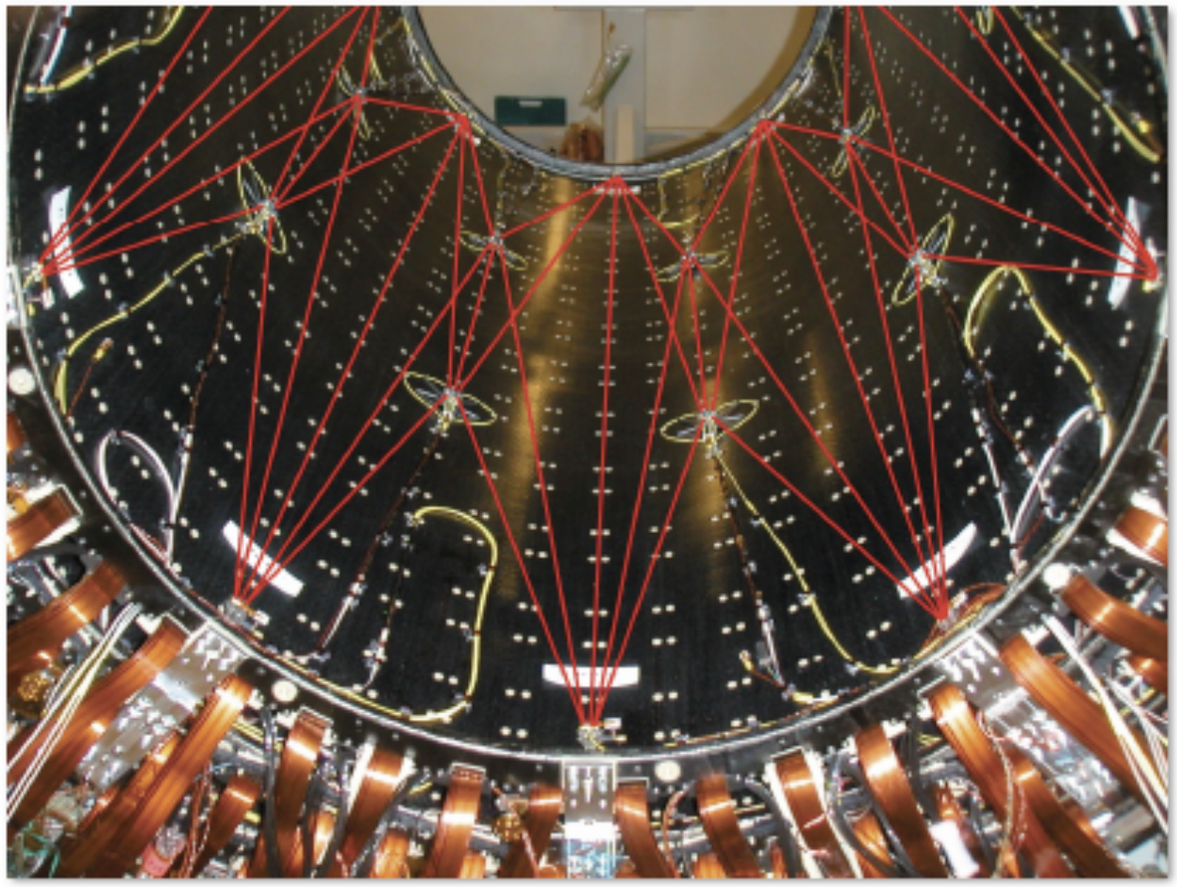


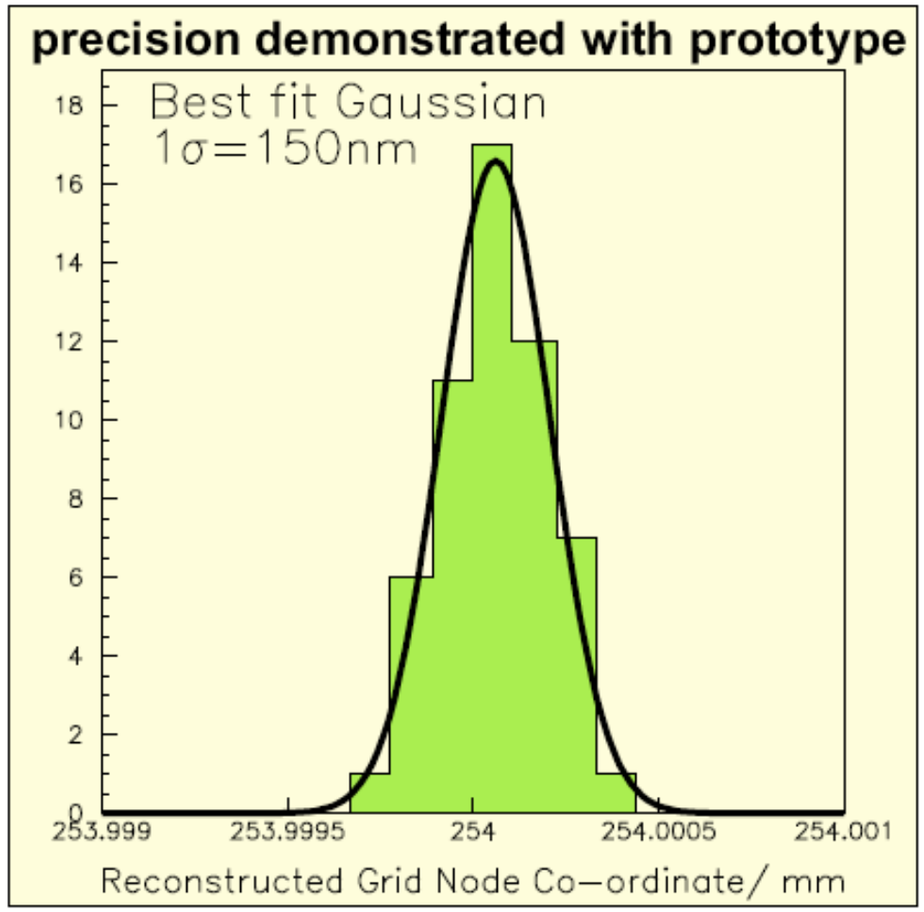
beam halo event seen in ATLAS

- Cosmics can be used to constrain
  - p_T-biasing modes
  - telescope modes: relates top to bottom hemispheres
  - twist and elliptical distortion: use off axis tracks

Hardware-based alignment

- Uses Frequency Scanning Interferometry (FSI) to align the SCT with a geodetic grid of 842 length measurements
  - measurement precision of 1 μm -> can reconstruct 3D grid geometry to a precision of 5 μm
  - complementary to track-based alignment



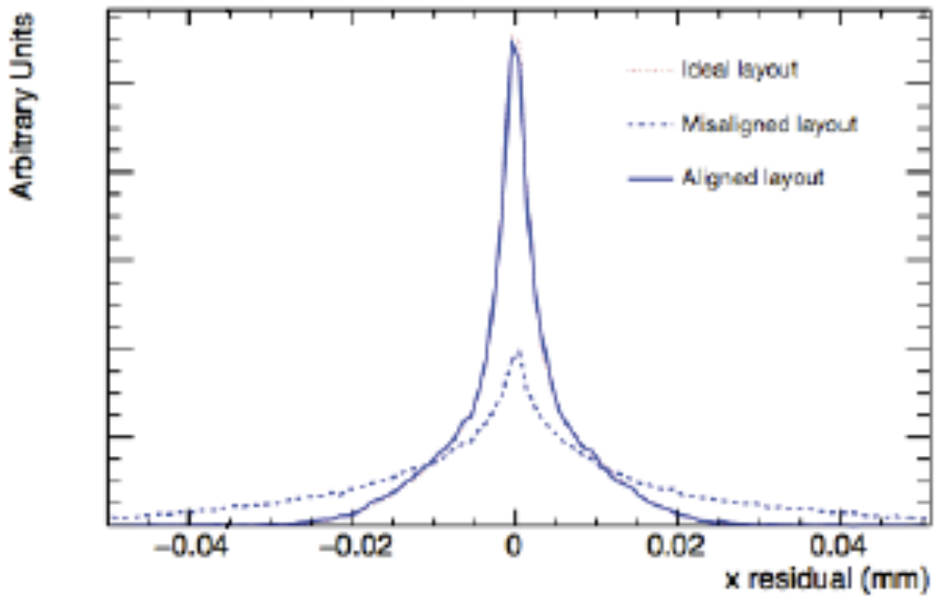


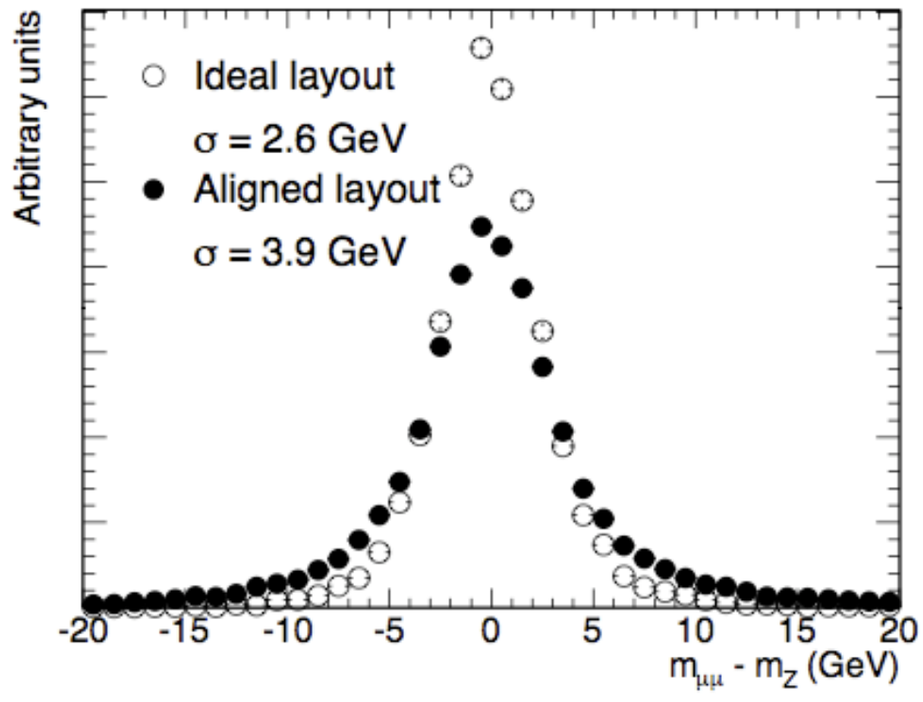
Testing alignment algorithms

- The Computer Systems Commissioning (CSC) was used to test the alignment algorithms over large datasets

- Multimuon Monte Carlo samples (10 muon/ events) were generated using a misaligned geometry

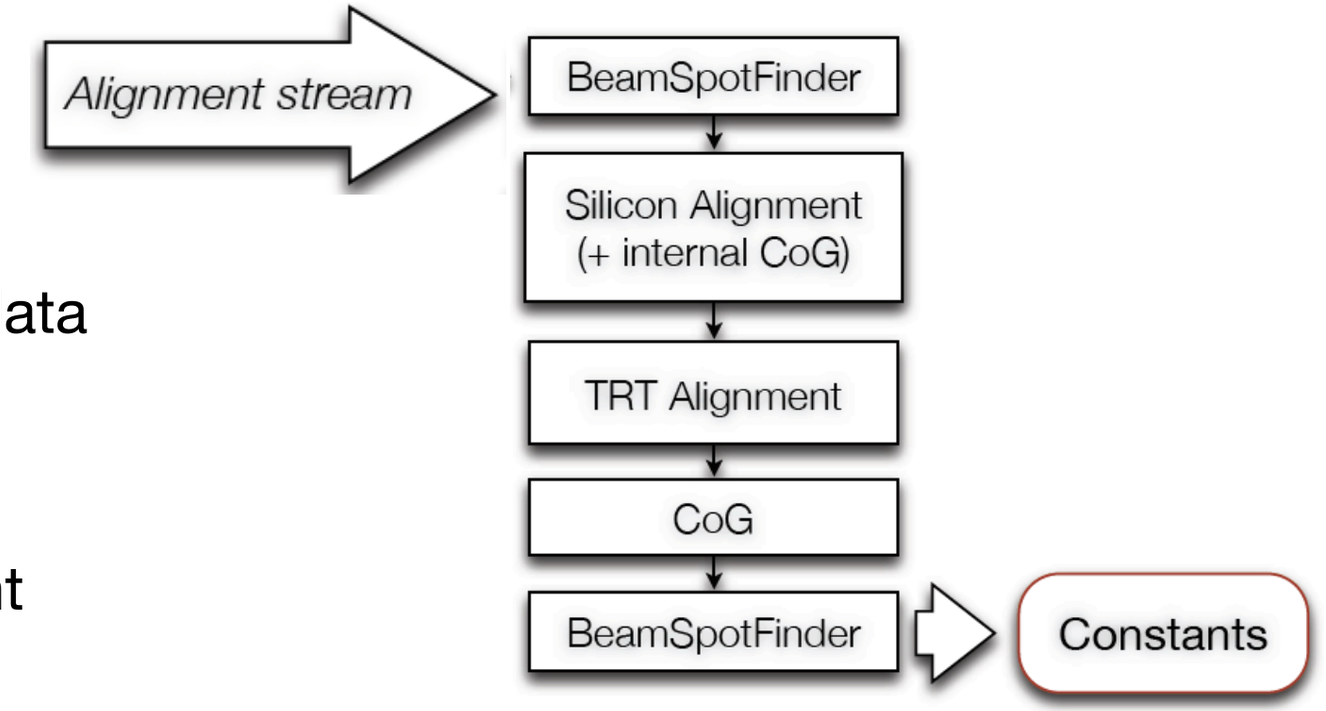
- Algorithms converged with almost perfect residuals
  - but track parameters were found to be biased (due to weak modes)
  - additional constraints are required
    - cosmics, beam halo, etc

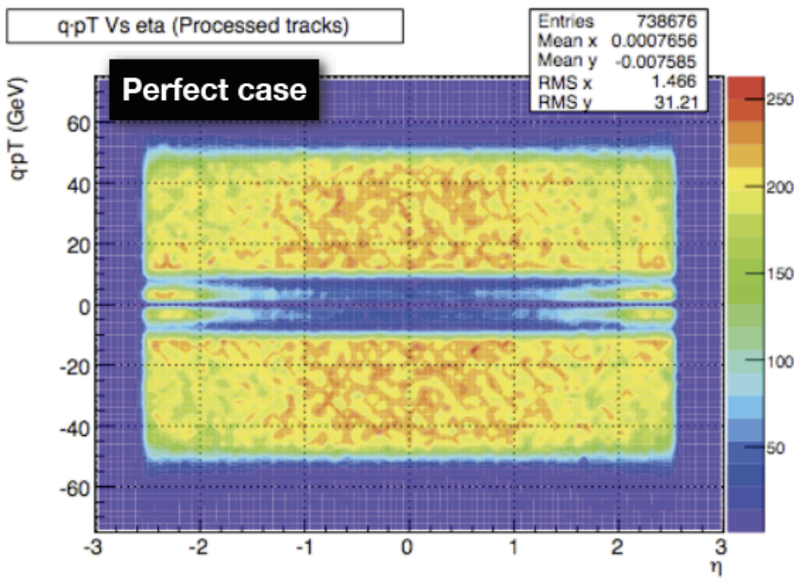


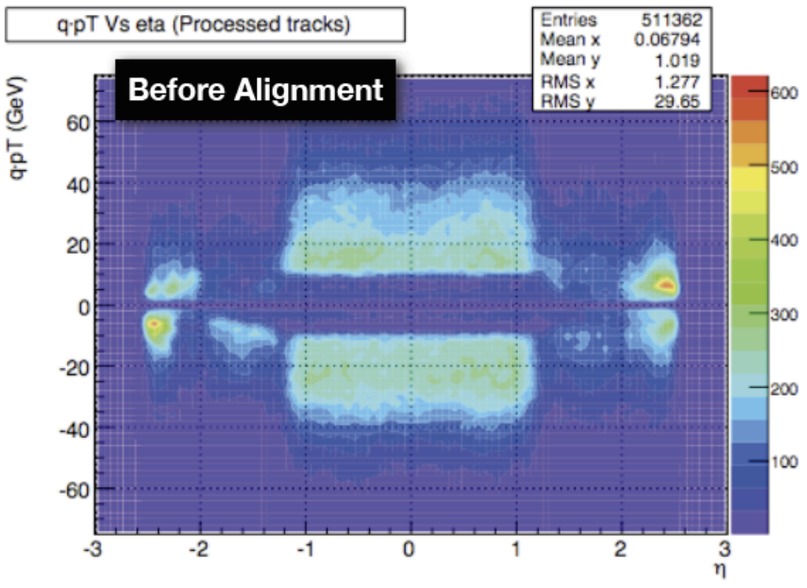


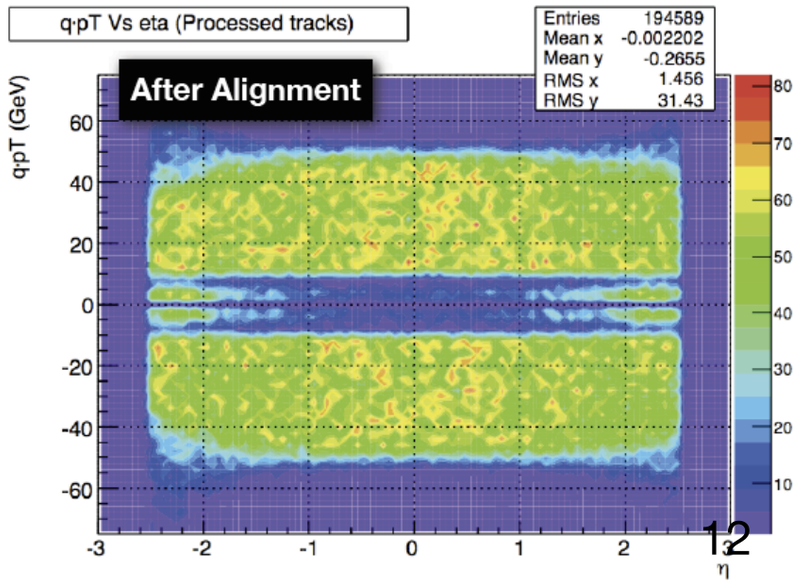
Testing the algorithms II

- Final Dress Rehearsal (FDR) was the final software test before data-taking
- Goal was to run whole ATLAS computing system to anticipate problems with early data
- Used Global X^2 algorithm
- Tested infrastructure to calculate alignment constants within a day
- Also validated online alignment monitoring



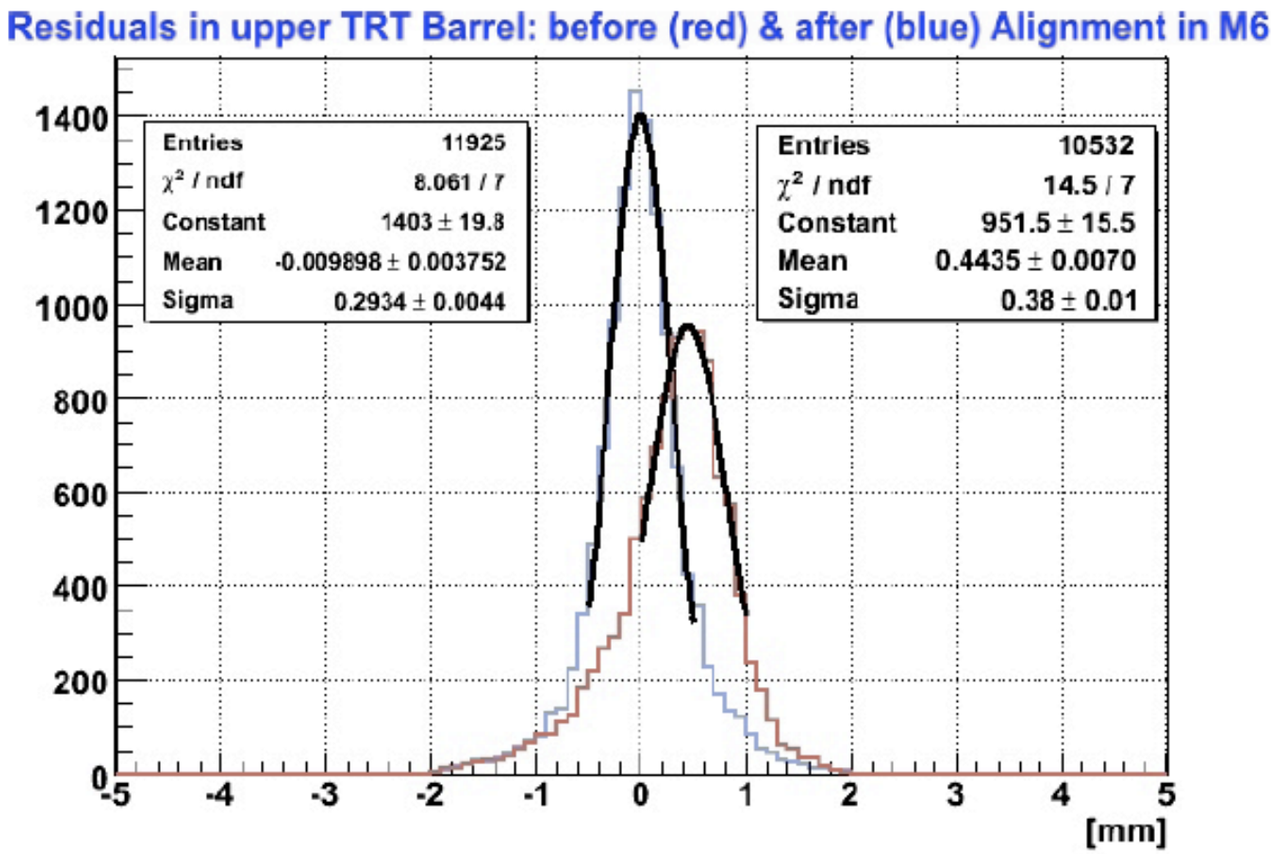


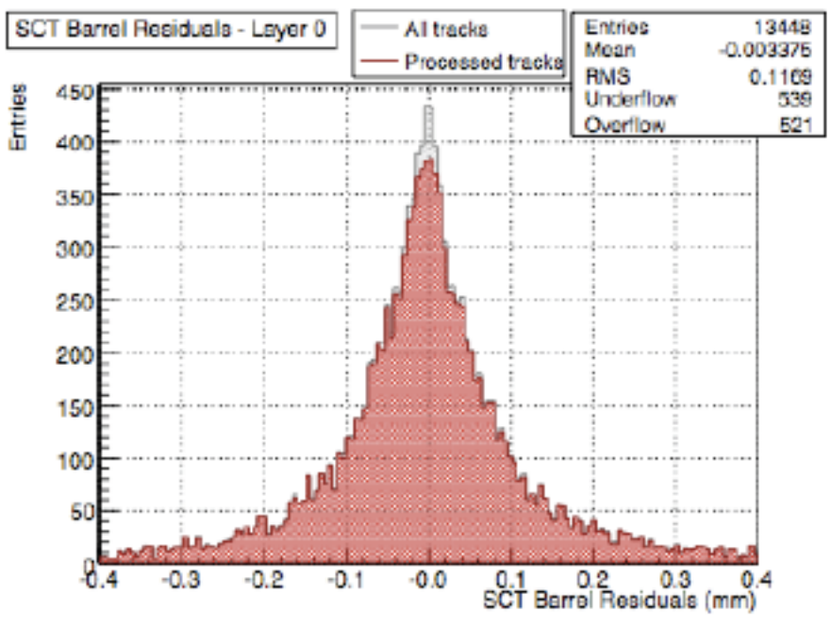


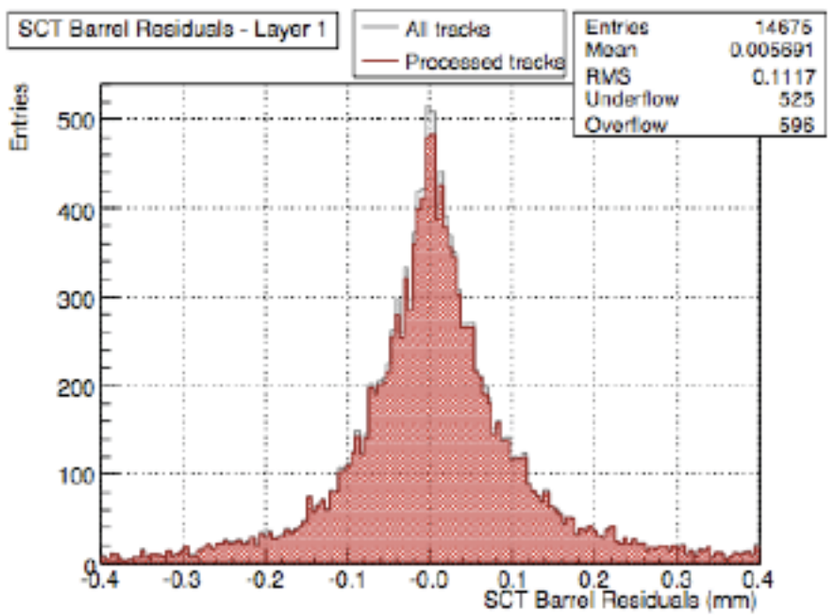


Alignment using cosmics

- Cosmic data is used to align the detectors before collision data is available
- Also can remove biases and constrain certain weak modes that could not be constrained in collisions
- Cosmics taken on the surface (2006) and in the pit (2008) have already been used to align the SCT and TRT

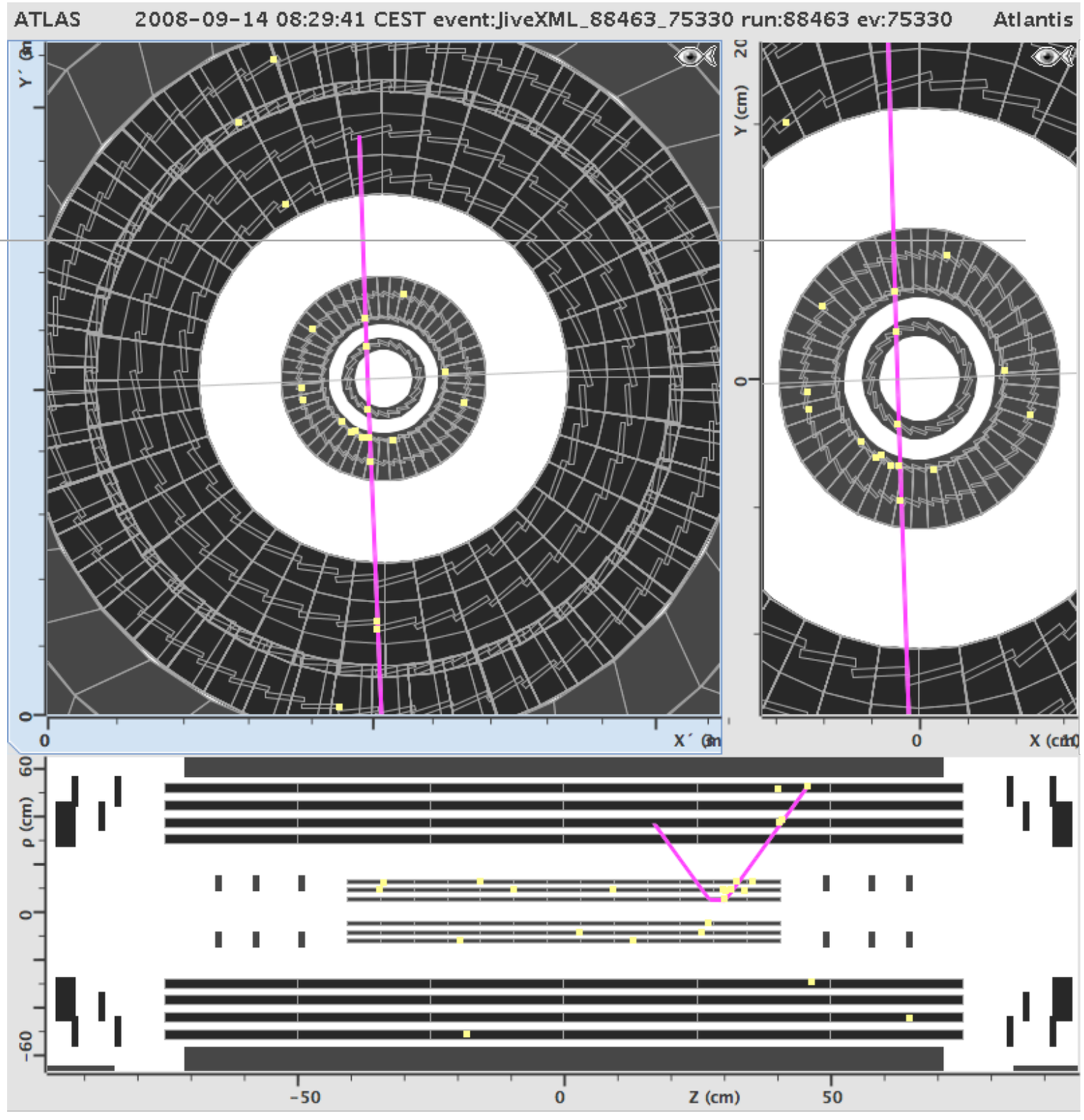


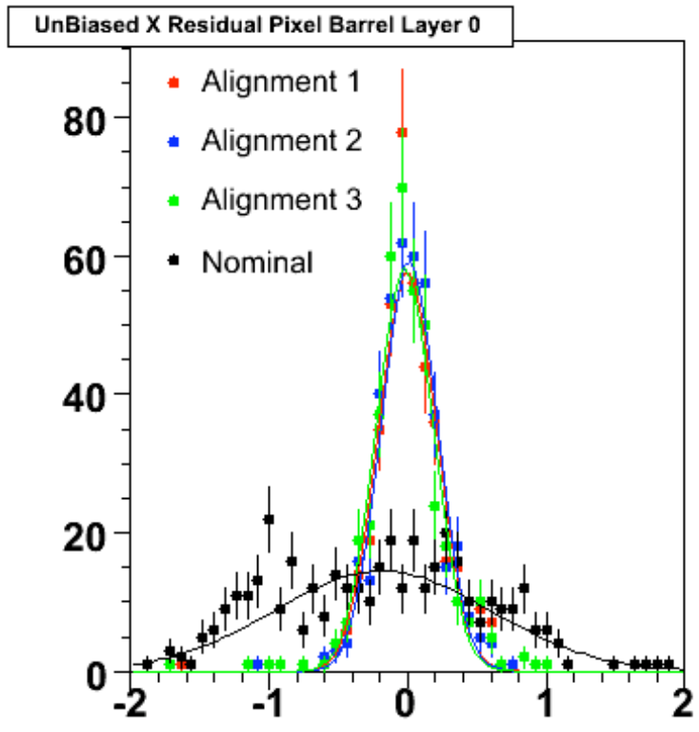




Pixel Cosmic Tracks

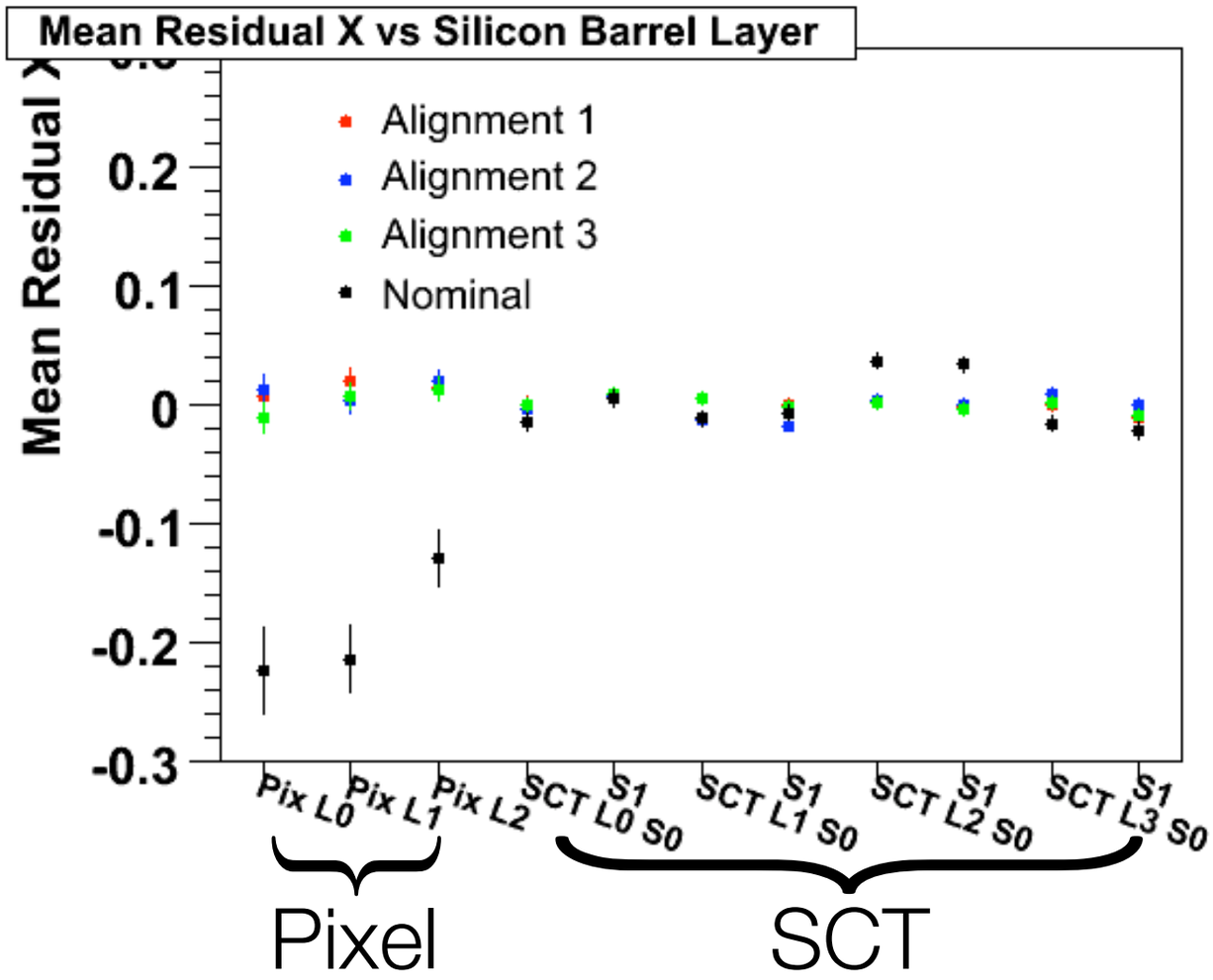
- First cosmic tracks were recorded in the pixel detector on 14 September
- 260 tracks have been recorded so far and analysis is ongoing
- Here I show some preliminary results





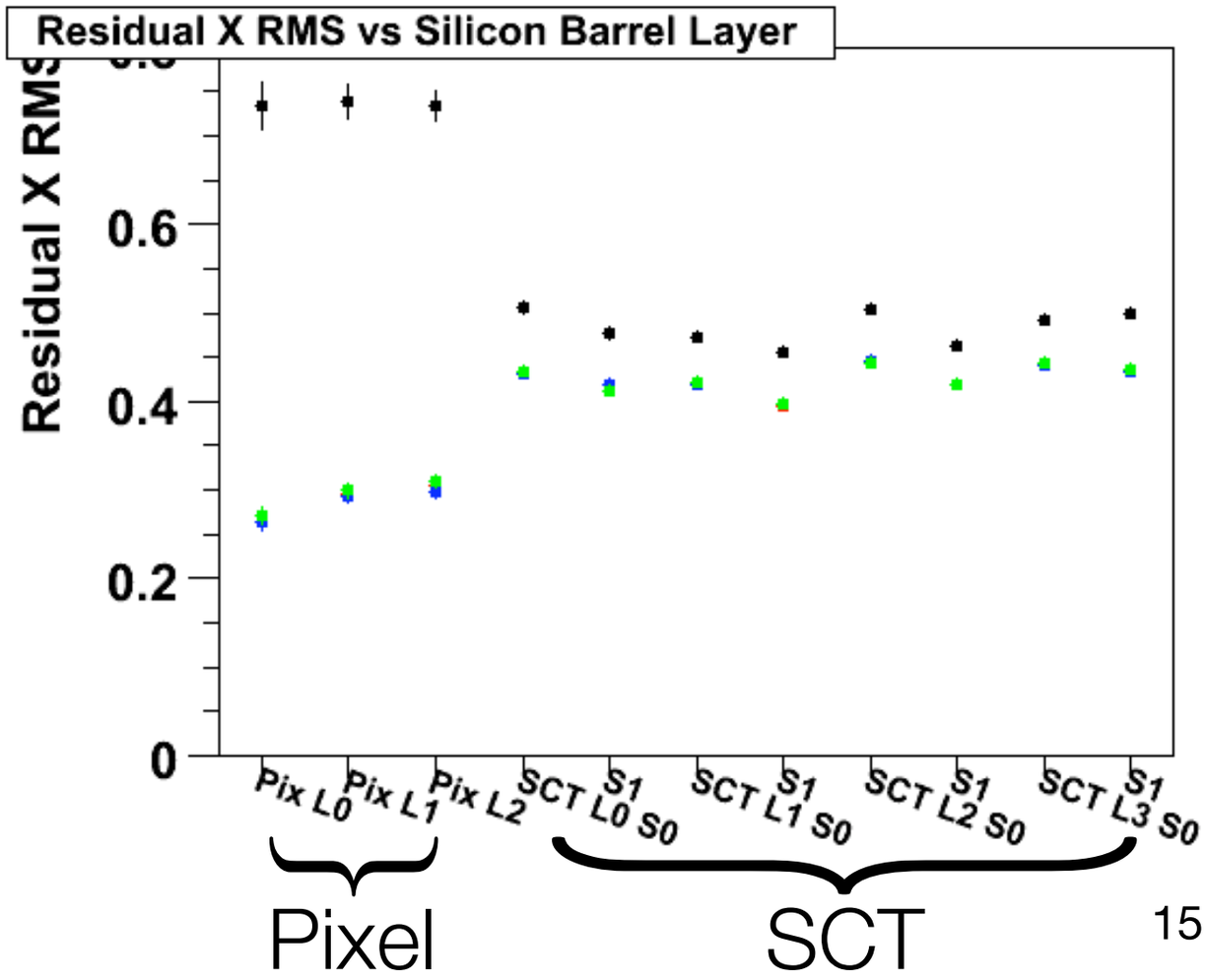
- **Alignment 1:** Global Chi2 L1/L2 + CoG
- **Alignment 2:** L2 from M6 + Survey + custom L2 Pixel + Global Chi2 L1 + CoG
- **Alignment 3:** Survey + Global Chi2 L1/L2 + CoG
- **Nominal**

First Pixel Alignment Results

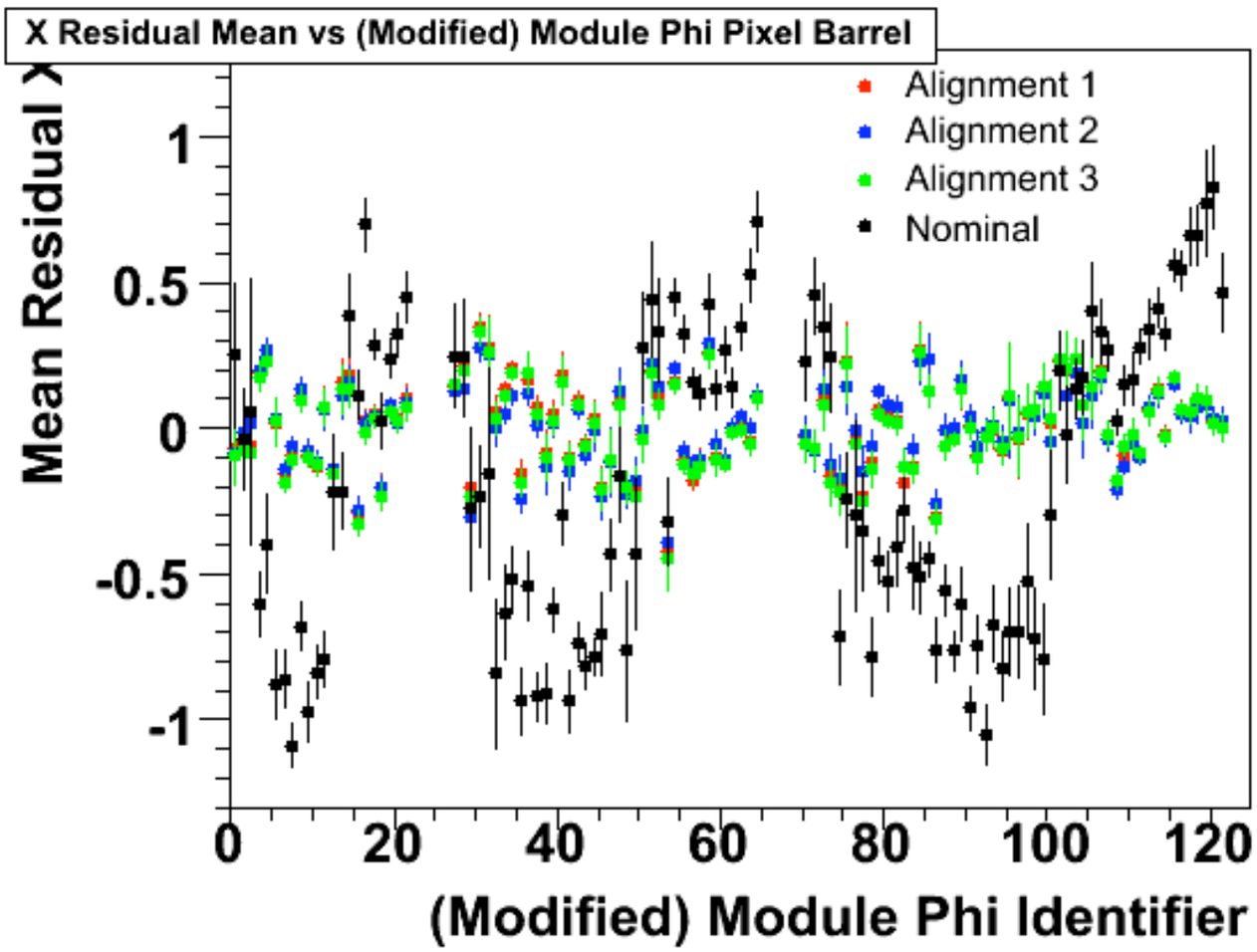


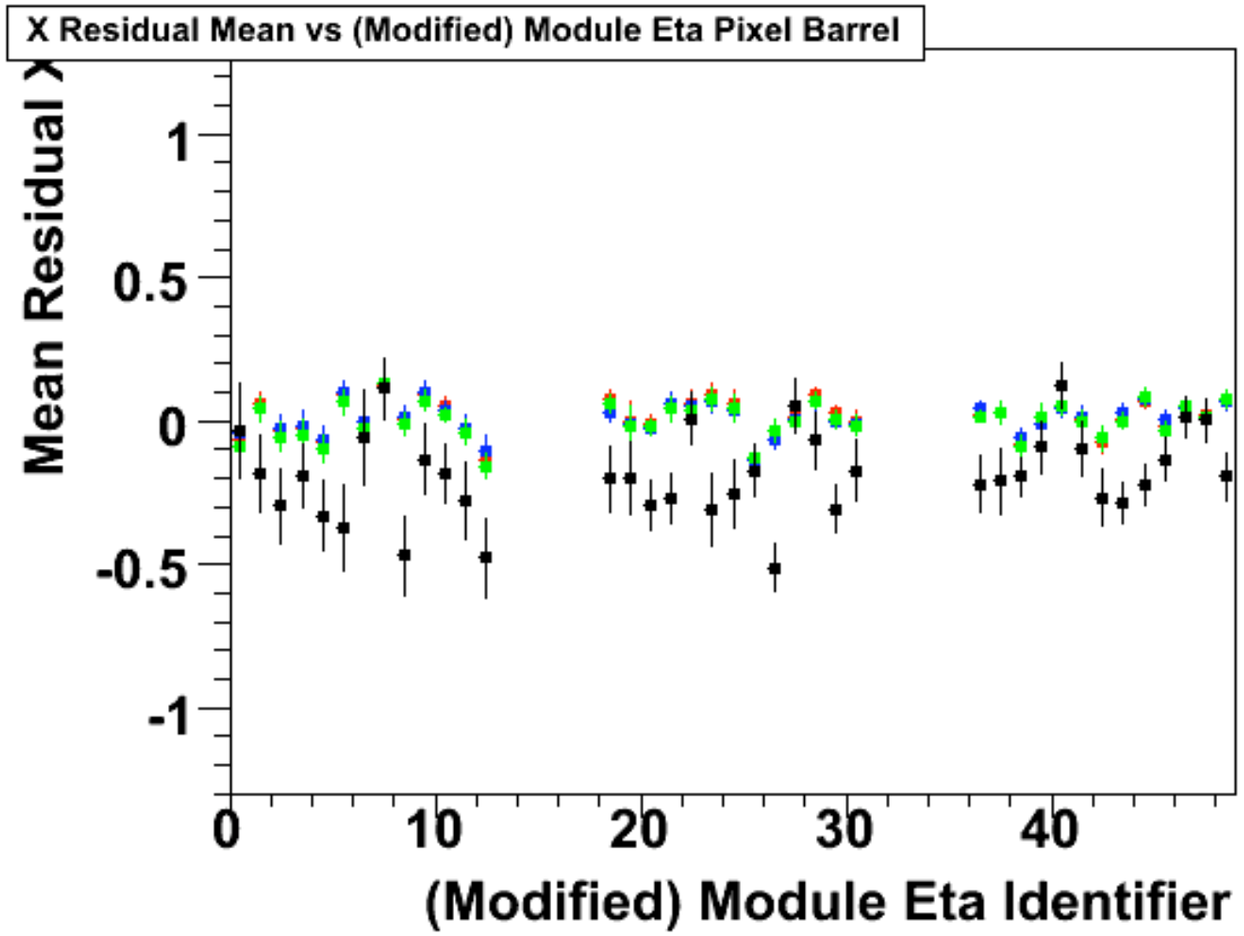
Misalignment between Pixel and SCT

Internal Pixel Misalignment between layers



First Pixel Alignment Results II





"Sinusoidal" Shape consistent with relative misalignment in transverse plane between Pixel and SCT barrel of ~0.75 mm

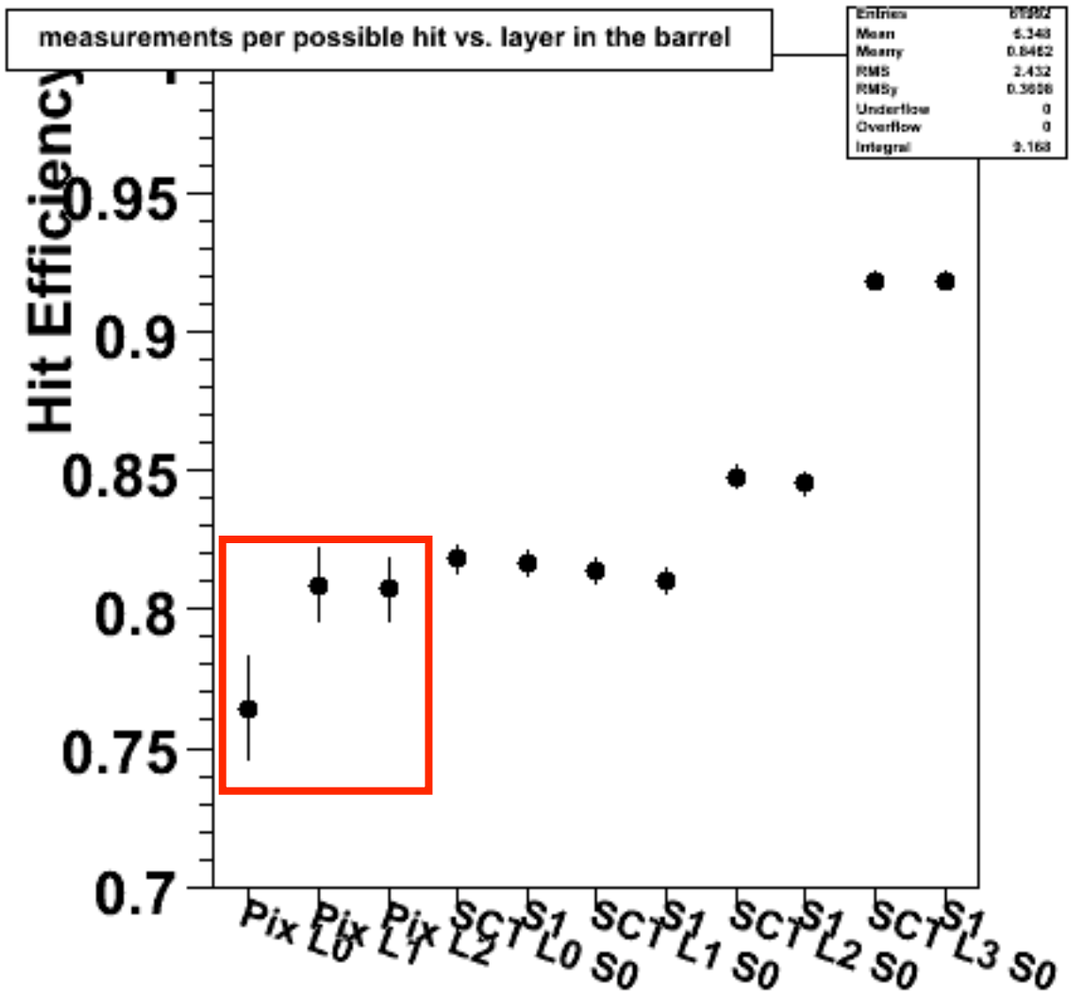
Estimate of Relative Pixel-SCT Alignment

	Relative offset of SCT wrt Pixel
x	960 μm
y	560 μm
R	1100 μm
z	500 μm
α	-0.2 mrad
β	0 mrad
γ	2 mrad

Preliminary

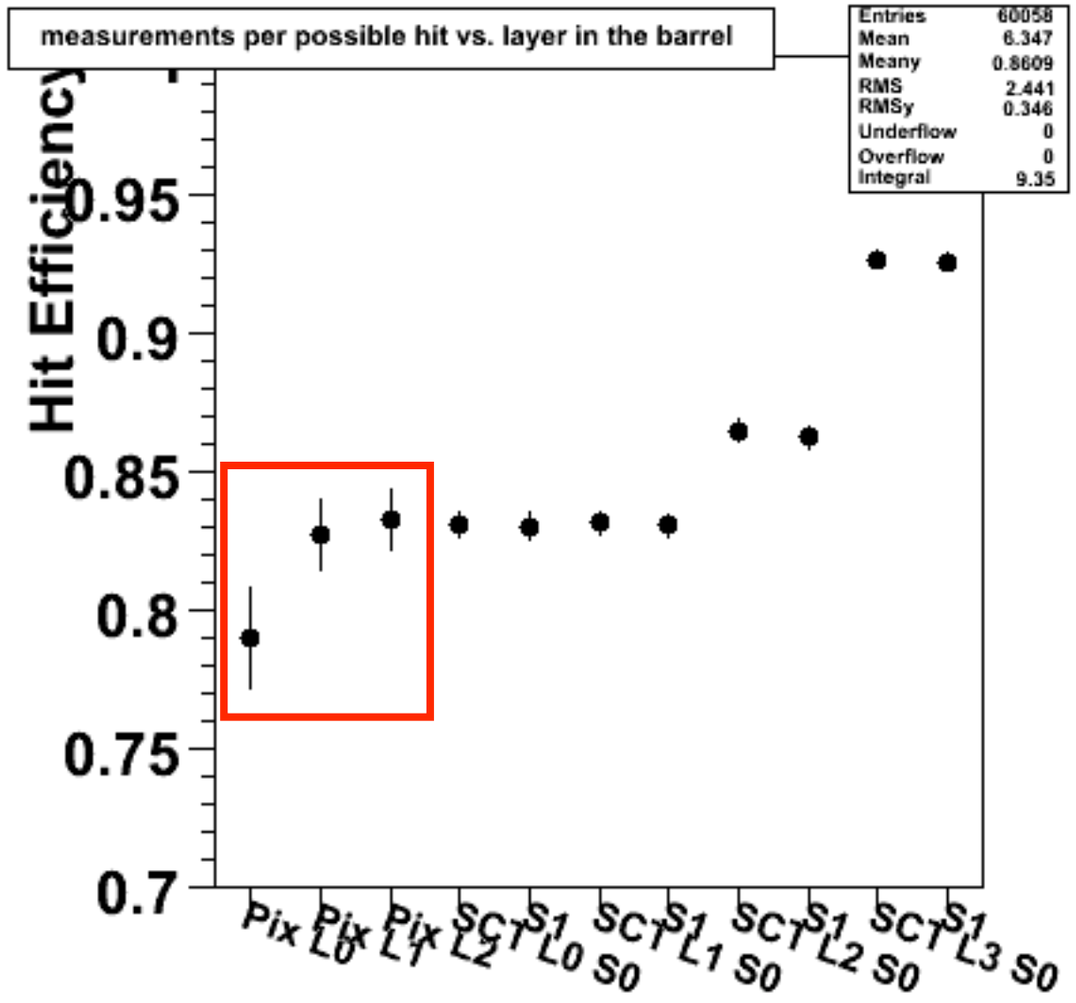
Hit Efficiency

Before alignment



Alignment after M6

After alignment

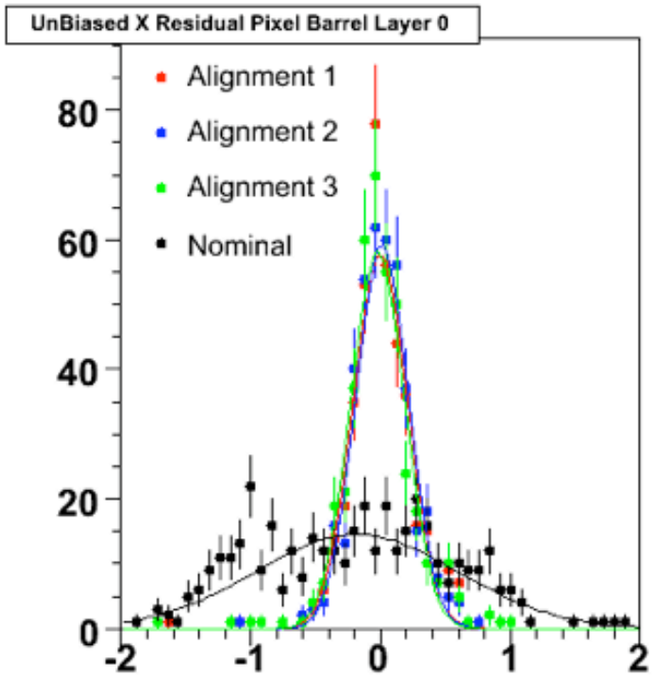


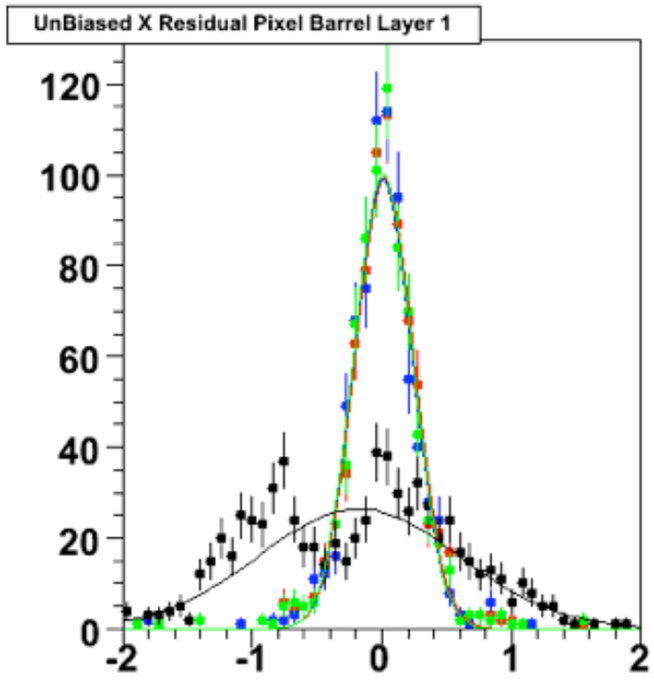
L2 constants from M6, Pixel survey data, rerun L2 and L1 alignment algorithms

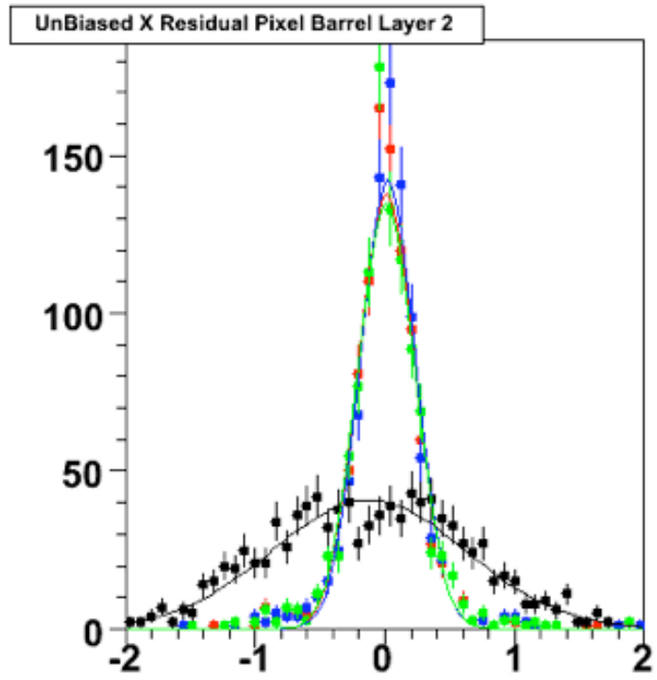
Conclusion

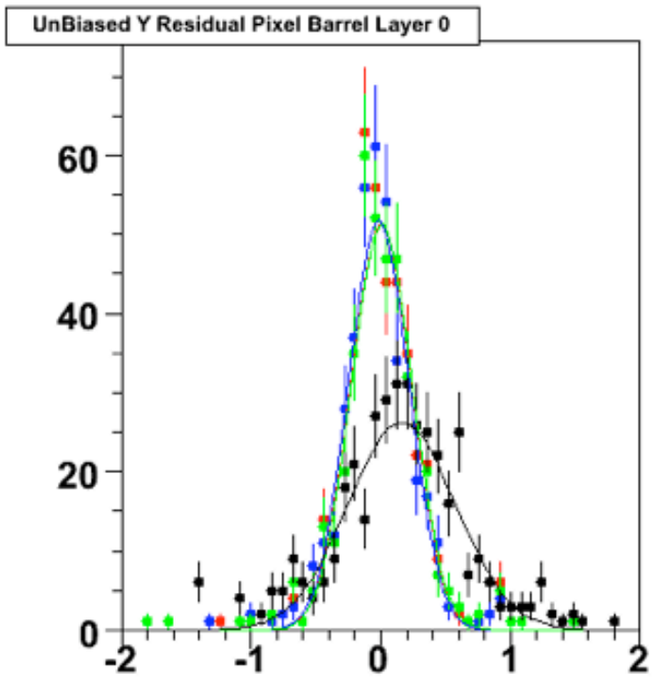
- The alignment of the Inner Detector is a challenging task with 35k silicon d.o.f. to be aligned to O(10 μm) precision
- Sophisticated algorithms have been developed and tested on order to achieve this
- All possible information is being exploited
    - survey data
    - hardware based alignment
    - track based alignment
        - collisions, cosmics, beam halo events
- Results from extensive software tests
- Recent results from cosmic data-taking in the pit
    - First results ready the next day

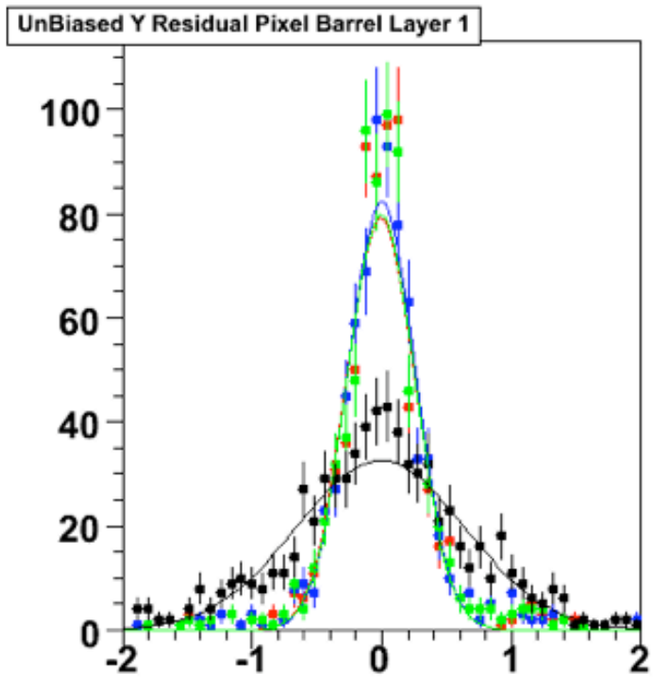
Pixel Residuals

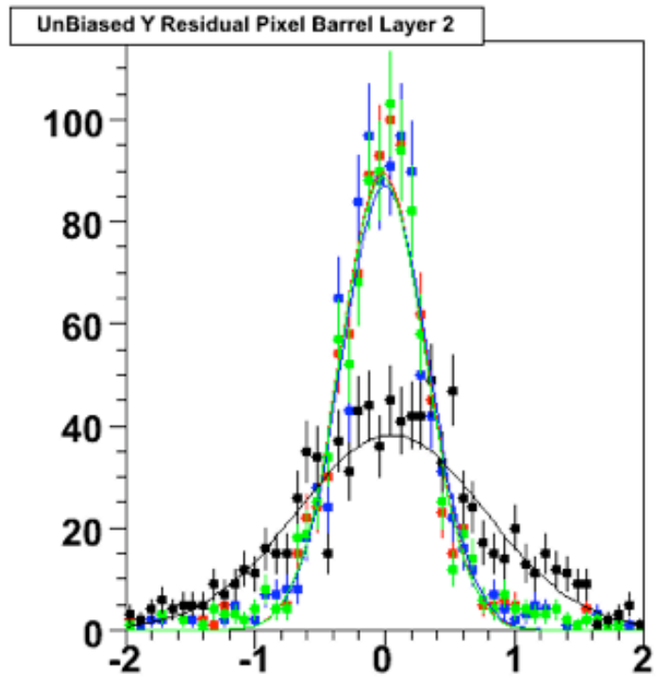




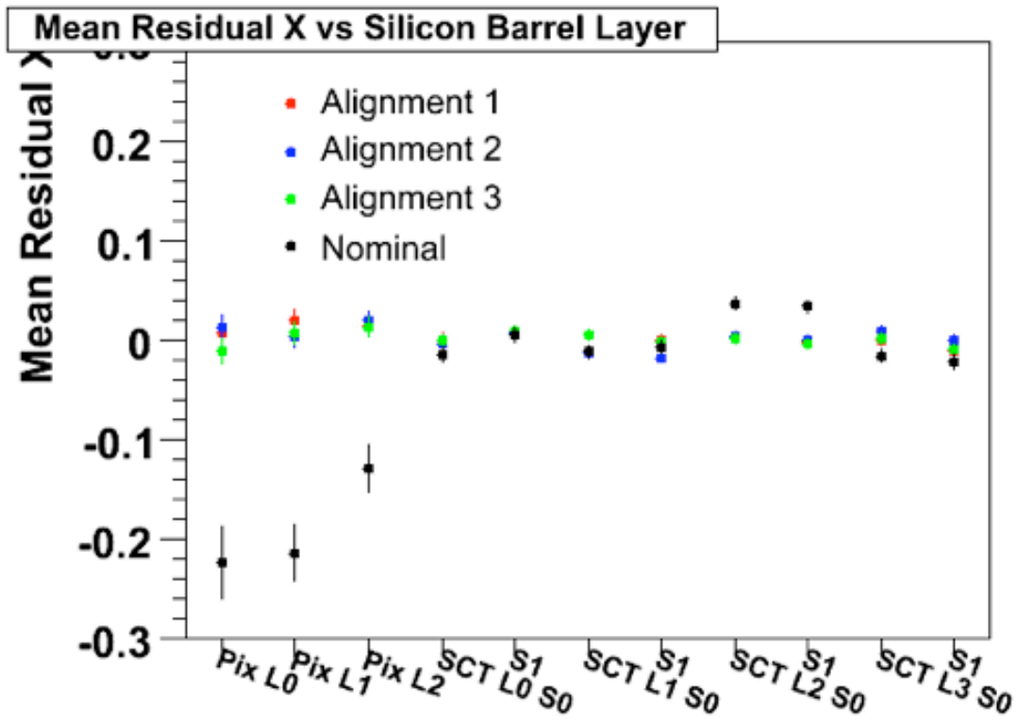


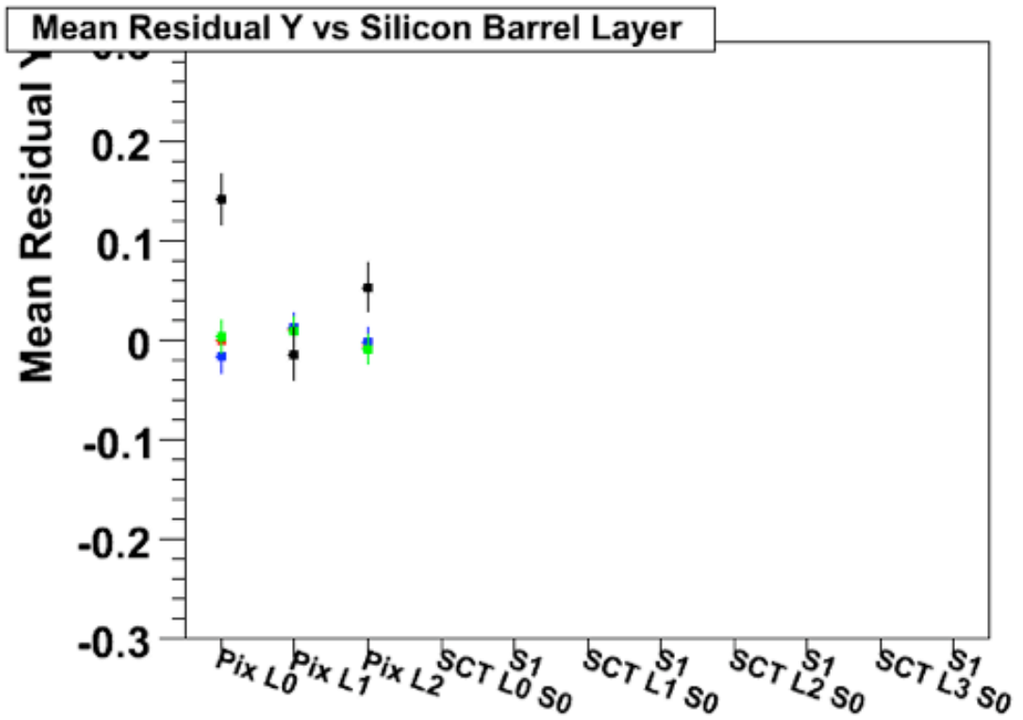


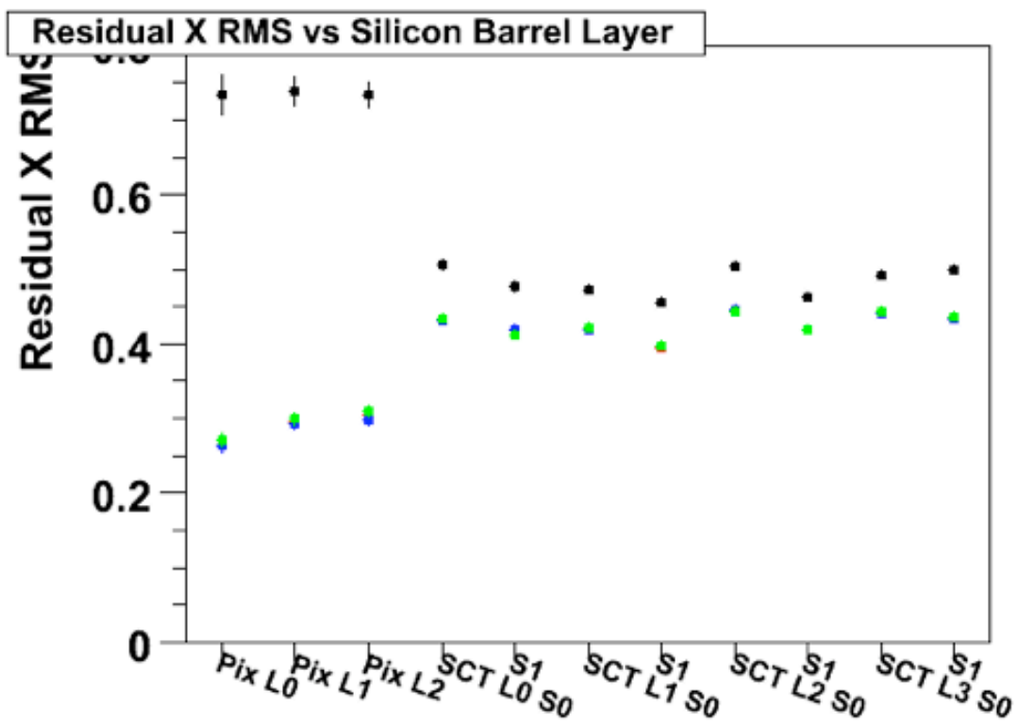


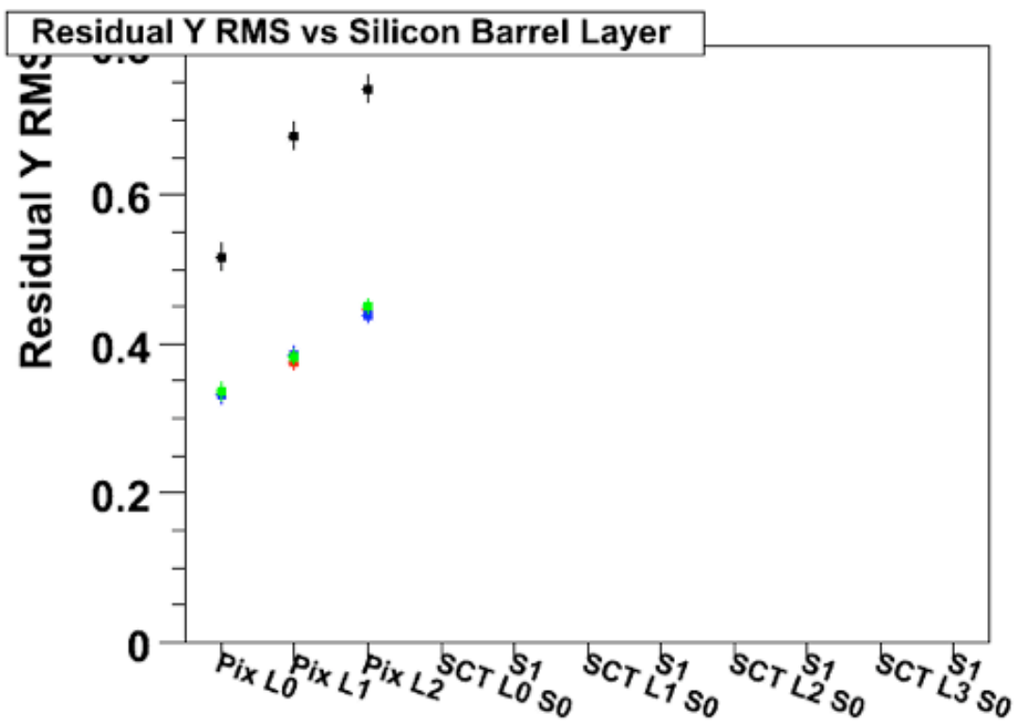


Pixel Residual Mean and RMS









Cosmic Pixel Alignment Strategies

- Alignment 1:
  - Global Chi2 L1/L2 + CoG
- Alignment 2:
  - L2 from M6 + Survey + custom L2 Pixel + Global Chi2 L1 + CoG
- Alignment 3:
  - Survey + Global Chi2 L1/L2 + CoG
- Nominal