Alignment Of The ATLAS Inner Detector

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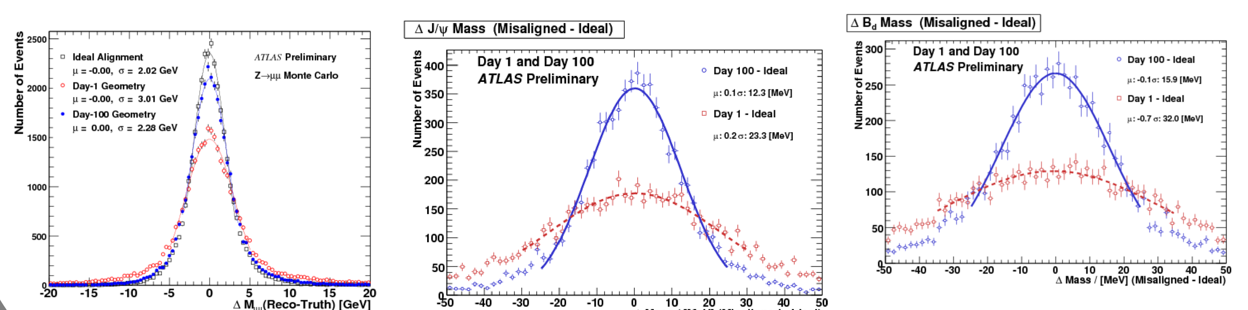
Introduction

Alignment of the precision tracking detectors to determine the true geometry is very important for the physics measurements. Imprecise knowledge of the position and orientation of the detector elements would cause biases and degradation in resolutions of physics quantities, e.g. mass resonances, transverse momentum. The geometry of as-installed detector is not the same as designed due to finite assembly tolerances, mechanical stress, electrical power consumption, humidity etc. Global deformations in the position and orientations of up to O(1) mm and O(1) mrad respectively, have been determined for the pixel detector relative to the SCT. At the smallest detector element scale (modules), the misalignments of O(100) μm in position and O(0.1) mrad have been measured. The misalignment actually determined using real tracks are consistent with expectations from the assembly tolerances.

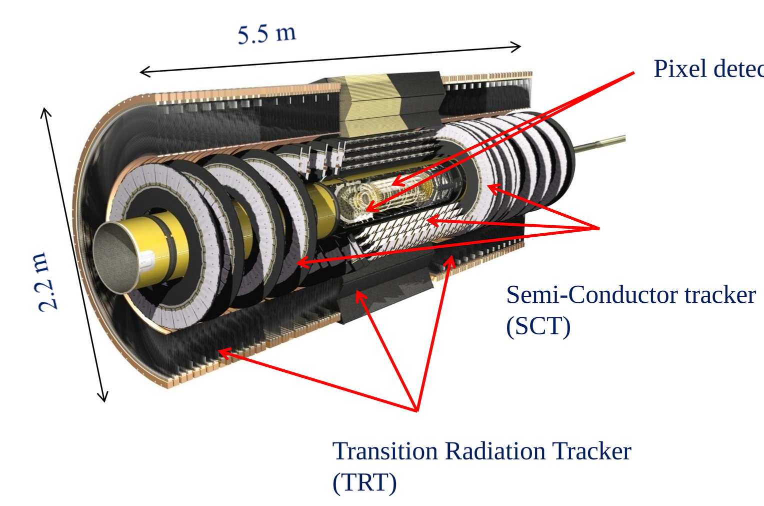
Available alignment techniques at ATLAS:

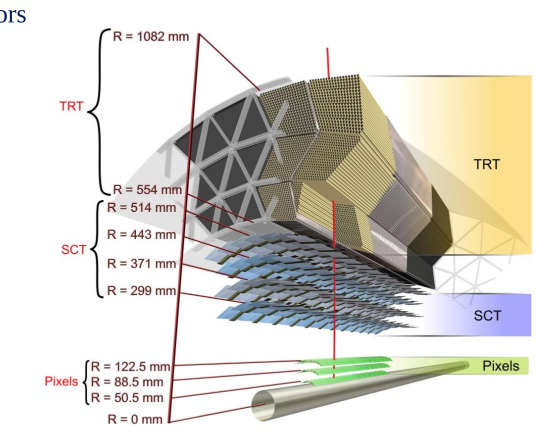
- Assembly survey and hard-ware based alignment
- Track-based alignment

Baseline: To achieve the physics goals, the position and orientation should be known to a precision so that the track parameter resolution is not degraded by more than 20% and precision in momentum scale less than 0.1%. The target is 7 μm for the pixels, 12 μm for the SCT and 30 μm for the TRT.



Example of degrading Z, J/ψ and B_d mass resonances due to misalignment

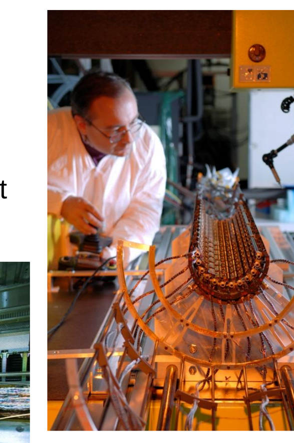


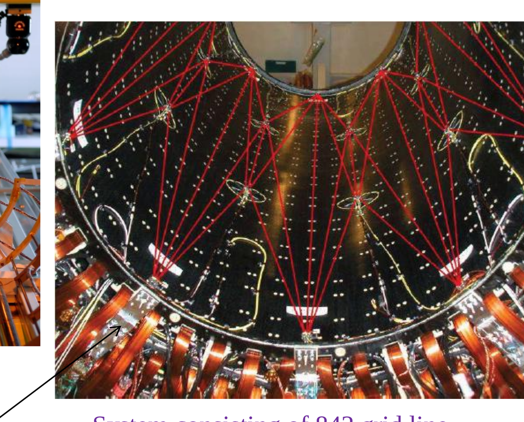


Detectors	Pixel		SCT		TRT	
	Barrel	End-cap	Barrel	End-cap	Barrel	End-cap
Element size	50 μm x 400 μm		80 μm x 12 cm		4 mm x 74 cm	
Resolution (rφx rz)	14 μm x 115 μm		17 μm (two set of strips)		130 μm	
No. of layers/disks	3	3x2	4	9x2	3	14x 2 disks
No. of modules	1456	144x2	2112	988x2	96 modules	28 disks
	1744		4088		124	
Total	5832 Silicon modules				124 TRT alignable elements	

Assembly survey & hardware-based alignment

- Mechanical or optical survey of as-built detector before and after installation
- Precise survey (at a few micron level) was done for limited substructures of the Pixels only
- Survey can be used as constraint in track-based alignment





System consisting of 842 grid line interferometers, reference interferometer, and tunable laser for frequency scanning. The grid lines are arranged into geodetic grid, separate for the barrel and end-caps

- Frequency Scanning Interferometry (FSI) in SCT
- Capable of monitoring in real time (~10 min) the movements at the micron level in the mechanical structure due to e.g. by temperature variations
- Has not been used for actual detector alignment. It is being commissioned.

Track-based alignment

The χ^2 depends on both the track parameters π and alignment parameters $\boldsymbol{a}$ through residuals

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

The track-to-hit residuals carry information about the track quality and the detector modules alignment.

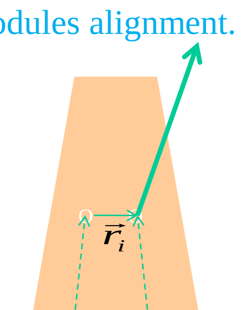
Minimize the χ^2 with respect to alignment parameters

$$\delta a = -\frac{\sum_{tracks} \frac{dr^T}{da} V^{-1} r}{\sum_{tracks} \frac{dr^T}{da} V^{-1} \frac{dr}{da}},$$

Huge (35k x 35k) matrix inversion!

Solved using MA27 fast linear solver

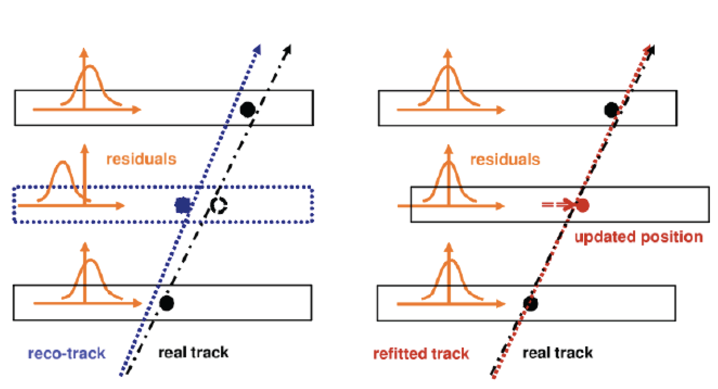
The matrix should be sparse



$$\vec{r}_i \equiv \vec{m}_i - \vec{e}_i(\pi, a)$$

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

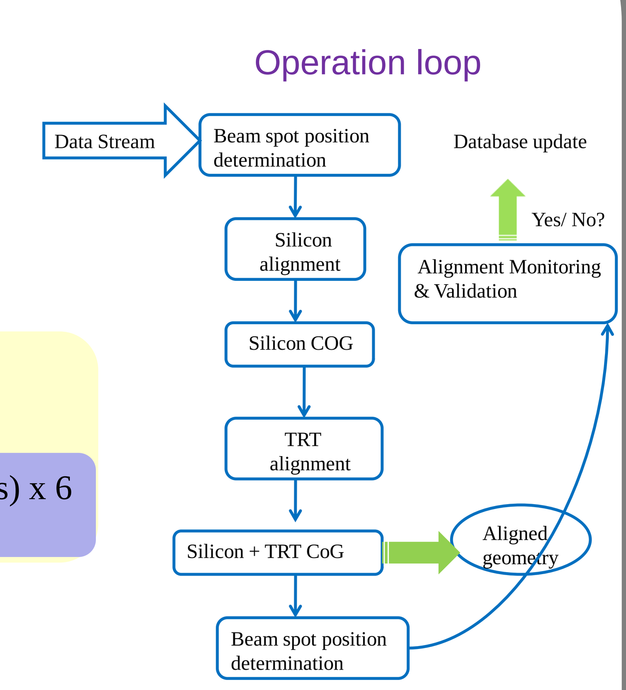
$$\delta\pi = -\frac{\sum_{tracks} \frac{\partial r^T}{\partial \pi} V^{-1} r}{\sum_{tracks} \frac{\partial r^T}{\partial \pi} V^{-1} \frac{\partial r}{\partial \pi}}$$



Alignment of large precision tracking system: A complex task!

- Data processing.
- Computing resources.
- Infrastructure and software implementations.
- Tracking algorithms.
- Monitoring & validations of alignment algorithms.
- Numerical & computational challenge.

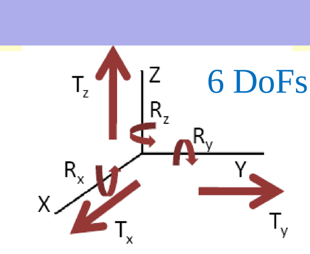
Operation loop



5832 (Silicon modules) x 6 = 34992 DoFs!

+

96 (TRT barrel modules) x 5 + 28 (TRT end-caps) x 6 = 648 DoFs.



- Typically, O(10) iterations are required to converge
  - Each iteration requires parallel jobs of O(100) CPUs for tracks reconstruction
  - Solving can be done on a single CPU

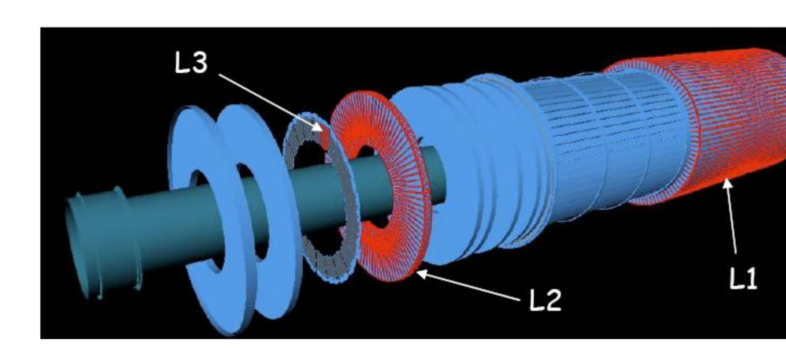
Track-based alignment algorithms at ATLAS

There are four algorithms developed at ATLAS:

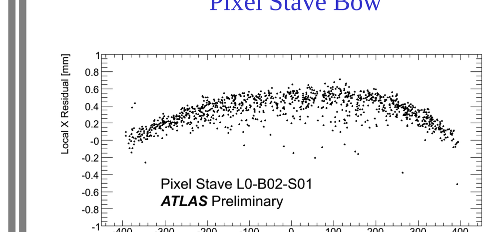
- Global χ^2 algorithm (GX2)
- Local χ^2 algorithm (LX2)
- Robust Alignment algorithm (RA)
- Pixel standalone algorithms (PSA)
  - –without overlap residuals
  - –with overlap residuals

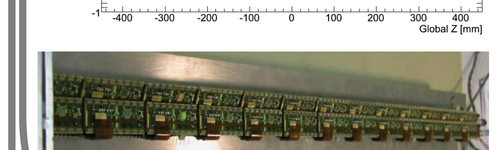
All of these algorithms produce consistent results

The LX2 and RA algorithms differ mainly from GX2 algorithm in the correlations between modules via the common track. The GX2 algorithm introduces correlations through the implicit track refit represented by $(\partial r/\partial \pi) \times (d\pi/d\boldsymbol{a})$ term, while LX2 and RA ignore this term.



Pixel Stave Bow





The inner-detector is aligned in three major stages.

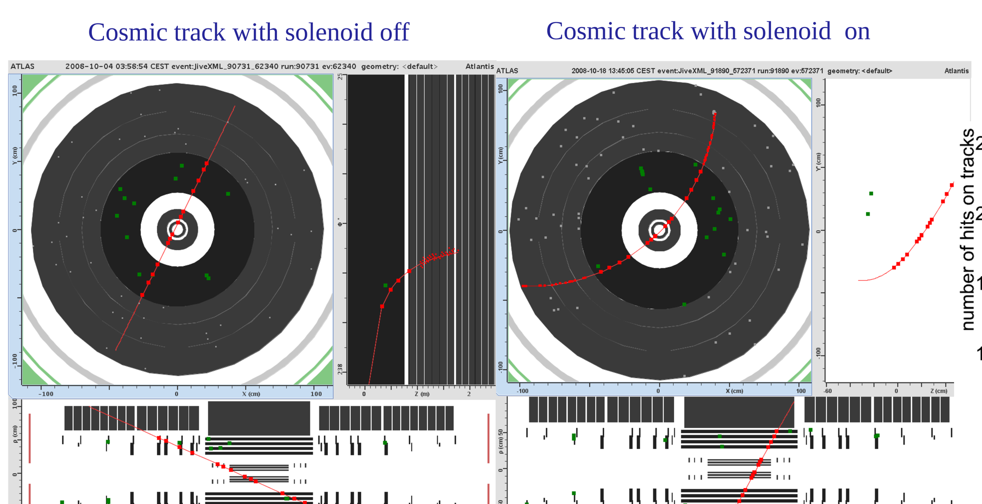
- Level 1: Alignment of the pixel detector in global coordinate frame with respect to the SCT barrels and the end-cap disks. The size of misalignments are O(1) mm translational and O(1) mrad for the rotations around the global z axis
  - –Full matrix solving with very low level of granularity in detector elements (24 DoFs)
- Level 2: Alignment between the pixel barrel layers and end-cap disks in the global coordinate frame. Pixel stave bow (shown on left) has been determined as the largest misalignment.
  - –Full matrix solving with moderate level of granularity in detector elements (upto ~300 DoFs)
- Level 3: Individual detector modules alignment within the local frame.
  - –Sparse matrix solving with full granularity of detector elements.

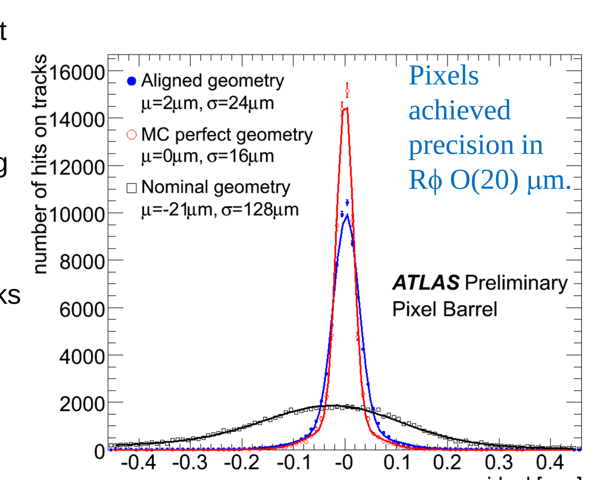
Performance

ATLAS has been collecting cosmic-ray data since Sep, 2008. The LHC pp collision data at √s= 0.9 TeV and 2.36 TeV have also been recorded by ATLAS in December, 2009. Alignment has been performed using the autumn 2008 cosmic-ray data comprising about 5 million tracks without the solenoid magnetic field and about 2.6 million tracks with the magnetic field. Of these about 0.2 million tracks have Pixel and SCT hits in each magnet configurations. The tracks collected until now with pp collision data are about 0.5 million that are being used for the alignment. The alignment after combining the cosmic-ray and the LHC collision data is imminent!

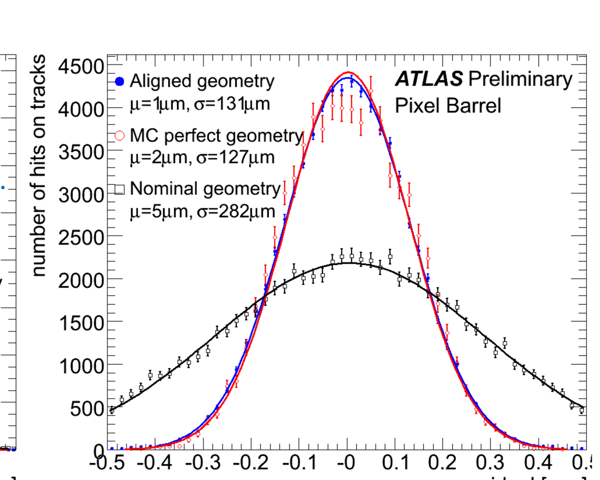
Tracks from cosmic-ray and pp-collisions provide different illuminations to the detector elements due to their different origins. The end-caps are less illuminated by cosmic-rays. The cosmic tracks are useful for removing some of the weak modes. The transverse momentum of the cosmic-ray track used for alignment are on average O (20) GeV. Majority of collected collision tracks are low momentum and hence are of limited use for alignment due to large multiple scattering in the traversed material.

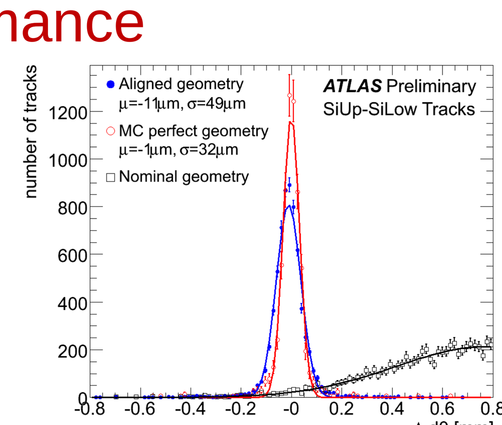
Cosmic track with solenoid off — Cosmic track with solenoid on



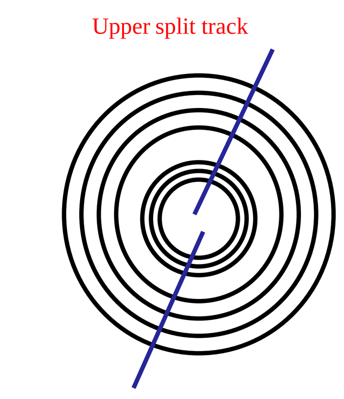


Pixels achieved precision in Rϕ O(20) μm.

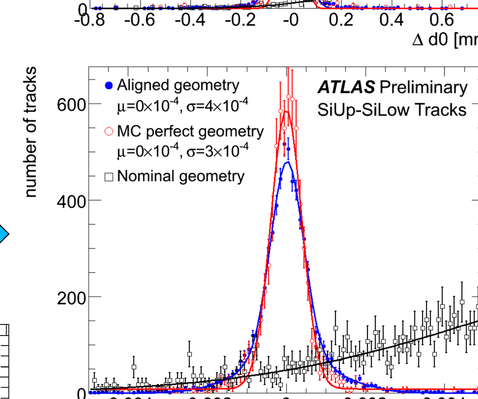


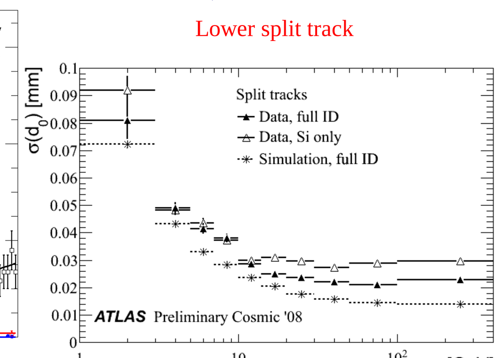


Upper split track

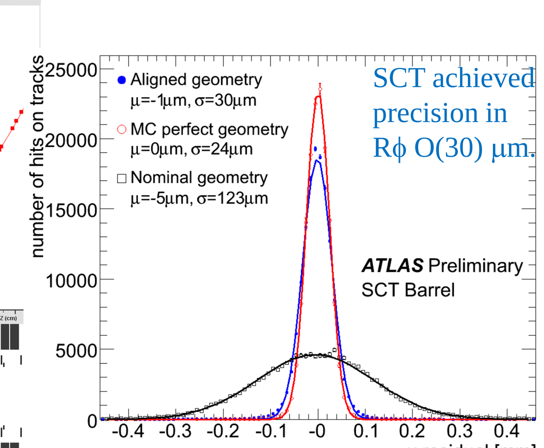


Lower split track

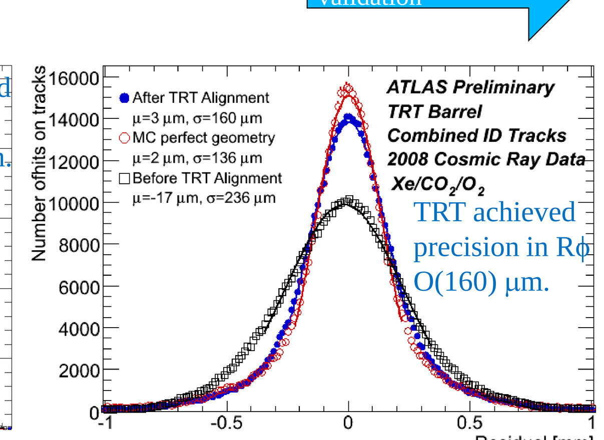




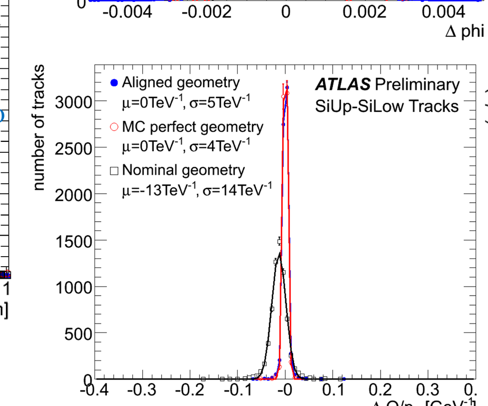
After alignment validation

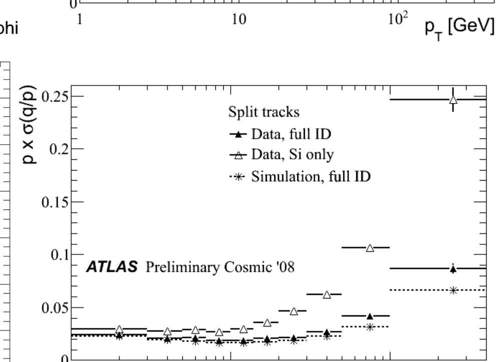


SCT achieved precision in Rϕ O(30) μm.

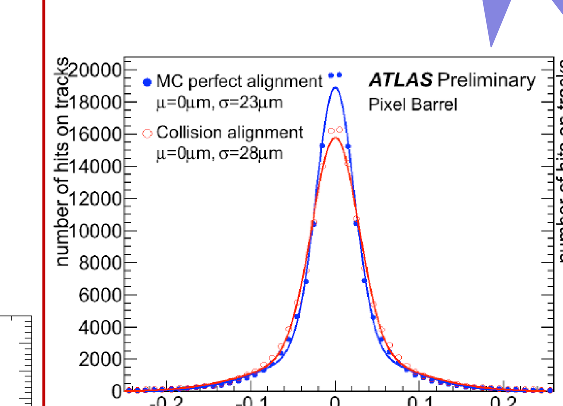


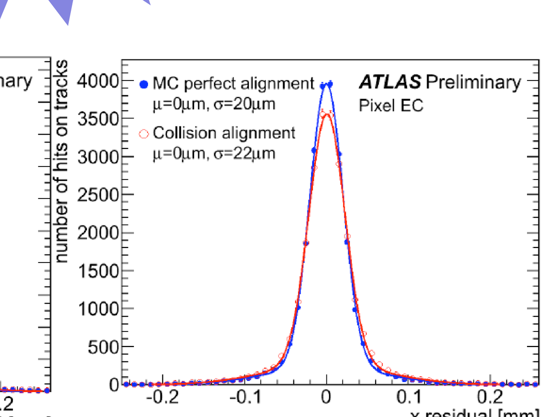
TRT achieved precision in Rϕ O(160) μm.

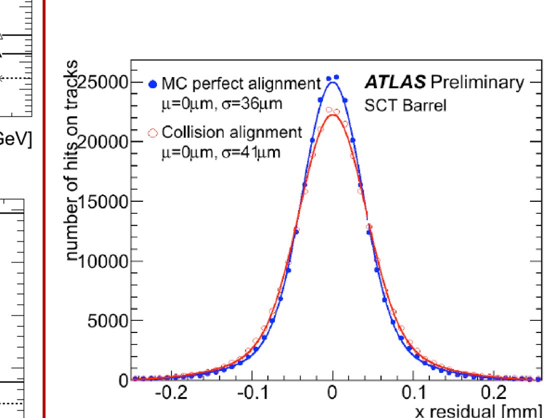


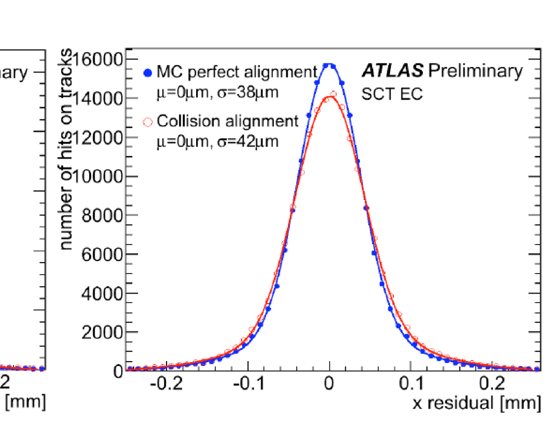


Alignment with LHC pp-collision tracks recorded at ATLAS (Very preliminary)



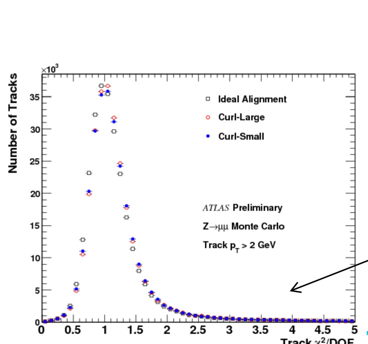




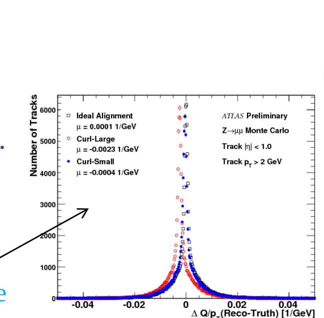


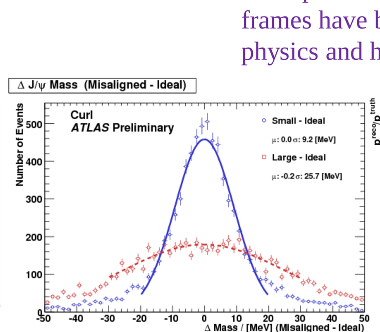
Collision tracks significantly improve the alignment for the end-caps

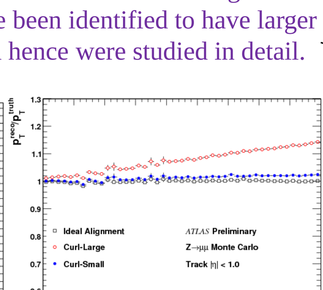
Limitations of track-based alignment using χ^2 approach: Systematic misalignments



The track-based alignment suffers from the detector deformations corresponding to the "weak modes", which keep the track χ^2 unchanged.



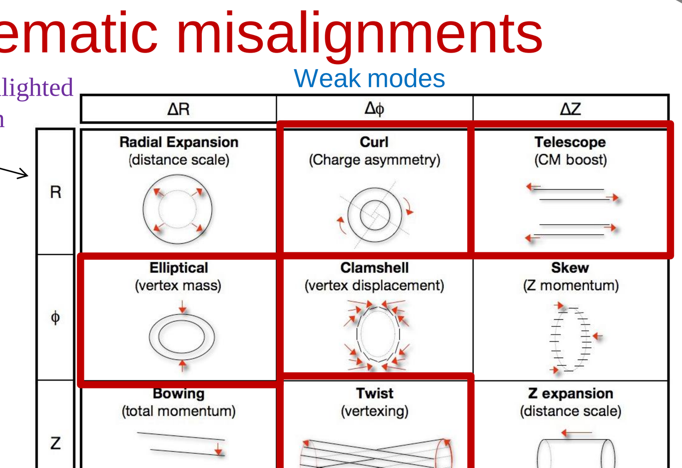




The detector deformations cause biases in the track parameter, e.g charge asymmetry due to 'curl'.

Example weak modes surrounding with the red highlighted frames have been identified to have larger impact on physics and hence were studied in detail.

Weak modes



Conclusions

Various alignment techniques employed at ATLAS have been performing very well, and proving the validity of the principle. The widths of the residual distributions are approaching those of the simulation with perfect knowledge of geometry. The track-based alignment has been performed using both the cosmic-ray and pp-collision data that have been collected so far since autumn 2008. We will collect more proton-proton collision data this year and in 2011 at the center-of-mass energy of 7 TeV. This will greatly help us to achieve our baseline goals for physics.

We thank the organizers of the ACAT2010 for inviting us to present a poster on this subject.