Alignment of the ATLAS Inner Detector Tracking System

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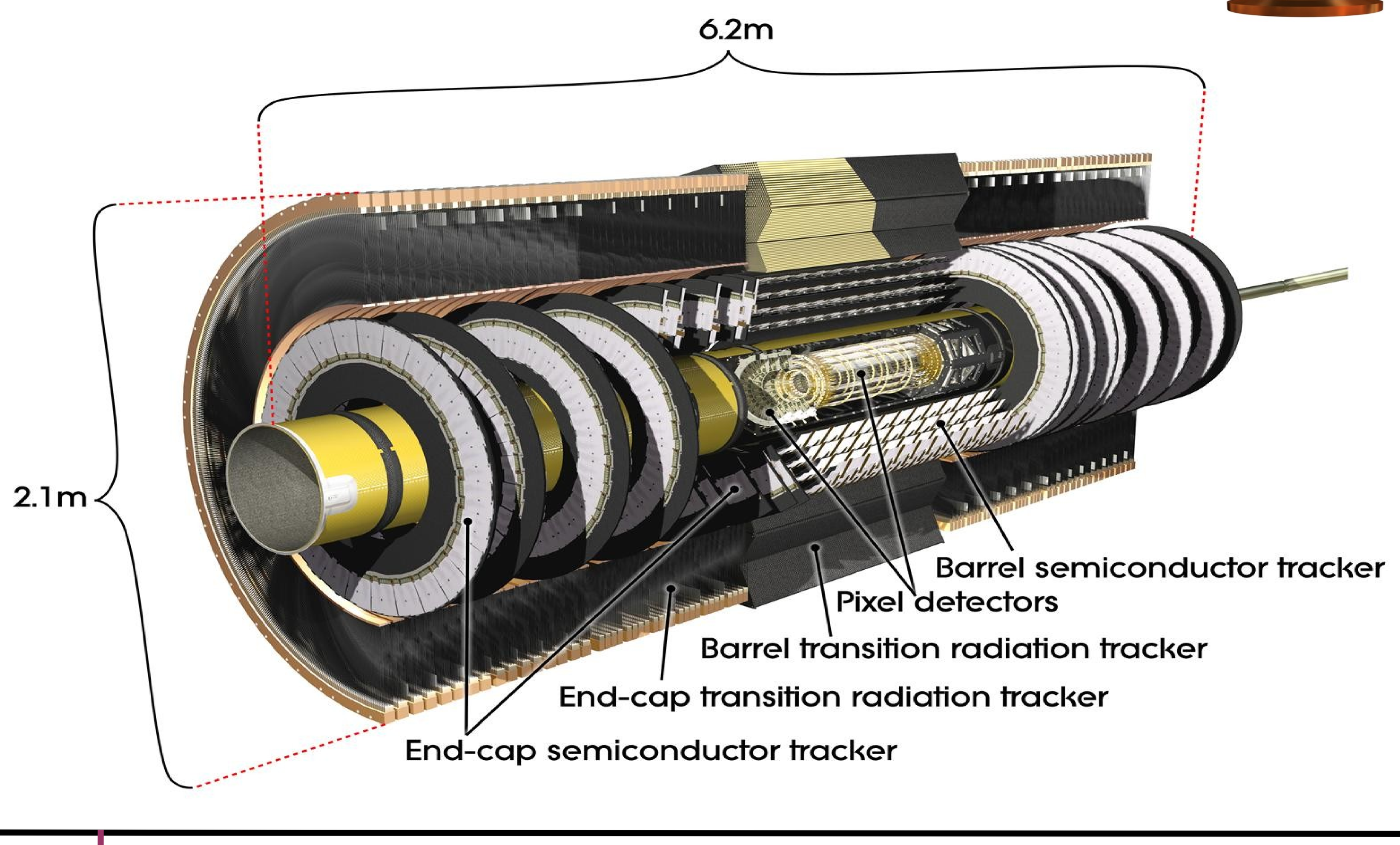
Introduction

The ATLAS Inner Detector (ID) consists of two silicon subsystems, the Pixel detector and the Semiconductor Tracker (SCT), complemented by the Transition Radiation Tracker (TRT) composed of drift tubes.

	Number of Modules	Technology	Intrinsic Resolution
Pixel	1774	silicon pixel	10 μm(rϕ), 115 μm(rz)
SCT	4088	silicon micro-strips	17 μm(rϕ), 580 μm(rz)
TRT	176	drift tubes	130 μm(rϕ)

After the assembly of the detector, the position of the individual modules is known with much worse accuracy than their intrinsic resolution. Therefore a track-based alignment procedure has to be applied.

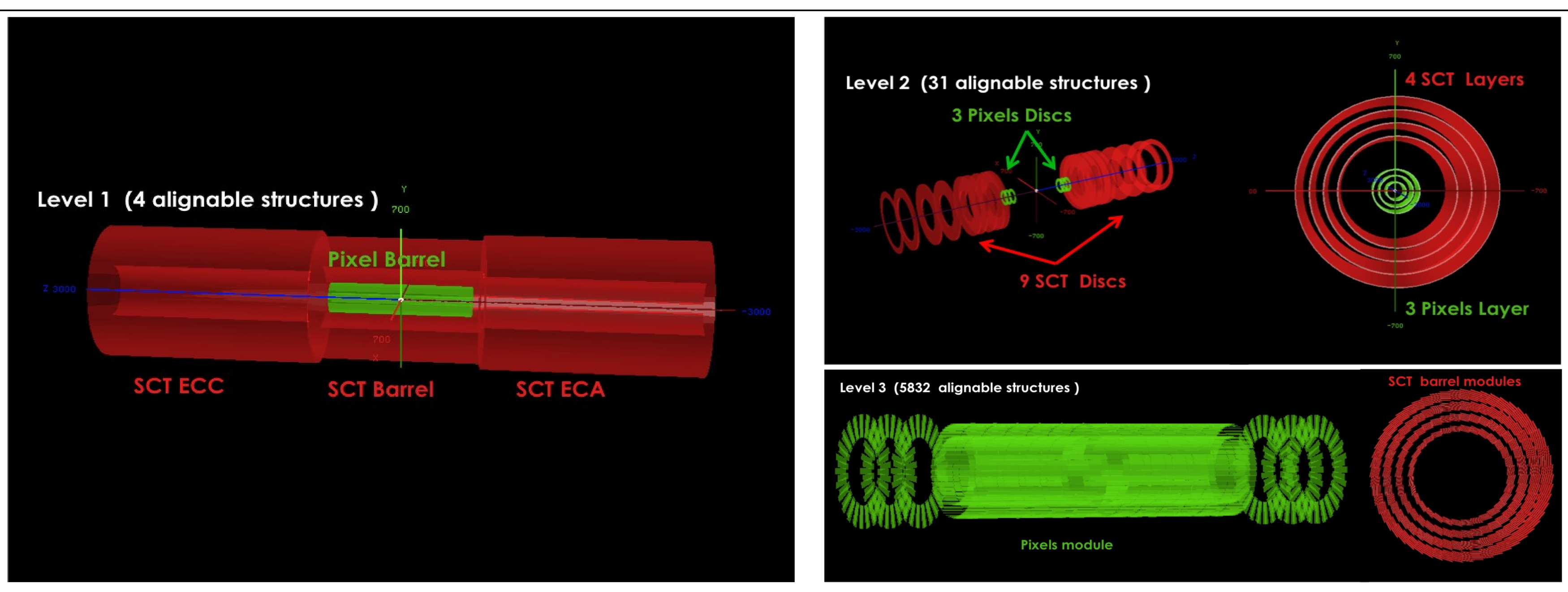
The baseline goal of the alignment is to determine the position and orientation of the modules with such precision that the track parameters' determination is **not worsened by more than 20%** with respect to that expected from the perfectly aligned detector. This is crucial for **efficient track reconstruction and precise momentum measurement and vertex reconstruction.**



Alignment Levels

Neglecting the module deformations, for each module 6 alignment degrees-of-freedom (DoF) can be defined: 3 translations of the center of the module (Tx,Ty,Tz) and 3 rotations around the Cartesian axes (Rx,Ry,Rz). In order to address the realistic misalignments of the detector, the alignment is done at different levels of granularity motivated by the mechanical structure of the ID.

	Silicon Alignable Structures				TRT Alignable Structures	
Level	**Pixel**	DoFs	**SCT**	DoFs	**TRT**	DoFs
1	whole Pixel	6	1 barrel + 2 endcaps	18	1 barrel + 2 endcaps, except Tz of barrel	17
2	3 barrel layers + 2×3 endcap discs	54	4 barrel layers + 2×9 endcap discs	132	32×3 barrel modules + 40×2 endcap wheels, except Tz of barrel	960
3	1456 barrel modules + 2×144 endcap modules	10464	2112 barrel modules + 2×988 endcap modules	24528	~300,000 individual tubes	**under preparation**
For Silicon level 3 alignment, in total about **36,000 DoFs** to be aligned						

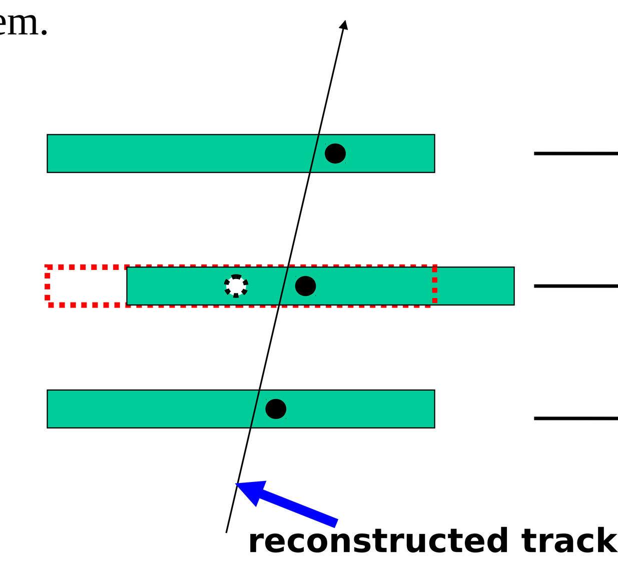


Alignment Strategy

Track-Based Alignment Algorithms

Three independent algorithms have been developed and validated in the ATLAS offline software framework. All are based on the residuals of the reconstructed hits on tracks.

- Global χ^2: It is the baseline alignment algorithm, which simultaneously fits all particle track parameters and alignment parameters by minimizing a large χ^2. It requires solving linear systems of the size equal to the number of the alignment DoFs. At level 3, this number becomes very large.
- Local χ^2: Solve a linearized equation for each detector module separately; only requires the inversion of a 6×6 matrix per alignable structure.
- Robust Alignment: Uses weighted mean residual and overlap residual distributions and centers them.



The middle module is shifted away from its nominal position. Real positions (green filled) are not known, thus the reconstruction uses the nominal position (red dashed). Consequently track fit quality is degraded. The residual distribution of the displaced module (and the others) will be biased away from 0. This bias measures the shift of the module and is the basis for the alignment.

Residual χ^2 Minimization

The total χ^2 to be minimized:

$$\chi^2 = \sum_{tracks} \mathbf{r}^T V^{-1} \mathbf{r} \qquad (1)$$

Here $\mathbf{r}(\mathbf{a},\tau)$ is vector of the residuals of the track hits - these depend on both the alignment parameters $\mathbf{a}$ and the track parameters τ. V is the covariance matrix of the hit measurements. The minimization of χ^2 requires:

$$\frac{d\chi^2}{d\mathbf{a}} = 0 \implies \sum_{tracks} \frac{d\mathbf{r}^T}{d\mathbf{a}} V^{-1} \mathbf{r} = 0 \qquad (2)$$

Then make linear expansion around $\mathbf{r}_0$(initial estimates of hit residuals). Finally can obtain:

$$\delta\mathbf{a} = -\left(\sum_{tracks} \frac{d\mathbf{r}^T}{d\mathbf{a}_0} V^{-1} \frac{d\mathbf{r}}{d\mathbf{a}_0} \right)^{-1} \sum_{tracks} \frac{d\mathbf{r}^T}{d\mathbf{a}_0} V^{-1} \mathbf{r}_0 = -A^{-1}B \qquad (3)$$

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Computing Challenges

1. Data are **processed in parallel on multiple CPUs**, then merged to obtain the final matrix A and vector B. An infrastructure to submit parallel jobs to the Grid has been put in place too.
2. Depending on the granularity of the alignment, different matrix solving techniques are used, such as **Lapack, ScaLapack, MA27** etc. The number of matrix DoF in equation (3) can reach 36,000 and can be far from sparse, then solving is very computationally intensive. New techniques (such as GPUs) are under investigation.

Beam-spot and Vertex Constraints

- Beam-spot and vertex constraints are essential for high quality alignment. The corresponding tools have been implemented.
- The basic idea consists of adding either beam-spot or vertex information to the collection of track measurements. A subsequent track refit provides updated measurement residuals and corresponding derivatives.

Weak Modes

Some global distortions preserve the helical trajectory of tracks and consequently track-based alignment algorithms are insensitive to them. These are called "weak modes" of alignment.

Table shows simplest examples of weak modes and their impact on physics measurements.

Methods to Deal with Weak Modes:

- **Different track topologies,** such as cosmics, beam-gas, beam-halo etc.
- **Use constraints,** such as beam-spot, vertex constraint, constraint on invariant masses of well known resonant decays, constraint on momentum from other systems etc.

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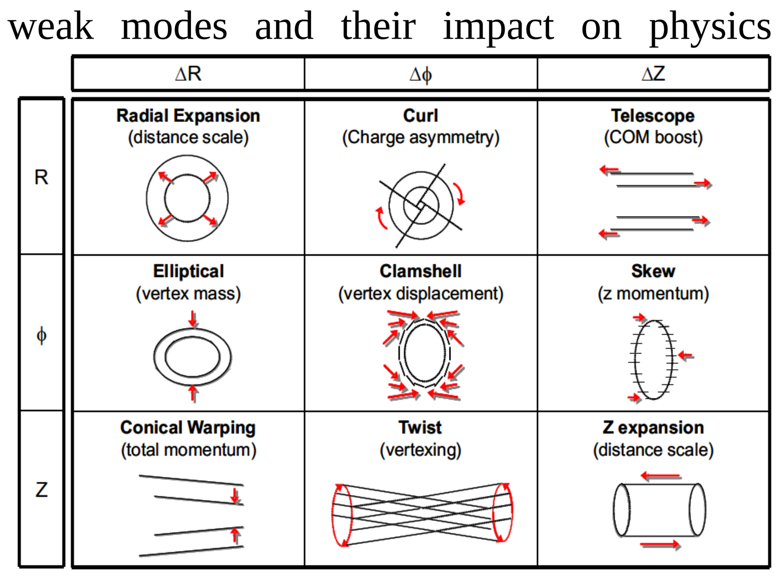
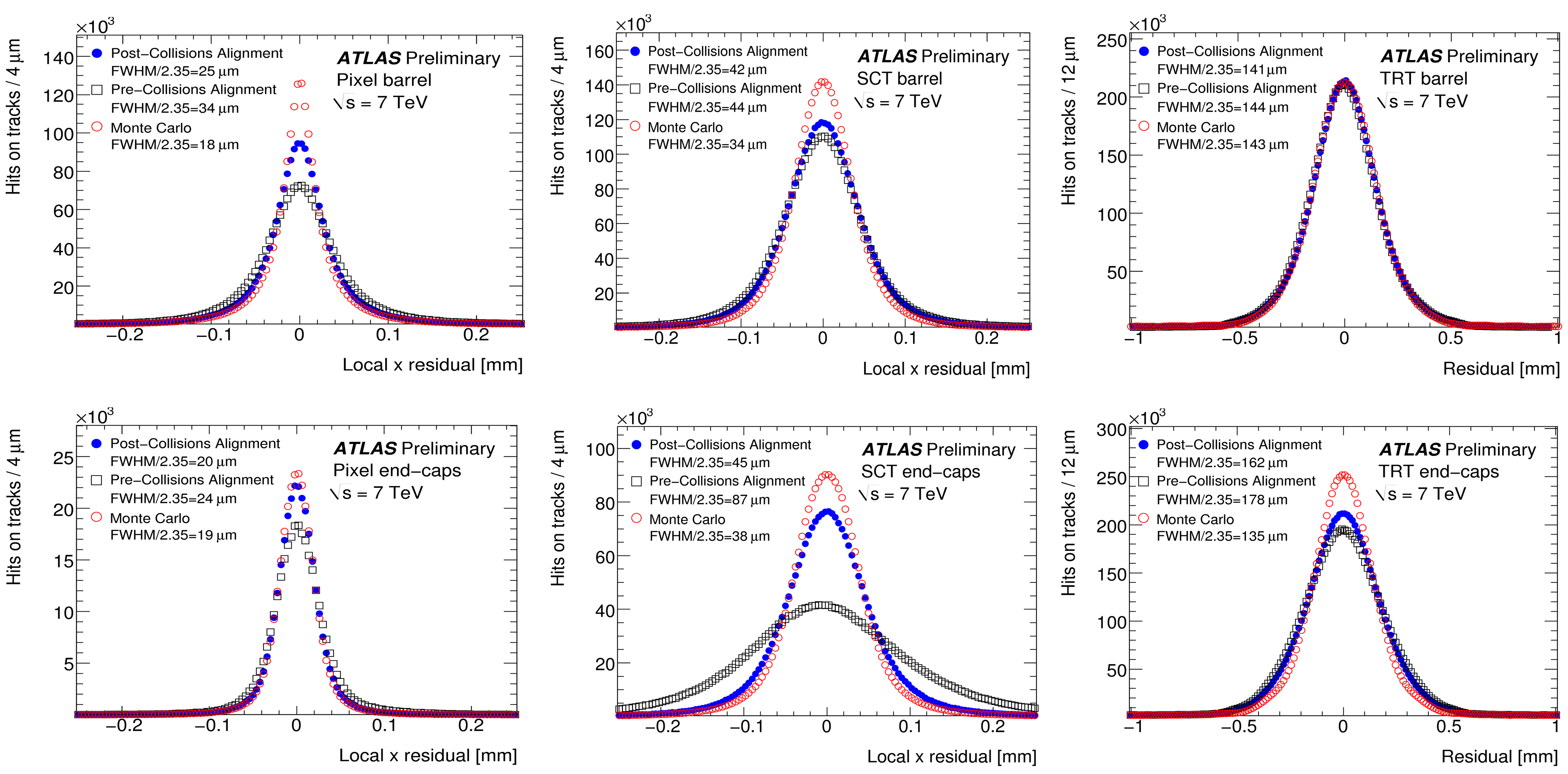
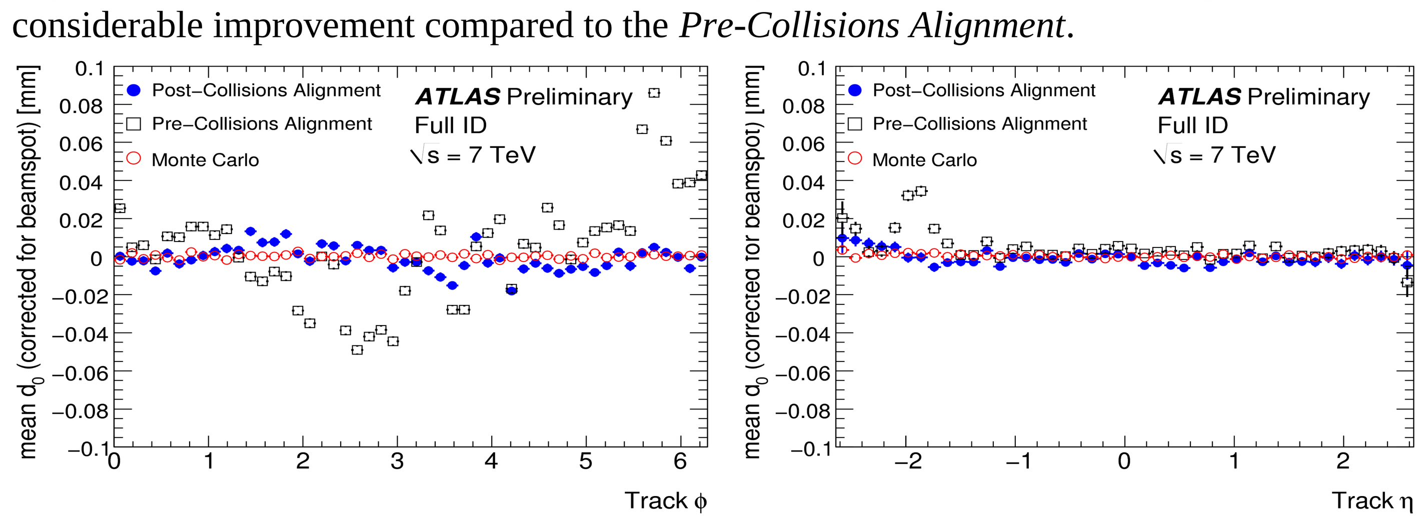


Alignment Performance with 7TeV Collision Data

Residuals: The 6 plots below are results for 7TeV data with *Post-Collisions Alignment* (using 2009 cosmics + 900GeV data), *Pre-Collisions Alignment* (using 2008 cosmics) and for Monto Carlo with perfect geometry. One can see that in general the width of the residual distributions are reduced using *Post-Collisions Alignment* compared with *Pre-Collisions Alignment*, indicating a significant improvement in the ID alignment after collision tracks have been used.



Transverse Impact Parameter: Shown is the mean transverse impact parameter, relative to the determined beam-spot position, as a function of track azimuthal angle, φ, (left) and track pseudo-rapidity, η, (right). The *Post-Collisions Alignment* shows considerable improvement compared to the *Pre-Collisions Alignment*.



Alignment Stability over Time: Figures are the Pixel alignment stability as a function of time. Shown is the mean (left) and the FWHM/2.35 (right) of the barrel, endcap A and endcap C residuals. The results indicate there are no significant changes in the module positions/orientations over the time.