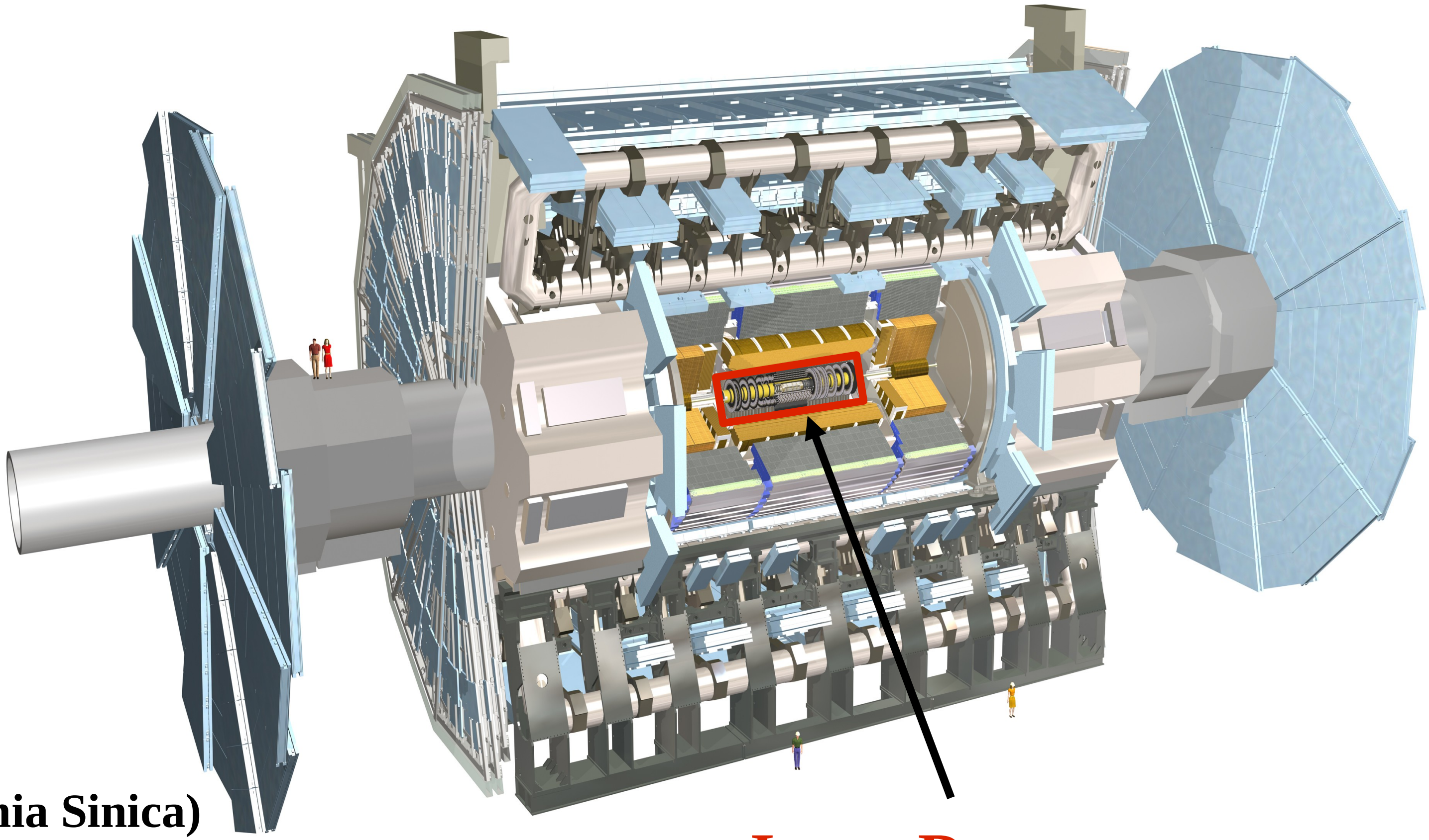
Alignment of the ATLAS Inner Detector Tracking System



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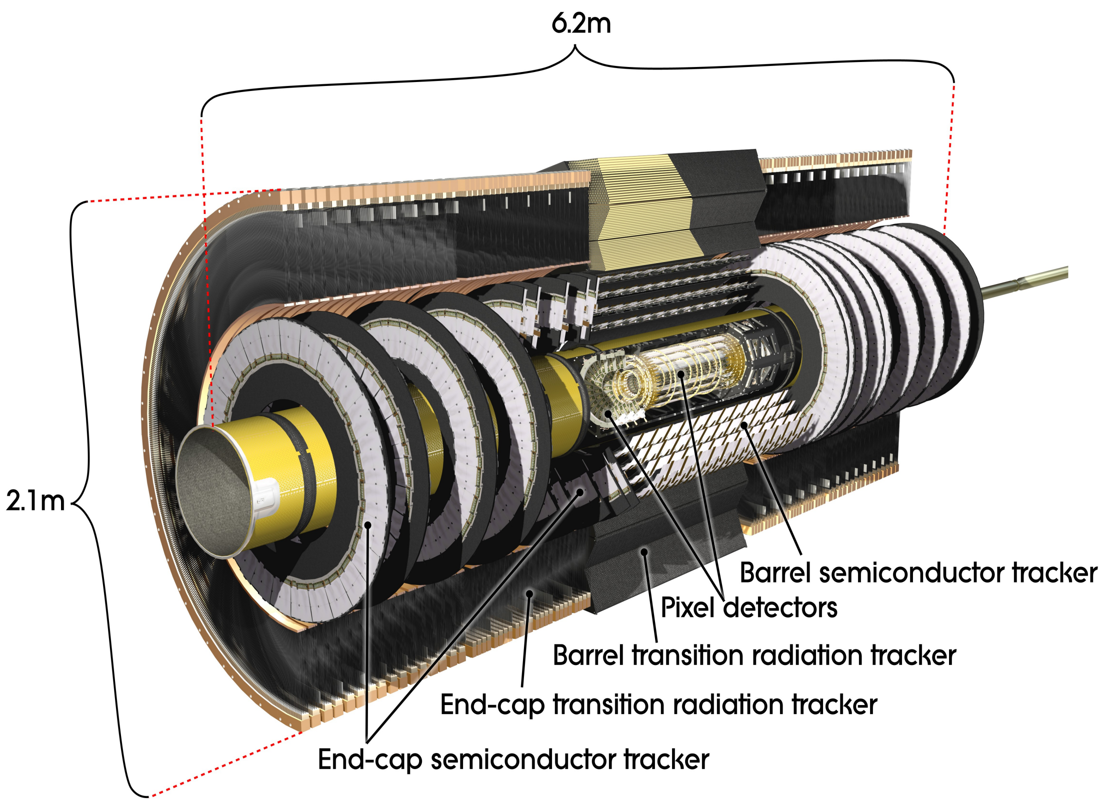
ATLAS Inner Detector



- **Coverage :** $|\eta|<2.5$
- **Magnetic Filed :** 2.0 T, along beamline
- **In the Barrel region**
  - **- the expected p_T resolution is :** $\sigma(p_T)/p_T=0.034\%\cdot p_T\,[\mathrm{GeV}]\oplus 1.5\%$
  - **- the expected d_0 resolution is :** $\sigma(d_0)=10\mu m\oplus 140\mu m/p_T\,[\mathrm{GeV}]$

	Modules	Technology	Channels	Intrinsic Resolution
Pixel	1774	silicon pixel	~80M	10 μm(rϕ), 115 μm(r,z)
SCT	4088	silicon micro-strips	~6M	17 μm(rϕ), 580 μm(r,z)
TRT	176	drift tubes	~350K	130 μm(r,z)

Alignment Goals and Challenges

Alignment Goals :

- After the assembly of the detector, the position of the individual modules is known with much worse accuracy than their intrinsic resolution. Therefore the alignment procedures have 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, precise momentum measurement and vertex reconstruction**

Alignment Challenges :

- Huge numbers of DoFs to be aligned :
  - For Silicon, 6DoFs/Module, in total **~35,000 DoFs**
  - For TRT, 2DoFs/Straw, in total **~700,000 DoFs**
- Huge statistics are needed. O(10M) high quality tracks
- Rather computing intensive, in one iteration several hundreds even thousand CPUs are simultaneously needed
- Due to the system memory limitation and the difficulties to interpret the results of the alignment, not all the DoFs are simultaneously aligned

Alignment Strategies

- **Initial knowledge of the modules' position based on :**
  - Optical and mechanical surveys data during the assembly and the integration.

- **Frequency Scanning Interferometer (FSI) system which monitors the relative movements in real time:**
  - The FSI system is installed just in the SCT and runs constantly
  - FSI information can be used to define the detector movement periods
  - Currently not fully integrated into the offline algorithms

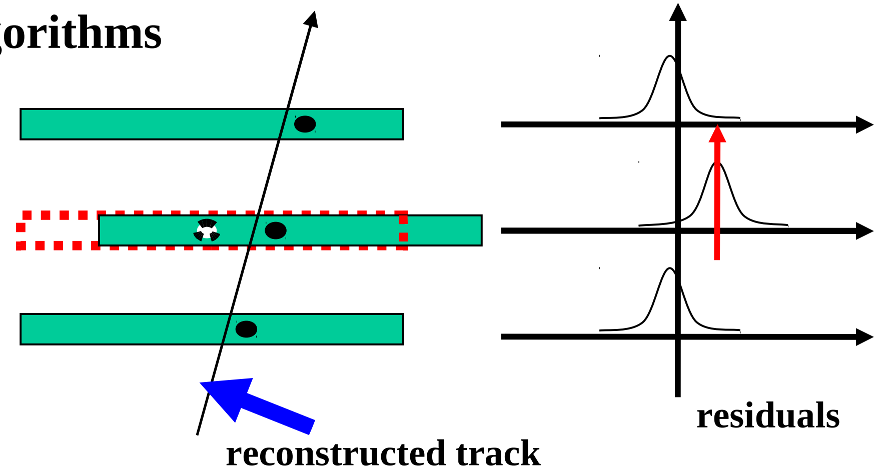
- **The offline Track-Based Alignment Algorithms**

  (focus of this talk)

  - 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. (See the explanation in the right plots)

  - All are **iterative**



The middle module is shifted away from its design 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.

Track-Based Alignment Algorithms

Global χ^2 : The baseline alignment algorithm

- Simultaneously fits all track parameters and alignment parameters by minimizing a large χ^2
- 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 linear equation for each detector structure separately

- Only requires the inversion of a 6×6 matrix per alignable structure

The advantage of Global over Local :

- The Global χ^2 can take the correlations between modules into consideration
- Can converge very soon; Local χ^2 needs many iterations to converge

$\boldsymbol{r}(\boldsymbol{a},\boldsymbol{\tau})$ - the vector of the residuals of the track hits, depending on both the alignment parameters $\boldsymbol{a}$ and the track parameters $\boldsymbol{\tau}$.

$\boldsymbol{V}$ - the covariance matrix of the hit measurements.

The alignment χ^2 is built as follows :

$$\chi^2 = \sum_{tracks} [\mathbf{r}(\mathbf{a},\tau)]^T V^{-1} \mathbf{r}(\mathbf{a},\tau)$$

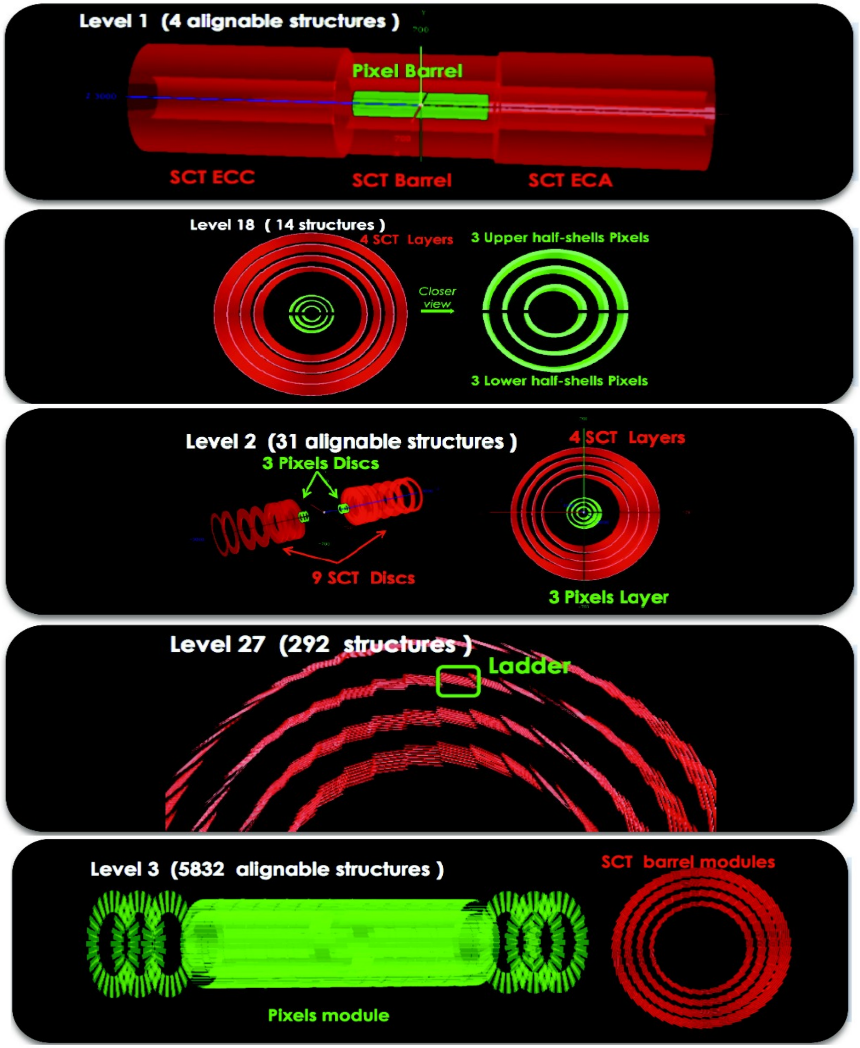
The alignment corrections $\delta\boldsymbol{a}$ are obtained by requiring the minimum condition to the χ^2 .

This requires solving linear systems of the size equal to the number of the alignment DoFs as follows:

$$\frac{d\chi^2}{d\mathbf{a}} = 0 \;\Rightarrow \delta\mathbf{a} = -\left[\sum_{tracks}\left(\frac{d\mathbf{r}}{d\mathbf{a}}\right)^T V^{-1}\left(\frac{d\mathbf{r}}{d\mathbf{a}}\right)\right]^{-1} \cdot \left[\sum_{tracks}\left(\frac{d\mathbf{r}}{d\mathbf{a}}\right)^T V^{-1}\mathbf{r}_0\right]$$

Alignment Levels

- 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.**
- Several **intermediate levels**, such as half-shell levels, stave levels.



Level 1: sub-detector bodies

	Objects	DoFs
Pixel	1	6
SCT	3	18
TRT	3	17

Level 2: Disks

	Objects	DoFs
Pixel	9	54
SCT	22	132
TRT	176	960

Level 3: Modules/Straws

	Objects	DoFs
Pixel	1744	10464
SCT	4088	24528
TRT	350848	701696

Computing Model: in Each Iteration

- **Tracks dressing :**
  - Calculate the hits residuals and pulls
  - Calculate derivatives of residuals wrt. the alignment parameters. There are two methods :
    1. **Analytical derivatives.** derivative and covariance matrix from track fitter
    2. **Numerical derivatives.** Shift module along one DoF then refit the track. Needs track fitting many times

- **Tracks accumulation :**
  - Based on the derivatives of residuals, for each selected track calculate the **first-order and second-order derivatives of χ^2 wrt. the alignment parameters**
  - Then store the derivatives into the big matrix and the big vector

- **Alignment corrections calculation :**
  - Very large linear matrix equation is solved to get the alignment corrections
  - Different matrix solvers have been implemented (see right table)

Methods	Library	Matrix Dimension
direct inversion diagonalization	ROOT,CLHEP, LAPACK	O(10,000)
fast solving, for sparse matrix	MA27	O(100,000)

Computing Model : the Whole Chain

- **The alignment runs over huge number of tracks, where possible from different event types**

  - Dedicated ID calibration streams (both collisions and cosmics) for alignment

  - In some cases also run over high quality physics stream tracks

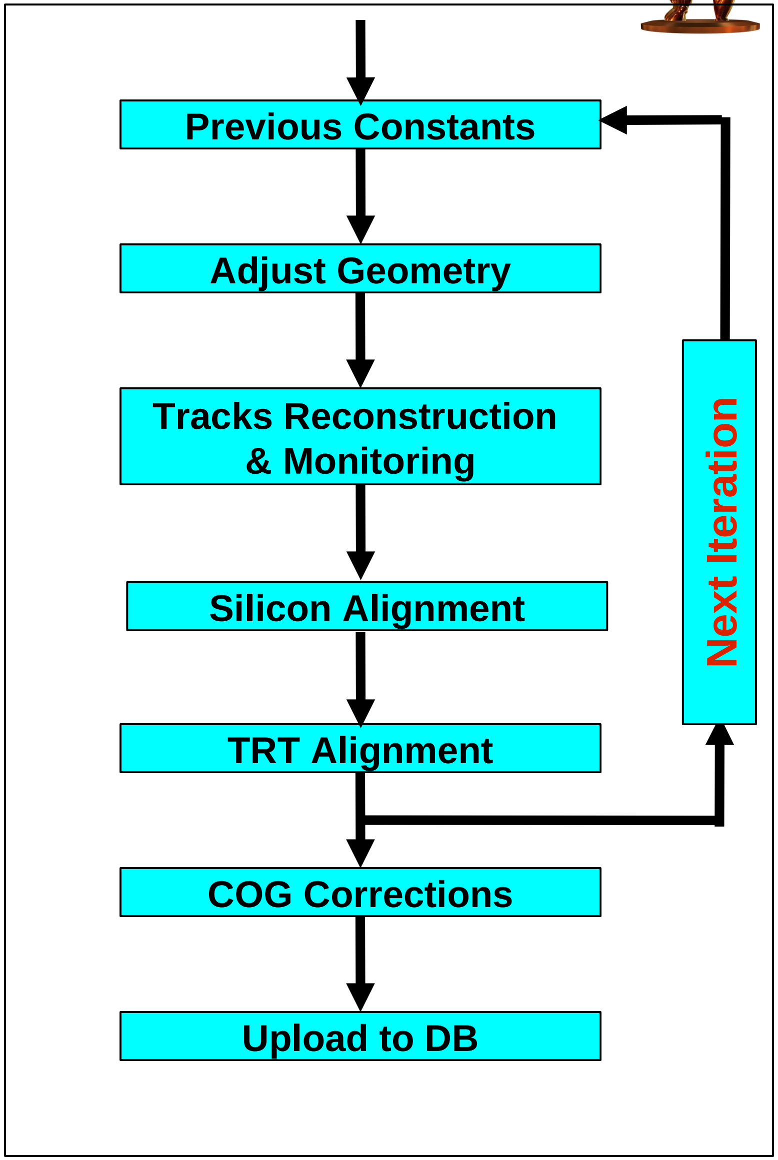
- **Align ID at different levels of granularity – from large structures to small structures**

- **Accumulation and matrix solving :**

  - Accumulation split into several hundred parallel sub-jobs, then merge all the matrices and vectors together

  - Matrix solving run over the merged big matrix and big vector to get the alignment corrections

- **Monitoring is quite important. It is run to watch over the correctness of the produced constants**



Computing Model : Run on Grid & Automatic Alignment

An infrastructure for running the alignment on Grid is also developed and being used

- Traditionally the alignment is running on the CERN's batch system (CAF), but :
  - The CPU and storage resources for the alignment are no longer sufficient
  - And the accessible datasets are quite limited

- However if run on Grid :
  - Can access nearly **all of the ATLAS datasets**
  - **Enormous CPU resource**, almost unlimited disk storage
  - Many powerful and convenient Grid tools and interfaces for management

Due to the iterative nature, lots of technical difficulties have been encountered and finally solved

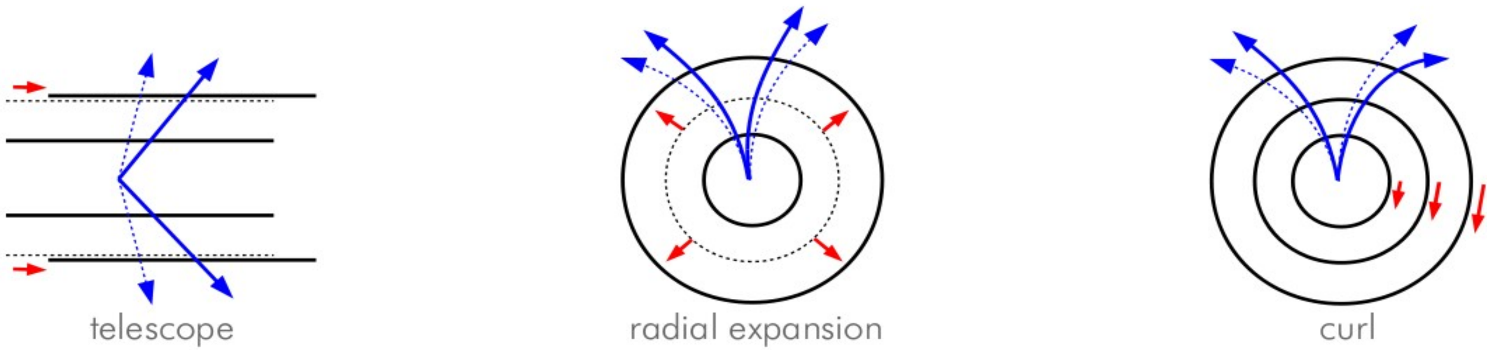
Last year found the detectors are slowly moving, hence decided to perform the alignment run by run to detect the movements

- Implemented to automatically run the L1/L2 alignment **in the calibration loop**
- Shifters watch the constants changes. If significant changes are observed then some detailed study will be triggered and an updated set of constants will be produced

Weak Modes & Constraints

Global distortions which preserve the helical trajectory of tracks and leave the χ^2 unchanged are known as "weak modes"

- The distortions are difficult to remove by the alignment algorithms which are based on the minimization of the residuals
- They are very dangerous to physics. See the examples in below :



Methods to deal with weak modes :

- **Different track topologies,** such as cosmics, beam-gas, beam-halo, B-off tracks etc.
- **Use constraints. Several constraint tools have been implemented and work quite effectively**
  - Used to obtain a solution to an inherently singular matrix problem
  - Beam-spot, vertex constraint, constraint on invariant masses of well known resonant decays
  - Constraint on momentum from other systems, such as the constraint from Muon Spectrometer standalone momentum measurement
  - E/p constraint from the curvature asymmetry between e^+ and e^-

A Short History of ID Alignment

2008
~
Dec., 2009

- Used millions of cosmics to align ID and prepare for the LHC collision. Endcaps were poorly illuminated
- First LHC 900 GeV collision data were used to do the alignment (also cosmics)

Commissioning Stage

May, 2010
- First LHC 7 TeV collision data were used. Applied precision errors and beam spot constraint

Sep., 2010
- Fine alignment for the autumn reprocessing. Used Pixel module deformation information

Dec., 2011
- Found detectors are moving. Perform the alignment in a stable period with quite large statistics

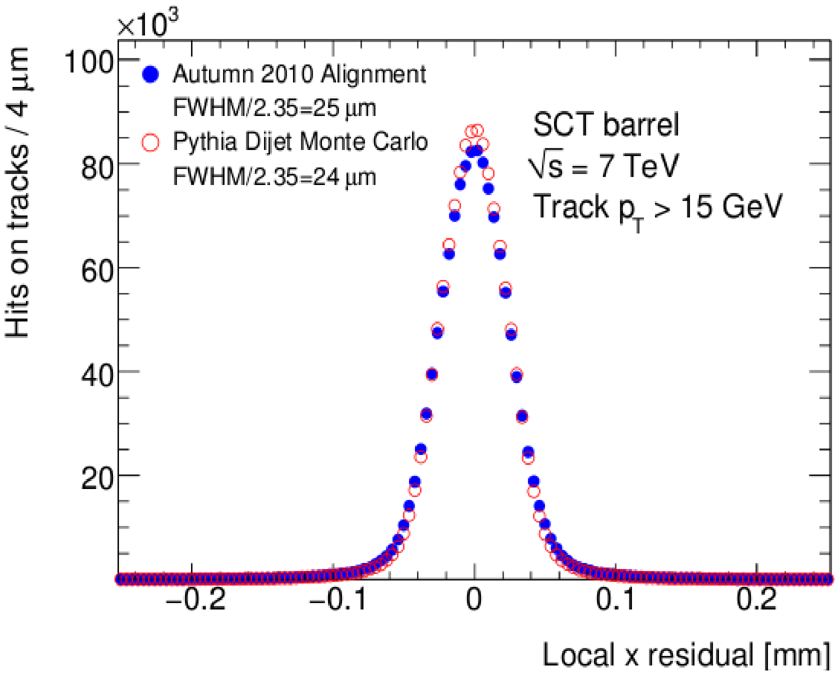
May, 2011
- Run-by-run alignment

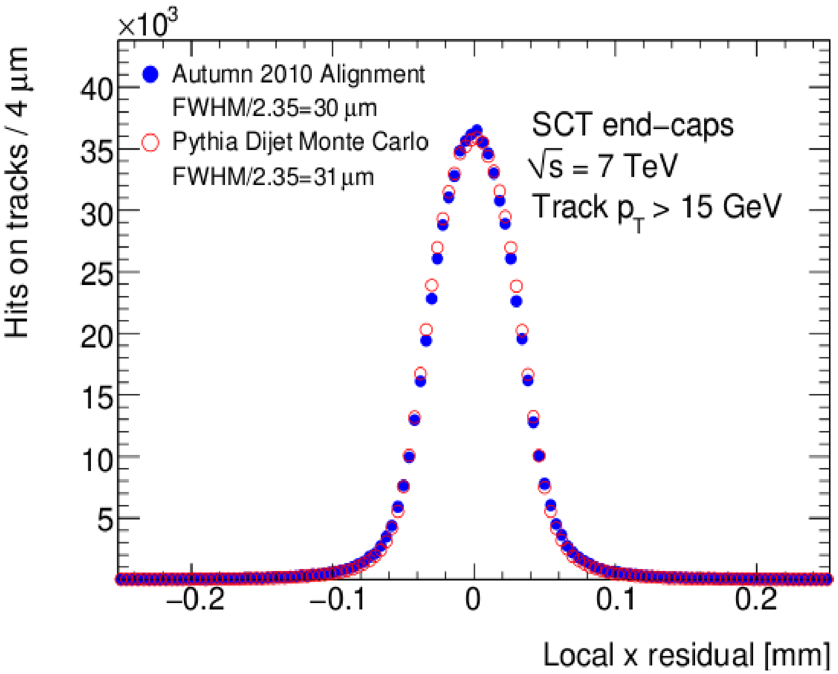
July, 2011
- Fine alignment with E/p constraint and based on new pixel clustering software

Operation Stage

Alignment Results : Overall Residuals

We have basically obtained **perfect residuals** (see plots in below), which indicates the algorithms are working correctly. Now we are focusing on effects that are beyond just getting the residuals correct



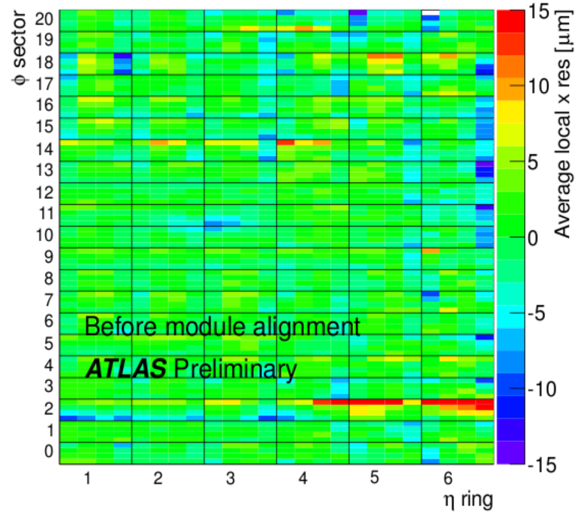


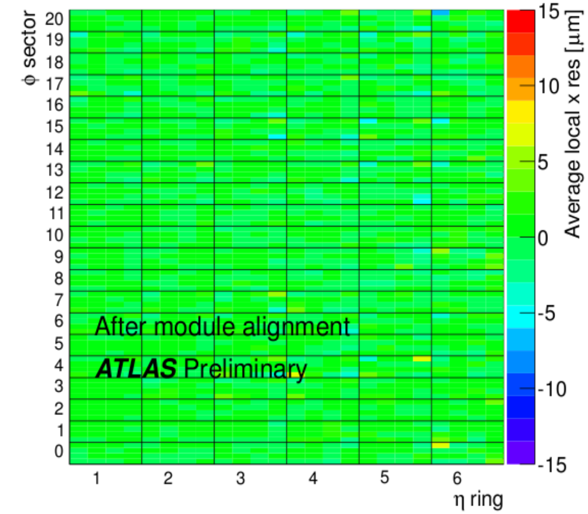
The SCT local x residual distributions for the jet trigger data sample reconstructed with the Autumn 2010 Alignment (full circles), compared with the dijet MC simulation sample (open circles). The distributions are integrated over all hits-on-tracks in barrel modules (left) and end-cap modules (right). Tracks are required to have pT > 15 GeV.

Alignment Results : Residuals Maps

Pixel Residuals Map

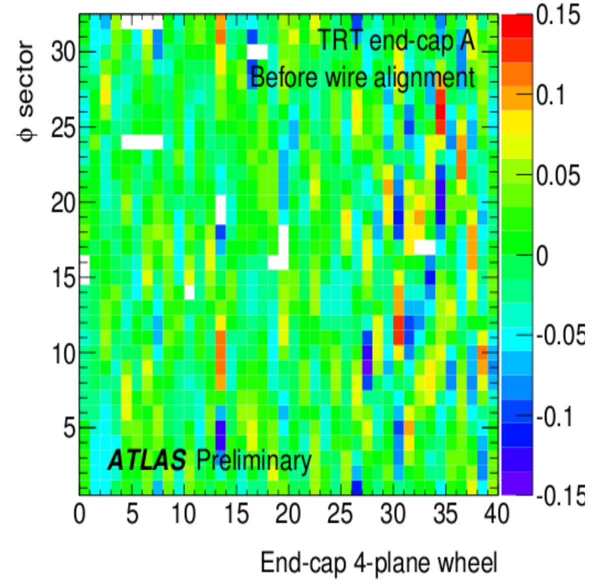
- Detailed residual maps of the Barrel pixel modules before and after module alignment
- Each pixel module has been split in a 4×4 grid
- Include pixel module distortions

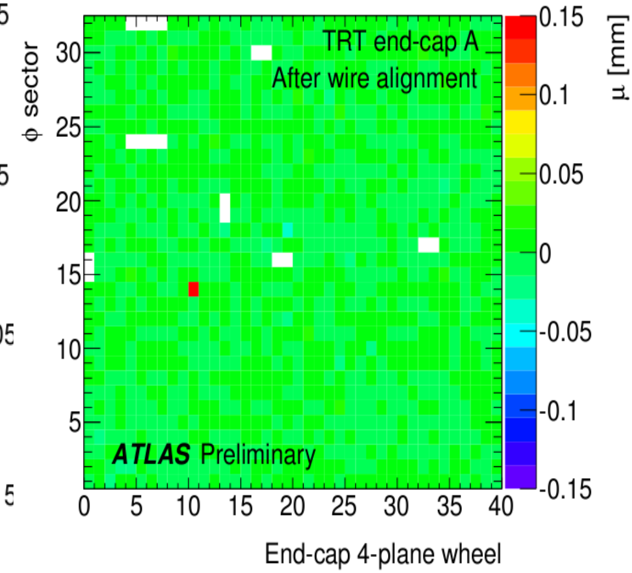




TRT Residuals Map

- TRT residuals vs. φ-sector and wheel before and after the wire-by-wire alignment
- The plots illustrate the end-cap A results
- The white bins are due to dead channels

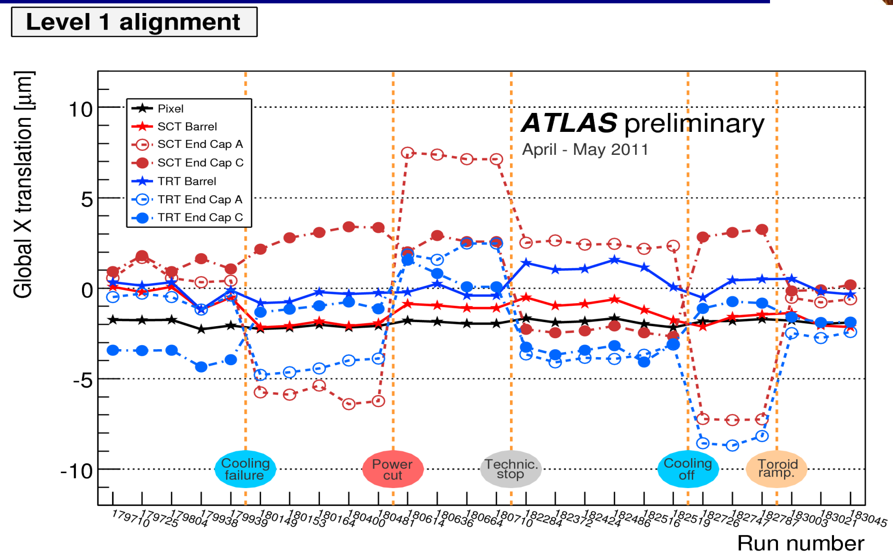




Alignment Results : Stability & Solenoid Field Tilt

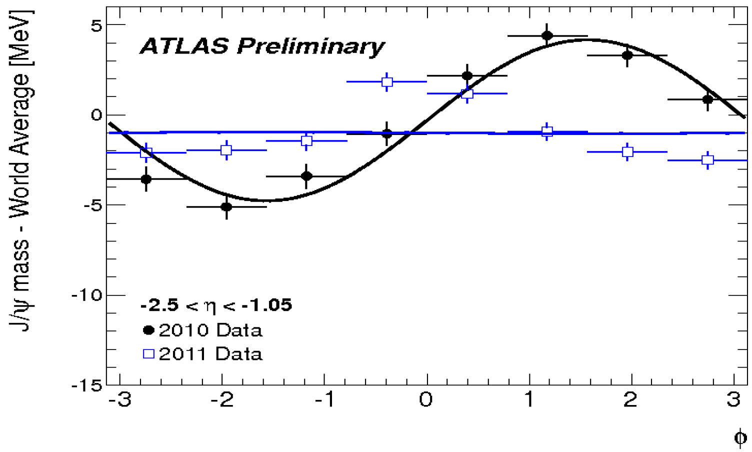
Detector Stability

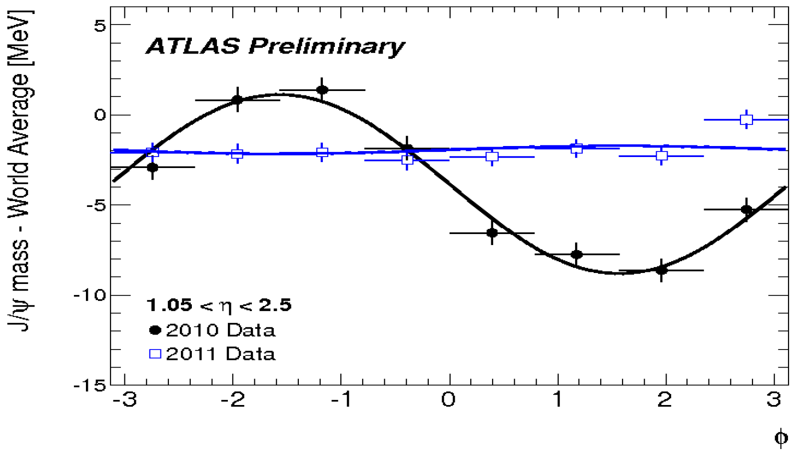
- Large movements of the detector are measured after hardware incidents (<10 μm)
- In between these periods little (<1 μm) movements are observed indicating that the detector is generally very stable



Solenoid Field Tilt

A tilt of the solenoid field was found as a bias in the K_s and J/ψ masses vs. φ. This was corrected by rotating the magnetic field in the reconstruction software by +0.55 mrad around the x-axis



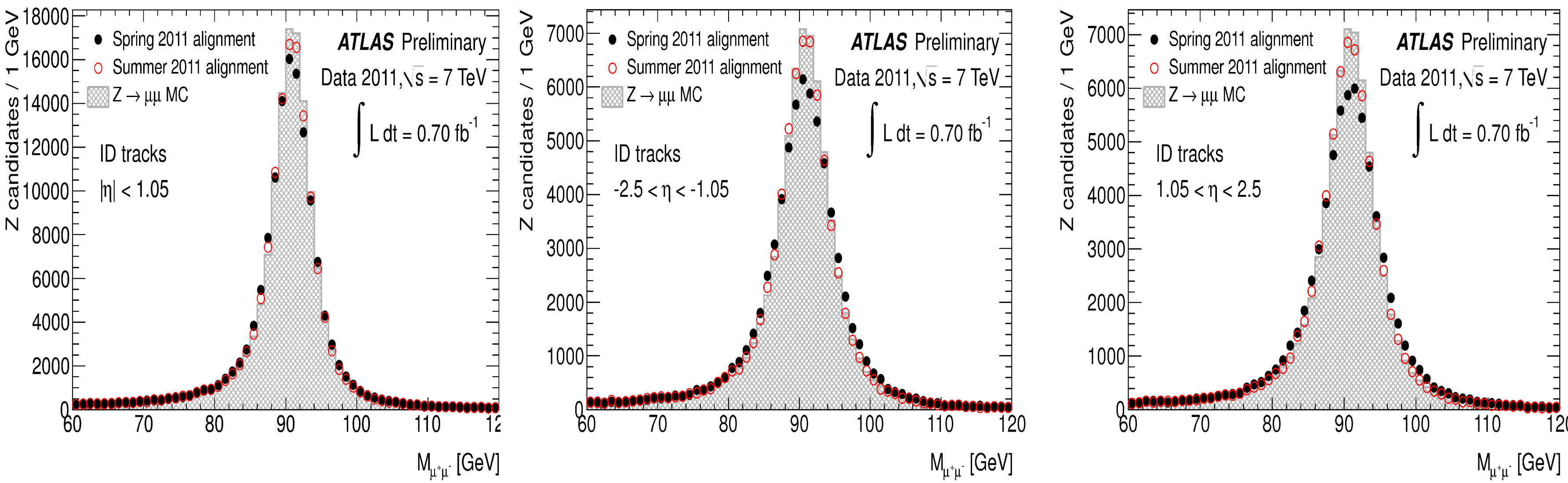


Alignment Results : $Z\rightarrow\mu^+\mu^-$

- For the ATLAS 2011 summer reprocessing, a new constants set was derived, on which the **E/p constraint** was first time employed

- Preliminary results indicate significant improvement from this new constants set especially in the endcap regions, and the $Z\rightarrow\mu^+\mu^-$ mass resolution **is quite close to the MC perfect geometry already**

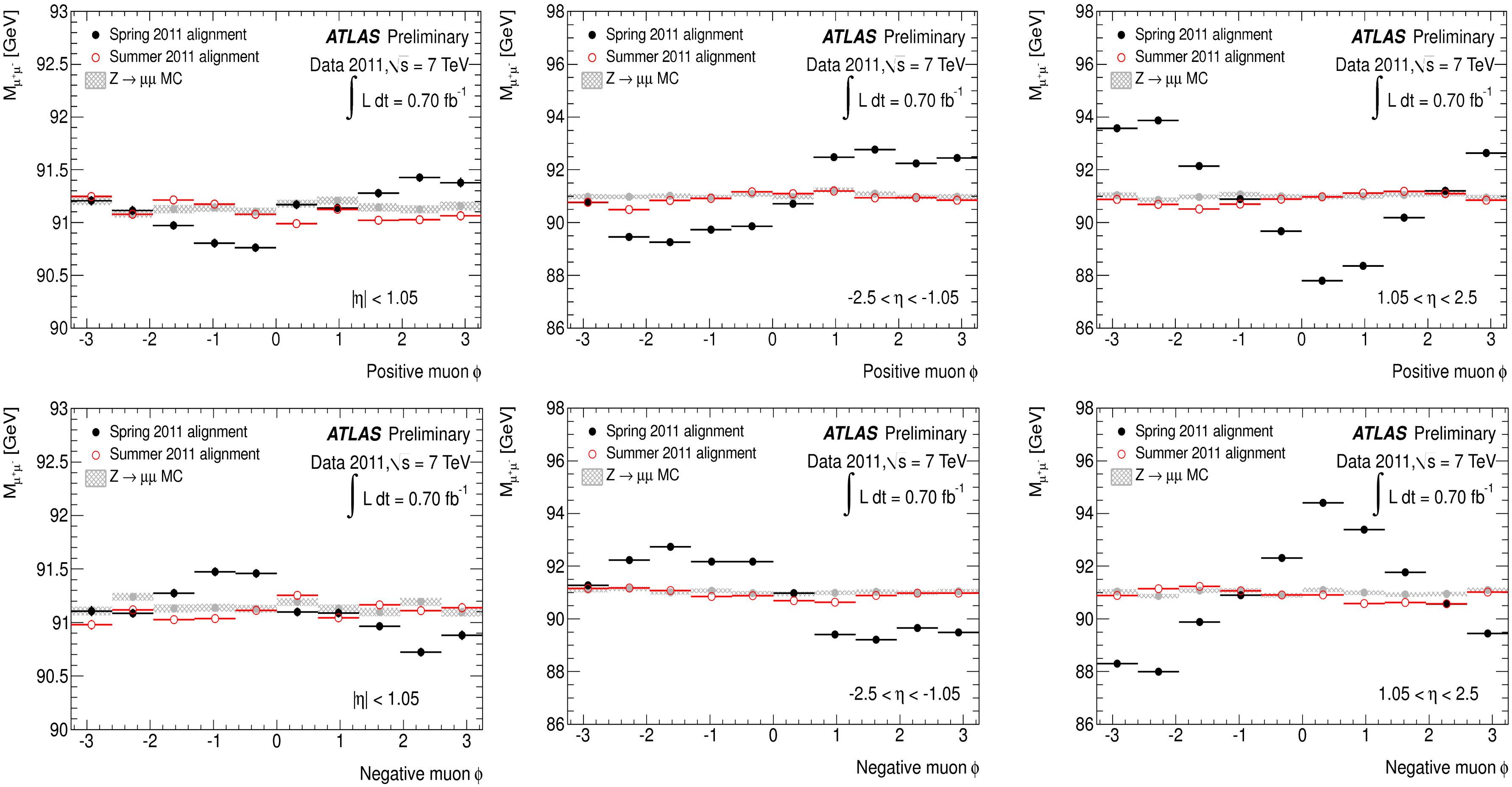
The 3 plots below are the Z mass resolution in different ID regions; the black circles are for the Spring 2011 alignment, the red circles for the September 2011 alignment, shadow area for the MC perfect geometry



Alignment Results : $Z \rightarrow \mu^+\mu^-$

The latest E/p constants also can **eliminate most of the weak modes**

The 6 plots below are Z invariant mass vs. φ for μ^+ and μ^- . Clearly can see the sinusoid structures in the Spring 2011 alignment which indicates there are weak modes. However most of the structures disappear in the summer 2011 alignment



Summary

• **ATLAS ID Alignment is very challenging. However, after our several years' hard work it currently works very well**

• **The performance of momentum measurements is quite close to MC perfect geometry already. The future plans :**

- Understand the alignment systematics
- More studies of the detector movements
- Better descriptions of the internal distortions of modules

• **The ID Alignment is making significant contributions to ATLAS physics searches !**