Track based Alignment of the ATLAS Inner Detector Tracking System

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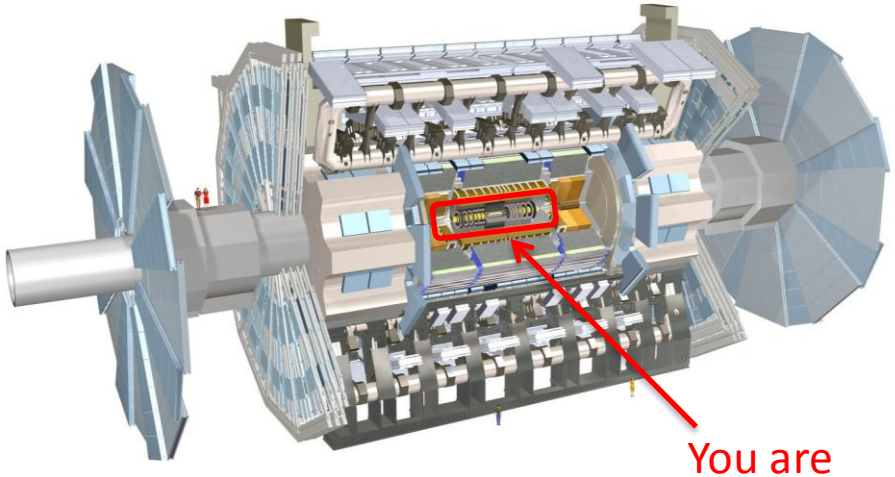
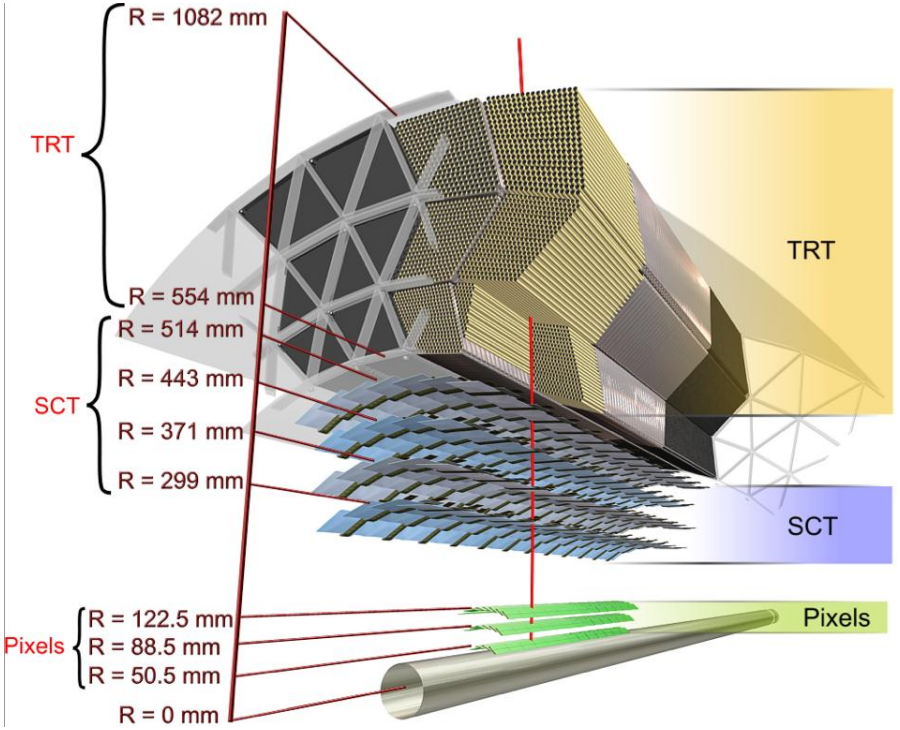
The ATLAS Detector



$$\frac{\sigma(p_T)}{p_T} = 0.05\% \cdot p_T\,[\mathrm{GeV}] \oplus 1\%$$

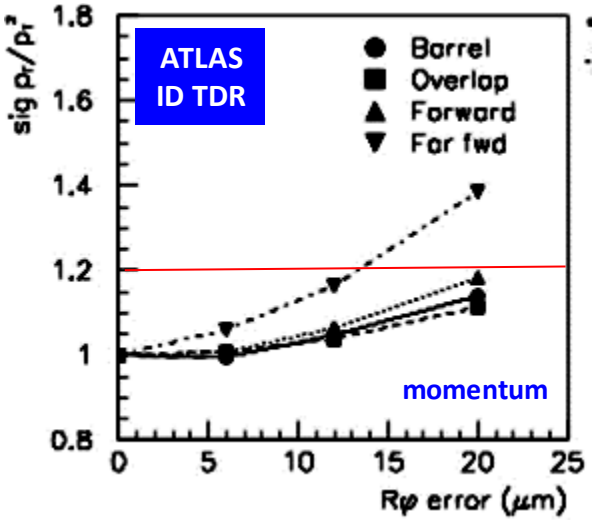
$$\sigma(d_0) = 10\,\mu\mathrm{m} \oplus \frac{140\,\mu\mathrm{m}}{p_T\,[\mathrm{GeV}]}$$

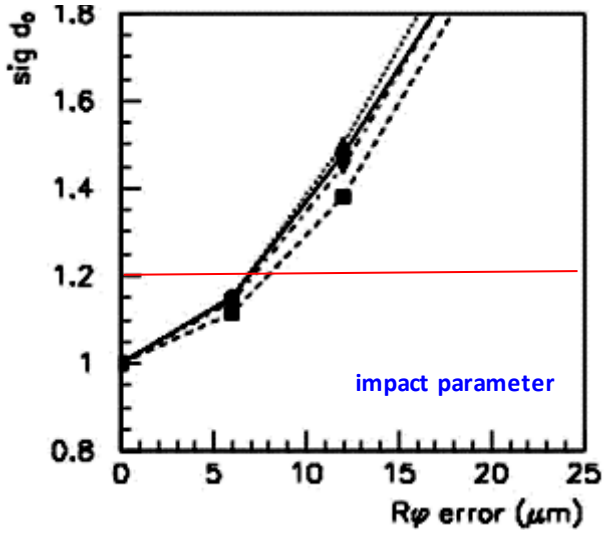


- ATLAS Inner Detector (ID) main tracking device of ATLAS
  - consists of Pixel, Silicon strip (SCT) and drift tube (TRT) detectors
  - single hit resolution between 10 µm (Pixel) and 130 µm (TRT)

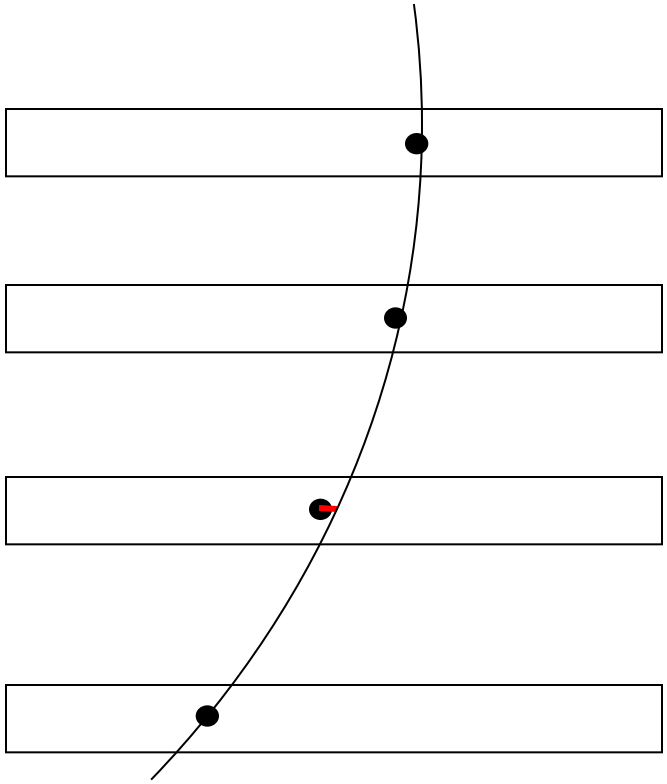
Requirements from Tracking

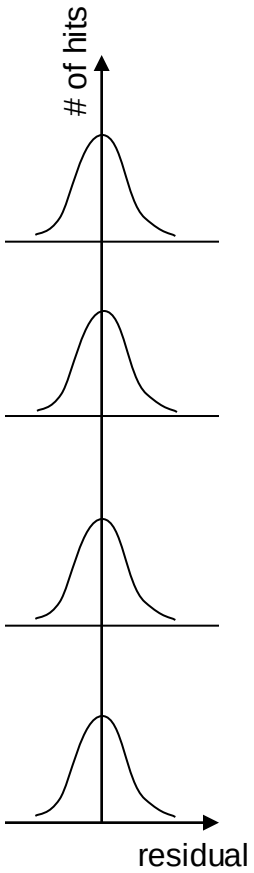
- construction and installation precision ~100 µm
- track parameter resolution should not be degraded by more than 20%
  - 7 µm precision in RΦ for Pixel
  - 12 µm precision in RΦ for SCT
- ultimate precision can be achieved with track based alignment procedure only
- hardware based system (FSI) available in the SCT to monitor fast movements of support structures





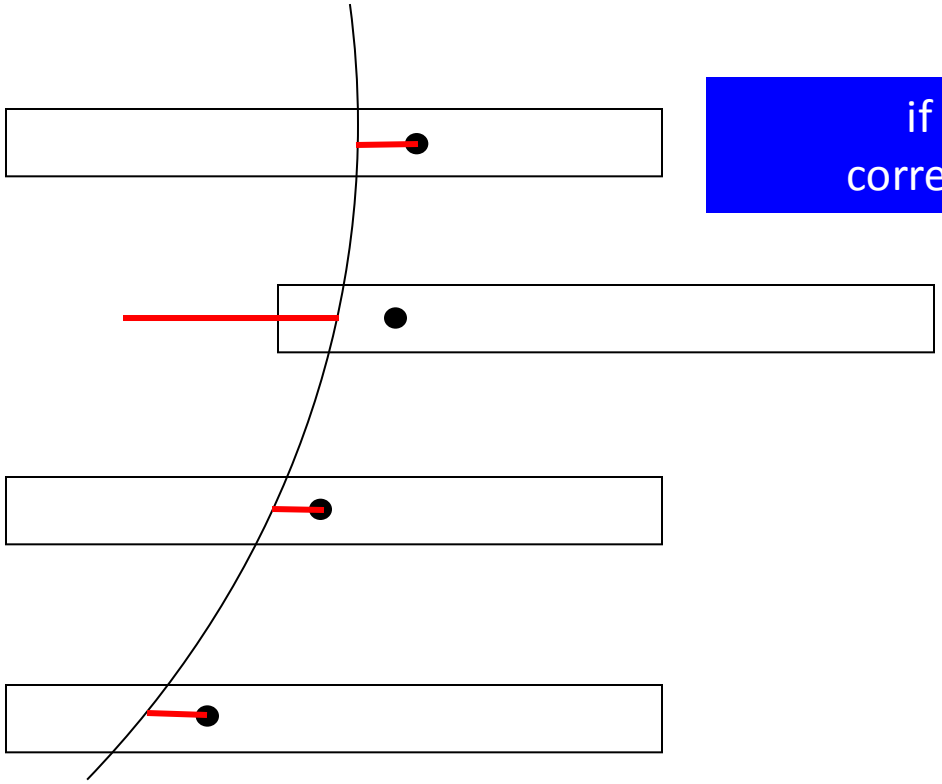
How to align a Detector



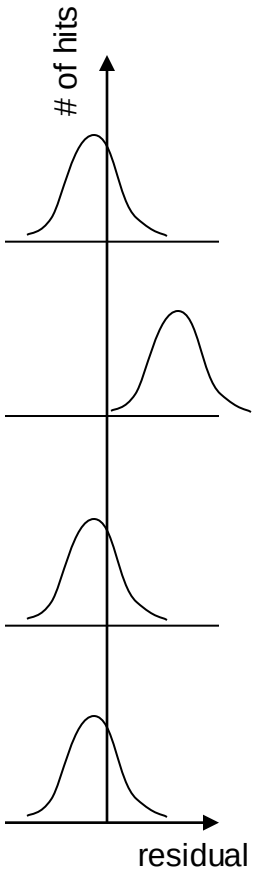


residual = distance between hit and the fitted track

How to align Detector



if we had the
correct knowledge:

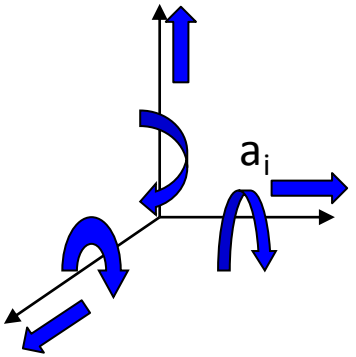


⇨ minimize residuals with respect to the module's positions

Track based alignment procedure

$$c_0^2 = \sum_{tracks} \left[r(a,p) \right]^T V^{-1} \left[r(a,p) \right]$$

$$\Rightarrow da = -\left[\sum_{tracks} \left(\frac{dr}{da} \right)^T V^{-1} \left(\frac{dr}{da} \right) \right]^{-1} \times \left[\sum_{tracks} \left(\frac{dr}{da} \right)^T V^{-1} r \right]$$



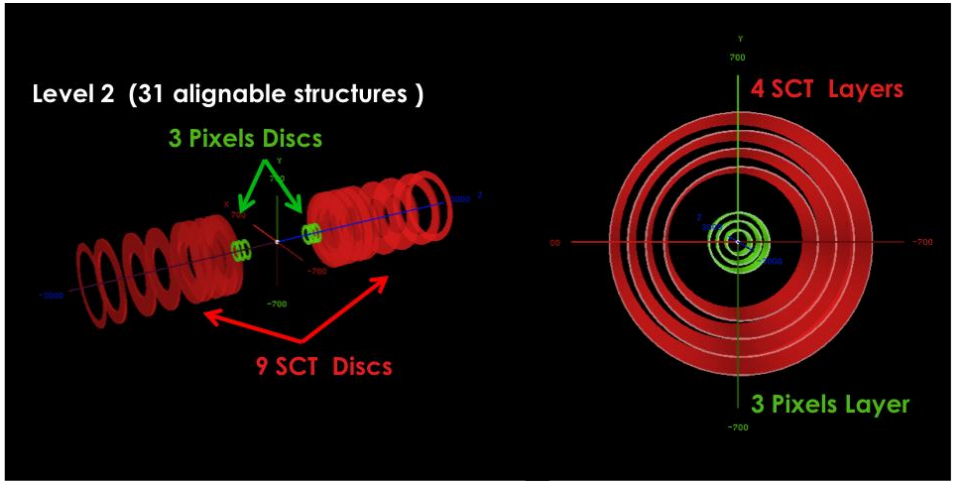
- collect residual distributions for each module and minimize with respect to the alignment parameters
- module-to-module correlations are taken into account by nested dependence on track parameters:
- increased convergence speed

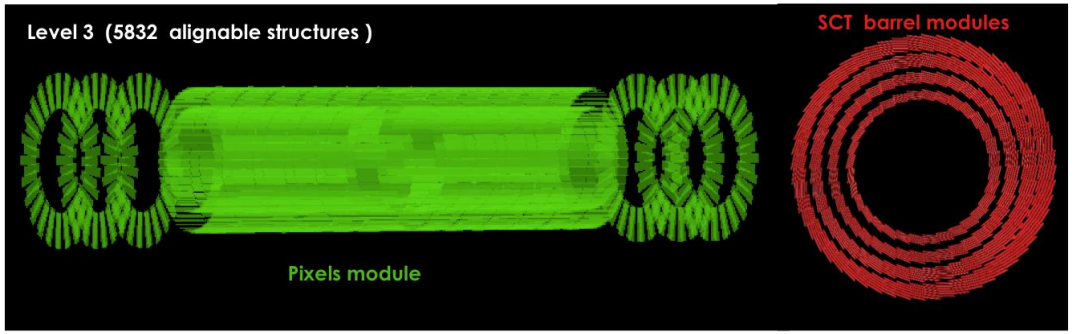
$$\frac{dr}{da} = \frac{\partial r}{\partial a} + \frac{\partial r}{\partial p}\frac{dp}{da}$$

- derivative of the residual w.r.t. track
- derivative of the track parameters w.r.t. alignment parameters
- derivative of the residual w.r.t. the alignment parameters

Track based alignment procedure

- start from survey information (Pixel)
- perform hierarchically alignment following detector structure
- align up to 6 degrees of freedom (d.o.f.) per structure
  - 35k d.o.f for Pixel and SCT (6 d.o.f. per module)
  - 700k d.o.f for TRT (2 d.o.f. per straw)
- iterative procedure
  - 10-20 steps for production of complete alignment set



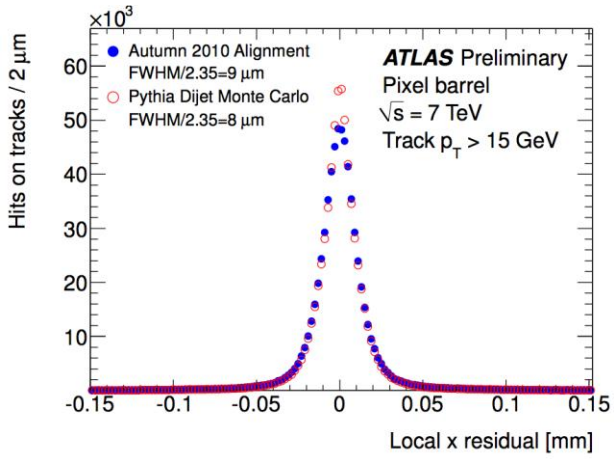


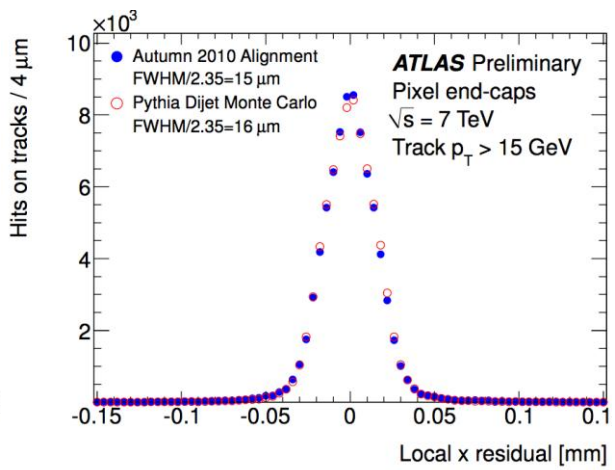
Input to the Alignment Algorithm

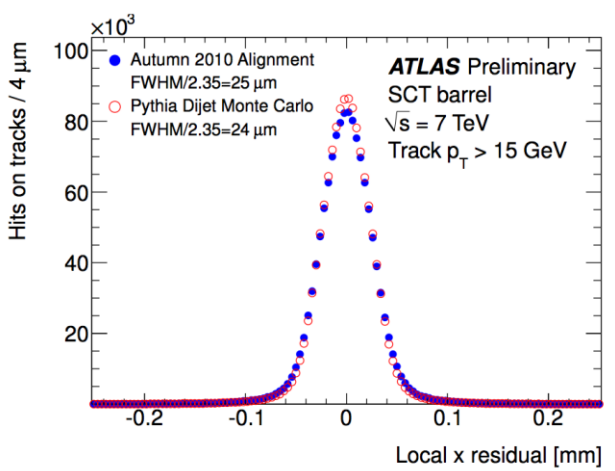
- high p_T–tracks to minimize multiple scattering effects
  1. tracks from collision events
     - enough tracks during collisions produced –statistics no problem
     - large time consumption due to repeating reconstruction of tracks in iterative alignment
     - production of reduced data stream with selected high p_T-tracks containing ID and track related information only
  2. tracks from cosmic ray events
     - different track topology
     - tracks connect top and bottom of ID
     - hardly any illumination of endcap

Residual Distribution

- alignment minimizes the X^2 all measurement residuals
  - alignment returns residual distribution which is almost consistent with MC residual distribution with perfect geometry
  - this is a necessary but not sufficient condition
  - resulting X^2-value may end up at a local X^2-minimum (or valley – weak modes of the solution)

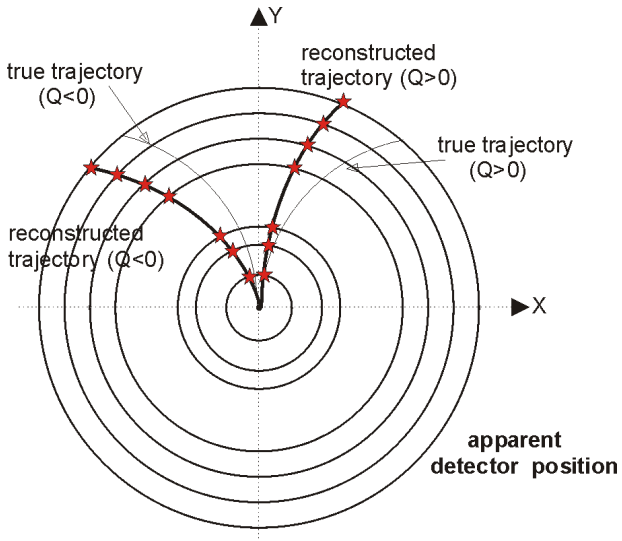


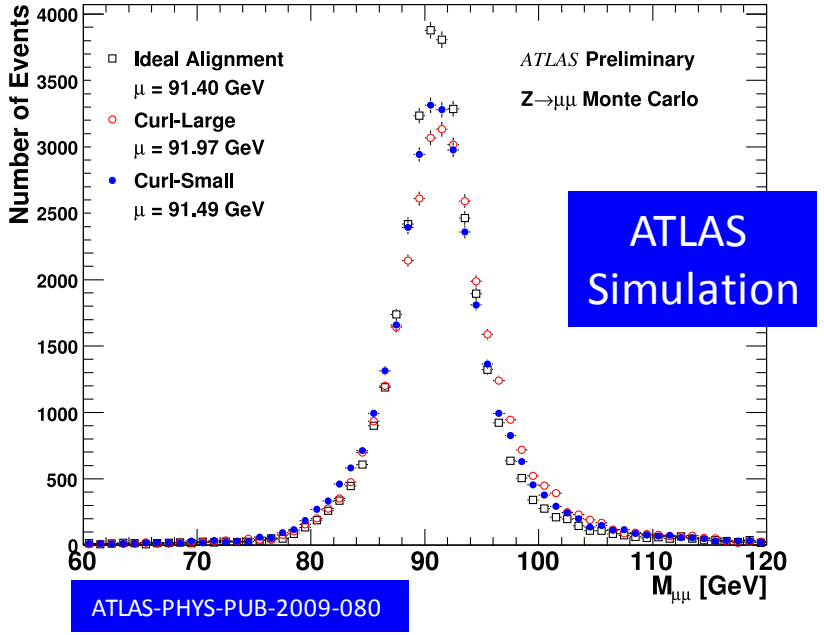




ID Alignment – Quality Assurance

- estimate alignment performance using control plots not based on residual distributions
  - main focus on the improvement of the momentum scale

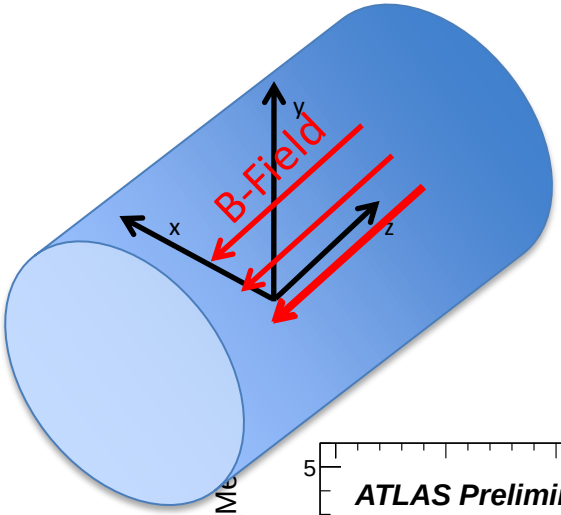


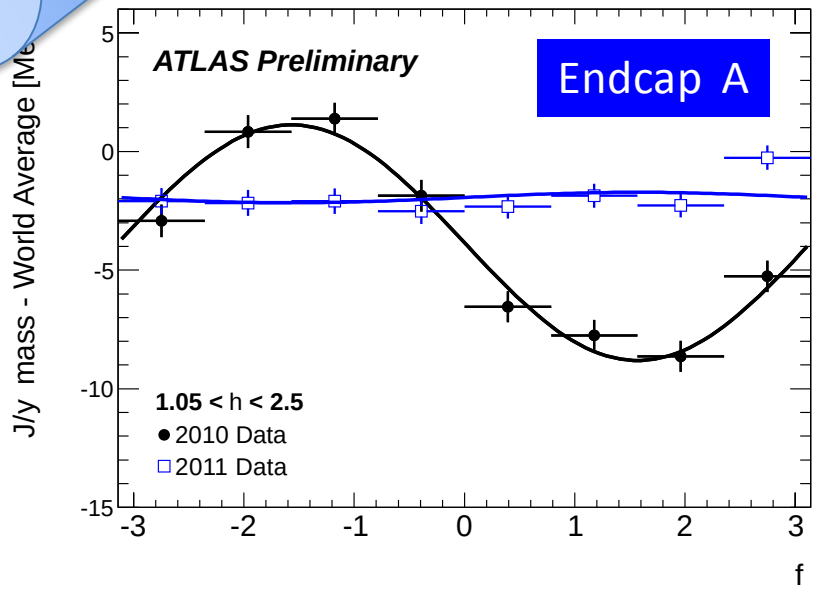


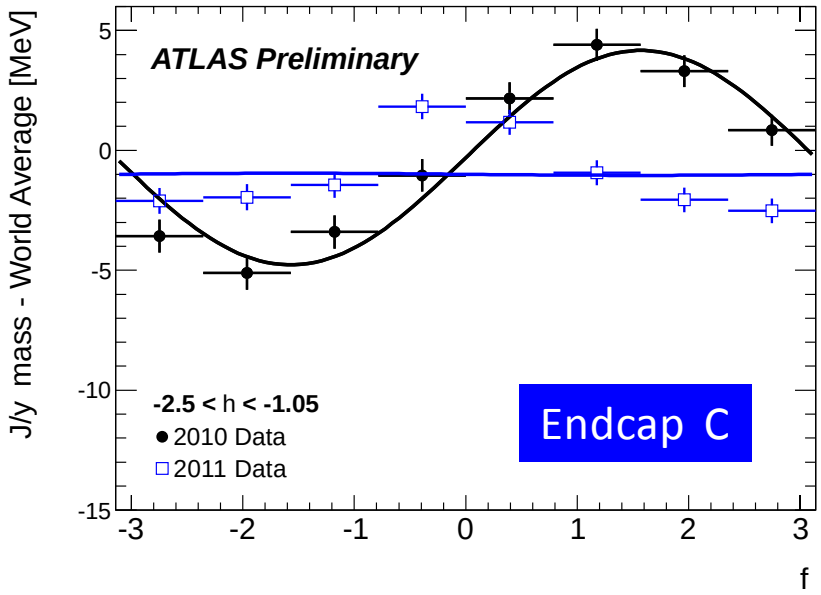
Overall Position of Detector

- alignment procedure returns internally consistent set of alignment constants
  - 6 d.o.f. (= overall position of detector) cannot be determined from alignment procedure
  - initial position determined by requiring minimal module-by-module deviation from the perfect geometry
- keep average position consistent for alignment updates (keep beam spot position constant)
  - ID may be misaligned with respect to the solenoidal magnetic field (relative tilt)

Solenoid Field Tilt







- measure the invariant mass variation with respect to PDG-value (ΔM) as function of Φ
  - tilt of the magnetic field is reflected in Φ-dependent J/ψ-mass
  - rotation around the x-axis by 0.55 mrad reduces Φ-dependence significantly

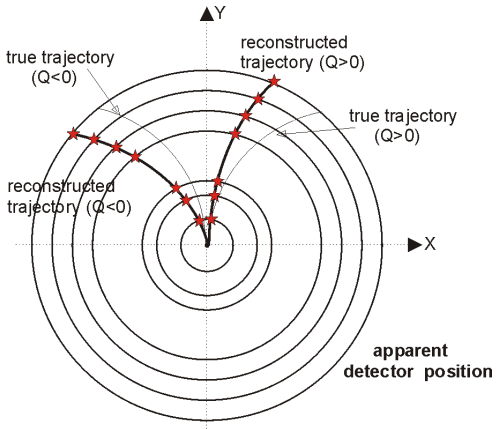
E/p Momentum Constraint

- identical calorimeter response for e^+ and e^-
- E/p measurement sensitive to charge asymmetric bias on p-measurement (like curl or sagitta distortions)
- measure E/p (η,Φ) and use offset between e^+ and e^- to constrain track momentum in alignment

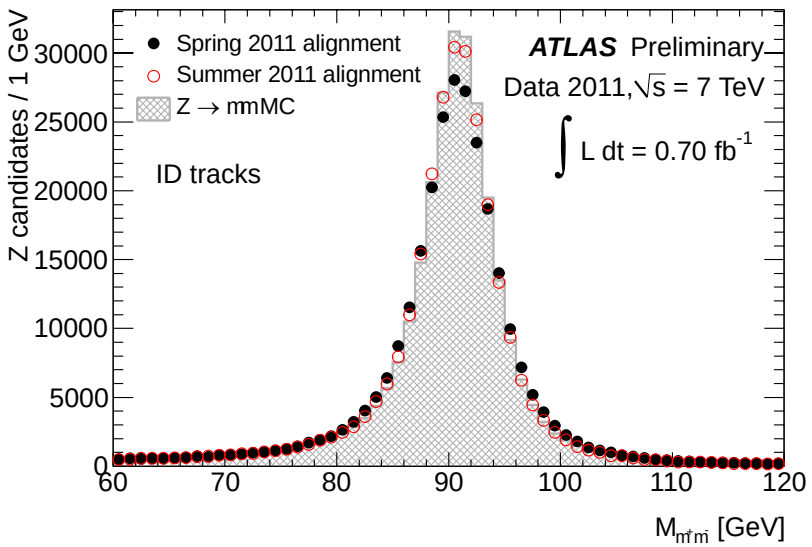
$$\frac{Q}{p^{correct}} = \frac{Q}{p^{reconst.}}\left(1 \pm p_T^{reconst.} \cdot d\right)$$

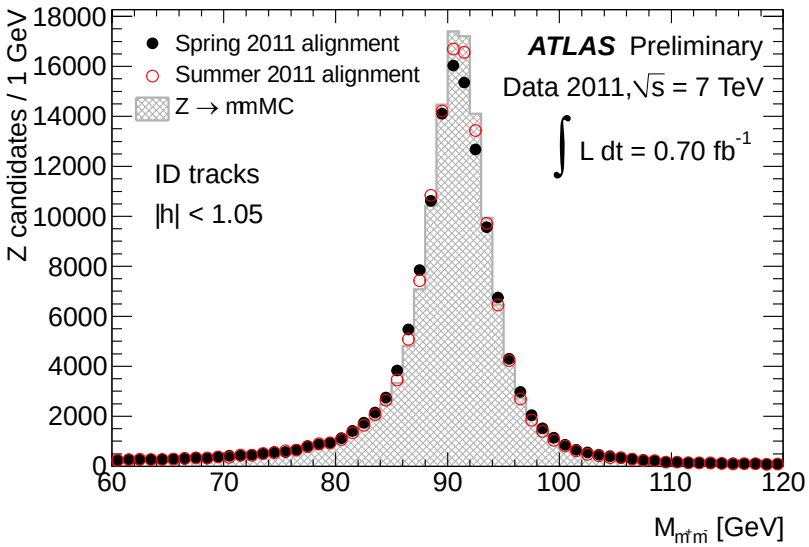
$$\left\langle \frac{E}{p^{correct}} \right\rangle^{+} = \left\langle \frac{E}{p^{reconst.}} \right\rangle^{+} \left(1 + \left\langle p_T^{reconst.} \right\rangle^{+} \times d\right)$$

$$\left\langle \frac{E}{p^{correct}} \right\rangle^{-} = \left\langle \frac{E}{p^{reconst.}} \right\rangle^{-} \left(1 - \left\langle p_T^{reconst.} \right\rangle^{-} \times d\right)$$



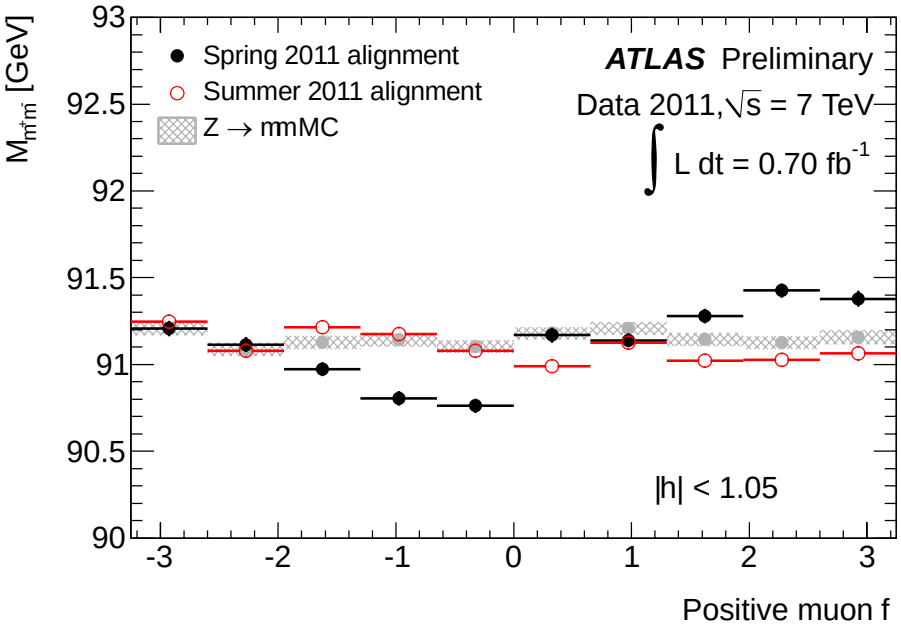
Improved Mass resolution using E/p constraint

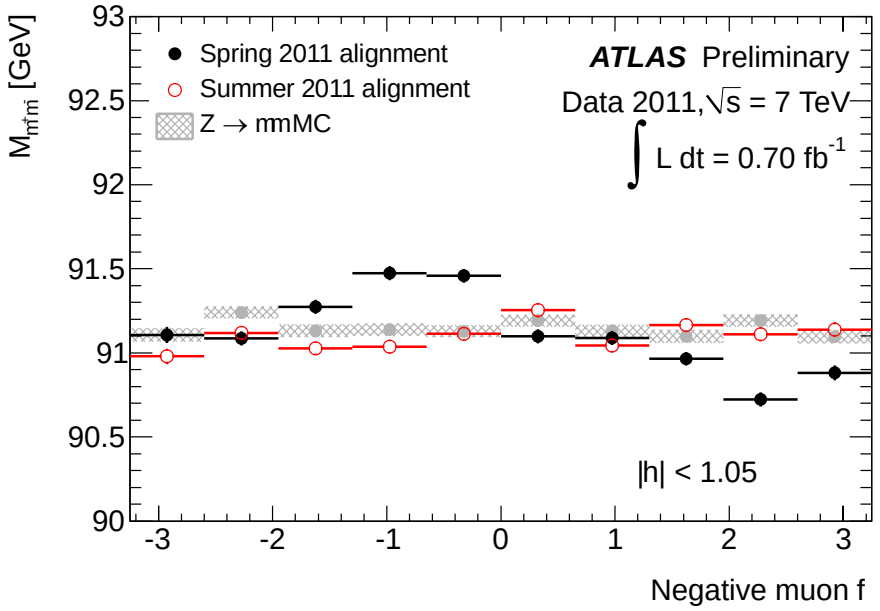




- mass resolution of Z significantly reduced with E/p constraint tracks used in the alignment procedure
- data performance nearly reproduces MC predictions

Improved Mass resolution using E/p constraint

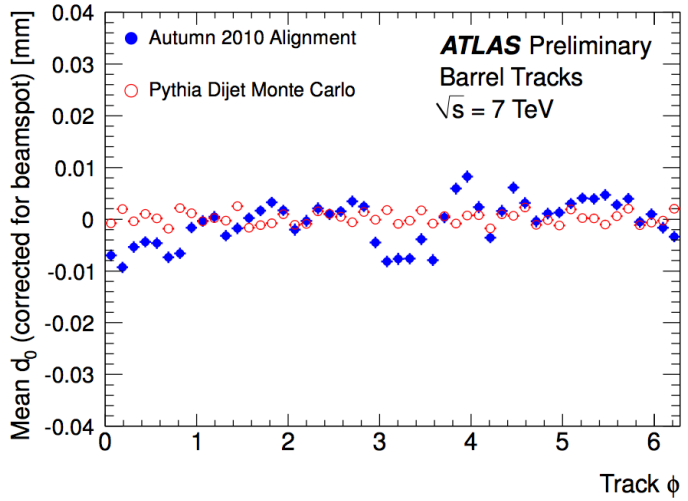


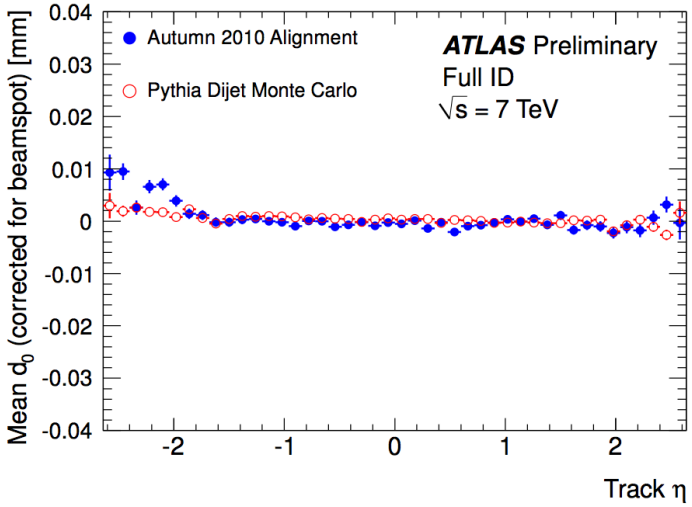


- E/p constraint removed Φ-dependence of Z-mass

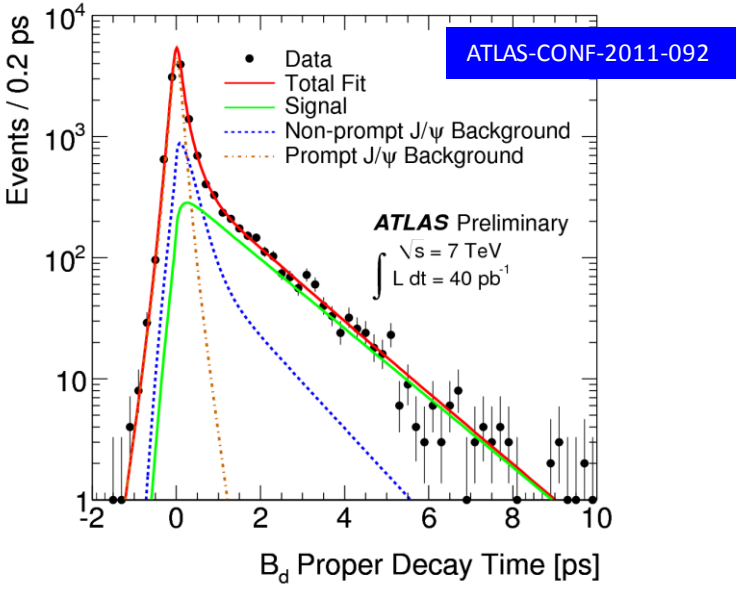
Effect on Impact Parameter Measurement

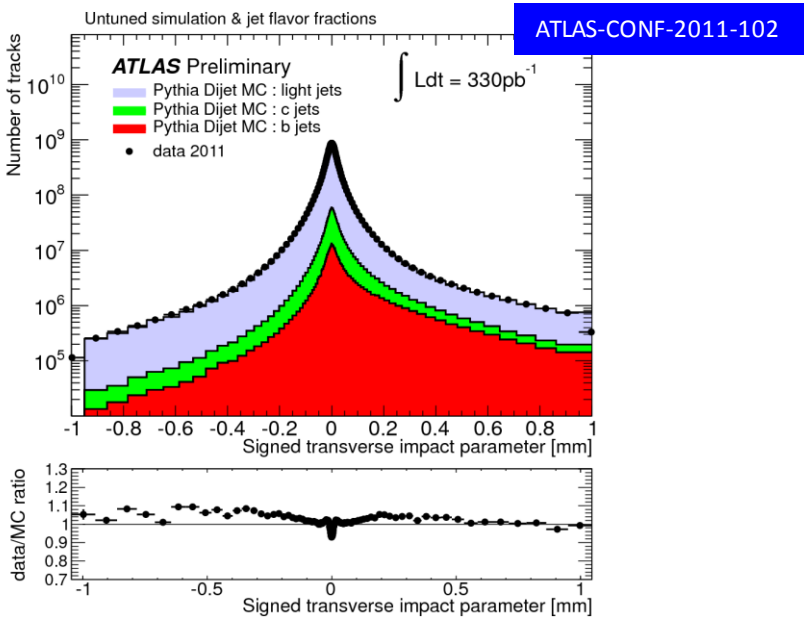
- input tracks for alignment constraint to originate from primary vertex ($d_0 = 0$)
- impact parameter measurements as a function of η and Φ indicate residual misalignments
  - Δd_0 up to 10 µm
- impact on impact parameter based measurements expected





Impact Parameter based Measurements





- exclusive B_d lifetime measurement
- τ_{Bd}=1.51±0.04+0.04 ps (PDG: 1.519±0.007 ps)
- (0.04 ps ~ 20 um for 10 GeV B-Meson)

- impact parameter based b-flavour tagging
- negative part of signed impact parameter (=resolution) returns up to 10% difference to Monte Carlo

Some Final Remarks

- production of alignment constants is time and computing intense
  - several iterations with track (finding and) reconstruction required
  - reduced data format (e.g. data stream with hits of high p_T-tracks only) improves turnaround and speeds up validation
- cosmic tracks are highly valuable for alignment performance
  - consider trigger of cosmic tracks during data taking
- minimizing residuals is the easy part
  - focus early on measurements sensitive to global distortions

Summary

- alignment of ATLAS ID uses track based alignment
  - minimization of residuals with respect to alignment parameters
- residual distribution almost identical to MC with perfect geometry
  - residual minimization necessary but not sufficient
- momentum measurement considerably improved by
  - realignment of B-field with respect to the ID
  - require identical E/p measurement for e^+ and e^-
- measurement of average offset of impact parameter d_0 better than 10 µm

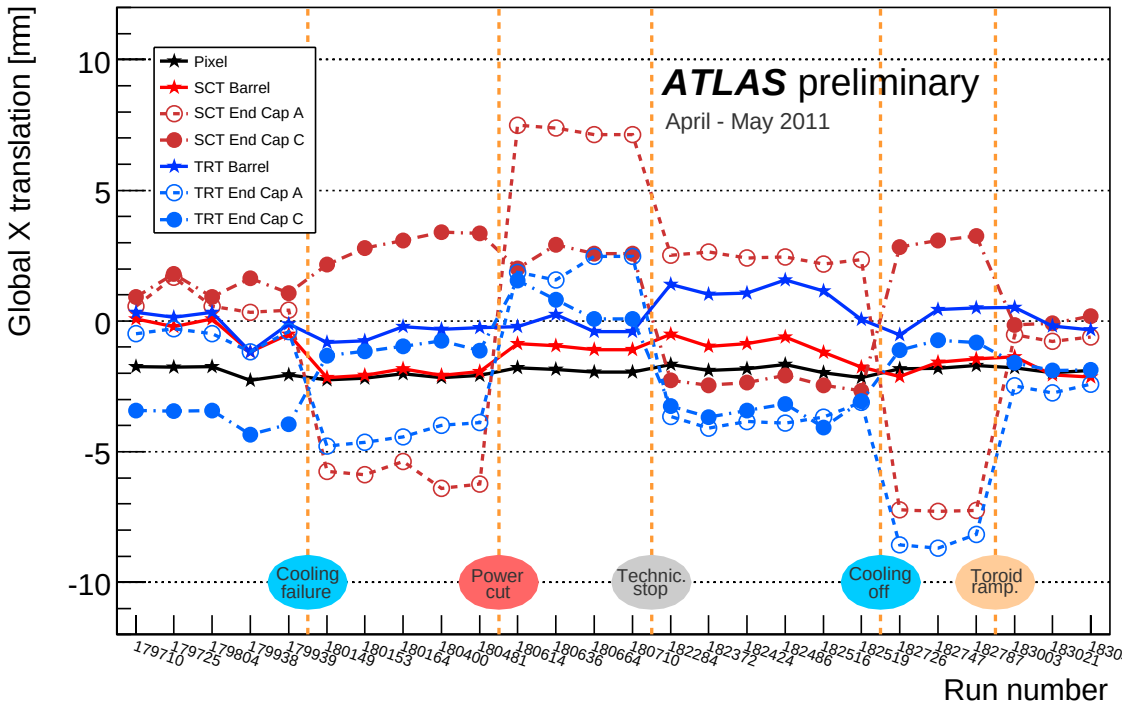
BONUS MATERIAL

The ATLAS Inner Detector

subdetector	r (cm)	element size	resolution (X * Y)	hits/ track (Barrel)	channels
Pixel (Silicon)	5-12.5	50μm * 400μm	10μm * 115μm	3	$80x10^6$
SCT (Silicon Strip)	30-52	80μm * 12cm (stereo)	17μm * 580μm	4	$6x10^6$
TRT (straw tubes)	56-107	4mm * 74cm	130μm	30	$0.4x10^6$

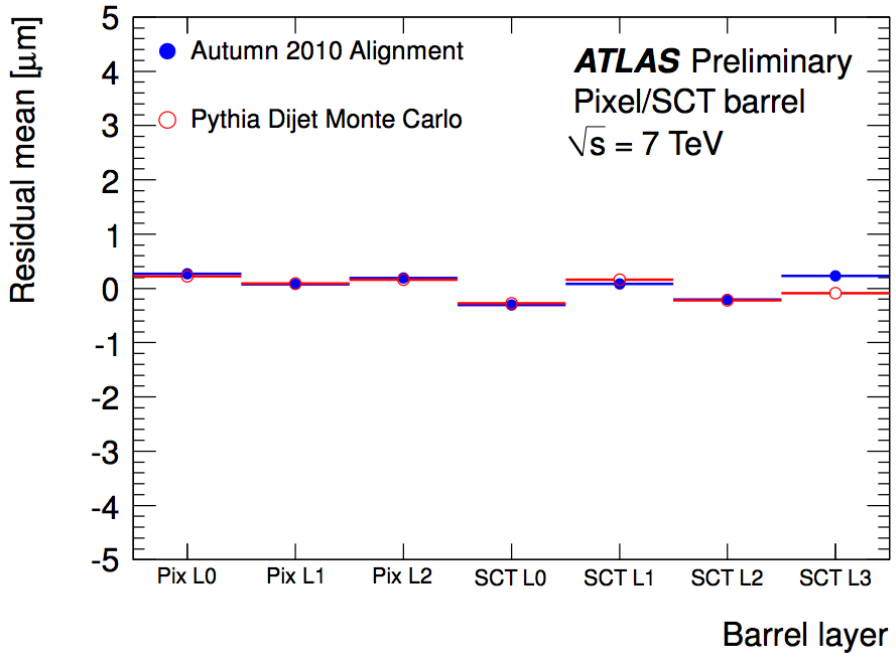
Time Dependence of Alignment

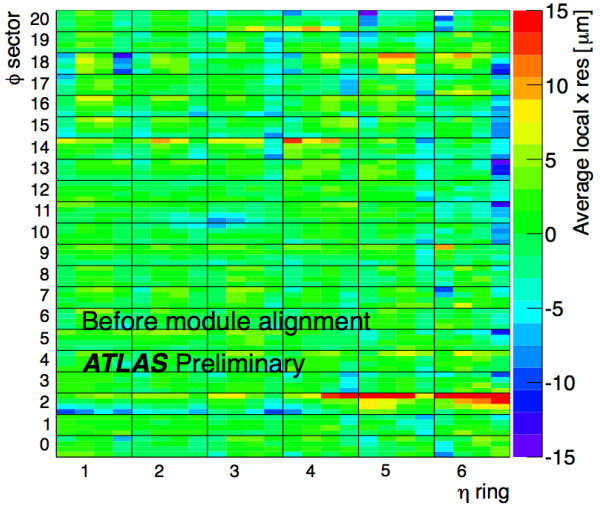
Level 1 alignment

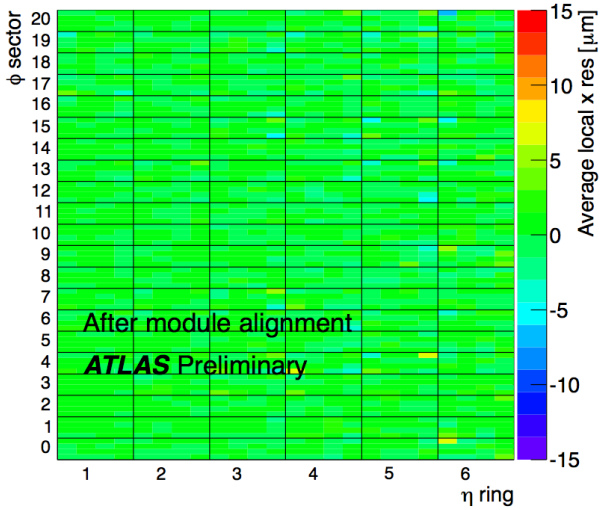


- single set of alignment constants used for 2011 data
- small (<10 µm) changes visible
  - changes related to mechanical interventions (ie. power cut)
- pixel stable during data taking period

Residual Distribution







- mean value of residual distribution consistent with expectations from Simulation
- significant improvement achieved by alignment using individual module DoFs