Alignment of the ATLAS Inner Detector for the LHC Run II

P. Butti
on behalf of the ATLAS collaboration

VERTEX2015
The 24th International Workshop on Vertex Detectors

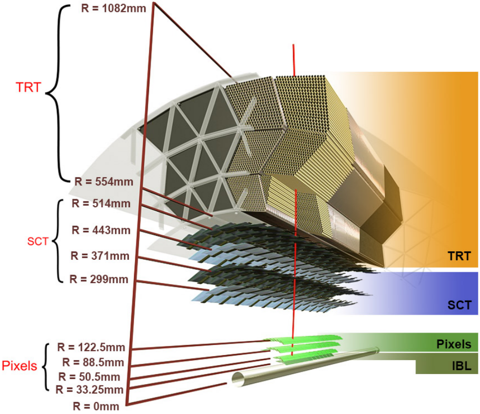
June 5, 2015

ATLAS Inner Detector in Run II

- Sub detectors are composed of silicon (pixel modules or microstrips) and gaseous drift tubes sub detectors

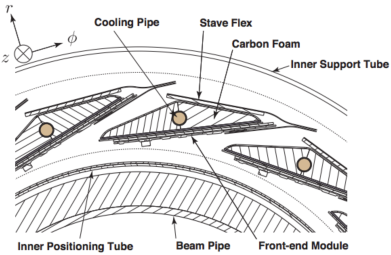
- Pixel System
- The Insertable B-Layer (IBL) (**NEW**)
- Silicon Tracker (SCT)
- Transition Radiation Tracker (TRT)

- Embedded in a 2T axial B Field
- Reconstruction of charged particles within $|\eta| < 2.5$



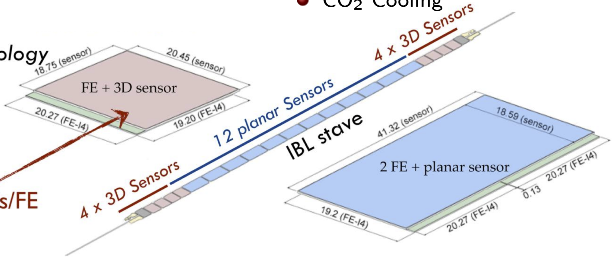
Subdetector	Element size	Intrinsic resolution [μm]	Radius barrel layers [mm]
IBL	$50\,\mu m \times 250\,\mu m$	8×40	33.45
Pixel	$50\,\mu m \times 400\,\mu m$	10×115	50.5, 88.5, 122.5
SCT	$80\,\mu m$	17	299, 371, 443, 514
TRT	4 mm	130	from 554 to 1082

Insertable B-Layer (IBL)

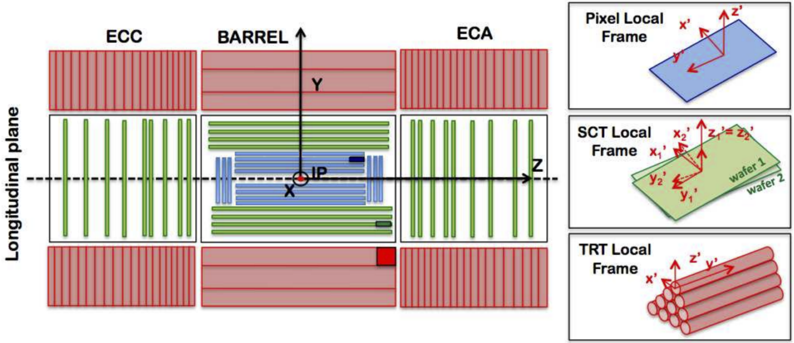


- New innermost layer in the Pixel System between the B-Layer and the Beam Pipe
- Preserve tracking performance versus increasing luminosity
- Improve b-tagging and vertexing
- 14 staves
  20 modules per stave (12 double FE-I4 chip planars + 2x4 3D single FE-I4 chip on the sides)
- CO_2 Cooling

- *2 sensor technology*
- *New FE-I4*



Inner Detector Coordinate System



Global Coordinates - Right Handed

- x: towards centre of LHC
- y: upwards
- z: along beam direction

Local Coordinates - Right Handed

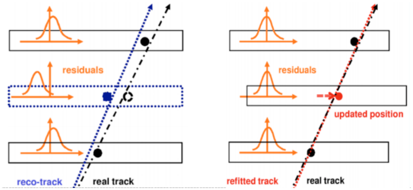
- x': module most sensitive direction (Pixel, SCT), orthogonal to the radial-wire plane (TRT)
- y': along the module side
- z': orthogonal to the $x' - y'$ plane

EF

Inner Detector Alignment

Aim:

- Correct the assumed ATLAS geometry to determine the actual relative positions of all active elements.



- **Track based technique** based on χ^2 minimisation
- $\chi^2 = \sum_{hits} \left(\frac{m_i - h_i(\vec{\alpha})}{\sigma_i} \right)^2$
  m_i measurements, h_i extrapolated hits, σ_i intrinsic resolution, $\vec{\alpha}$ align parameters

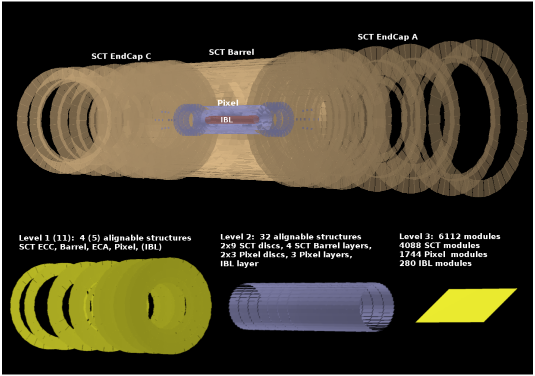
- Solve for small corrections $\delta\vec{\alpha} = M(\alpha)^{-1}\nu(\alpha)$ where:
- $M(\alpha) = \sum_{tracks} \left(\frac{d\vec{r}}{d\vec{\alpha}}\right)^T V^{-1} \frac{d\vec{r}}{d\vec{\alpha}}$
  $\nu(\alpha) = \sum_{tracks} \left(\frac{d\vec{r}}{d\vec{\alpha}}\right)^T V^{-1} \vec{r}_0$
- V is the covariance matrix and $\vec{r}_0$ are the initial residuals

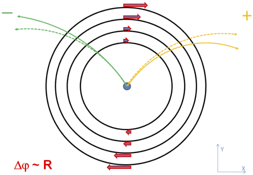
- Alignment is an iterative procedure, that adds corrections to a defined initial condition

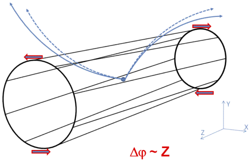
Inner Detector Alignment

- Every alignable structure is assumed to be a rigid body with 6 Degrees of Freedom (DoF) :
  - 3 translations : T_x, T_y, T_z
  - 3 rotations: R_x, R_y, R_z
- Alignment procedure split in hierarchical Levels according to the mechanical structure of the detector (different number of DoF)
- *Weak Modes*: deformations that basic track-based alignment is barely sensitive to
- Need external constraints to avoid biases

- **L1:** large structures
- **L2:** layer/disk alignment
- **L3:** module by module



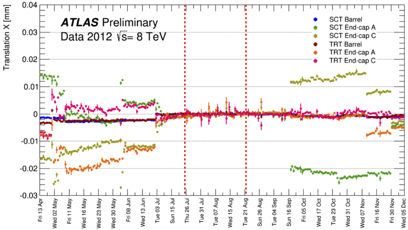


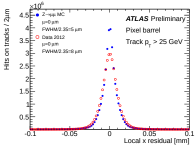


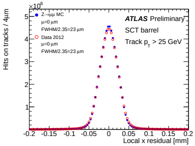
Highlights from Run 1

Level	Description	Structures	DoF	Constraints
1	Pixel detector kept fixed			
	SCT split into barrel and 2 end-caps	3	All	
	TRT split into barrel and 2 end-caps	3	All except T_z	
2	Pixel barrel split into layers	3	All	
	Pixel end-caps split into disks	6	T_x, T_y, R_z	Beam spot,
	SCT barrel split into layers	4	All	Momentum bias and
	SCT end-caps split into disks	18	T_x, T_y, R_z	Impact parameter bias
	TRT split into barrel and 2 end-caps	3	All except T_z	
Si 3	Pixel barrel modules	1456	All	
	Pixel end-caps modules	288	T_x, T_y, R_z	Beam spot,
	SCT barrel modules	2112	All	Momentum bias and
	SCT end-caps modules	1976	T_x, T_y, R_z	Impact parameter bias
	TRT barrel split into barrel modules	96	T_x, R_z	Module placement accuracy
	TRT end-caps split into wheels	80	T_x, T_y, R_z	
TRT 3	Pixel and SCT are fixed			
	TRT straw level	351k	T_x, R_z	

- Comparison between unbiased residuals in data to those of perfectly aligned MC simulation
- Alignment at μm level
- Correction of p_T, d_0 biases
- ID subdetectors movement monitored run by run basis



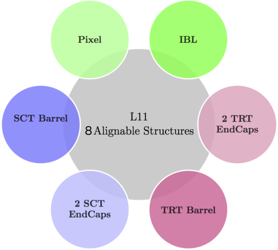




ATLAS-CONF-2014-047

Toward Run II : inclusion of the IBL in the ID Alignment

- Alignment levels updated to accommodate the IBL
- As IBL is mechanically attached to the new beam pipe:
  at **L11** it is treated as separate structure from Pixel



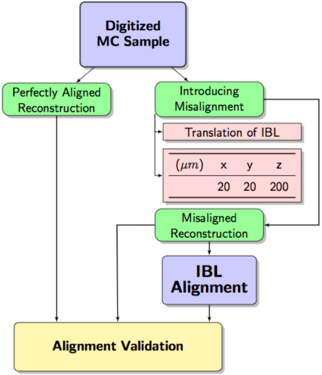
	Alignable Structures			
	IBL	Pixel	SCT	TRT
L11	1	1	3	3
L2	-	9 + 1	22	96
L3	-	1744+280	4088	350848

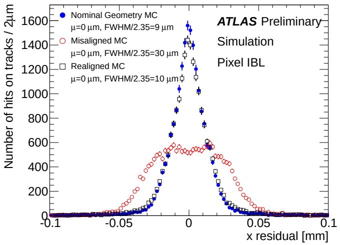
- Considering IBL as separate structure at L11 allows to account for movements during ATLAS operation
- At more refined alignment levels, IBL is treated as integrated in the Pixel

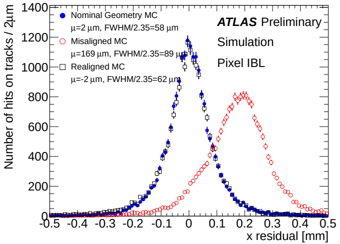
NIKHEF

IBL Framework integration closure test

- Monte Carlo simulation of single muons tracks originating from centre of ATLAS
- Reconstruction using perfect and misaligned geometry
- Alignment iterations over the displaced IBL
- Residual Distribution comparison



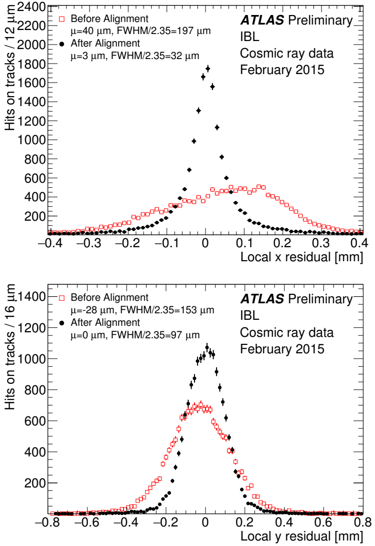




Submitted to Nuclear Physics B.

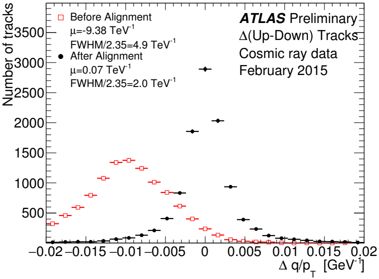
ID Alignment Commissioning with Cosmic Data - Feb '15

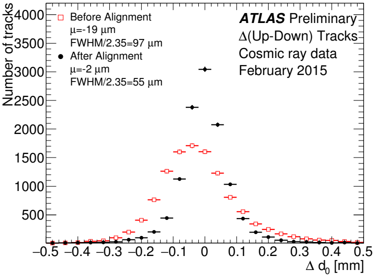
- First alignment attempt using cosmic-ray data in Feb 2015
- Track selection targeting down-going muon tracks.
- Average trigger rate 4.84 Hz Total Tracks: 3×10^5
- Alignment quality tracks $\sim 50k$
- $\sim$ 50k hits in the IBL
- IBL and Pixel system Full L3 alignment: IBL $\times 5$ resolution improvement



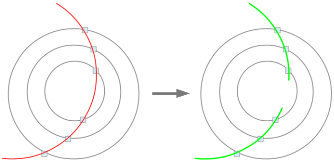
ATL-PHYS-PUB-2015-009

ID Alignment Commissioning with Cosmic Data - Feb '15





- *Split Tracks*: cosmic rays tracks are split in the top and bottom halves of the ID
- The perigee parameters of the up / down tracks are compared before and after the alignment
- The split tracks come from the same particle $\rightarrow$ resolution of the perigee parameters



ID Alignment Commissioning with Cosmic Data - March ’15

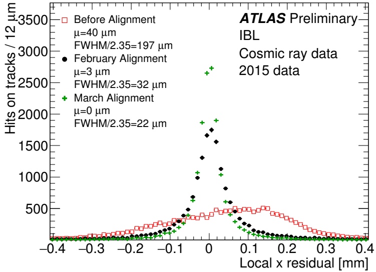
- Pixel, SCT and TRT from last Run1 positions
- Combined use of

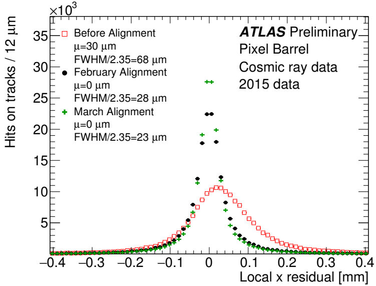
B Field Off Data

- Straight tracks, more robust against weak modes and momentum biases
- No p_T information, uncertainty dominated by material effects
- Full structures→Layers→Staves (Pix/IBL only)

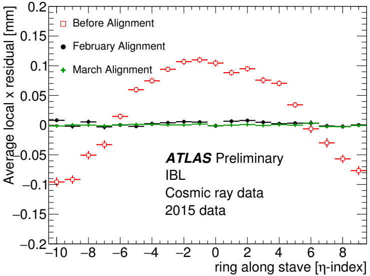
B Field On Data

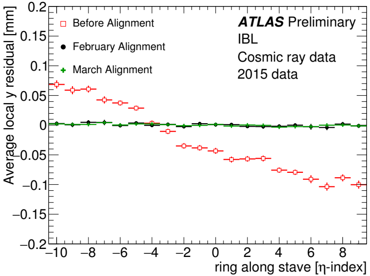
- Curved tracks can introduce biases
- $p_T > 2$ GeV to remove tracks dominated by multiple scattering.
- Full structures→Layers→Staves (Pix/IBL only)→ Pixel and IBL modules





ID Alignment Commissioning with Cosmic Data - March '15





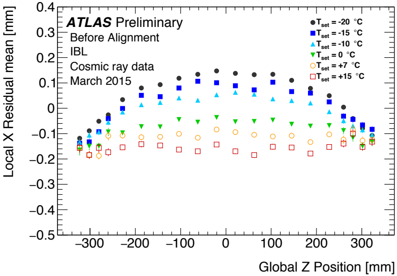
- During alignment a dependence of the residuals on the η position of the modules was observed
- Local X: Understood to be caused by the IBL movements with operation temperature
- Local Y: Correspond to a wider spacing between the modules during the gluing phase

IDTR-2015-002

IBL Stave Bowing

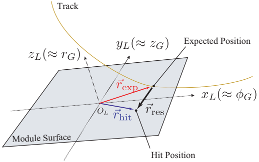
Measurement on Data:

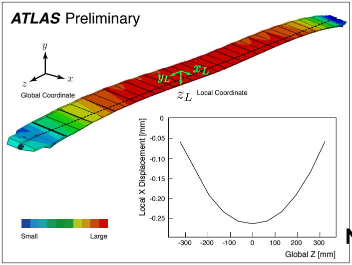
- Different IBL operating temperatures during March 2015 Cosmic Ray data taking



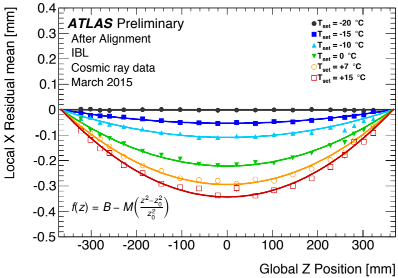
Finite Element Analysis Simulation:

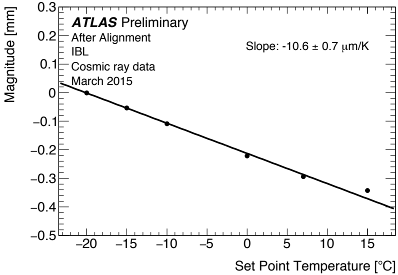
- Simulate the displacement of the modules due to an exaggerated $\Delta T = -60\ ^\circ\text{C}$
- The distortion is caused by a mismatch between the coefficients of thermal expansion of the components in the IBL staves





IBL "Stave Bowing" with temperature





- L3 Alignment performed at the lowest temperature point (-20 °C) using 3×10^6 cosmic ray events
- IBL Bowing distortion parametrized using a parabolic function

$$\Delta x_L(z) = B - \frac{M}{z_0^2}(z^2 - z_0^2)$$

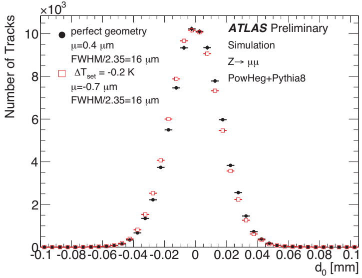
where $z_0 = 366.5$ mm is the fixing point of the stave, B is the baseline and M is the bowing magnitude

- B fixed to 0 $\rightarrow$ $dM/dT = -10.6 \pm 0.7\ \mu$m/K

Bowing impact and correction

- Investigated the module and cooling pipe temperature stability during Cosmic rays data taking
- Estimated $\Delta T = 0.2$ K during stable collisions data taking at 13 TeV $\rightarrow$ 2μm bowing
- The d_0 impact parameter is very sensitive to IBL distortion.

- A set of alignment constants have been generated to mimic the bowing in Monte Carlo simulation
- Used $Z \rightarrow \mu\mu$ at $\sqrt{s} = 13$ TeV
- **Negligible impact**



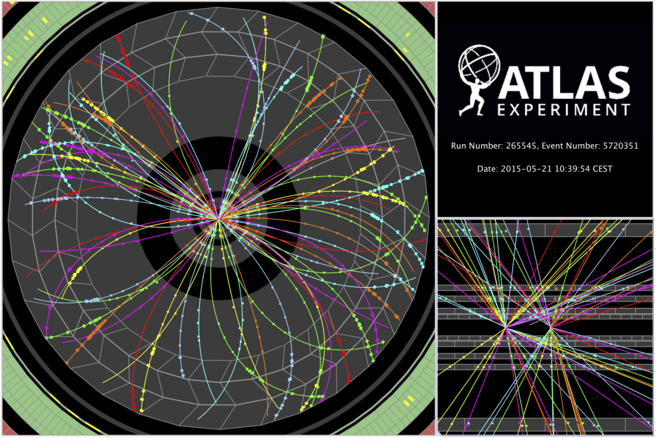
Implementation of the IBL distortion in the ID Alignment

- The above expectation are based on stable beam conditions
- The estimate can be underestimated in case of:
  - Cooling failures
  - Humidity issues
  - Manual operation temperature changes
  - ...

Under Development and Validation:

- Inclusion of the IBL stave bowing DoFs in the alignment framework
- Lumiblock-based and run by run distortion monitoring
- Provide new correction to reconstruction if needed

First collisions at 13 TeV

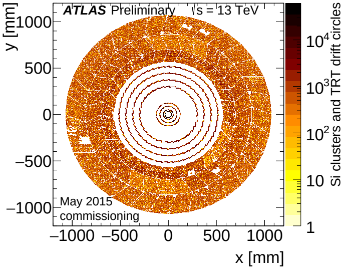


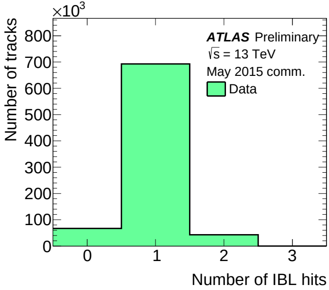
- The first 2015 13 TeV p-p collisions events shown a successful Inner Detector track reconstruction
- The event reconstruction used Cosmic ray data derived alignment constants
- Prove of a very successful commissioning phase

NIKHEF

First collisions with 13 TeV data

- Collisions events provide high number of hits-on-tracks in the sub detectors
- Alignment team used May 21st collisions events to provide a more refined alignment for Run2 data taking.
- Initial point: March 2015 cosmic ray data alignment
- Performed a more precise L3 alignment of the IBL





Run 2 Data Processing Plans

Short term alignment tasks

- First week of collisions with stable beam is **ongoing**
- Alignment starting point: May 21 13 TeV p-p collisions
- Alignment will follow the Run 1 procedure
- Use combined set of track topology: fighting weak modes

- Collisions data: seeded by Level 1 τ triggers
  - Partial event reconstruction
  - tracks $p_T > 10$ GeV offline
  - rate 100 Hz
- Cosmics data: seeded by μ triggers
  -Full ID reconstruction during empty bunches
  -rate 5Hz

Long term alignment tasks

- Full and complete alignment following the Run 1 strategy
- Investigation of presence of weak modes using resonances reconstruction
  $Z \to \mu\mu \quad W \to e\nu \quad Z \to ee \quad K_s \to \pi\pi \quad J/\psi \to \mu\mu$ ...
- ... and their correction
- Study of the impact of the alignment systematics
- Residual misalignment estimate

Summary and Conclusions

- Alignment of the ATLAS Inner Detector is a track-based technique that iteratively corrects the assumed geometry to find the real positions of the active modules.
- During the Long Shutdown 1, the inclusion of the IBL required a major upgrade of the Alignment framework.
- First, an alignment on simple Monte Carlo was carried out, then on cosmic data. The alignment team is working on 13 TeV data alignment as we speak.
- Several studies to be carried out in the following weeks: systematics, weak mode deformations, refined alignment procedure during Run 2.

BACKUP

Offline and Online Data Quality Monitoring updates

- Alignment framework is used for both online and offline Data Quality monitoring
- The monitoring framework is composed by two parts:

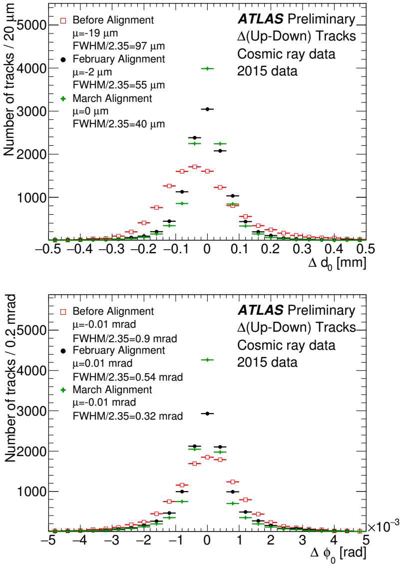
Alignment Monitoring

- Checking the tracks parameters, hit efficiencies, residual distributions
- Number of plots enlarged and refined to give faster feedback on data acquisition issues

Performance monitoring

- Reconstructions of the resonances as $Z \to \mu\mu$
- Updated to the new data format used in Atlas for Run2
- Give estimate of alignment impact on physics quantities

Split Tracks plots for March 2015



First Cosmics Alignment

- First time the full chain of IBL alignment
- Track selection driven by Cosmic ray topology
- B Field On data
- First Alignment on Data after Run 1

Level	Description	Structures	DOF
1	IBL	1	All except R_x
	Pixel detector	1	All except R_x
	SCT barrel (end-caps fixed)	1	T_x, R_y, R_z
2	IBL and Pixel barrel split into layers	4	All except R_x
	Pixel end-caps split into discs	6	T_x, T_y, R_z
	SCT barrel split into layers	4	T_x, R_y, R_z
	SCT end-caps split into 2	2	T_x, T_y, R_z
PIX-stave 2	IBL and Pixel barrel split into staves	126	T_x, T_y, R_y
	Pixel end-caps split into discs	6	T_x, T_y, R_z
	SCT barrel split into layers	4	T_x, R_y, R_z
	SCT end-caps split into 2	2	T_x, T_y, R_z
PIX 3	IBL and Pixel barrel modules	1736	T_x, T_y, R_y, R_z
	Pixel end-caps split into discs	6	T_x, T_y, R_z
	SCT barrel split into layers	4	T_x, R_y, R_z
	SCT end-caps split into 2	2	T_x, T_y, R_z

NIKHEF

Momentum Biases

- 2 categories: *sagitta* and *radial* biases, respectively orthogonal (charge asymmetric) and parallel (charge symmetric) to the track trajectory
- Difficult to remove due to small impact on the χ^2 of a track fit

Sagitta bias

- $q/p_T \rightarrow q/p_T + \delta_{sagitta}$ or $p_T \rightarrow p_T(1 + qp_T\delta_{sagitta})^{-1}$
- $\delta_{sagitta}$ is a universal bias parameter for all measured momenta $\rightarrow$ defines the deformation
- The reconstructed polar angle doesn't change $\longrightarrow$ p$\rightarrow p(1 + qp_T\delta_{sagitta})^{-1}$
- Two methods: $Z \rightarrow \mu\mu$ invariant mass and E/p method for electrons

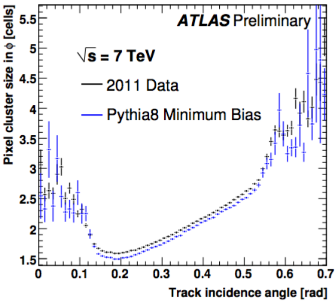
NIKHEF

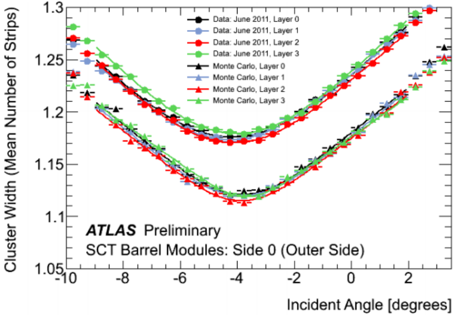
Cluster Studies

- Pixel cluster shape data/mc discrepancy exists for a long time
- They could degrade our performance/analysis
- Still not totally understood

- Energy loss follows Landau distribution with expectation value given by Bethe-Bloch formula
- A particle doesn't deposit energy in a continuously way through the material, but rather in a discrete way.
- If we divide the material in very thin layers, we should expect the energy deposited in each pieces follows some much discrete function, rather than Landau
- In digitisation simulation we assume energy deposits in each layer evenly distributed.

Cluster Size





Cluster size as a function of the incidence angle for the PIX (left) and the SCT (right). For SCT the cluster is calculated on S0

- "Could be" an hint for the pix-sct discrepancy in the residual distributions

Pixel Module distortion studies

- It's well known that the pixel modules are distorted out-of-plane with respect to flat geometry
- Data from a full pixel survey is used during reconstruction in order to include the distortion in the determination of the hit position
- For Run2 Alignment team is coordinating efforts to provide an in-situ out-of-plane distortion measurement
- This might improve the results and the disagreement observed in the comparison Data/MC in 2012 alignment campaign

NIKHEF

Calibration loop strategy

- During Run1 alignment ran on run by run basis at L1
- Express processing of the current run
- Run2 strategy to be fully defined

- Monitoring of the ID movements
- New constants manually uploaded if needed
- L2 alignment at CL using external constraints