

Alignment of the ATLAS Inner Detector

Student Seminars



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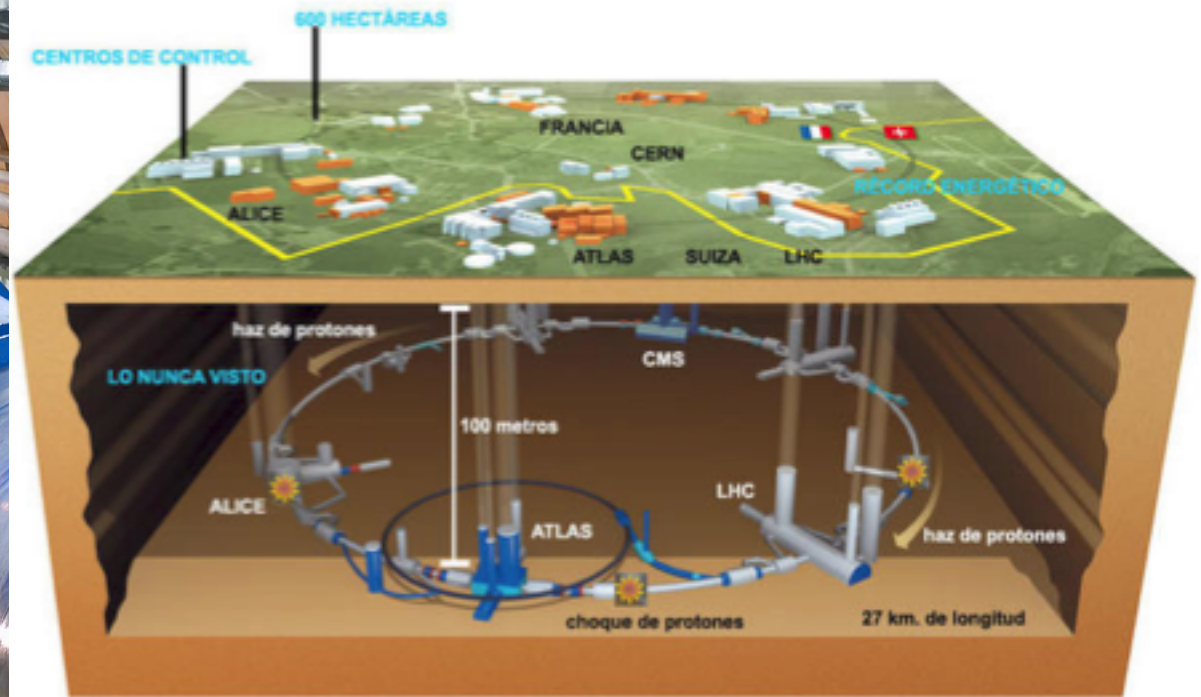
LHC & ATLAS

- The Large Hadron Collider (LHC) is the largest proton-proton collider ever built, with a 27 km perimeter ring, where collisions at 7 and 8 TeV were recorded between 2009-2012, expecting an energy in the center of mass of 13 TeV for the upcoming collisions in 2015.



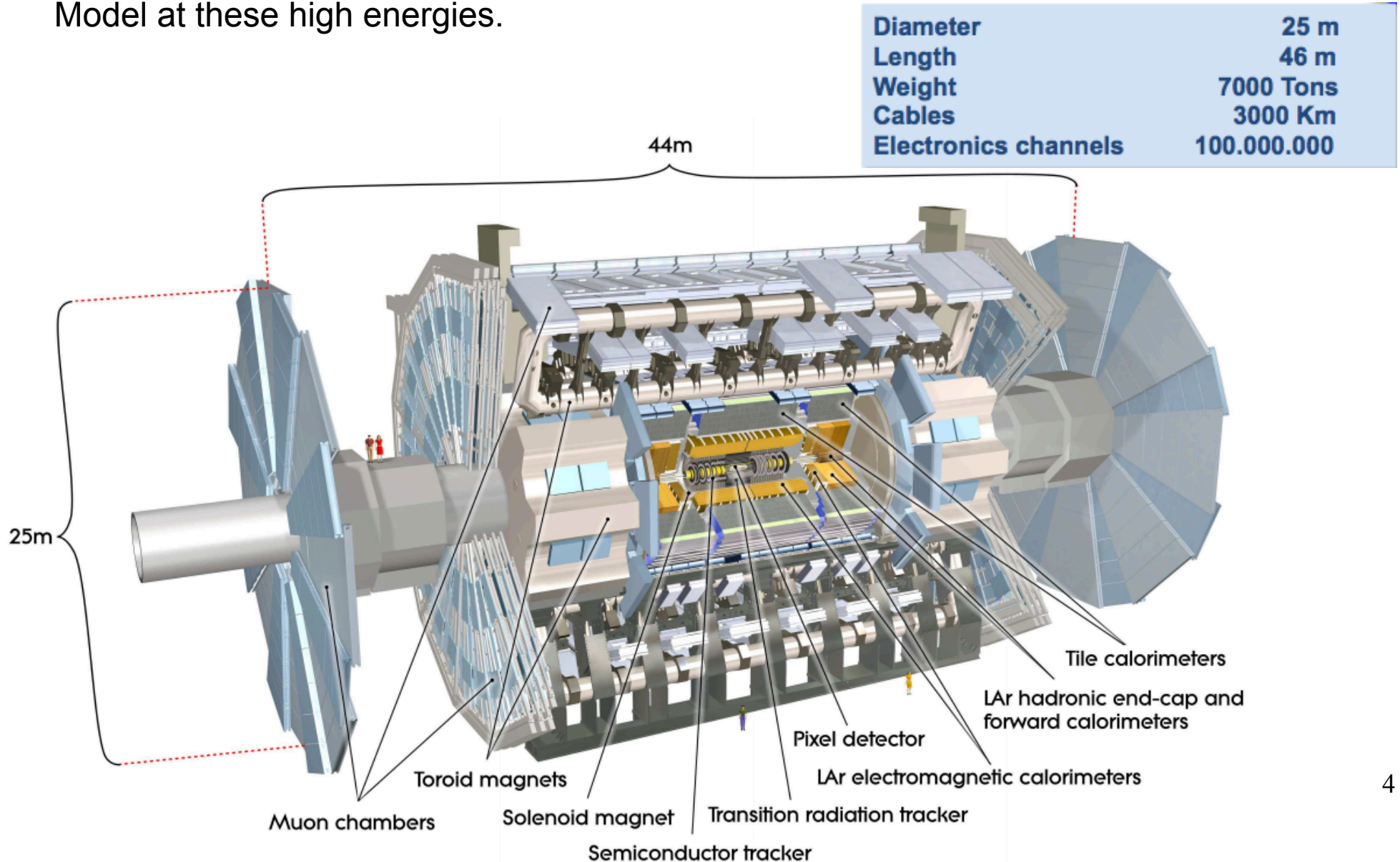
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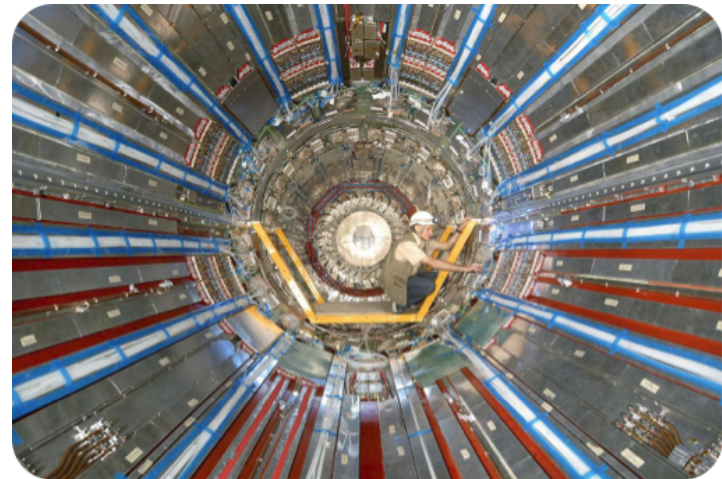
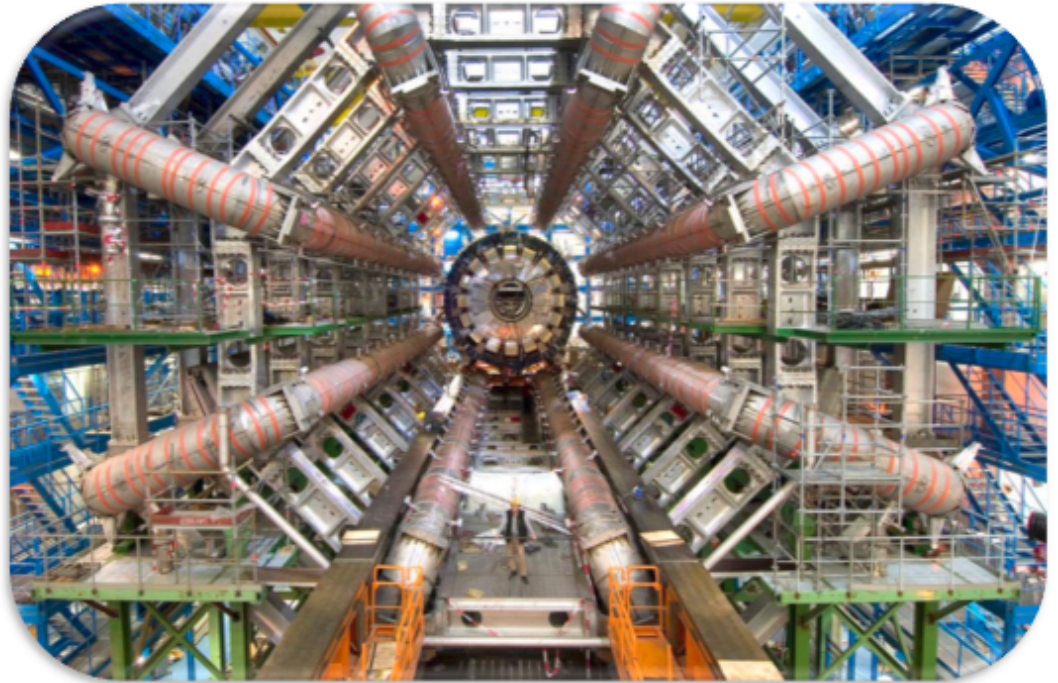
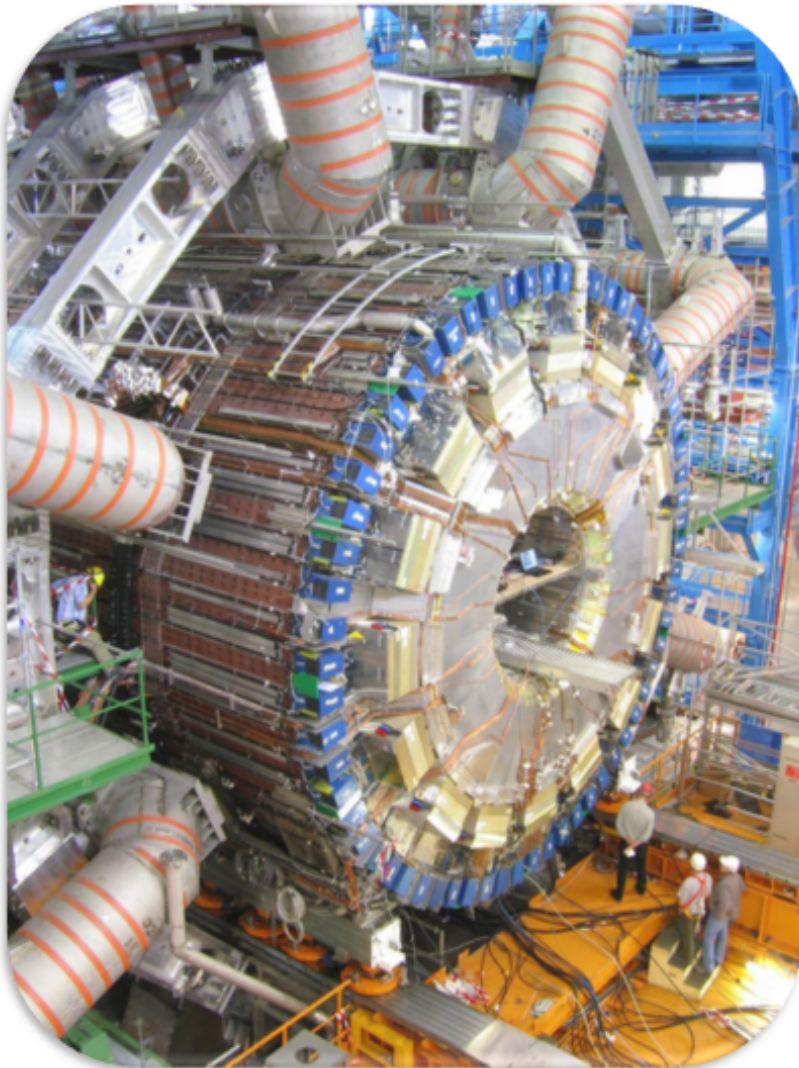
LHC & ATLAS

- ATLAS is one of the four experiments situated in the LHC, a general purpose experiment designed to search for new physics phenomena and to test the Standard Model at these high energies.



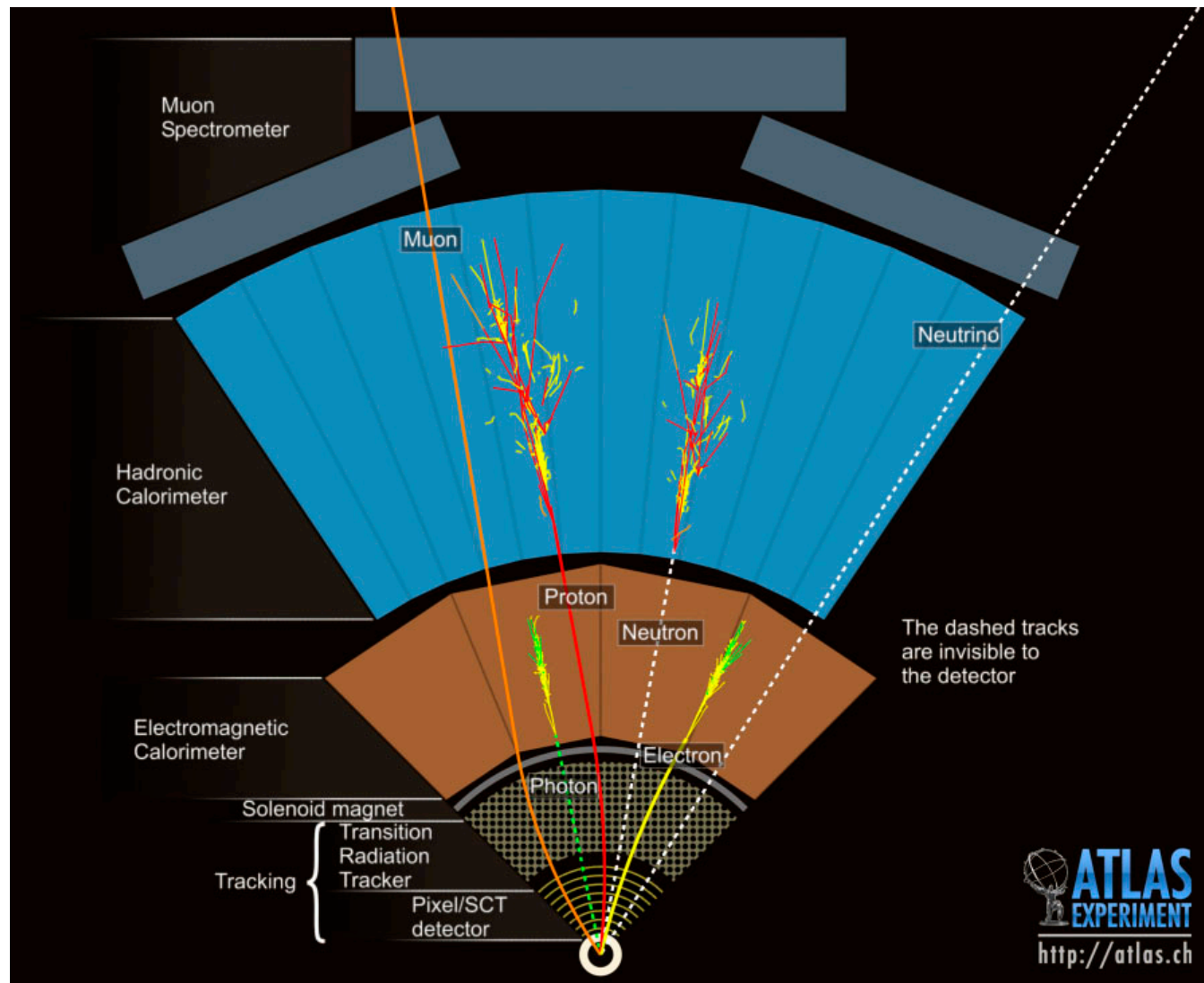
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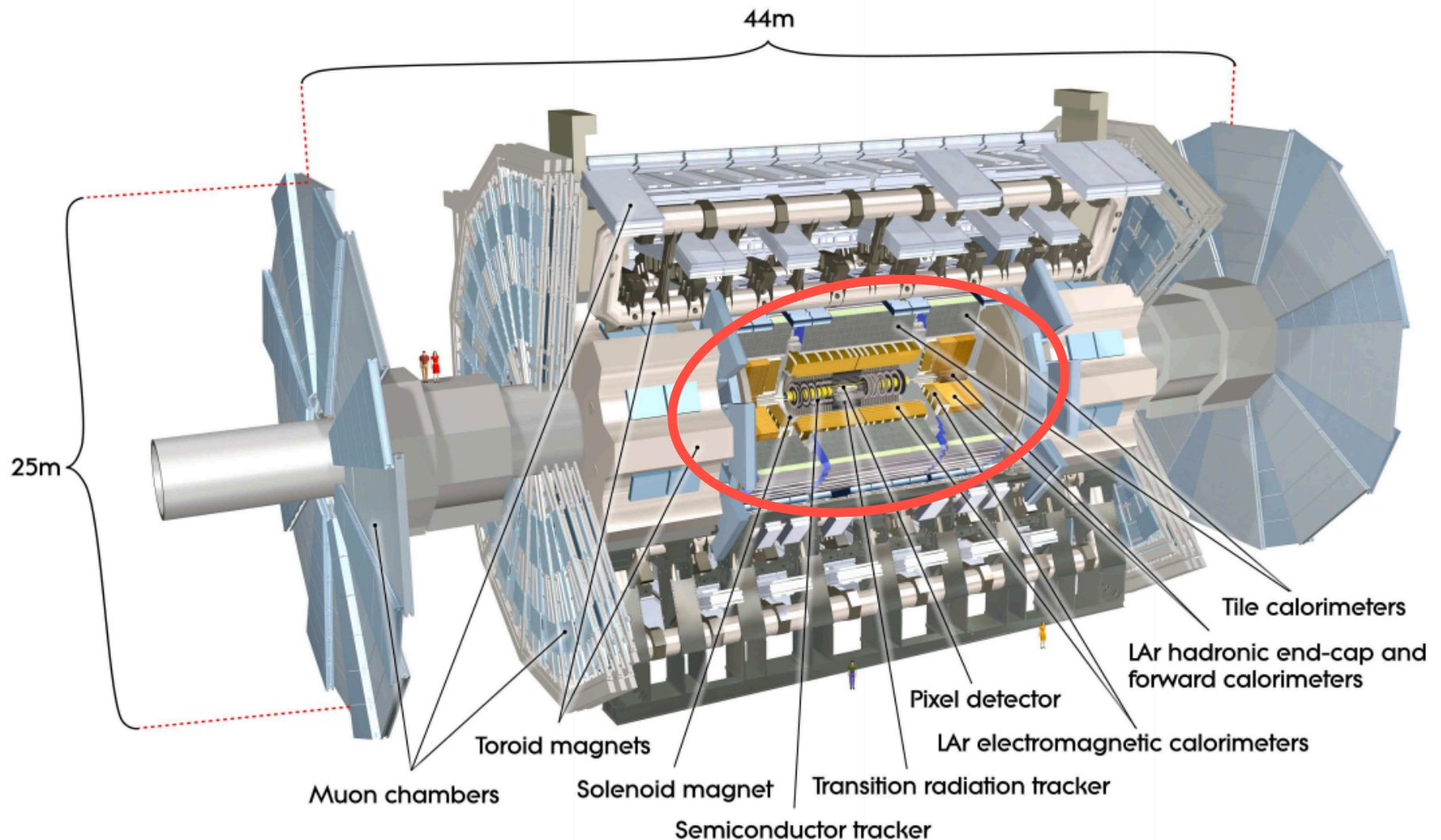
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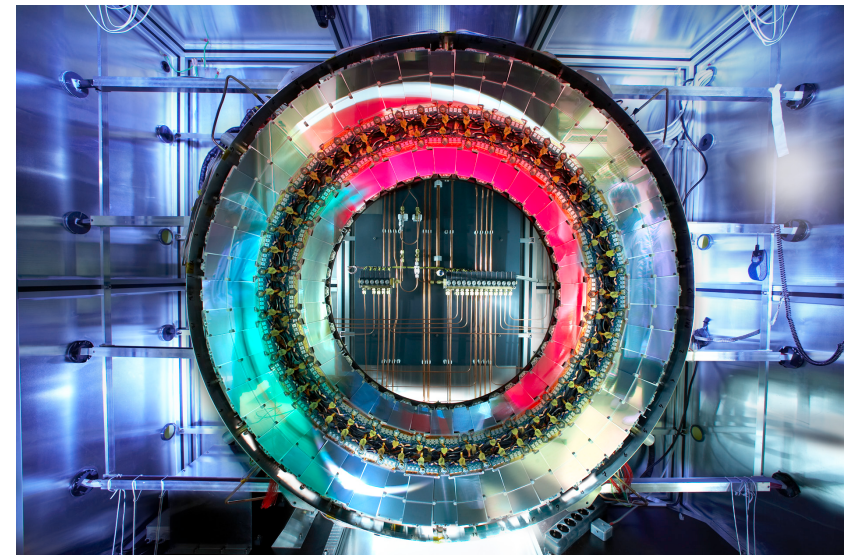
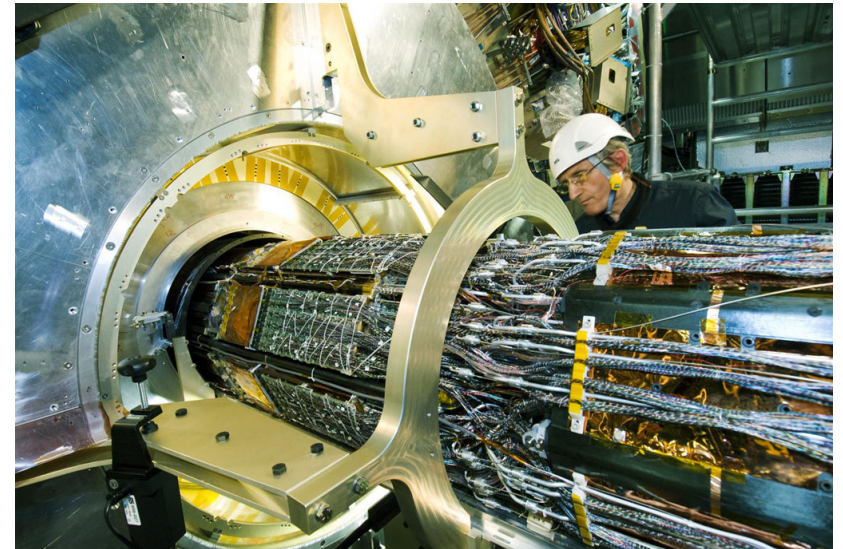
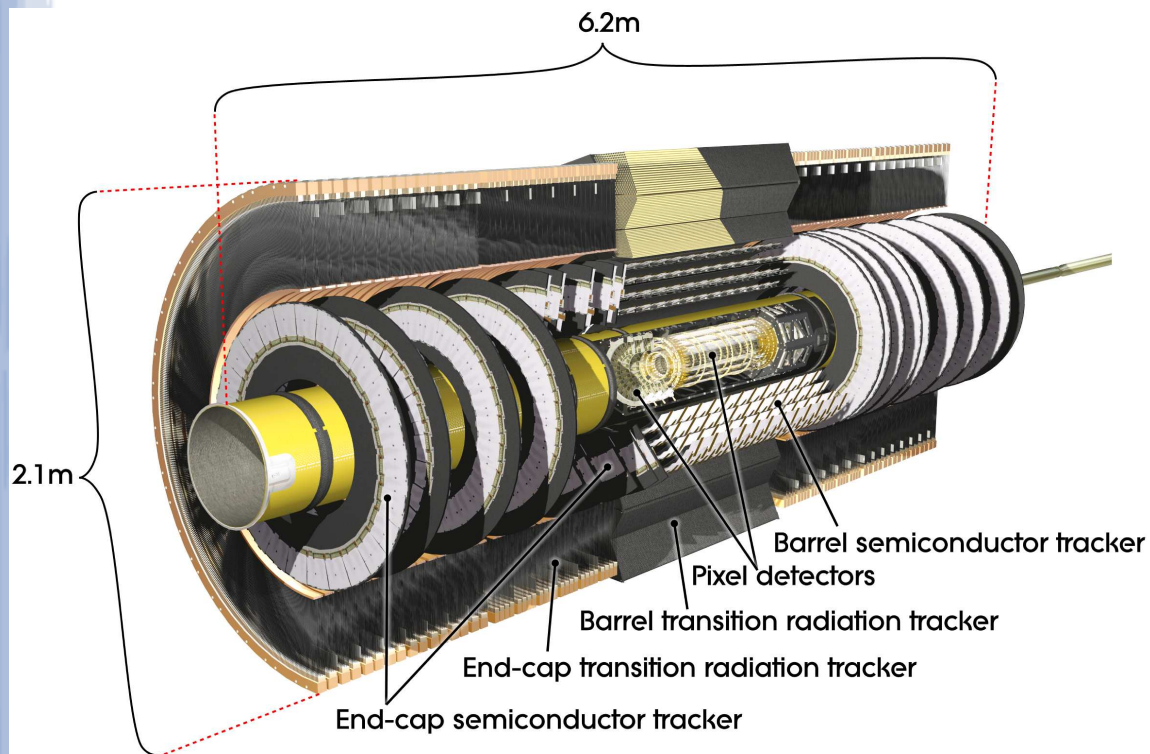
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ATLAS Inner Detector (ID)

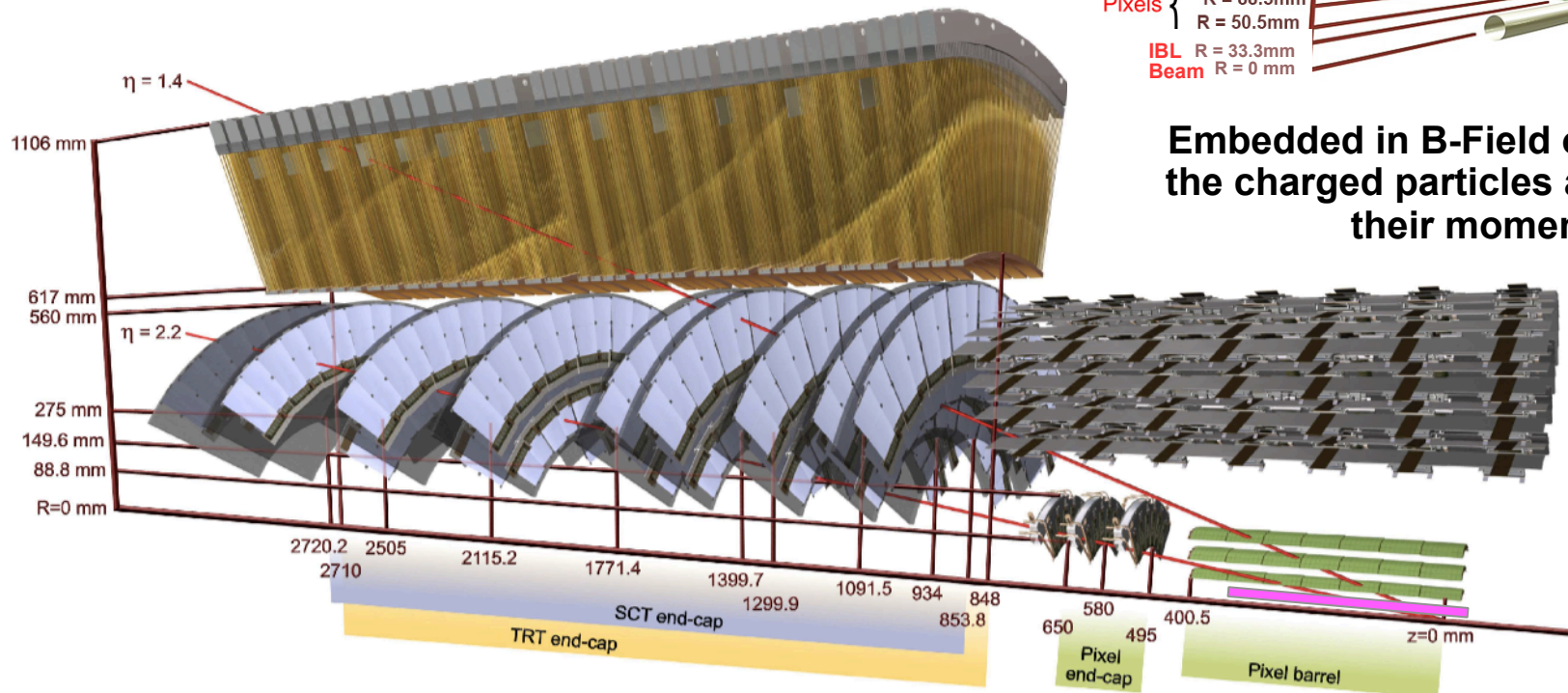
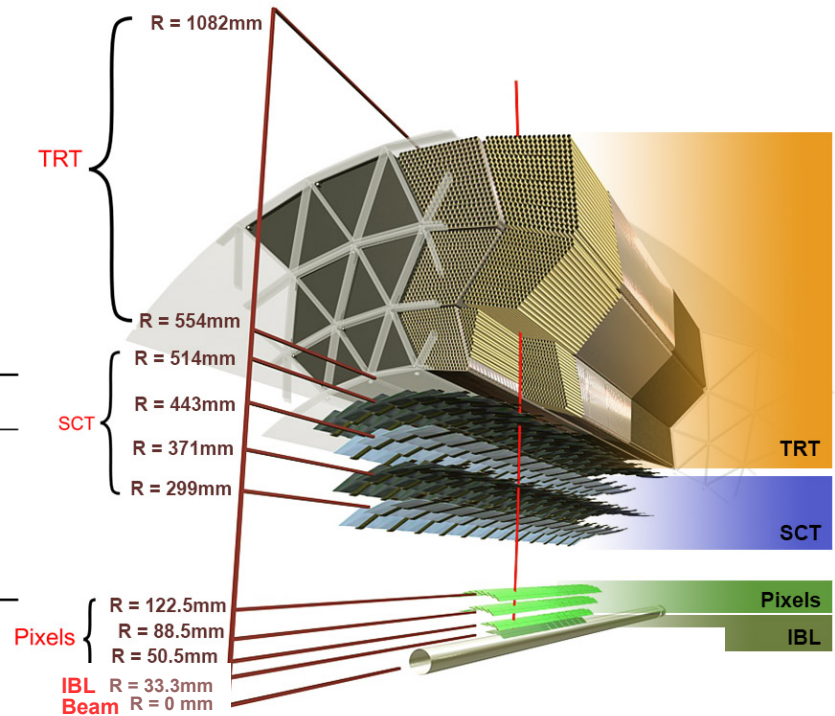
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ATLAS Inner Detector (ID)

- ATLAS relies in the Inner Detector (ID) tracking system for reconstruct the trajectories of the charged particles produced in the collisions.
- It is composed by three sub detectors: Pixel, SCT and TRT.
- A new pixel layer, the IBL, has been added.

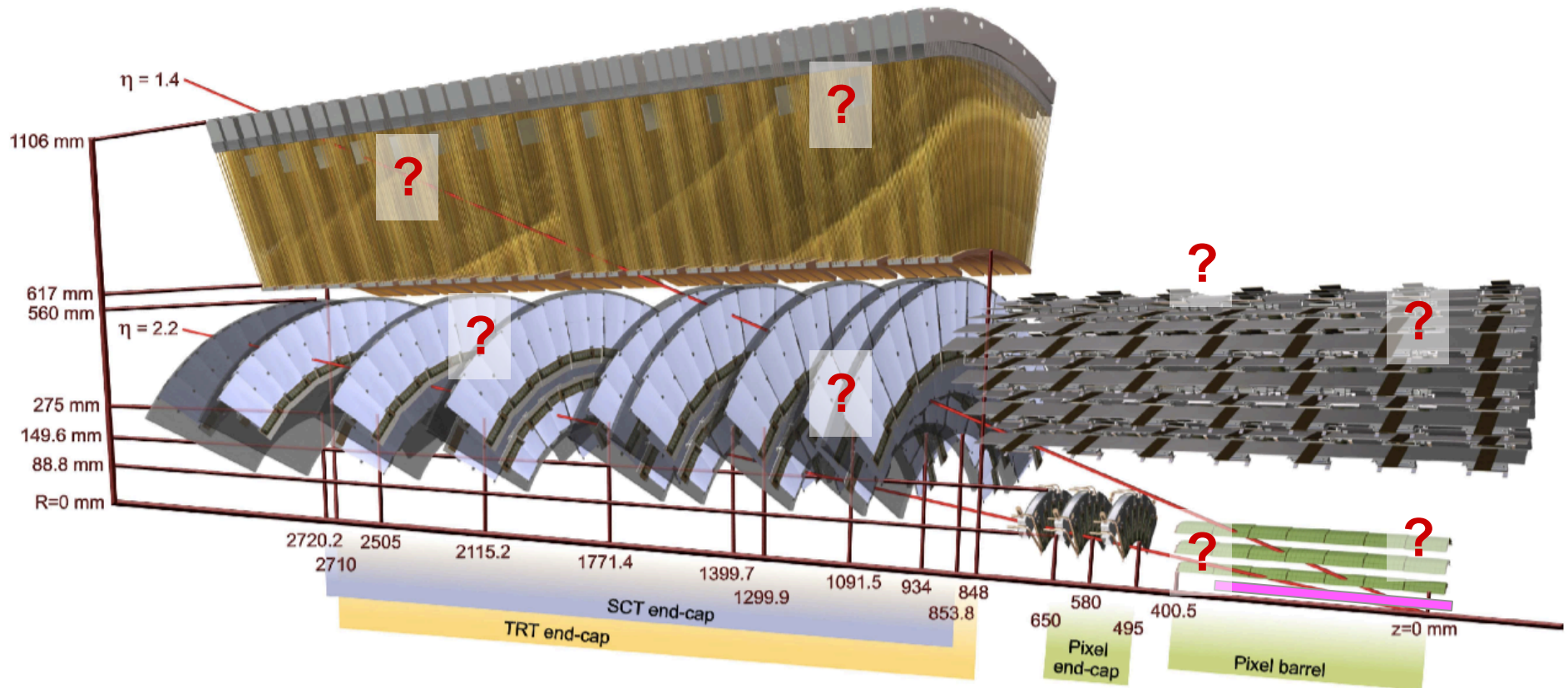
Subdetector	Element size	Intrinsic resolution [μm]	Radius barrel layers [mm]
IBL	$50\mu\text{m} \times 250\mu\text{m}$	8×40	33.3
Pixel	$50\mu\text{m} \times 400\mu\text{m}$	10×115	50.5, 88.5, 122.5
SCT	$80\mu\text{m}$	17	299, 371, 443, 514
TRT	4mm	130	from 554 to 1082



Embedded in B-Field of 2 T to curve the charged particles and determine their momentum

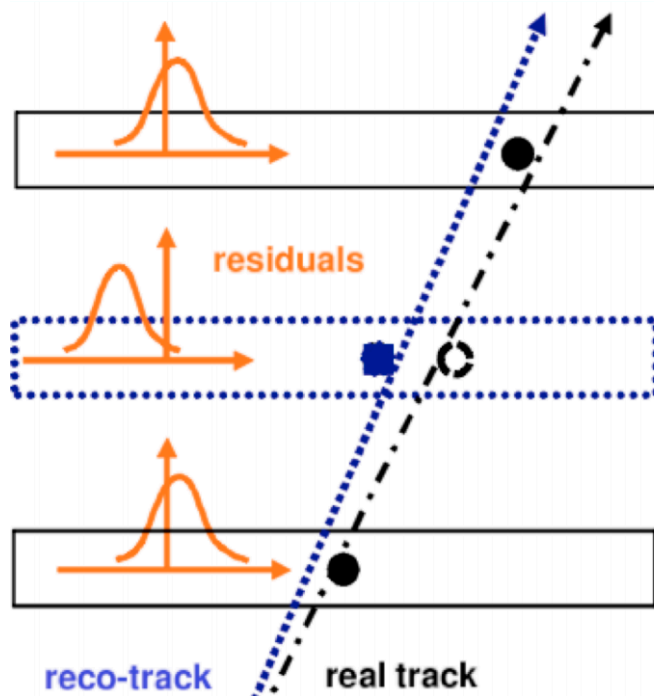
The importance of the alignment

- After the assembly of the ID, the position of every individual detector was known with less precision than their intrinsic resolution.
- In order to fully exploit their excellent spatial resolution, an alignment procedure has to be applied to accurately determine their position and orientation.



- The normal operation of ATLAS introduces additional misalignments, so the alignment has to be maintained during the Runs of LHC.

The importance of the alignment



- A misalignment is understood as a difference between the assumed position for a detector and its real position.
- If the position of a detector is incorrect, its hits would be placed in a wrong position, biasing the reconstructed tracks and worsening the resolution.
- The baseline goal of the ID alignment is to determine the position of the individual detectors such that the track parameter resolutions are not significantly degraded (no more than 20%) with respect “perfect geometry”.
- This means that, for example, Pixel modules position has to be known with a 10 μm precision.

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Alignment Algorithm

- It uses track-based alignment algorithms. The alignment is performed by minimizing a χ^2 function, which takes into account the residuals of every module.
- Every aligned structure has six degrees of freedom: 3 translations and 3 rotations.

RESIDUAL:

$$r = hit_{measured} - hit(\pi, a)_{extrapolated}$$

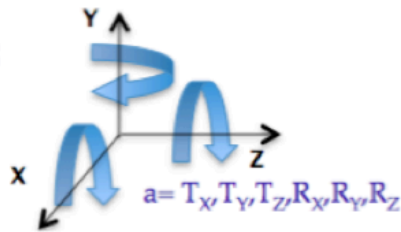
χ^2 DEFINITION:

$$\chi^2 = \sum_{Tracks} r^T(\pi, a) V^{-1} r(\pi, a)$$

a : alignment constants; π : track parameters
 V : covariance matrix of the hit measurement

χ^2 MINIMIZATION.

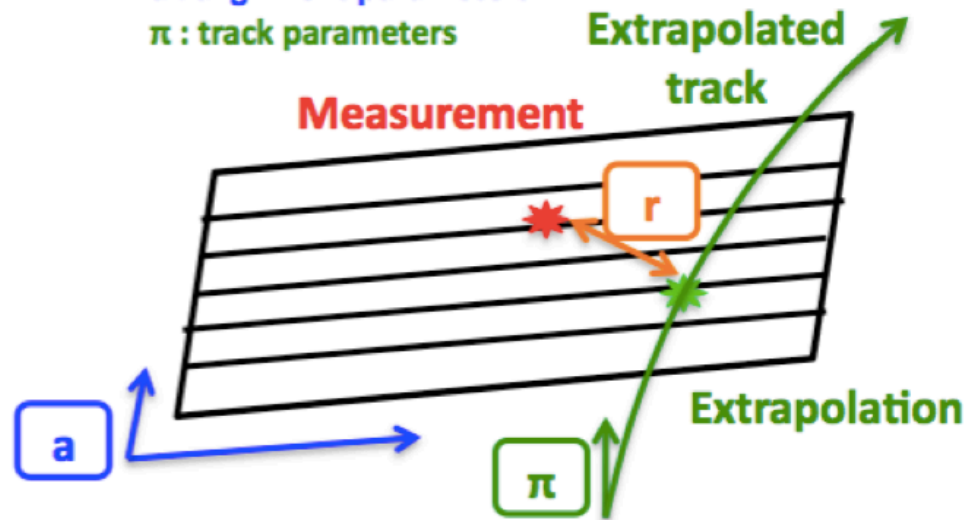
$$\frac{d\chi^2}{da} = 0$$



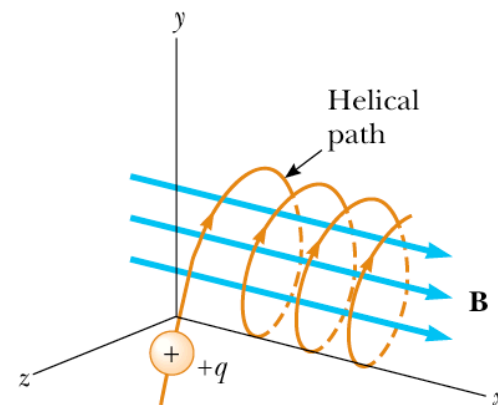
r : residual

a : alignment parameters

π : track parameters



$$\pi = (d_0, z_0, \phi_0, \theta, q/p)$$



Alignment Algorithm

- In other words, the alignment algorithm works as a huge fitting function, in which thousand or millions of events are analyzed to solve a system of equations with can reach more than 700k parameters.

$$\chi^2 = \sum_{tracks} [r(a, \tau)]^T V^{-1} [r(a, \tau)] , \quad \frac{d\chi^2}{da} = 0$$

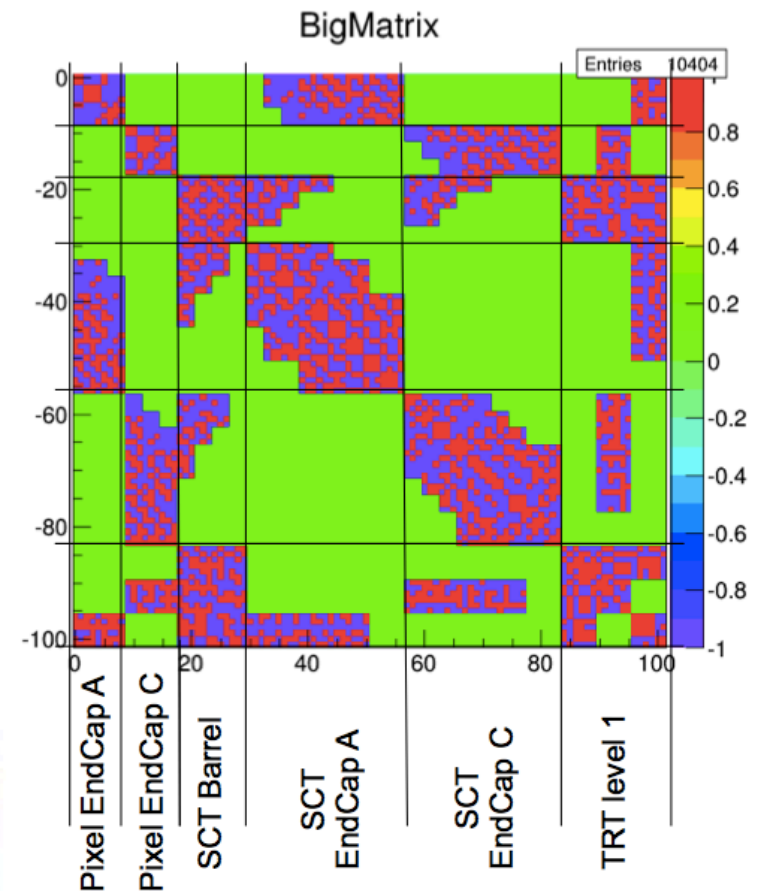
r is vector of residuals, that is a function of the track parameters, τ , and the alignment parameters, a .

V is the covariance matrix of the detector measurements.

There are two solving modes, global and local matrix:

The global matrix method introduces in the correlation matrix the correlation between all the detectors. More powerful, but it is also more difficult to invert and solve.

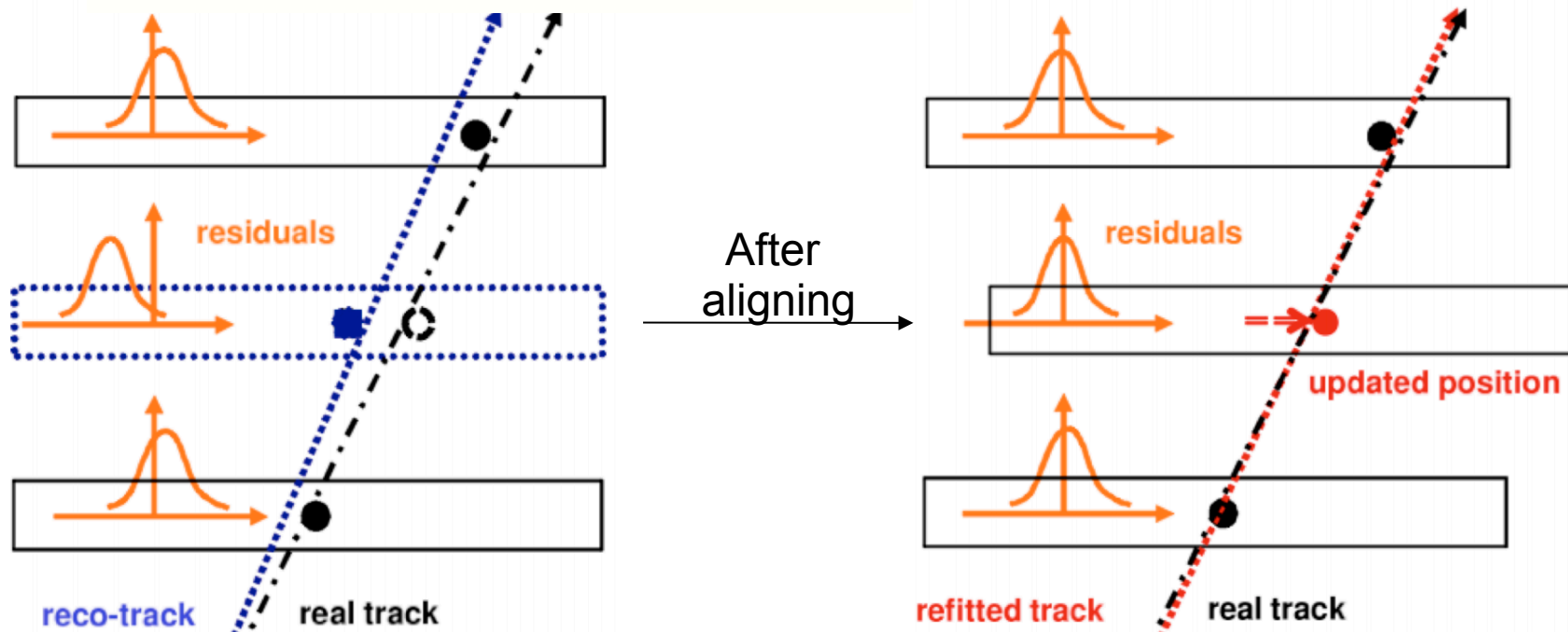
The local method treats each detector independently. Useful when there are many d.o.f. to solve.



Alignment Algorithm

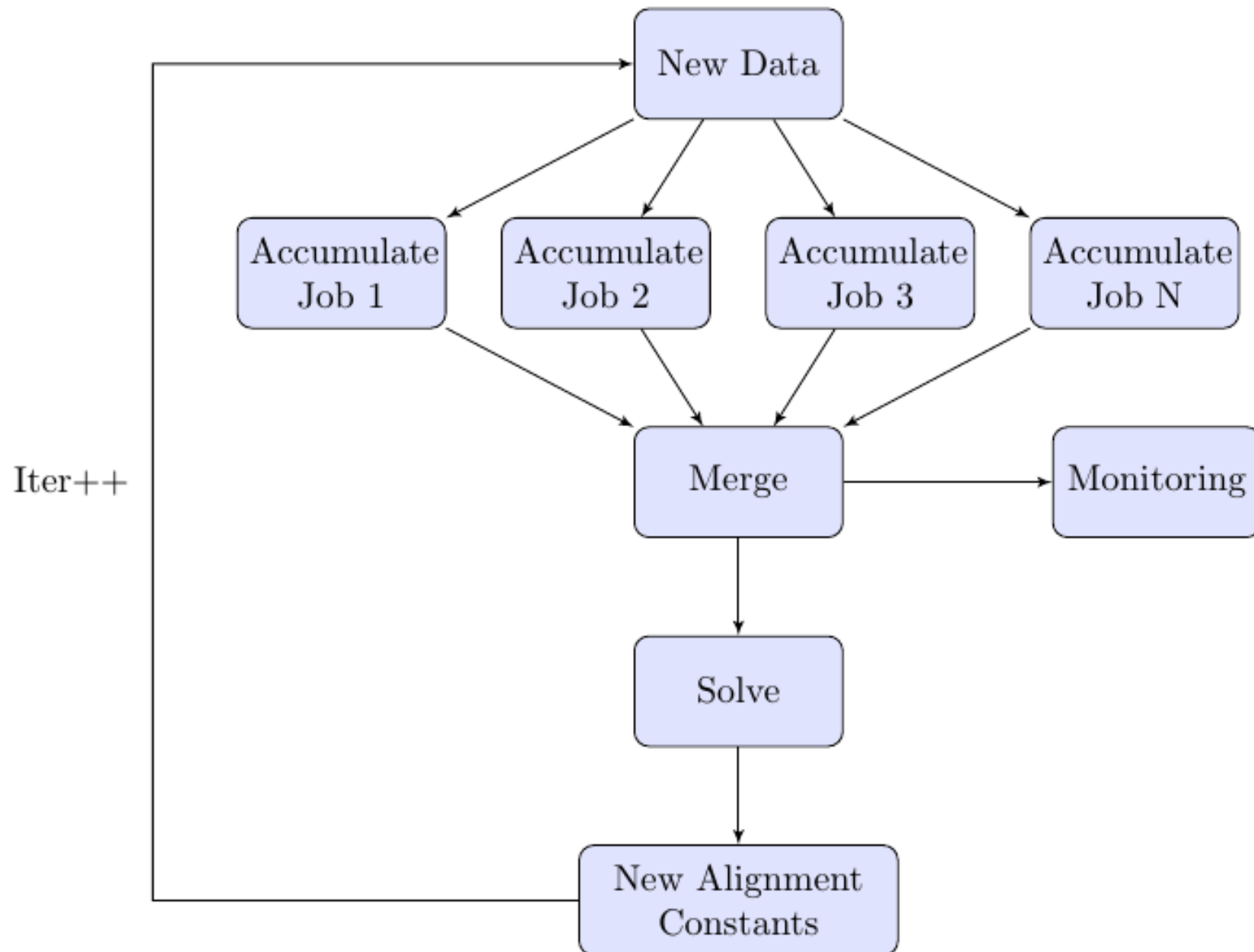
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$$\chi^2 = \sum_{tracks} [r(a, \tau)]^T V^{-1} [r(a, \tau)], \quad \frac{d\chi^2}{da} = 0$$



	Structures				DoF	
	IBL	Pixel	SCT	TRT	Silicon	TRT
Level 1/11	1	1	3	3	30	18
Level 2	-	12	22	96	204	576
Level 3	280	1744	4088	350848	36672	701696

Alignment procedure



Alignment Levels

Alignment is performed at different levels corresponding to mechanical detector structures, in a consecutive way, starting with large structures and ending at the module level.

Level 1 – Level 11:

The largest structures are aligned independently, as the SCT barrel or the whole pixel.

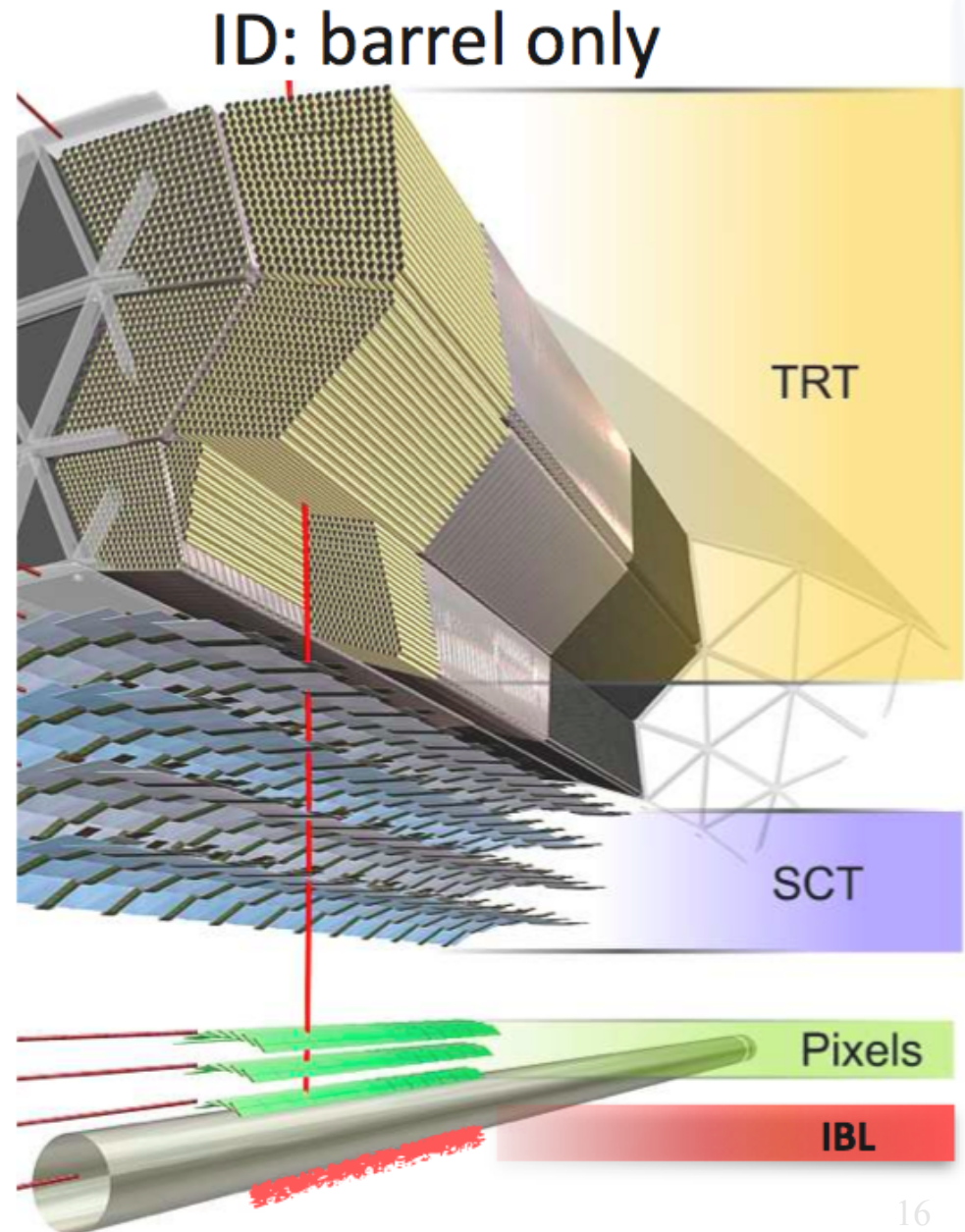
IBL has been added as a new structure separated from the old pixel as it is attached to the beam pipe.

Level 2:

Each of the previous structures is divided into smaller ones. Ex: Pixel is divided into barrel layers and EC disks.

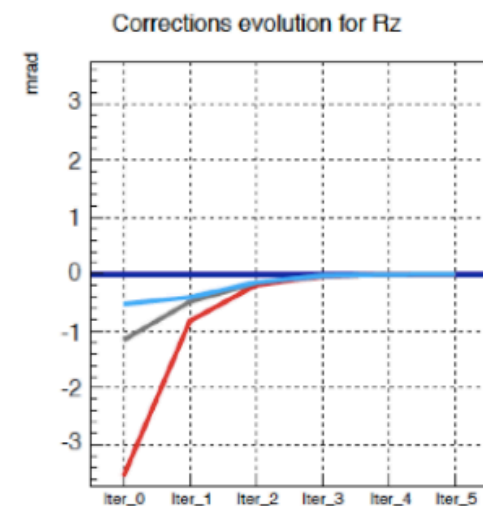
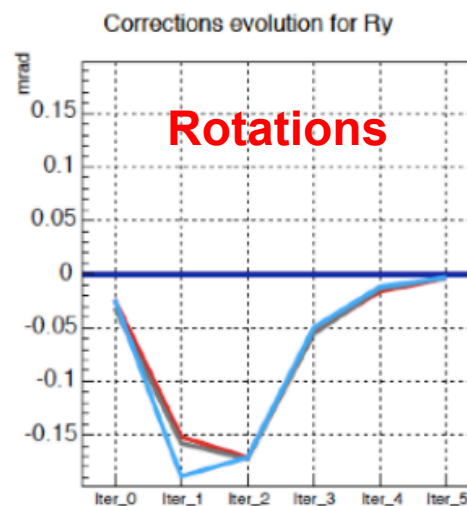
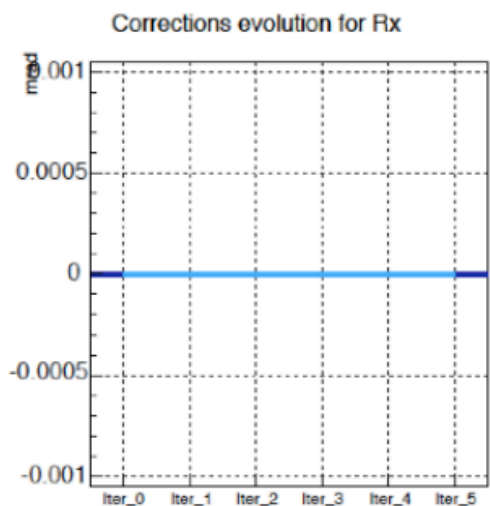
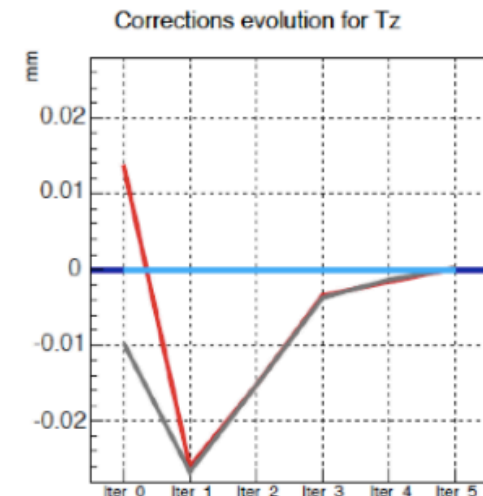
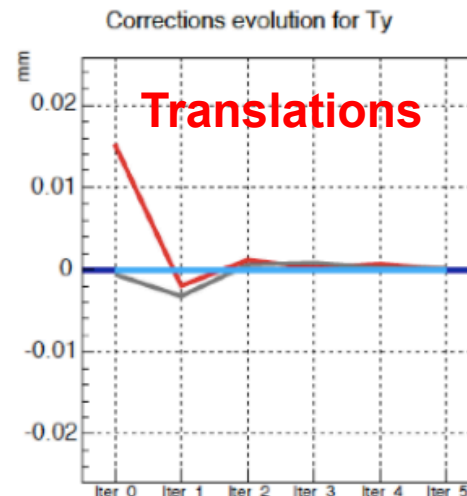
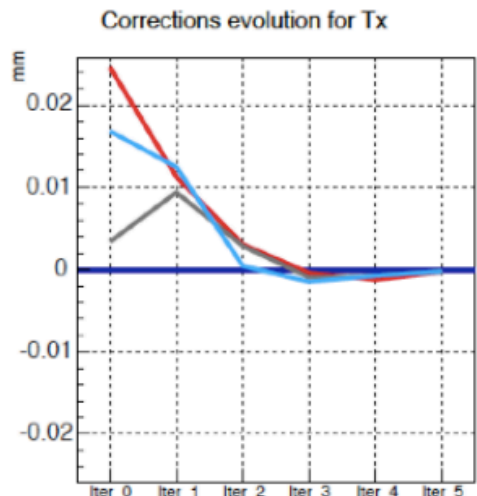
Level 3:

Each module or straw is aligned independently.



Alignment Iterations

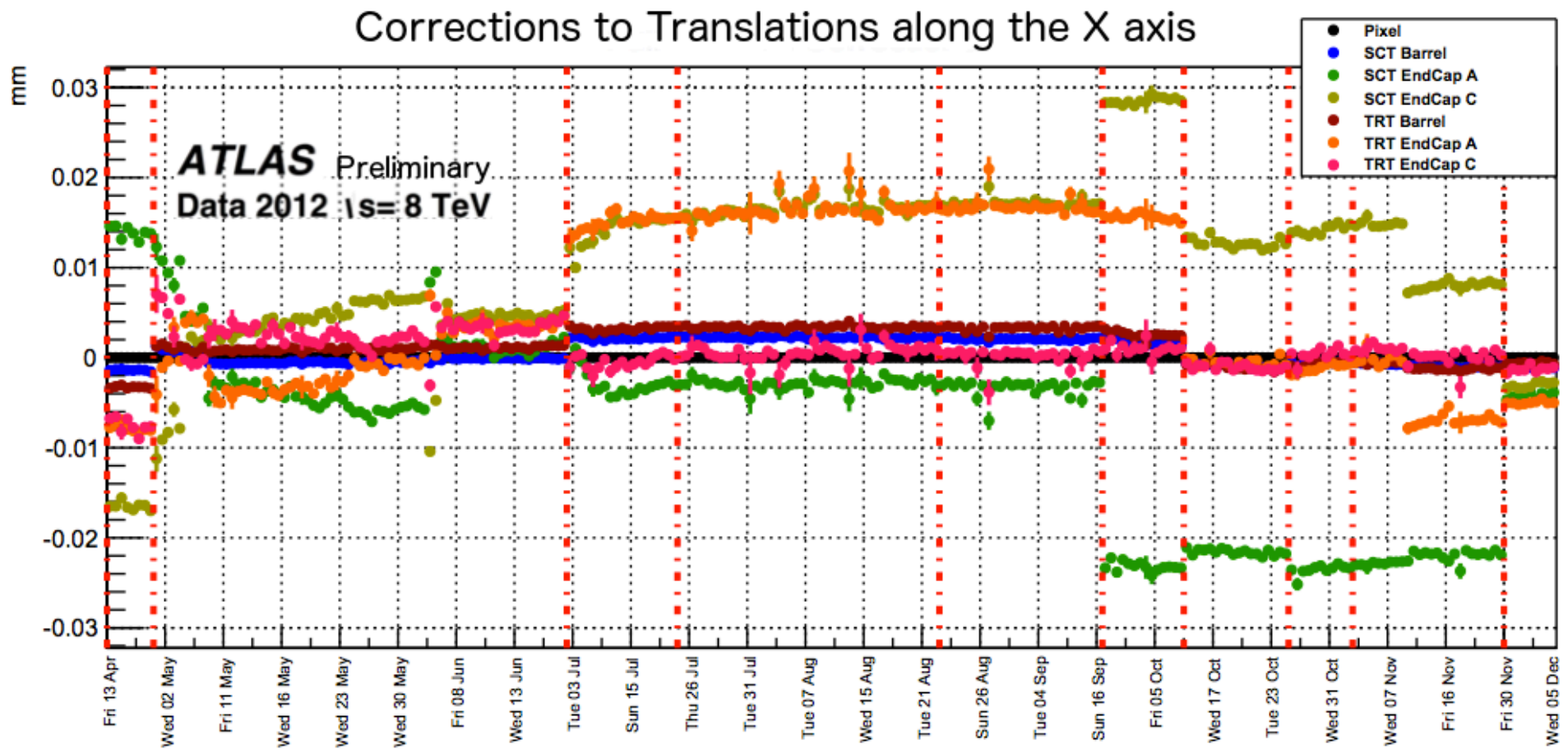
- Additionally to the separation into levels of alignment, the alignment is performed in an iterative way to ensure the convergence of the solution.
- This example correspond to an alignment of the IBL, pixel and SCT barrel at level 1.



IBL
PIX
SCT

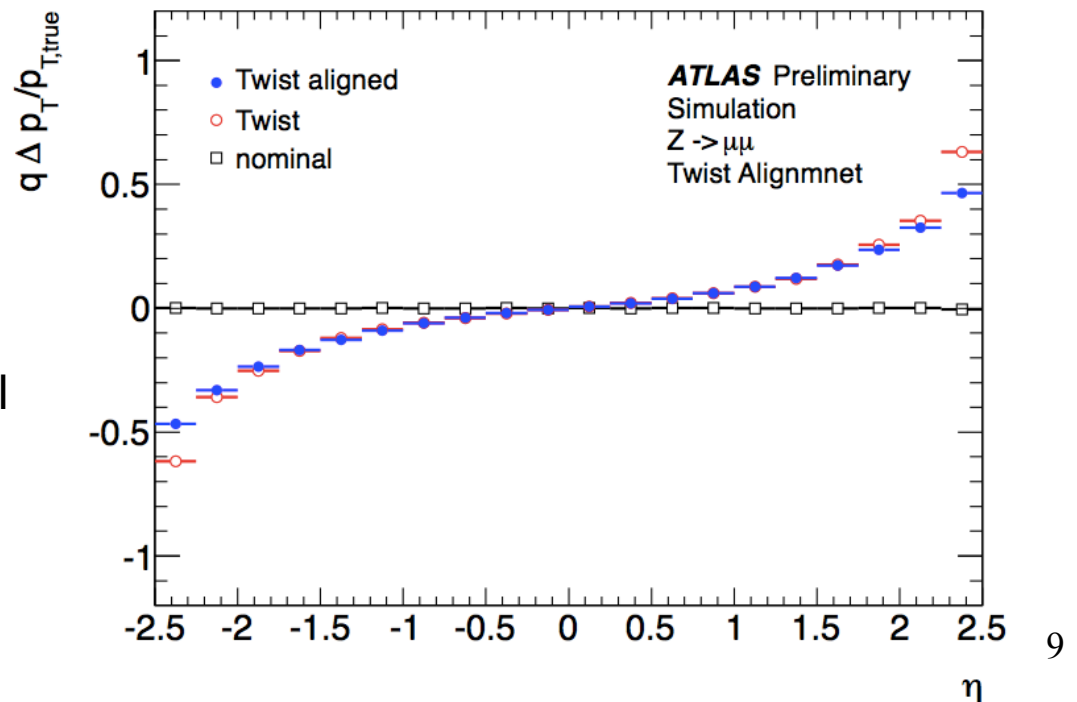
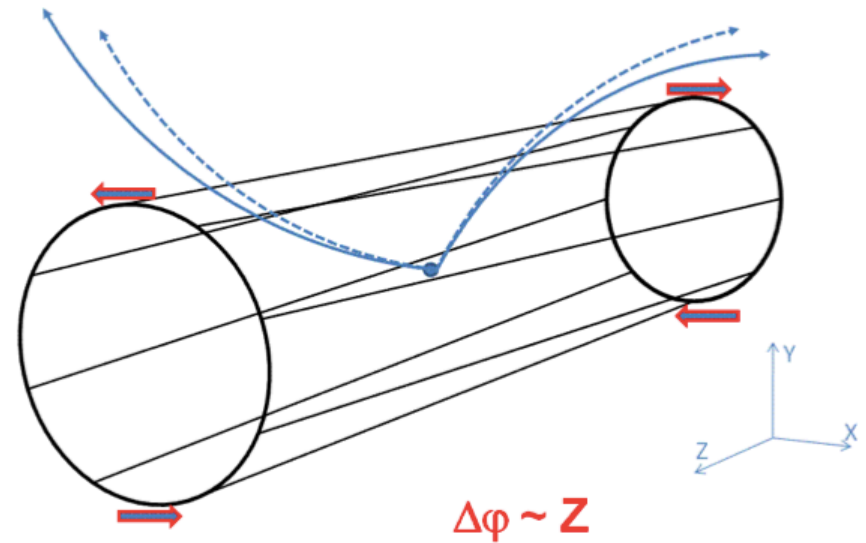
Performance during Run-I

- Alignment showed a good performance during the Run-I of the LHC.
- An automatic alignment of every new recorded run in ATLAS was implemented.
- Plot below shows the obtained Tx corrections for 2012 runs.



Weak Modes

- The residual based algorithm is not sensitive to some kind of deformations.
- It is based on the reconstruction of helical trajectories, so it can detect deformations that modify this shape.
- In the other hand, deformations that do not affect the helical shape of the tracks, can't be detected with this method. This kind of deformations are known as weak modes.
- Weak modes transform one helical trajectory into another helical trajectory, without (or minimally) affecting the quality of the track fit, and its associated χ^2 .
- This example shows how the residual based method is unable to correct a twist deformation introduced in a MC simulation.

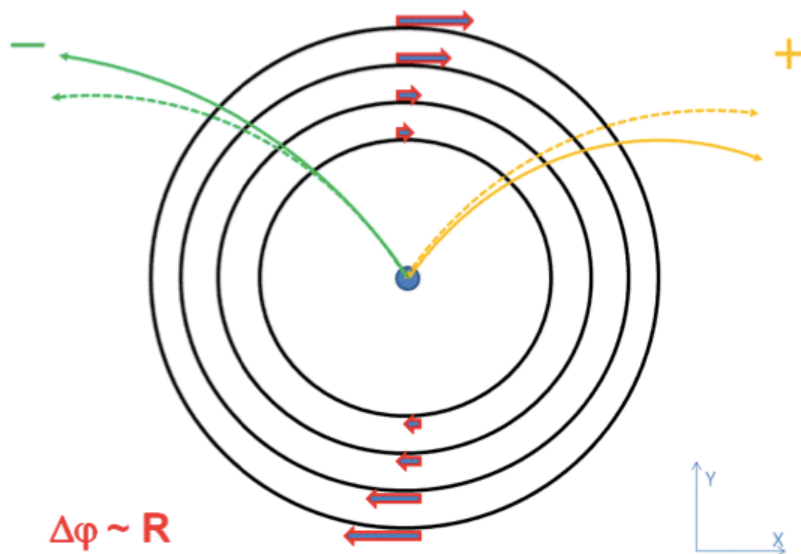


Weak Modes

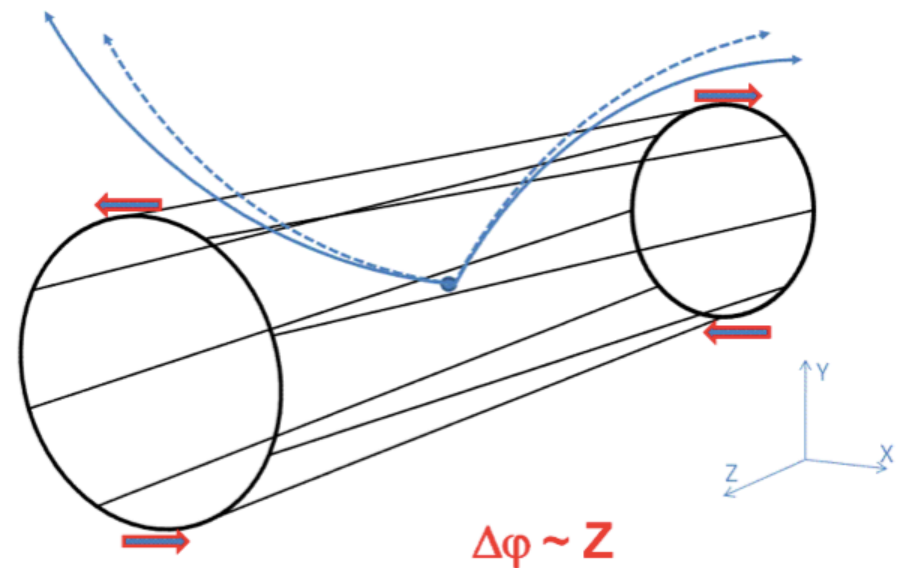
- The *weak mode* deformations cannot be identified just by studying the quality of individual track fits.
- In order to identify these deformations, one needs to rely on measurements which are universal and dependent on the reconstructed track parameters.
- An example of such an observable are the reconstructed invariant mass of a known particle.
- Neutral particles decaying into two particles of the same mass are a notably case widely used in the ATLAS ID alignment: $Z \rightarrow \mu^+ \mu^-$, $J/\psi \rightarrow \mu^+ \mu^-$, $K_S^0 \rightarrow \pi^+ \pi^- \dots$

Examples of weak modes biasing the reconstructed momentum

(a) *curl*



(b) *twist*



Weak Modes detection with neutral boson decays

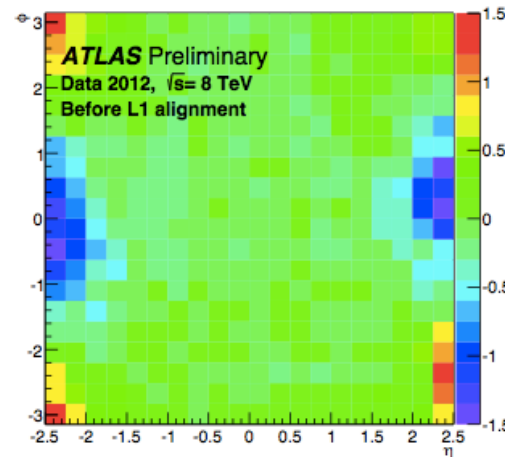
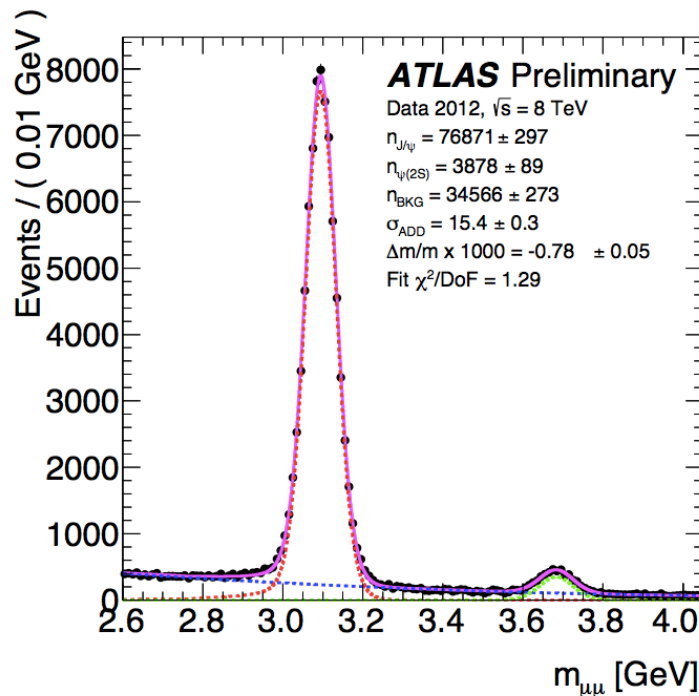
- The momentum of the particles is obtained by measuring the curvature of the tracks.
- If the curvature is biased by a weak mode, the momentum is badly measured.
- The reconstructed mass of the parent particles would be also biased.

$$q/p_T \longrightarrow q/p_T + \delta_{\text{sagitta}}$$

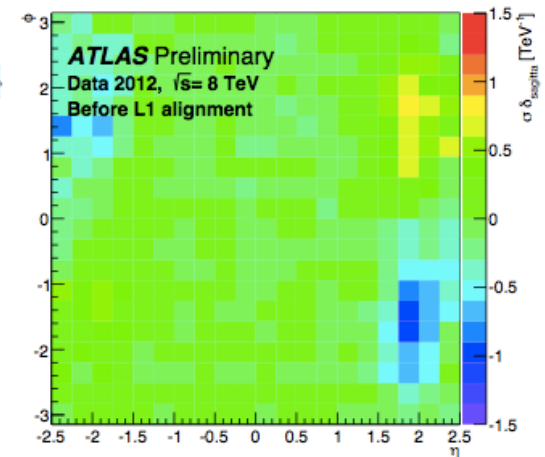
$$p_T \longrightarrow p_T(1 + qp_T \delta_{\text{sagitta}})^{-1}$$

$$p \longrightarrow p(1 + qp_T \delta_{\text{sagitta}})^{-1}$$

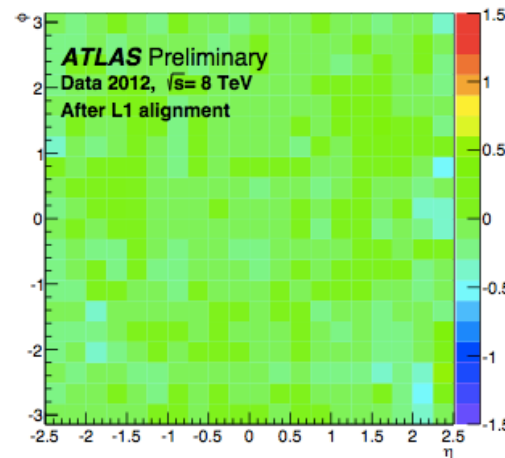
$$M \sim (\delta_{\text{sagitta}})^2$$



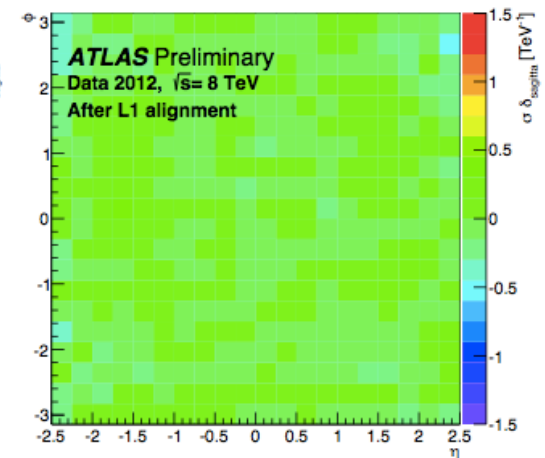
(a) Period A before end-cap alignment



(b) Period H before end-cap alignment



(c) Period A after end-cap alignment



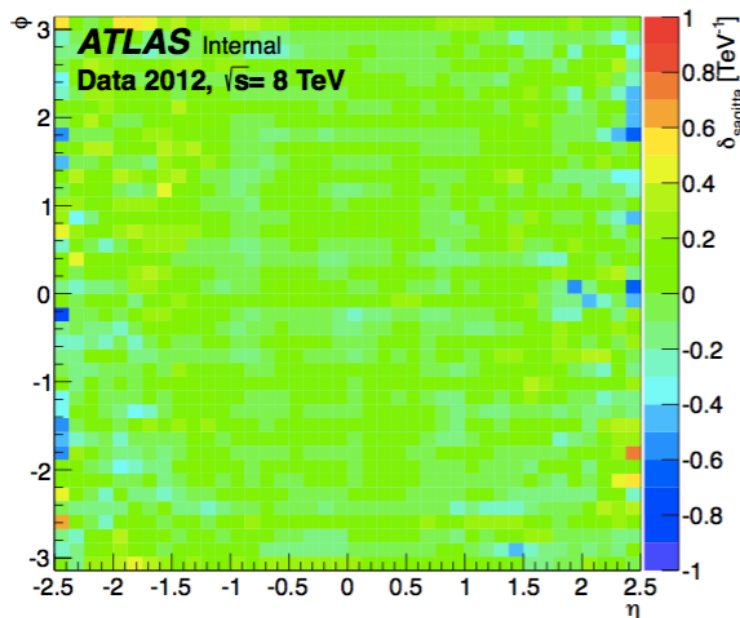
(d) Period H after end-cap alignment

Weak Modes detection with calorimeter information

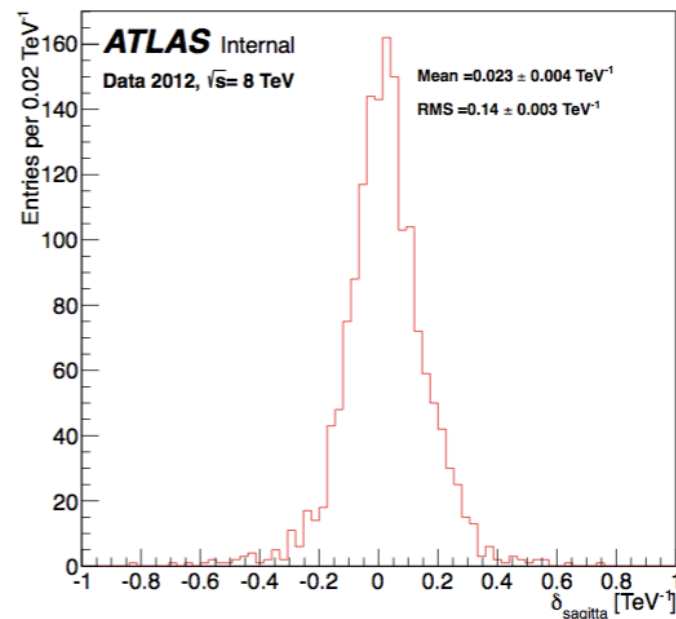
- A calorimeter is a detector that measures the energy of a particle.
- Knowing the mass of a particle, the measure of a particle energy is equivalent to the measure of its momentum.
- A technique that has been used for the removal of weak modes in the ATLAS ID is to compare the information of the calorimeters with the measure of the inner detector.
- W decaying into an electron plus a neutrino events has been widely used, measuring the ratio of the energy (calorimeter) and the momentum (ID), which should be equal to 1 in a well aligned detector.

$$p \longrightarrow p(1 + qp_T \delta_{\text{sagitta}})^{-1}$$

$$E/p \sim \delta_{\text{sagitta}}$$



(a) 2D map

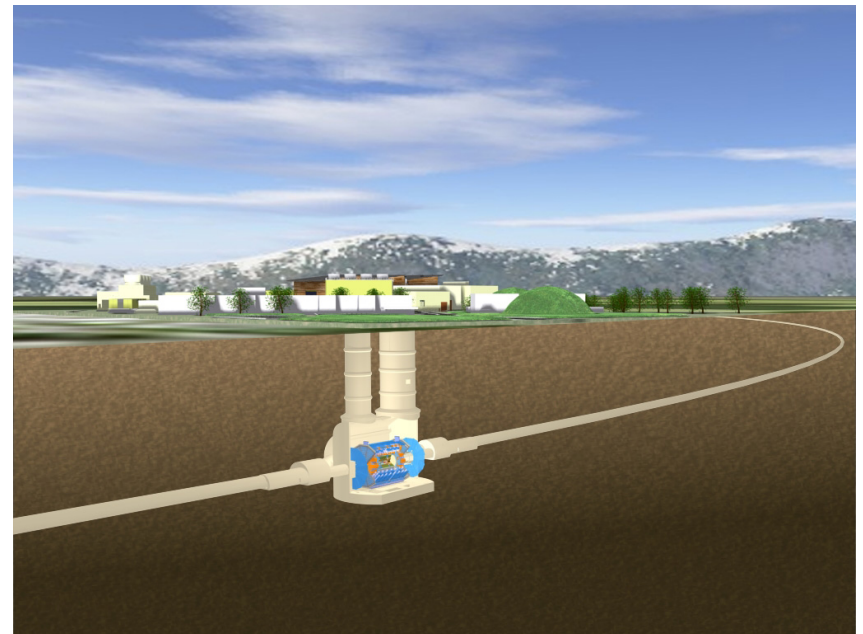
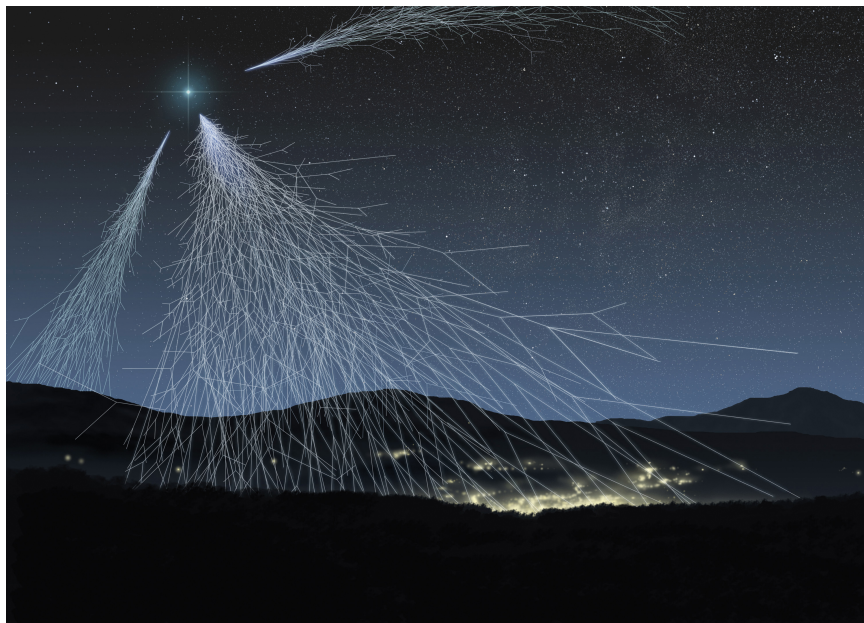


(b) 1D projection

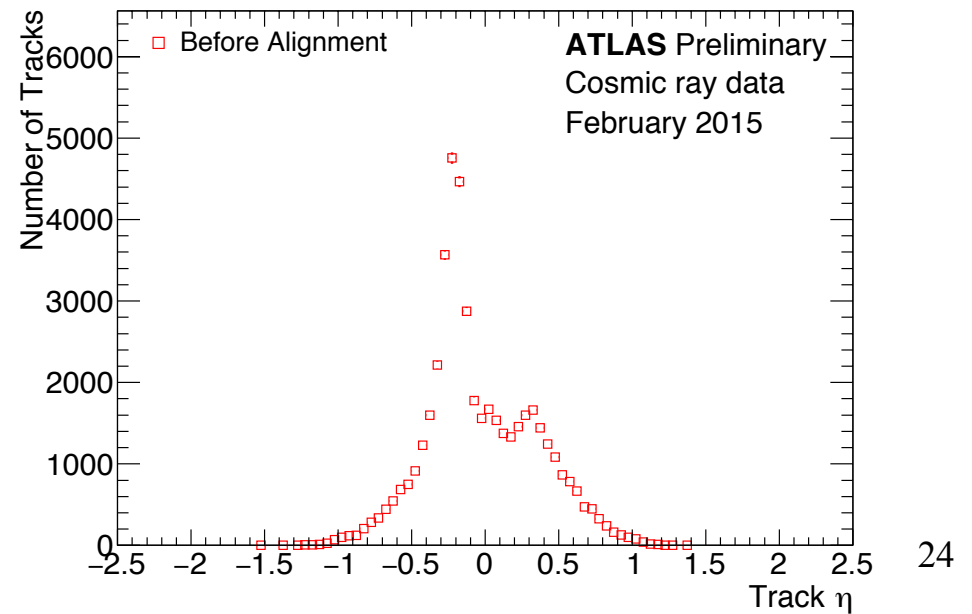
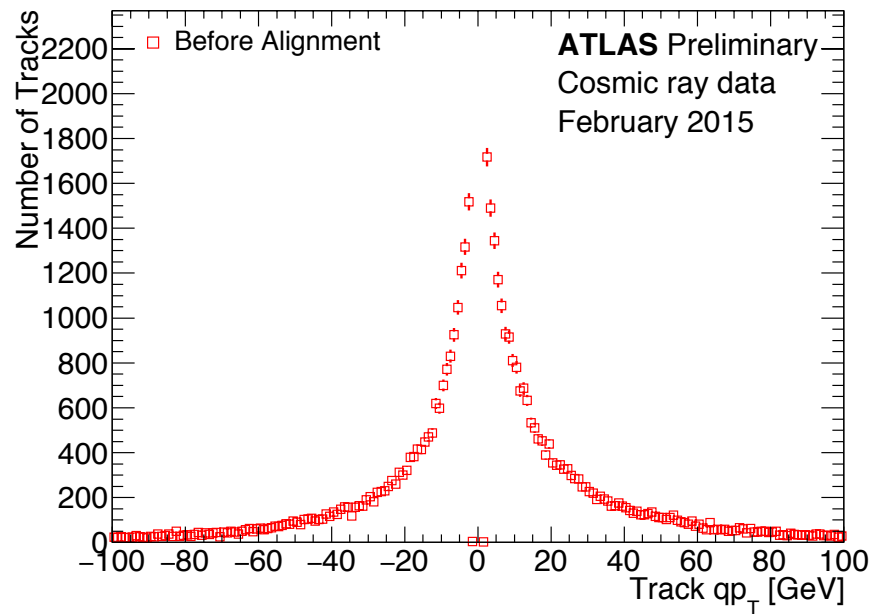
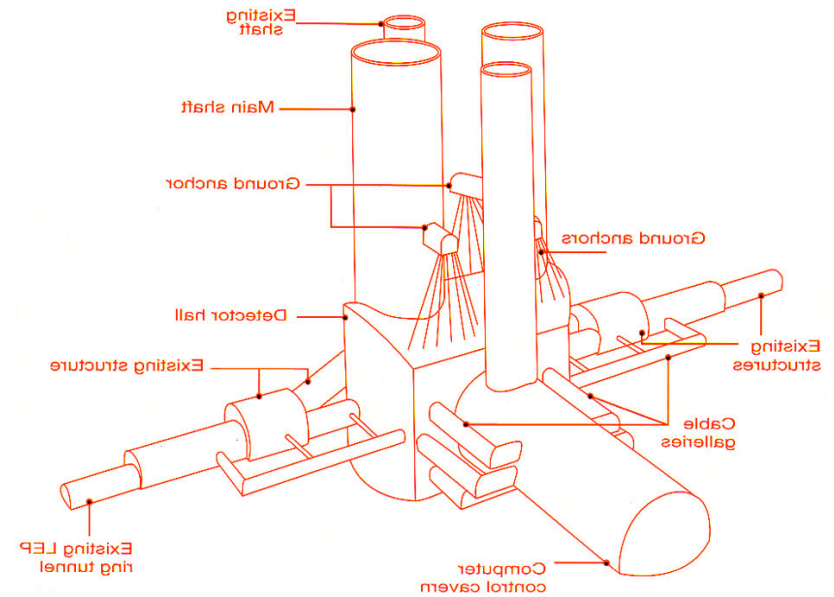
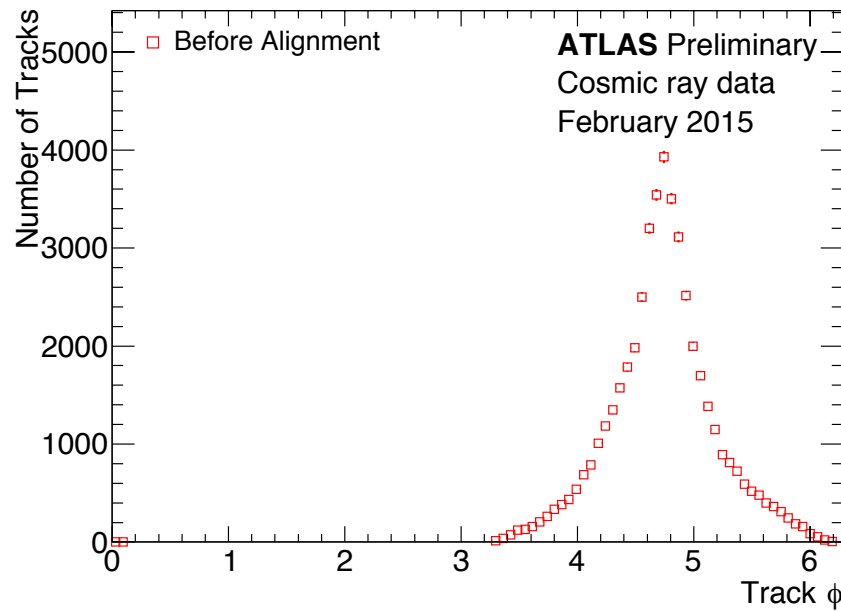
LHC Run-II preparation

- Between the Run-I and the future Run-II of the LHC a long technical stop, known as the Long Shutdown 1 (LS1), took place.
- During the LS1 several maintenance works were performed in the Inner Detector (ID) and new detectors as the IBL or the DBM were installed.
- The alignment framework has been upgraded to cope with these new features.

Cosmic rays are a natural source of radiation that provides lots of muons (perfect for alignment). Even when ATLAS is 100 m below ground, lots of muons reach the detector. Cosmic ray data has been used to perform a first alignment of the ATLAS ID.



Cosmic rays



Status of the Detector after LS1

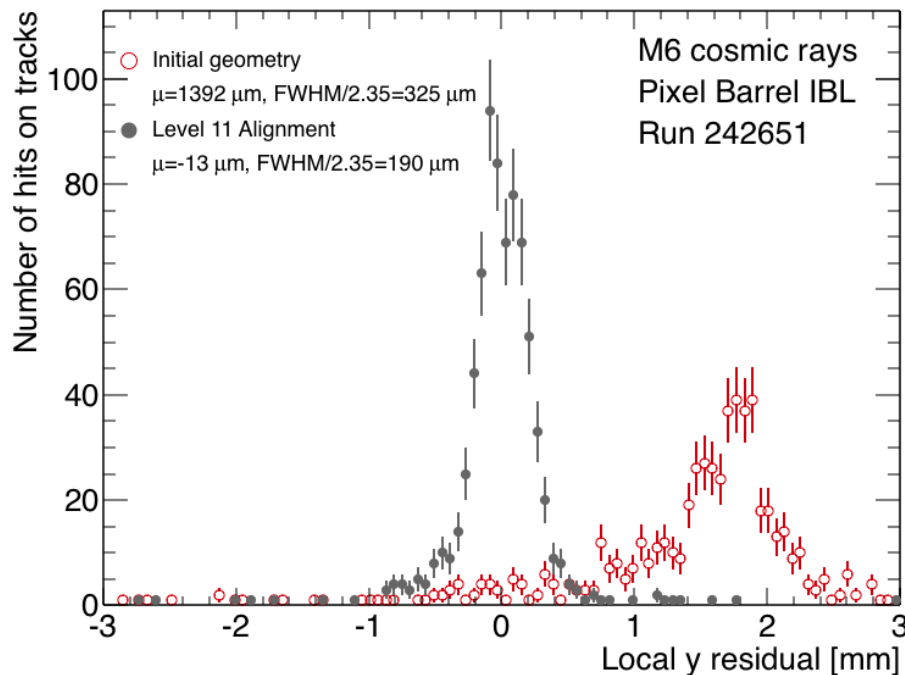
During the Long Shutdown 1, several maintenance jobs have been done. Also new detectors were added. The expectations for the initial misalignments for each sub-detector were:

- **SCT & TRT** : The barrel have not been moved during LS1. Same positions than during Run I were assumed for them. EC were removed to access to the inner parts of the detector.
- **Pixel**: It was removed and put back in place during LS1. From the survey, the expectation was that it would be back to same position with a precision of 100 μm .
- **IBL**: It has been installed during LS1. No previous experience from Run I. Initial position was totally unknown.



Results of the alignment with cosmics

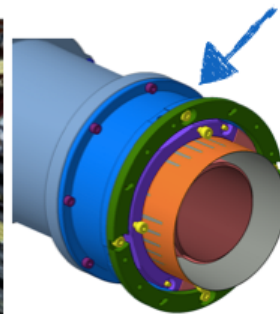
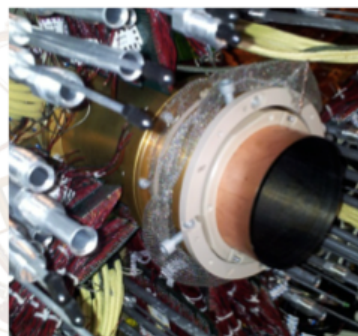
With the alignment of the first data collected in the cosmic campaigns, it was found that the new IBL was shifted by 2 mm in the beam line direction from its nominal position.



It was found that the origin of this shift was that a piece had been built 2 mm wider than in the model.

2 mm is a huge shift for a detector with an intrinsic resolution of $8 \mu\text{m}$.

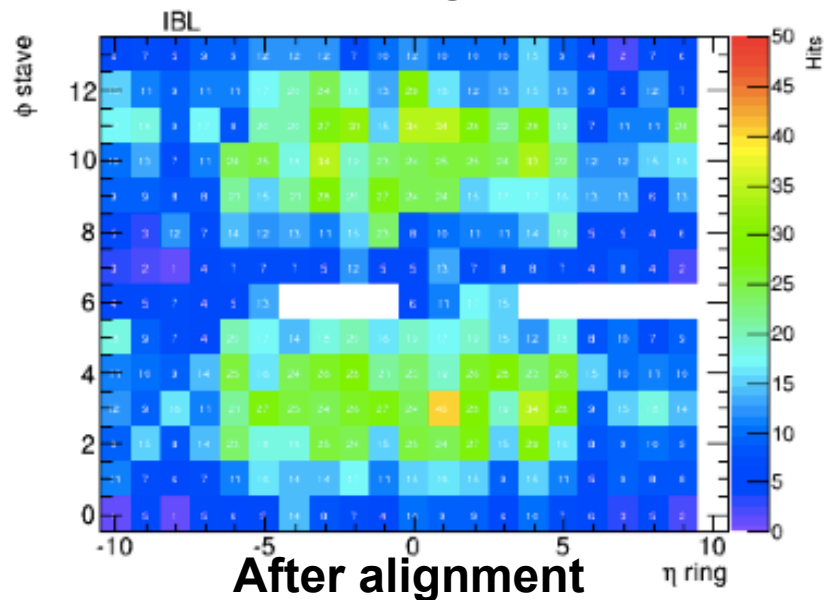
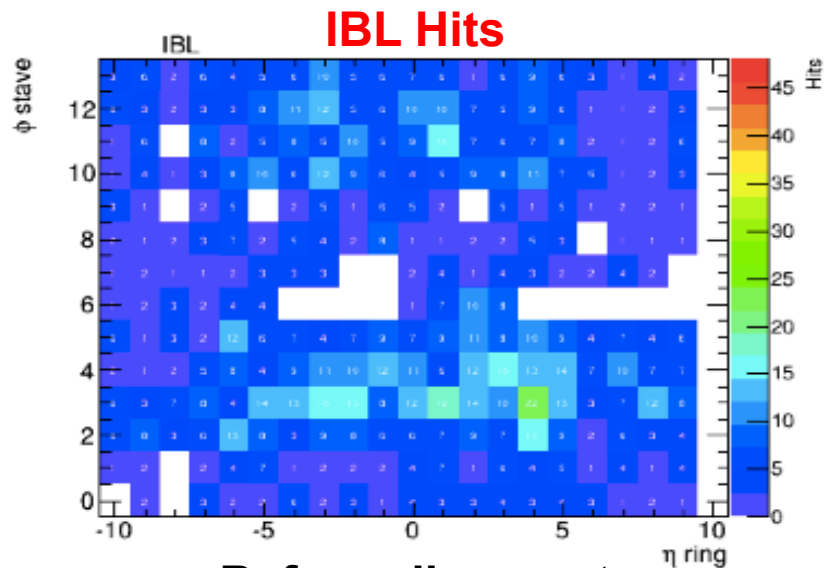
This was causing that no IBL hits were being added to the tracks.



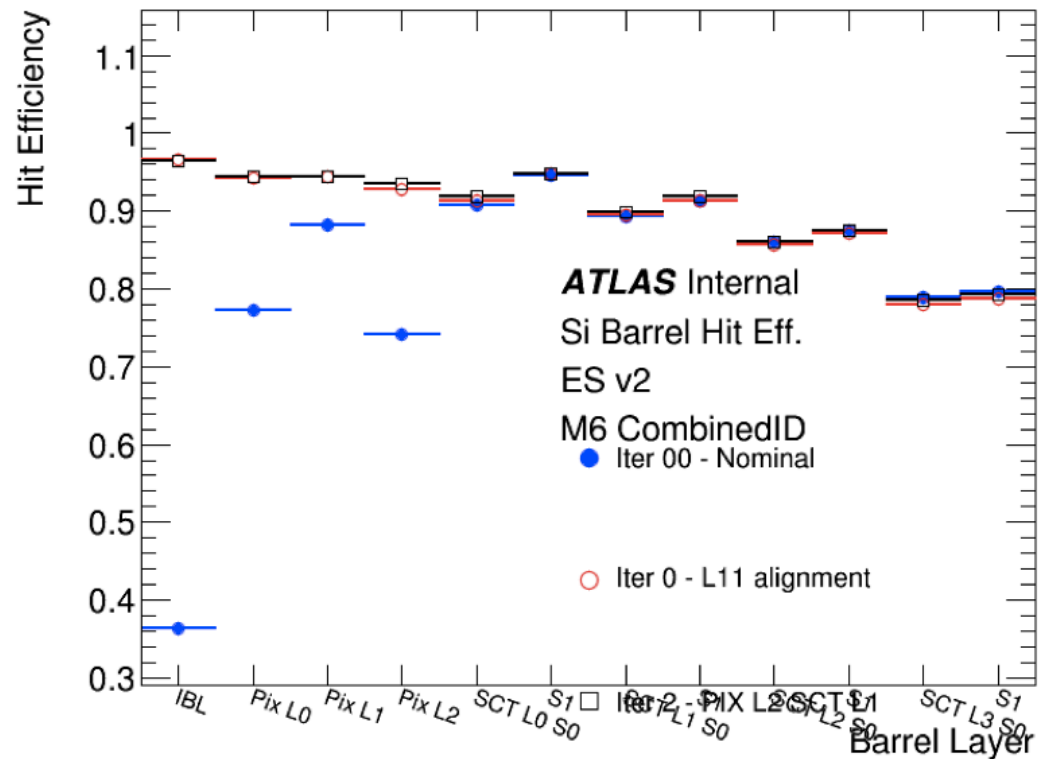
48 vs. 50 mm

After discussions with mechanical experts, **closing flange of sealing cone** identified as suspicious

Results of the alignment with cosmics

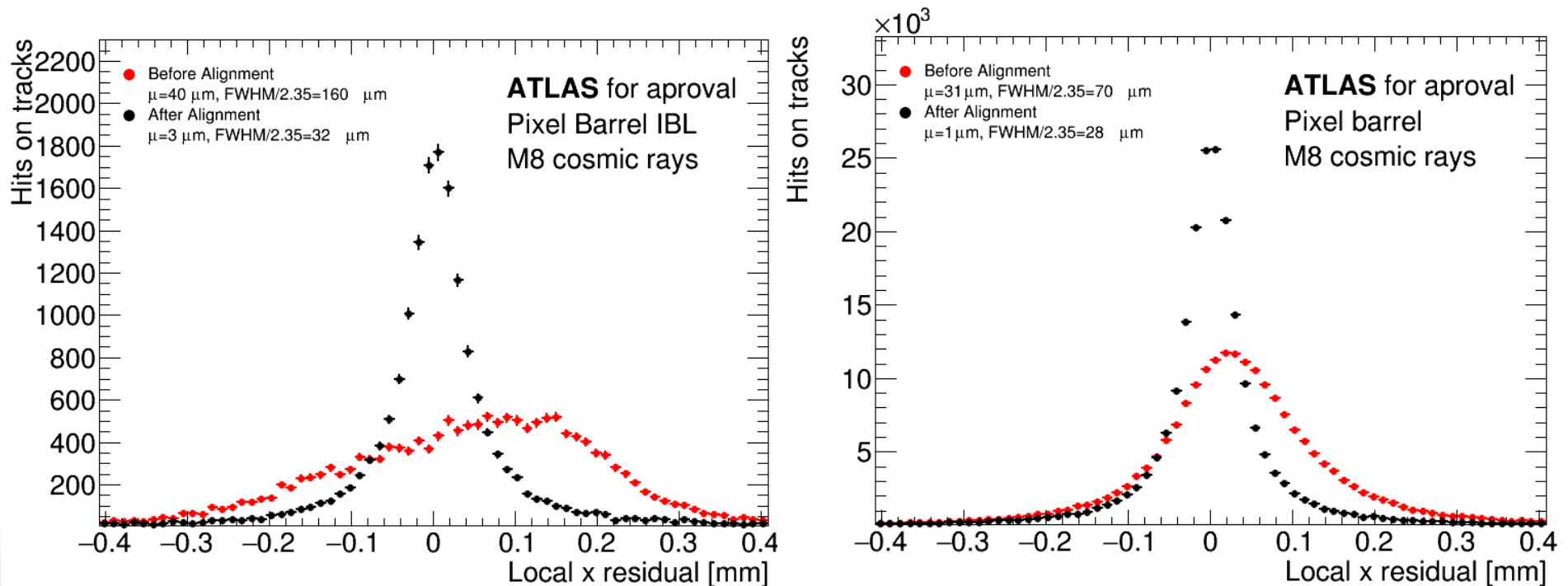


With the first alignment, a huge improvement of efficiency of the IBL and the rest of the ID was gotten.



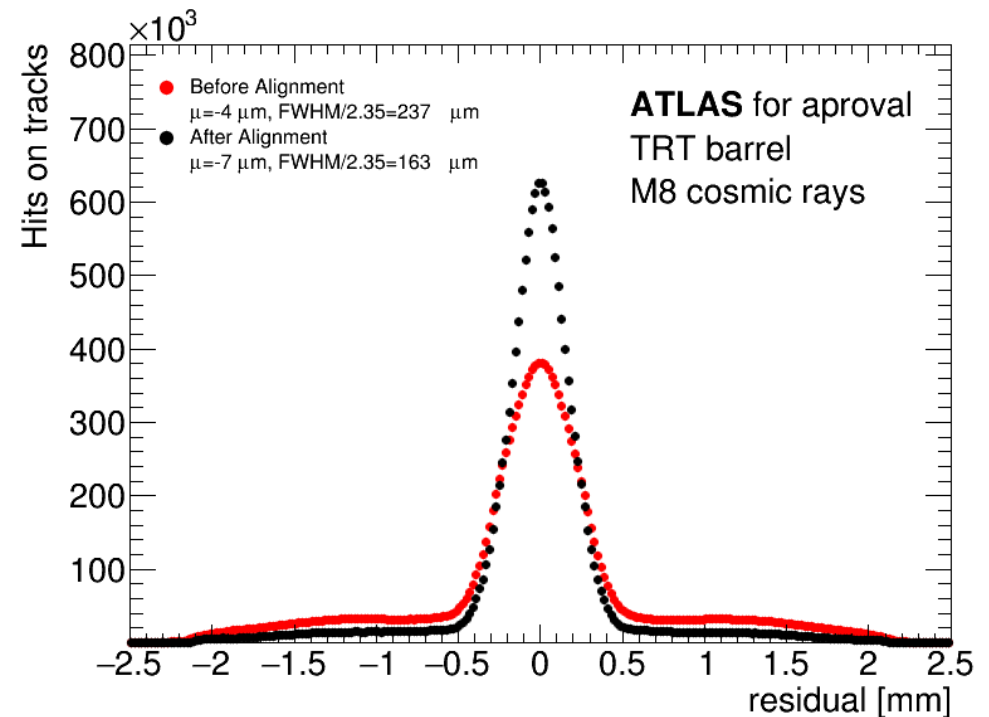
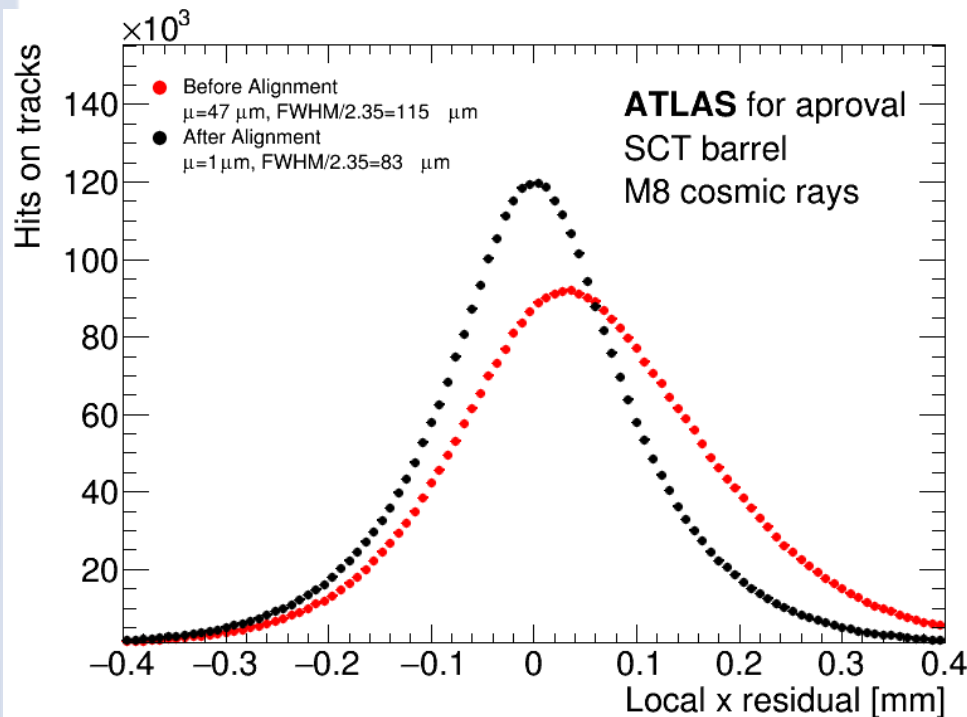
Results of the alignment with cosmics

When enough data were collected, a more detailed alignment of the full ID was performed, reaching up to module level alignment for the pixel and the IBL.



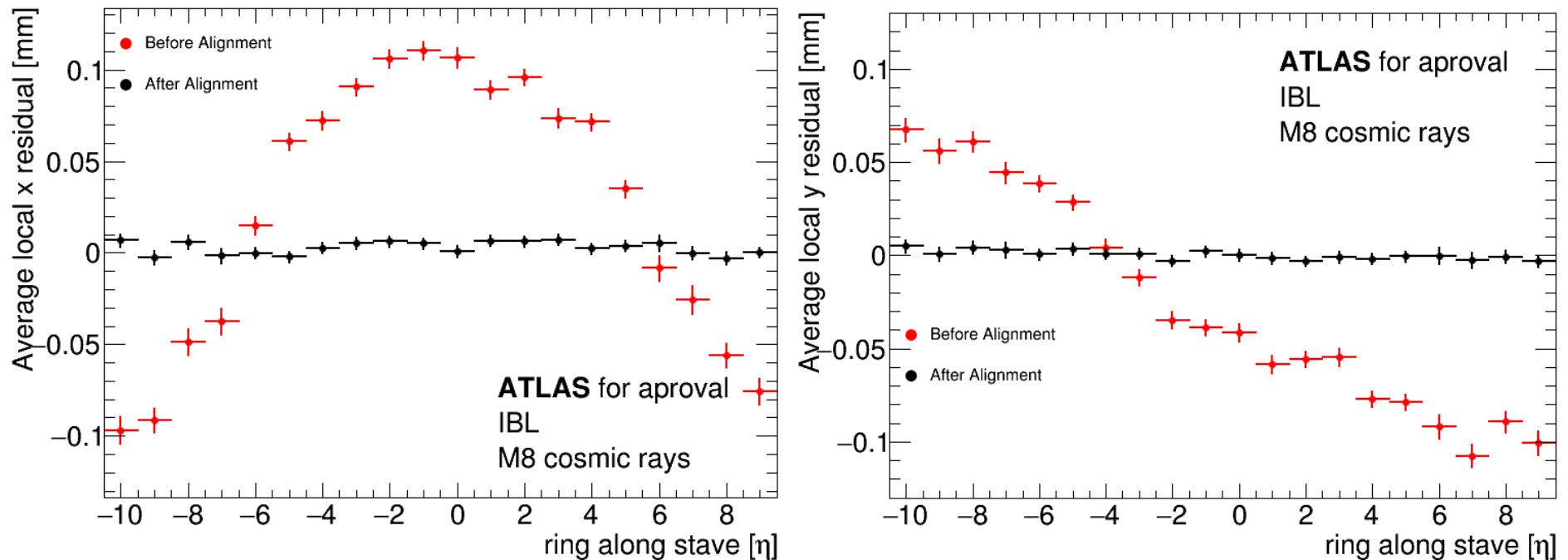
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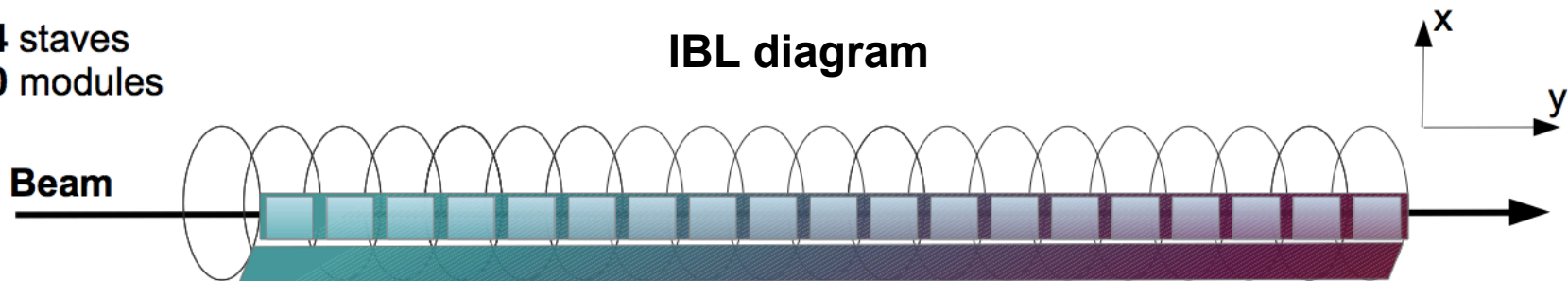
Results of the alignment with cosmics

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14 staves
20 modules

IBL diagram



Results of the alignment with cosmics

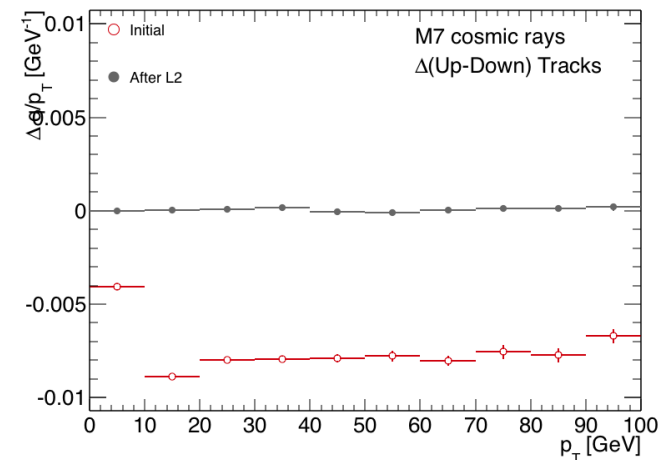
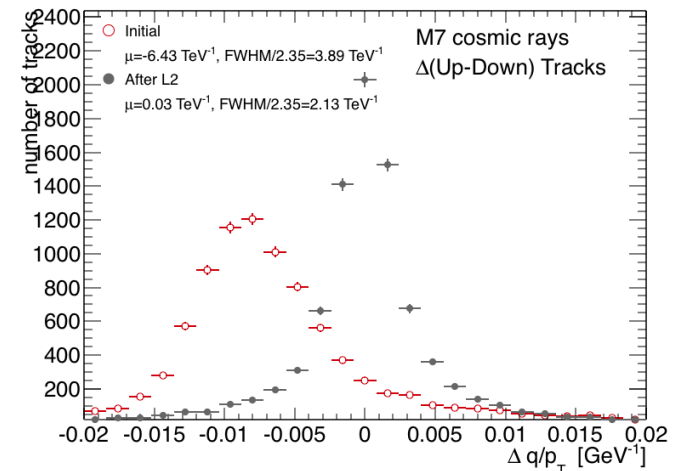
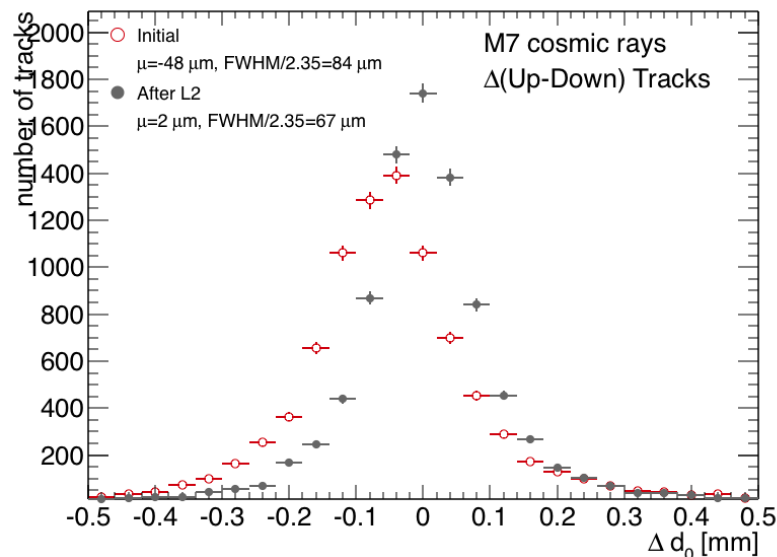
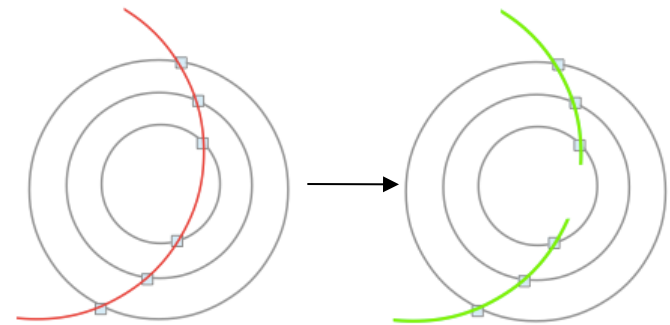
Track segment method:

This technique divide the cosmic track that traverses the whole detector into two half-tracks.

Each half is reconstructed independently and their parameters are compared.

This plots show the difference between up-down track parameters.

Used to test the goodness of the alignment.



Conclusions

- ATLAS is one of the detectors placed at the LHC.
- ATLAS relies on the Inner Detector for the tracking of produced particles.
- Without a proper alignment is not possible to fully exploit the excellent resolution the Inner Detector
- The alignment is a major task as it affects the quality of all data recorded in ATLAS, which is used for analysis.
- Apart from correcting deformations with the developed alignment algorithm, weak modes have to be detected and corrected.
- During the long shutdown 1 after the Run-I, the Inner Detector has been upgraded for facing the Run-II requirements.
- From the alignment team, a big work has been done during the cosmic ray data campaigns to prepare the detector for the upcoming collisions.

Thanks for your attention