Alignment of the ATLAS Inner Detector

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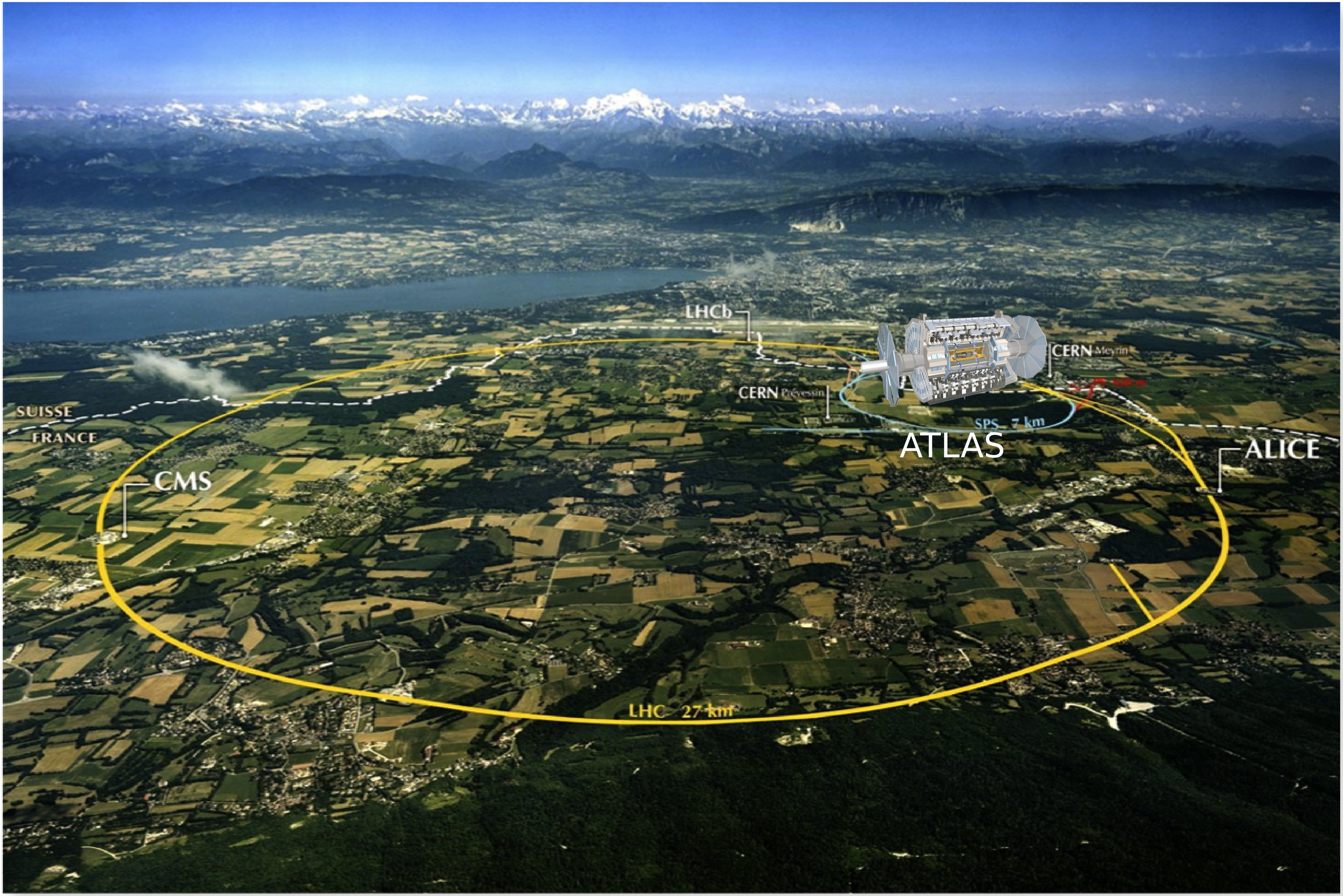
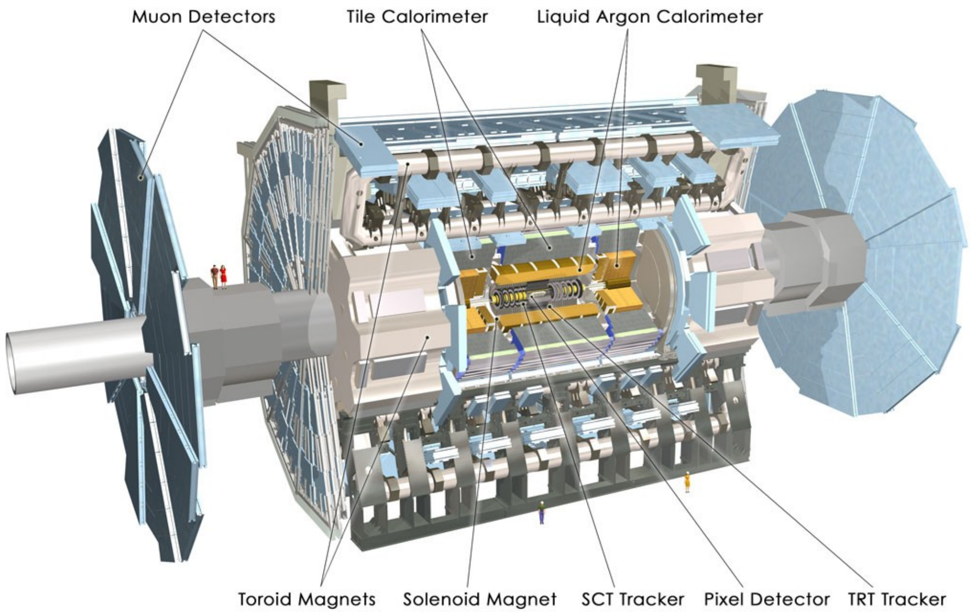
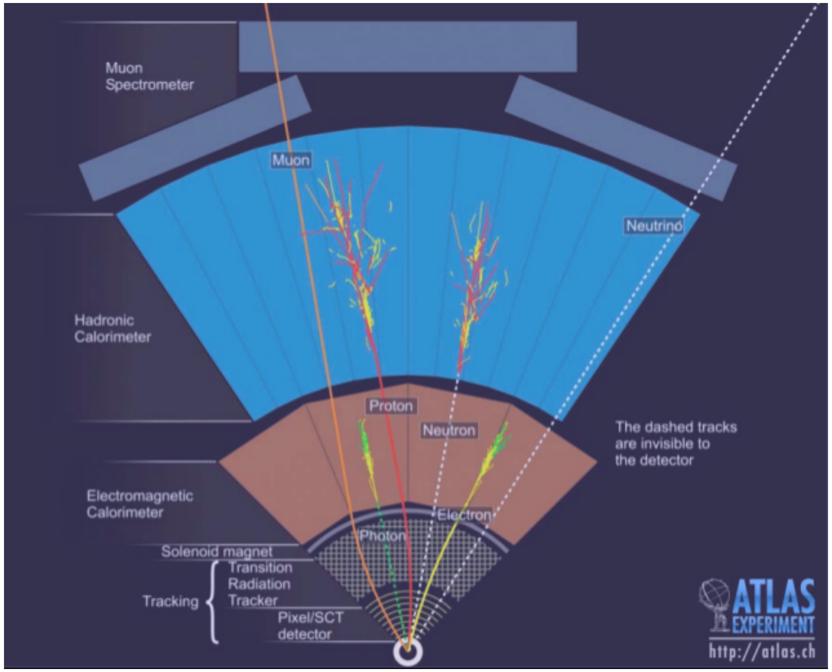
- ATLAS: the detector.
- Alignment of the Inner Detector.
- Weak modes.
    - Weak modes using J/Psi resonance.
- Summary.

ATLAS: the detector.



ATLAS: the detector.

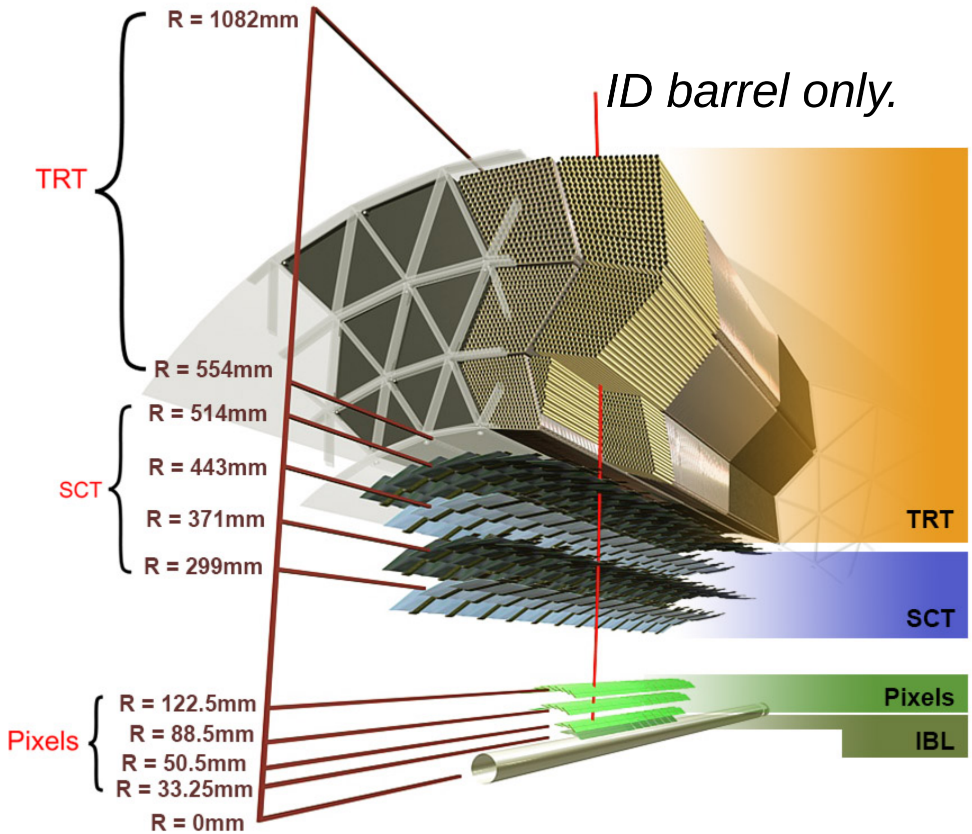




- ATLAS is a general-purpose detector equipped with different subsystems (e.g. tracking systems, calorimeters, muon spectrometer).
- Goal is to detect all kind of particles produced in the proton beam collisions.

ATLAS: the detector.

- The tracking system of ATLAS is located in the Inner Detector (ID).
- ID mission: reconstruct the trajectory of the charged particles and to estimate their kinematic parameters.
- 3 different subsystems embedded in 2 T axial magnetic field:
  - **Pixel**: silicon pixel sensors.
    - **IBL** (Insertable B-layer): new innermost pixel layer for Run 2.
  - **SCT** (Semiconductor tracker): silicon micro-strips sensors.
  - **TRT** (Transition radiation tracker): gaseous drift tubes.
- Each subsystem consists of **a barrel** with cilyndrical layers and **two end-caps** of silicon sensors disks.

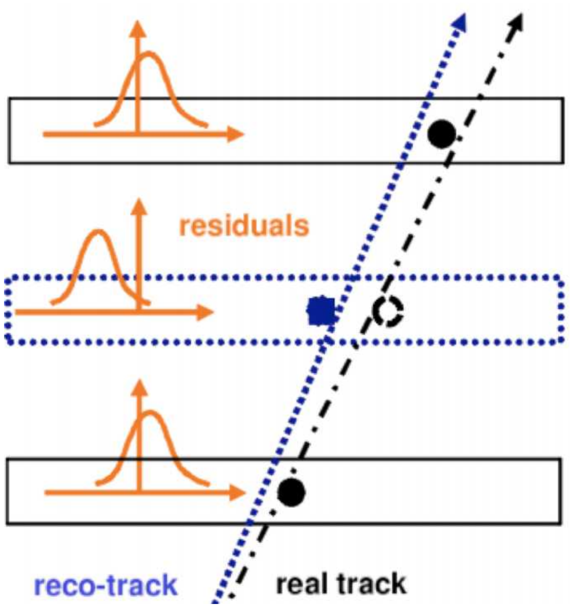


Subdetector	Element size (ηm)	Intrinsic resolution (ηm)	Number of modules
Pixel	50x400	10x115	1744
IBL	50x250	8x40	280
SCT	80	17	4088
TRT	4000	130	176

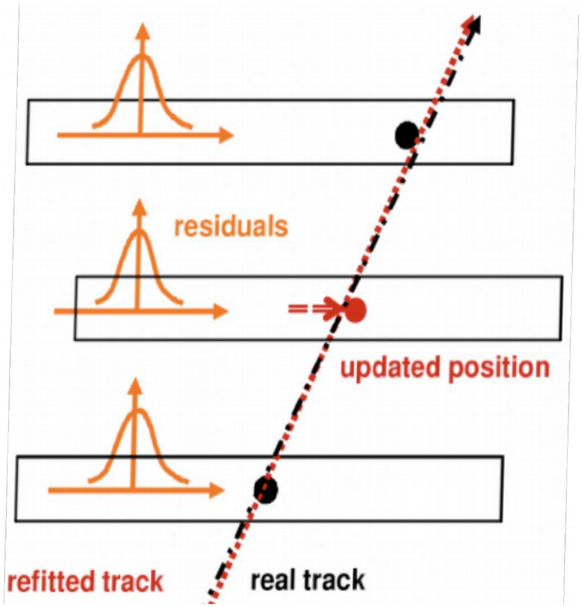
Alignment of the Inner Detector.

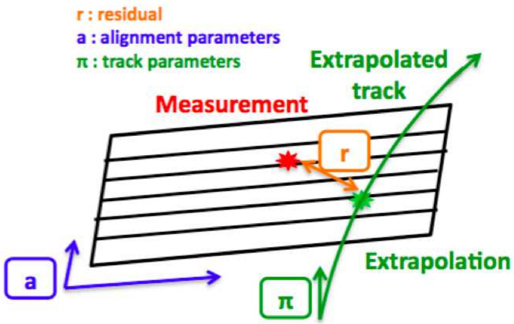
- Nominal position of the active detector modules is not the real position.
- These misalignments as well as geometrical distorsions → degradation of the reconstructed tracks resolution → affect the physics performance studies.
- Goal of alignment: determine the alignment parameters that correct the assumed positions of all active detector elements.

Before alignment



After alignment





- The technique to align is a track-based algorithm.
- The alignment is performed by minimizing a χ^2 function, which accounts for the residuals of every module.

RESIDUALS:

$$\vec{r} = \vec{m} - \vec{e}(\pi, \mathbf{a})$$

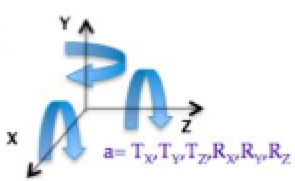
X² DEFINITION:

$$\chi^2 = \sum_{hits} \left(\frac{\vec{r}_h(\pi, \mathbf{a})}{\sigma_h} \right)^2 = \vec{r}(\pi, \mathbf{a})^T \, V^{-1} \, \vec{r}(\pi, \mathbf{a})$$

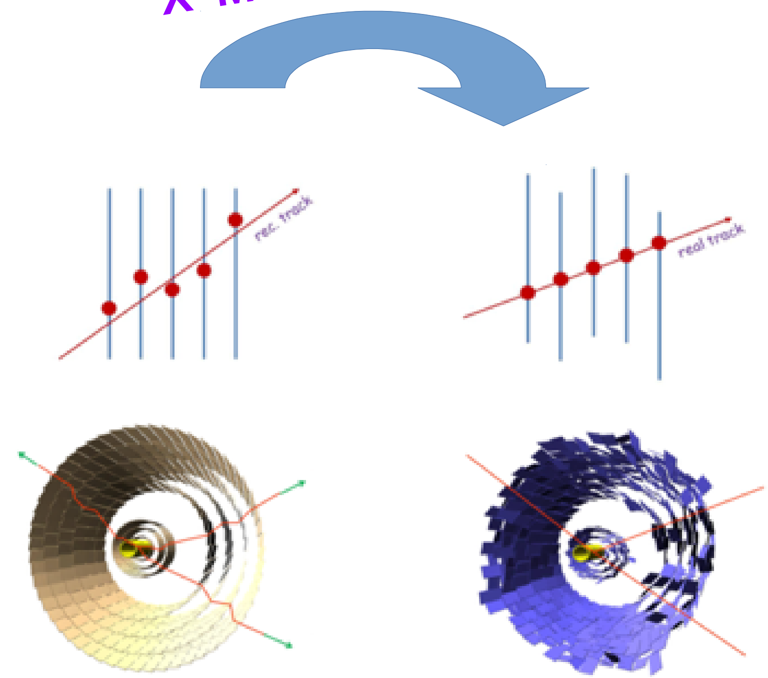
$$\chi^2_{tot} = \sum_{tracks} \chi^2_t$$

X² MINIMIZATION:

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



X² MINIMIZATION:



Assumed geometry.

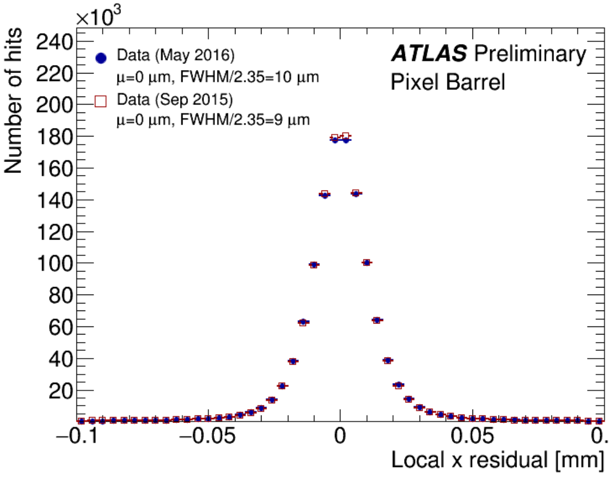
Real geometry.

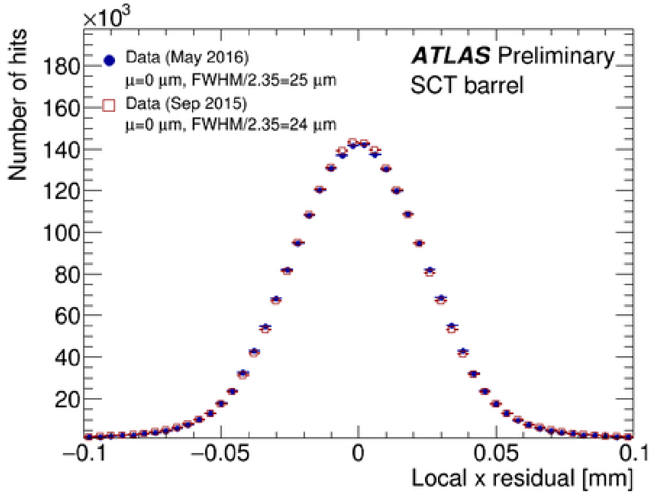
Alignment is done in hierarchial levels, starting with large structures and finishing at modules levels.

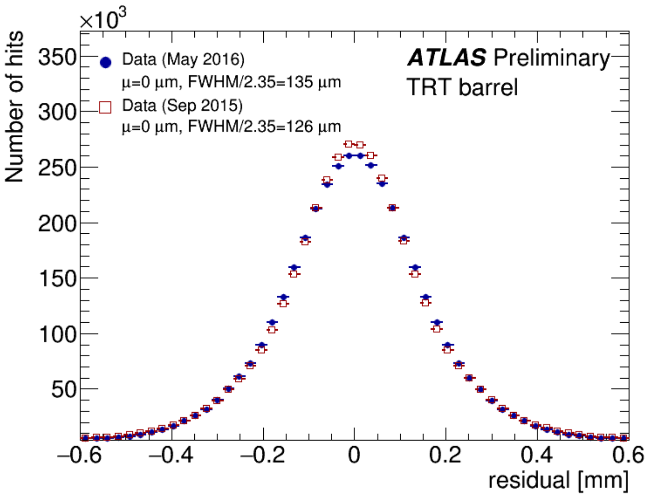
- **Level 1:**
  - The largest structures are aligned independently, such as SCT barrel, end-caps or the whole pixel.
- **Level 2:**
  - Previous structures are divided into smaller structures . For example, pixel is divided into barrel layers and end-cap disks.
- **Level 3:**
  - Each module (or straw of the TRT) is aligned individually.

Level		Structures	d.o.f
L1	Large structures	8	47
L2	Si layers and disks, TRT modules and wheels.	208	792
L3	Si modules	6112	36672
L3	TRT wires	350848	701696

Alignment of the Inner Detector.



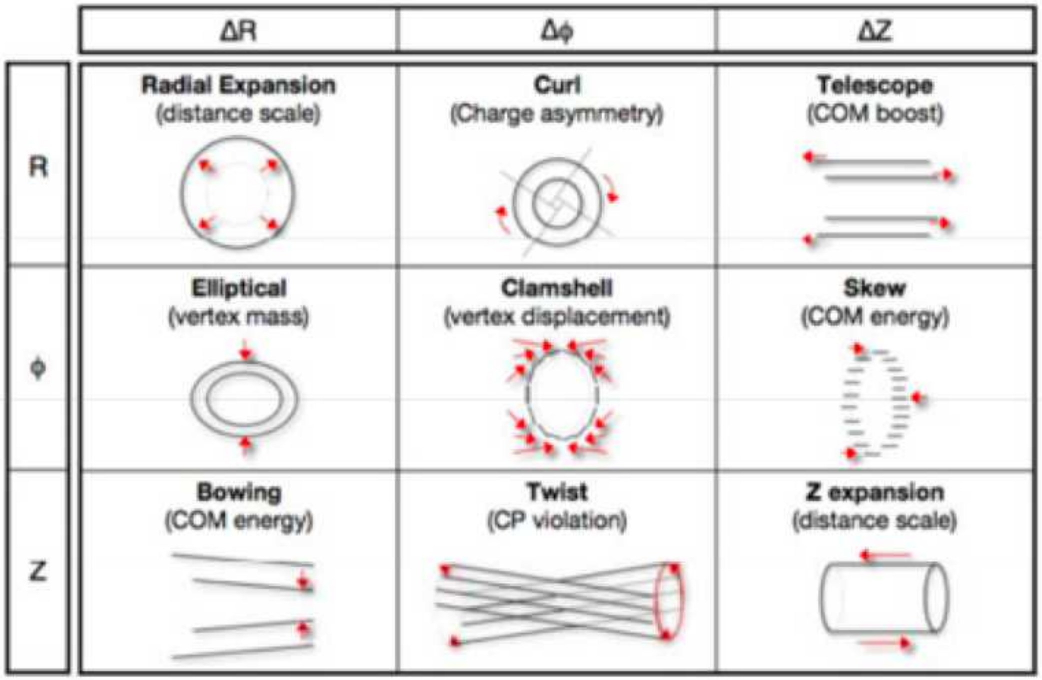




Unlike in the LHC Run 1, in which the Inner Detector was relatively stable for long periods of time, during Run 2, some subdetectors of the Inner Detector have undergone time-dependent deformations or movements that required to introduce a new dynamic alignment scheme.

The alignment correction output of 2016 gives same alignment accuracy as the reprocessed data in 2015.

But…Weak modes: detector deformations to which the χ^2 of the track fit remains invariant.

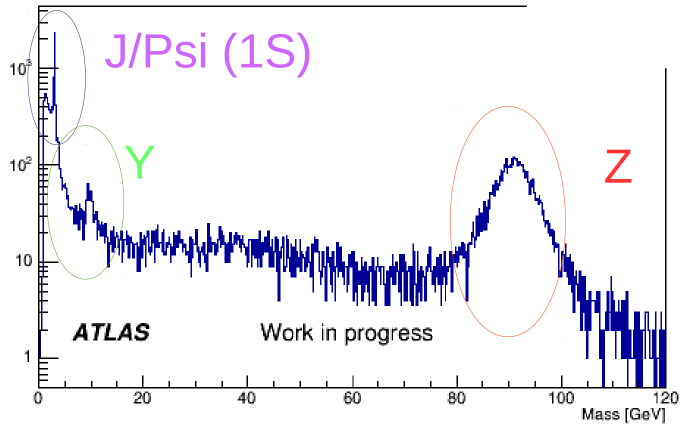


General alignment procedure is invisible to these deformations. Extra information is needed (i.e. beam spot determination, mass resonances, external detectors,…).

$J/\Psi \rightarrow \mu\mu$

Several resonances decay to two muons in the mass spectrum (e.g., Ks, J/Psi, Upsilon or Z).

$m_{J/\Psi} = 3.096\, GeV$



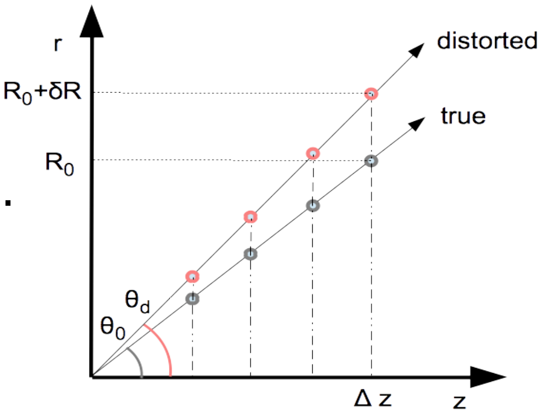
- J/Psi is a resonance sensitive to radial expansions.

$$p_{\mathrm{T}} = 0.3\, q\, B \frac{R^2}{8s} = q \frac{0.3\, B}{8} \frac{R^2}{s} = q\kappa \frac{R^2}{s}$$

- Observed through changes in momentum of the muons.

$$\begin{aligned} p_{\mathrm{T}_d} &= p_{\mathrm{T}_0}(1+2\epsilon) \\ p_{z_d} &= p_{z_0}(1+\epsilon) \\ \cot\theta_d &= \cot\theta_0 (1+\epsilon)^{-1} \end{aligned}$$

being $\epsilon = \dfrac{\delta R}{R_0}$



- If a detector suffers from radial distortion, the momentum of the muons will be badly reconstructed, and thus, the invariant mass of the J/Psi.

$$m^2_{\mu\,\mu\,0} = \left(p_0^+ + p_0^-\right)^2 = p_0^{+\,2} + p_0^{-\,2} + 2\,p_0^+\,p_0^- = 2\,m_\mu{}^2 + 2\,p_0^+\,p_0^-$$

Being, $p_0{}^+ \cdot p_0{}^- = \left(E_0^+, \vec{p_0^+}\right) \cdot \left(E_0^-, \vec{p_0^-}\right)$

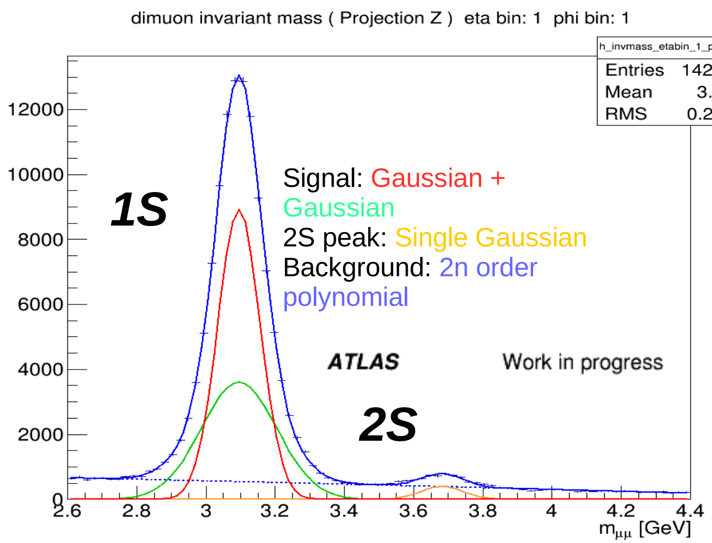
$$m^2_{\mu\mu 0} = m^2_{\mu\mu d} - 2\epsilon\, m^2_{\mu\mu d} - 2\epsilon \left[\frac{(E_d^+)^2 (p_{\mathrm{T}_d}^-)^2 + (E_d^-)^2 (p_{\mathrm{T}_d}^+)^2}{E_d^+ E_d^-} - 2\overrightarrow{p_{\mathrm{T}_d}^+}\,\overrightarrow{p_{\mathrm{T}_d}^-} \right] + 4\epsilon\, m^2_\mu$$

We get to a formula depending on distorted quantities and the Jpsi truth mass.

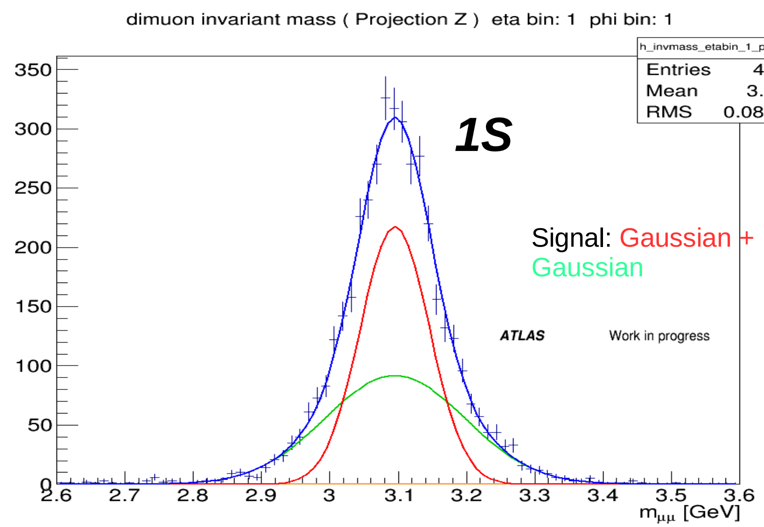
$$\epsilon = \frac{1}{2}\boxed{\left[m^2_{\mu\mu d} - m^2_{\mu\mu 0}\right]}\left[\frac{(E_d^+)^2 (p_{\mathrm{T}_d}^-)^2 + (E_d^-)^2 (p_{\mathrm{T}_d}^+)^2}{E_d^+ E_d^-} - 2\overrightarrow{p_{\mathrm{T}_d}^+}\,\overrightarrow{p_{\mathrm{T}_d}^-} + m^2_{\mu\mu d} - 2m^2_\mu \right]^{-1}$$

Radial corrections must be computed comparing fitted mass values of J/Psi from data (i.e. distorted) wrt truth mass (as well as other kinematical quantities).

Data



MC

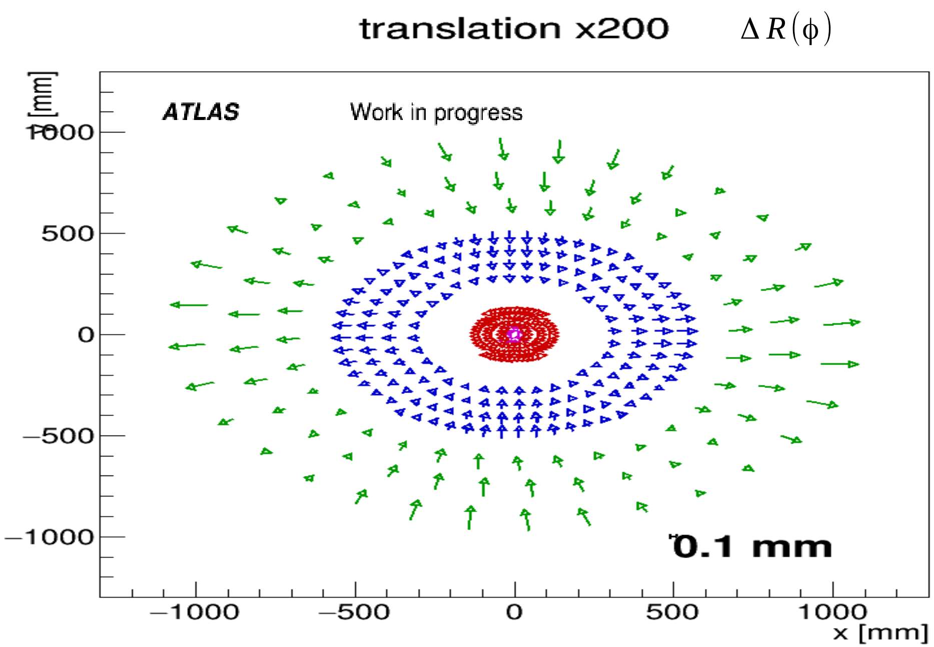


Similar fitting model for real data and Monte Carlo based on two gaussian with same mean but different sigma.

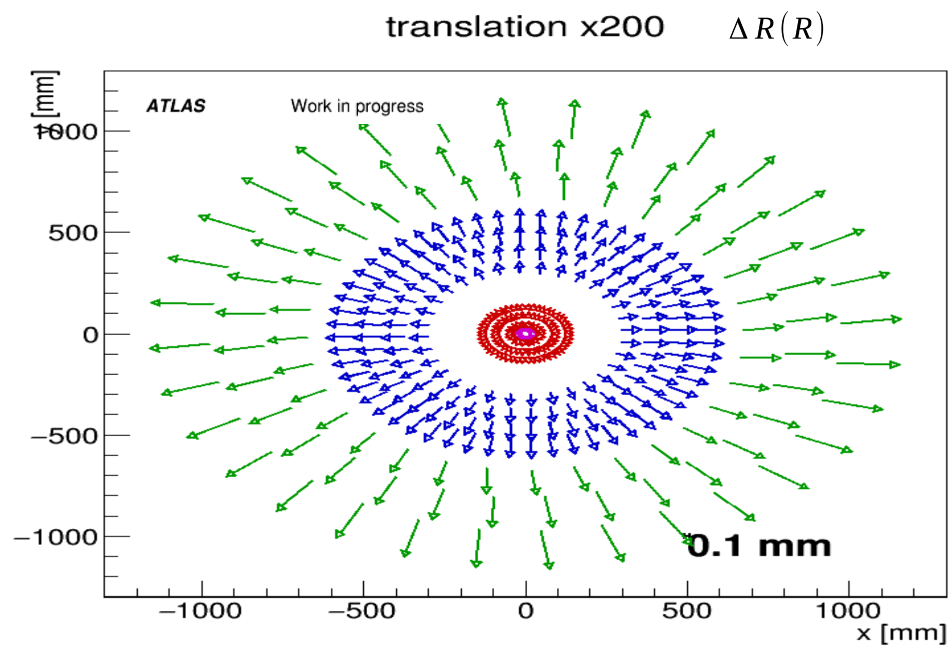
Using MC samples we can check the sensitivity to different weak modes by simulating a misaligned geometry.

TRT
SCT
Pixel

Elliptical distortion



Radial expansion



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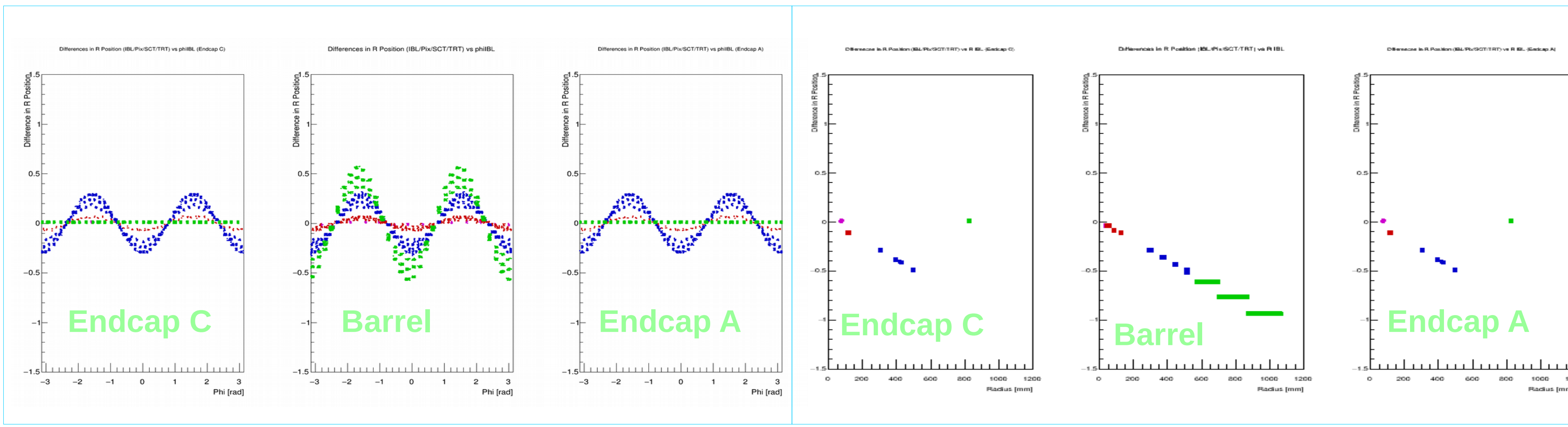
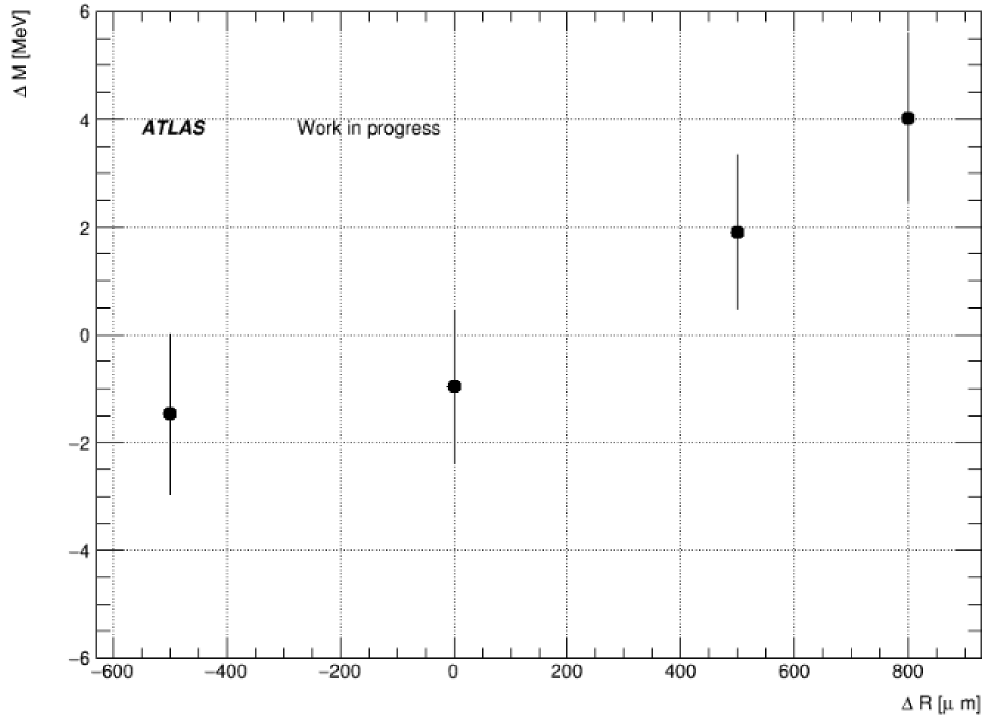


$J/\Psi \rightarrow \mu\mu$

Radial expansion

Barrel

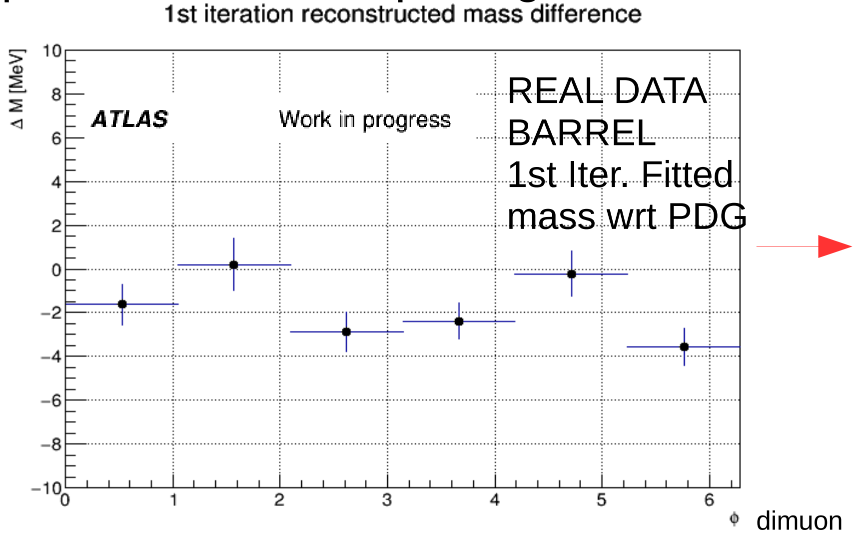


MC distorted geometry samples show that J/ψ is sensitive to the different radial misalignment shifts .

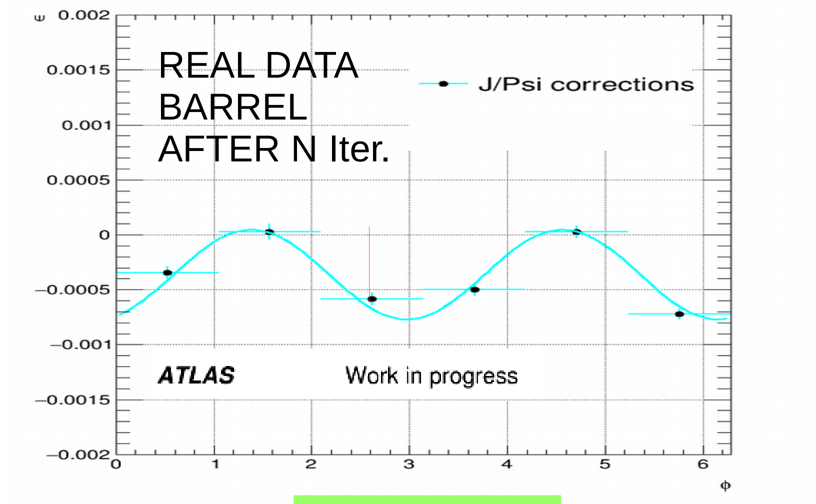
Barrel

Split the barrel in 6 phi regions.

2015



J/Ψ mass



corrections

2015 Jpsi results pointed to an elliptical deformation.

Using $\epsilon = \frac{\delta R}{R_0}$ $\Delta\epsilon \sim 0.0006 \Rightarrow 300\, \mathit{microns\ difference\ within\ the\ ellipsis\ axis}\,(\mathit{for\ silicon\ tracks}\ R_0 = 0.5\, m)$

Summary

- Tracks of the ID must be correctly reconstructed in order to detect all the particle decay products from known (or new) particles.
- Any misalignment of the ID worsen the resolution of the reconstructed track parameters. Weak modes can lead to distortions of physical measurements.
- This implies a correct alignment of all the components of the ID.
- The general alignment procedure is based on a chi^2 minimization function of the alignment parameters.
- Since this procedure is invisible to weak modes, extra information is needed. For example, the resonance mass of the J/ψ.
- J/ψ decay to two muons is sensitive to radial distortions. A MC sample samples has been used to test the sensitivity to a linearly radial expansion.
- Data of 2015 points to a little elliptical deformation.

Global X^2 scheme

1

Choice of the alignment level:

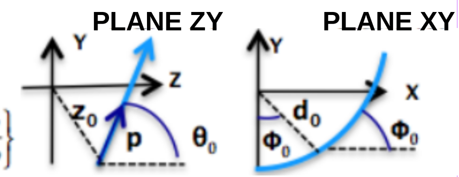
- L1: bigger structures.
- L2: disks and layers.
- L3: modules.

2

Track fitting:

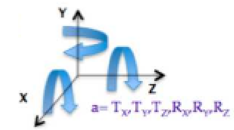
$$\frac{d\chi^2}{d\pi} = 0$$

with $\pi = \left\{d_0, z_0, \phi_0, \theta_0, \frac{q}{p}\right\}$



3

Alignment parameters:



$$\delta a = -\left[\sum_{tracks}\left(\frac{\partial r}{\partial a}\right)^T V \left(\frac{\partial r}{\partial a}\right)\right]^{-1} \sum_{tracks}\left[\left(\frac{\partial r}{\partial a}\right)^T V r\right]$$

Notation:

$$M = \sum_{tracks}\left[\left(\frac{\partial r}{\partial a}\right)^T V \left(\frac{\partial r}{\partial a}\right)\right] \qquad \nu = \sum_{tracks}\left[\left(\frac{\partial r}{\partial a}\right)^T V r\right]$$

V : covariant matrix..

X^2 definition:

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

Evaluation of $\frac{d\pi}{da}$

X^2 minimization:

$$\frac{d\chi^2}{da} = \frac{\partial\chi^2}{\partial\pi}\frac{d\pi}{da} + \frac{\partial\chi^2}{\partial a}$$

No convergence: $a = a_0 + \delta a$

4

Alignment parameters corrections:

$$\delta a = -M^{-1}\,\nu$$

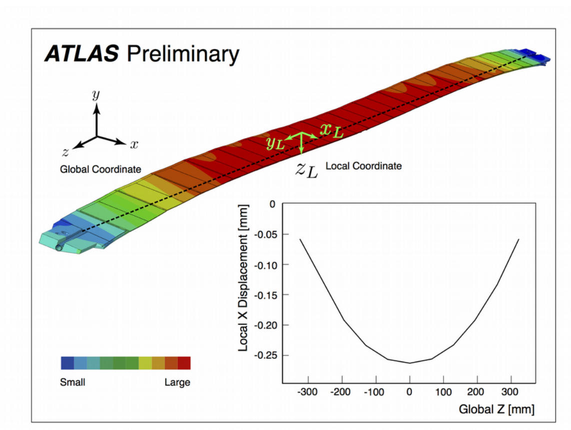
Solving methods:
Inversion, diagonalization, ...

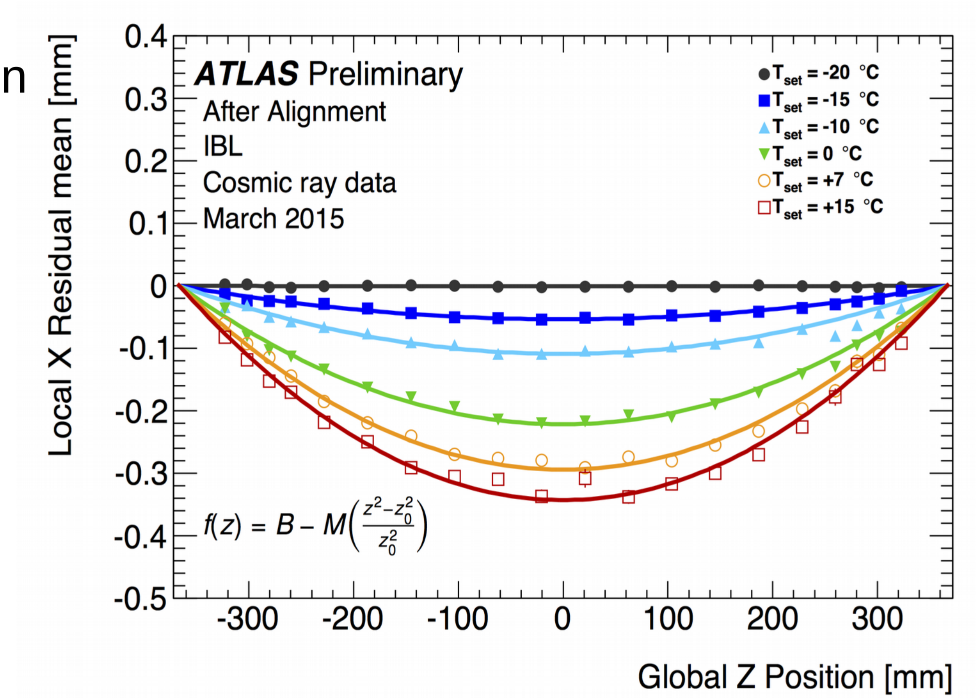
If convergence is reached: $\delta a \approx 0$ or X^2 remains invariant:

Final alignment constants

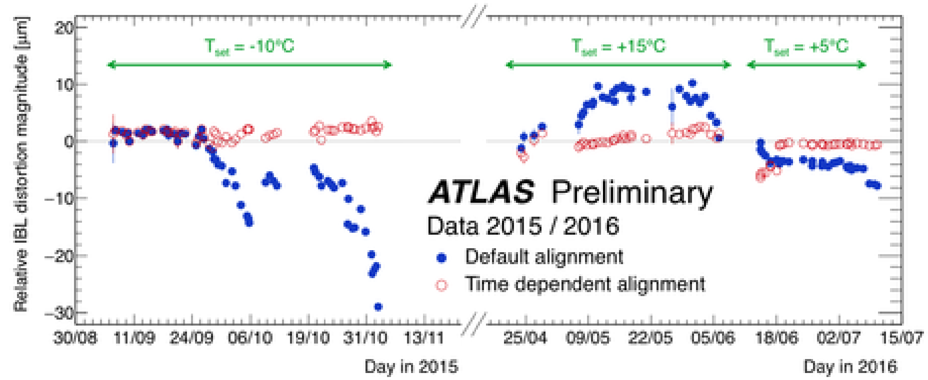
Alignment of the Inner Detector.

The IBL staves were found to bow in plane **depending on their temperature**. Introduced dofs to describe the bowing distortion.





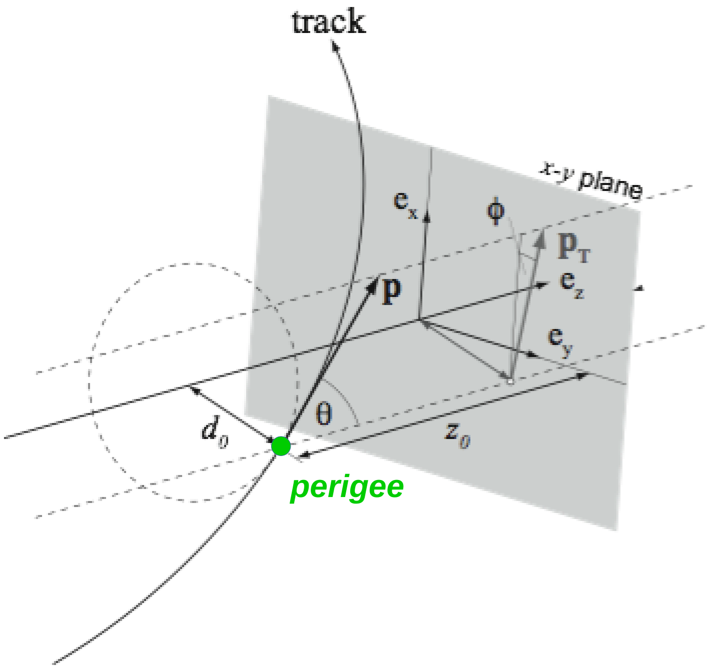
During collisions data taking, the IBL staves were seen to bow within a run. A **time-dependent** alignment correction was introduced.



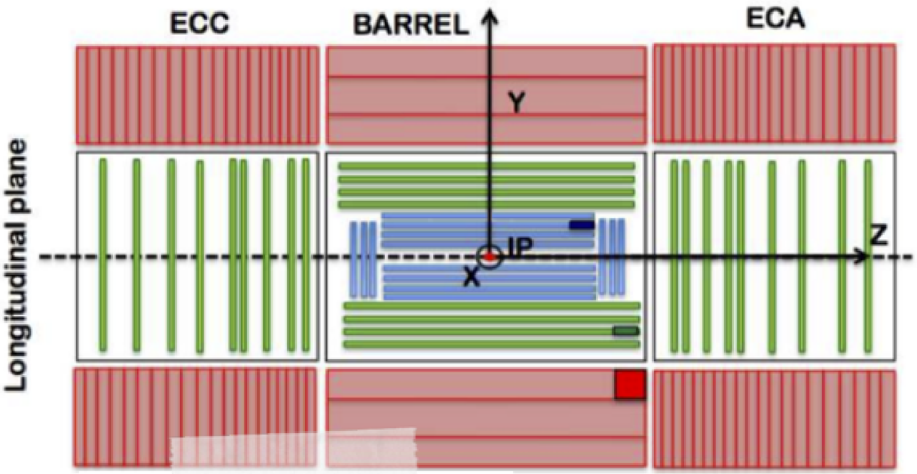
Charged particles describe helicoidal trajectores in the ID due to magnetic field.

Parametrized using a set of five parameters , I.e, $\boldsymbol{d_0}$ **,** $\boldsymbol{z_0}$ **,** $\boldsymbol{\Phi_0}$ **,** $\boldsymbol{\theta}$ **, *q/p.***

Defined at the perigee (point of closest approach of the track to z-axis) at the global coordinate system.

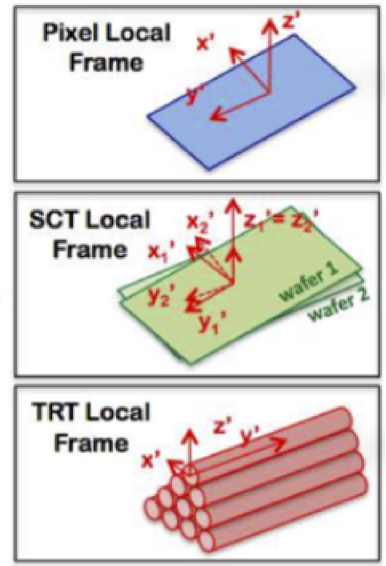


Backup: Radial distortion corrections



Global Coordinate System
(right-handed)

X: towards center of LHC
Y: upwards
Z: beam direction



Local Coordinate System

PIX

- 1744 modules
- 46K pixel per module

Dimension

- (50 x 400) µm

Resolution

- (14 x 115) µm

SCT

- 4088 modules
- 768x2 channels per module

Dimension

- 80 µm x 120 mm

Resolution

- 23 µm (Rϕ)

TRT

- 96+28 modules
- 300K straw tubes

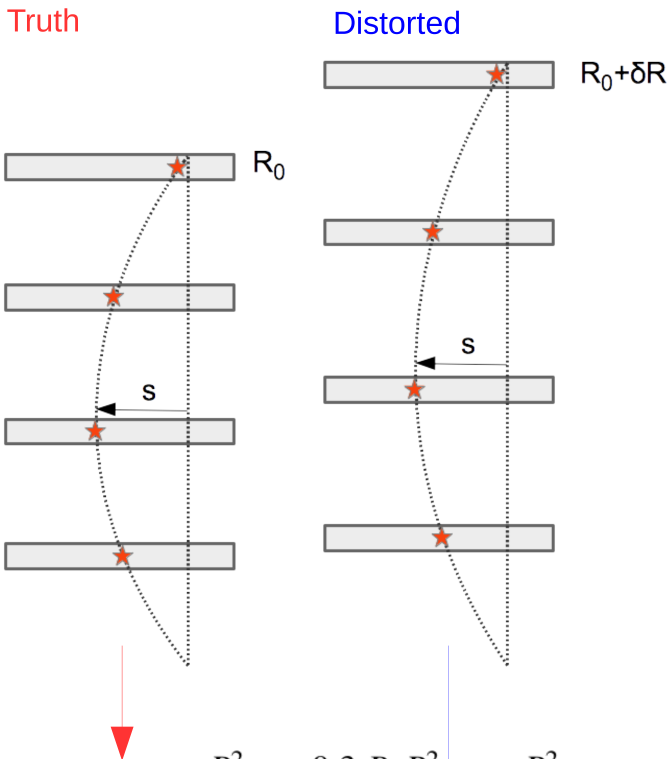
Dimension

- r = 4 mm

Resolution

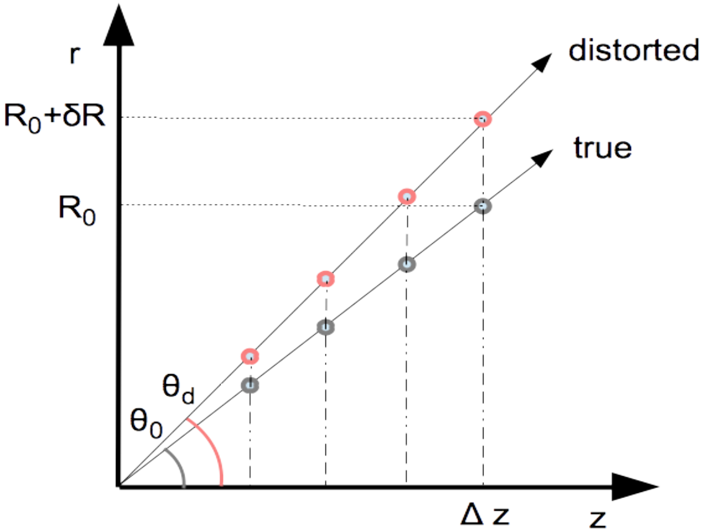
- 170 µm

Backup: Radial distortion corrections



$$p_T = 0.3\ q\ B\ \frac{R^2}{8s} = q\frac{0.3\ B}{8}\frac{R^2}{s} = q\kappa\frac{R^2}{s}$$

$$p_{T_d} = q\kappa\frac{R_d^2}{s} = \frac{q\kappa}{s}(R_0+\delta R)^2 = \frac{q\kappa}{s}(R_0^2 + 2R_0\delta R) = q\kappa\frac{R_0^2}{s}\left(1+2\frac{\delta R}{R_0}\right)$$

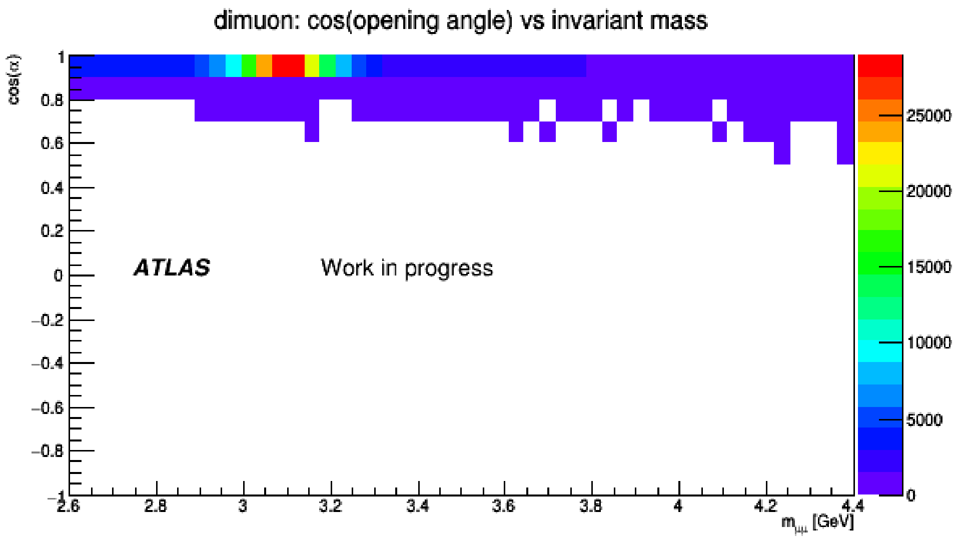


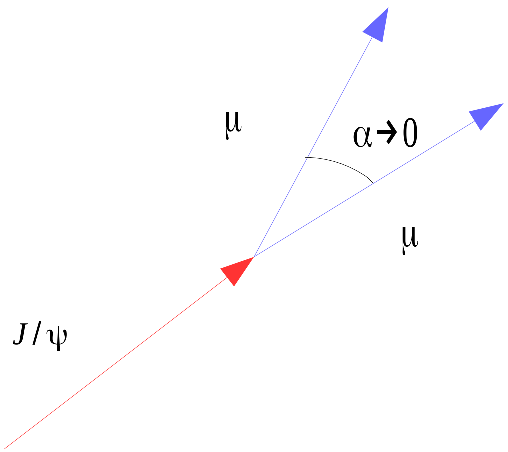
$$\begin{aligned} p_{T_d} &= p_{T_0}(1+2\epsilon) \\ p_{z_d} &= p_{z_0}(1+\epsilon) \\ \cot\theta_d &= \cot\theta_0(1+\epsilon)^{-1} \end{aligned}$$

being $\epsilon = \frac{\delta R}{R_0}$

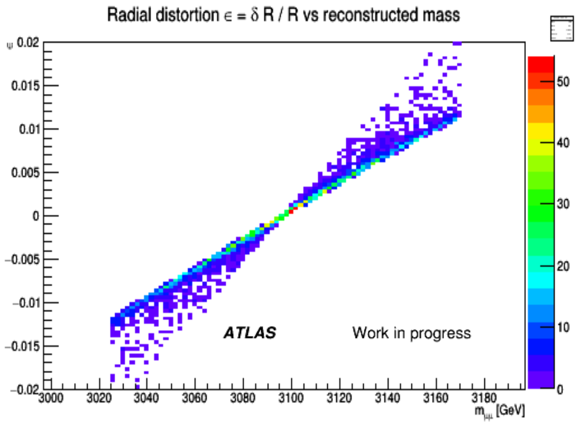
Backup: Radial distortion corrections

- Consider that the positive and negative radial correction is approximately the same, since both positive positive and negative muons goes in almost the same direction.





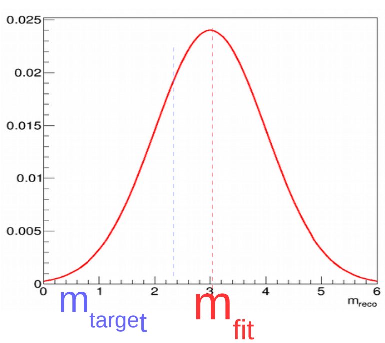
Backup: Radial distortion corrections

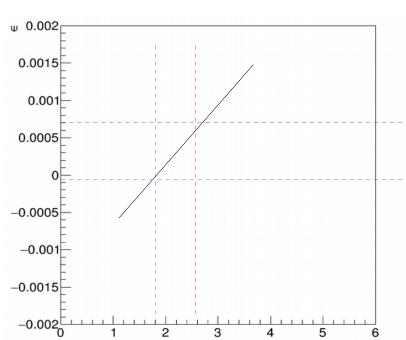


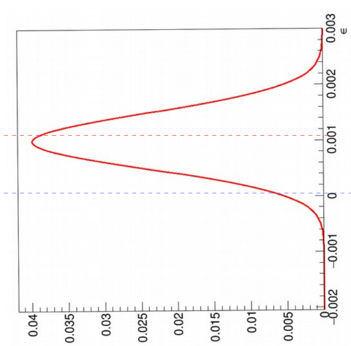
$$\begin{aligned} p_{\mathrm{T}_d} &= p_{\mathrm{T}_0}\,(1+2\epsilon) \\ p_{z_d} &= p_{z_0}\,(1+\epsilon) \\ \cot\theta_d &= \cot\theta_0\,(1+\epsilon)^{-1} \end{aligned}$$

$$\epsilon = \frac{\delta R}{R_0}$$

$$\epsilon = \frac{1}{2}\,\frac{m^2_{\mu\,\mu\,d} - m^2_{\mu\,\mu\,0}}{\left[\frac{\left(E_d{}^{-2}\,p_{T\,d}{}^{+2} + E_d{}^{+2}\,p_{T\,d}{}^{-2}\right)}{E_d{}^{+}E_d{}^{-}} - 2\overrightarrow{p^{+}_{T\,d}}\cdot\overrightarrow{p^{-}_{T\,d}}\right] + m^2_{\mu\,\mu\,d}}$$





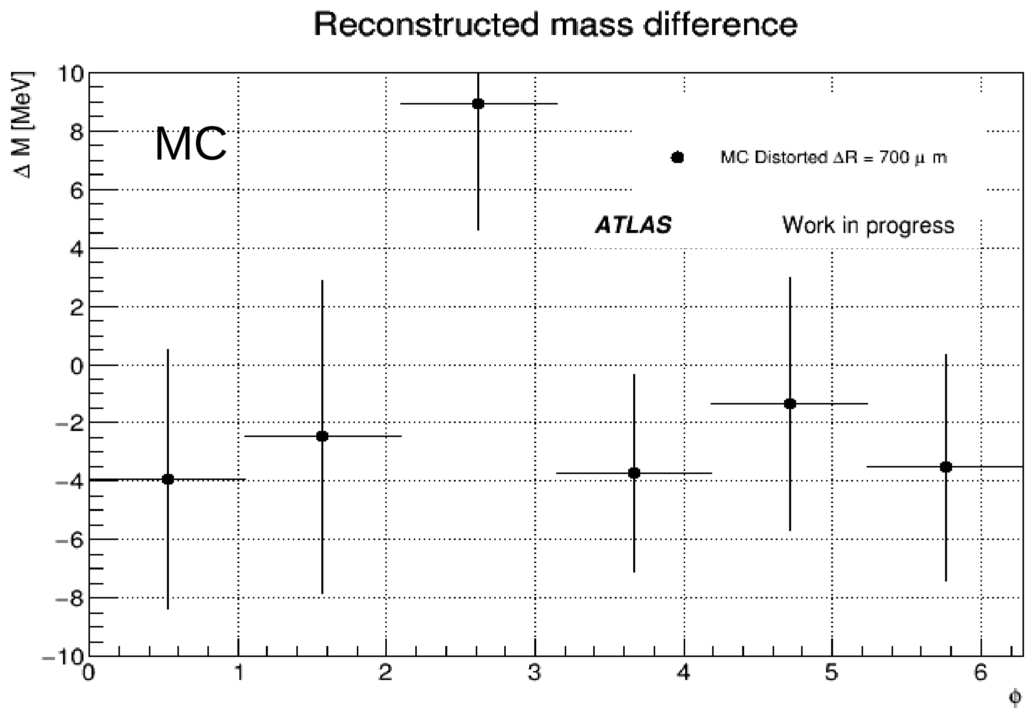


ϵ input for next iteration

Backup: Radial distortion corrections.

Barrel

Elliptical

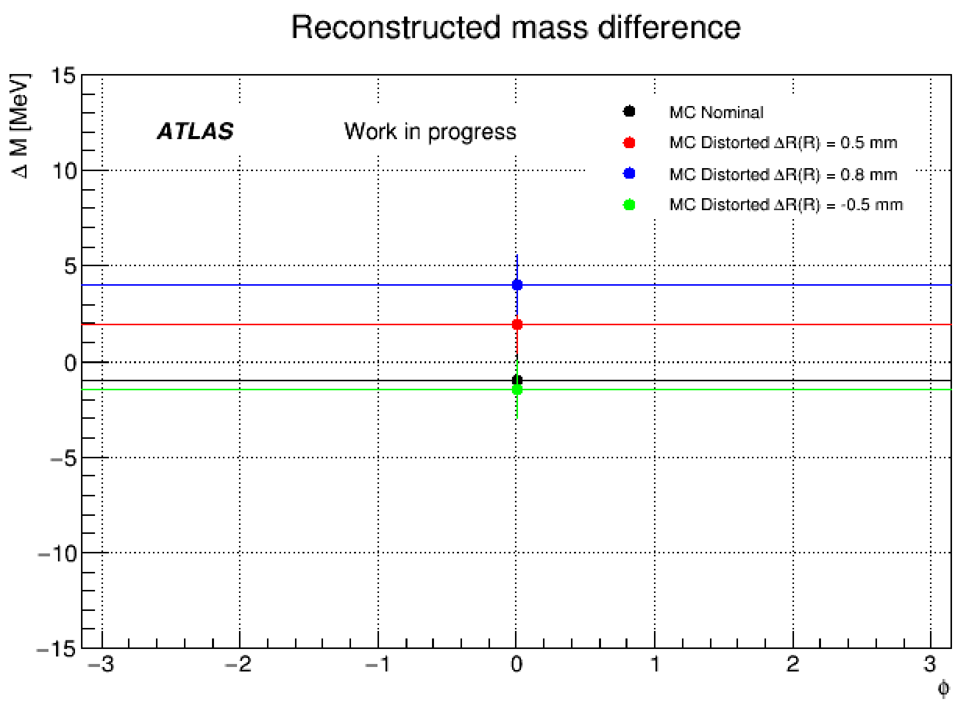


With the current Jpsi MC statistics one cannot be sensitive to small deformations, as the tested one (i.e. 300 - 700 microns elliptical shape) → need more Jpsi MC.

$J/\Psi \rightarrow \mu\mu$

Radial expansion

Barrel



MC distorted samples show that J/ψ is sensitive to the different radial misalignment shifts .