Alignment of the ATLAS Inner Detector in Run 2

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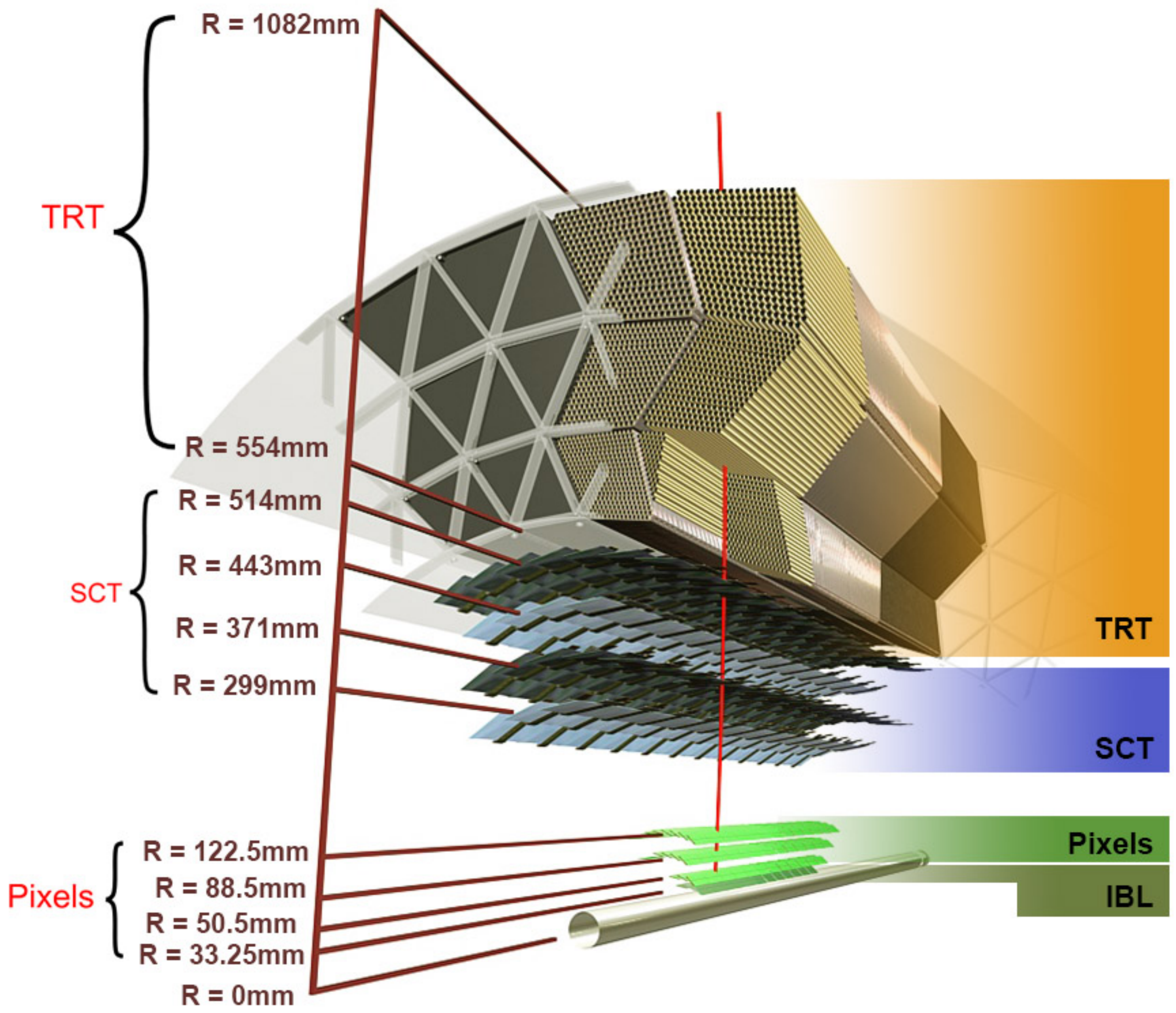
Jesús Guerrero Rojas
On behalf ATLAS Collaboration

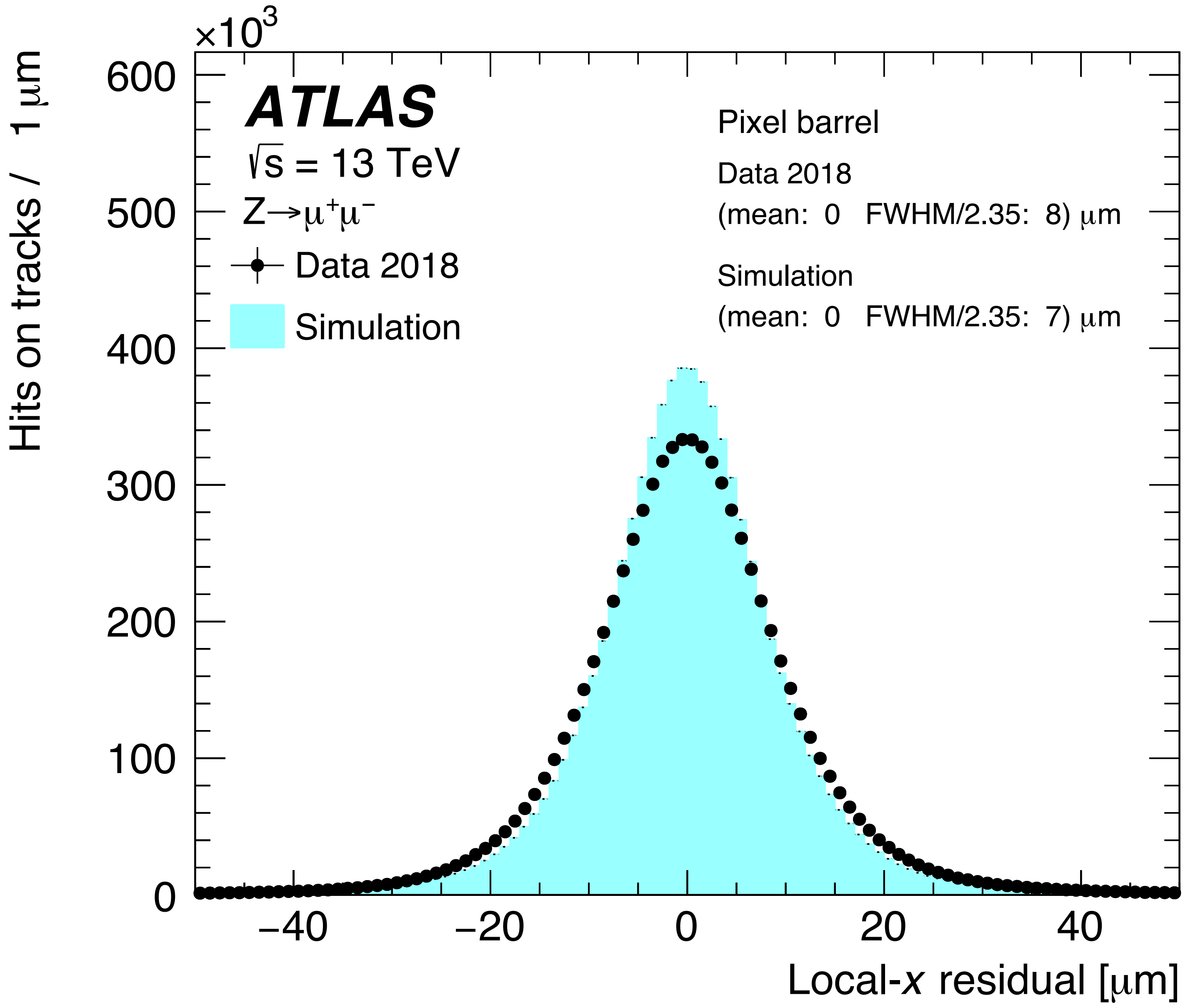
Introduction

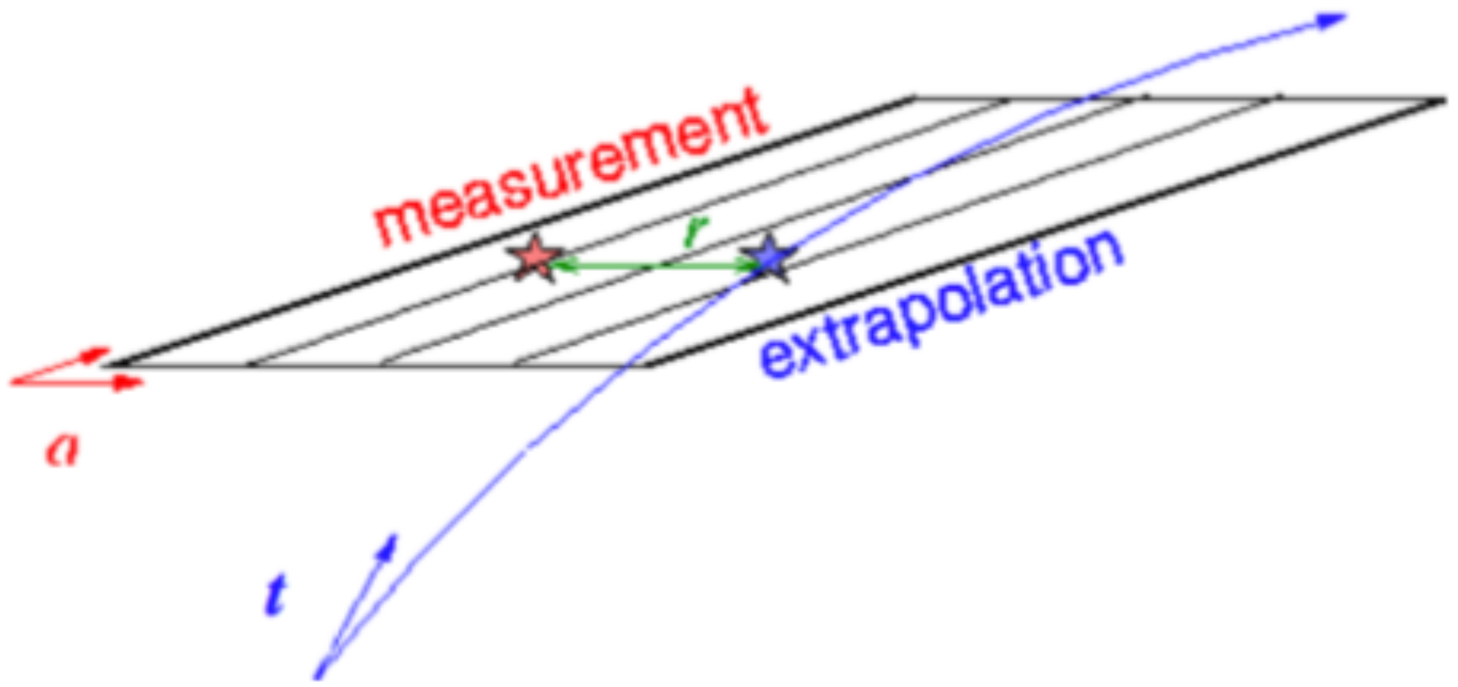
- The Inner Detector (ID) is the main tracking system of ATLAS. The ID is composed:
  - TRT : straw tubes
  - SCT : silicon strip detector
  - Pixels & IBL : silicon pixel detector
- The knowledge of the geometry of the ID determines the accuracy of the track reconstruction
- The actual geometry of the ID could differ from the nominal due to:
  - The assembly of the detector itself
  - The operation of the ATLAS detector
- The alignment process determines the actual geometry of the ID and also its possibles changes in time



Alignment process

- The alignment of the ID is a track based alignment
- Track fit residuals (r) are defined as the distance between measured hits and extrapolated tracks :
  1. The alignment consist of a minimization of a χ^2 function of the residuals
  2. Non-zero residuals indicate displacements of the detector from the nominal geometry





Alignment parameter : 3 Rotation + 3 Translation

$$a = (T_x, T_y, T_z, R_x, R_y, R_z) \times N_{struct}$$

Track parameter:

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

$$\chi^2 = \sum_t \left[r^T(t,a) V^{-1} r(t,a) \right]$$

$$V = \begin{pmatrix} \sigma^2_{hit} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \sigma^2_{hit} \end{pmatrix}$$

$$\frac{d\chi^2}{da} = 0 \rightarrow \sum \left[\left(\frac{dr}{da}\right)^T V^{-1} \left(\frac{dr}{da}\right) \right] \delta a + \sum \left(\frac{dr}{da}\right)^T V^{-1} = 0$$

Alignment corrections

Alignment process

- The alignment process is performed at different levels following the assembly structure of the ID
- The alignment corrections are obtained through an iterative process, increasing the complexity level sequentially

Level	Description	Structures
1	IBL, Pixel, SCT endcaps, TRT barrel and 2 endcaps	7
Si2	Pixel endcap disks and barrel layers, IBL layers, SCT endcaps disk and barrel layers	32
Si3	Pixel modules,IBL modules, SCT modules	6112
TRT2	TRT barrel modules and endcaps wheels	176
TRT3	TRT straws	351k

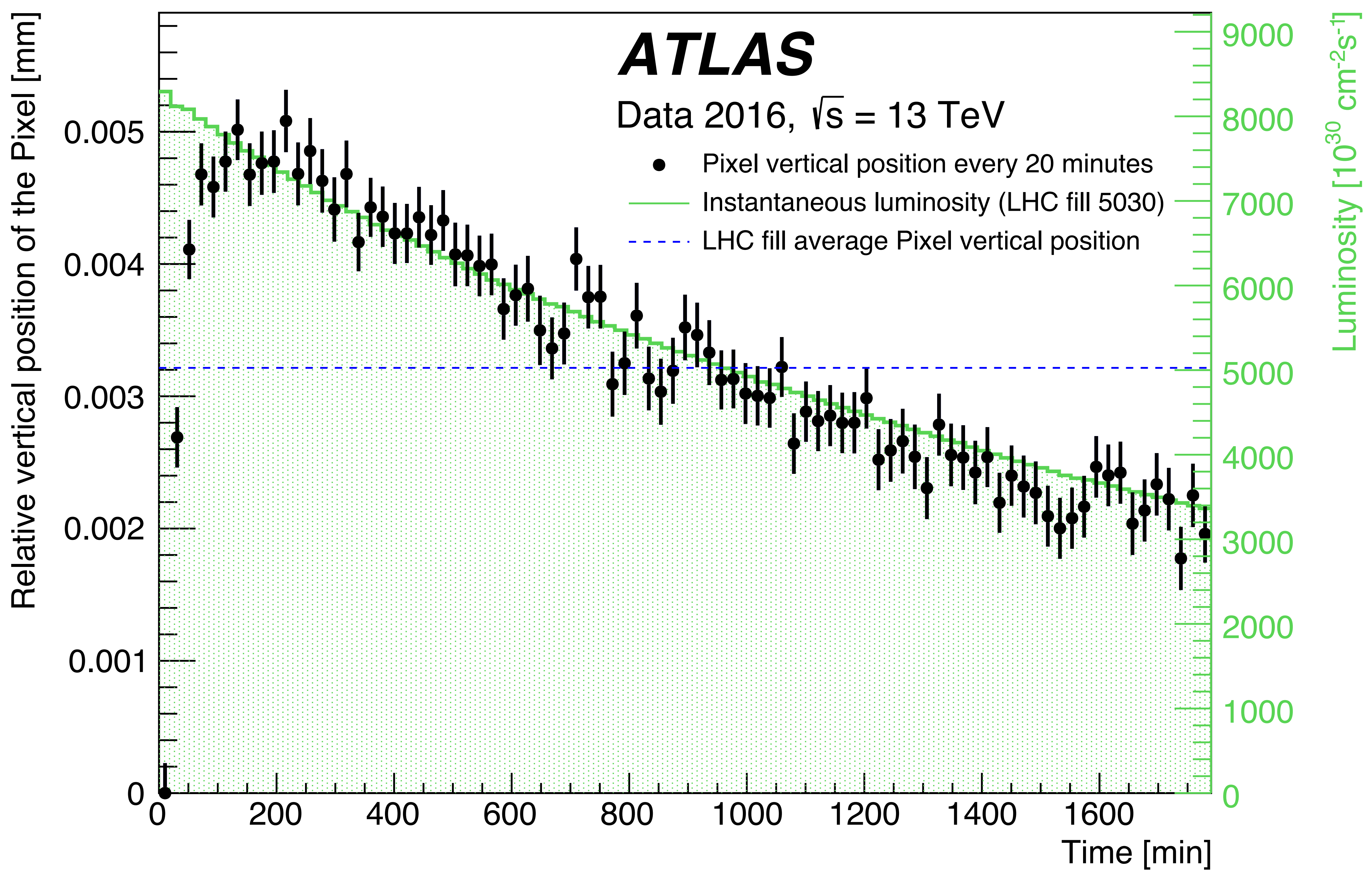
- The χ^2 function could be extended to add constraints on both the tracks parameters and the alignment parameters

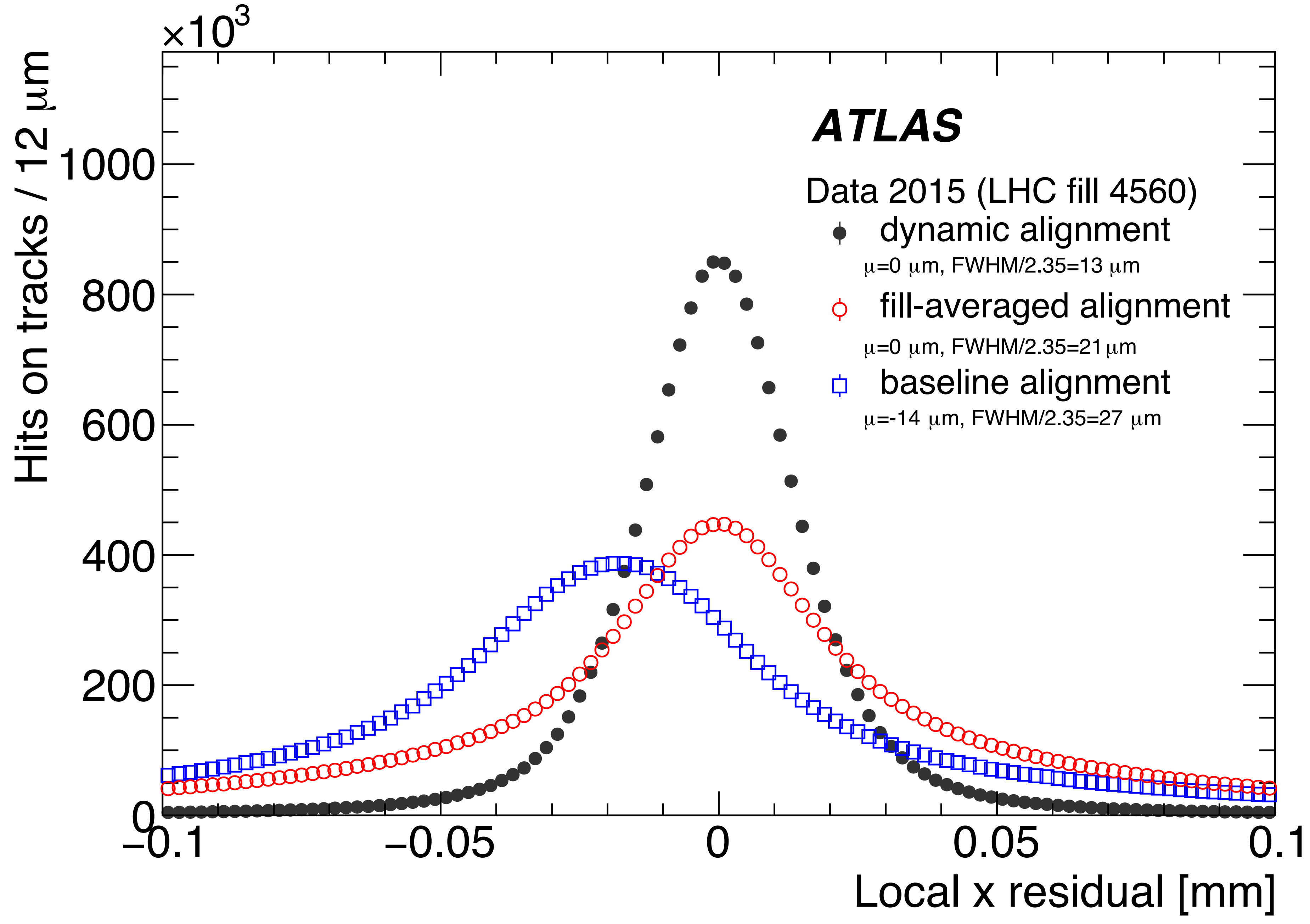
$$\chi^2 = \sum \left[r^T(t,a)V^{-1}r(t,a) + R^T(t)V_t^{-1}R(t) \right] + R'^T(a)V_a^{-1}R'(a)$$

Track constraint   Alignment constraint

Time dependent alignment

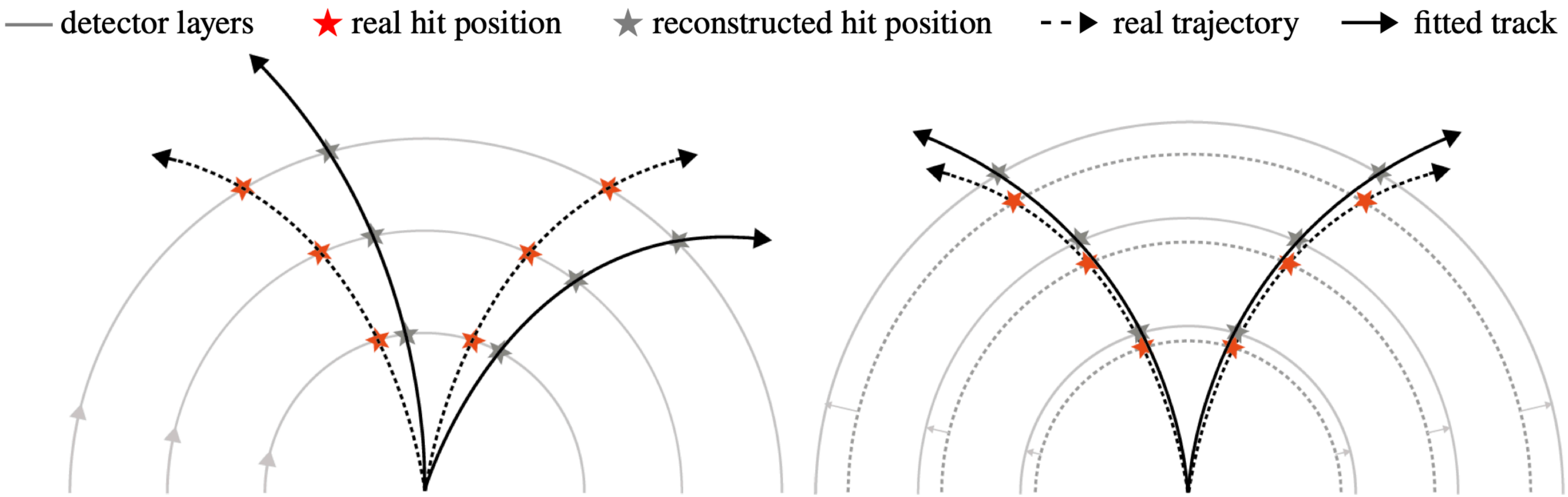
- An automated time-dependent alignment is performed within the ATLAS prompt calibration loop
- The time-dependent alignment is performed for every new LHC fill prior to data reconstruction
- The obtained corrections are automatically uploaded and the result are monitored
- An example of a movement within a run is the vertical position of the Pixel detector VS time shown in the left figure





Weak Modes

- The track based alignment process is not sensitive to some kinds of geometrical distortion known as weak modes
- A Weak Mode is a geometrical deformation in a such way that:
  - It leaves the χ^2 function of the track fit invariant
  - It can bias the reconstructed track parameters
- The bias produced by a weak mode can be mitigated adding parameters constraints in the χ^2 function



Sagitta bias   Length scale bias

Weak Modes: Length scale bias

- Length scale bias is a charge-symmetric alteration of the measured track curvature
- The bias could be produced by a radial expansion(ϵ_r) or a longitudinal expansion (ϵ_z) of the ID, or a bias on the magnetic field B (ϵ_s).

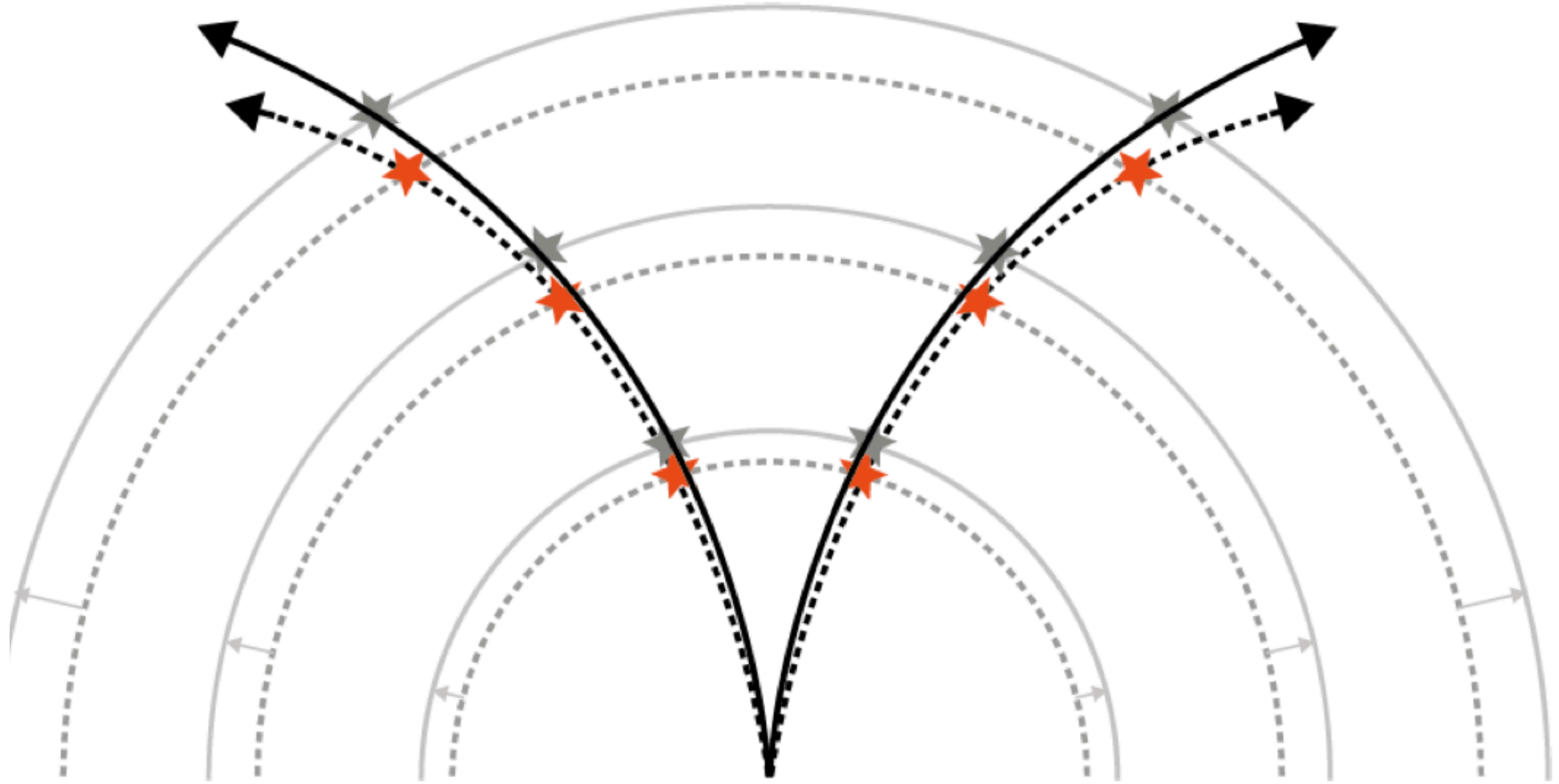
Radial expansion	Longitudinal expansion	Magnetic field bias
$p'_T = p_T(1+\epsilon_r)$	$p'_T = p_T$	$p' = p(1+\epsilon_s)$
$p'_z = p_z$	$p'_z = p_z(1+\epsilon_z)$	

- The reconstructed mass of the decay of a particle into $\mu^+\mu^-$ in the barrel is used to measure the bias
- In the limit where the muon mass is ignored

$$m'^2_{\mu\mu} \approx m^2_{\mu\mu} + 2m^2_{\mu\mu}\ (\epsilon_s + \epsilon_{r'}\ sin^2\alpha)$$

$$sin^2\alpha = E^+E^-\ [\beta_T^+ - \beta_T^-]\ /\ m^2_{\mu\mu} \qquad \epsilon_s = \epsilon_z \qquad \epsilon_{r'} = \epsilon_r - \epsilon_z$$

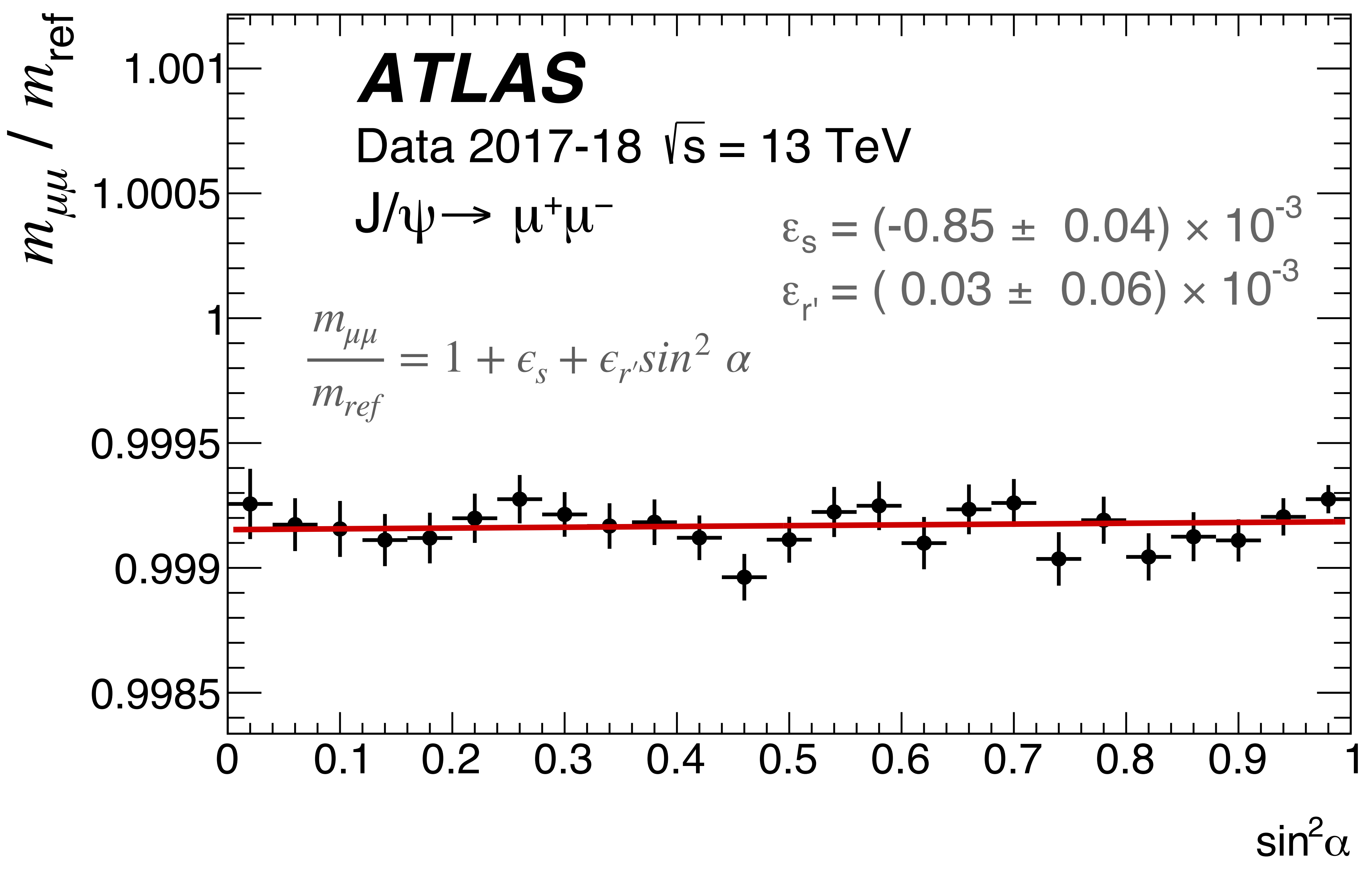
- A radial distortion and a scale bias can be distinguished by measuring the reconstructed mass as a function of $sin^2\alpha$

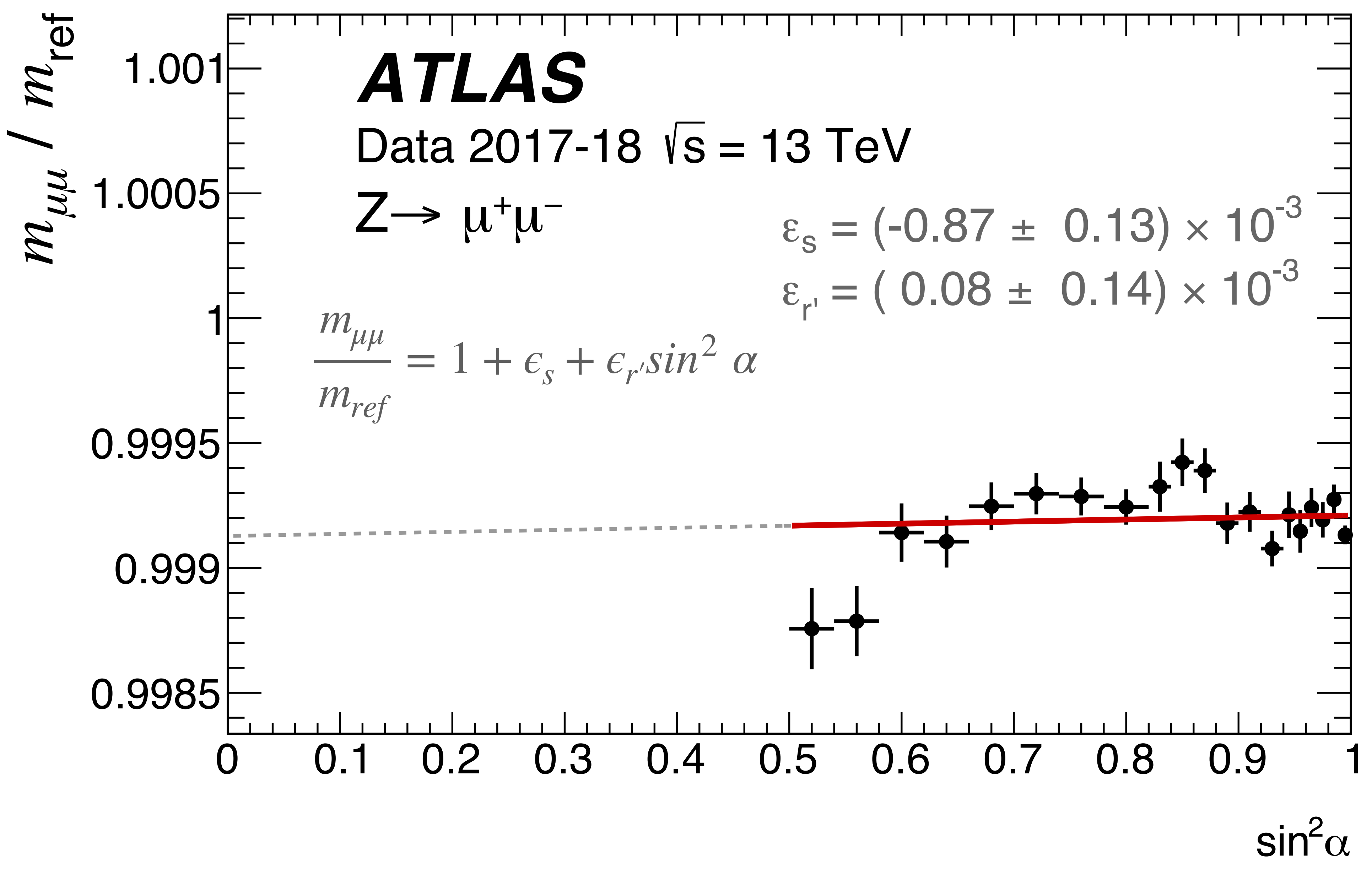


Length scale bias

Weak Modes: Length scale bias

- The length scale bias has been measured using J/ψ and Z decays into $\mu^+\mu^-$ in the barrel of the ID





- The results show a momentum scale bias ($\epsilon_s \sim 0.9 \times 10^{-3}$) but not a significant radial scale ($\epsilon_{r'}$)

- The value of the scale bias is consistent for both samples

Weak Modes: Sagitta bias

- A sagitta bias ($\delta_{sagitta}$) is caused by a distortion in the bending plane of the tracks and it is a charge-antisymmetric alteration

$$p' = p(1 + q\ p_T\ \delta_{sagitta})^{-1}$$

- There are two methods to evaluate the $\delta_{sagitta}$:

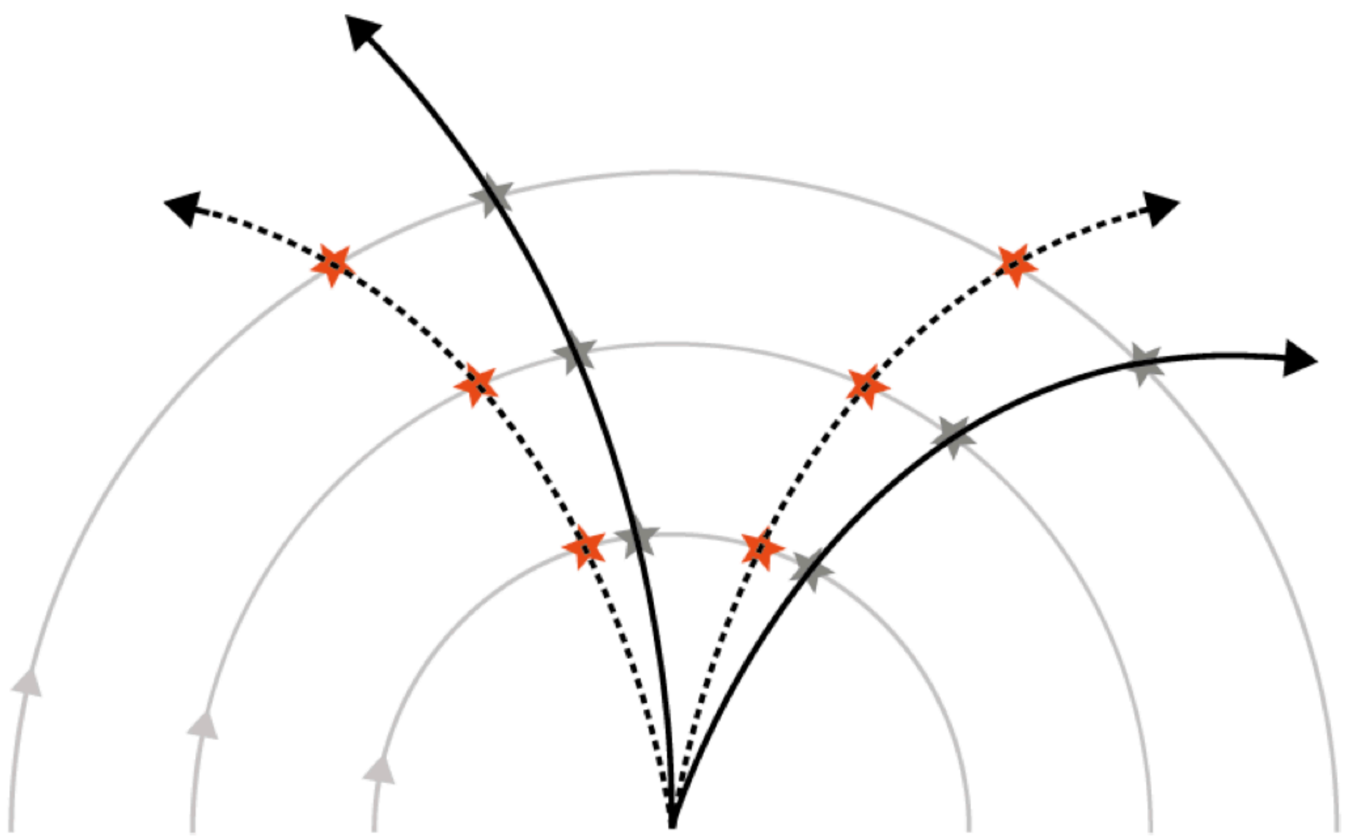
  - $Z \to \mu^+\mu^-$ method: it is an iterative process to determine $\delta_{sagitta}$. For the i-th iteration, $\delta_{sagitta}$ is computed for every muon in the samples with:

$$\delta_{sagitta,i}(\eta,\phi) = -q\frac{m_{\mu\mu}^2 - m_Z^2}{2m_Z^2}\frac{1 + qp'_T\delta_{sagitta,i-1}(\eta,\phi)}{p'_T} + \delta_{sagitta,i-1}(\eta,\phi)$$

  - E/p method: assuming that the average transverse energy of positron and electron are equal, $\delta_{sagitta}$ can be estimated

$$\delta_{sagitta}(\eta,\phi) = \frac{\langle E/p'\rangle^+ - \langle E/p'\rangle^-}{2\left\langle E_T\right\rangle}$$

Where $E_T = E\ /cosh\ \eta$



Sagitta bias

Weak Modes: Sagitta bias

$$p' = p(1 + q\ p_T\ \delta_{sagitta})^{-1}$$

For example if :

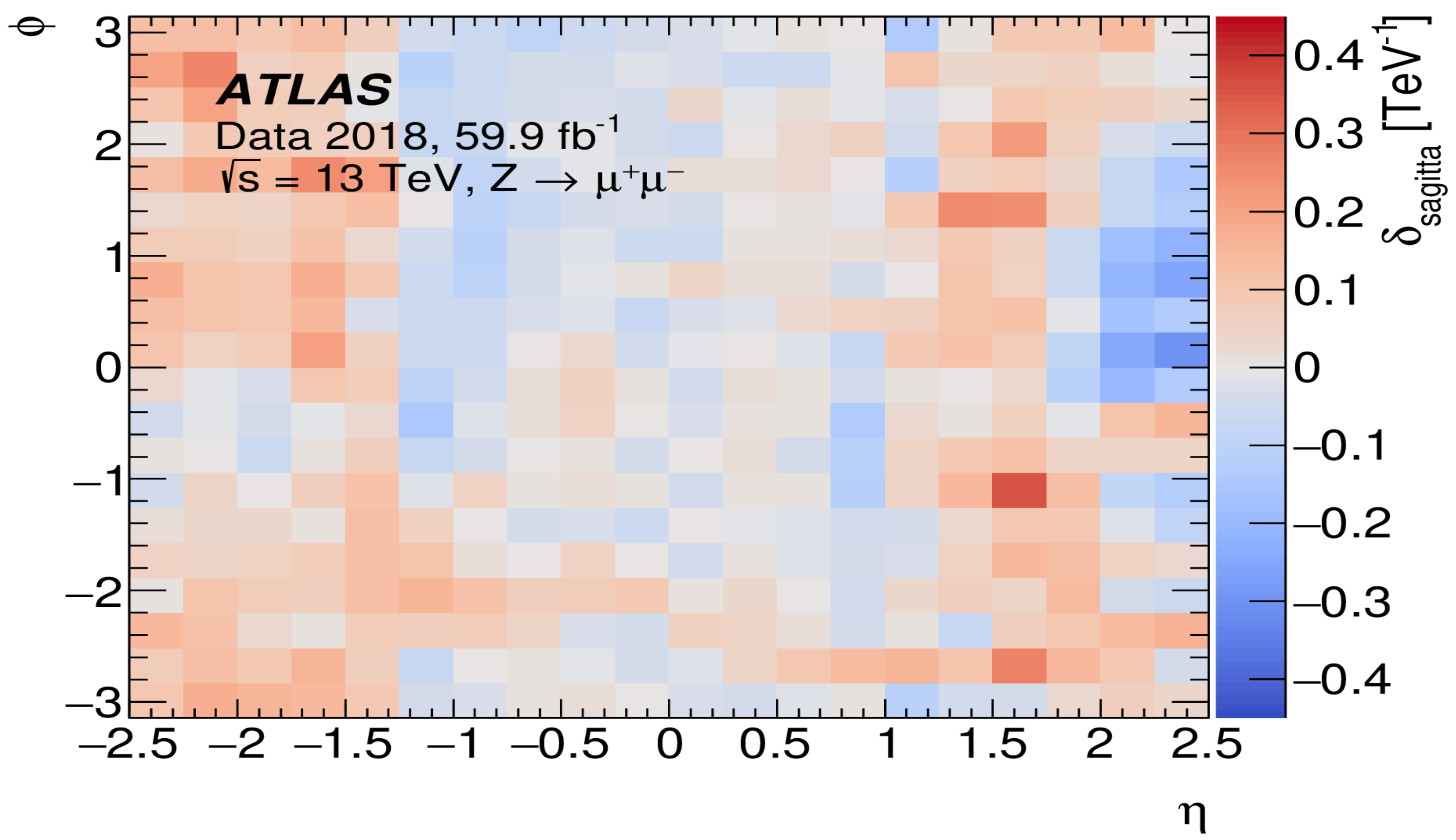
$$\delta_{sagitta} = 0.1\ TeV^{-1}$$

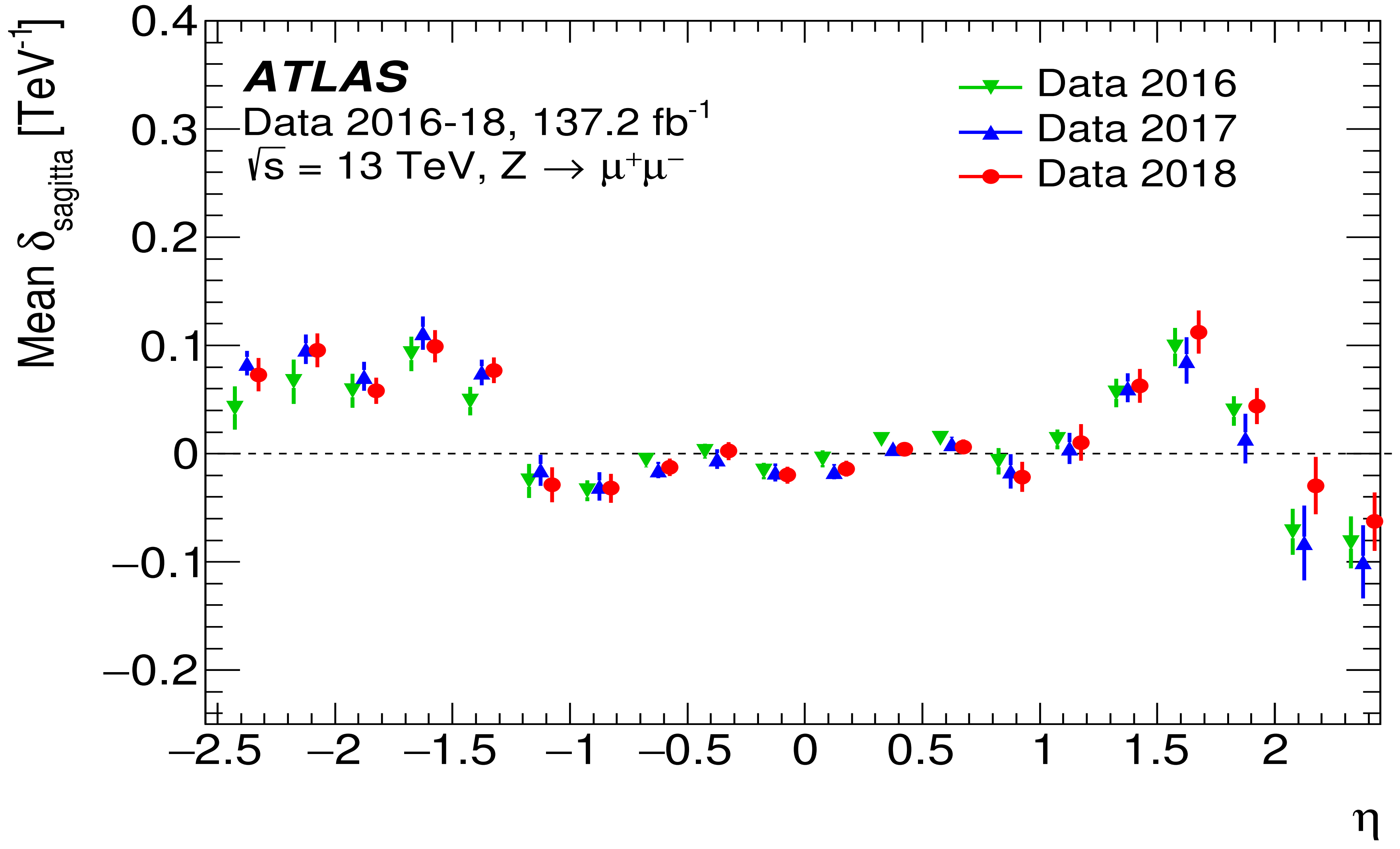
$$p_T = 50\ GeV$$

$$\downarrow$$

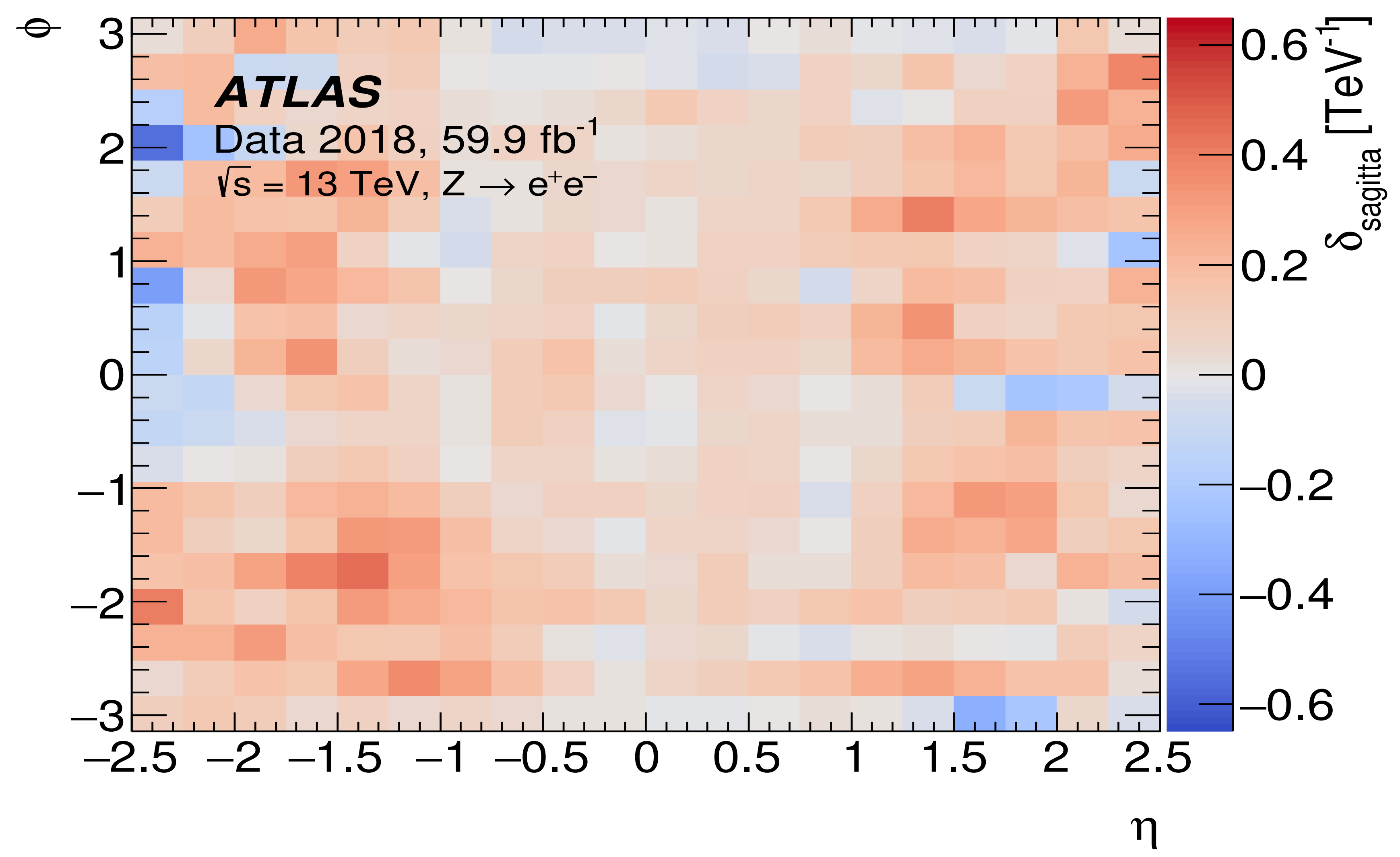
$$p' - p = 0.25\ GeV\ (0.5\%)$$

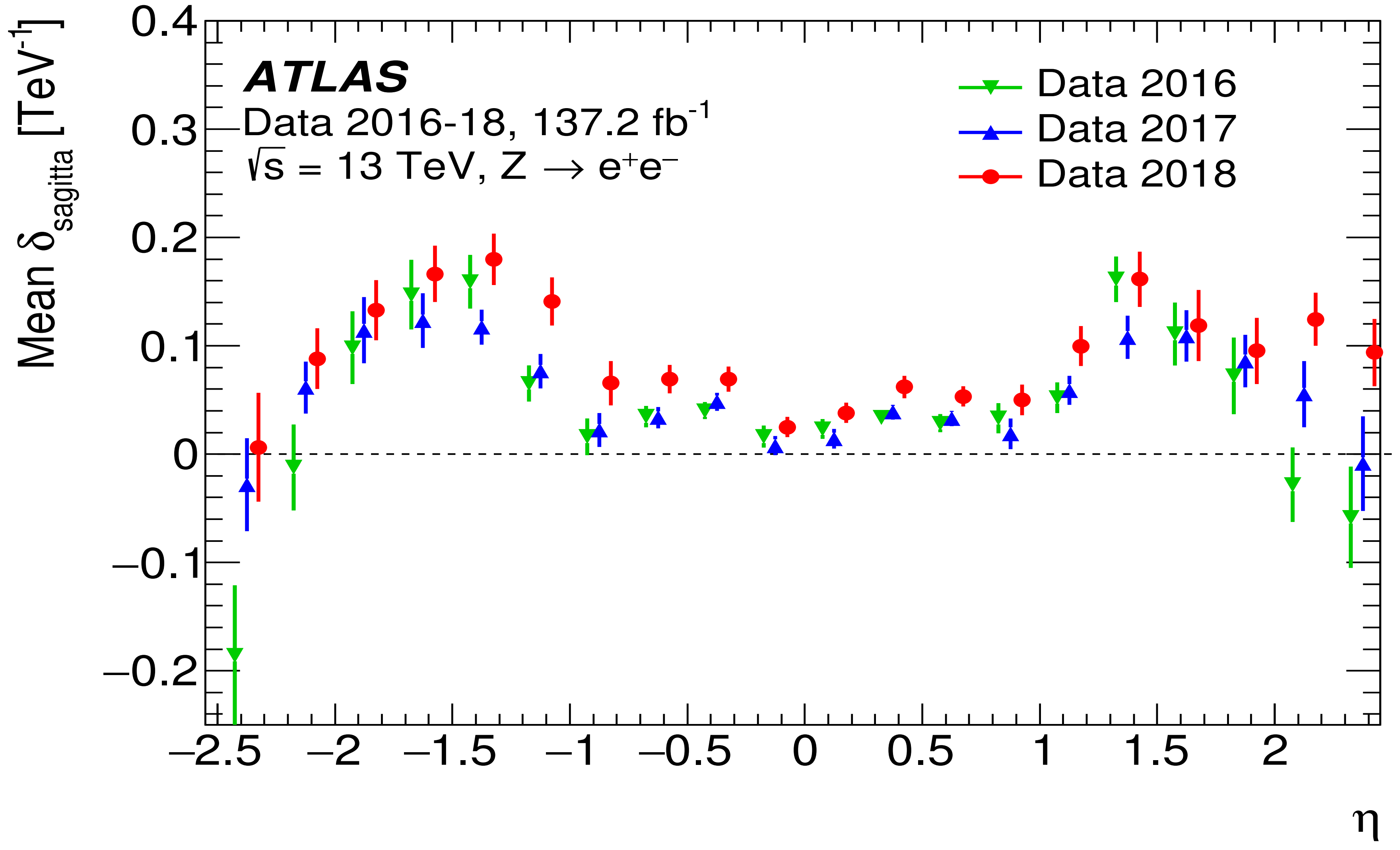
$Z \rightarrow \mu^+\mu^-$ method





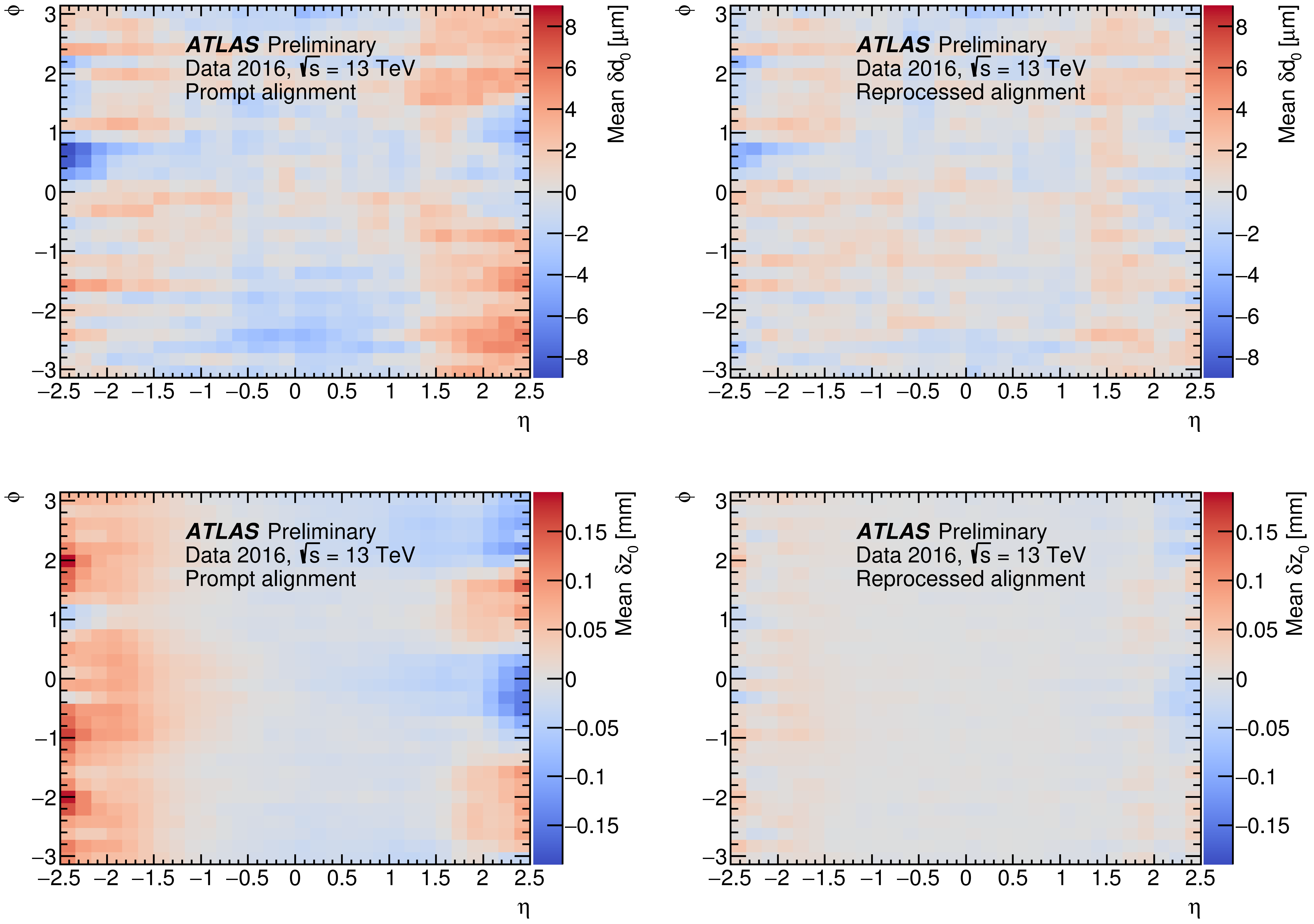
E/p method





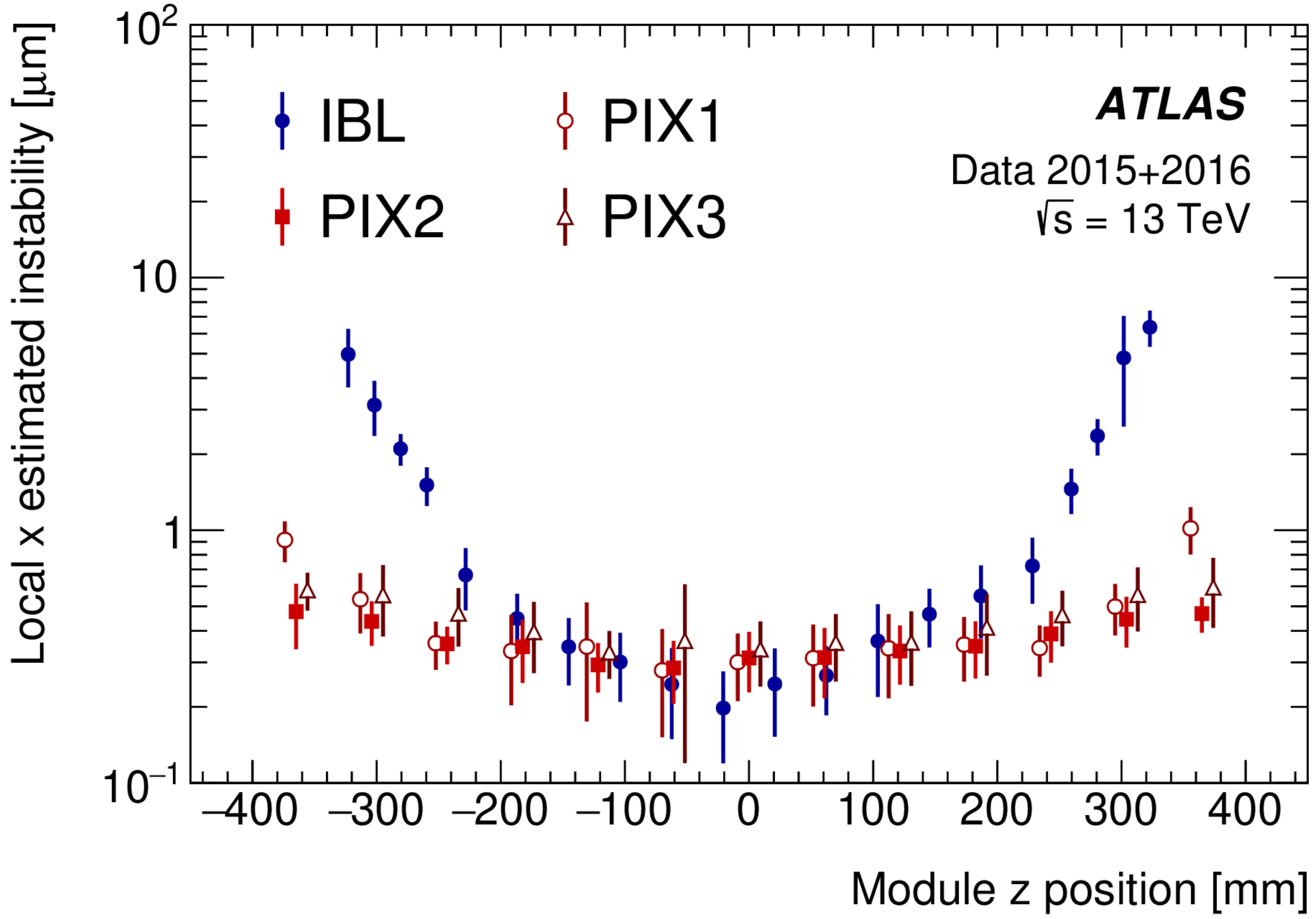
Impact parameter bias

- The fact that both muons from $Z \rightarrow \mu^+\mu^-$ come from the same vertex can be exploited to measure the bias on d0 and z0
- The differences between the values of d_0 and z_0 of each pair of muons from $Z \rightarrow \mu^+\mu^-$ give a measurement of the bias



Stability of the alignment process

- The stability is estimated for each layer and module z-position by integrating over all the ϕ
- The standard deviations of the residuals in x and y position across the fills give a measurement of the stability



Estimated instability

$$\sigma_{x,y}^{time} = \sqrt{\sigma^2_{\langle r_{x,y} \rangle} - \left(\frac{\sigma_{r_{x,y}}}{\sqrt{N}} \right)^2}$$

Conclusion

- A brief introduction to the ATLAS ID track based alignment method has been presented
  - The techniques to measure and minimize track parameter biases has been described
  - The adopted alignment strategy has proven to describe and correct time dependent misalignments within a run
- The effect of several Weak Modes have been studied: Impact parameters, sagitta and length scale biases
  - Results show no hint of a radial expansion of the ID but a global scale bias $\sim 0.9 \times 10^{-3}$
  - The sagitta bias is reduced to less than $\sim 0.1\ TeV^{-1}$ after the full Run 2 Alignment
- Impact parameters biases are reduced at the level of μm
- The description of the detector geometry is measured to be stable at the level of μm for most part of the detector

Backup

Weak Modes: Length scale bias

- Length scale bias is a charge-symmetric alteration of the measured track curvatures

- If the actual radius of a detector module, R, is assumed to be $R(1+\epsilon_r)$, then for small distortions ($|\epsilon_r| \ll 1$), the reconstructed momentum will be

$$p_T' = p_T(1+\epsilon_r)$$

$$p_z' = p_z$$

- Similarly, if the actual longitudinal dimension of a detector module, z, is assumed to be $z(1+\epsilon_z)$, the reconstructed momentum will be:

$$p_T' = p_T$$

$$p_z' = p_z(1+\epsilon_z)$$

- There is a degeneracy between the effects of a bias in the magnetic field and a global scaling of the detector (radial and longitudinal: ϵ_s), as both lead to a momentum bias of the form $p(1+\epsilon_s)$. Then, if the magnetic field B is assumed to be $B(1+\epsilon_s)$ the particle momentum will be:

$$p' = p(1+\epsilon_s)$$

Weak Modes: Length scale bias

- In case of a global radial and longitudinal bias are presented, the relation between the reconstructed invariant mass of a particle decaying to two muons $(m'_{\mu\mu})$ and the true mass $(m'_{\mu\mu})$ is:

$$m'_{\mu\mu} \approx m^2_{\mu\mu} + 2E^+E^-[\beta^+_T - \beta^-_T]^2\epsilon_r + 2E^+E^-[\beta^+_T - \beta^-_T]^2\epsilon_z$$

Where $\beta = E/p$ and this approximation is valid to firs order in ϵ

- In the limit where the muon mass is ignored lead to

$$m'^2_{\mu\mu} \approx m^2_{\mu\mu} + 2m^2_{\mu\mu}\ (\epsilon_s + \epsilon_{r'}\ sin^2\alpha)$$

where

$$sin^2\alpha = E^+E^-\ [\beta^+_T - \beta^-_T]\ /\ m^2_{\mu\mu} \qquad \epsilon_s = \epsilon_z \qquad \epsilon_{r'} = \epsilon_r - \epsilon_z$$

- Measuring the reconstructed mass as a function of $sin^2\alpha$ is possible differentiate the radial distortion from a scale bias

Weak Modes: Sagitta bias

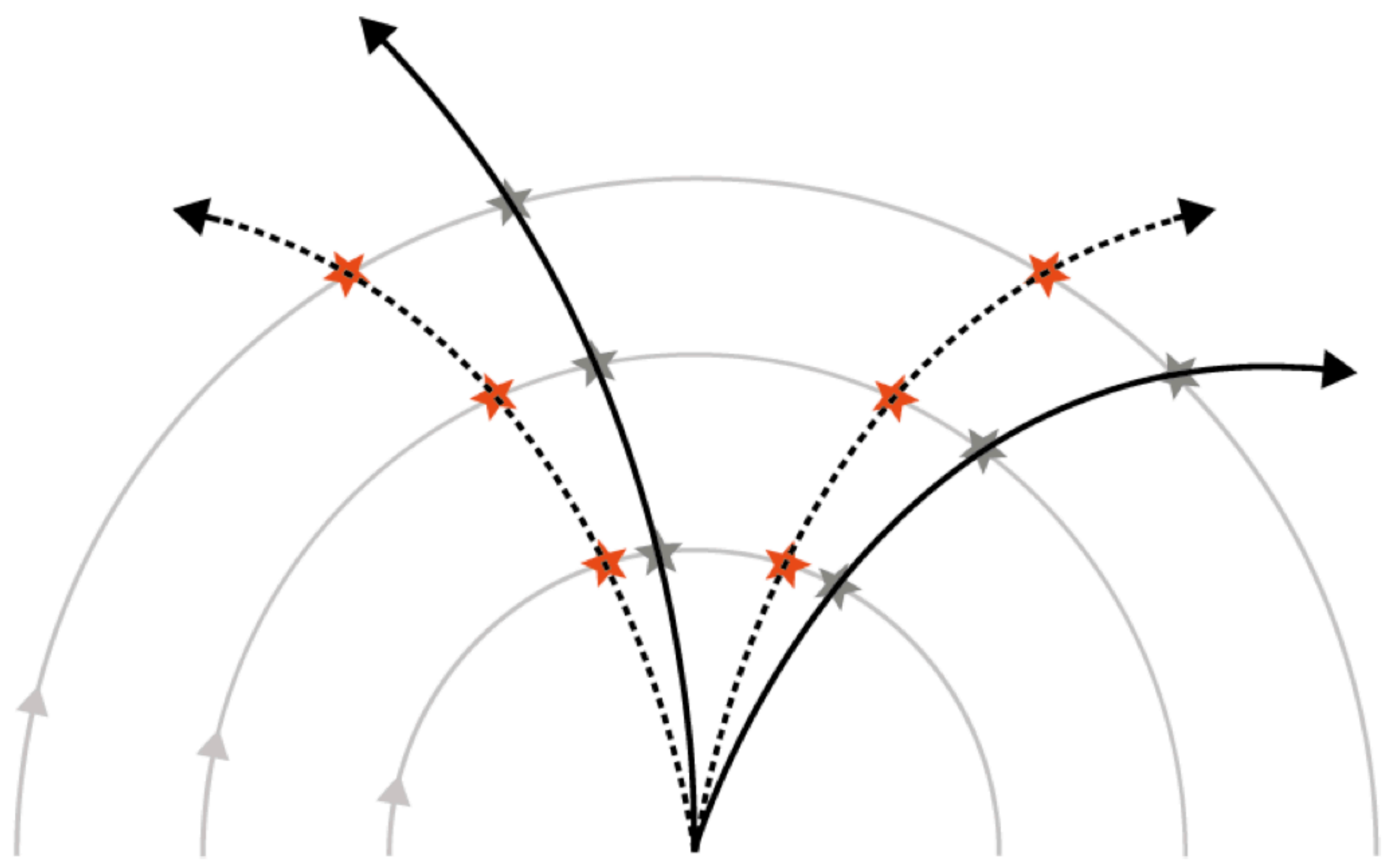
- A sagitta bias is caused by a displacement in the bending plane of the tracks, and a charge-antisymmetric alteration
- The sagitta bias is parametrized as

$$p' = p(1 + q\ p_T\ \delta_{sagitta})^{-1}$$

where q is the charge of the particle and $\delta_{sagitta}$ the value of the distortion

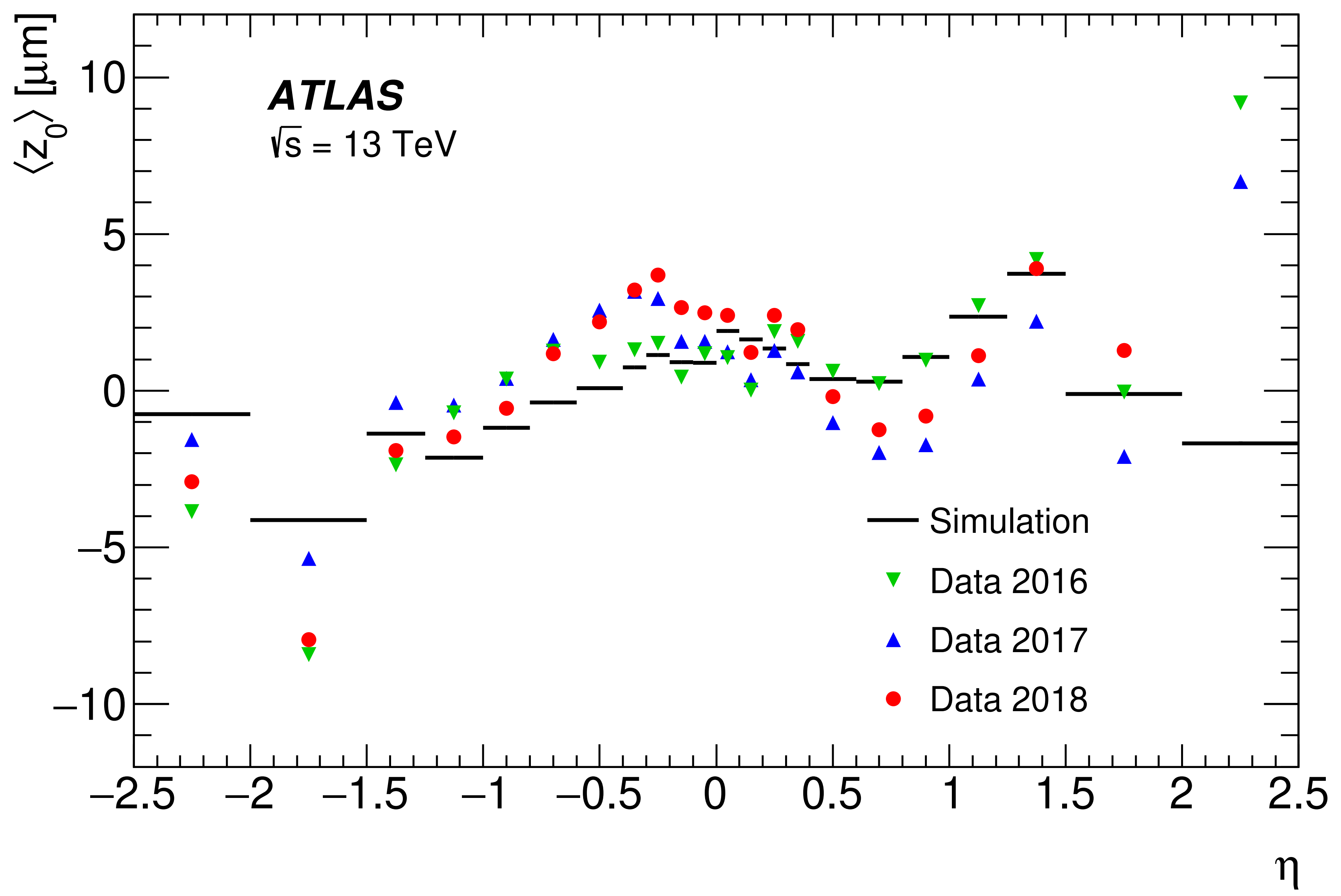
- The $Z \to \mu^+\mu^-$ decays are used to determine the value of the $\delta_{sagitta}$
- An iterative process is used to determine $\delta_{sagitta}$. For the i-th iteration, $\delta_{sagitta}$ computed for every muon in the $Z \to \mu^+\mu^-$ samples with:

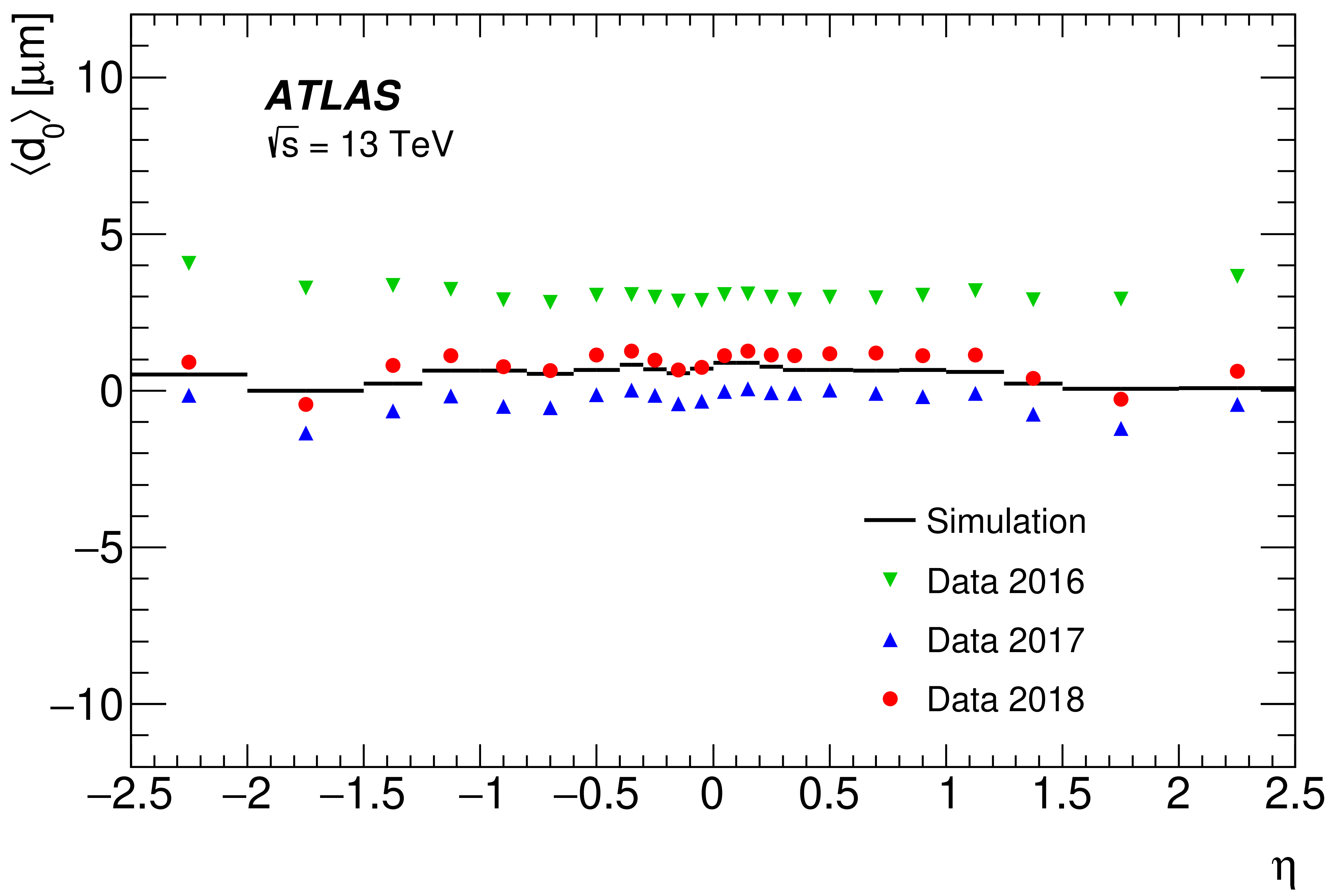
$$\delta_{sagitta,i}(\eta,\phi) = -q\frac{m_{\mu\mu}^2 - m_Z^2}{2m_Z^2}\frac{1 + qp'_T\delta_{sagitta,i-1}(\eta,\phi)}{p'_T} + \delta_{sagitta,i-1}(\eta,\phi)$$



Weak Modes: Impact parameter bias

- The weak mode can also lead to a bias in the transverse (d_0) and longitudinal (z_0) impact parameter
- This bias can be extracted from the difference values of d_0 and z_0 of each pair of muons
- This measure for Dijet samples are:

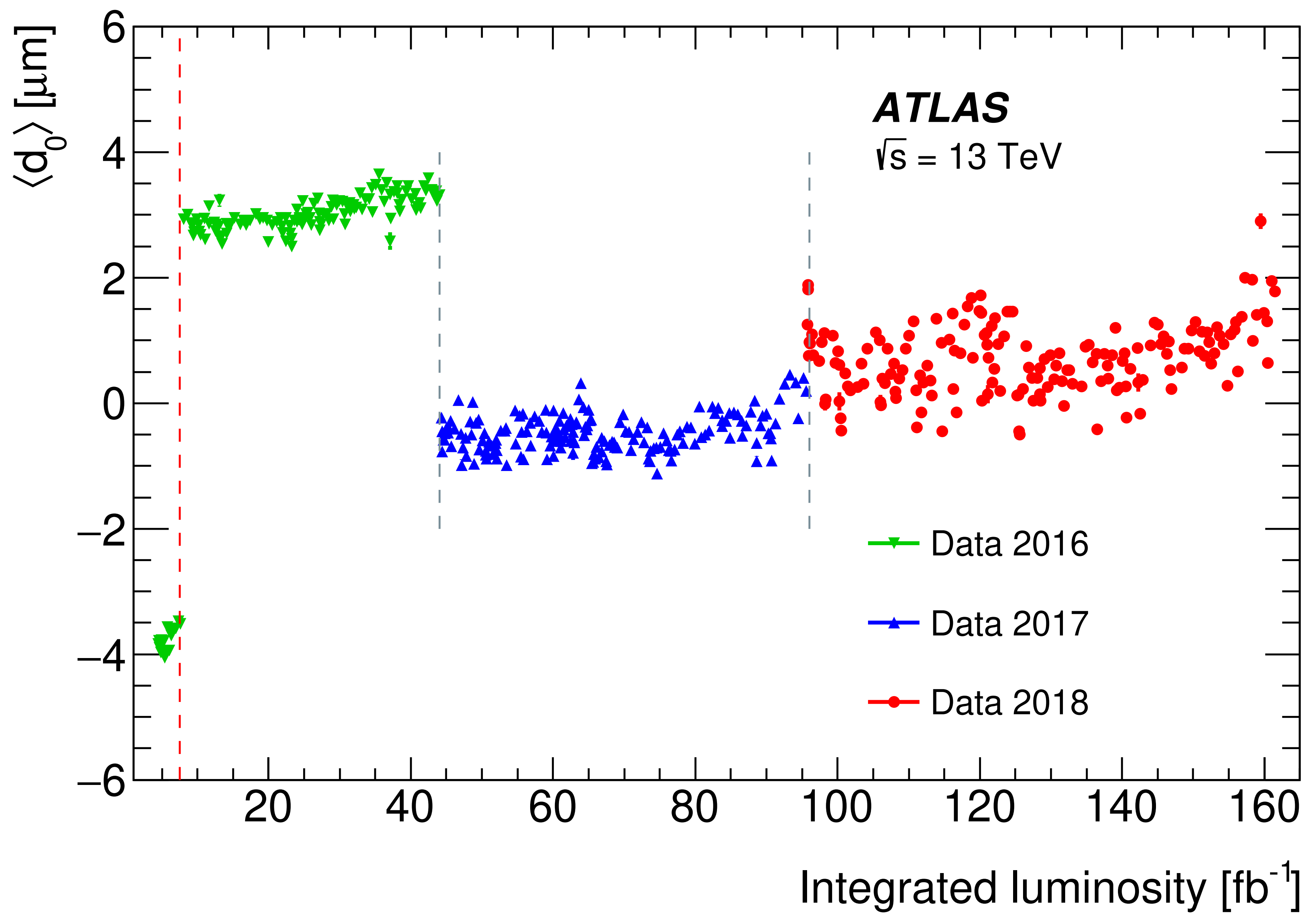


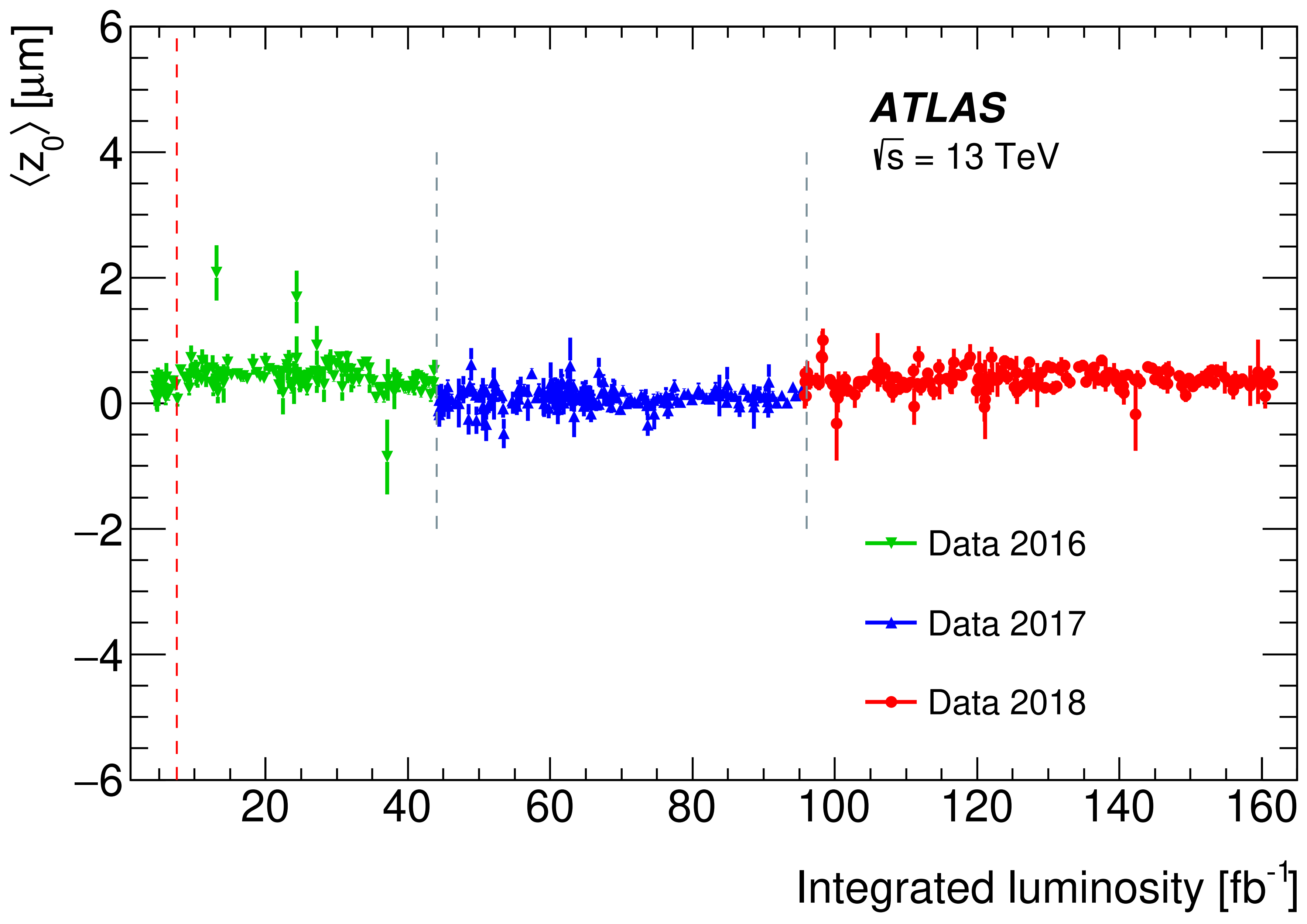


- The small bias in z_0 is not introduced by the track based alignment

Impact parameter bias

- The transverse (d_0) and longitudinal (z_0) impact parameter bias as a function of the Run 2 delivered luminosity





- The bias in Data collected 2016 was introduced by a change in the underlying geometry of the ATLAS ID
- Overall d_0 biases of less than 1μm for Data collected in 2017 and 2018
- The z_0 bias is negligible and constant across the year (below $0.5\ \mu m$)

Stability of the alignment process

- The stability is estimated for each layer and module z-position by integrating over all the ϕ
- The standard deviations of the residuals in x and y position across the fills give a measurement of the stability