Inner Detector Alignment development and performance in preparation for Run 3

Paolo Sabatini, on the behalf of the ATLAS Tracking Group
Instituto de Física Corpuscular (IFIC), UV/CSIC, Valencia

Connecting The Dots 2022 —02/06/22

ATLAS Inner Detector

ATLAS detector: a general-purpose experiment located on LHC @ CERN.
Collecting and analysing data from pp collisions @ $\sqrt{s} = 13$ TeV — moving to 13.6 TeV !

Inner Detector (ID) is the **closest** detector to the **interaction point**

Composed by **3 sub-detectors** using **3 different technologies**.

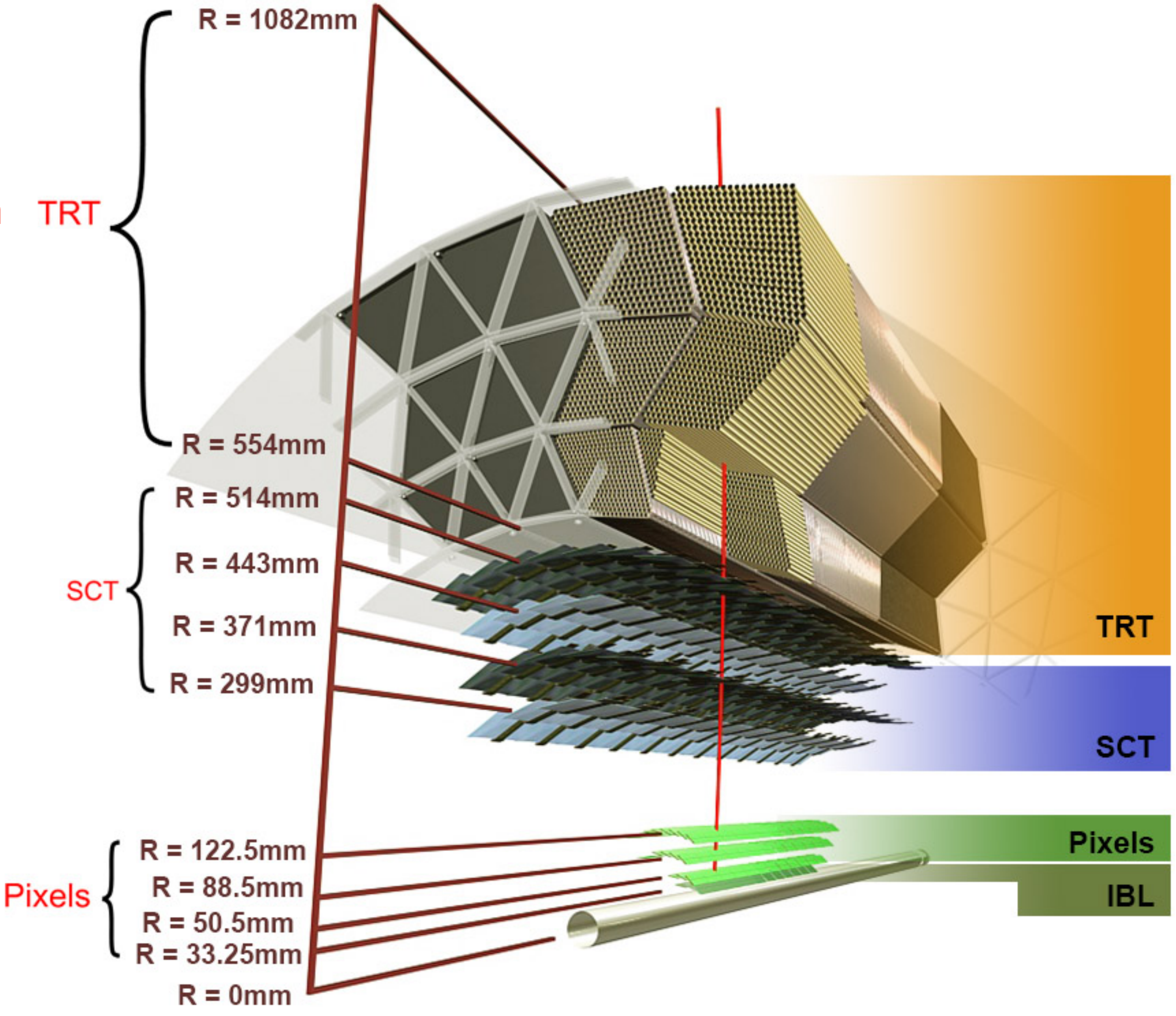
All structured in barrel layers + endcaps:

Complex geometry Almost **750k** DoFs

Transition Radiation Tracker
350k straw tubes

Silicon strips detector
4088 strip modules

Pixel +
Insertable B-Layer
1744+280 modules



ATLAS ID alignment

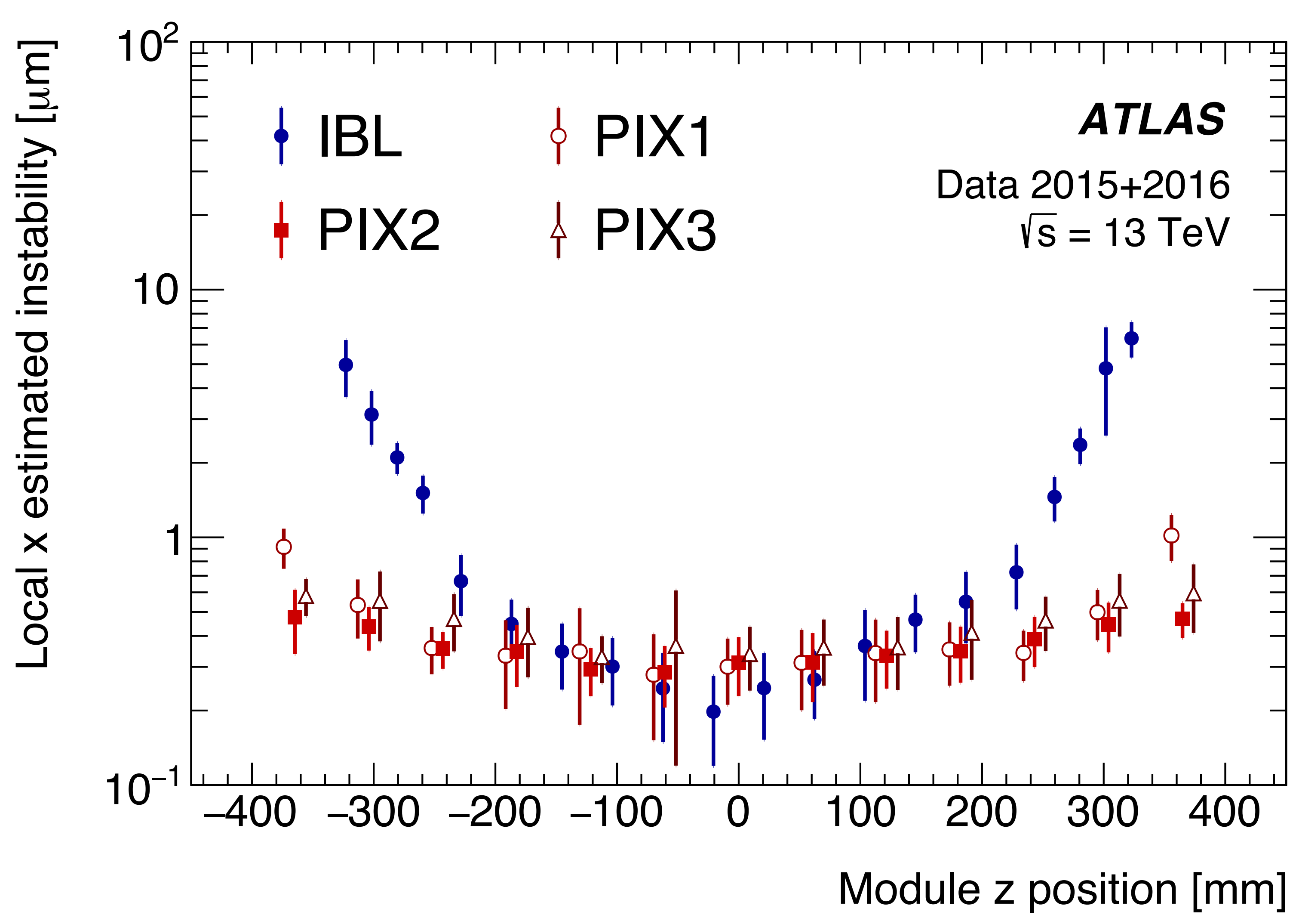
Eur. Phys. J. C 80 (2020) 1194

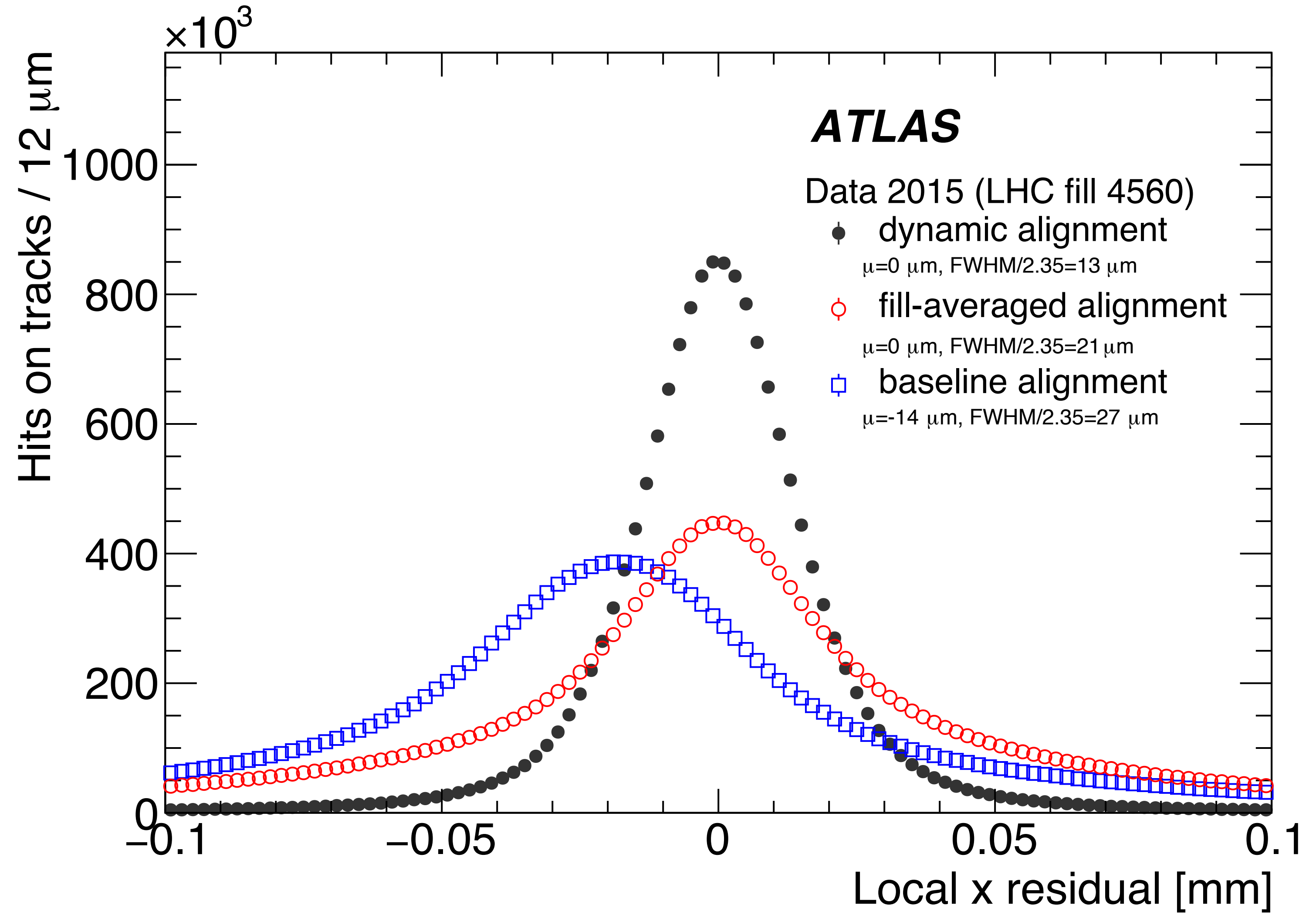
Track-based alignment: track-hit residuals minimisation

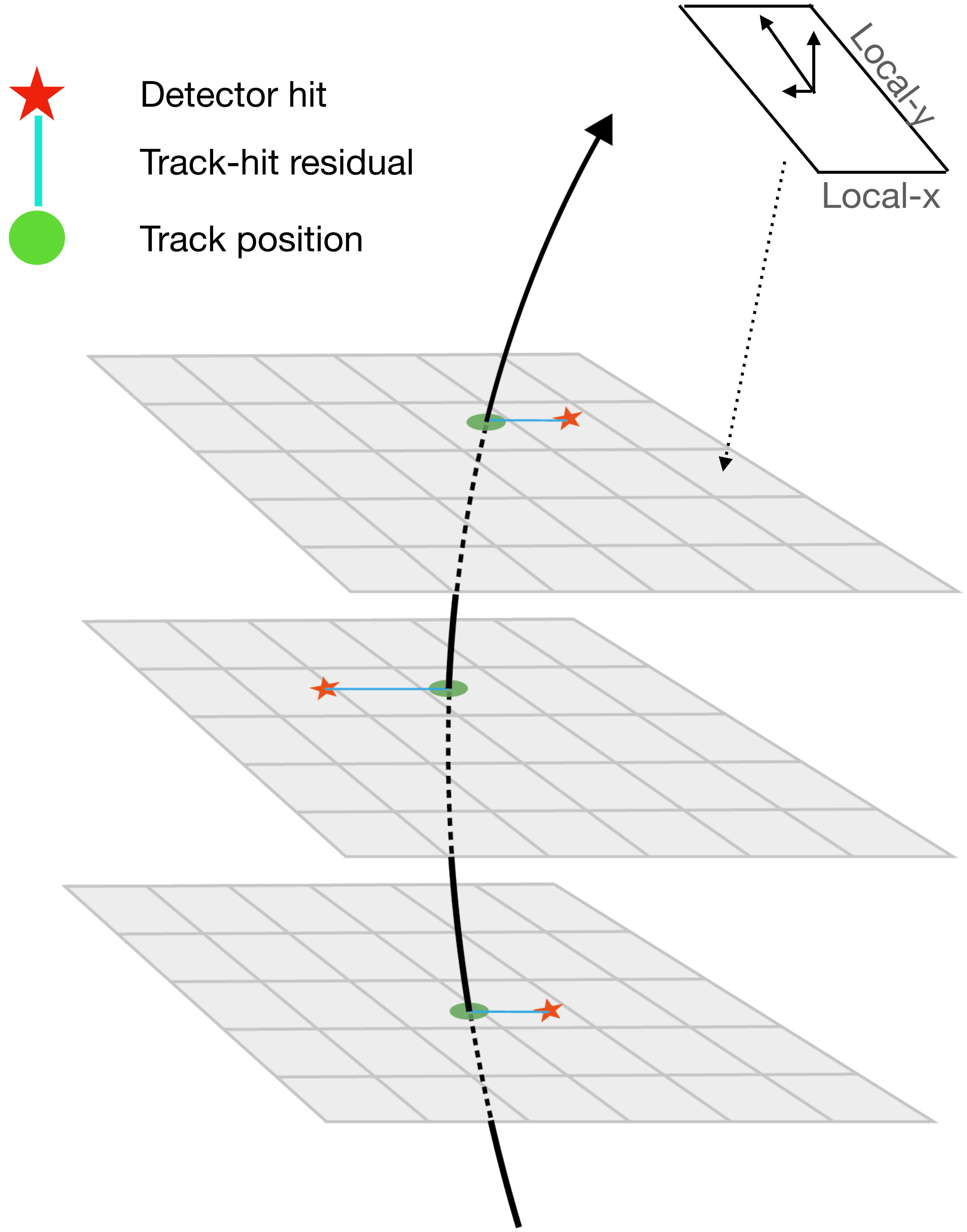
Alignment proceeds in a sequence hierarchical levels:

- Global mechanical assembly: aligned multiple times within the LHC fill
- Module level alignment: updated only few times a year.

Detector geometry described at the level of μm in $r\phi$ direction.







Alignment weak modes

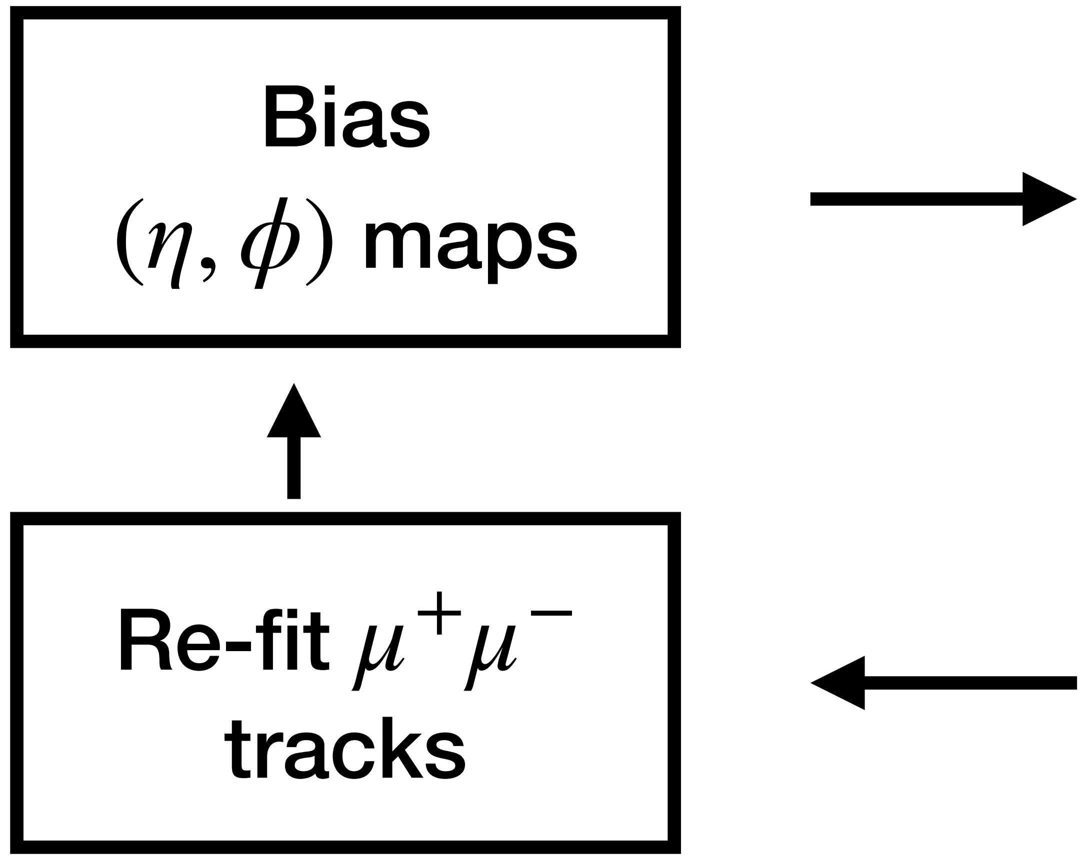
Eur. Phys. J. C 80 (2020) 1194

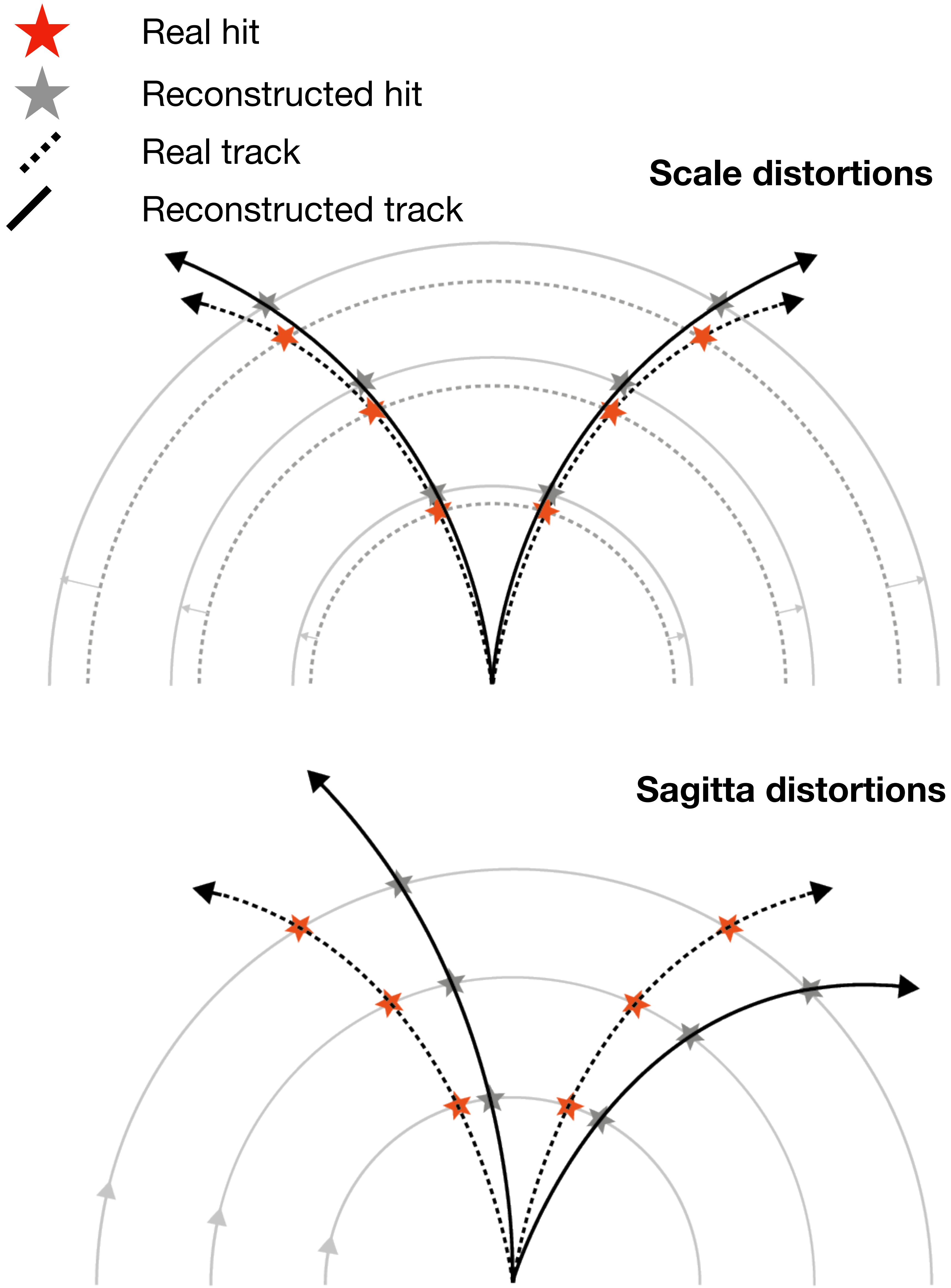
Weak modes: coherent detector distortions

- Track-hit residuals unchanged
- Bias in track parameters introduced

Biases measured with $\mu^+\mu^-$ (or e^+e^-) resonances ($Z, J/\psi$)

Biases used as **track parameter constraints** in the alignment





Goal: keep residual to zero and remove the track biases

Tracking development for Run 3

ATL-PHYS-PUB-2021-012

IDTR-2021-001

Many developments introduced in the reconstruction suite:

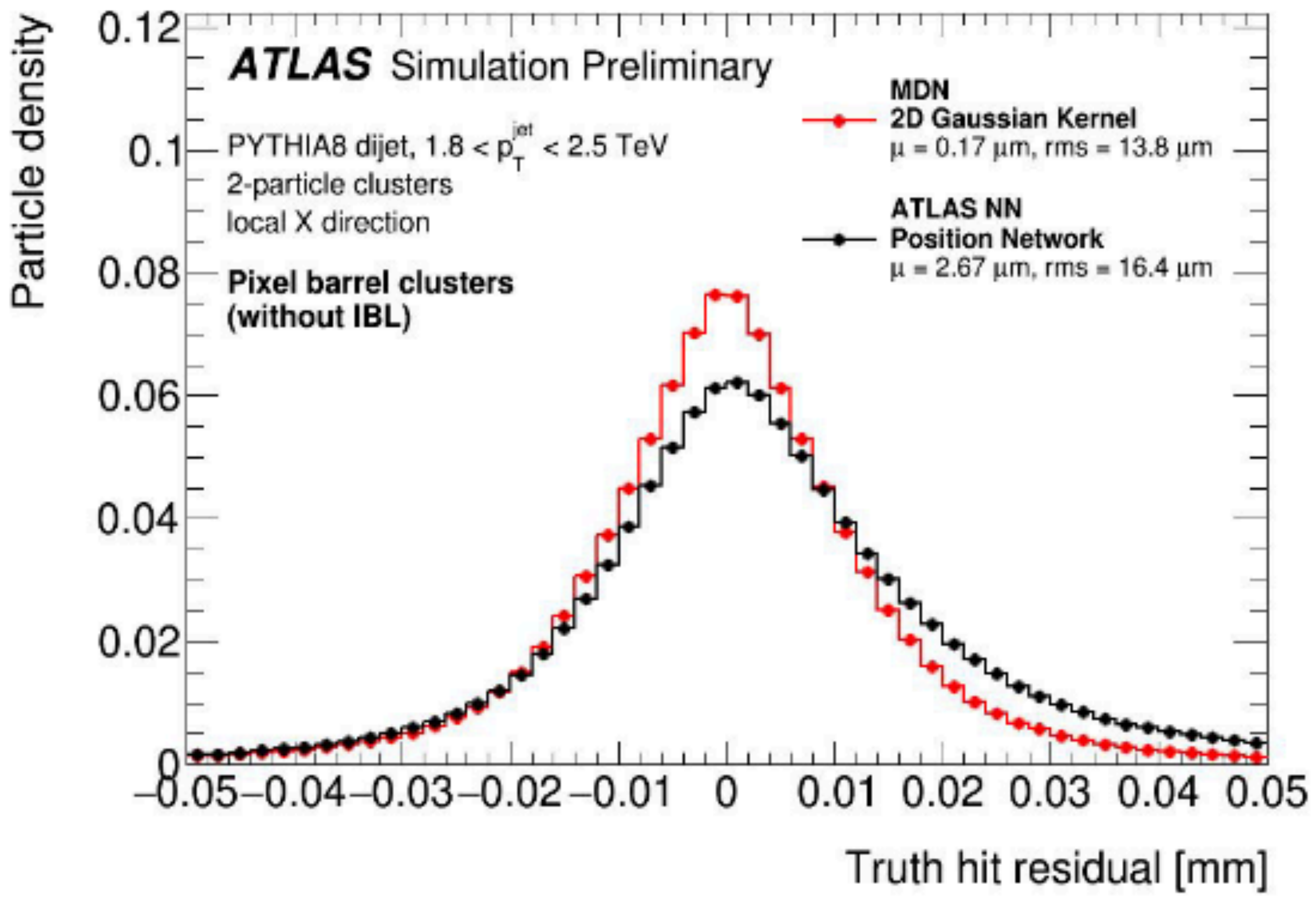
- **Quicker**: up to 2 times faster and memory saving!
- **Better**: less fake tracks, high efficiency on “real” tracks.

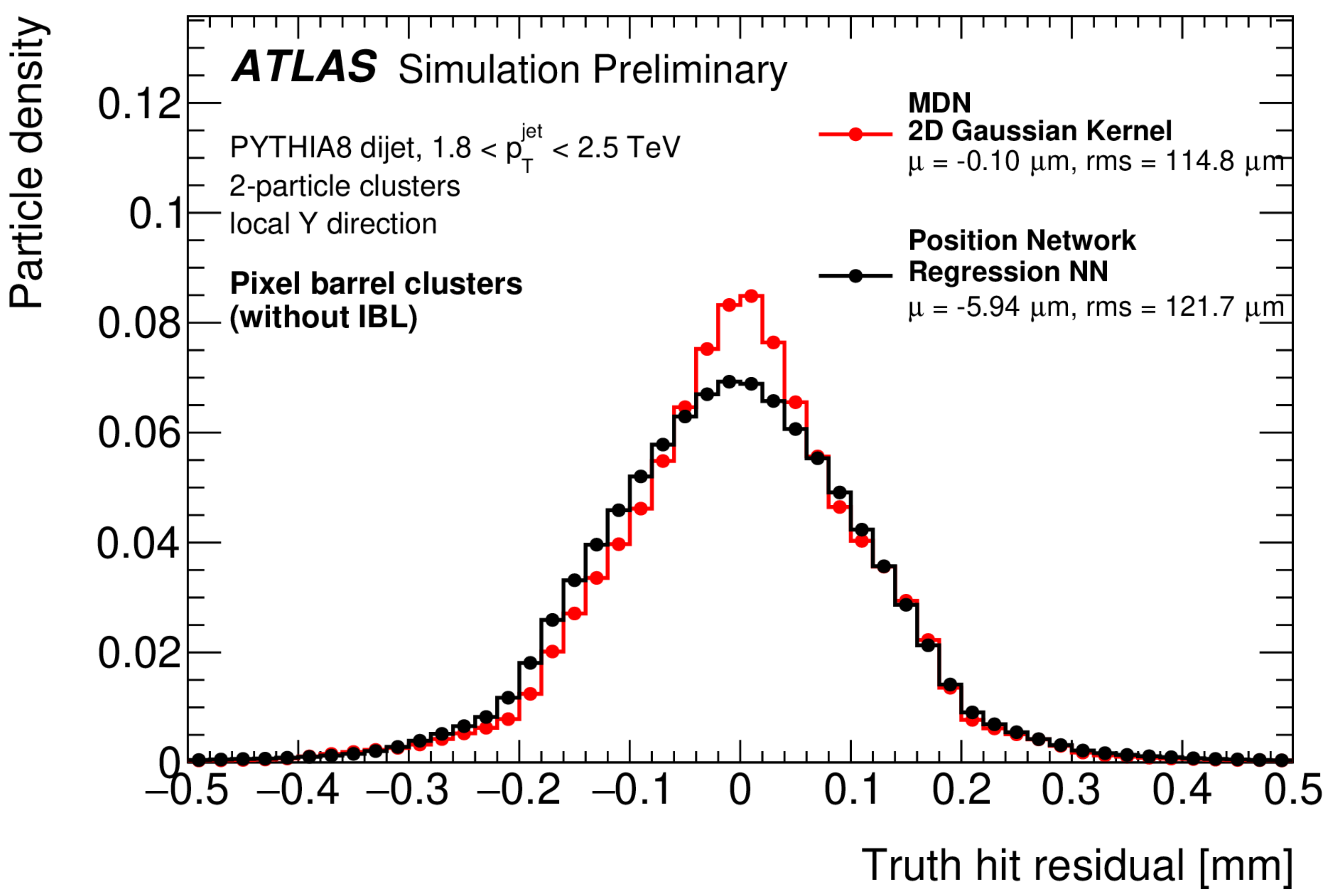
Interested?
Check out Makayla’s poster!

New Pixel cluster position estimation based on **Mixture Density Network (MDN)**

- **Better resolution** compared to Run 2 NN in crowded detector expected in Run 3

Run 2 data reprocessed with these developments!



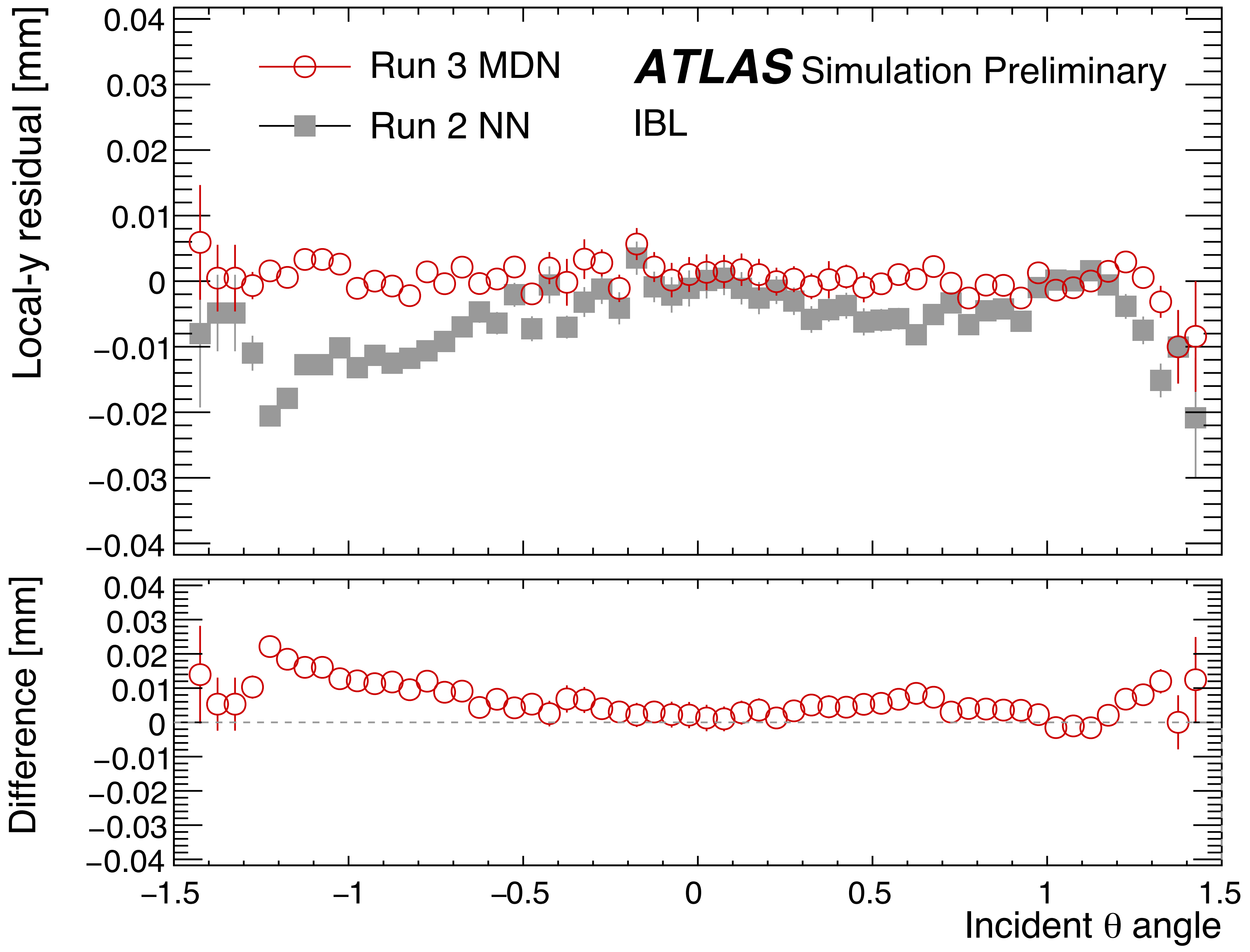


Why another alignment?

Bias in position along beam axis (local-y) introduced by the Run 2 version of the algo. (Run 2 NN)

- Strong dependence on the incident angle = track η
- No such bias in MDN — new alignment needed

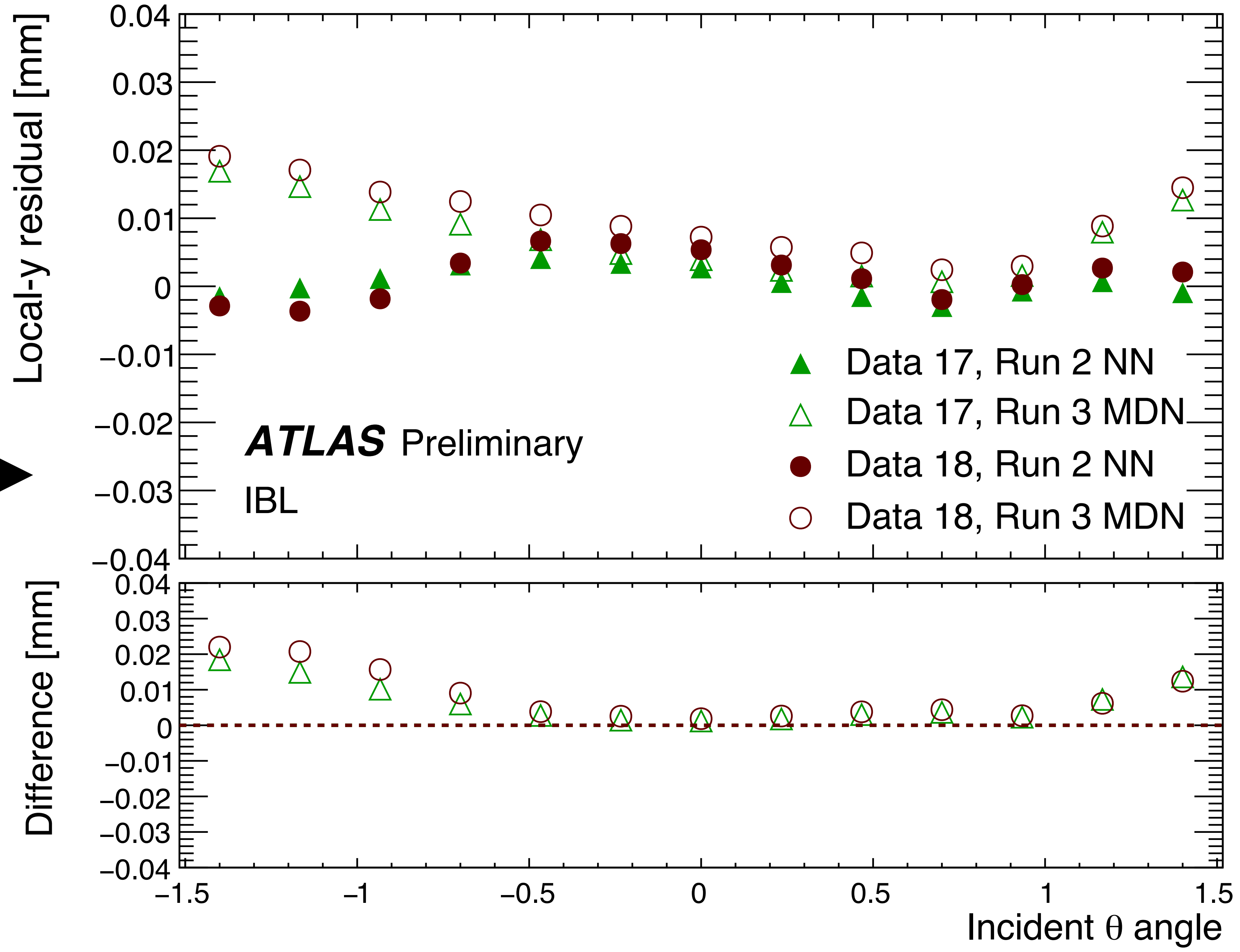
MC events



Alignment constants

- Derived with Run 2 NN
- Absorb the bias in the constants
- Over-compensates in data with MDN

Data events

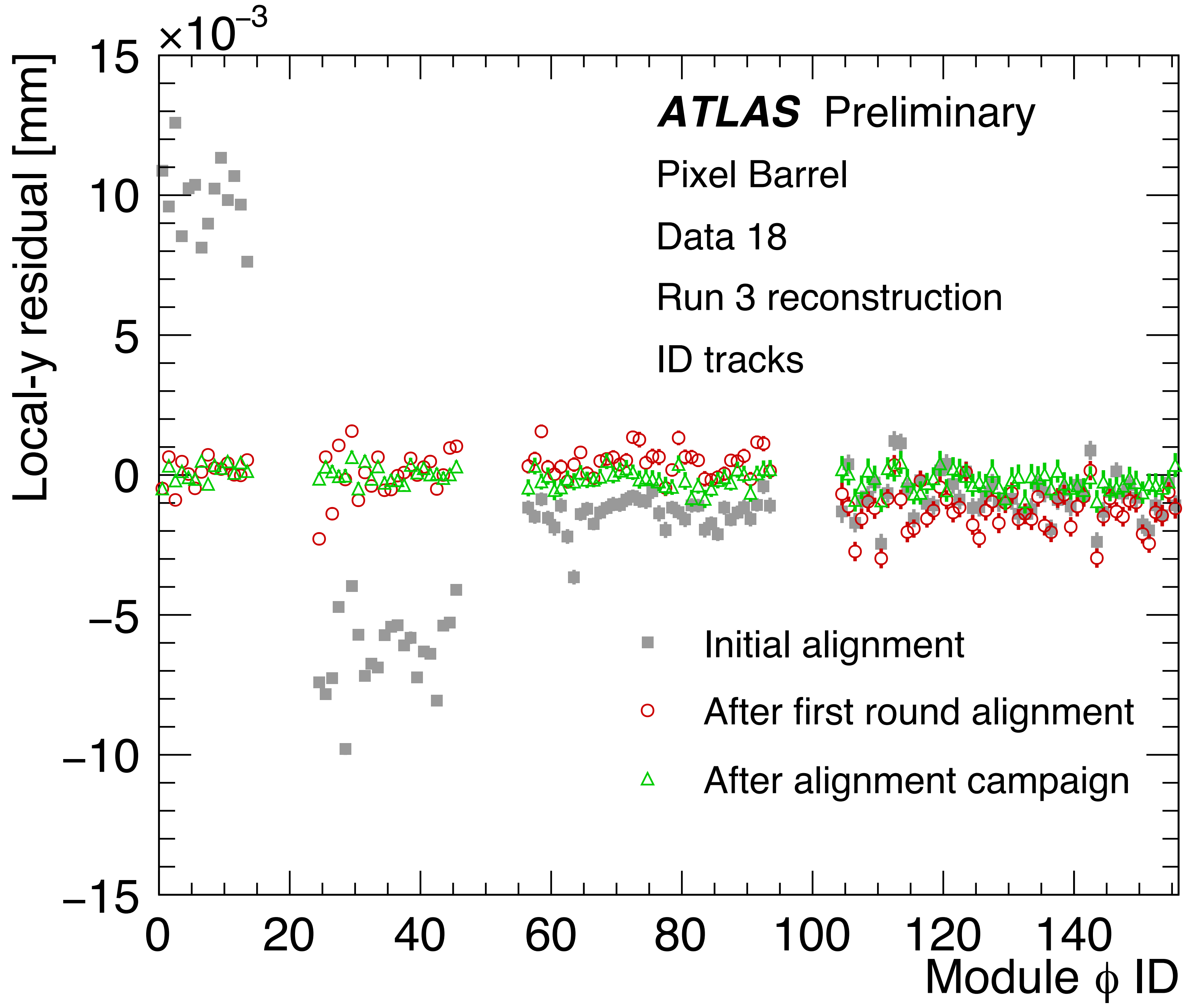


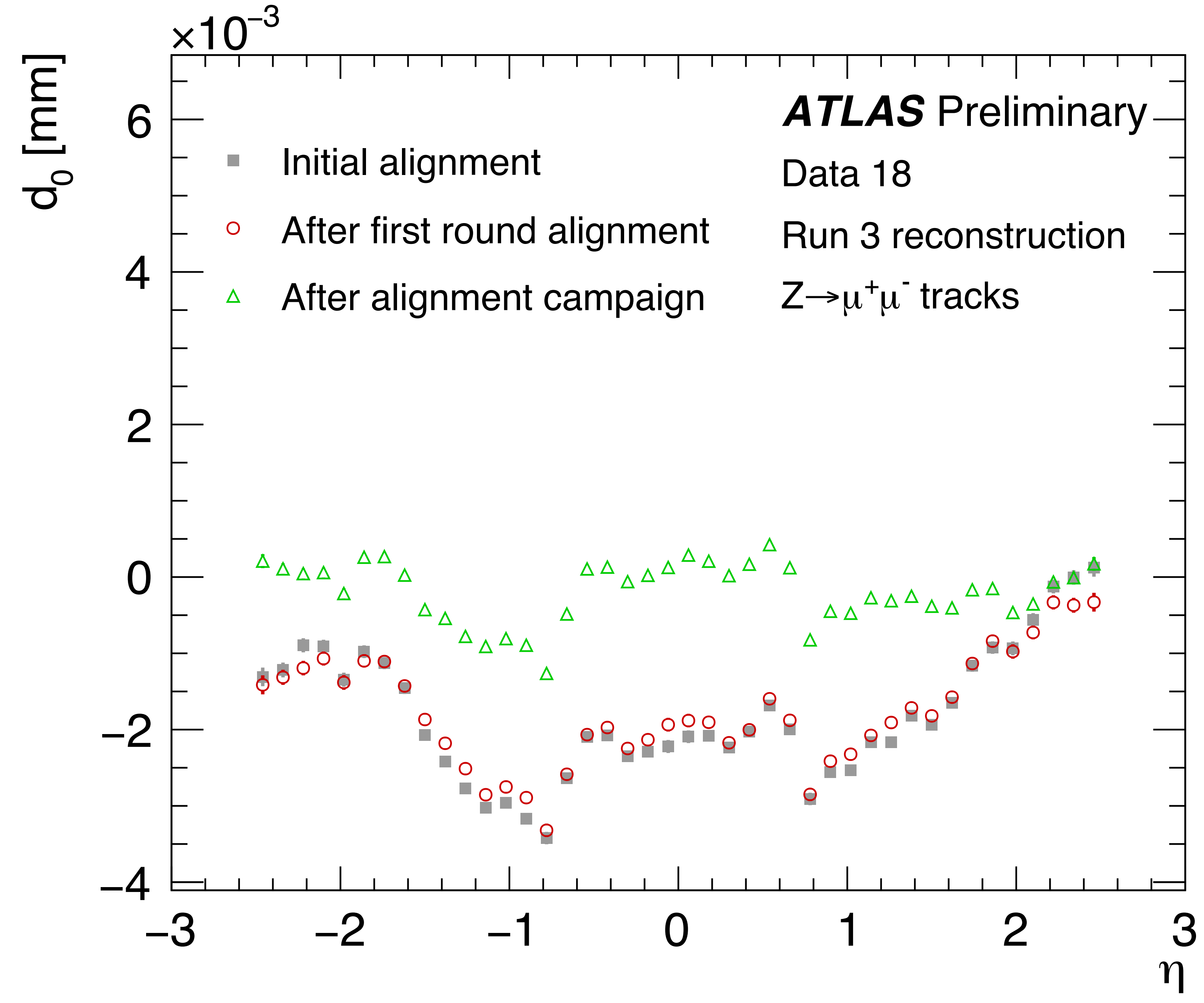
ATL-PHYS-PUB-2022-028

Alignment strategy

Two rounds of module-level alignment iterations are performed (Pixel barrel layers + endcaps)

- First round: minimisation of track-hit residuals. **grey points** ⟶ **red points**
- Second round: track parameter biases (IP, sagitta) measured on $Z(\mu^+\mu^-)$ events **red points** ⟶ **green points**
  - Weak mode found and cured: (η, ϕ) maps of IP and sagitta biases used as constraints for tracks in alignment iterations





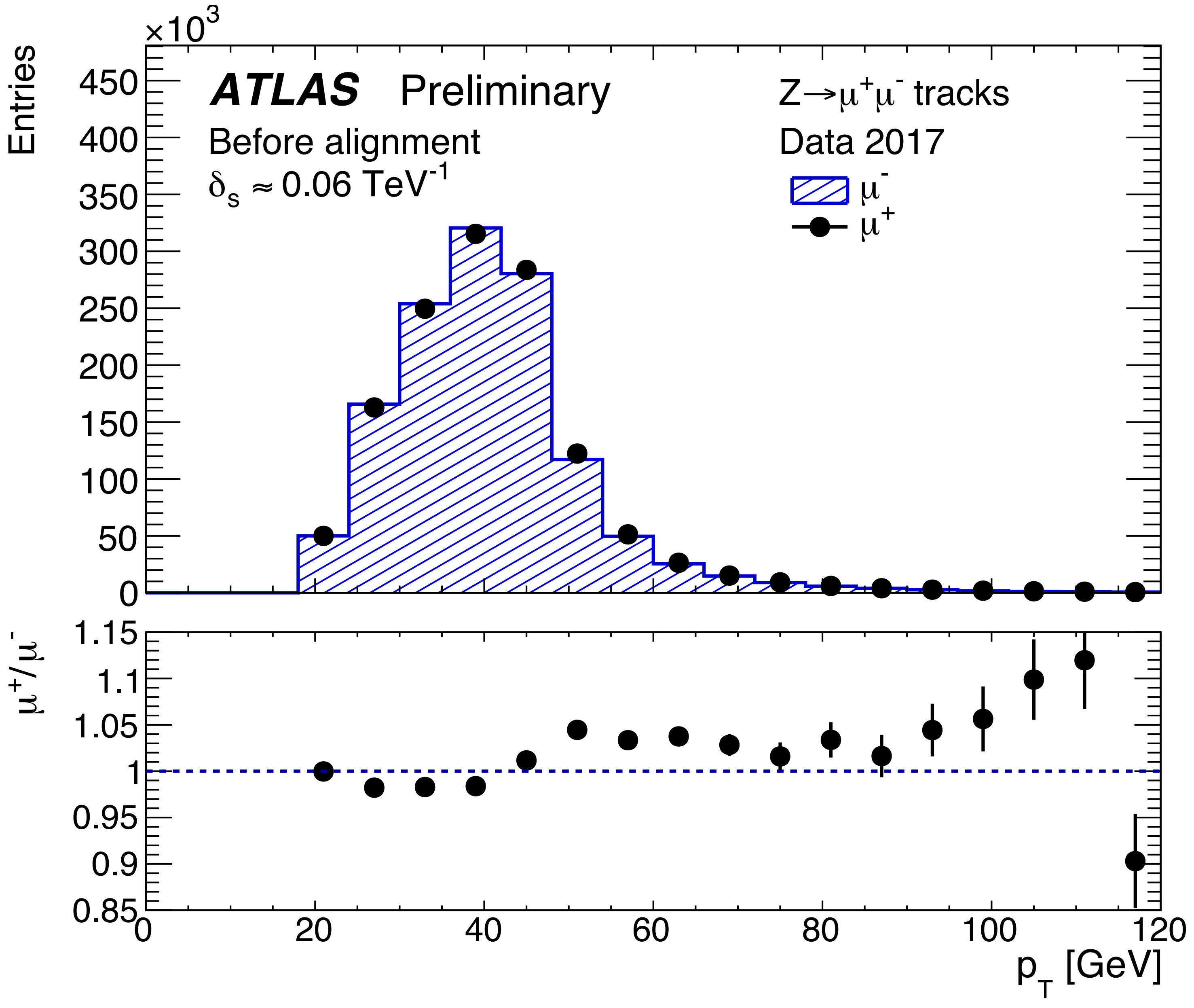
Global sagitta bias reduction

[Eur. Phys. J. C 80 (2020) 1194](#)
[ATL-PHYS-PUB-2022-028](#)

Sagitta bias (δ_s) used as constraints in the alignment iteration for the re-alignment campaign

- ***Mass*** method currently used: not sensitive to global biases, only to local ones
- **Workaround**: differences in p_T distribution of positive and negative muons to estimate global bias

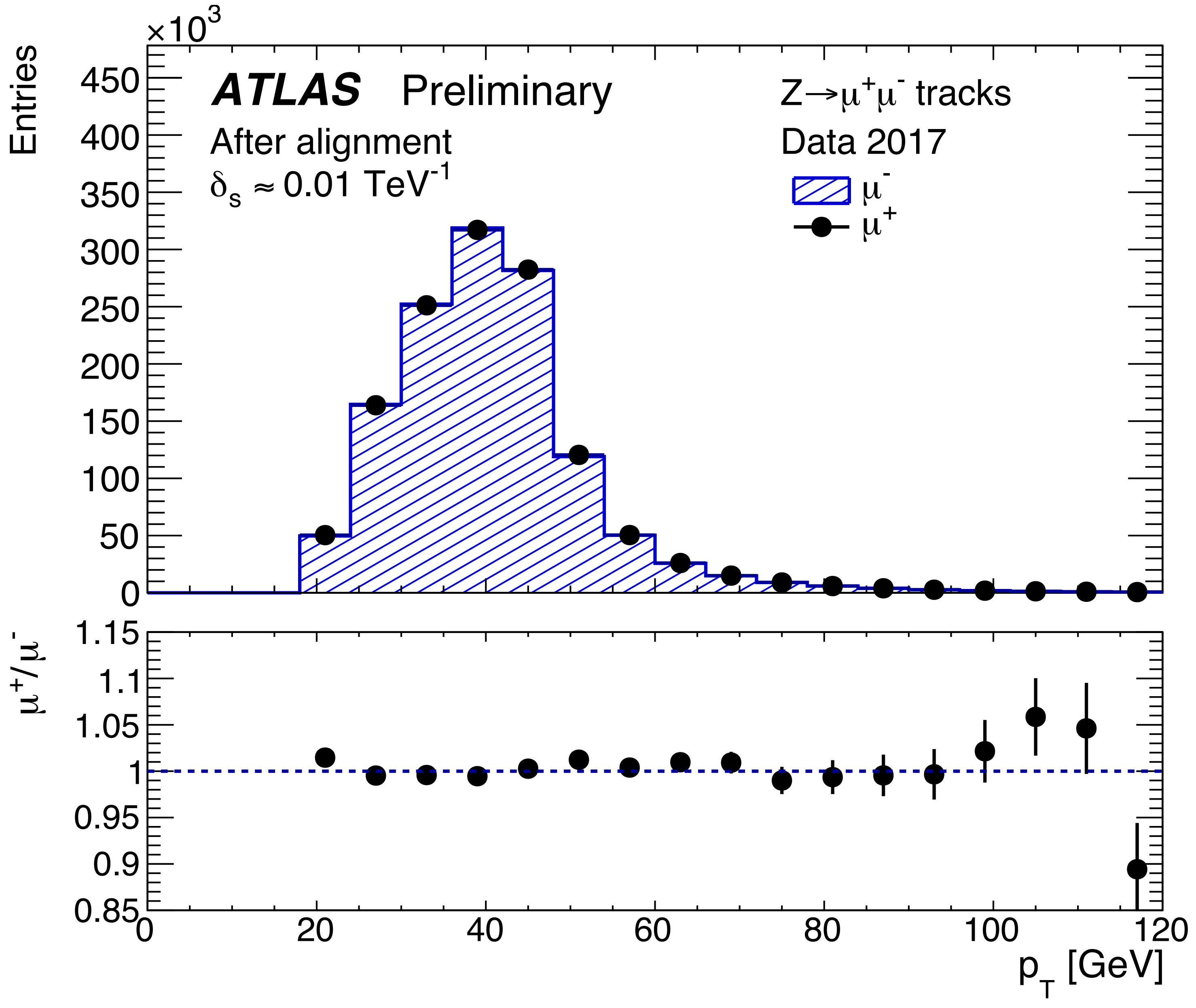
This technique reduces the global bias from 0.06/TeV to 0.01/TeV.



Measure the global bias and inject in maps

$$p'_{\mathrm{T}} = p_{\mathrm{T}}\left(1 + q\,p_{\mathrm{T}}\delta_s\right)^{-1}$$

$$\delta_s = -\frac{1}{\langle p_{\mathrm{T}}\rangle}\frac{\langle p_{\mathrm{T}}^{+}\rangle - \langle p_{\mathrm{T}}^{-}\rangle}{\langle p_{\mathrm{T}}^{+}\rangle + \langle p_{\mathrm{T}}^{-}\rangle}$$



Global sagitta bias reduction (II)

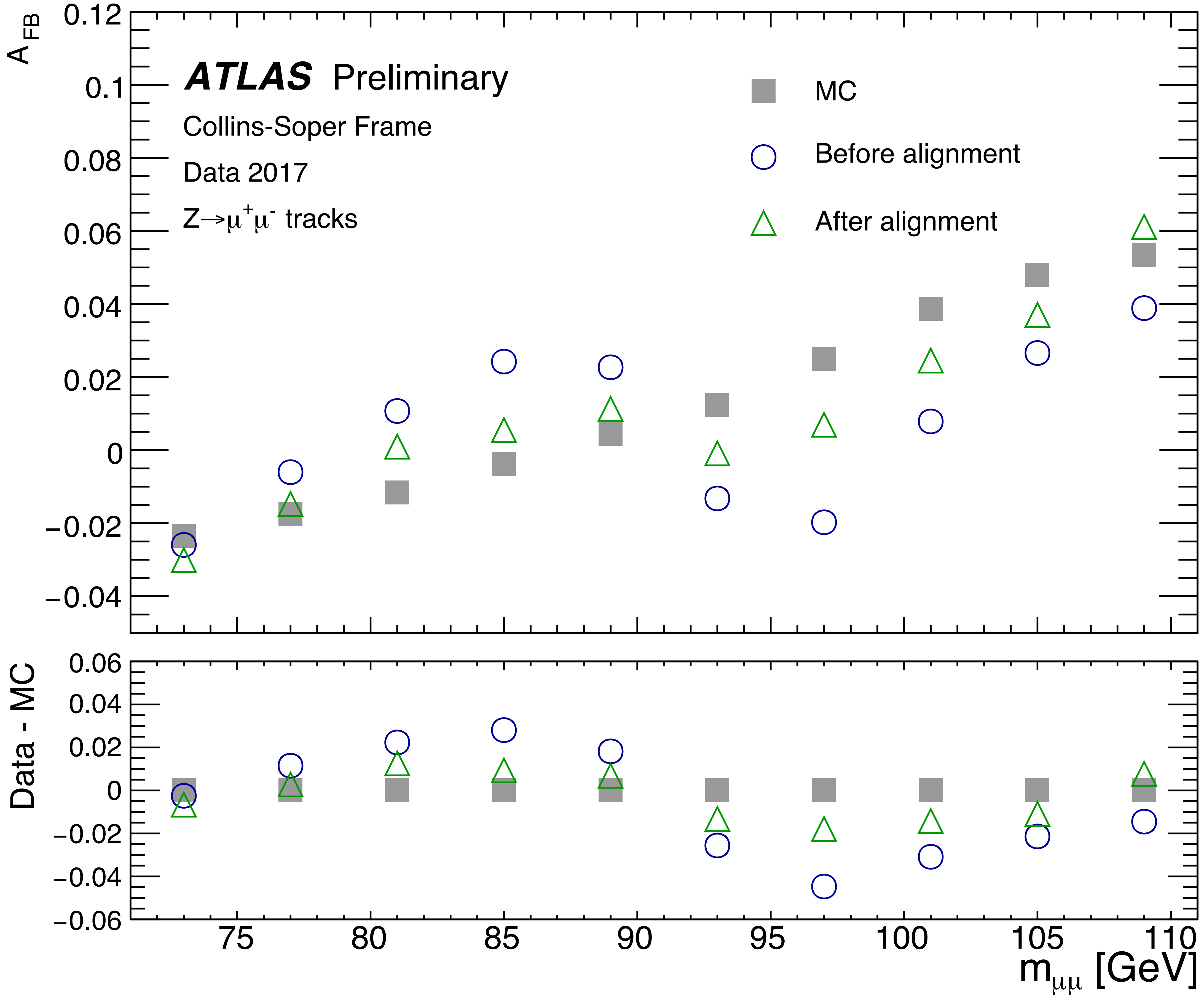
ATL-PHYS-PUB-2022-028

Do we cancel any physics here?

Looking at the reconstructed **forward-backward asymmetry** (A_{FB}) in $Z(\mu^+\mu^-)$ events.

Fortunately **not canceled in data events**:

- Asymmetry still present in data
- Sagitta bias appear as a "**wiggle**"
- Wiggle reduced after alignment!



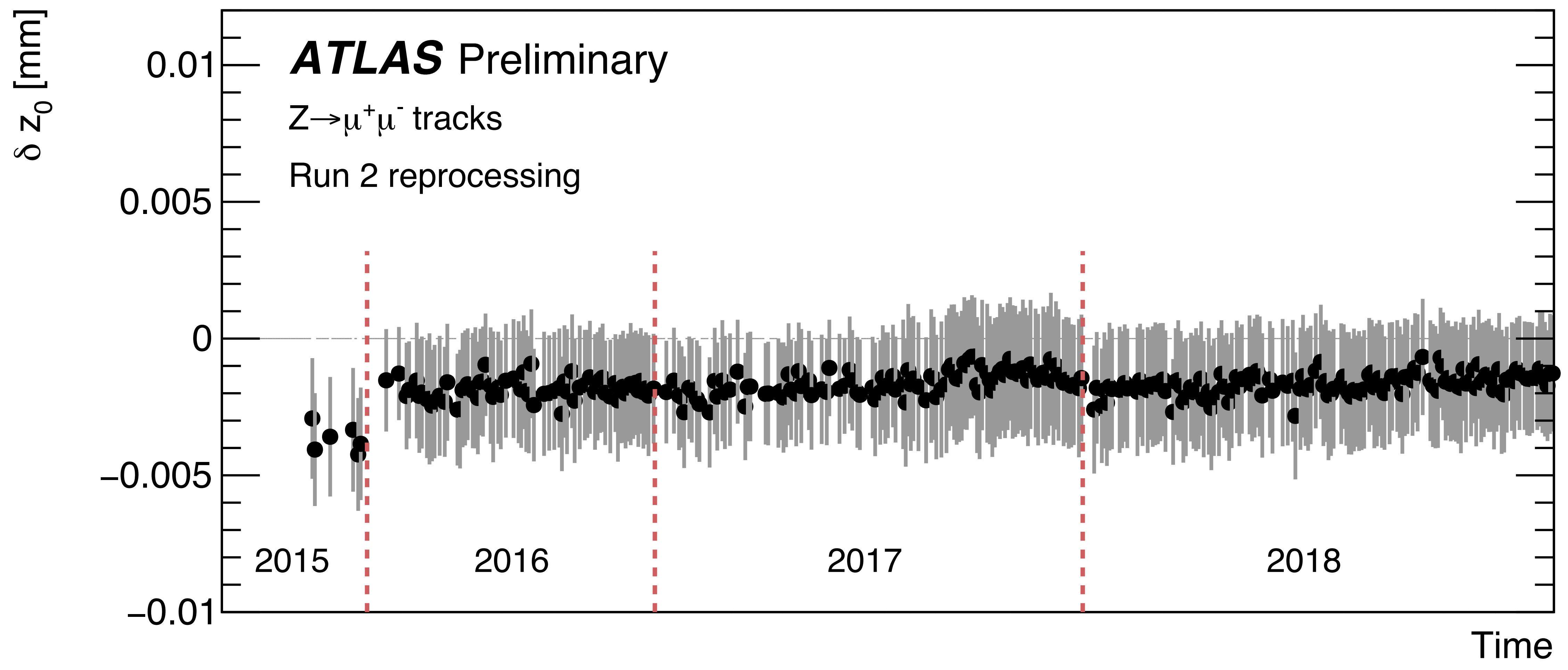
Re-alignment performance

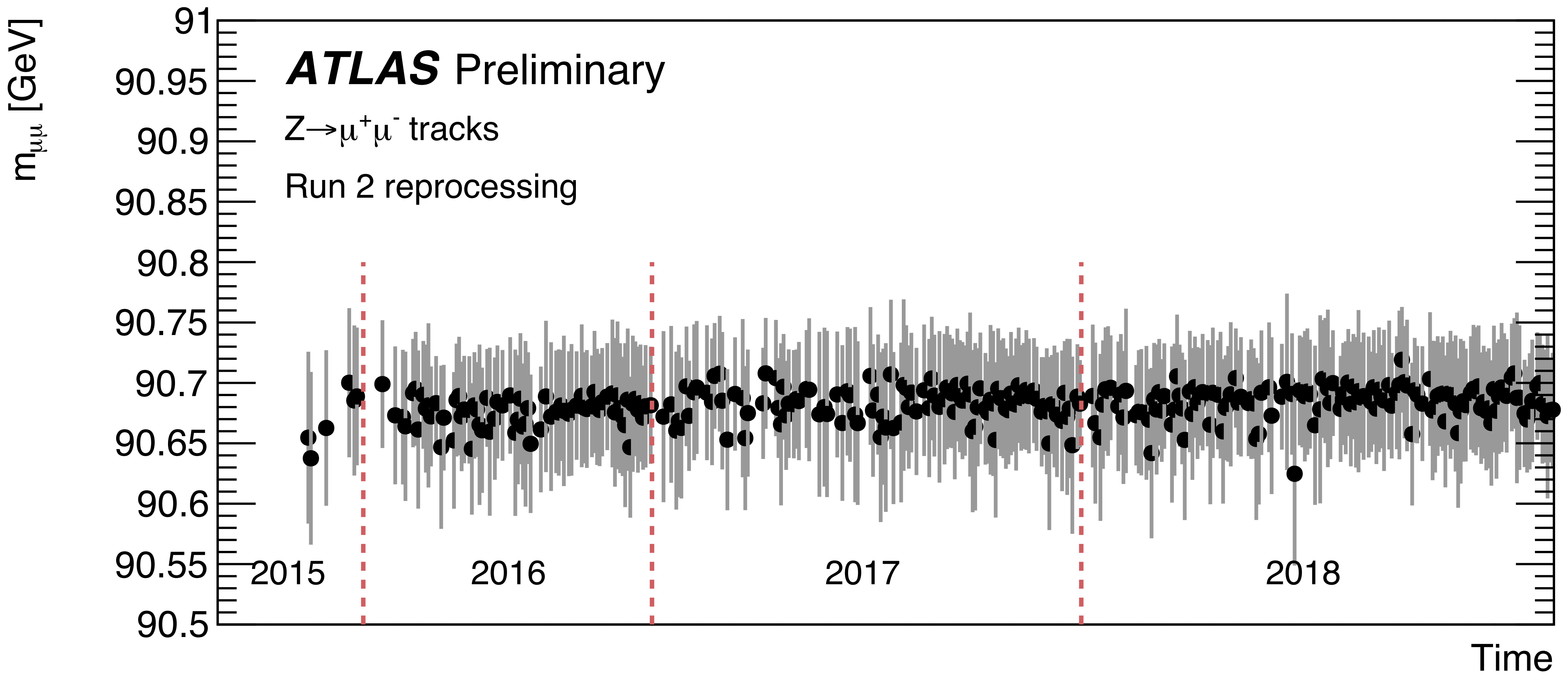
Bias on track IP, estimated by $\delta \mathrm{IP} = (\mathrm{IP}_{+} - \mathrm{IP}_{-})$ in $Z(\mu^{+}\mu^{-})$ are small and stable in time

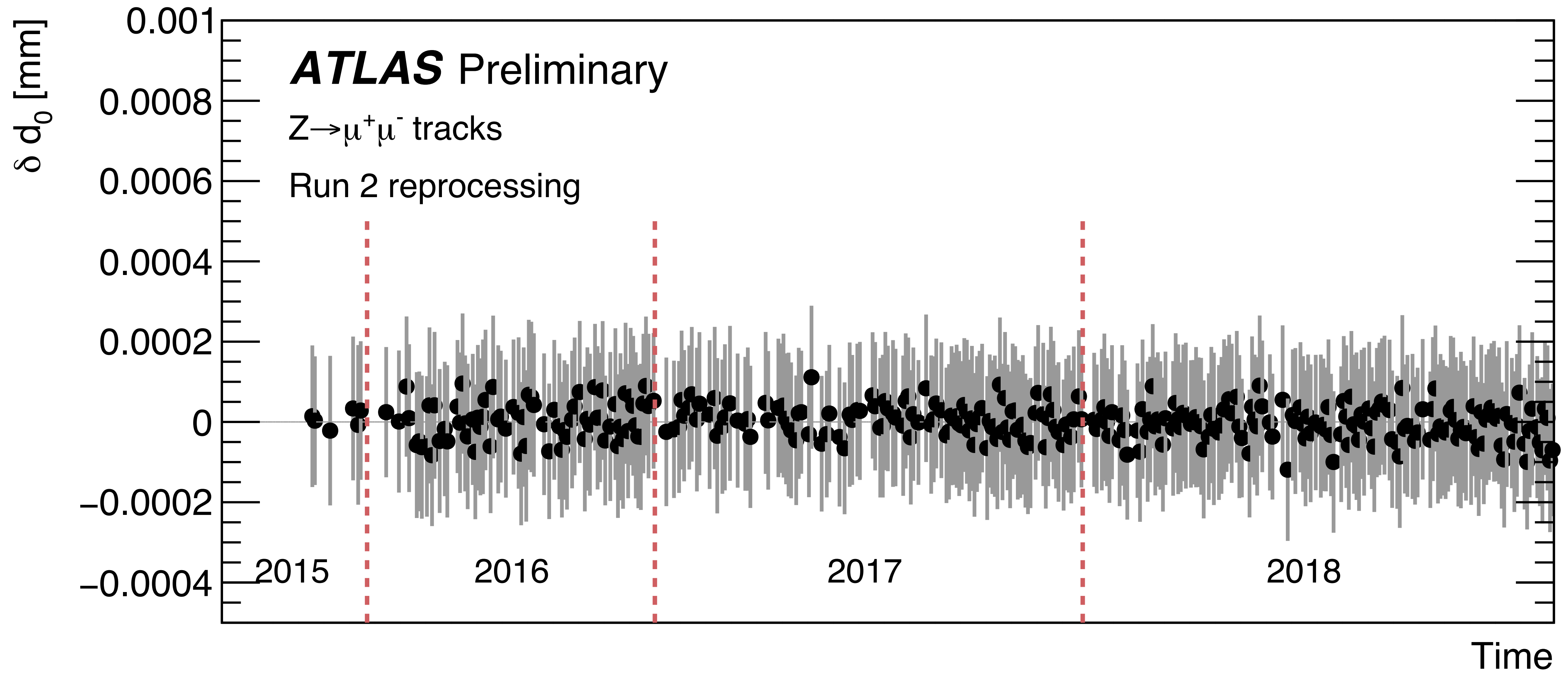
- δd_0 (δz_0) contained within 1 (5) μm

Reconstructed $m_{\mu\mu}$ stable in time: robust physics performance.

What about sagitta biases?







ATL-PHYS-PUB-2022-028

New method for sagitta bias

$m_{\mu\mu}$	= reconstructed μμ mass
$m_{\mu\mu,0}$	= reference mass (e.g m_Z)

Why ***Mass* method is not sensitive to global bias**?

Mass method based on $m^2_{\mu\mu} - m^2_{\mu\mu,0}$ measurement over (η, ϕ) coordinates

Effect of δ_s on p_T: $p'_{\mathrm{T}} = p_{\mathrm{T}}\left(1 + q p_{\mathrm{T}} \delta_s\right)^{-1}$

Effect on $m_{\mu\mu}$: $$\frac{m^2_{\mu\mu} - m^2_{\mu\mu,0}}{m^2_{\mu\mu}} = (p^-_{\mathrm{T}}\delta^- - p^+_{\mathrm{T}}\delta^+)$$

Global bias: $\delta^+ = \delta^-$

On average: $\langle p_T^+ \rangle \approx \langle p_T^- \rangle$

⟶ $\langle m^2_{\mu\mu} \rangle \approx m^2_{\mu\mu,0}$

Global bias: mean of the $m_{\mu\mu}$ distribution is **unchanged** ⟶ Mass method not sensitive to it!

The variance of the $m_{\mu\mu}$ distribution increases instead: **VarMin method!**

VarMin method

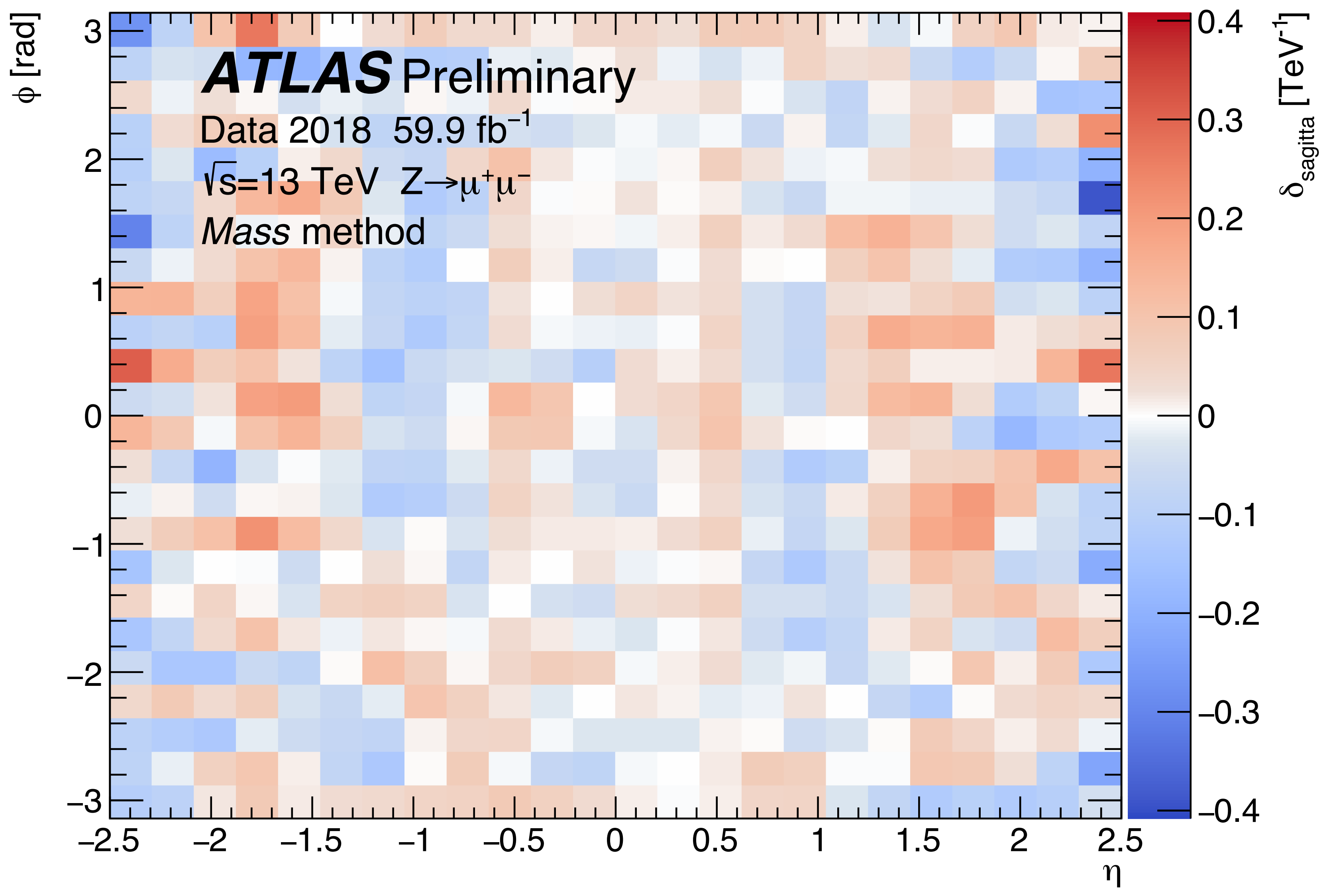
A little of formalism: $m^2_{\mu\mu,\bullet} = \Delta m^2_{\mu\mu,i} - \boldsymbol{e}_i \cdot \boldsymbol{\delta}$ where $\boldsymbol{e}_i = m^2_{\mu\mu,i}\,(0,\ldots,\ p_{\mathrm{T}_i}^{+},\ldots,\ p_{\mathrm{T}_i}^{-},\ldots,0)$ ⟵ map over (η, ϕ)

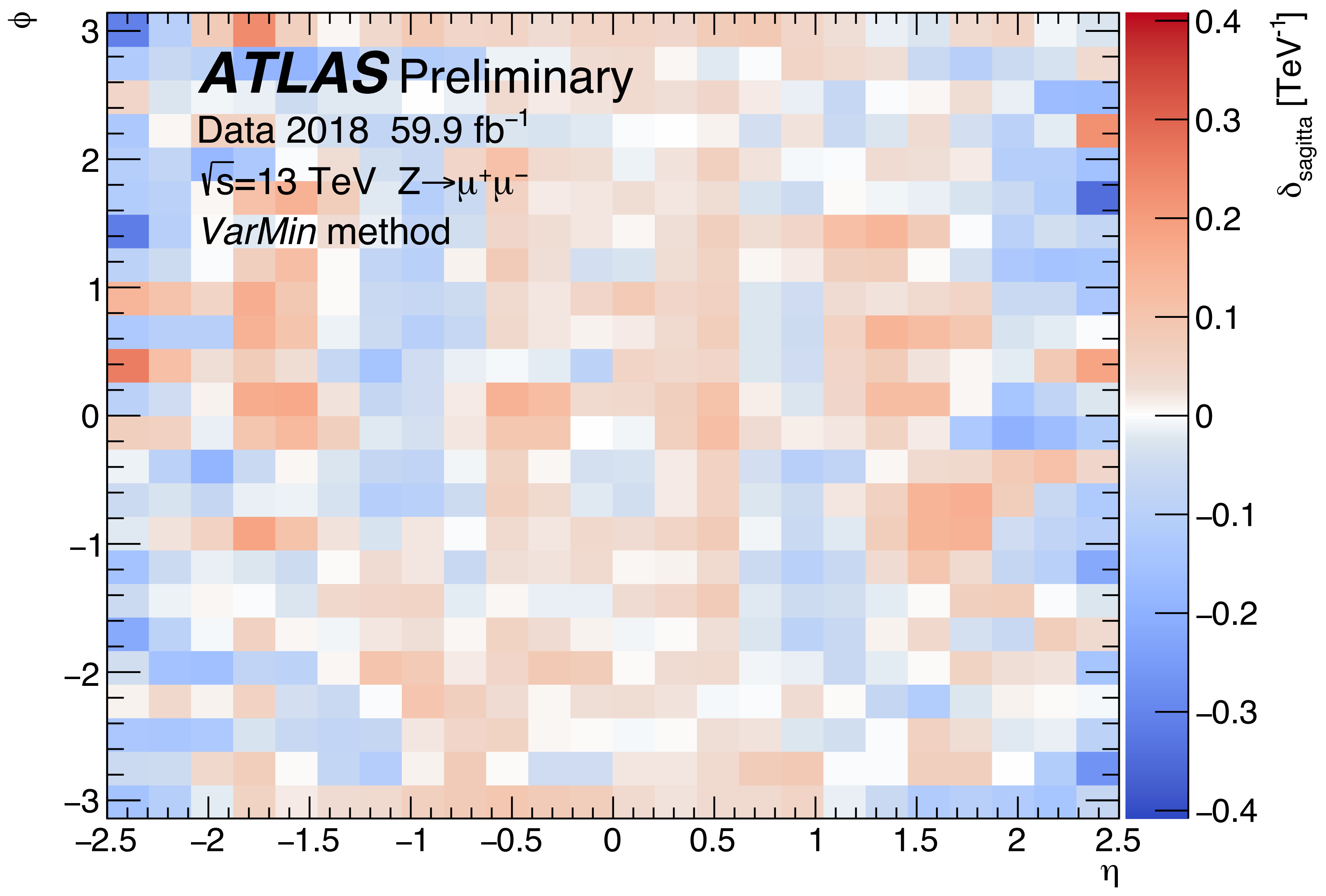
Variance of the mass: $$\mathrm{Var}[m^2_{\mu\mu,\bullet}] = \mathrm{Var}[\Delta m^2_{\mu\mu,i}] - \sum_{\alpha,\beta} \mathrm{Cov}[(\boldsymbol{e}_i)_\alpha,\ (\boldsymbol{e}_i)_\beta]\ \delta_\alpha \delta_\beta - 2\sum_\alpha \mathrm{Cov}[\Delta m^2_{\mu\mu,i},\ (\boldsymbol{e}_i)_\alpha]\ \delta_\alpha$$

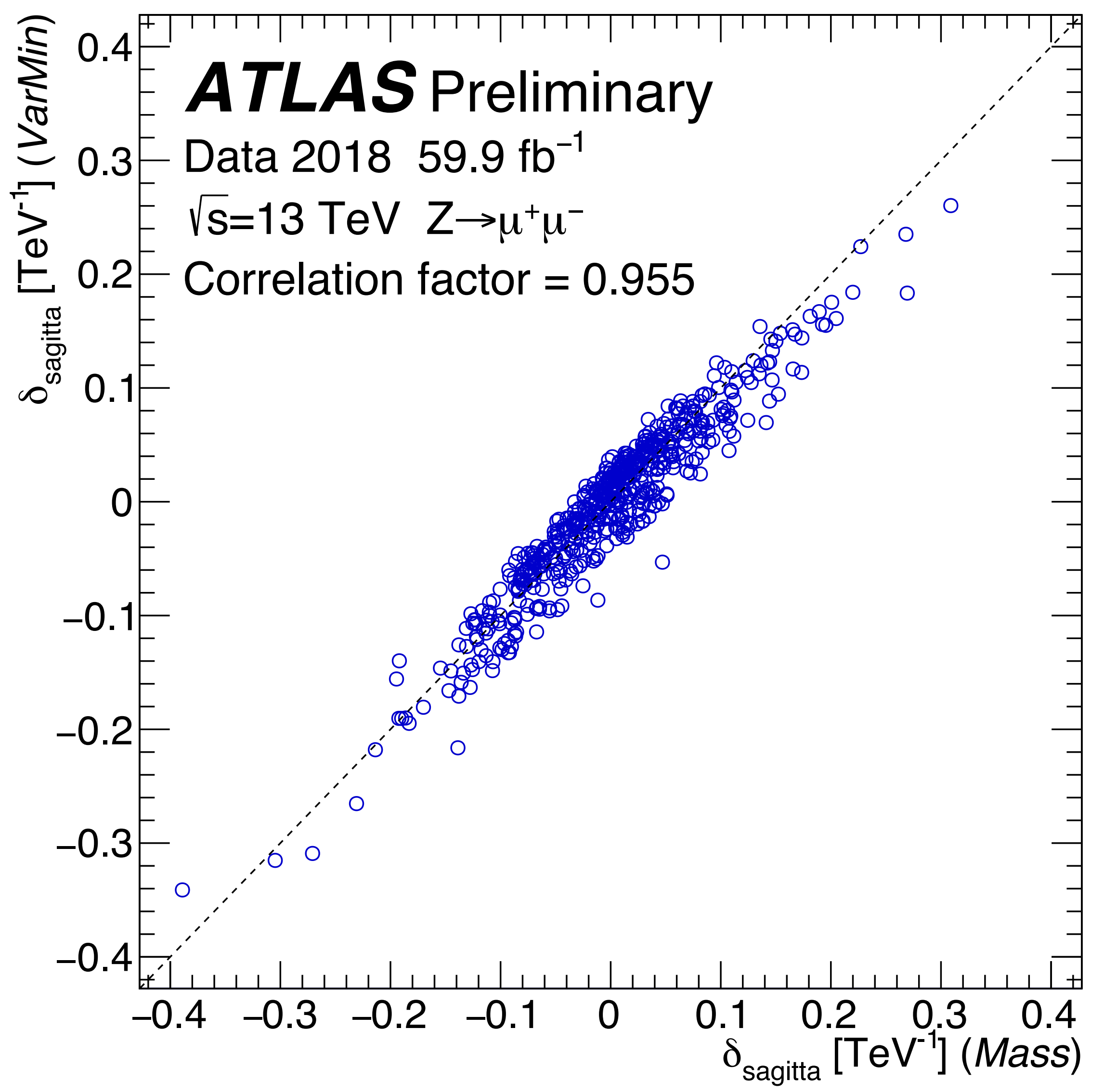
$$d\mathrm{Var}[m^2_{\mu\mu,\bullet}]/d\delta_\beta = 0 \longrightarrow \begin{aligned} k_\alpha &= \mathrm{Cov}[\Delta m^2_{\mu\mu,i}, (\vec{e}_i)_\alpha] \\ M_{\alpha,\beta} &= \mathrm{Cov}[(\vec{e}_i)_\alpha, (\vec{e}_i)_\beta] \end{aligned}$$

System of N equation (N = # bins of (η, ϕ) maps). Solve it and get the δ_s map!

- Nice closure with respect to *Mass* method — **spoiler alert**: meaning small global sagitta bias!



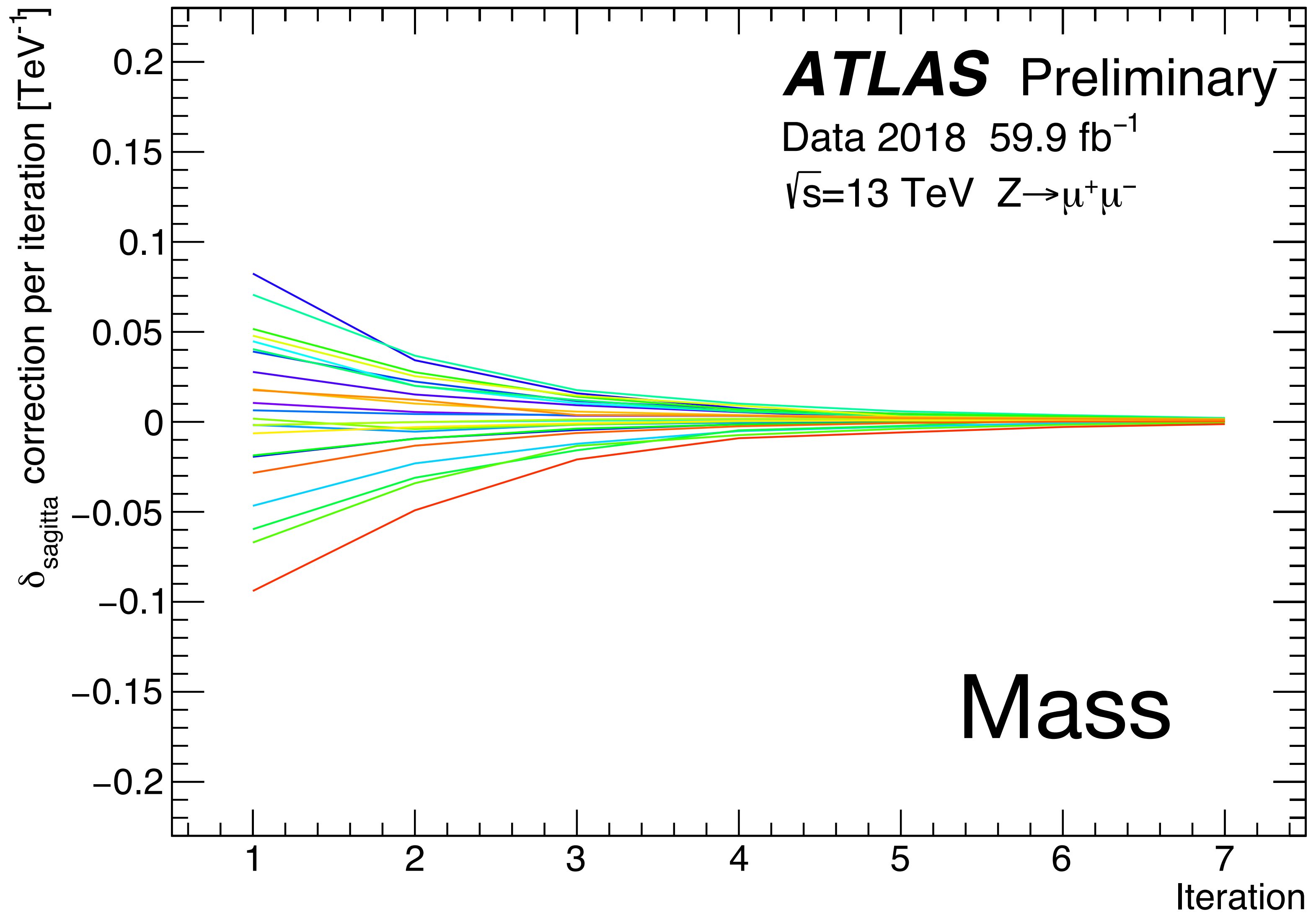




VarMin performance in Run 2 towards Run 3

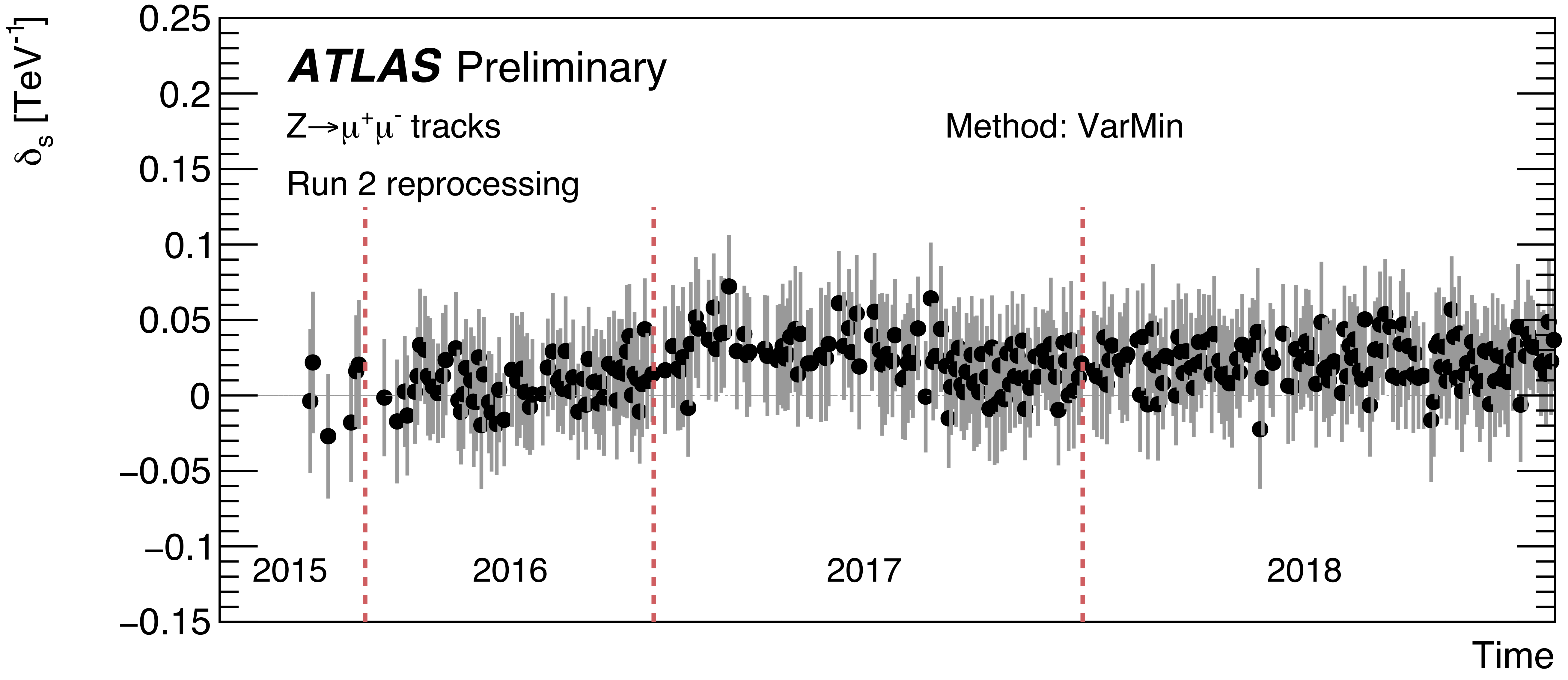
VarMin is a great improvement for Run 3:

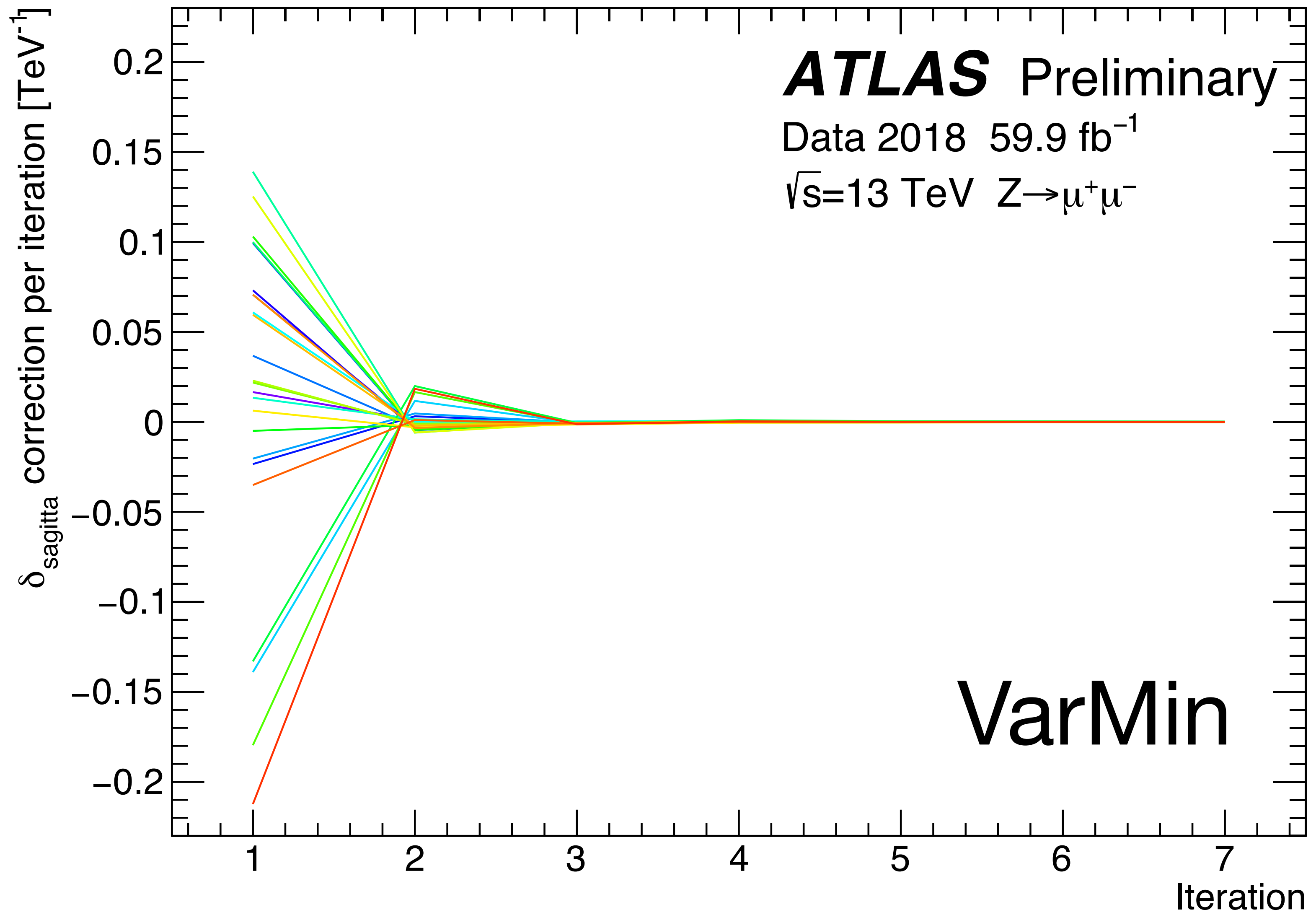
- **Sensitive to global bias**: automatic minimisation with VarMin maps
- **Quicker**: much less time consuming to run



Mass method not sensitive to global bias.
Using p_T asymmetry technique: global bias ~0.02 TeV^{-1}

→ we can do even better with VarMin!





Conclusions

ATLAS is getting ready for the coming Run 3

- Many changes in reconstruction software to cope with the harsher data-taking condition
- Cluster position estimated via **Mixture Density Network (MDN)** not affected by **position bias** present from the previous version and absorbed by alignment.

Run 2 re-alignment campaign performed using Run 3 reconstruction algorithms:

- Two main goals: **remove the position bias** in data and **minimise the remaining biases** in the track parameters.
- Residuals recovered, minimal biases in track impact parameter and momentum.

Challenging reduction of global sagitta bias during campaign: **VarMin** method implemented

- Quick and sensitive to global biases, new baseline for Run 3!
- Semi-automatic reduction of global sagitta bias during alignment iterations: great news for precision measurements!

Thank you for your attention!

Backup

Tracking development for Run 3

ATL-PHYS-PUB-2021-012

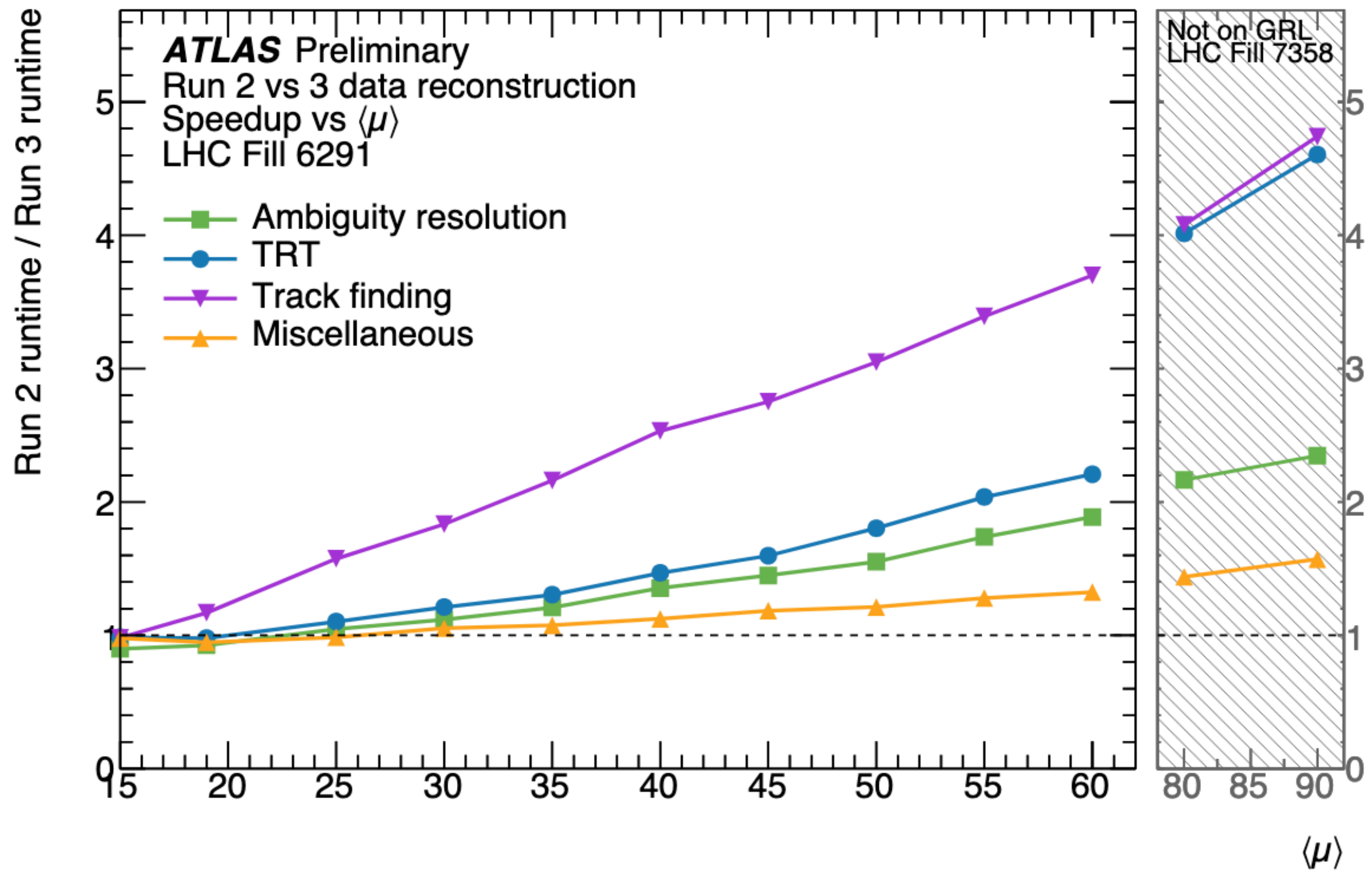
Runtime of all steps of track reconstructions is significantly improved.

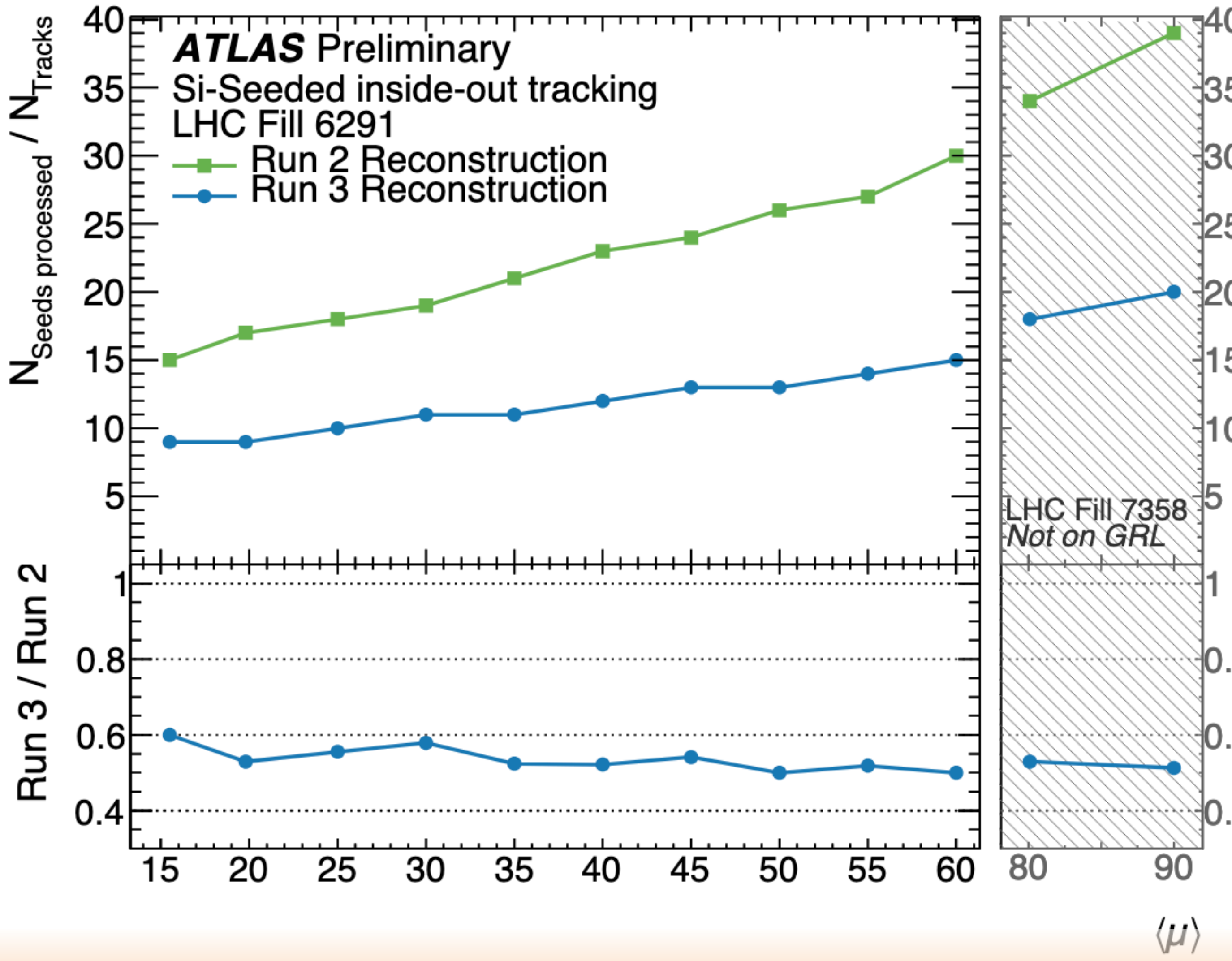
Better scaling of the runtime with pile-up: track finding step more robust.

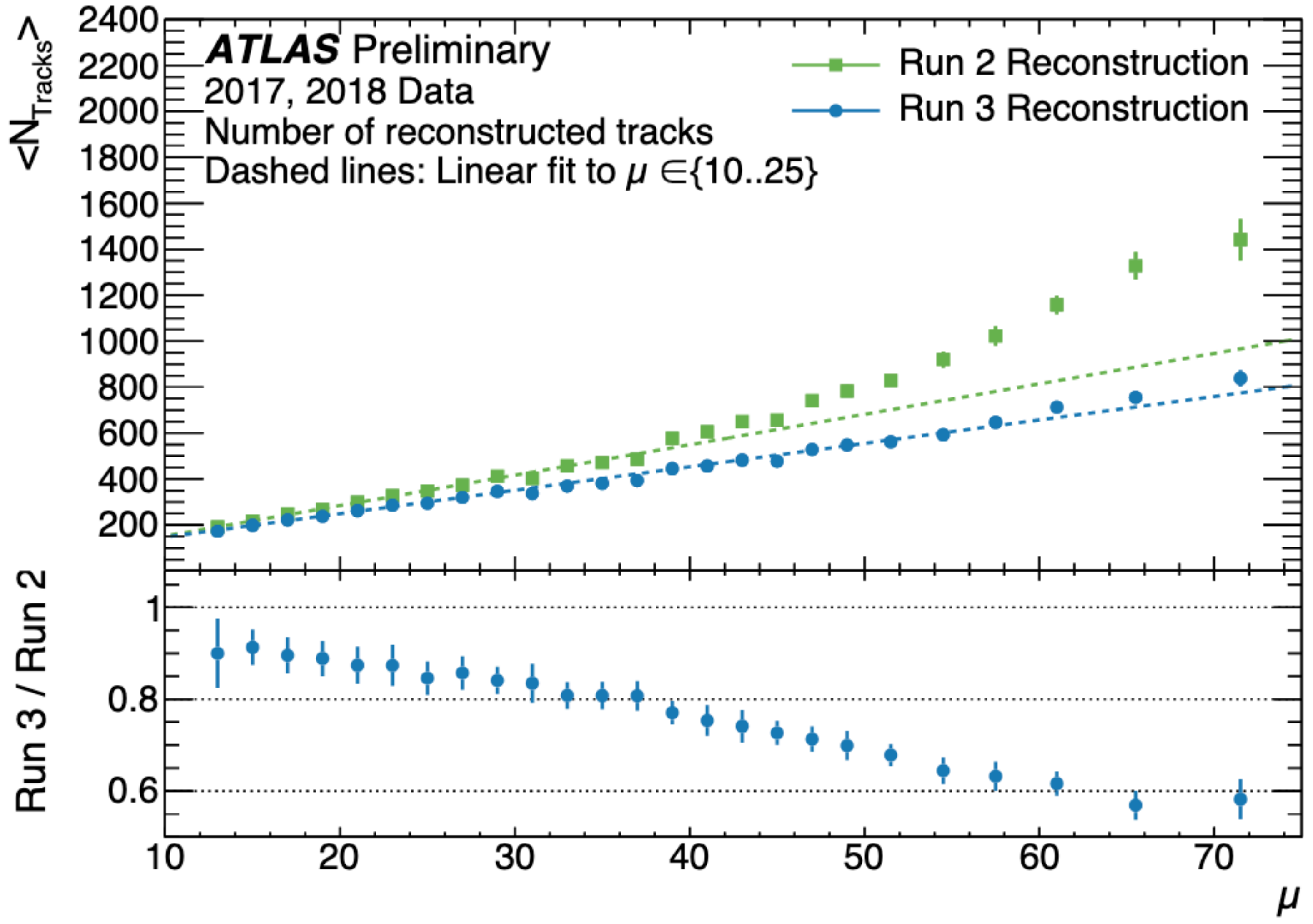
More efficient seeding: lower ratio of N(seeds) / N (tracks)

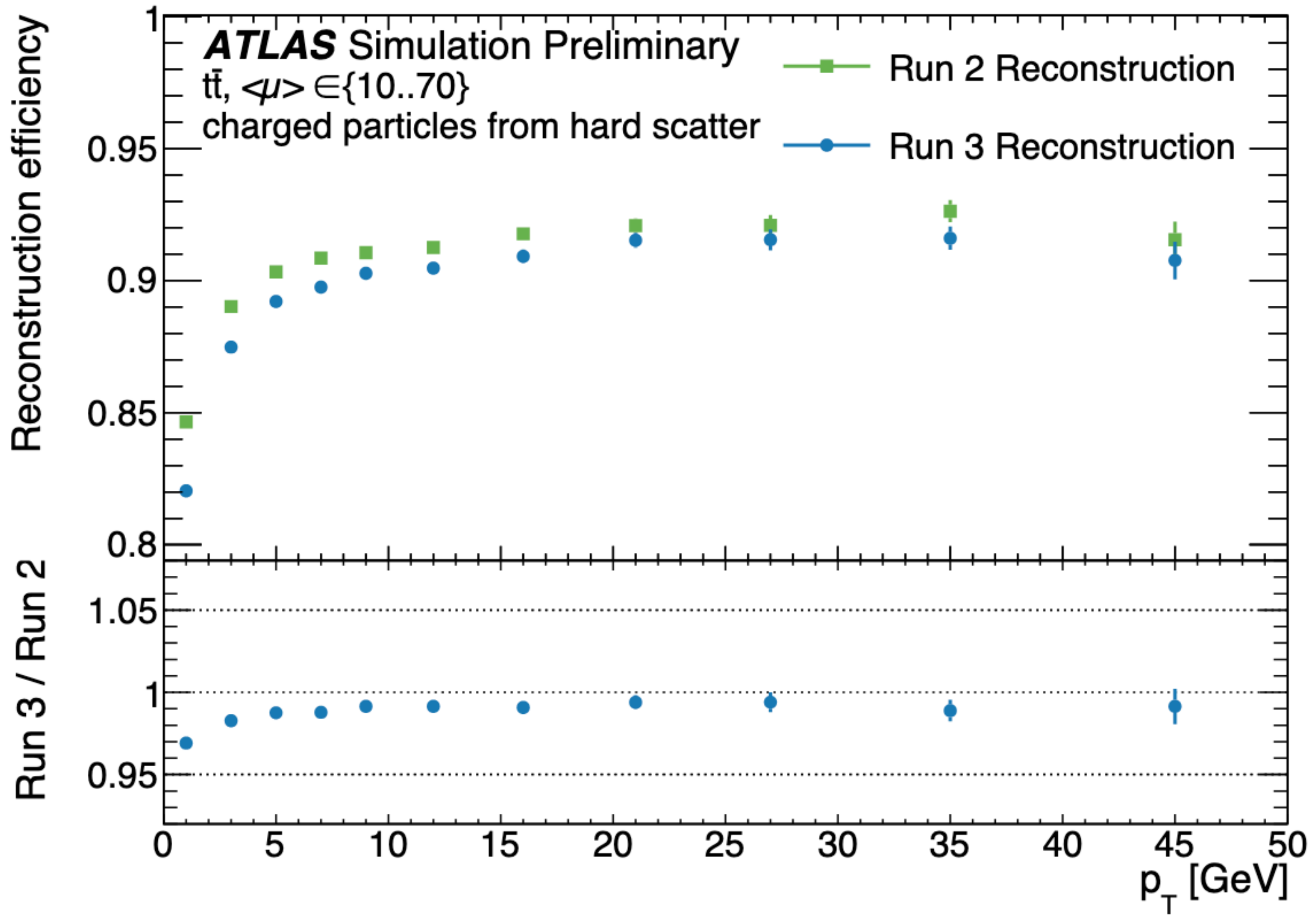
Limited impact on the track efficiency

Nice linear scaling with pile-up both in data and MC: more pure, less fakes!









Large-Radius Tracking

ATL-PHYS-PUB-2021-012

LRT is now part of the main reconstruction stream as std. physics objects

- only limited impact in CPU (10%)

Great scalability with pile-up:

- **CPU**: max increase 20%/30% at <μ>=90. Still <half CPU usage with respect to Run2.
- **Disk space**: max increase 20%/30% at <μ>=90. Still half space with respect to Run2.

Vertexing

ATL-PHYS-PUB-2019-015

ATL-PHYS-PUB-2021-012

First Common-Tracking-Software (ACTS) implementation in running experiment.

- Factor 2 reduction of CPU time with respect to Run 2!

Including AMVF algorithm for vertex reconstruction

- Higher vertex reconstruction efficiency