Inner Detector Track Reconstruction and Alignment at the ATLAS Experiment

— INSTR 2017, BINP, Novosibirsk —

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On behalf of the ATLAS Collaboration

2017-03-03

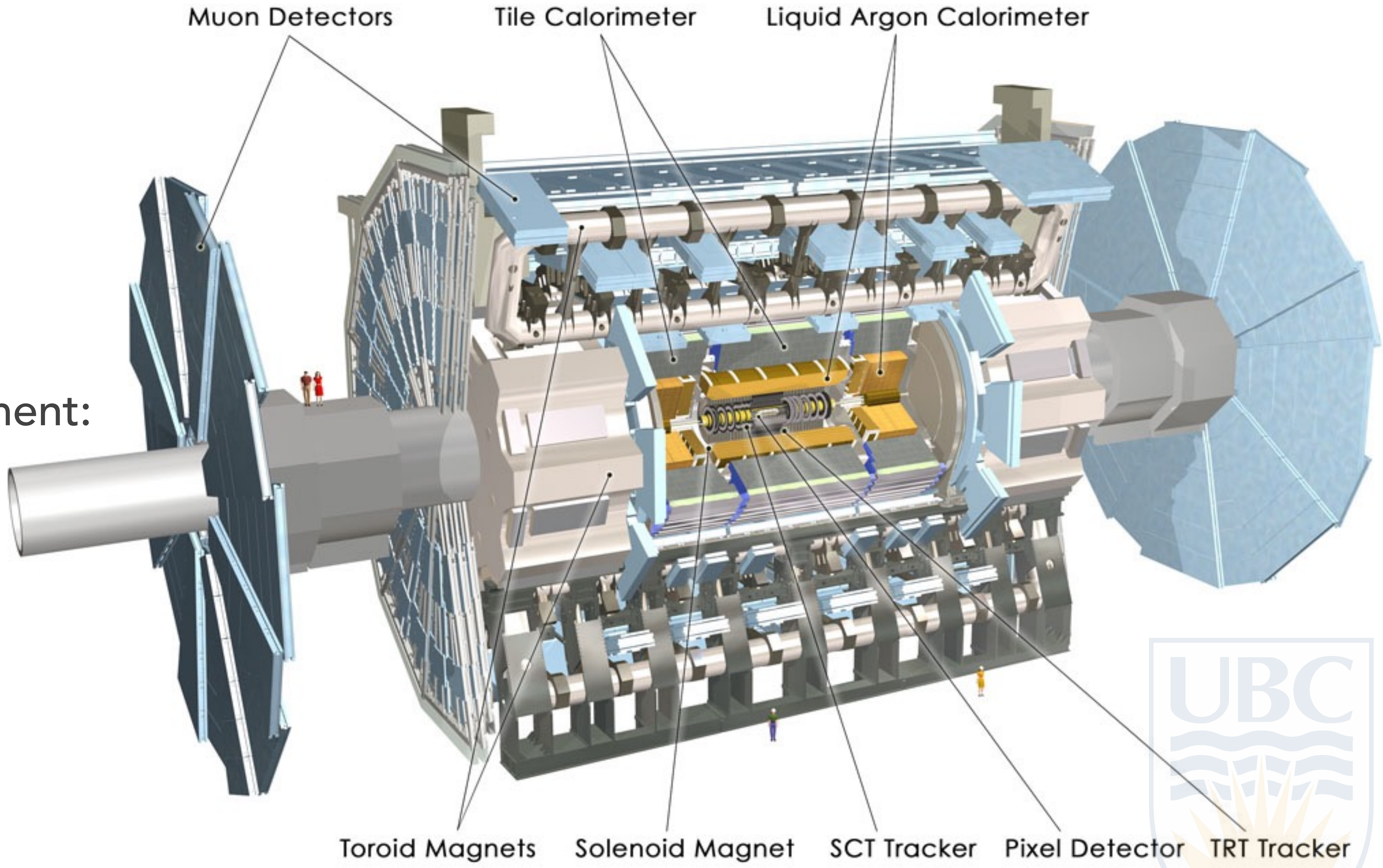
The ATLAS experiment at the LHC

LHC, the Large Hadron Collider:

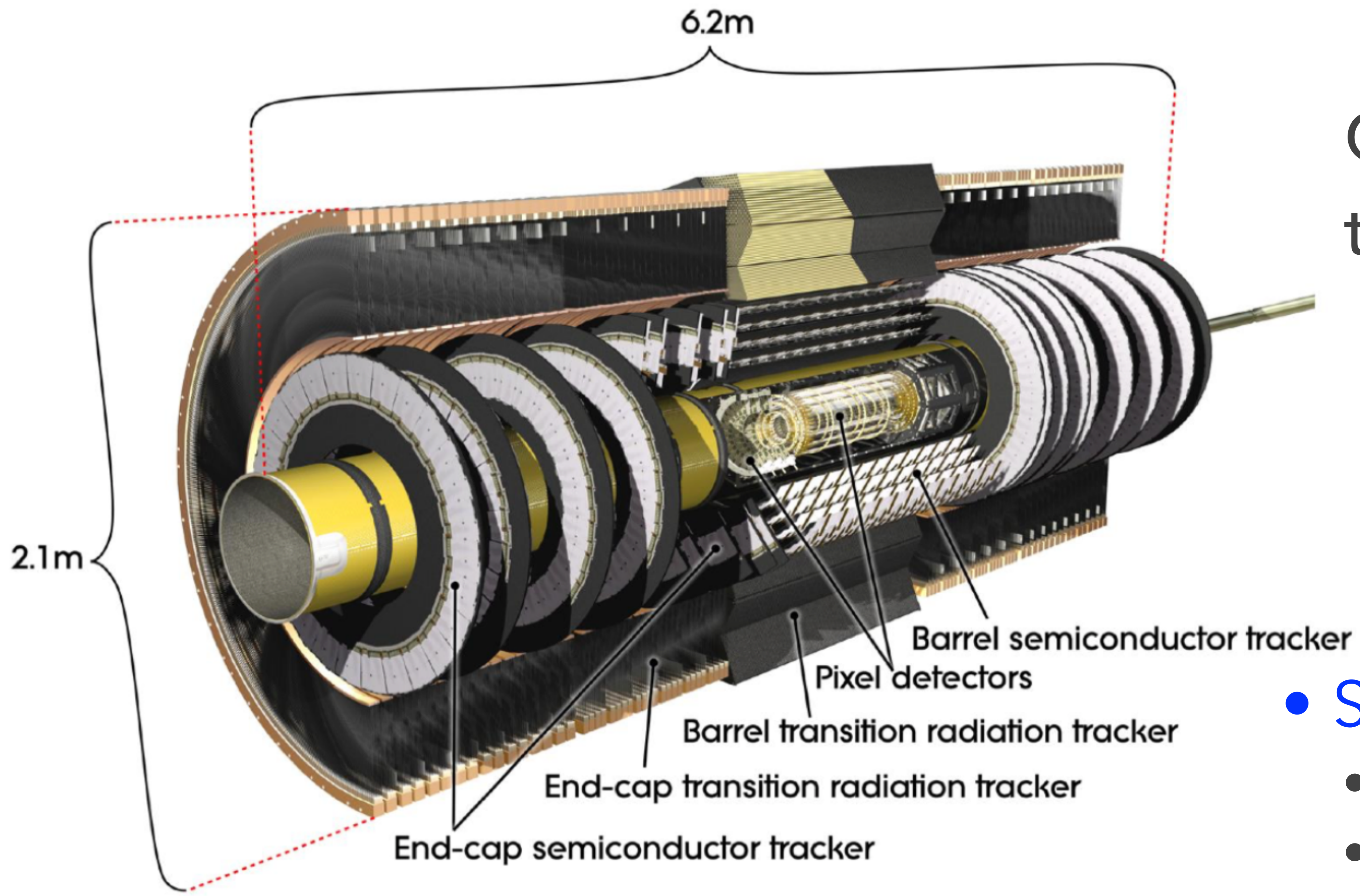
- proton-proton collisions at:
  - 900 GeV (2009)
  - 7 TeV (2010-11)
  - 8TeV (2012)
  - 13TeV (2015-16)
- Also Pb-Pb & Pb-p collisions

ATLAS, a general purpose experiment:

- Inner tracking system
- Calorimetry systems:
  - Electromagnetic
  - Hadronic
- Muon system

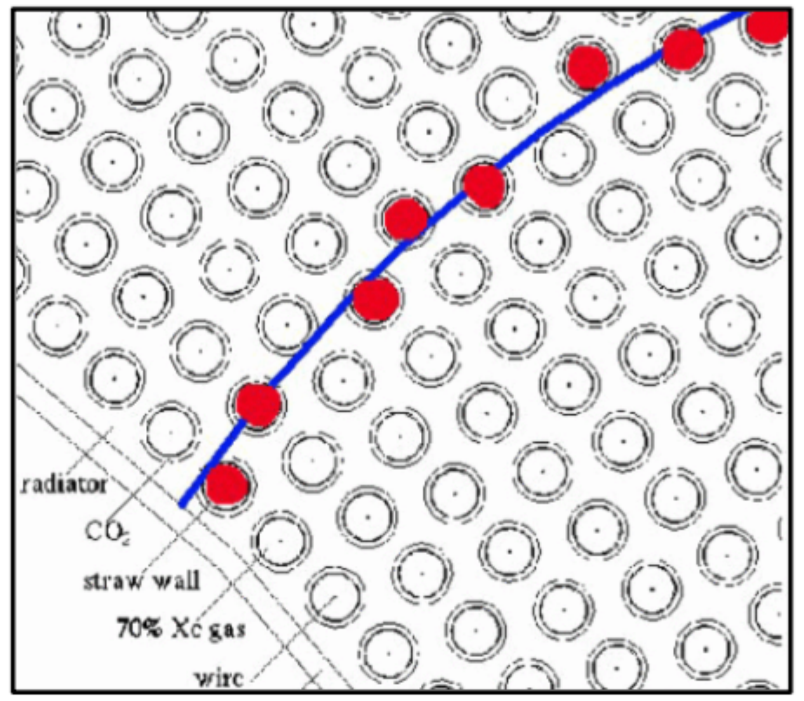


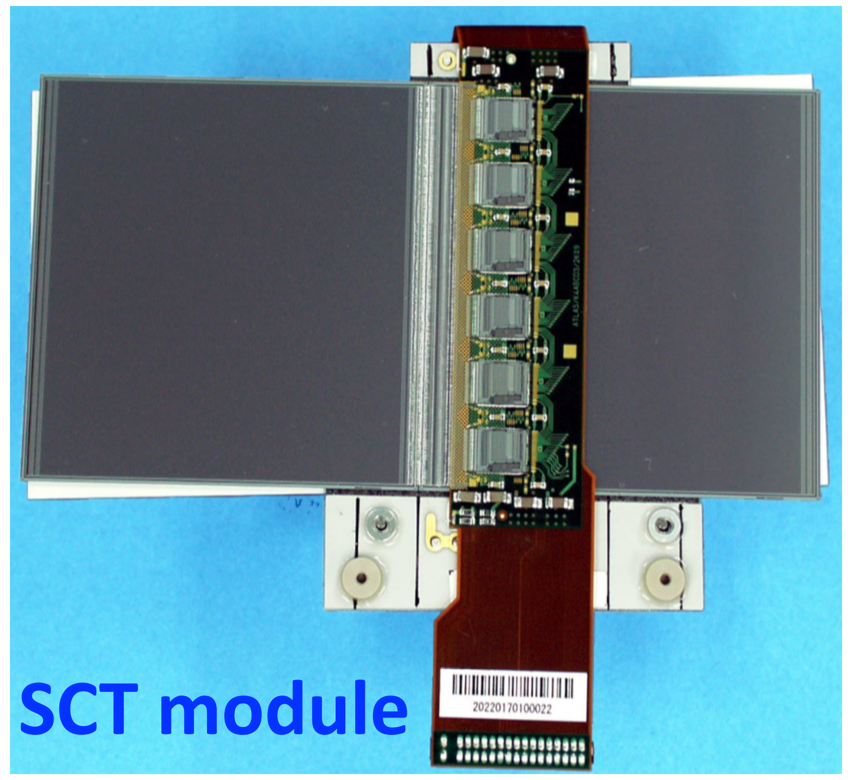
ATLAS Inner Detector



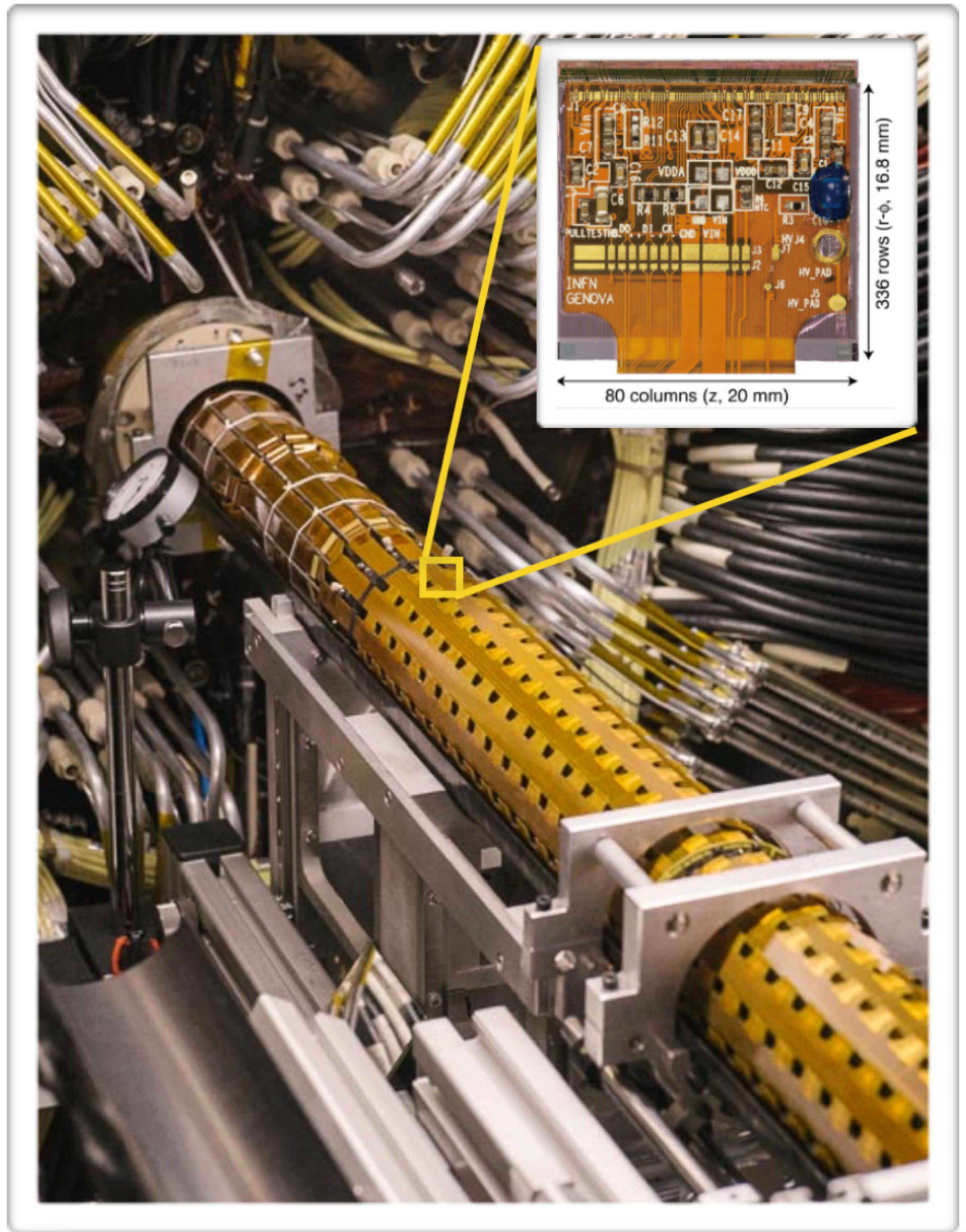
Comprises 3 detector technologies:

- Silicon Pixels
  - 1744 modules (50x400μm^2)
  - 280 modules (50x250μm^2)
  - 4 barrel layers + 2x3 end-caps
- SCT: silicon microstrip sensors
  - double-sided modules (40μm pitch)
  - 80 mrad stereo angle
  - 4 barrel layers + 2x9 end-caps
- TRT: Transition Radiation Tracker
  - Drift tubes: ∅4mm, up to 1440mm length
  - ~298,000 straws
  - Using *Xe* and *Ar*
  - 3 barrel layers + 2 end-caps





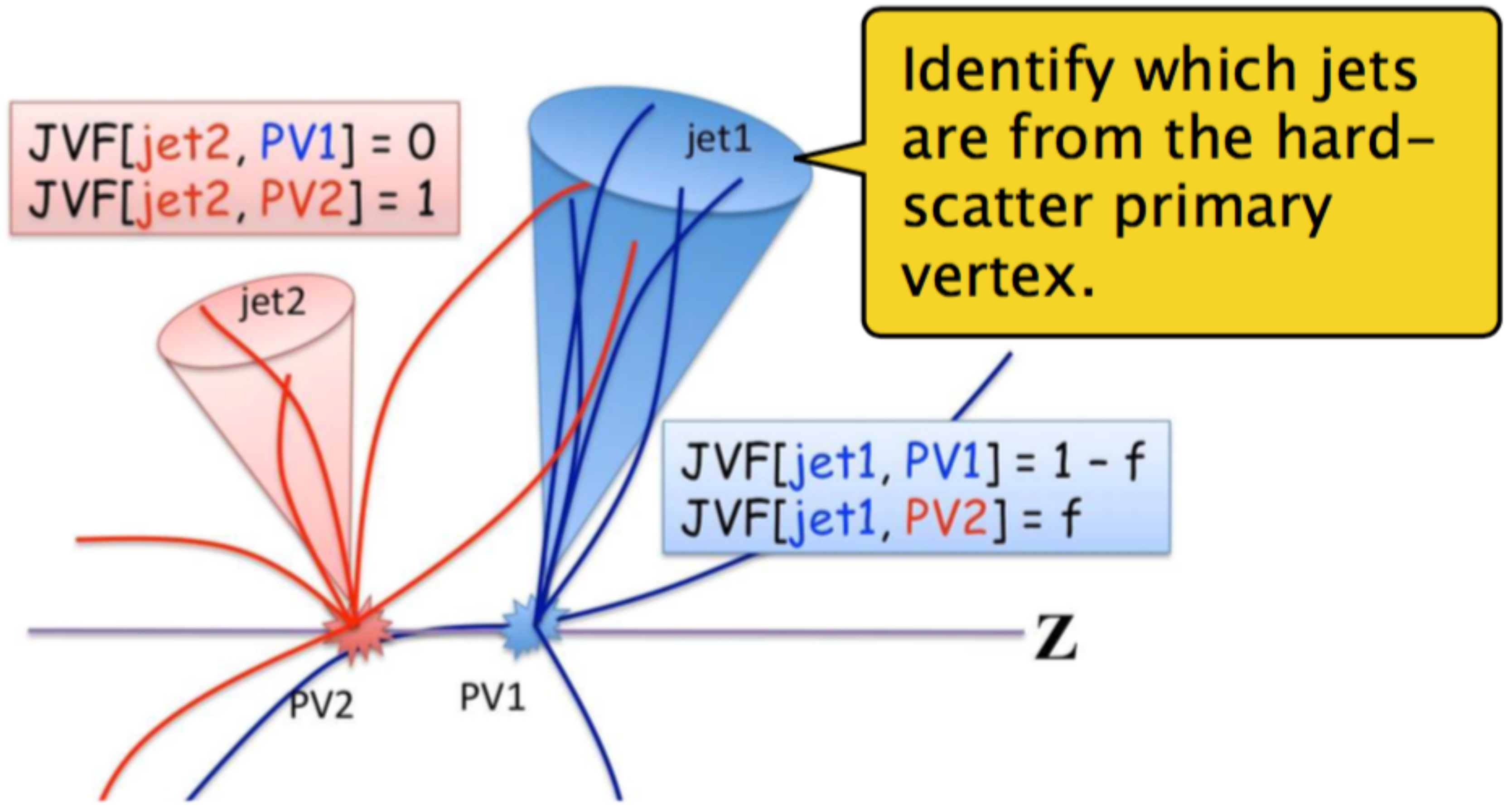
New Insertable B-Layer (IBL) for Run 2

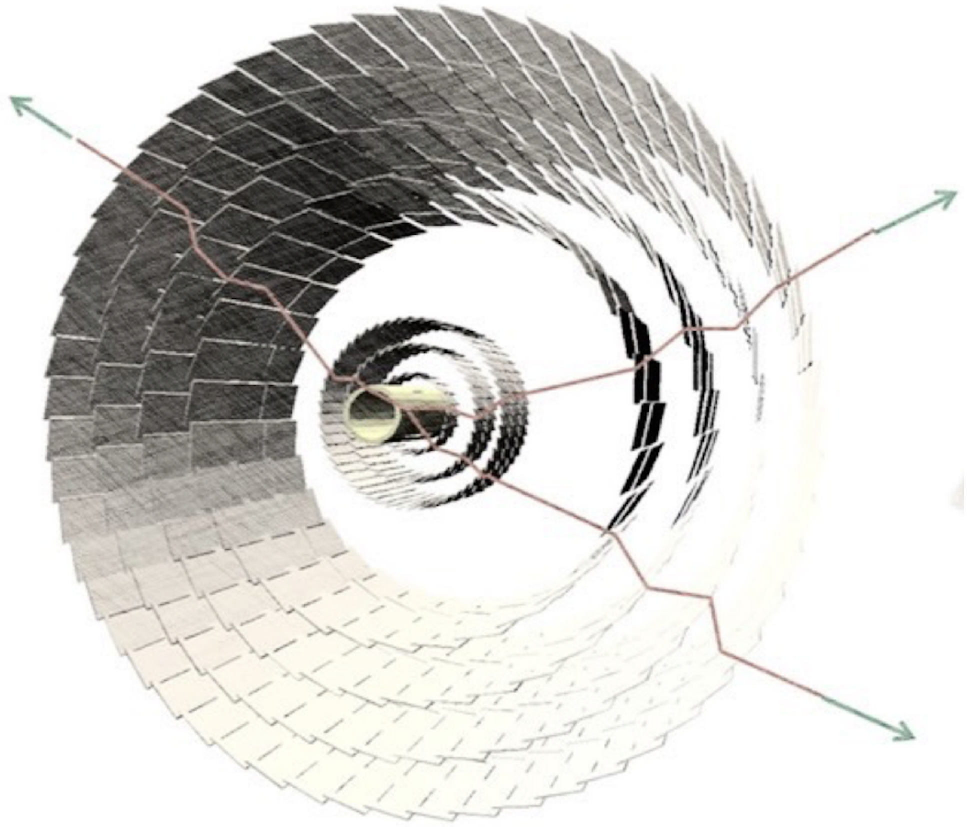


- r ~ 33 mm. 14 staves surrounding the new beam pipe.
- Each stave hosts 32 front-end chips (FE-I4).
- 50 μm (r—ϕ) × 250 μm (z) pixel size (~12 Mpx total).
- Planar (|η| < 2.5) and 3D (2.5 < |η| < 3.0) silicon sensors.
- Readout bandwidth tolerable up to <μ> ~ 80.

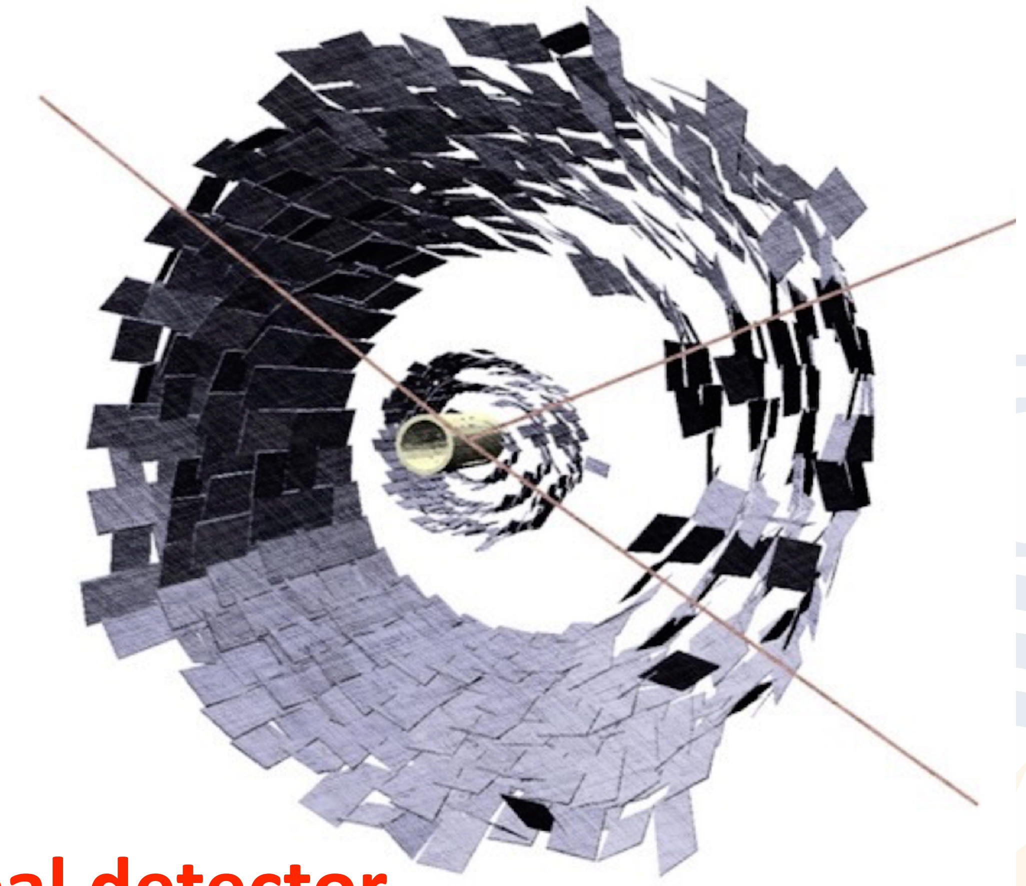
Tracking: A crucial ingredient for successful physics program

- Reconstruction of charged particle trajectories (tracks) is fundamental input into many ATLAS physics objects and analysis quantities
- Flavour tagging jets
    - Crucial tool for majority of analysis channels in ATLAS
- Helps to mitigate effects of pile-up
    - Provides precise measurements distinguishing the primary vertex from pile-up vertices
- Provides precise information on the topology of the jet substructure
    - A key ingredient in identifying e.g. boosted objects
    - Improves the jet-mass resolution and uncertainty
- Tracks can be physics objects in themselves (electron & mu
    - H →ZZ* →4μ was detected thanks to performant tracker
- Precise knowledge of positions of detector elements is paramount for a good tracking performance
—> Alignment



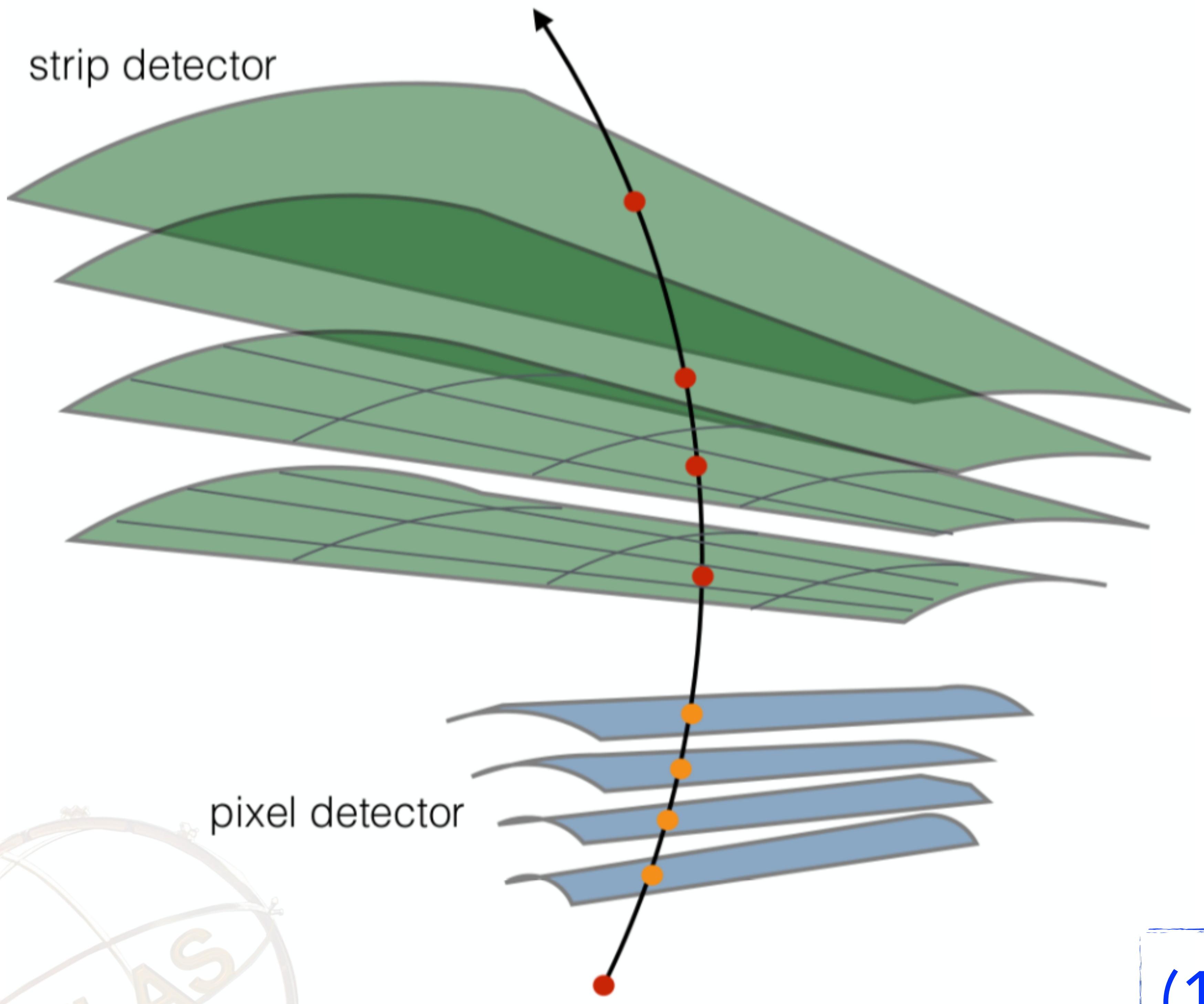


ideal detector



real detector

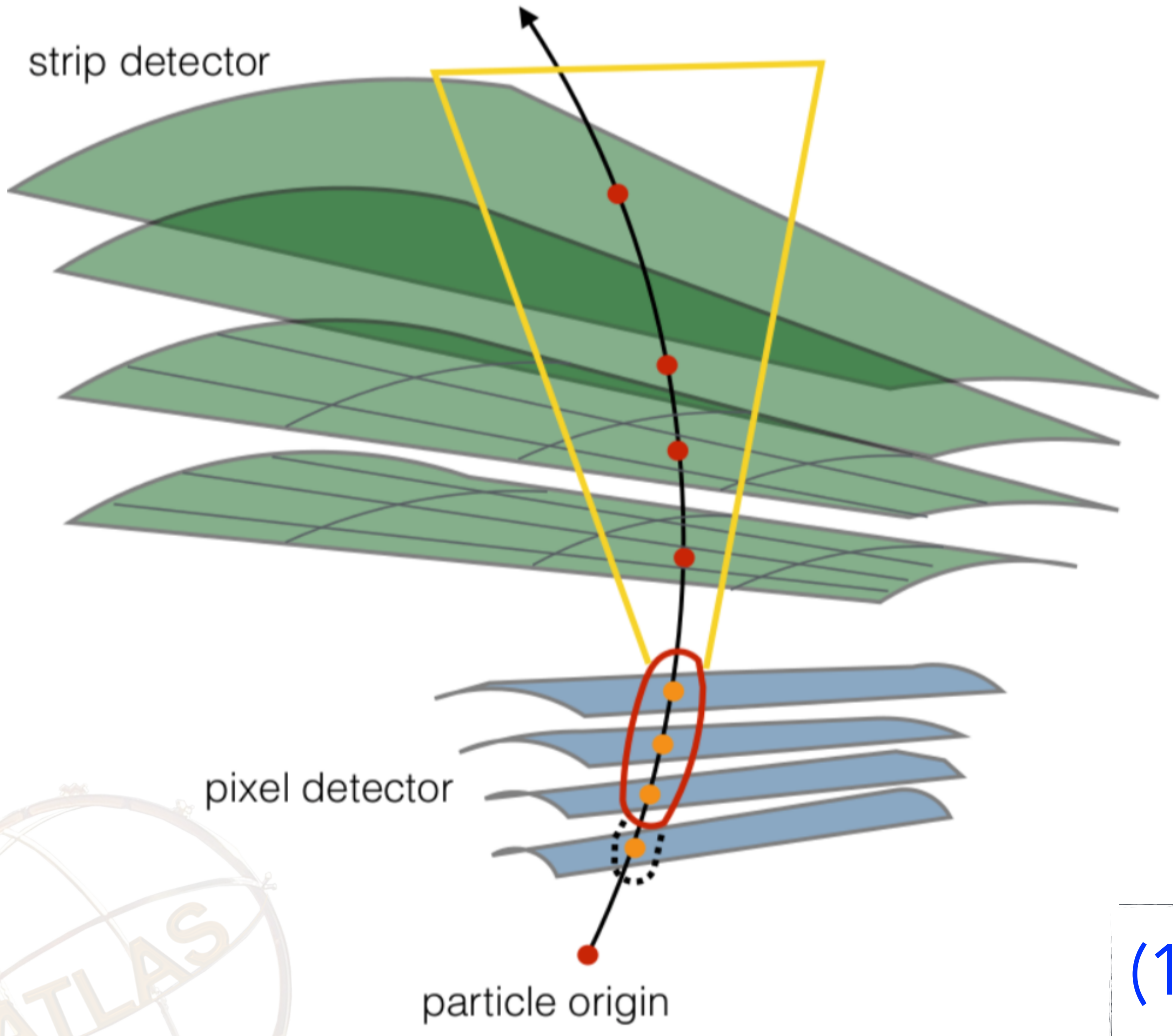
ATLAS track reconstruction in a nutshell



(1) pre-processing:

- Pixel+SCT clustering
- TRT drift circle formation
- space points formation

ATLAS track reconstruction in a nutshell



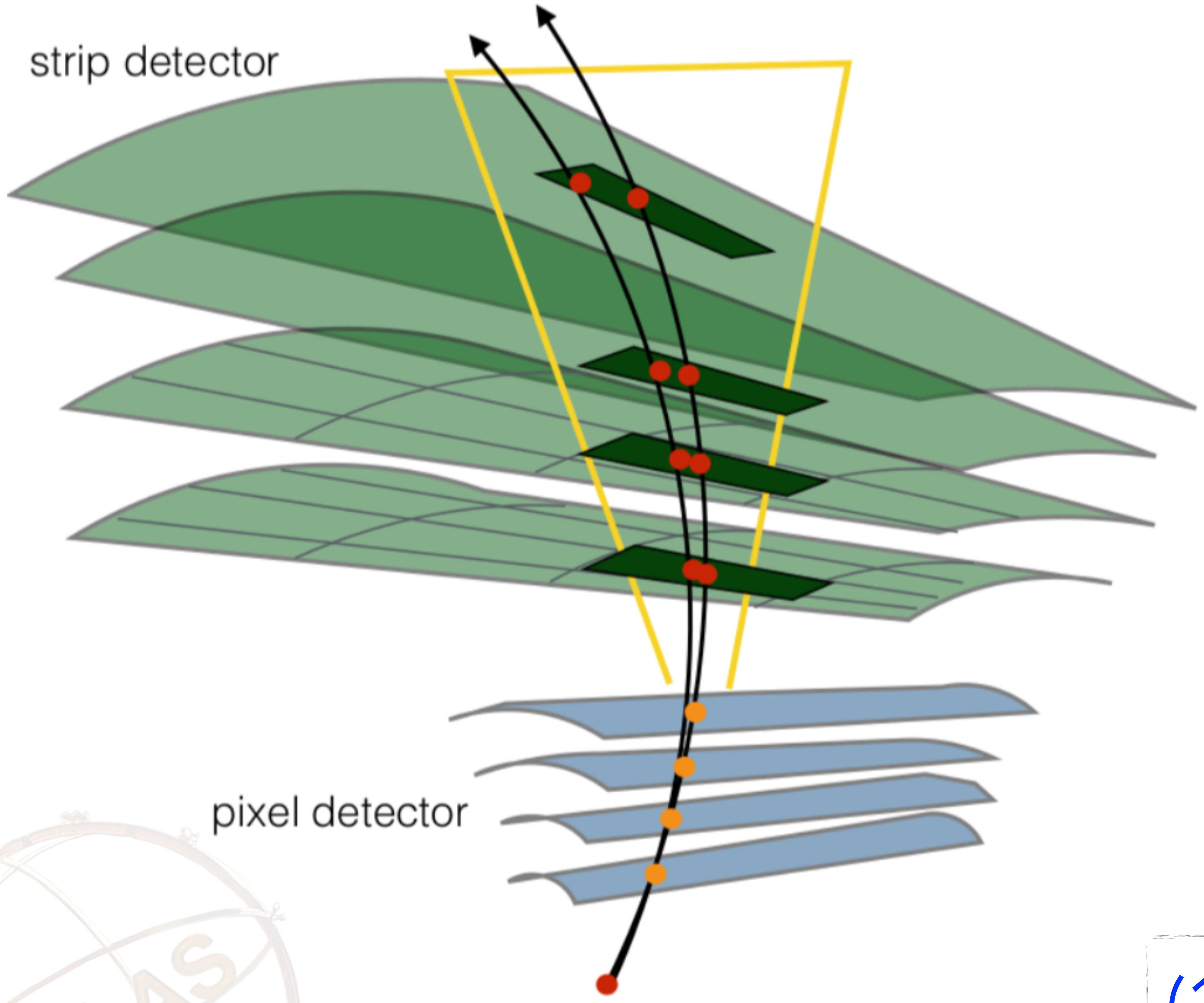
(2) Combinatorial track finder:

- constructing seeds first
- track finding restricted to roads

(1) pre-processing:

- Pixel+SCT clustering
- TRT drift circle formation
- space points formation

ATLAS track reconstruction in a nutshell



(3) Ambiguity solving:

- precise least square fit with full geometry
  —> using measurement residual **r(*t*)**
- selection of best silicon tracks using:
  - hit content, holes
  - number of shared hits
  - fit quality...

track parameters:

$$t = (d_0, z_0, \eta, \phi, q/p)$$

$$\chi^2 = \mathbf{r}^T(t)\mathbf{V}^{-1}\mathbf{r}(t)$$

hit covariance matrix

(2) Combinatorial track finder:

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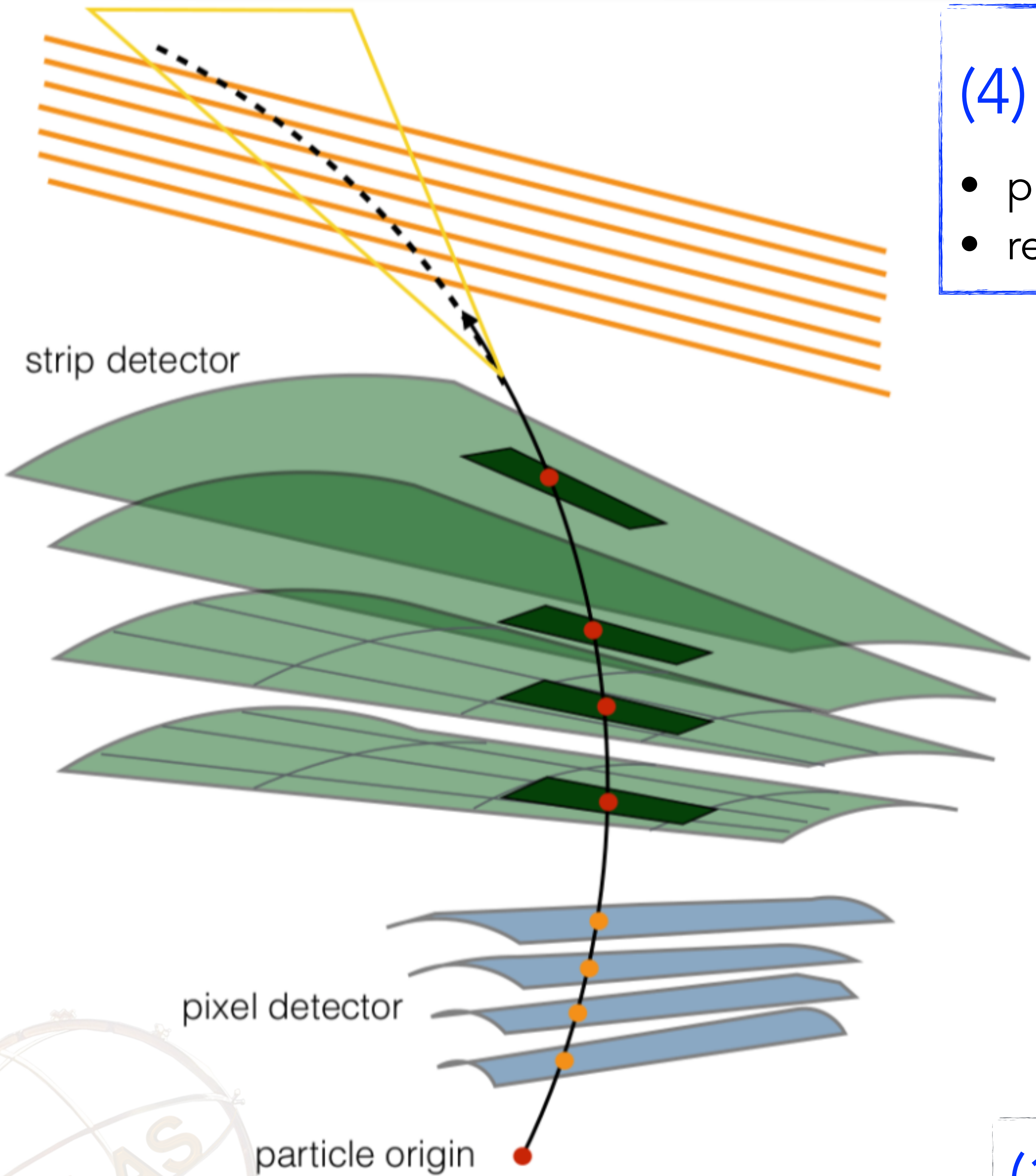
ATLAS track reconstruction in a nutshell



(4) Extension into TRT

- progressive finder
- refit of track and selection

(3) Ambiguity solving:

- precise least square fit with full geometry
  —> using measurement residual **r(*t*)**
- selection of best silicon tracks using:
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  - number of shared hits
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hit covariance matrix

(2) Combinatorial track finder:

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(1) pre-processing:

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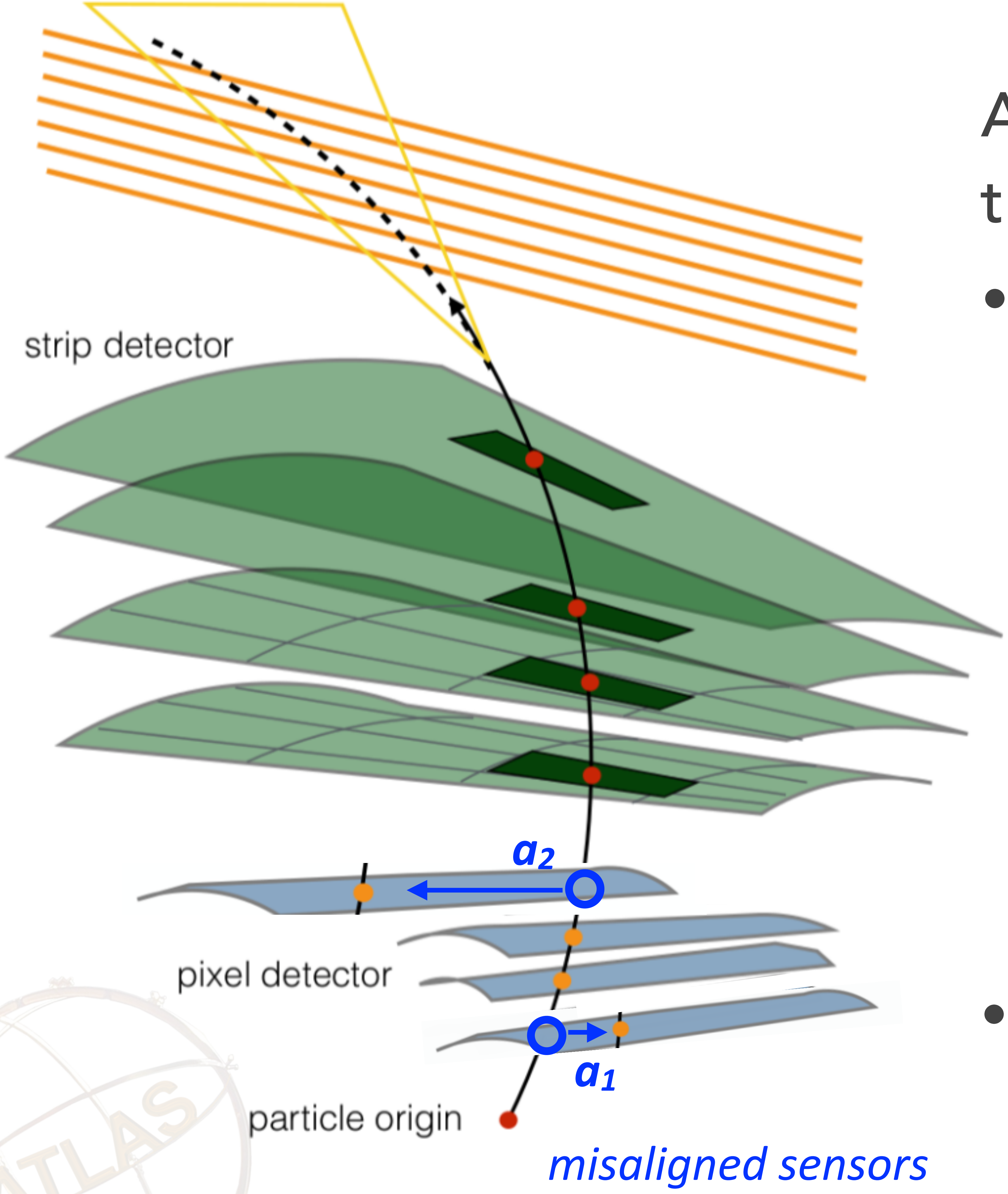
Method extension: Track based alignment



Alignment is concerned with determining the actual geometry of the tracking system and following its eventual changes in time

- In-situ determination of detector positions using Chi2 minimization
  - track parameters: $t = (d_0, z_0, \eta, \phi, q/p)$
  - alignment parameters: $a = (T_x, T_y, T_z, R_x, R_y, R_z)$

can be of the order O(100000) DoFs!!

$$\chi^2 = \mathbf{r}^T(t)\mathbf{V}^{-1}\mathbf{r}(t)$$

now dependent on alignment parameters

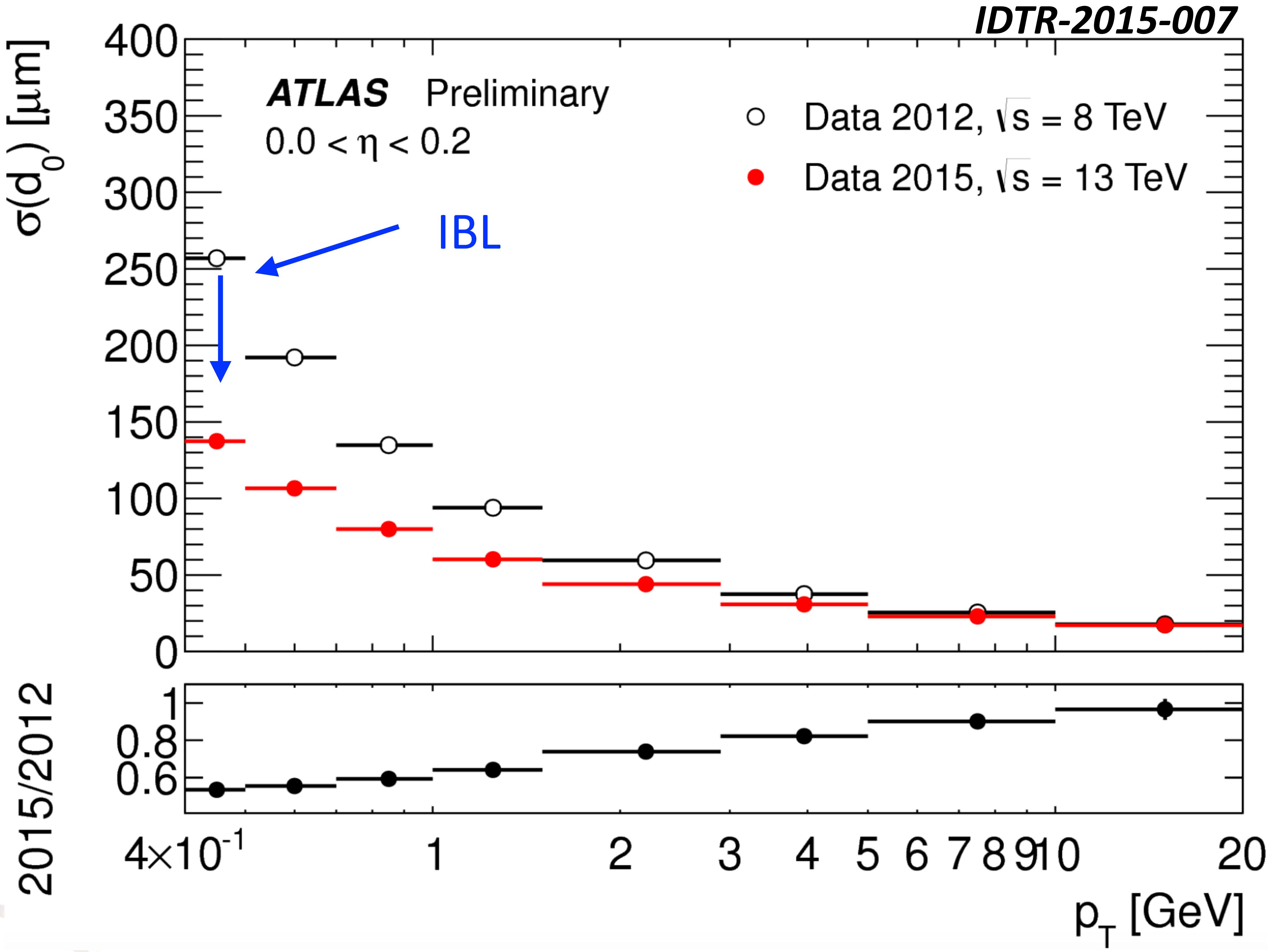
$$\chi^2 = \sum_{tracks} \mathbf{r}^T(t,a)\mathbf{V}^{-1}\mathbf{r}(t,a)$$

- Additional information can be used in form of constraints:
  - on track parameters (e.g. beam spot, resonance inv. mass (Z->μμ))
  - and/or alignment parameters (e.g. assembly survey)

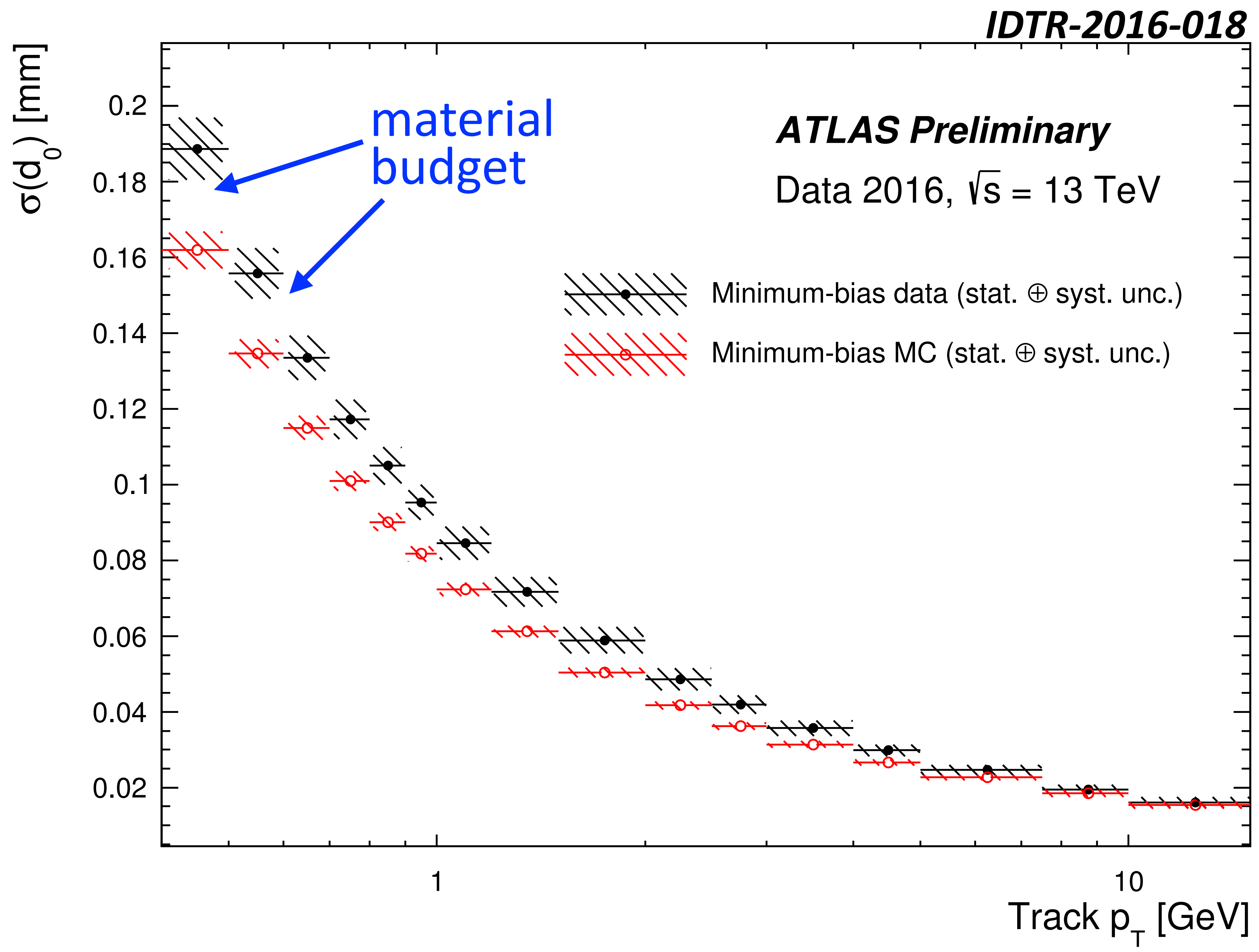
Examples and performance of alignment later in this talk

Reconstruction performance in Run 2

σ(d_0) vs. p_T — Run 1 vs. Run 2



σ(d_0) vs. p_T — data vs. MC

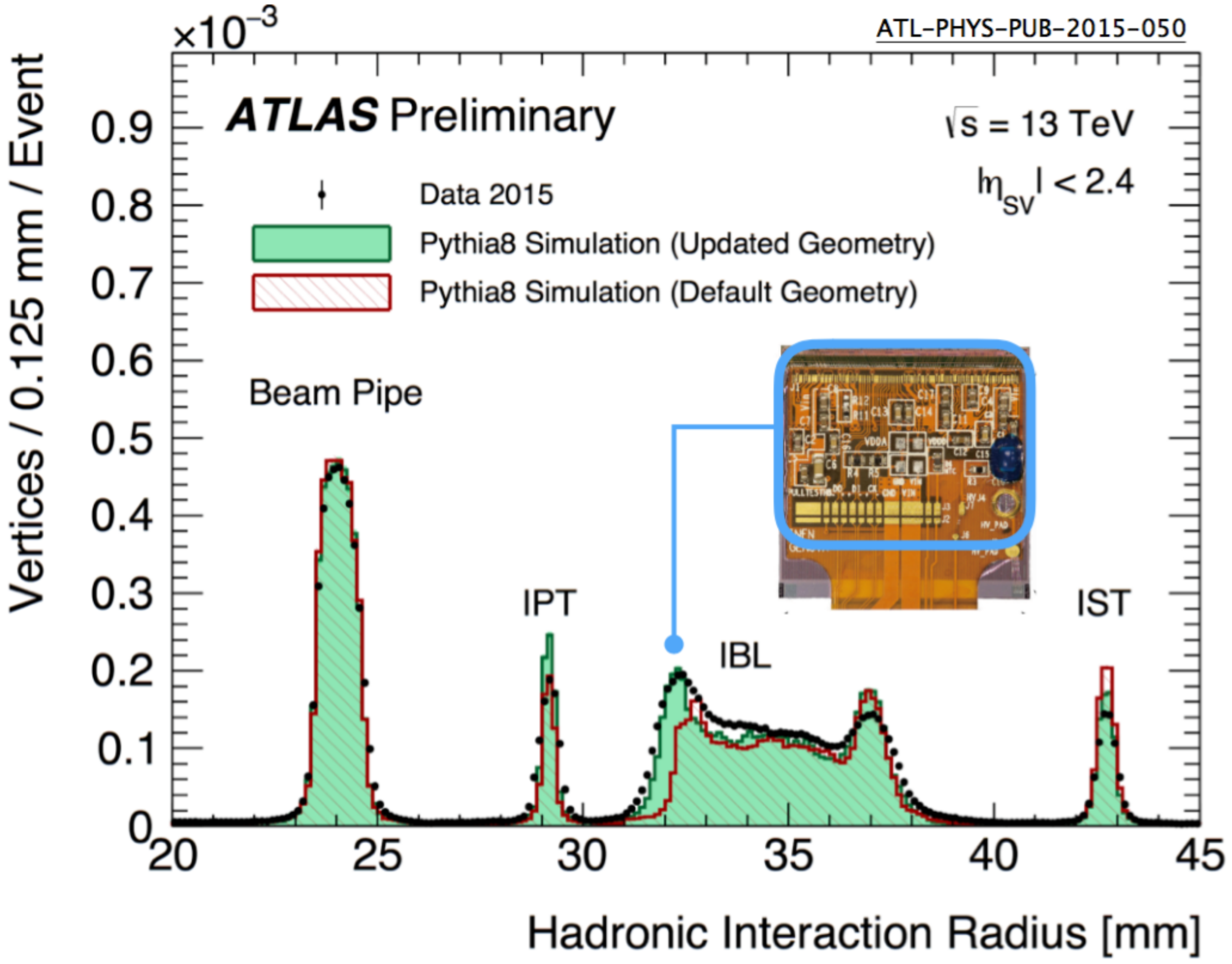


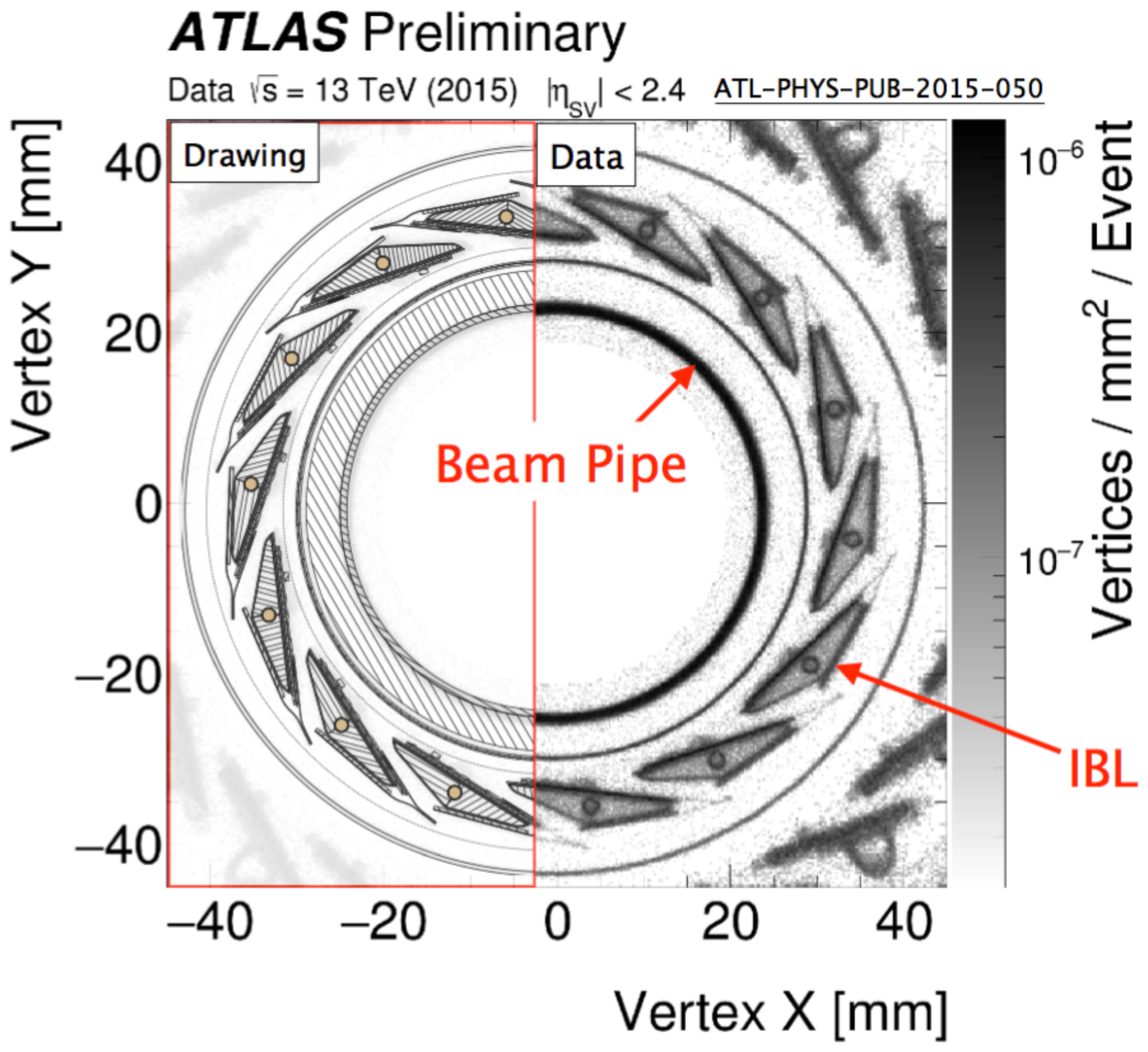
- ~40% improved impact parameter (d_0, z_0) resolution in Run 2 thanks to IBL
- Measurement of impact parameter resolution sensitive to
  - Material description at low p_T
- Material uncertainty is dominating tracking efficiency uncertainty —> Studied using in-situ techniques

ID material and geometry validation

"Radiographic diagnosis":

- Material budget probed using techniques complementary in systematics and coverage
  - Displaced vertices from hadronic interactions and photon conversions
  - Check "extensibility" of pixel "tracklets" to outer layers

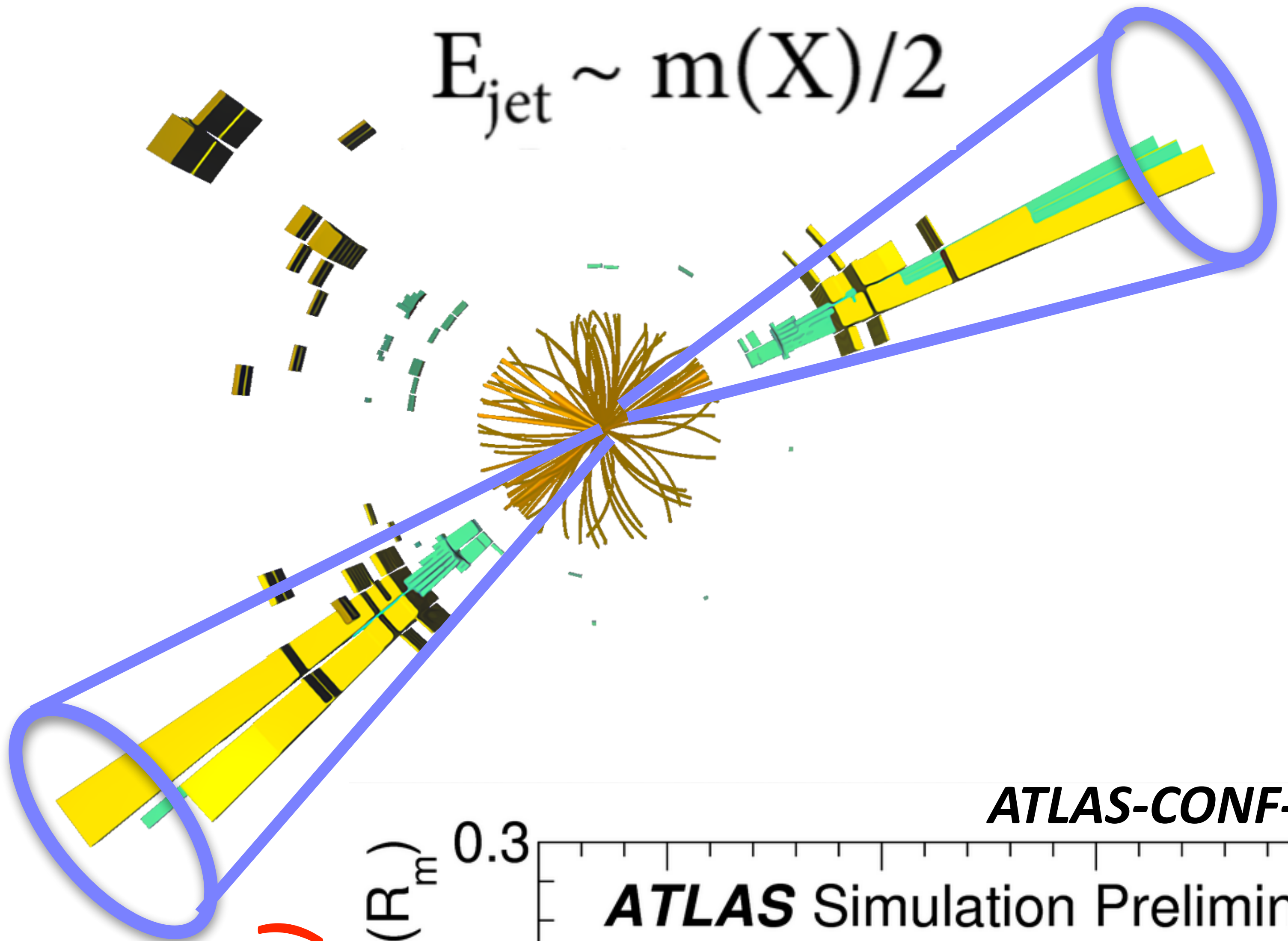




Updated geometry for Run 2:

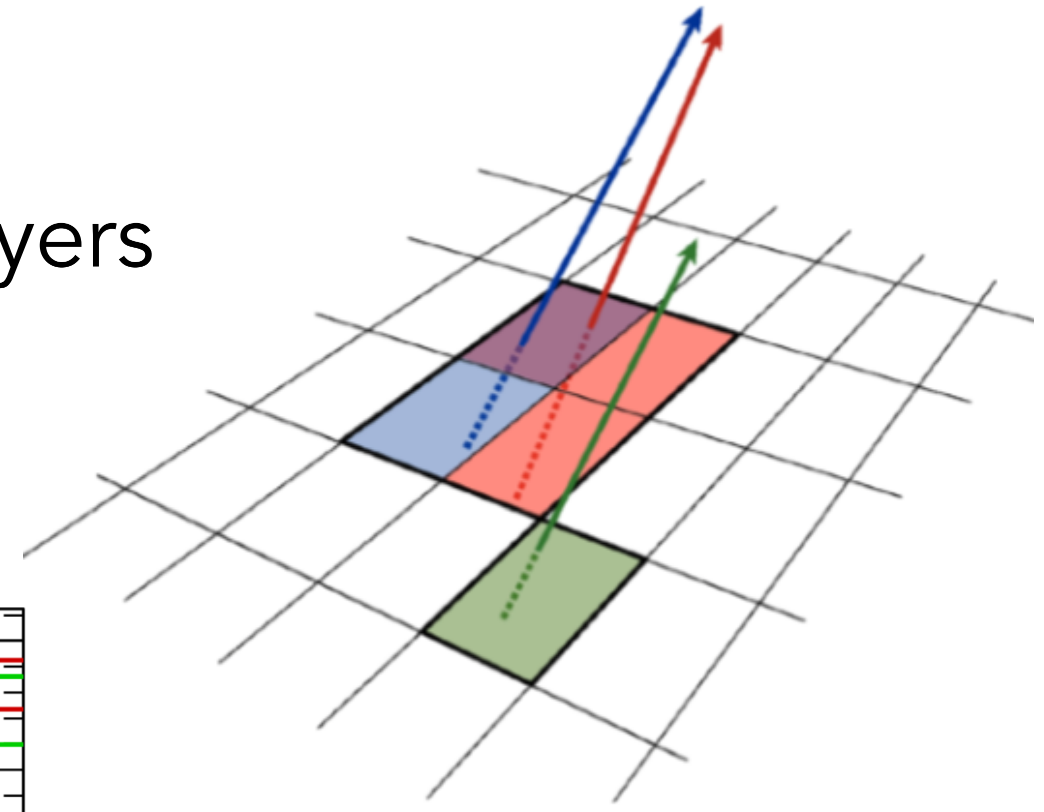
- Missing capacitors on the IBL front-end chips identified
- Initial under-estimation of IBL material corrected
  —> cause of over-optimistic d_0 resolution in MC

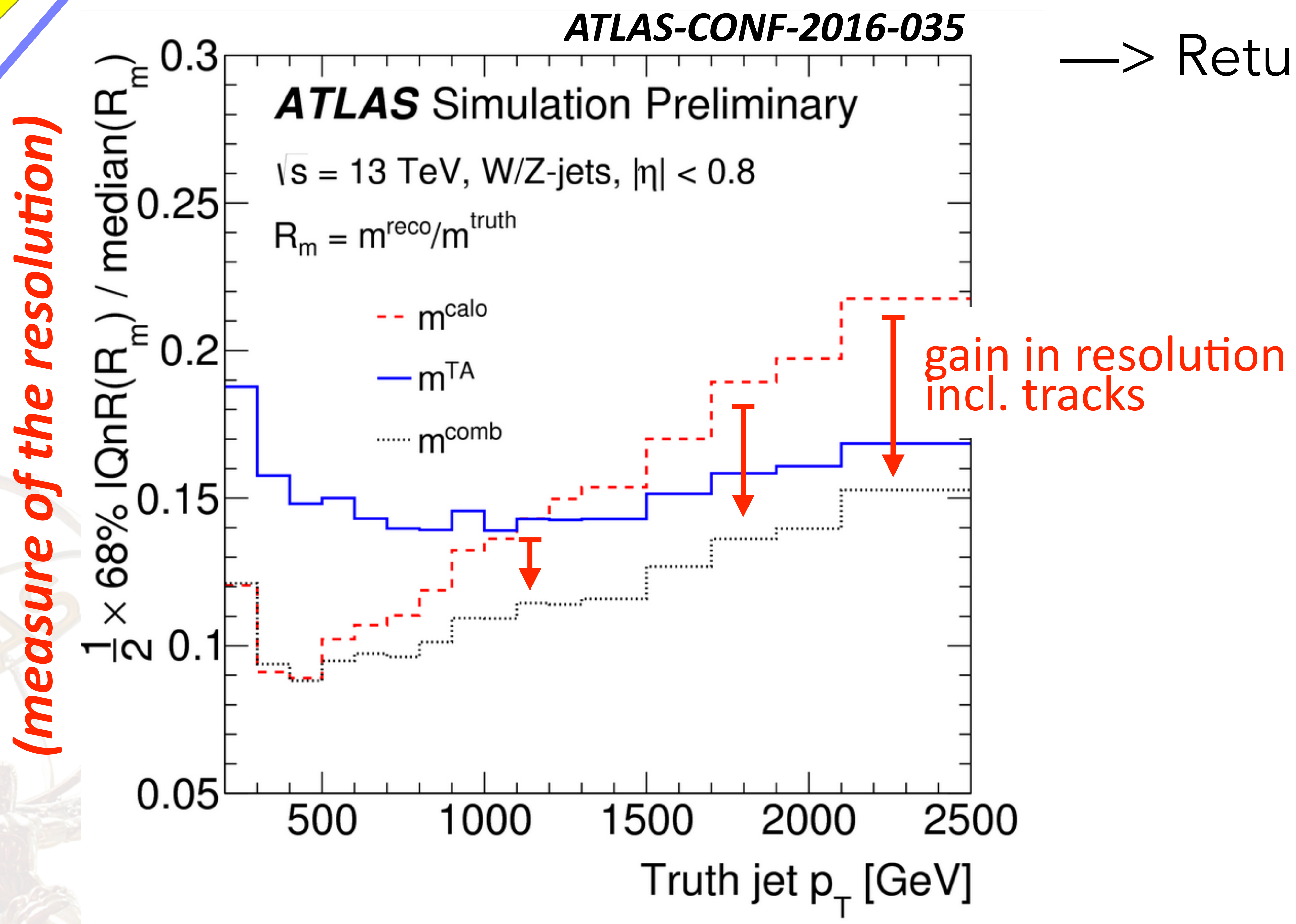
Tracking in Dense Environments (TIDE)

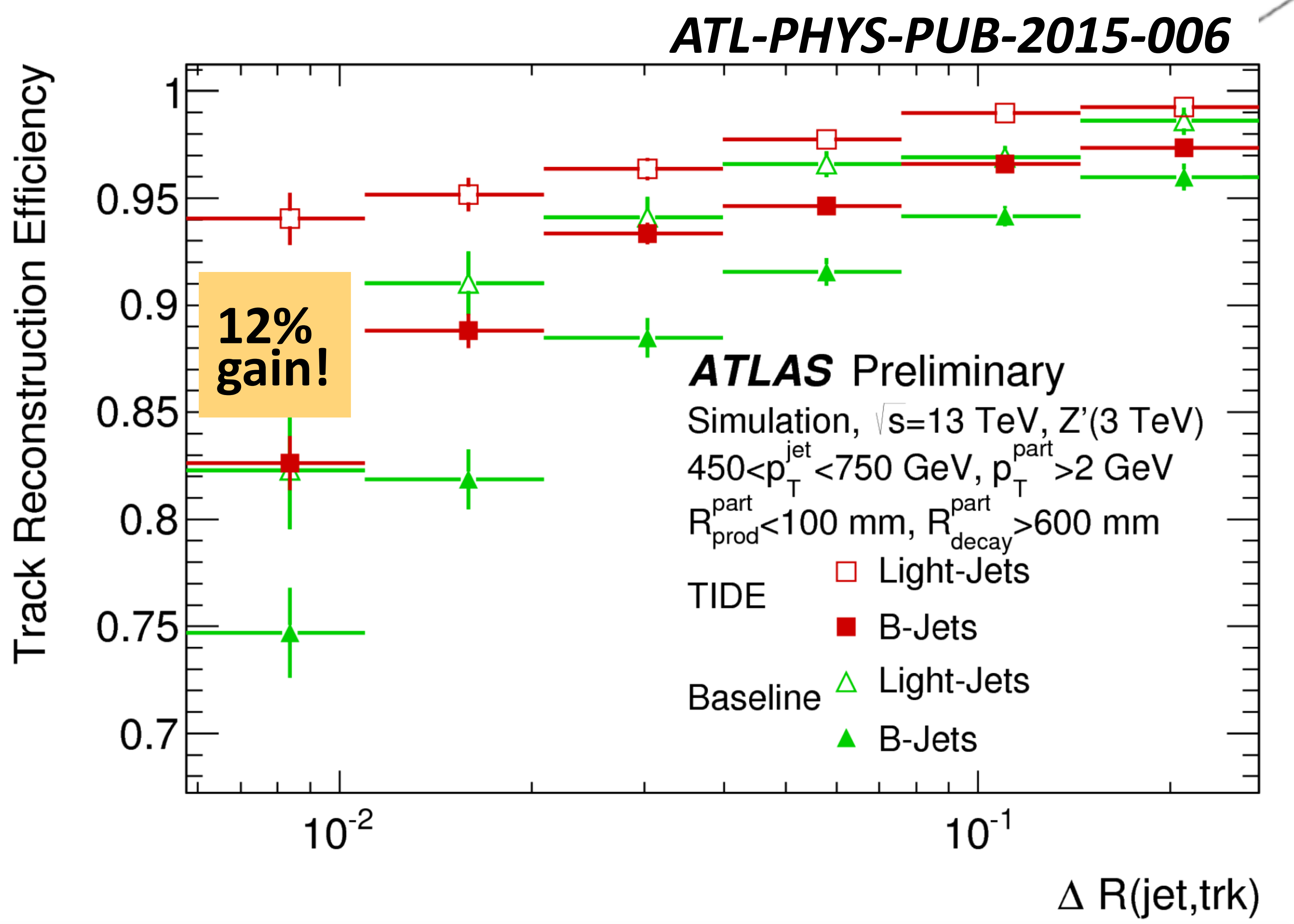


Physics at the Energy Frontier — Jets at 13 TeV:

- Jet mass resolution (& uncertainties) a key to new BSM discoveries !
- Using tracks improves jet-mass resolution when combined with calorimeter
- **The Challenge:** Resolve close-by particles leading to merged pixel clusters without increasing fakes
- Multivariate techniques exploit information on cluster charge and shape, correlated across layers —> Returns # of particles, positions, errors







TIDE performance measured in data

Technique 1: Geometrical extrapolation

- Separating into single/multiple particle clusters from the overlap region in phi of the detector
(Extrapolation is also checked between layers)

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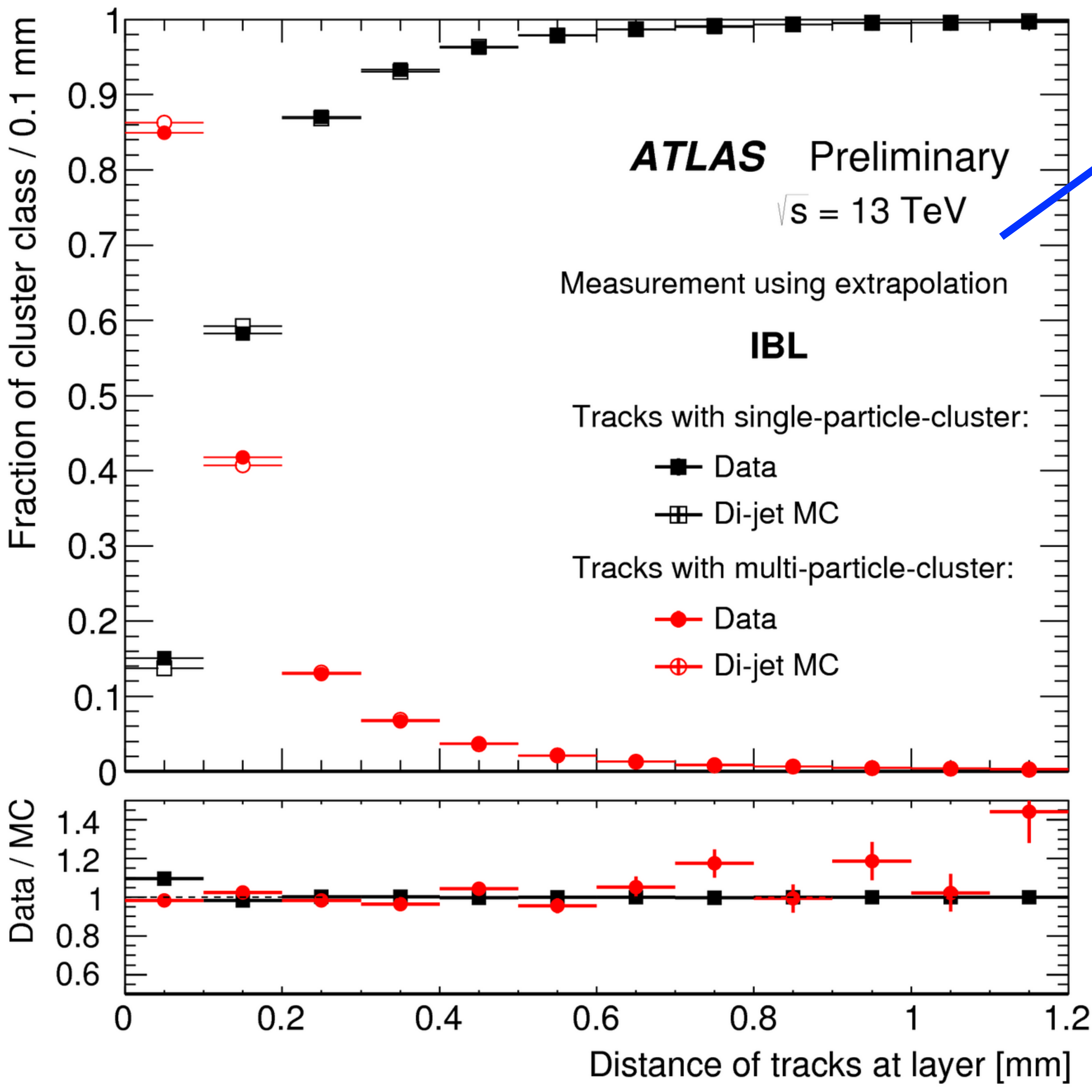
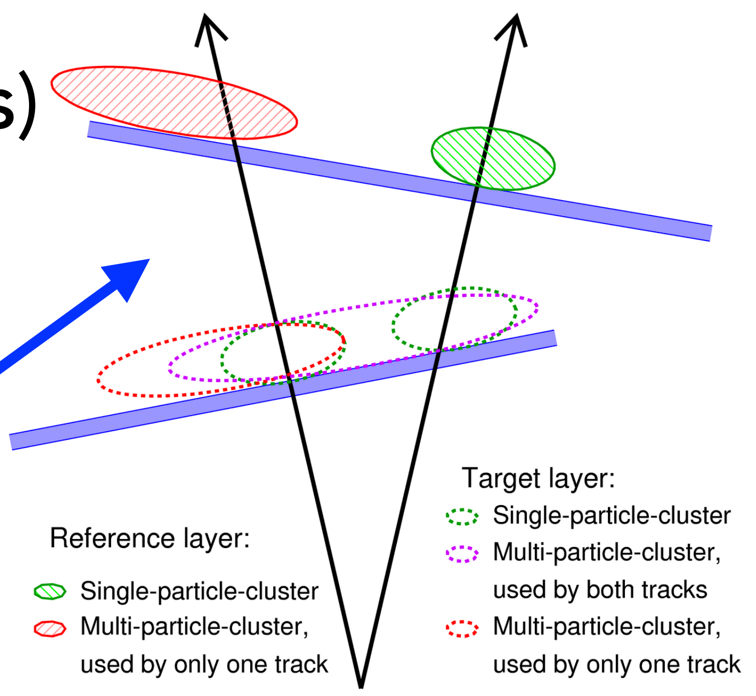
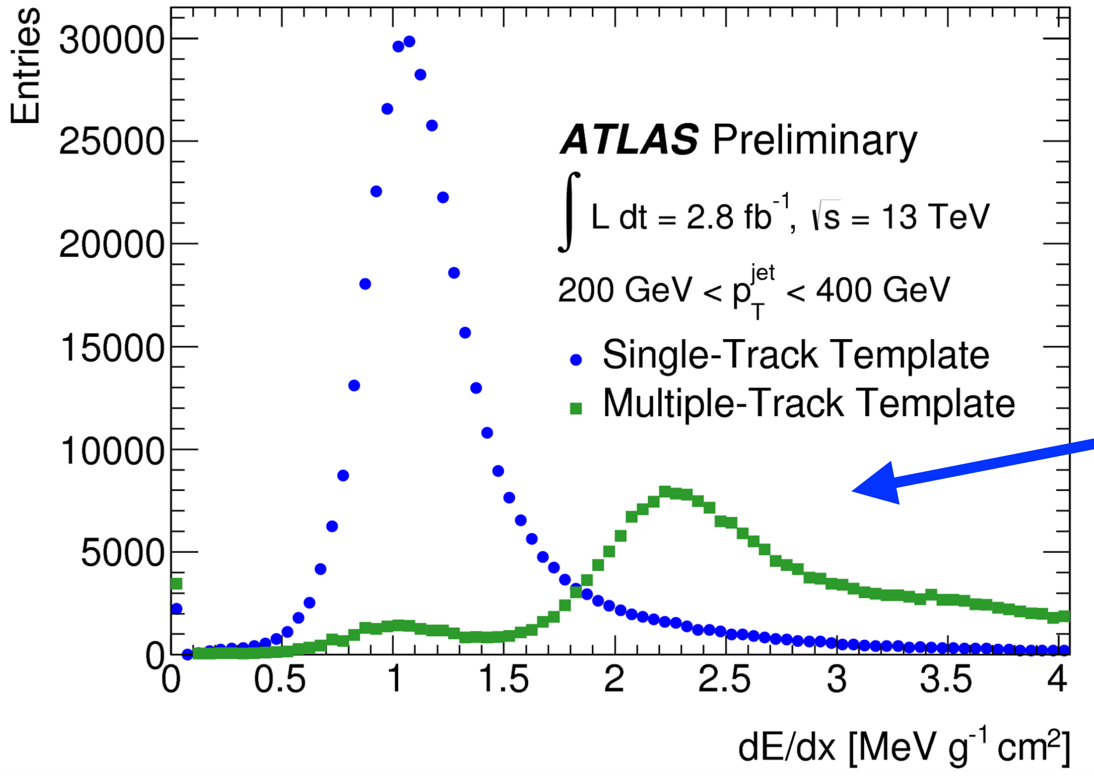




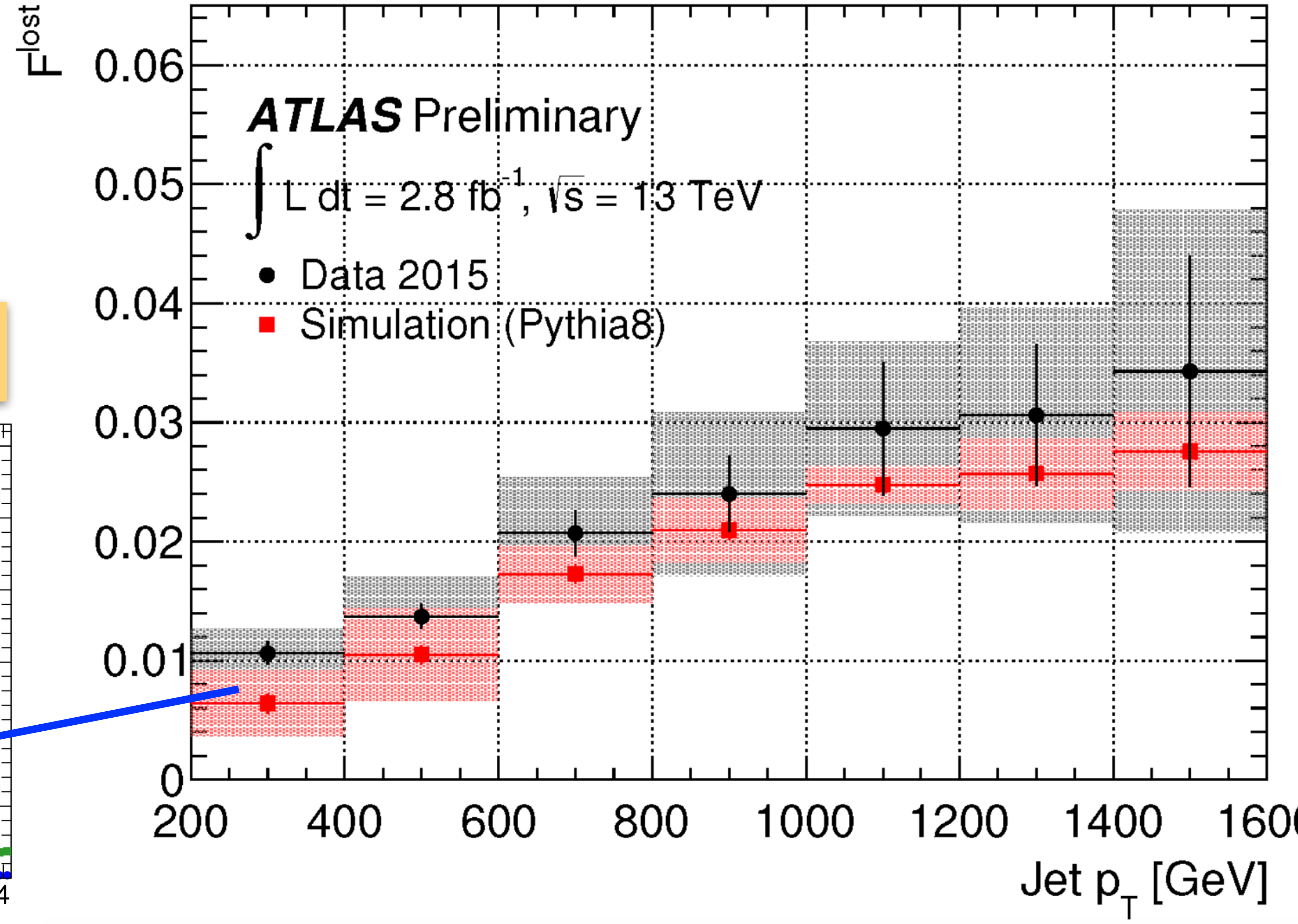
Technique 2: Energy loss in Pixels (dE/dx)

- Measure fraction of particles not reconstructed inside jets F^{lost}
- Statistically disentangle single/multiple particles from dE/dx in innermost layer (template fitting)

example of dE/dx template



ATL-PHYS-PUB-2016-007

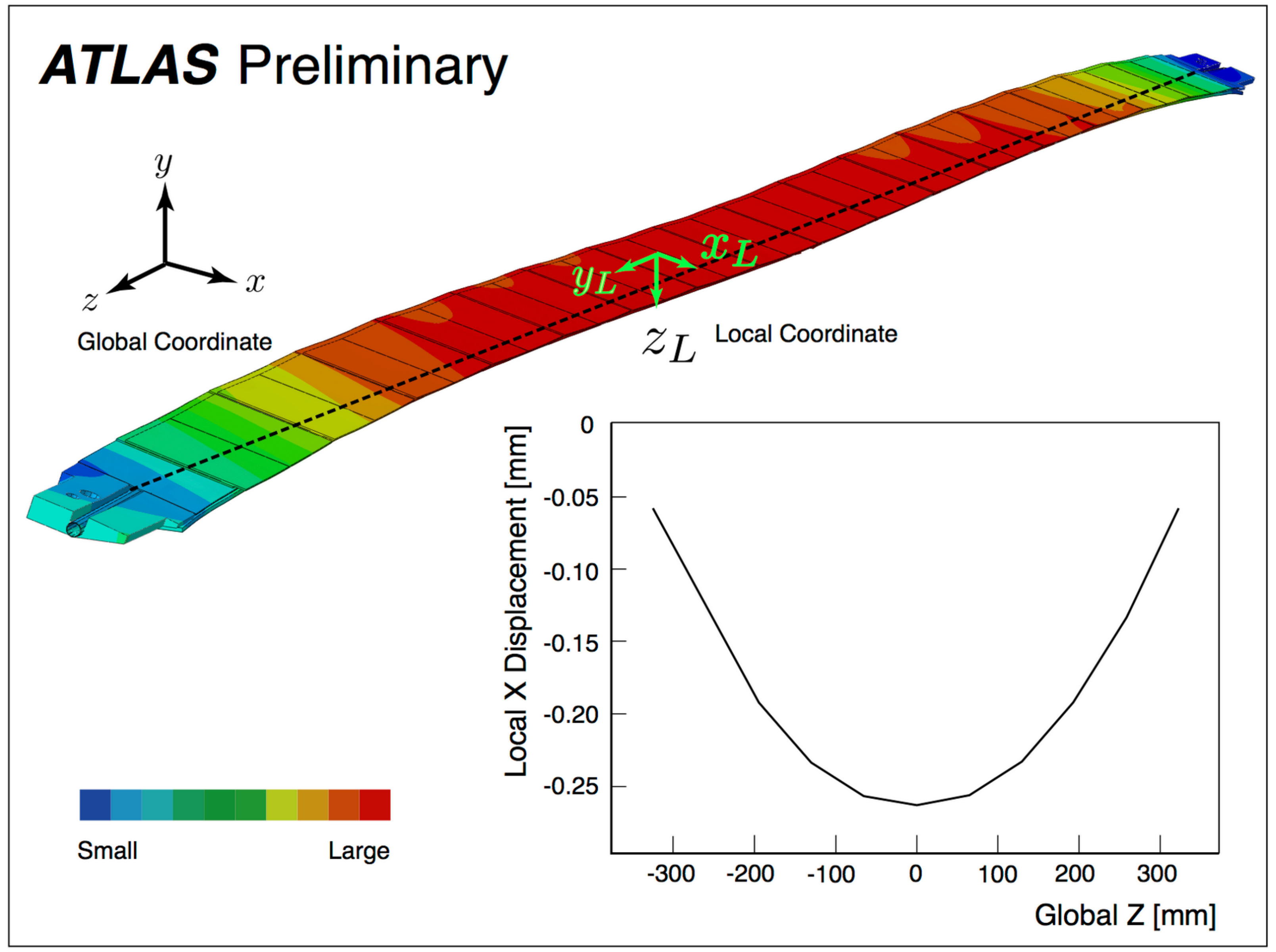


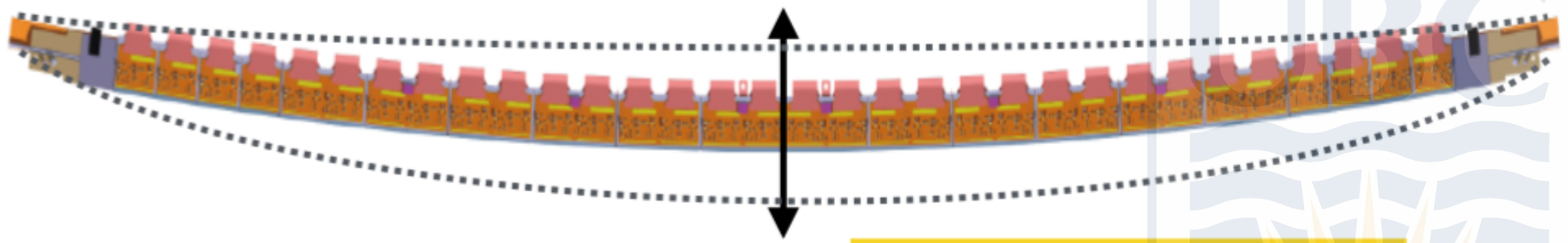
ID alignment — dynamically adjusting the ATLAS ID

Run by run and the within-run stability of the ATLAS ID:

- Detector generally stable on longer time-scales except for "seismic events" (power cut, magnet ramp, cooling failure)
- Short time scale movements within a run —> currently 2 known movements
  - Vertical up- and down-movement of the Pixels package within fill
  - IBL mechanical instability with temperature
    - Radiation damage of IBL electronics making IBL power consumption unstable
    - Thermal expansion mismatch inside IBL stave is sensitive to power consumption
    - Consequently, causing rapid change of IBL stave's bowing distortion
- Strategy: determine "perturbation" of the detector package/stave movement from an accurate alignment baseline every
  - ~20 minutes (first hour of fill)
  - ~100 minutes (rest of fill)
- Running automatically inside the prompt calibration process (updated within 24h after run finished)

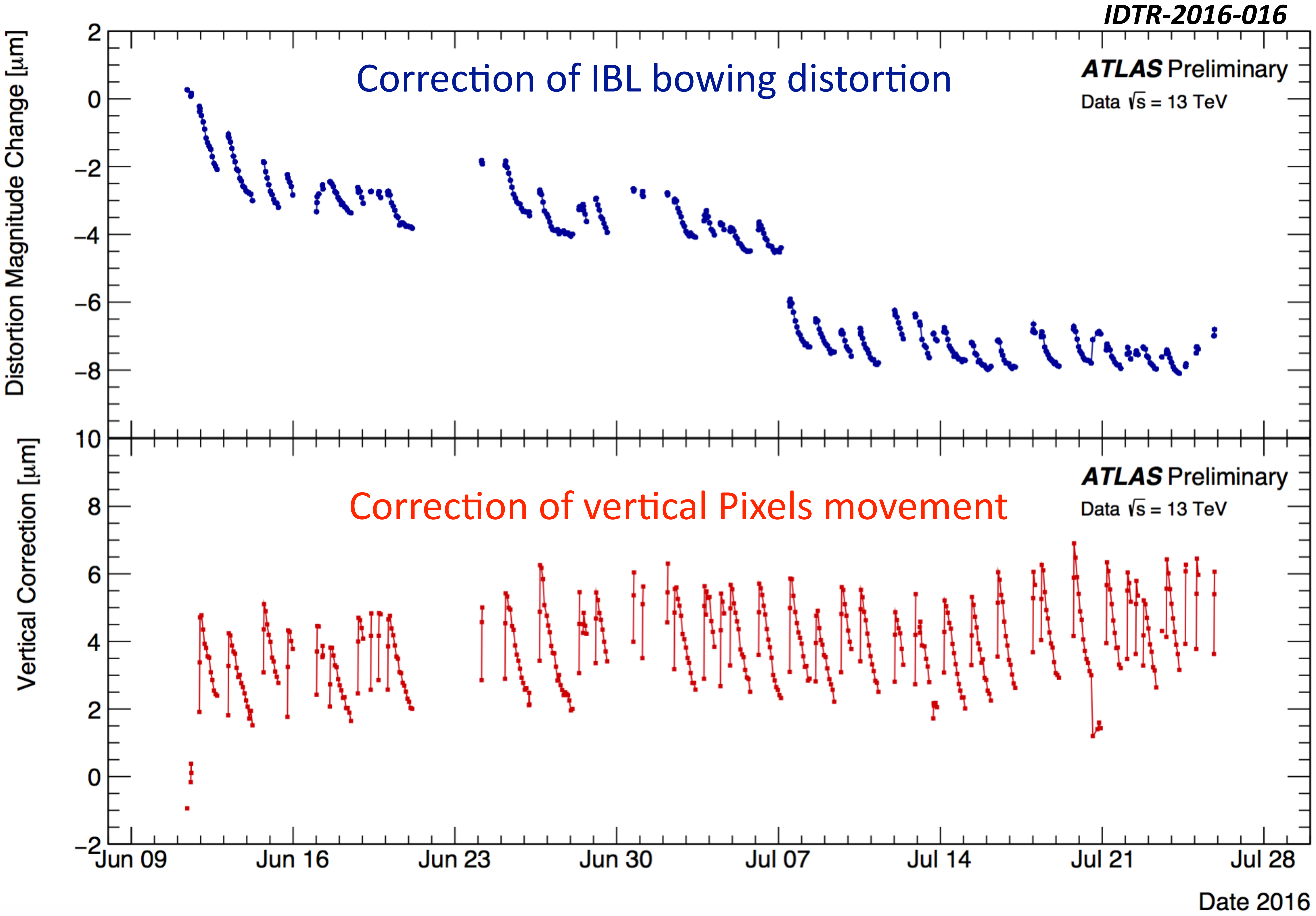
PIX-2015-008
ATL-INDET-PUB-2015-001

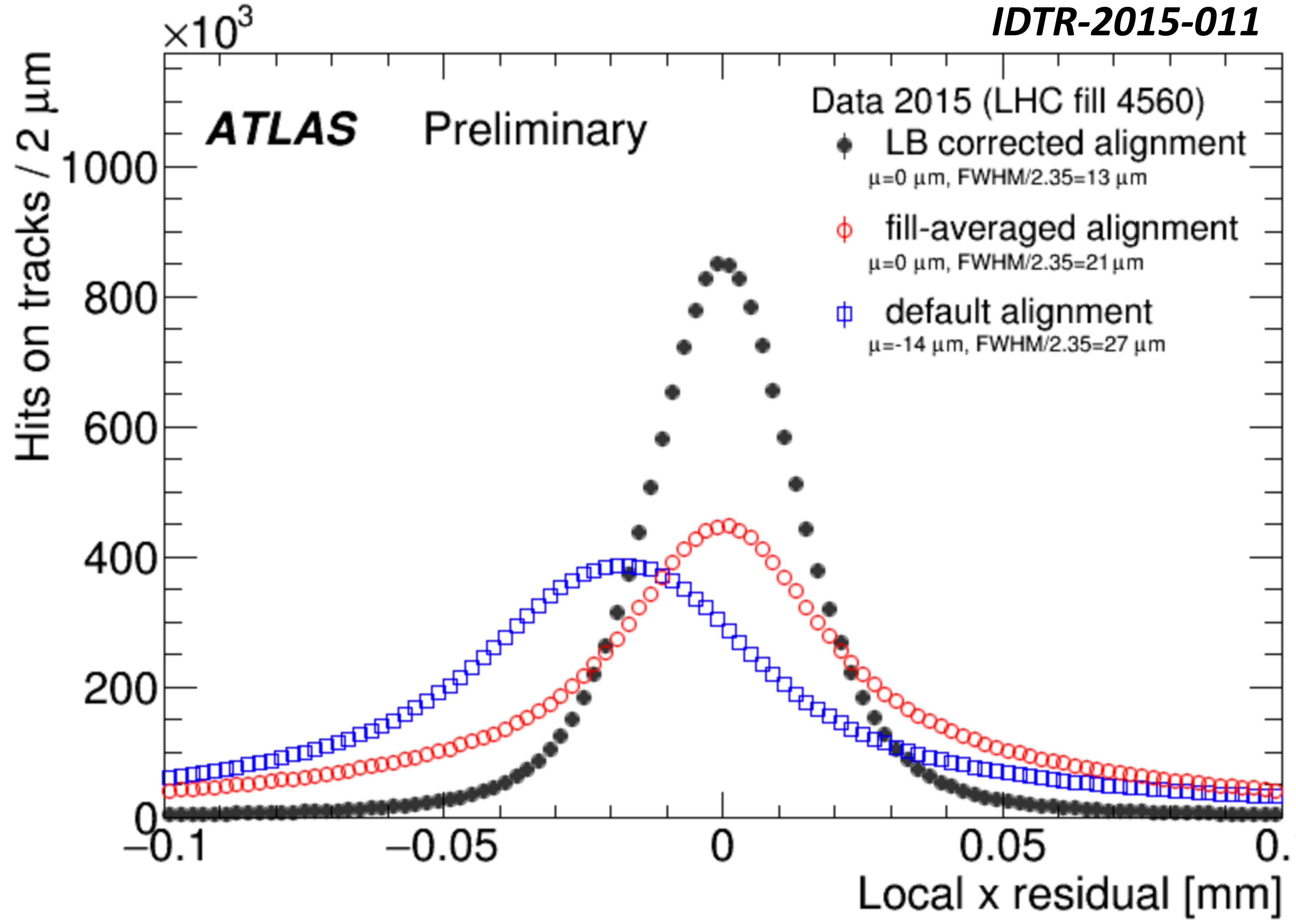




~11 μm/Kelvin

ID alignment — dynamically adjusting the ATLAS ID



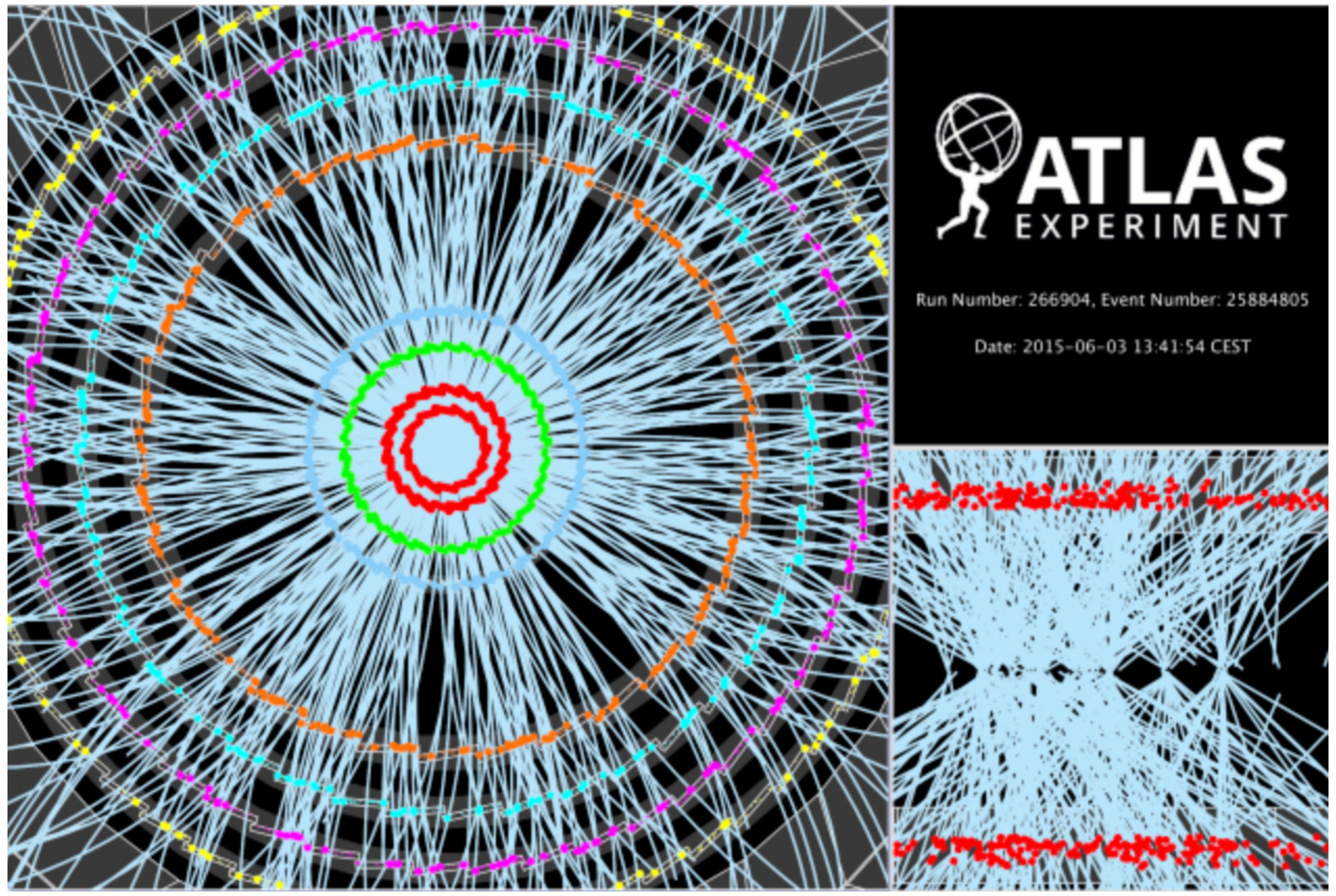


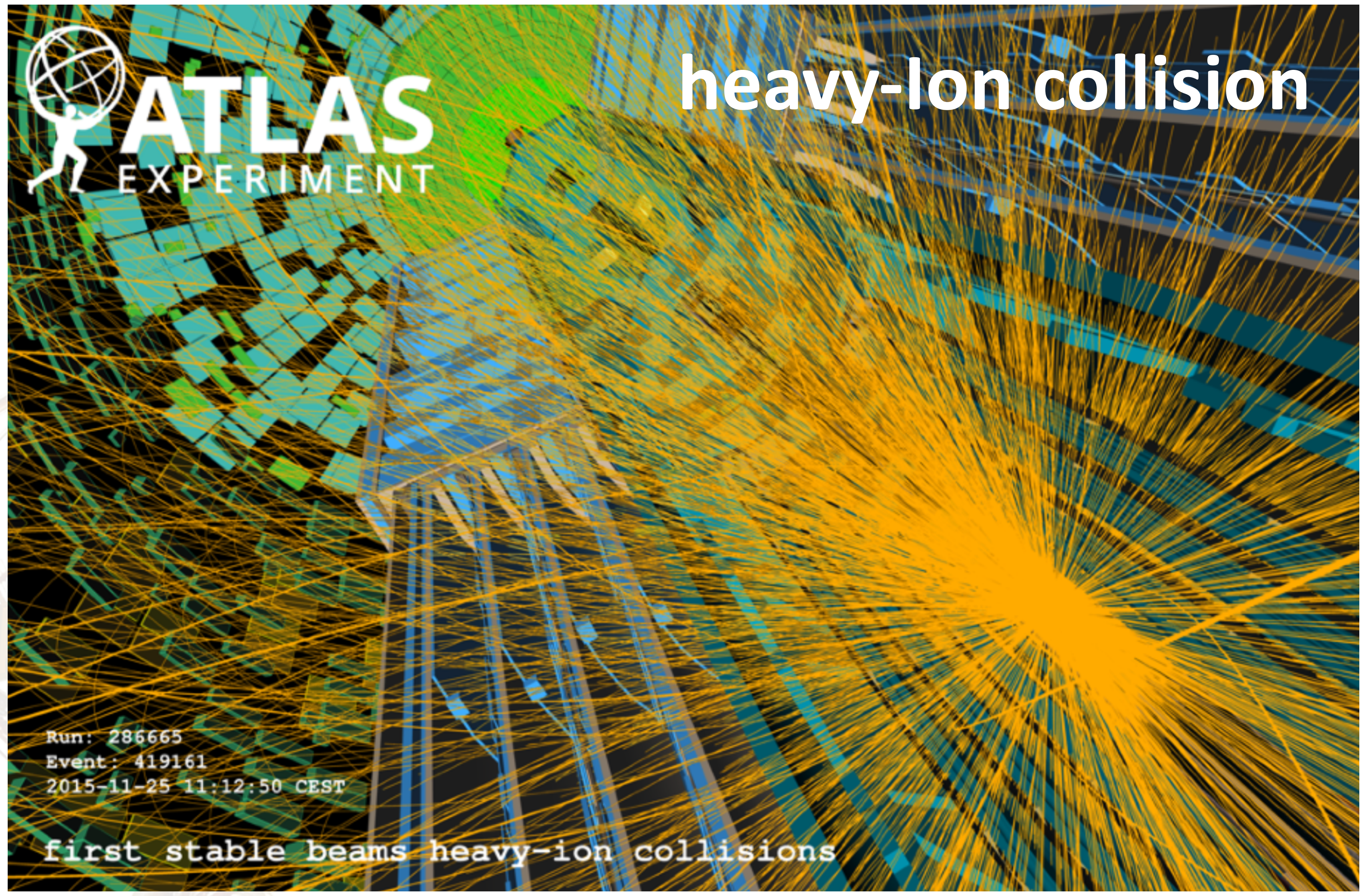
- Clear improvement also seen in track to hit residual distributions

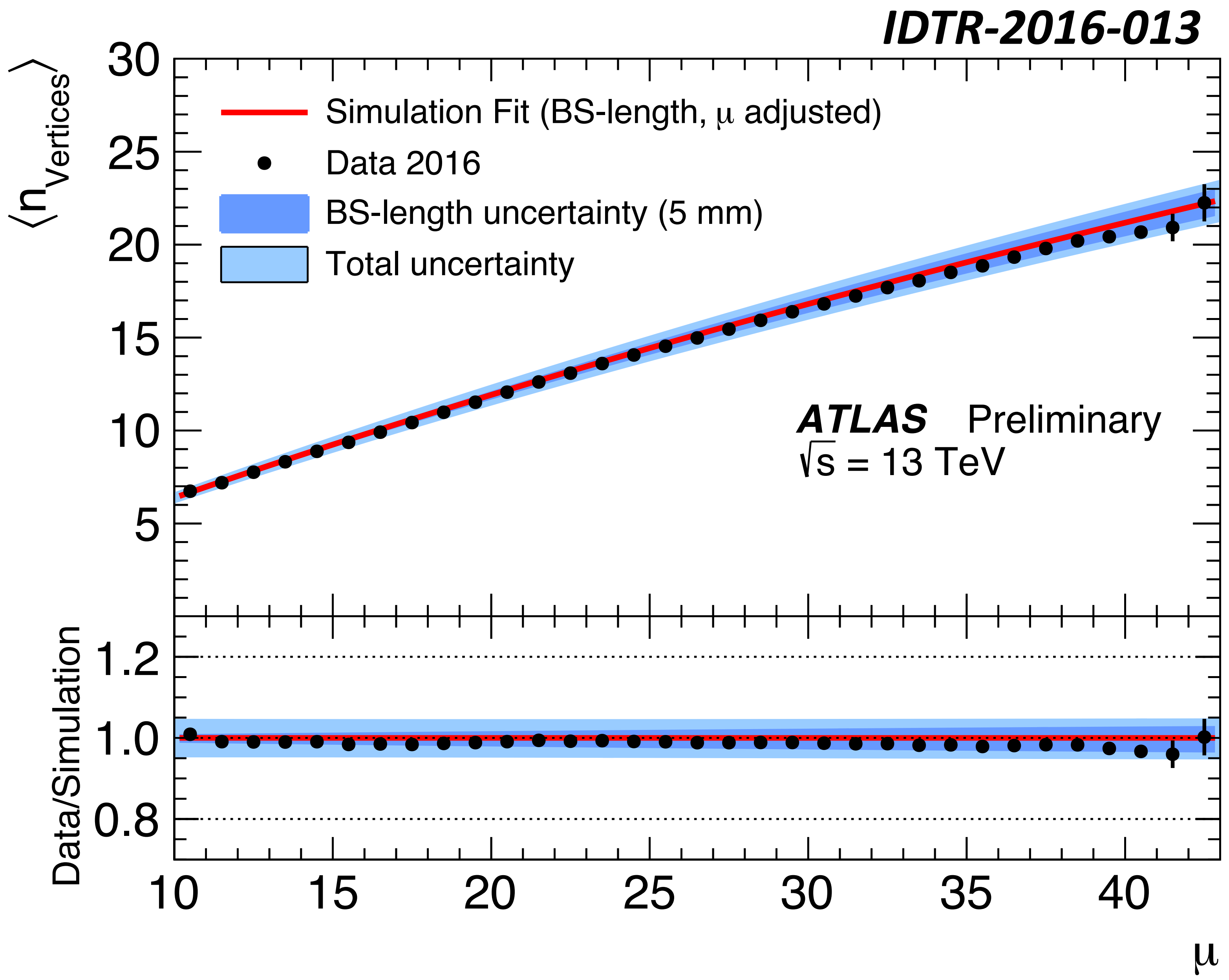
Correcting these short-time scales effects —> excellent alignment accuracy is achieved

- ATLAS is capable of time-dependent re-alignment of full ID for each run within the prompt calibration process

Other performance highlights







Vertex reconstruction:

- Iterative vertex reconstruction
- Vertices merge when closer than the resolution
- Non-linearity due to merging is largely dependent on beam spot shape

Dedicated tracking setup for specific needs:

- Minimum-bias → “single-interaction” mode, p_T from 400MeV to 100MeV
- Heavy-Ion → “high-occupancy” ensuring low p_T ~300MeV
- Short-tracks → pixel-only tracks. Now reconstructed by default (p_T > 5GeV)
- **Large-radius tracking** →decay products within whole Pixel volume (large d_0)

Conclusions

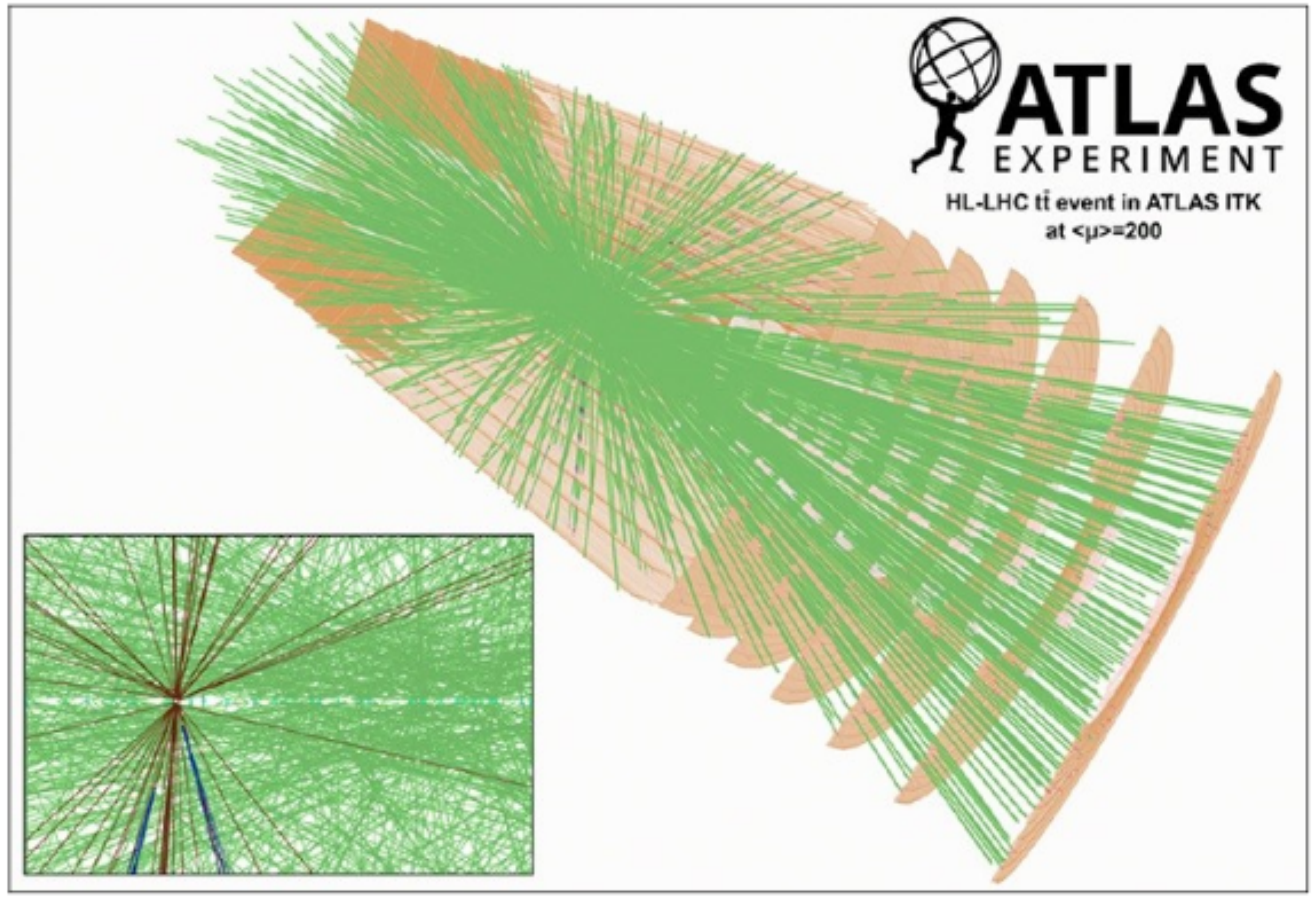
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/InDetTrackingPerformanceApprovedPlots

- Upgraded detector and rapidly changing running conditions pose new challenges to track reconstruction in Run-2
- Performed a comprehensive set of in-situ measurements of key observables
- Developed mechanisms to mitigate new problems & achieve better or similar performance than in Run-1
- Ready for the ongoing luminosity ramp-up to make the best use of the large dataset ahead of us
- Already working on the future Inner Tracking system for the HL-LHC
  - TRT removed
  - 5 pixel layers
  - 4 strip layers

—> see for details ***ATL-PHYS-PUB-2016-025***

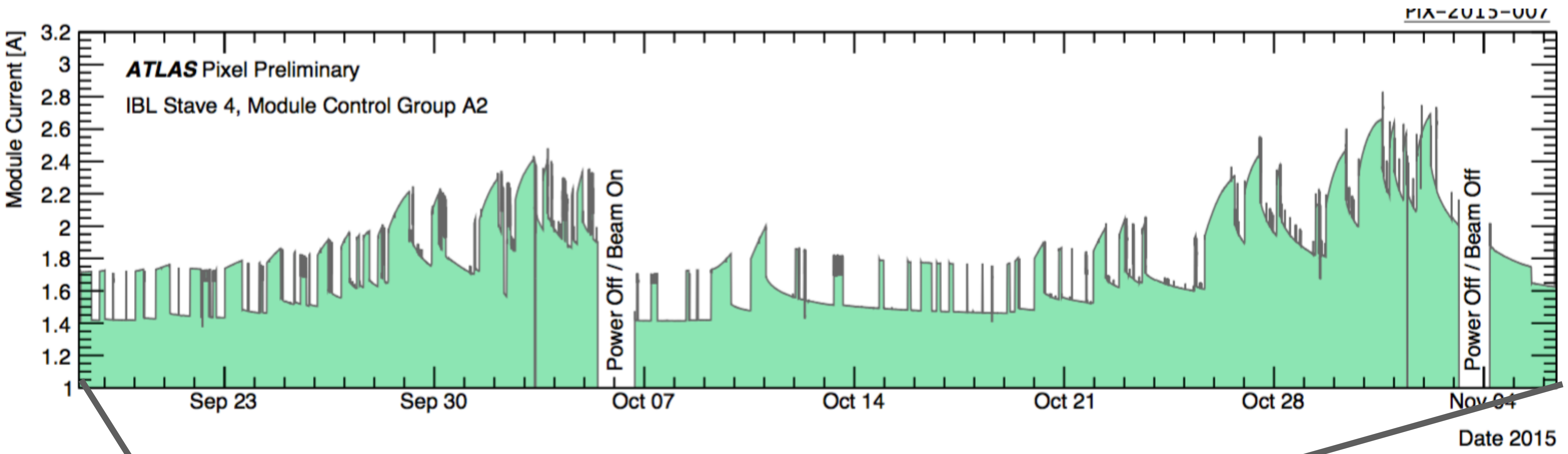
2026: $\sqrt{s}$ = 13-14 TeV
$\mathcal{L}_{peak}$ > 10^{35} cm^{-2}s^{-1}
$\langle\mu\rangle$ = 200

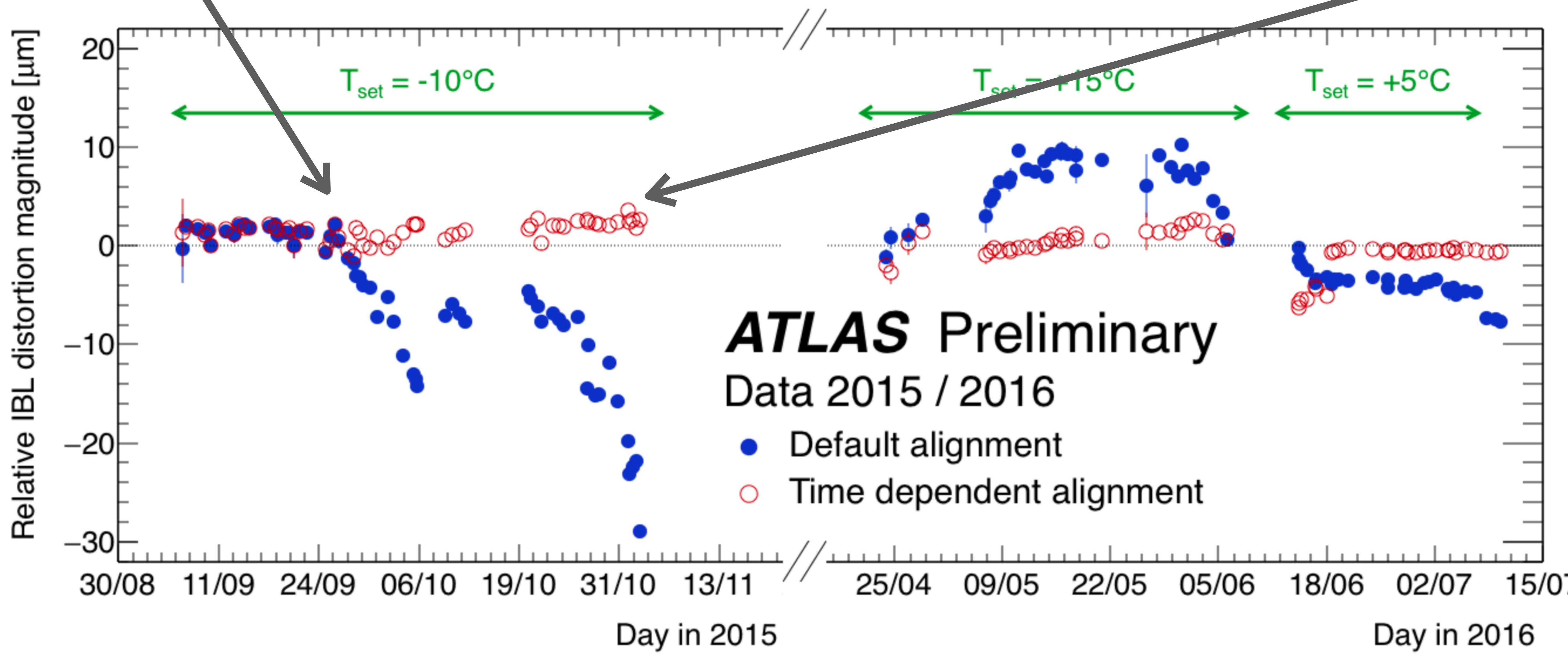
see also poster 16
for more details!

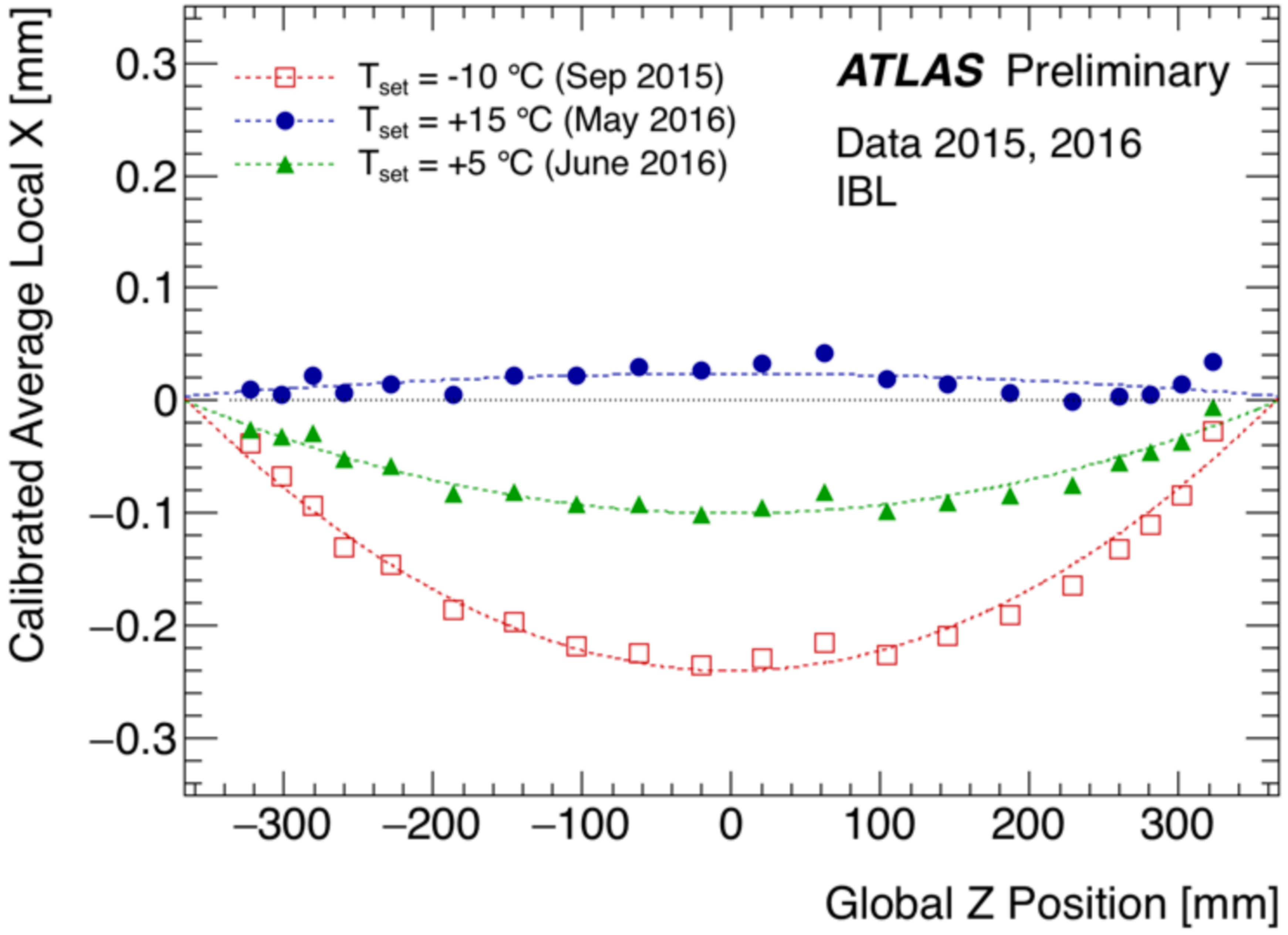


Back up

ID alignment — dynamically adjusting the ATLAS ID







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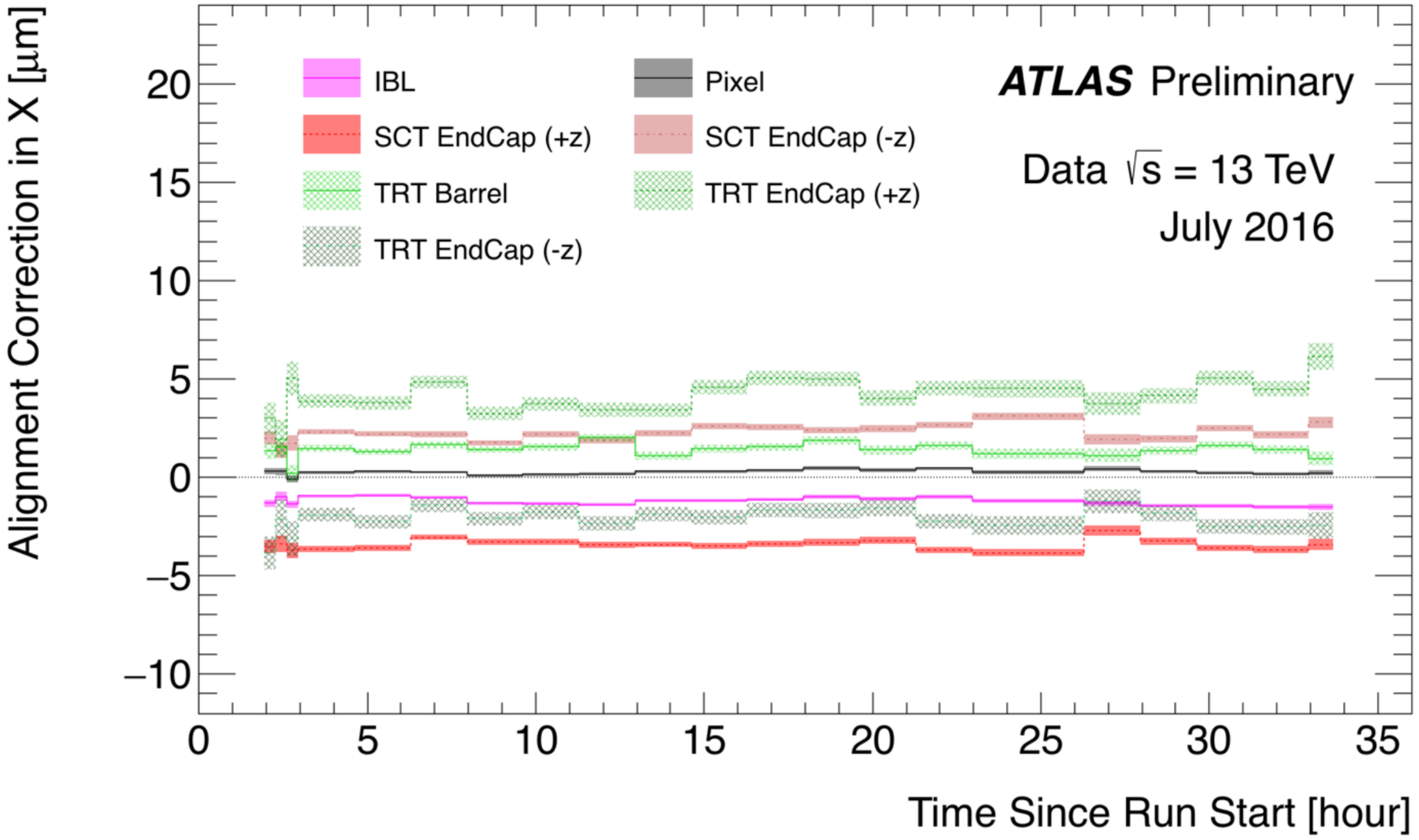
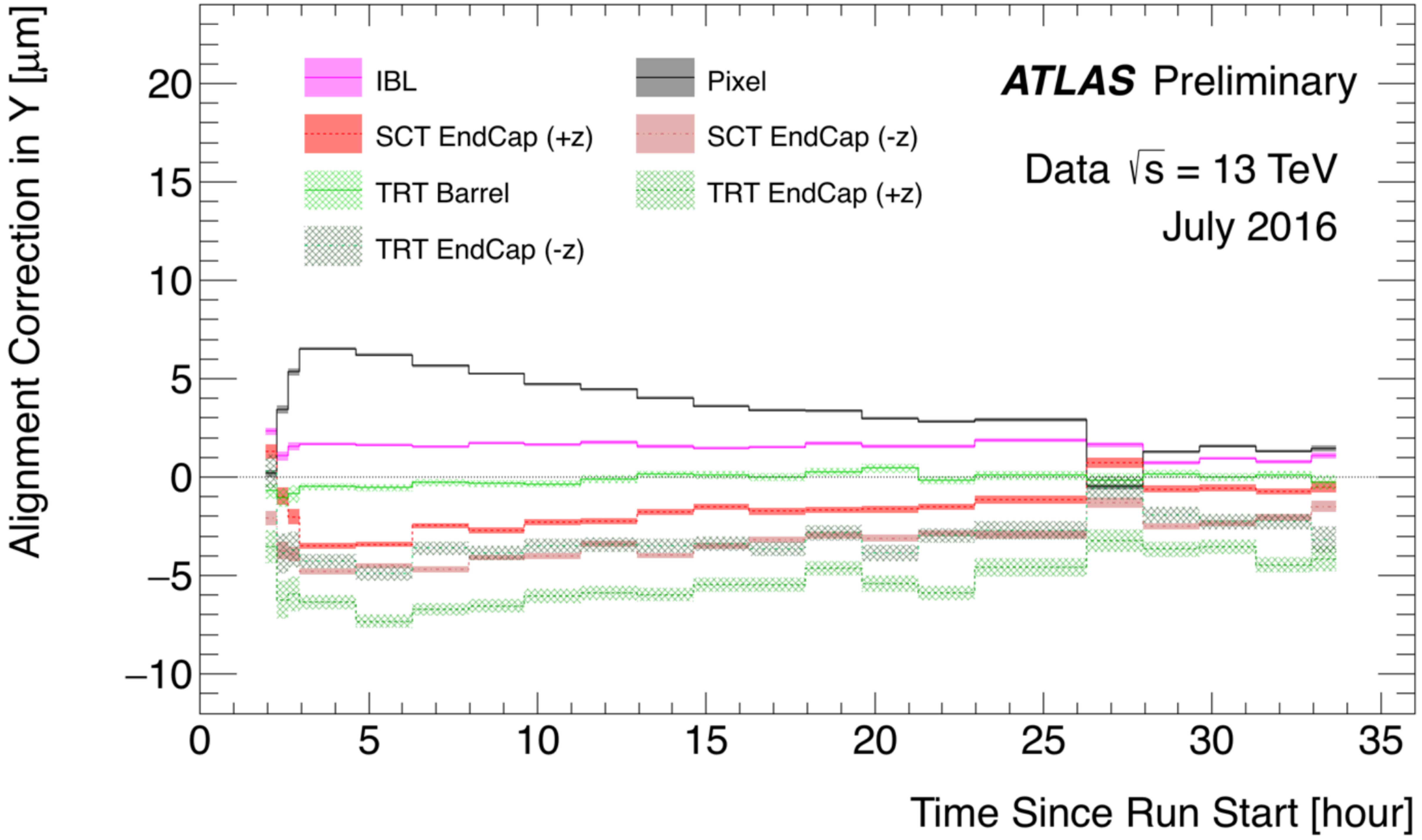
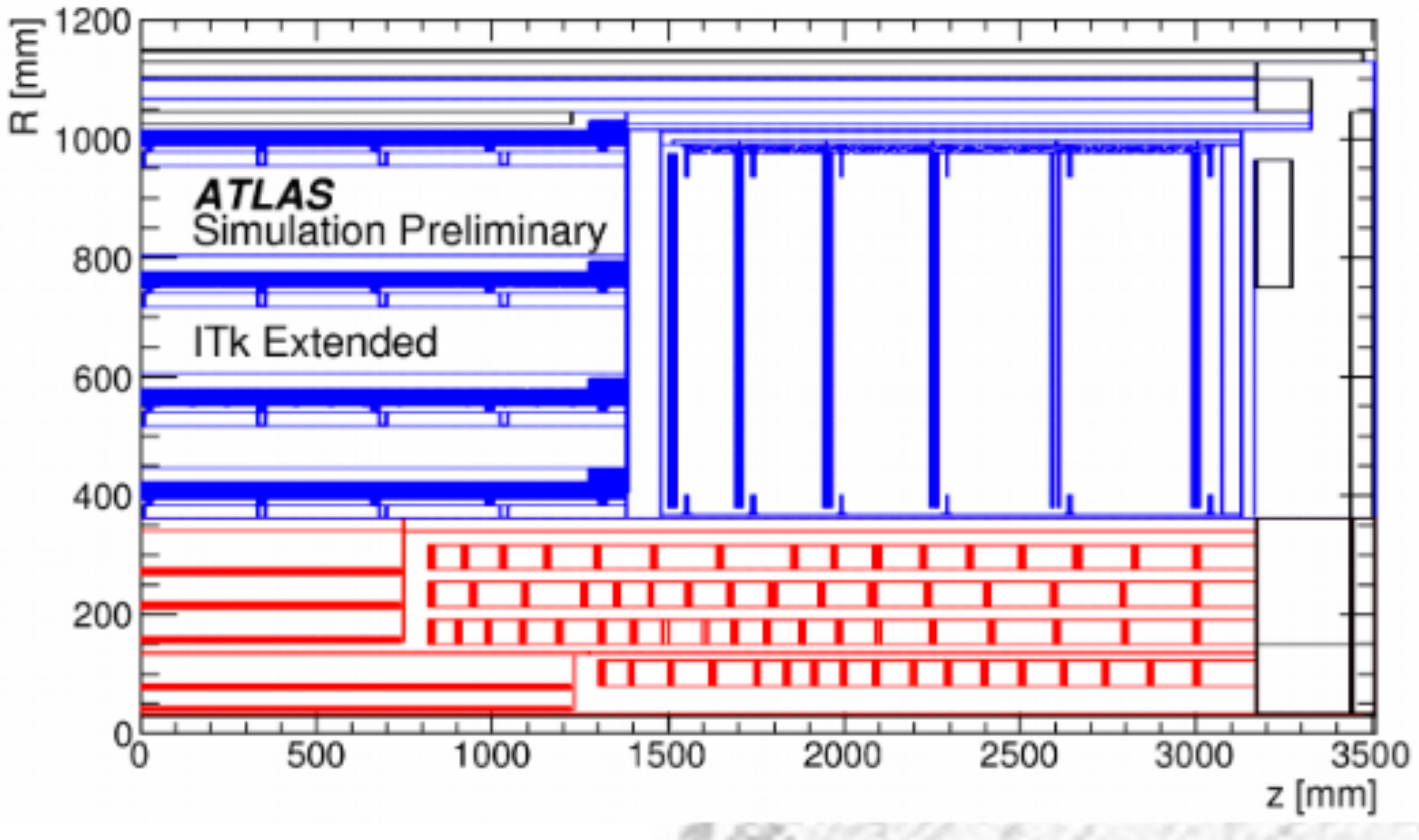
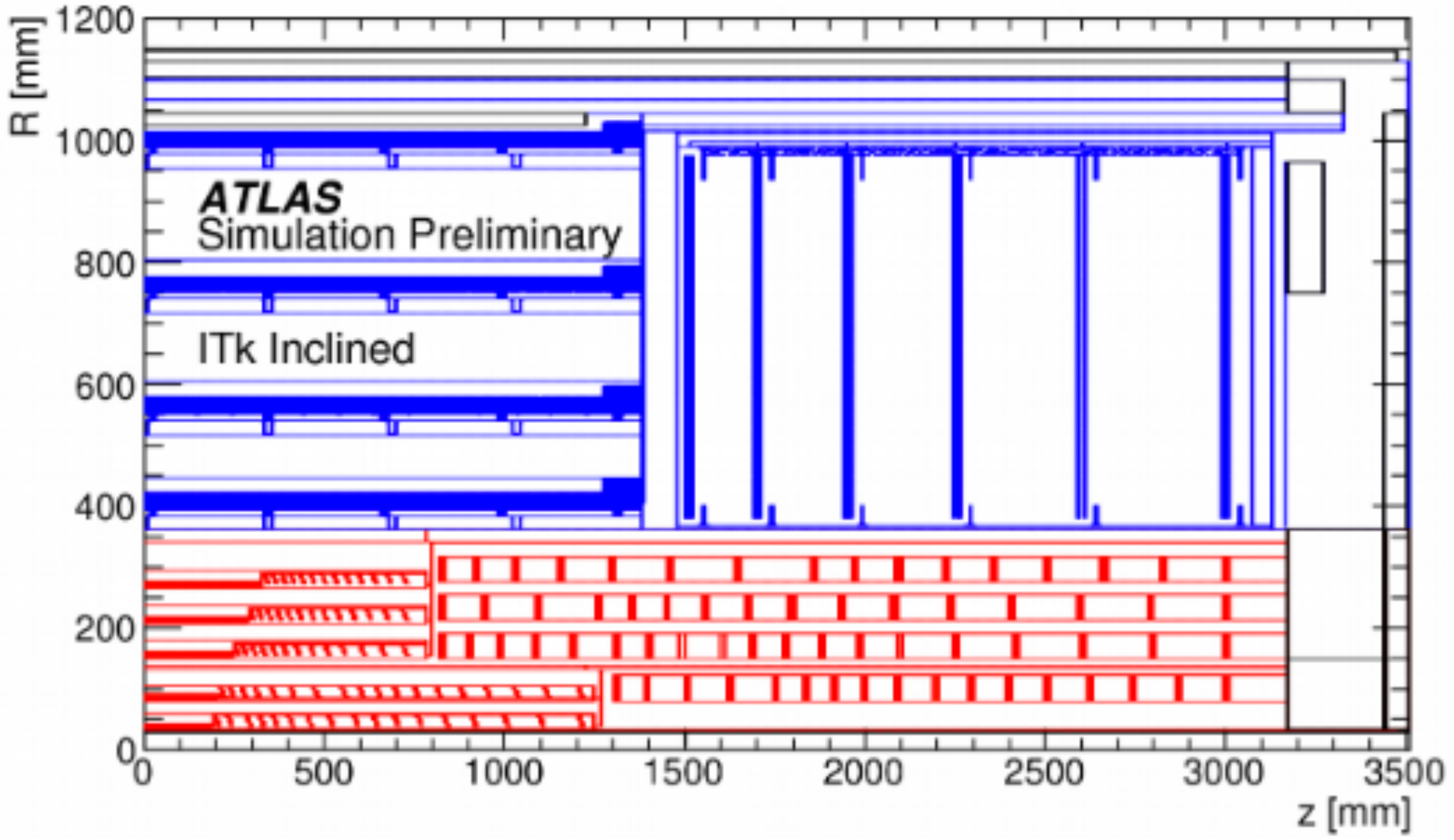




ITk Simulation

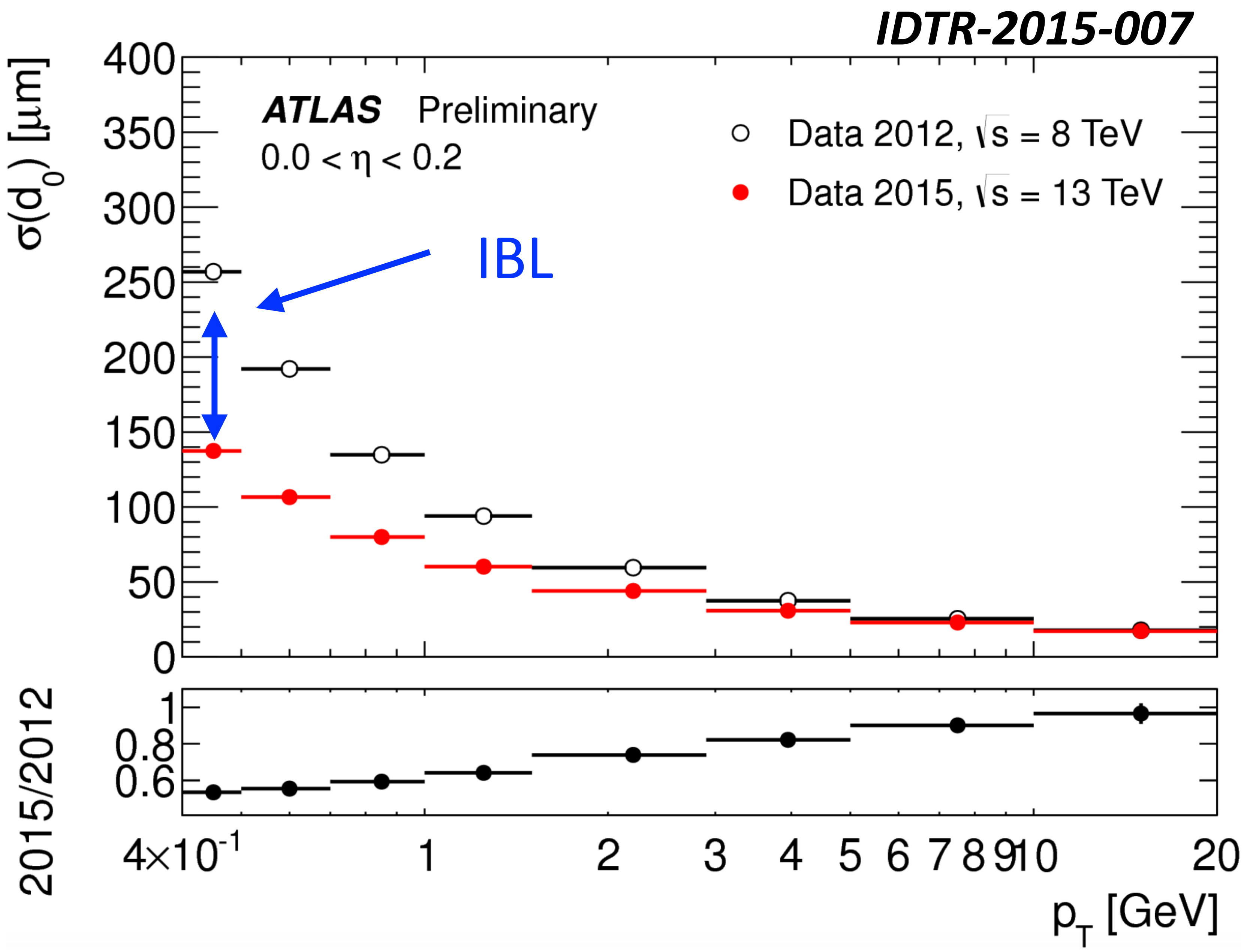
- GEANT4 simulation
- Pixel Sensors:
  - → planar n-in-n with FE-I4
  - → 50x50 μm²
  - → 150 μm thick
  - → threshold 600e
  - → 1x1, 1x2, 2x1, 2x2 modules
- Strip Sensors:
  - → n-in-p sensors
  - → strip length 19-60 mm
  - → 320 μm thick
  - → 75.5 μm pitch
  - → 20/26 mrad stereo angle



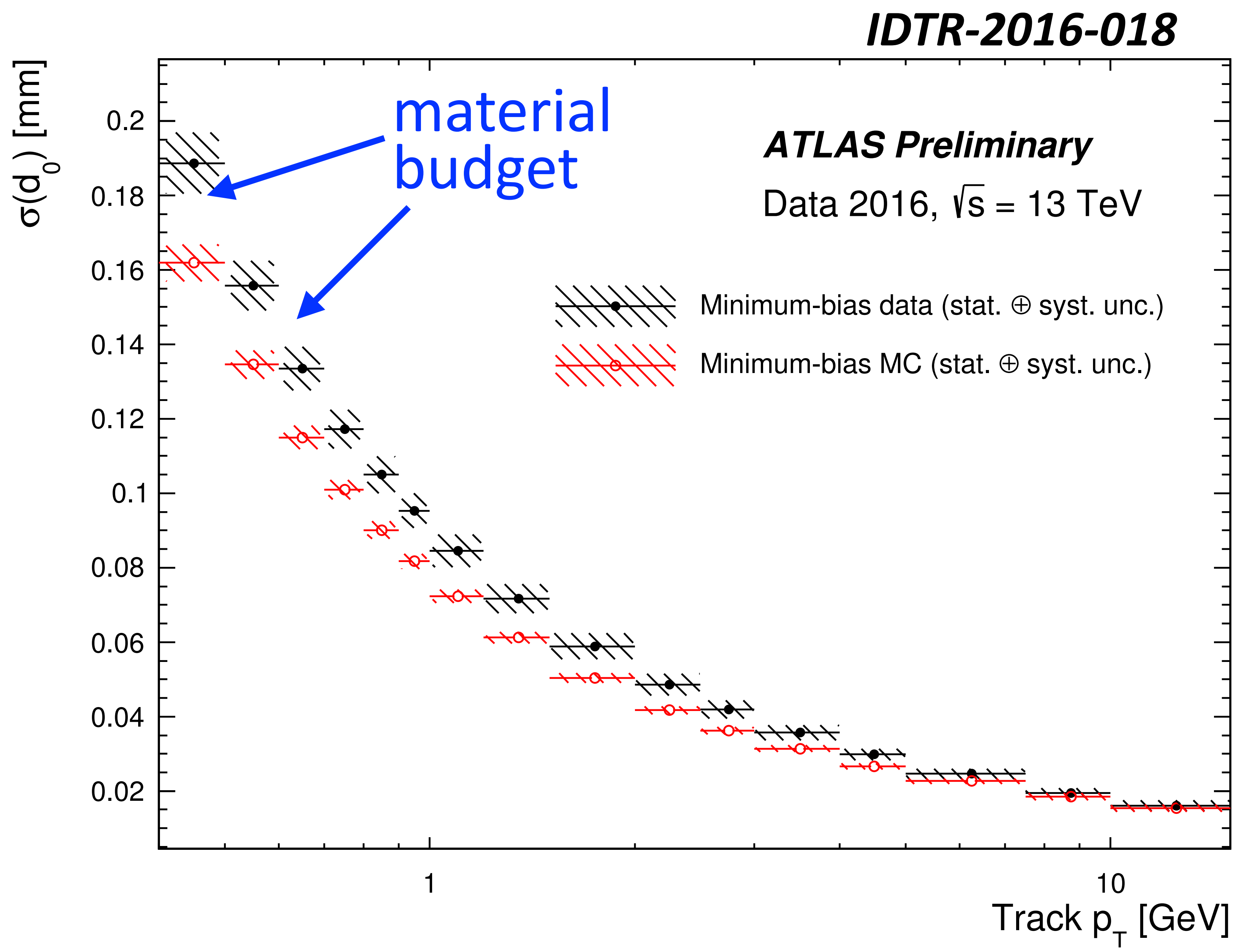


Reconstruction performance in Run 2

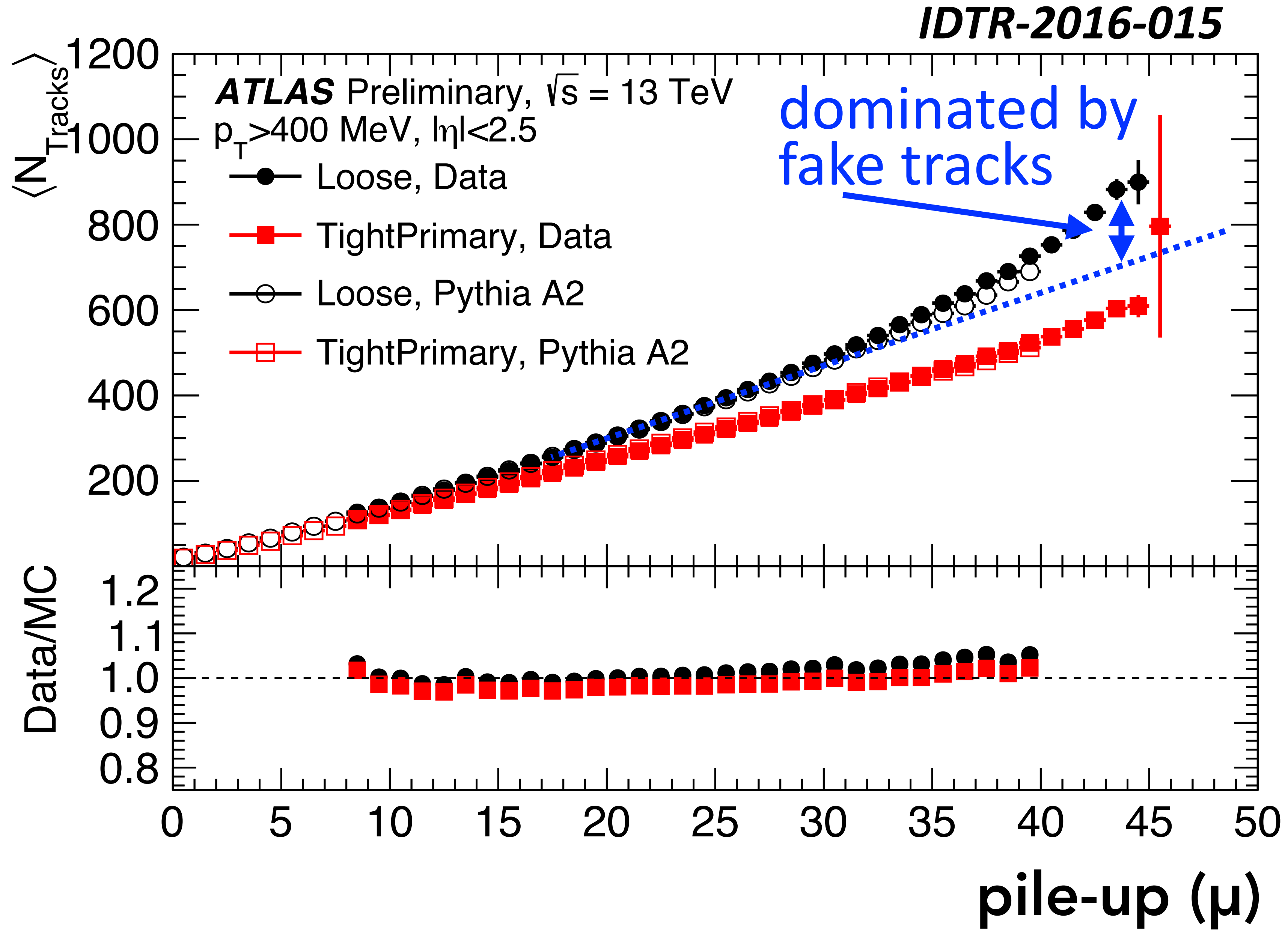
$\sigma(d_0)$ vs. p_T — Run 1 vs. Run 2



$\sigma(d_0)$ vs. p_T — data vs. MC



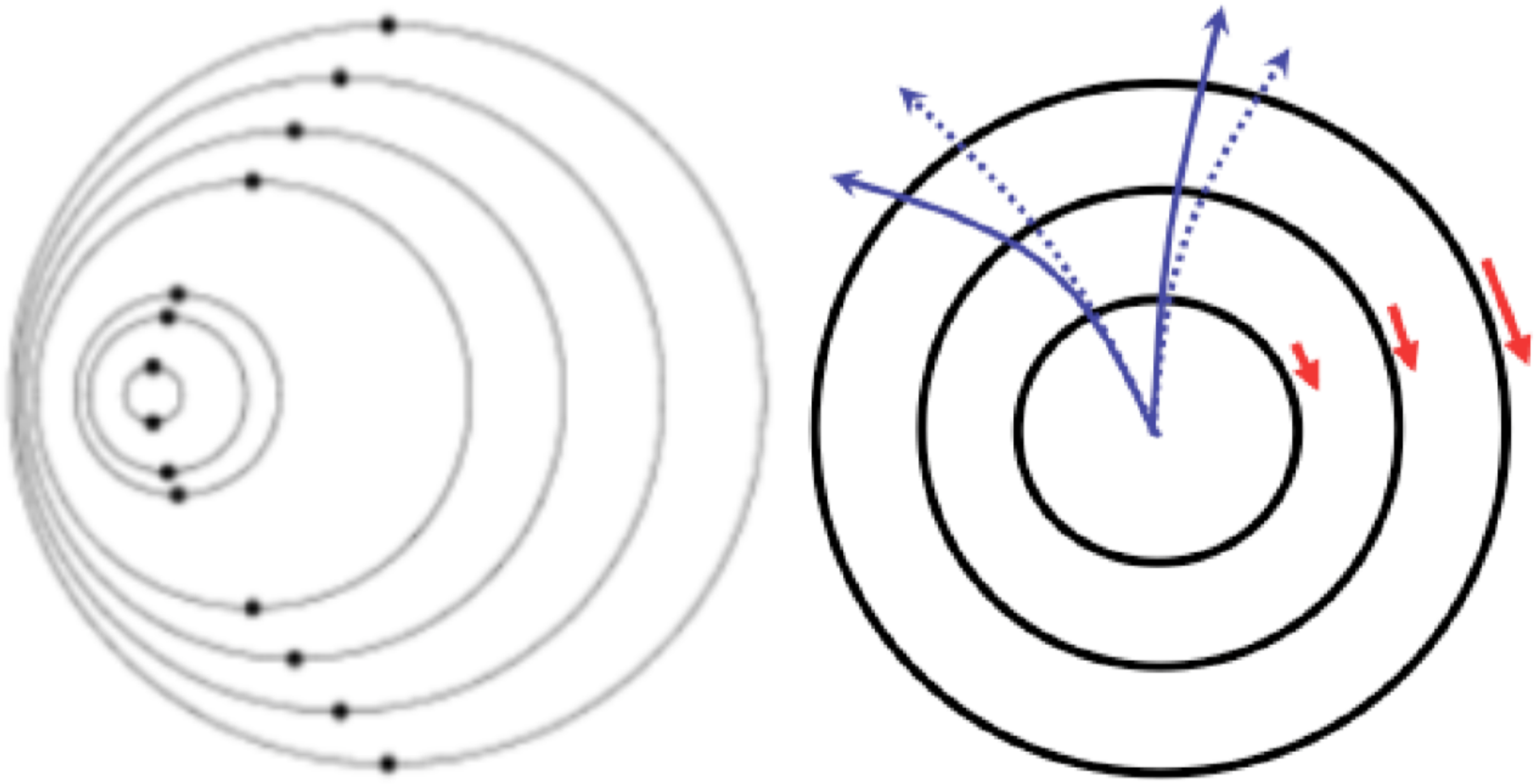
#tracks vs. μ — data vs. MC



- ~40% improved impact parameter (d_0, z_0) resolution in Run 2 thanks to IBL
- Measurement of impact parameter resolution sensitive to
  - Material description at low p_T
- Fake track rate increases with pile-up (μ)
- Material uncertainty is dominating tracking efficiency uncertainty —> Studied using in-situ techniques

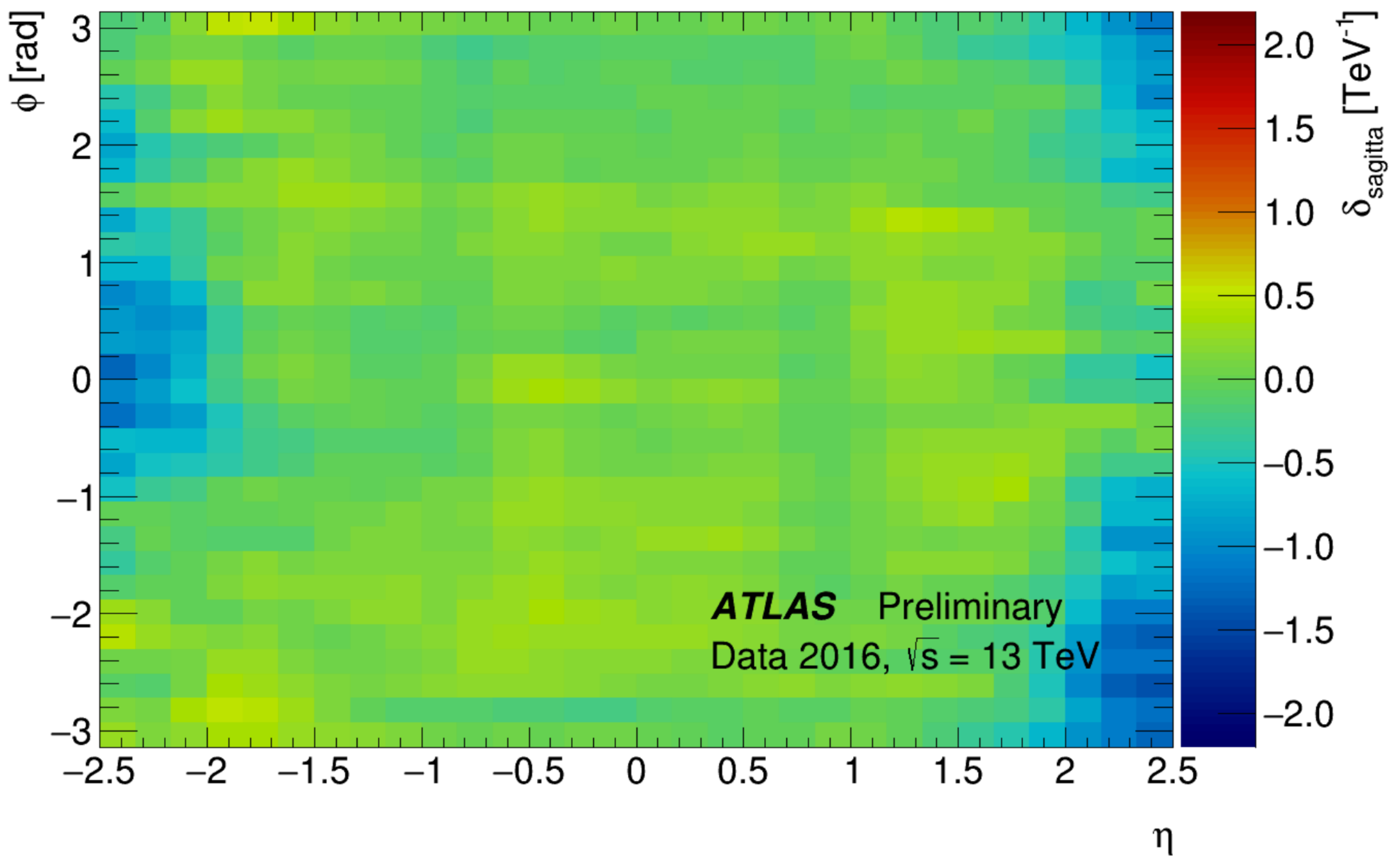
ID alignment — precision alignment

$$p_T^{reco} = p_T^{true}\left(1 + q\, p_T^{true}\, \delta_{sagitta}\right)^{-1}$$



Charge symmetric deformation

Charge antisymmetric deformation



Run 2 — LHC operations