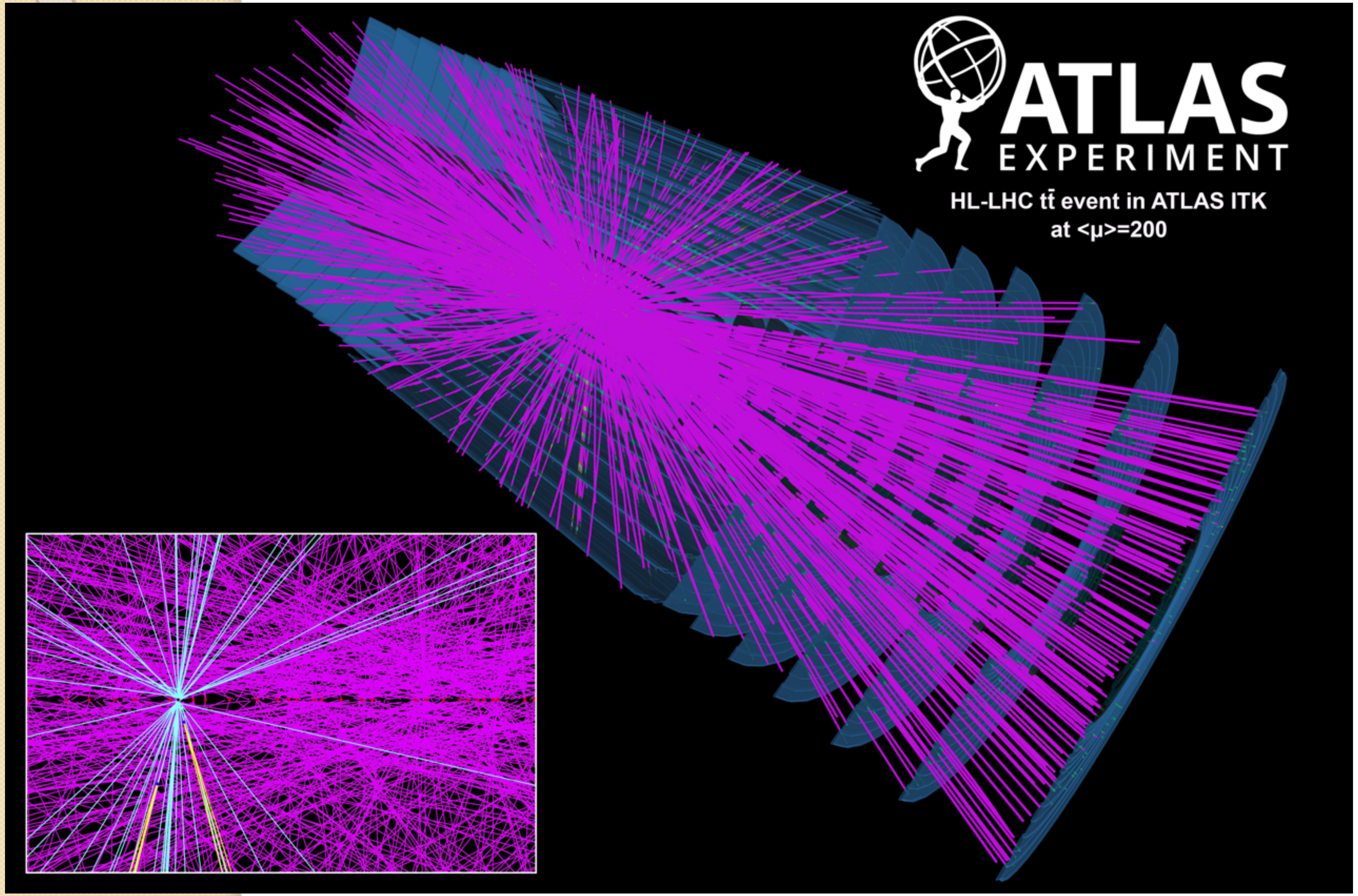
Expected performance of the ATLAS Phase-II Inner Tracker

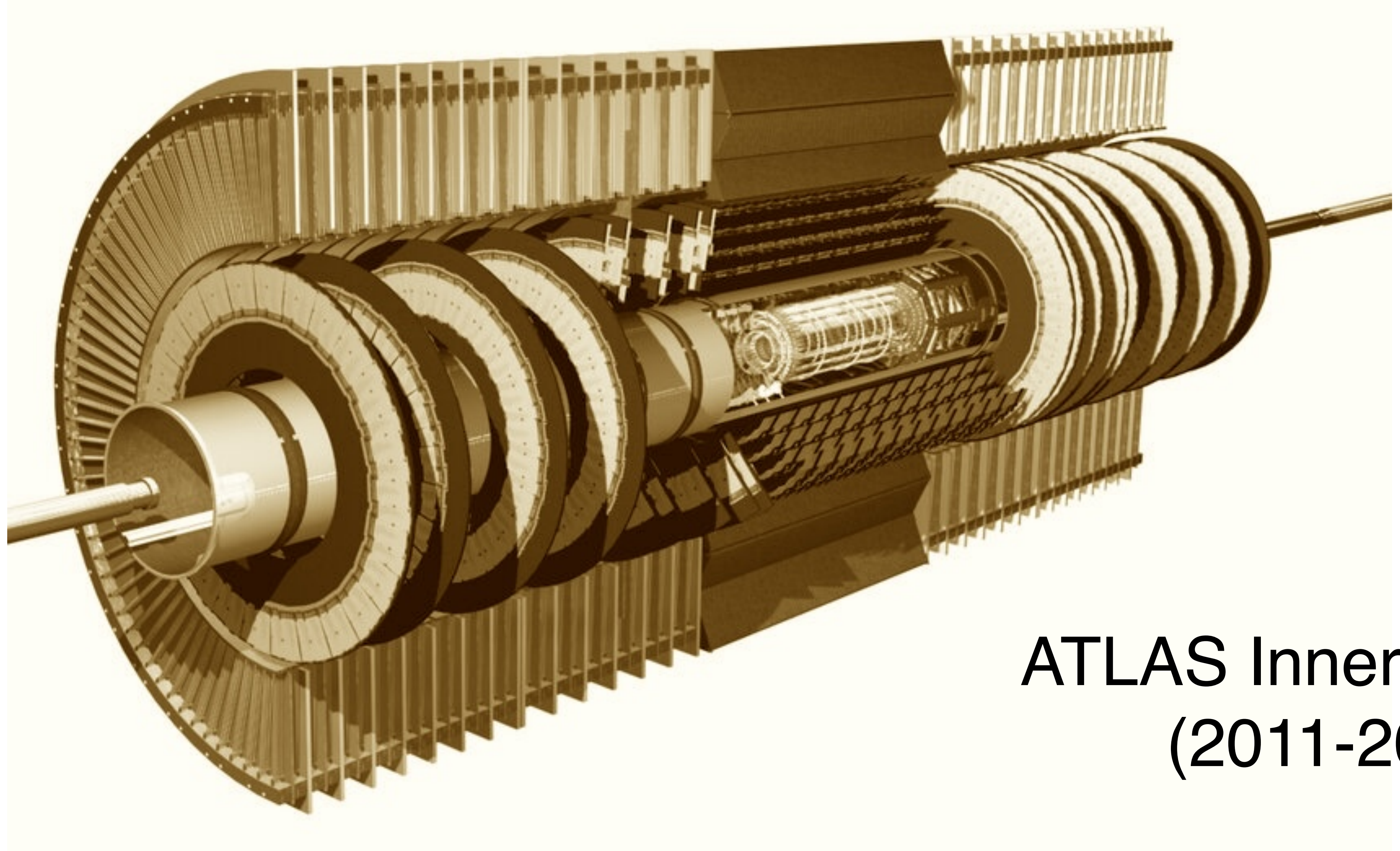


Thomas Strebler

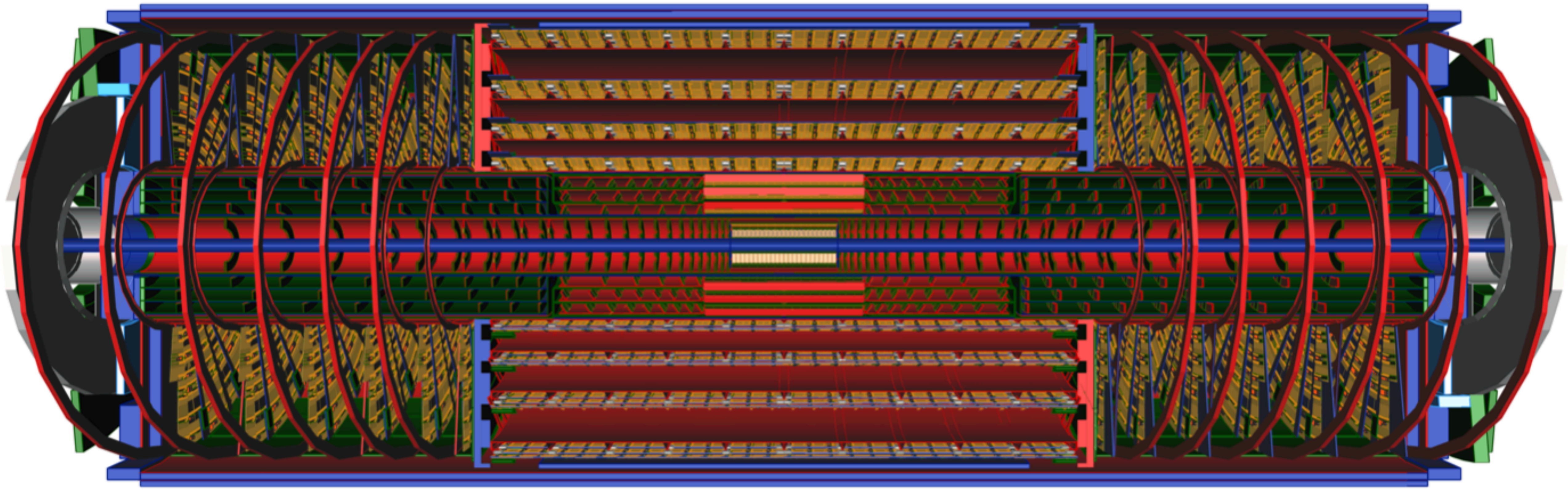
Centre de Physique
des Particules de Marseille
Aix-Marseille Université / CNRS-IN2P3

CPPM seminar
June 10th, 2024

Summary of this talk



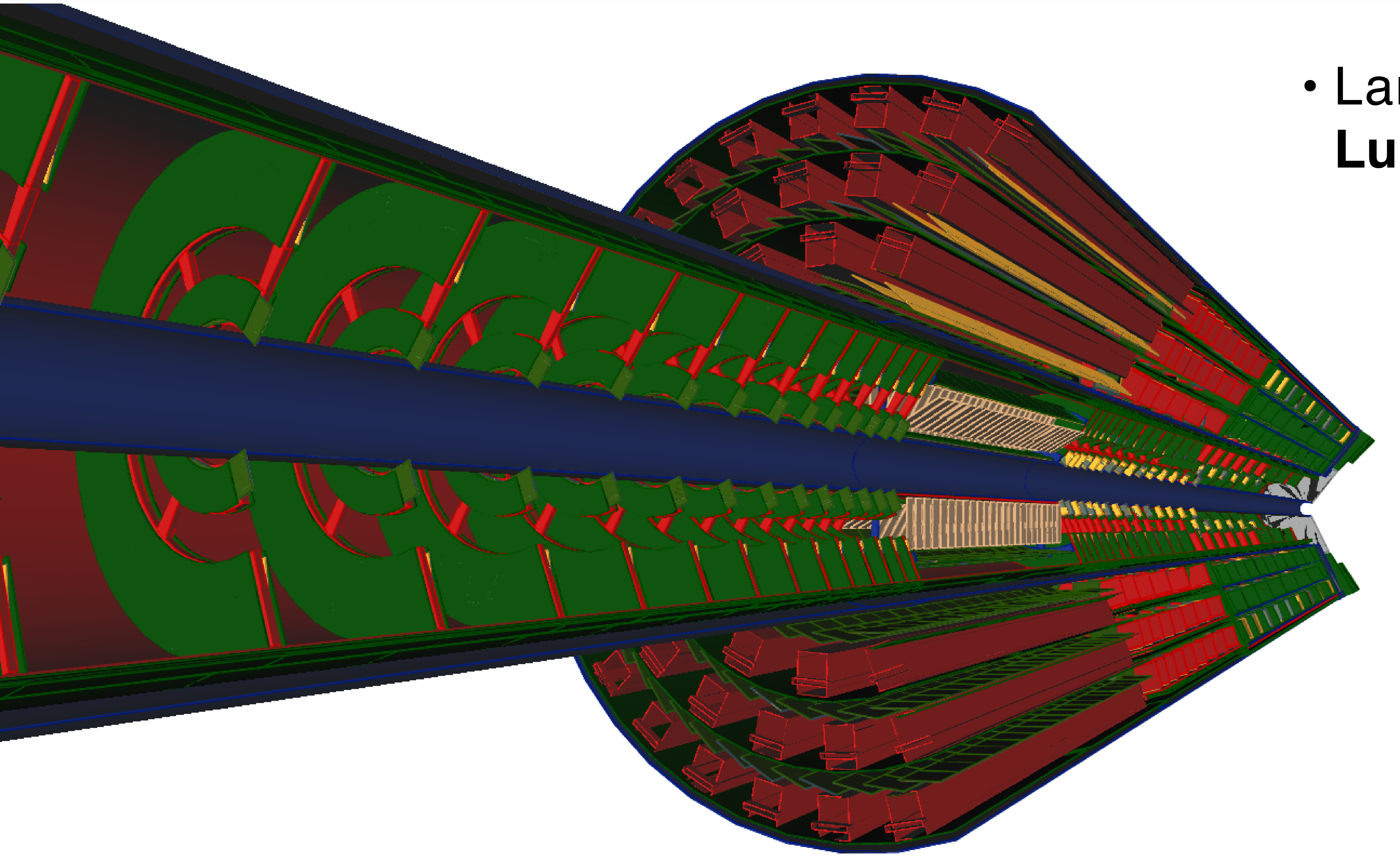
ATLAS Inner Detector
(2011-2025)



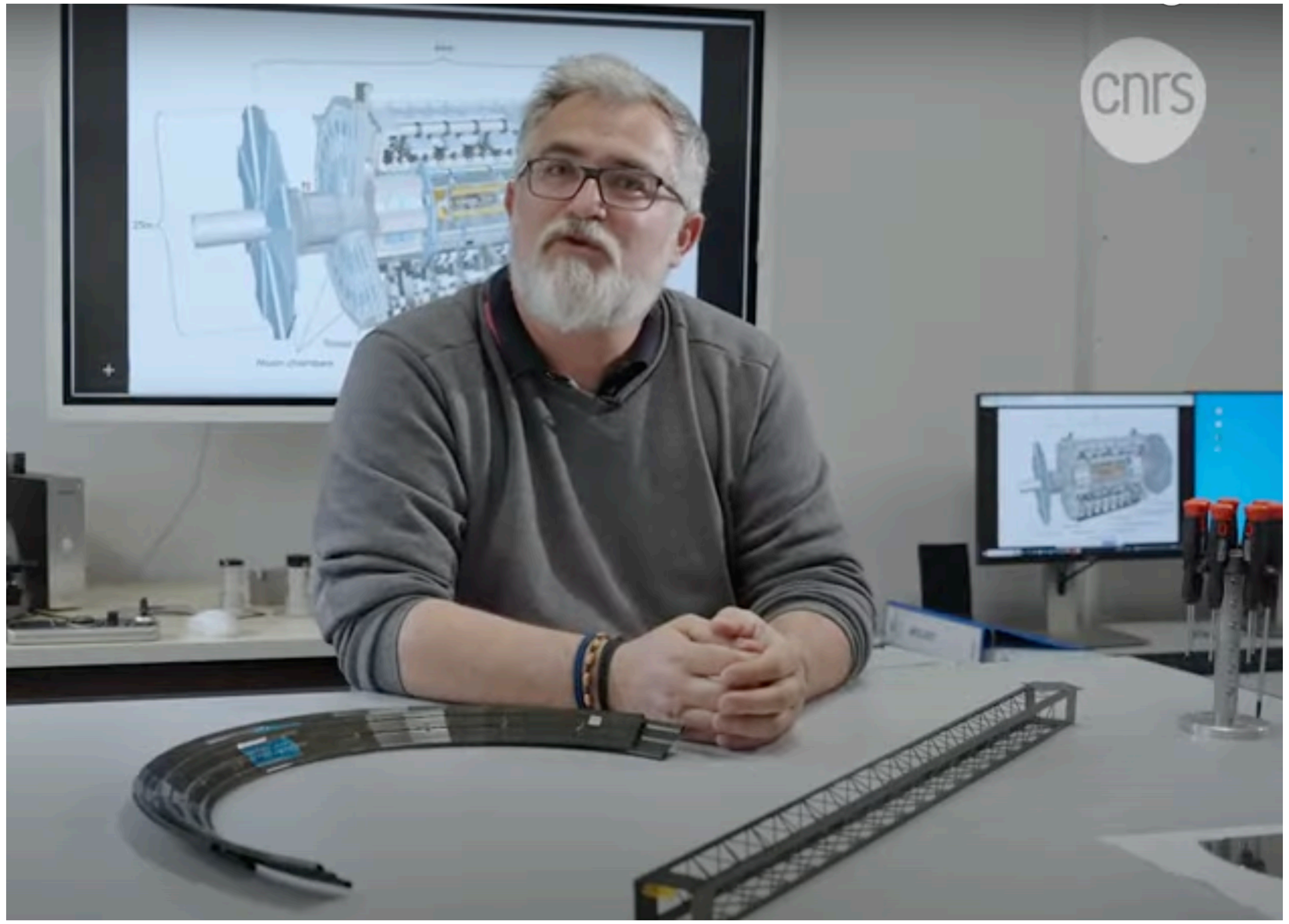
ATLAS Inner Tracker (2029-2041)

Introduction

- Large program of **ATLAS Phase-II upgrades** for **High-Luminosity LHC (HL-LHC)** data-taking starting in 2029



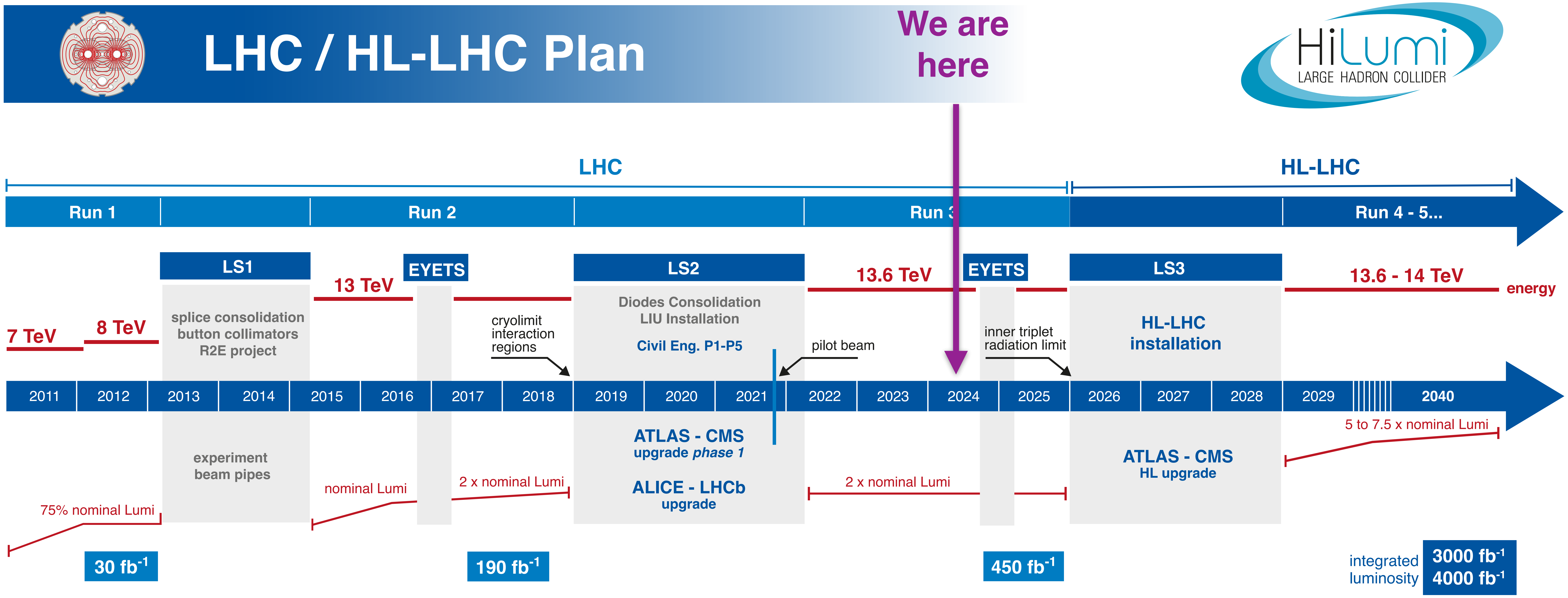
- ATLAS **Inner Tracker (ITk)** one of the **most ambitious upgrades for a particle physics detector**



- **ATLAS CPPM group** heavily involved since the beginning:
  - Technical design, production and installation of the ITk Pixel detector => see Eric Vigeolas's seminar next week
  - Simulation, reconstruction and physics object performance
  - Prospect for physics analyses at HL-LHC

High-Luminosity LHC & ATLAS Phase-II upgrades

High-Luminosity LHC



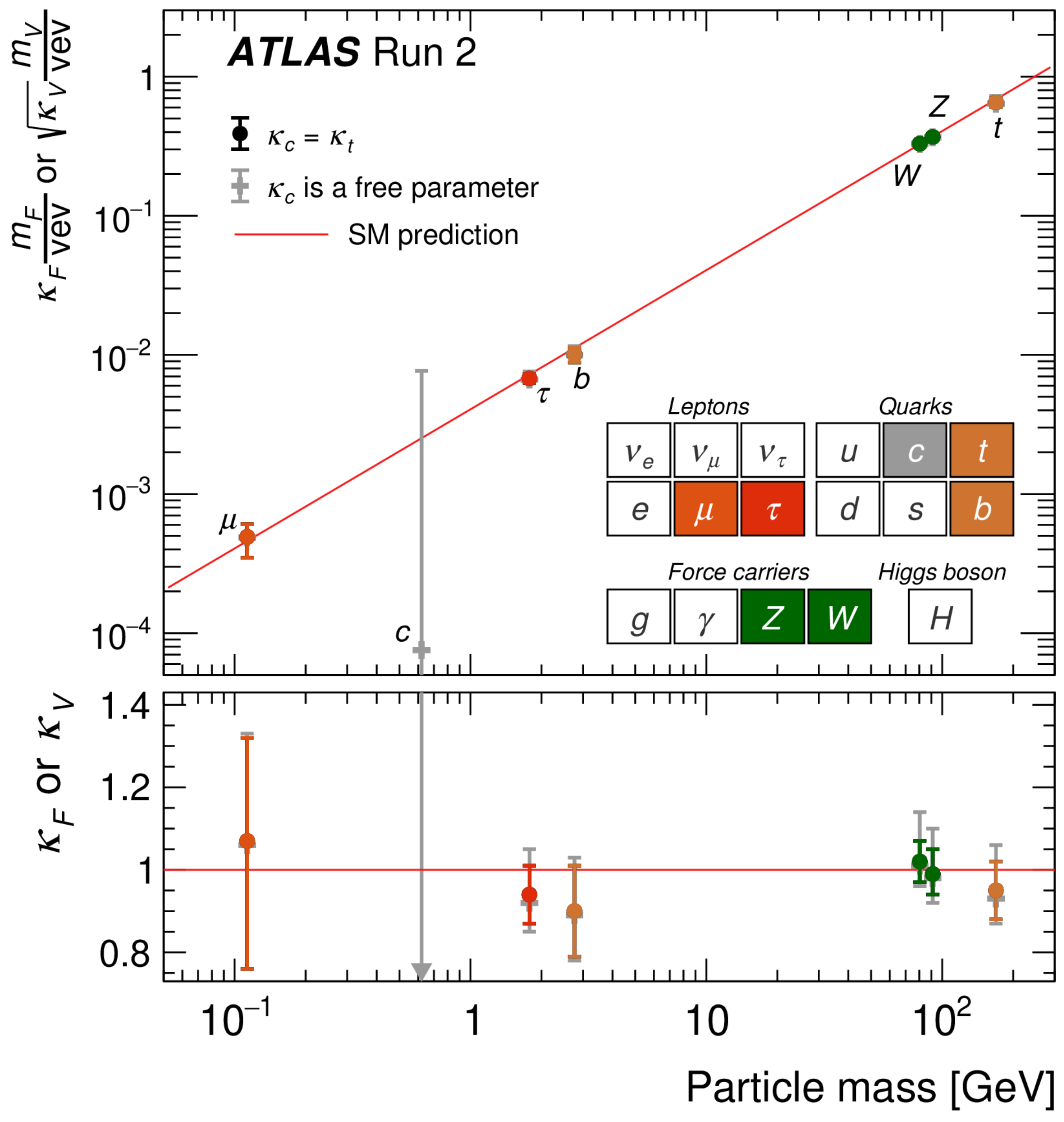
	Pile-up	*Instantaneous luminosity*	*Integrated luminosity in 2025*
Run 3	*60*	2×10^{34} cm^{-2}s^{-1}	*450 fb^{-1}*

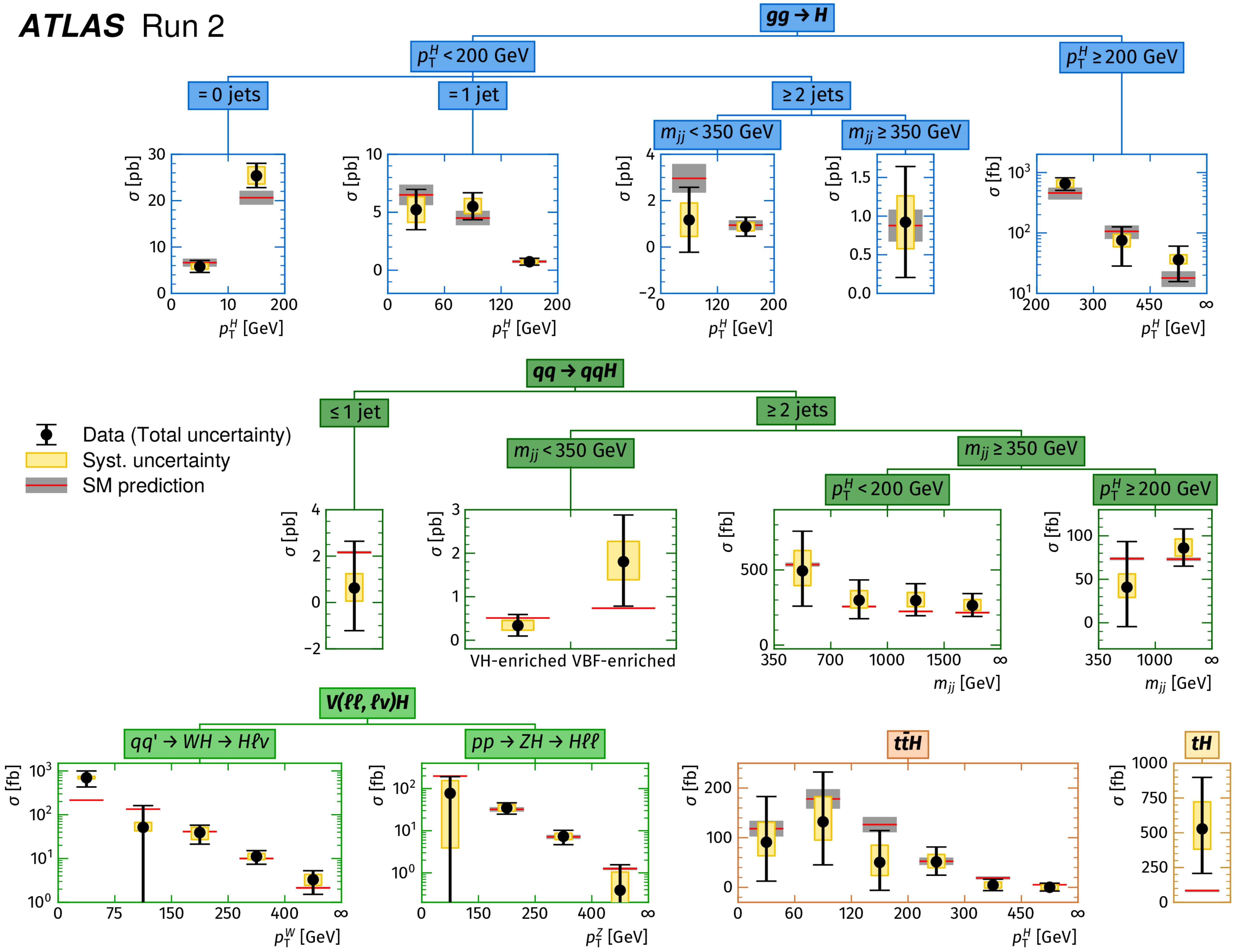
	Pile-up	*Instantaneous luminosity*	*Integrated luminosity by end 2041*
Nominal *(Run 4 to 6)*	*140*	5×10^{34} cm^{-2}s^{-1}	*3000 fb^{-1}*
Ultimate *(from Run 5)*	*200*	7.5×10^{34} cm^{-2}s^{-1}	*4000 fb^{-1}*

Higgs physics prospects

- Since its discovery in 2012, many detailed studies to confirm **Higgs boson properties:**
  - couplings established to EW bosons + 3rd gen. fermions
  - CP properties
  - differential measurements

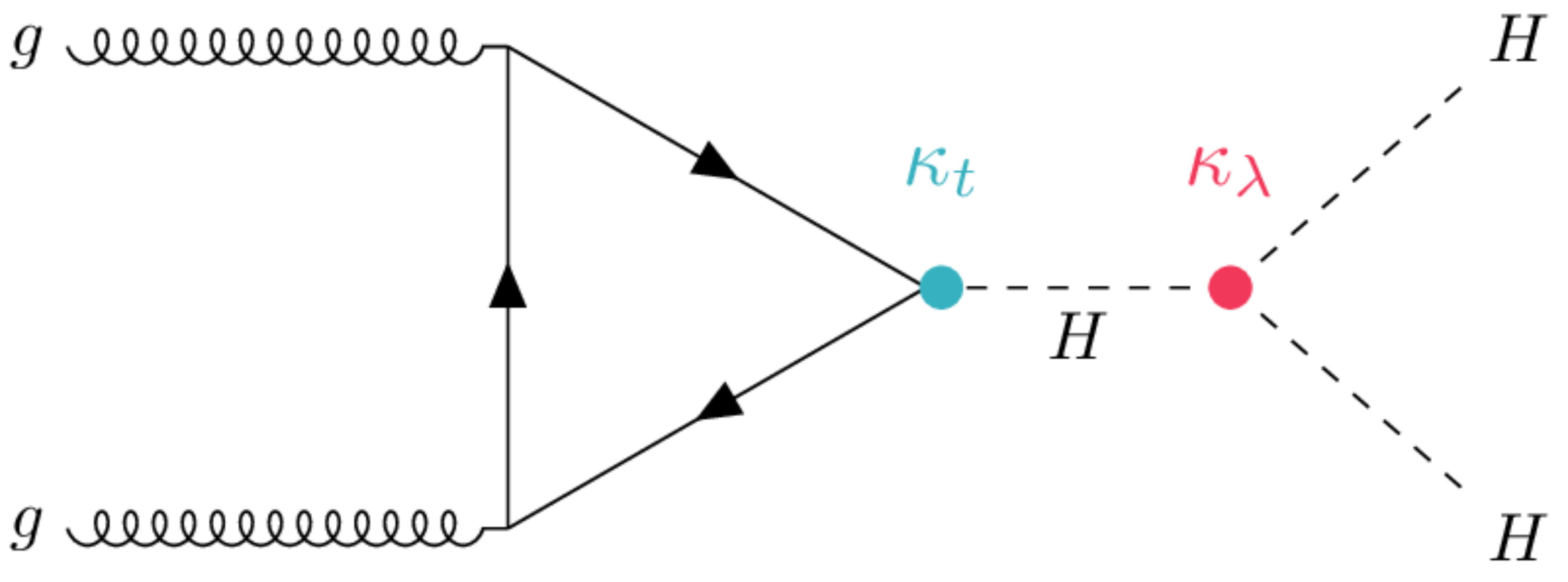
- Some channels now dominated by systematics, **some still stat. limited**





Nature 607, 52 (2022)

Higgs physics prospects



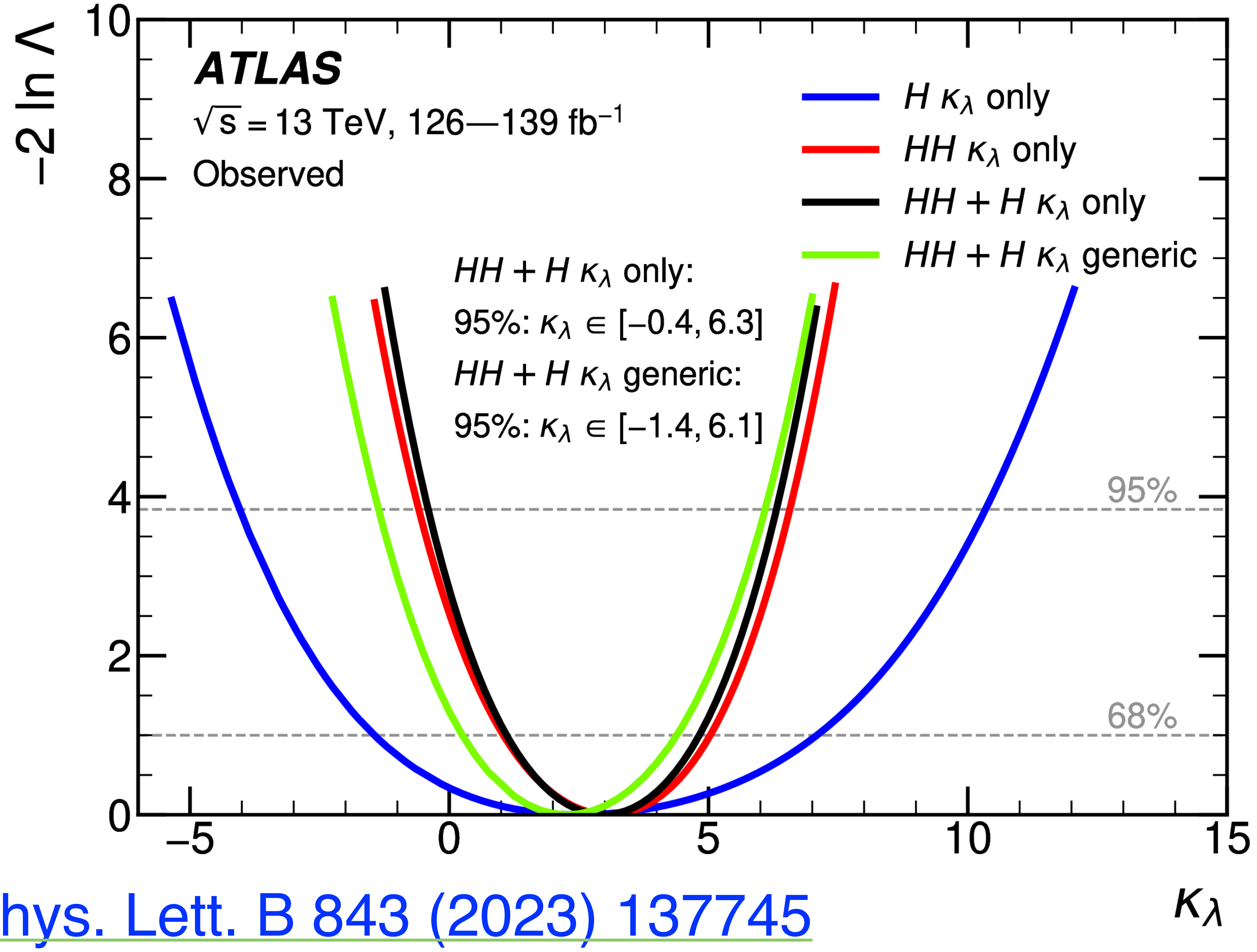
- **Higgs self-coupling κ_λ still to be measured precisely:**

  latest combined ATLAS results (single + di-Higgs)

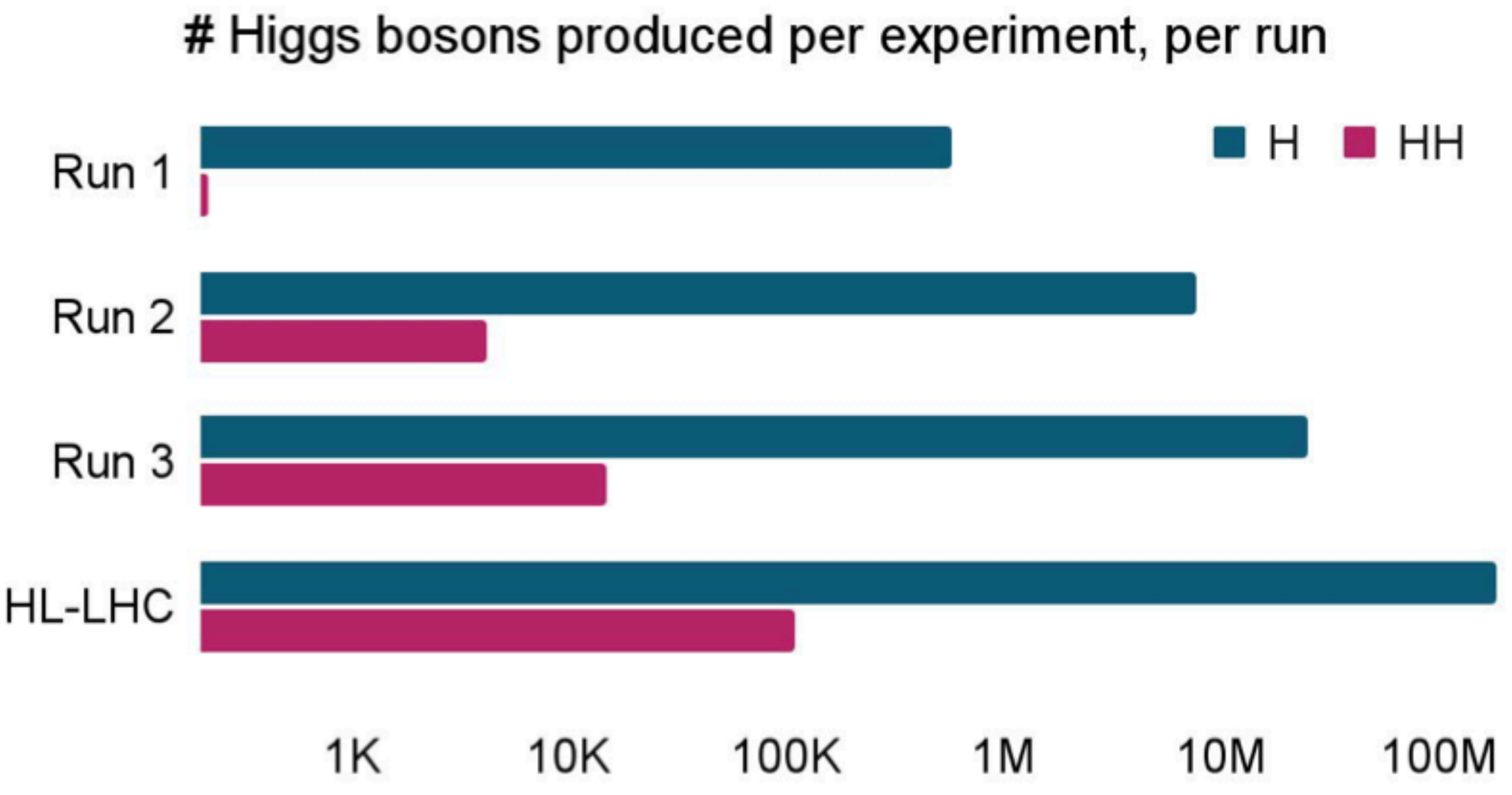
  $-0.4 < \kappa_\lambda < 6.3$ @95% CL

- **Increase in instantaneous luminosity:**

  => ~10 times more HH pairs to be produced by 2040



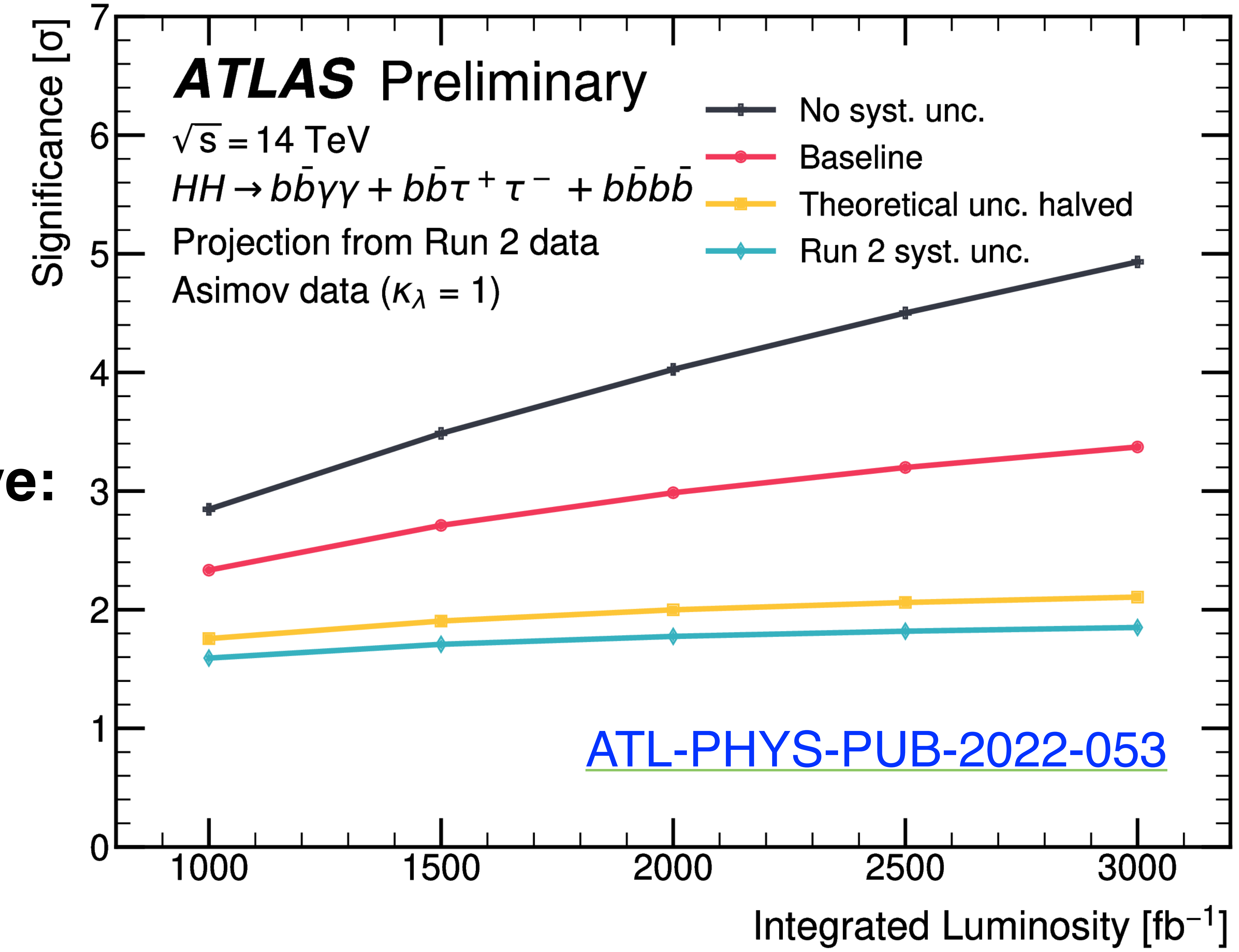
Phys. Lett. B 843 (2023) 137745



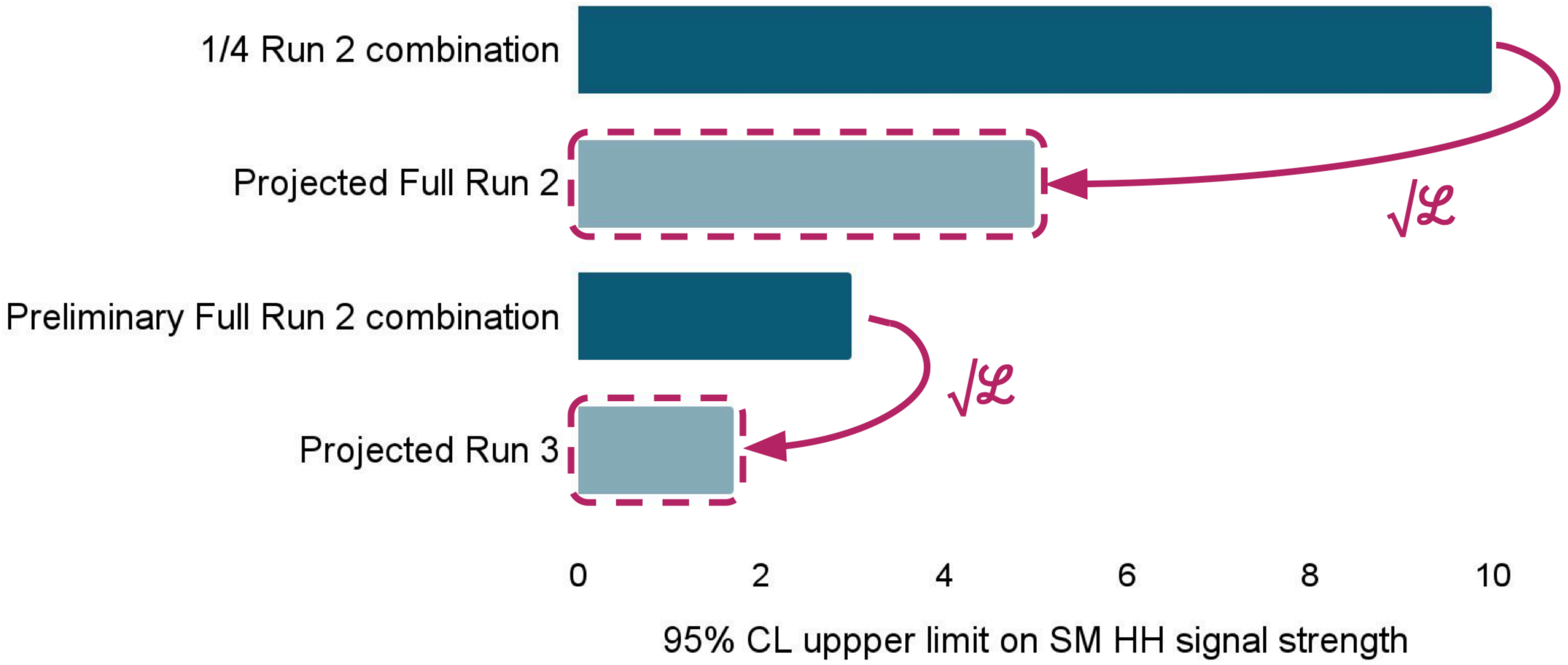
E. Brost - Higgs@10 Symposium

Higgs physics prospects

- **HL-LHC sensivity expected with 3000 fb-1:**
  3σ evidence for HH production with ATLAS
  5σ observation with ATLAS+CMS
  50% uncertainty on κ_λ



- **Experience demonstrates that projections tend to be conservative:**
  - object performance assumed to be unchanged
  - extrapolation of existing analysis strategies

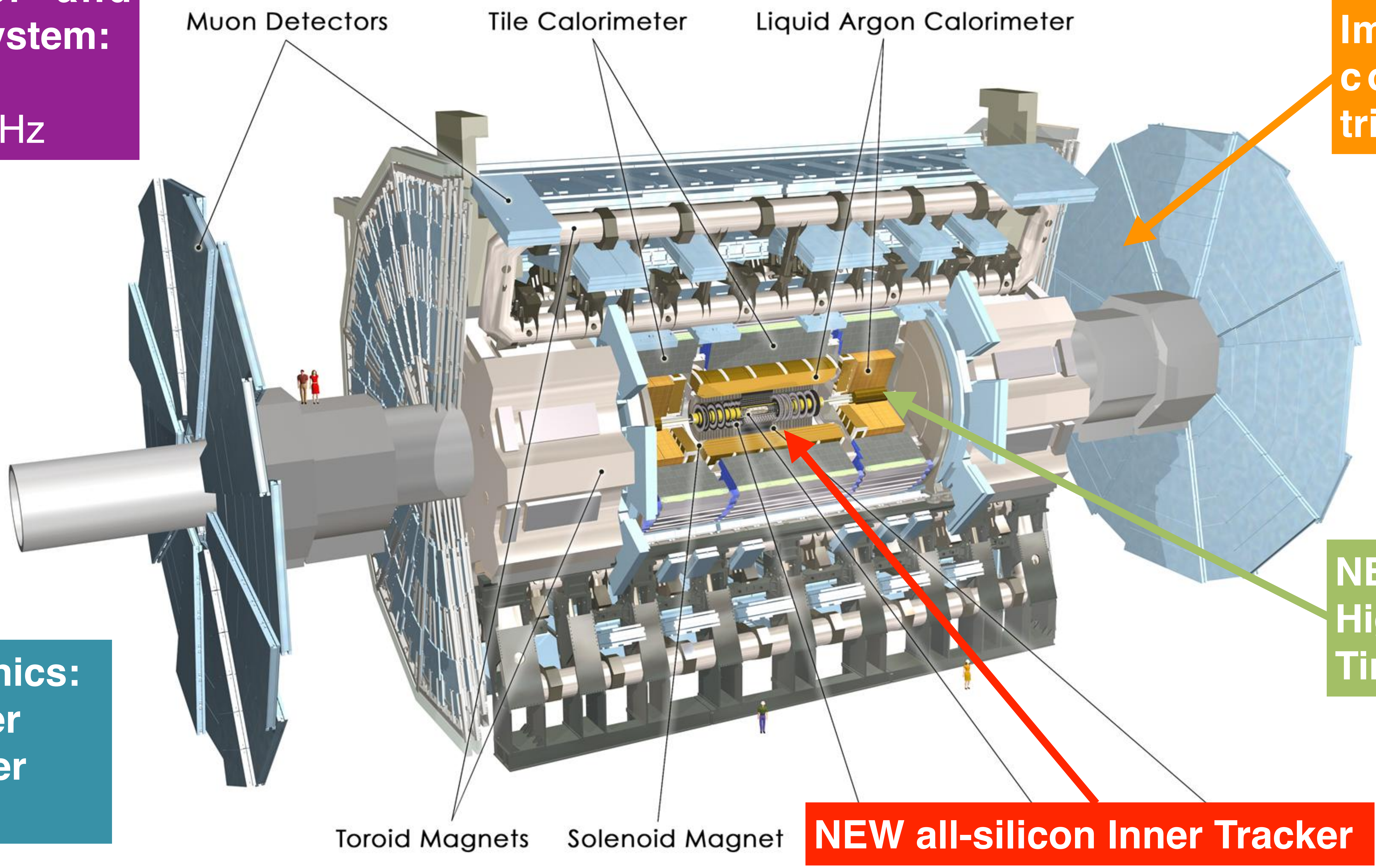


E. Brost - Higgs@10 Symposium

- **Maintaining object performance up to pile-up 200 extremely challenging:**
  - Run 3 detector already operating well beyond nominal lumi. + pile-up design
  - Phase-II detector upgrades critical to guarantee ATLAS physics programme

ATLAS Phase-II upgrades

Upgraded Trigger and Data Acquisition System:
- L0 rate: 1 MHz
- Event Filter: 10 kHz



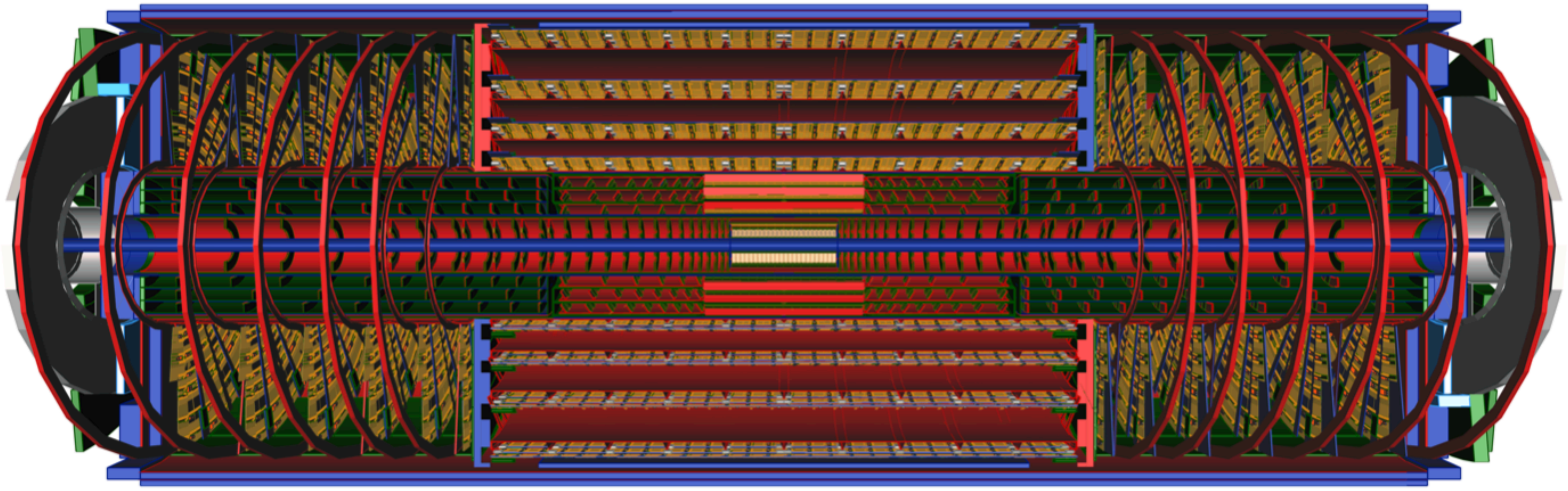
Improved muon coverage and trigger

NEW endcap High-Granularity Timing Detector

NEW all-silicon Inner Tracker

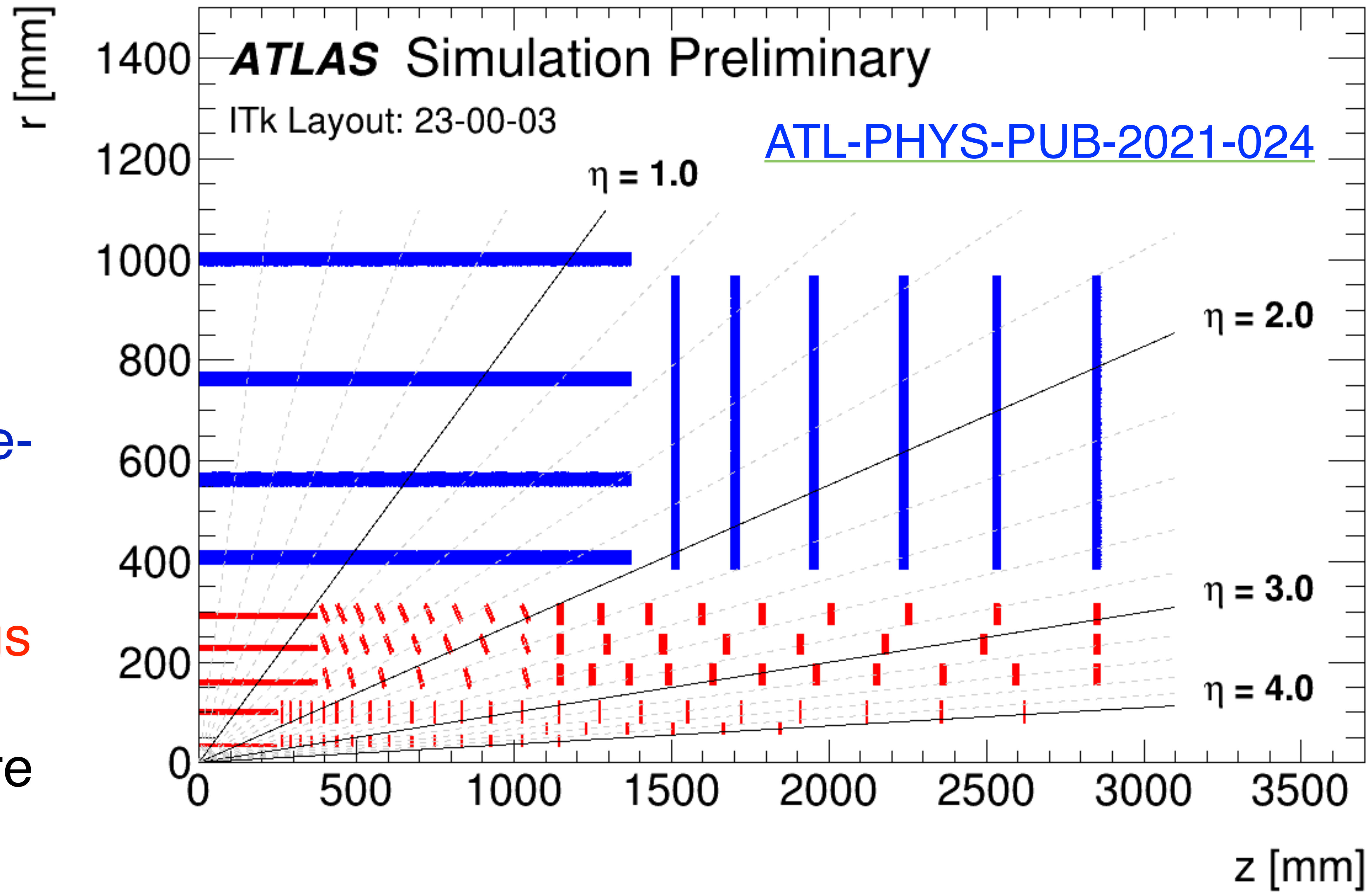
Upgraded electronics:
- LAr calorimeter
- Tile Calorimeter
- Muon system

ATLAS Phase-II Inner Tracker upgrade



- To guarantee tracking performance + good data-taking conditions, **full replacement of ATLAS tracking detectors with new all-silicon Inner Tracker (ITk)**

- **Extended tracking acceptance** up to |η|=4:
  - increased lepton reconstruction + jet flavour-tagging acceptance
  - improved pile-up suppression

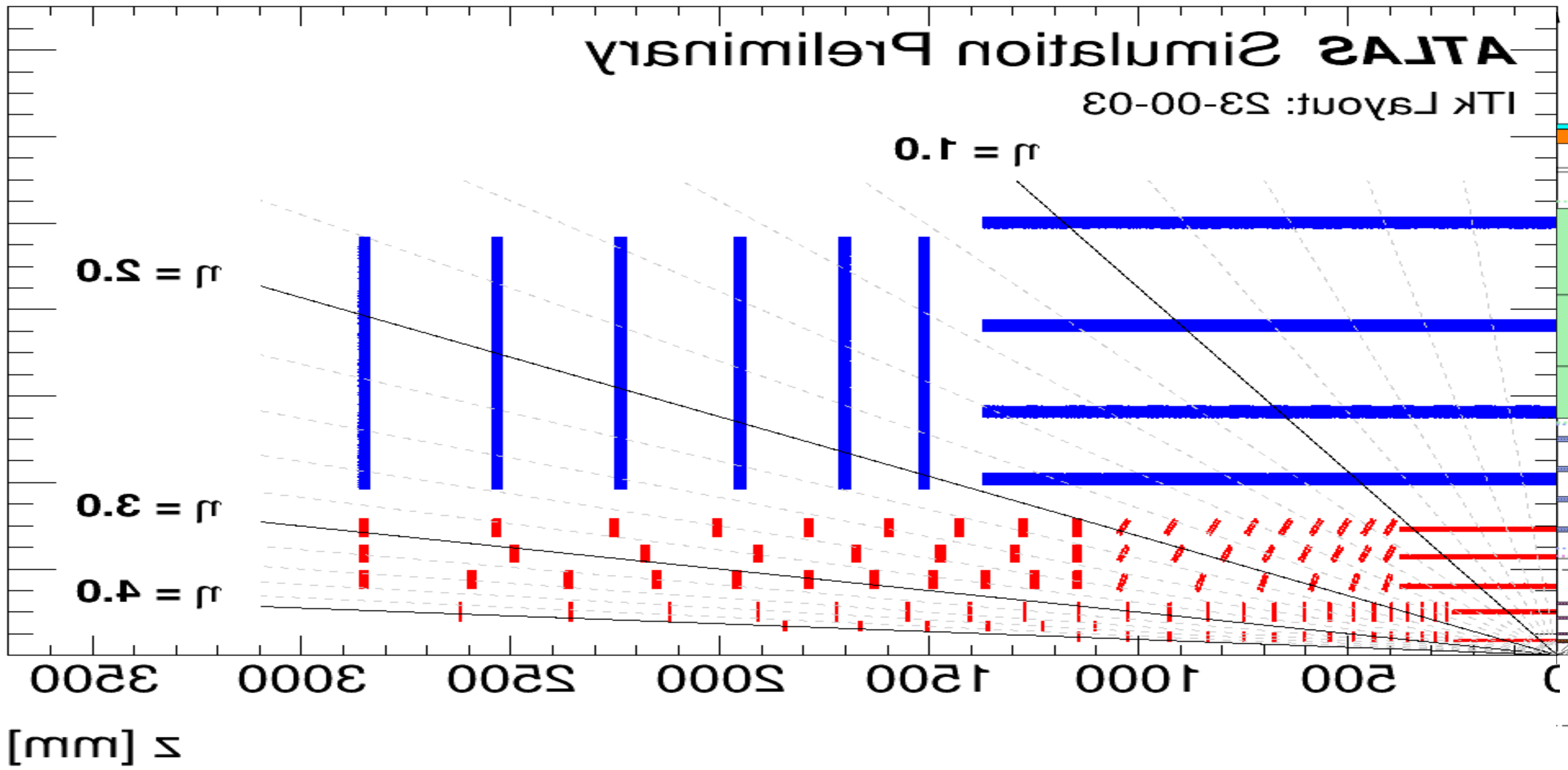


Outer strip detector: 4 barrel layers + 6 end-cap disks (double-sided)

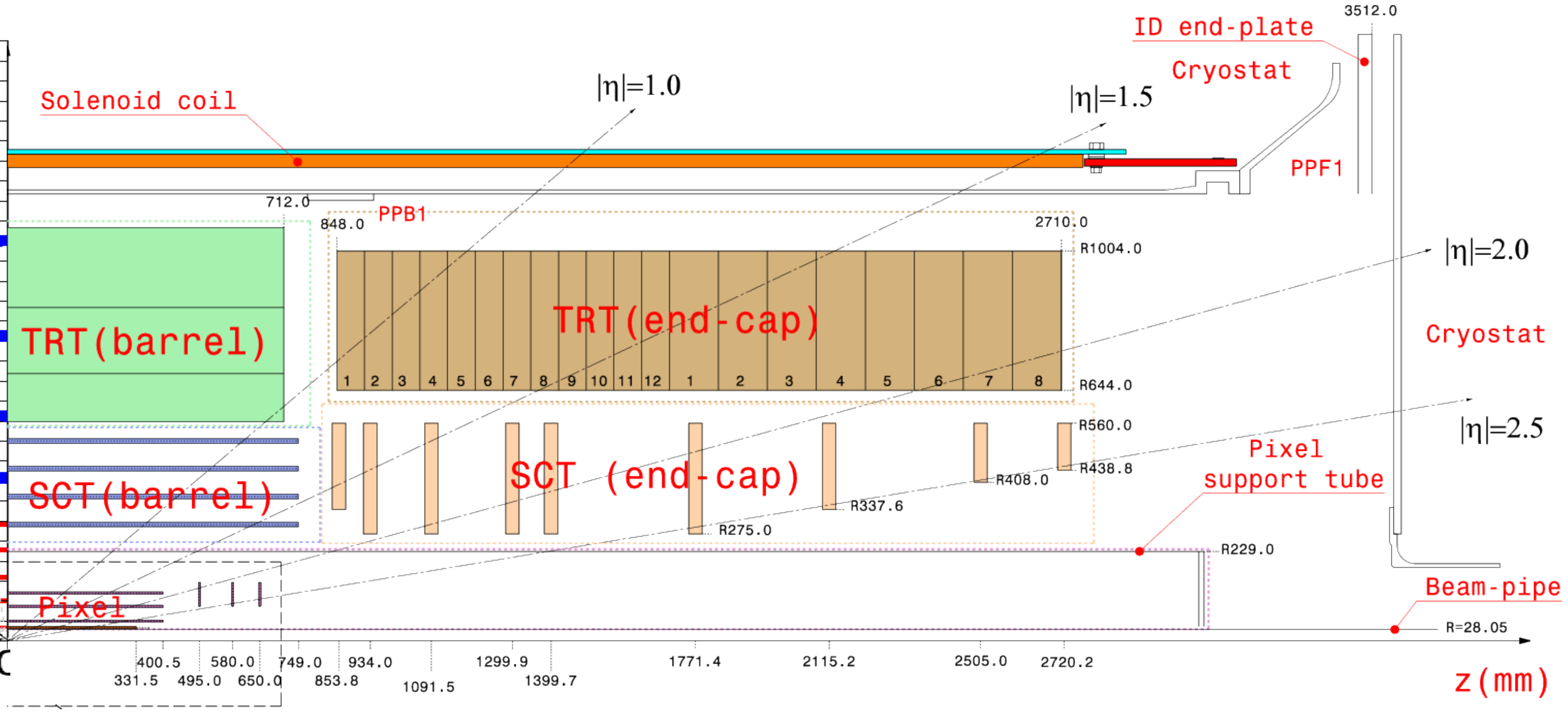
Inner pixel detector: 5 barrel layers + inclined and vertical rings
  - innermost layer (L0) at radius ~34 mm [IBL 33.25mm]
  - pixel pitch: 25x100 μm² for L0 barrel / 50x50 μm² elsewhere [IBL 50x250 μm²]

ATLAS Phase-II Inner Tracker upgrade

ITk (Run 4-6)



Inner Detector (Run 2-3)



Significant increase in number of pixels $10^8 \rightarrow 5 \times 10^9$:

- smaller pixel pitch
- increased coverage

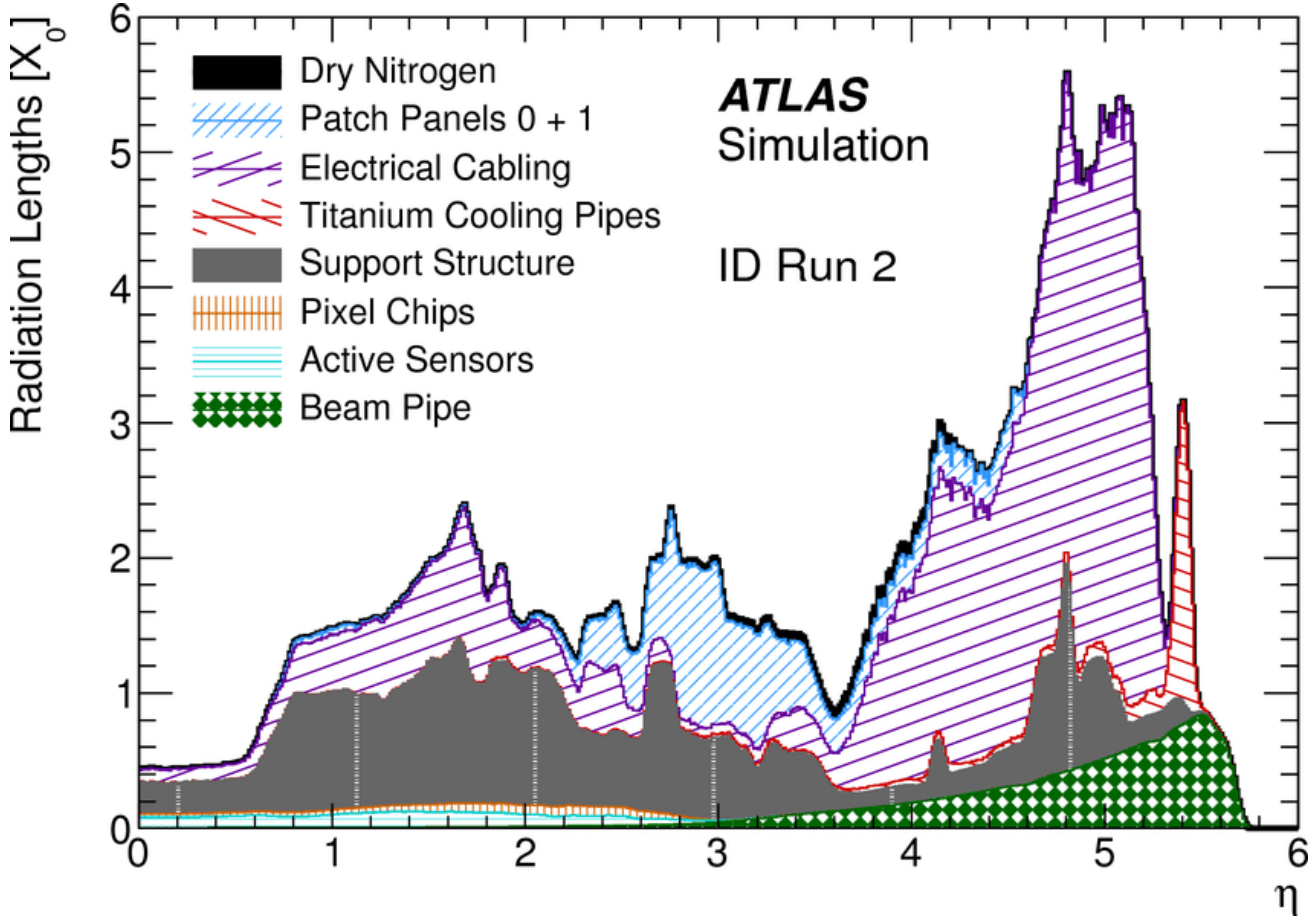
No more gaseous detector (TRT):

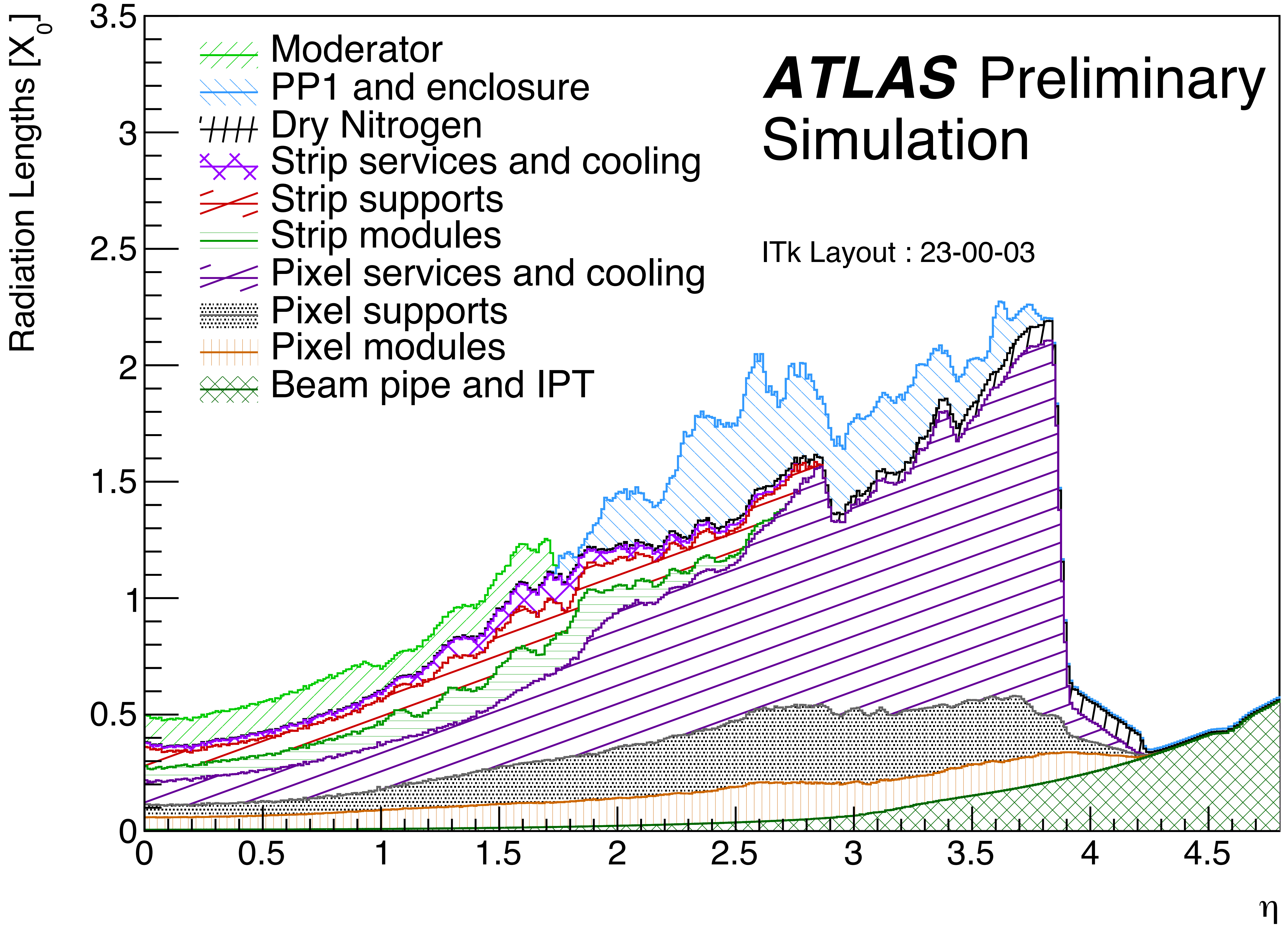
- not adapted to PU=200
- already challenging to operate in Run 3

Replaceable innermost pixel layers: opportunity for potential hardware upgrade

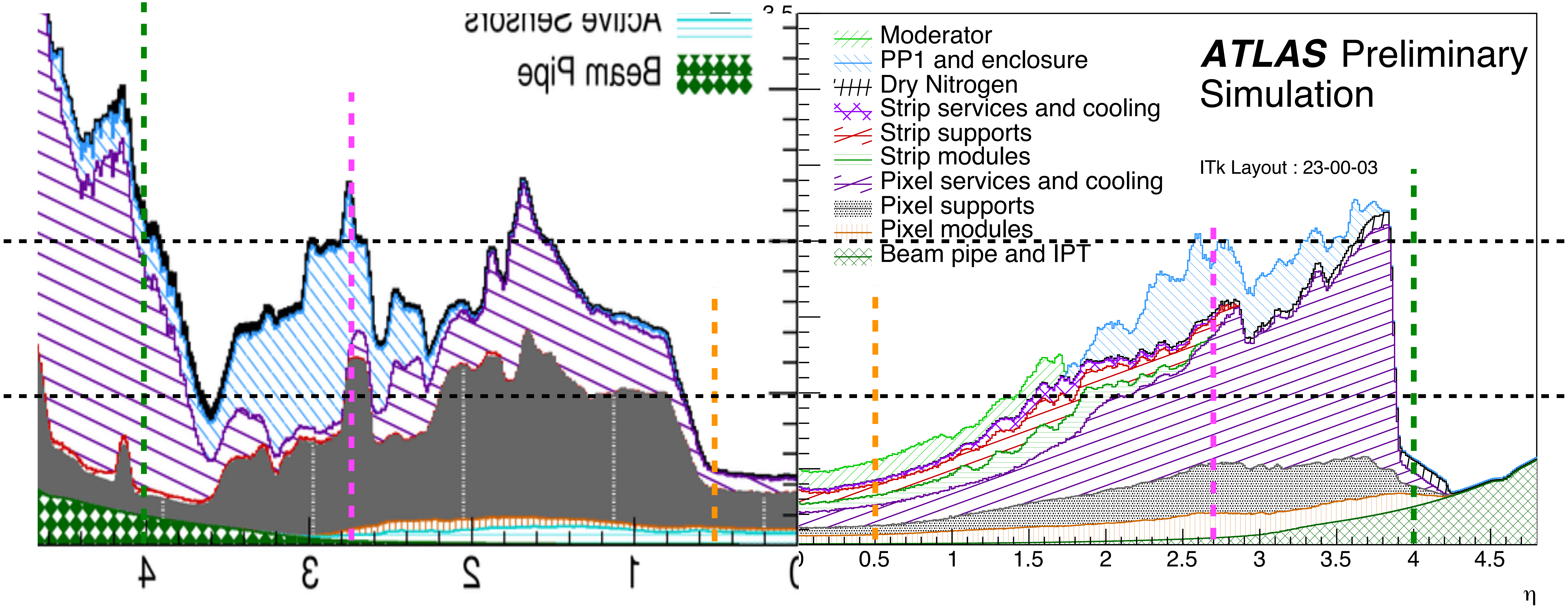
ATLAS Phase-II Inner Tracker upgrade

Comparison of material budget





Comparison of material budget



Equivalent X_0 for |η|<0.5

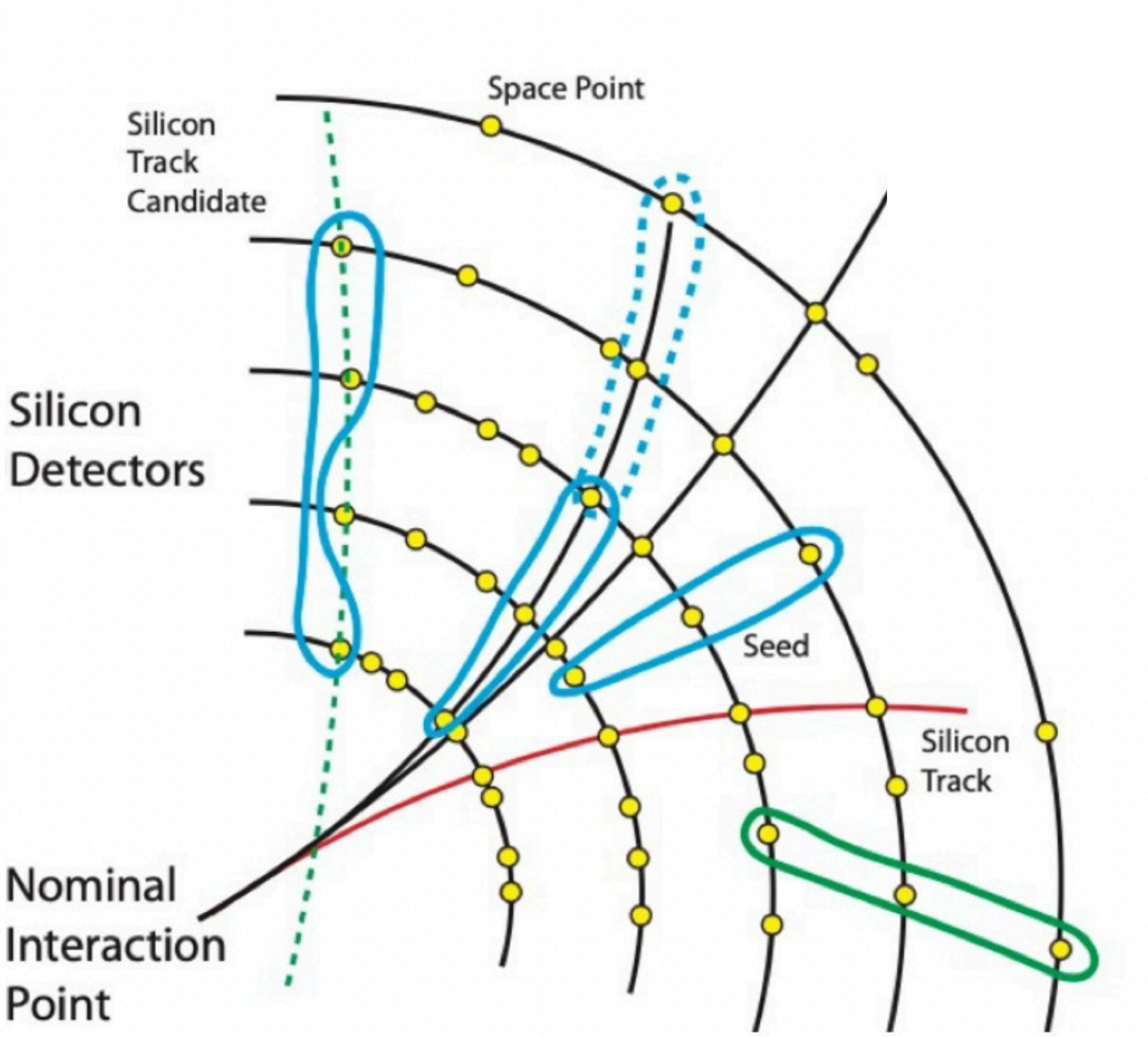
Much improved for 0.5<|η|<2.7

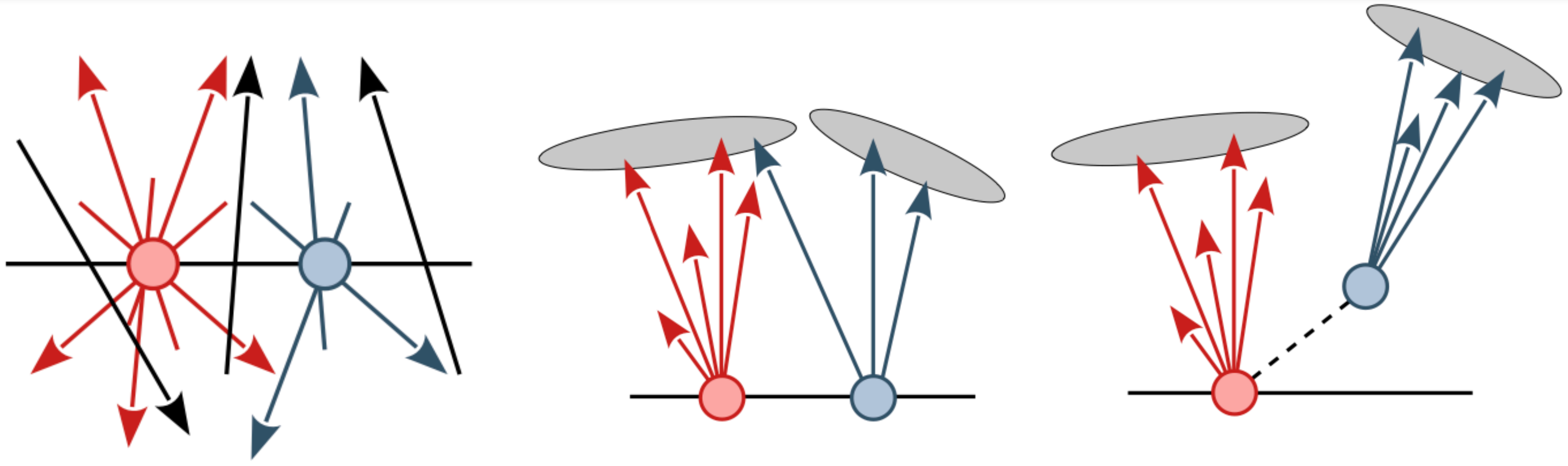
Increased tracking acceptance for 2.7<|η|<4.0

Expected ITk tracking performance

Tracking challenges at HL-LHC

- Tracking is a **key ingredient for full event reconstruction:** used for almost every physics object reconstruction or identification





Primary vertex reconstruction *Pile-up removal* *Jet flavour-tagging*

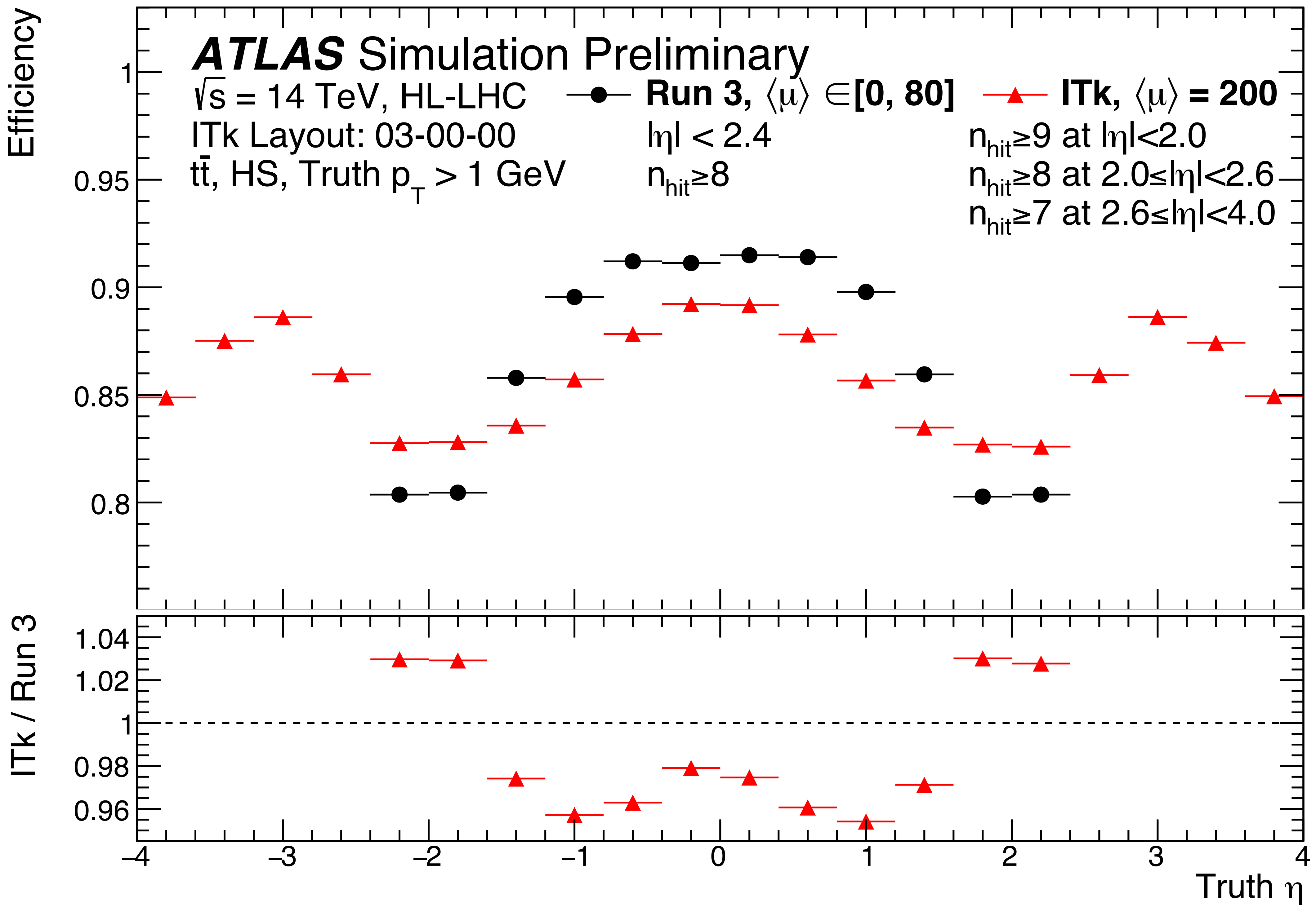
- **Main requirements:**
  - high efficiency
  - precise track parameter estimations
  - very low fake rate
  - within computing budget

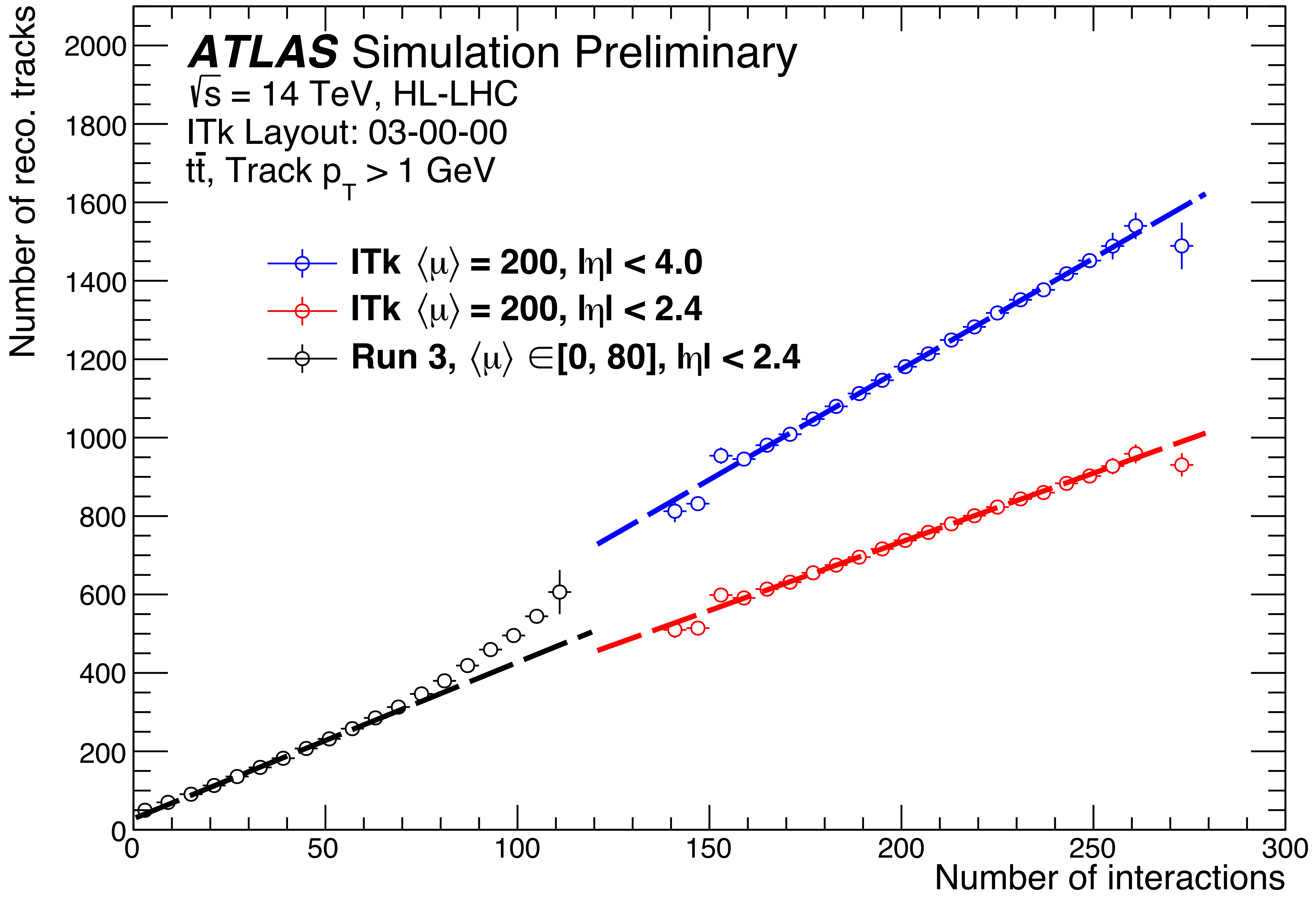
- Track reconstruction from detector hits **complex combinatorial problem**
  => very challenging in HL-LHC pile-up conditions
  - **larger hit combinatorics** (CPU, fake rate)
  - **wrong cluster-track association** (track parameter resolution)

Tracking efficiency and fake rate

IDTR-2023-05

- **Excellent tracking performance** achieved thanks to **optimal exploitation of ITk layout**
- **Inclusive tracking efficiency at μ=200** for particles with p_T>1 GeV **within 5% of Run-3 efficiency**

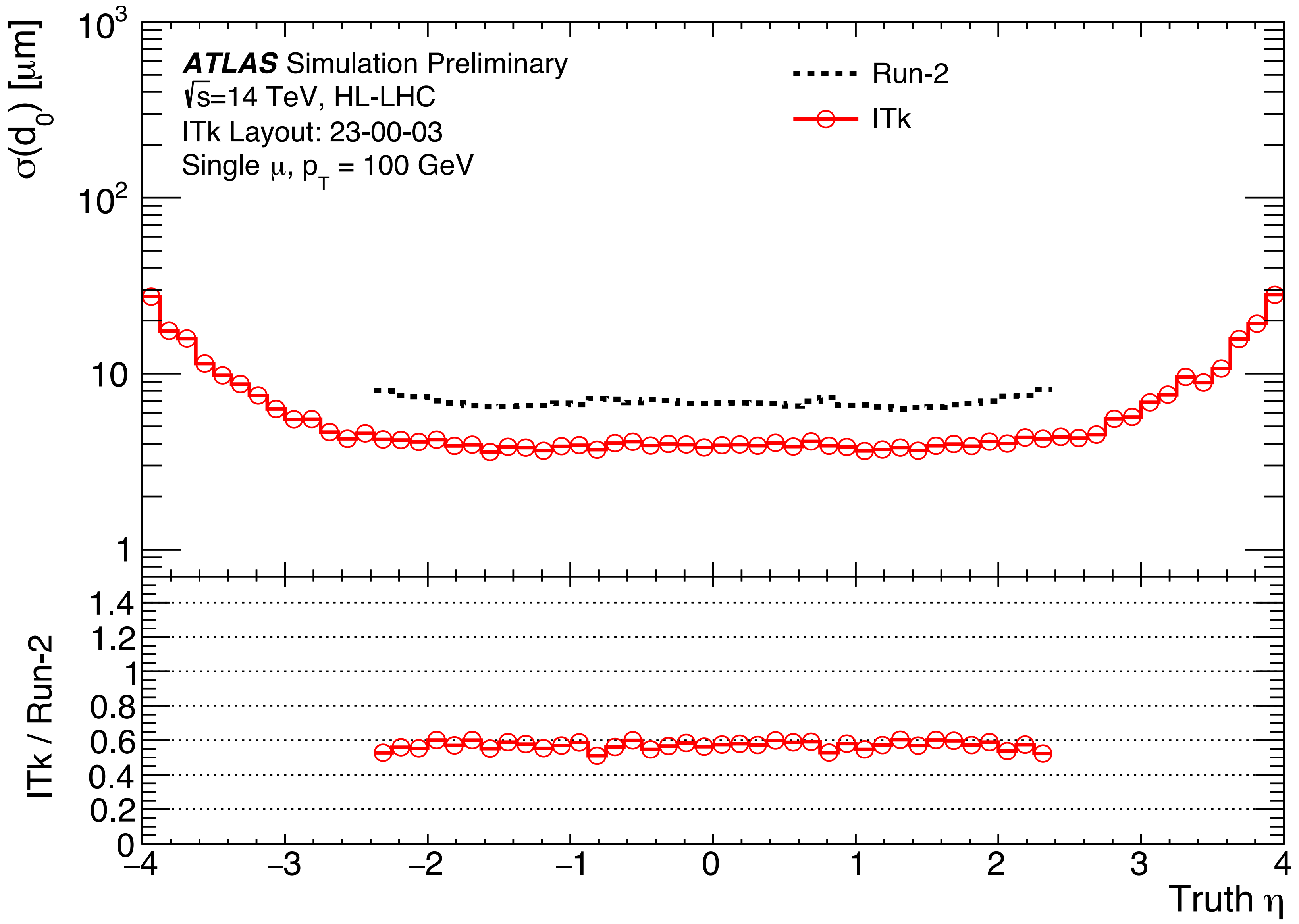


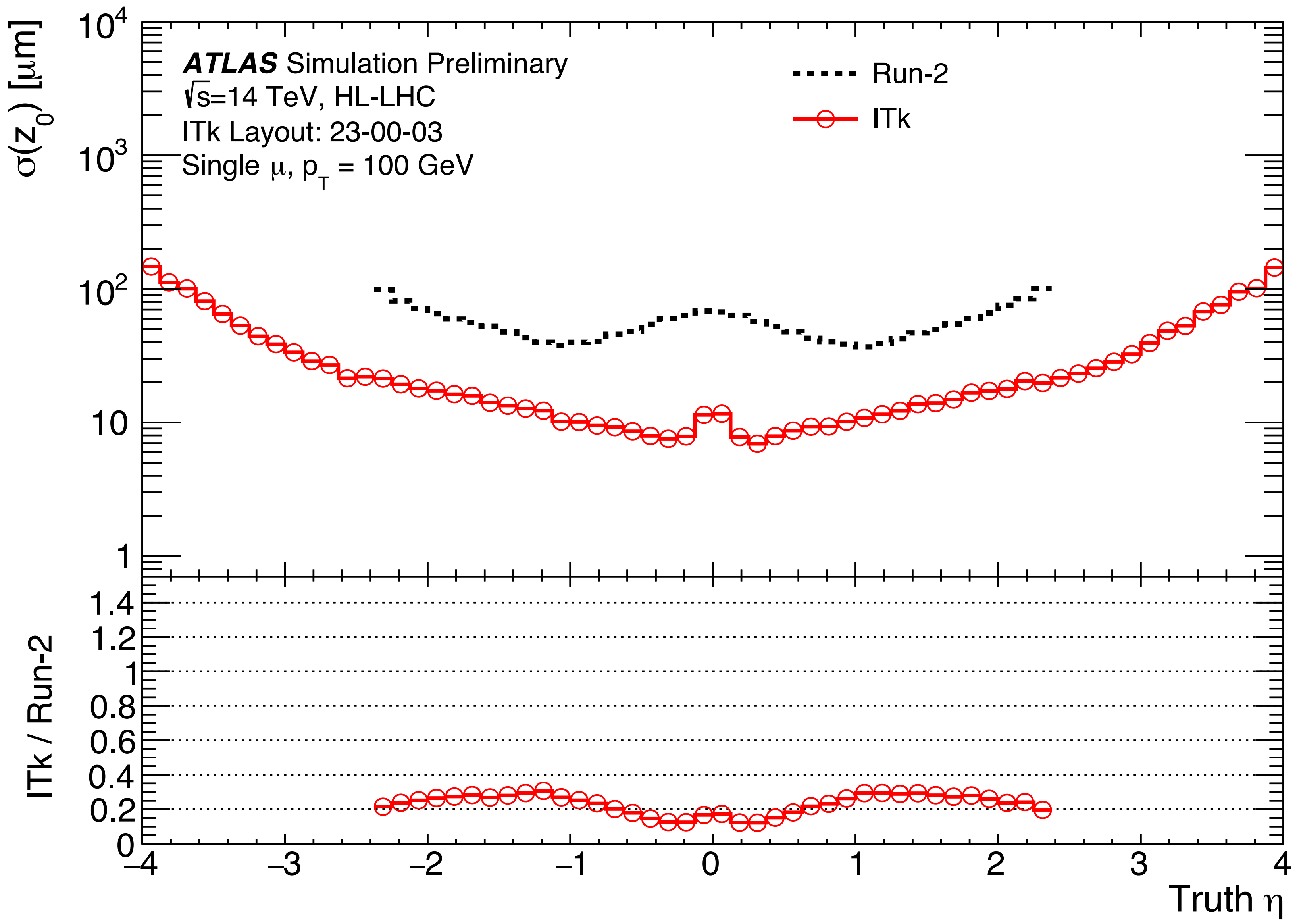


- **Very high track purity achieved,** exploiting optimised seeding strategy + hit requirements (≥ 9 expected): **negligible fake rate O(10^{-4})** associated with linear increase in number of tracks with number of interactions

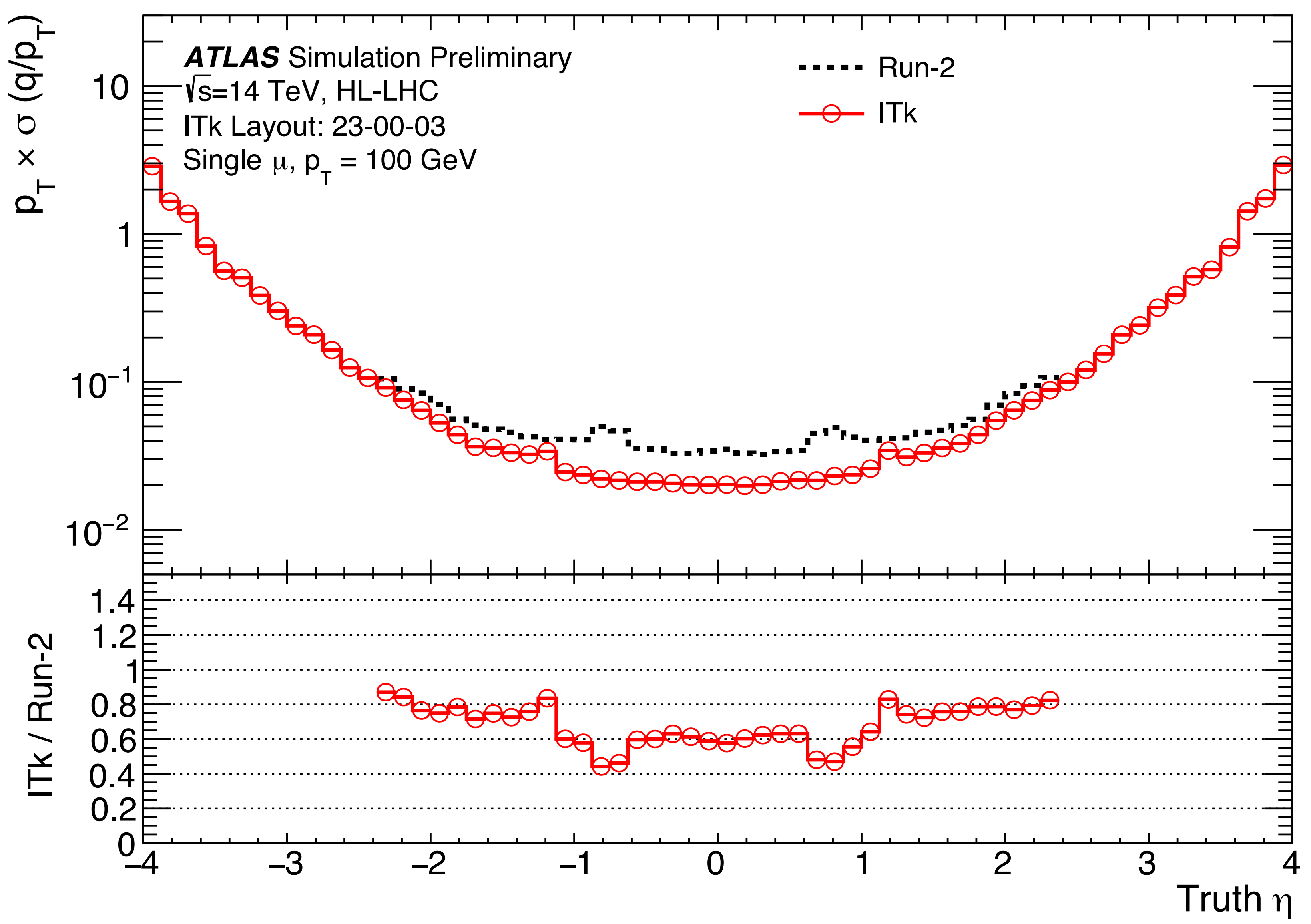
Tracking resolutions

ATL-PHYS-PUB-2021-024





- **Improved impact parameter resolutions** wrt current detector **thanks to smaller pixel pitch**
  => instrumental for **pile-up rejection and jet flavour-tagging**

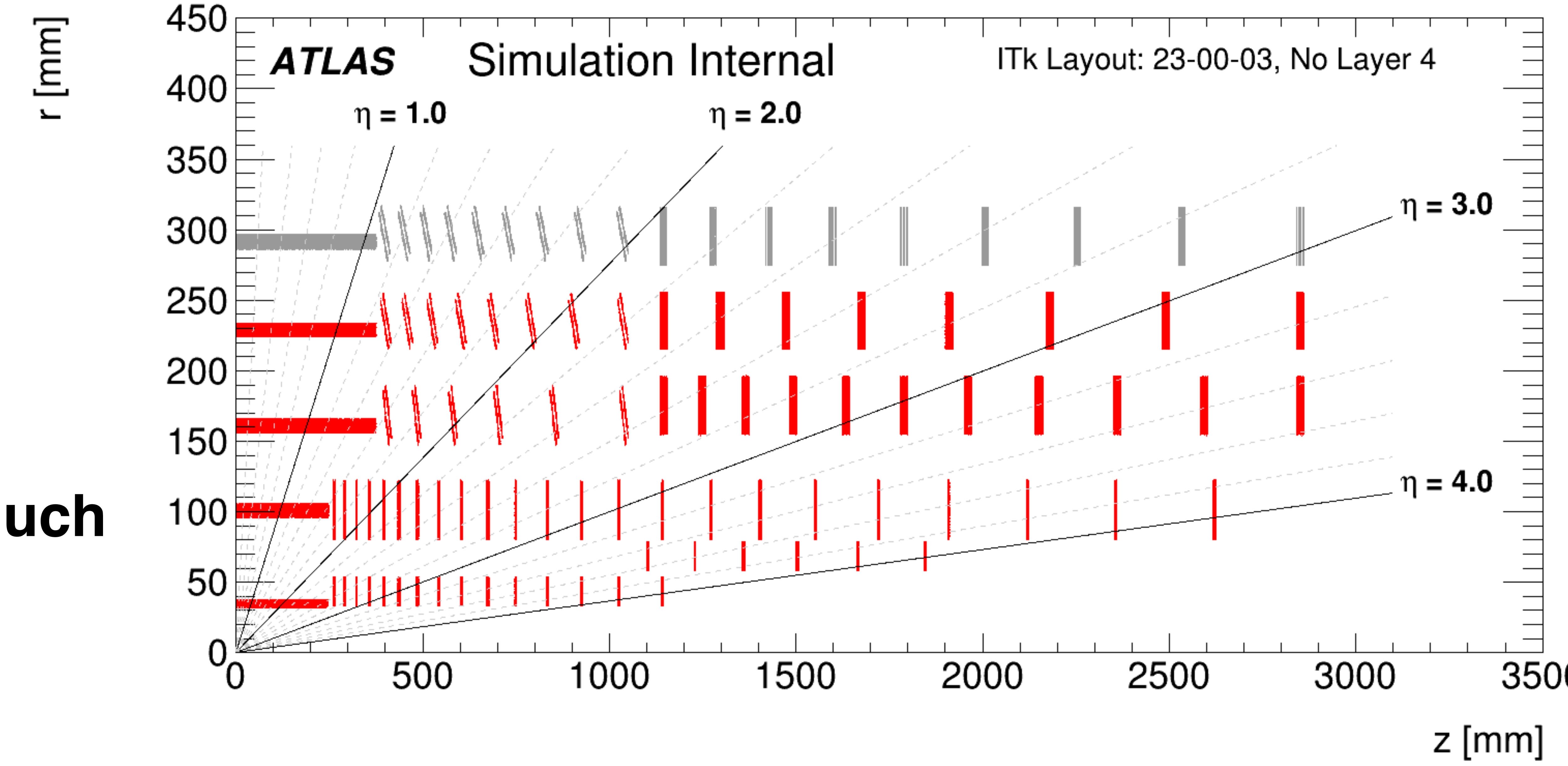


- **Improved transverse momentum resolution** thanks to better silicon strip sensors resolution in bending direction, compared to current TRT detector

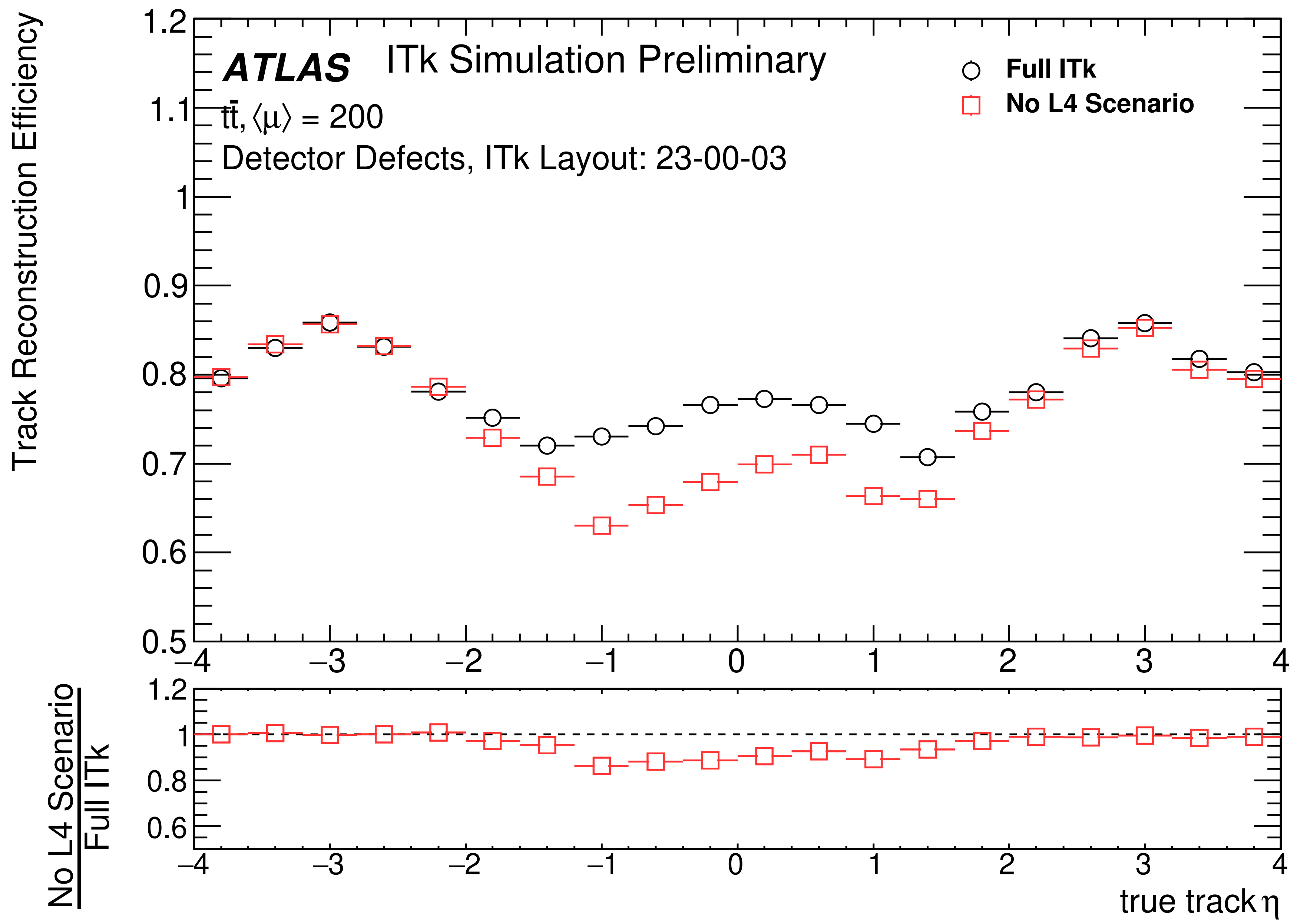
Impact of ITk layout on tracking performance

ATL-PHYS-PUB-2021-040

- To allow for contingency with tight HL-LHC schedule, **options for staged-installation of ITk Pixel detector investigated** in particular **for outermost layer**
  => opportunity to **confirm impact of ITk layout** on tracking performance
  Options not pursued ultimately



- Extra redundancy brought with five pixel layers ensures **much better robustness against detector defects**

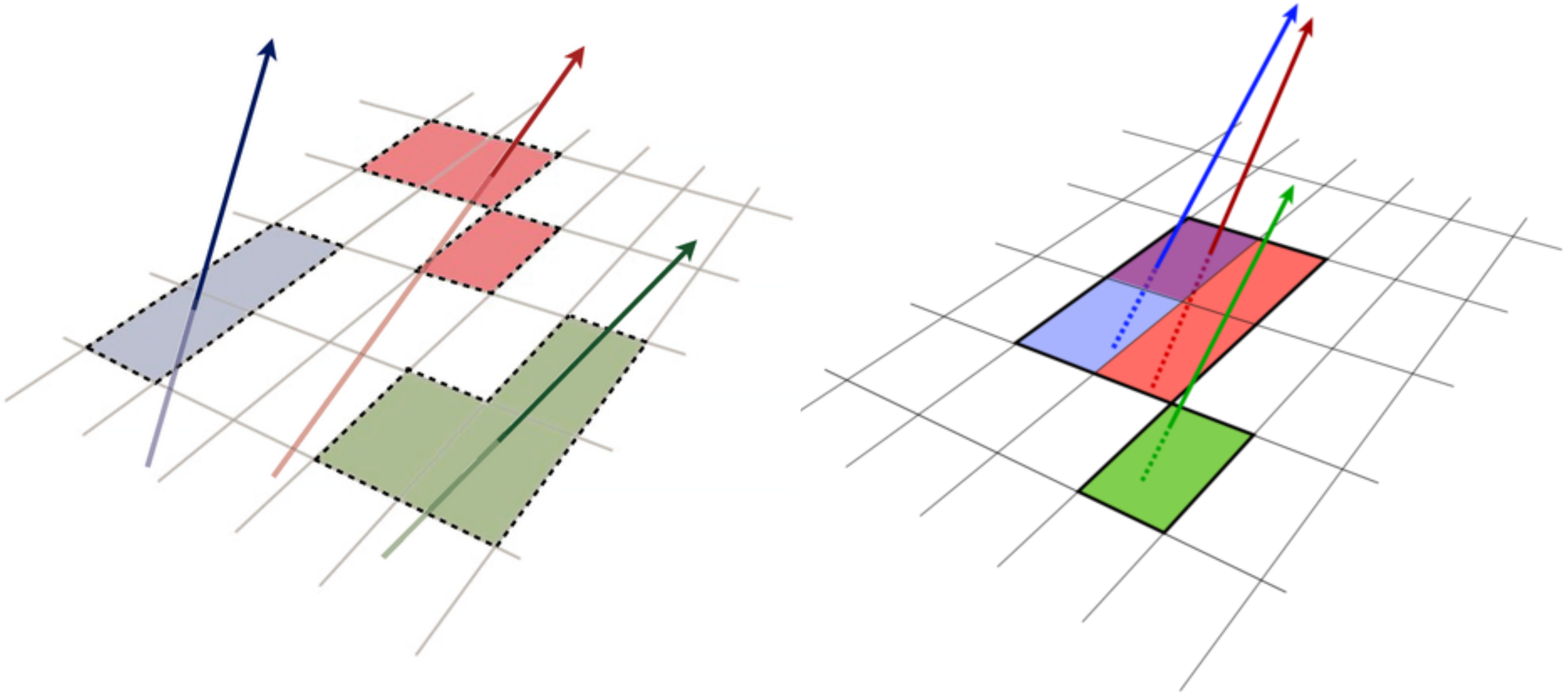


- With five layers, possibility to implement quality criteria at early stage to **reduce combinatorics and CPU**
  => critical element for trigger reconstruction (fast tracking)

	Number of Pixel seeds per event	Track Finding CPU[s]
Full Detector Default Tracking	26017	5.04
Full Detector Fast Tracking	9468	1.48
	Number of Pixel seeds per event	Track Finding CPU[s]
“No L4” Detector Default Tracking	51047	7.32
“No L4” Detector Fast Tracking	19340	2.04

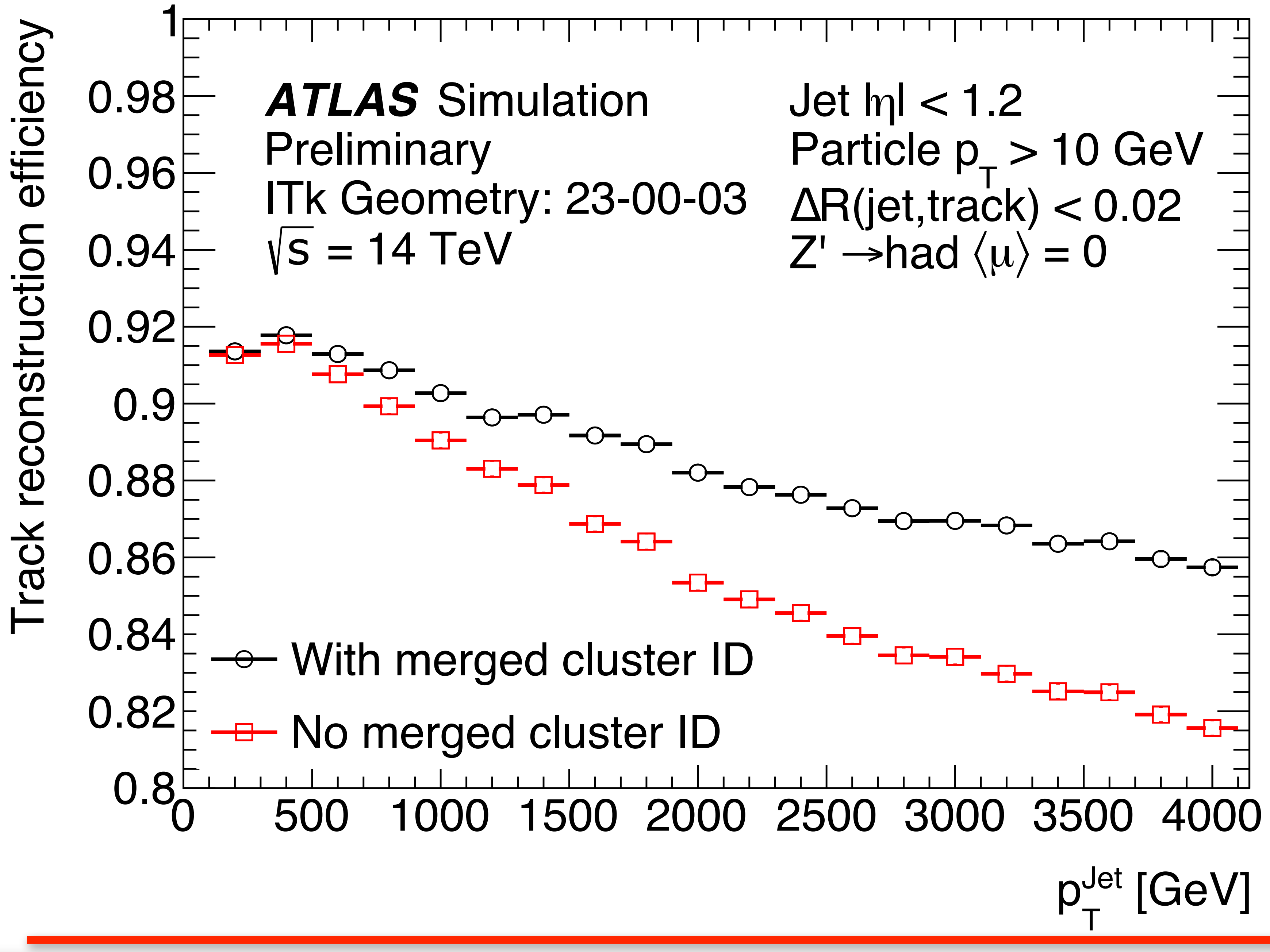
Tracking in dense environment

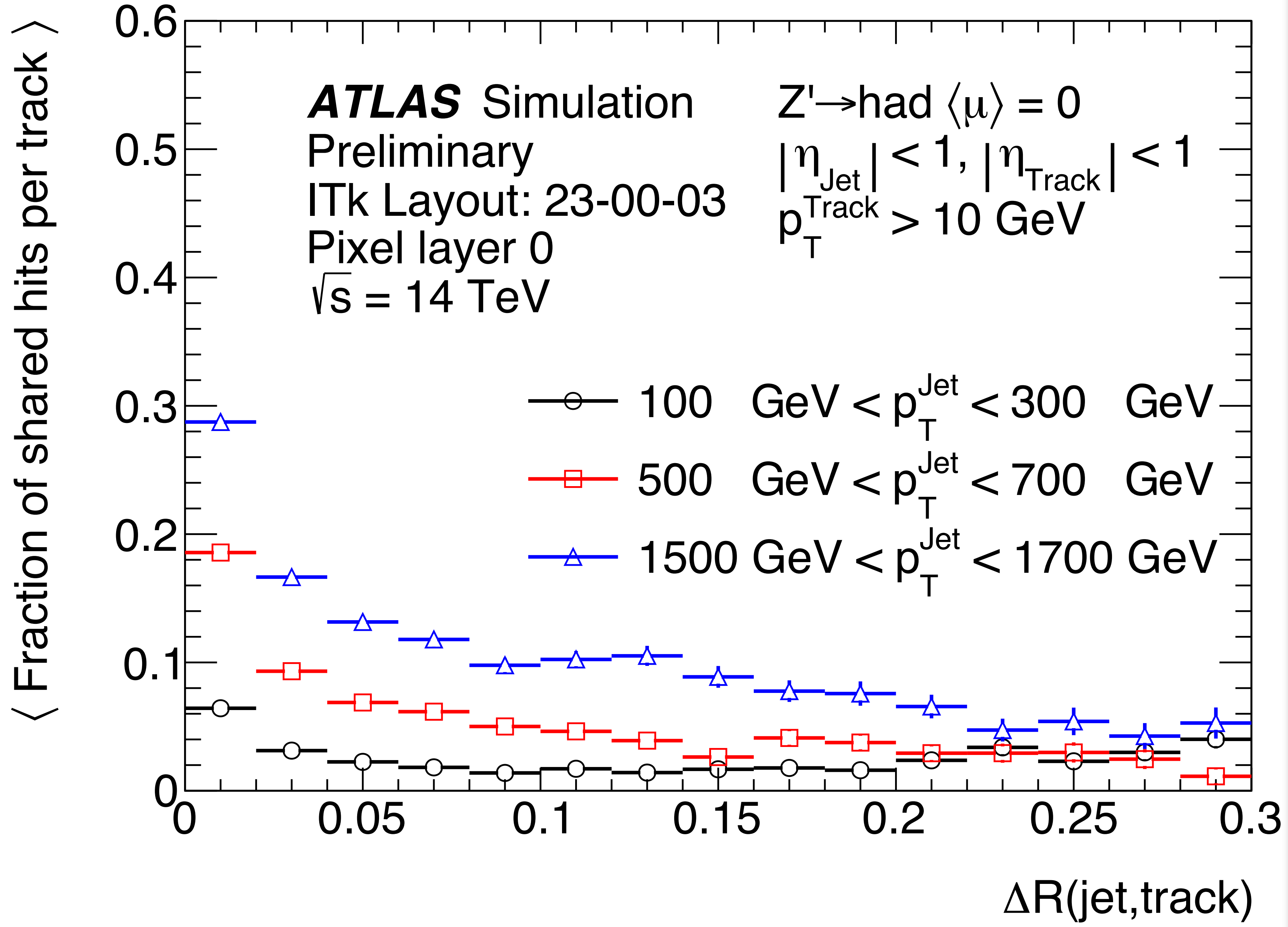
ATL-PHYS-PUB-2023-022



- In **core of high pT jets**, very high particle density => **pixel cluster merging**
- Track reconstruction allows for **shared hits between several tracks**: trade-off between tracking efficiency and fake rate
- **Merged pixel identification developed** based on Neural Networks continuously improved since Run 1

- Studies started to **adapt those with ITk**, expected to benefit from smaller pixel pitch
- Instrumental for **boosted hadronic decay tagging**

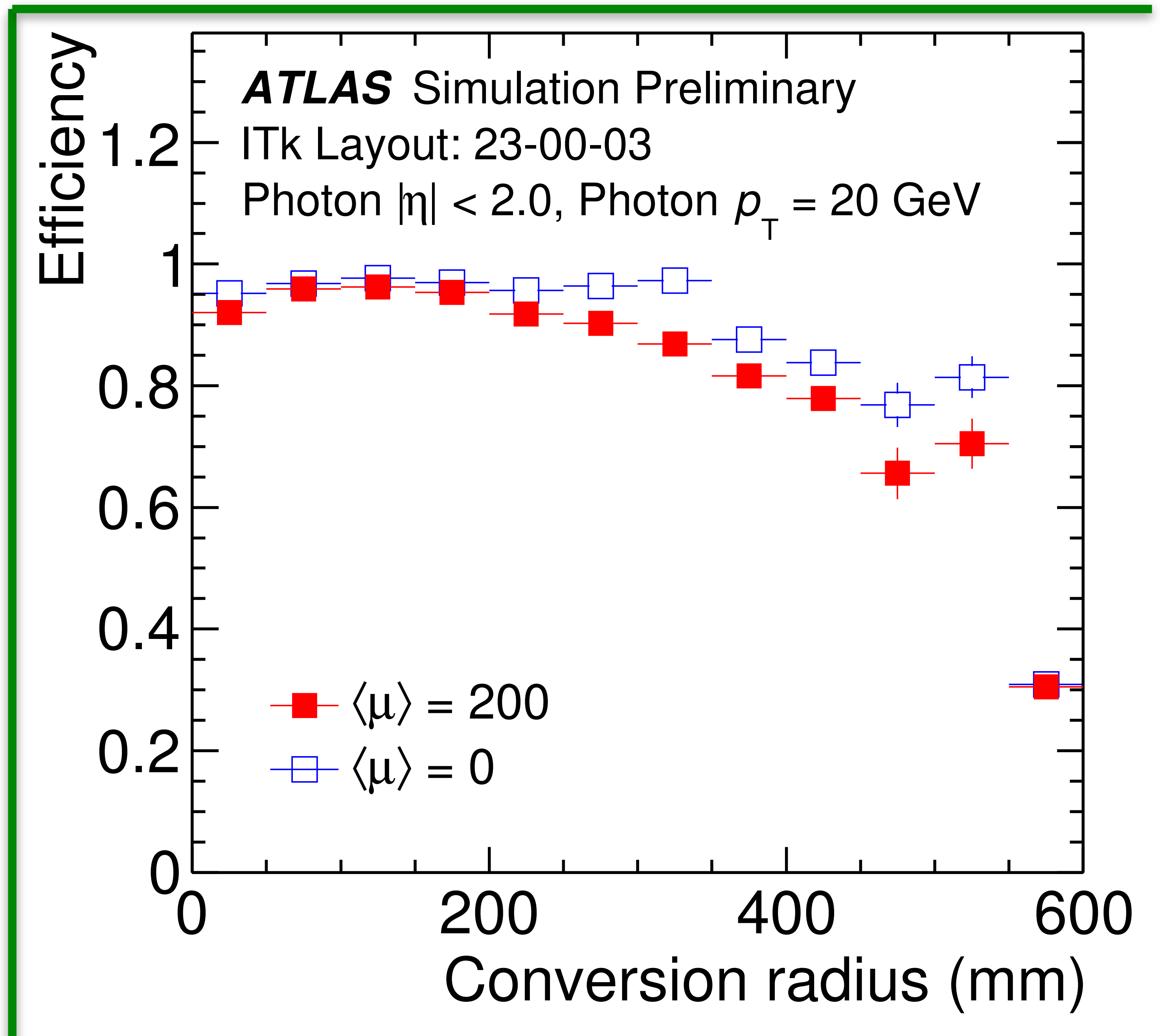




Tracking reconstruction beyond primary interaction

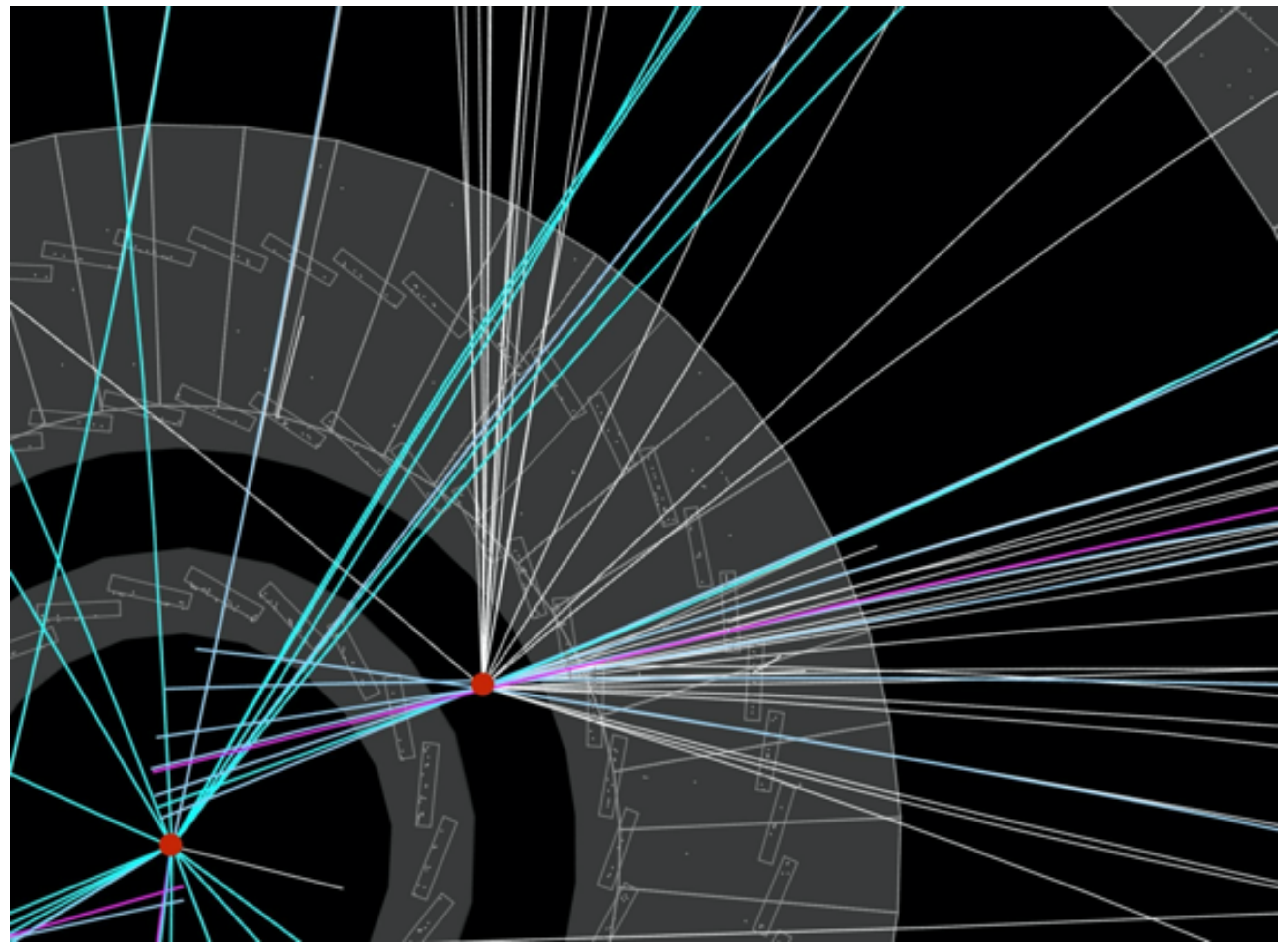
ATL-PHYS-PUB-2021-040

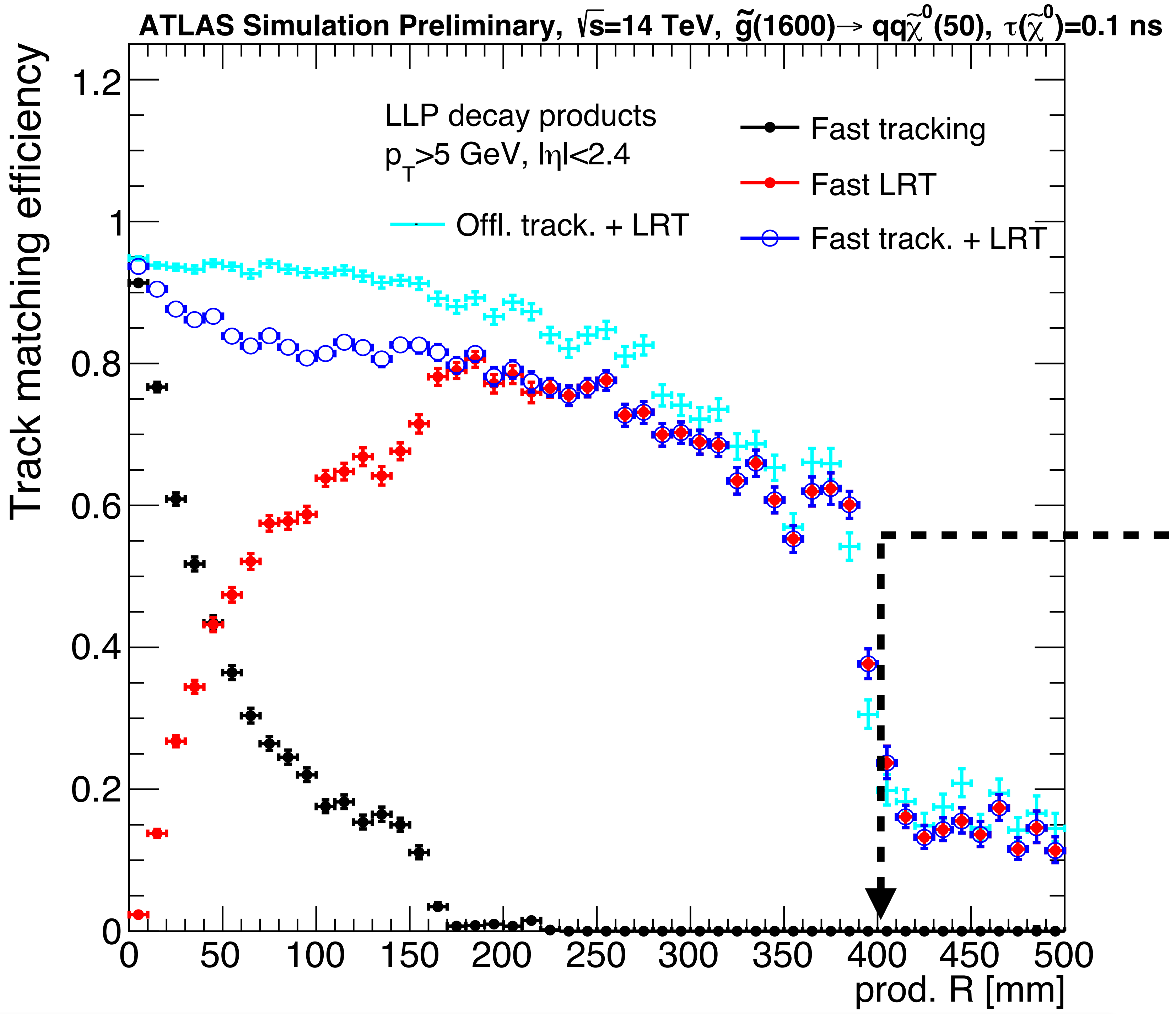
ATLAS-TDR-029-ADD-1



- **Default tracking reconstruction** optimised for charged particles produced in **primary interaction or secondary vertices with limited displacements** (τ or B-hadron decays)

- **Secondary passes** through left-over space-points aimed at reconstructing **charged particles with larger displacement:**
  - **photon conversion** reconstruction seeded by EM calo cluster





Offline reconstruction = default + LRT

Trigger reconstruction = default + LRT

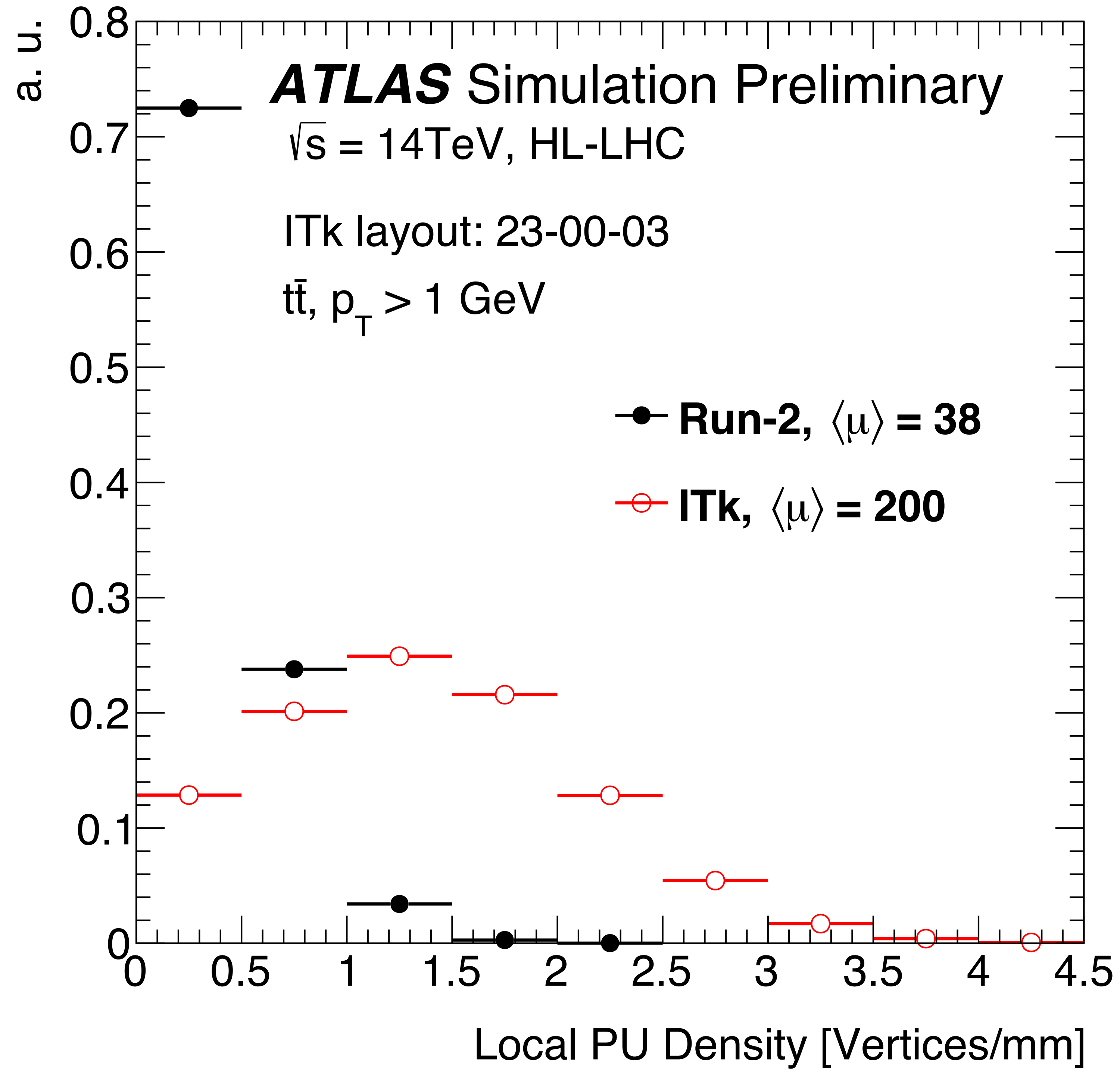
First ITk Strip layer

- **long-lived particle** decay products with Large Radius Tracking (LRT)
  => efficient reconstruction algorithms adapted to ITk

Expected high-level objects performance

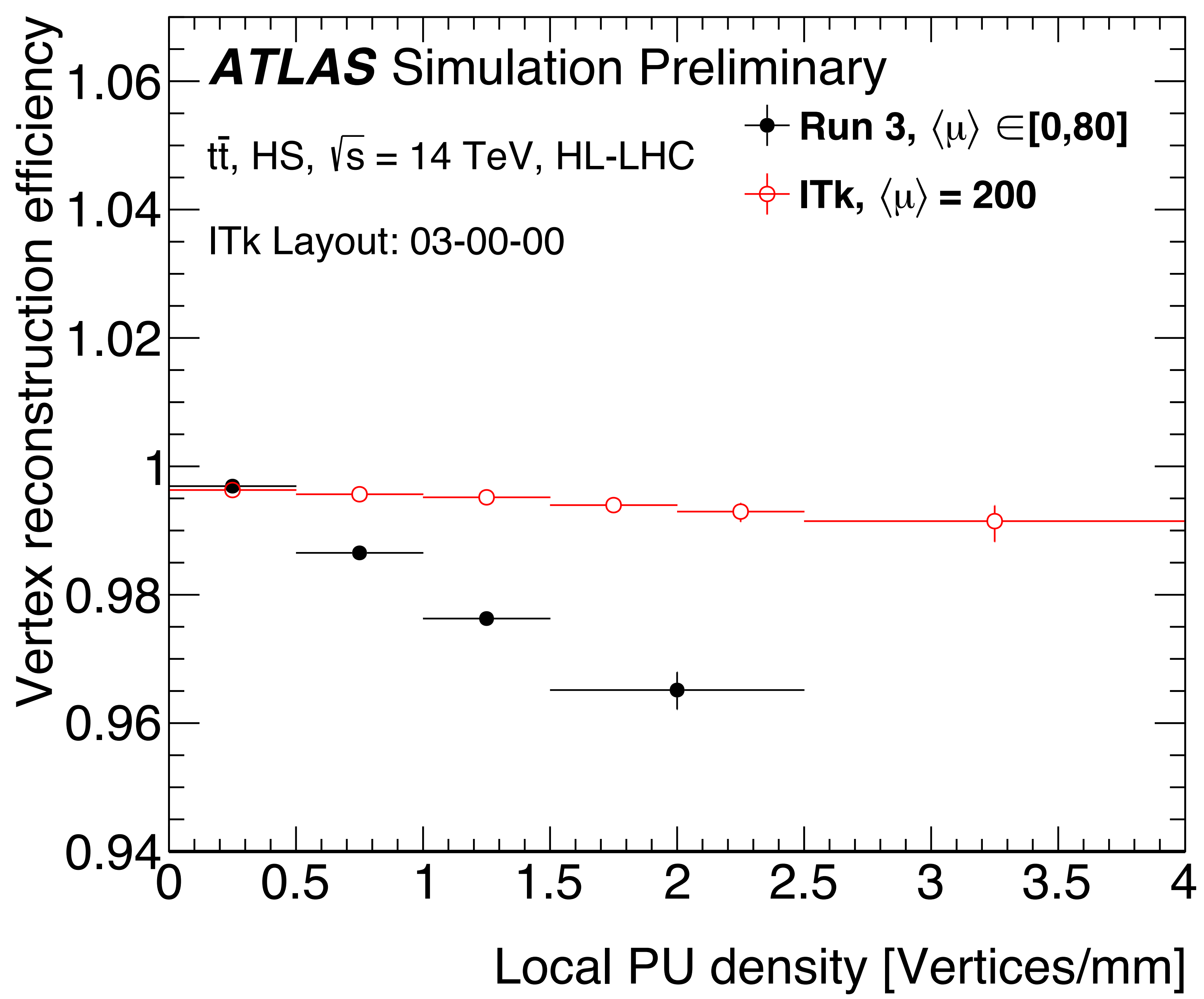
Primary vertexing performance

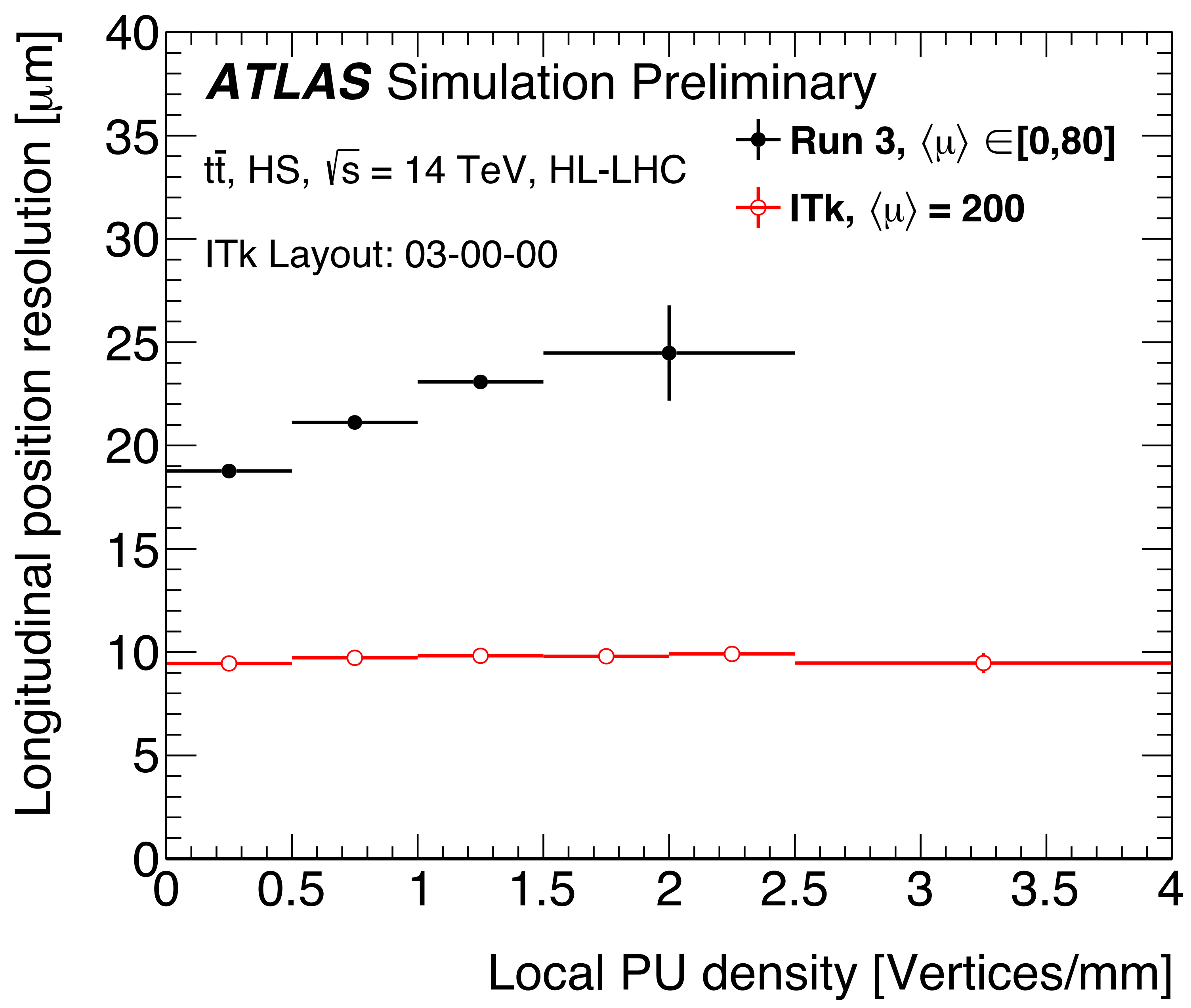
ATL-PHYS-PUB-2021-024
IDTR-2023-05



- Ultimate pile-up scenario <μ>=200 associated with **significant increase in local pile-up density around primary vertex**
- Primary vertexing aims at reconstructing **positions of proton-proton interactions** (hard-scatter + pile-up): based on Adaptive Multi-Vertex Finder algorithm
- Strong benefit from **improved track longitudinal impact parameter resolution**

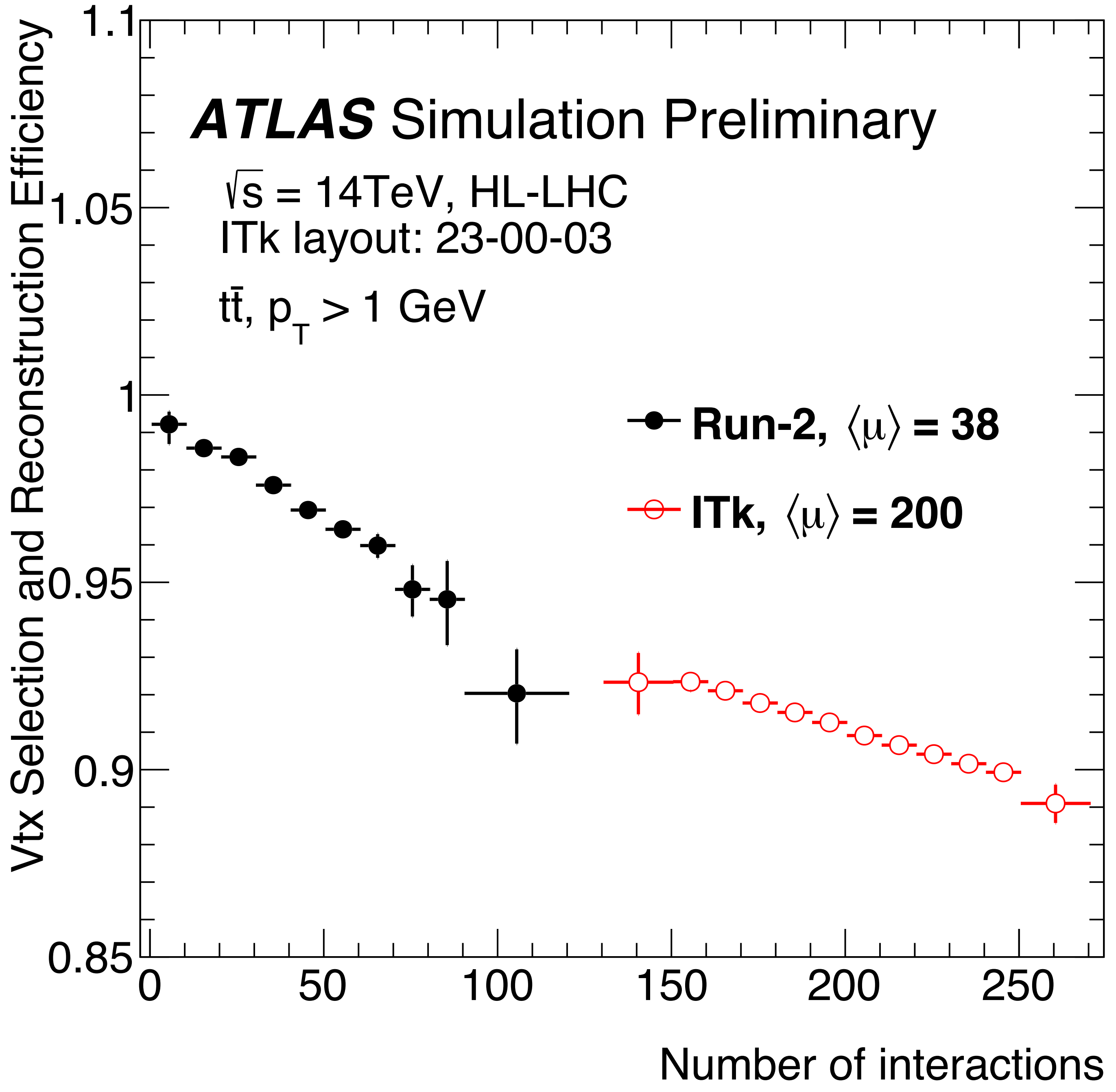
- Direct impact on **object performance relying on precise primary vertex reconstruction:**
  - lepton isolation
  - pile-up jet rejection
  - flavour-tagging

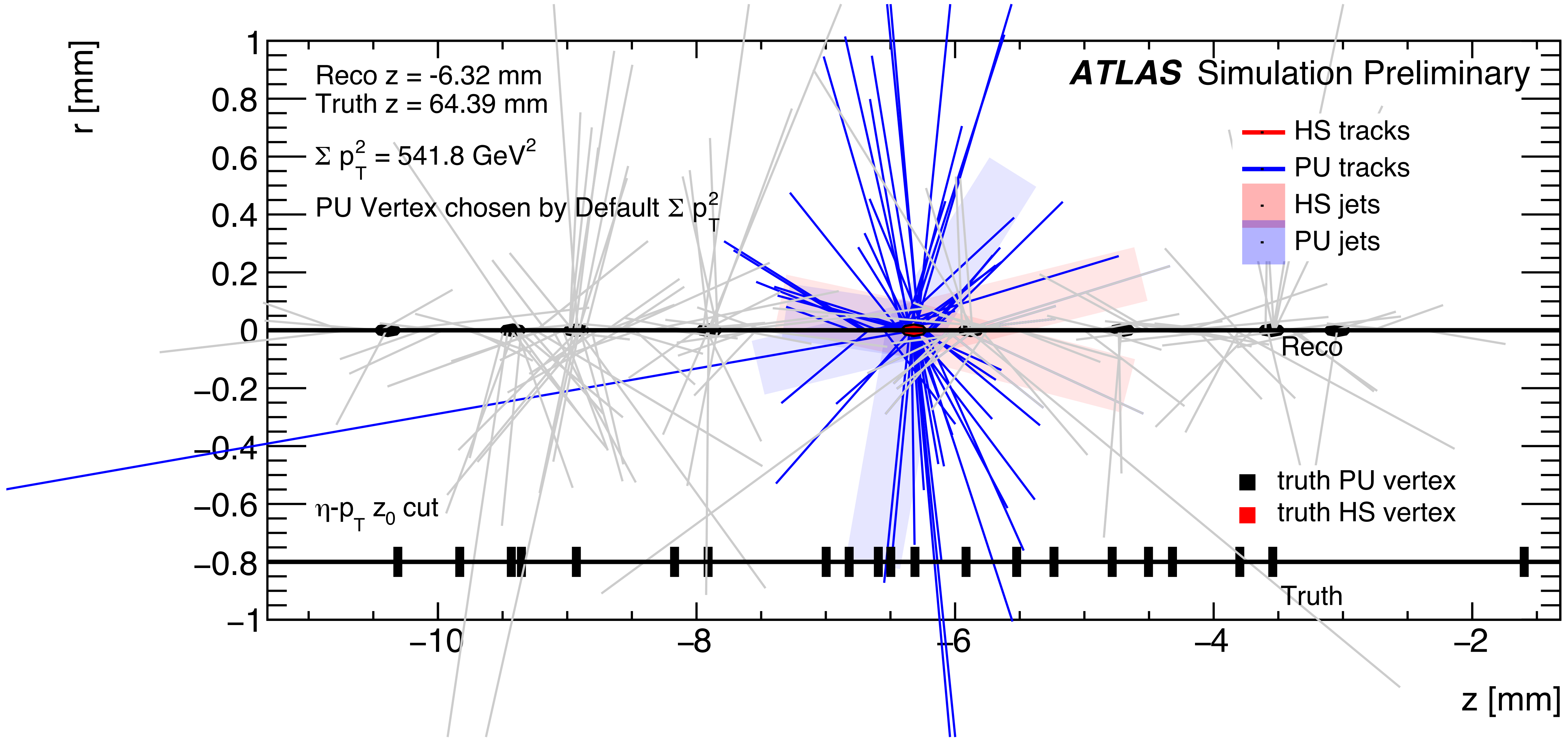


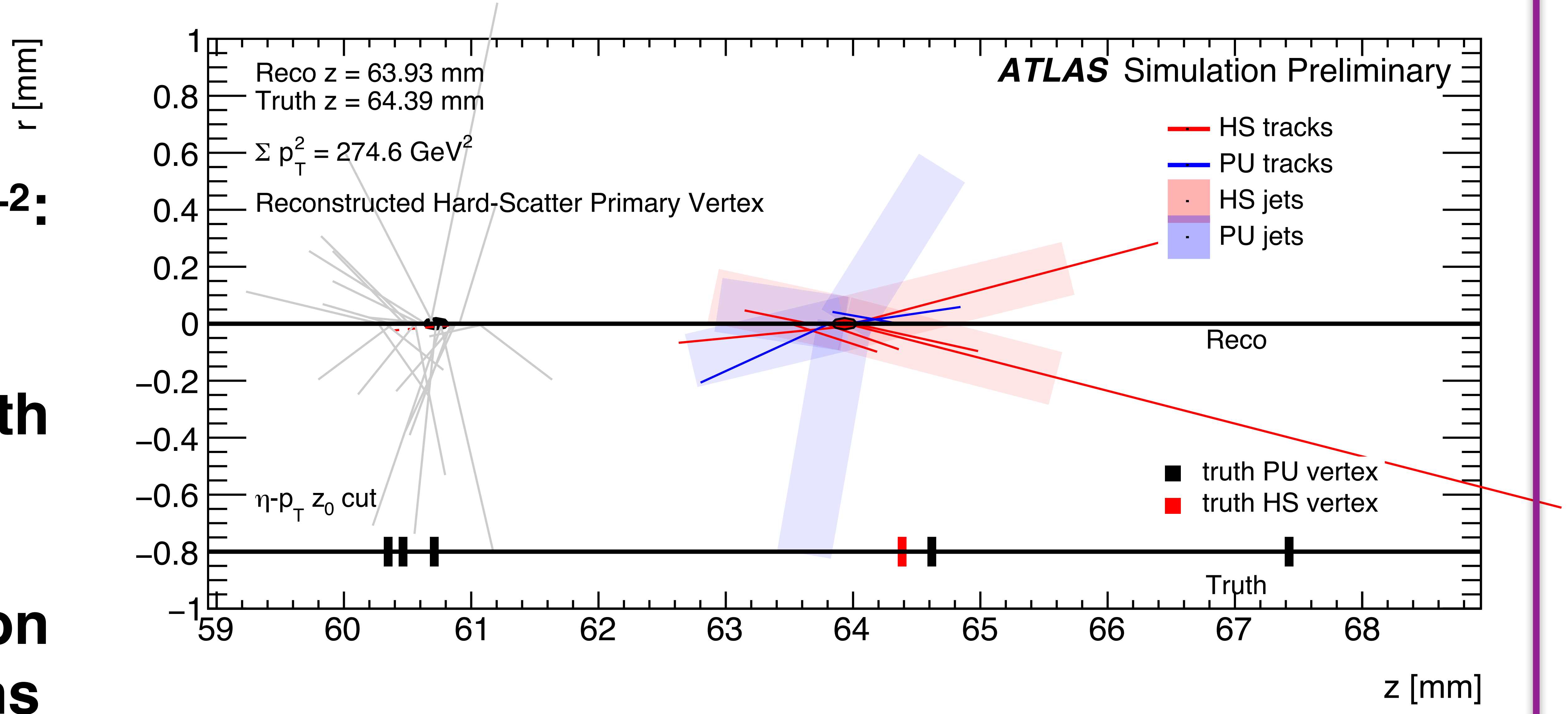


Primary vertexing performance

- Need to **pick the hard-scatter vertex** among all of the reconstructed primary vertices



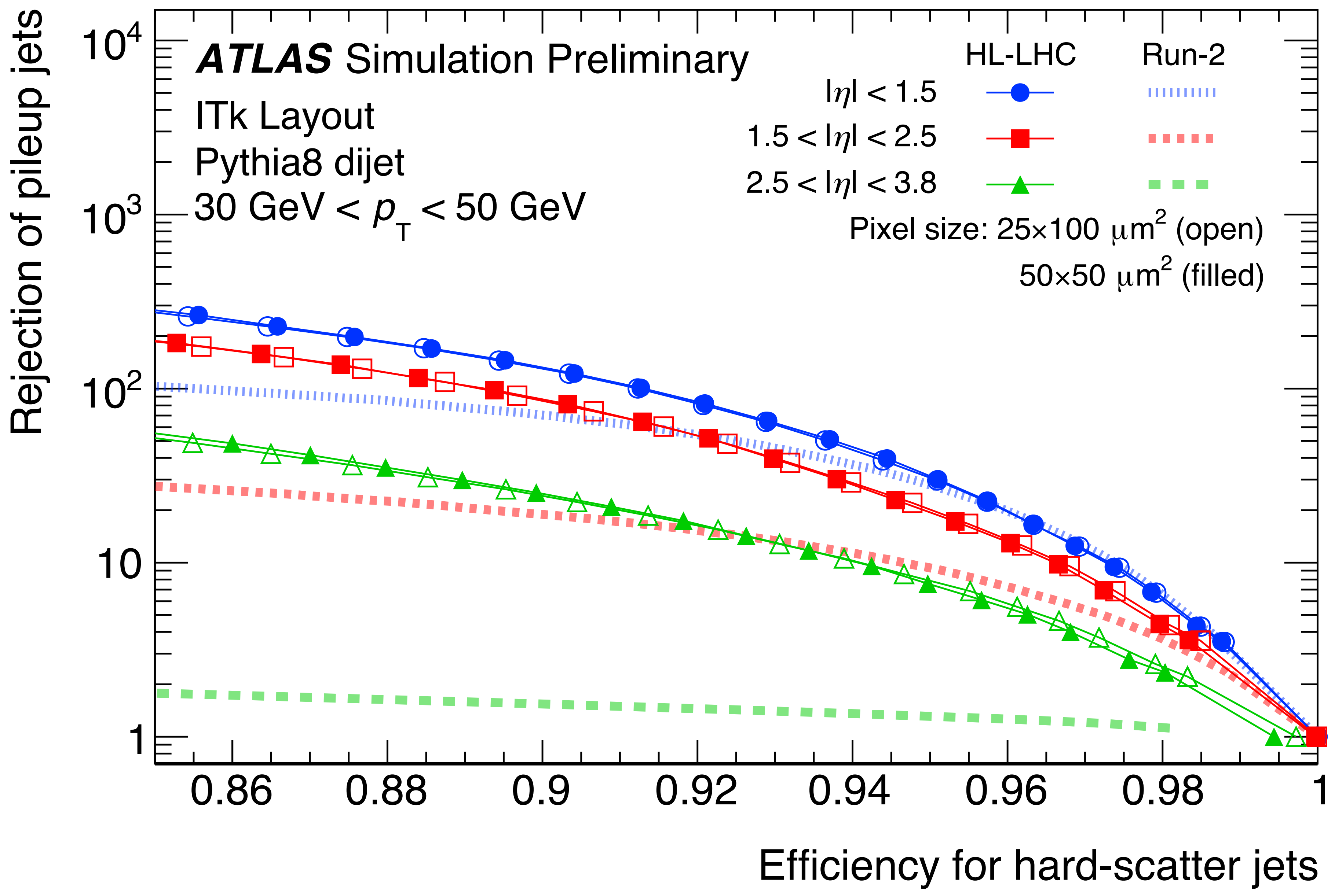




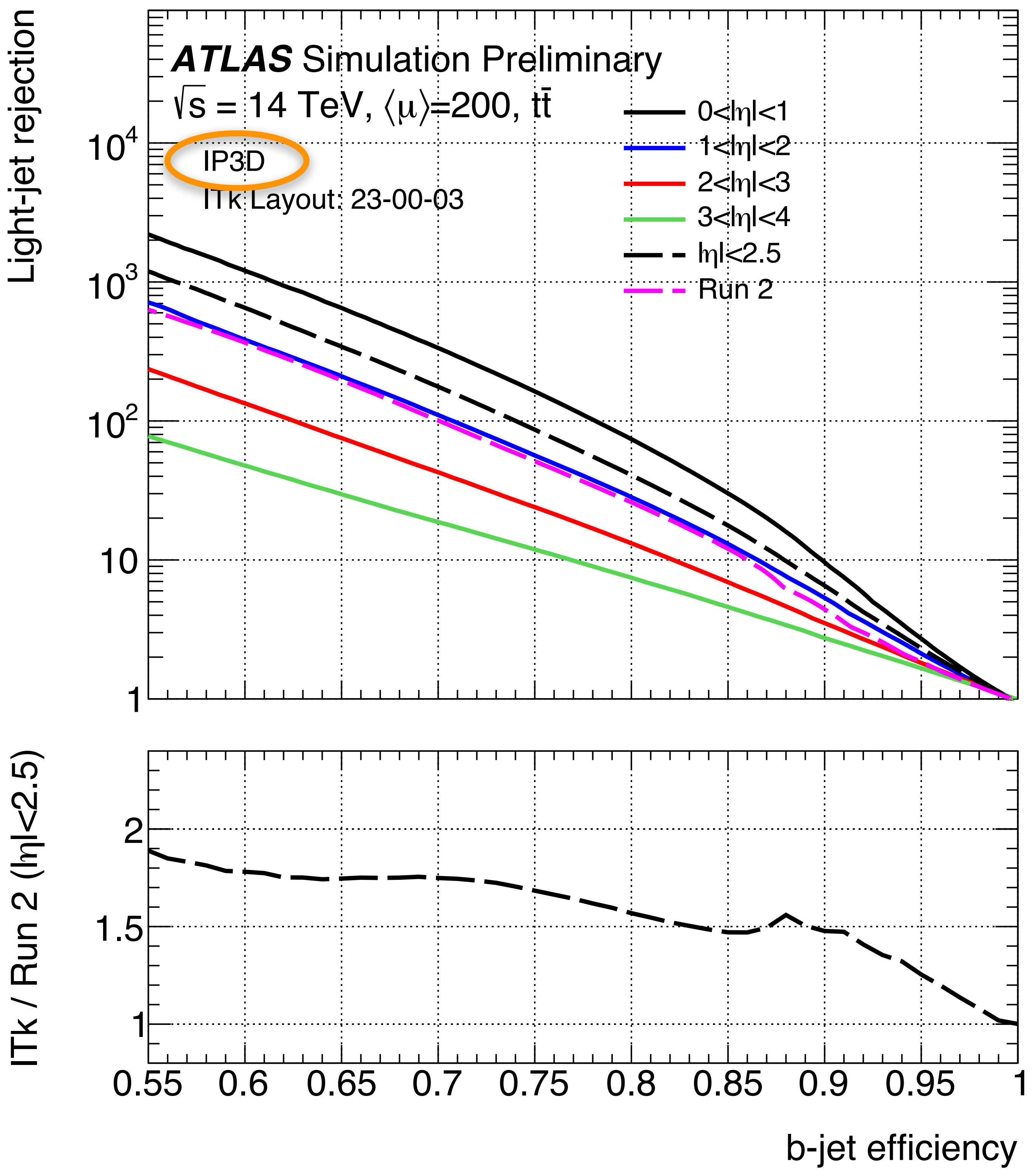
- **Default HS vertex selection criteria based on Σp_T^2:** getting harder with increasing number of vertices
- Σp_T^2 known to perform poorly on **signal topologies with low central track multiplicity:** $H\to\gamma\gamma$, VBF $H\to$invisible
- Ongoing effort to develop improved **unified vertex selection criteria based on NN** to be adapted for **HL-LHC conditions**

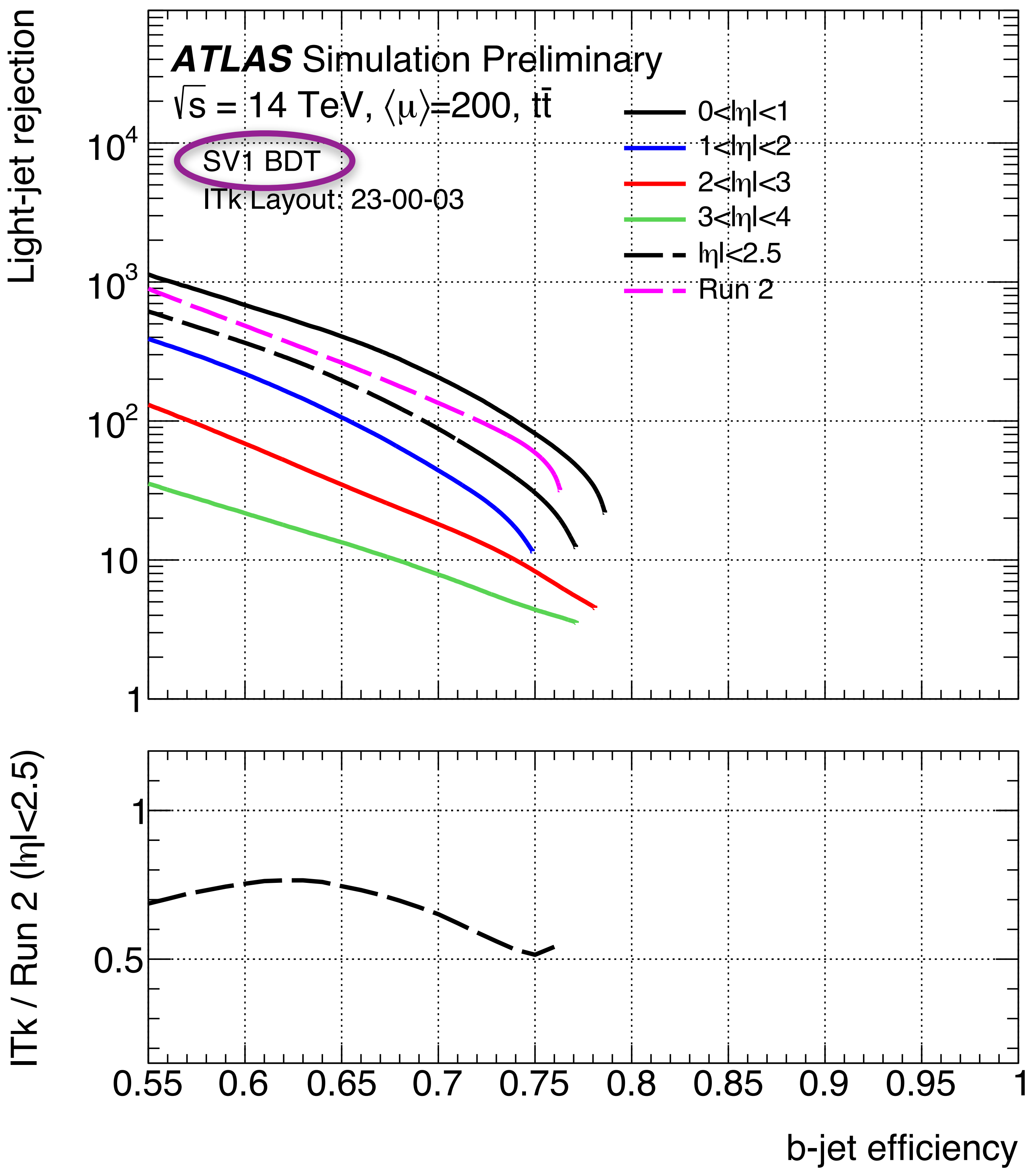
Jet tagging performance

ATL-PHYS-PUB-2019-014
ATL-PHYS-PUB-2021-024



- **Pile-up jet rejection performance directly connected to z0 resolution:** better performance in central region with lower material
- **Dramatic improvement in forward region with respect to Run 2** with no tracking coverage for current detector (PU jet rejection based on calorimeter timing), to be further improved with HGTD timing information **=> direct impact on VBF/VBS analyses**

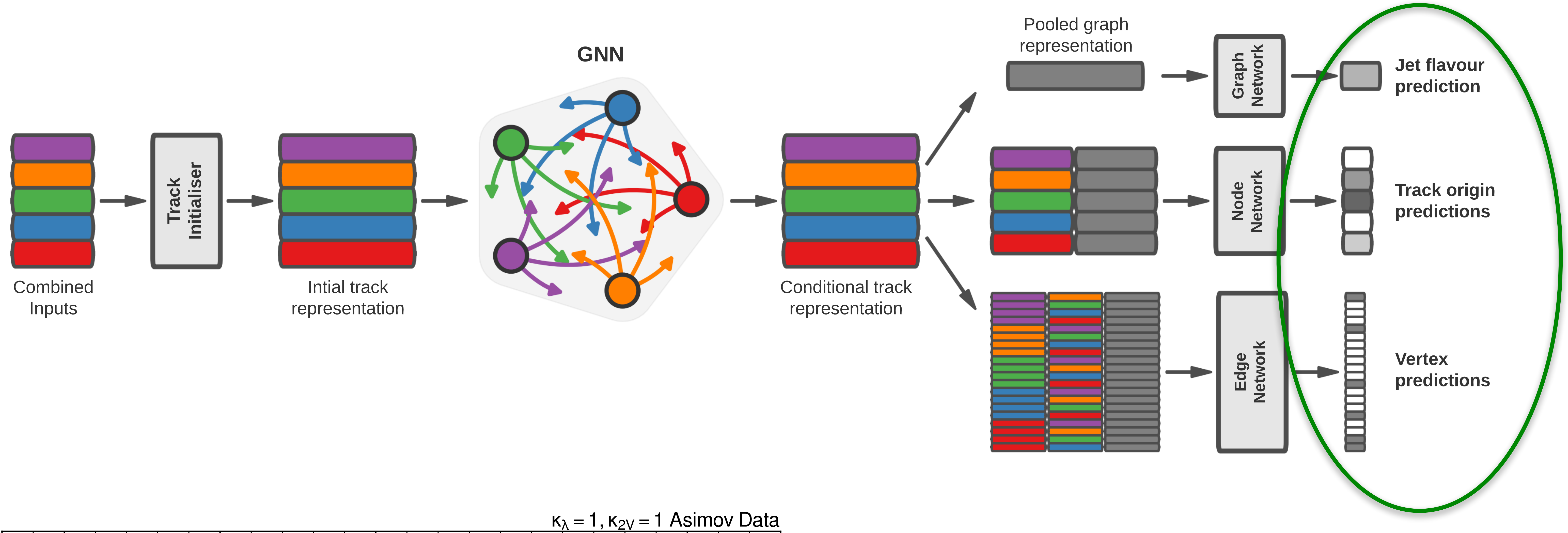


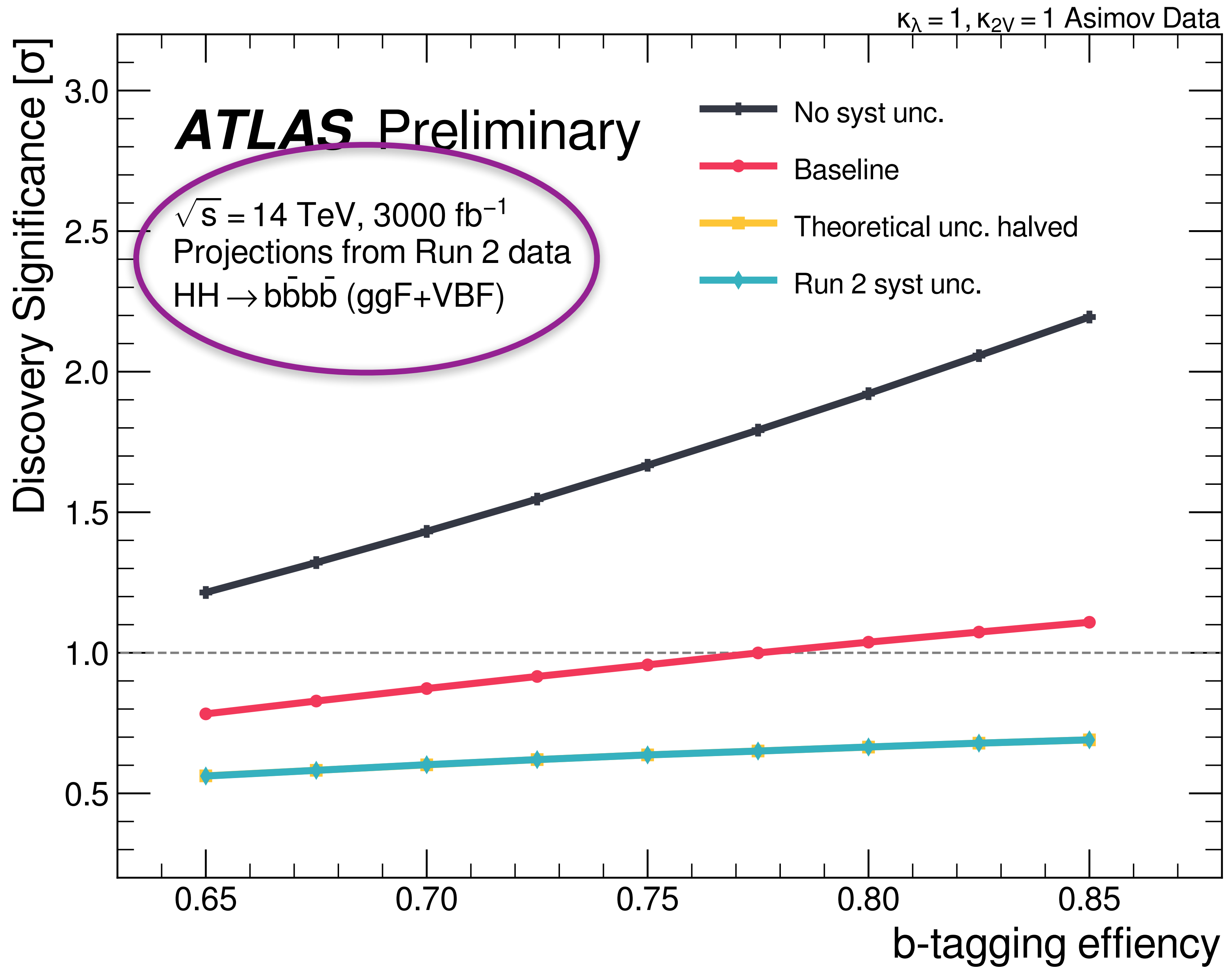


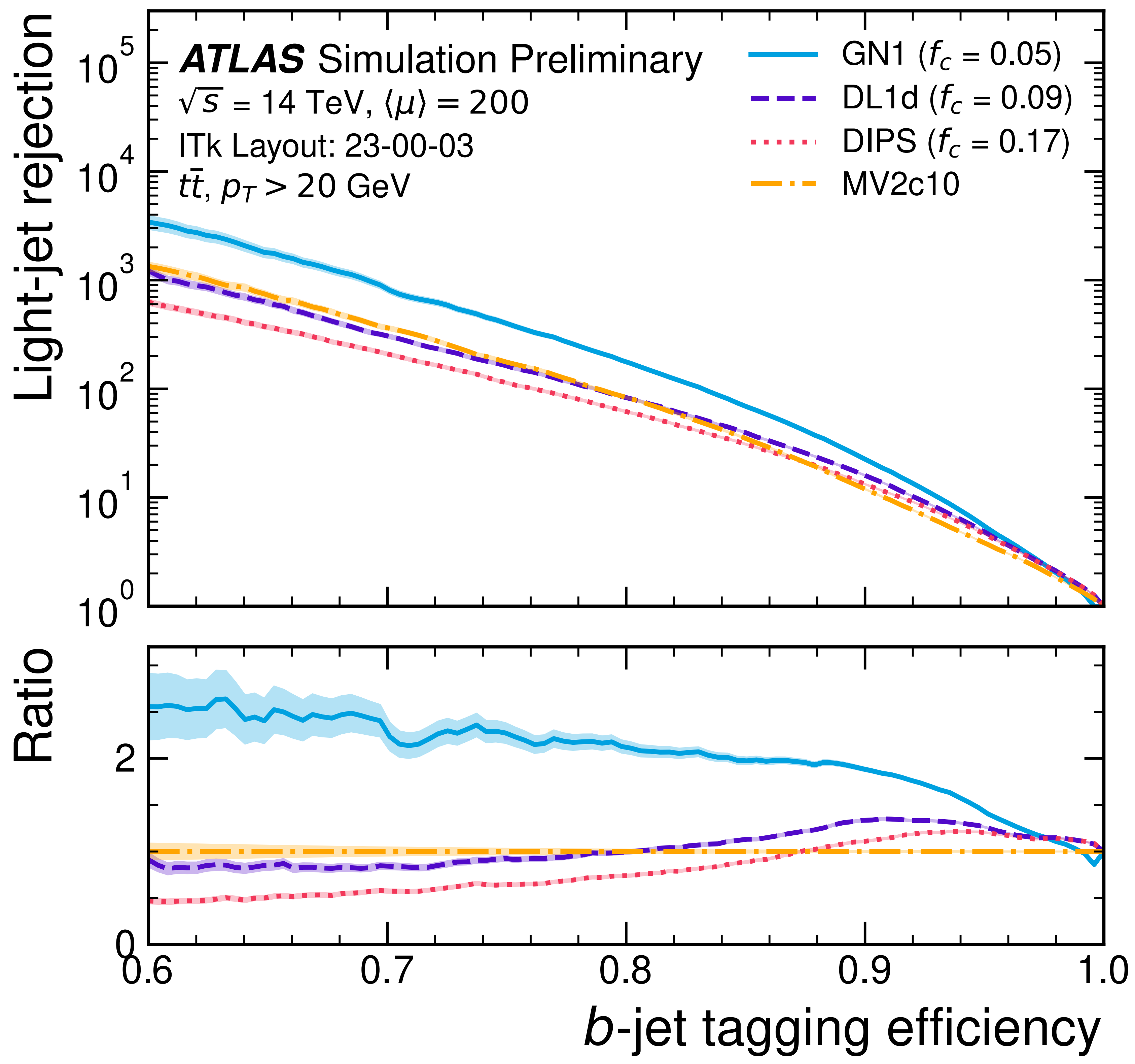
- **Impact-parameter based flavour-tagging algorithm** (IP3D) directly benefits from **improved ITk IP resolutions** + track categorisation optimised for new detector layout
- **Secondary vertexing** (SV1) **to be studied in more details**

Jet tagging performance

ATL-PHYS-PUB-2022-047
ATL-PHYS-PUB-2022-053







- New generation of flavour-tagging algorithms based on **Graph Neural Networks** being adapted to HL-LHC conditions, combining several aux. tasks

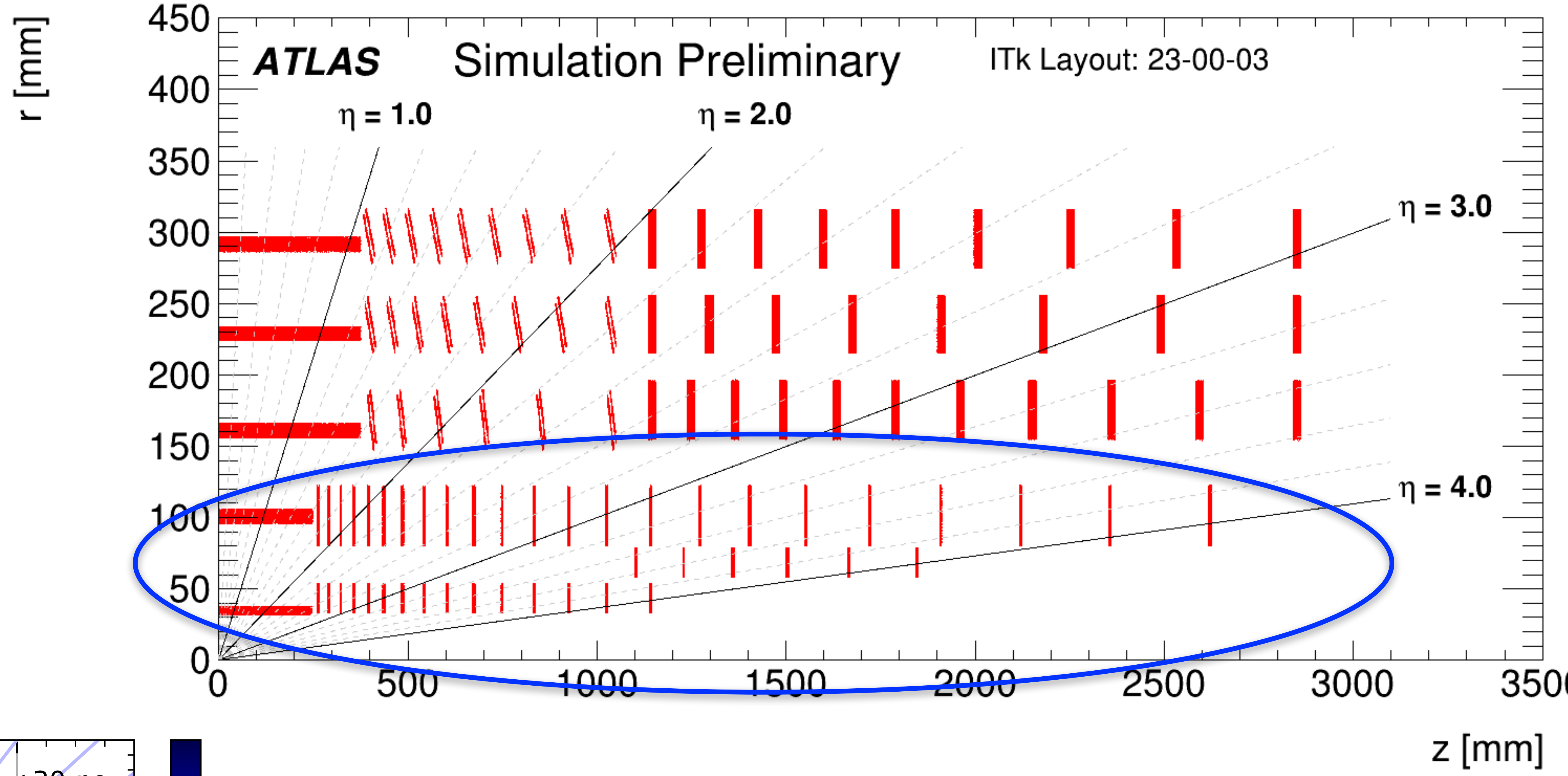
- **Large improvement expected with respect to previous taggers** but optimisation more complex

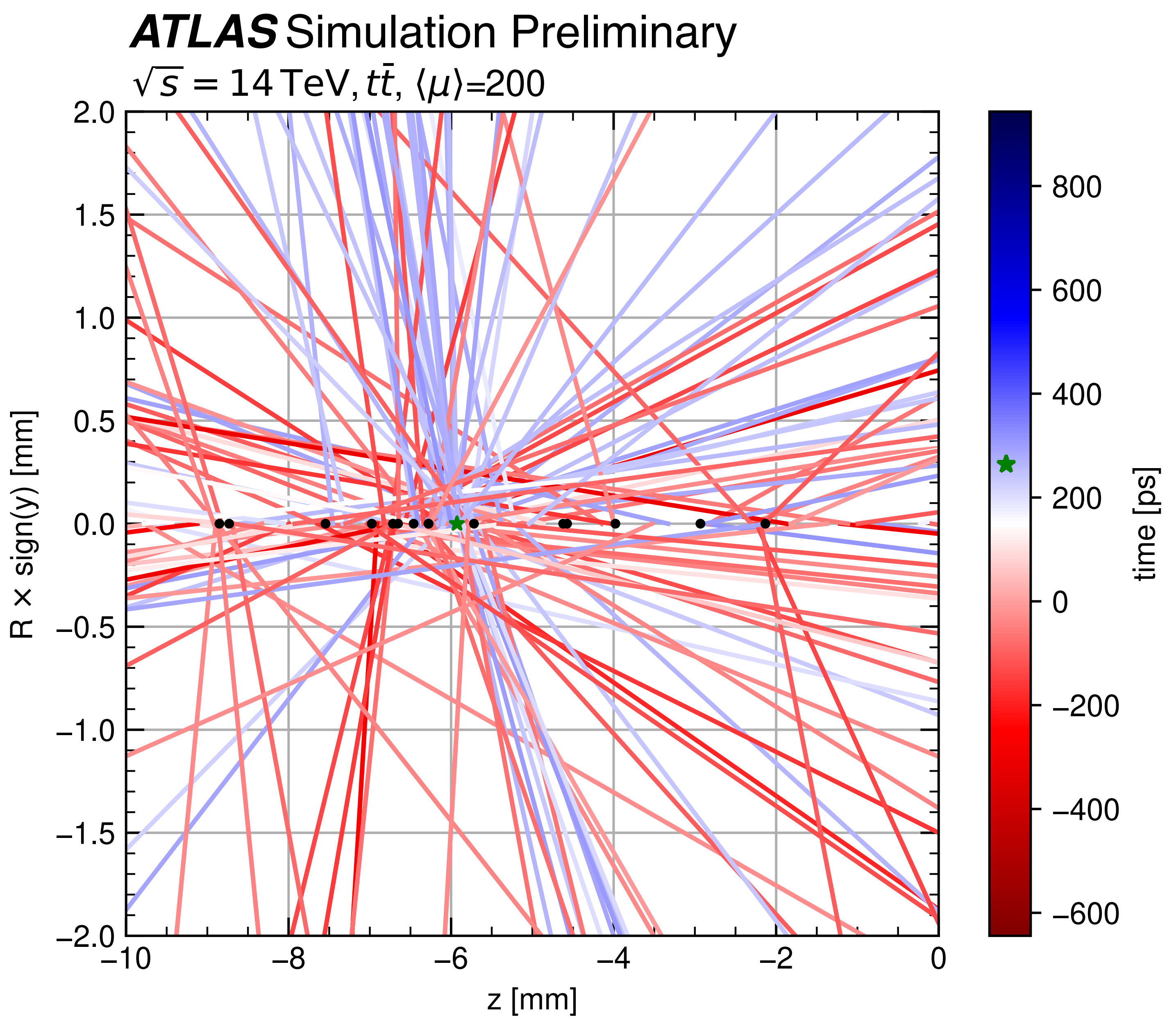
- **Interplay between performance and benchmark physics analyses closely monitored**

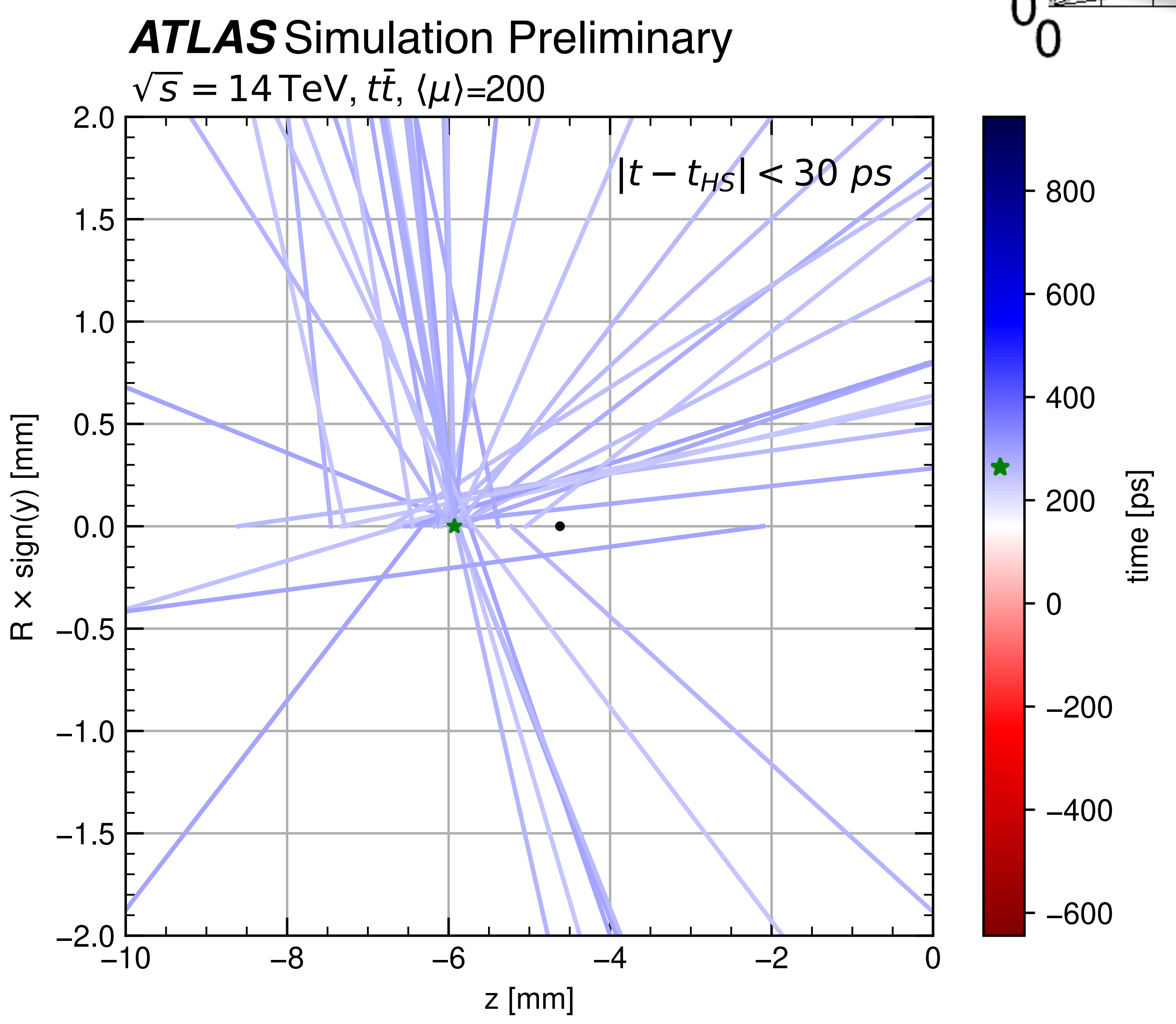
Towards 4D Tracking?

- **Two innermost ITk pixel layers designed to be replaced after 2000 fb^{-1}** (after Run 4 or Run 5): opportunity for potential hardware upgrade

- **Technology for pixels with 4D measurements** (x/y/z + time) mature enough by then to be considered for upgrade
  => 30 ps timing resolution expected



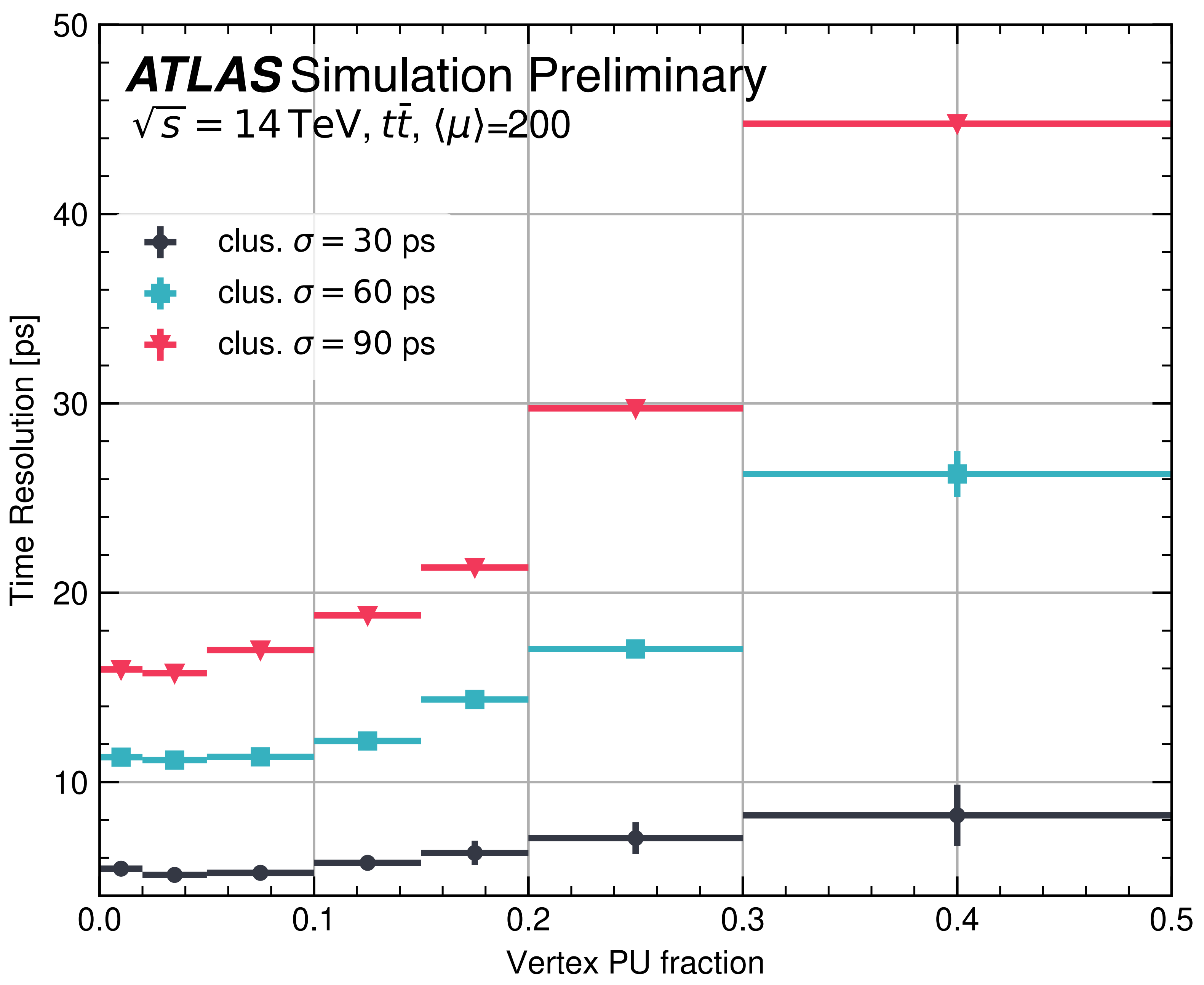


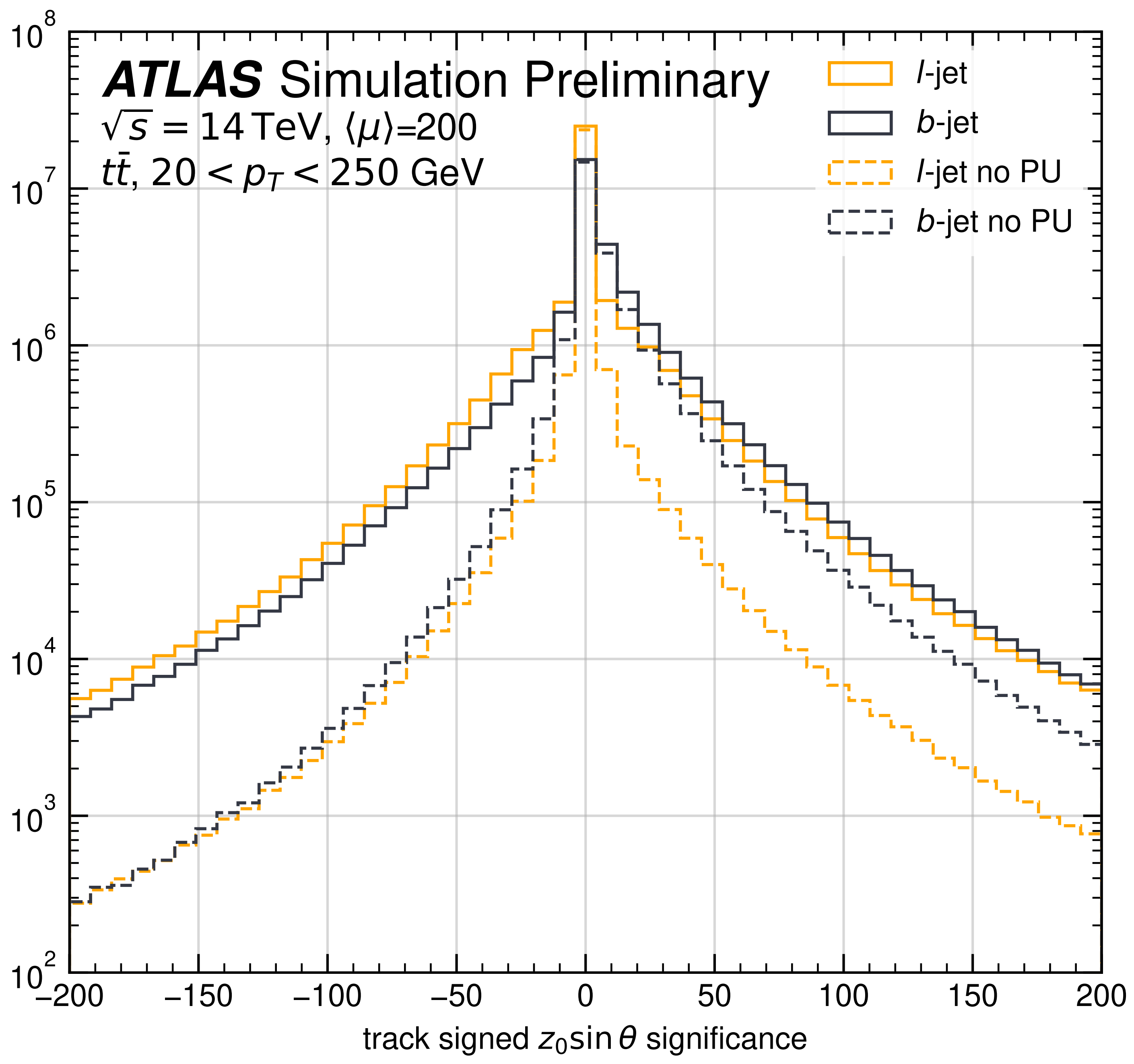


- **Expected improvement on performance investigated:** possibility to clean up pile-up tracks in combination with z0 impact parameter + overcome limited HGTD η acceptance

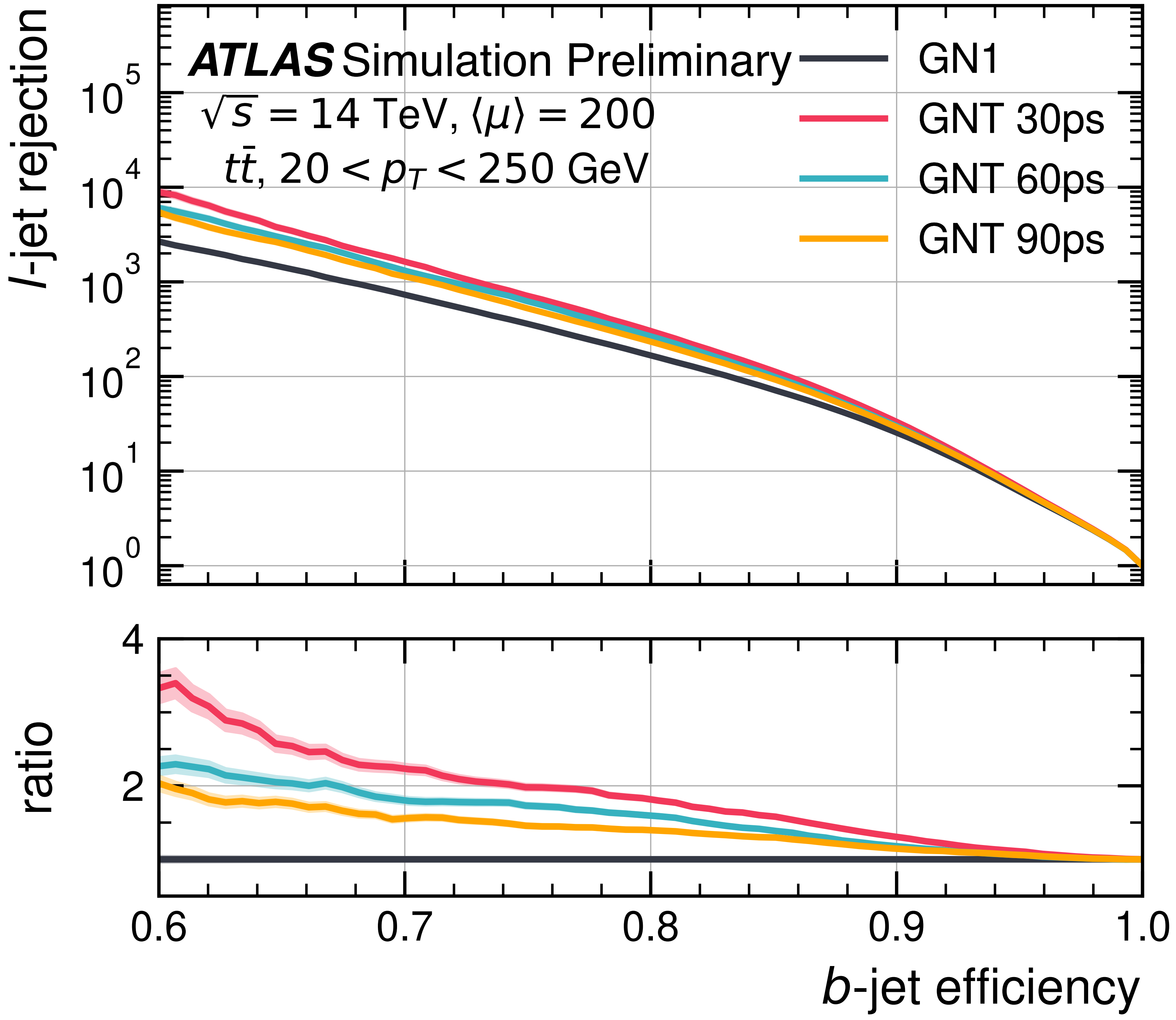
Towards 4D Tracking?

ATL-PHYS-PUB-2023-023



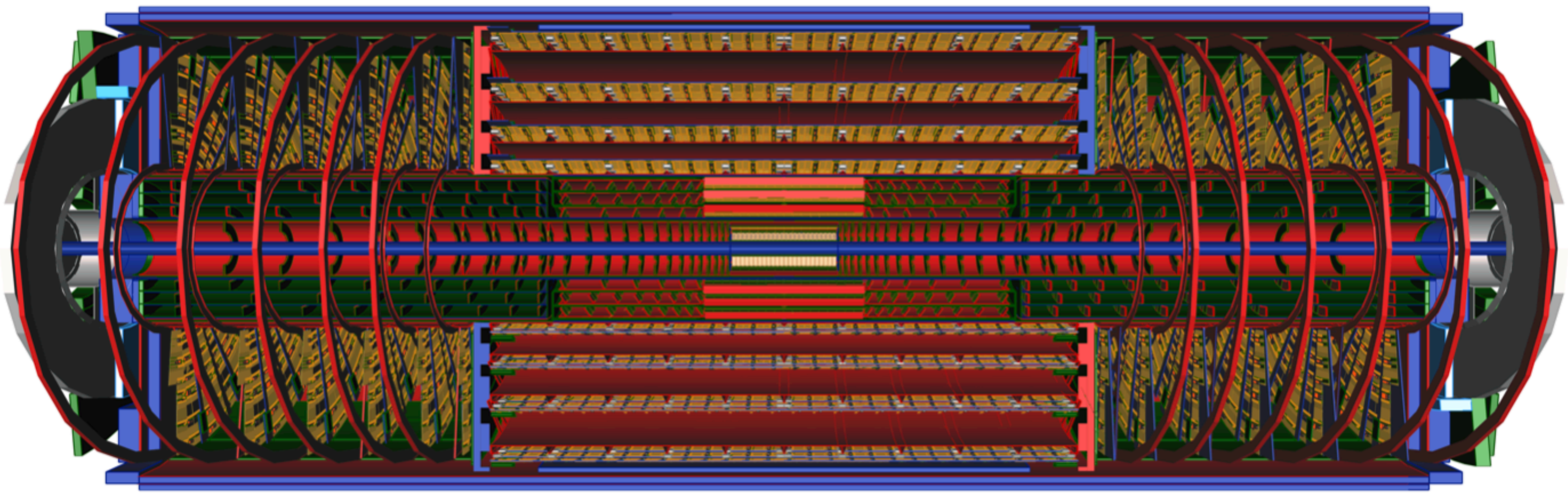


- **Time resolution better than 10 ps for all vertices**



- Benefit from reduction of pile-up tracks faking large-IP tracks from b hadron decays **=> strong improvement on b-tagging performance**
- Can also benefit to:
  - pile-up jet rejection
  - search for long-lived particle exploiting calorimeter timing

Conclusion



- **ITk detector will face unprecedented challenges for tracking reconstruction:** sizeable increase in detector occupancy due to increased pile-up

- **Excellent tracking performance expected**, both for particles produced in primary interaction or displaced vertices, directly benefitting from **optimised ITk detector layout** and **years of experience in tracking reconstruction** with current ATLAS detector

- Will directly benefit to **high-level object reconstruction and identification** and ultimately to **sensitivity of physics analyses** with datasets collected at HL-LHC

- **Future upgrades beyond Run 4** exploiting timing information could further improve the performance


30/01/1933
-
09/06/2024

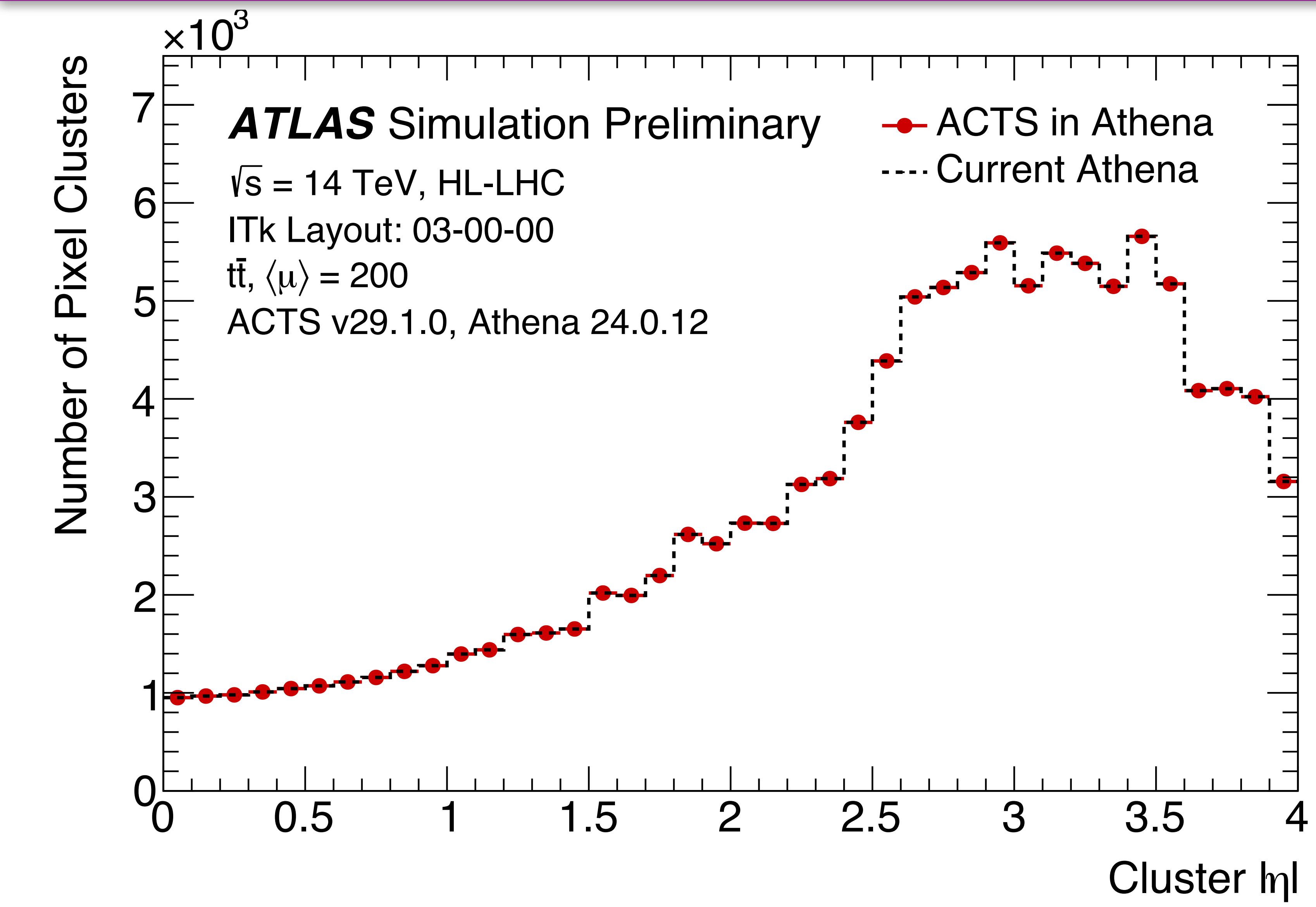
Thank you for your attention

Back up

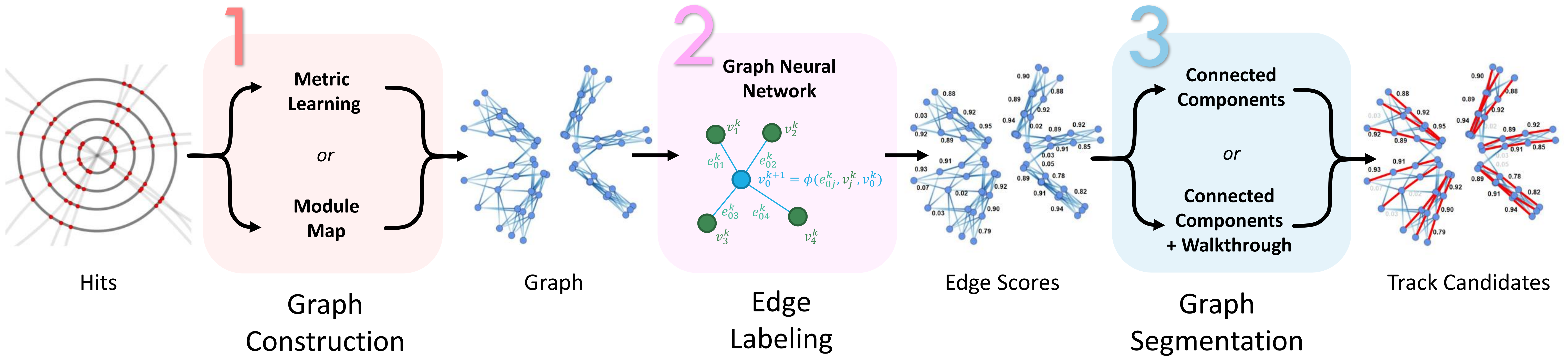
Software developments

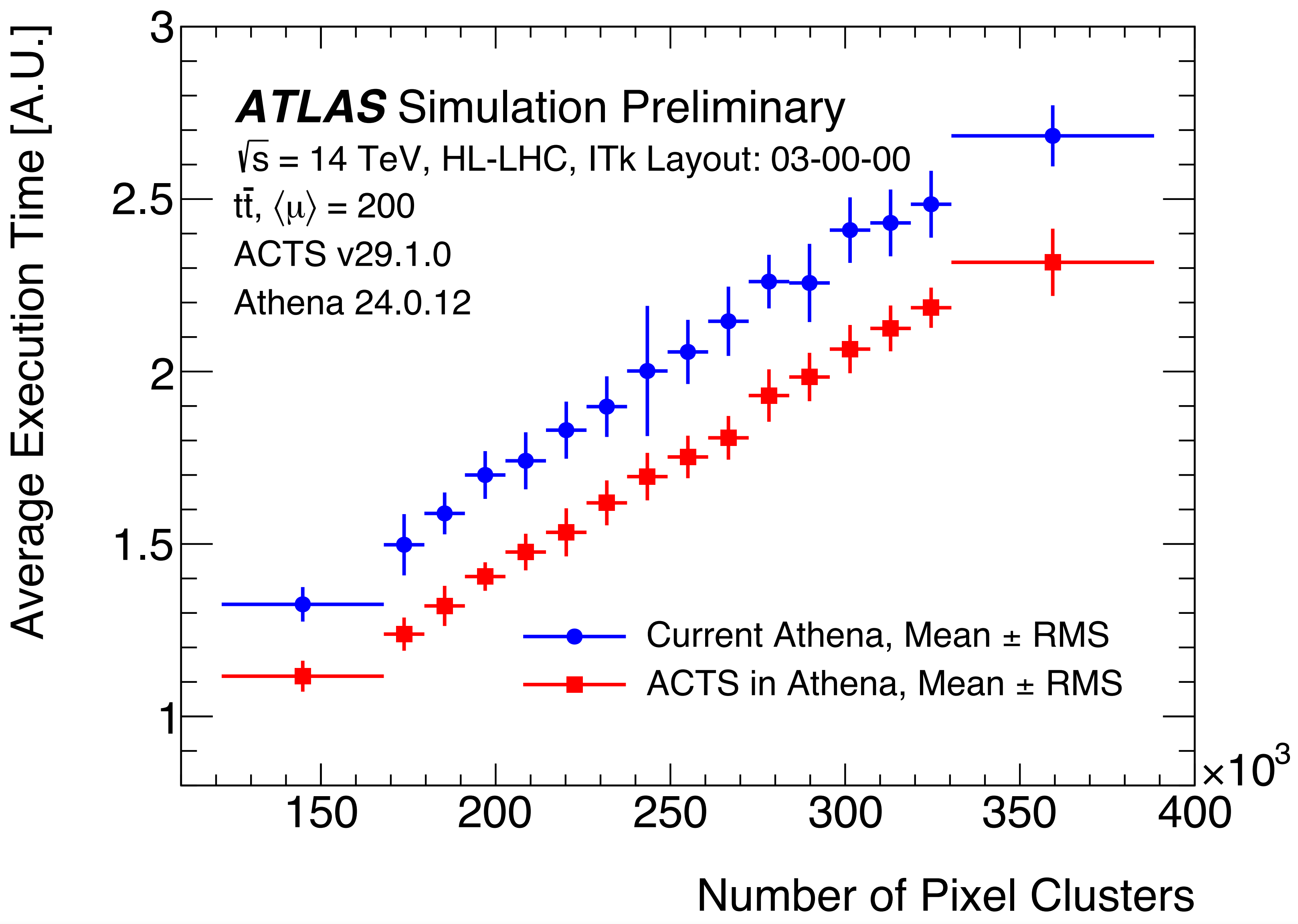
IDTR-2023-04
IDTR-2022-01

- For Run 4, **ATLAS tracking reconstruction software** CERN-LHCC-2022-005 to be updated to use **detector-generic software library** ACTS
  => aims at reproducing **current tracking performance** with **optimised implementation**

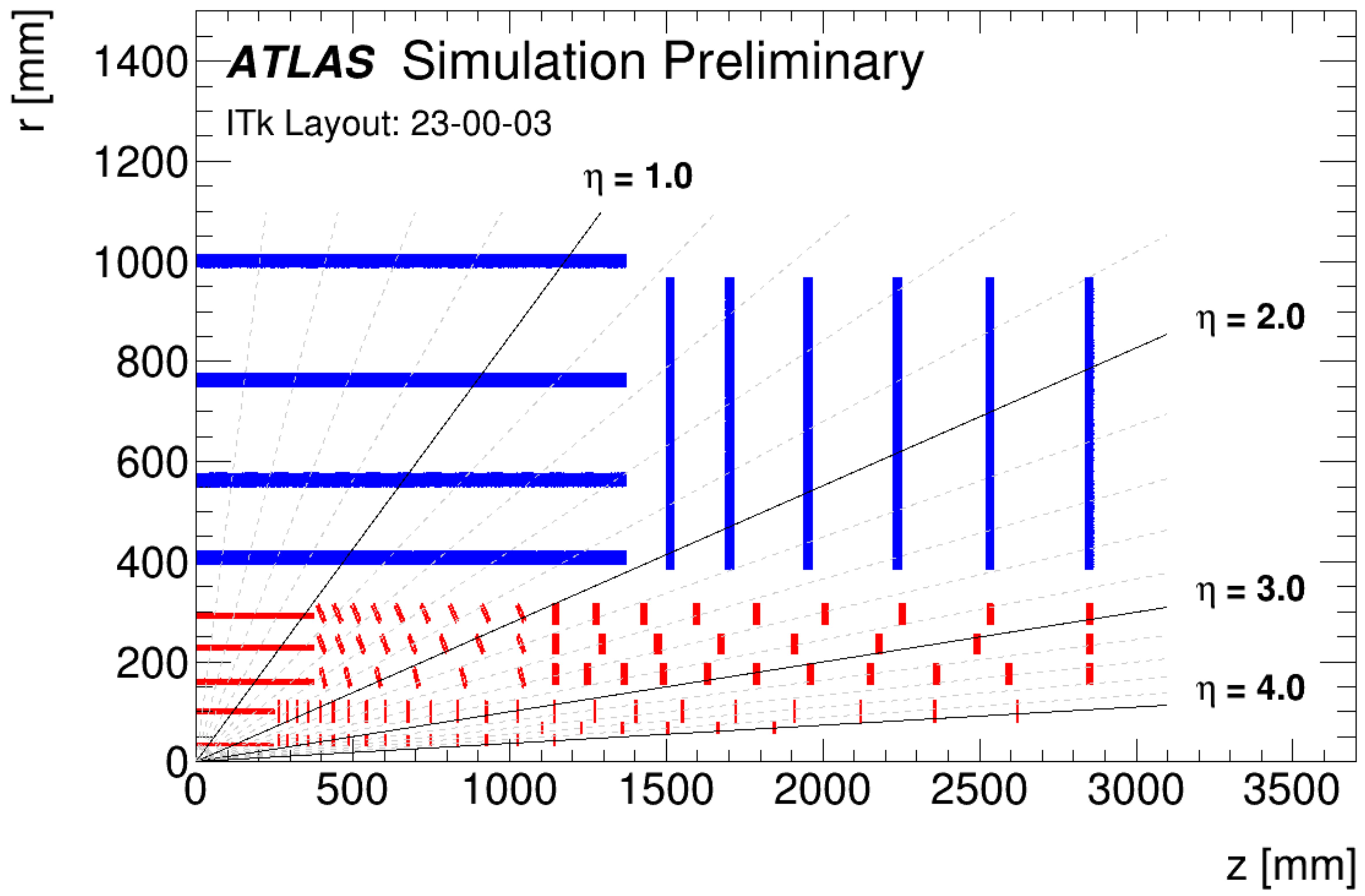


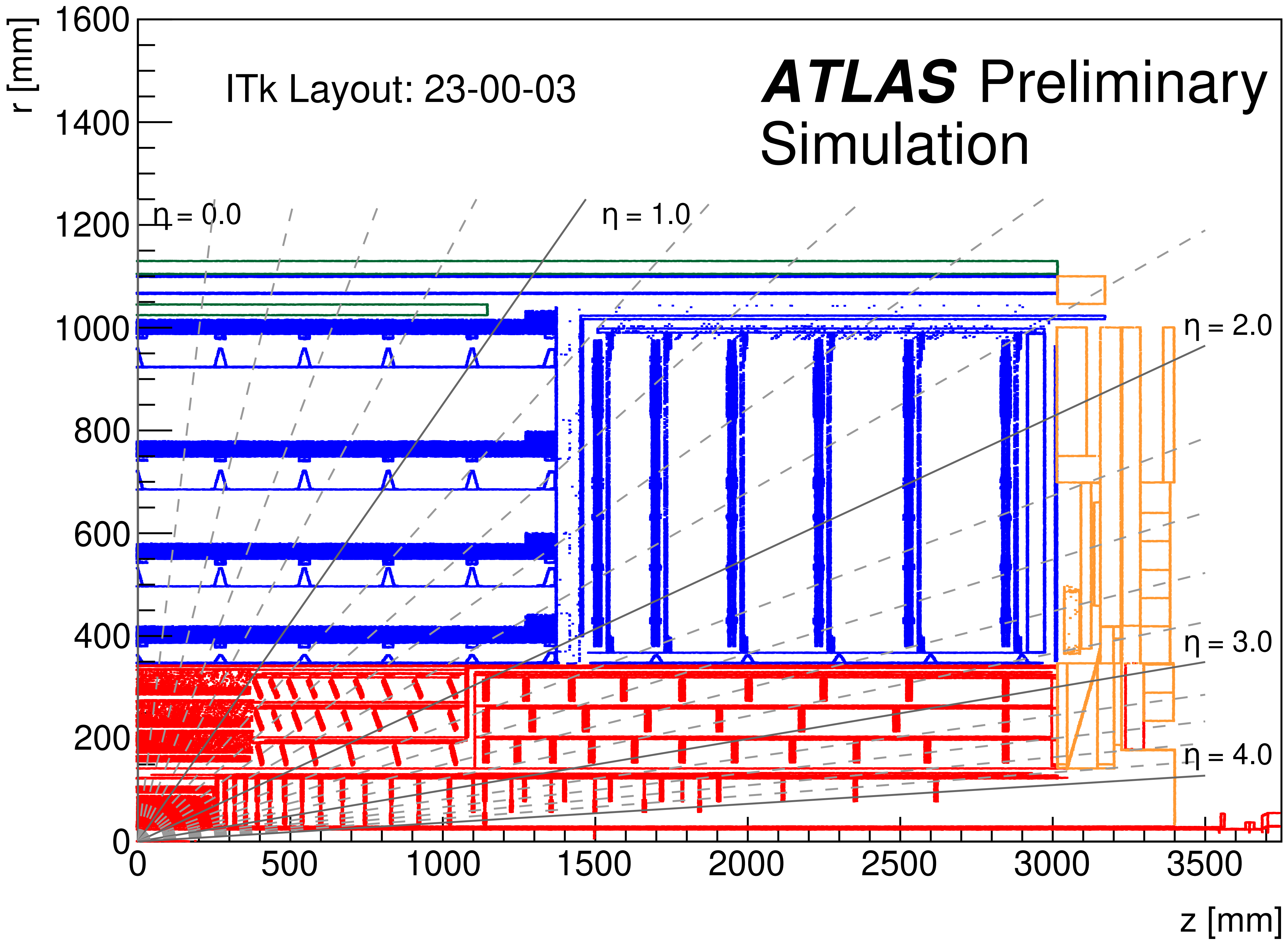
- Will thus benefit from:
  - **optimised and efficient code design**, instrumental to fulfil Run 4 CPU constraints
  - **improved maintainability**
  - **modularity** to investigate **machine-learning-based approaches for track reconstruction**



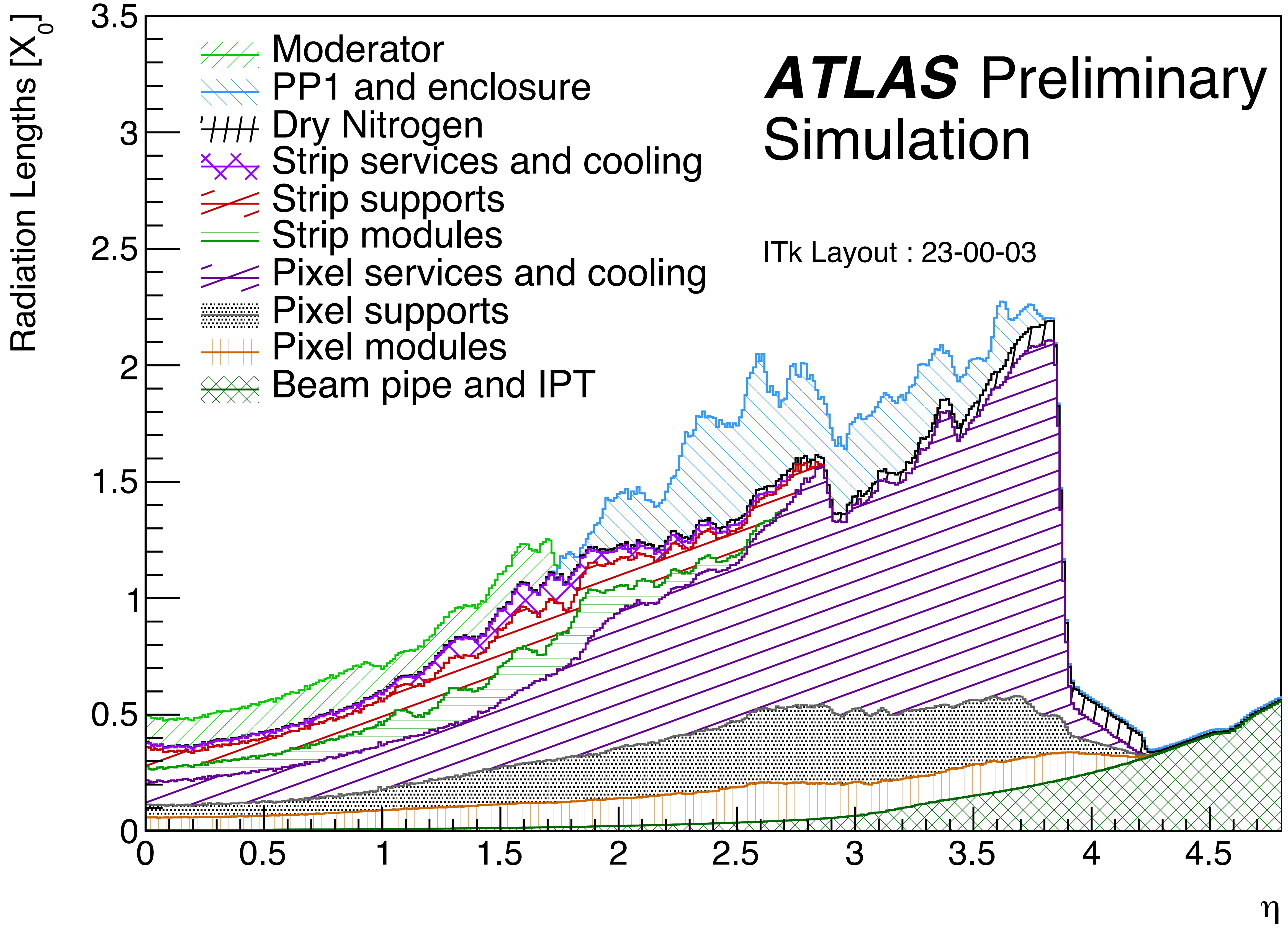


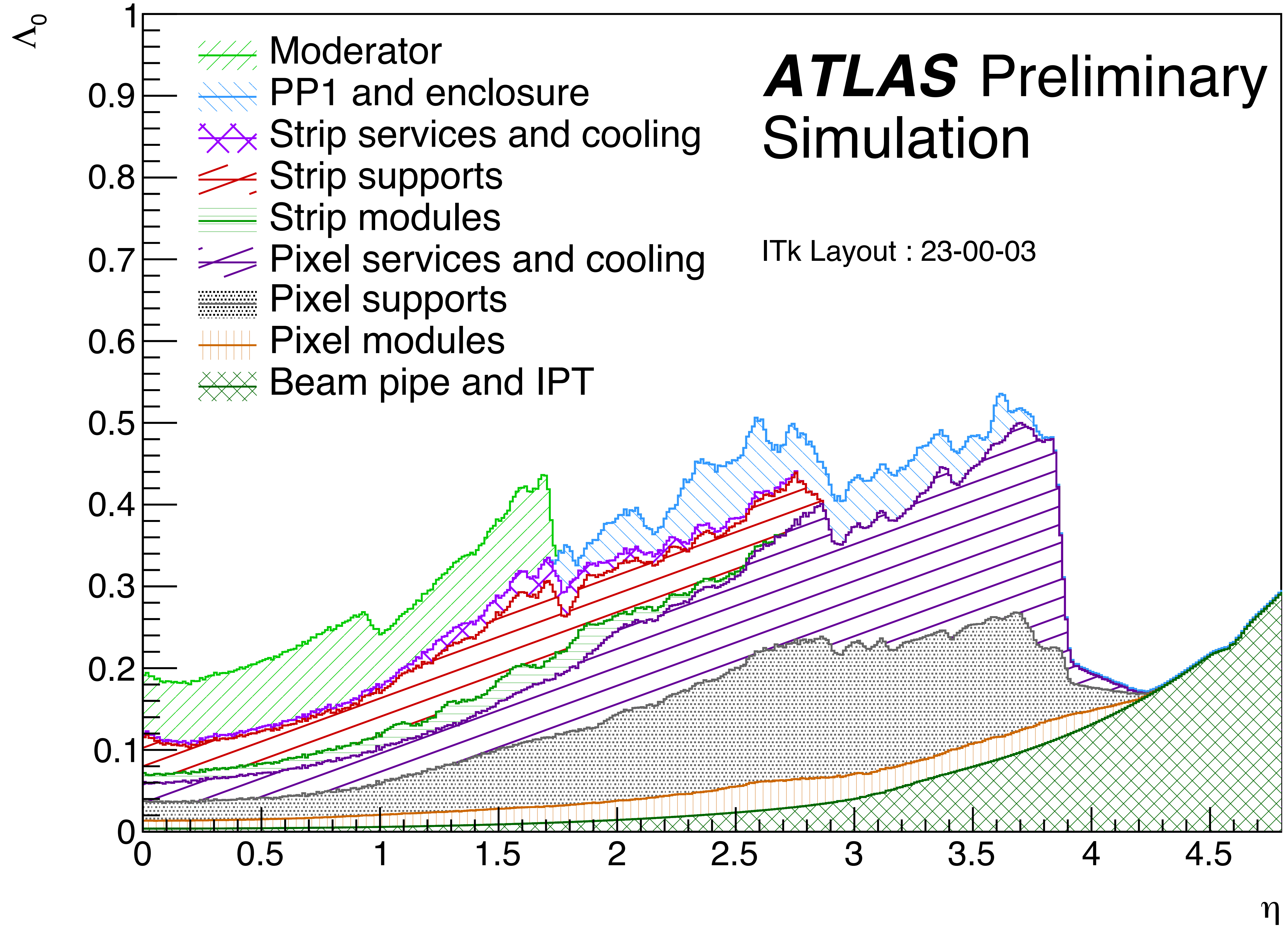
ATLAS Phase-II Inner Tracker upgrade





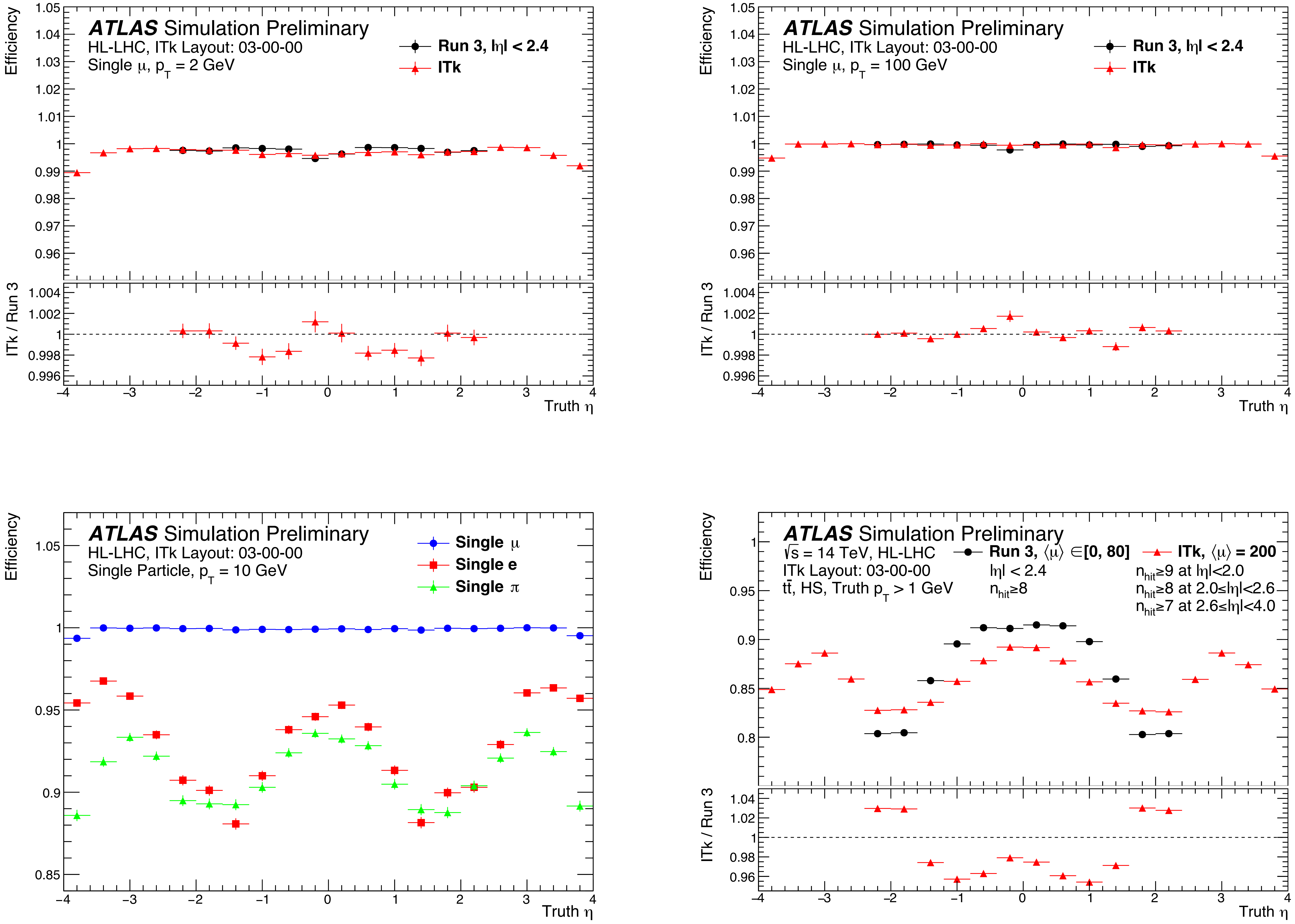
ATLAS Phase-II Inner Tracker upgrade





Tracking efficiency and fake rate

IDTR-2023-05



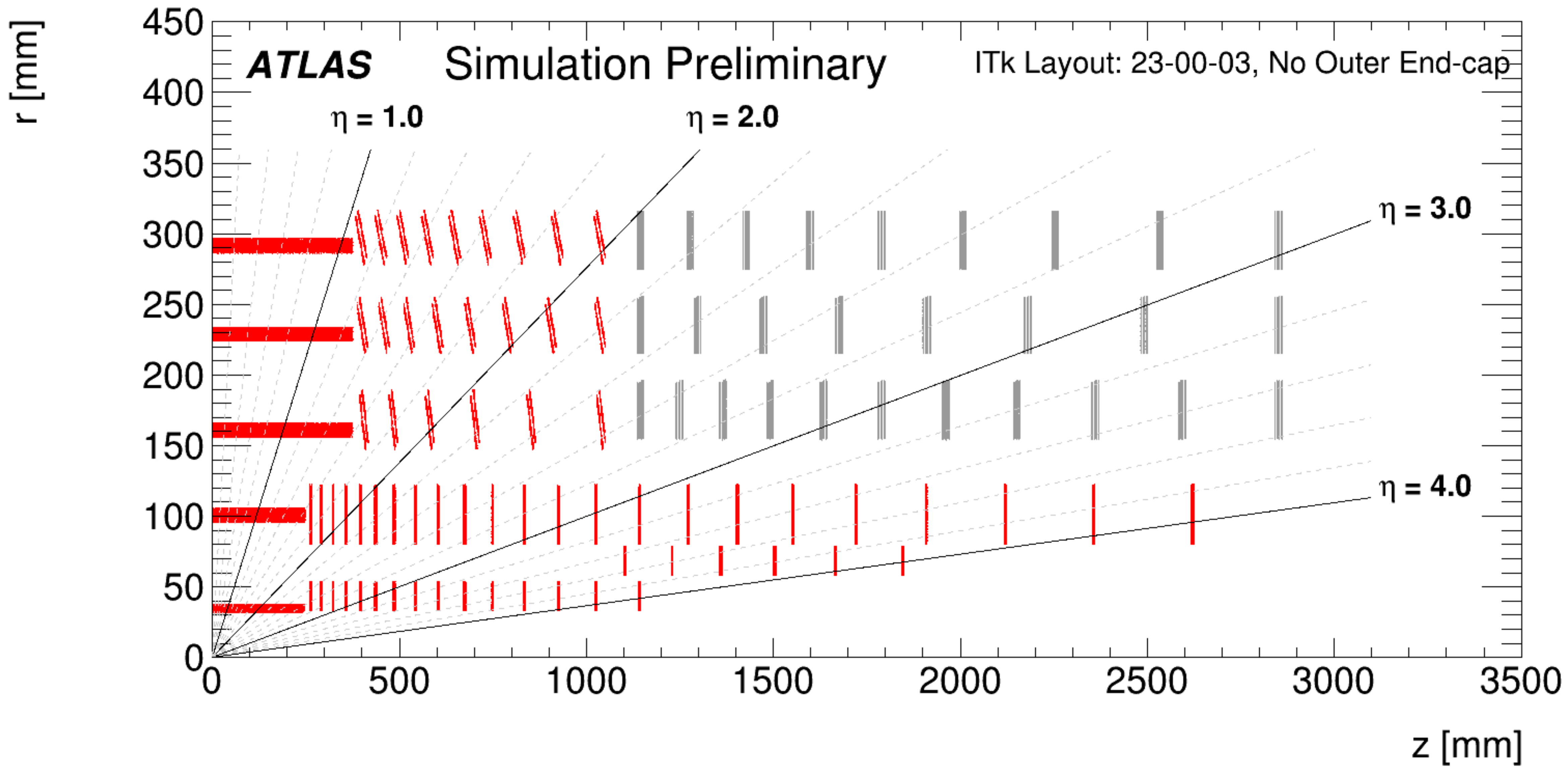
Tracking resolutions

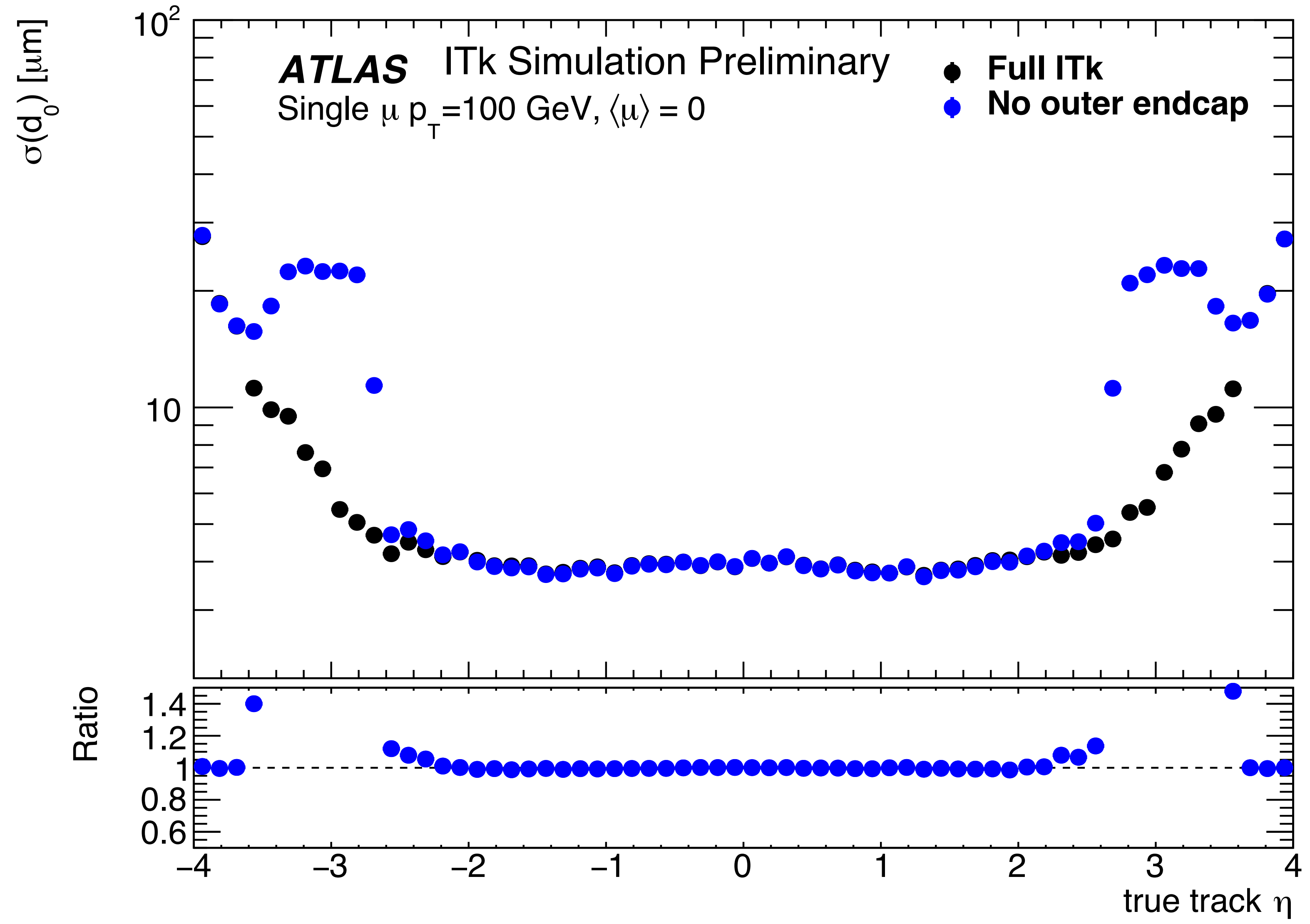
ATL-PHYS-PUB-2021-024

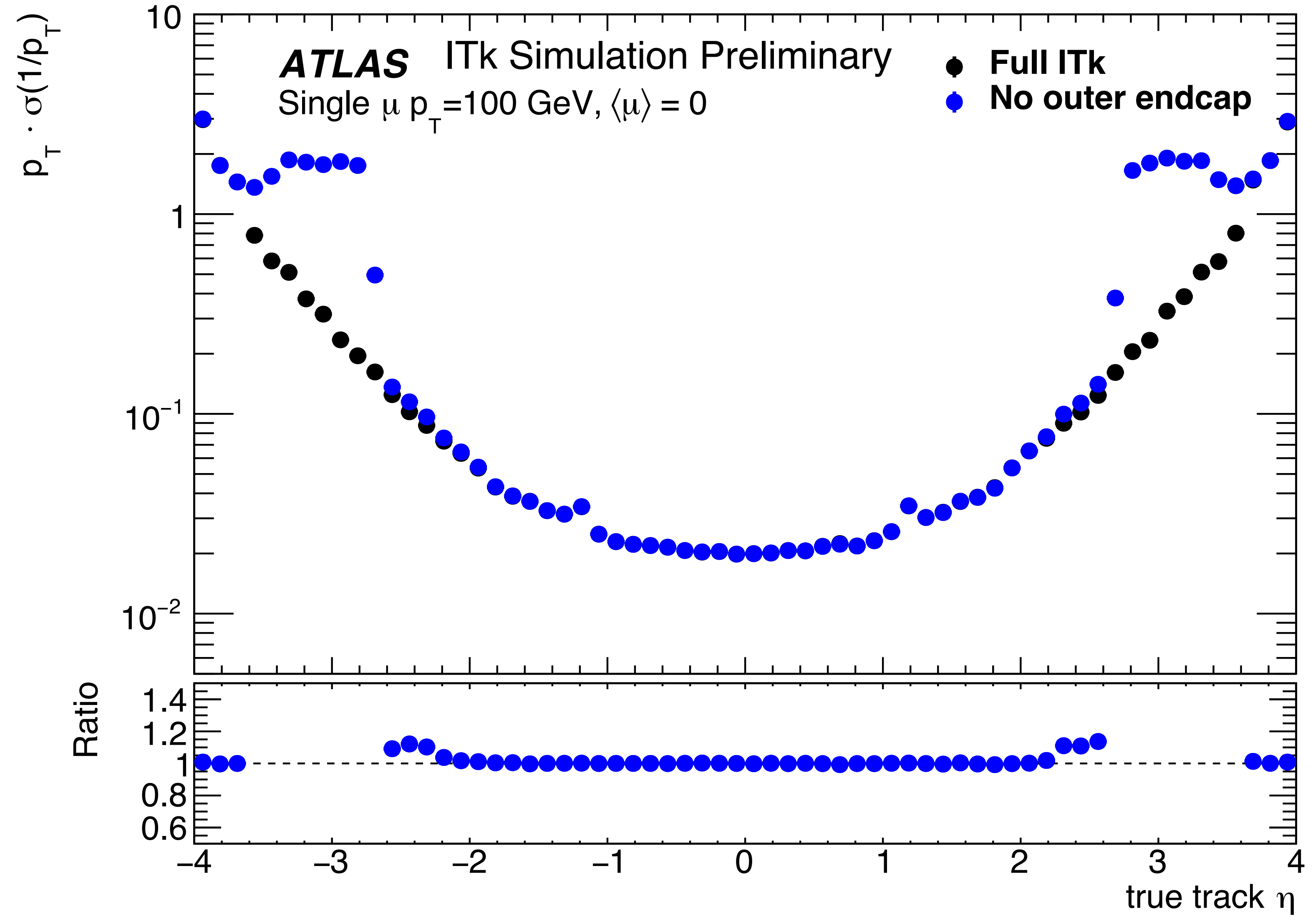
Impact of ITk layout on tracking performance

ATL-PHYS-PUB-2021-040

- **No outer endcaps**



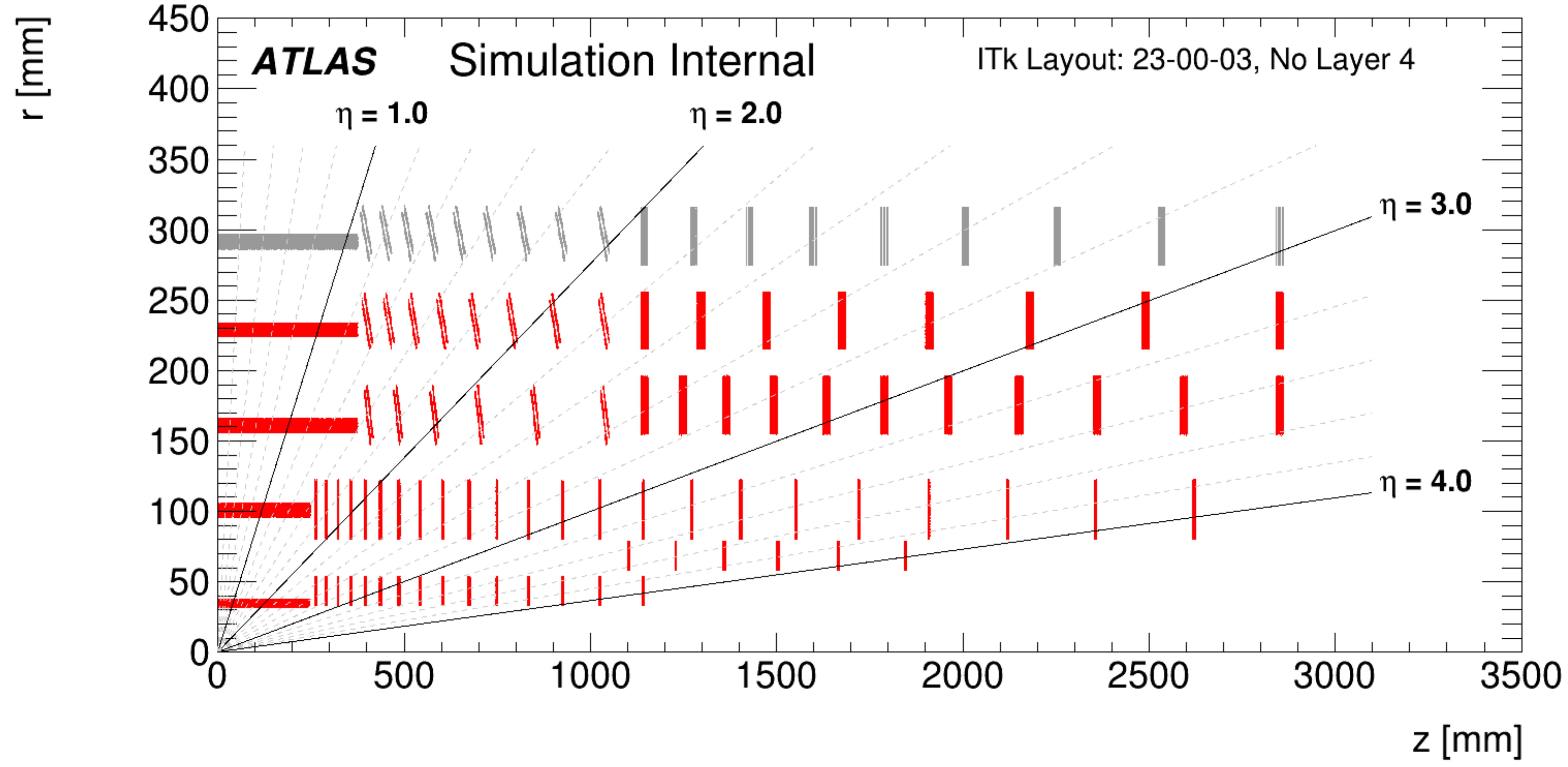


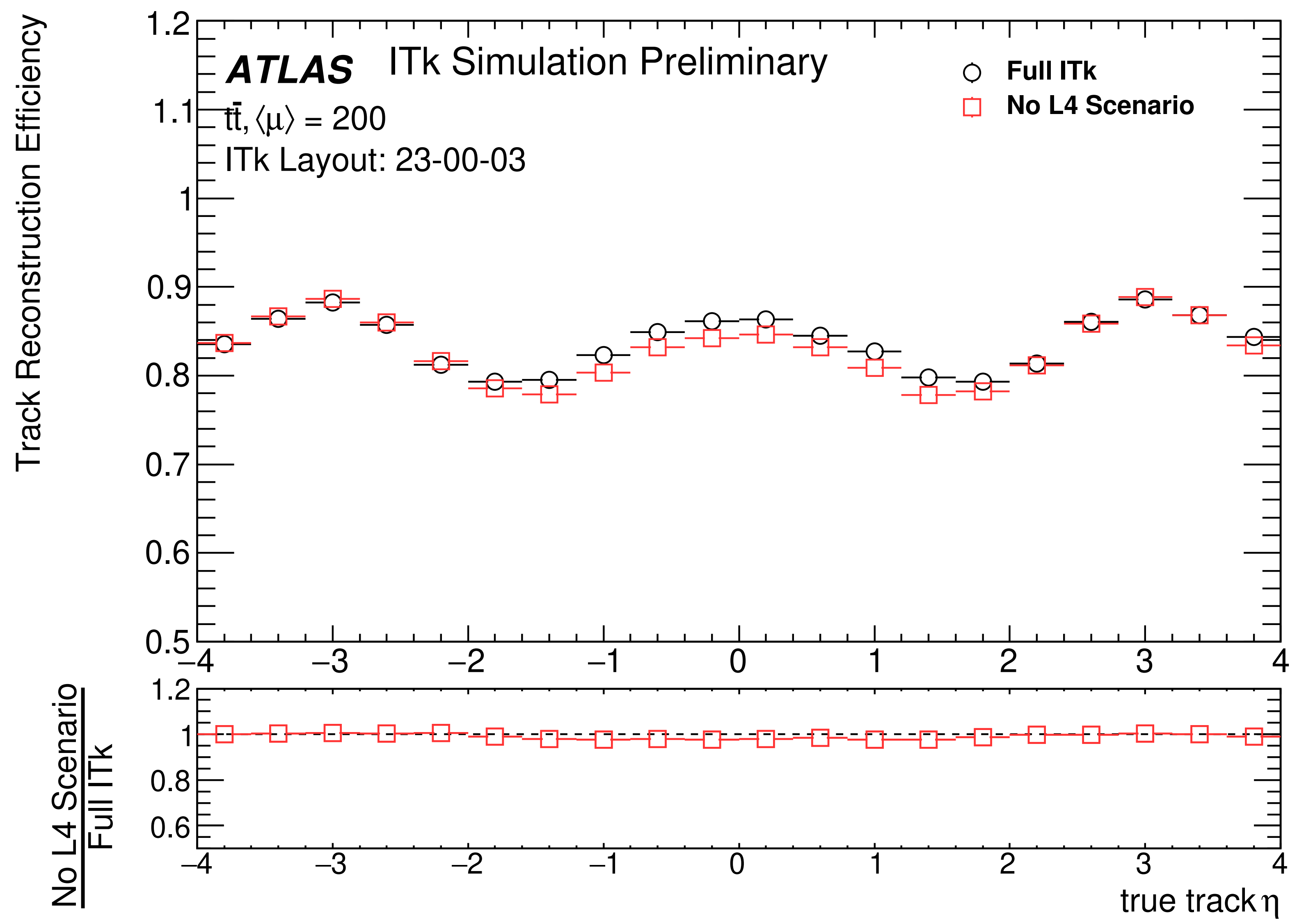


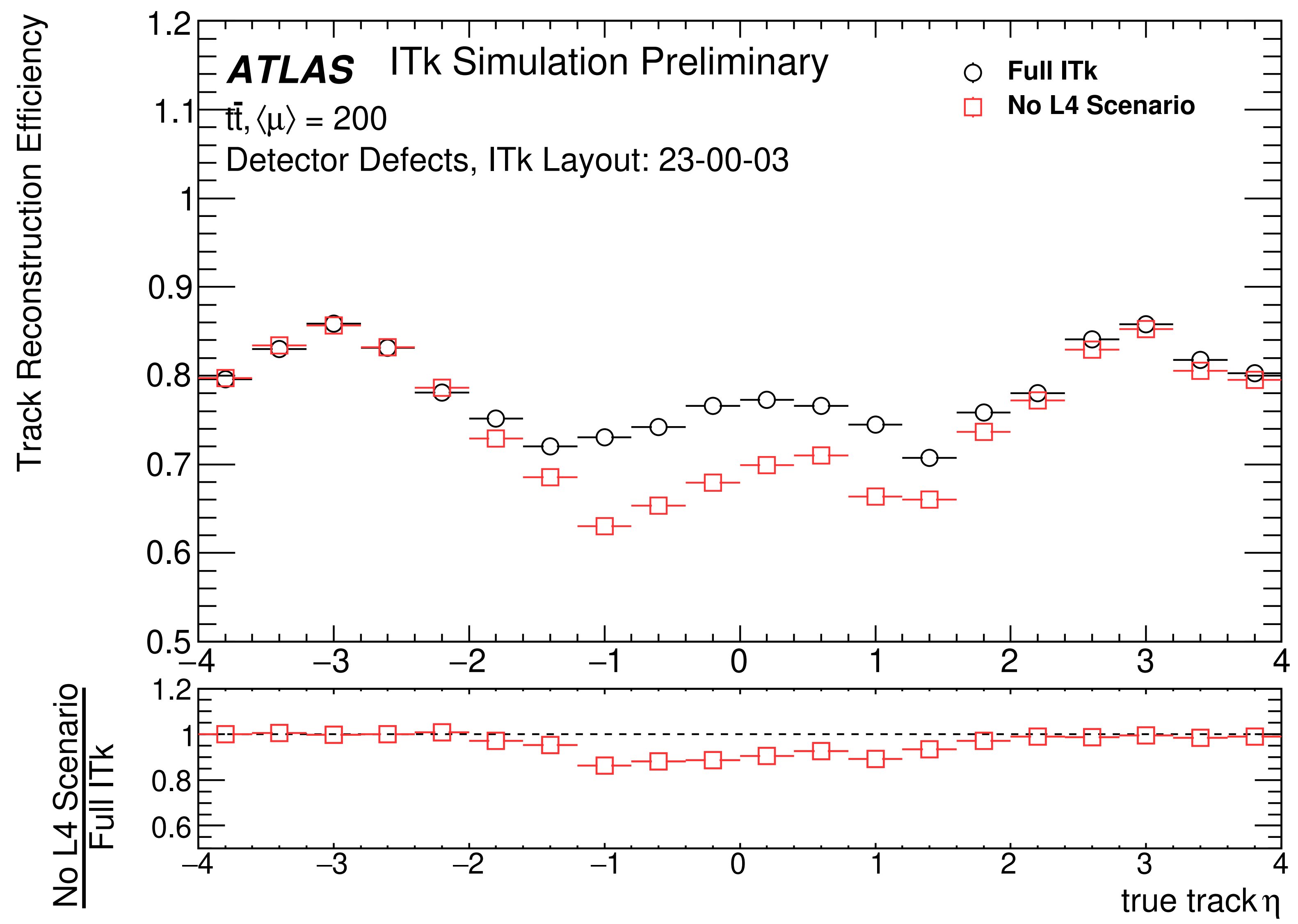
Impact of ITk layout on tracking performance

ATL-PHYS-PUB-2021-040

- **No outermost layer**

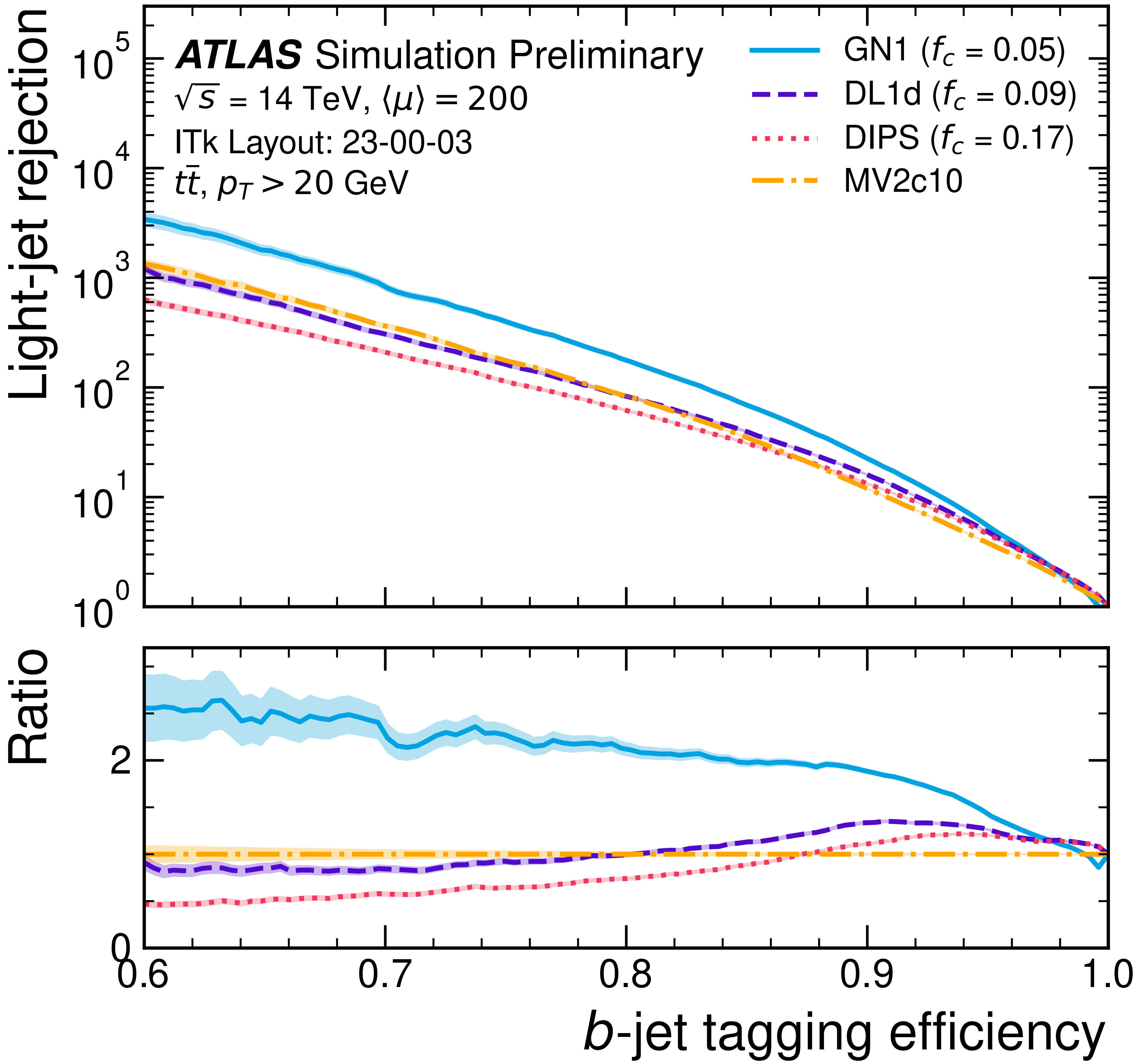


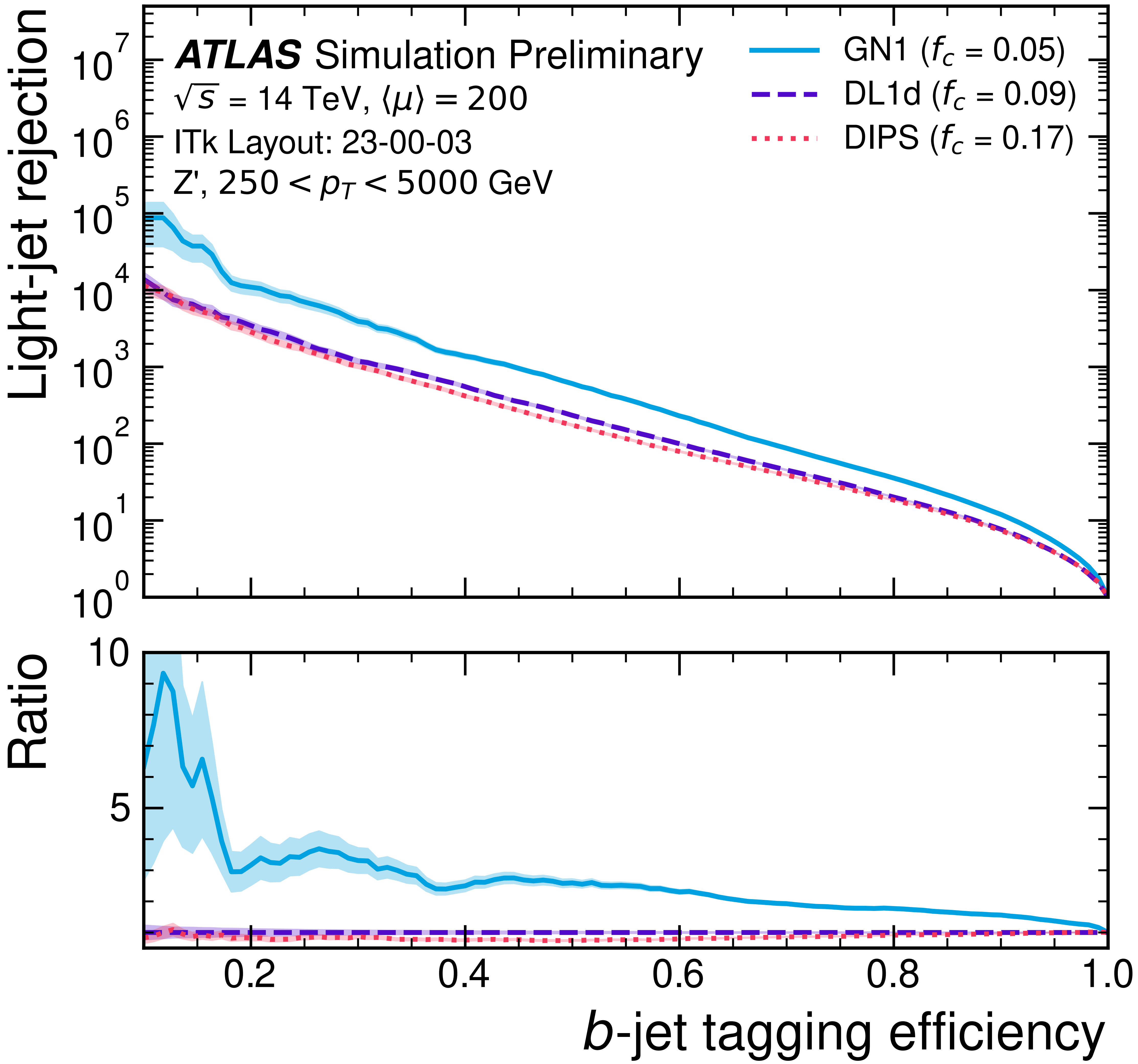




Jet tagging performance

ATL-PHYS-PUB-2022-047





Jet tagging performance

ATL-PHYS-PUB-2022-047