Tracking Performance with the HL-LHC ATLAS Detector

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On behalf of the ATLAS Collaboration

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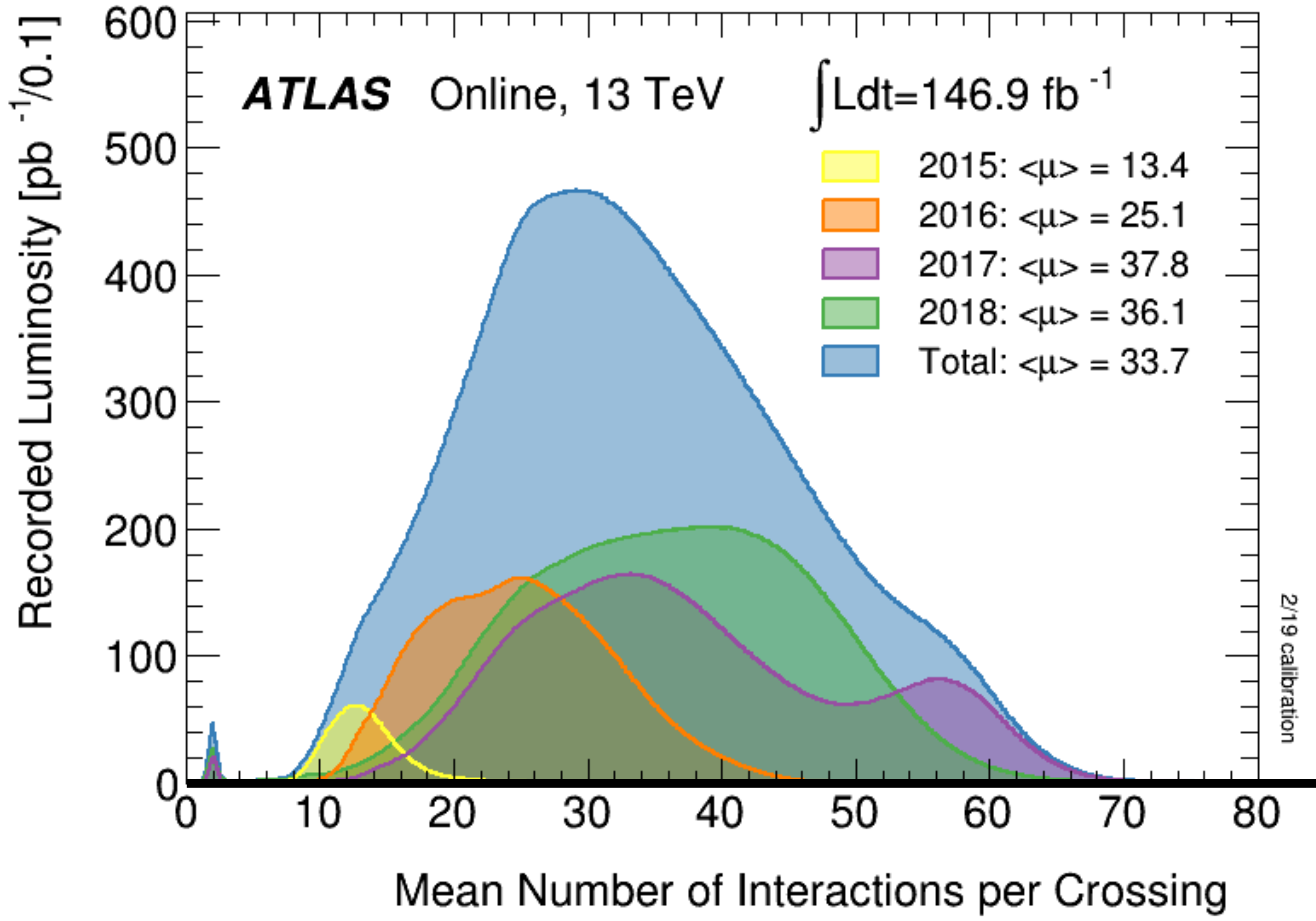
High Luminosity LHC

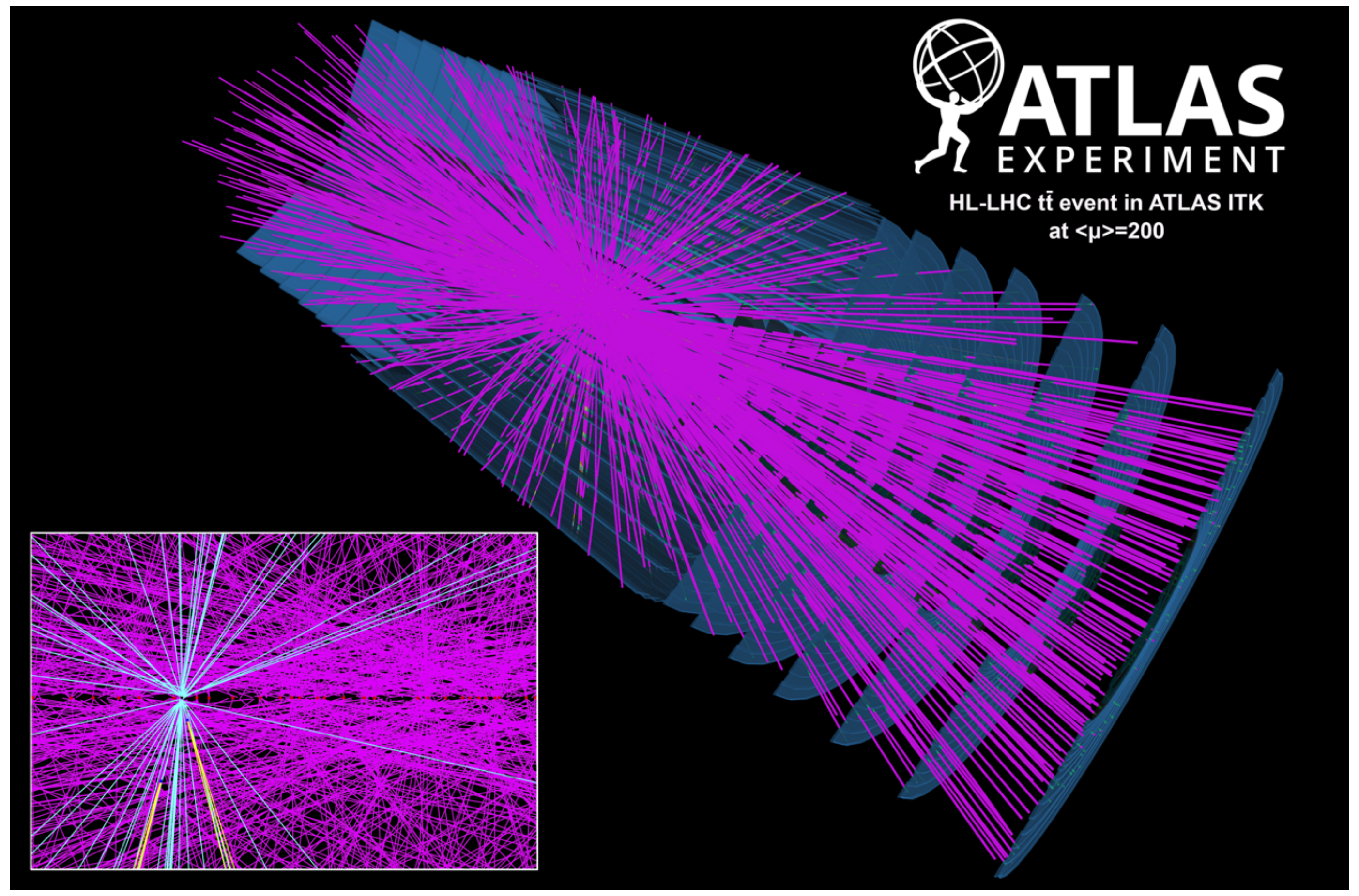
- The future of the **Large Hadron Collider** is **high luminosity** → **HL-LHC**
  - **Center-of-mass energy** of 14 TeV
  - **Instantaneous luminosity** up to 7.5×10^{34} cm^{-2}s^{-1}
  - **Integrated luminosity** up to 4000 fb^{-1} (over decade-long program)
  - **Average pile-up** of $\langle \mu \rangle$ = 200 (*p-p* interactions per bunch crossing)
- **ATLAS** must be **upgraded** to maintain high performance requirements in **challenging HL-LHC environment**

Run 2



Average Pile-up

HL-LHC



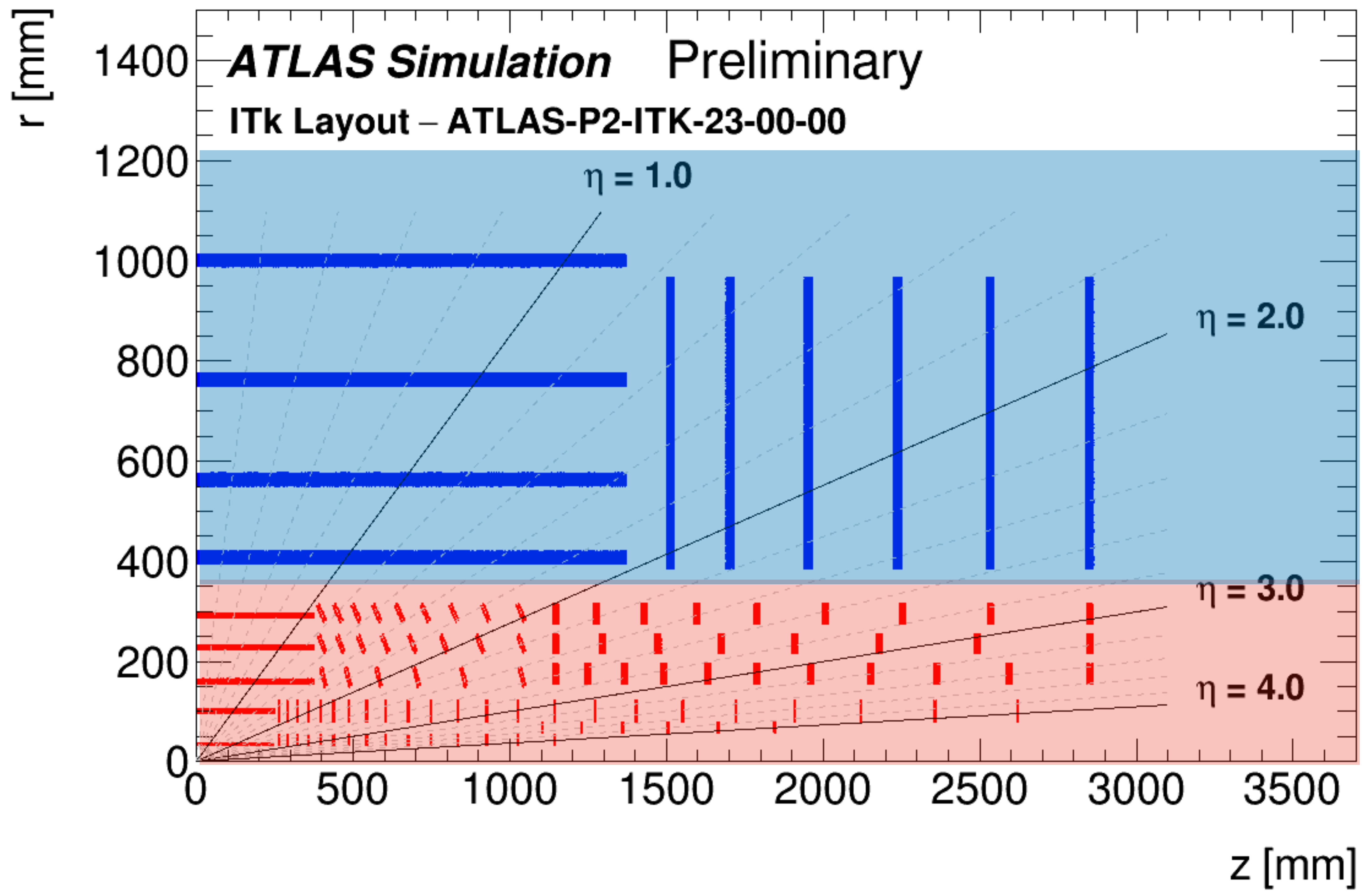
$\langle \mu \rangle$ = 200

The ATLAS Inner Tracker (ITk)

- **Complete replacement** of current **ATLAS Inner Detector** for the **HL-LHC**
- **Finer granularity** and **improved radiation hardness** to cope with high fluences
- Extended **forward pseudo-rapidity coverage** for increased tracking acceptance
- **All-silicon** design consisting of **inner pixel** and **outer strip sub-detectors**

See more related ICHEP talks!
- ITk Pixel (Stefano Terzo)
- ITk Strip (Dennis Sperlich)

- **Strip subsystem covering** $|\eta| < 2.7$
  - **4 Barrel layers**
  - **6 End-cap** disks
- **Pixel subsystem covering** $|\eta| < 4.0$
  - **5 Barrel** layers + **Inclined** modules
  - **Barrel** + **End-cap** rings
- Nominal **pixel pitch** of $50 \times 50\ \mu m^2$ and **innermost barrel layer (L0) radius** of 39 mm
  - Alternative pixel pitch of $25 \times 100\ \mu m^2$ also studied
  - New baseline **L0** of 34 mm and **R0** of 33.2 mm

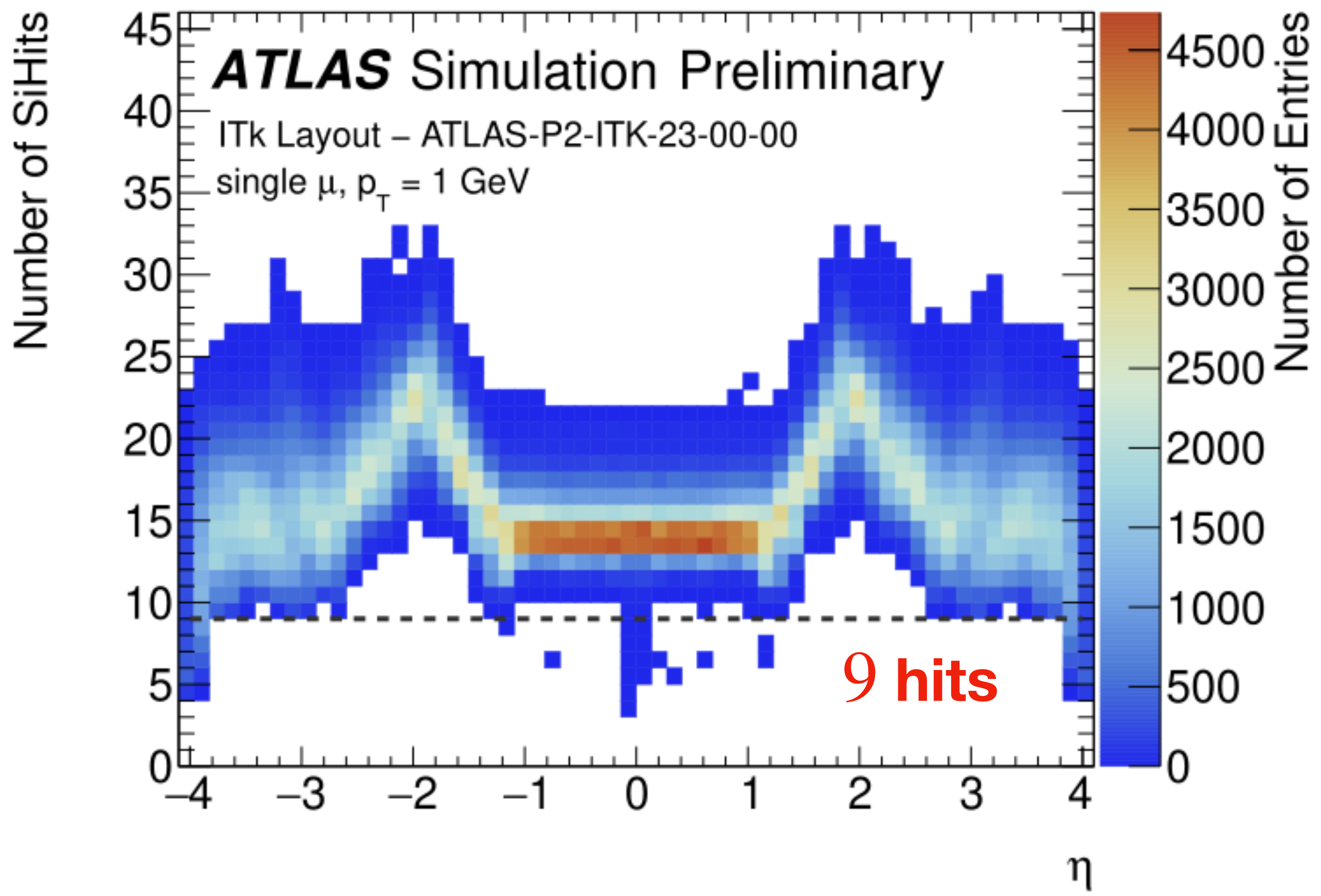


The ATLAS Inner Tracker (ITk)

- ITk layout designed to guarantee **heremetic coverage** within $|\eta| < 4.0$
  - Provides ≥ 9 hits for all particles with $p_T > 1$ GeV and $|z_{\text{vertex}}| < 150$ mm
- Allows for **tighter track selections** without compromising reconstruction efficiency
- Maintain **high efficiencies** and a **low fake rate** in dense environments

Run-2 Inner Detector (Run-2 ID)

- **Silicon Pixel** Detector
- **Strip Semiconductor** Tracker
- Outer **Transition Radiation Tracker**
- Coverage of $|\eta| < 2.5$
- Innermost layer radius of 33 mm
- Pixel pitch of $50 \times 250\ \mu\text{m}^2$ in innermost layer

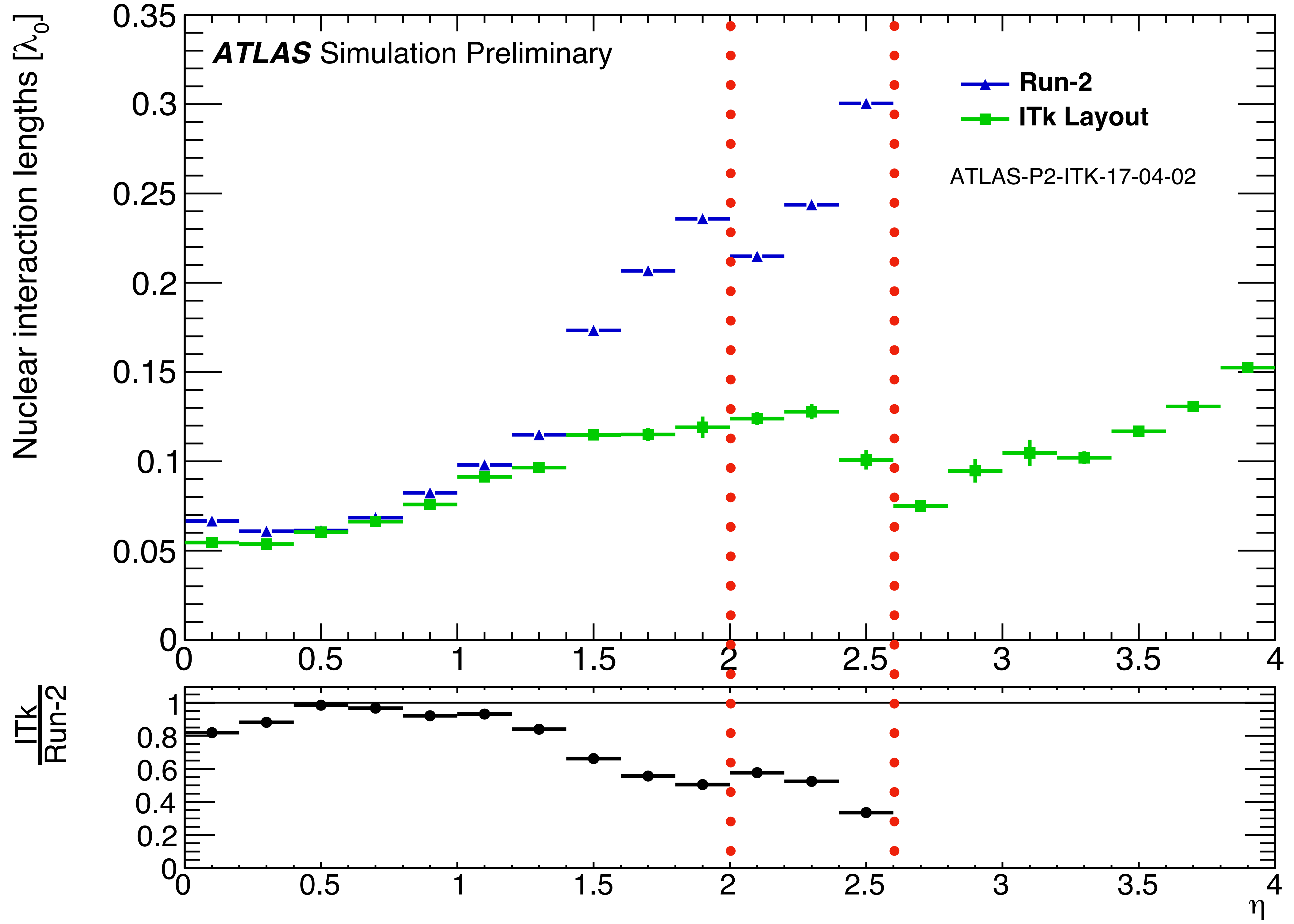


ITk Material Budget

- Greatly reduced forward material budget of **ITk**, up to $50\,\%$ reduction versus **Run-2 ID**
  - **Minimize effects of multiple-scattering and energy losses before outer detectors**
- Fewer **nuclear interactions lengths** traversed before satisfying **minimum hit requirements**
  - **Tighter hit selections** for **ITk**, compared to flat cut of ≥ 7 silicon hits for **Run-2 ID**

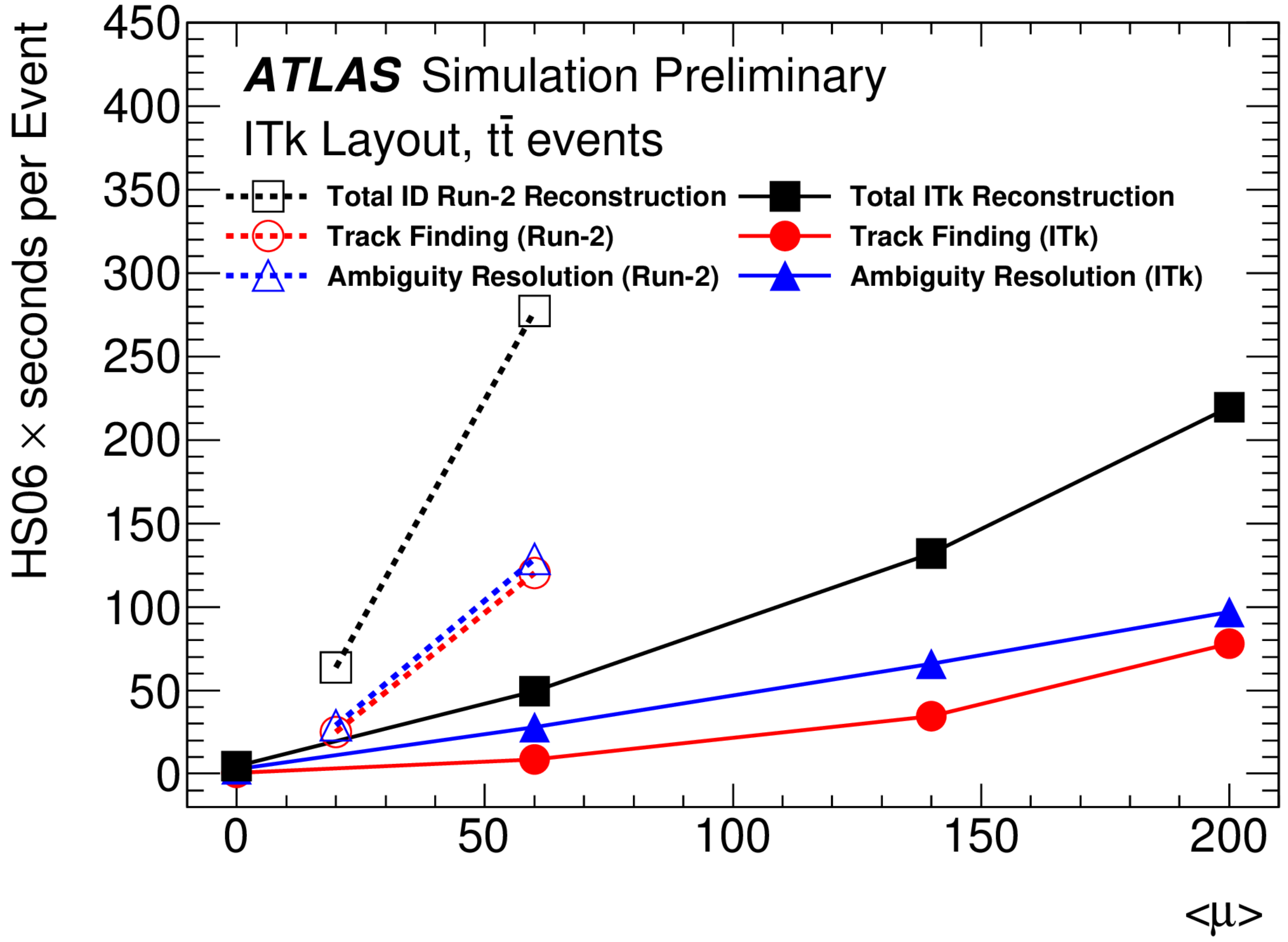
ITk Reconstruction

Requirement	Pseudorapidity interval		
	$\lvert\eta\rvert < 2.0$	$2.0 < \lvert\eta\rvert < 2.6$	$2.6 < \lvert\eta\rvert < 4.0$
pixel+strip hits	≥ 9	≥ 8	≥ 7
pixel hits	≥ 1	≥ 1	≥ 1
Holes	< 2	< 2	< 2
p_{T} [MeV]	> 900	> 400	> 400
$\lvert d_0\rvert$	≤ 2 mm	≤ 2 mm	≤ 10 mm
$\lvert z_0\rvert$	≤ 20 cm	≤ 20 cm	≤ 20 cm



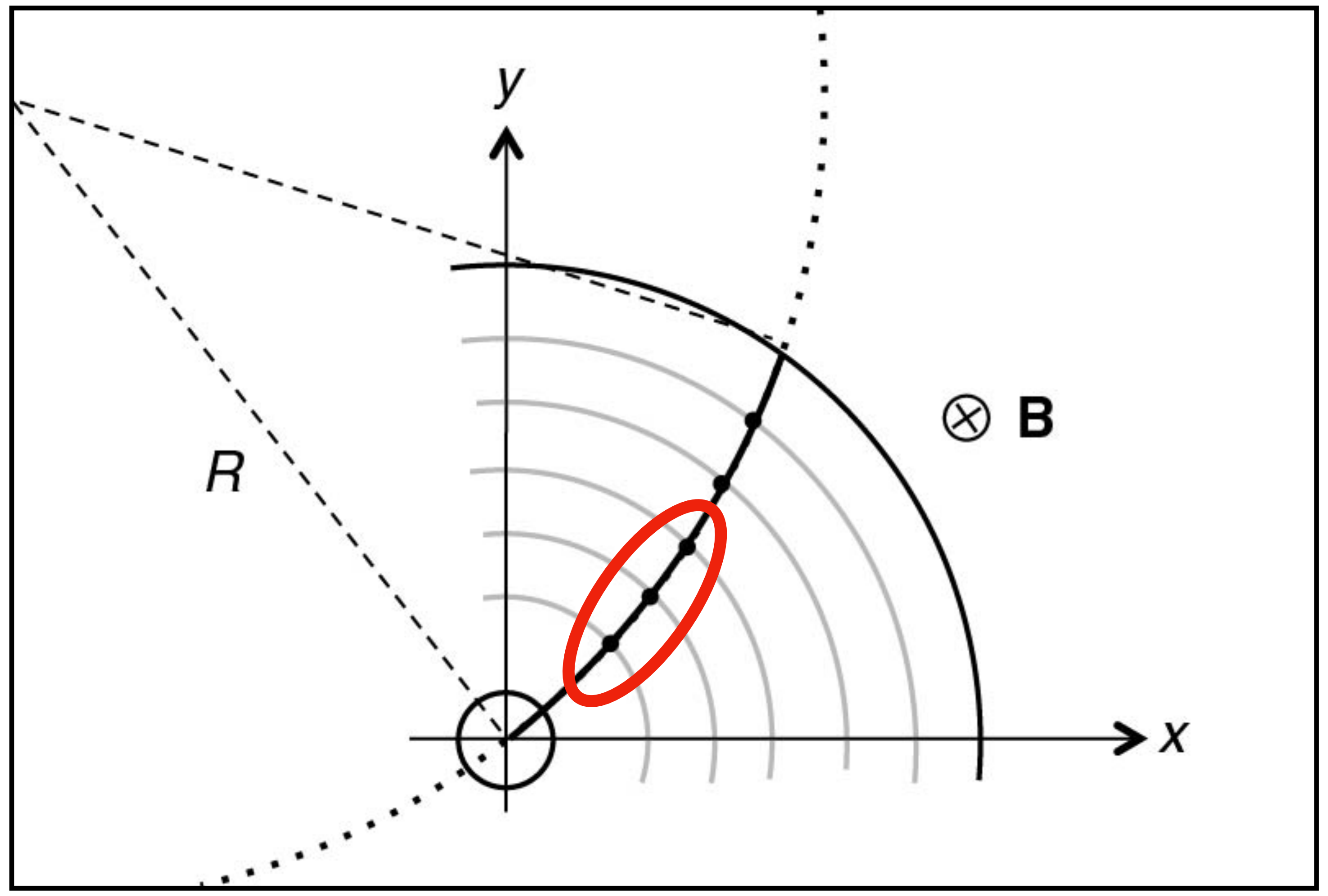
Reconstruction Overview

- ITk design and reconstruction is **optimized** for **track-dense HL-LHC conditions**
  - **Reconstruction at $\langle\mu\rangle = 200$ is faster than Run-2 ID at $\langle\mu\rangle = 60$**
  - **Decreased scaling with pile-up**
- Further improvements done and still ongoing to speed up the algorithms



Seeding

- ***Cluster*** formation from adjacent channels with a hit
- Search for hit triplets of 3 space points (***seeds***)
  - Must be compatible with helical track model
  - Satisfying minimum p_T and *IP* requirements



Track Finding

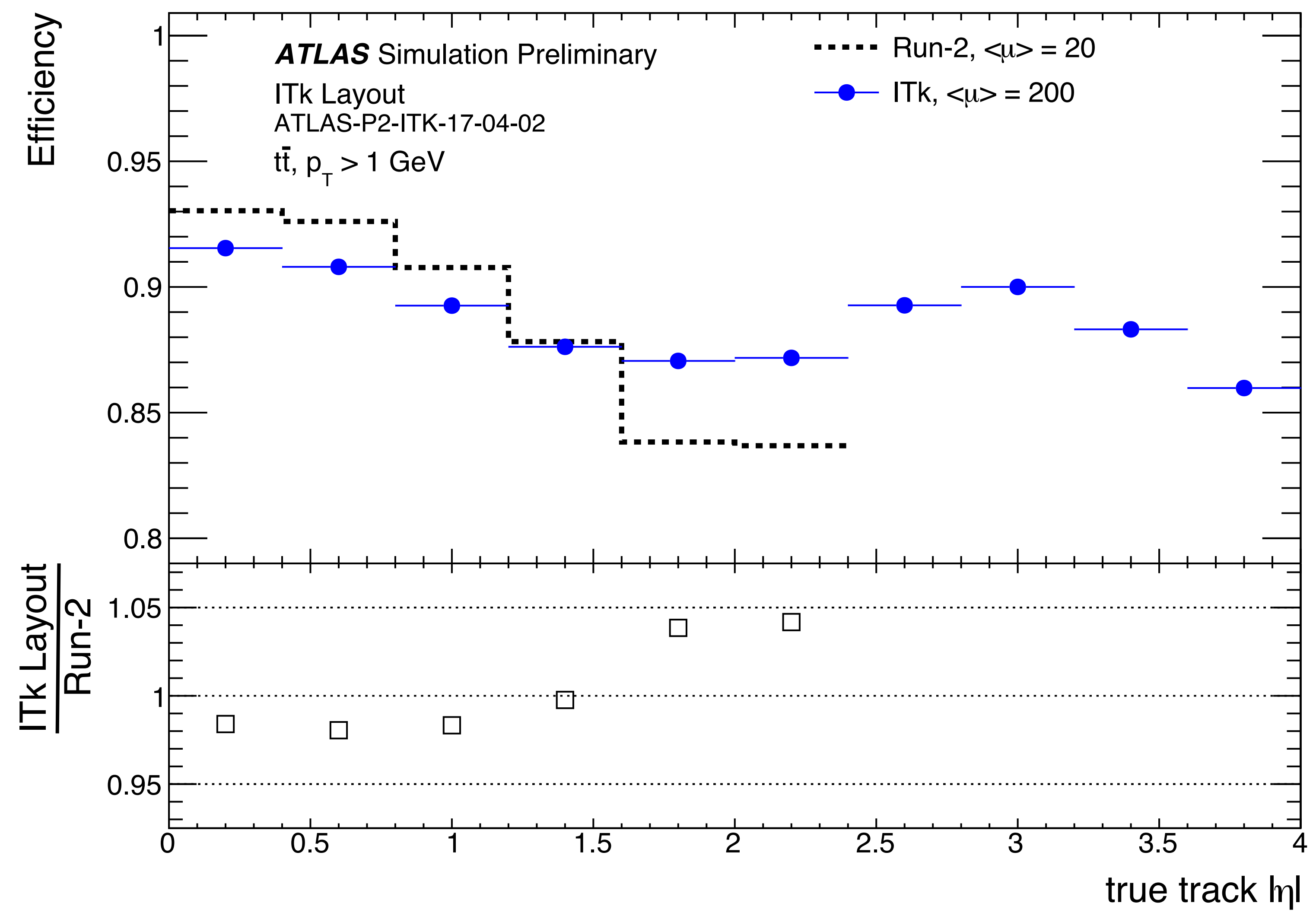
- Combinatorial **Kalman filter** run over accepted ***seeds*** to find ***tracks***
- First **track-cluster** pairing

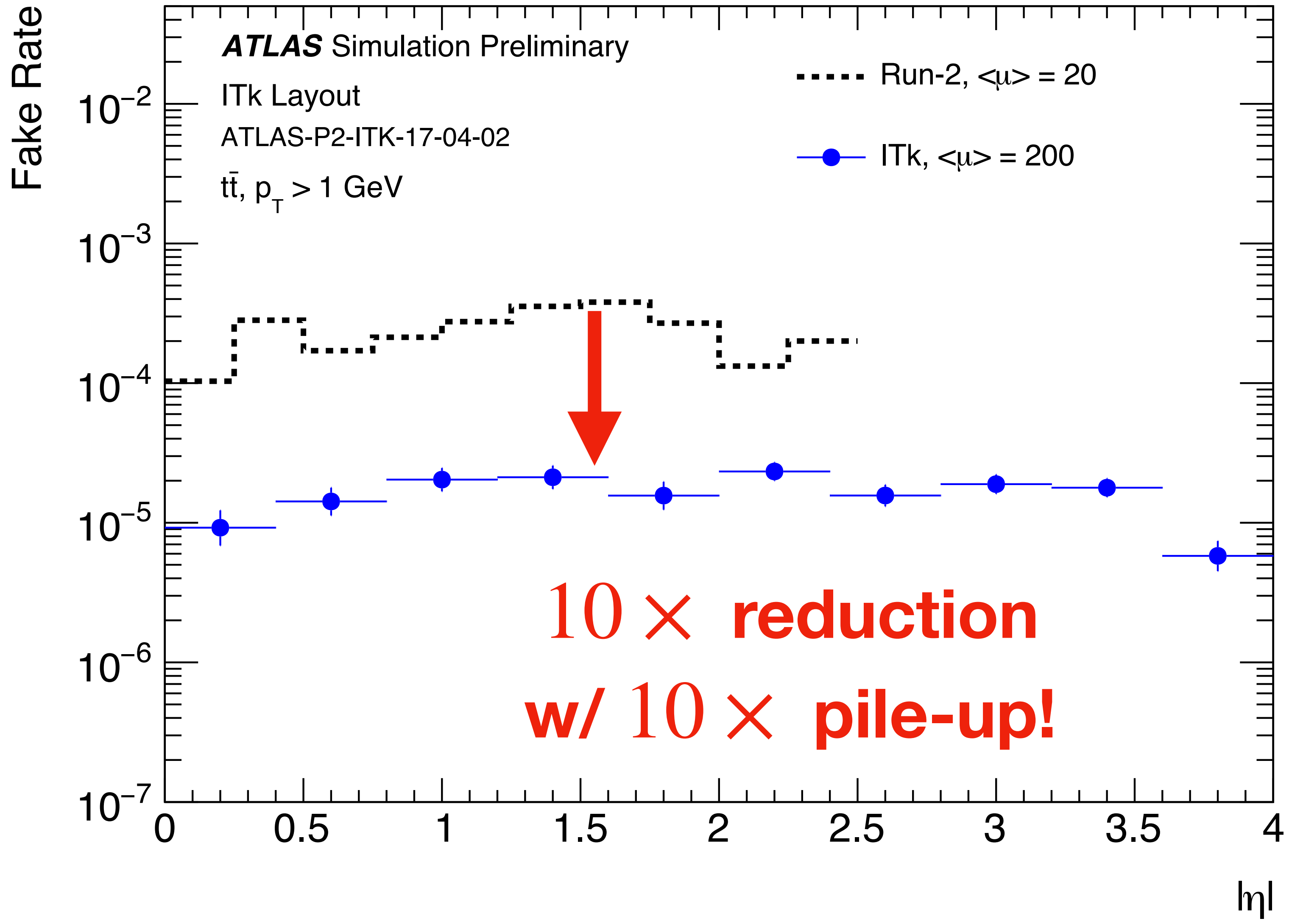
Ambiguity Resolution

- Tracks fitted using **global-χ^2** fit
- Final **track-cluster assignment** based on scoring algorithm of competing tracks

Efficiency & Fake Rate

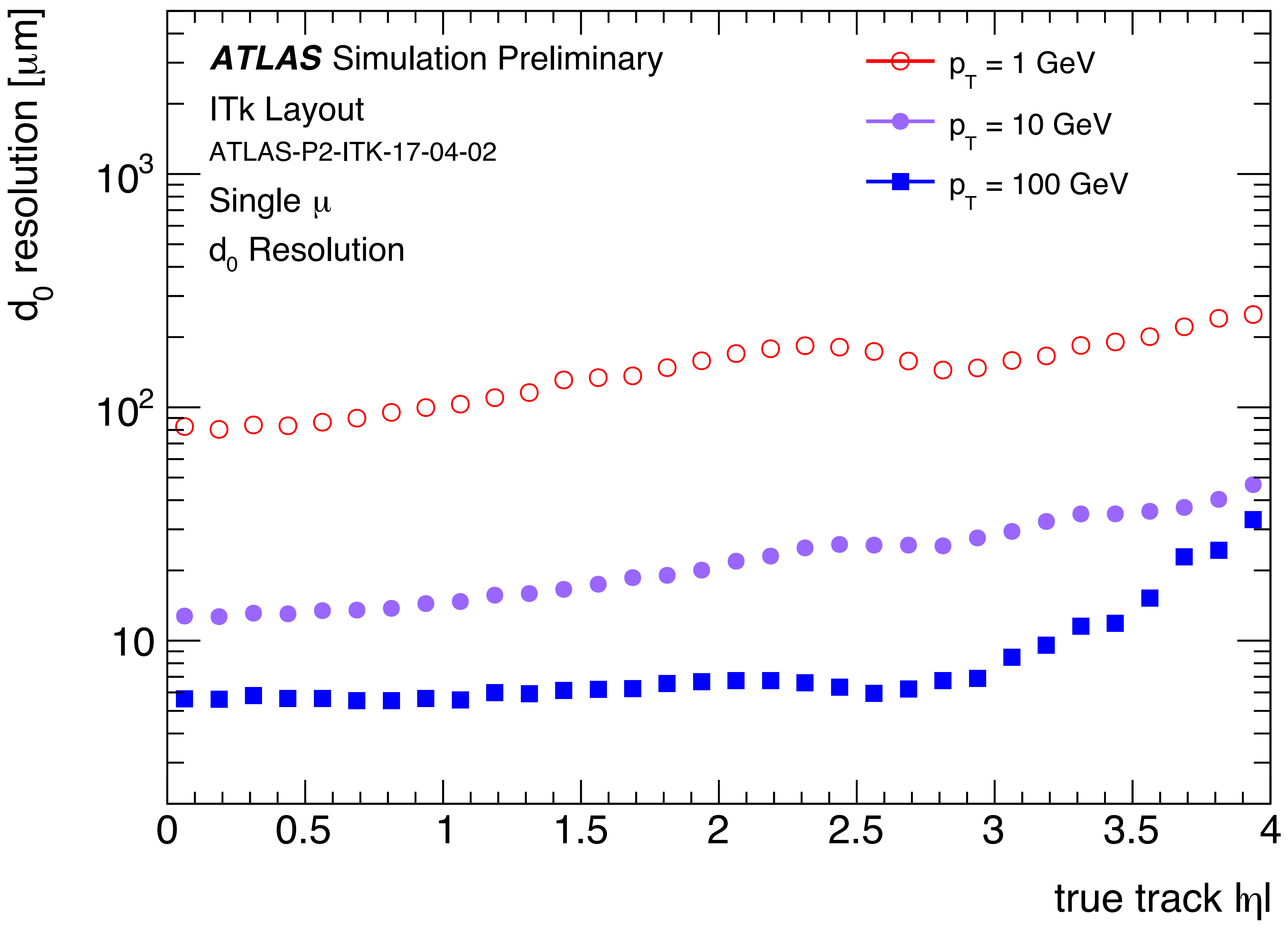
- **Efficiency** is the fraction of all **reconstructed true prompt particles**
  - Maintain **over 85%** efficiency up to $|\eta| = 4.0$
  - Comparable with Run-2 ID at $\langle\mu\rangle = 20$
- **Fake rate** is the fraction of all **reconstructed tracks unmatched** to a **true particle**
  - Excellent improvements over Run-2 ID, even with $10\times$ pile-up
- Overall significant improvements in forward region up to extent of Run-2 ID, plus extended coverage!
  - Reduced **material budget** → minimize material interactions
  - Increase in overall **hit counts** → tighter track selections
  - Improved **hermiticity** → more hits + fewer holes on track





Transverse IP Resolution

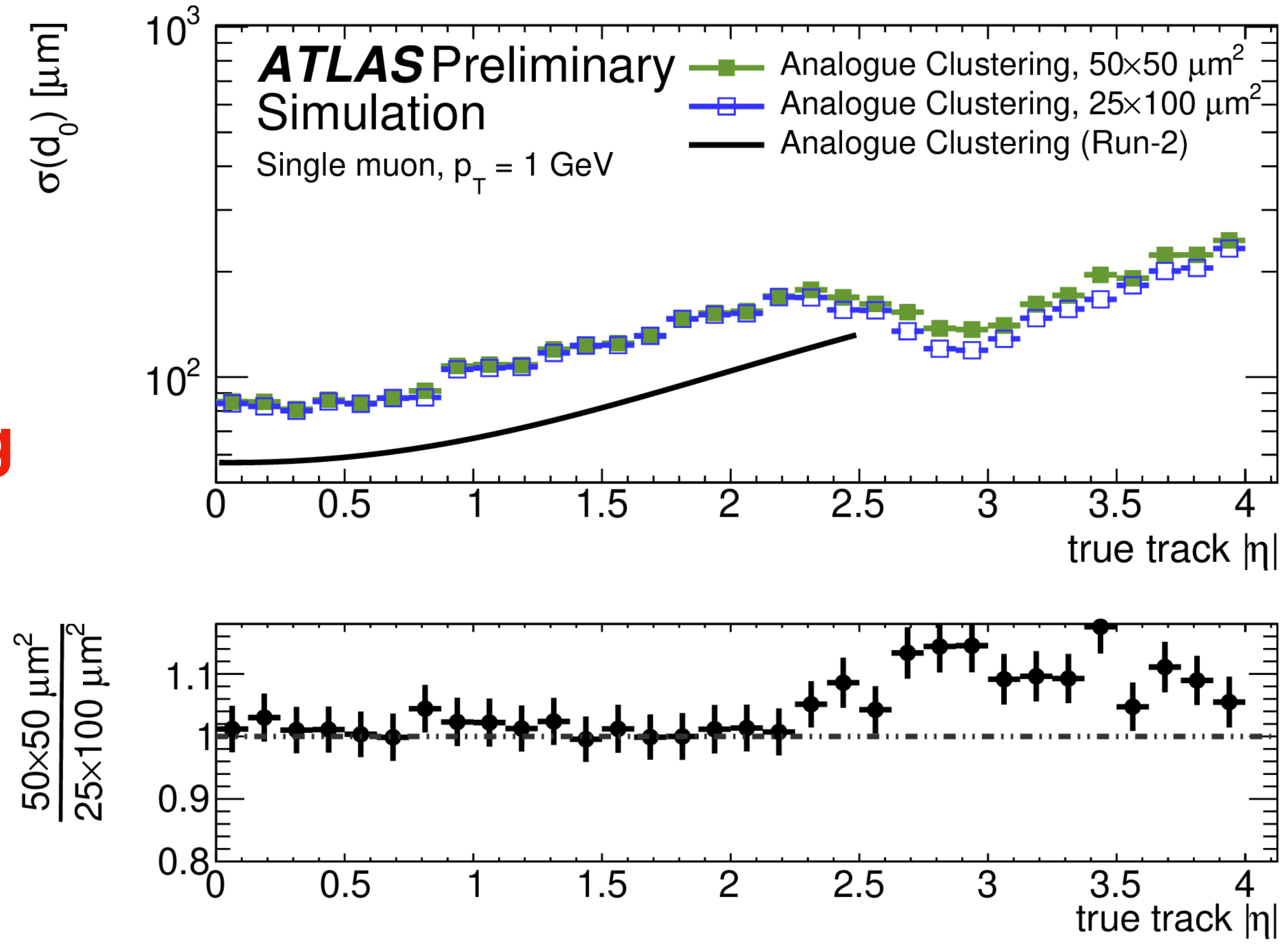
- Distance of a track's closest approach to the beam spot in the **transverse** xy-plane (d_0)
- **Comparable resolution** with Run-2 ID, with possibility to improve performance given layout optimization
  - **Pixel pitch** of $25 \times 100\ \mu m^2$ in **inner barrel layer**
  - Reduction of **inner pixel layer radius**

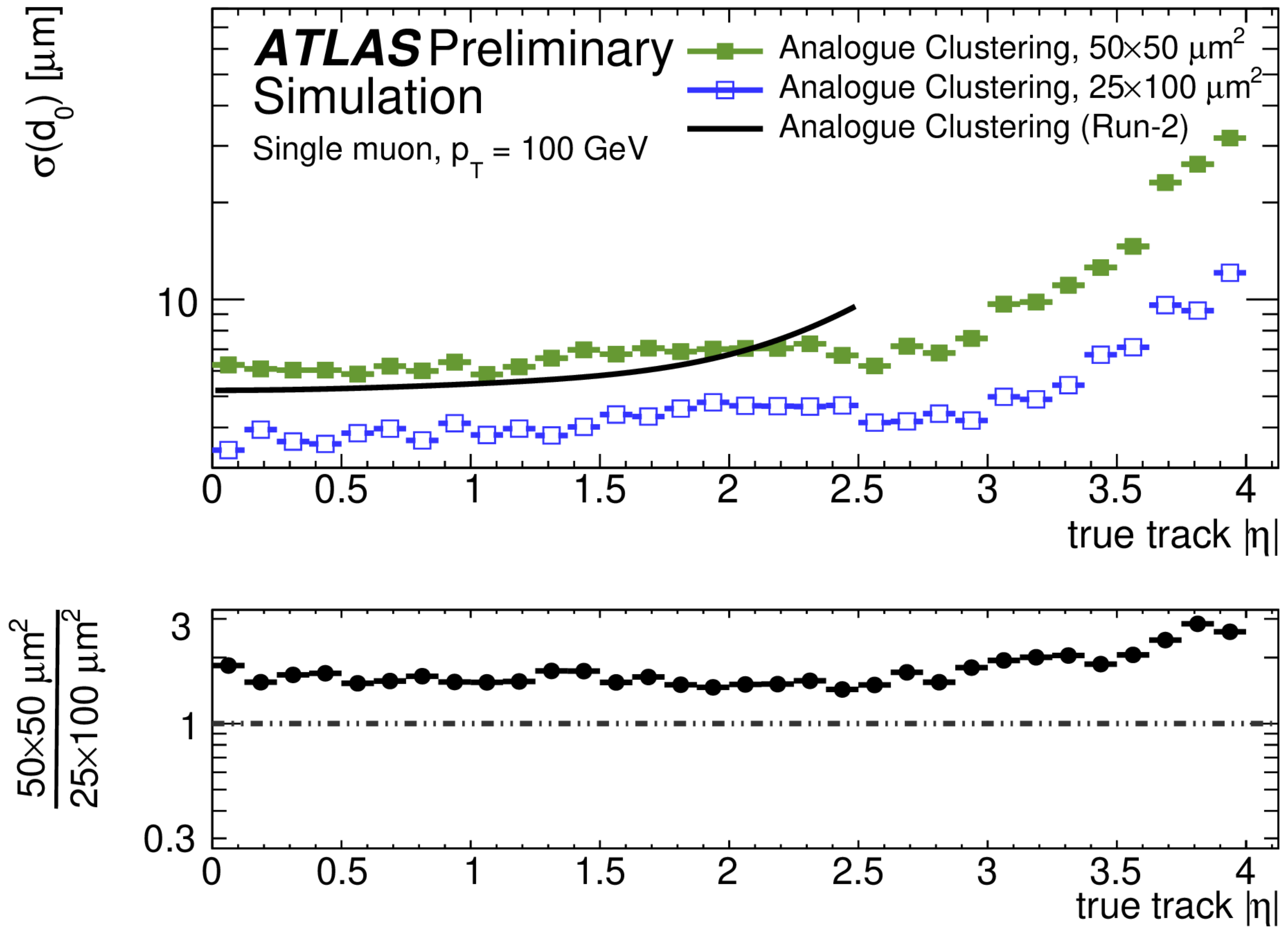


Low-p_T driven by **multiple scattering**

p_T

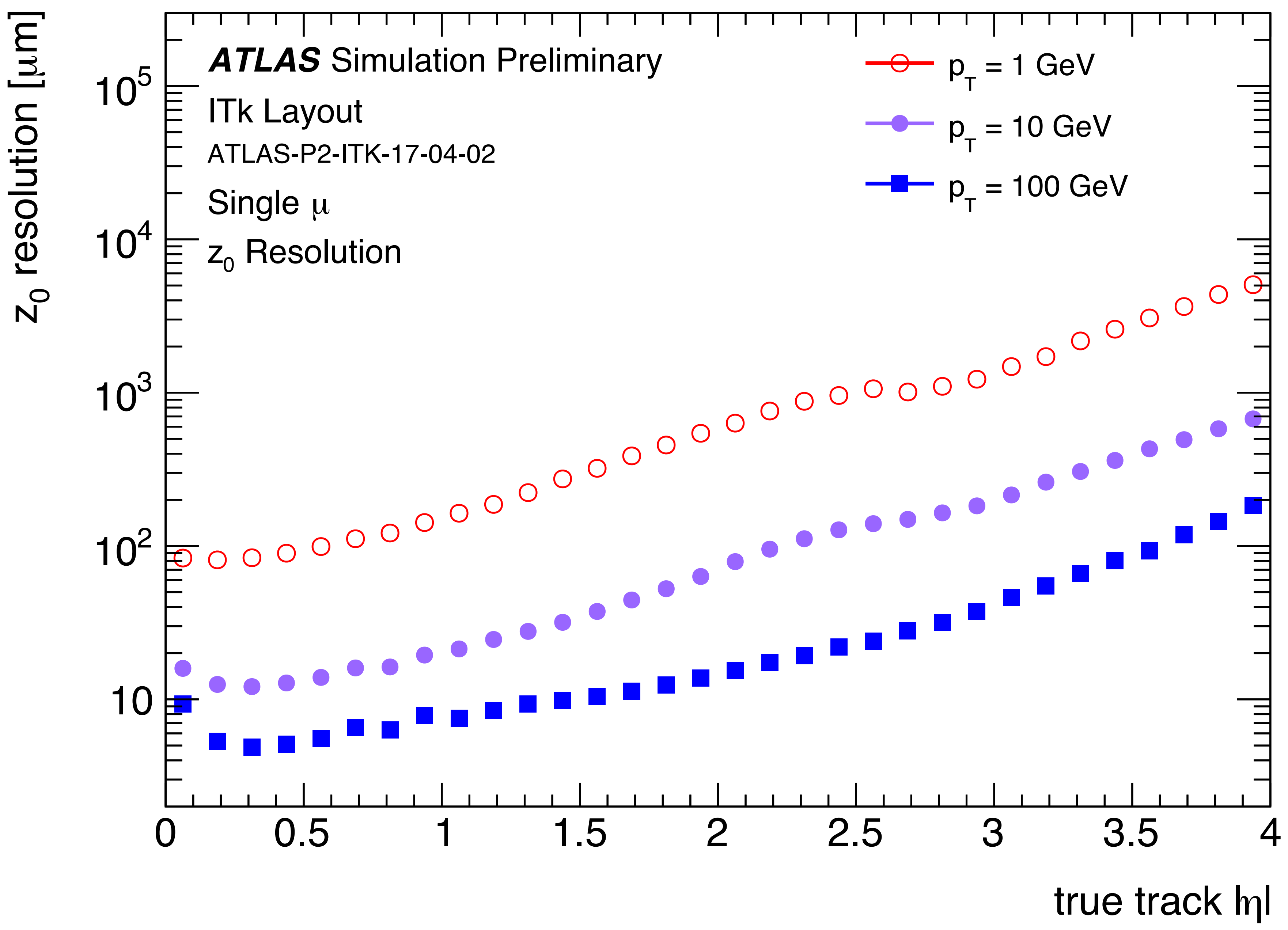
High-p_T driven by **intrinsic detector resolution**





Longitudinal IP Resolution

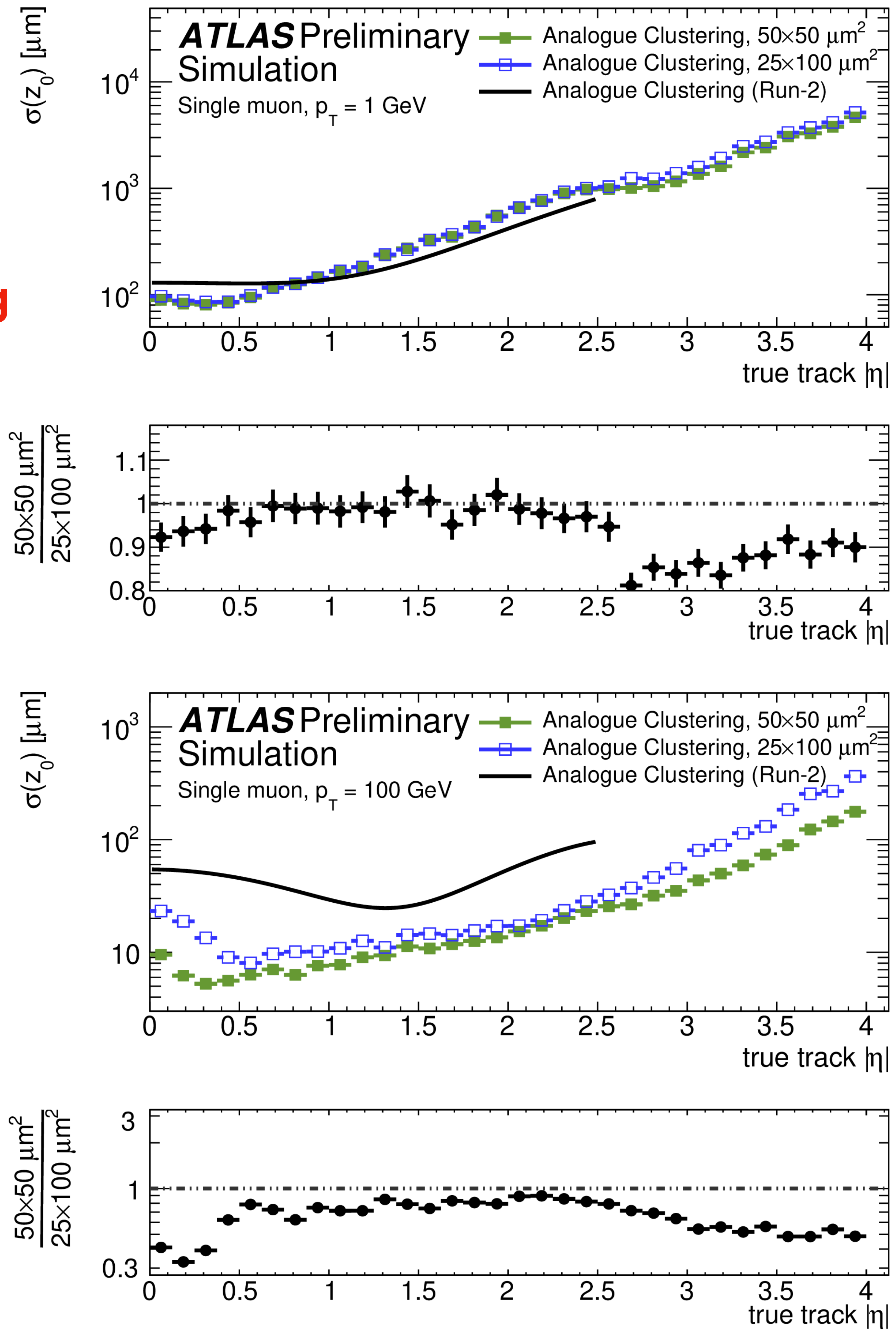
- Distance of a track's closest approach to the beam spot along the **longitudinal** z-axis (z_0)
- **Significant improvements** over Run-2 ID, with resolutions under $10\ \mu$m for high p_T central muons
  - Important for **vertexing** in high-density environments
  - Crucial for **pile-up mitigation**



Low-p_T driven by multiple scattering

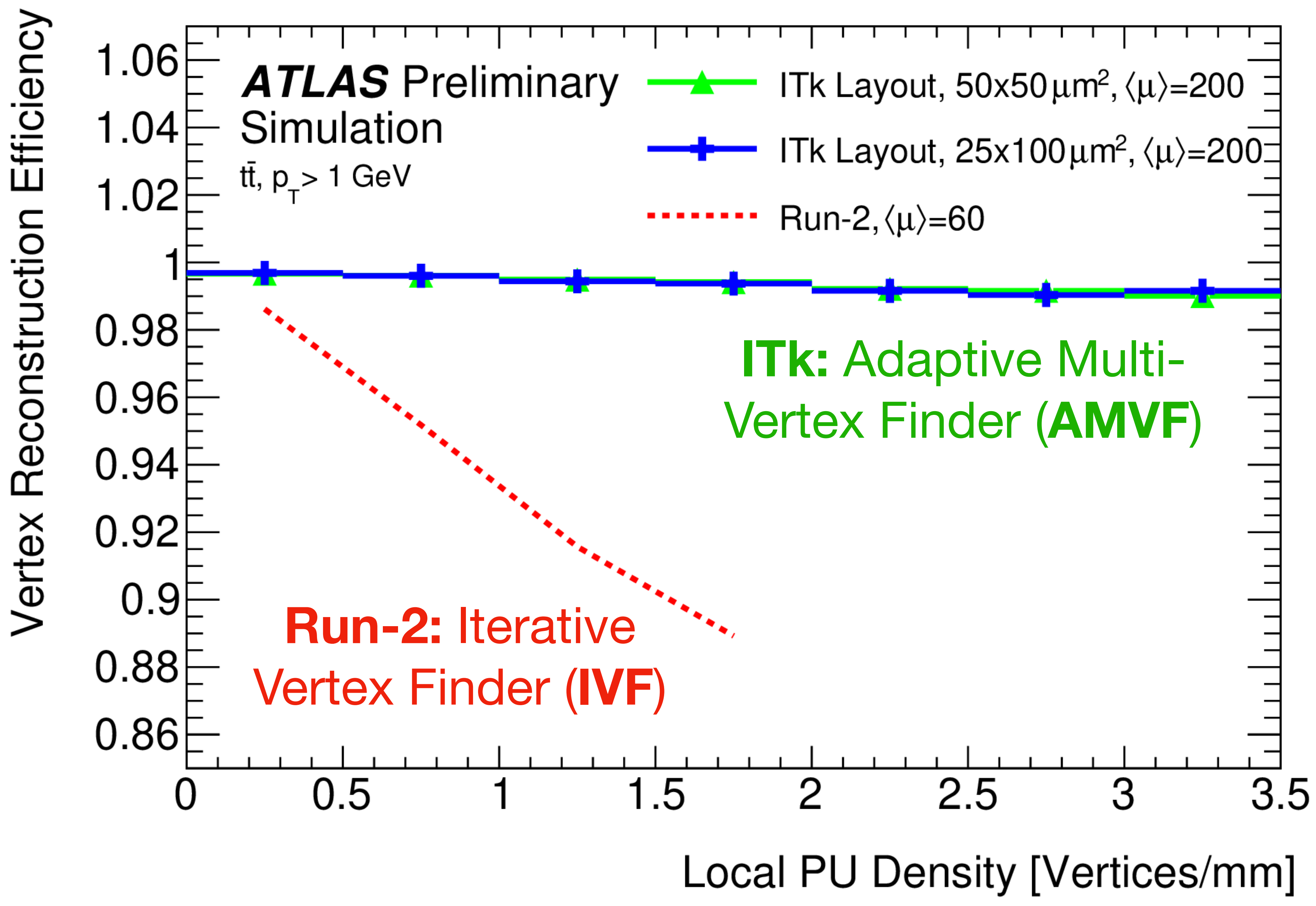
p_T

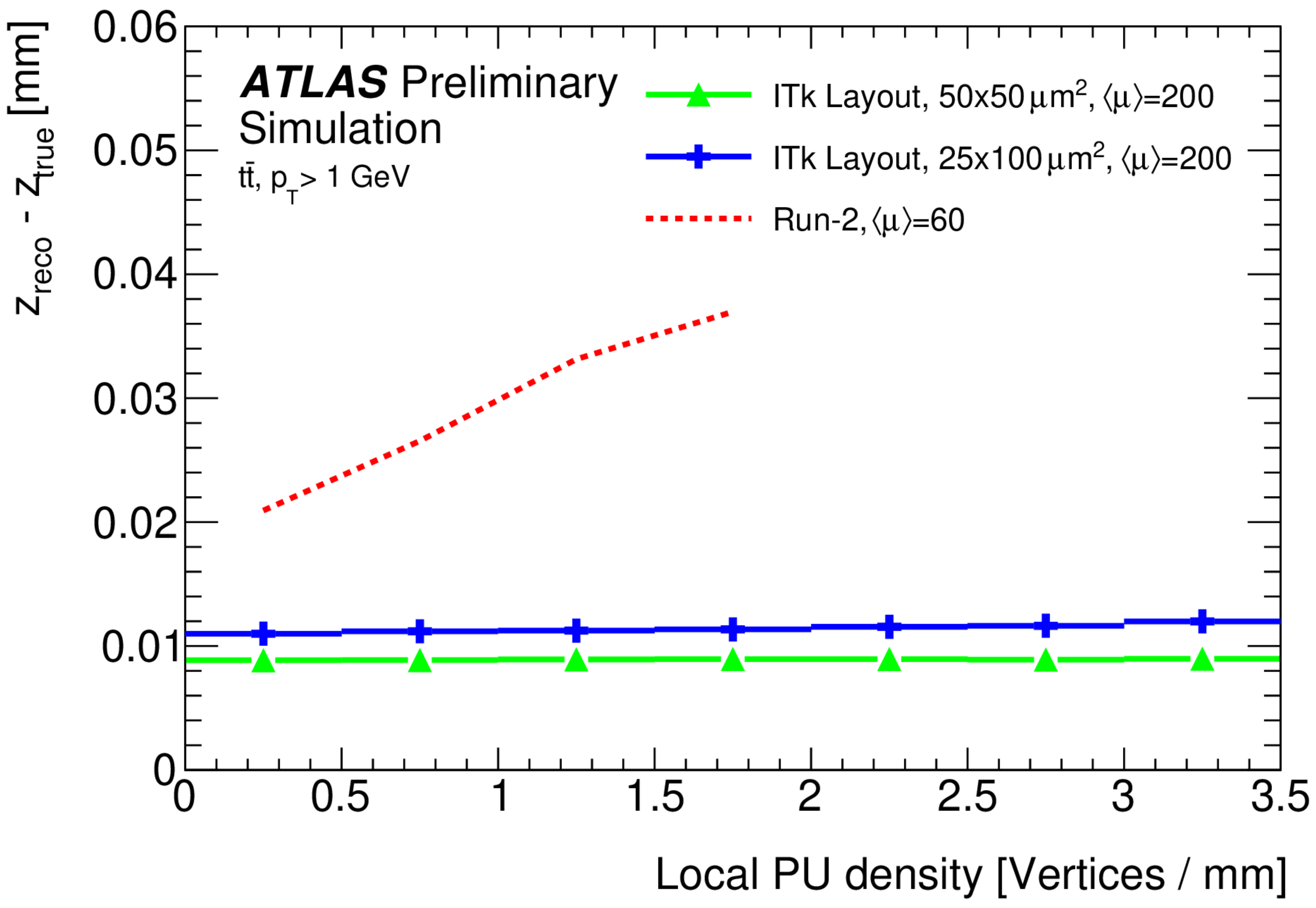
High-p_T driven by intrinsic detector resolution



Vertex Reconstruction

- **Vertexing** is the process of **reconstructing** and **identifying** the primary **hard scatter** and **pile-up vertices**
  - Difficult given high pile-up, expect many nearby vertices → must be individually resolved
- **Significant improvements** over Run-2 ID especially under **high pile-up** conditions
  - **Vertex reconstruction efficiency** for $t\bar{t}$ at $\langle\mu\rangle = 200$ has little dependence on **pile-up density**
  - **Precise reconstruction** of vertex position within 0.01 mm of truth with **minimal pile-up degradation**

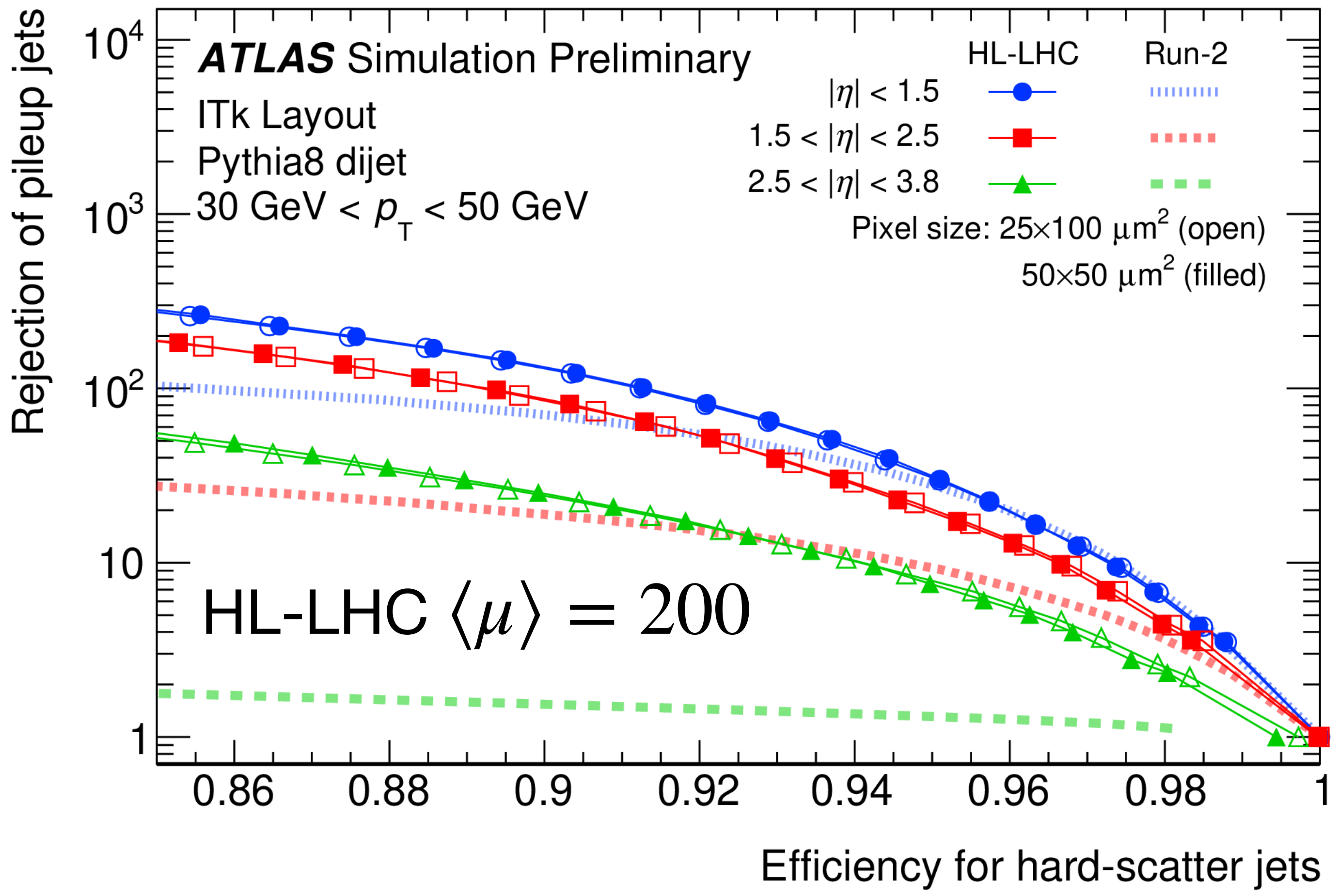




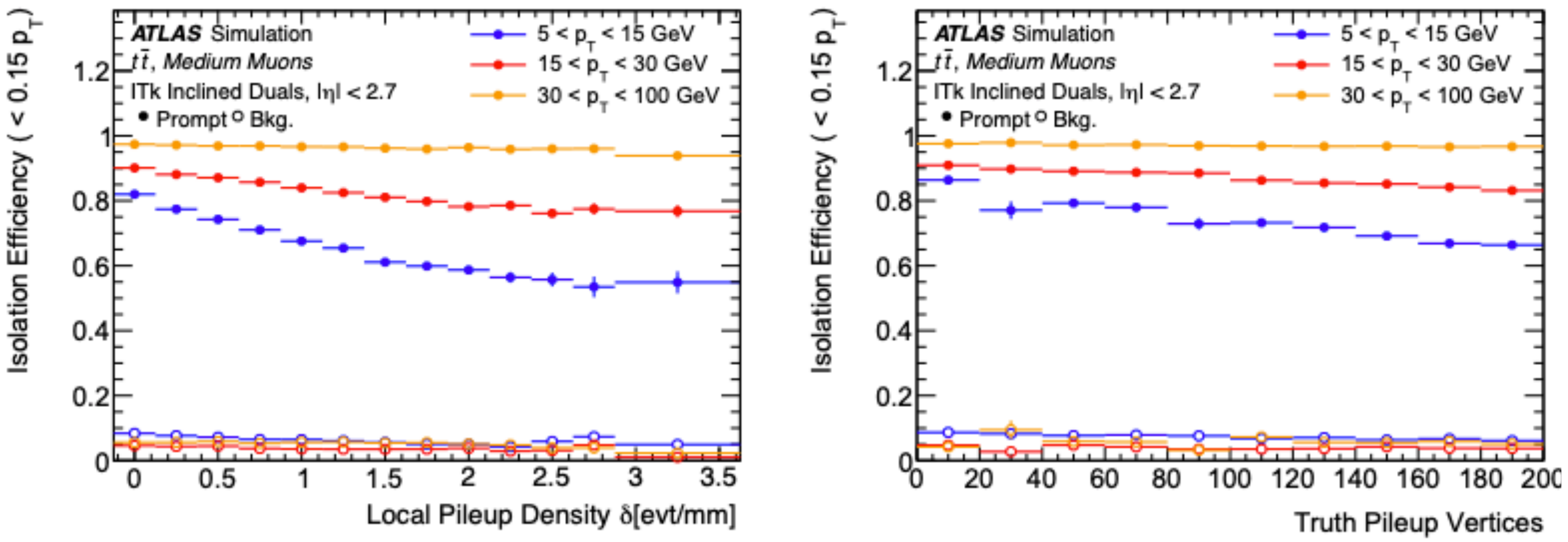
Impact on Physics Objects

- Excellent prospects for future developments of **object reconstruction** and **combined performance** for the HL-LHC
- **Significant improvements** in **pile-up jet rejection** particularly in the forward region (Run-2 ID limited to $|\eta| < 2.5$)
- Prompt **muon track isolation efficiency** **stable** against increasing **local** and **global pile-up** for $p_T > 30$ GeV
    - Background rejection essentially flat with pile-up regardless of muon p_T
- **Comparable** b-tagging **performance** to Run-2 ID, even at much larger pile-up
    - Large room for **improvements** from **ITk-specific optimization**

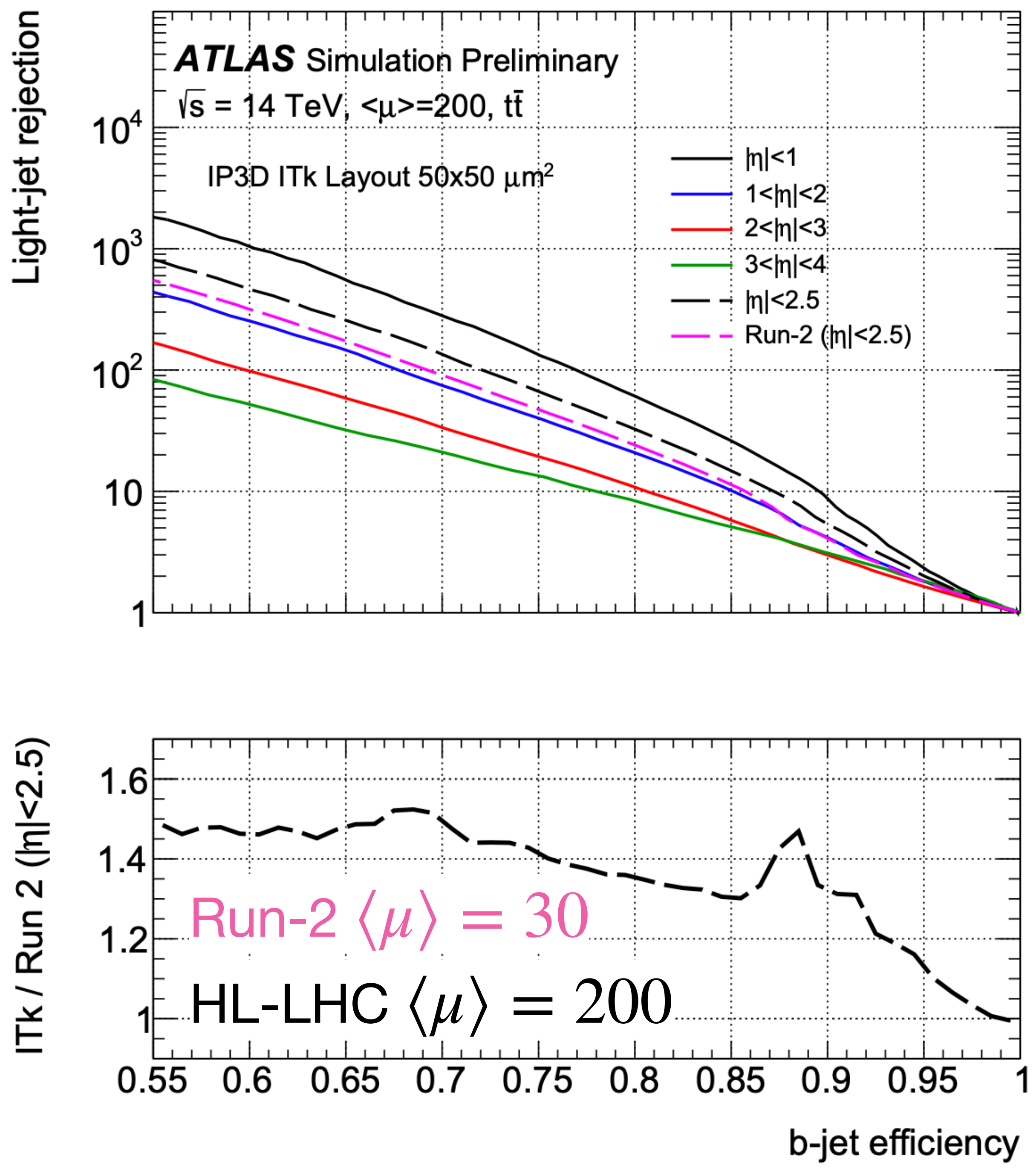
Pile-up Jet Rejection



Muon Track Isolation Efficiency



b-tagging



Summary

- The **ATLAS Inner Tracker (ITk)** upgrade is well-designed to cope with the **track-dense HL-LHC environment**
  - **All-silicon** design, **finer granularity**, **extended forward coverage**, improved **hit hermiticity**
- **ITk** will be key to the **continued success** of **ATLAS** during the HL-LHC
  - **Reconstruction** is **optimized** for **high luminosity**, with significant speed improvements over Run-2 ID
  - Maintain **high track reconstruction efficiency** with a **low fake rate**
  - Provides **superior momentum resolution** and **competitive impact parameter resolutions**
  - Excellent prospects for physics objects (b**-tagging**, **lepton reconstruction** and **isolation**, etc…)
- Expect **ongoing optimization** and evolution of **ITk layout** to further **improve performance**
  - New **baseline** L0 barrel pixel pitch of 25×100 μm^2 and innermost radius of 34 mm $(33.2$ mm$)$ for barrel (end-cap)
- **Track-time assignment** possible with new **forward timing detector (HGTD)** → further improving pile-up rejection

Backup Material

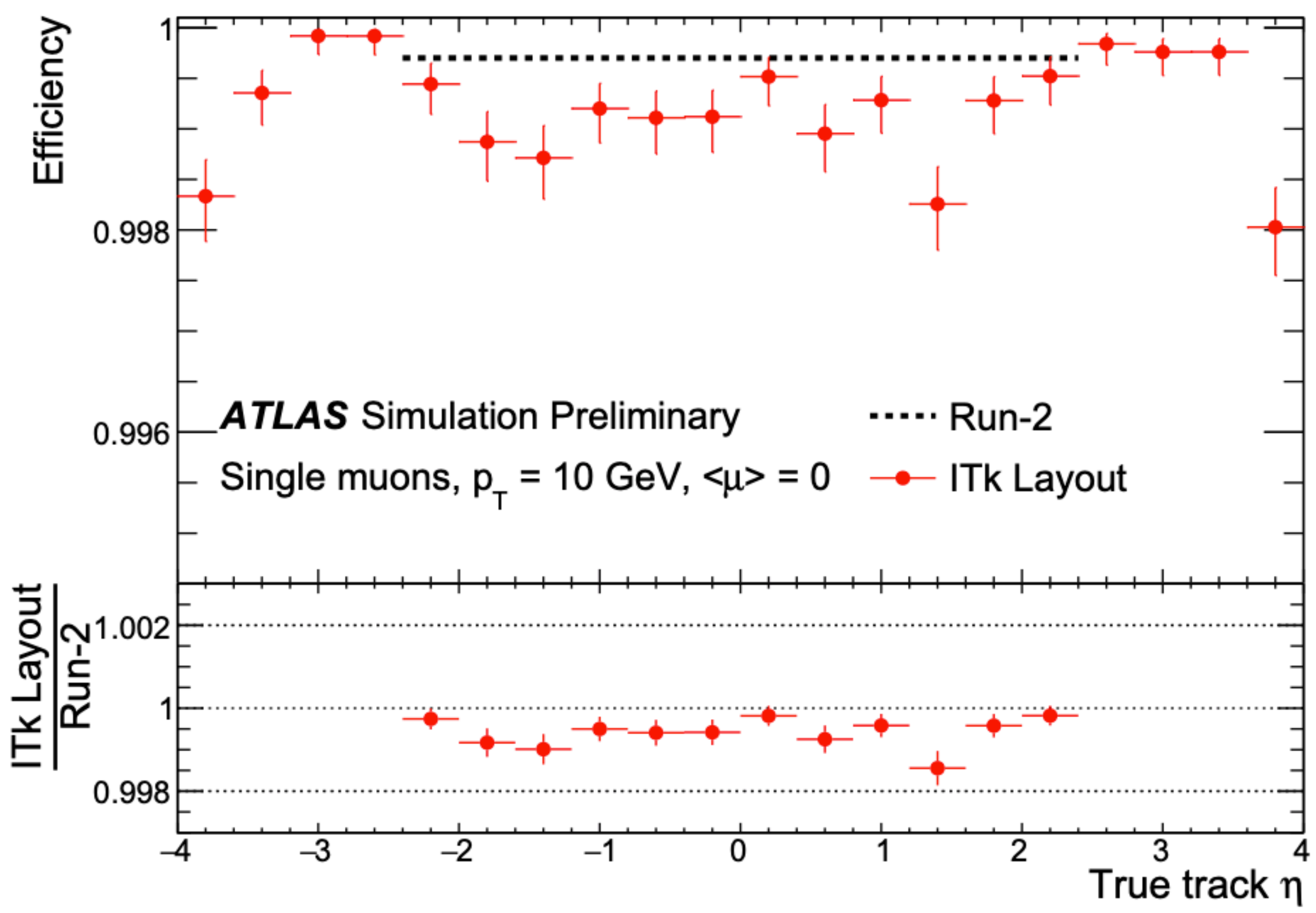
CDS Reference: ATL-COM-ITK-2020-022

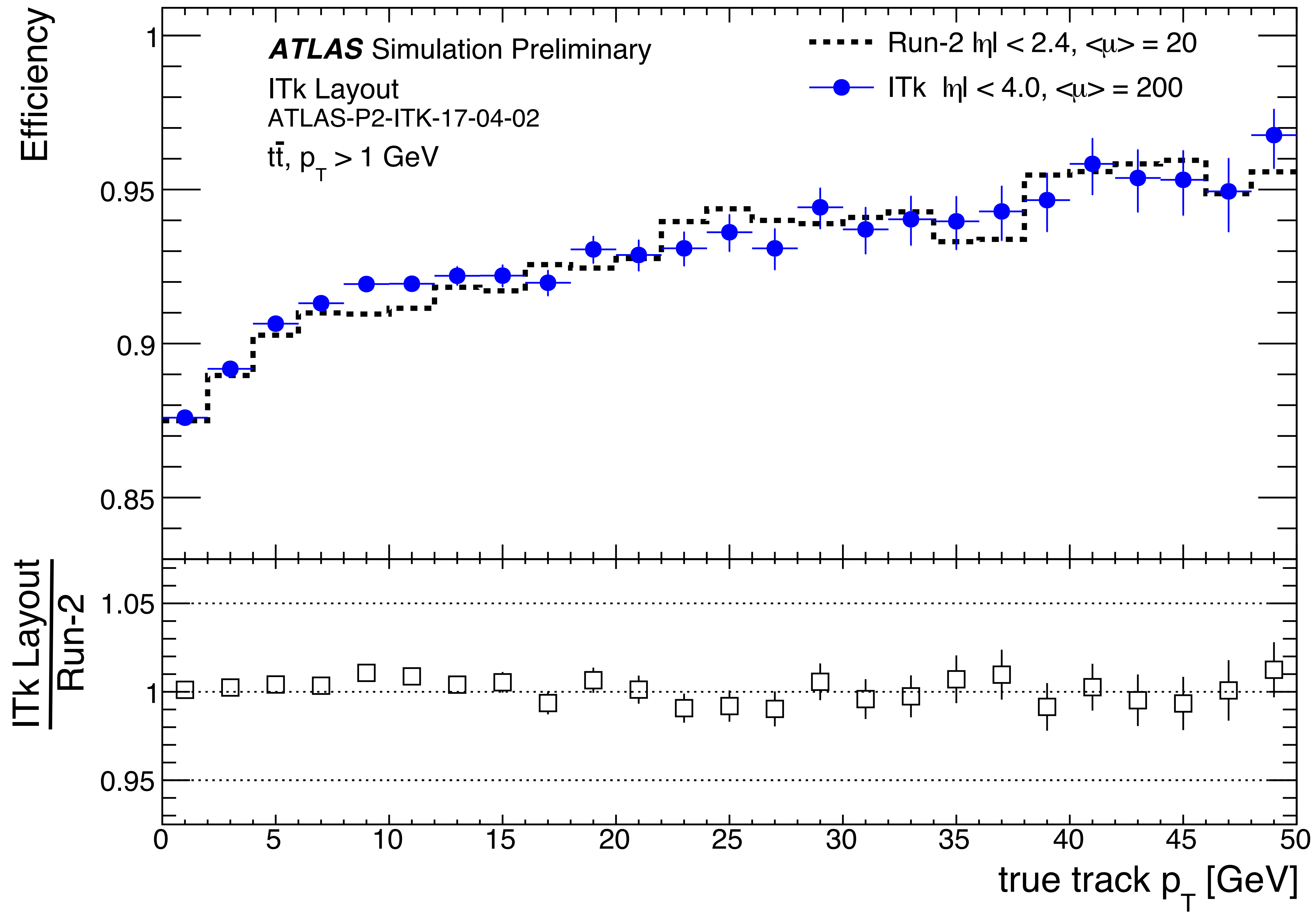
Other References:

- **Tracking Schematic:** https://www.hep.phy.cam.ac.uk/~thomson/MPP/ModernParticlePhysics.html
- **Pileup Distribution:** https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2
- **Event Display:** https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradeEventDisplays
- **ITk Pixel Detector TDR:** https://cds.cern.ch/record/2285585/files/ATLAS-TDR-030.pdf
- **HGTD TDR:** https://cds.cern.ch/record/2714406
- **ATLAS Public Results:** ATL-PHYS-PUB-2020-005, ATLAS-PHYS-PUB-2019-014, ITK-2020-002, IDTR-2019-009

Efficiency

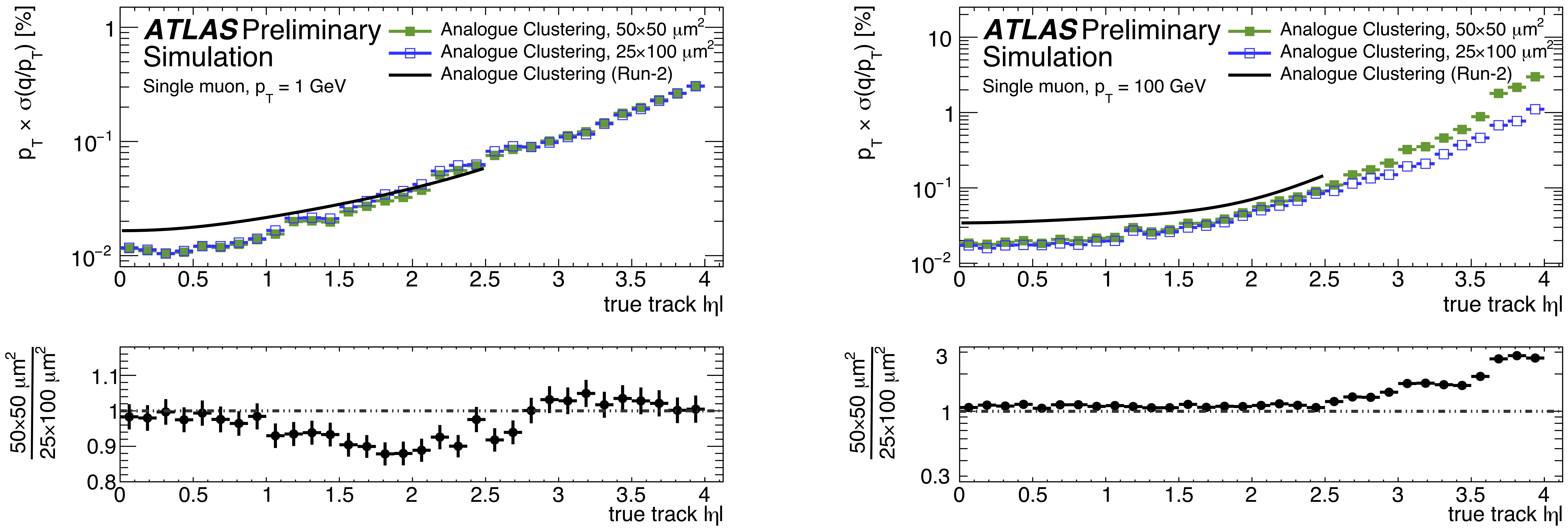
- **Without pile-up**, **ITk reconstruction efficiency** is **compatible** with Run-2 ID across $|\eta| < 2.4$
  - Run-2 selection requires ≥ 7 silicon hits while **ITk** requires ≥ 9 hits for $|\eta| < 2.0$
- **ITk** at $\langle\mu\rangle = 200$ provides **comparable performance** as a function of p_T w.r.t. Run-2 ID at $\langle\mu\rangle = 20$





Momentum Resolution

- **Momentum resolution** is significantly **improved** over Run-2 ID, particularly at high p_T
- ITk benefits from **reduced material budget** and **full silicon coverage**, providing **high precision measurements** along the full track length

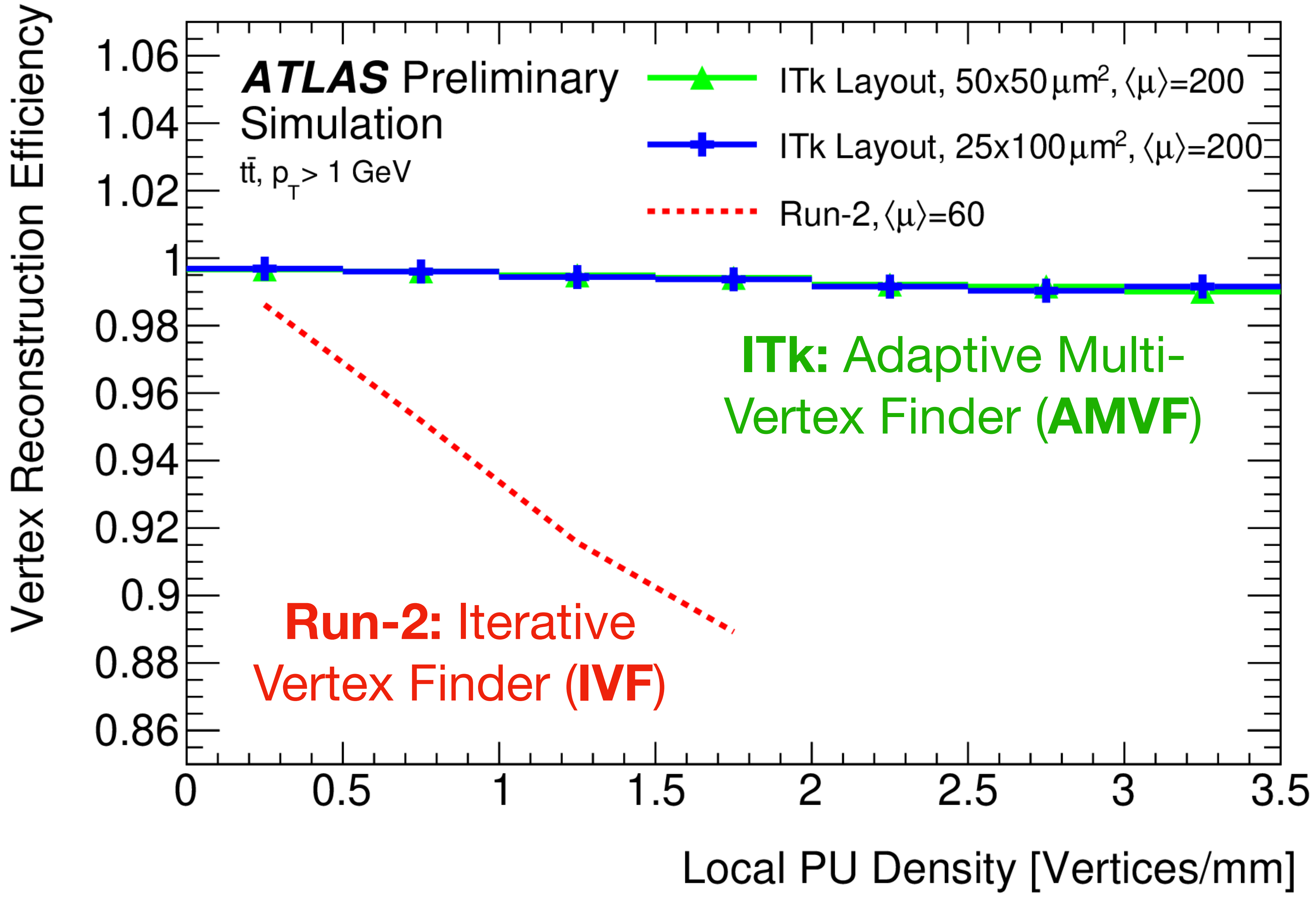


Low-p_T driven by **multiple scattering** → p_T → **High-p_T** driven by **intrinsic detector resolution**

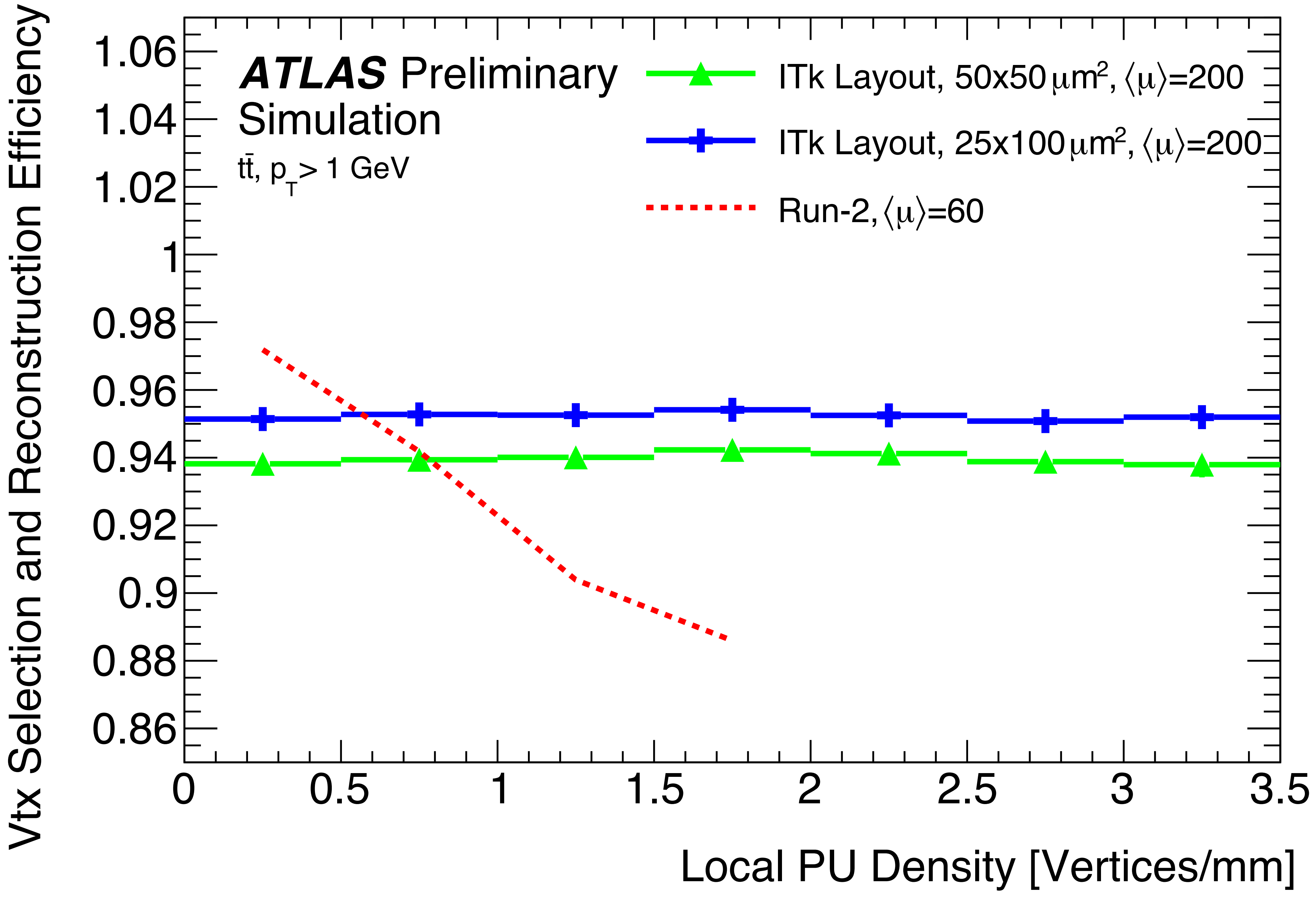
Vertex Reconstruction and Selection

- **Vertexing** is the process of **reconstructing** and **identifying** the primary **hard scatter** and **pile-up vertices**
- **Vertex selection** is the process of both **successfully reconstructing** the hard scatter vertex and **selecting** it as the **primary vertex candidate**, based on the $\Sigma\ p_T^2$ of associated tracks
  - **ITk outperforms Run-2 ID in terms of both reconstruction and selection in high pile-up environments**

Reconstruction

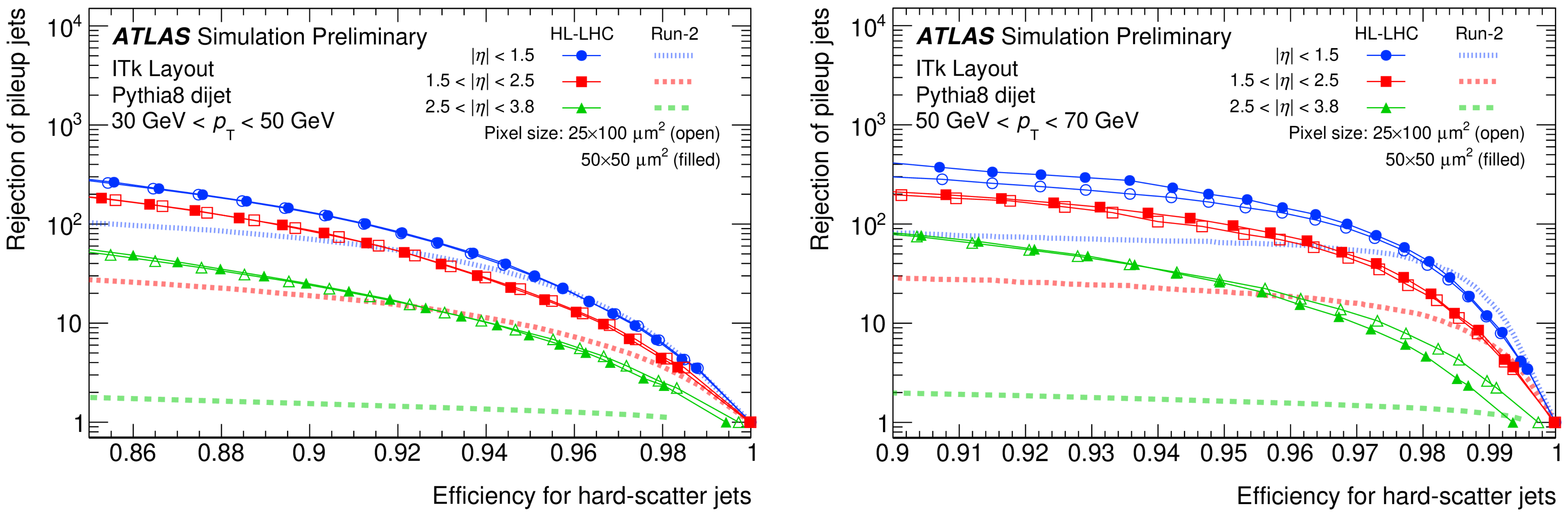


Reconstruction and Selection

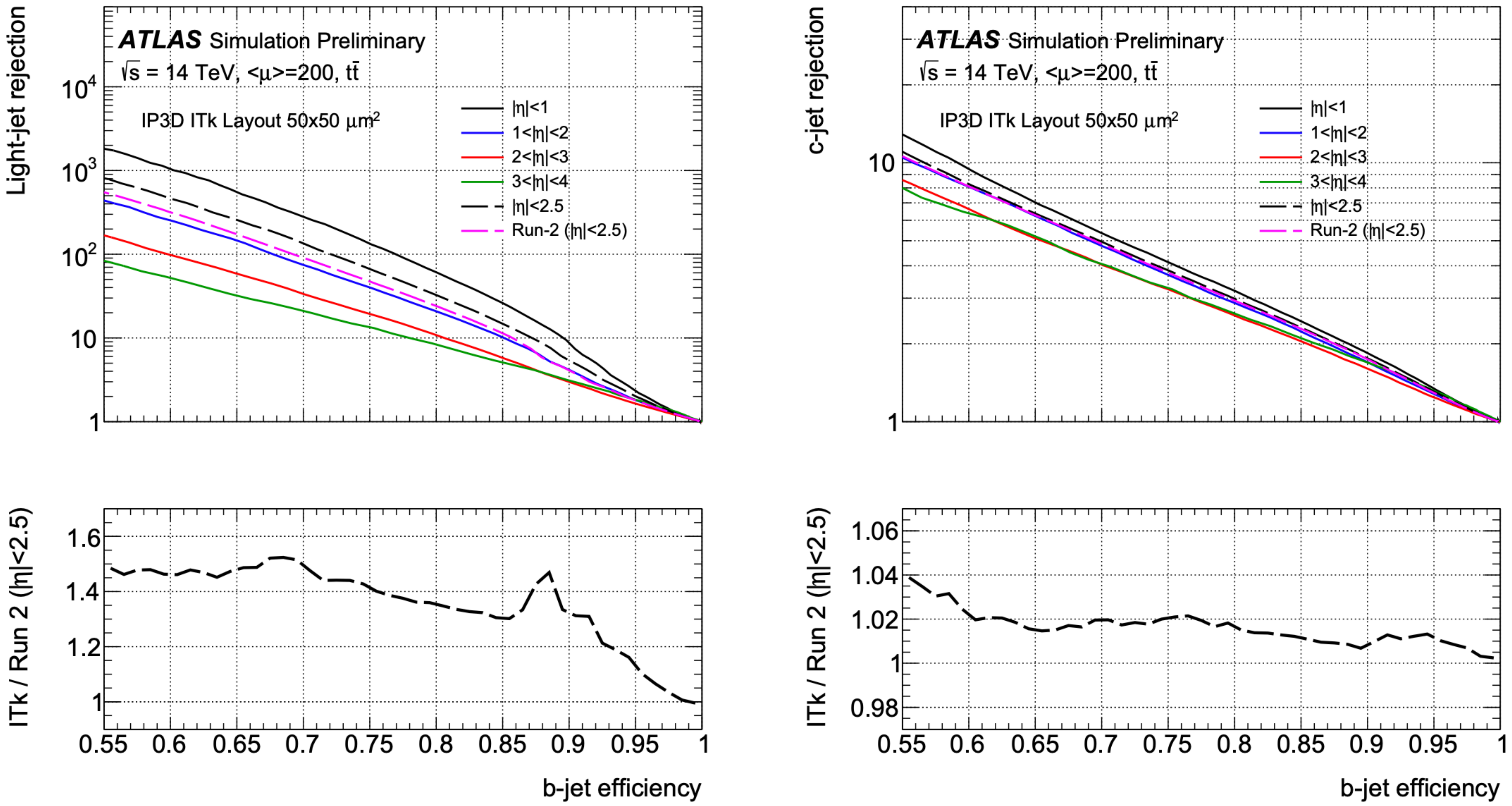


Impact on Physics Objects

Pile-up Jet Rejection



b-tagging



Muon Track Isolation Efficiency