ATLAS ITk GNN Track Reconstruction Chain

Expected Tracking Performance

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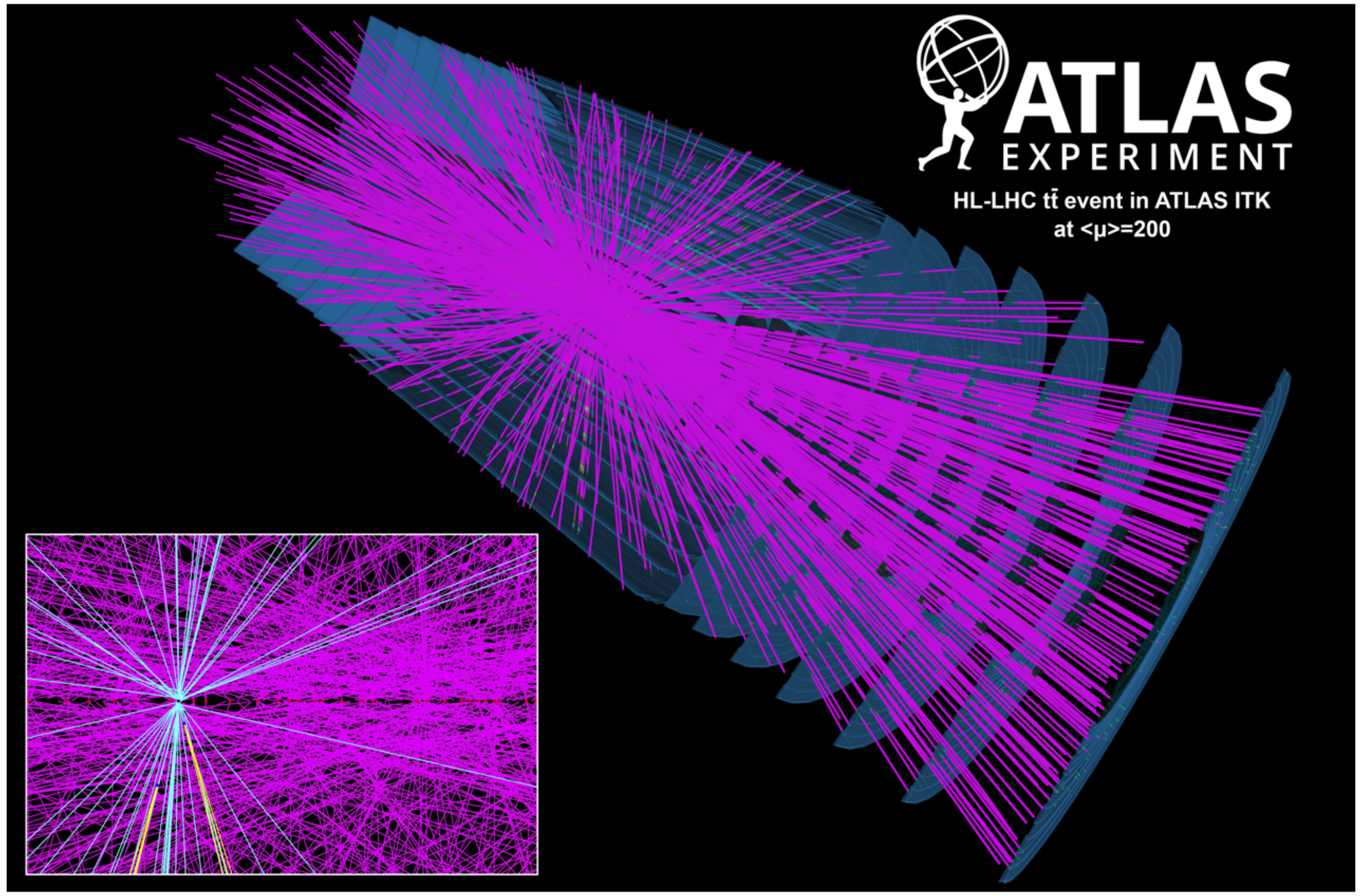
Track Reconstruction

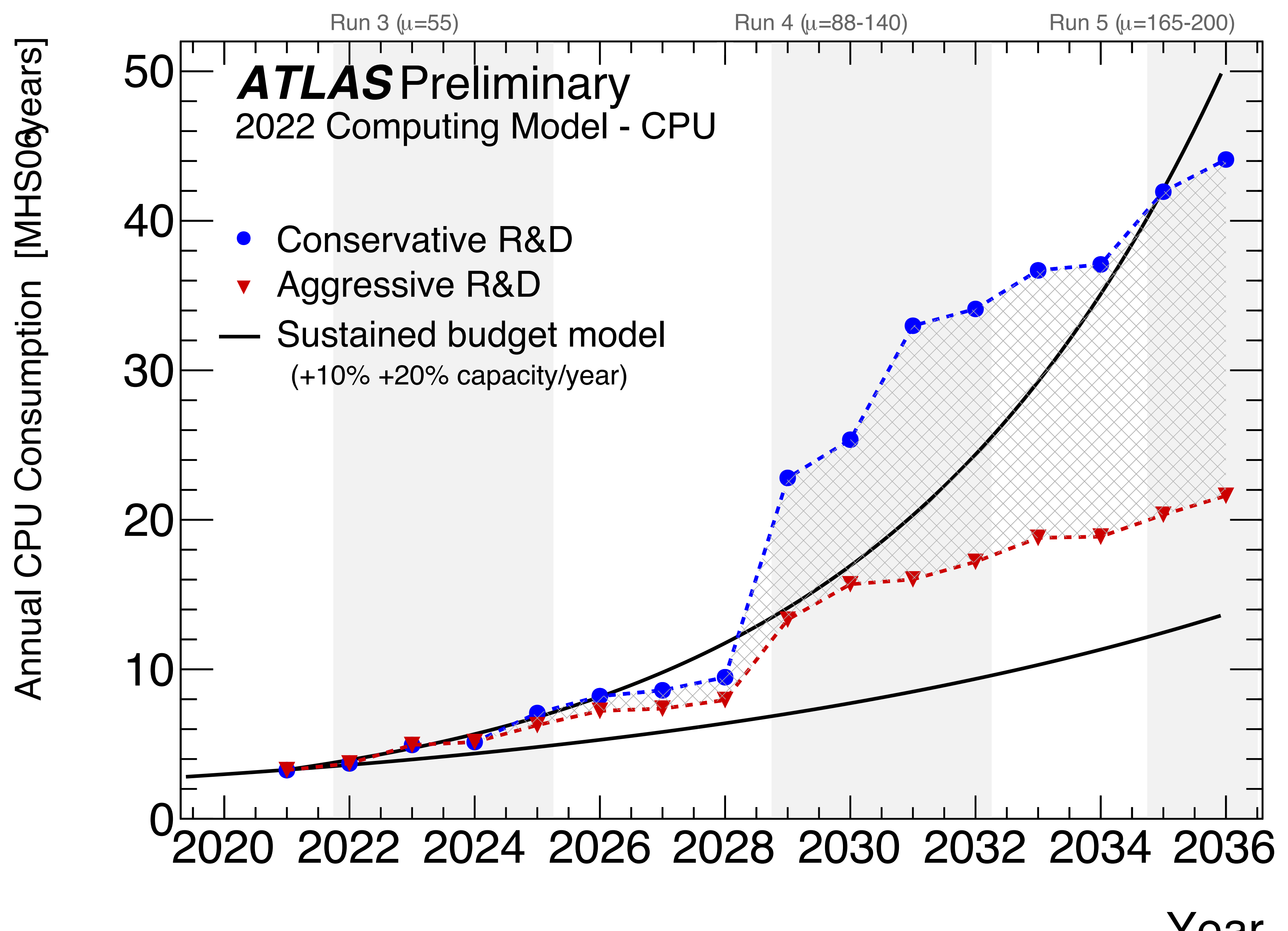
In hadron collision @ High Luminosity

2030-2041 : High-Luminosity Phase of Large Hadron Collider (HL-LHC)

Detector occupancy pushed to extreme regime

Very high number of simultaneous pp interactions : $\langle \mu \rangle = 200$



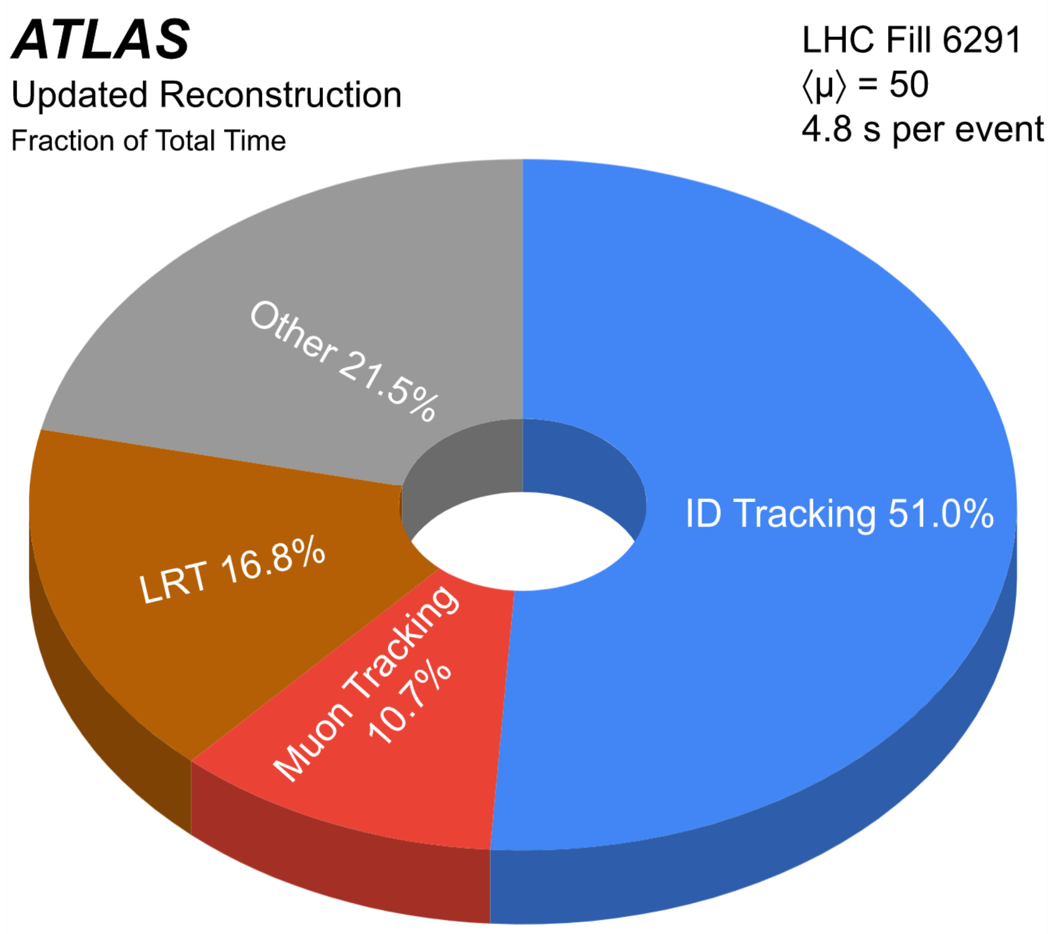


ATLAS Software and Computing HL-LHC Roadmap (2022)

Need **aggressive Computing R&D** to process all the data recorded by ATLAS experiment

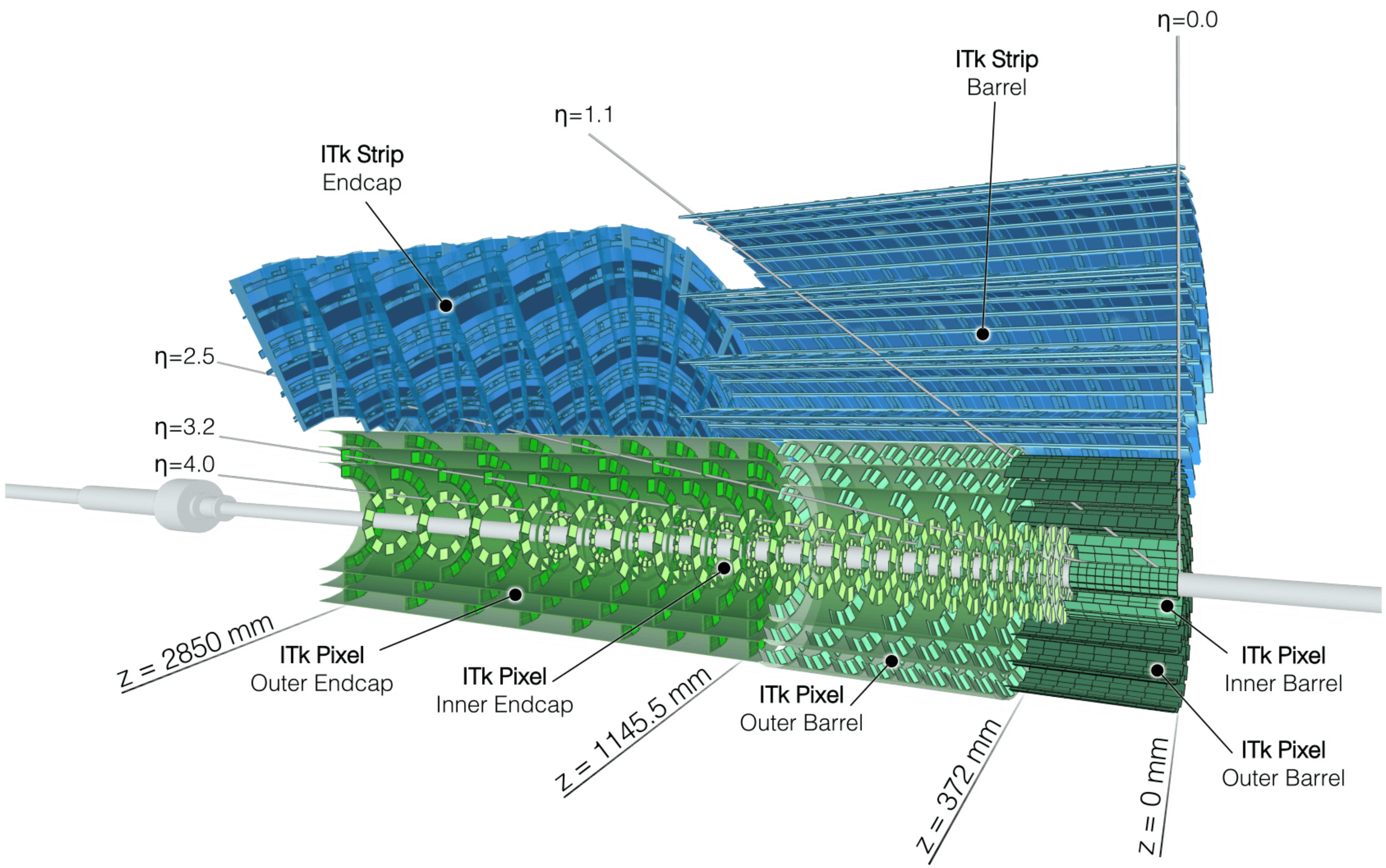
In event reconstruction **main part** is dedicated to charged particle **track reconstruction**

Must make faster tracking for HL-LHC



Comput Softw Big Sci 8, 9 (2024)

ATLAS ITk detector for HL-LHC



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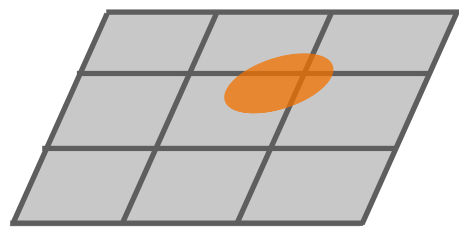
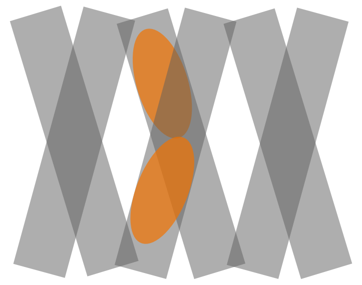
- Full silicon-based detector
  - pixel and strip
- Extended pseudorapidity coverage
  - up to η = 4
- Aims to reconstruct track of particles with $p_{\rm T} > 1$GeV
  - leave on average 9 hits in the detector

Pixel



1 Cluster = 1 **Space Point**

Strip

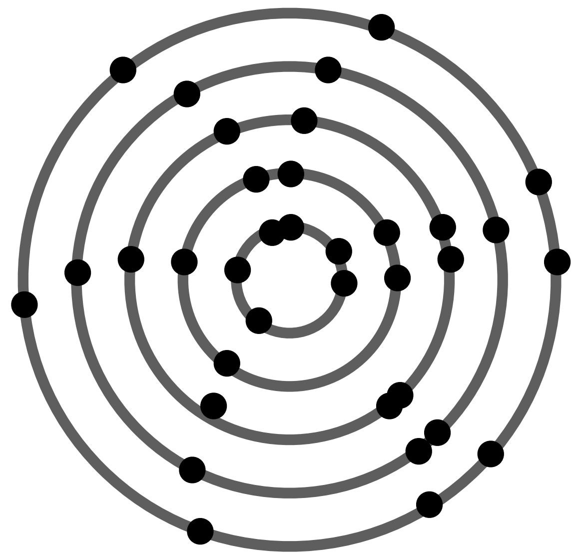


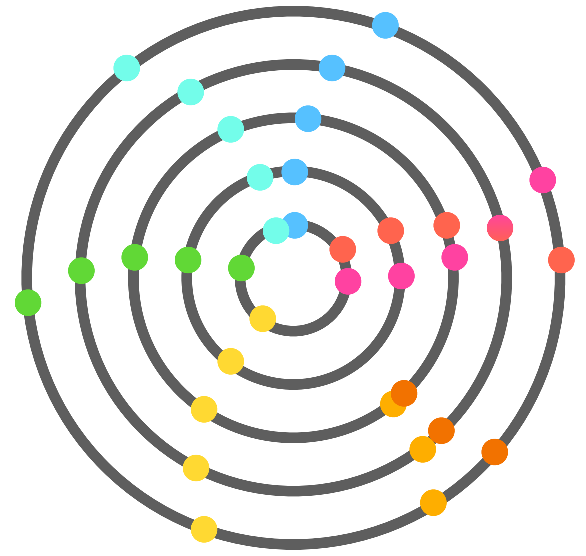
2 Clusters = 1 **Space Point**

Track Reconstruction in ATLAS

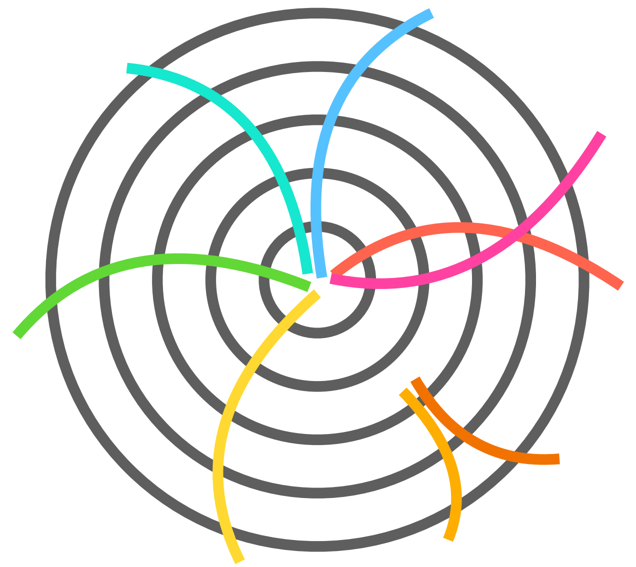
And Speed-up plans

Data Preparation	Track Finding	Track Fit & Ambiguity Resolution
Clusters and Space Points formation	Track candidate = list of clusters	Track parameters (origin, direction, momentum)





Algo: Combinatorial Kalman Filter (CKF)



Algo: Global χ^2

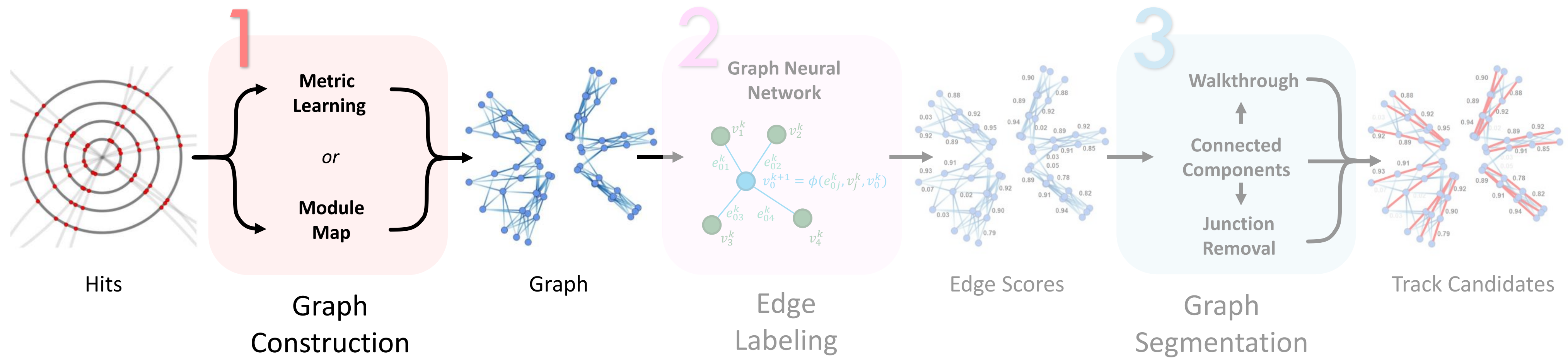
- Projects for **faster track reconstruction** in ATLAS
  - Modern and **optimised CPU code** : use **ACTS** software in ATLAS framework (athena)
  - Port **classic algorithms to GPU** accelerator: **traccc**
  - Use modern Machine Learning algorithm on GPU accelerator: **GNN4ITk [this talk]**

ATLAS GNN Track Reconstruction for Run 4

GNN4ITk project

- Replace CKF track finding with GNN inference on graph made from Space Points
- Python based R&D framework public: acorn
- Being put in production in ATLAS athena software and ACTS (including CUDA parts)

Graph Construction

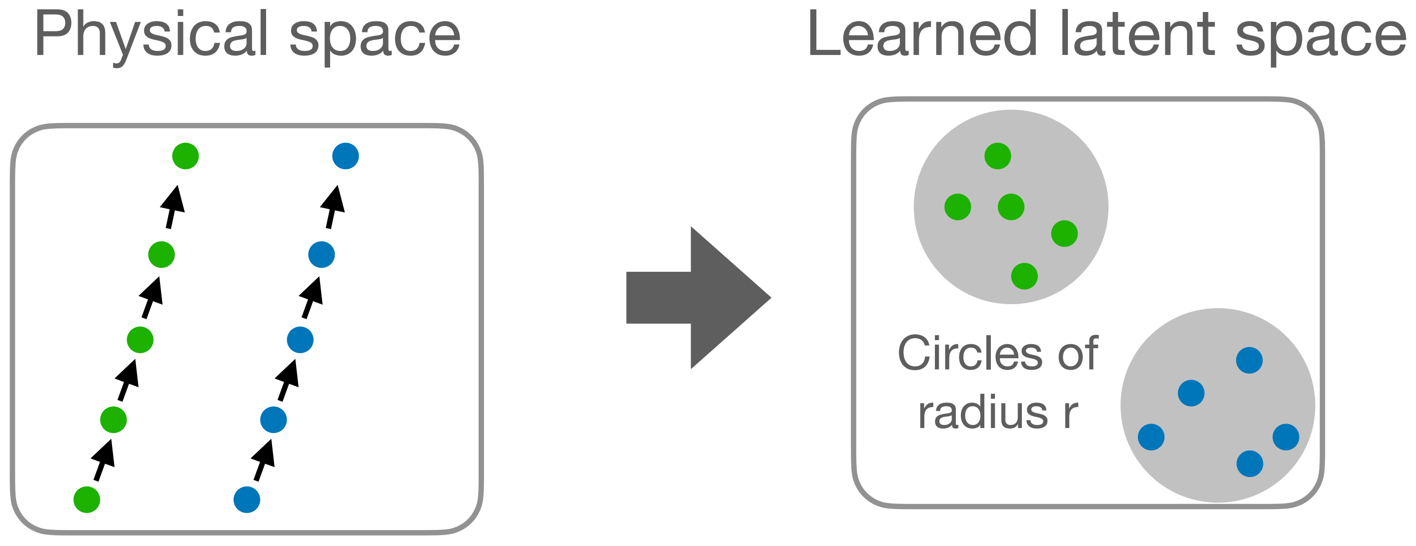


One event has **O(300k) Space Points** : it would make **fully connected graphs of O(10^{10}) edges**, too large!

Need efficient methods to build **smaller & purer graphs**:

- **Metric Learning**

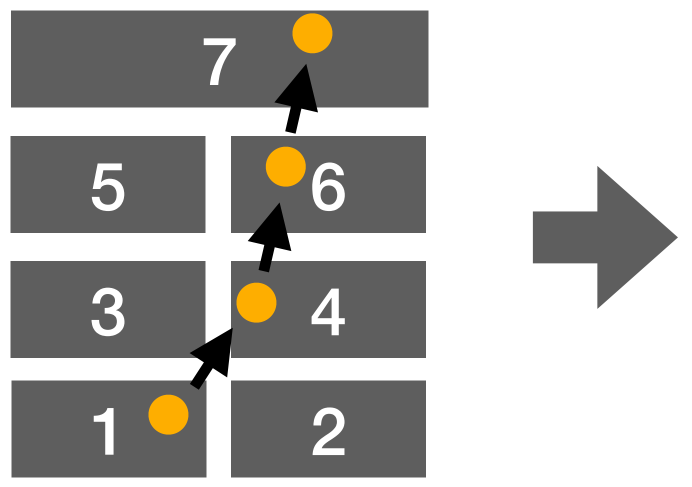
  1. MLP is trained to embed nodes into latent space, where common particles hits are close
  2. Additional filtering by GCN to reduce graph size



- **Module Map**

  Lookup table of all possible module triplet connections, with [min,max,mean,rms] of geometric features ($\Delta\eta_{\text{edge}}$, Δr_{edge}, …)

  Computed from 90k $t\bar{t}$ simulated events



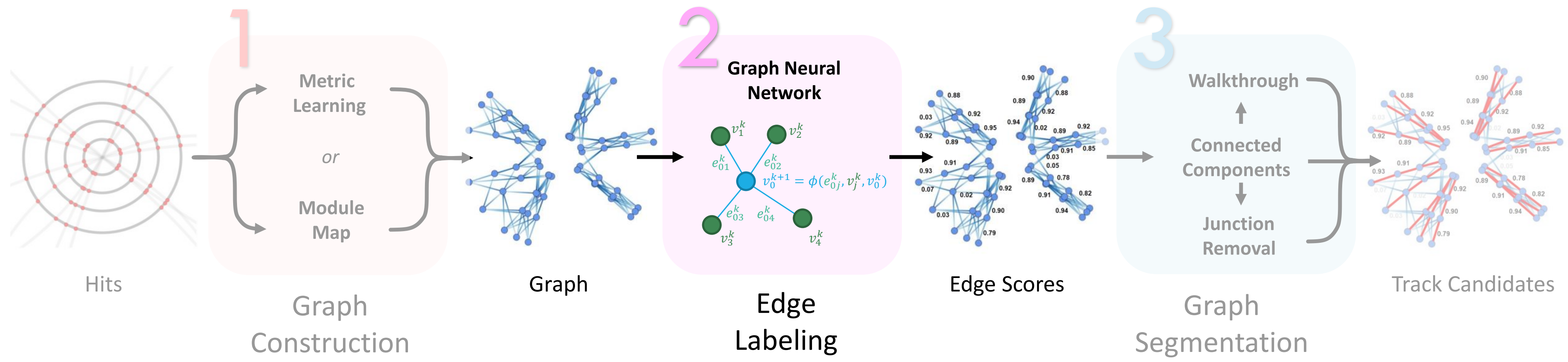
Allowed Triplets:

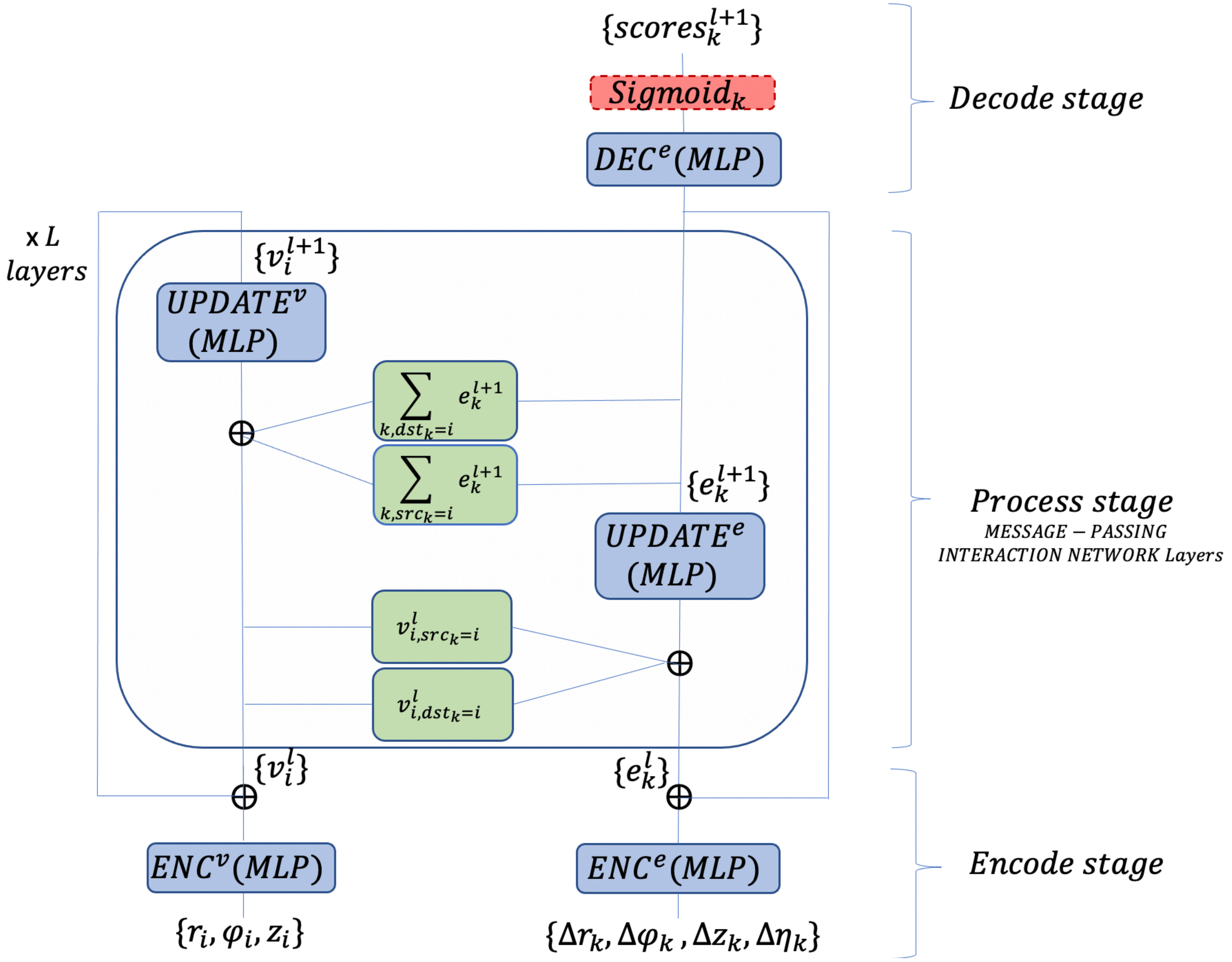
1→4→6 with $x_{\text{edge}} \in [\text{mean} \pm n \times \text{rms}]$

4→6→7 with $x_{\text{edge}} \in [\text{mean} \pm n \times \text{rms}]$

(capped by min and max for each feature x)

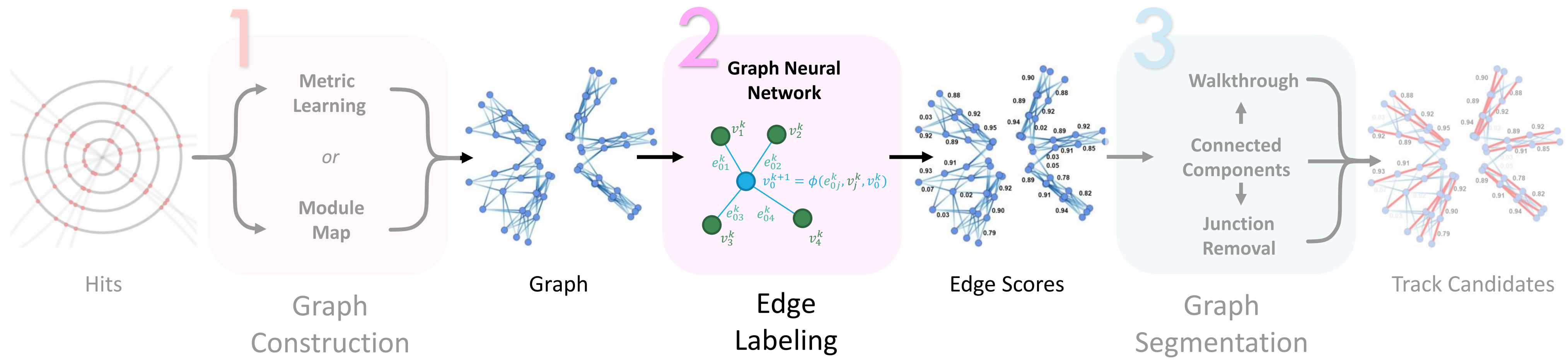
GNN Model & Training



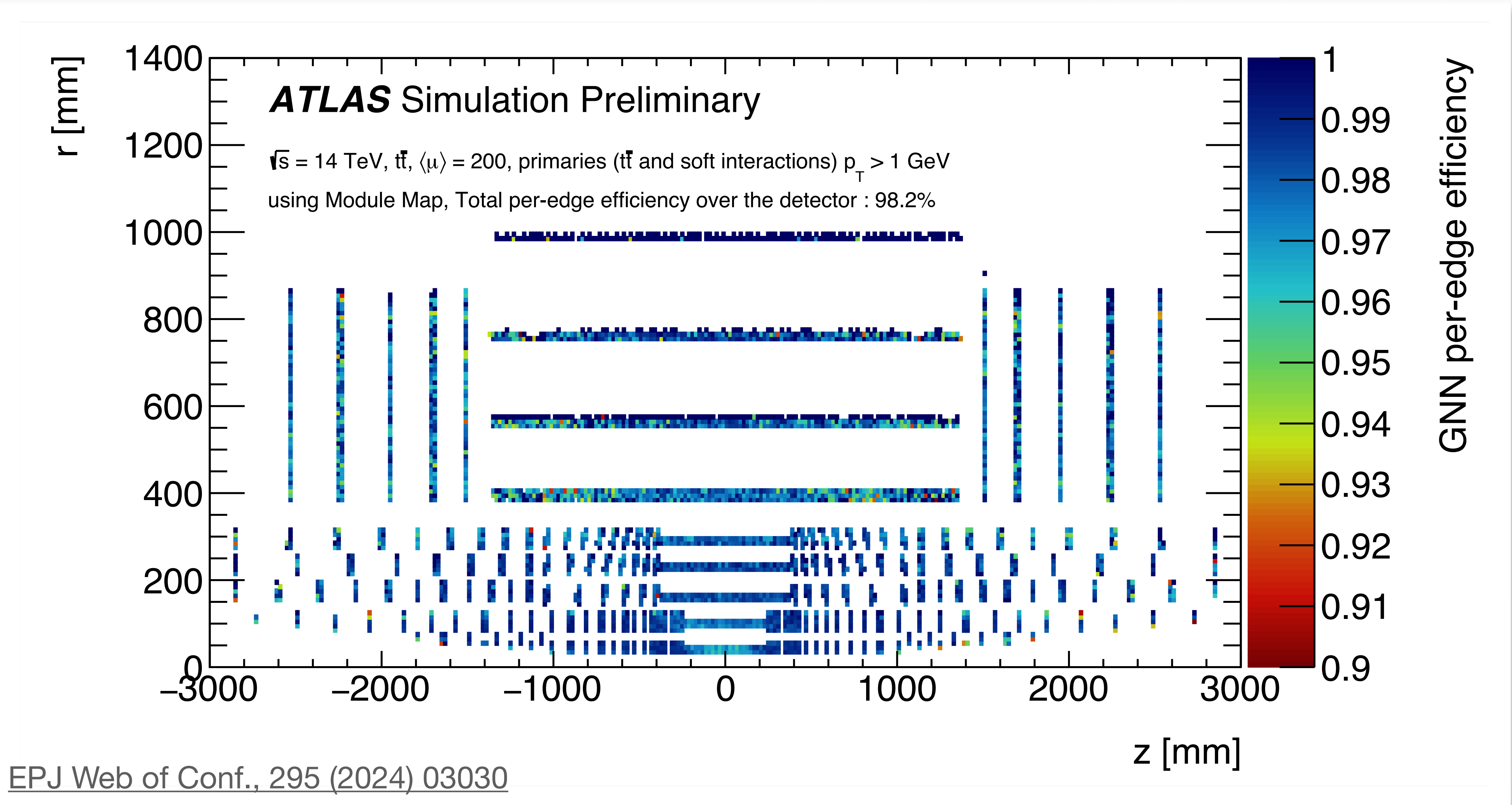


- GNN config:
  - 3 layers per MLP
  - 128D latent space
  - 8 message-passing
  - layer normalisation
  - Heterogeneous data (Pixel vs strips)
- Training sample: 10k $t\bar{t}$ at $\langle\mu\rangle = 200$
- Target particles:
  - $p_T > 1$ GeV, $R_{\text{production}} < 26$ cm
  - Primary particles with at least 3 space points
  - electrons are masked (at the moment)

GNN performance
edge-wise efficiency and purity

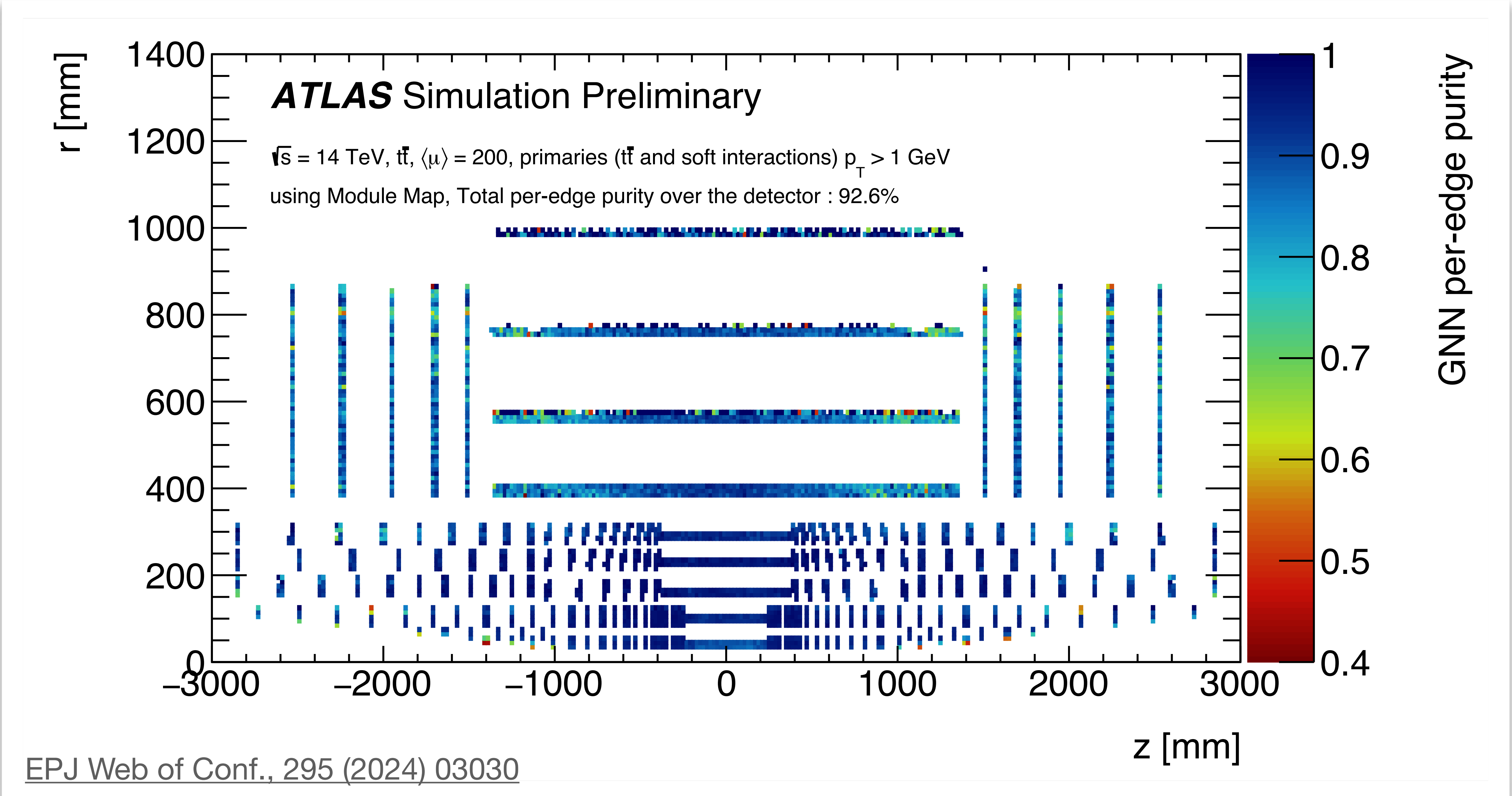


Edge efficiency for score > 0.5



EPJ Web of Conf., 295 (2024) 03030

Edge purity for score > 0.5



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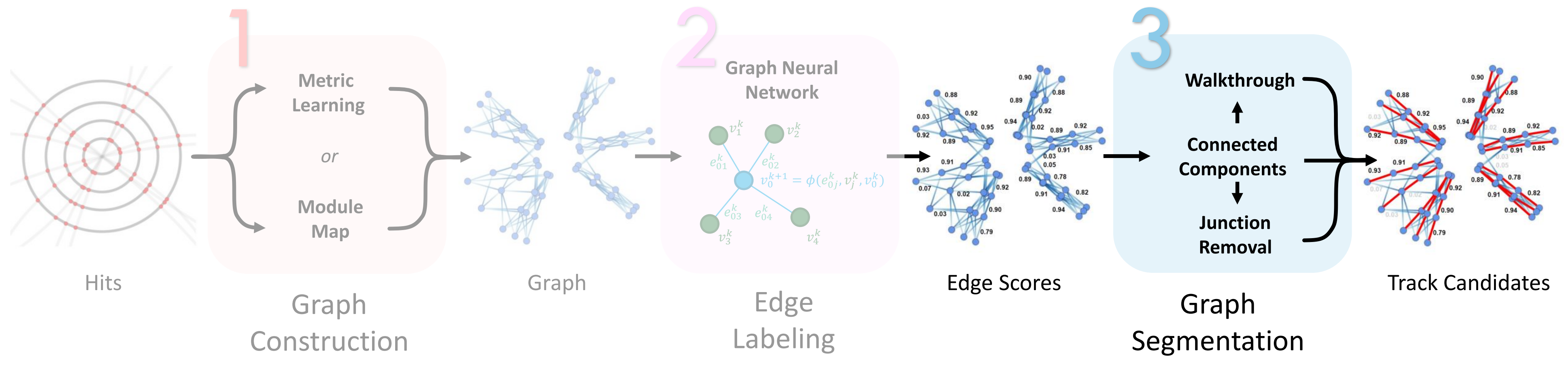
$$\text{efficiency} = \frac{N_{\text{true edges}}(score > X)}{N_{\text{true edges}}}$$

$$\text{purity} = \frac{N_{\text{true edges}}(score > X)}{N_{\text{true edges}}(score > X) + N_{\text{fake edges}}(score > X)}$$

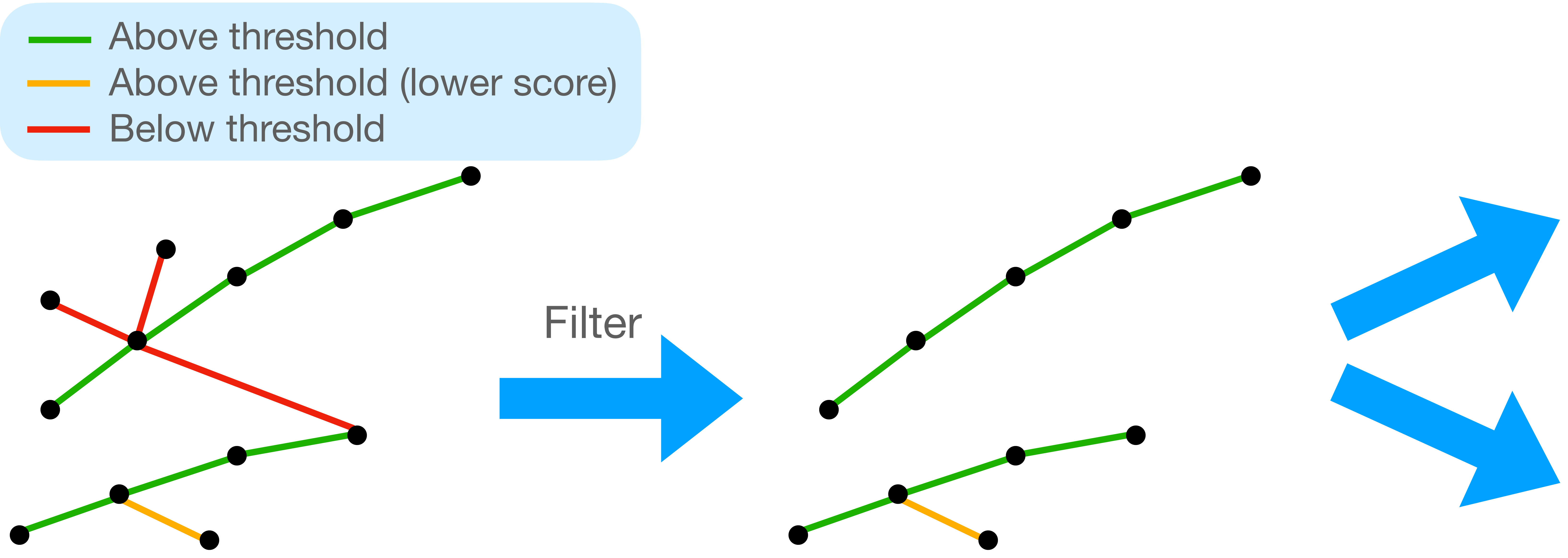
- GNN is **able to identify edges** that connects hits from same particle
- Most **challenging regions**: luminous region **close to beamspot** & **strips**

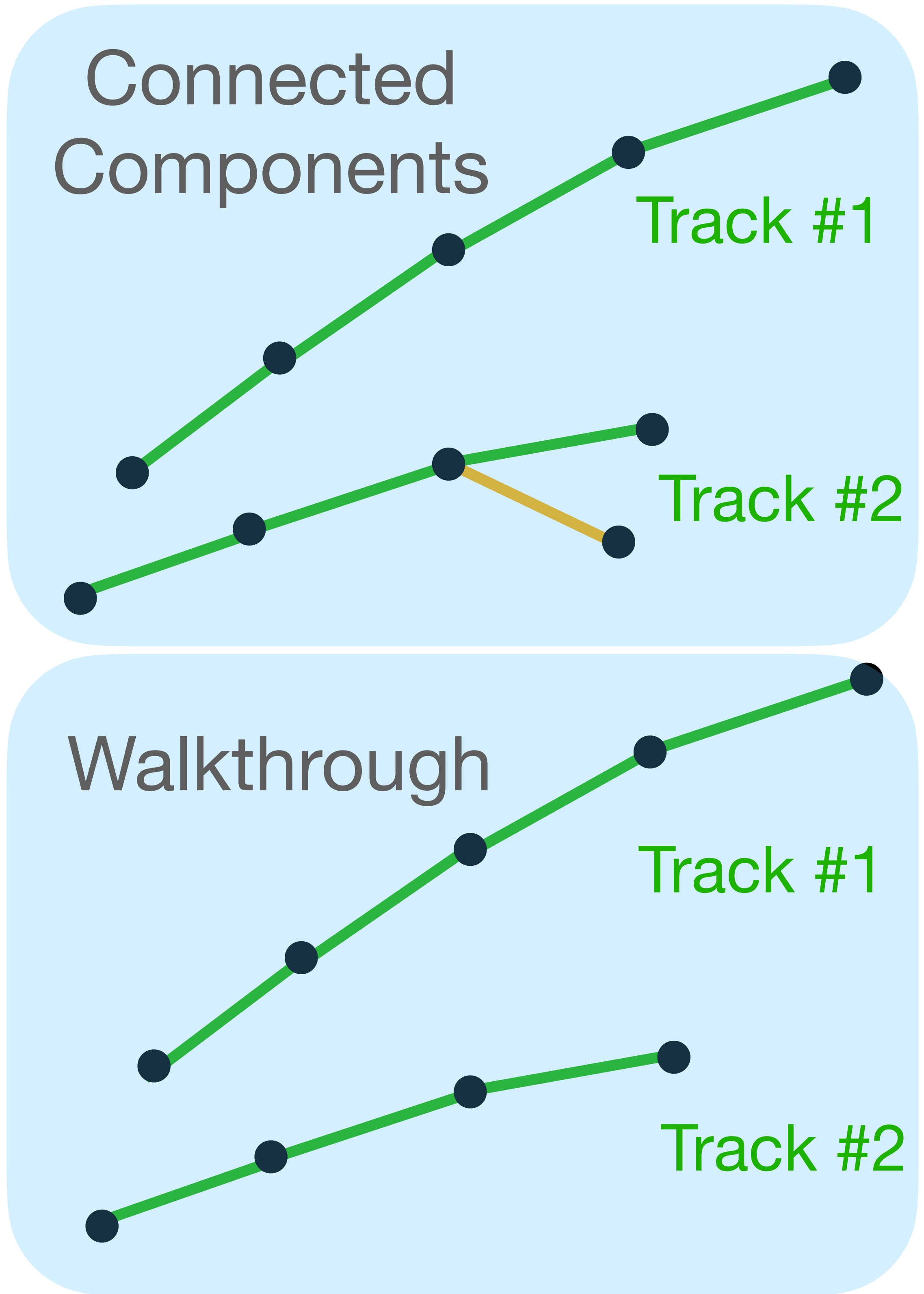
Graph segmentation

aka Track candidates Building

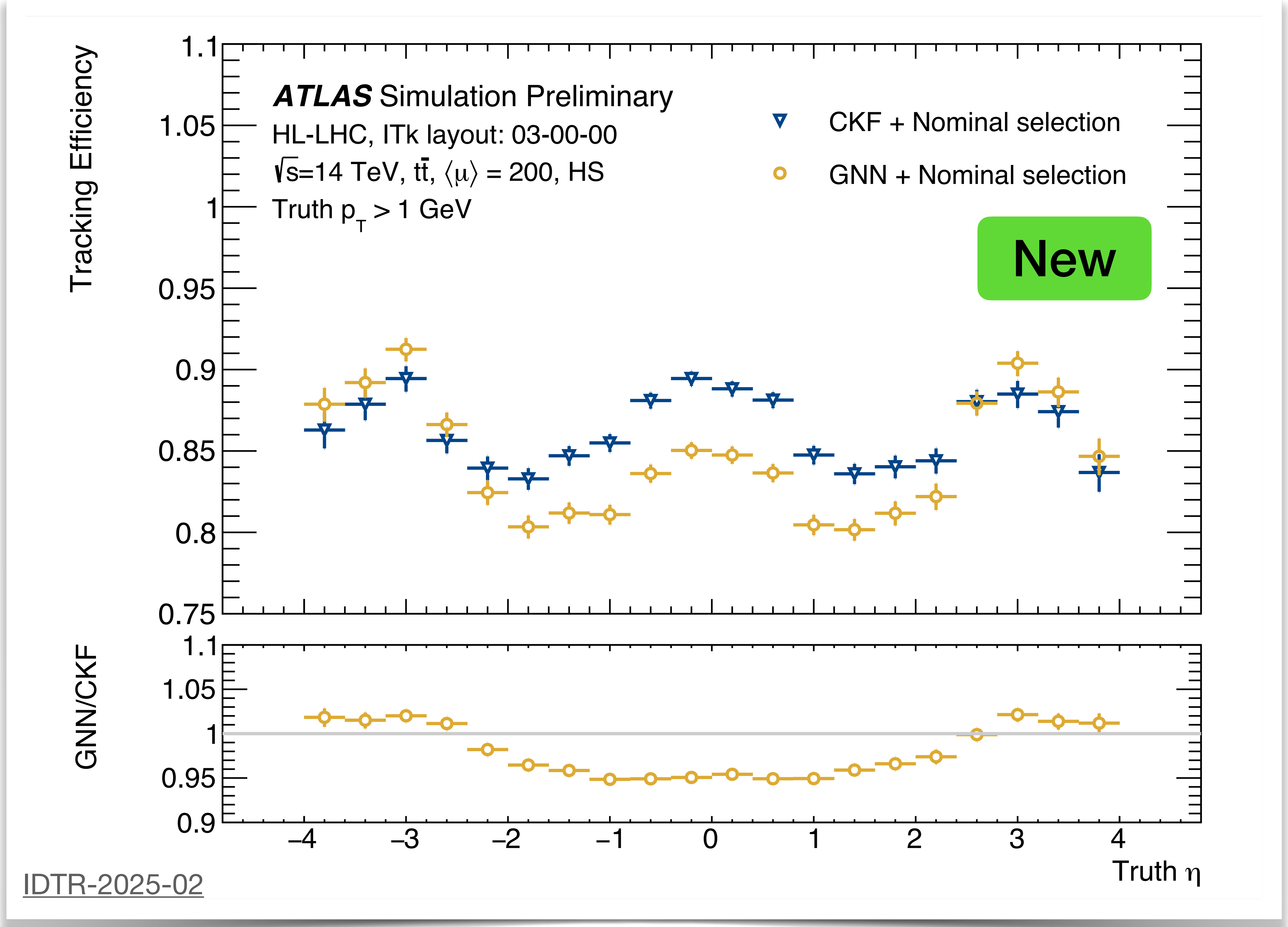


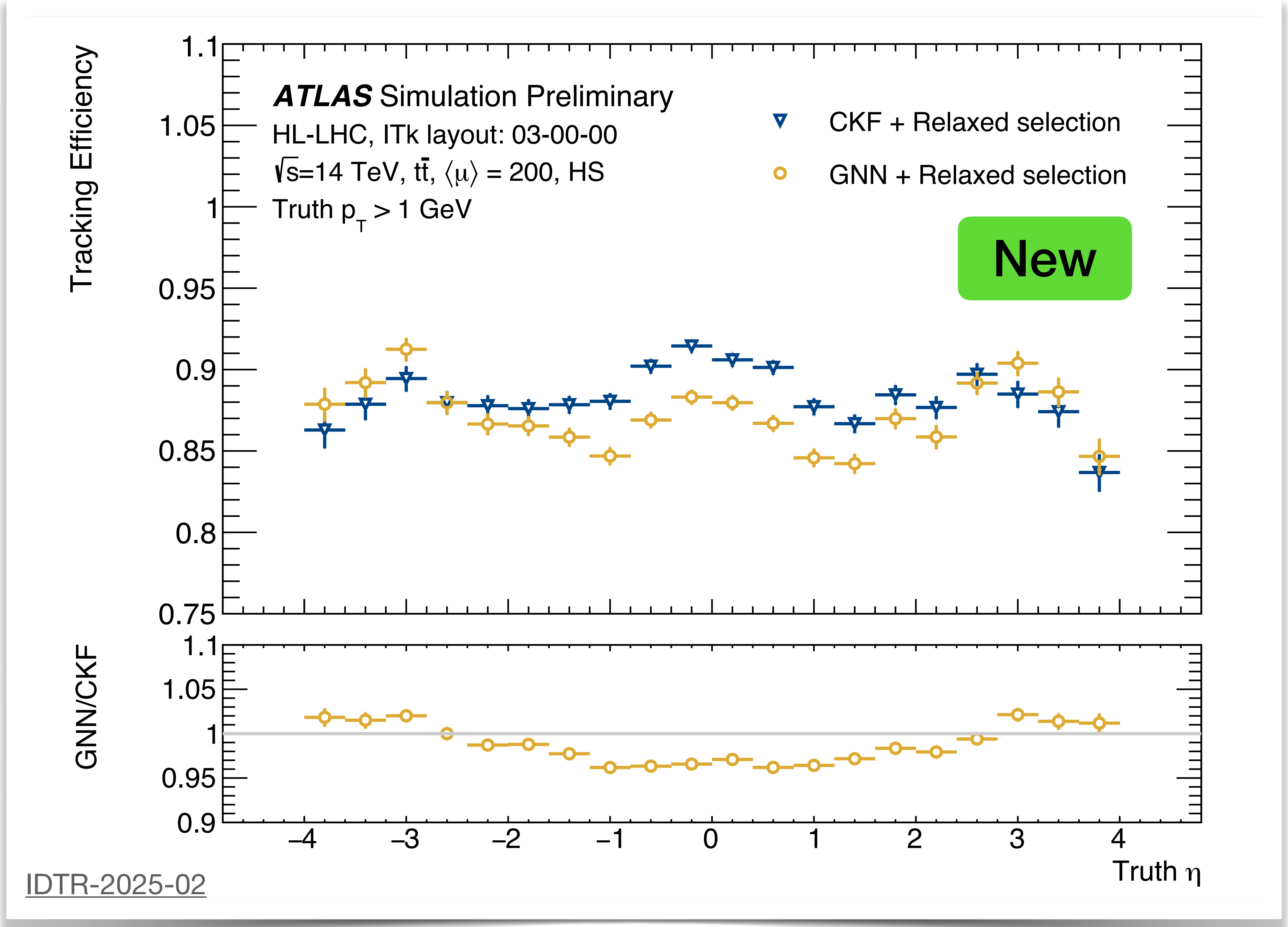
- Start from filtered graph (edge score cut)
  - Connected Component : one track candidate = 1 set of connected nodes
  - Walkthrough : walk through the graph, keep longest paths





Track efficiency vs η



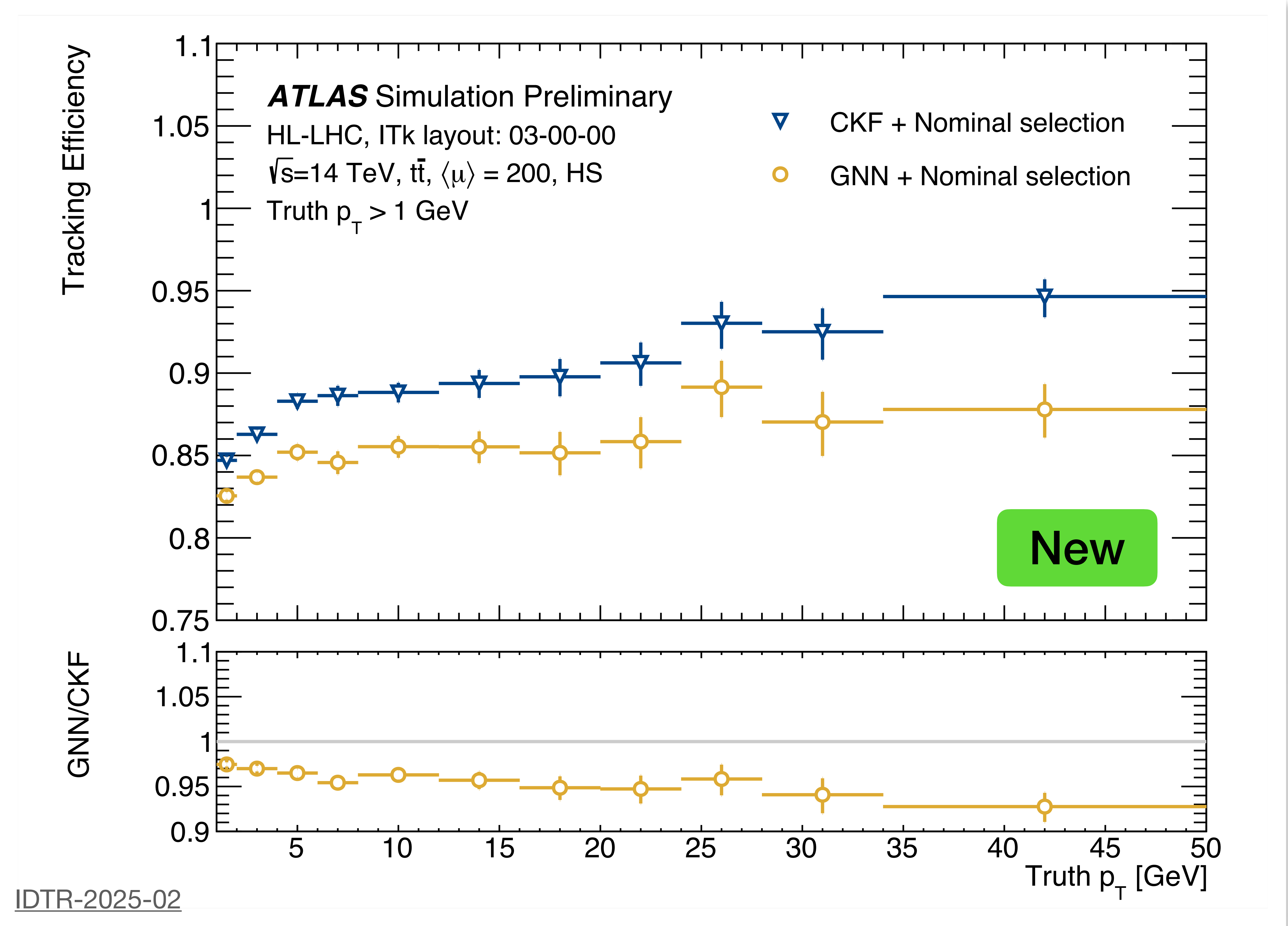


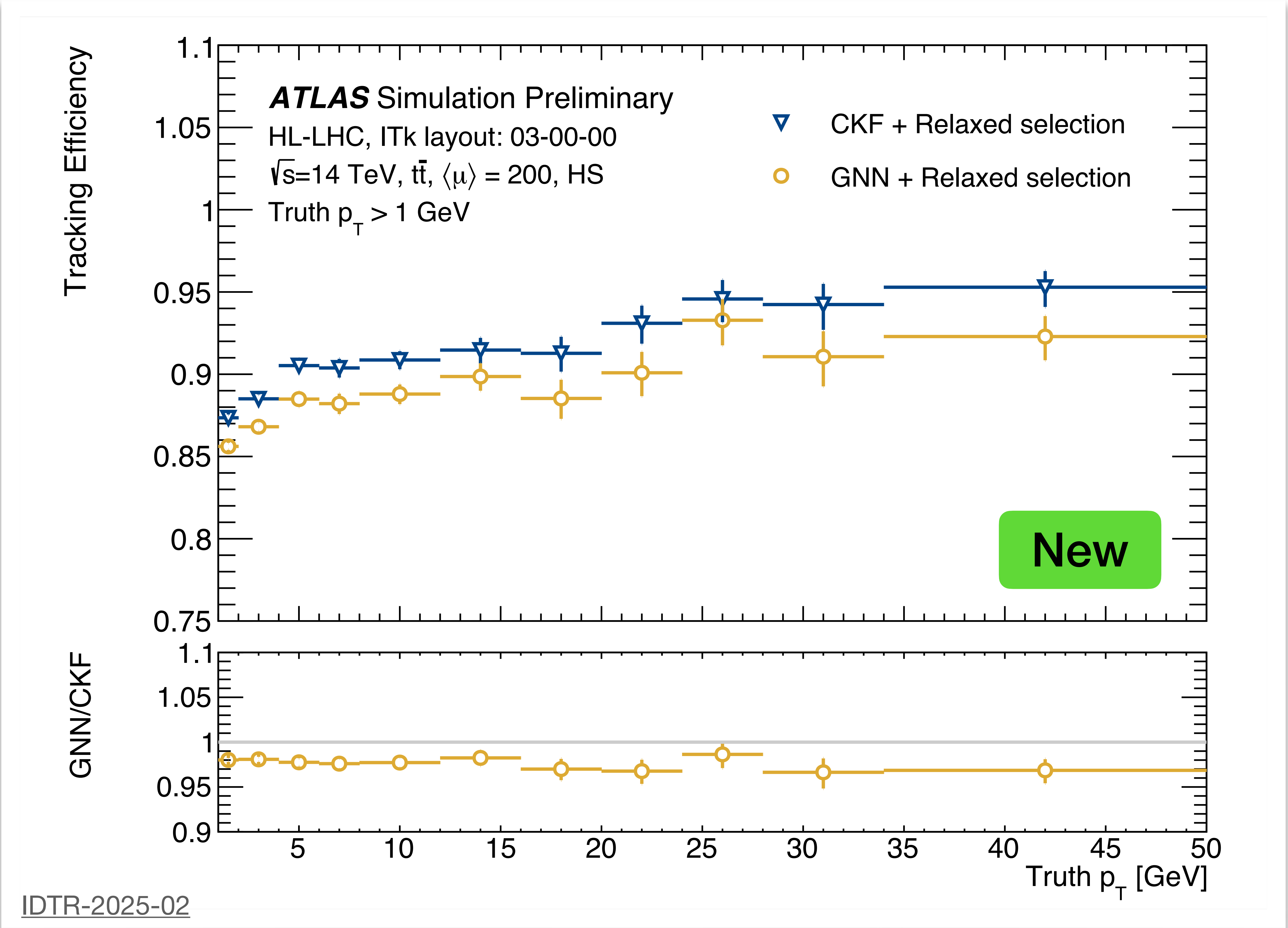
Nominal track selection defined for classic CKF reconstruction

GNN track finding based on Space Points not cluster: need to adapt selection due to Space Point formation inefficiencies → Relaxed selection (lower required number of clusters per track)

GNN tracking chain is able to reconstruct tracks with a good efficiency

Track efficiency vs p_T

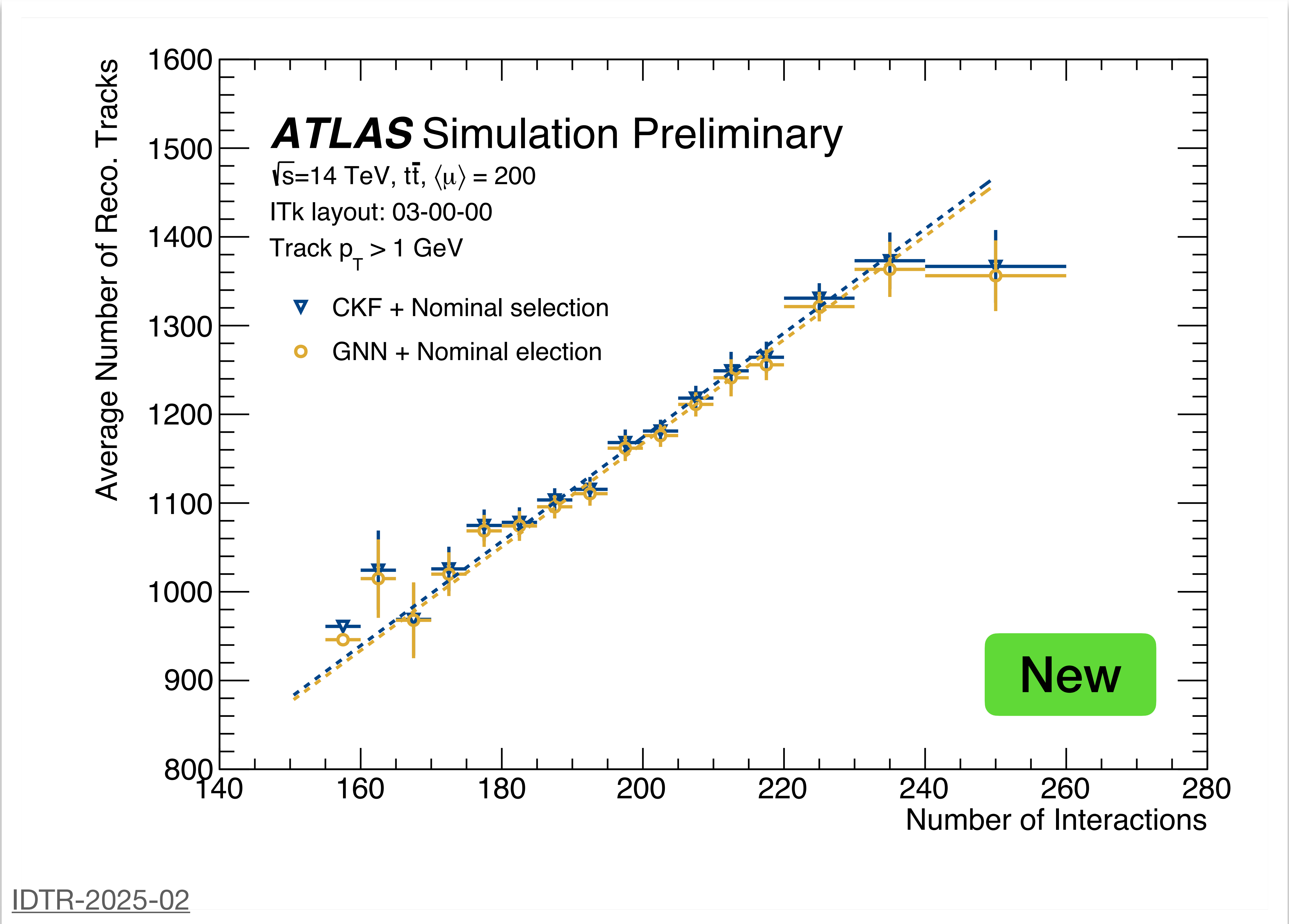


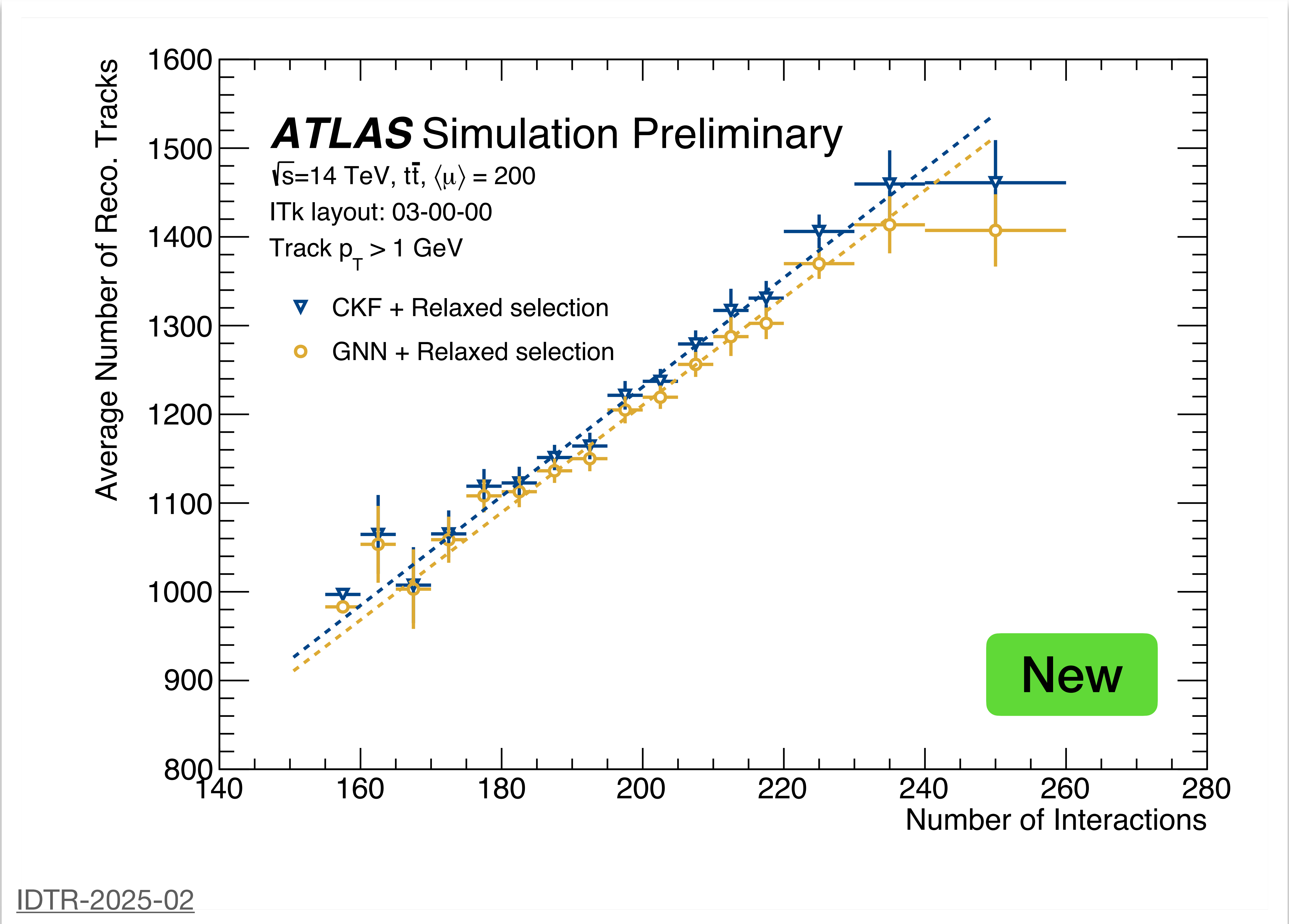


GNN tracking suffer a bit at high p_{T} because of reduced training statistics with $t\bar{t}$ sample

Should be mitigated in the future to use additional processes

Number of tracks vs μ

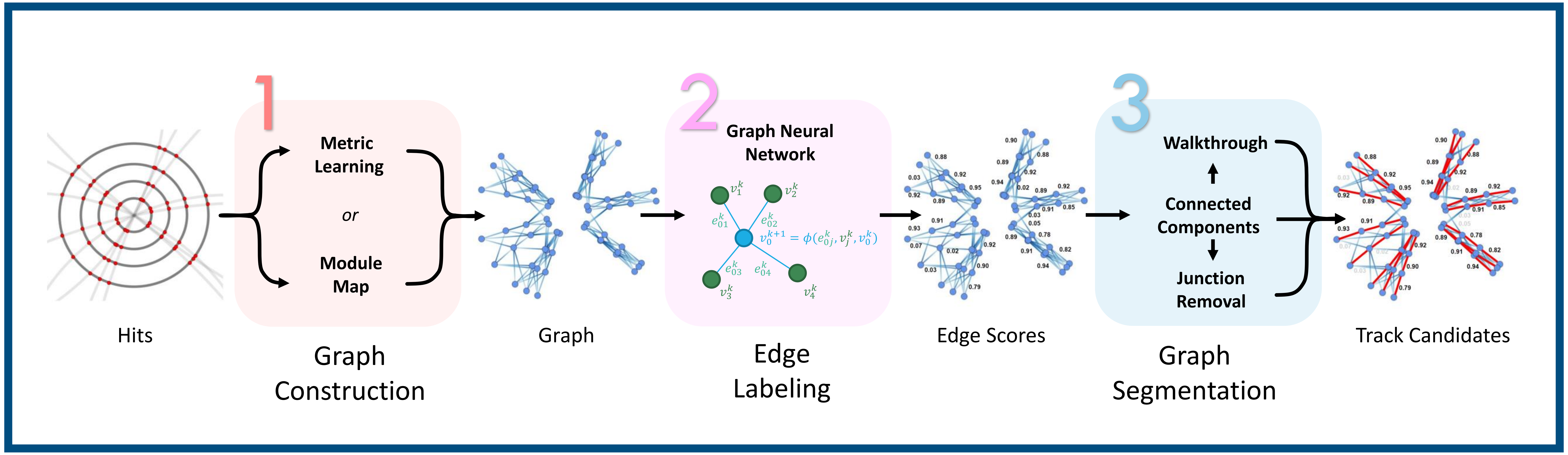




- Linear scaling : Fake and mis-reconstructed tracks are very low
- Even with relaxed cuts, fake rates for GNN does not significantly inflates

Compute Performance

Are we fast enough?



Module Map:	69 ms	+	323 ms	+	118 ms	=	510 ms
Metric Learning:	505 ms	+	108 ms	+	118 ms	=	731 ms

ATL-PHYS-PUB-2024-018

Several optimisation already made: graph building in CUDA, model compilation, automatic mixed precision

Already sub-second event processing

Even more are coming: model reduction & quantization, graph segmentation in CUDA…

Conclusion
& Outlook

We have designed a **GNN-based track finding algorithm** that is **competitive** with the standard **Combinatorial Kalman Filter** in terms of tracking performance

The **compute time is promising** to help processing HL-LHC data…

… and computing optimization have just started

The algorithm **is being integrated to the official ATLAS software**

Coming soon: **robustness studies** (non ideal detector) and **more detailed physics studies** (other processes than $t\bar{t}$, electrons, boosted jets, displaced vertices)

BACKUP

Track Selection

Nominal (Relaxed) Requirements	Pseudorapidity Interval		
	$\|\eta\| \leq 2.0$	$2.0 < \|\eta\| \leq 2.6$	$2.6 < \|\eta\| \leq 4.0$
Pixel + Strip hits	≥ 9 (7)	≥ 8 (7)	≥ 7
Pixel hits	≥ 1	≥ 1	≥ 1
Holes	≤ 2 (4)	≤ 2 (4)	≤ 2
p_T [MeV]	> 900	> 400	> 400
$\|d_0\|$ [mm]	< 2.0	< 2.0	< 10.0
$\|z_0\|$ [cm]	< 20.0	< 20.0	< 20.0

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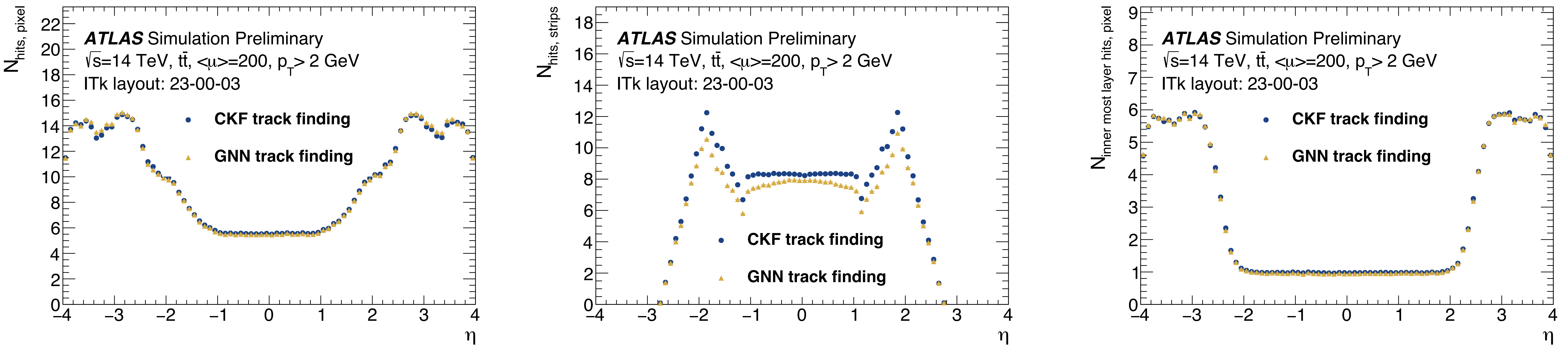
Previous results

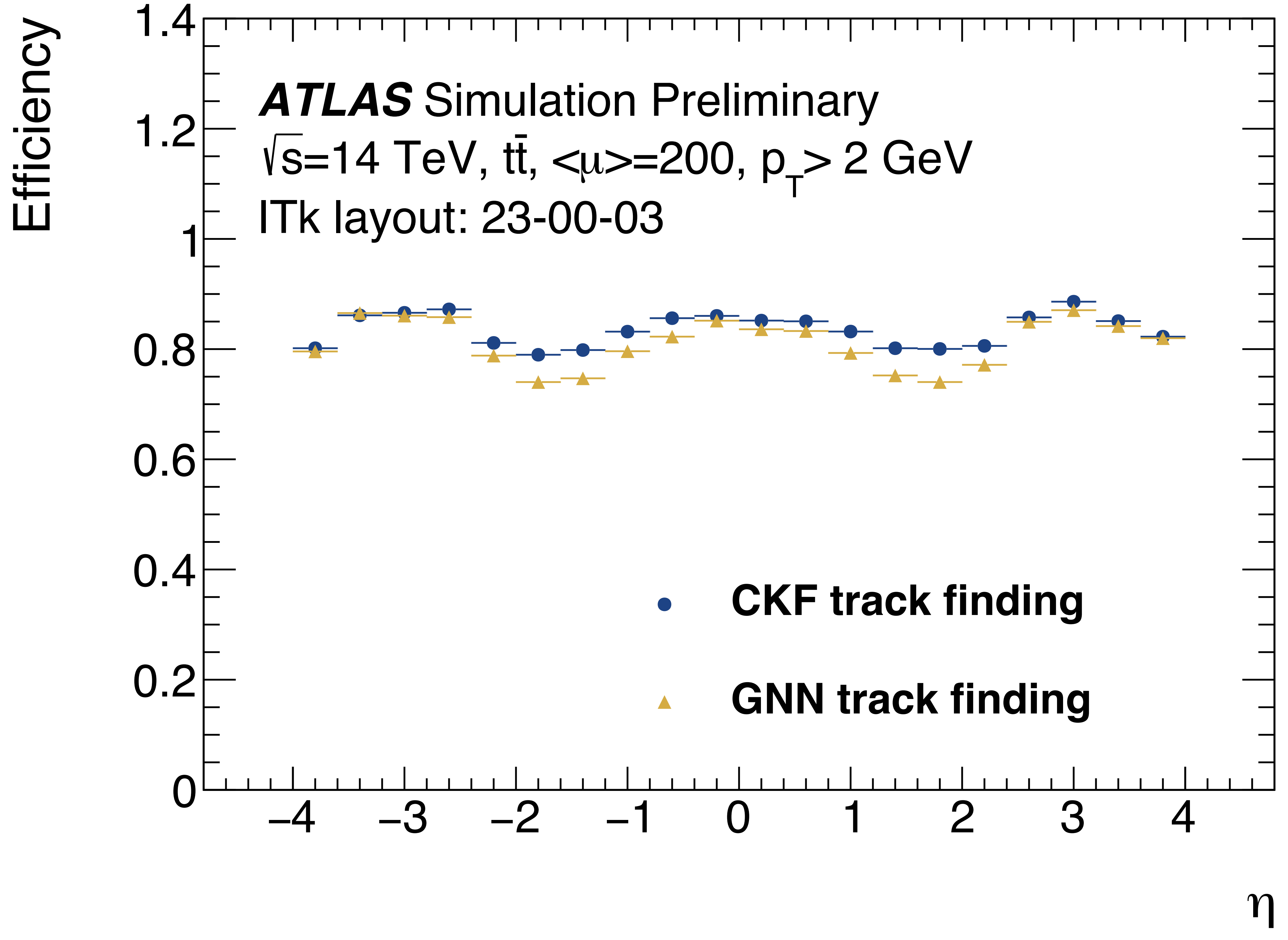
hit content

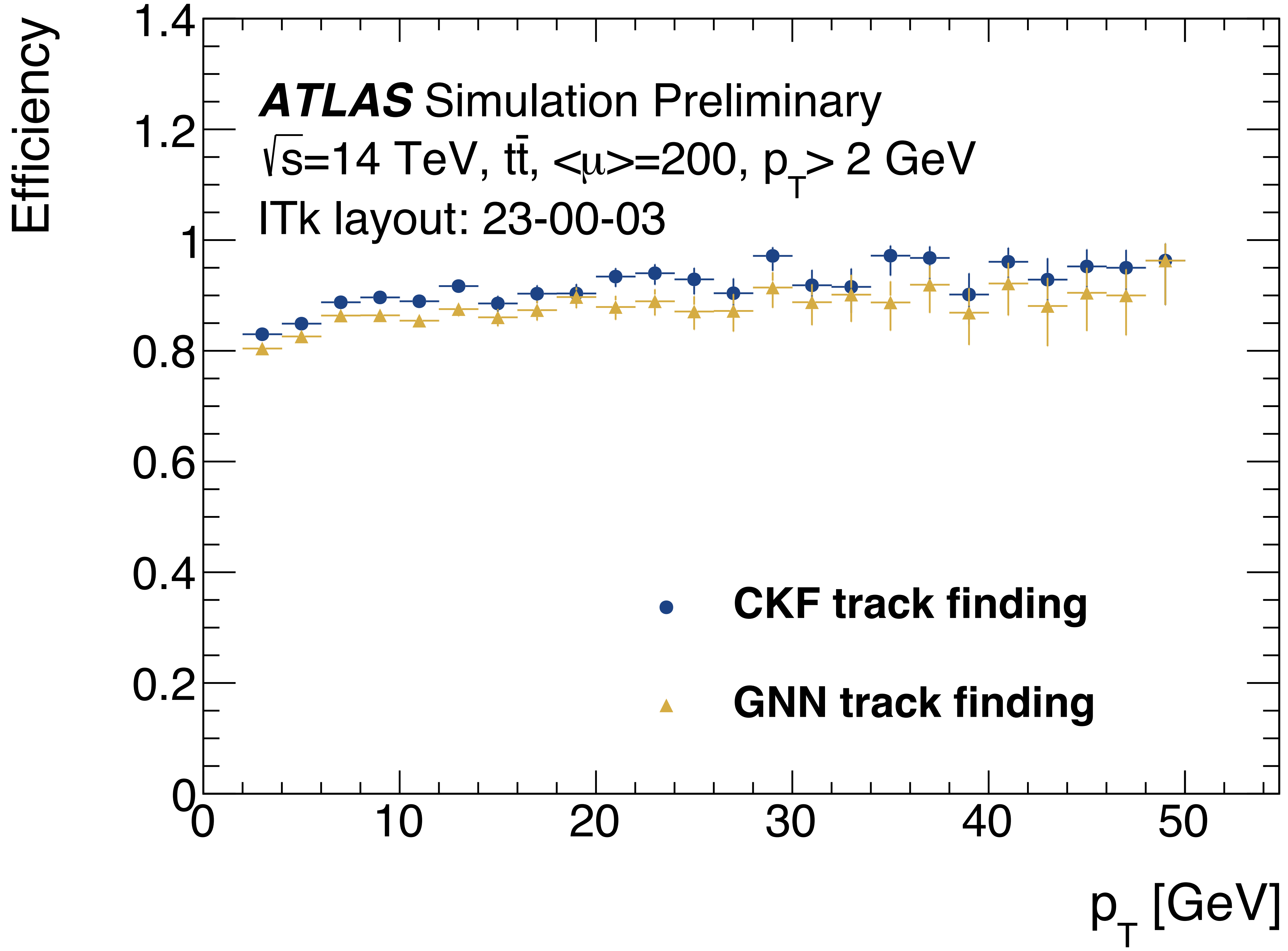


Torres, H., et al (2024, March 7). Physics Performance of the ATLAS GNN4ITk Track Reconstruction Chain. Connecting The Dots Workshop 2023 (CTD2023), Toulouse (France).

Previous results

Efficiencies





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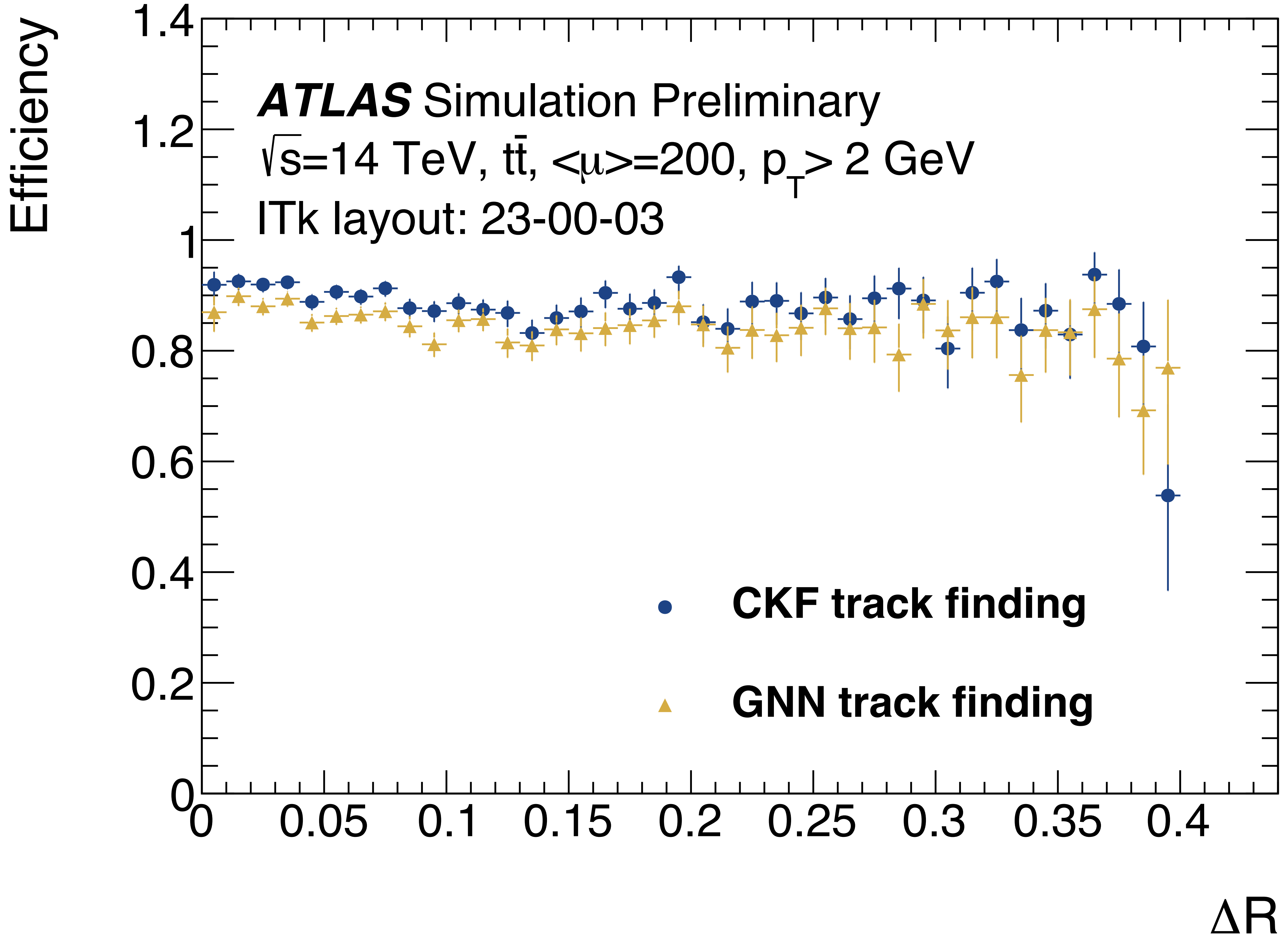
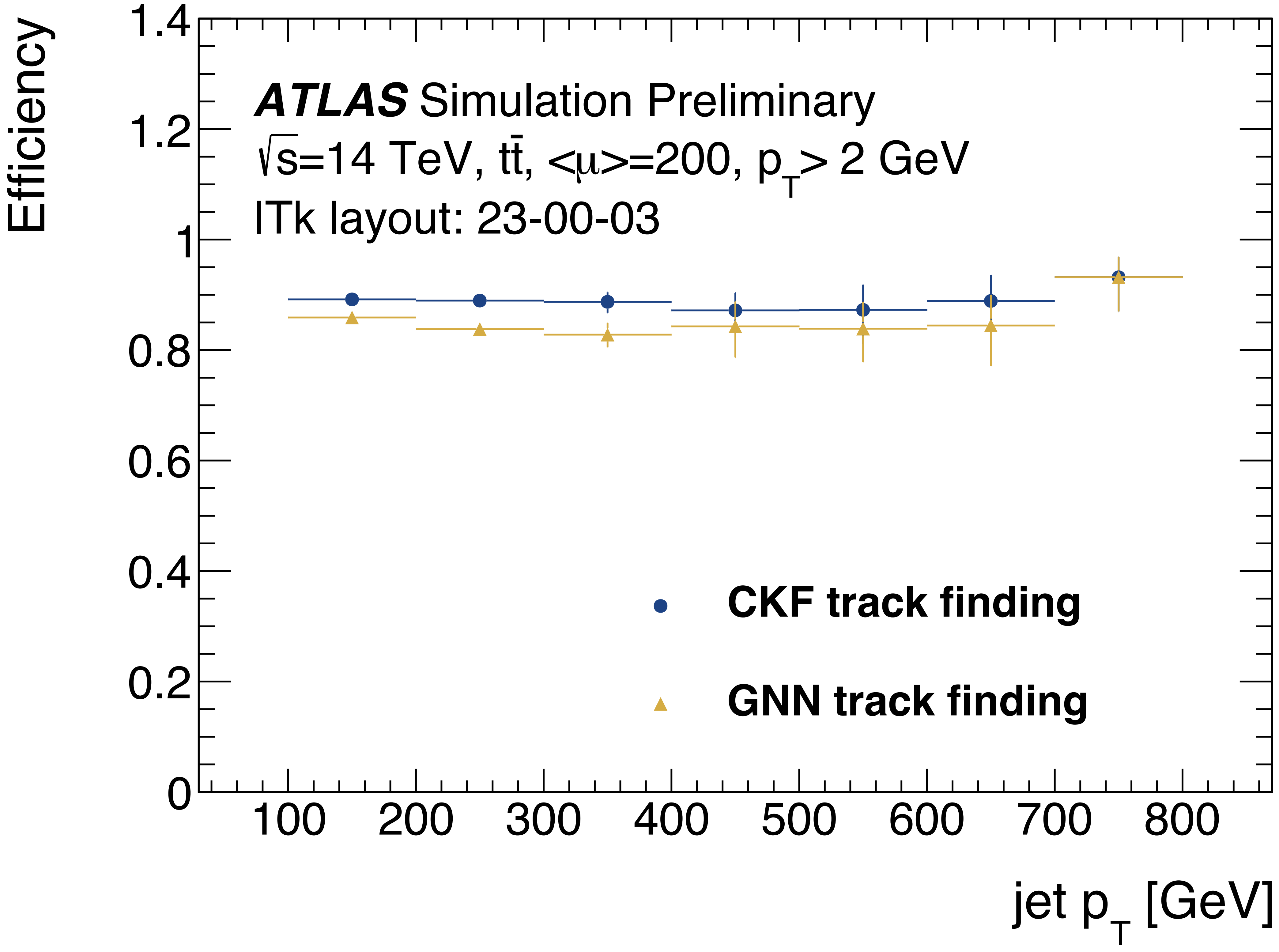
Previous results

Jets





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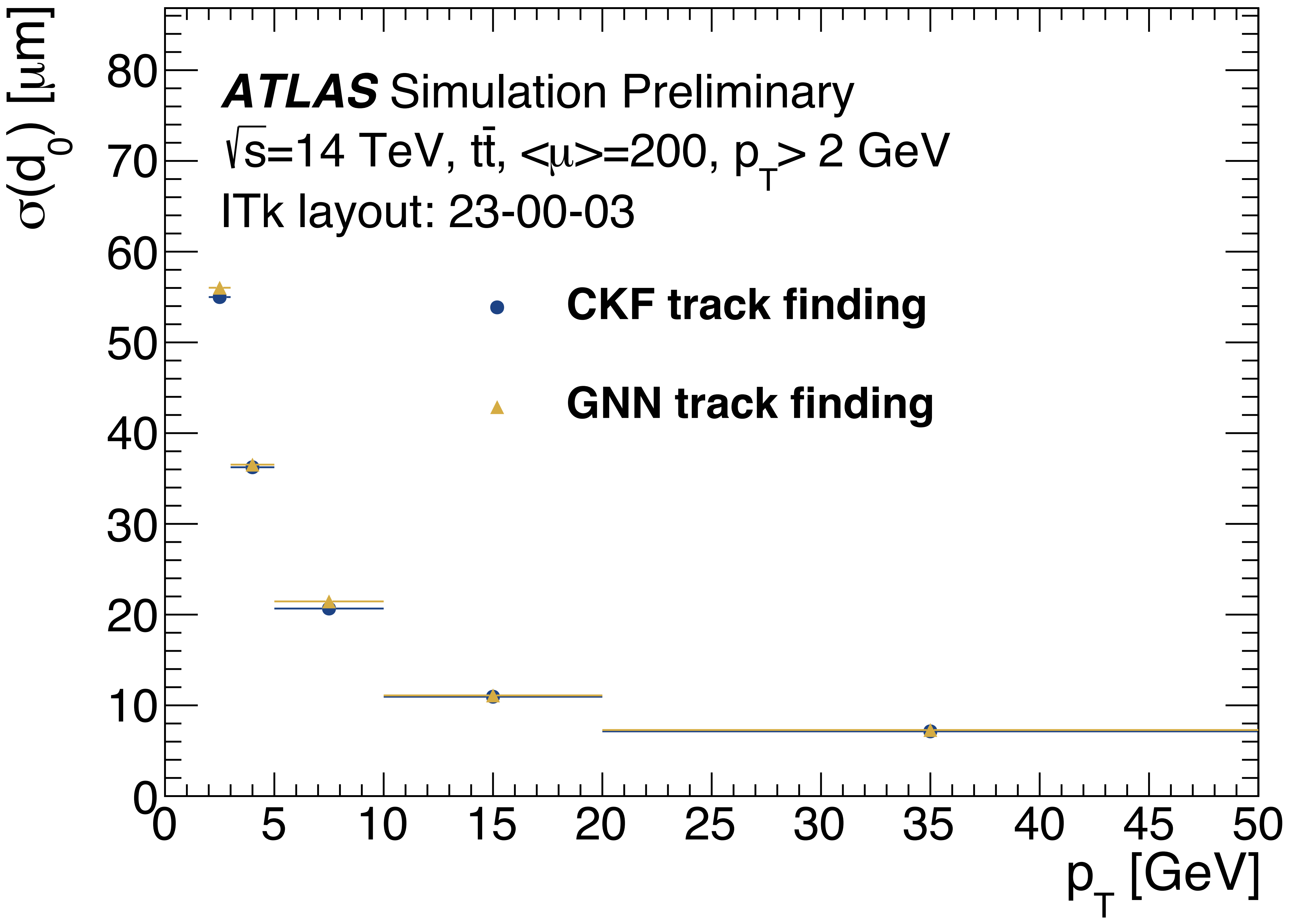

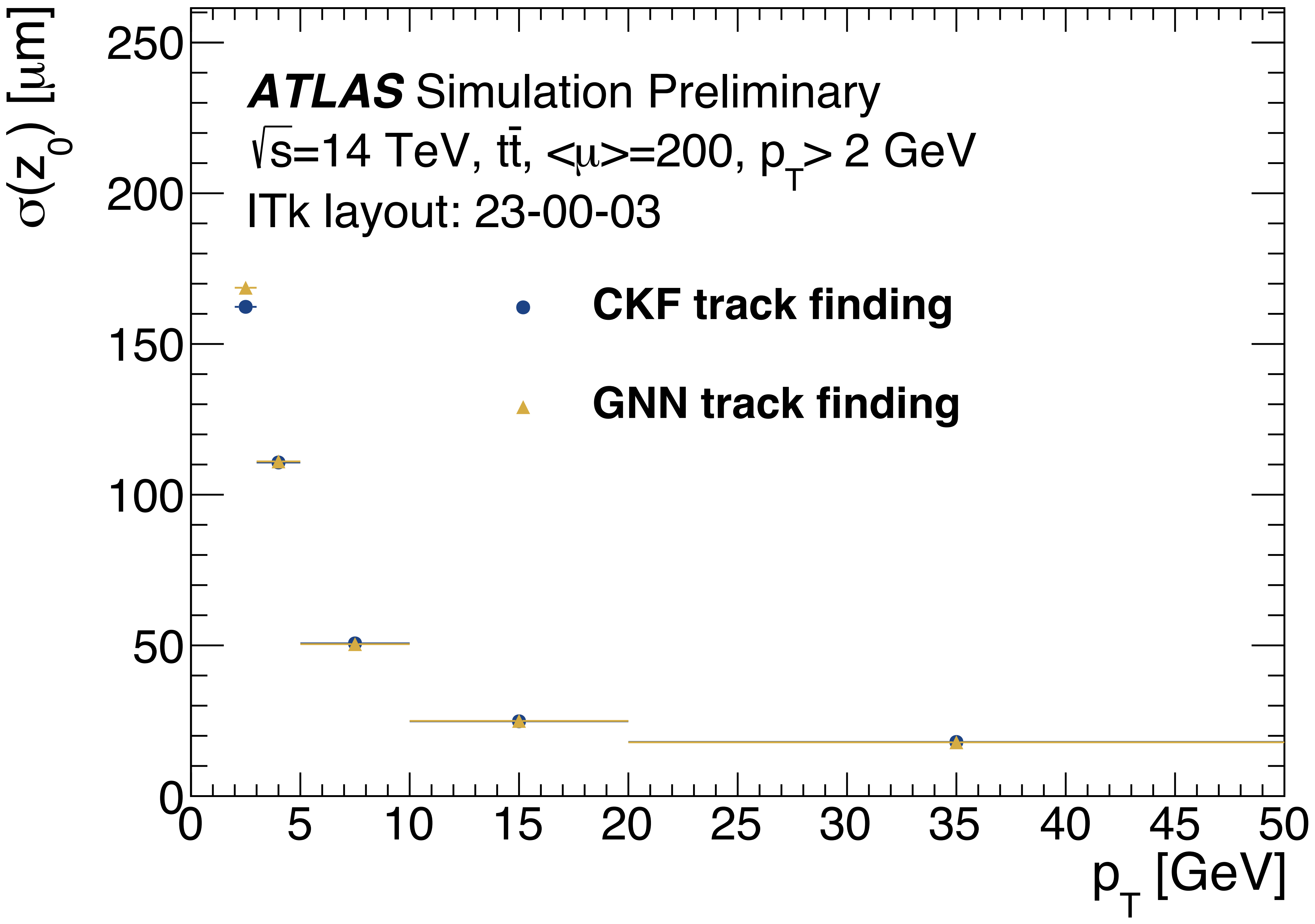

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