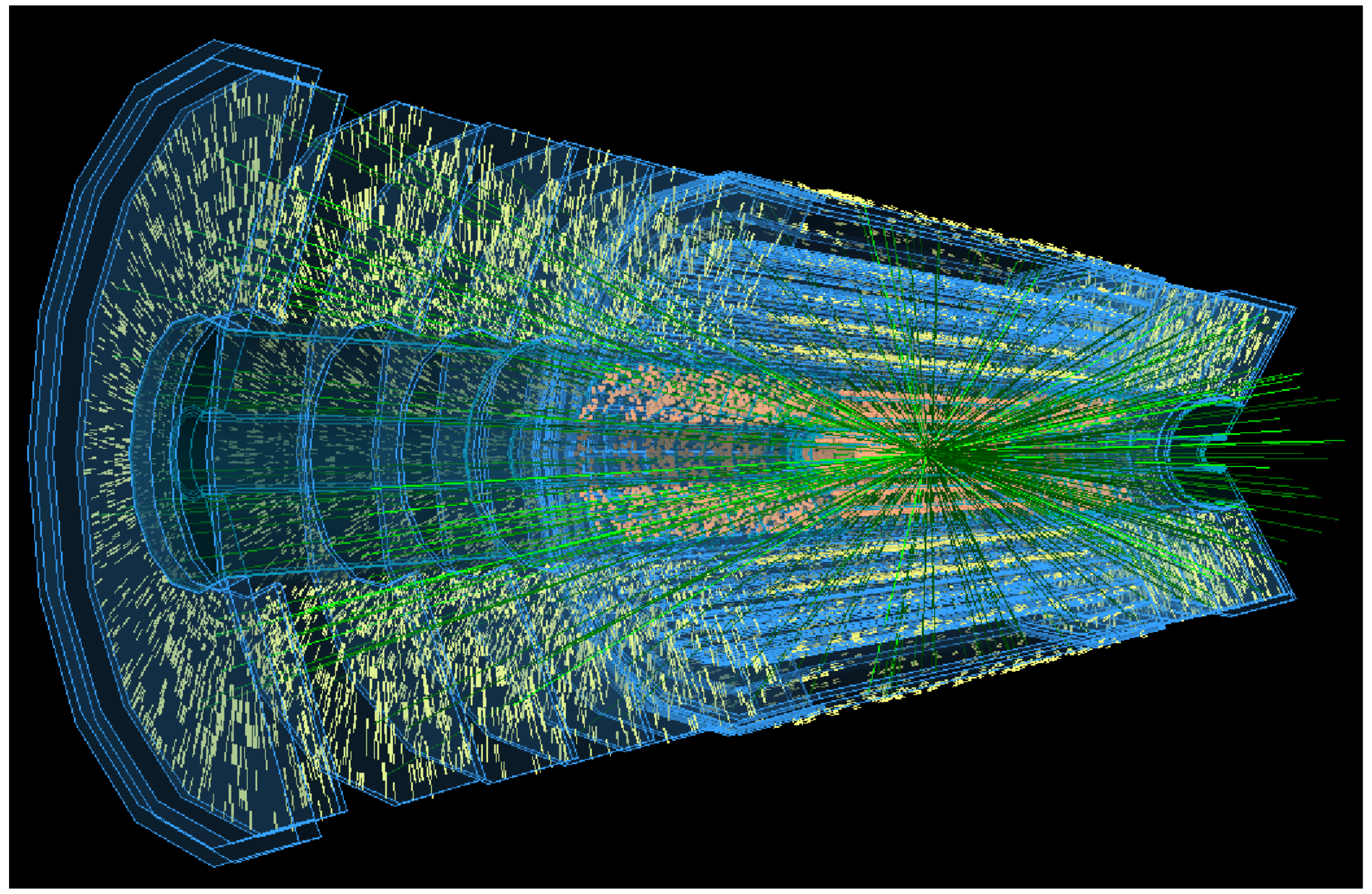
Physics Performance of the
ATLAS GNN4ITk
Track Reconstruction Chain

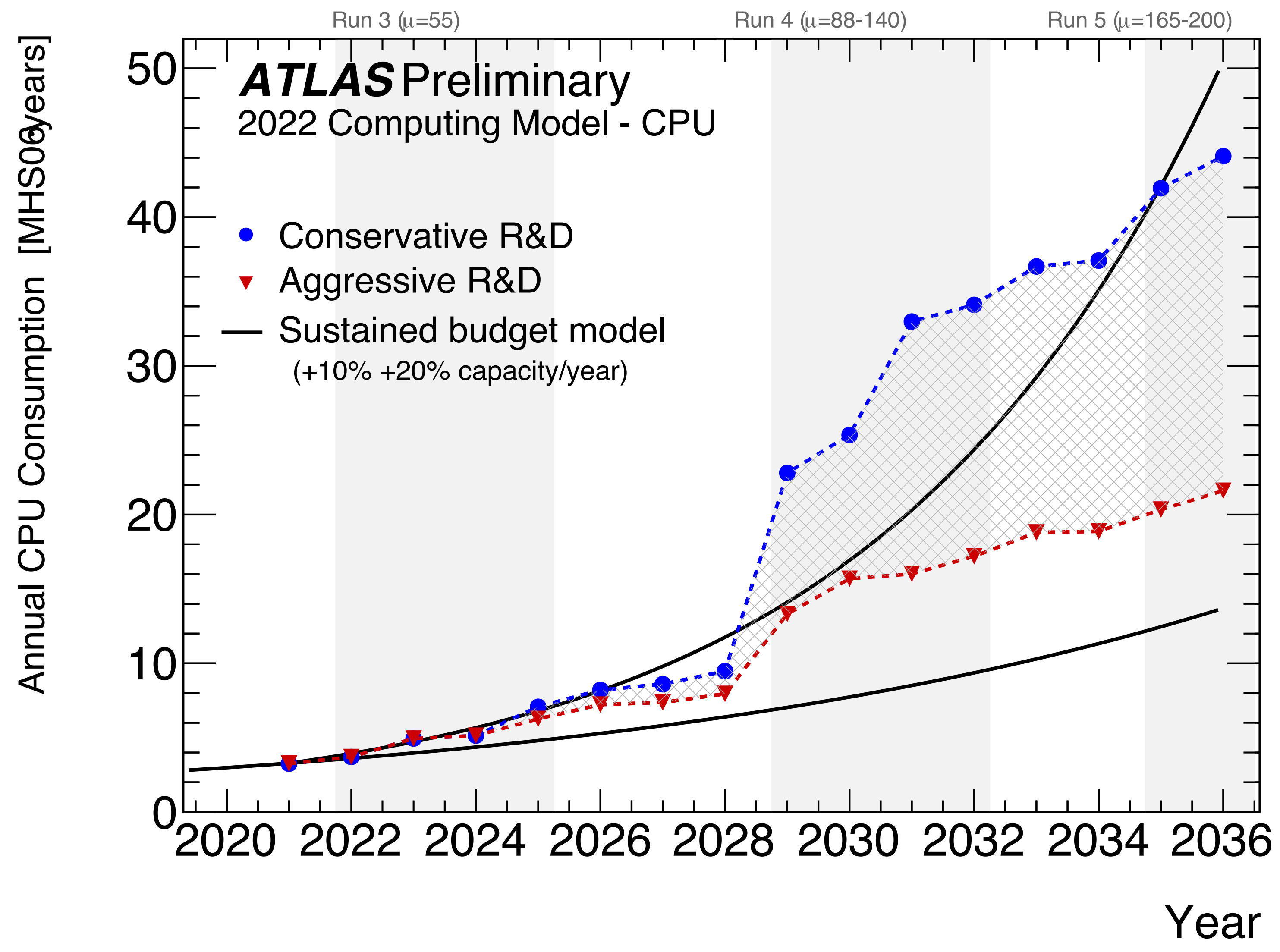


Heberth Torres (L2I Toulouse)
on behalf of the ATLAS Collaboration

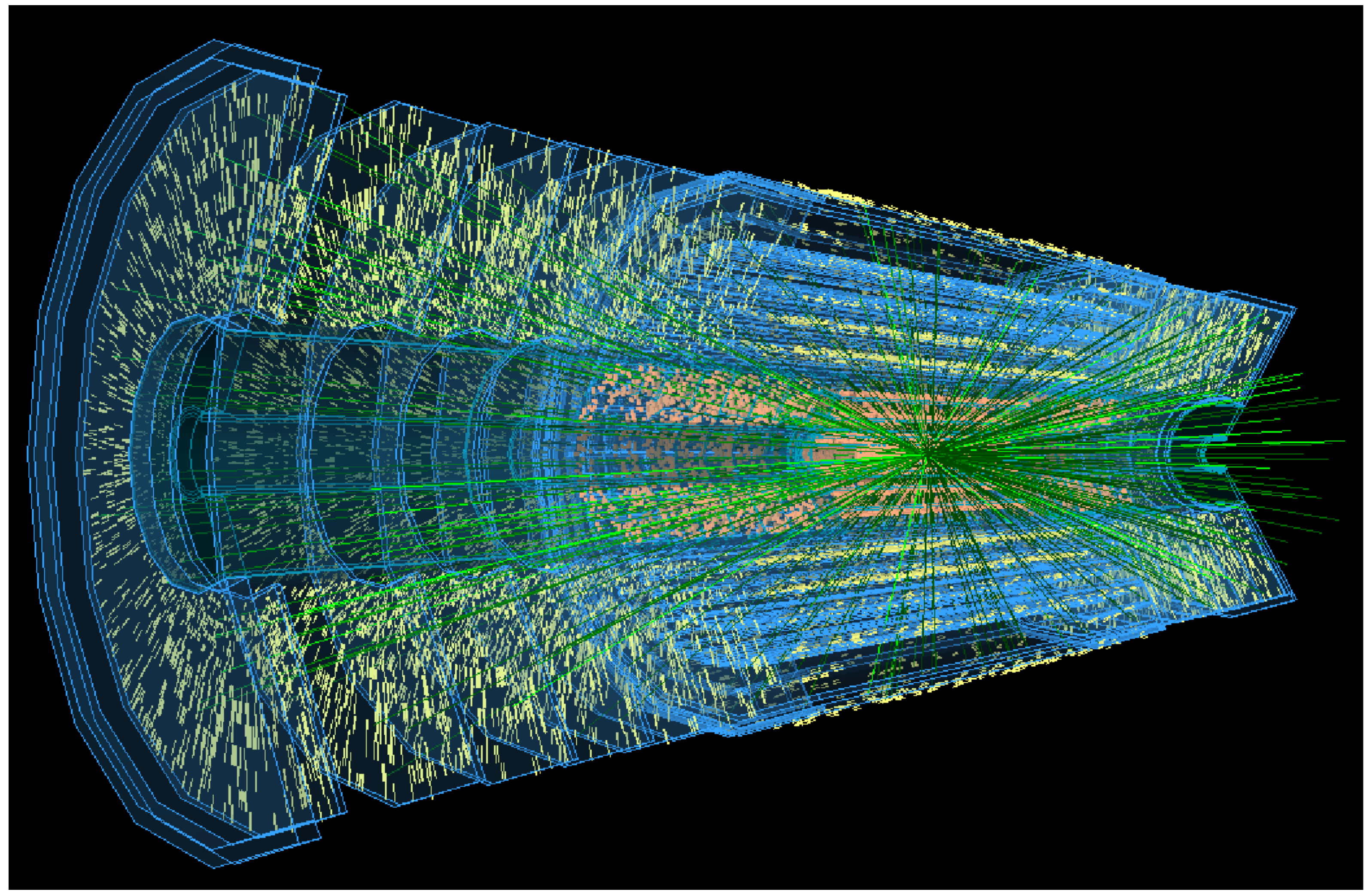
Connecting The Dots Workshop
10/10/2023

Introduction

ATLAS GNN4ITk

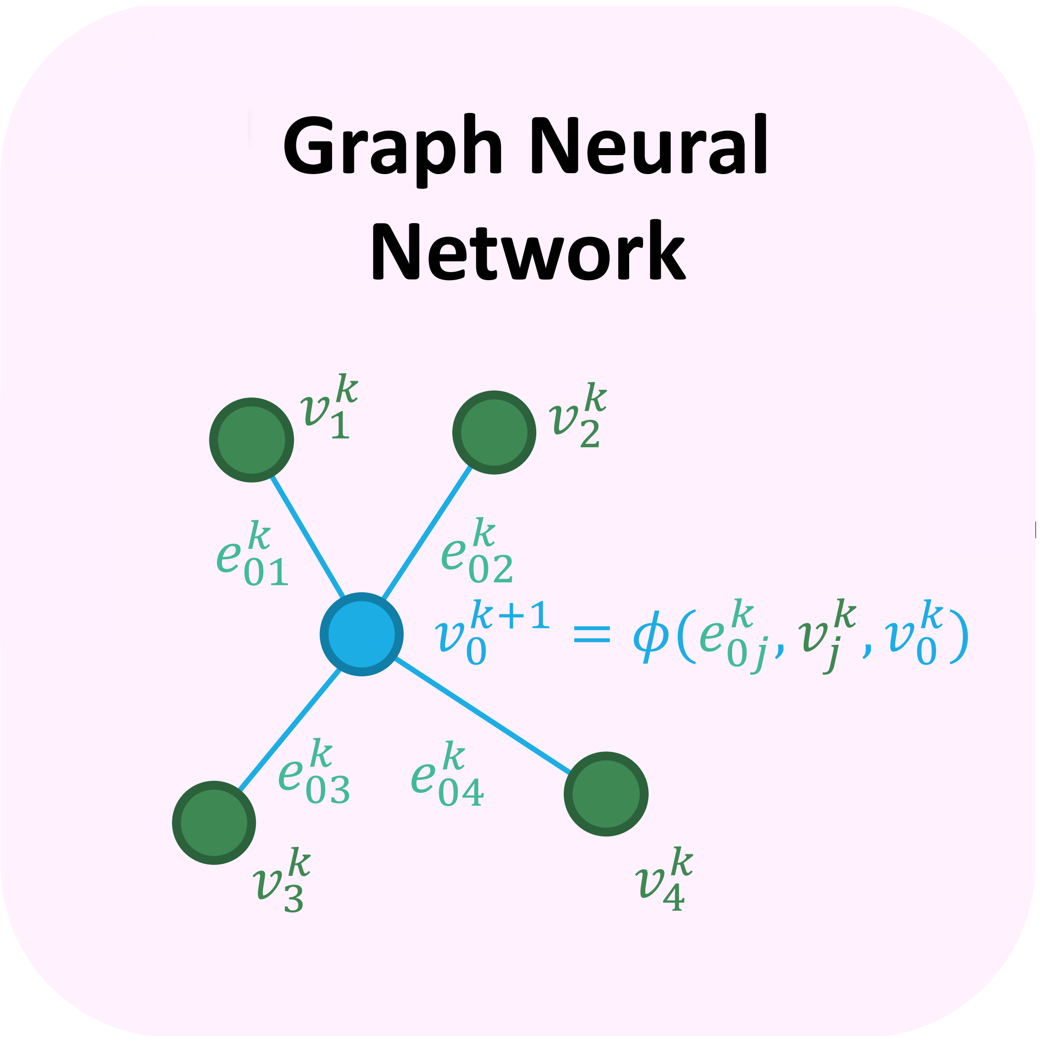


Future ATLAS Inner Tracker ITk
for the High Luminosity LHC
with extended coverage $|\eta| < 4$
expect 10^5 hits per event
(200 pp interaction pileup)



Projection of ATLAS compute usage
shows the need for
aggressive computing R&D

Graph Neural Networks GNN
shown as promising solution
for charged particle track reconstruction
using GPUs
(Exa.TrkX, L2IT, within ATLAS)

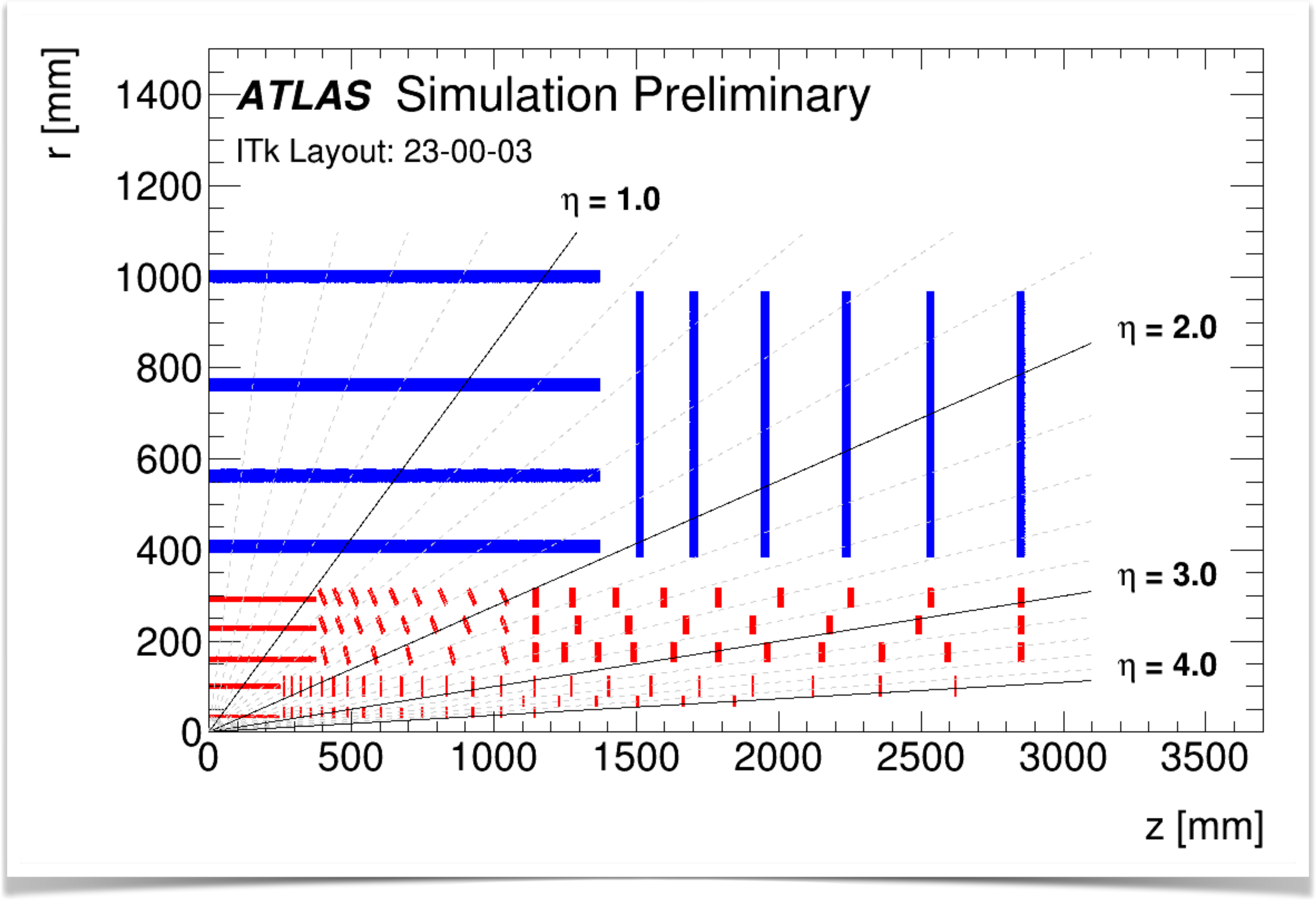


Outline

- Description of the GNN4ITk tracking
- Physics performance
  - Efficiency
  - Track hit content
  - Resolution of track parameters

(ATLAS GNN4ITk plot references: May 2022, May 2023, **Oct. 2023**)

Simulation data



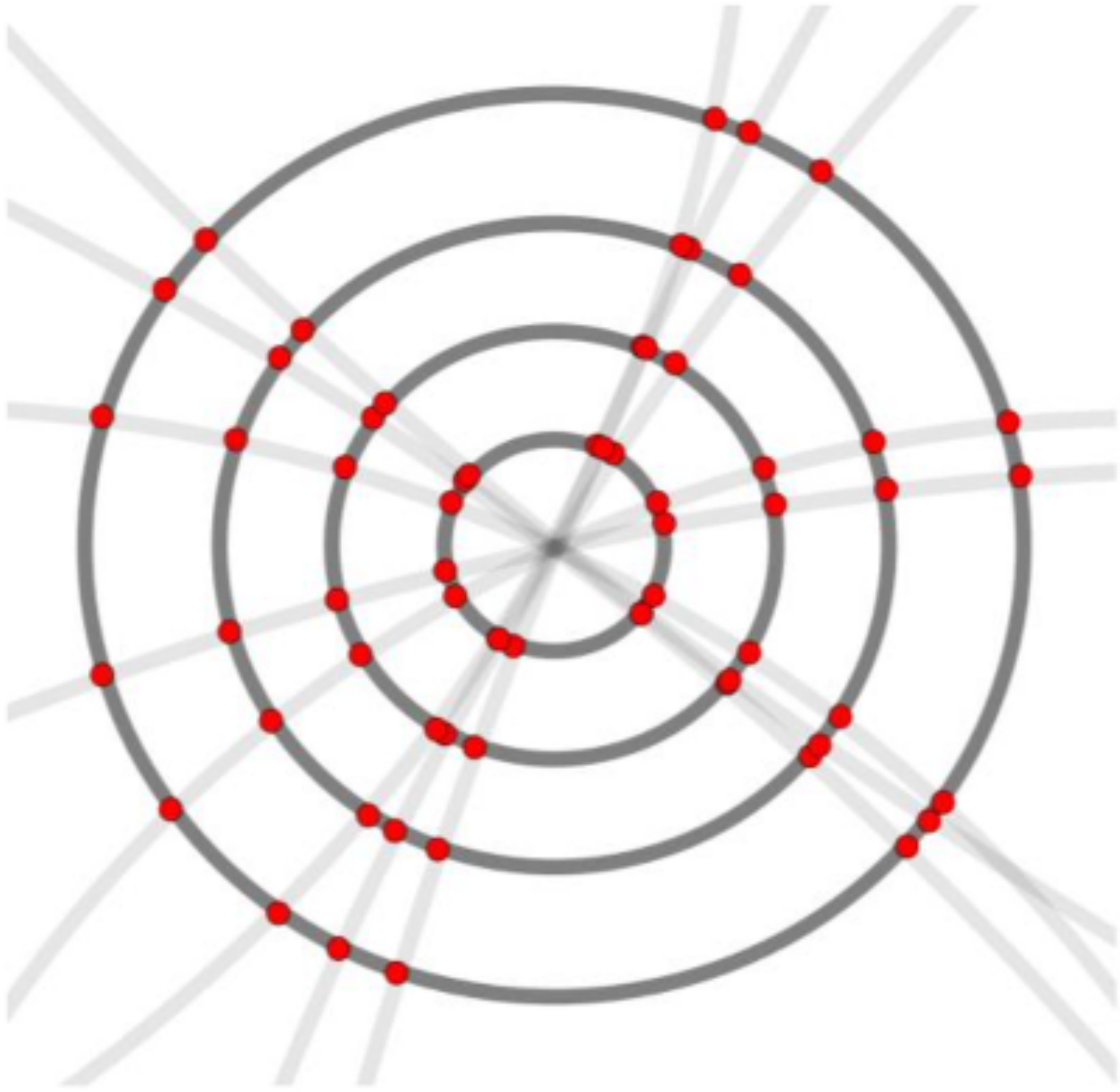
- Using ATLAS simulation event sample:
  pp collisions at $\sqrt{s} = 14$ TeV, $t\bar{t}$ process,
  $\langle \mu \rangle = 200$ pp interaction pileup

- For today's new physics performance plots: updated ITk layout 23-00-03
  (reduced radius of innermost pixel layer, and distribution of passive material with greater detail and accuracy)

- Target particles:
  - $p_T > 1$ GeV, with at least 3 hits or space points, no electron,
  - only primary particles (including B hadron decays)
    (without "secondary" Geant4 particles from material interactions)

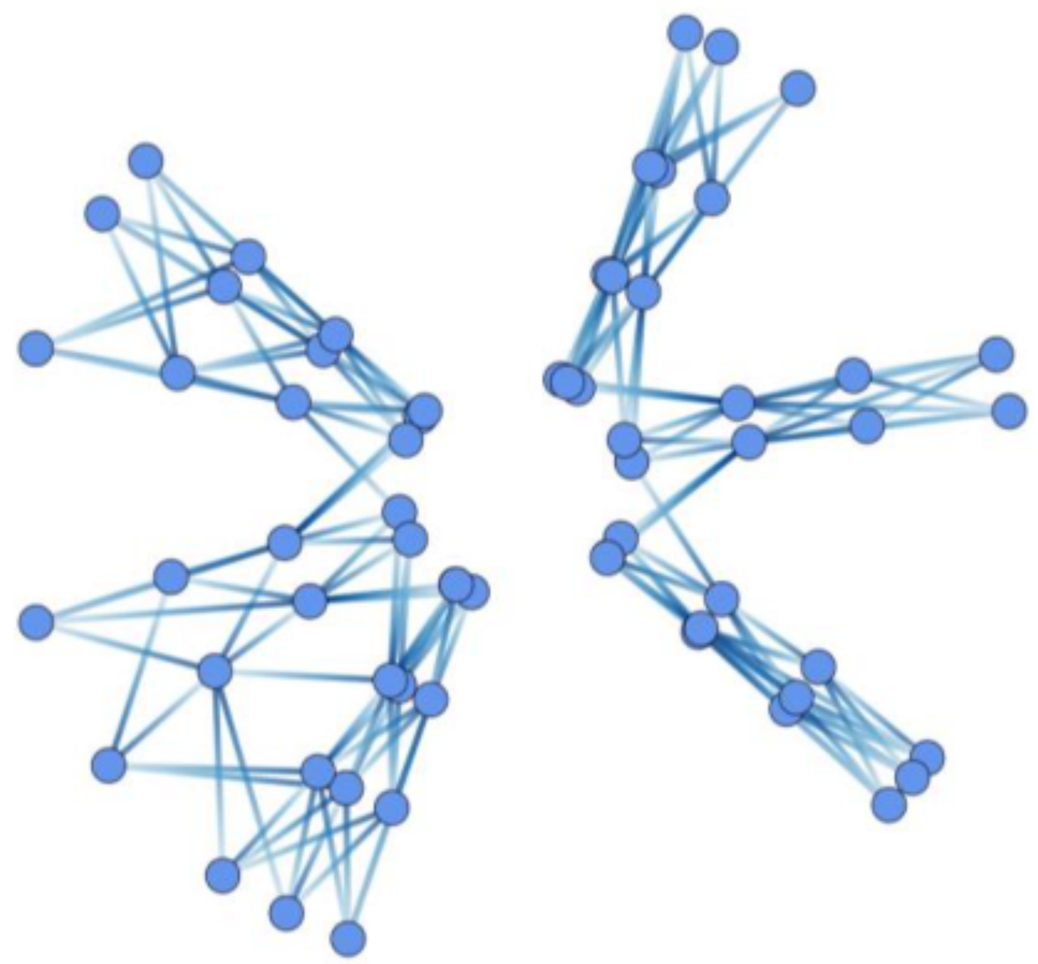
ATLAS GNN4ITk

Our graph definition



Hits

- Hit or space point in ITk

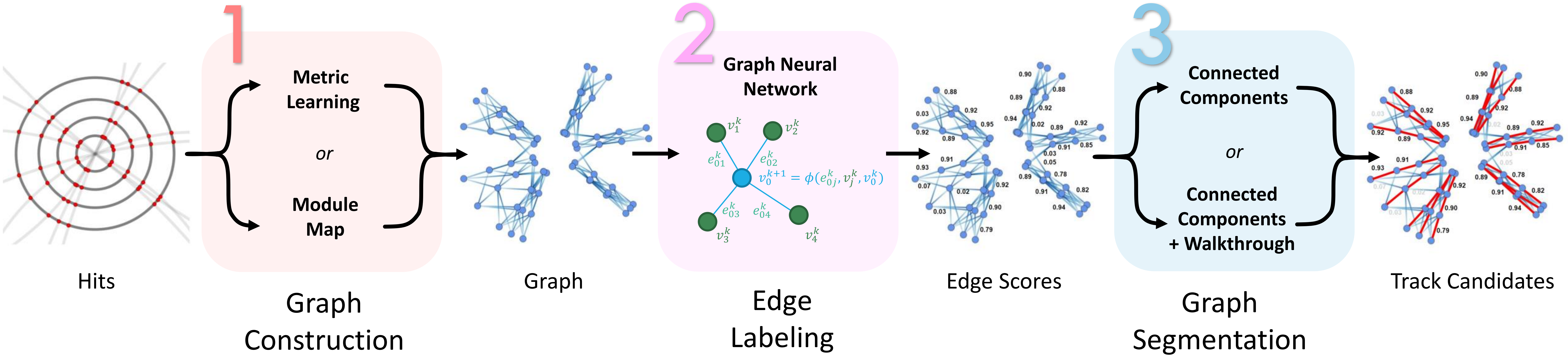


Graph

- **Graph:** Set of nodes and edges
- **Node:** Hit or space point
- **Edge:** Hypothesis: The two associated nodes represent two successive **hits of the same particle**

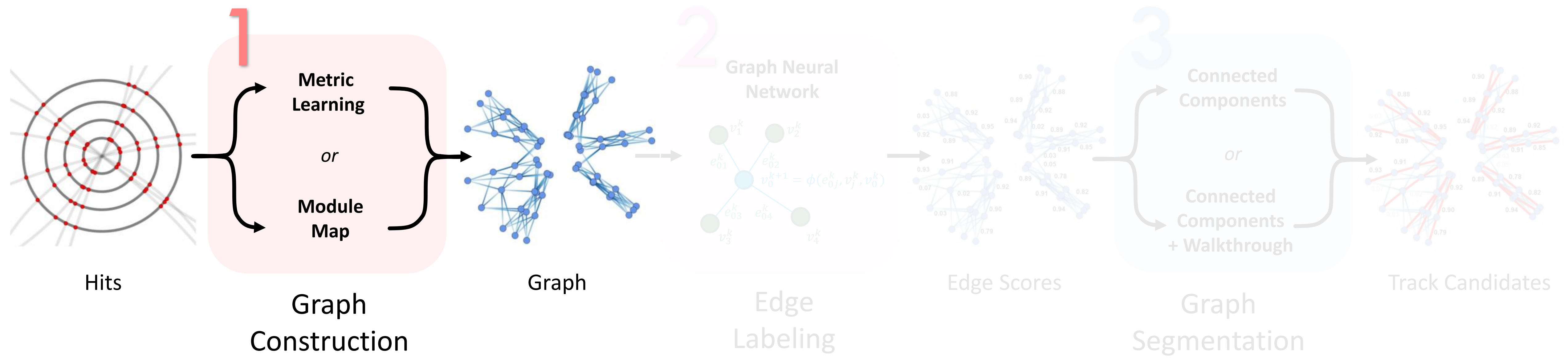
ATLAS GNN4ITk

Track Reconstruction Chain



GNN4ITk

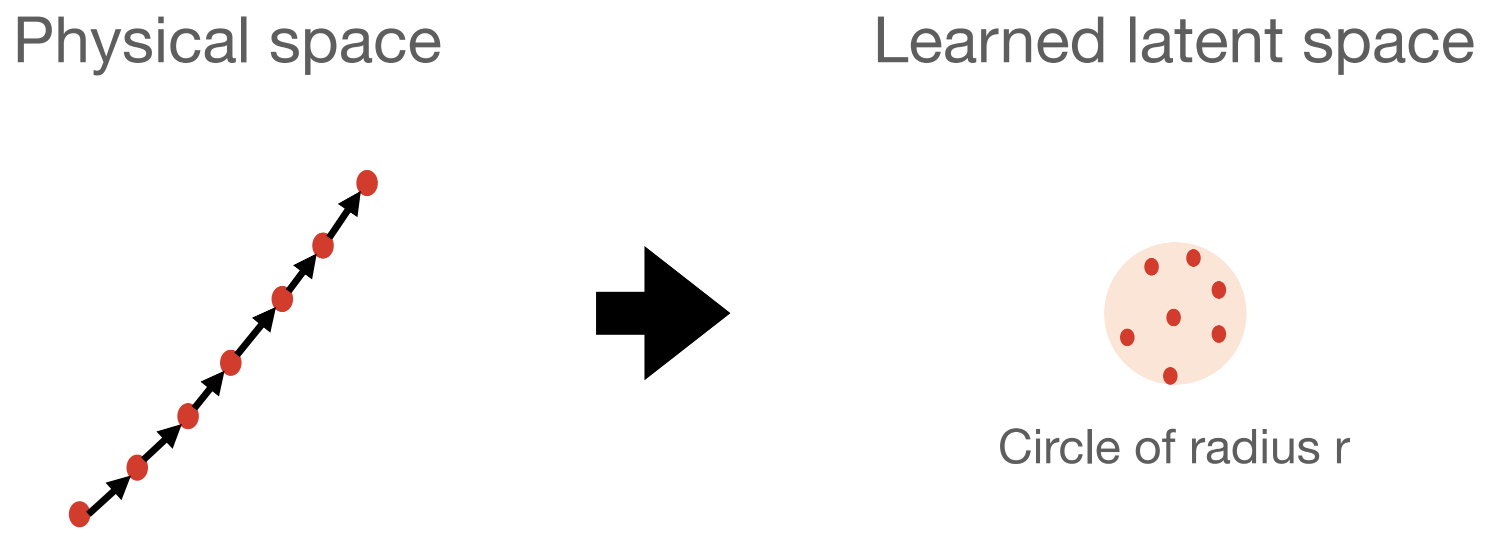
Graph construction



300k nodes fully interconnected yield 10^{10} edges, too many!
Two filtering alternative methods reduced edges to 10^{6}:

- Metric Learning

  1. MLP is trained to embed nodes into a space, where common particle nodes are close



  2. Additional filtering by another MLP

- Module Map

  Module Map: Lookup table of 1M possible triple-module directional connections
  (table built with 90k simulation events)

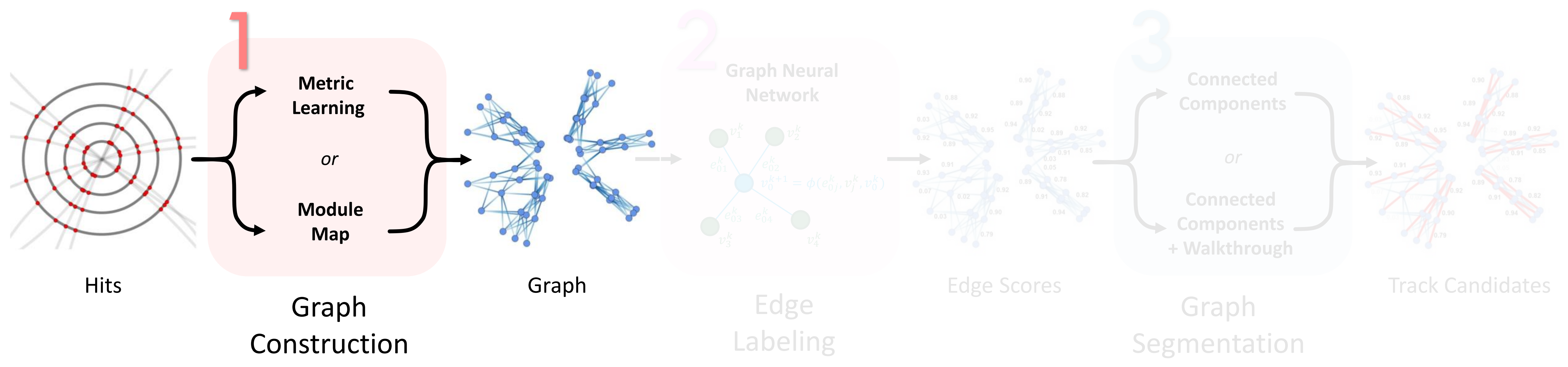
  1. Build edges based on the Module Map

  2. Additional filtering with geometric cuts

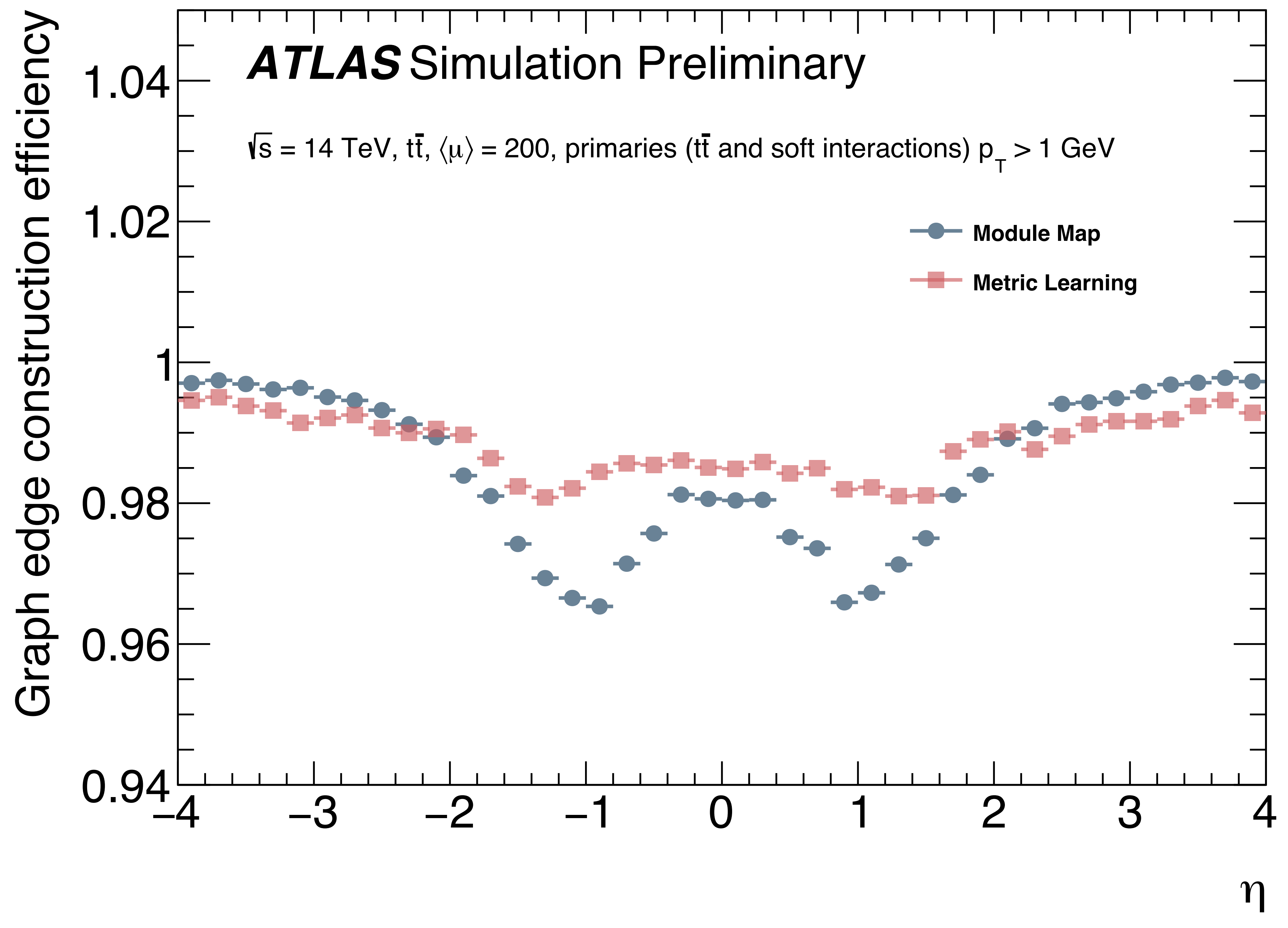
  (For today's new physics performance plots: used Module Map)

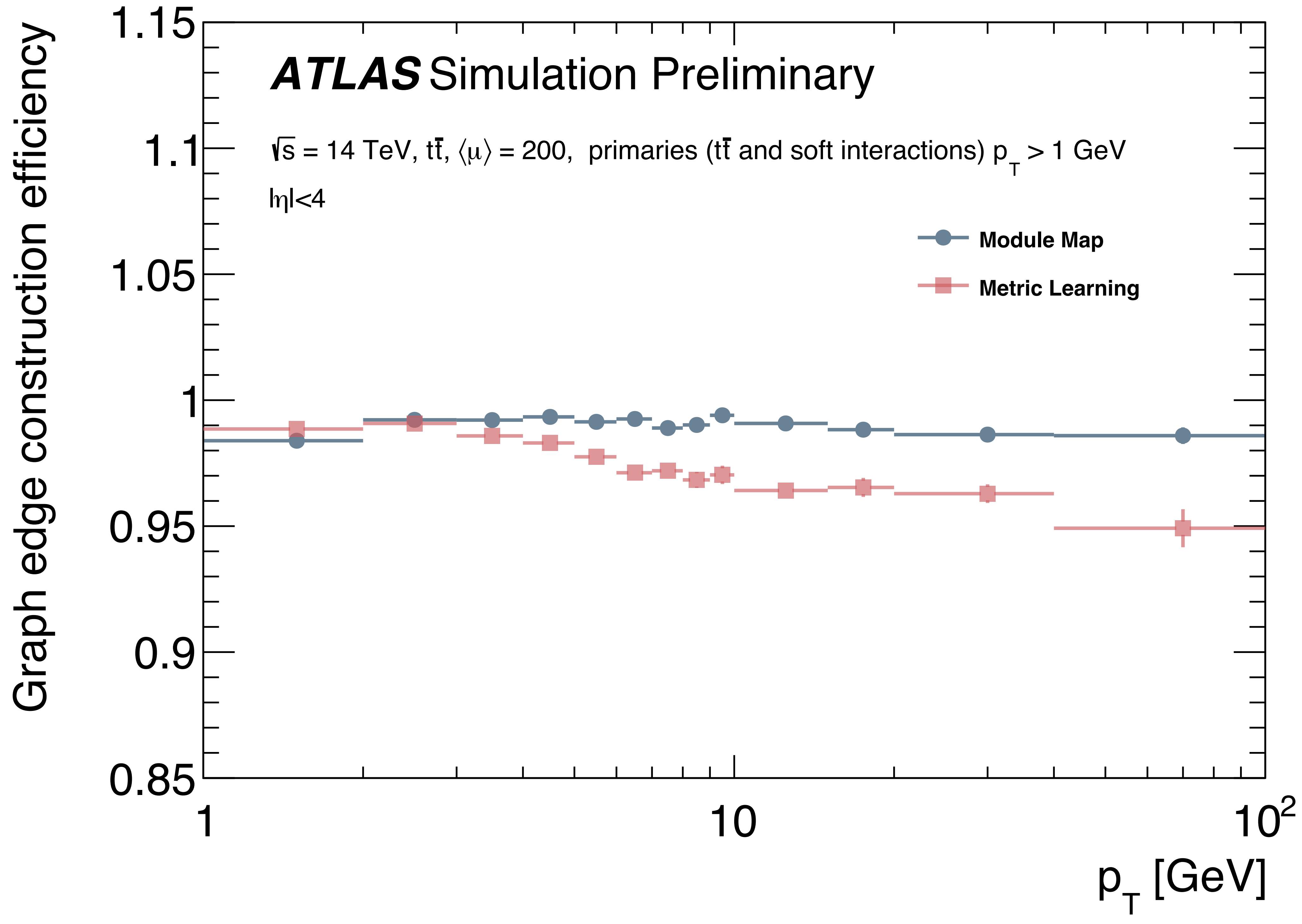
GNN4ITk

Graph construction



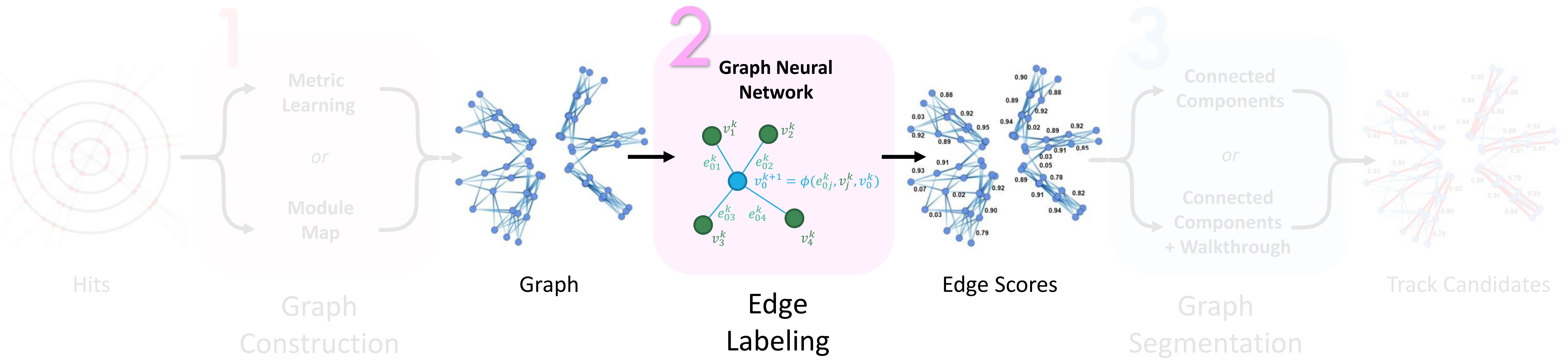
- Performance



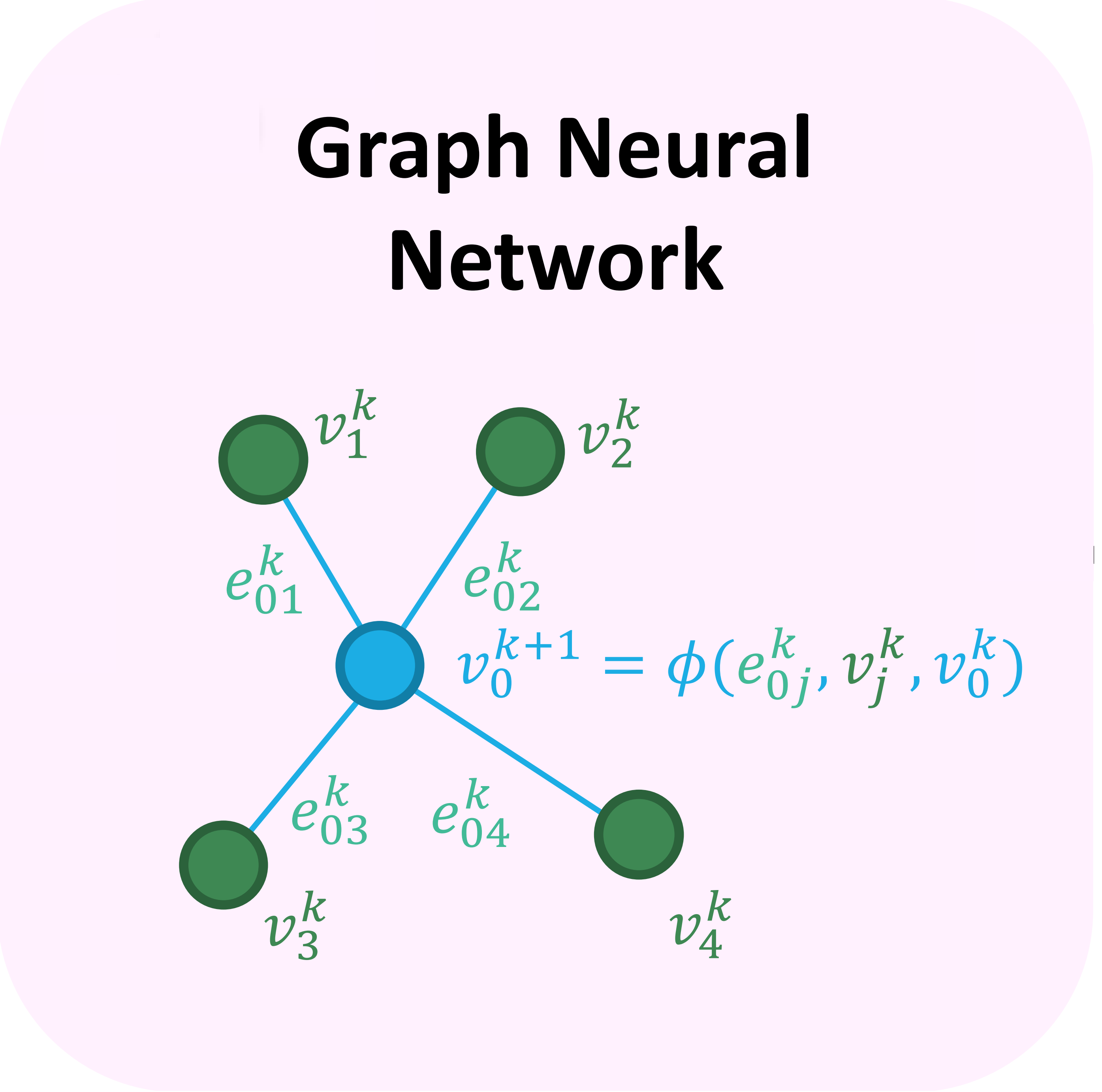


GNN4ITk

Edge labeling with GNN

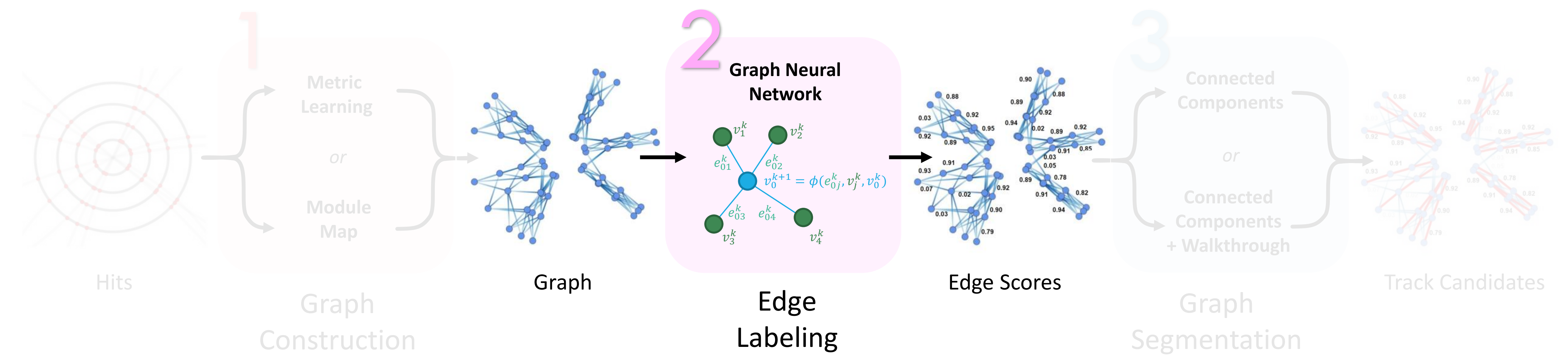


- Train Graph Neural Network to identify true edges based on geometric node and/or edge features
- It reduces number of edges: $10^6 \rightarrow 10^4$



GNN4ITk

Edge labeling with GNN

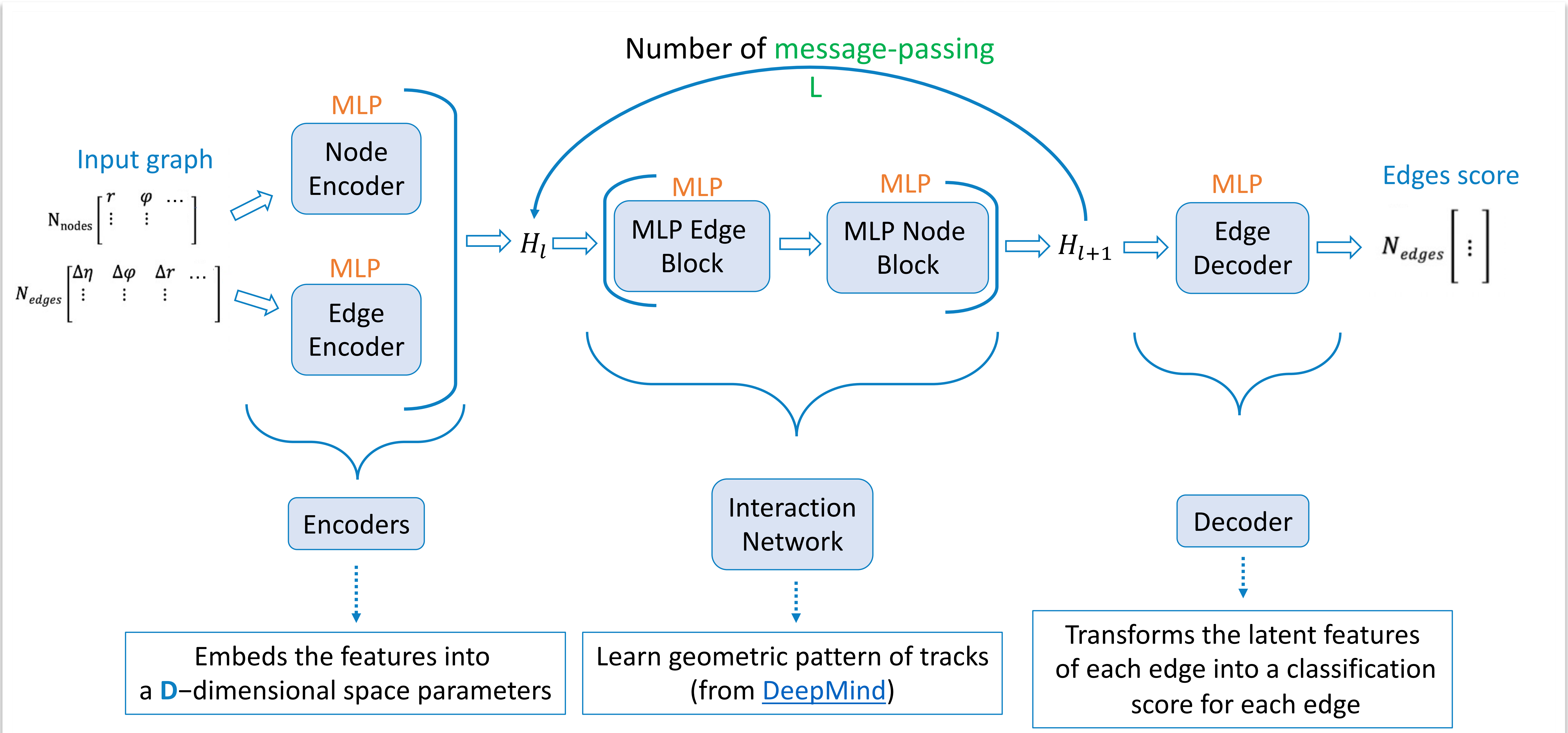


GNN config:

- 2 layers per MLP
- 128D latent space
- 8 message-passing

New w.r.t. CTD 2022:

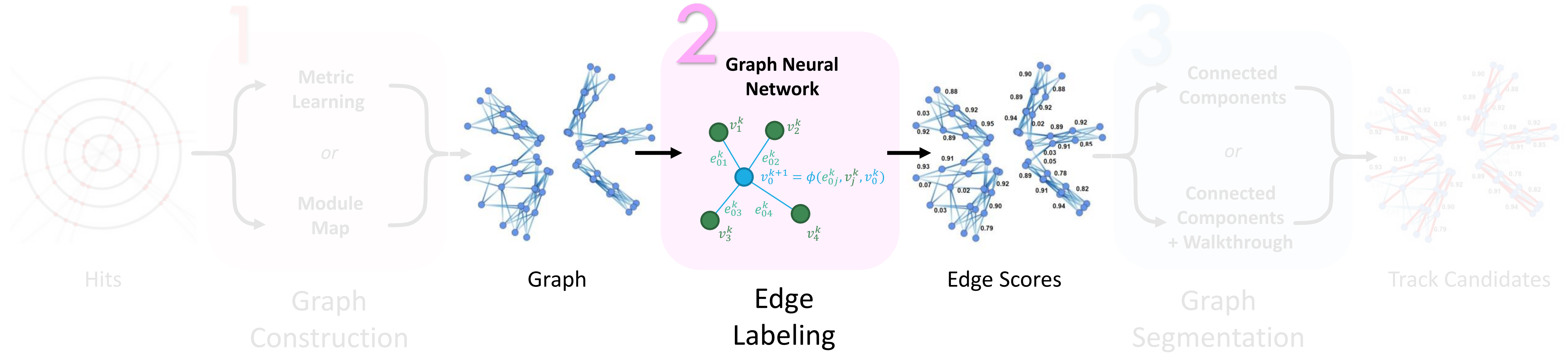
- Non-recurrent interaction network
- Doing batch norm
- Heterogeneous data



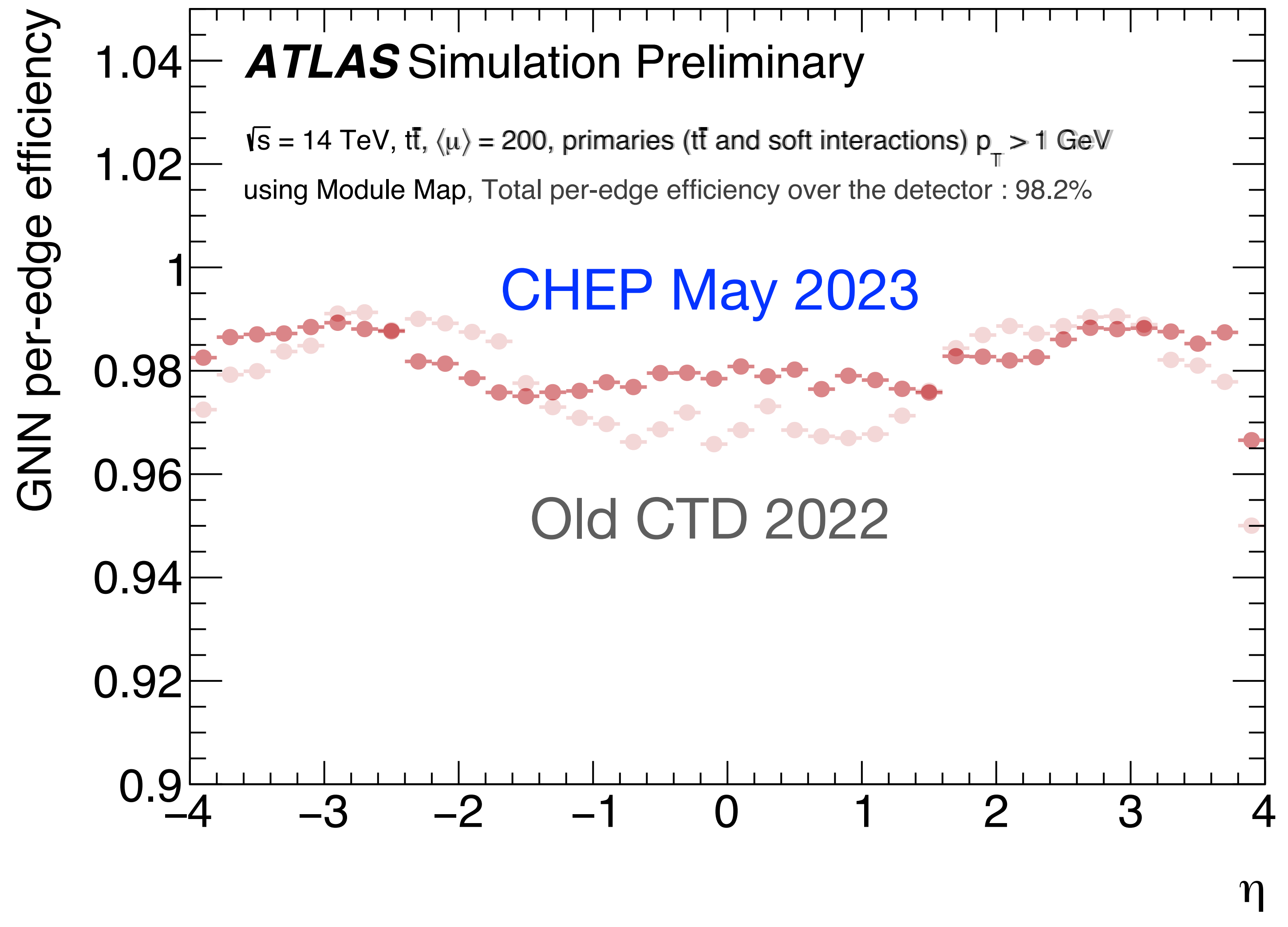
Charline Rougier at CTD 2022

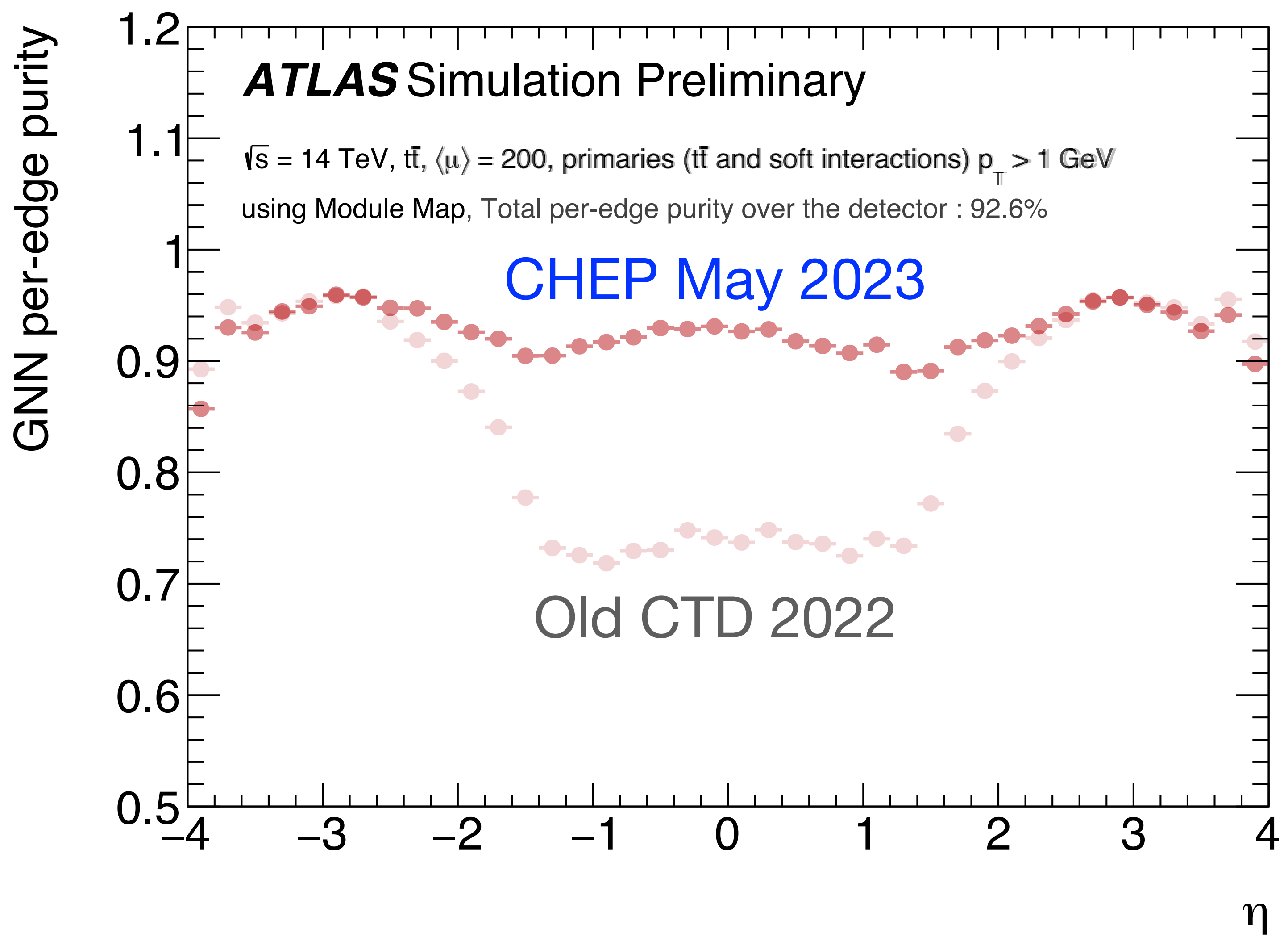
GNN4ITk

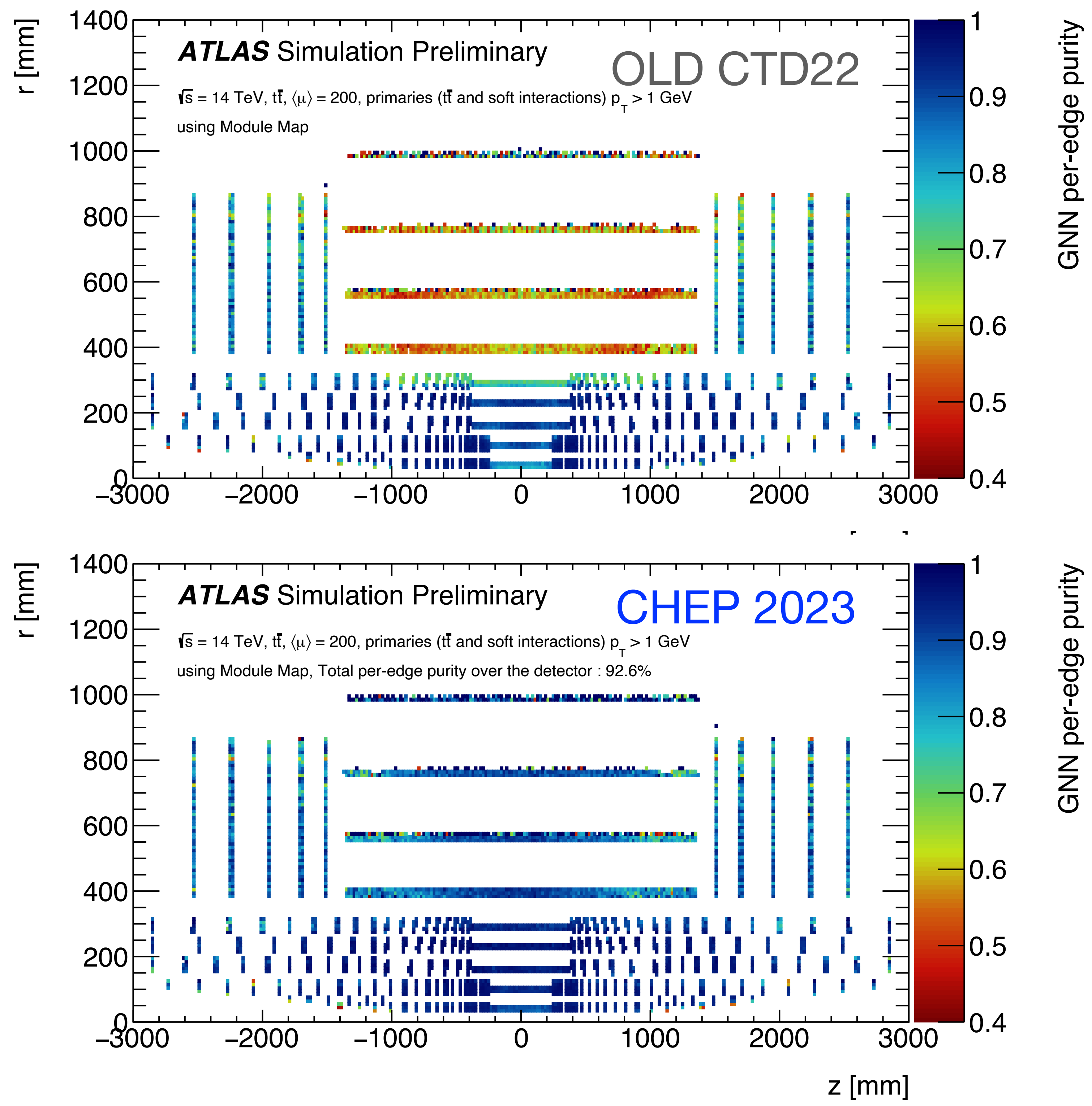
Edge labeling with GNN



- Performance: Significant improvement compared to CTD22
  (low spacial-resolution strip hits was affecting the GNN performance)



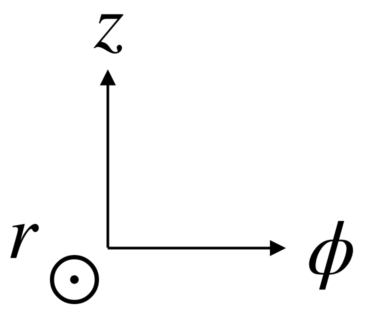


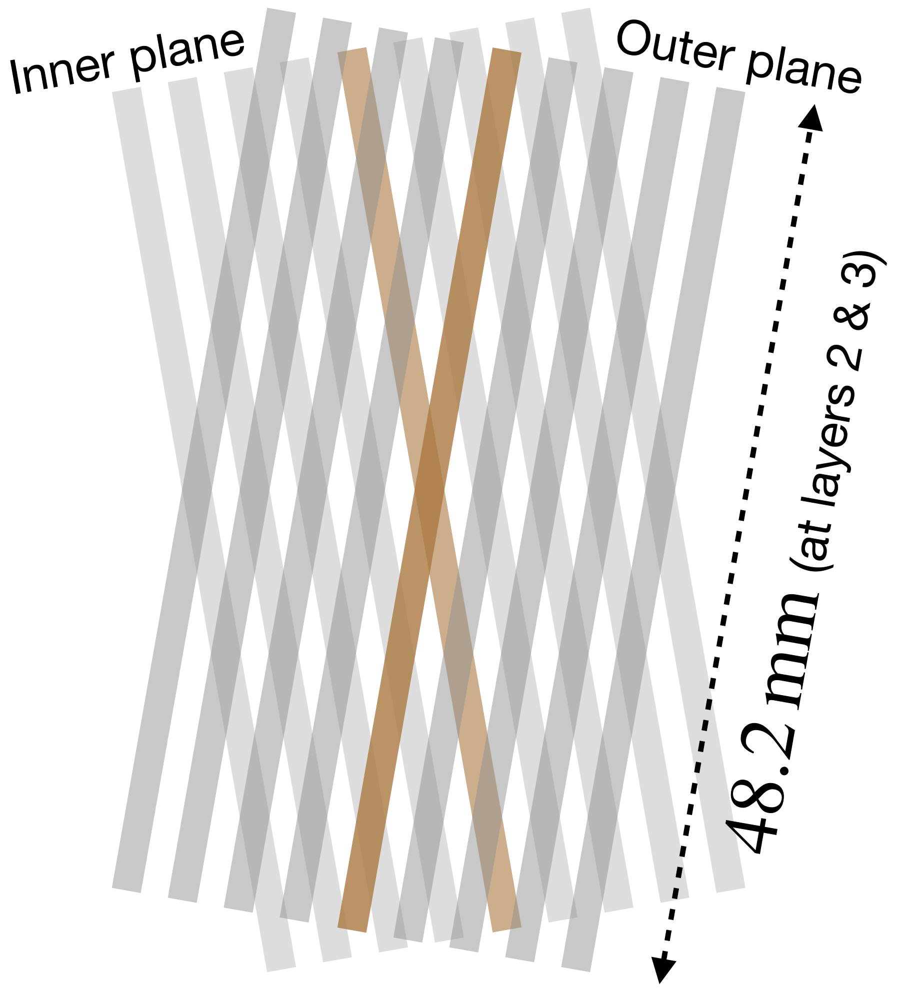


GNN4ITk

Edge labeling with GNN

- Strip hits

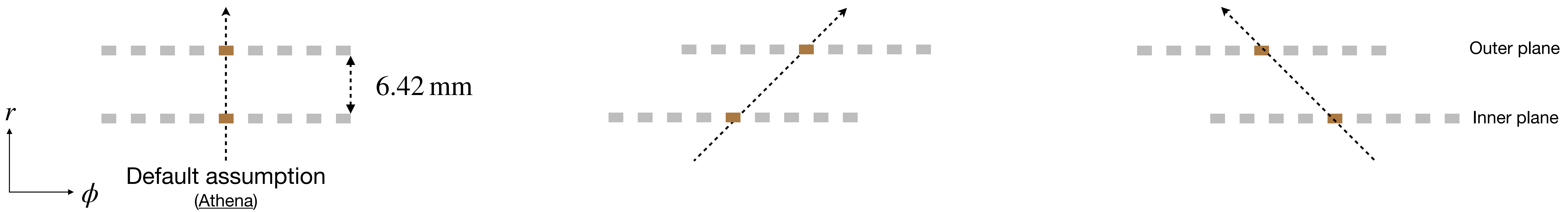




Double strip sensor planes in barrel module
Two strips fired by a particle in brown
Where did the particle hit the inner plane?

Default hits:
Poor σ_z ~ 1-3 cm
(was limiting GNN performance)

Some possible options:



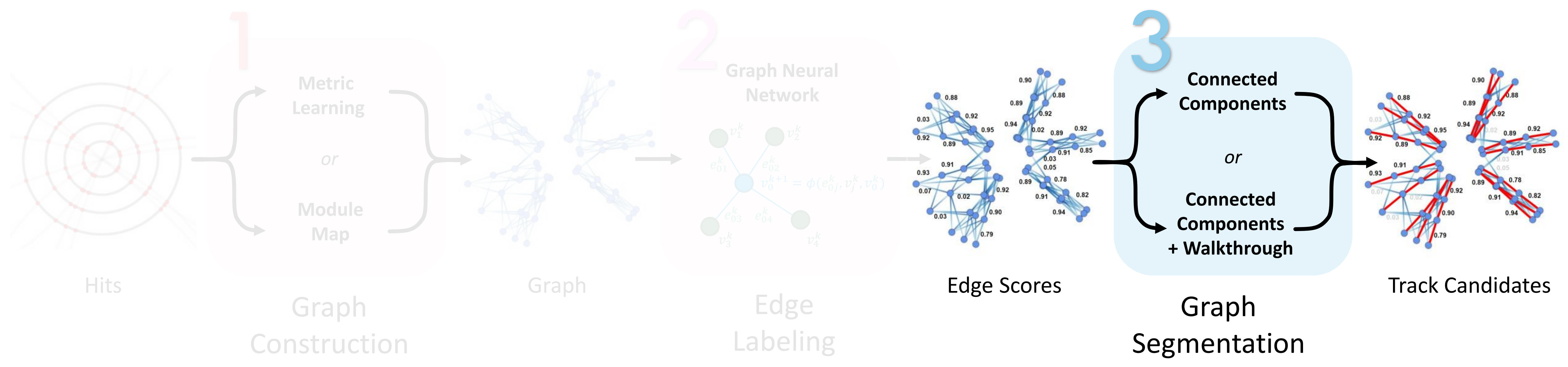
- Problem addressed by passing info of the two individual strip clusters to the GNN; node features:
  - Strip barrel: $r_{\text{hit}}, \dots, r_{\text{cl1}}, \dots, r_{\text{cl2}}, \dots$
  - Pixel: $r_{\text{hit}}, \dots, r_{\text{hit}}, \dots, r_{\text{hit}}, \dots$

  (**Heterogeneous data** format)

- Other alternatives under study: hand-engineered edge features based on hit pair info, & heterogeneous GNN model

GNN4ITk

Graph segmentation

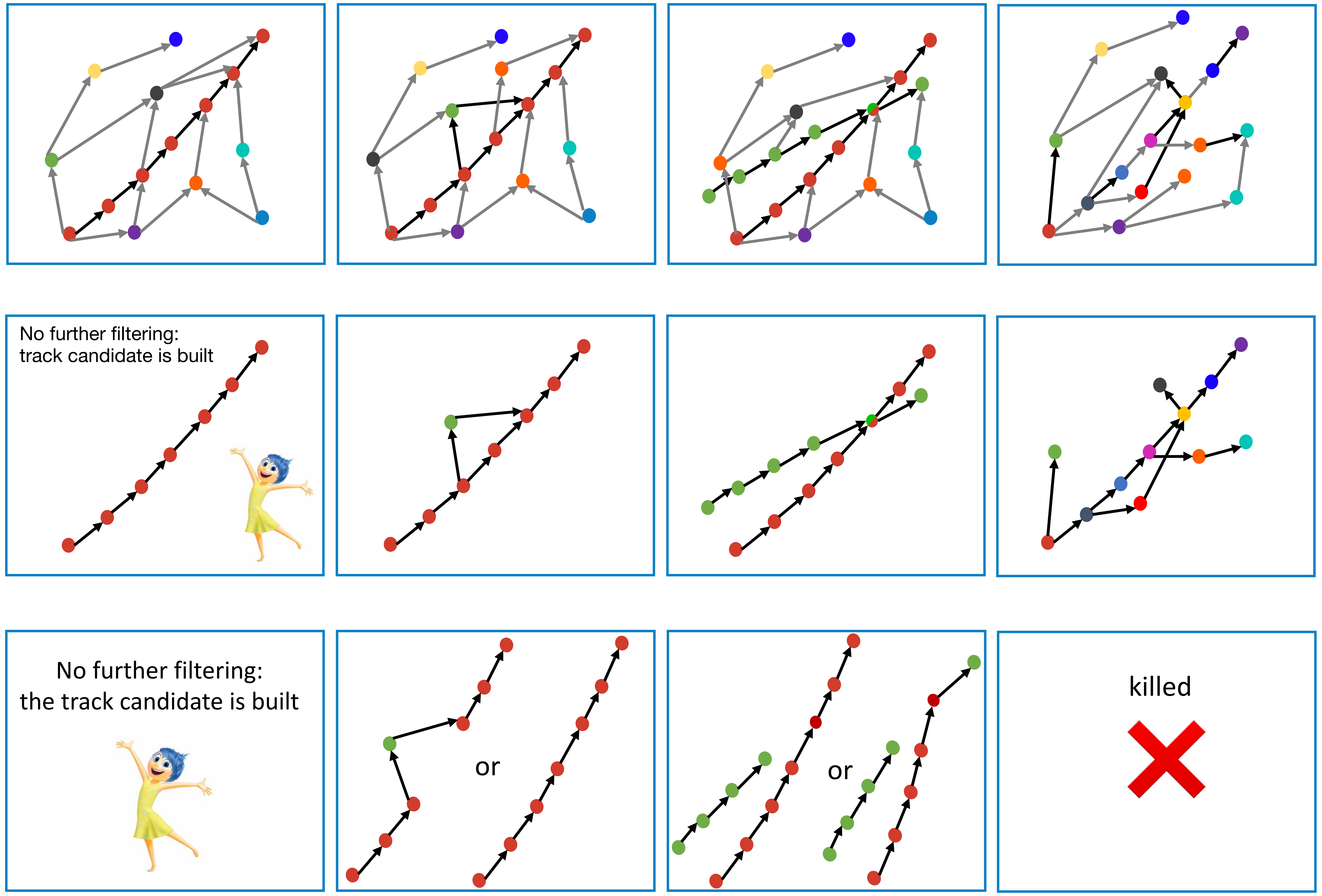


Legend:
Edge below threshold
Edge above threshold
Same color nodes = same particle nodes

Connected component algorithm,
with loose edge score cut

The better GNN performance
the more tracks are ready at this stage
and the faster the reconstruction is

Walk-through algorithm,
with tighter edge score cut

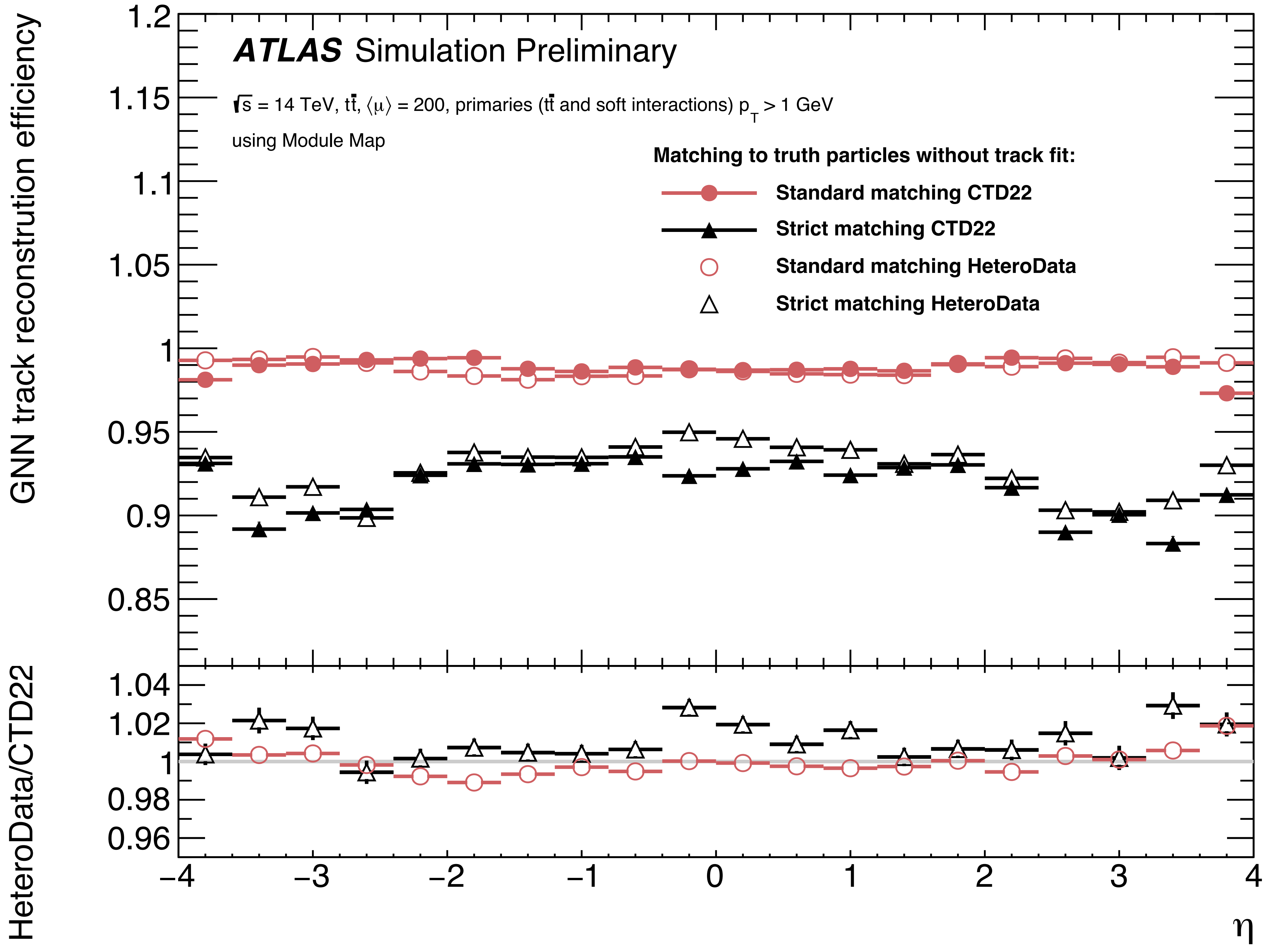


Charline Rougier at CTD 2022

(Current graph segmentation mainly developed to complete the chain.
Not yet optimized, e.g. could be combined with a Kalman Filter.)

Technical check

- Full chain performance: “Technical” tracking efficiency
  (defined based on our current target particles)



Standard matching:
- Track has 50% hit purity

Strict matching:
- Track includes 100% of the particle hits
- Track has 100% hit purity

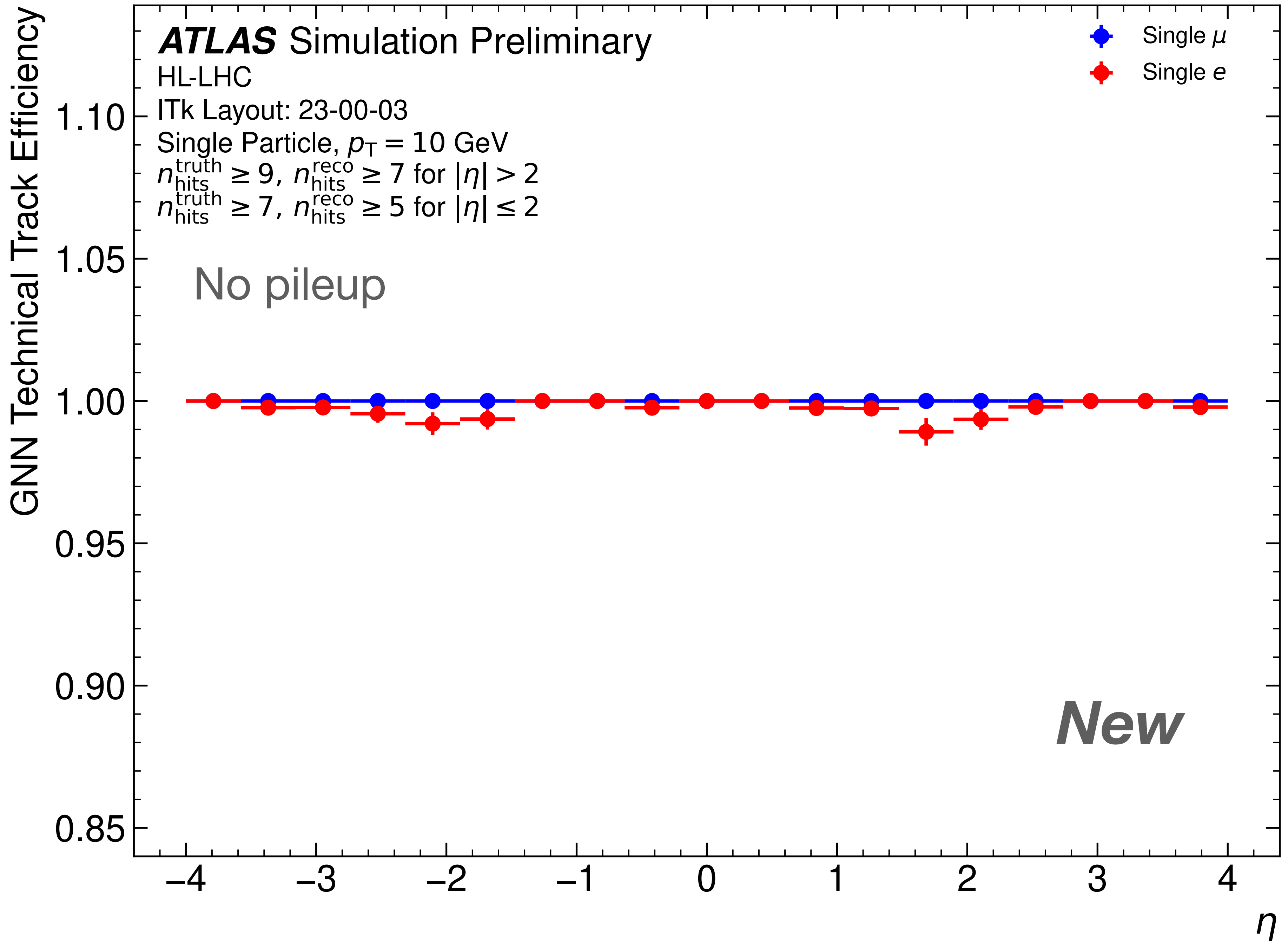
O(10^{-3}) fake tracks:
Track candidates not matched to any particle

Technical check

- Easy task: Single particle tracking

First time test for GNN4ITk

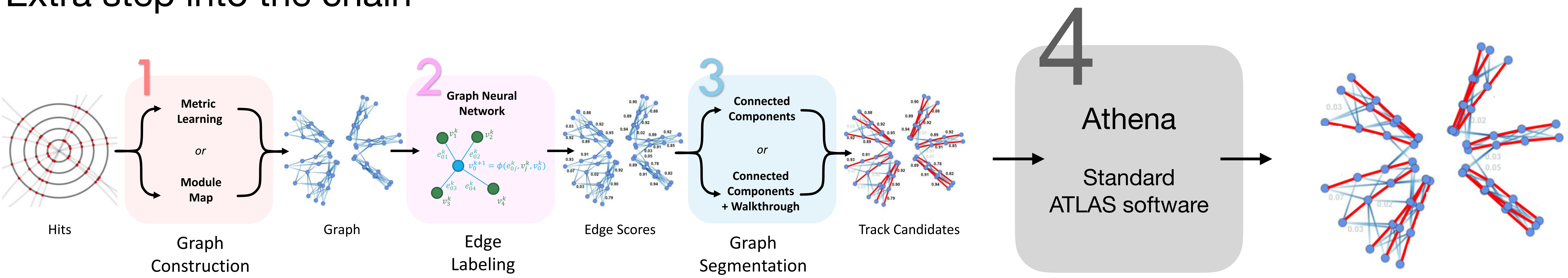
For the moment:
Test done with Metric Learning graphs,
with GNN model trained on $t\bar{t}$ events artificially altered
to contain only hits from particles with $p_T > 1$ GeV



Physics Performance of the
ATLAS GNN4ITk

Physics Performance of the ATLAS GNN4ITk and apples-to-apples comparison against ATLAS Combinatorial Kalman Filter

- Extra step into the chain



χ^2 fit
accounting for expected multiple scattering effects

ATLAS track candidates with track parameter
(p_T, θ, ϕ, d_0, z_0)

- Applying standard ATLAS selection

Requirements	Pseudorapidity interval		
	$\|\eta\| < 2.0$	$2.0 < \|\eta\| < 2.6$	$2.6 < \|\eta\| < 4.0$
pixel + strip hits	≥ 9	≥ 8	≥ 7
pixel hits	≥ 1	≥ 1	≥ 1
holes	≤ 2	≤ 2	≤ 2
p_T [MeV]	> 1000		
$\|d_0\|$ [mm]	≤ 2.0	≤ 2.0	≤ 10.0
$\|z_0\|$ [cm]	≤ 20.0	≤ 20.0	≤ 20.0

For GNN4ITk 3 cuts are looser:
pixel + strip hits ≥ 8,
$|d_0| < 20$ mm
$|z_0| < 25$ cm

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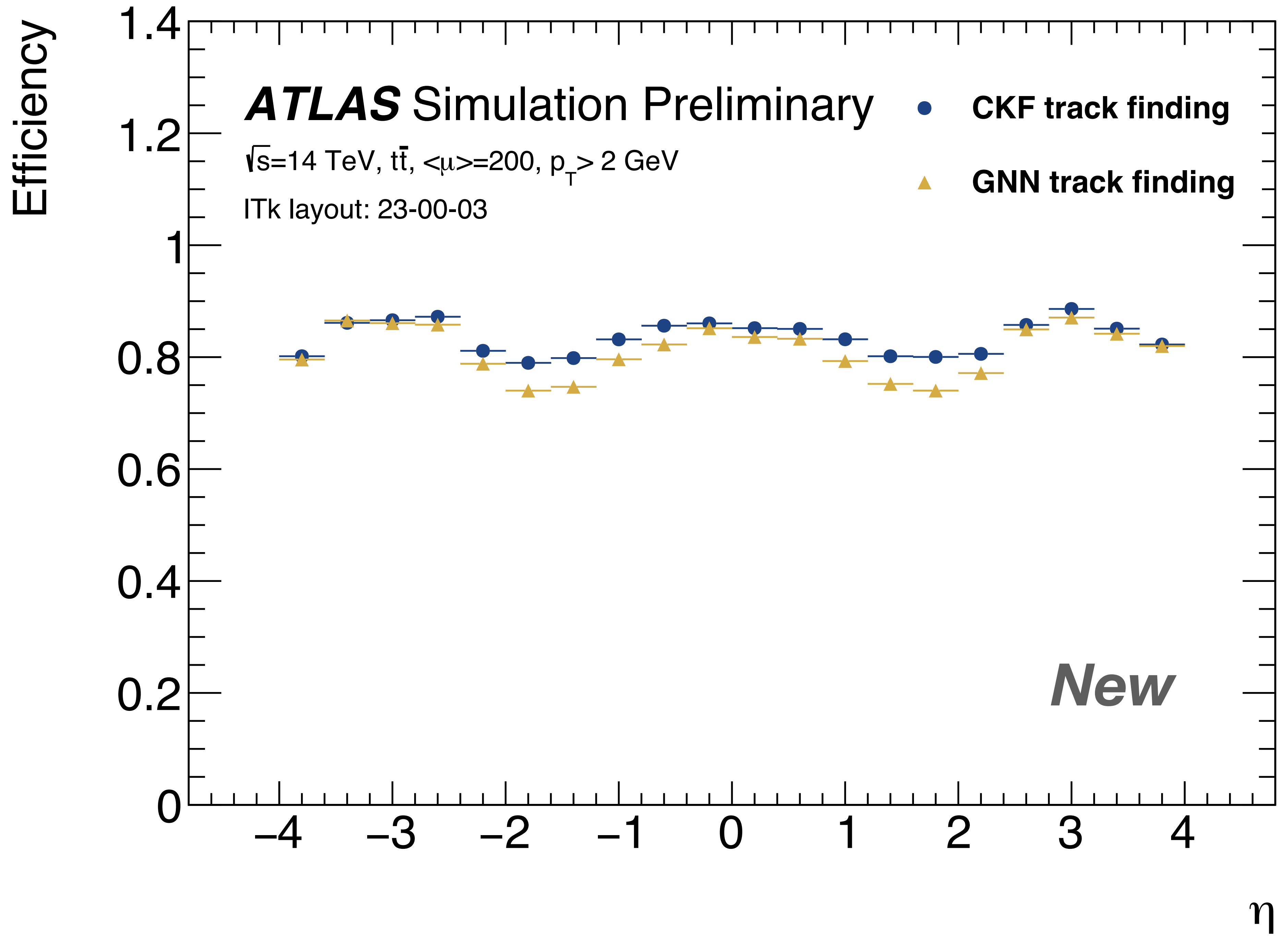
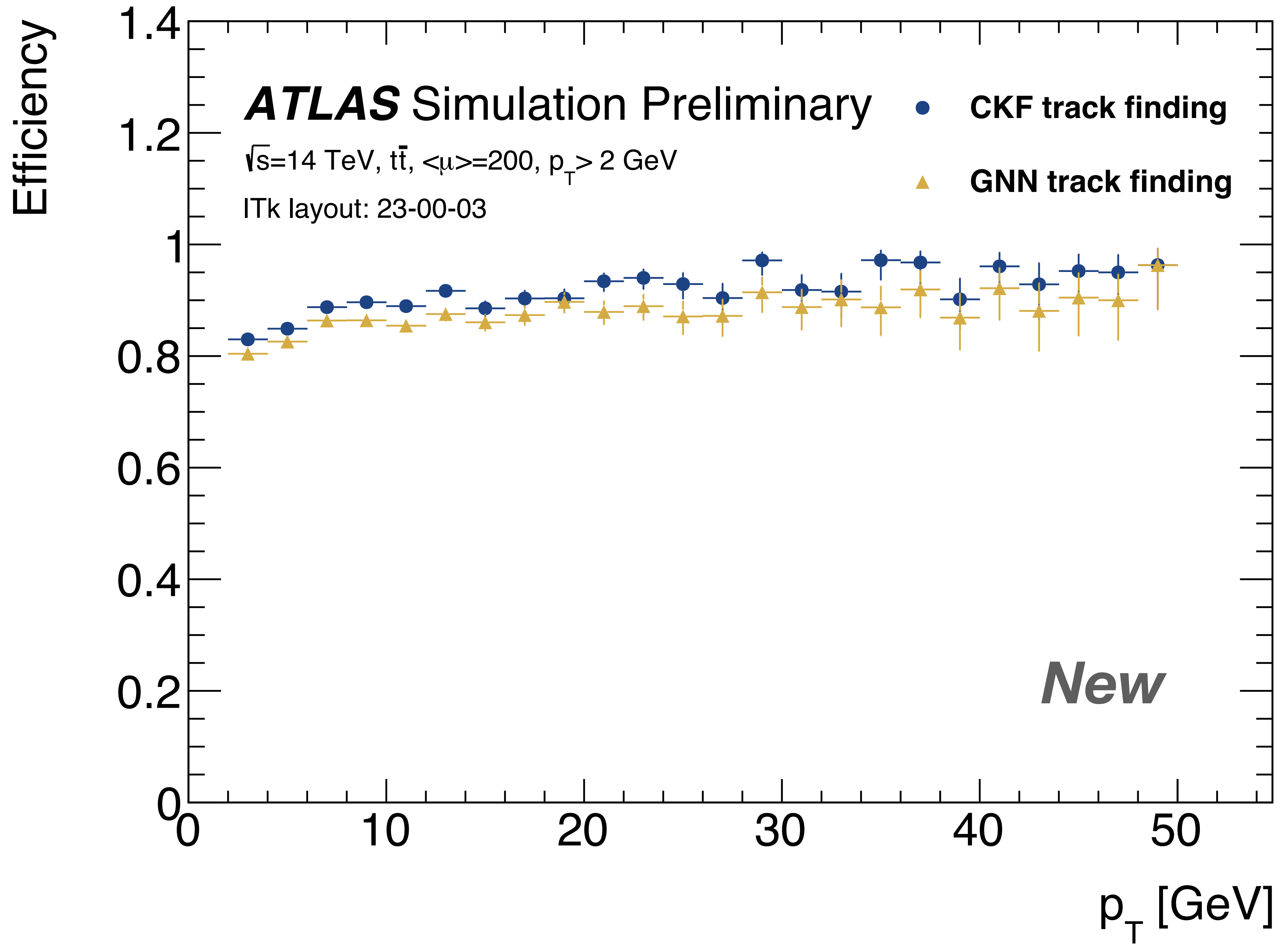
Tracking efficiency

- Competitive "physics" efficiency
  (excluding electrons)

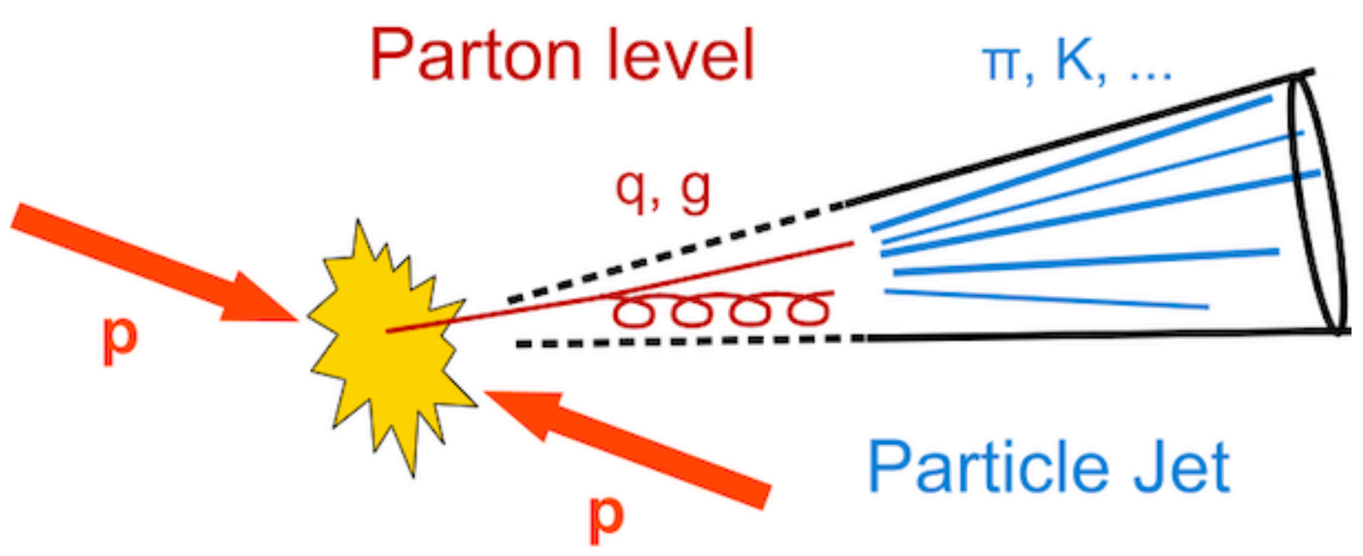
[O(10^{-3}) fake tracks:
Track candidates not matched to any particle]



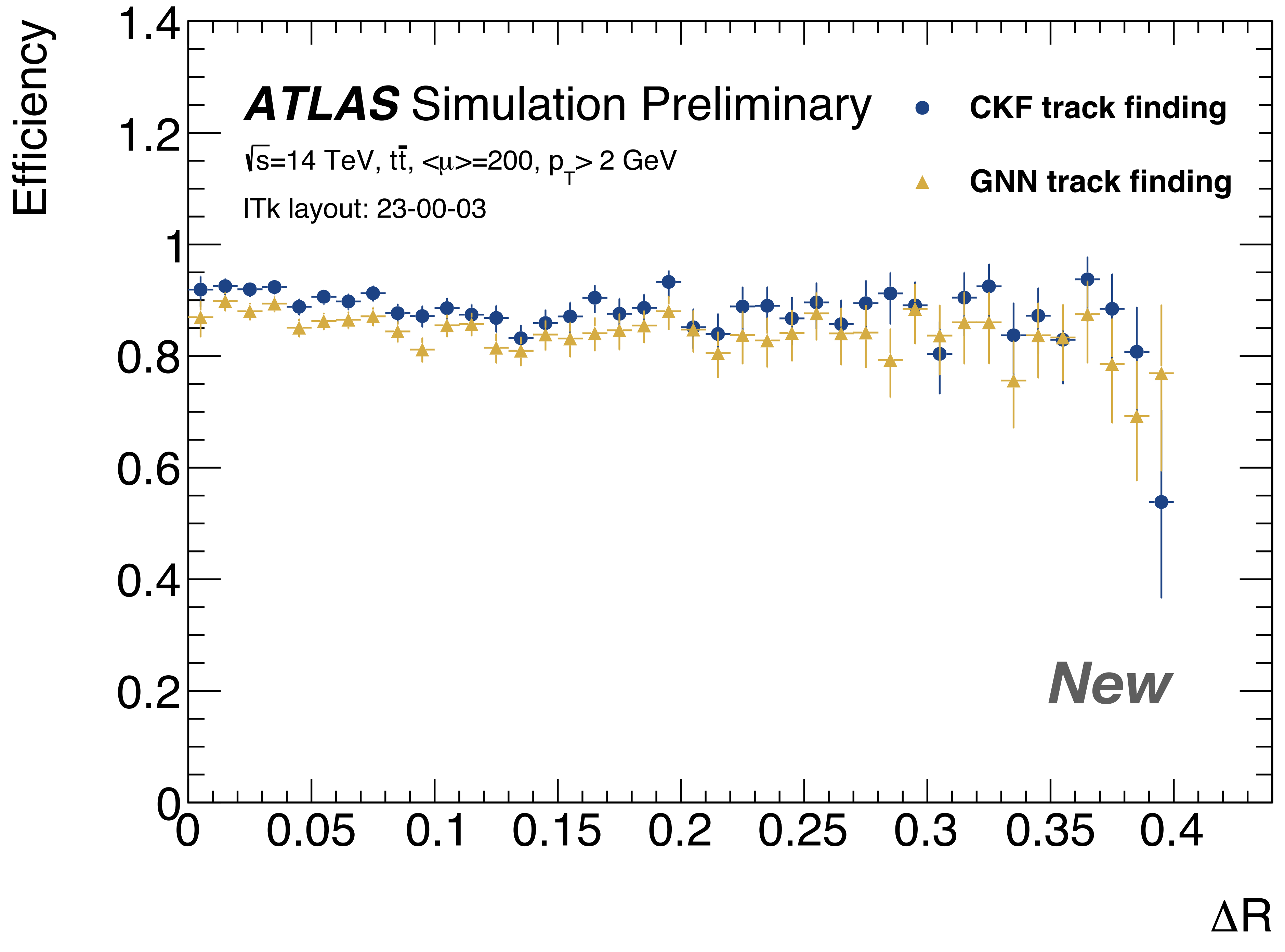


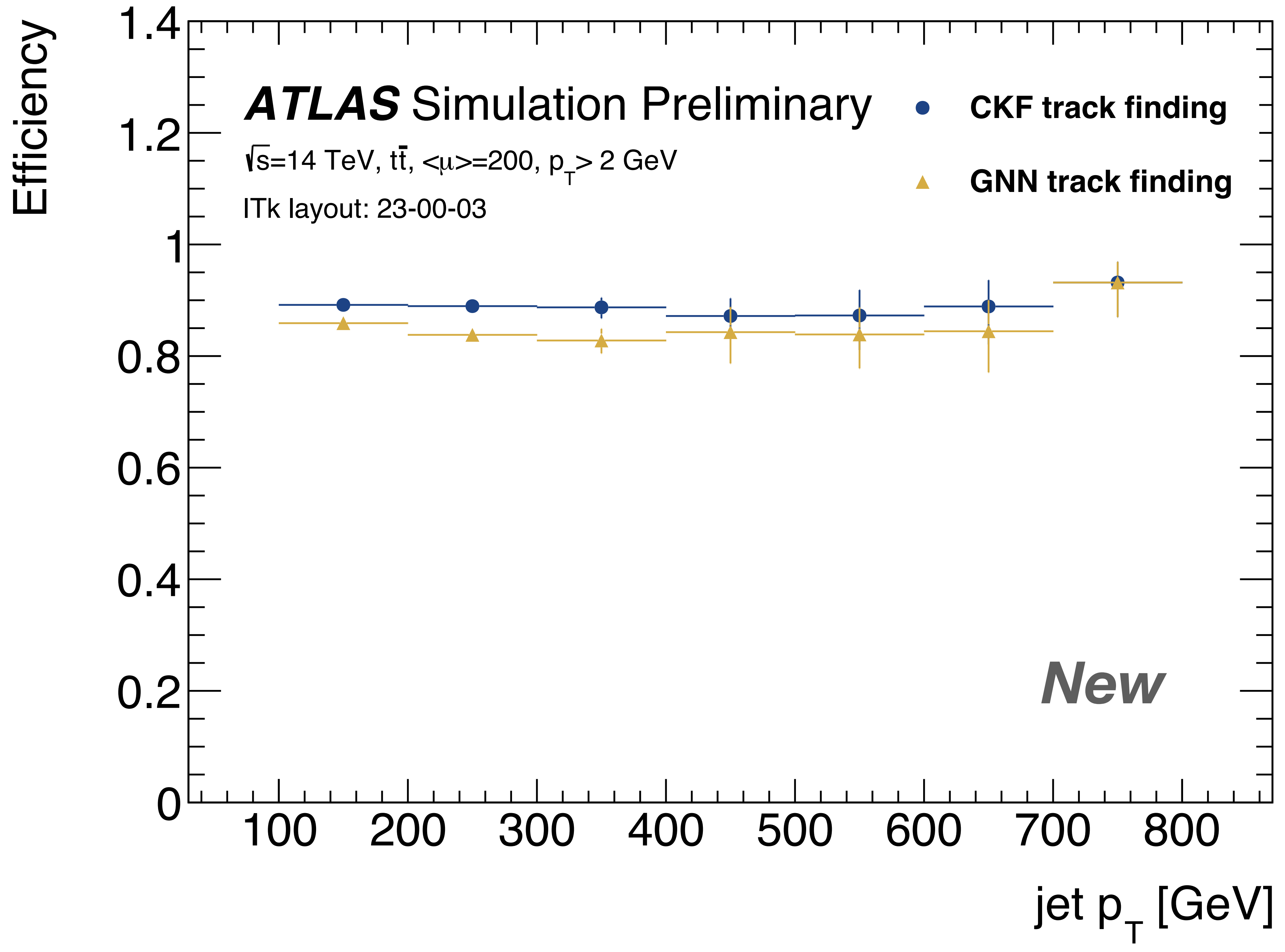
Tracking efficiency

Tracking inside jets



- Competitive "physics" efficiency even in dense environment
  (excluding electrons)

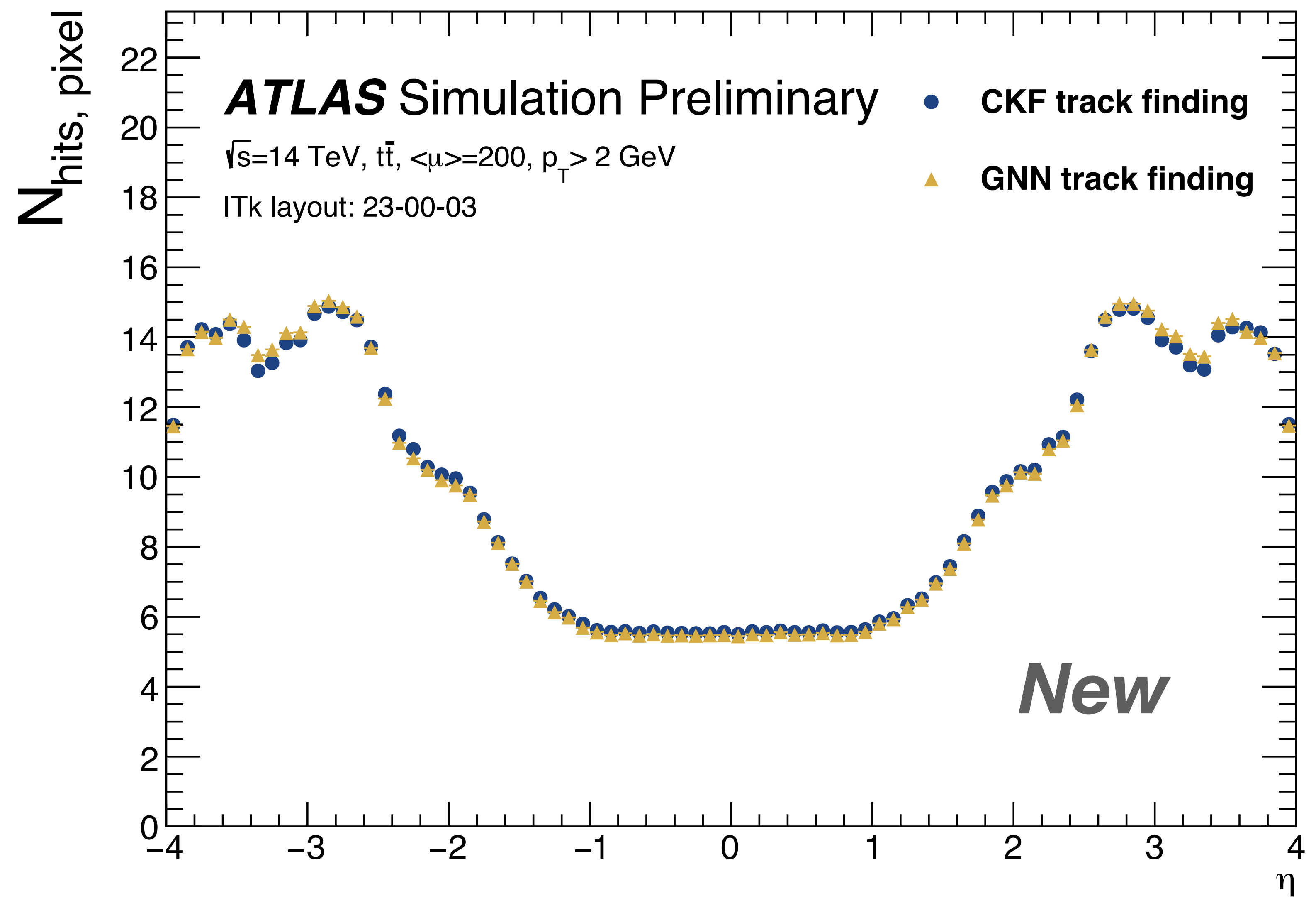


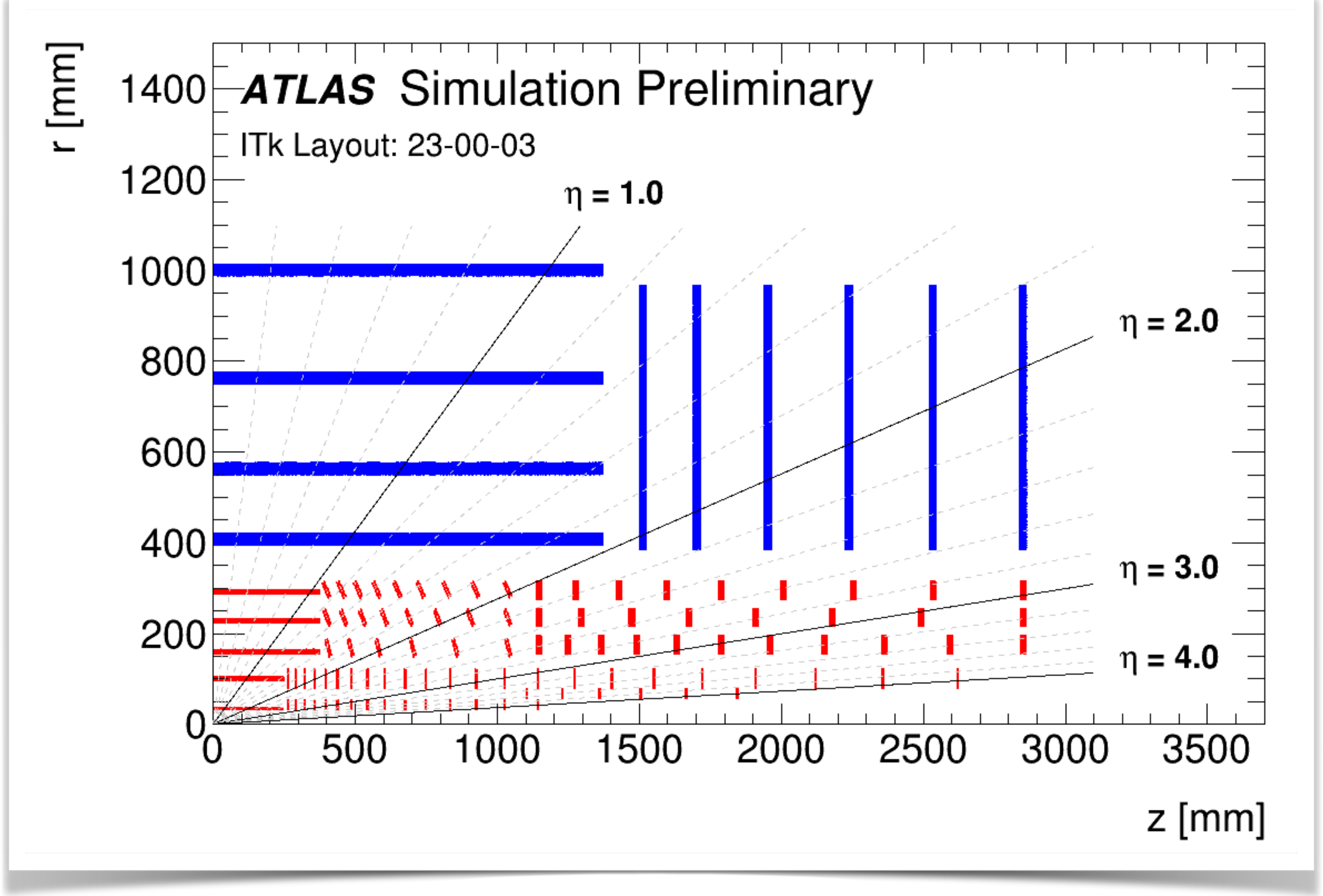


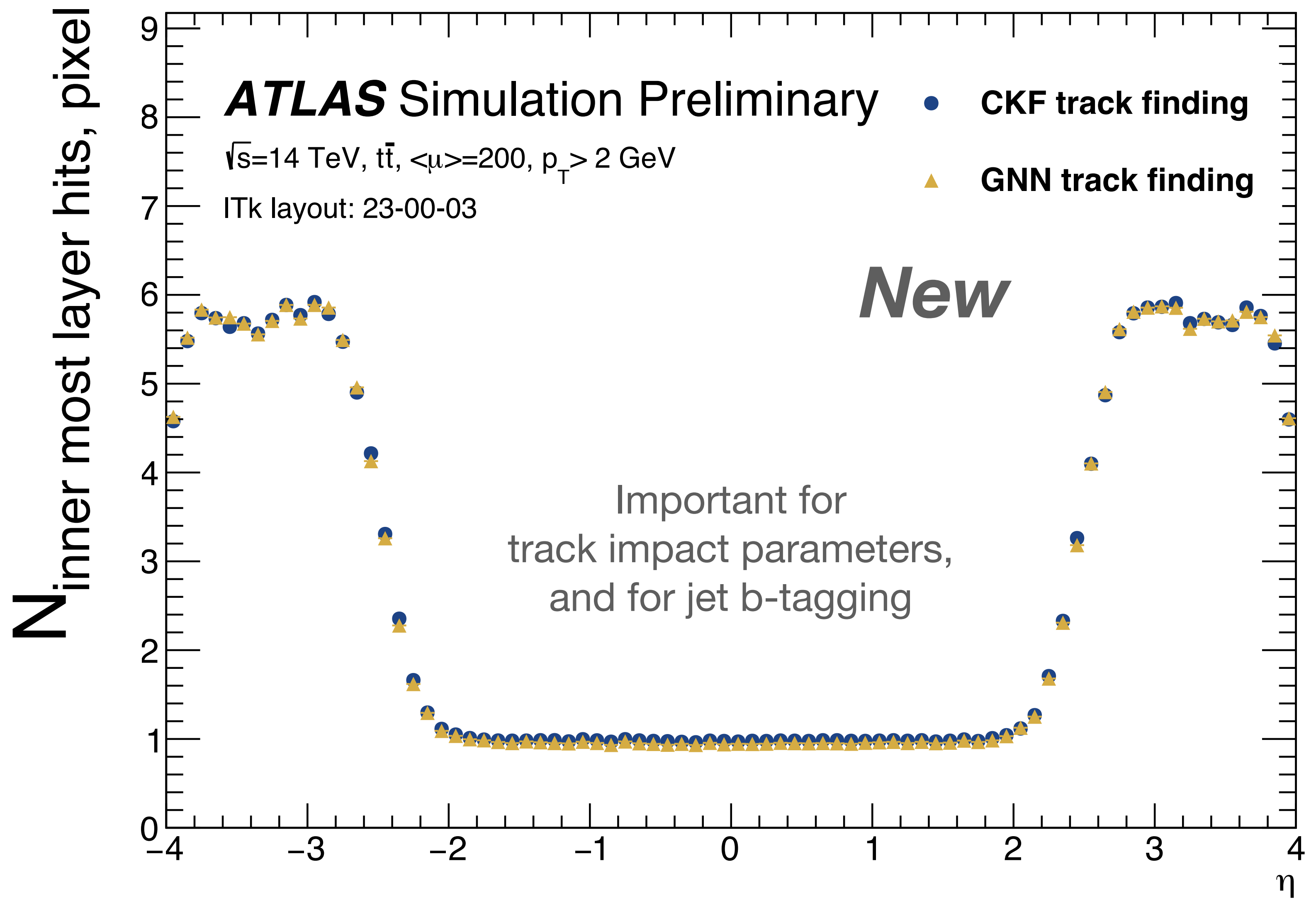
Track hit content

Pixel hits

- Compatible with the detector, and with the CKF

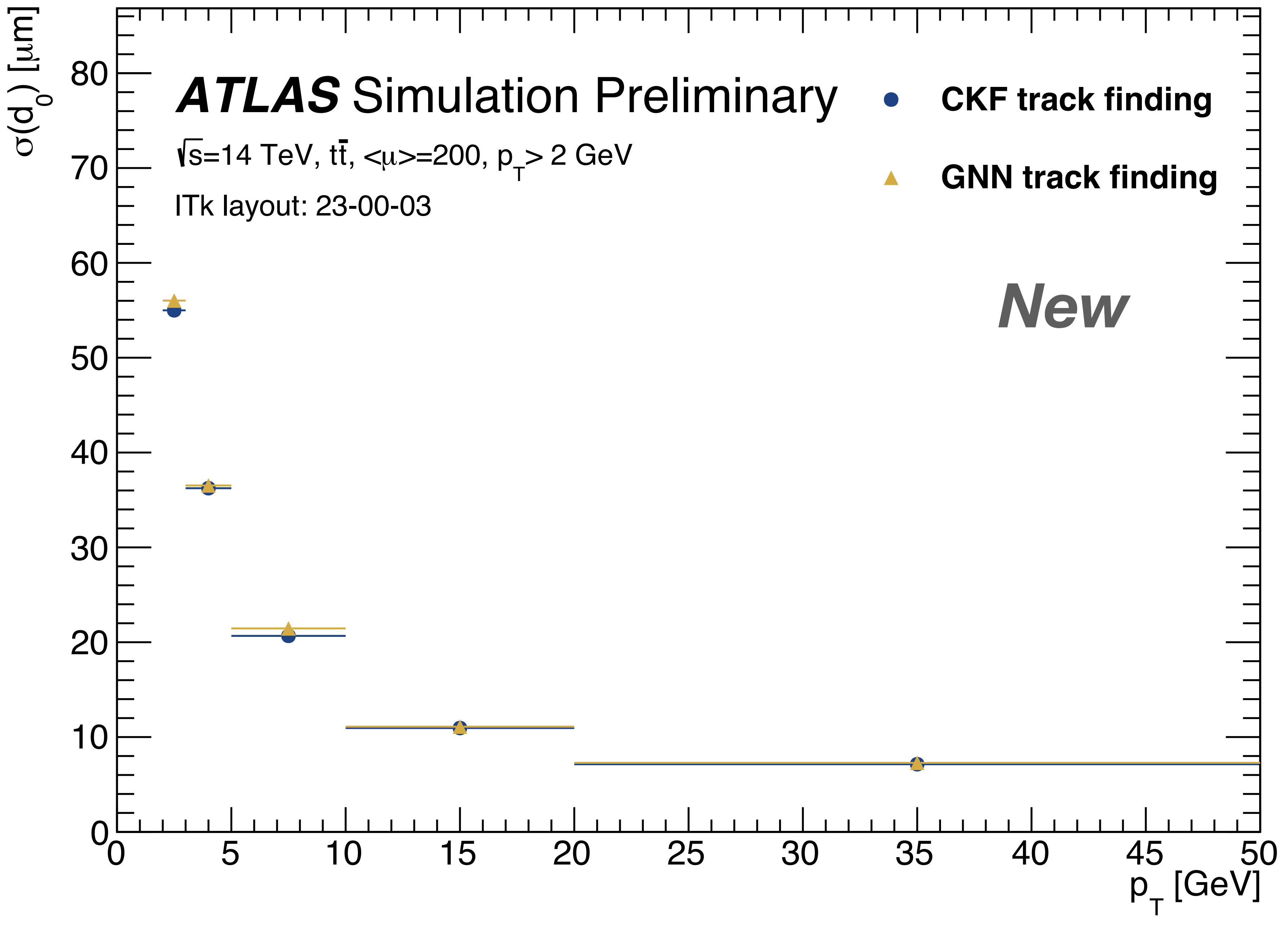


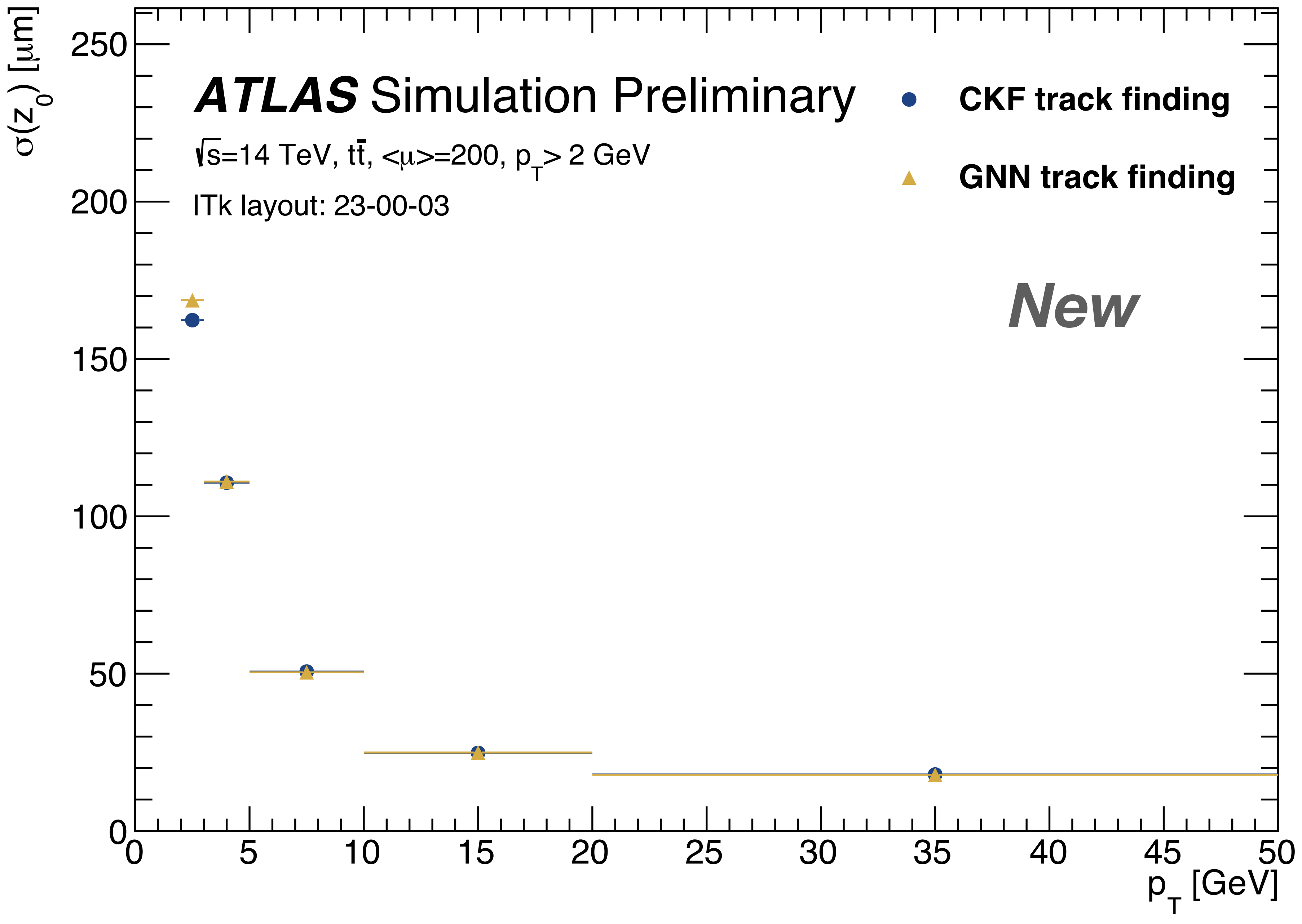




Impact parameter resolution

- Given the good pixel hit content, good impact parameter resolution



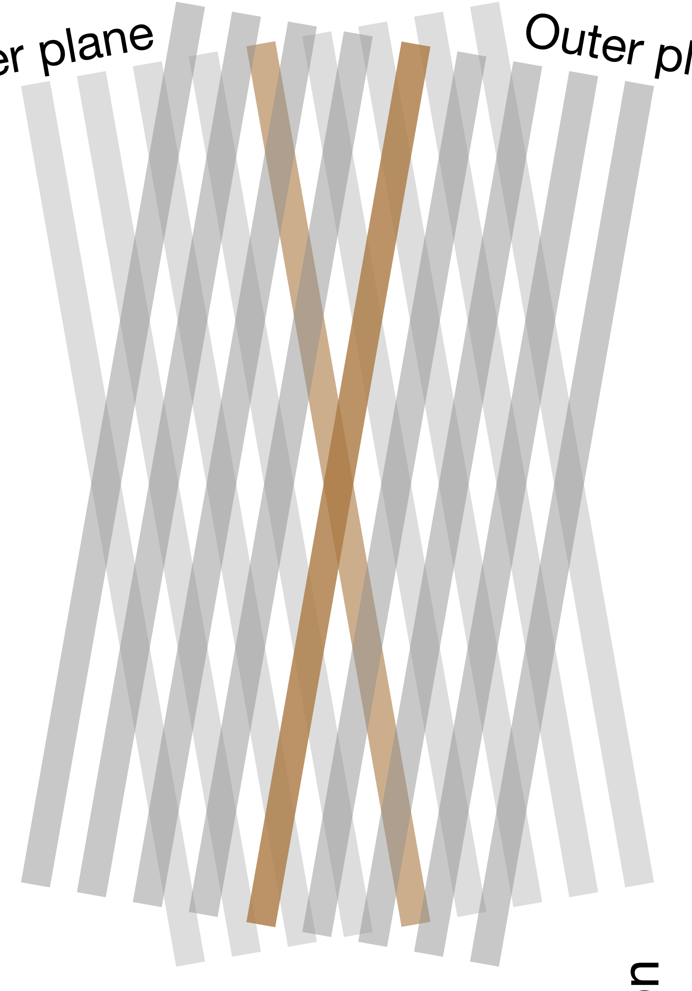


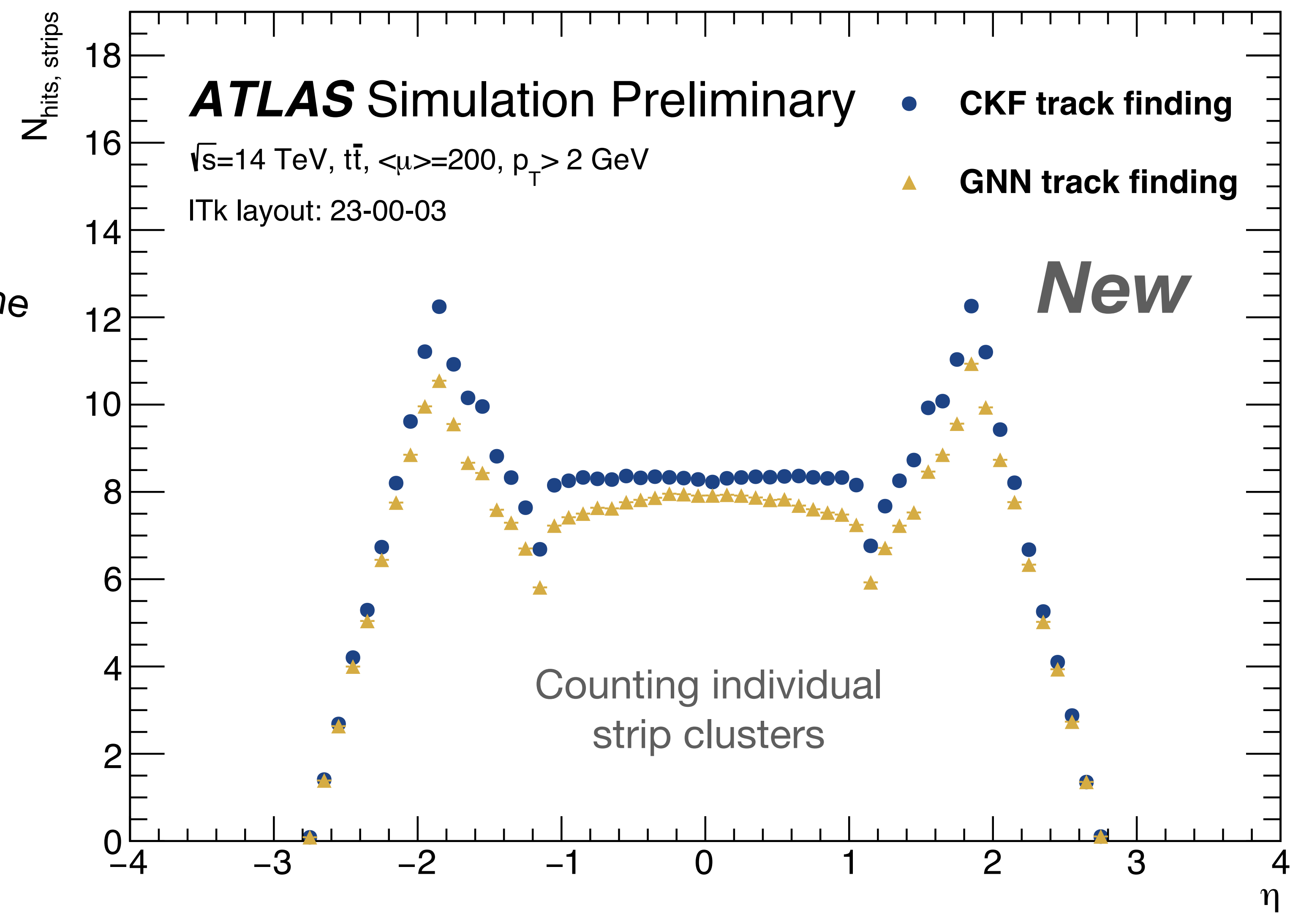
Track strip-hit content

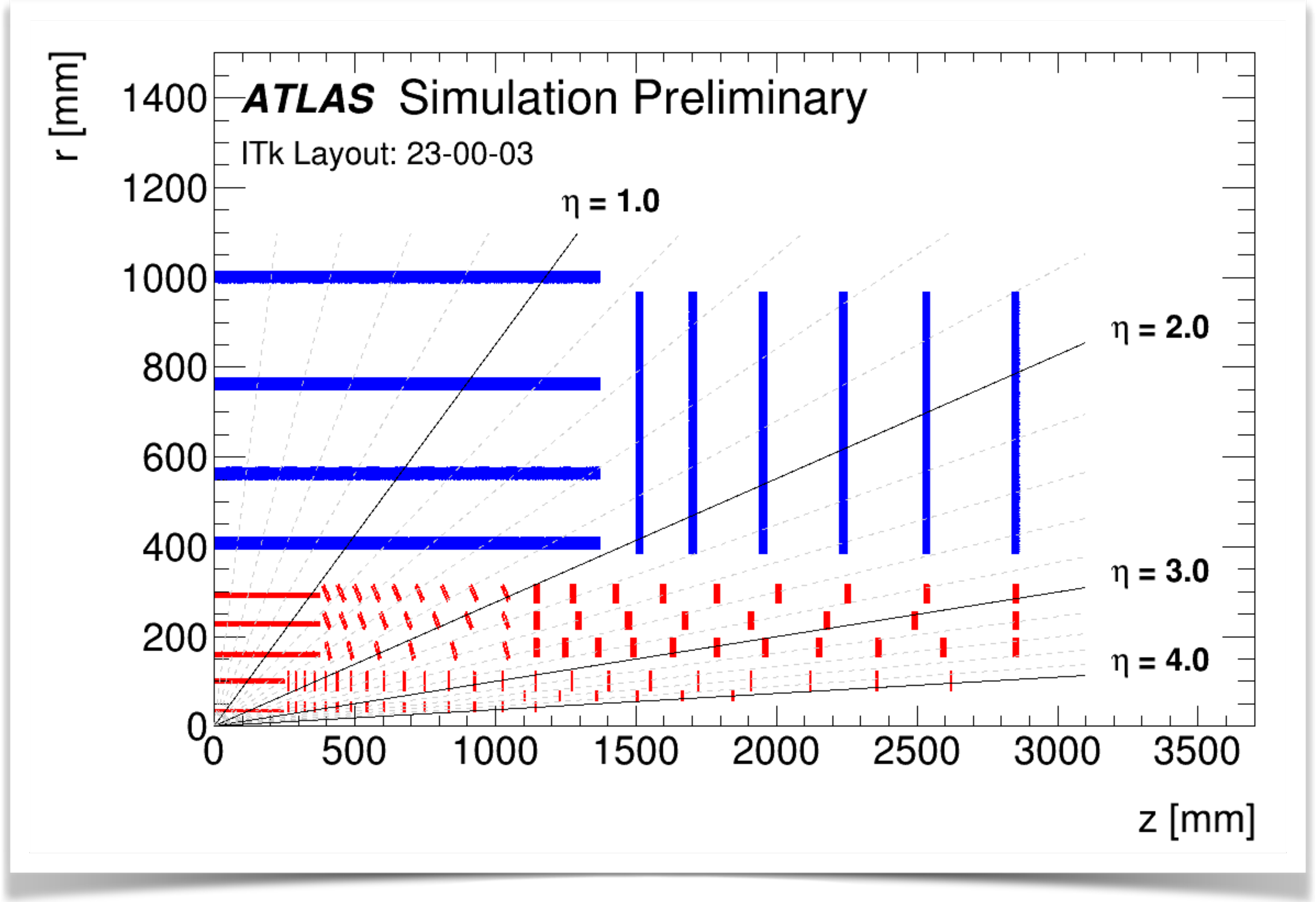
and p_T resolution

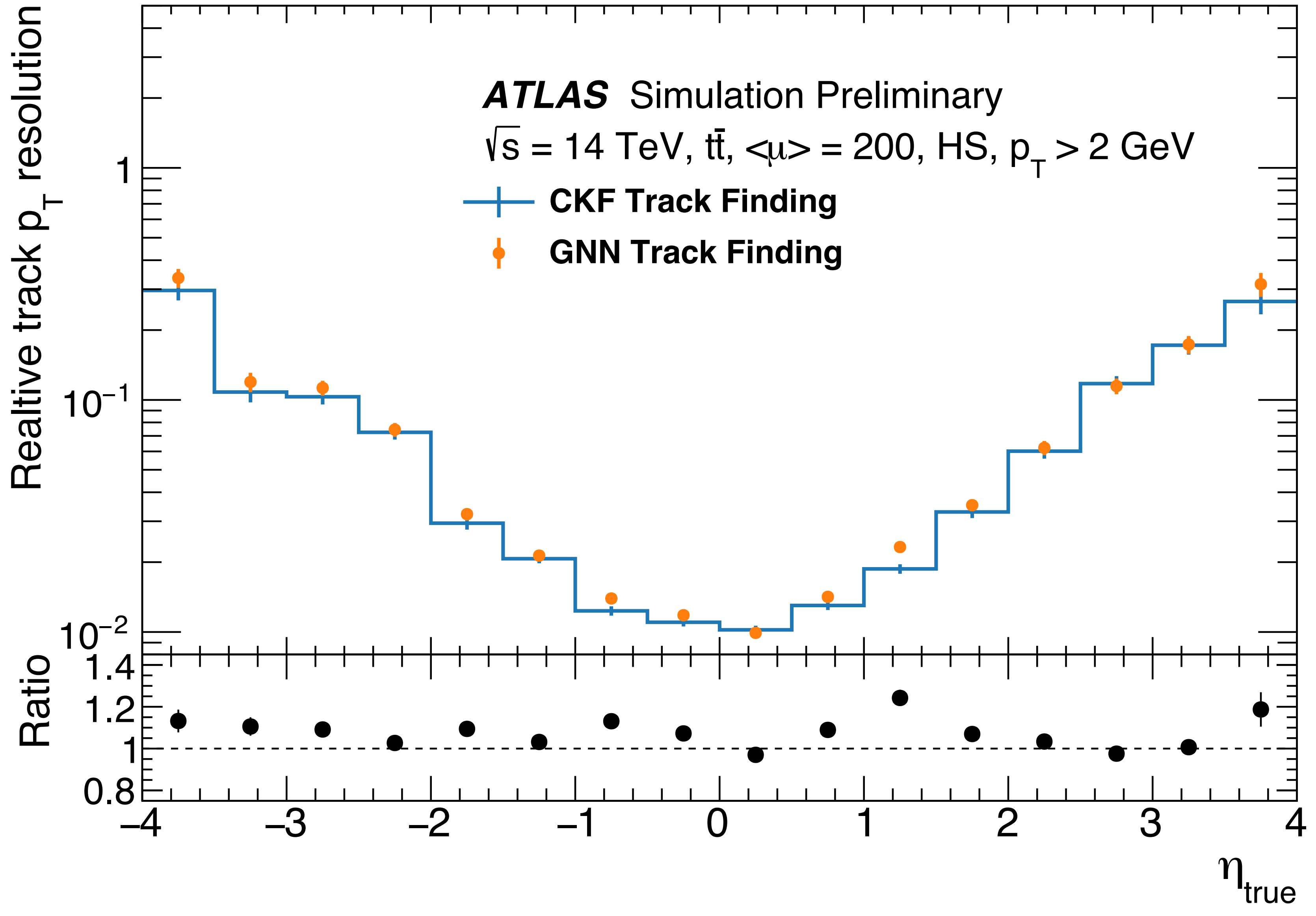
- Strip-hit content as expected
  GNN4ITk considers only “full” strip hits / space points, consisting of two strip clusters
  CKF considers also individual strip clusters

- Competitive p_T resolution,
  even with
  lower strip cluster counts









Prospects

- Further optimization and acceleration of the full GNN4ITk chain
  - Acceleration of graph construction with GPU
  - Machine Leaning model and heterogeneous GNN architectures
  - Study of corrections to strip-spacepoint positions
  - Investigate impact of missing strip-cluster singlets
- Continue physics performance studies
  (B-hadron decays tracks, electron tracks, etc.)
- Study robustness against detector effects
  (dead modules, mis-alignment, beam-spot variations)
- Integration of the GNN4ITk software into ACTS and the ATLAS Athena
- Already proven promising GNN inference speed with GPUs on TrackML dataset (Exa.TrkX)

Conclusion

First look at the physics performance of the GNN4ITk tracking chain
(apples-to-apples comparison against the Combinatorial Kalman Filter).

✓ The GNN4ITk provides competitive tracking efficiency,

✓ even in challenging dense environment,

✓ and high quality track parameter resolution.