Track reconstruction with timing in ATLAS during the HL-LHC for Run 4 and beyond

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Polarized Perspectives:
Tagging and Learning in the SM
20.02.2025

Being on time

HL-LHC is a **unique opportunity** to **test future frontier** detectors such as **4D Trackers**

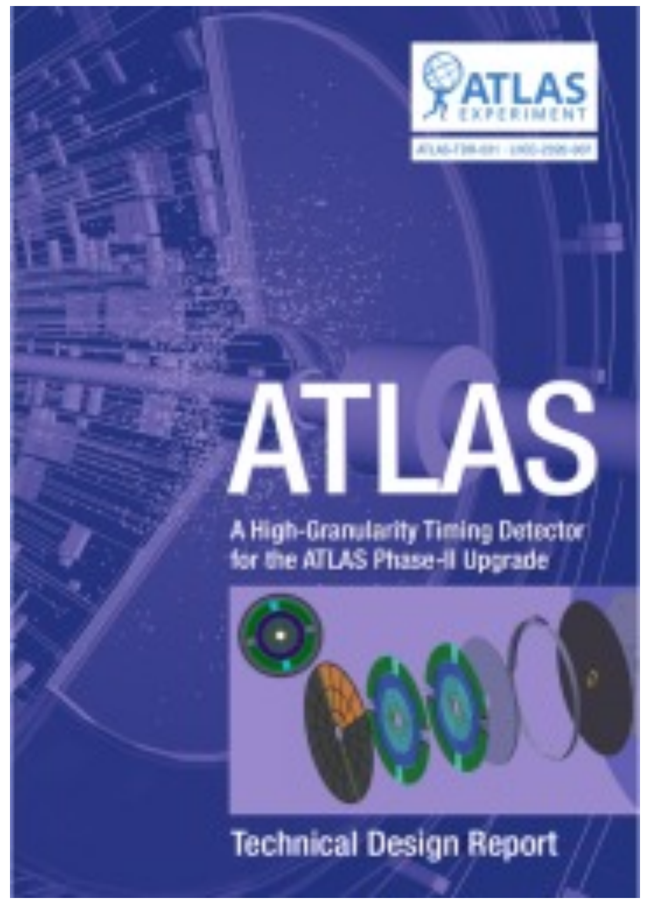
Timing detectors are a **growing area** of interest in HEP

i.e. **HGTD** in ATLAS and **MTD** in CMS will be installed in Run4!

The **next phase** in technological advancement **is the developement** of **silicon trackers** carachterized by $\mathcal{O}(10\mu m) \otimes \mathcal{O}(10ps)$:

In Run4 ATLAS will install a fully silicon tracker: **ITk**

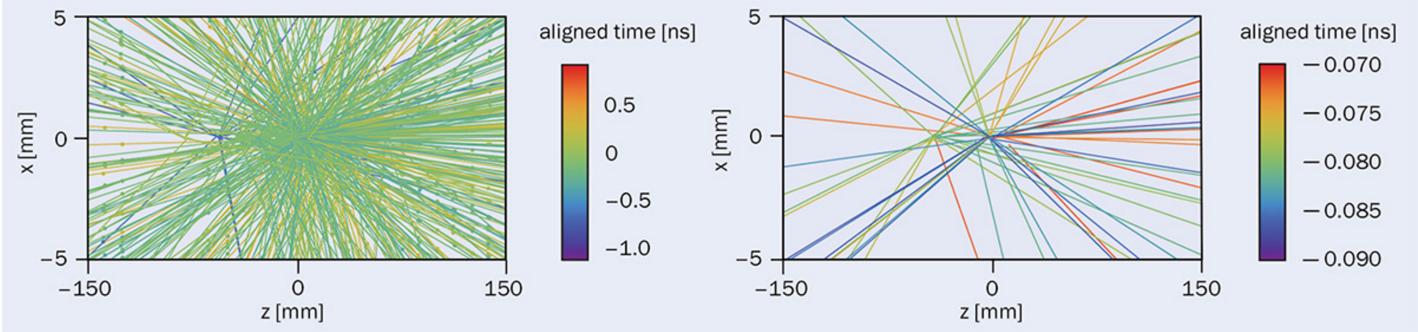
The presented work is a study of a potential impact of a hermetic timing coverage in ATLAS in ITk, eventually beyond Run4: link



FLAVOUR PHYSICS | FEATURE

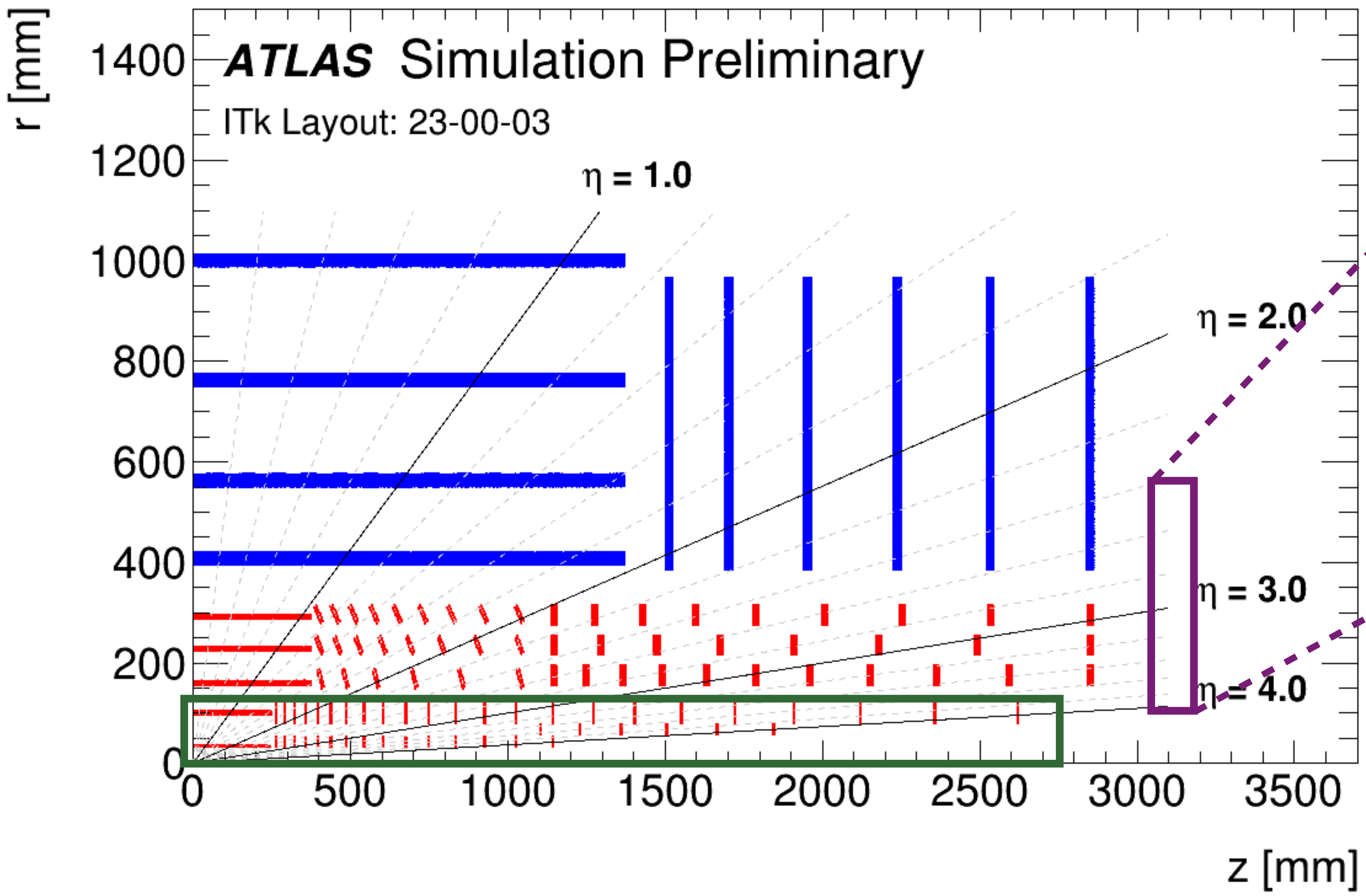
LHCb looks forward to the 2030s

1 March 2023



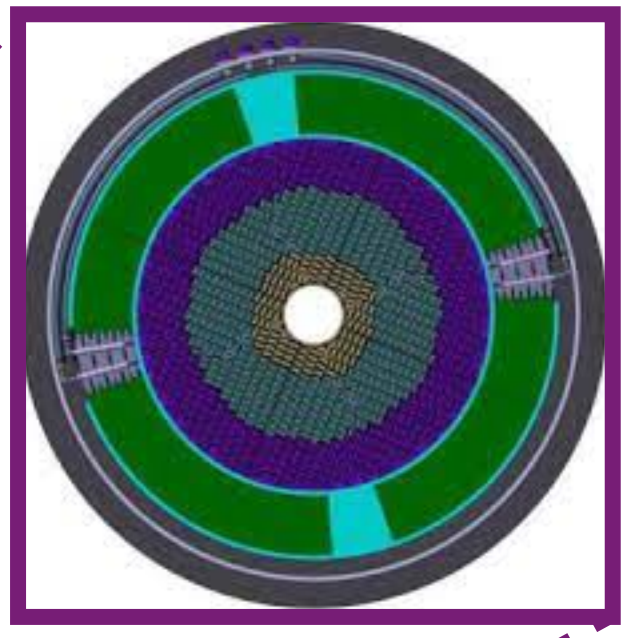
The future VELO will be a true 4D-tracking detector

Timing opportunities in ATLAS



Two innermost pixel **layers** of ITk need to be replaced due to hard radiation after $2000\ fb^{-1}$ of data at HL-LHC

High Granularity Timing Detector (HGTD) installed for Run4



Coverage:

$2.4 < \eta < 4$

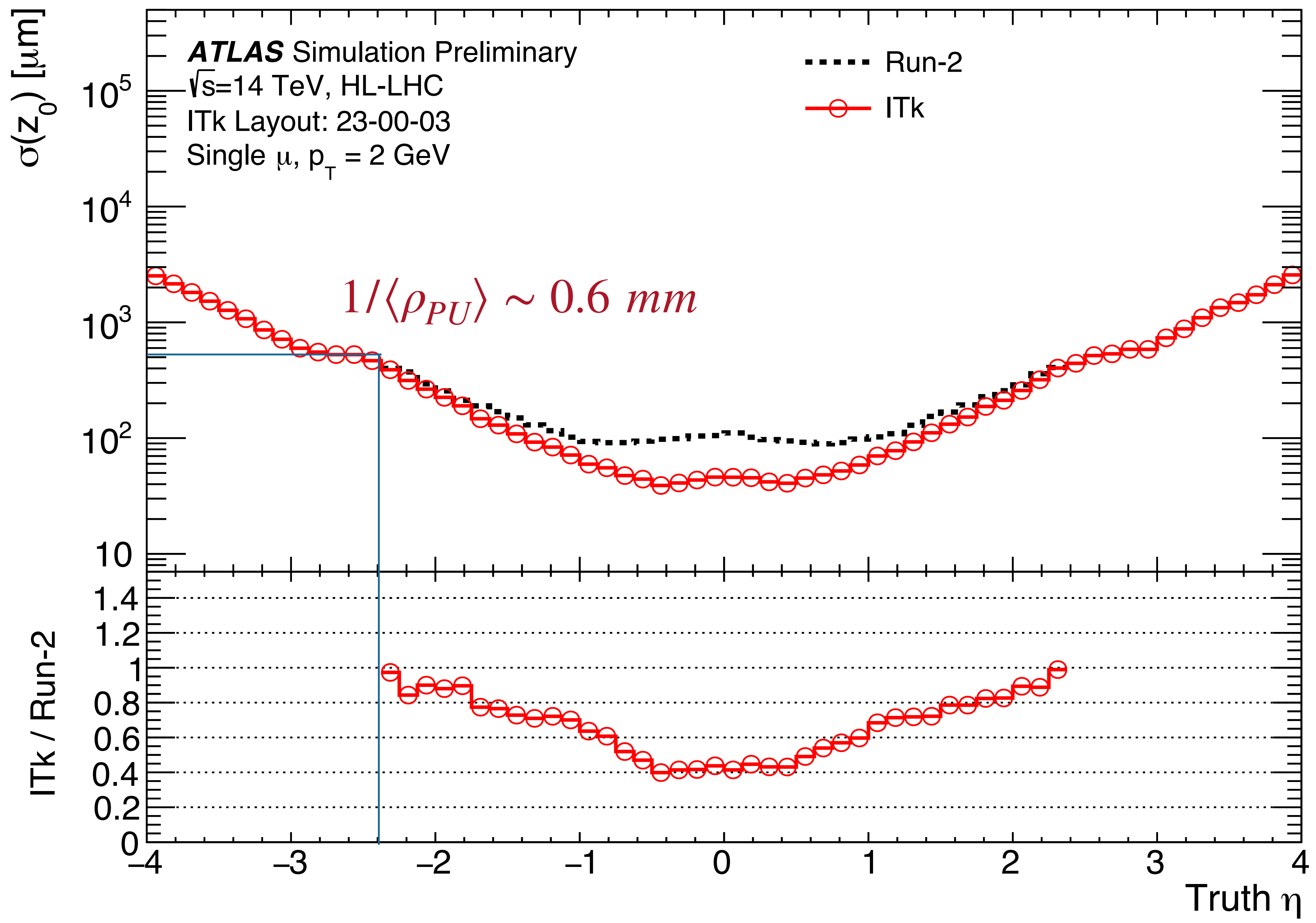
track time resolution:

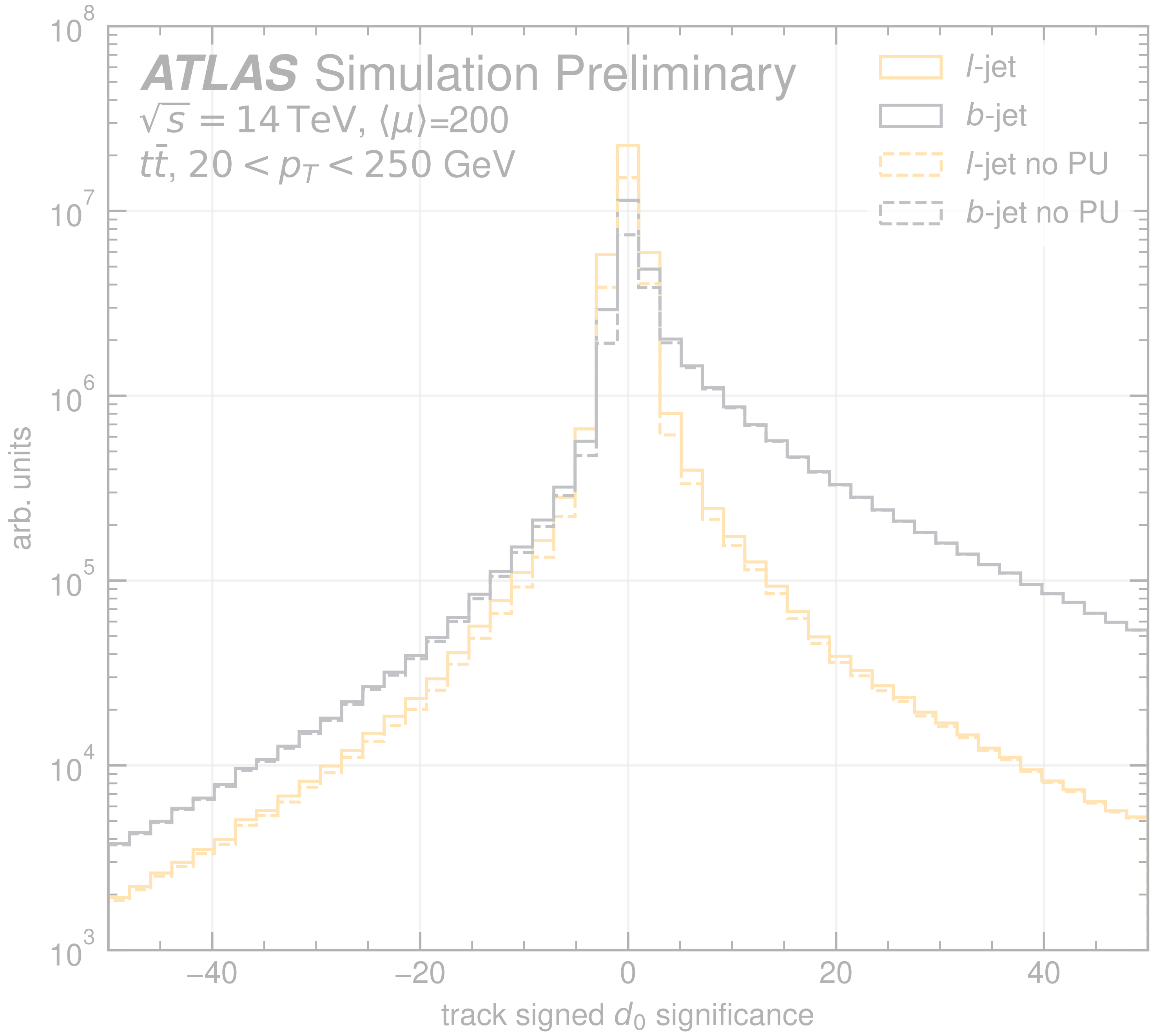
$t_{trk} \sim 30ps$

Main questions:

- How *precisely* we can determine the **vertex time** t_{HS} on **all** events?
- Can we improve b-tagging?

Motivations





HGTD motivation:

Pile-Up removal in forward region

Where the IP_{z0} resolution is lower

What if we have hermetic coverage with timing in the barrel?

Performance: Vertexing, FTag ...

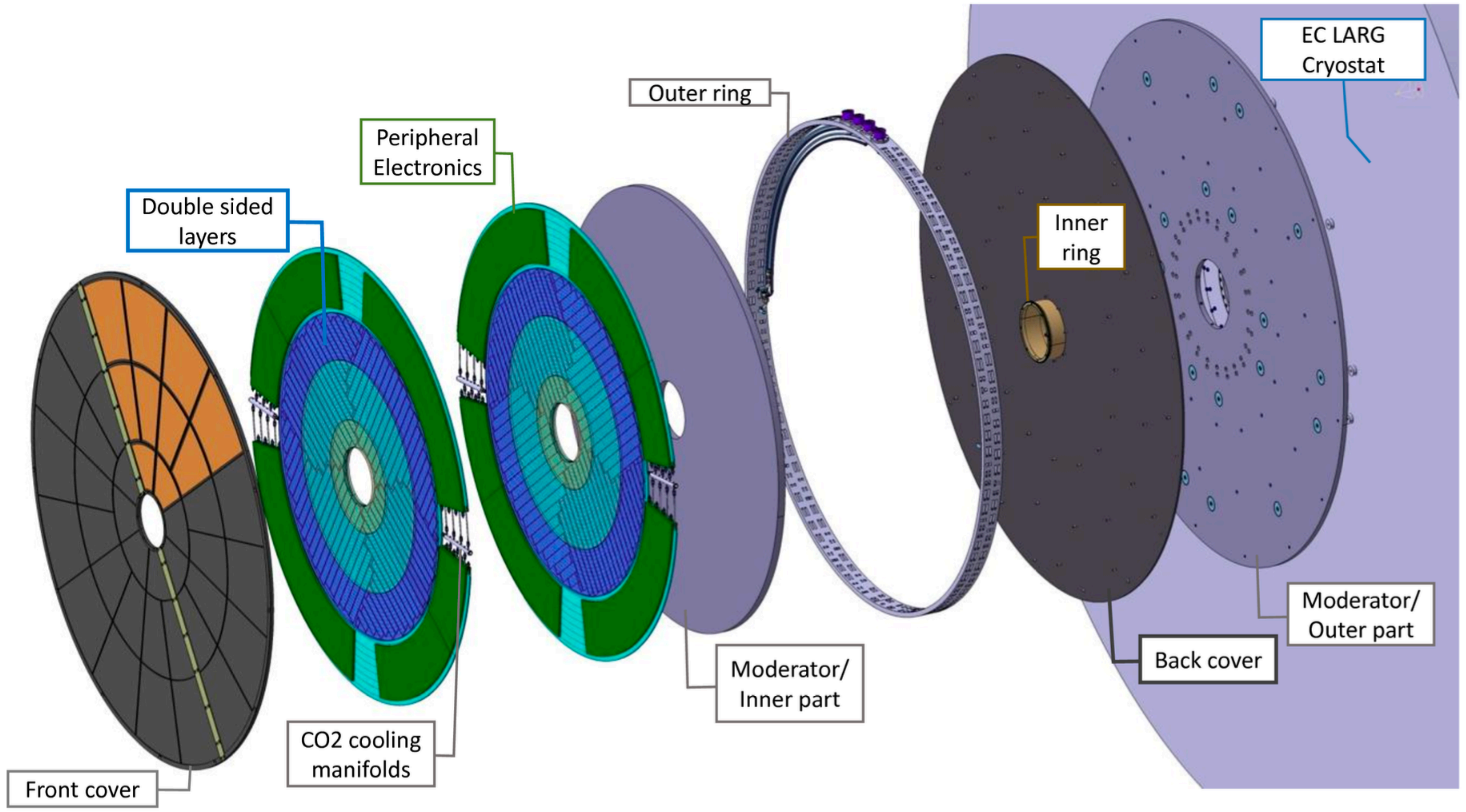
Physics case: HH, LLP ...

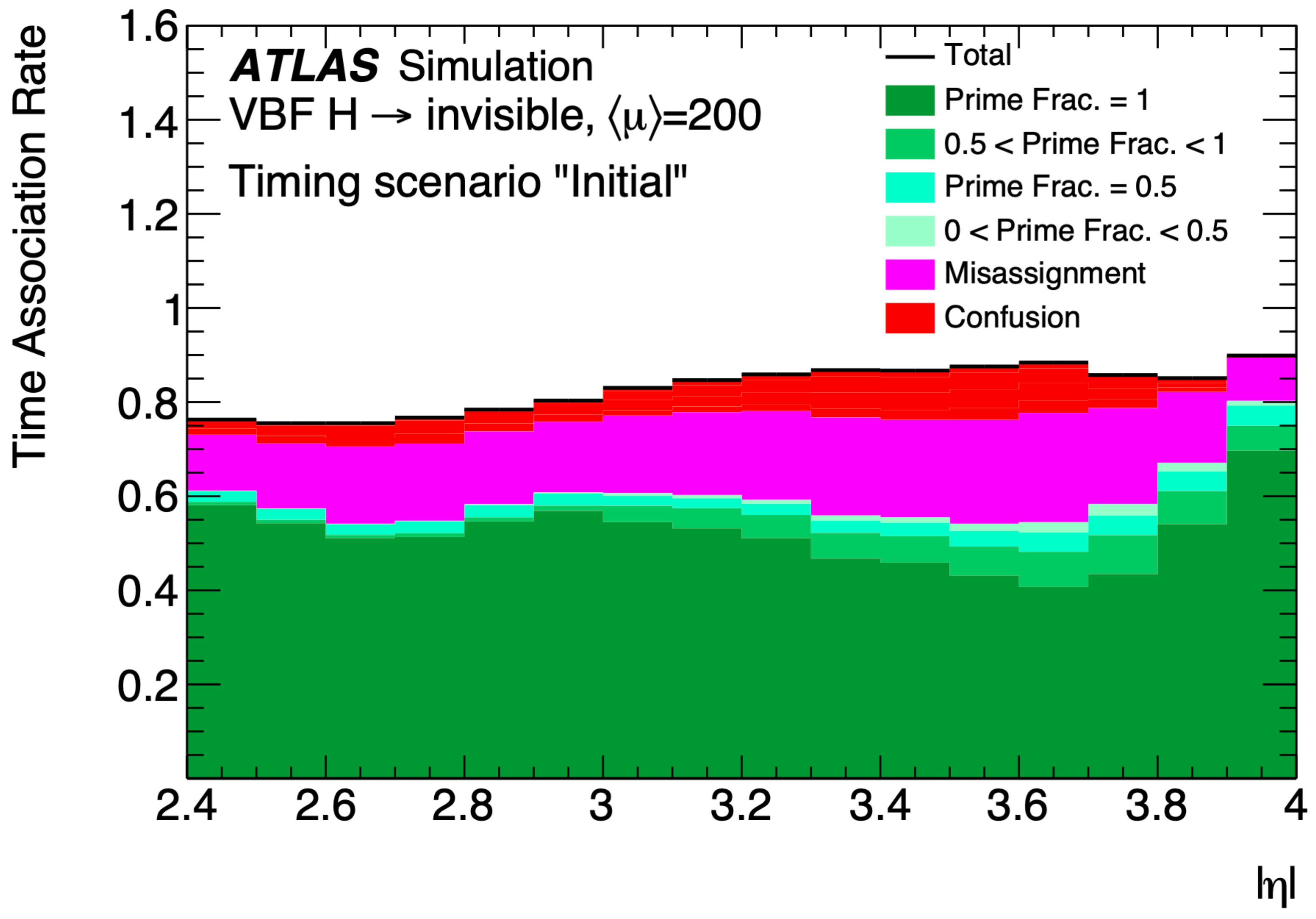
HGTD: tracks and time

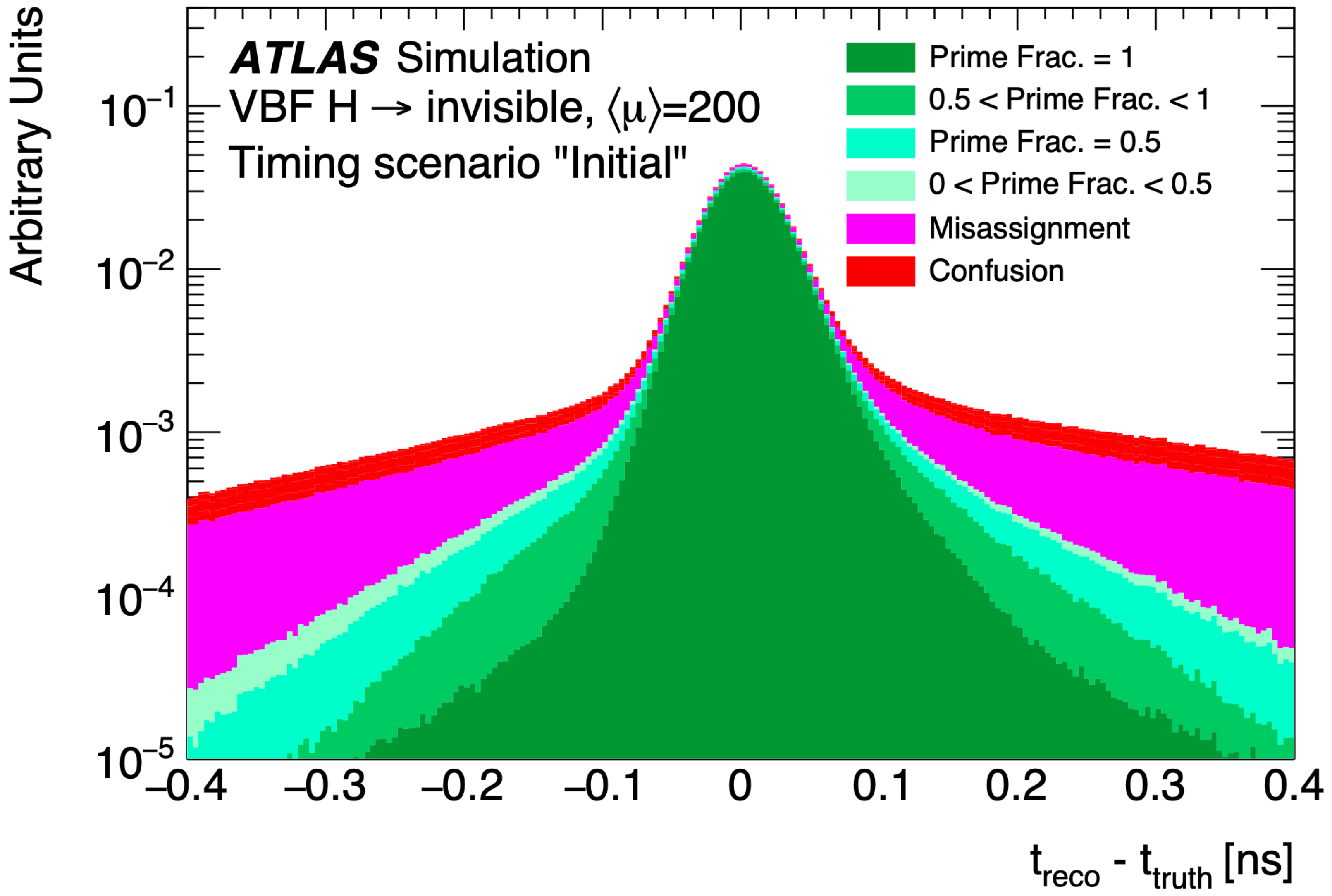
Based on Low Gain Avalanche Detectors (LGAD)

Track time resolution: from **30ps** (initial) to **50ps** (final)

On VBF $H \to inv$. time association rate ~60%







HGTD: physics objects

HGTD allows to have for the first time a t_0 of the vertex

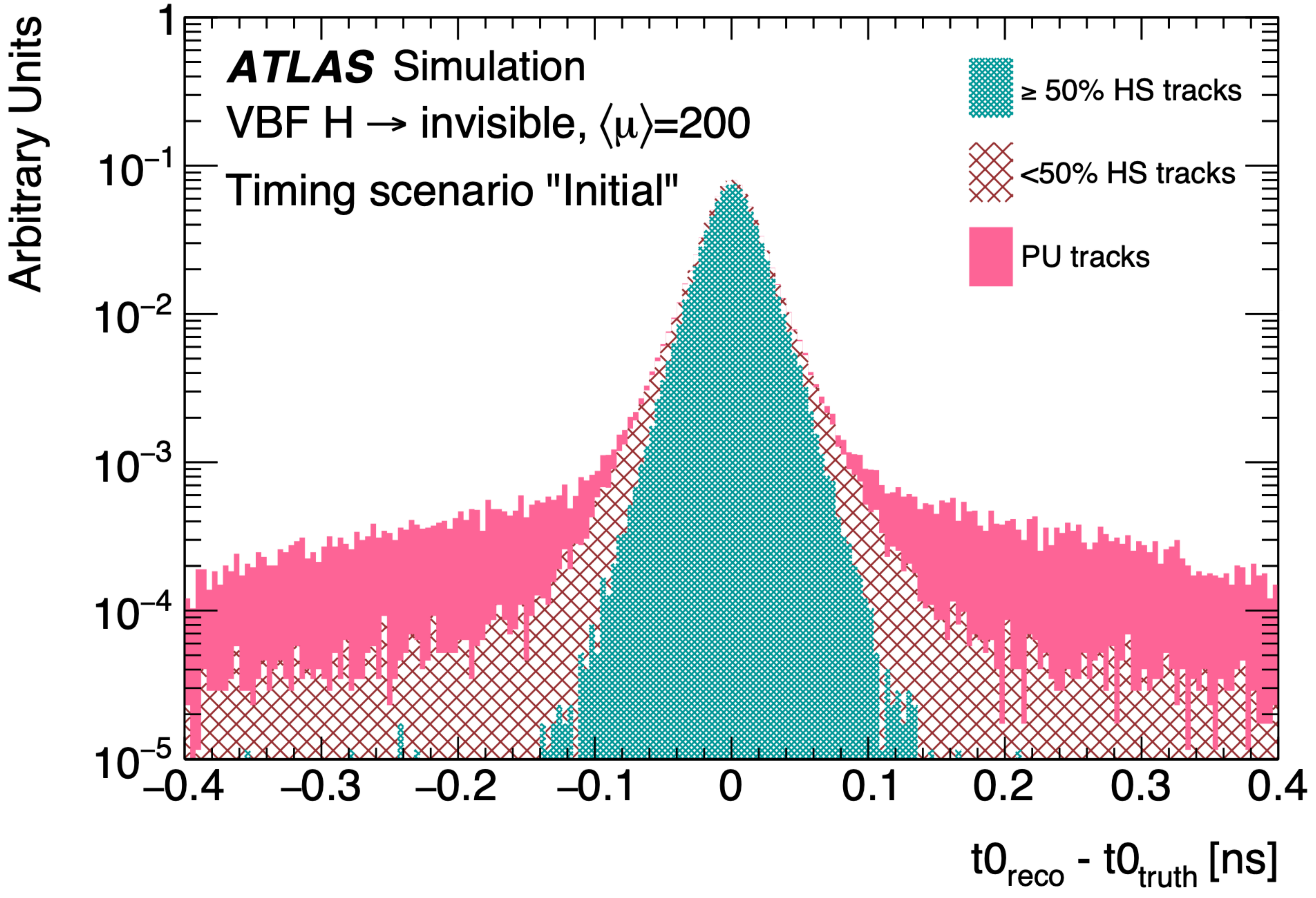
t_0 resolution gets up to **22ps** if more than 50% of the tracks come from HS

track to vertex association can be extended with time:

$$\frac{z - z_0}{\sigma_z} < s \quad \rightarrow \quad \frac{t - t_0}{\sigma_t} < s$$

with the caveat that **not always** it is possible to reconstruct the t_0:

On VBF $H \rightarrow inv$. about 65% of the events have a t_0

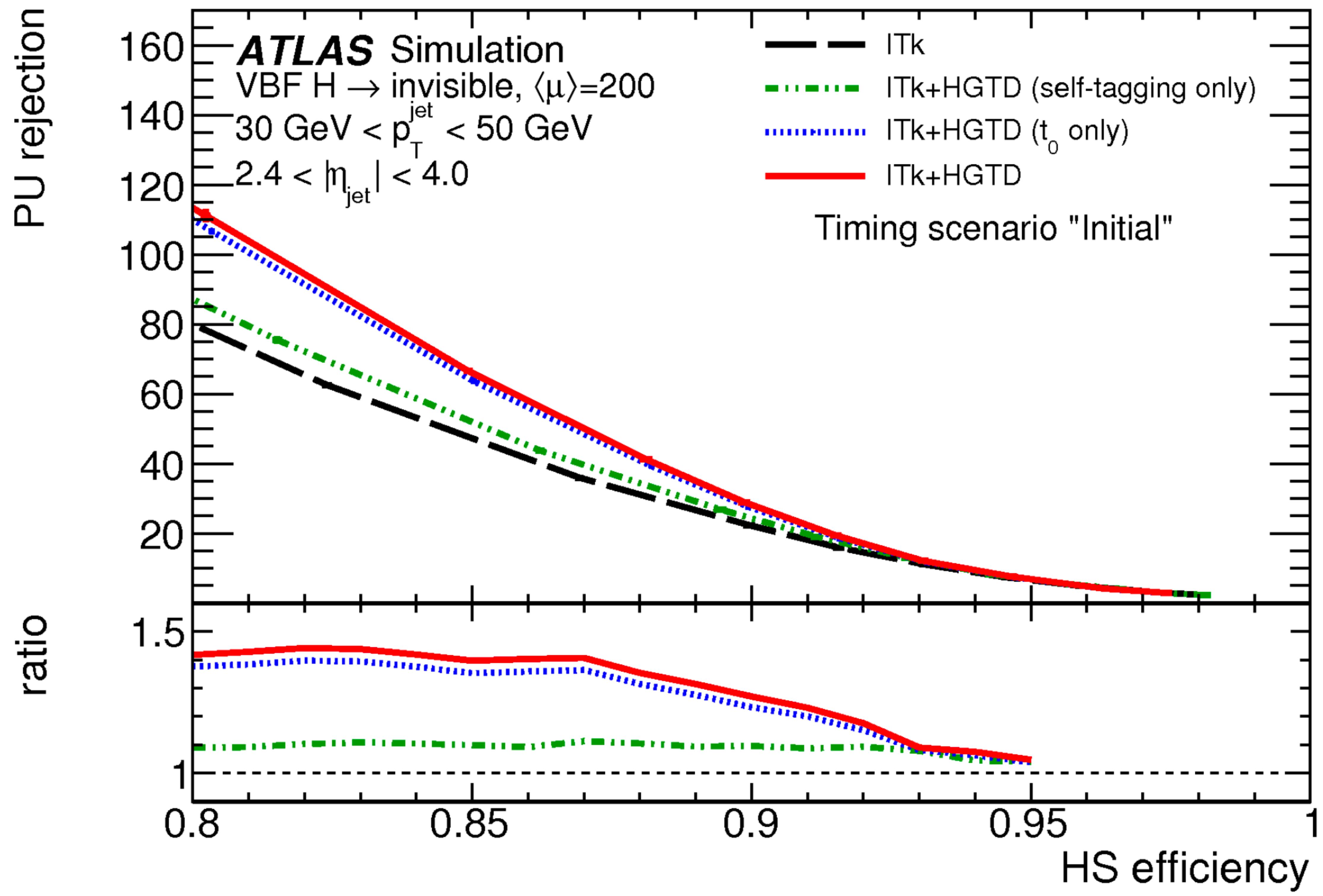


HGTD: physics objects

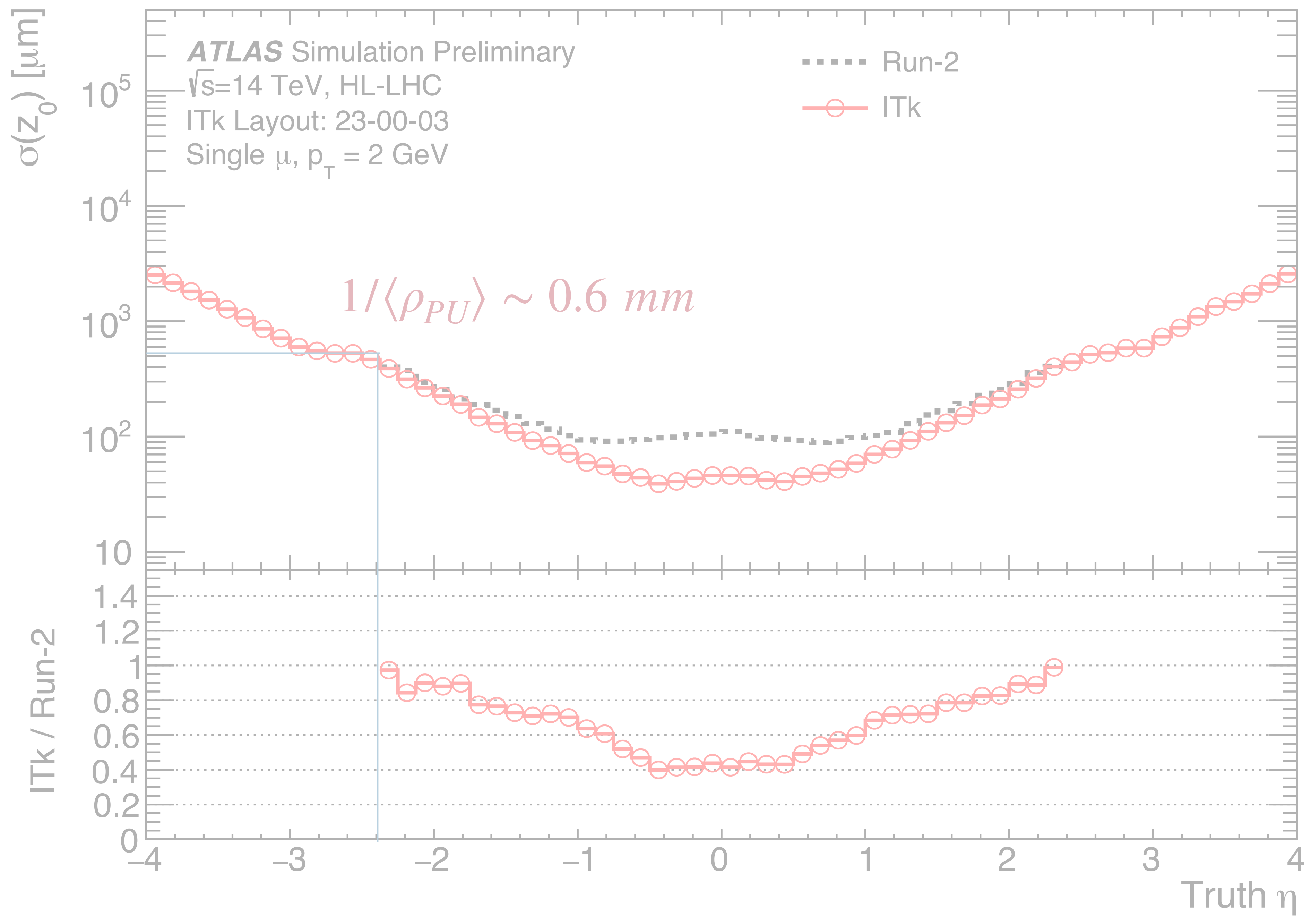
It allows also to suppress Pile-Up jets suppression

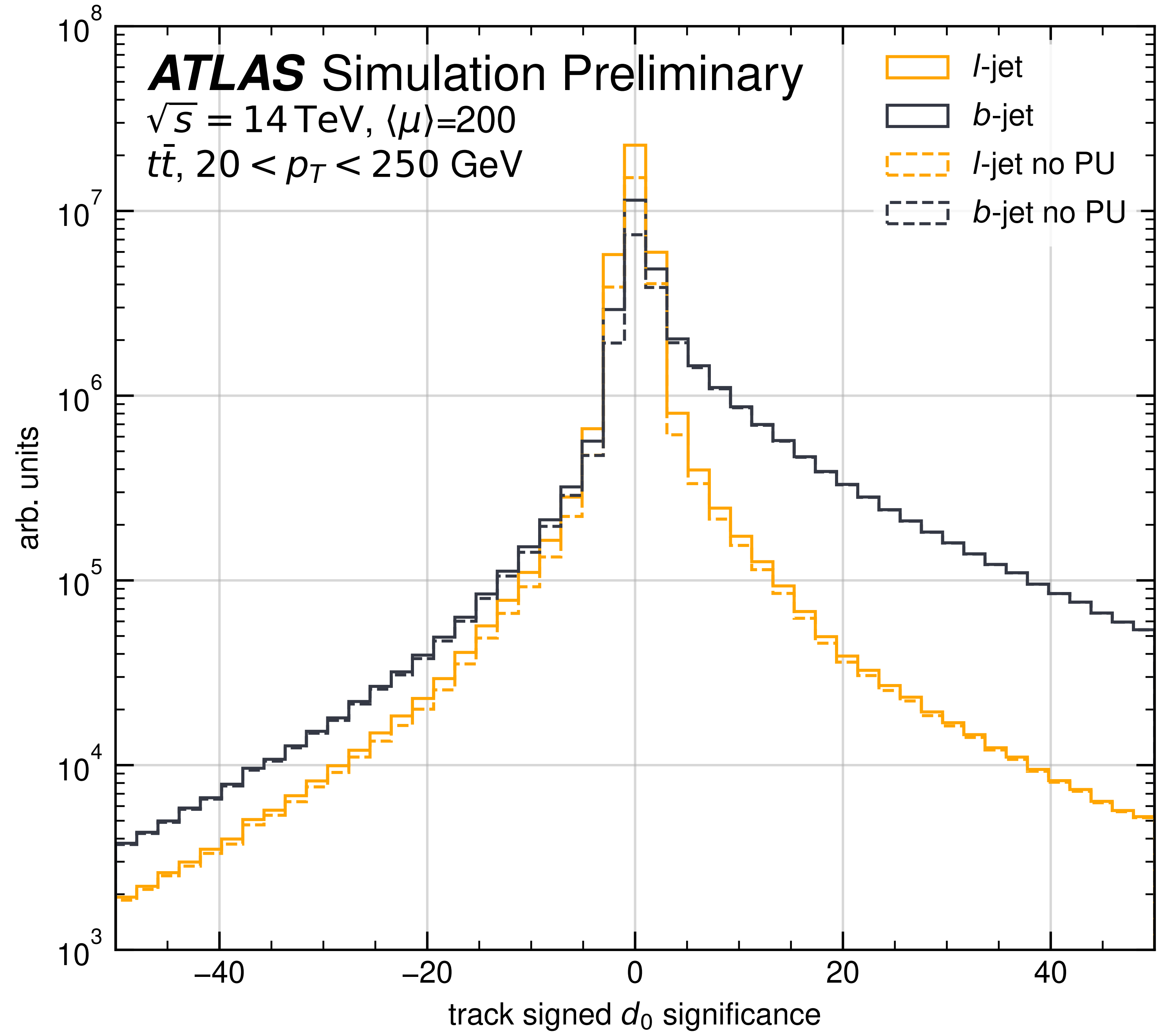
the PU rejection increases around 50%
for an HS efficiency of 85%!

This requires a precise measurement on t_0



Motivations





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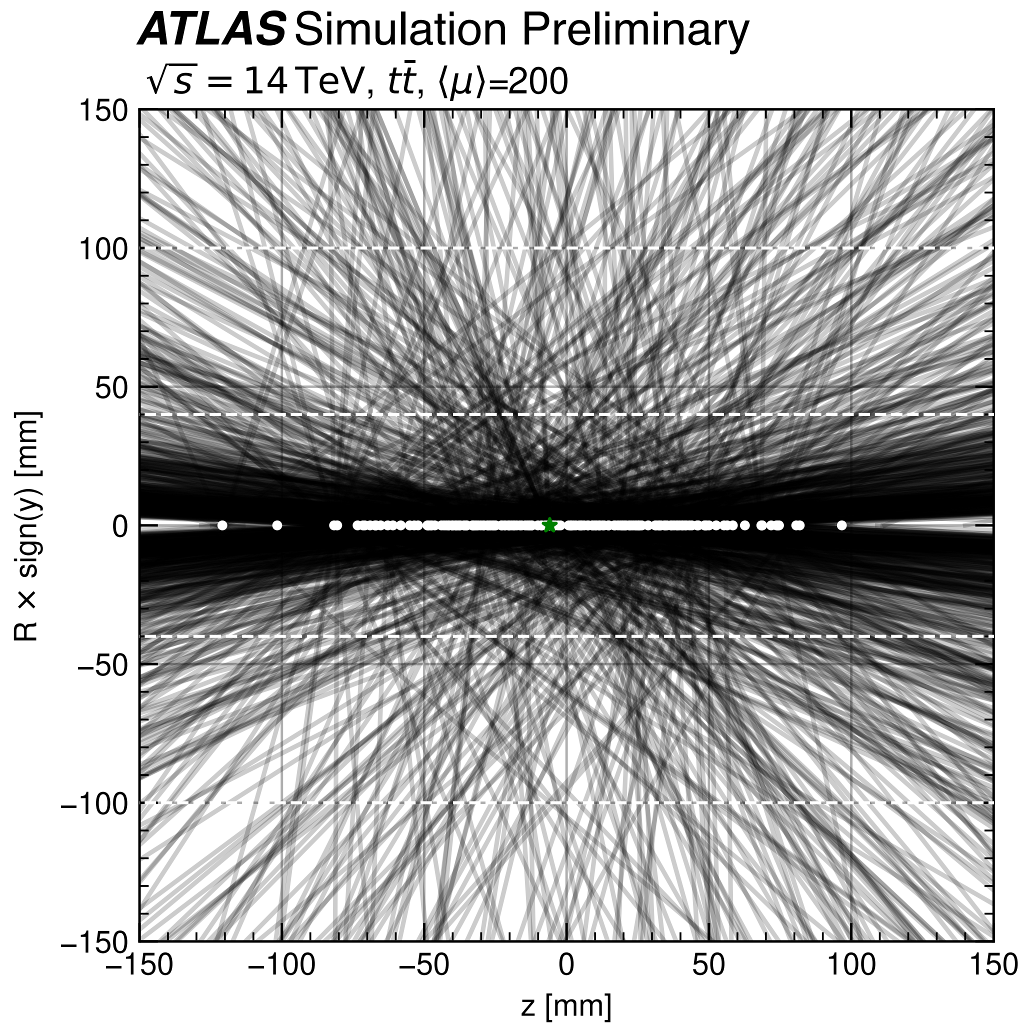
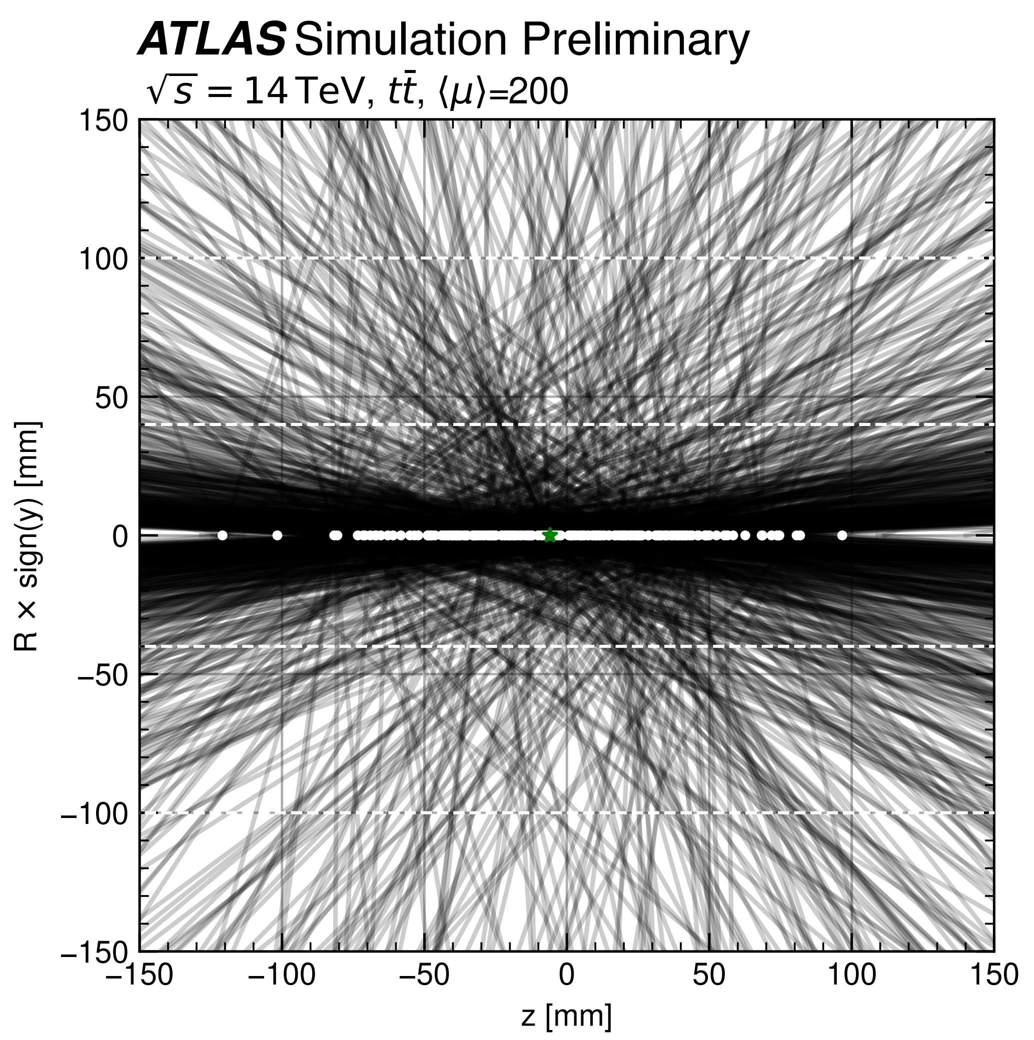
Unfolding the 4-th Dimension



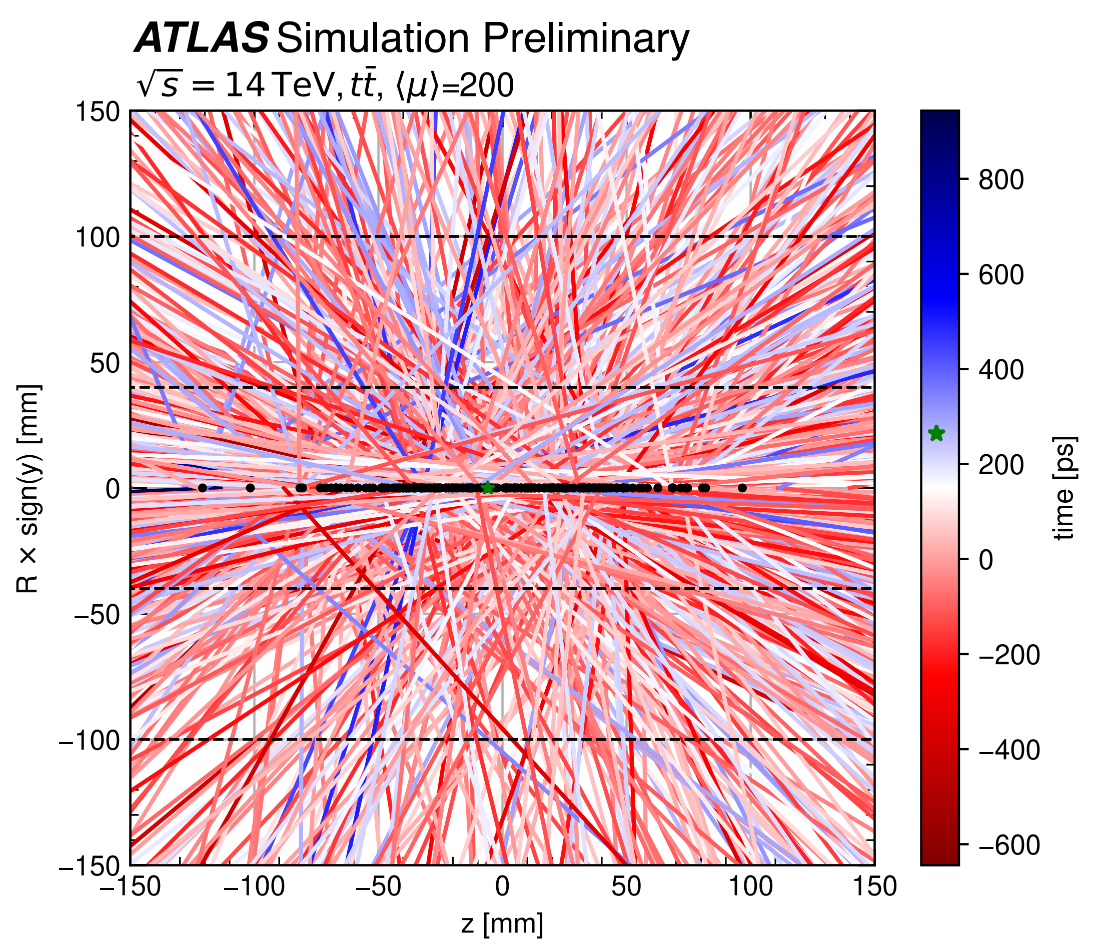
without time

All presented studies are based on MC simulations: [PUB Note]

Unfolding the 4-th Dimension



without time



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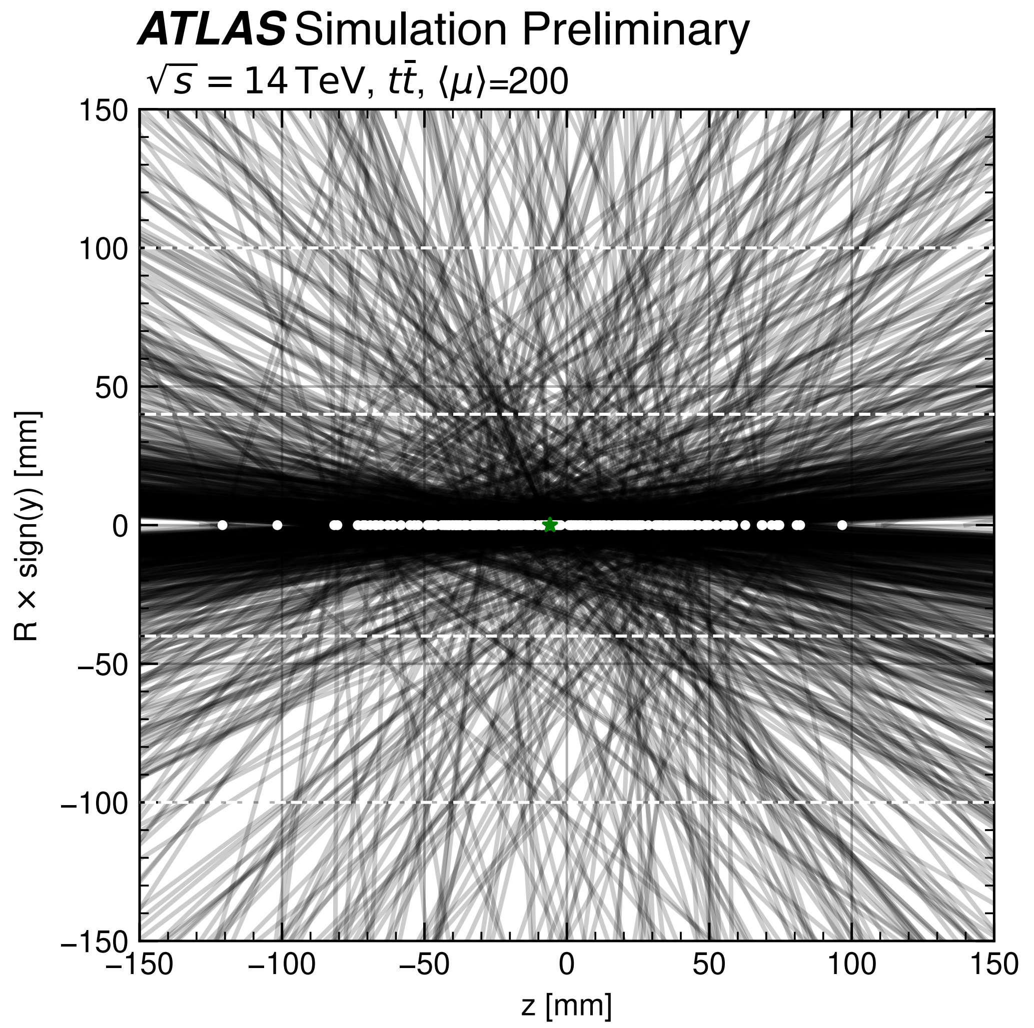
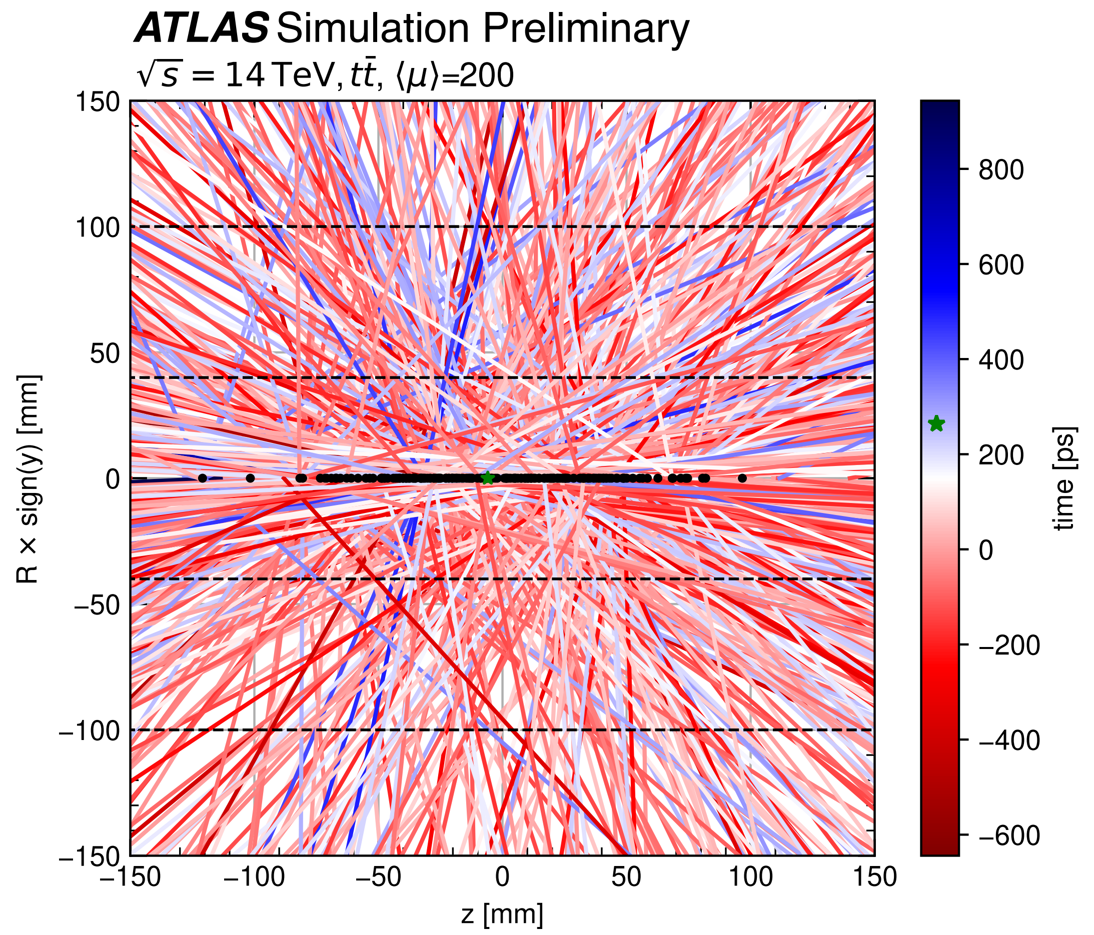
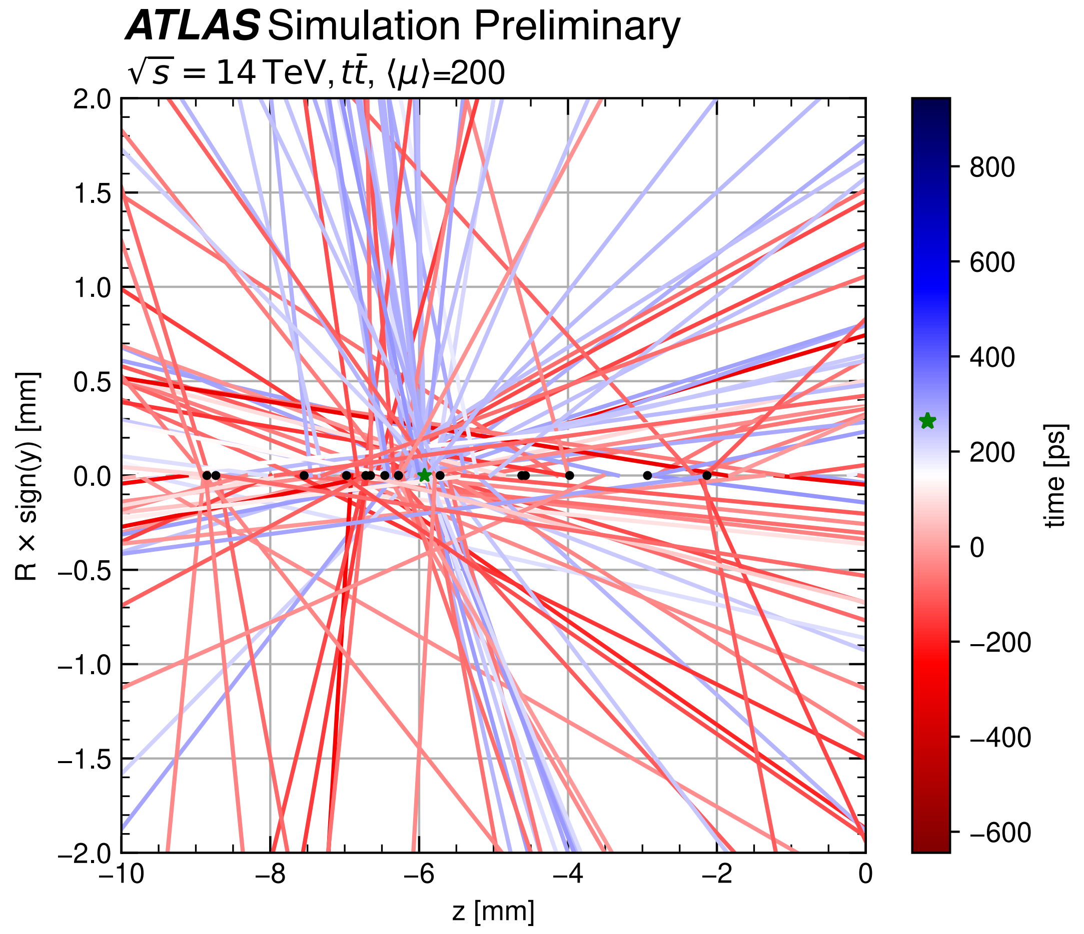


without time



with time

zoom in space



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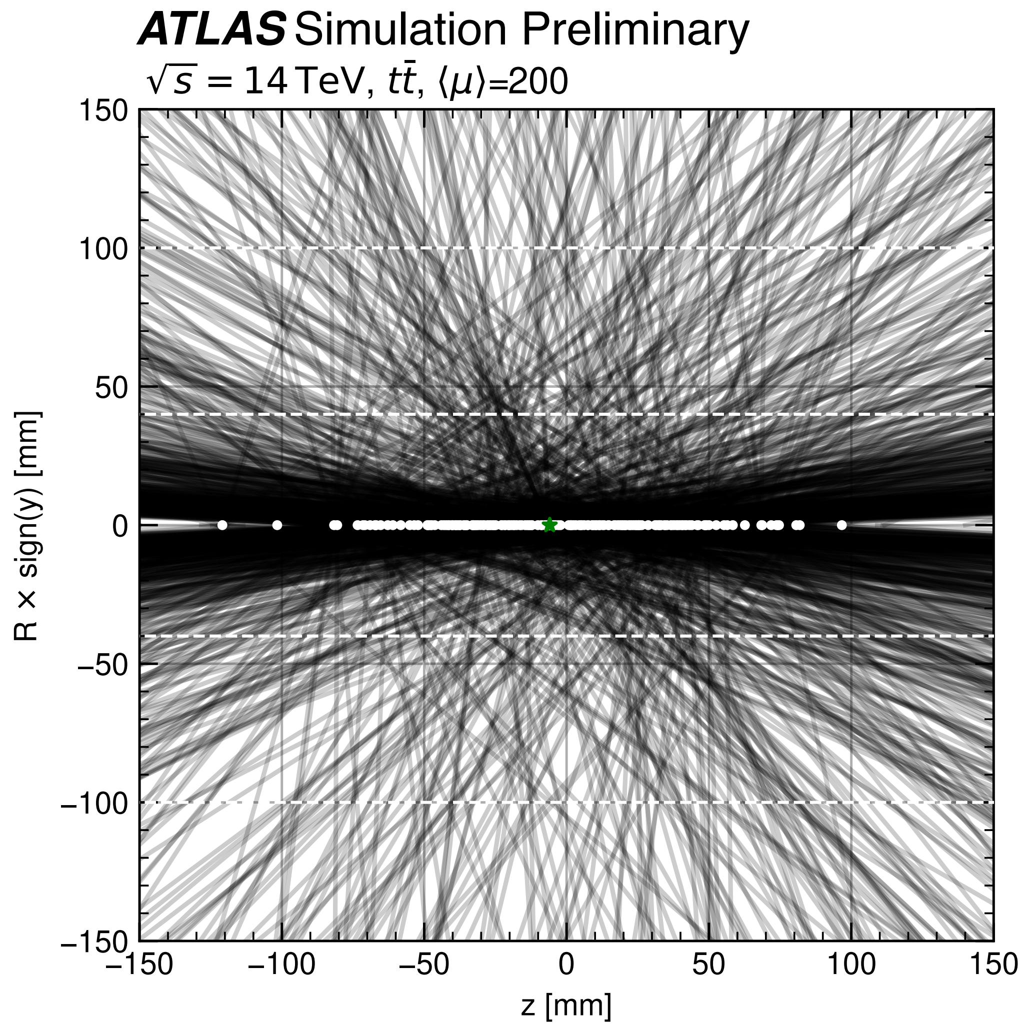
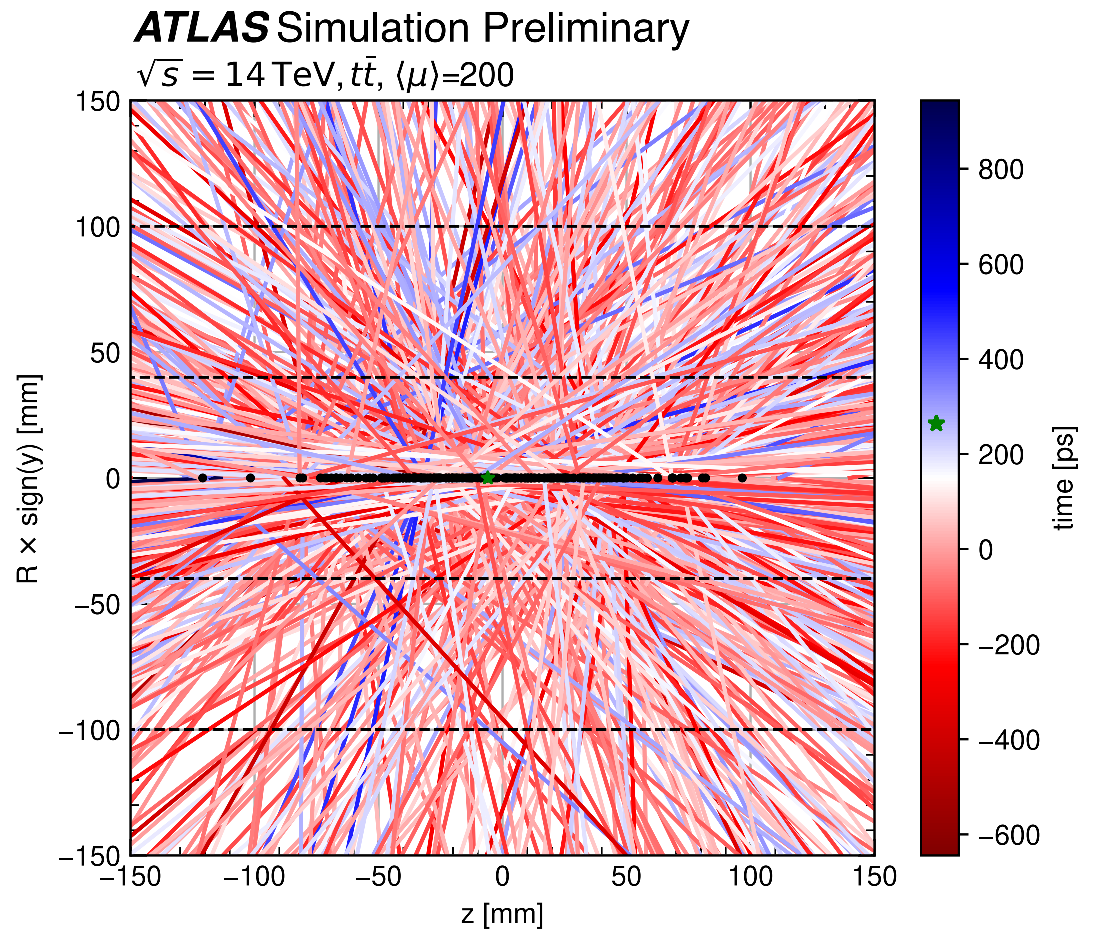


without time



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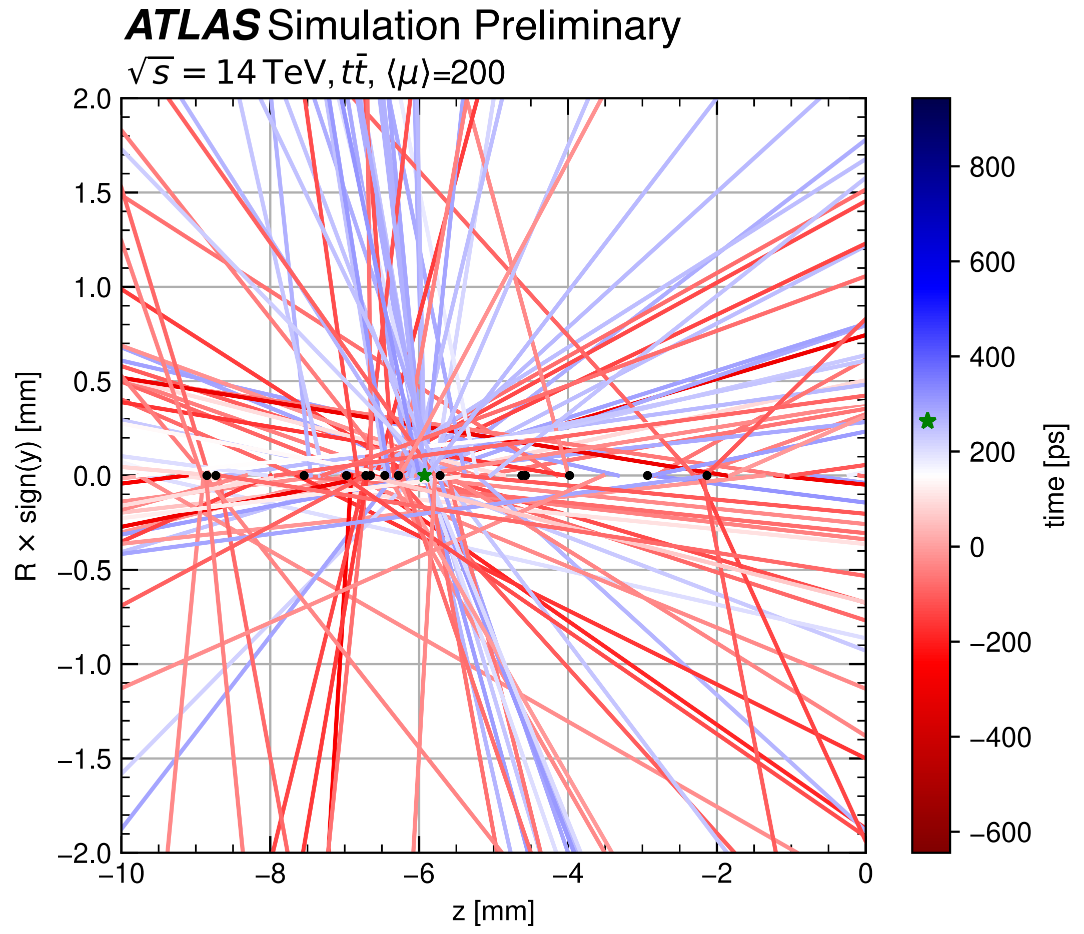
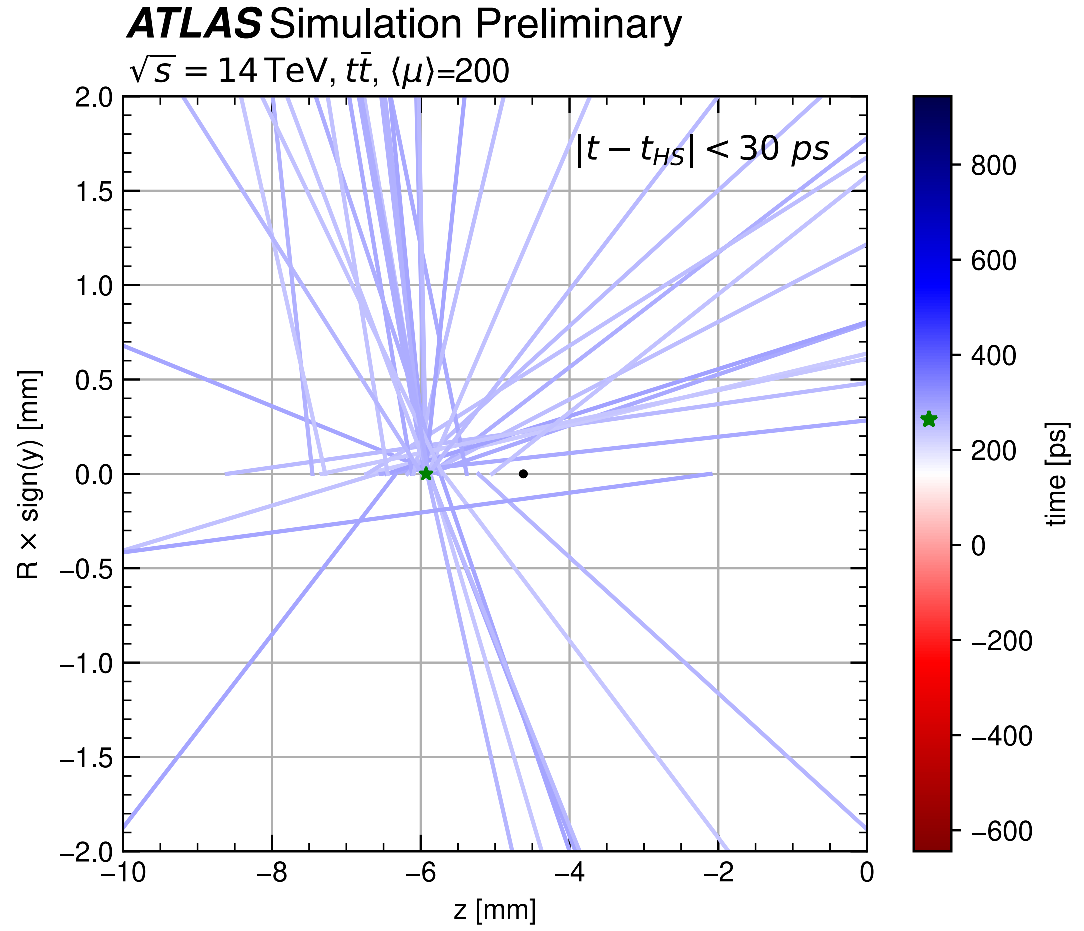


zoom in time



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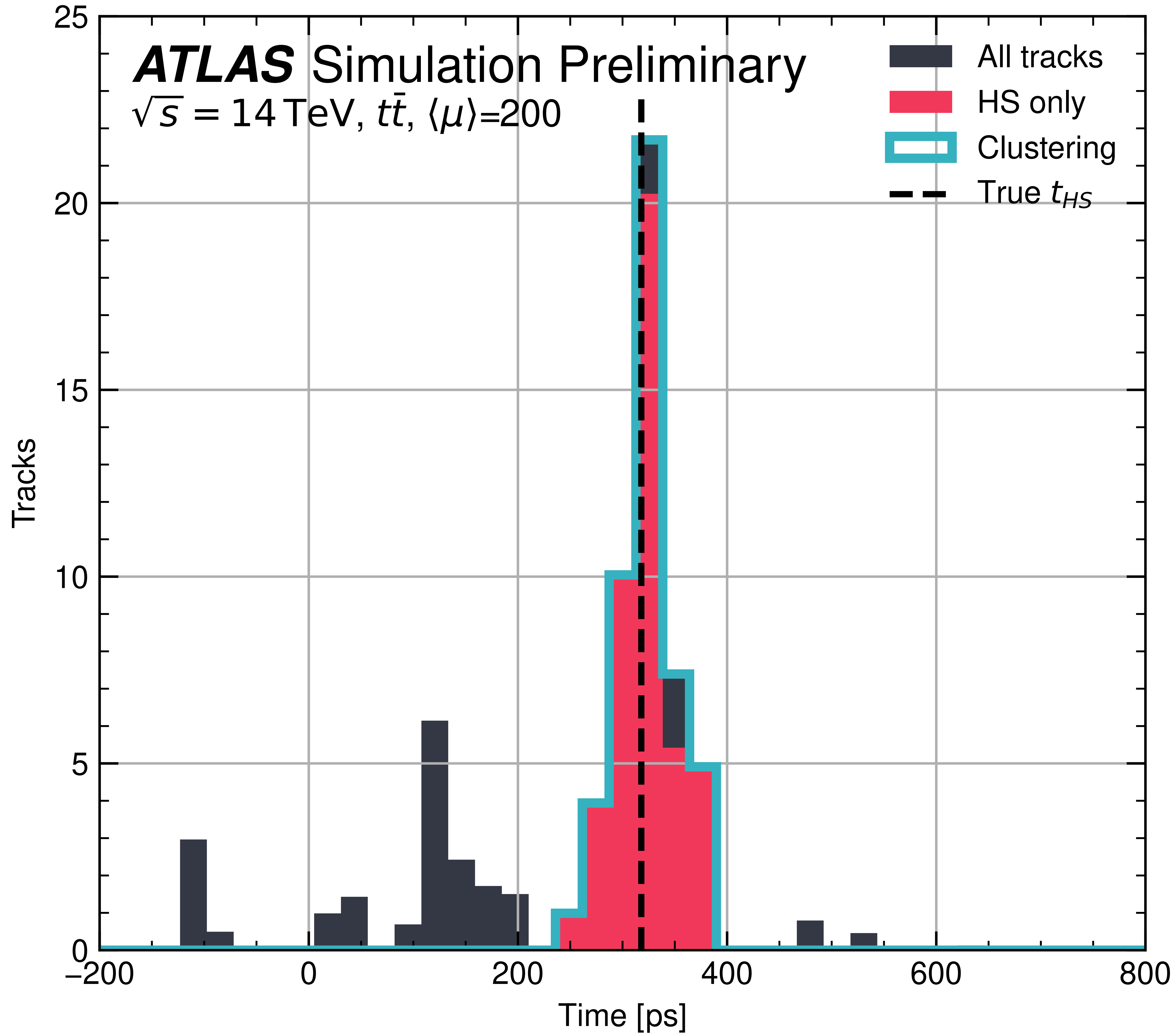
Determination of t_{HS}



Track time emulated **from truth** level MC information

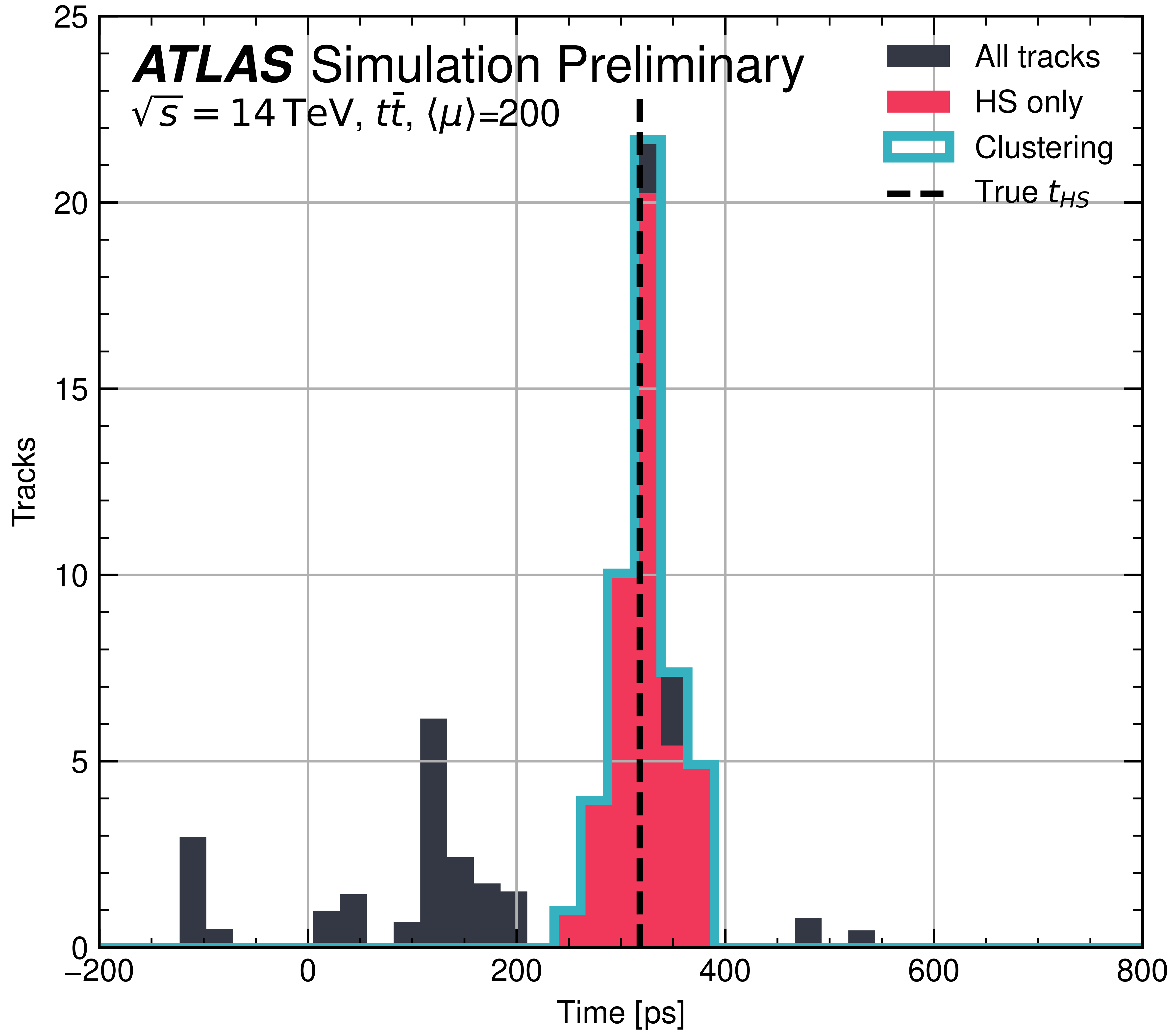
Track time distribution of *vtx*

$$t_{all}^{reco} = \sum_{trk} t_{trk} w_{trk}$$

if we consider all the tracks associated to vertex from 3D-vertexing

Obs: this scan be seen as the case where no time information is available

Vertexing: Determination of t_{HS}



Track time emulated **from truth** level MC information

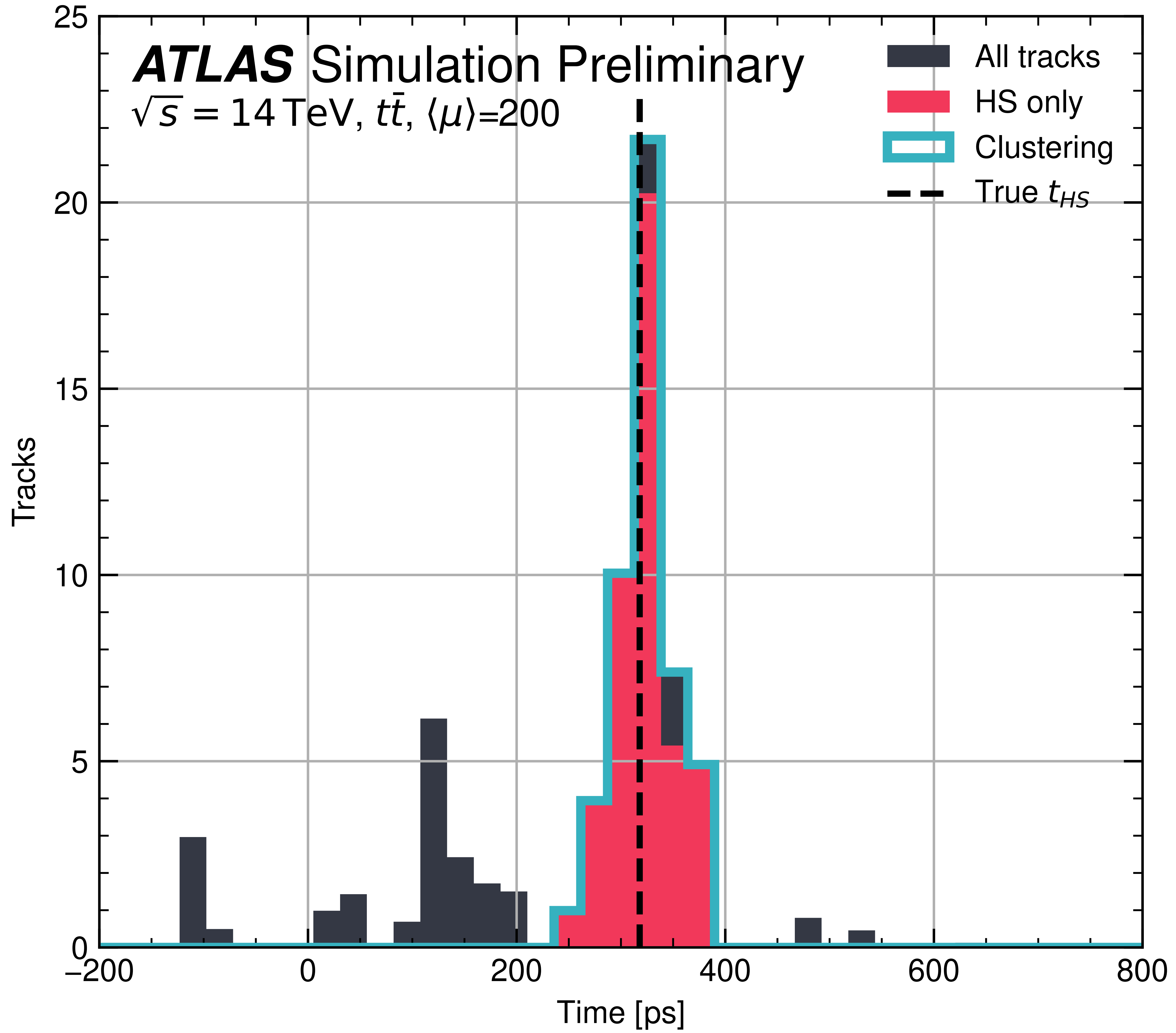
Track time distribution of *vtx*

$$t_{all}^{reco} = \sum_{trk} t_{trk} w_{trk}$$

$$t_{HS}^{reco} = \sum_{trk \in HS} t_{trk} w_{trk}$$

Ideal Case selecting tracks from the HS

Vertexing: Determination of t_{HS}



Track time emulated **from truth** level MC information

Track time distribution of *vtx*

$$t_{all}^{reco} = \sum_{trk} t_{trk} w_{trk}$$

$$t_{HS}^{reco} = \sum_{trk \in HS} t_{trk} w_{trk}$$

$$t_{clus}^{reco} = \sum_{trk \in clus} t_{trk} w_{trk}$$

DBSCAN Timing Clustering algorithm

Obs: This algorithm emulates a 4D Vertexing, 3D+1D

Vertex time resolution

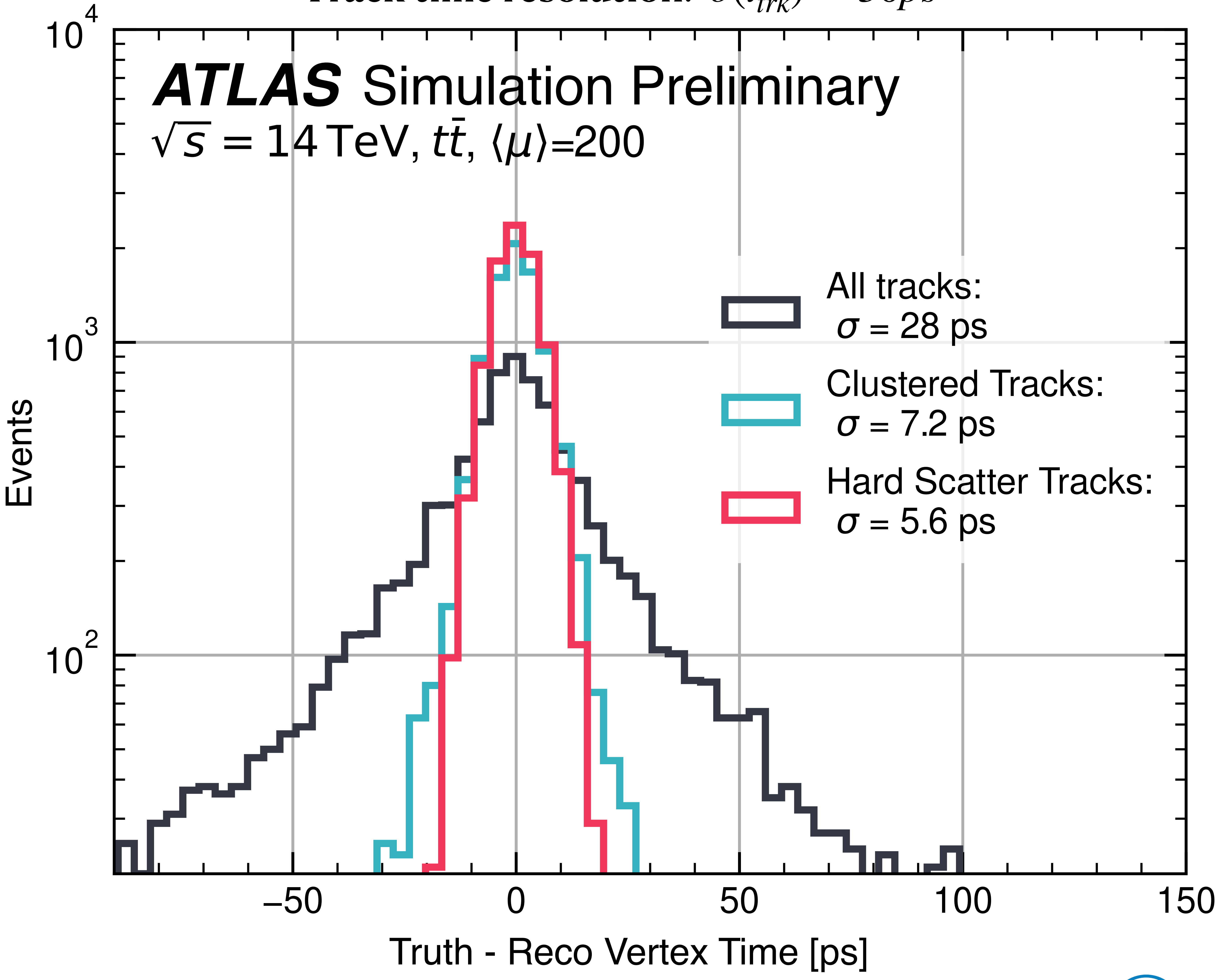
To extract the **vertex time resolution,** $\sigma(t_{HS})$**,** we can consider the standard deviation on the $t_{HS}^{reco} - t_{HS}^{truth}$ distribution for the aforementioned cases

The distribution with ***All tracks*** corresponds to the case where no timing information is accessible.

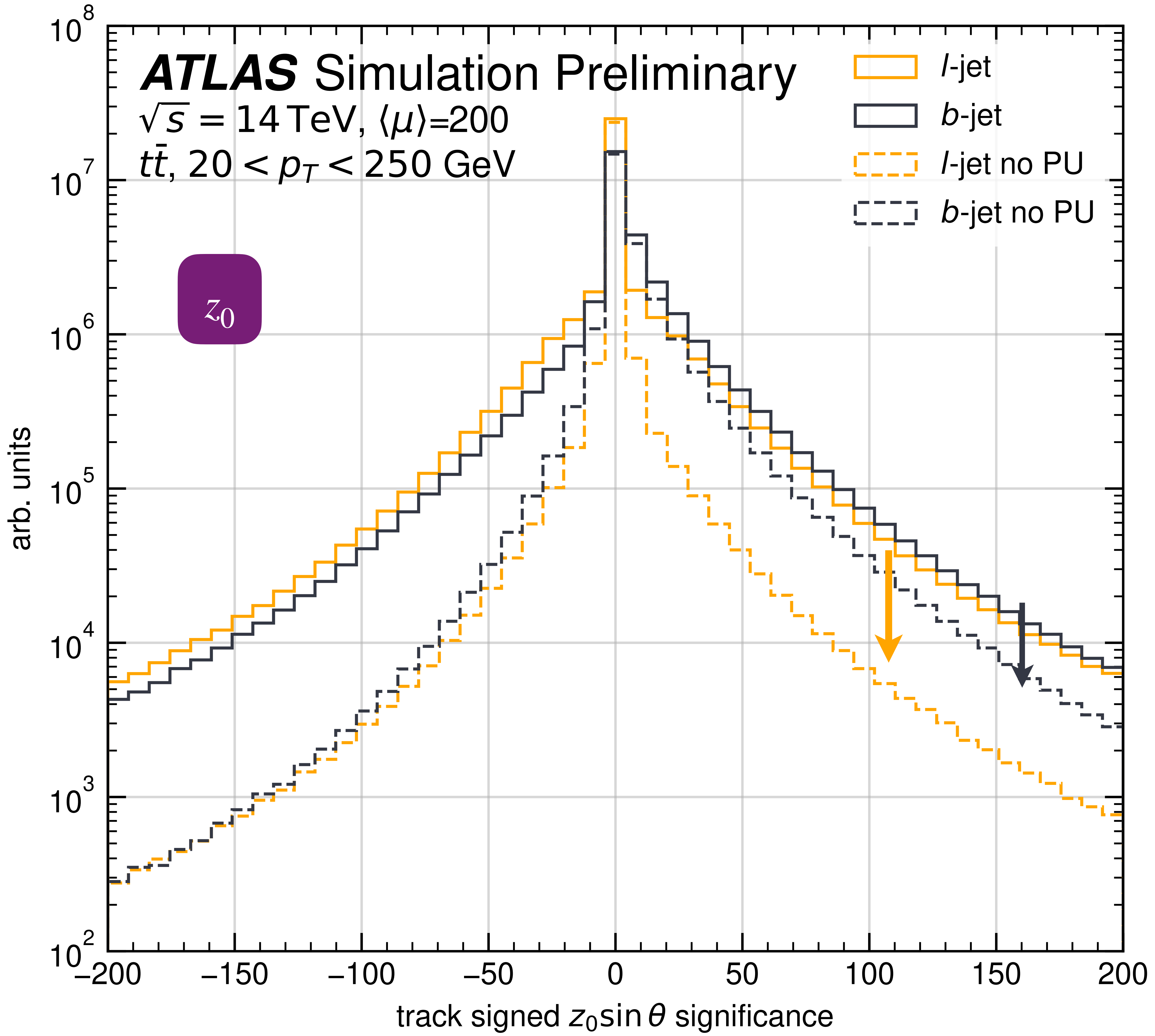
The **vertex time resolution** obtained with the ***Clustering*** is close to the ***HS tracks*** one corresponding to the ideal case where all the PU has been removed:

$\sigma(t_{HS})$: 28ps → 7.2ps (5.6ps)

Track time resolution: $\sigma(t_{trk}) = 30ps$

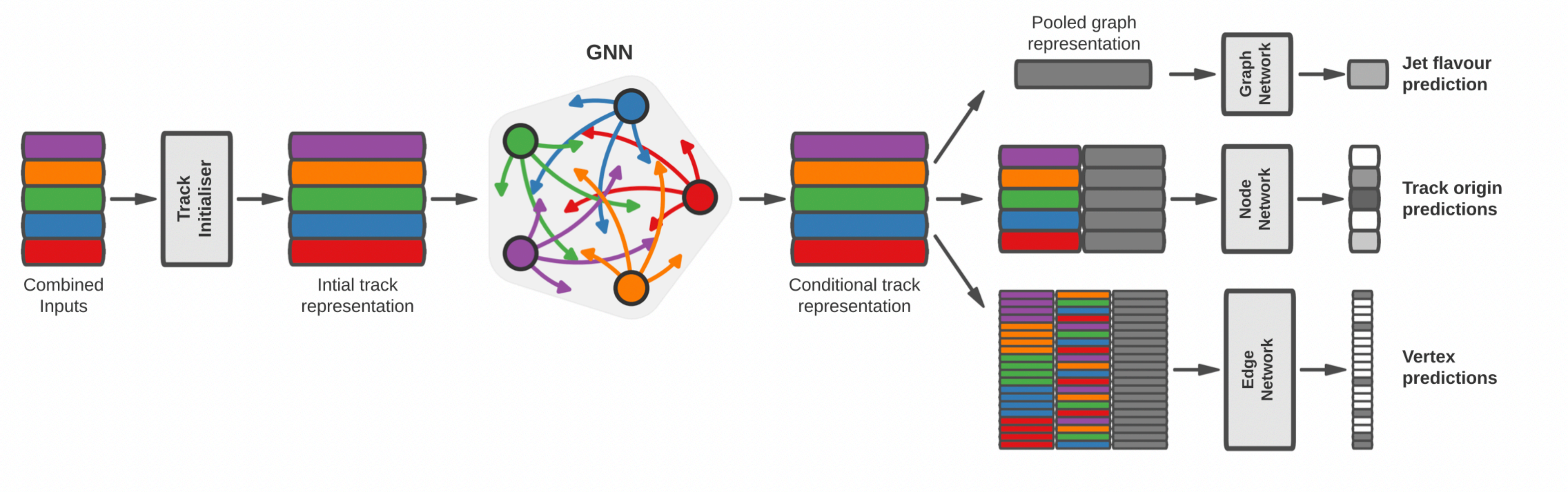


Impact on Flavour Tagging



Impact parameters are the **most discriminant** variables in FTAG: (d_0, z_0)

Being produced randomly along z **Pile-Up** will contaminate b-jets with **high longitudinal impact parameter** (z_0)



This study shows the impact of timing on the state-of-the-art GNN for FTag: GN1*

*GN1 evolving to GN2

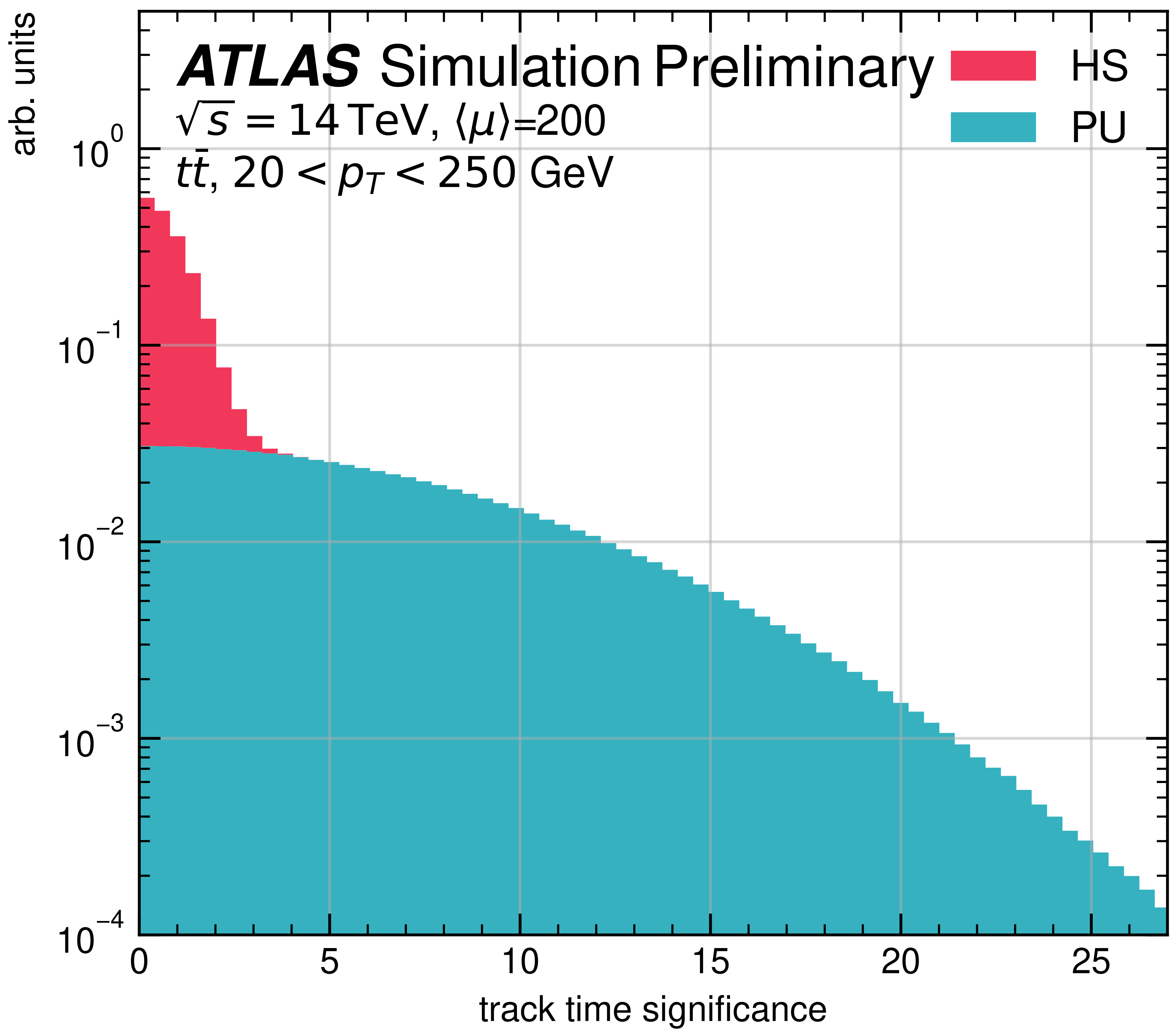
Timing in GN1: GNT

Introduce a **new track** input **variable** based on time to discriminate between Pile-Up and HS

Track time significance:

$$s(t) = \frac{|t_{trk} - t_{HS}|}{\sigma_t}$$

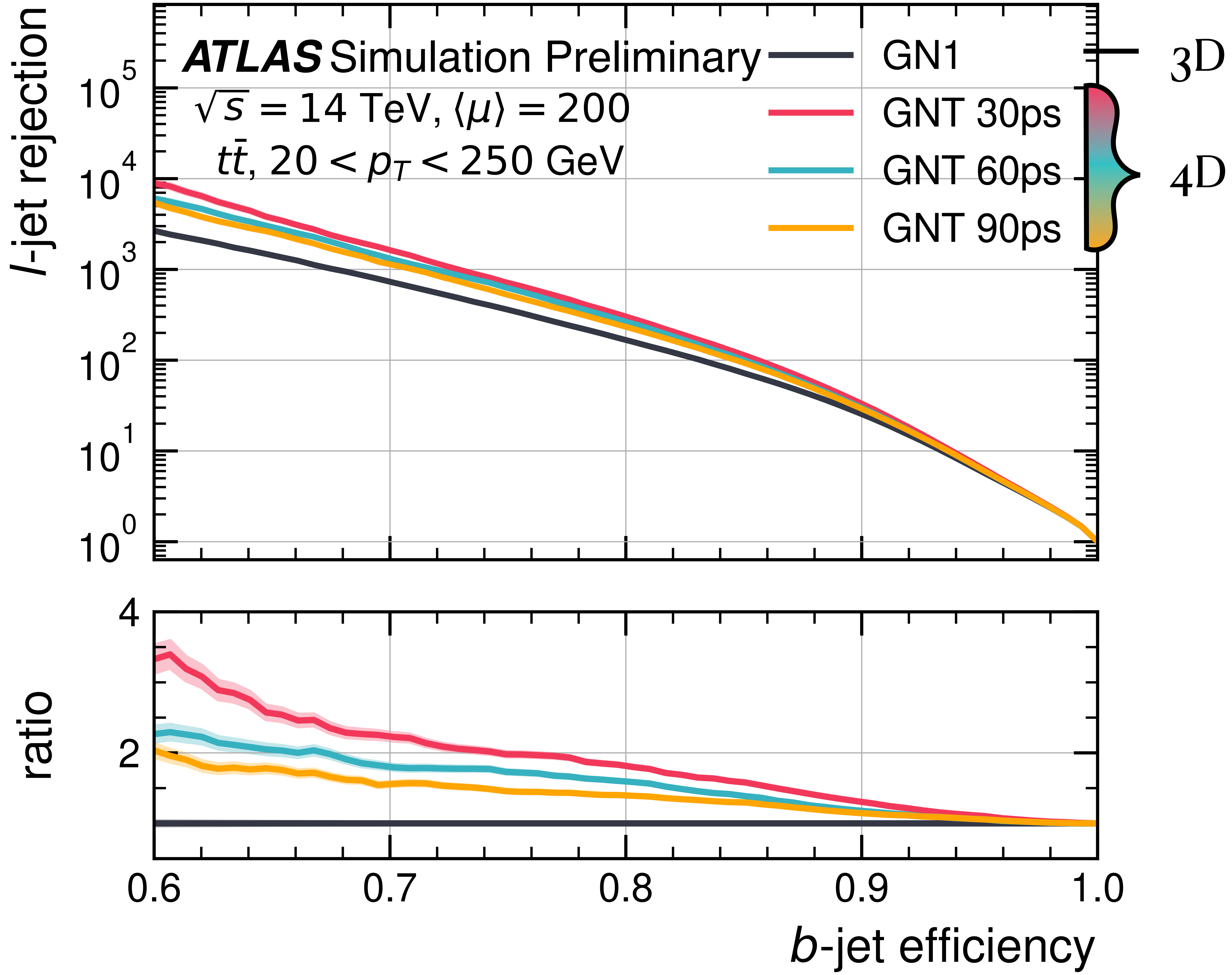
Having a precise t_{HS} is extremely important



Track Variables	GN1 ITk	GNT
d0	x	x
z0SinTheta	x	x
σ(Theta)	x	x
qOverP	x	x
σ(qOverP)	x	x
φ	x	x
σ(φ)	x	x
signed d0 significance	x	x
signed z0 significance	x	x
Δη(trk, jet)	x	x
Δφ(trk, jet)	x	x
n pix hits	x	x
n pix hits (11 variables)	x	x
$(t-t_{HS})/\sigma(t)$		x

GNT = GN1 + time significance

Performances: ROC



GN1 is the baseline without time

GNT 30ps is GN1+timing and 30ps smearing

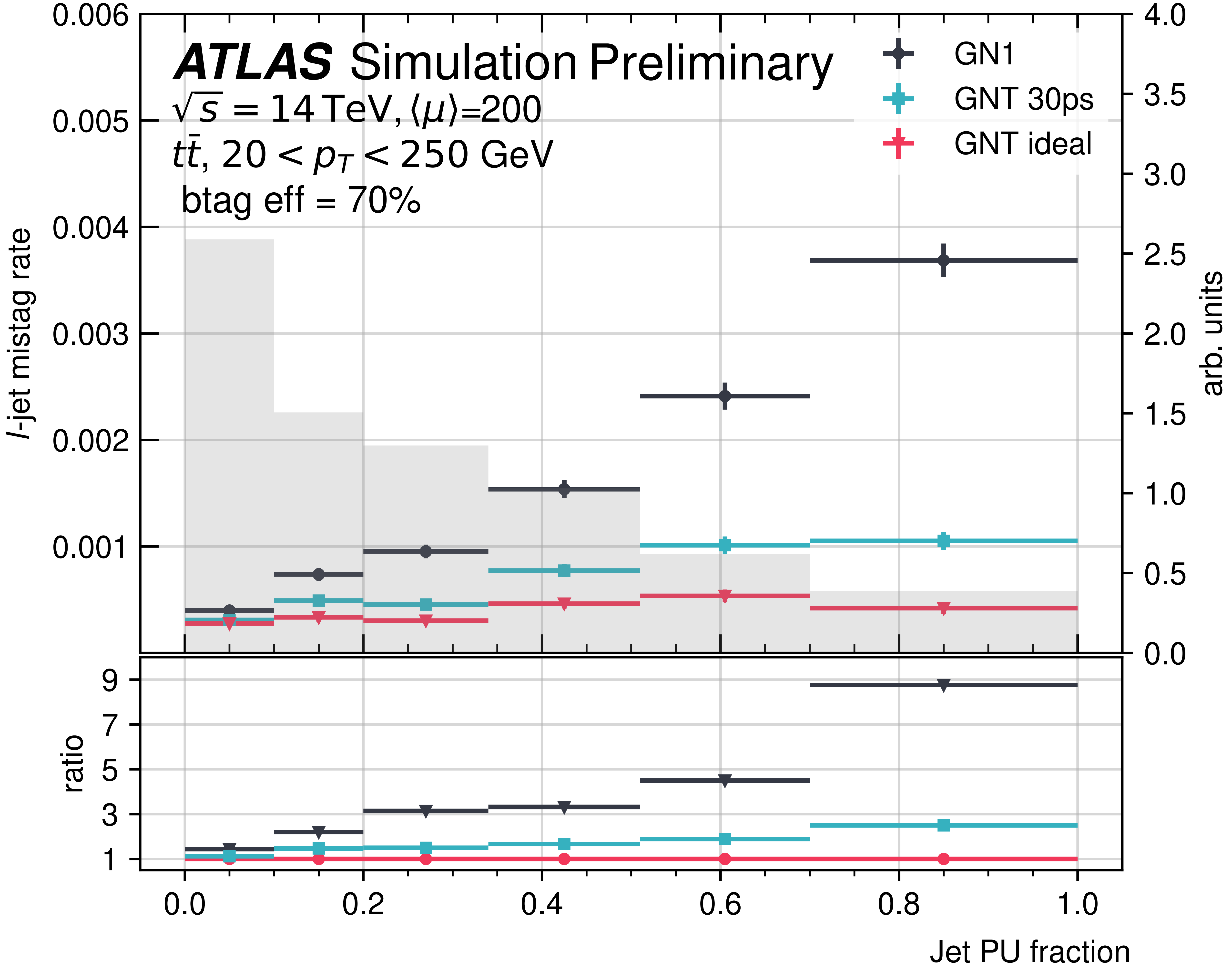
GNT 60ps is GN1+timing and 60ps smearing

GNT 90ps is GN1+timing and 90ps smearing

Up to a factor of 3 improvement in l-jet rejection **with 30ps** smearing on already great performances of GN1

With lower track time resolution the improvement is less prominent but still solid

Jet Pile-Up Contamination



To **understand the improvement** obtained it is possible to define:

$$\text{Jet PU fraction} = \frac{\#trk_{PU}}{\#trk}$$

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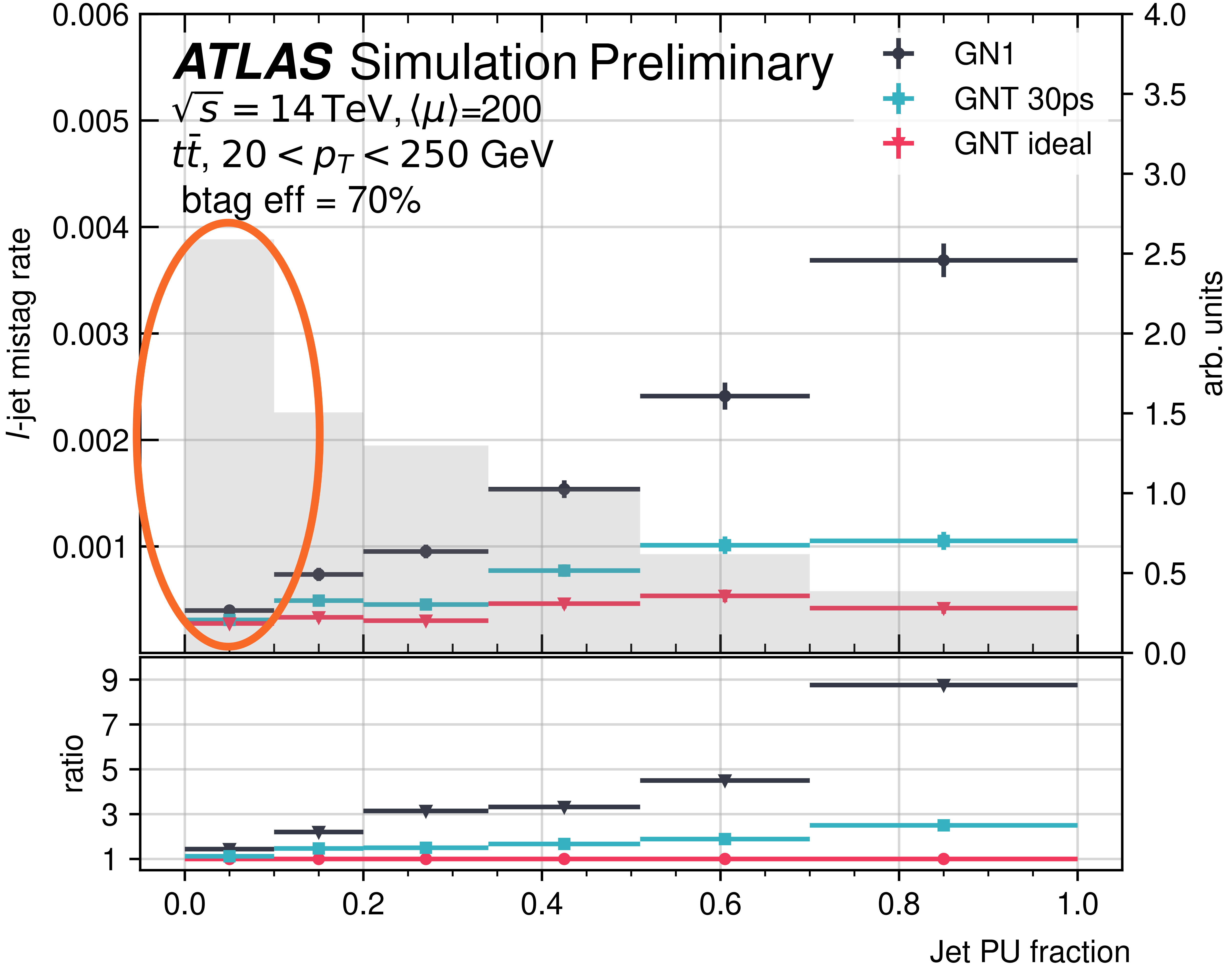

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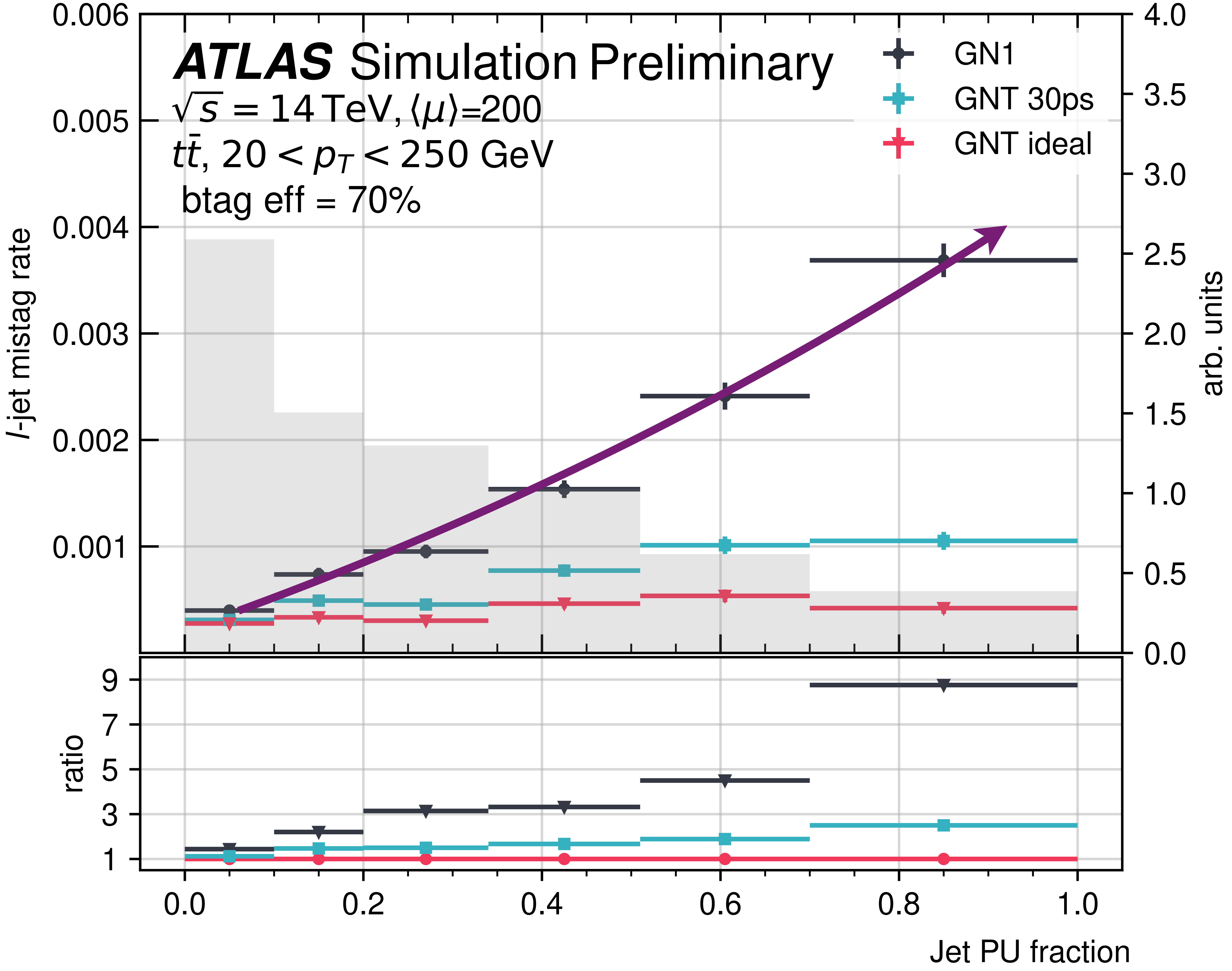

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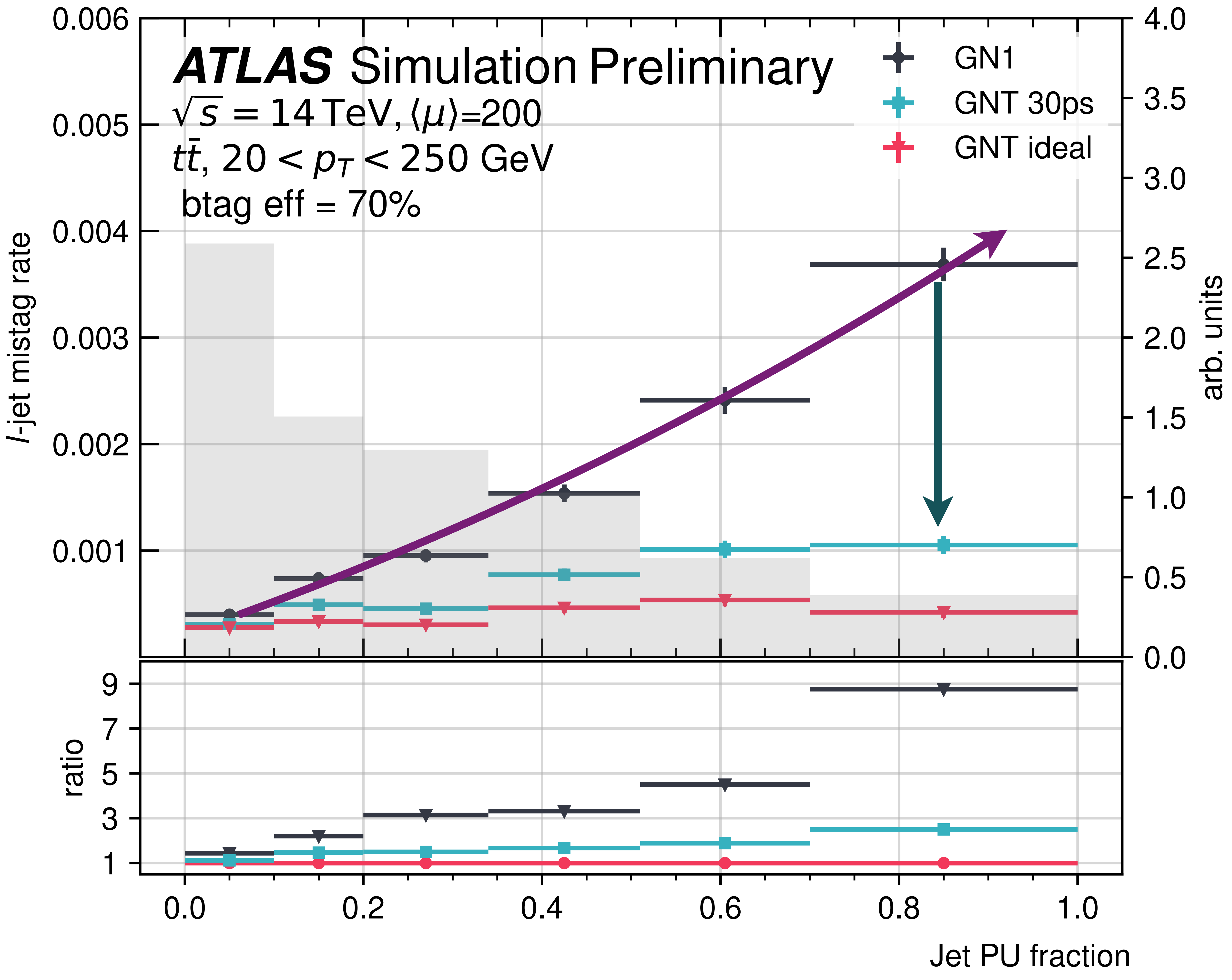

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The PU fraction distrbution **peaks at low values** meaning that with ITk Jets are mainly *"clean"*

Nonetheless the **light-mistag** rate **increases** with Pile-Up contamination

With timing information this trend **gets flattened**

Impact on Physics Analysis: HH

Timing could have **great impact** on all the Higgs program

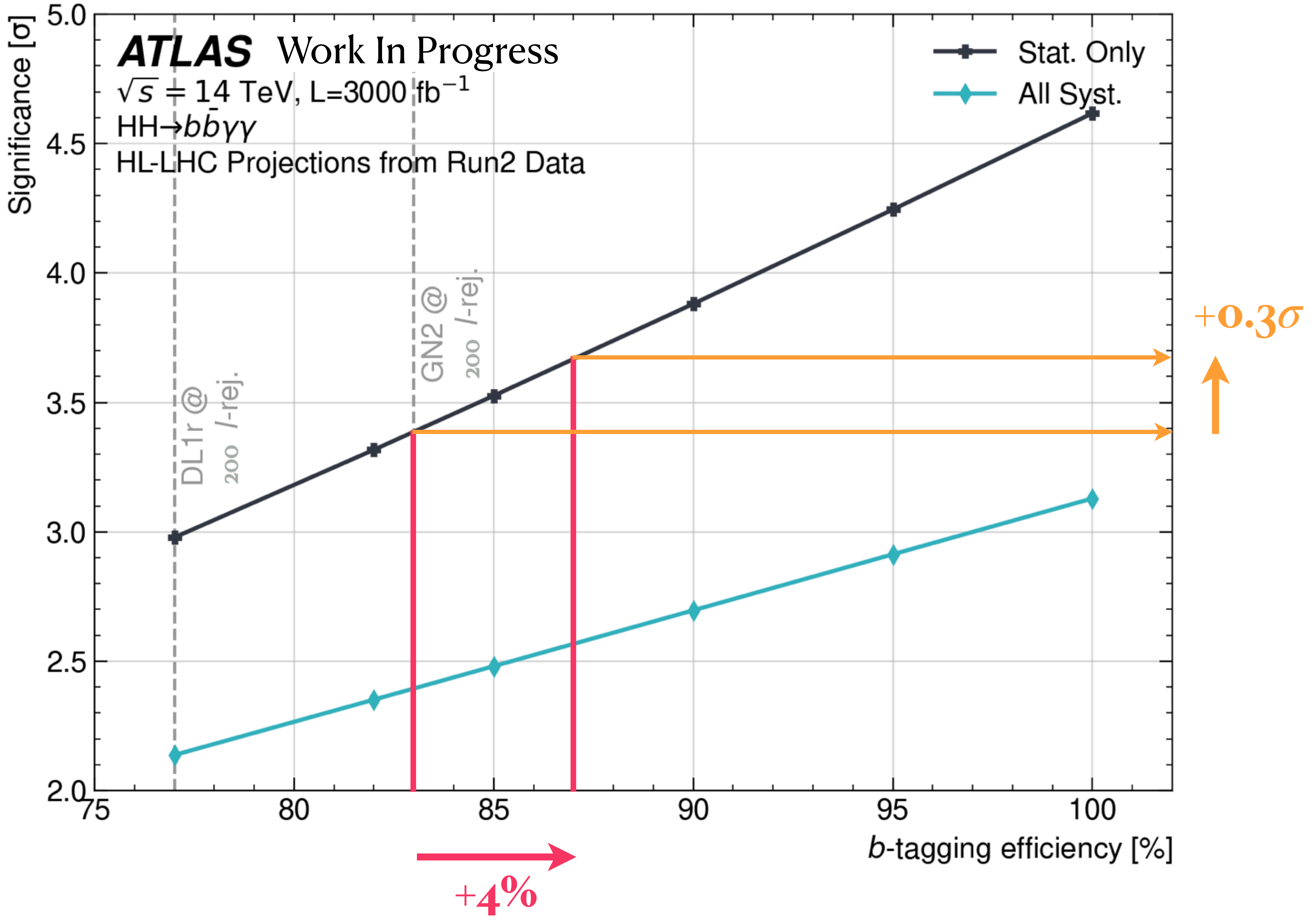
b-tagging has a huge impact on **Di-Higgs** analyses

$HH \rightarrow bb\gamma\gamma$ in the right plot

How the **HH sensitivity improve** as a function of the **b-tagging** efficiency?

4% b-tagging improvement can lead to up to **0.3σ significance improvement**!

Obs: Timing could be **available only** on **partial HL-LHC statistics**



Conclusion

This presentation shows the impact of **track reconstruction with timing** on the **physics program** ATLAS for the HL-LHC program

Modern detectors and algorithms are s**olid against Pile-Up**, but a fraction is still observed

The work suggest that 4D tracking with **hermetic coverage** can potentially **improve performances impacting physics cases**

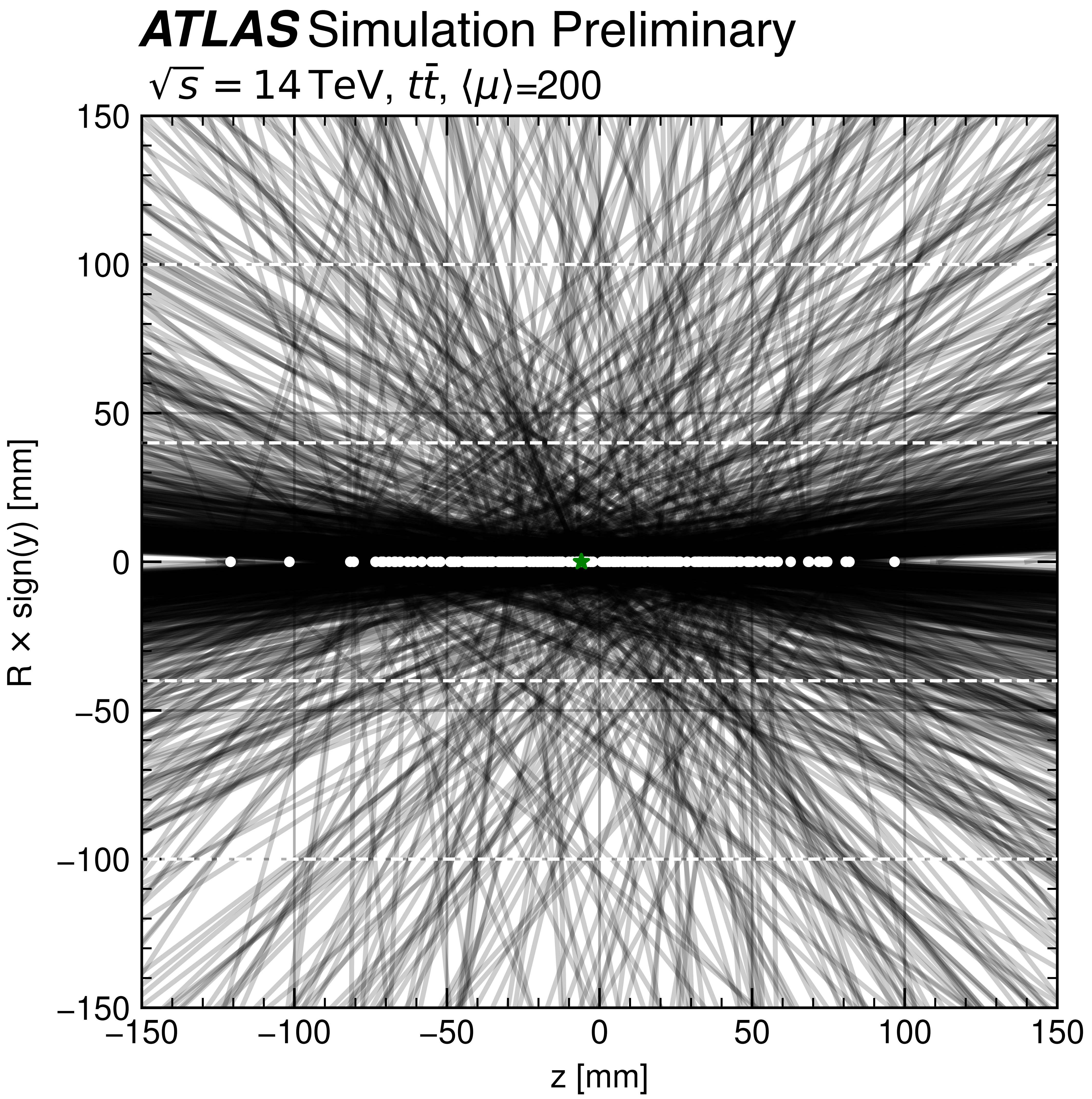
These results motivate in-depth studies with **more realistic detector** assumptions and also state of the art algorithms such as GN2

Similar studies are on-going to see the impact on **c-tagging/tau-identification**

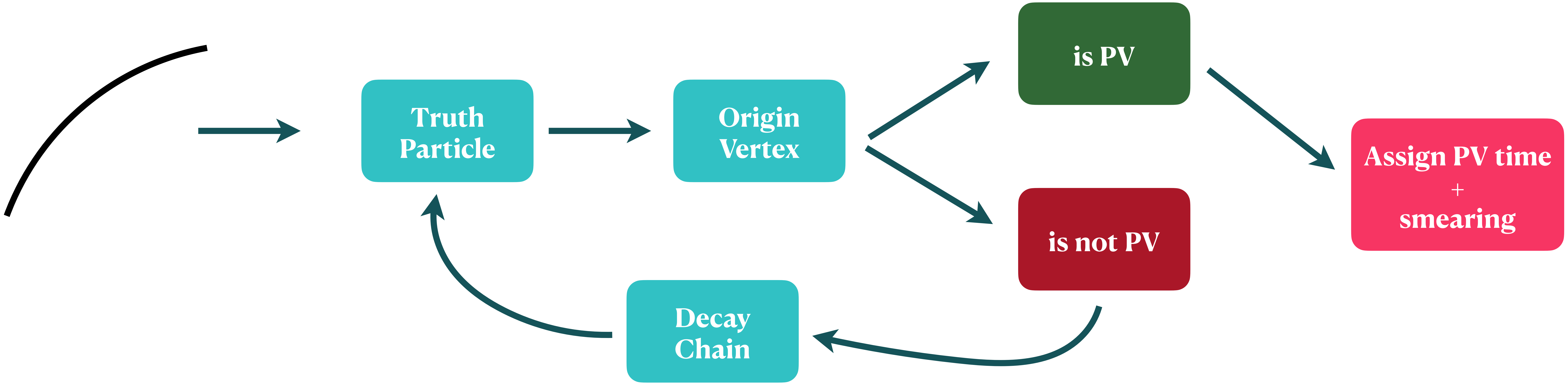
Technology challenge requires great effort and R&D

Backup

Unfolding the 4-th Dimension



Track Time assignment



Track time assignment from truth level information

Gaussian smearing to emulate the timing resolution

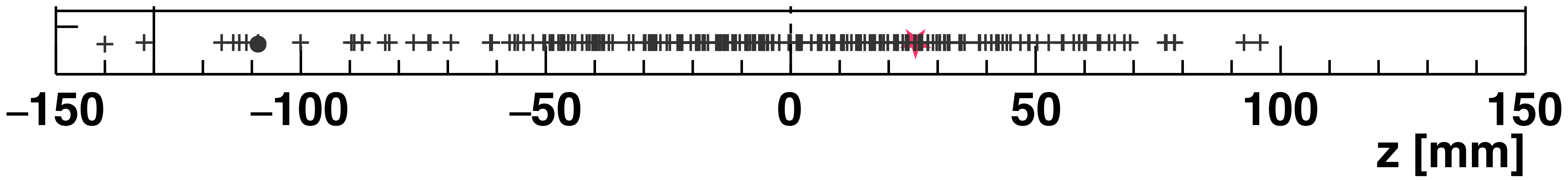
Cases considered: $\sigma(t_{trk}) = 30ps,\ 60ps,\ 90ps$

Perfect resolution when no smearing is applied

A relevant quantity is the relative time with respect to the Hard Scatter as:

$$t_{trk} - t_{HS}$$

What if we have time?



Event display from **truth** MC $t\bar{t}$

PU: $\langle \mu \rangle = 200$

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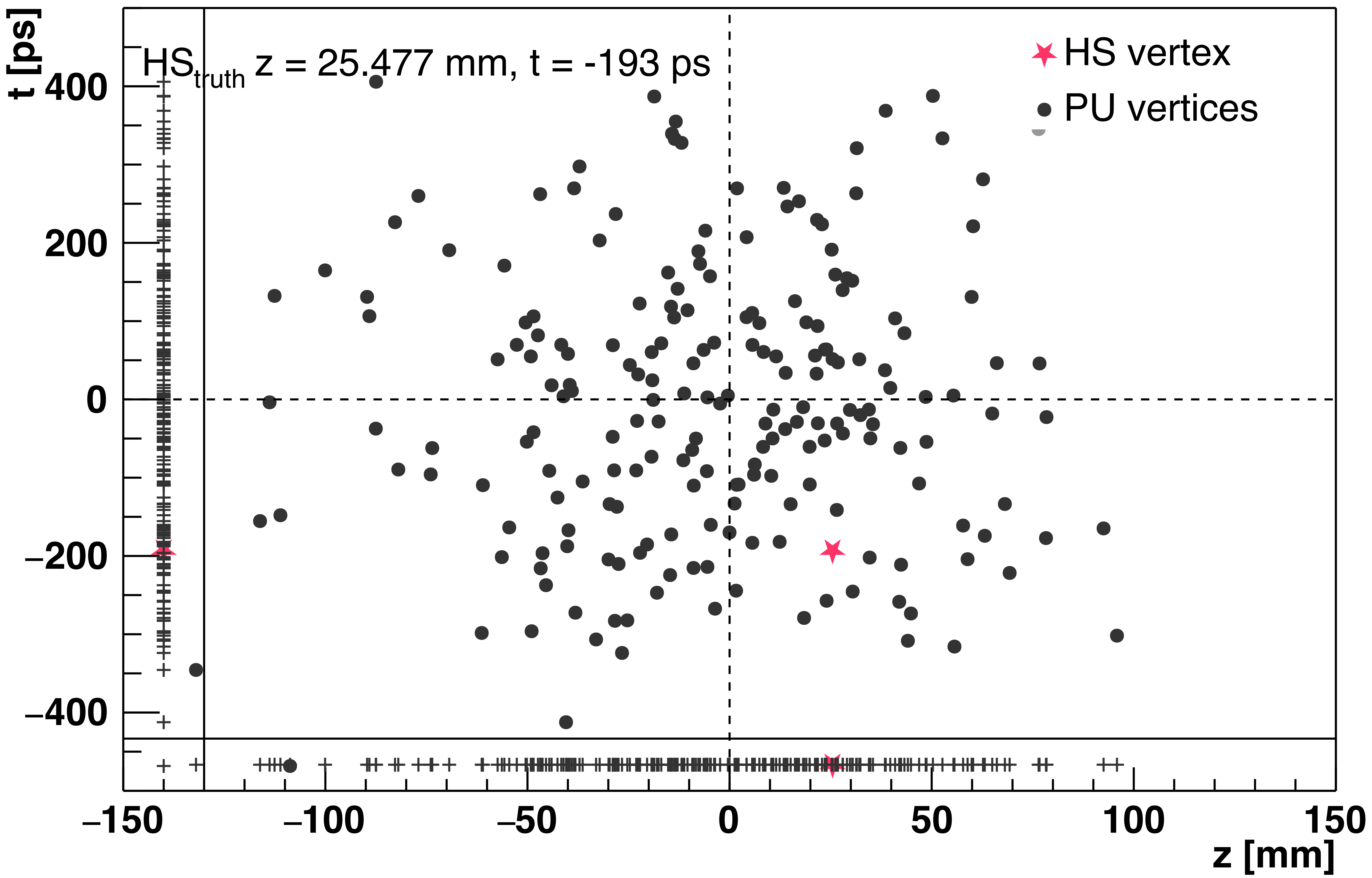

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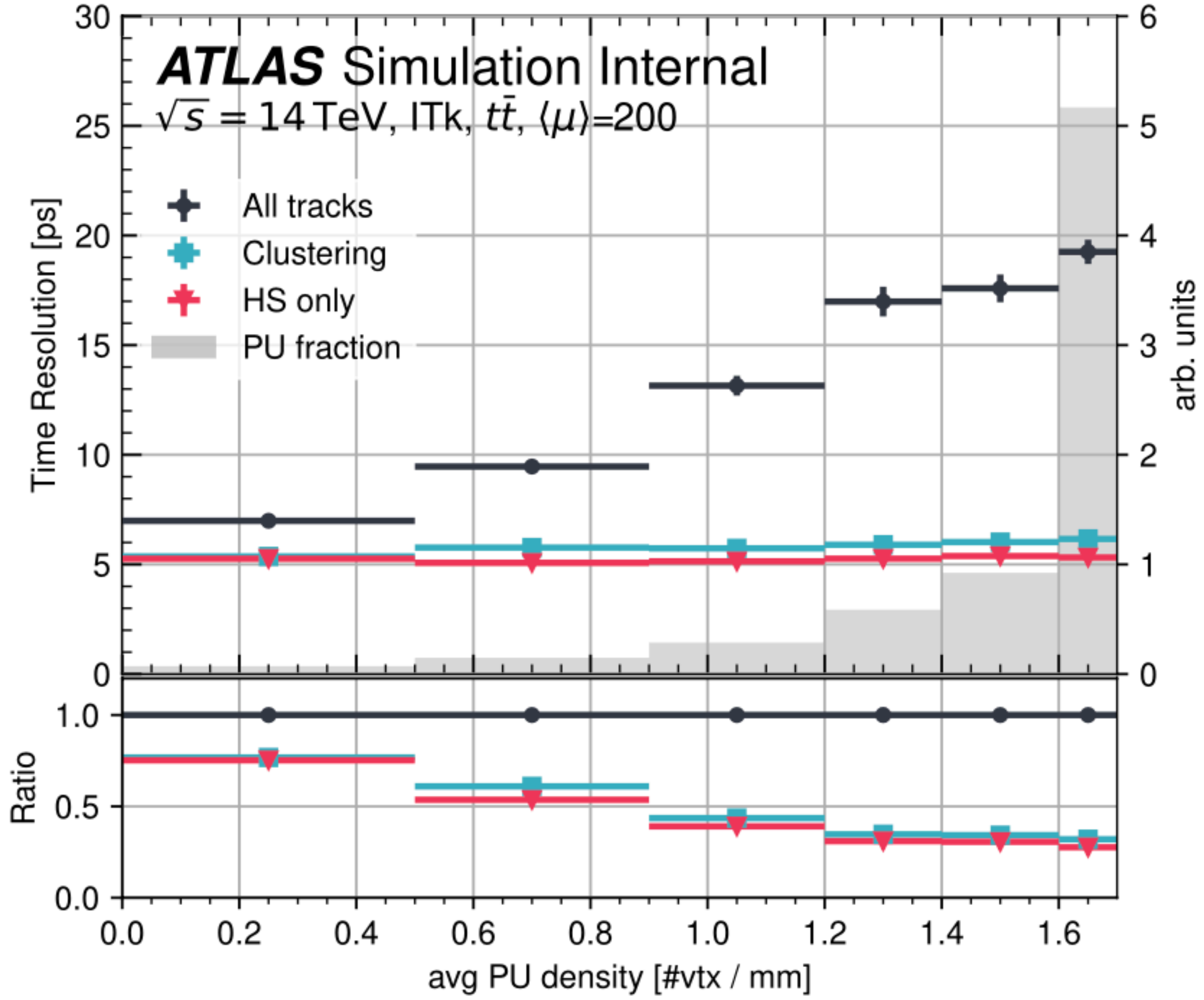
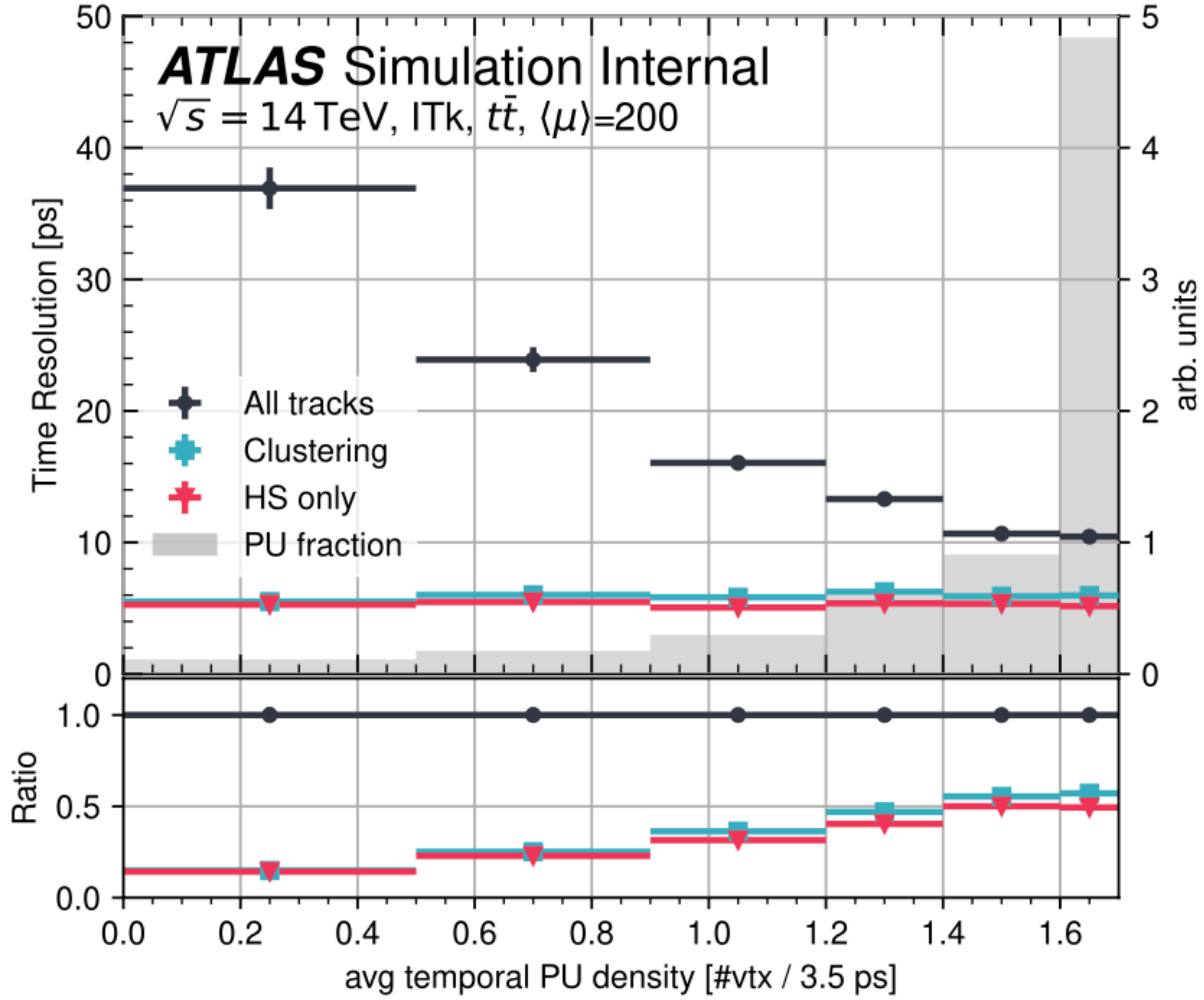
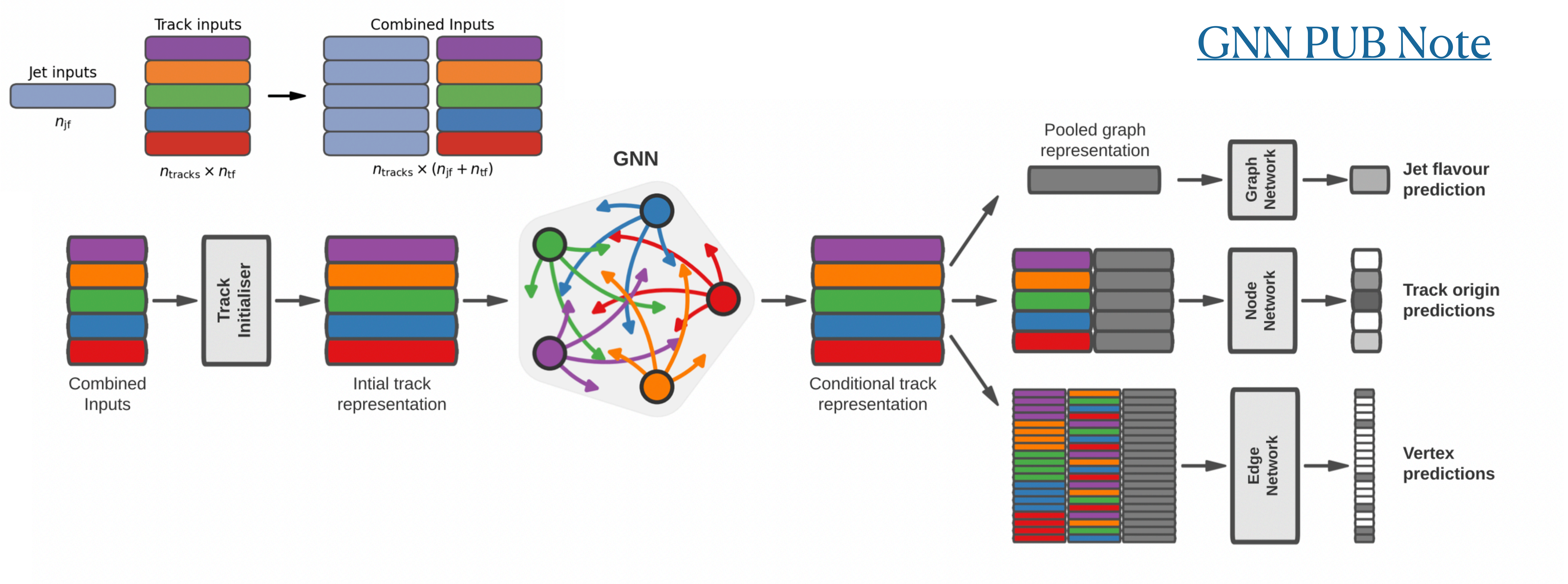




In both cases the distribution gets flattened

Graph Neural Networks for FTAG



GNN PUB Note

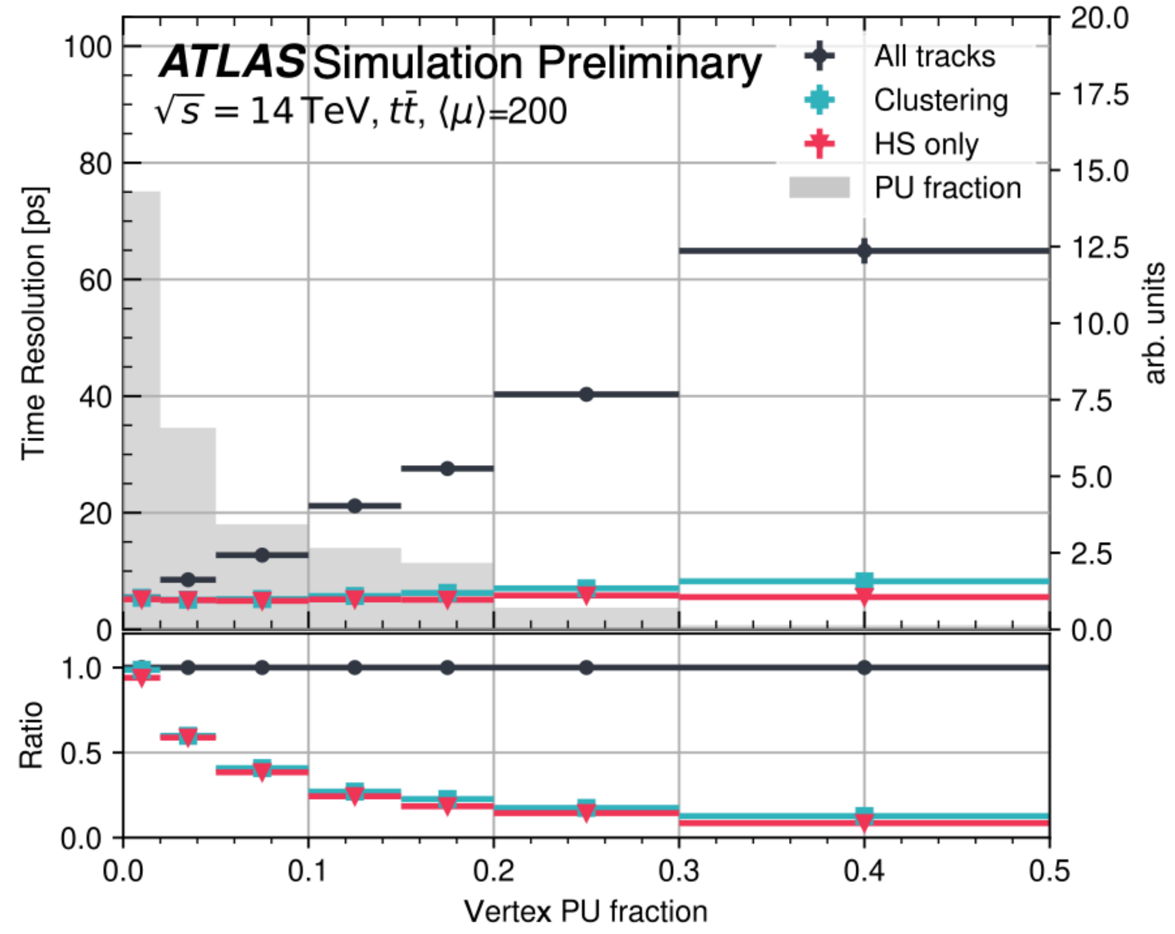
Impact of timing on the state-of-the-art GNN for FTag: GN1*

Tracks associated to the Jet as input to the GNN predicting the flavour

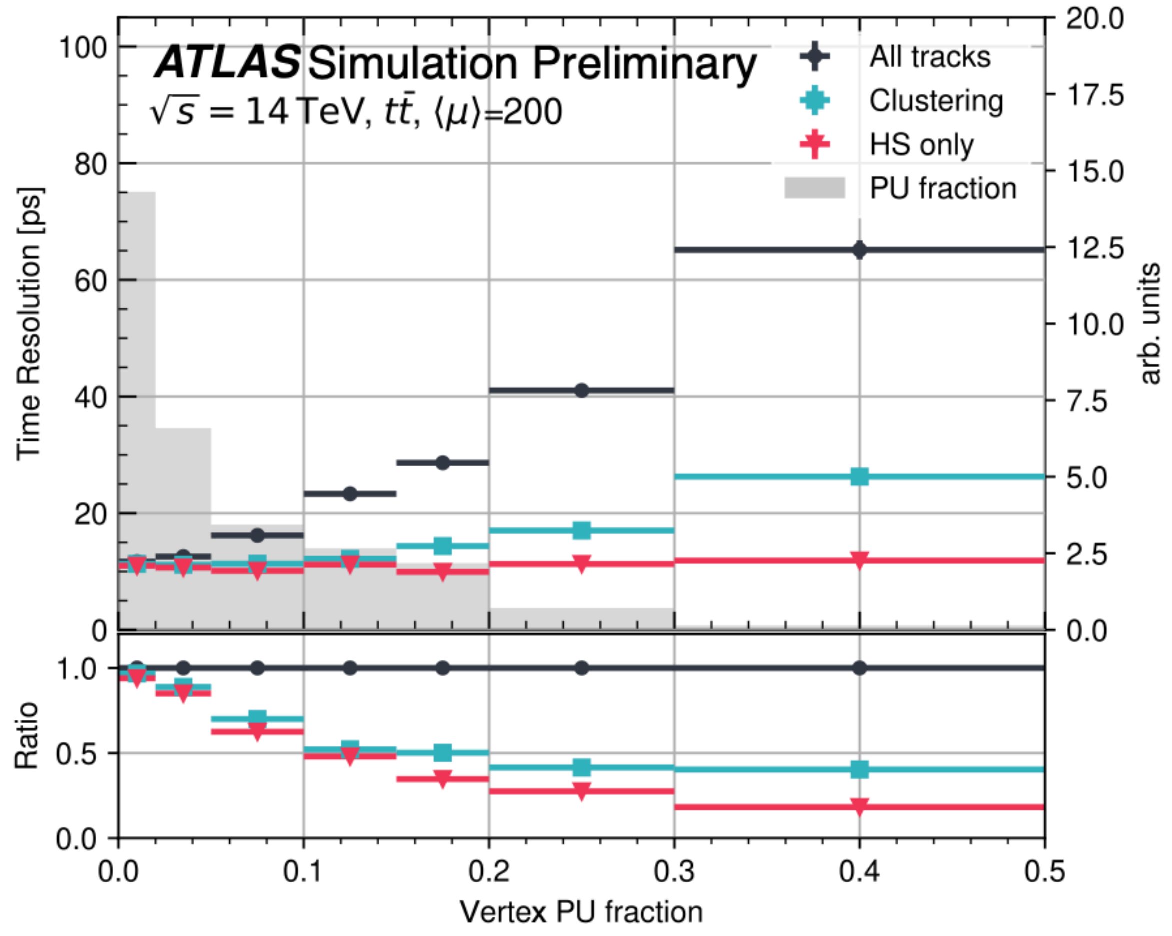
Auxiliary tasks for Vertex prediction and Track classification

*GN1 evolved to GN2

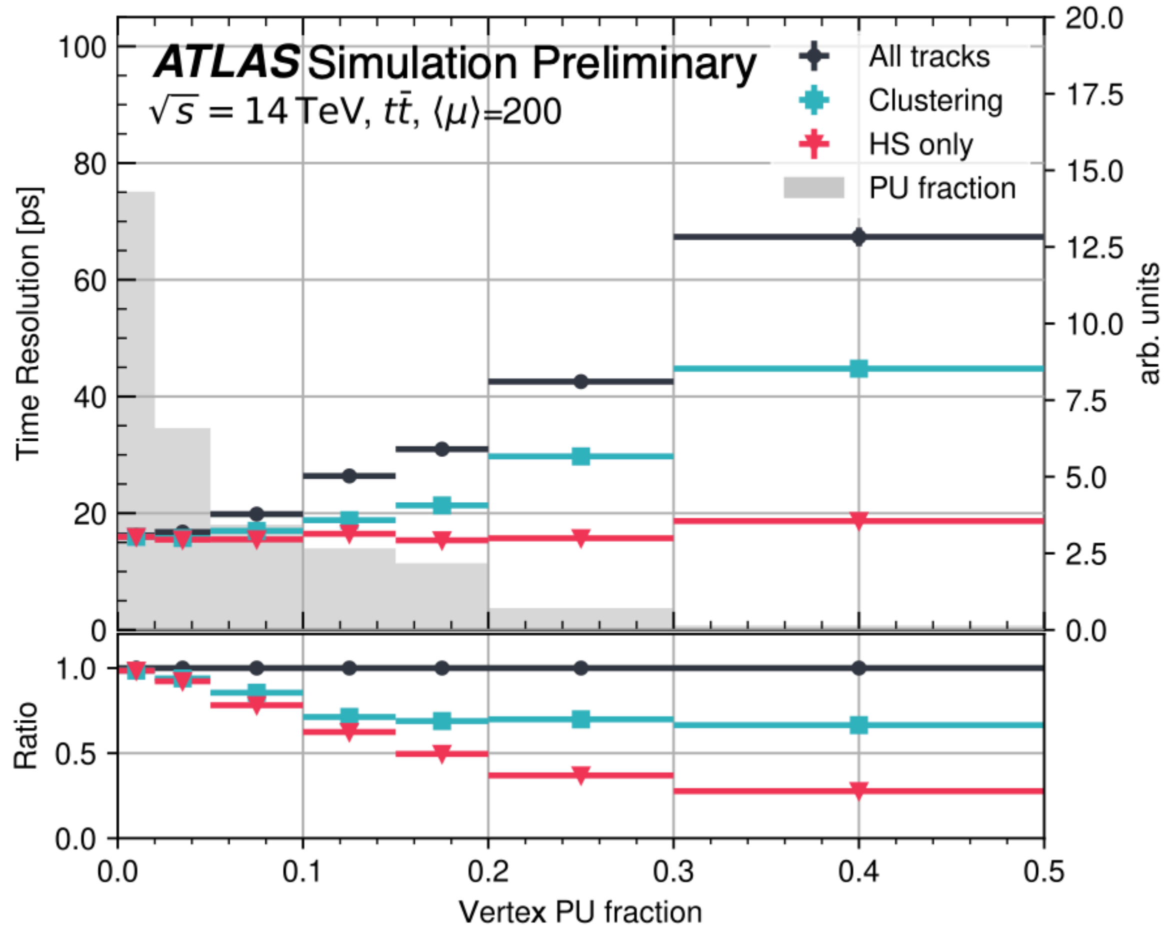
Vertex Pile-Up Contamination



(a) 30 ps track-time resolution



(b) 60 ps track-time resolution



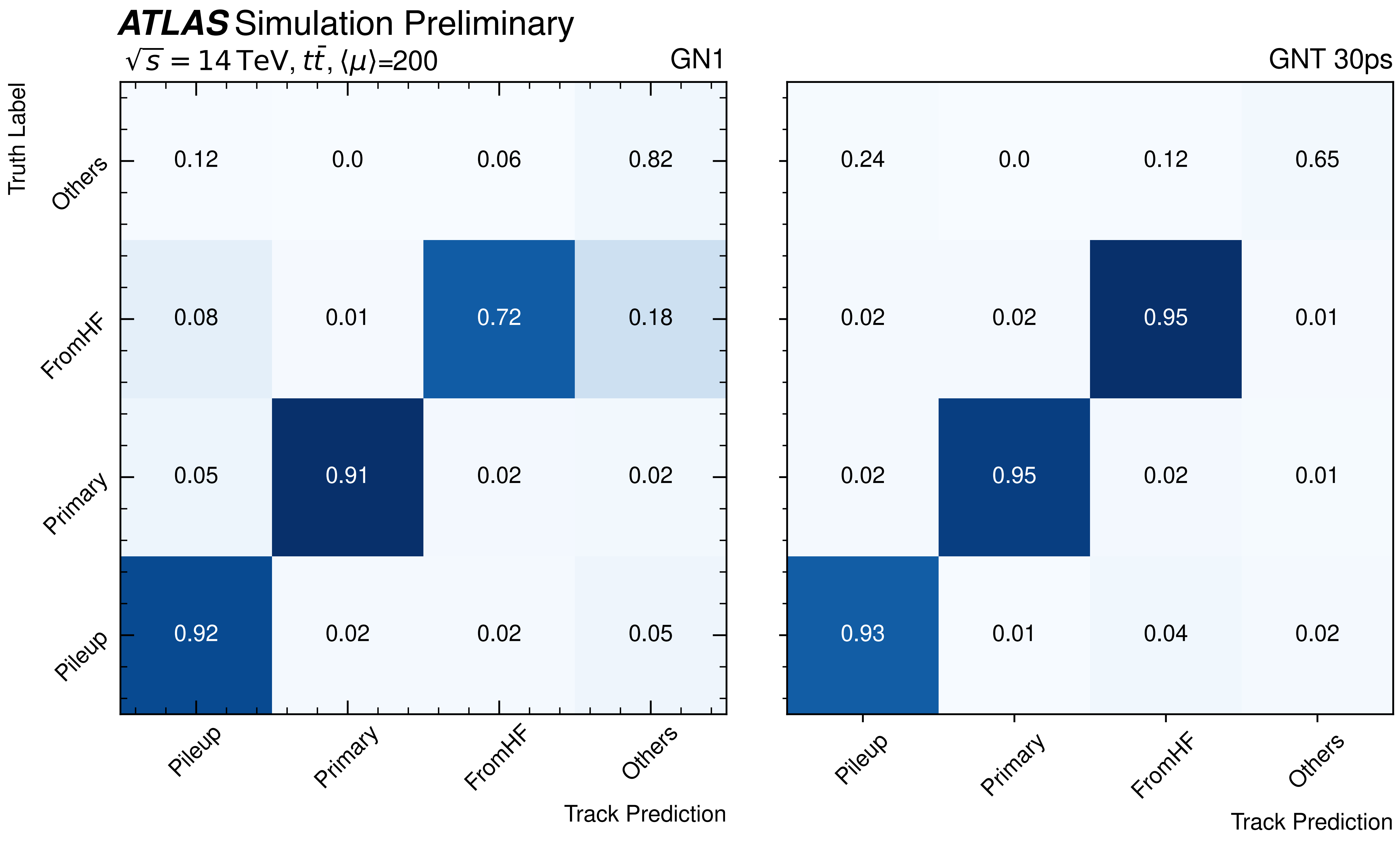
(c) 90 ps track-time resolution

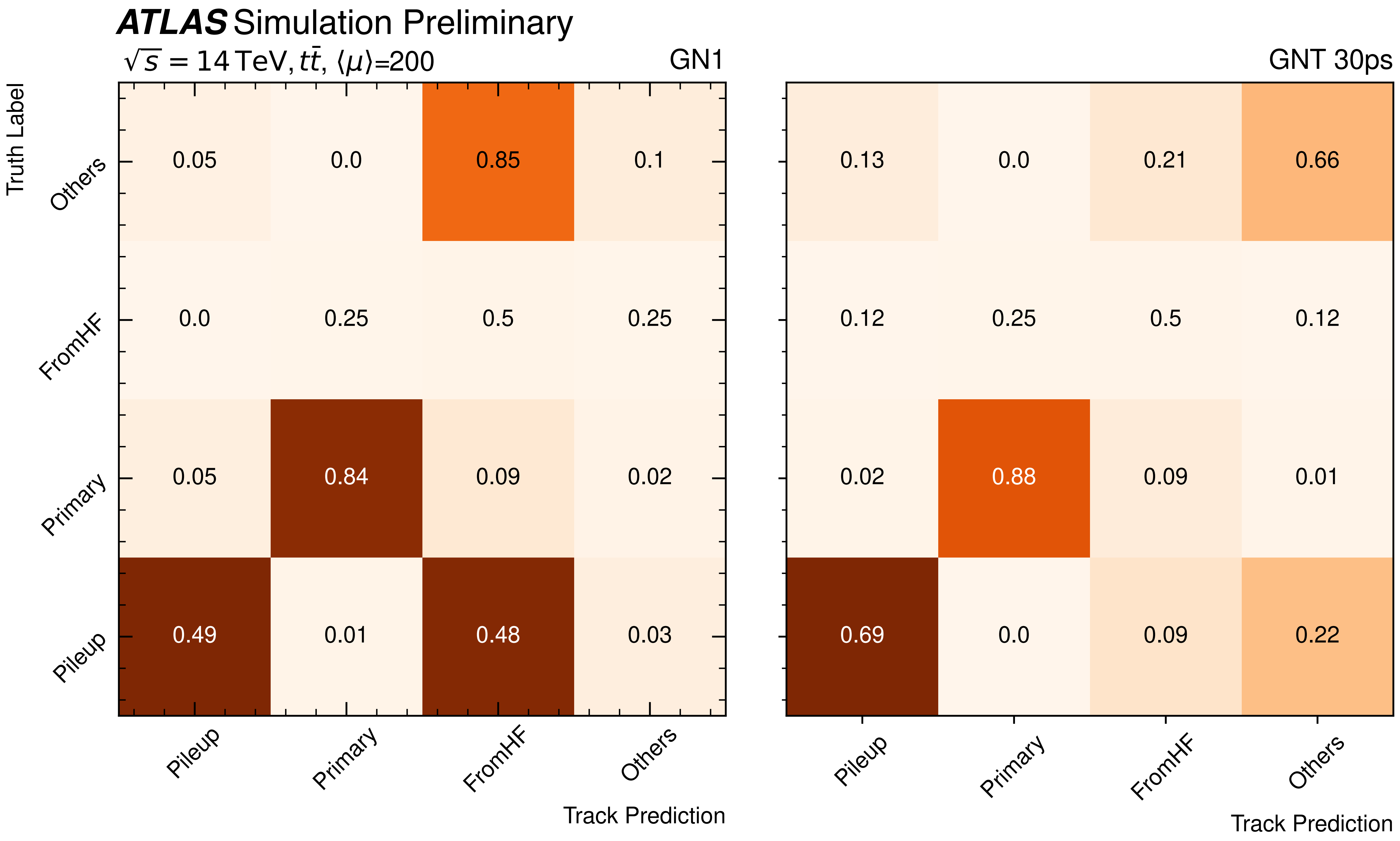
To understand where the improvement comes from a Pile-Up dependent variable is built:

$$\text{vtx PU fraction} = \;= \frac{\#trk_{PU}}{\#trk}$$

Dependence of $\sigma(t_{HS})$ vs *PU fraction*

Degrading the track time resolution $\sigma(t_{HS})$ the improvement is lower as expected and the distribution is less flat


ATLAS Simulation Preliminary
$\sqrt{s}$ = 14 TeV, $t\bar{t}$, ⟨μ⟩=200
GN1
GNT 30ps
Truth Label
Others
FromHF
Primary
Pileup
Track Prediction
0.12 0.0 0.06 0.82
0.08 0.01 0.72 0.18
0.05 0.91 0.02 0.02
0.92 0.02 0.02 0.05
0.24 0.0 0.12 0.65
0.02 0.02 0.95 0.01
0.02 0.95 0.02 0.01
0.93 0.01 0.04 0.02


ATLAS Simulation Preliminary
$\sqrt{s}$ = 14 TeV, $t\bar{t}$, ⟨μ⟩=200
GN1
GNT 30ps
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FromHF
Primary
Pileup
Track Prediction
0.05 0.0 0.85 0.1
0.0 0.25 0.5 0.25
0.05 0.84 0.09 0.02
0.49 0.01 0.48 0.03
0.13 0.0 0.21 0.66
0.12 0.25 0.5 0.12
0.02 0.88 0.09 0.01
0.69 0.0 0.09 0.22

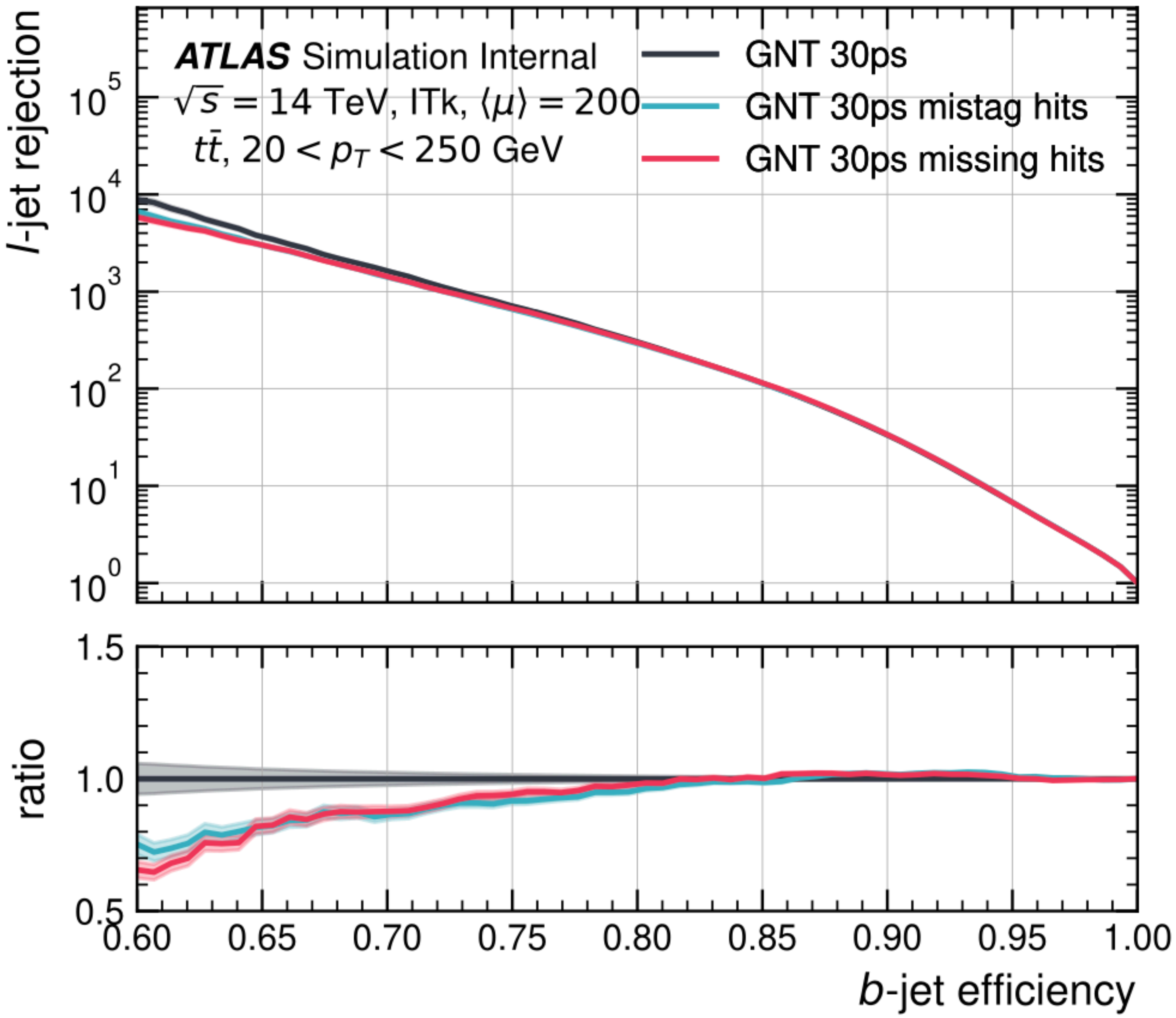
Missing and mistagged hits

A complete simulation is needed for an accurate study

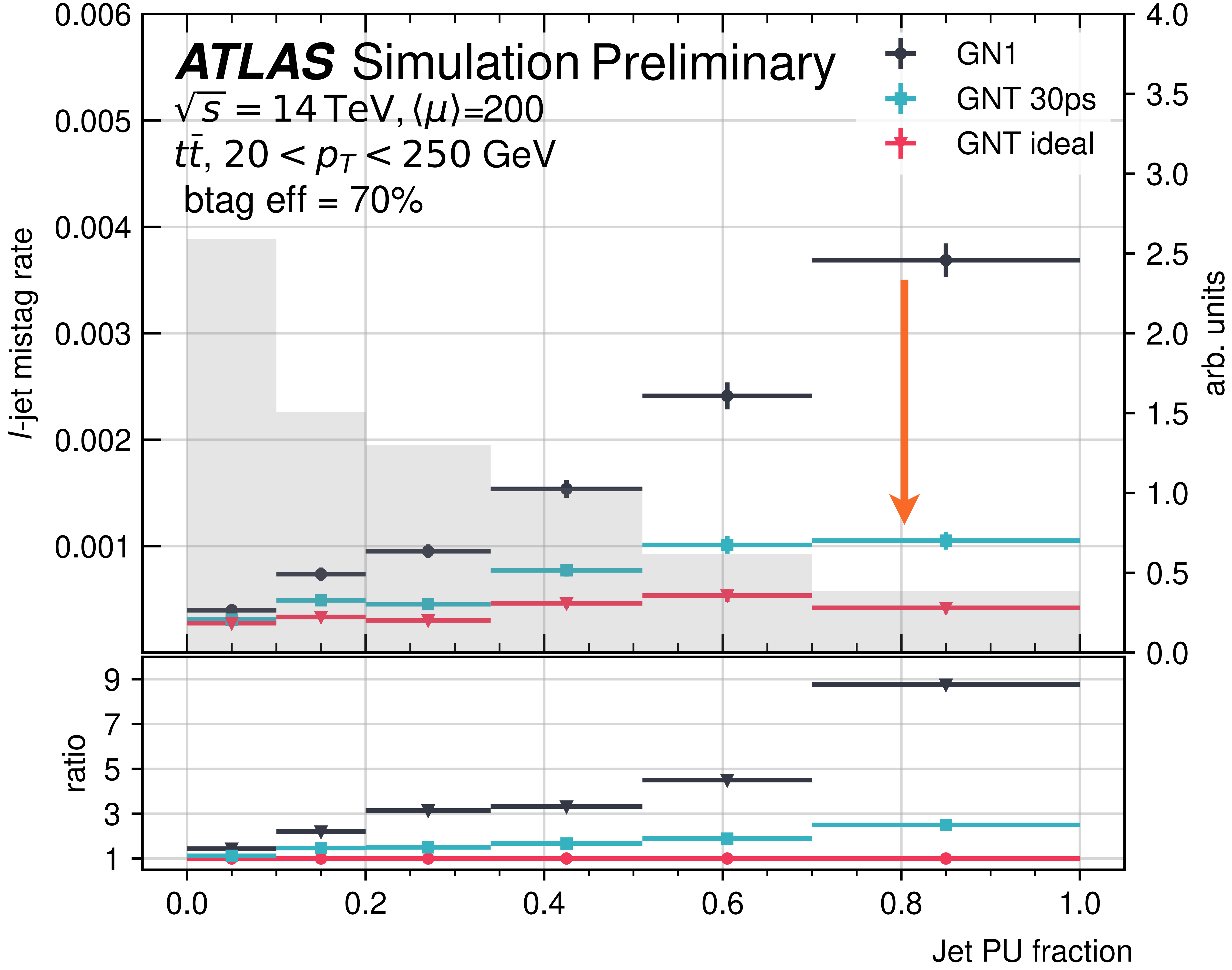
We investigated independently the impact of **missing hits** and **mistag hits** showing that the performances get degraded mostly at low b-jet efficiencies

missing hit: assuming time only in 2nd layer; if a track has no hit the significance of the track is randomly emulated as HS

mistag hit: for tracks with Truth Match Probability < 80% the significance is randomly emulated as PU



Jet Pile-Up Contamination



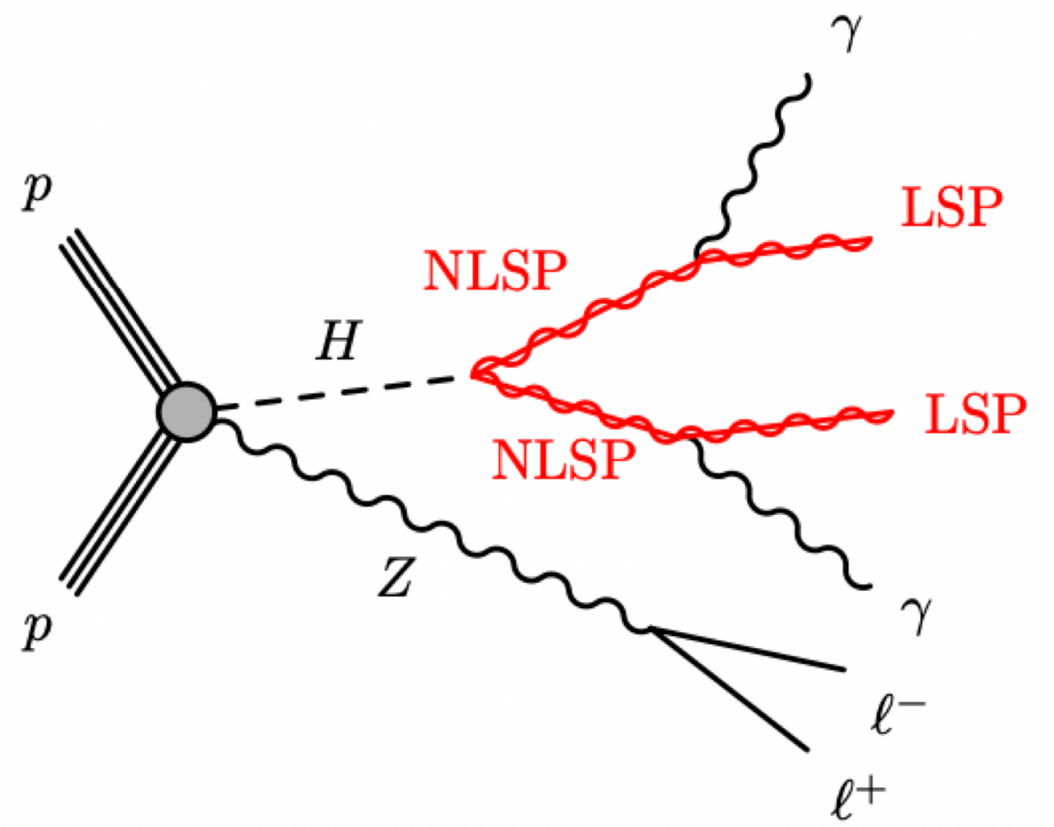
Similarly to the vertex case we can define

$$\text{jet PU fraction} = \frac{\#trk_{PU}}{\#trk}$$

Dependence of light-jet mistag rate vs *jet PU fraction* gets flattened with time information

Large improvement comes from highly Pile-Up contaminated jets

Impact on Physics Analysis: LLP



4D tracking can also improve the sensitivity to LLP:

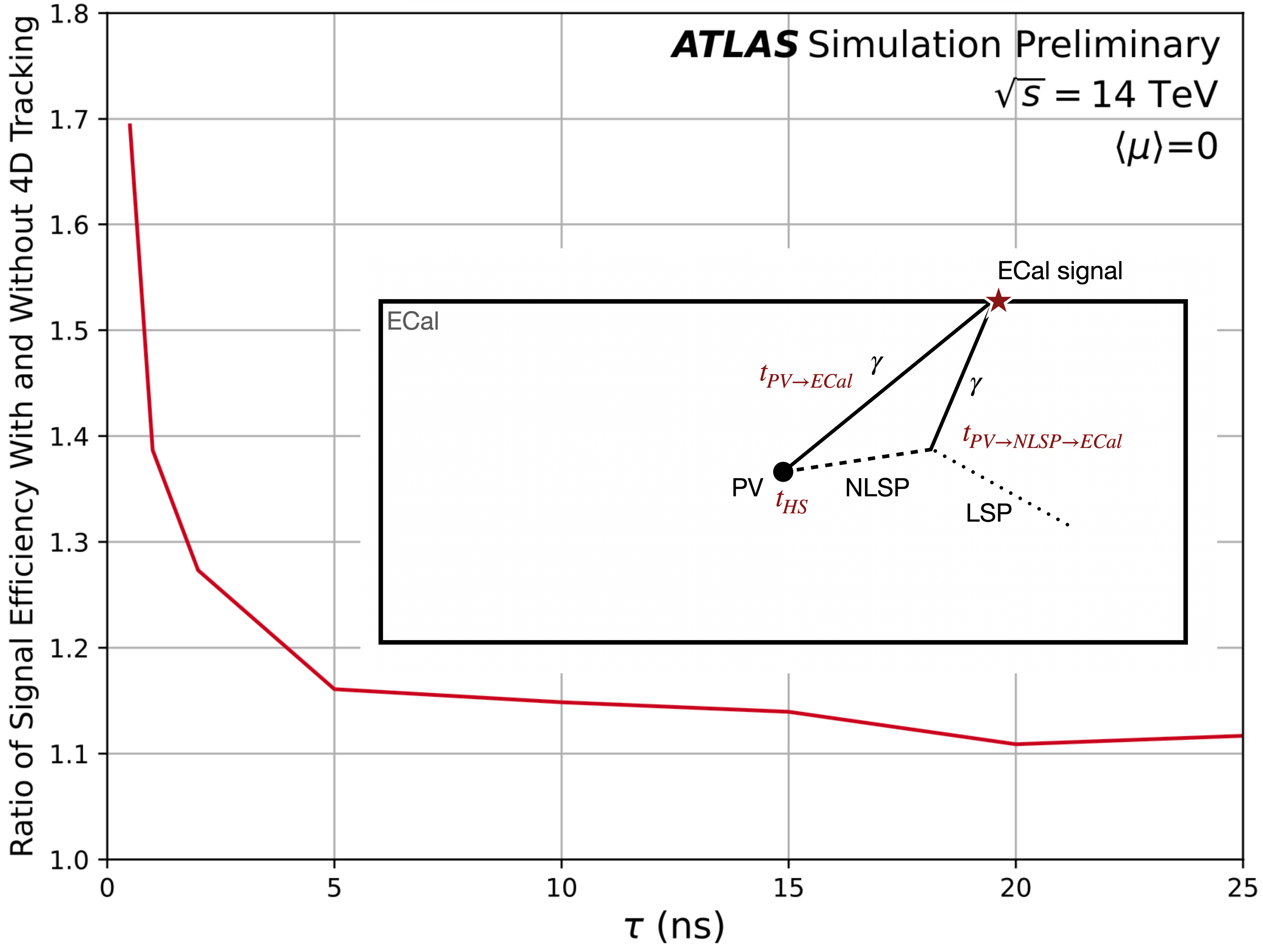
- LLP with small $c\tau$
- displaced photons

$H \rightarrow inv$. studied in the HGTD TDR

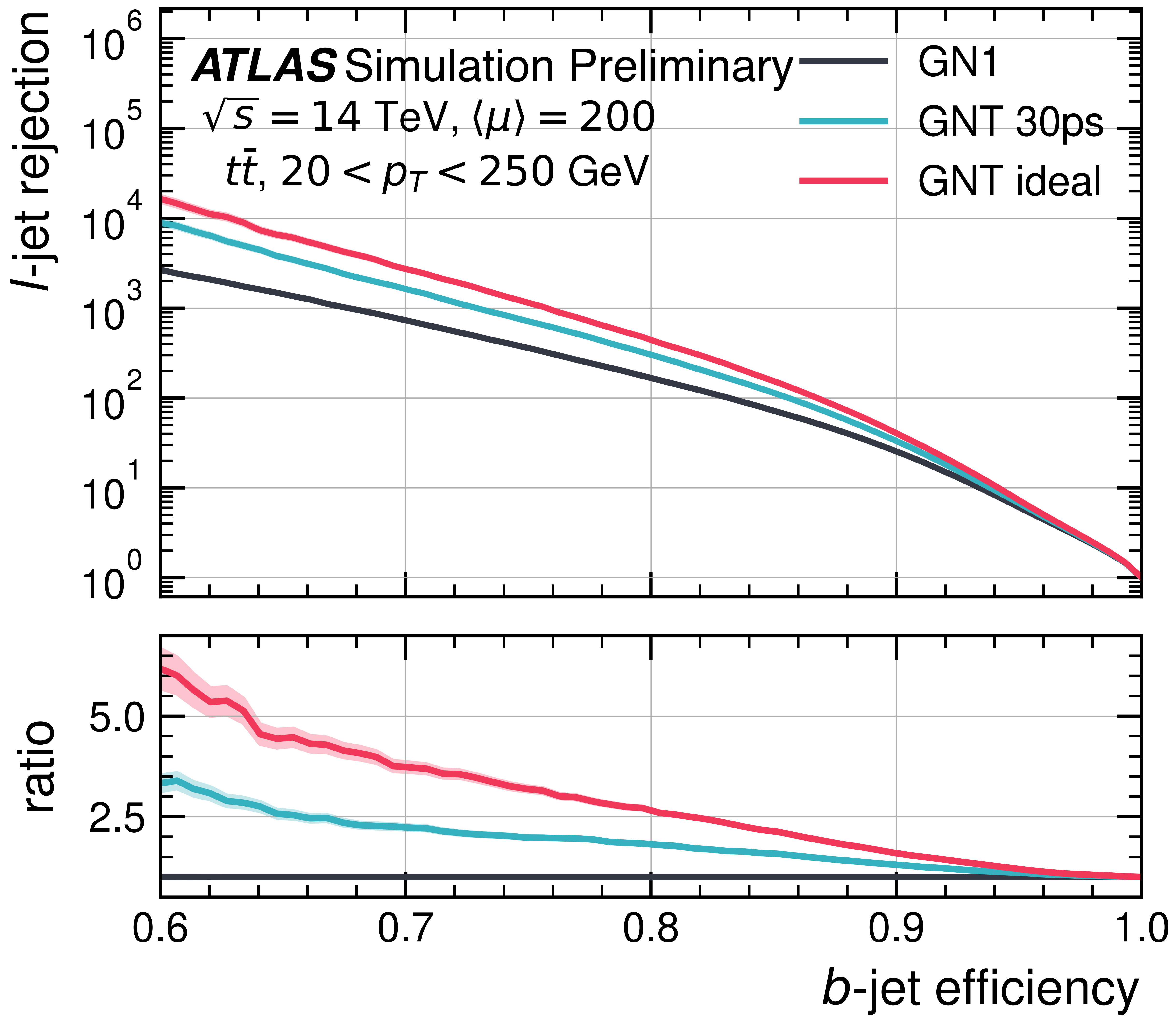
Time resolution of ***delayed photons*** is 190ps due to the lack of knowledge about t_{HS}

$$\Delta t = t_0 + t^{\text{Reconstructed}}_{\text{IP}\to\text{ECal}} - t_{\text{IP}\to\text{ECal}} - t^{\text{Reconstructed}}_0$$

180ps 100ps 4D improves!



Performances: ROC



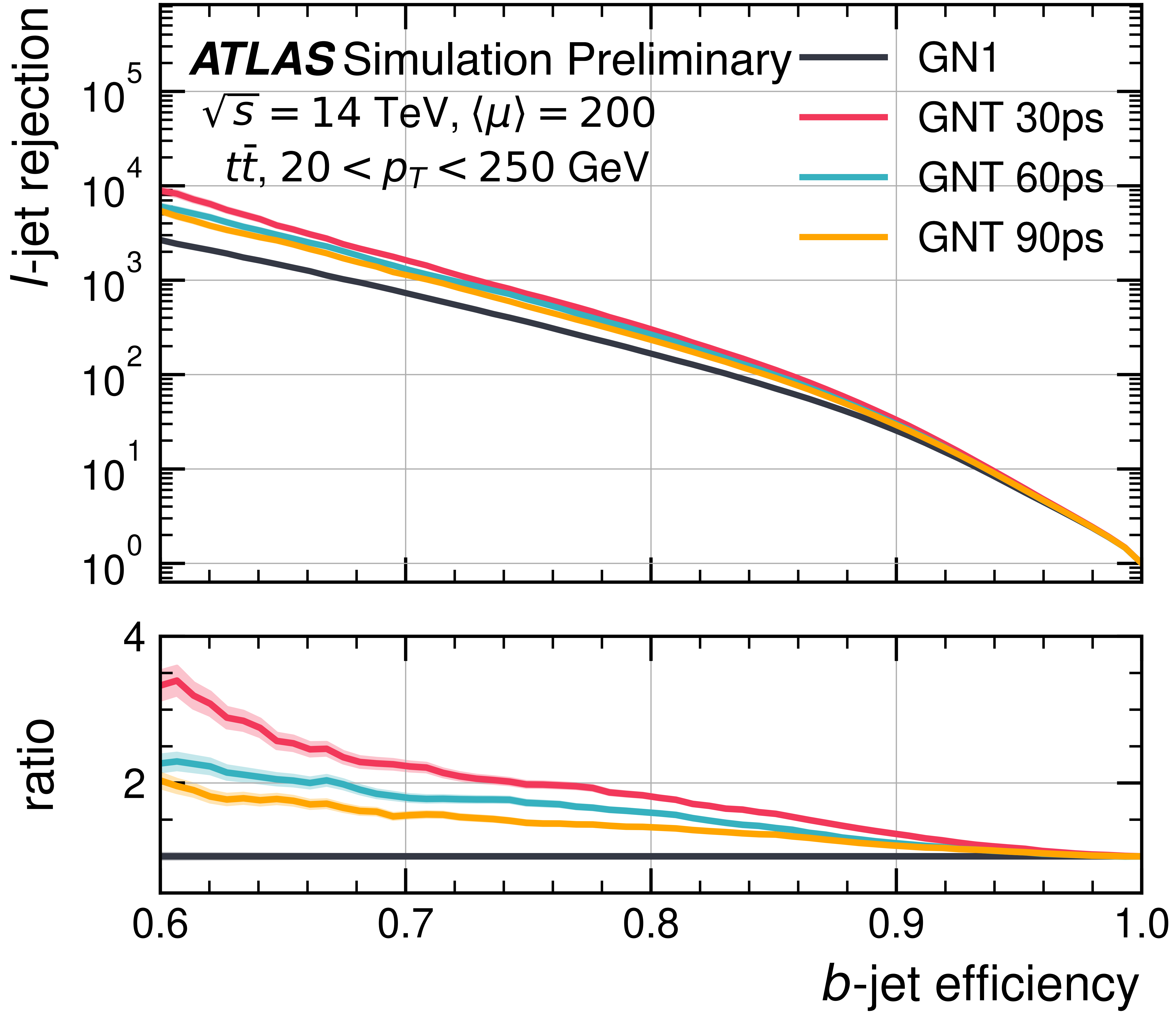
GN1 is the baseline without time

GNT 30ps is GN1+timing and 30ps smearing

GNT ideal is GN1+timing and no smearing

Up to a factor of 3 improvement in l-jet rejection with 30ps smearing on already great performances of GN1

Performances: ROC



GN1 is the baseline without time

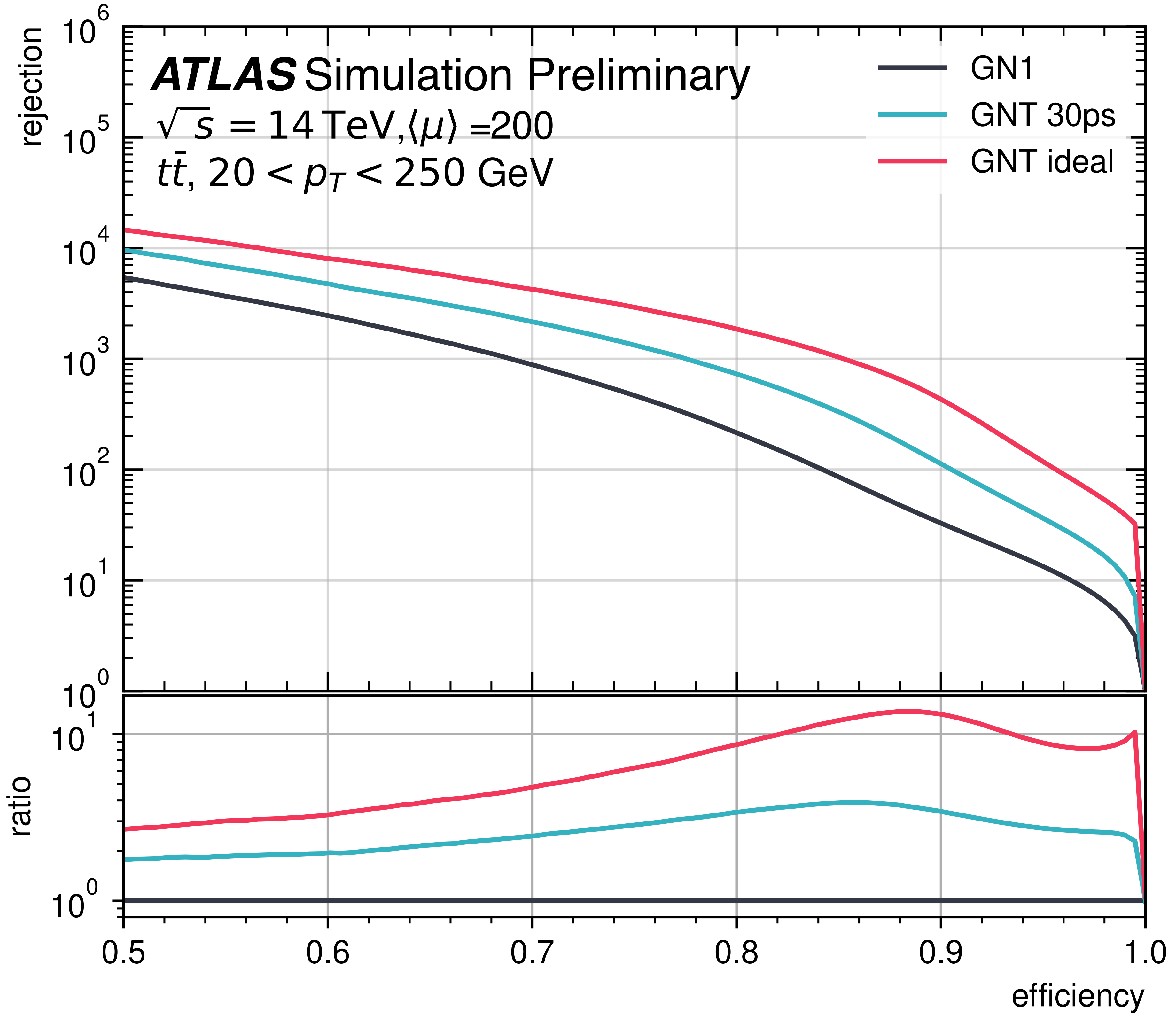
GNT 30ps is GN1+timing and 30ps smearing

GNT 60ps is GN1+timing and 60ps smearing

GNT 90ps is GN1+timing and 90ps smearing

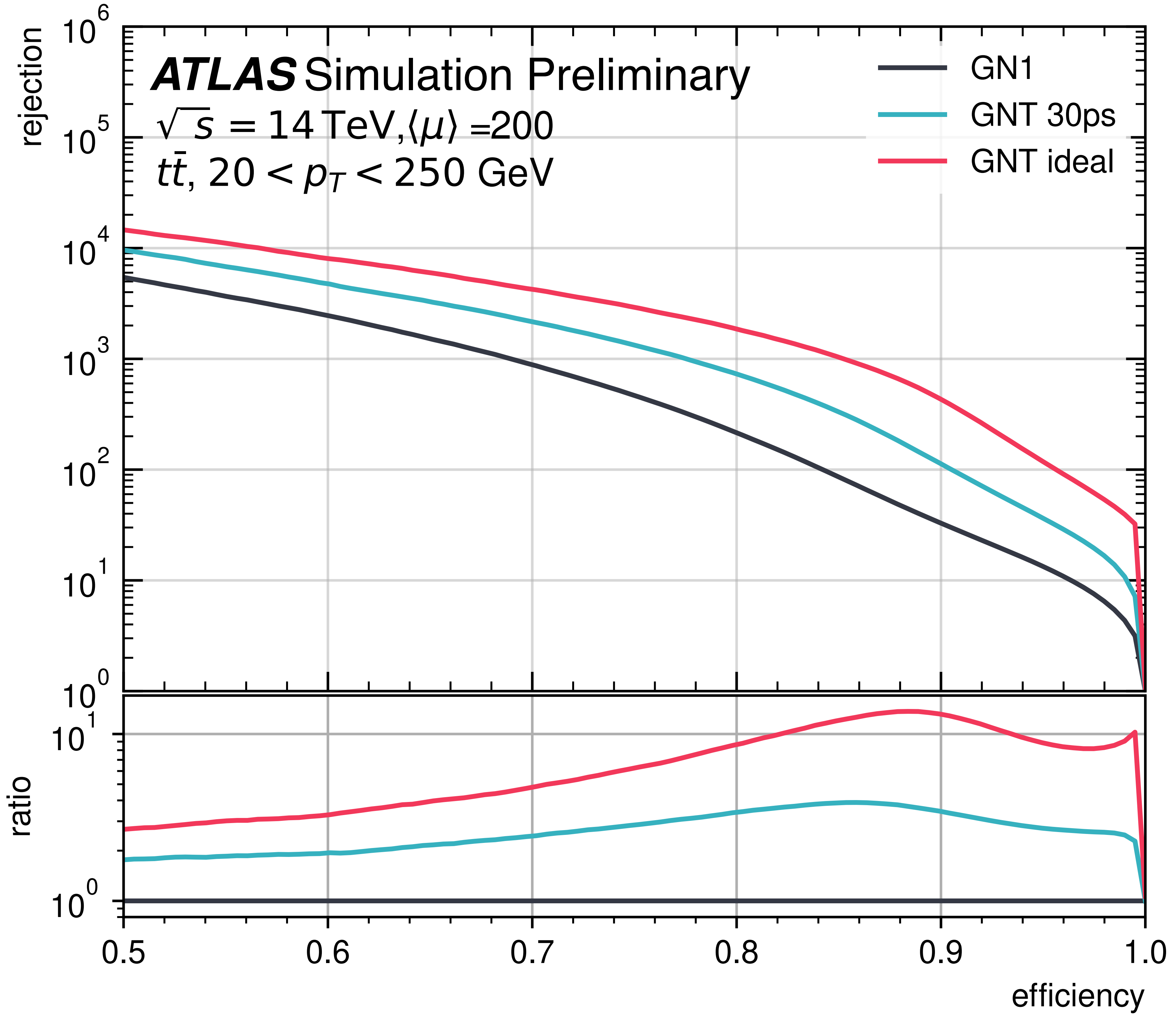
With lower track time resolution the improvement is less prominent but still solid

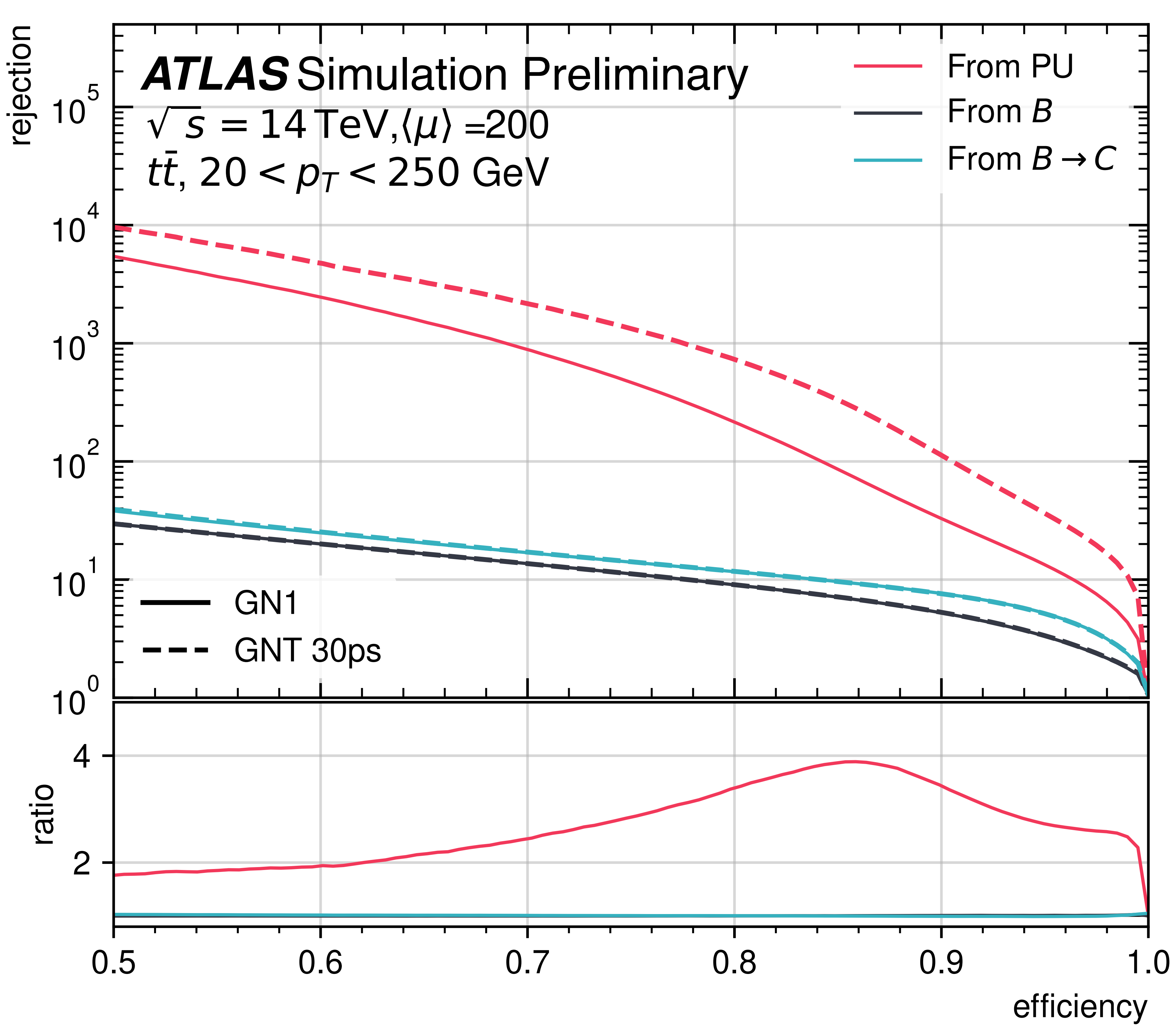
Track classification



Largest improvement in discriminating Pile-Up tracks from non Pile-Up tracks

Track classification





Largest improvement in discriminating Pile-Up tracks from non Pile-Up tracks

Not evident impact on Track from Heavy Flavour Tracks