

Advances in Hadronic Tau Reconstruction and Identification in ATLAS Using Graph Neural Networks

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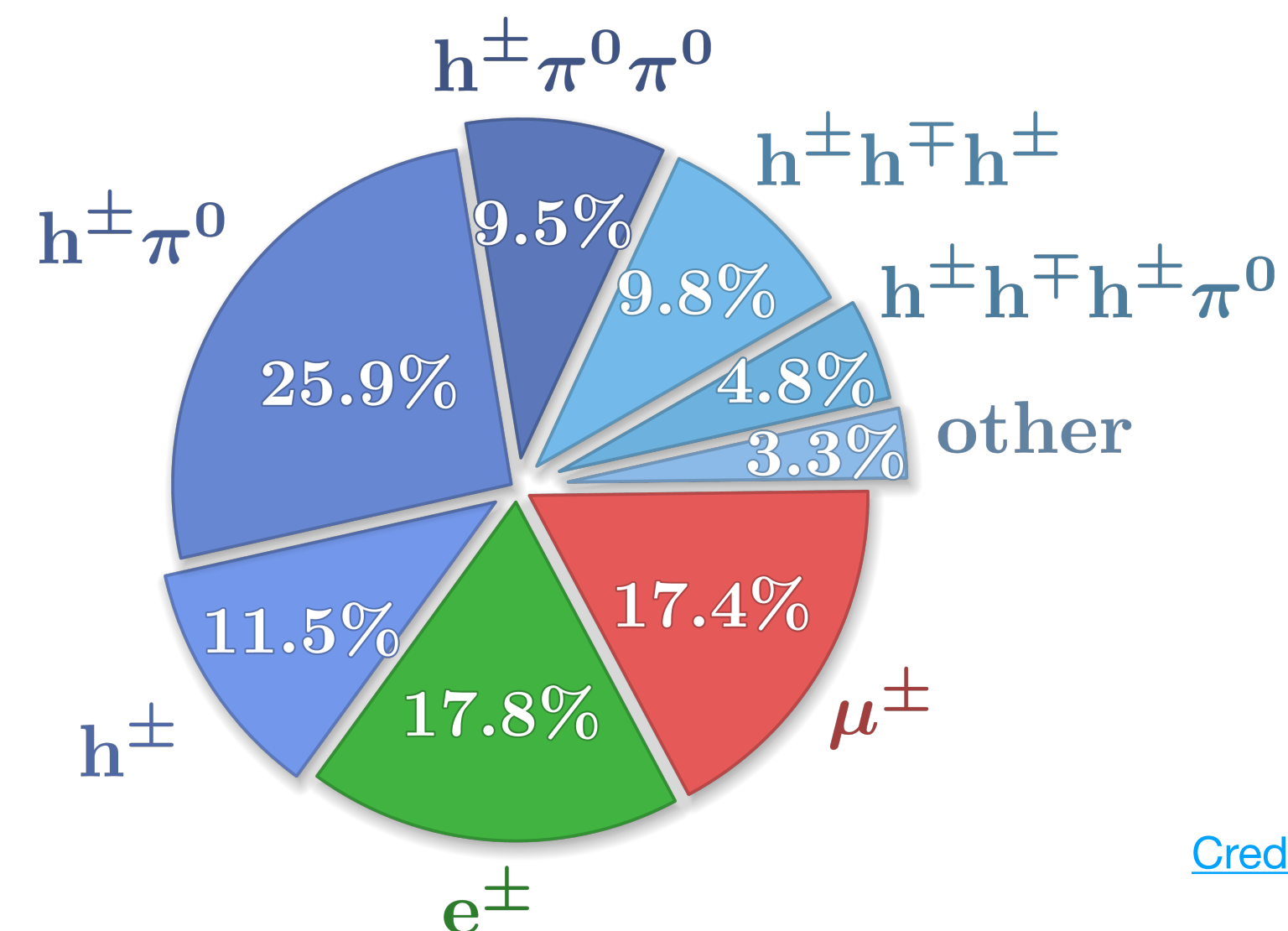
FSP ATLAS
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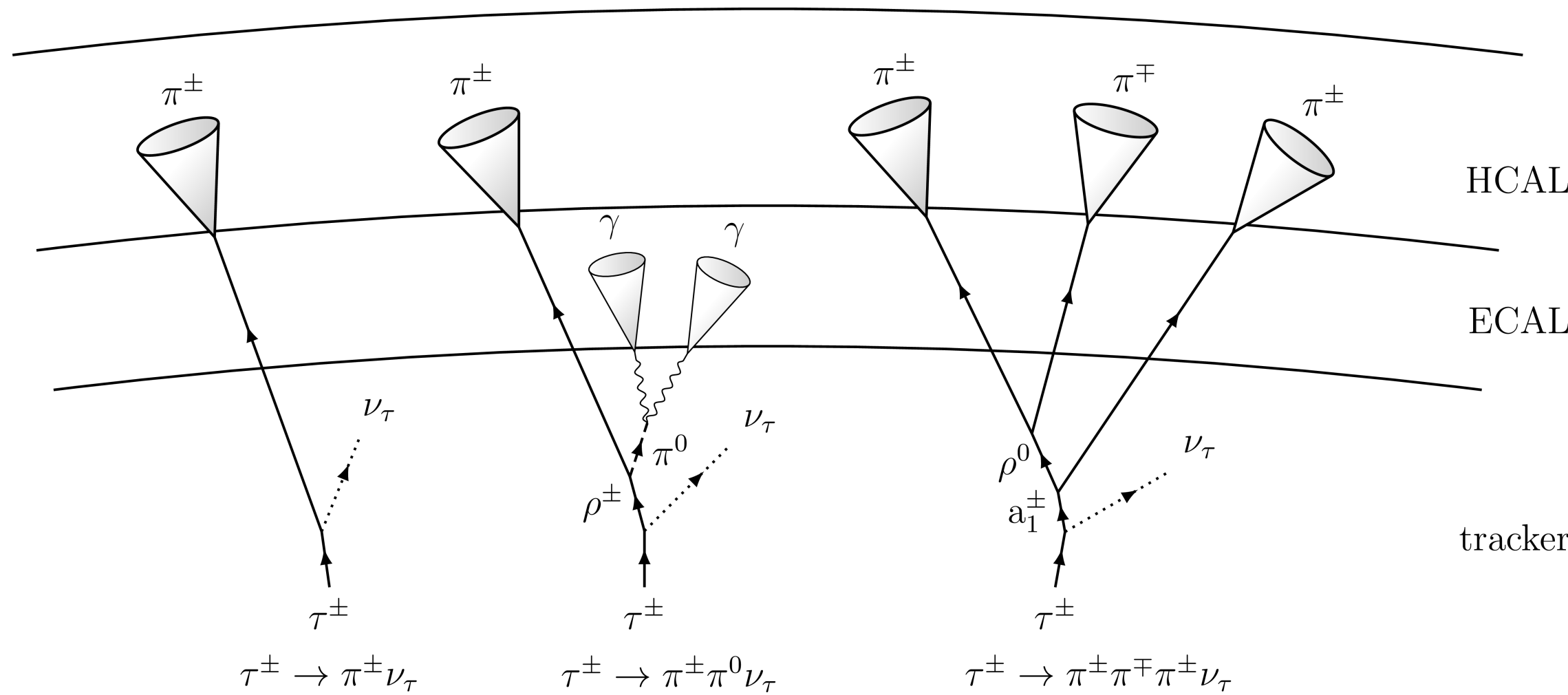
ATLAS
EXPERIMENT

The tau lepton

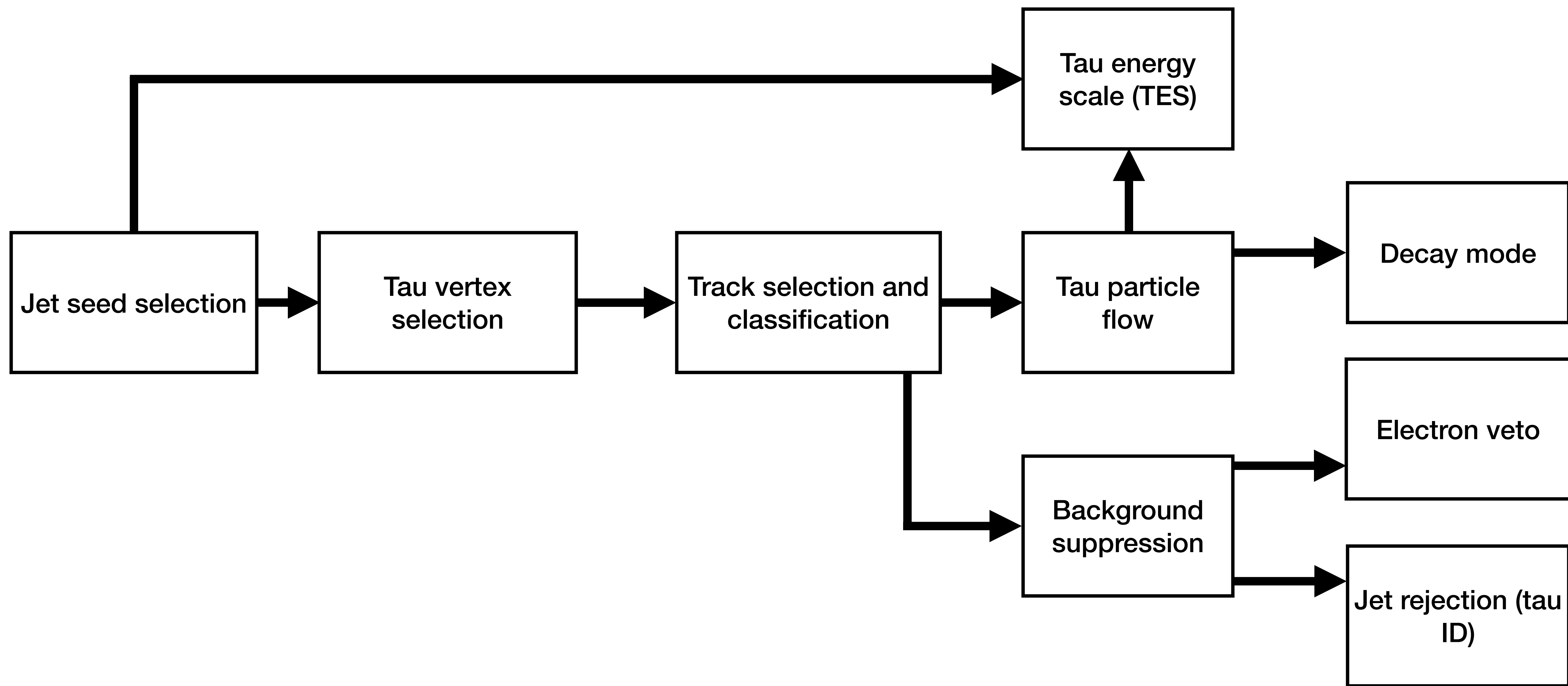
- The tau is the 3rd generation charged lepton:
 - Mass of 1777 MeV and mean lifetime of 0.293 ps.
 - Useful for Higgs measurements due to a comparably large BR (~6%).
 - Decays to $e\nu_e\nu_\tau$ or $\mu\nu_\mu\nu_\tau$ (35%) or hadrons + $1\nu_\tau$ (65%).
- Leptonically decaying taus are reconstructed as e or μ .
- ATLAS detector signature for hadronically decaying taus (τ_{had}):
 - Narrow jet of tracks and deposits in the calorimeters from the 1 or 3 charged pions (1- and 3-prong).
 - Photons from neutral pion decays leave energy deposits in the ECAL.



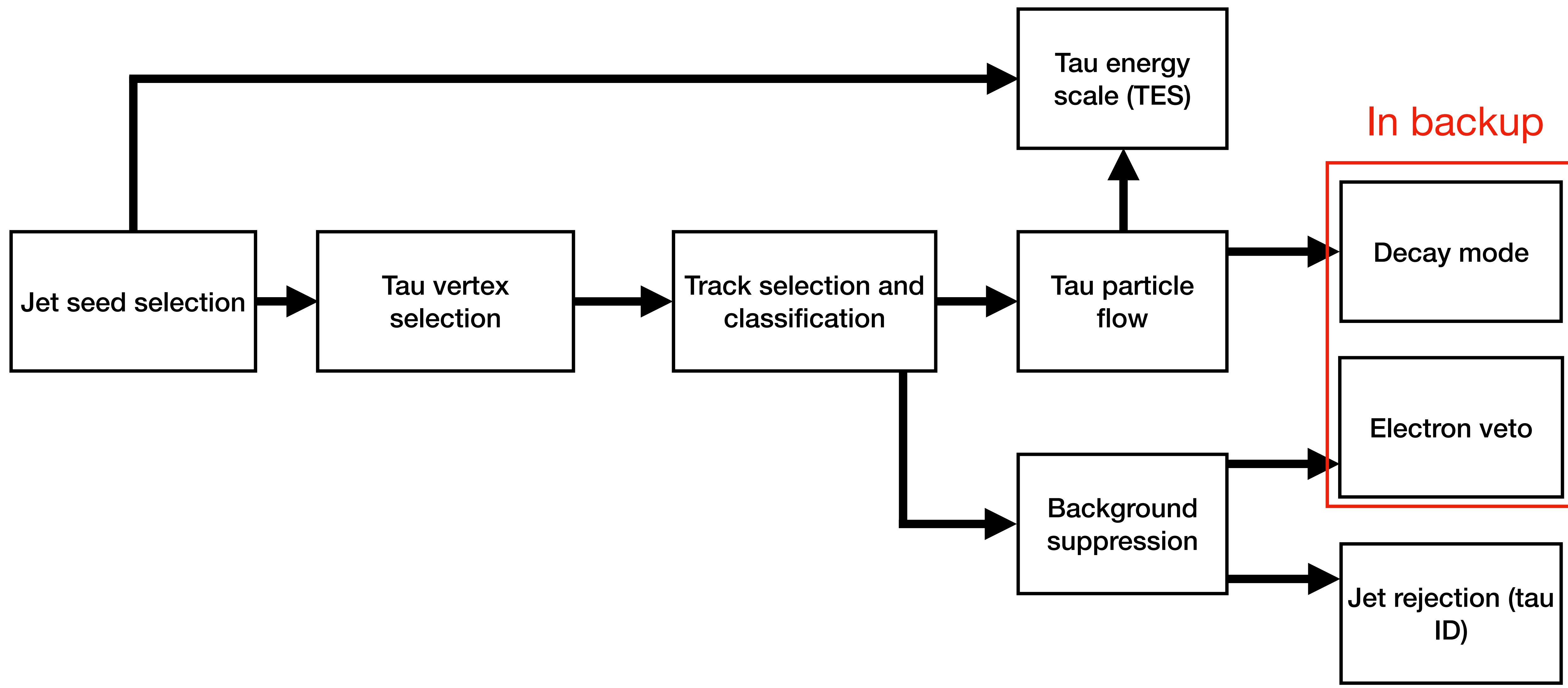
[Credit](#)



τ_{had} reconstruction and identification chain



τ_{had} reconstruction and identification chain



τ_{had} reconstruction: jet seed and vertex association

- **Seed jet selection:**

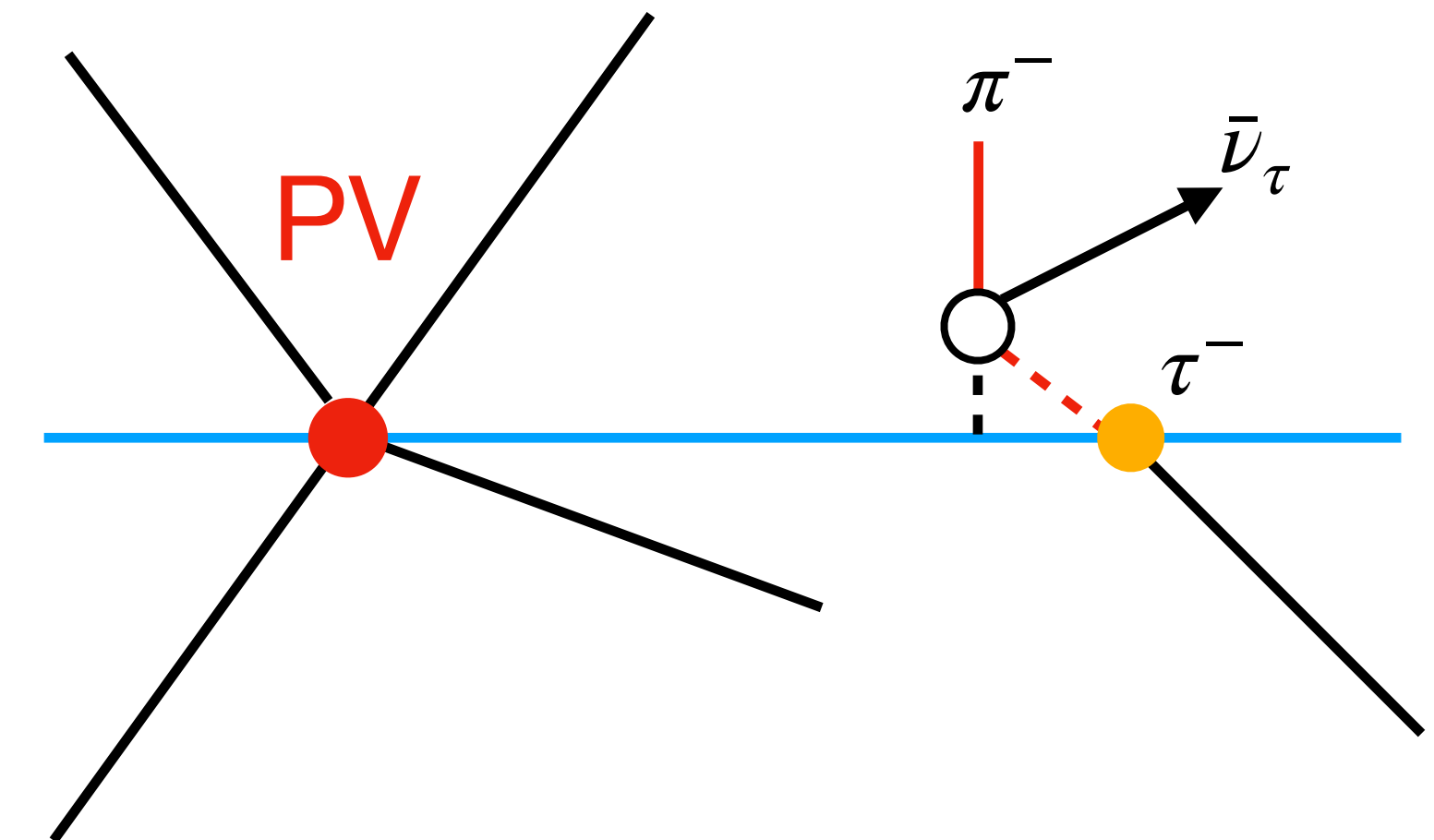
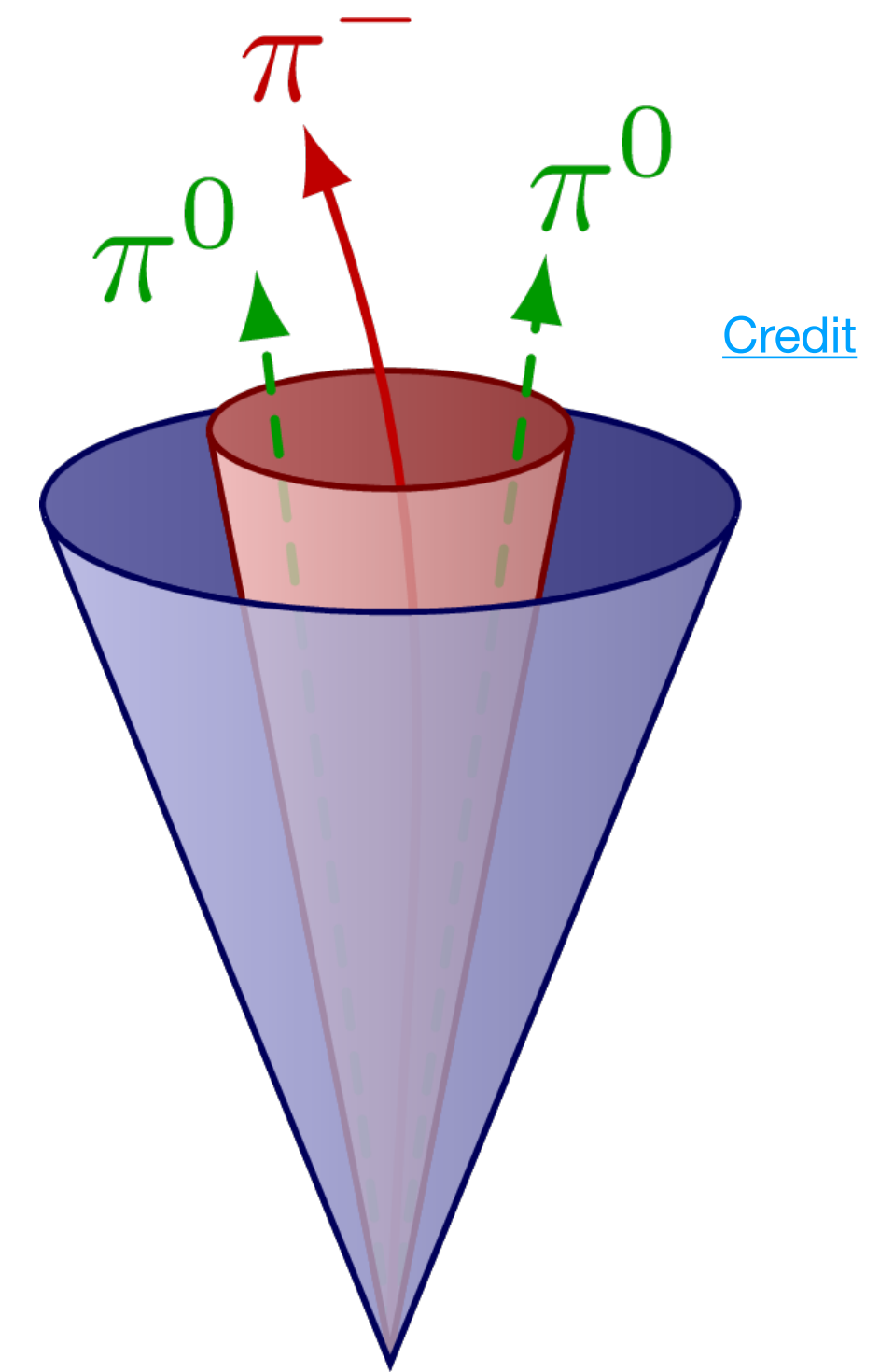
- τ_{had} reconstruction starts with a jet seed formed by the anti- k_t algorithm using $R = 0.4$.
- 3D energy clusters in the calorimeter (LCTopo) serve as input to the jet seed.
- Kinematic selection: $p_{\text{T}} > 5 \text{ GeV}$, $|\eta| < 2.5$.

- **Vertex Association:**

- Primary vertex selection (highest $\sum p_{\text{T}}^2$ of tracks) can miss the tau production vertex if the neutrinos and neutral pions from the τ_{had} decay carry a large fraction of the momentum or charged pion tracks may not be counted to the PV due to the large impact parameter.
- Instead, a dedicated Tau Jet Vertex Association (TJVA) algorithm selects the vertex with the highest p_{T} fraction of all the tracks within $\Delta R < 0.2$ of the jet seed.

$$f_{p_{\text{T}}} = \frac{\sum p_{\text{T}}(\text{tracks associated to vertex})}{\sum p_{\text{T}}(\text{all tracks})}$$

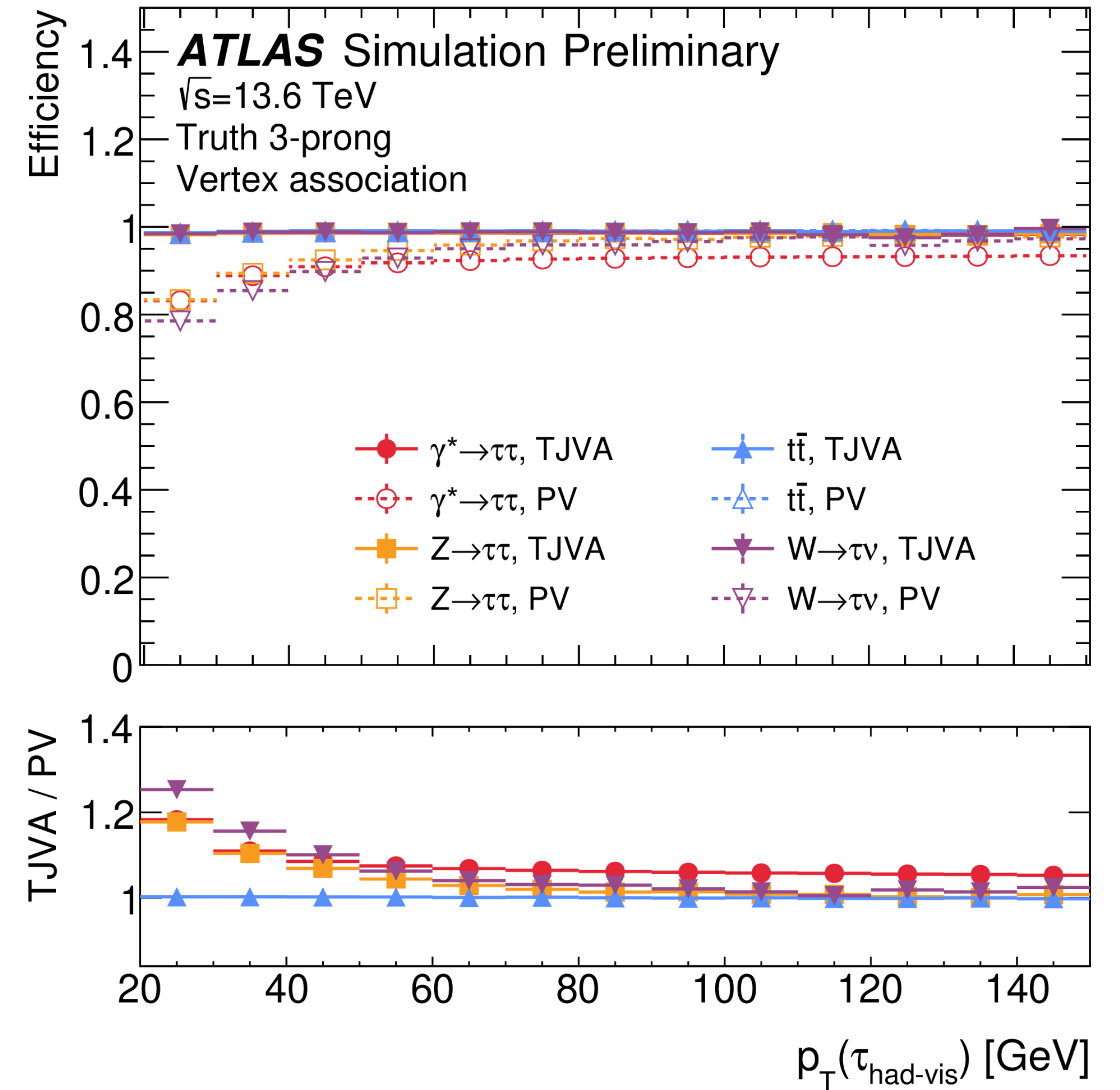
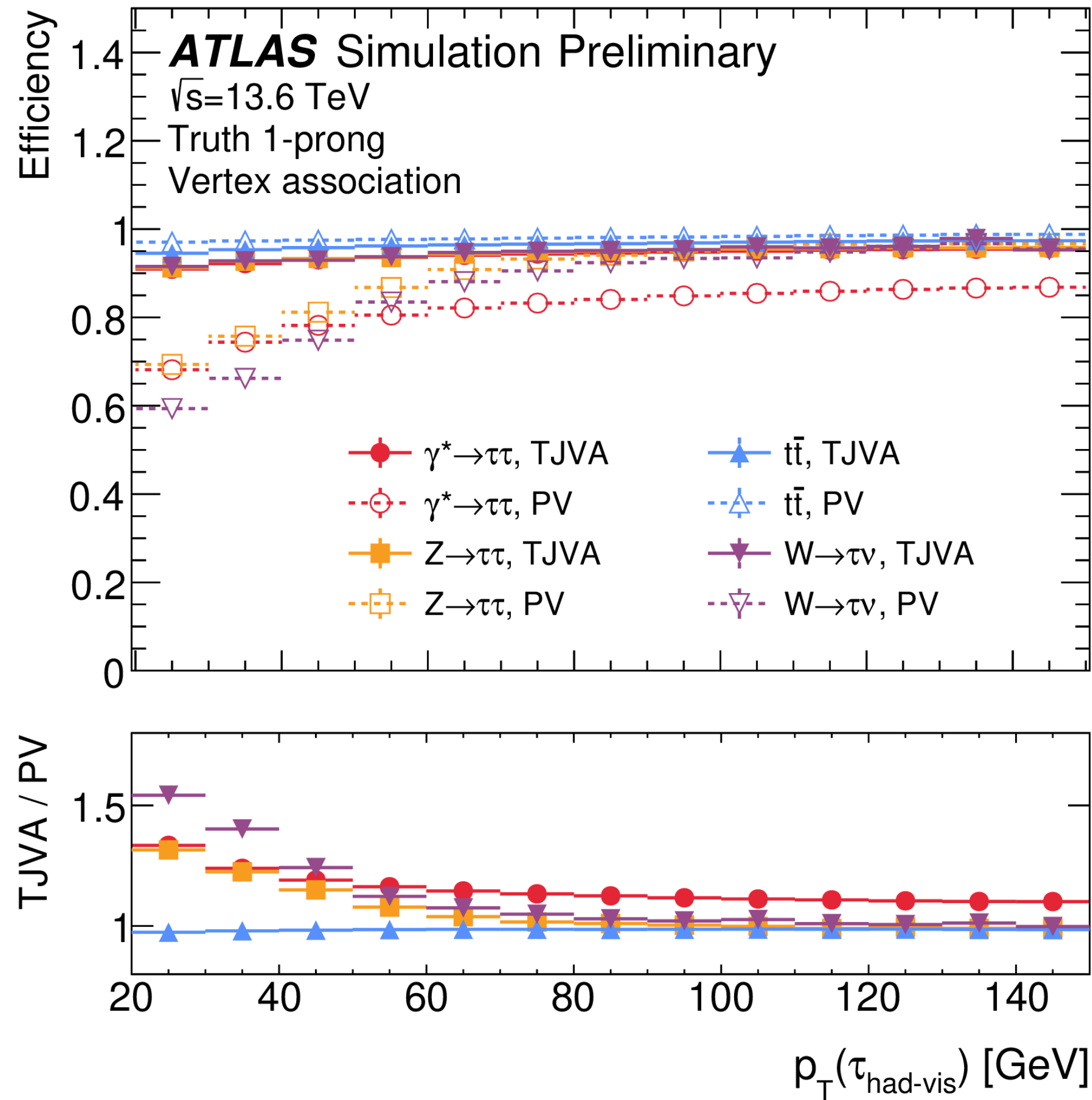
- τ_{had} direction and impact parameters are corrected for the new vertex.



τ_{had} reconstruction: vertex association

- TJVA is more efficient than the standard PV selection, especially at low visible $\tau_{\text{had}} p_T$.

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τ_{had} reconstruction: track classification

- Tracks are associated with the τ_{had} if:

Within $\Delta R < 0.25$ of the τ_{had} direction:

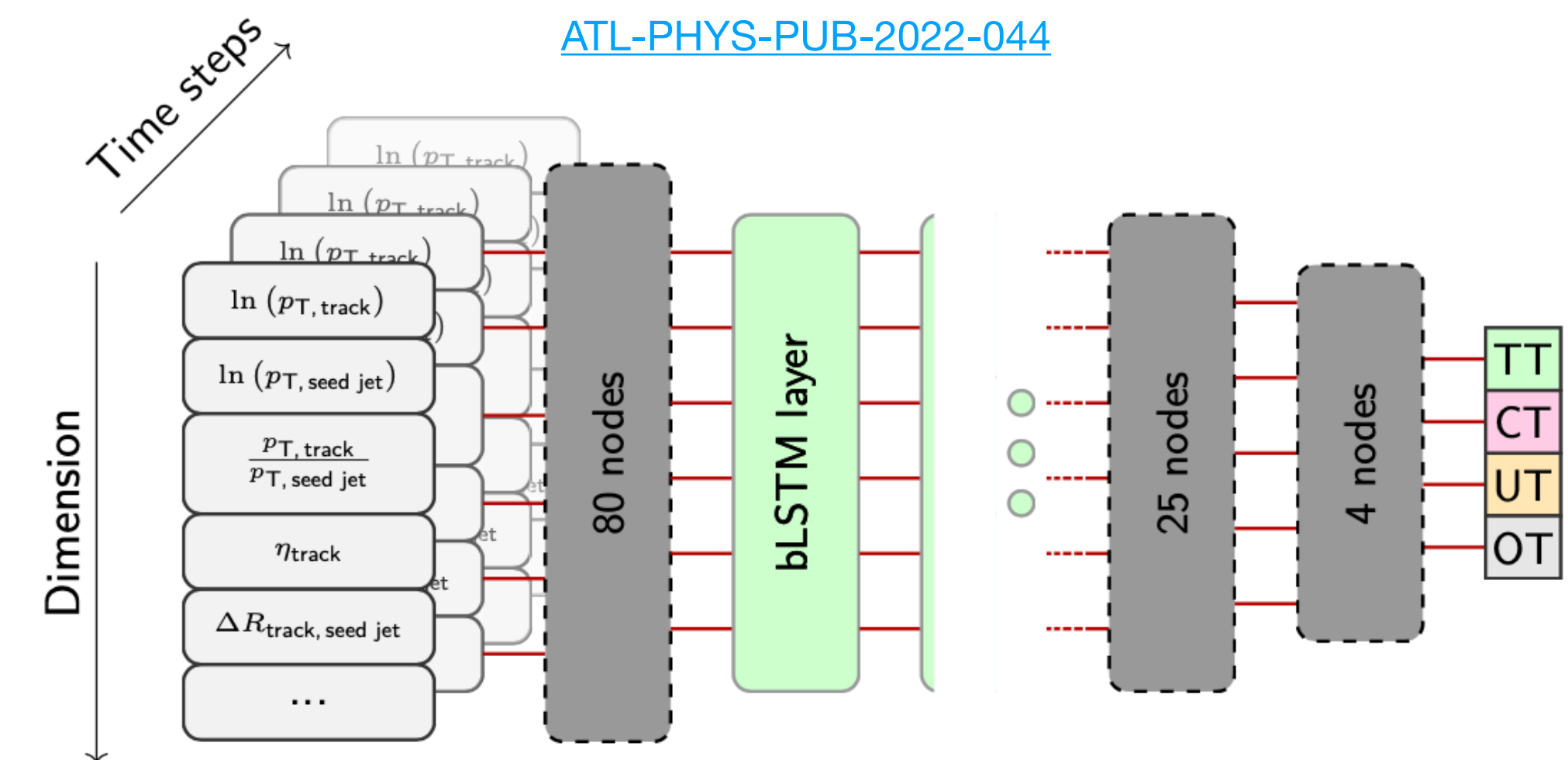
- $p_{\text{T}} > 1 \text{ GeV}$, $|d_0| < 1.0 \text{ mm}$, $|z_0 \sin \theta| < 1.5 \text{ mm}$
- ≥ 2 hits in the pixel layers, ≥ 7 hits in total for pixel and SCT layers.

Within $0.25 < \Delta R < 0.4$ of the τ_{had} direction:

- The seed jet is the closest jet in terms of ΔR .
- Ghost-associated with the seed jet.

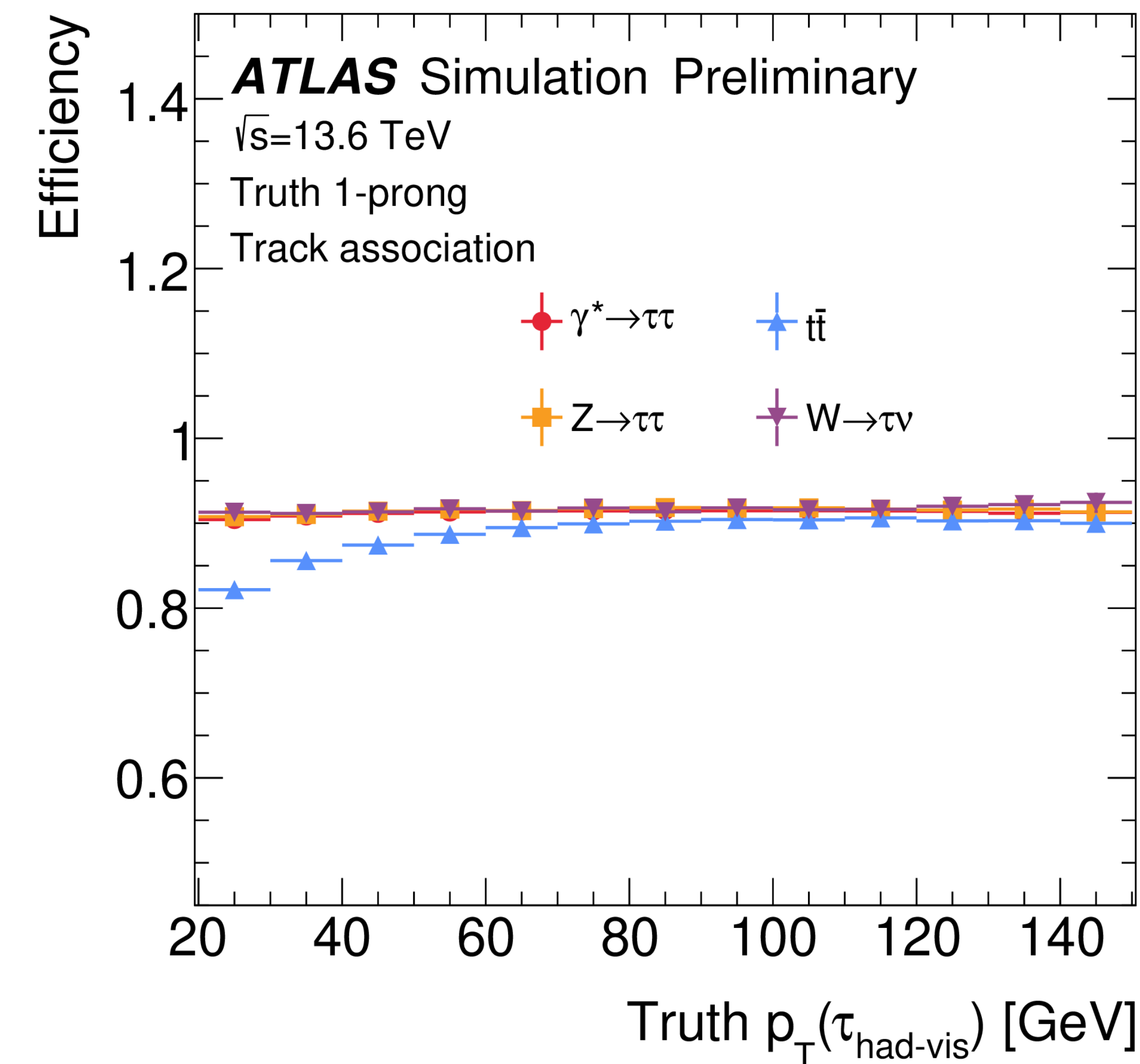
- An RNN classifies associated tracks into 4 categories in order to determine the τ_{had} charge and number of charged decay products:

- Tracks from the charged decay products ($\pi^\pm$), determine charge and prongness.
- Photon conversion tracks coming from neutral decay products (π^0).
- Isolation tracks from quark/gluon jets from the remnant of hard scattering.
- Fake tracks from pile-up and mis-reconstruction.

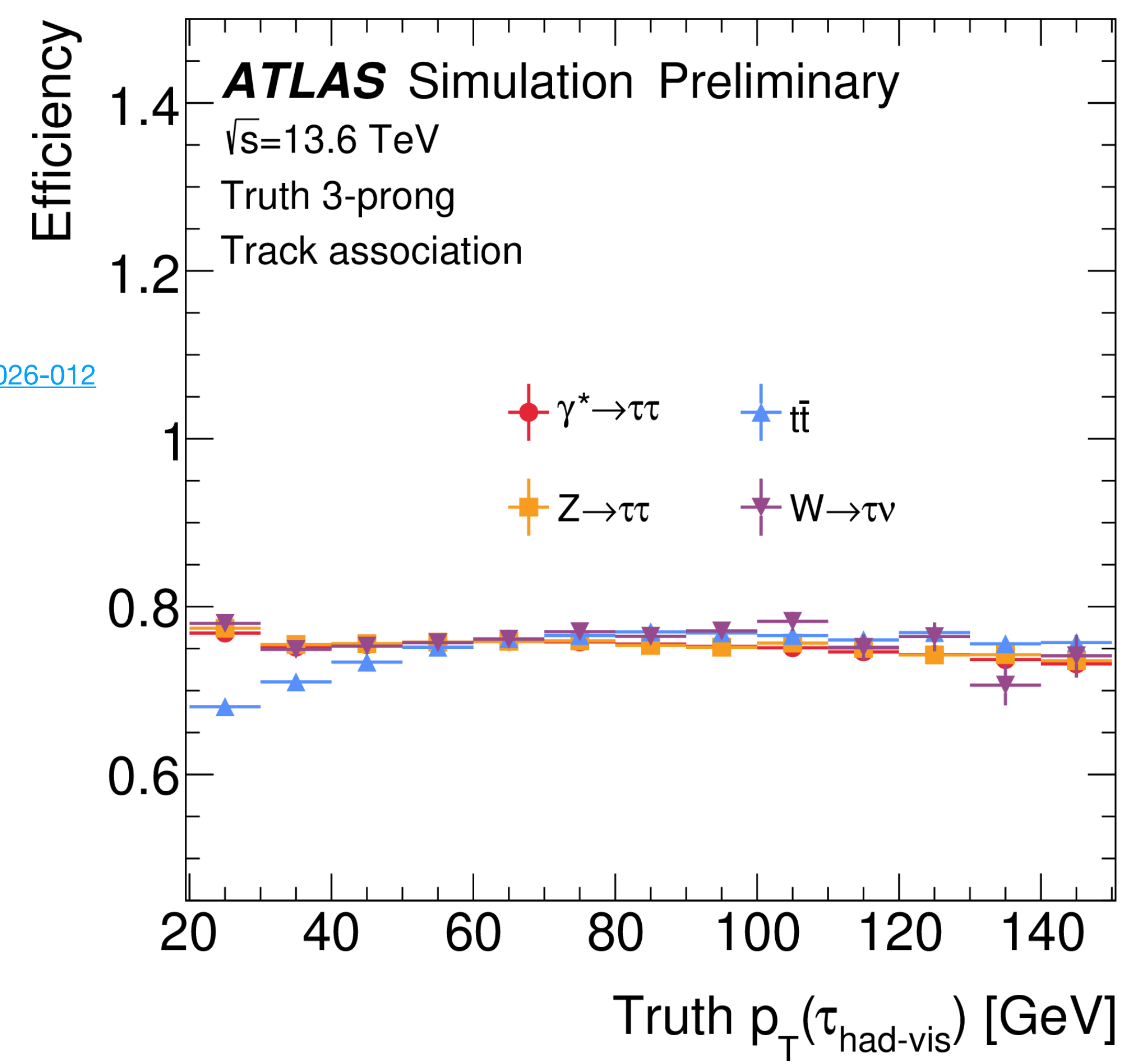


τ_{had} reconstruction: track classification

- The RNN is 70-90% efficient in correctly reconstructing the number of tracks for a τ_{had} candidate.



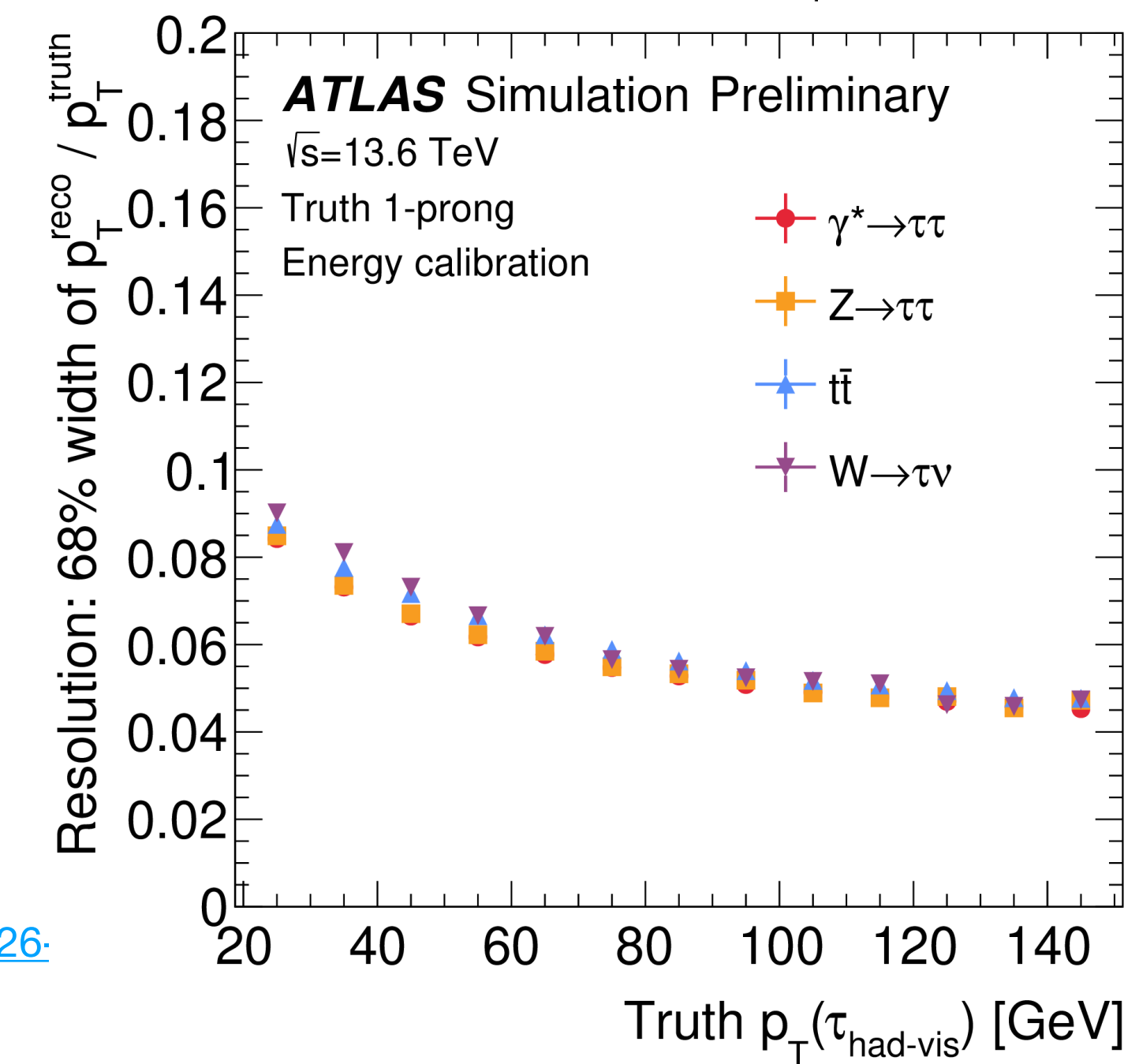
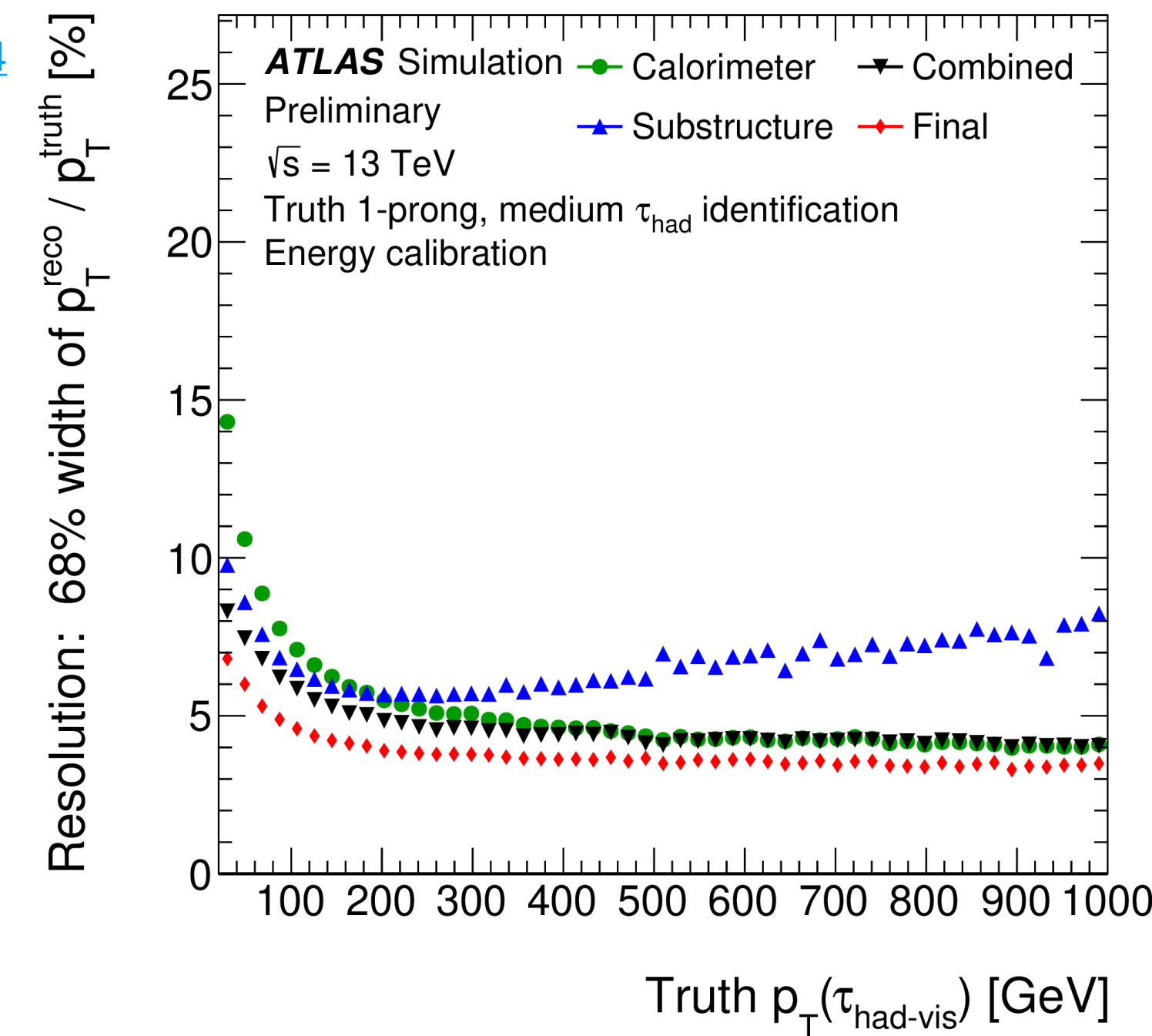
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Tau energy calibration:

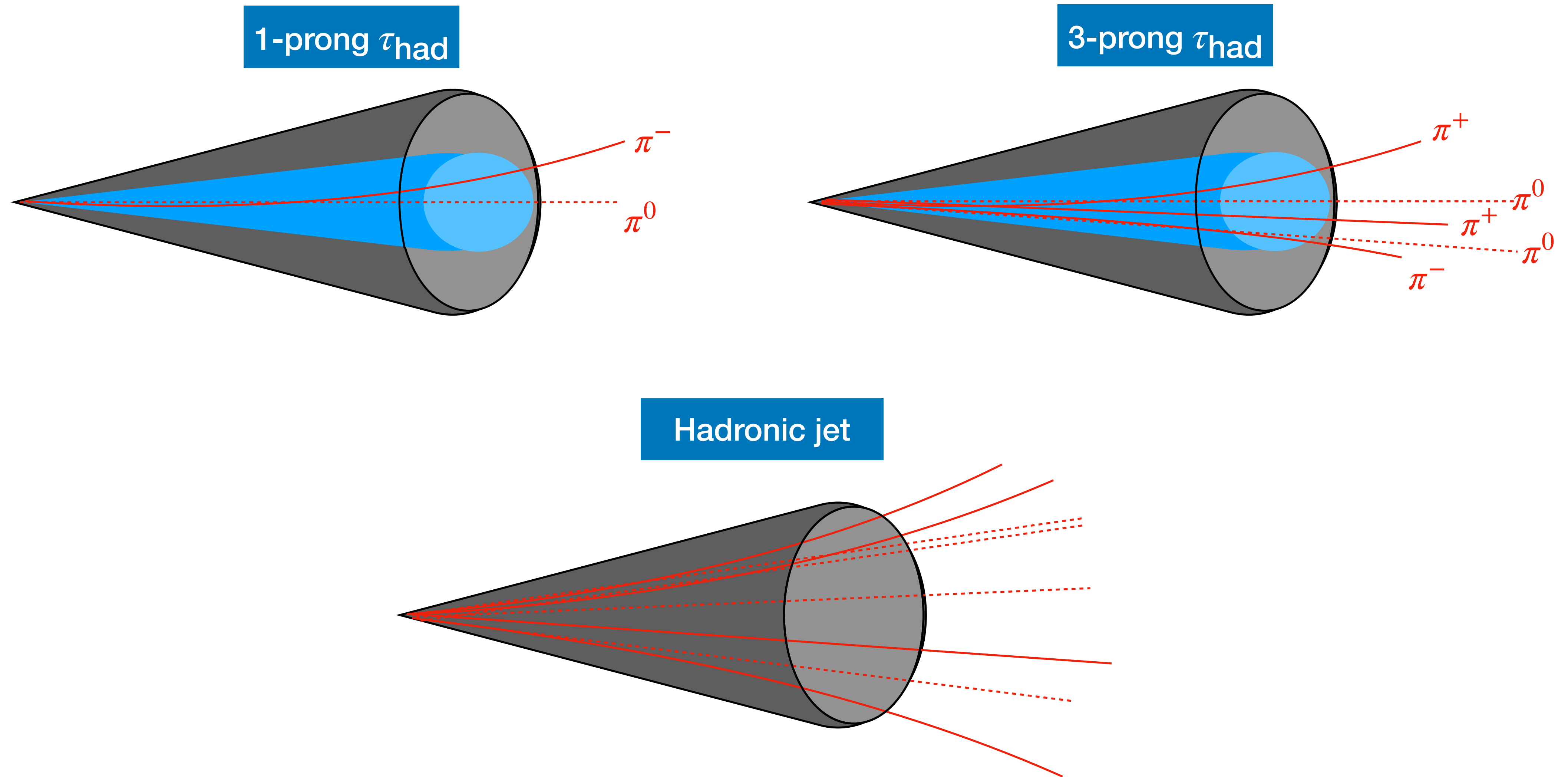
- The tau energy scale is determined using two methods:
 - **Calorimeter TES:**
 - Sums the energy of all LCTopo clusters within $\Delta R < 0.2$ of the τ_{had} candidate.
 - Subtract the energy contribution from pile-up interactions and apply a detector response correction.
 - **Substructure TES:**
 - Momenta of charged pions are measured based on tracks.
 - The decay mode of the τ_{had} is determined by BDTs and the substructure TES is determined by the sum of charged tracks and π^0 s in this decay mode.
- The two TES estimates are combined, $p_{\text{T}}^{\text{comb}}$ using a weighted average, giving priority to the calibration with the best expected energy resolution:
 - Substructure TES has better resolution at low p_{T} , calorimeter TES has higher resolution at high p_{T} .
- The final TES is determined with Boosted Regression Trees targeting $\frac{\text{truth } p_{\text{T}}}{p_{\text{T}}^{\text{comb}}}$.

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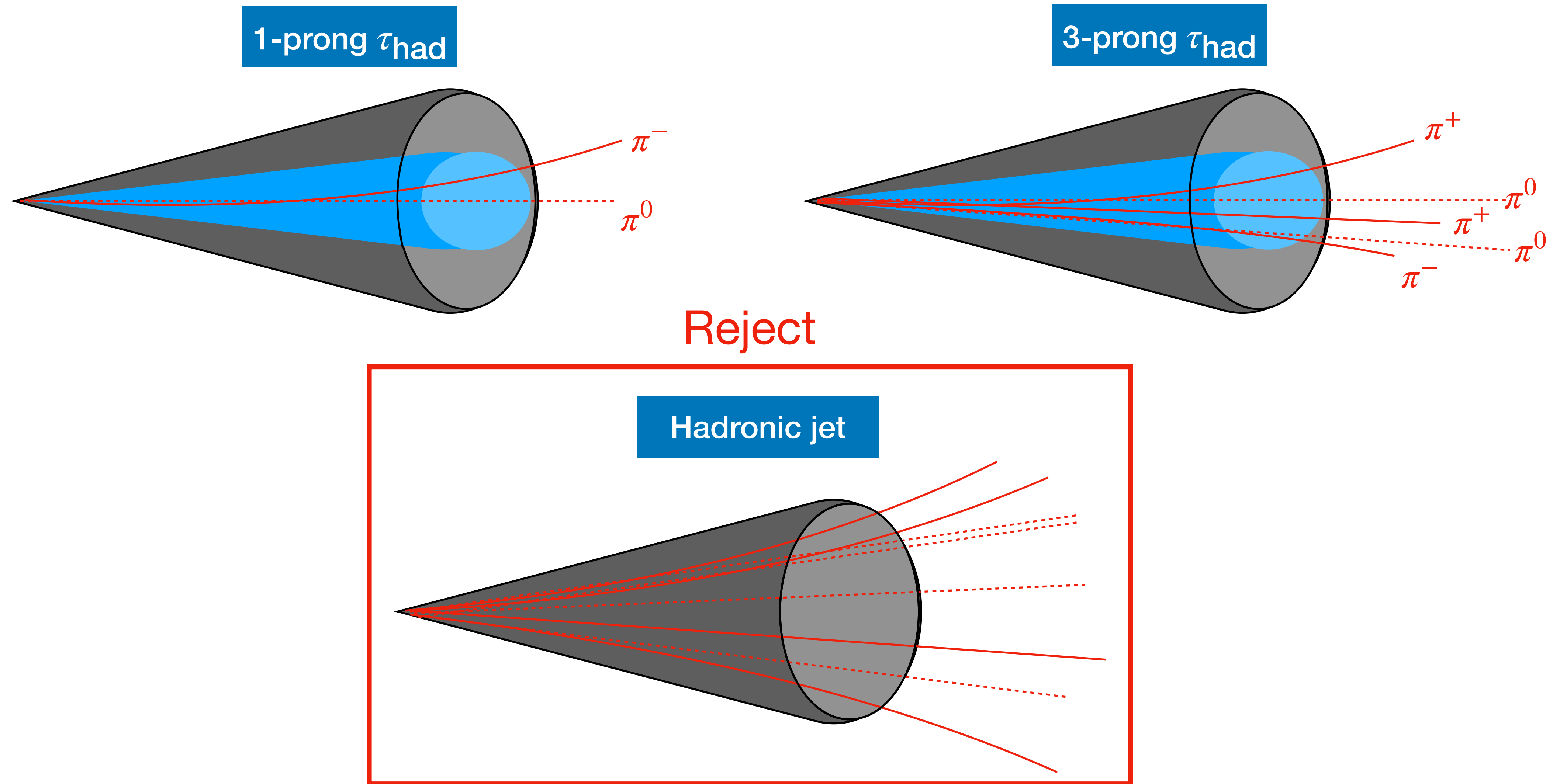
Tau identification

- Similar detector signatures can lead QCD jets to be reconstructed and misidentified as τ_{had} candidates.



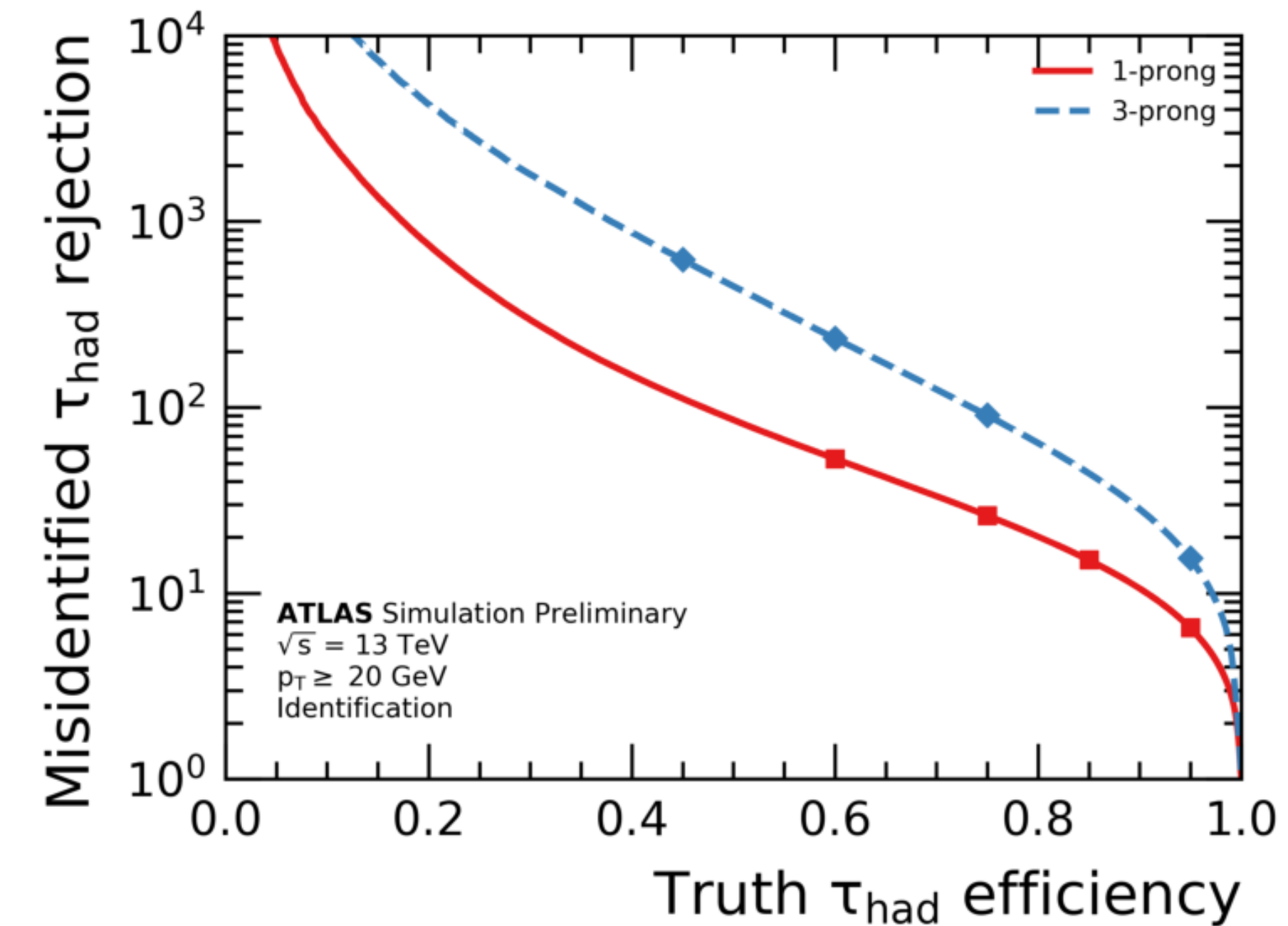
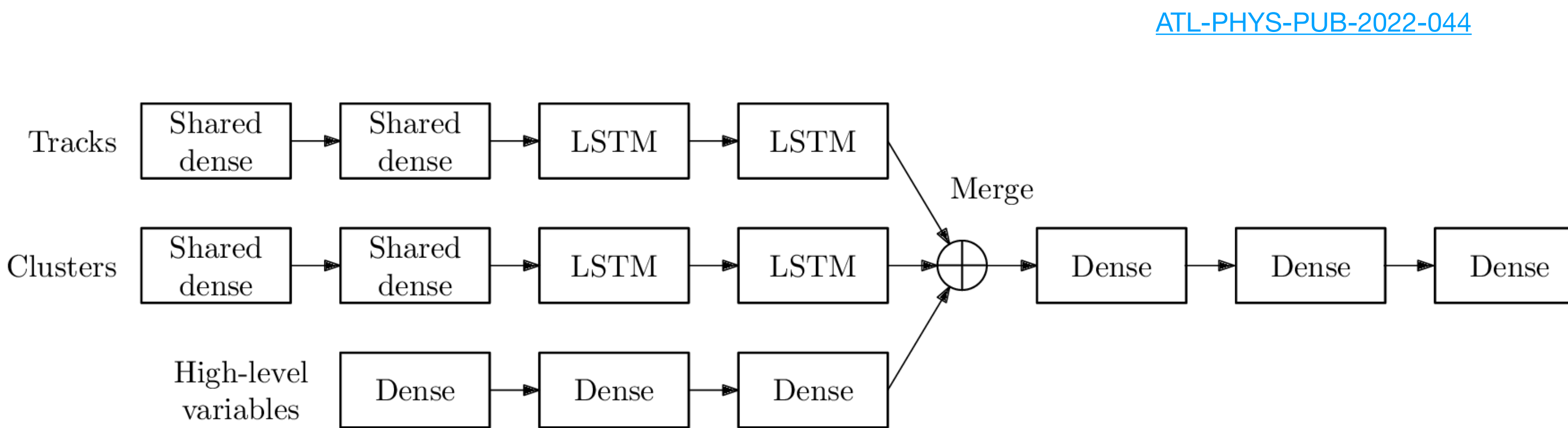
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Tau identification

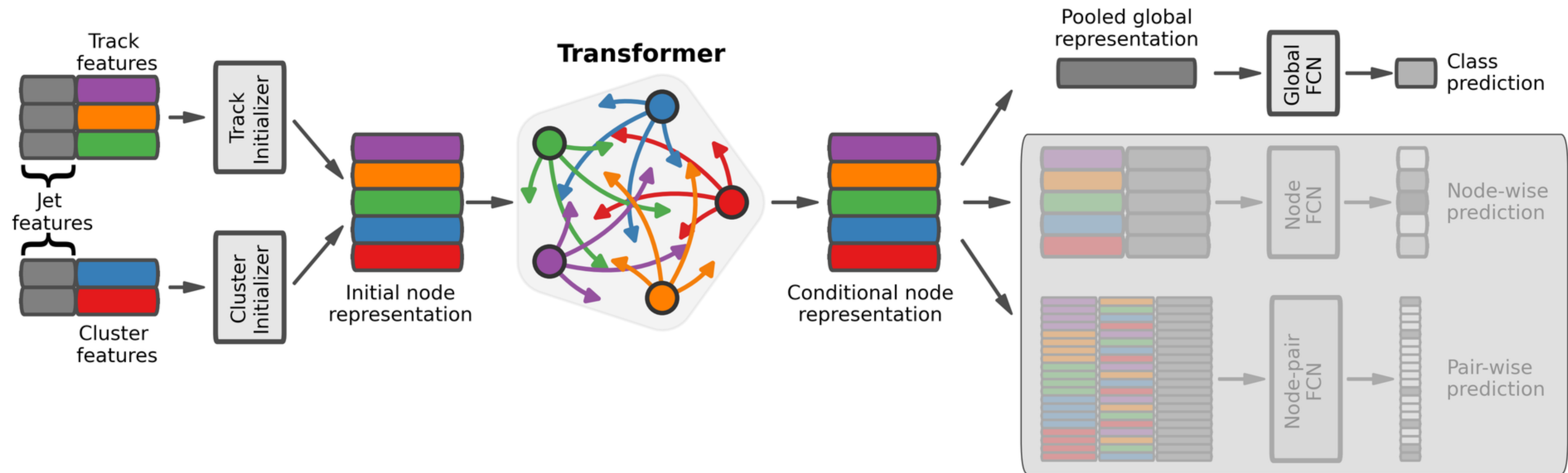
- Run 2 used an algorithm based on RNN architecture to provide discrimination between true τ_{had} and fakes.
- The architecture allows for a variable number of tracks and clusters associated to a τ_{had} candidate.
- The network uses three different input branches: track variables, cluster variables and high-level jet variables.
- Two networks trained separately for 1-prong and 3-prong τ_{had} .



Tau identification: GNTau

- A new algorithm has been developed.
- This uses a transformer-based architecture similar to the [GN2 algorithm](#) used for jet-flavour discrimination.
- GNTau builds a graph to encode relationships between tracks and clusters.
- Inputs are similar to the RNN: individual tracks, individual clusters and global jet variables.

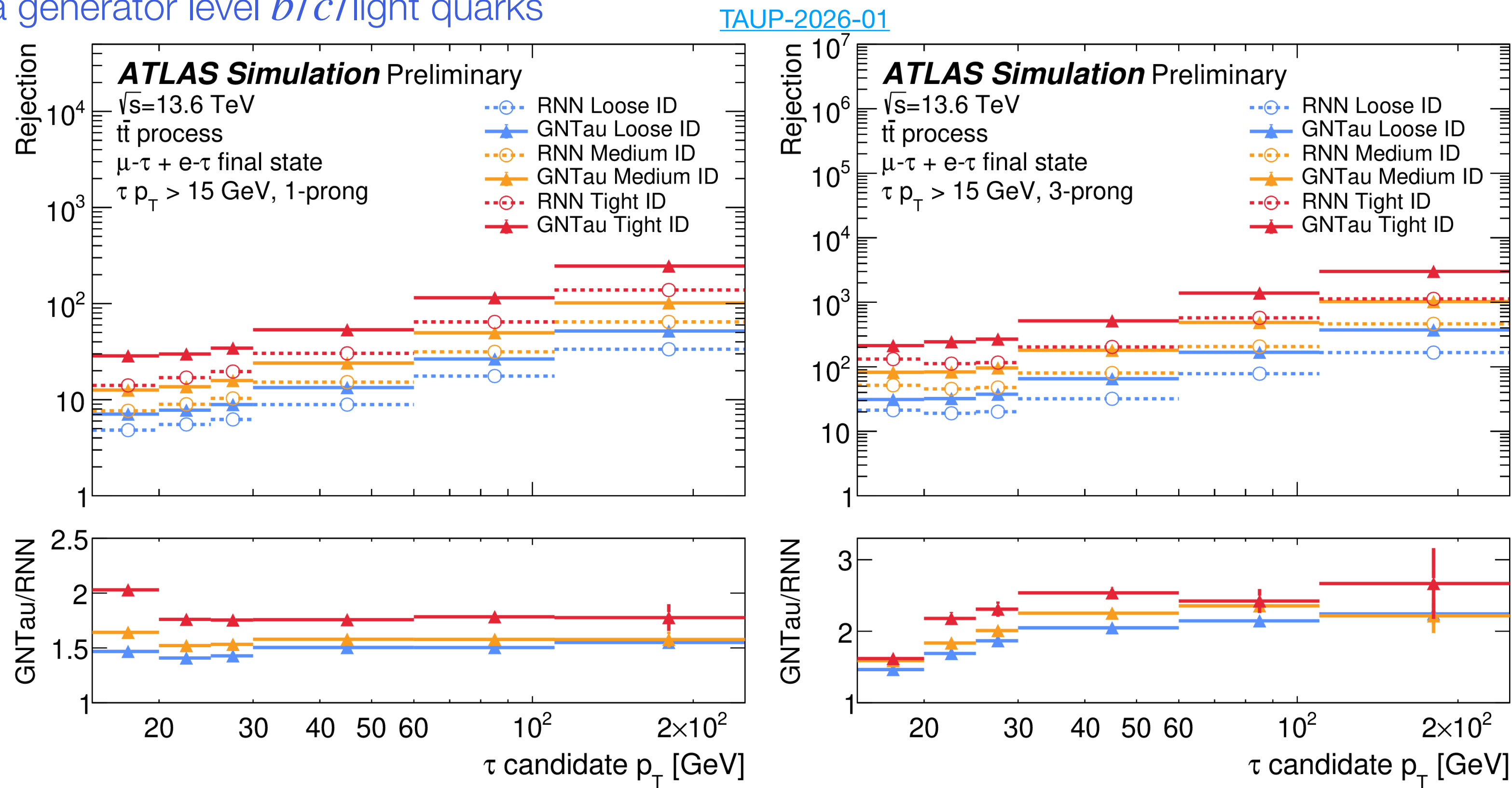
Example of transformer architecture



Improvements in background rejection

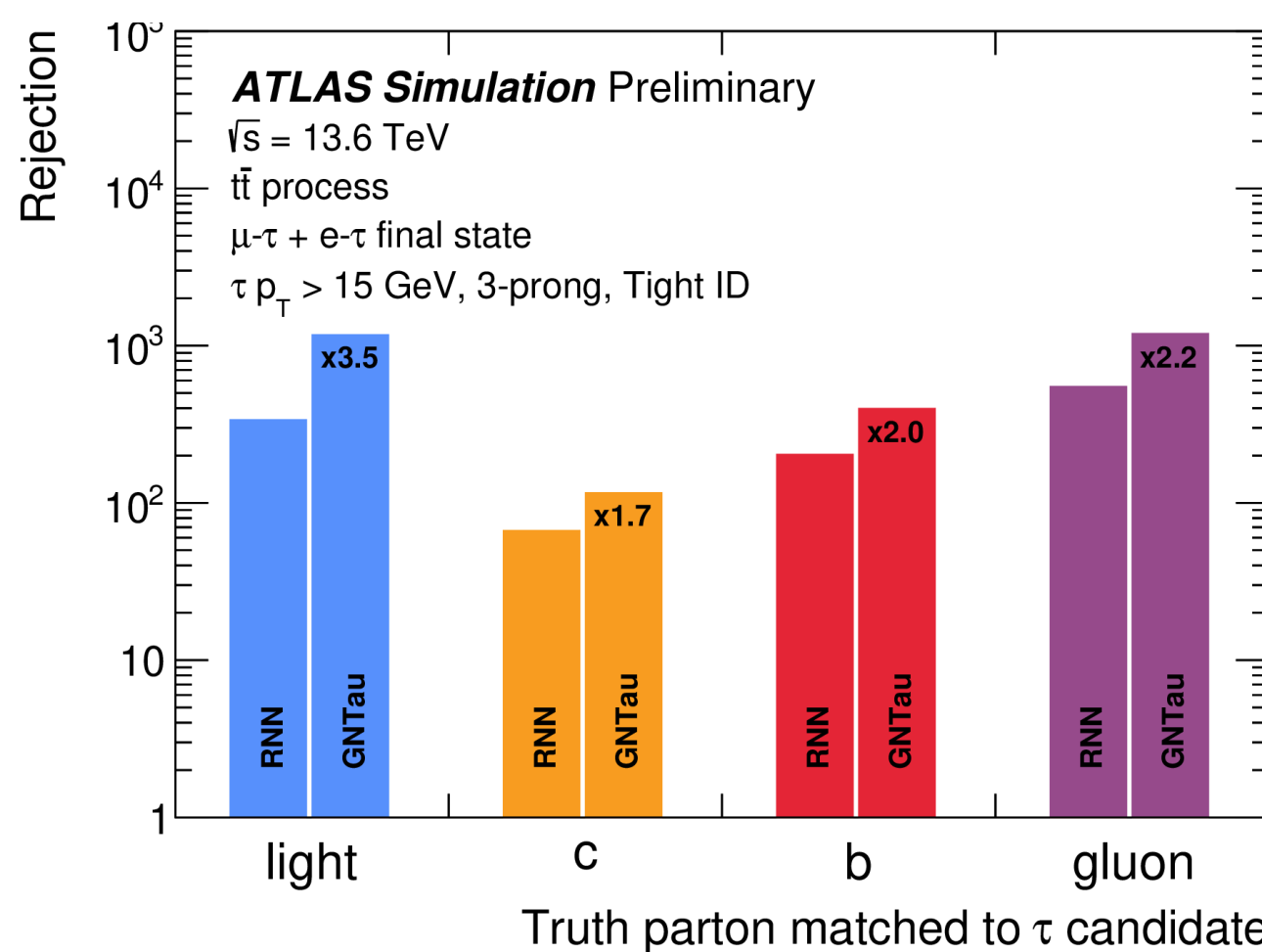
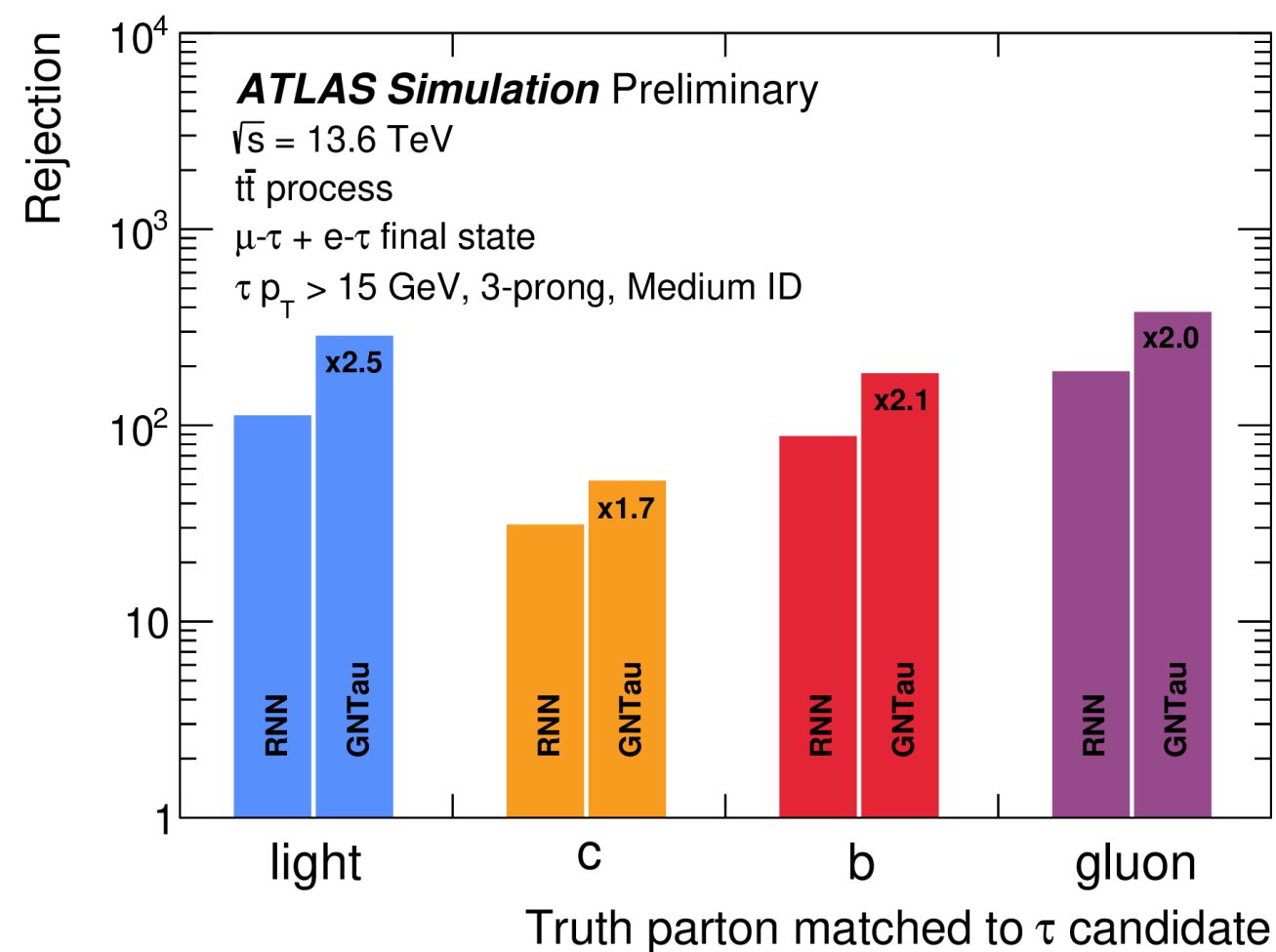
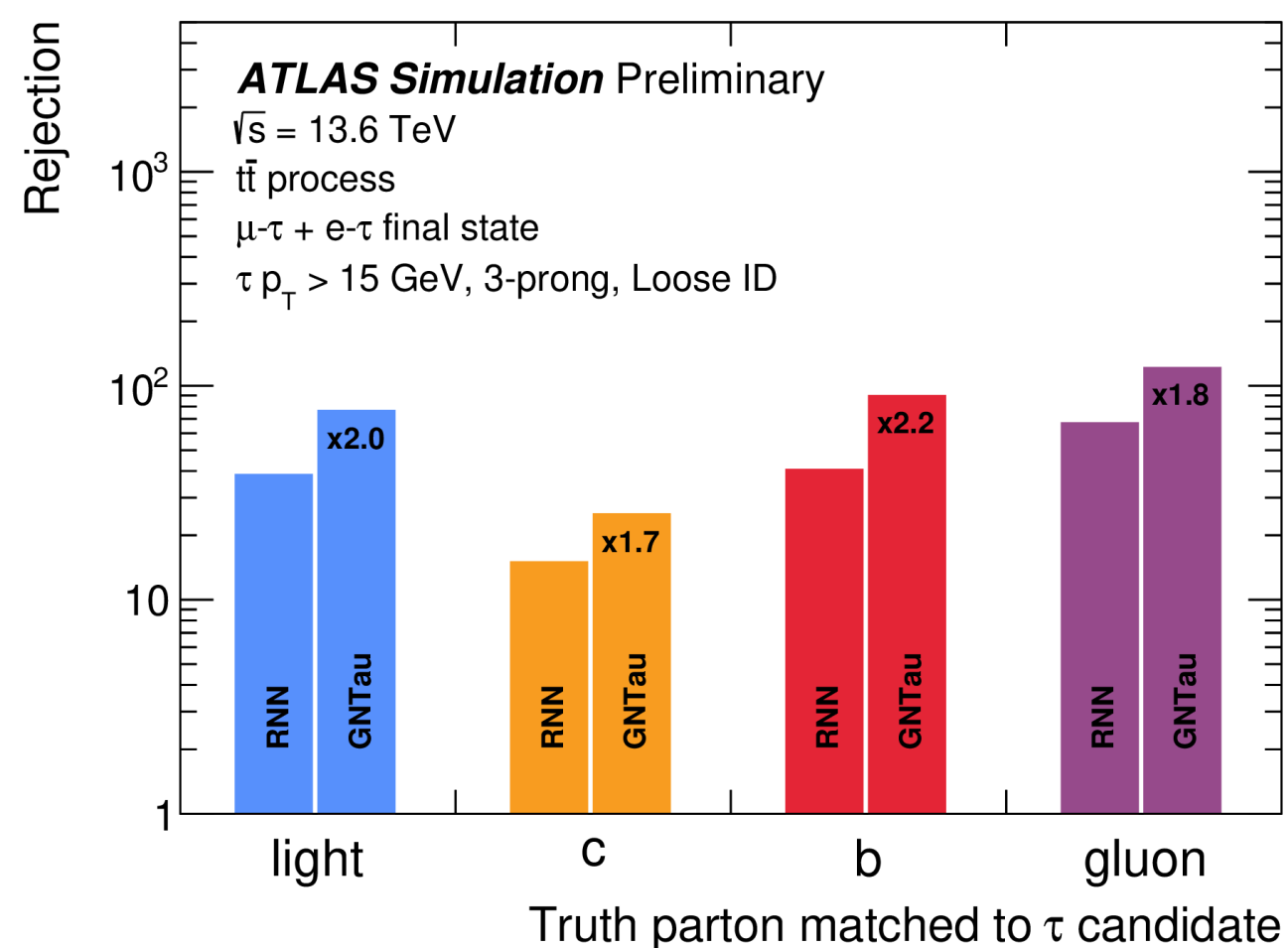
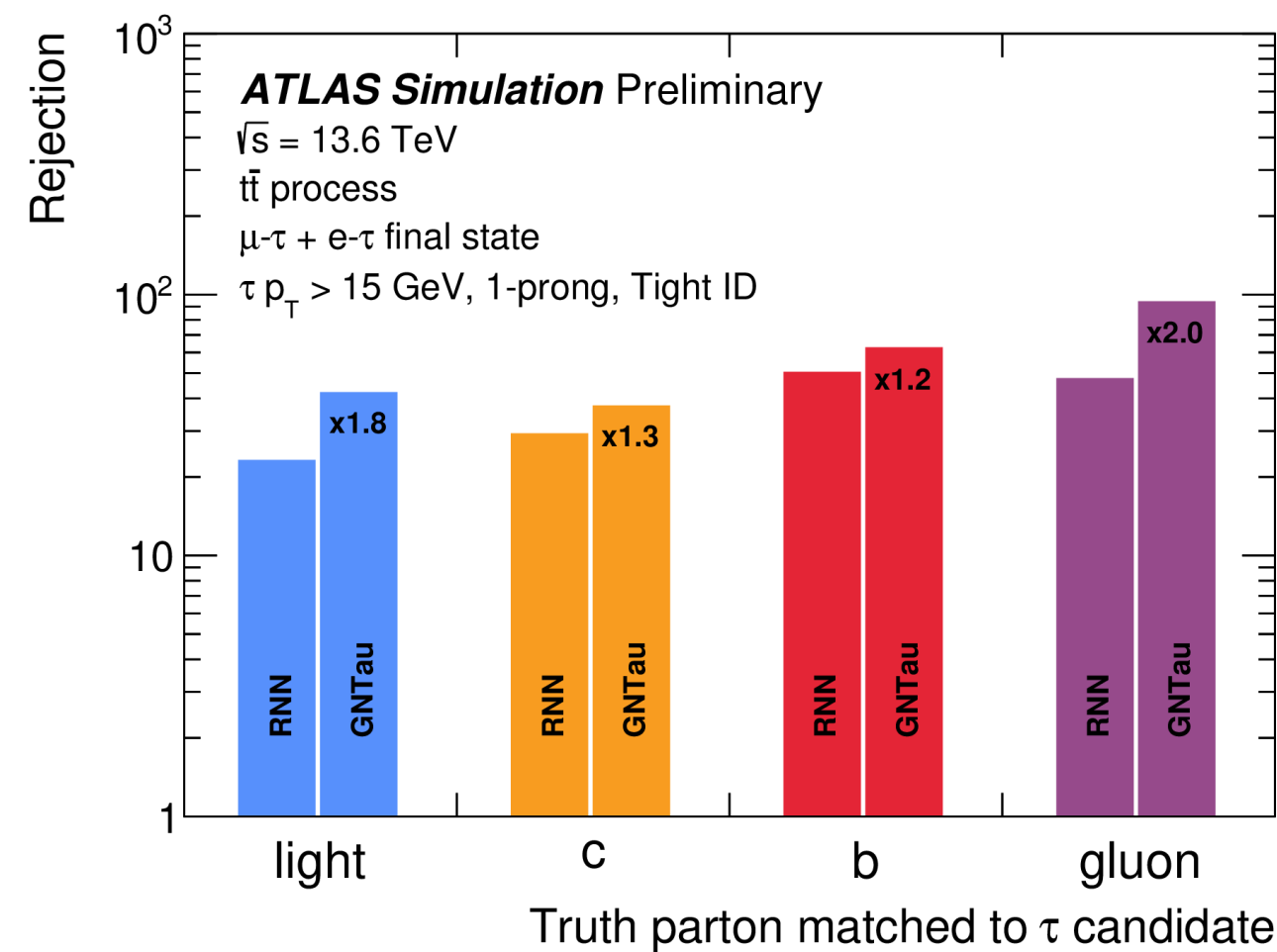
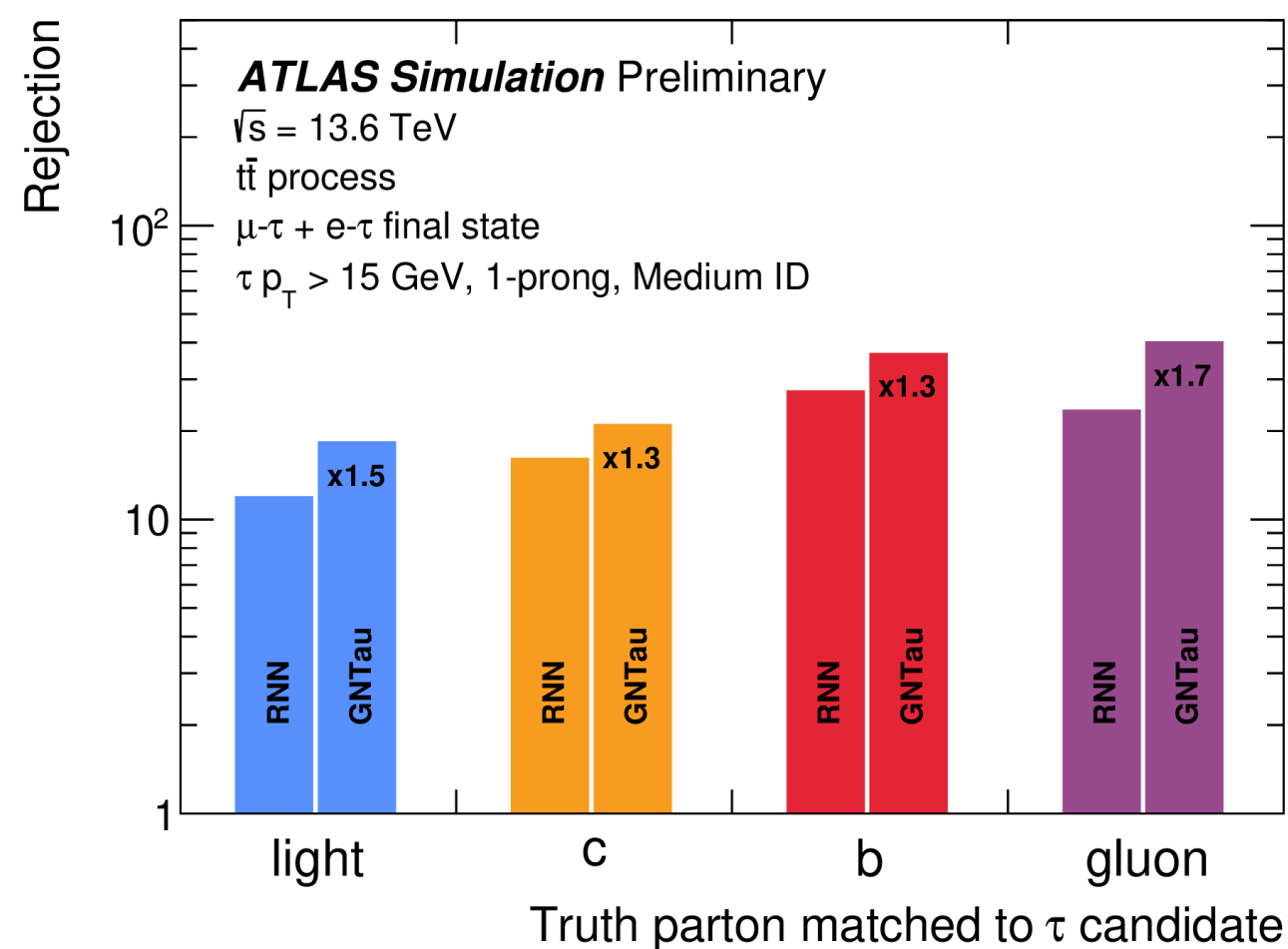
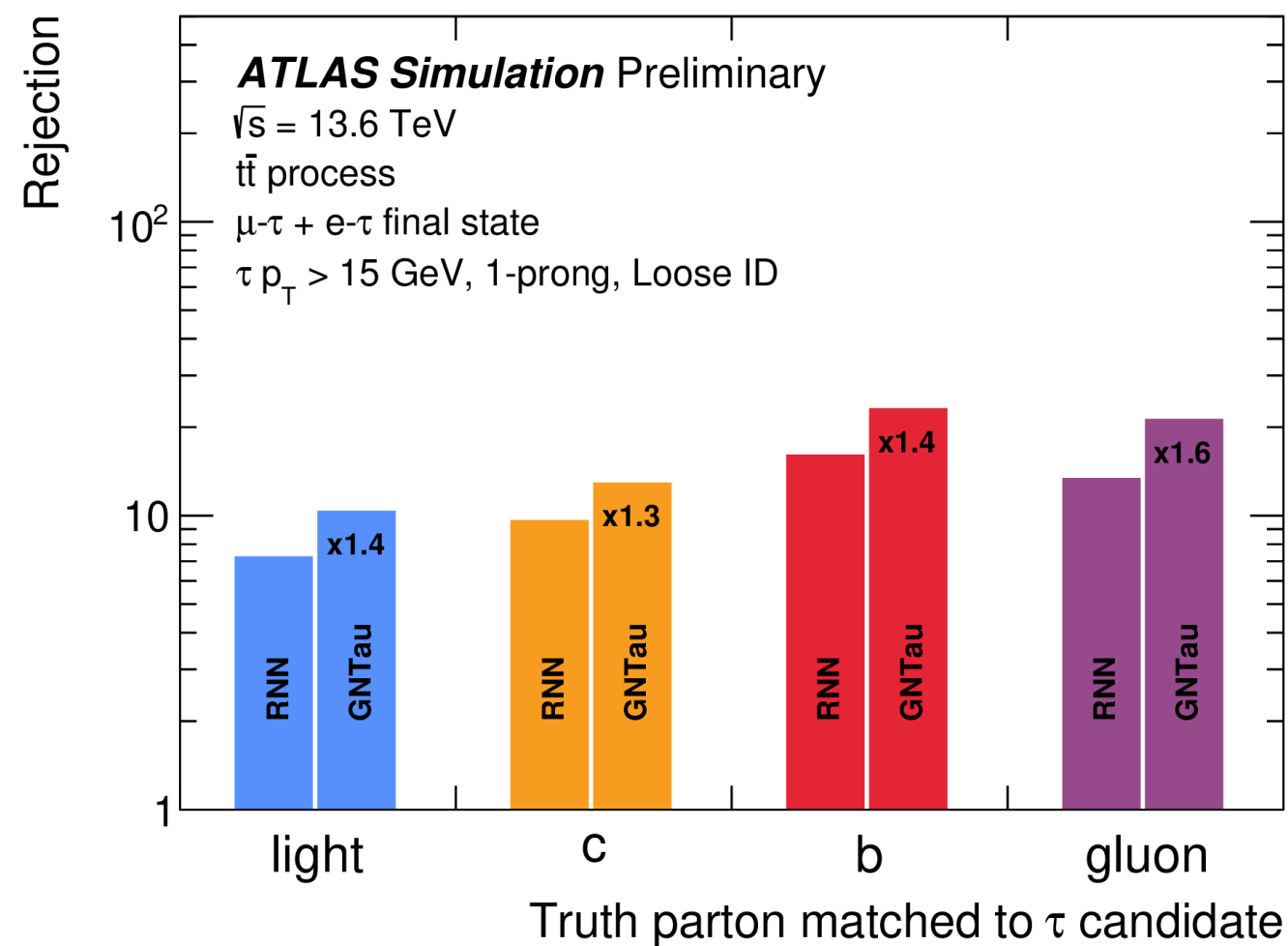
- Improvement of GNTau in b/c/light-jet rejection tested with respect to the RNN.
- Using simulated $t\bar{t}$ in $e/\mu + \tau_{\text{had}}$ final state according to 2022 data taking conditions.
- τ_{had} candidates: $p_T > 15$ GeV, $|\eta| < 2.5$, (excluding $1.37 < |\eta| < 1.52$), must have 1 or 3 charged tracks.
- τ_{had} candidates must be geometrically matched to a generator level b/c /light quarks or gluons.
- Up to x2 better rejection of misidentified τ_{had} candidates for 1-prong
- Up to x3 better rejection for 3-prong.
- Tighter efficiency working points show larger improvements.

Working point	Truth τ_{had} efficiency 1-prong	Truth τ_{had} efficiency 3-prong
Tight	60%	45%
Medium	75%	60%
Loose	85%	75%



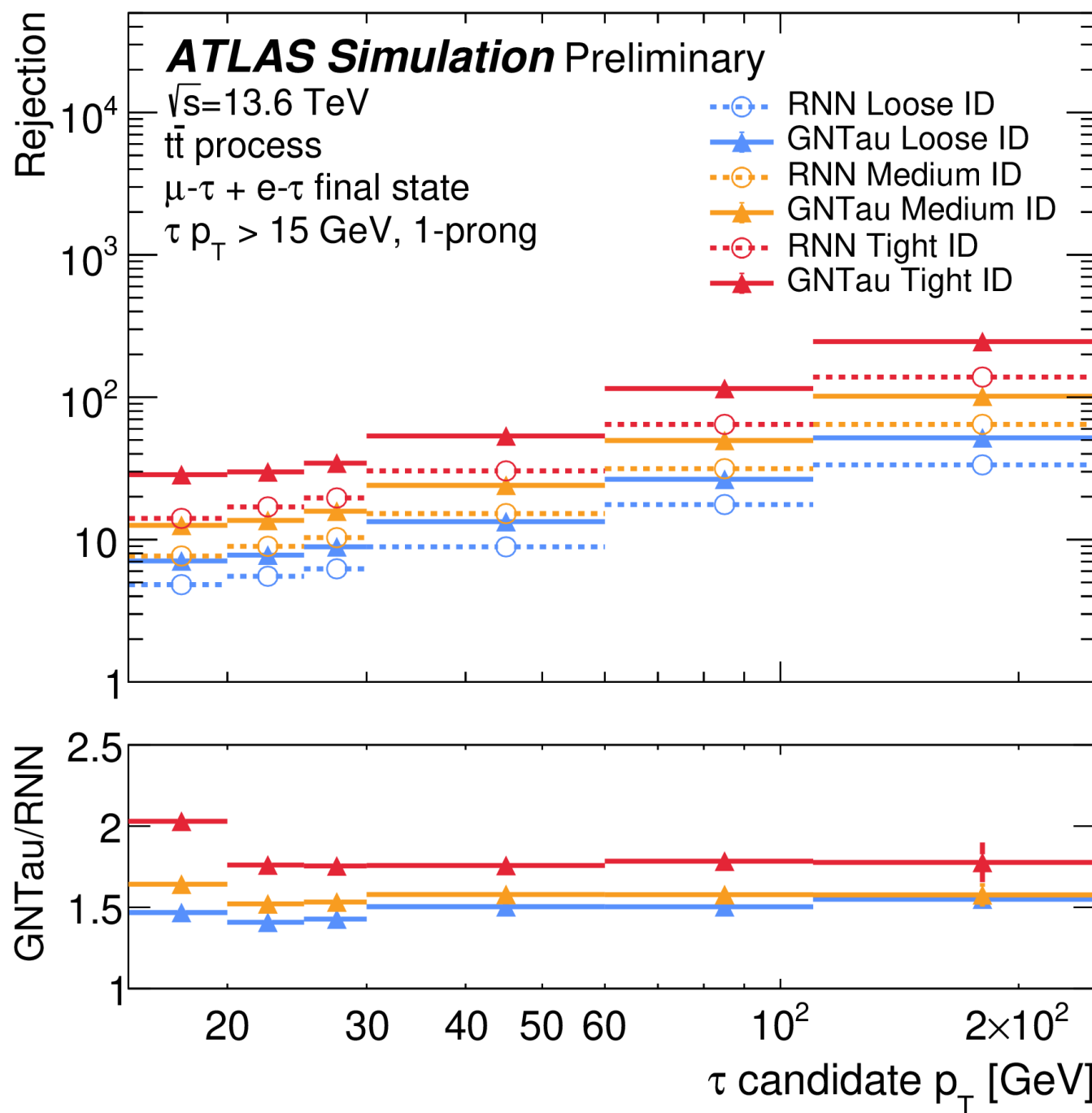
Improvements in background rejection per jet flavour

[TAUP-2026-01](#)

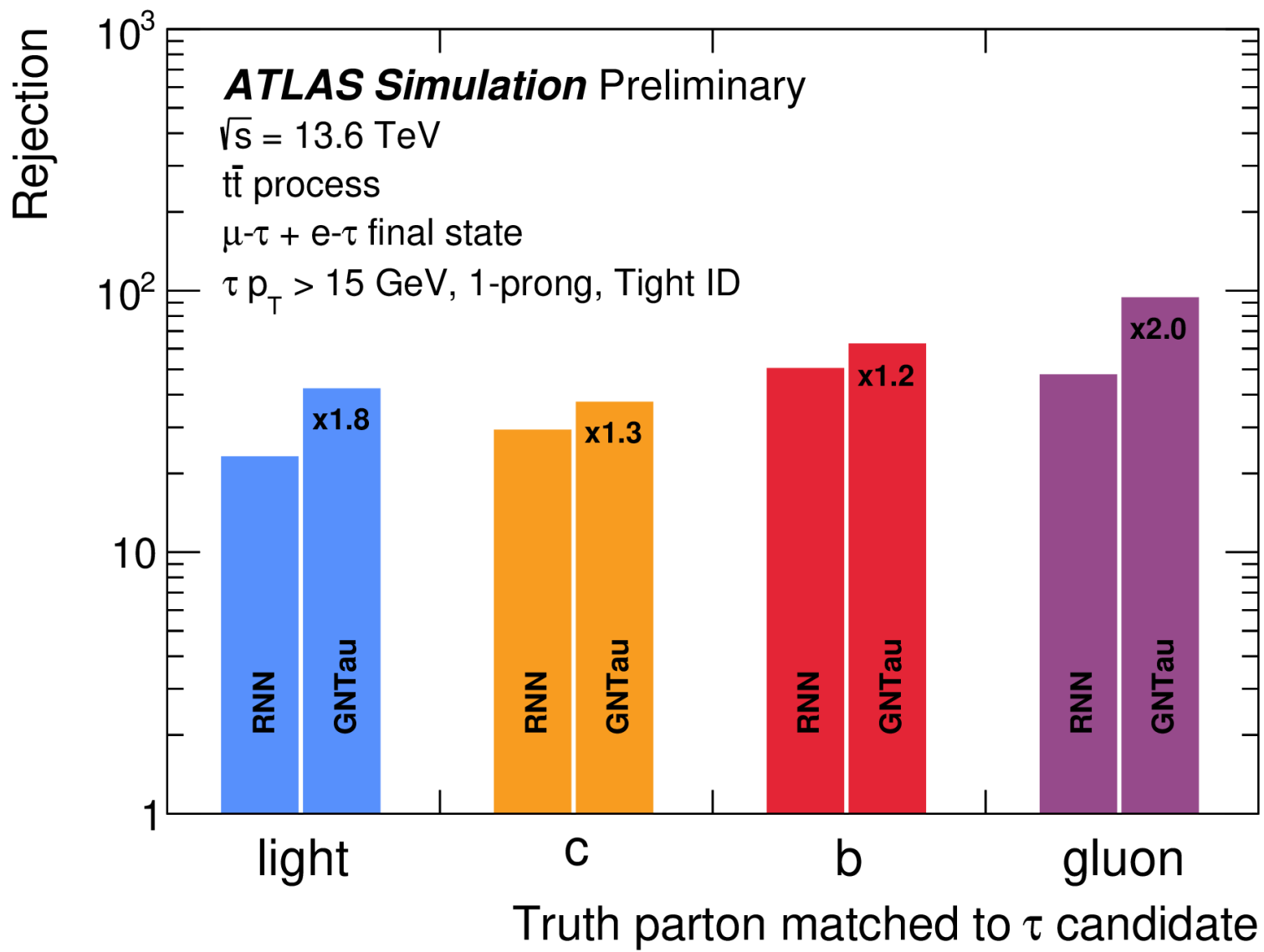


Conclusion

- Tau leptons play an important part in many searches and measurements.
- τ_{had} reconstruction by itself does not provide adequate rejection of quark- and gluon-initiated jets being misidentified as τ_{had} candidates.
- A new transformer-based algorithm, GNTau, offers superior performance compared to the RNN-based algorithm used thus far, showing increased rejection of fake τ_{had} candidates.
- The improved rejection is already being used for physics analyses involving taus, such as measurements of $t\bar{t}H$ production ([HIGP-2024-52](#)).



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Backup

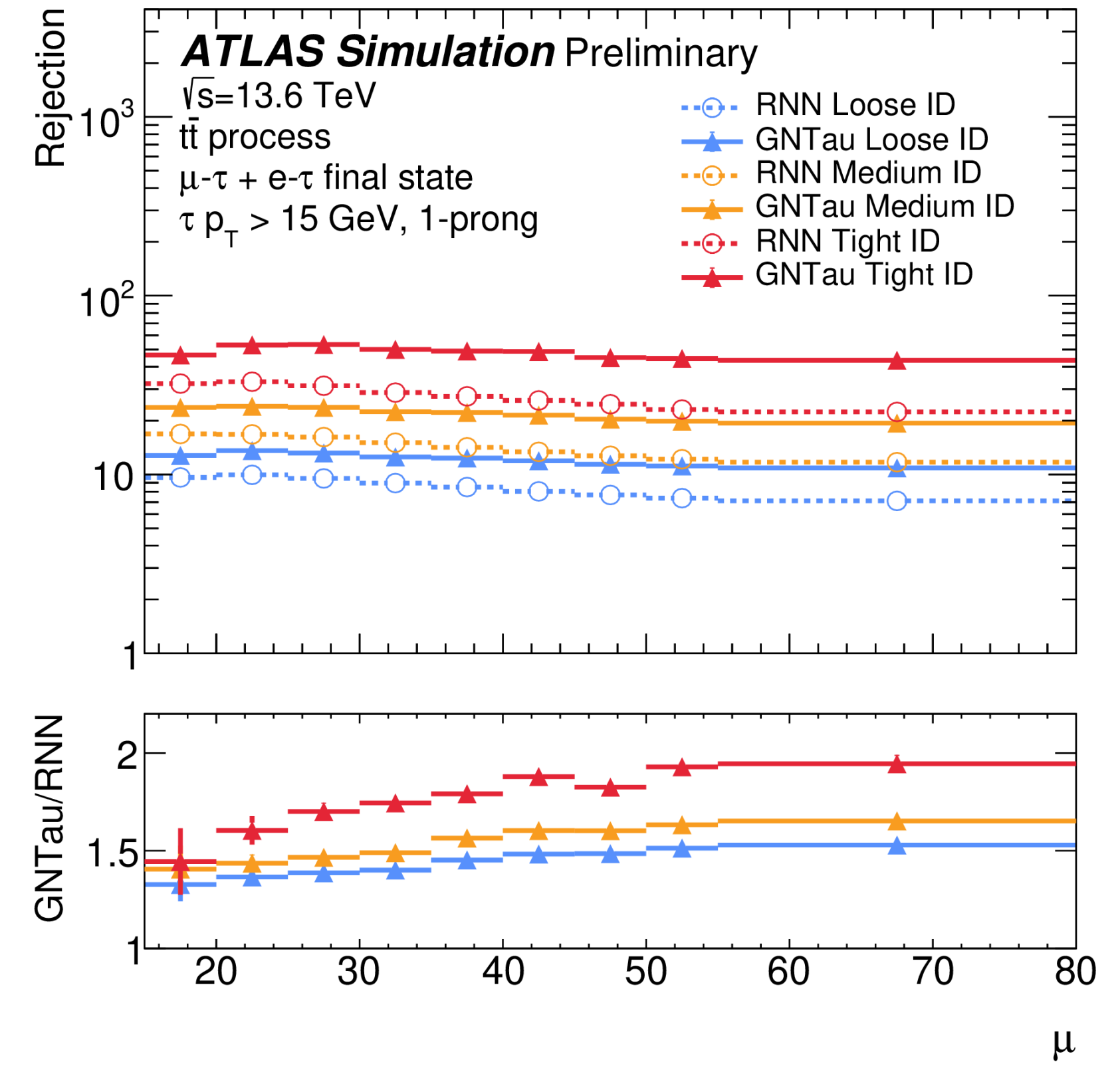
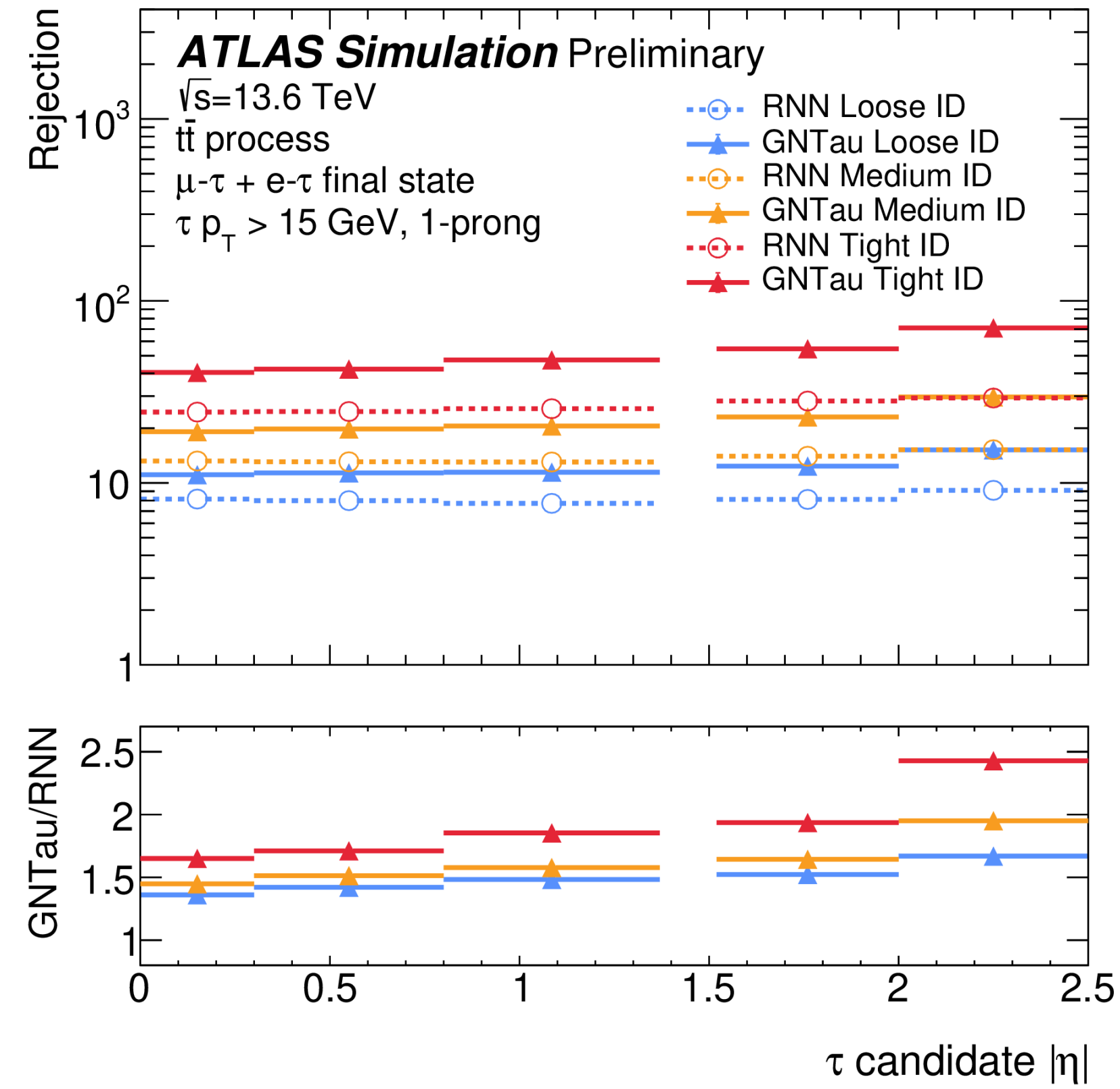
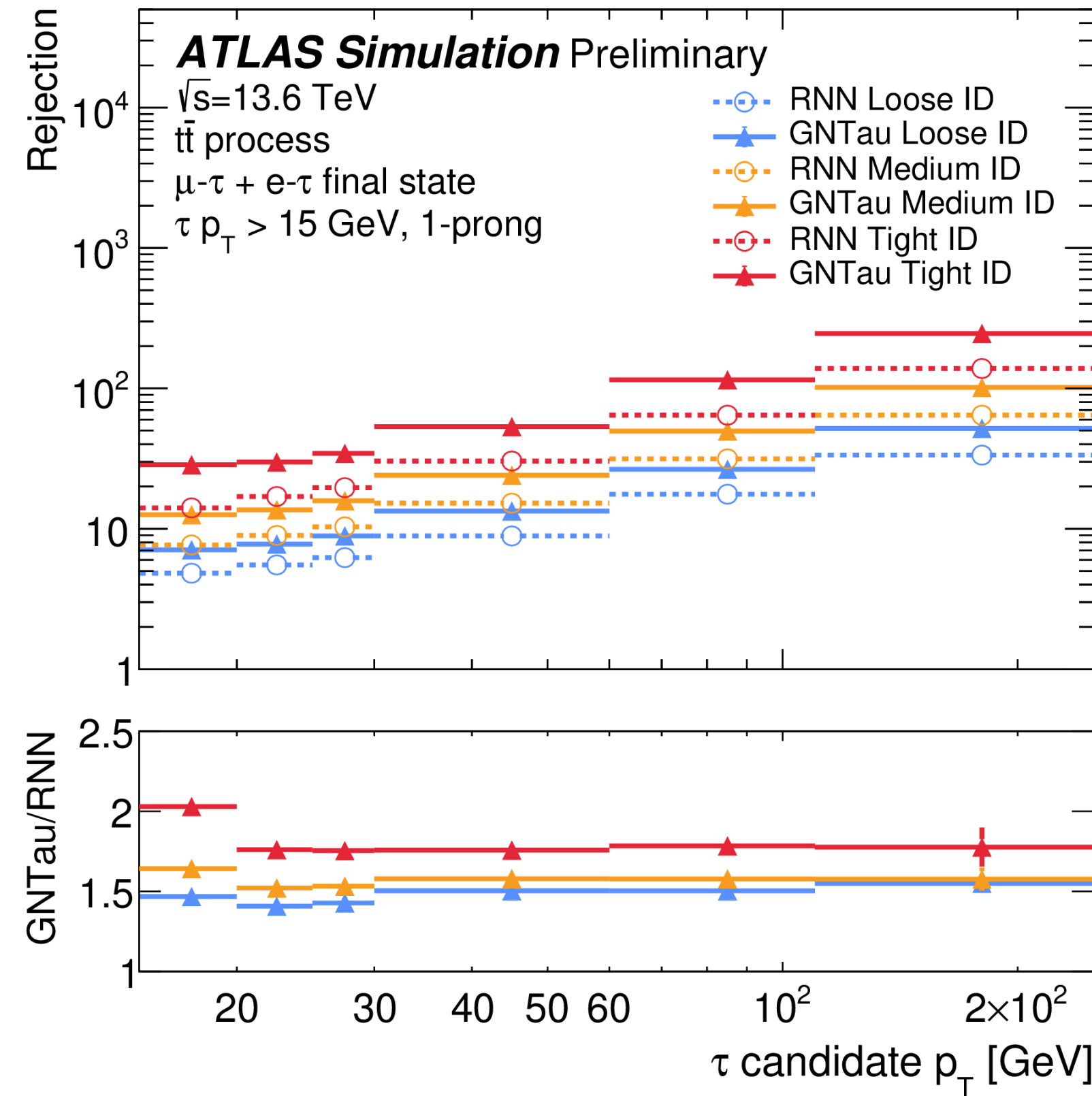
RNN input variables ([ATL-PHYS-PUB-2022-044](#))

	Variable	Description	1-prong	3-prong
Track inputs	$p_T^{\tau_{\text{had-vis}}}$	Transverse momentum of the $\tau_{\text{had-vis}}$ candidate	✓	✓
	p_T^{track}	Transverse momentum of each associated track	✓	✓
	$\Delta\eta^{\text{track}}$	Angular distance between the track and $\tau_{\text{had-vis}}$ axis	✓	✓
	$\Delta\phi^{\text{track}}$	Angular distance between the track and $\tau_{\text{had-vis}}$ axis	✓	✓
	N_{IBL}	Number of hits in the innermost layer of the pixel detector	✓	✓
	N_{pixel}	Number of hits in the pixel detector	✓	✓
	N_{SCT}	Number of hits in the SCT	✓	✓
	$z_0^{\text{TJVA}} \sin \theta$	Tau vertex longitudinal impact parameter	✓	✓
	d_0^{TJVA}	Tau vertex transverse impact parameter	✓	✓
	$S(z_0^{\text{TJVA}} \sin \theta)$	Tau vertex longitudinal impact parameter divided by its uncertainty	✓	✓
Cluster inputs	$S(d_0^{\text{TJVA}})$	Tau vertex transverse impact parameter divided by its uncertainty	✓	✓
	$p_T^{\tau_{\text{had-vis}}}$	Transverse momentum of the $\tau_{\text{had-vis}}$ candidate	✓	✓
	E_T^{cluster}	TopoCluster transverse energy	✓	✓
	$\Delta\eta^{\text{cluster}}$	The angular distance between the TopoCluster and the $\tau_{\text{had-vis}}$ axis	✓	✓
	$\Delta\phi^{\text{cluster}}$	The angular distance between the TopoCluster and the $\tau_{\text{had-vis}}$ axis	✓	✓
	$\langle\lambda_{\text{centre}}\rangle$	Mean distance of the cluster shower centre from the calorimeter front face measured along the shower axis.	✓	✓
	$\langle\lambda^2\rangle$	Mean distance of a cell from the shower centre along the shower axis	✓	✓
	$\langle r^2\rangle$	Second moment in the radial distance of cluster cells from the cluster axis.	✓	✓

	Variable	Description	1-prong	3-prong
High-level inputs	$p_T^{\tau_{\text{had-vis}}}$	Transverse momentum of the $\tau_{\text{had-vis}}$ candidate	✓	✓
	$f_{\text{cent}}^{\Delta R < 0.1}$	Fraction of transverse energy at EM scale deposited in the region $\Delta R < 0.1$ with respect to all energy deposited in $\Delta R < 0.2$ around the $\tau_{\text{had-vis}}$ candidate axis	✓	✓
	$f_{\text{lead-track}}^{-1}$	The transverse energy sum, calibrated at the EM energy scale, deposited in all cells belonging to TopoClusters in the core region, divided by the transverse momentum of the highest- p_T core track of the $\tau_{\text{had-vis}}$ candidate.	✓	✓
	$\Delta R_{\text{max}}(\text{track}, \tau_{\text{had}})$	The maximum ΔR between a core track associated with the $\tau_{\text{had-vis}}$ candidate and the $\tau_{\text{had-vis}}$ direction.	✓	✓
	S_T^{flight}	The decay length of the secondary vertex in the transverse plane, calculated with respect to the τ vertex, divided by its estimated uncertainty		✓
	$f_{\text{track}}^{\text{iso}}$	Scalar sum of the p_T of isolation tracks associated with the $\tau_{\text{had-vis}}$ candidate divided by the sum of the p_T of all the associated core and isolation tracks.	✓	✓
	$f_{\text{track}}^{\text{EM}}$	Ratio of the sum of cluster energy deposited in the electromagnetic part of the TopoClusters (pre-sampler, first and second layers of the LAr calorimeter) to the sum of the momentum of core tracks.	✓	✓
	$p_T^{\text{EM+track}}/p_T$	Ratio of the $\tau_{\text{had-vis}}$ p_T , estimated using the vector sum of core track momenta and up to two most energetic EM clusters in the core region to the calorimeter-only measurement of $\tau_{\text{had-vis}}$ p_T .	✓	✓
	$m^{\text{EM+track}}$	Invariant mass of the system composed of the core tracks and up to two most energetic EM clusters in the core region and the four-momentum of an EM cluster is calculated assuming zero mass and using TopoCluster seed direction.	✓	✓
	m^{track}	Invariant mass calculated from the sum of the four-momenta of all core and isolation tracks, assuming a pion mass for each track		✓

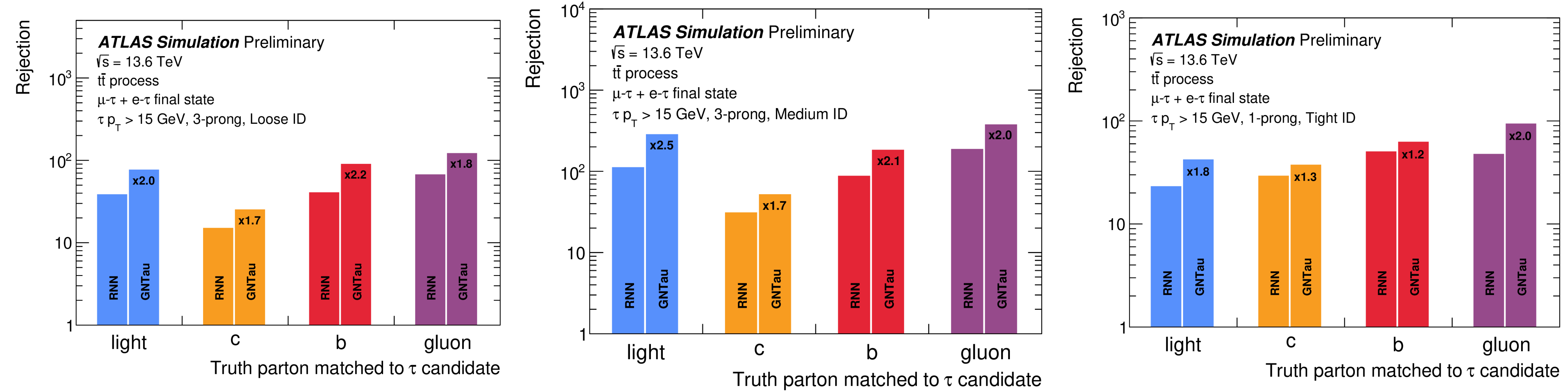
Improvements in background rejection: 1-prong

[TAUP-2026-01](#)



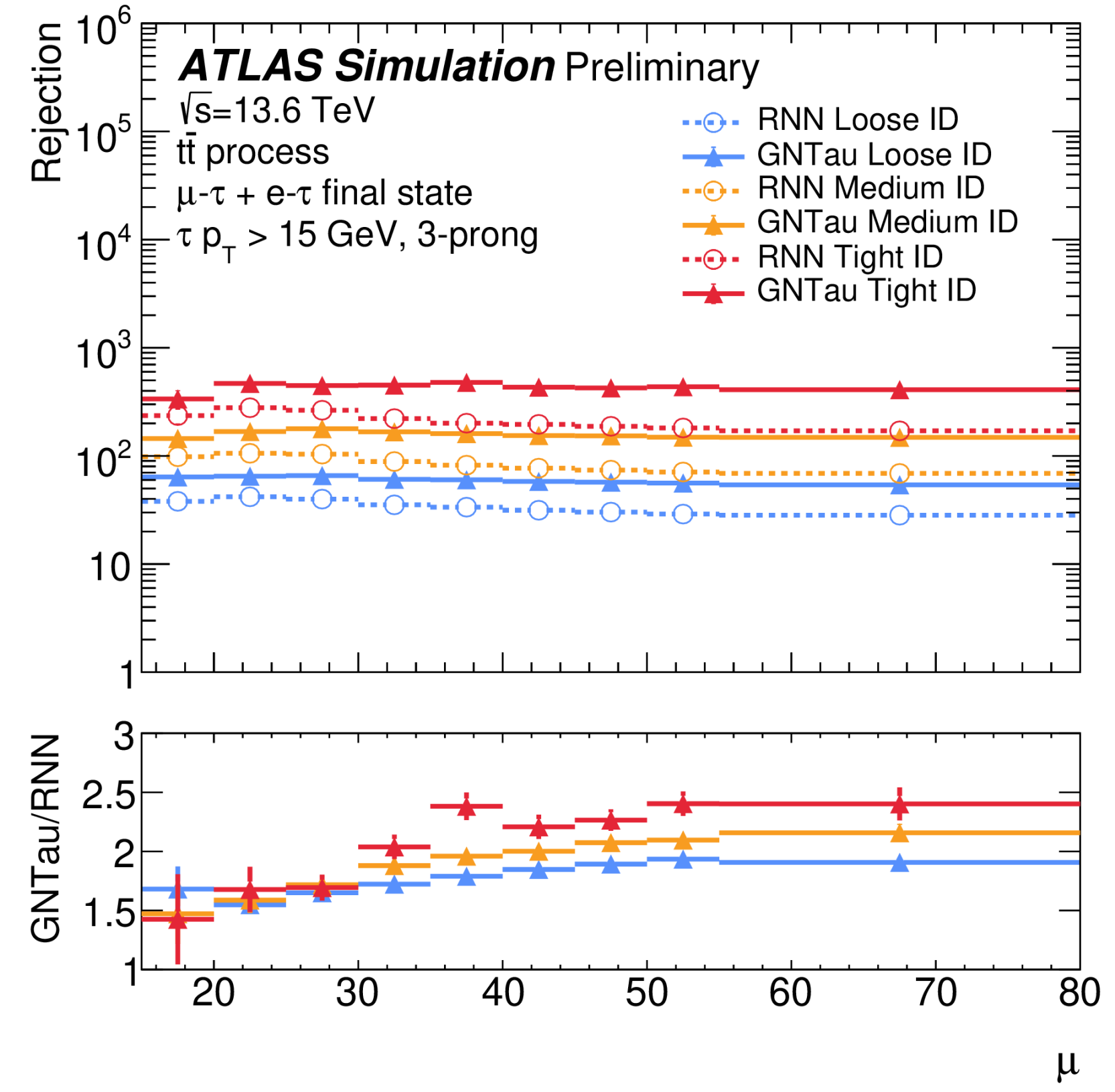
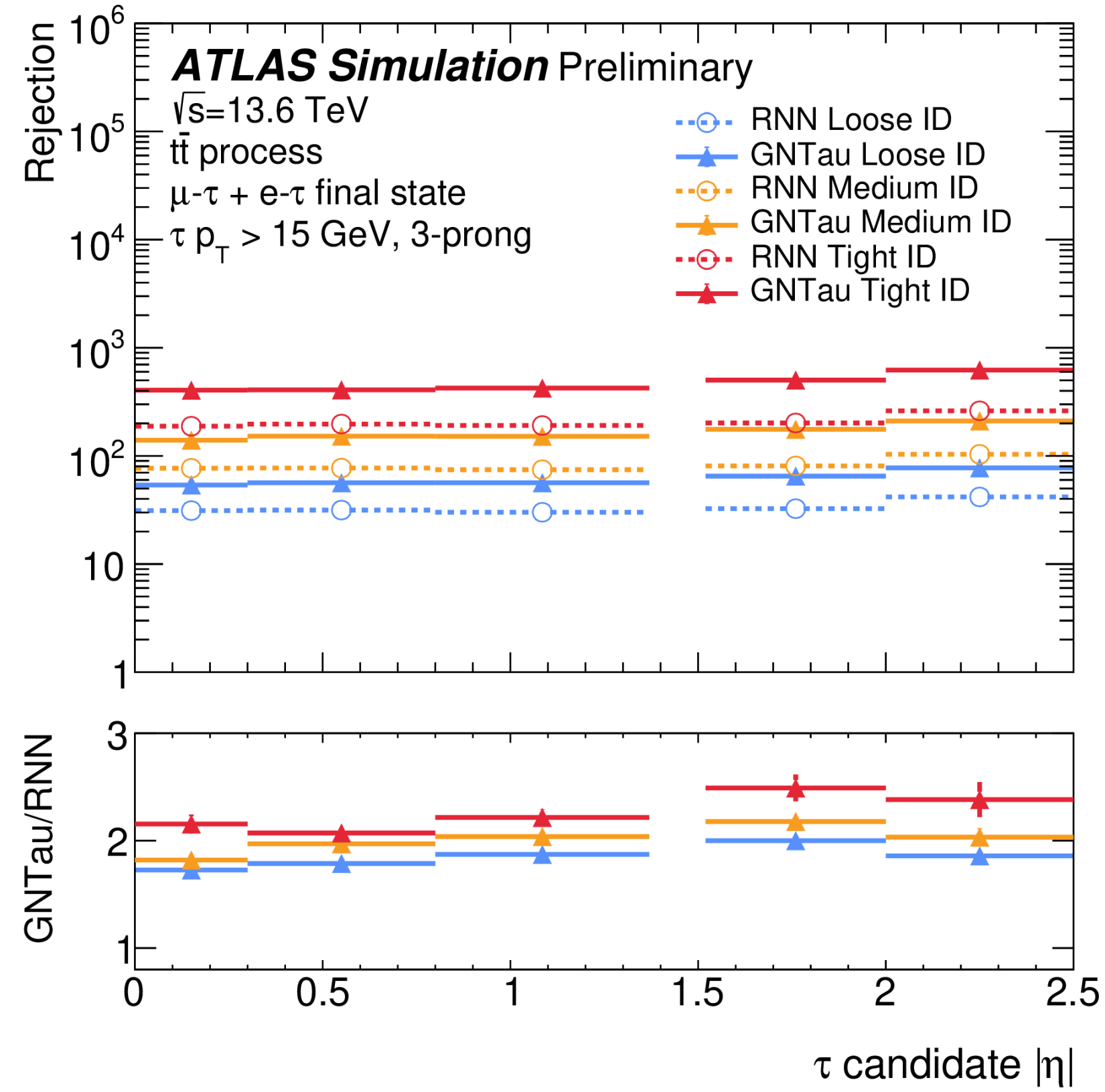
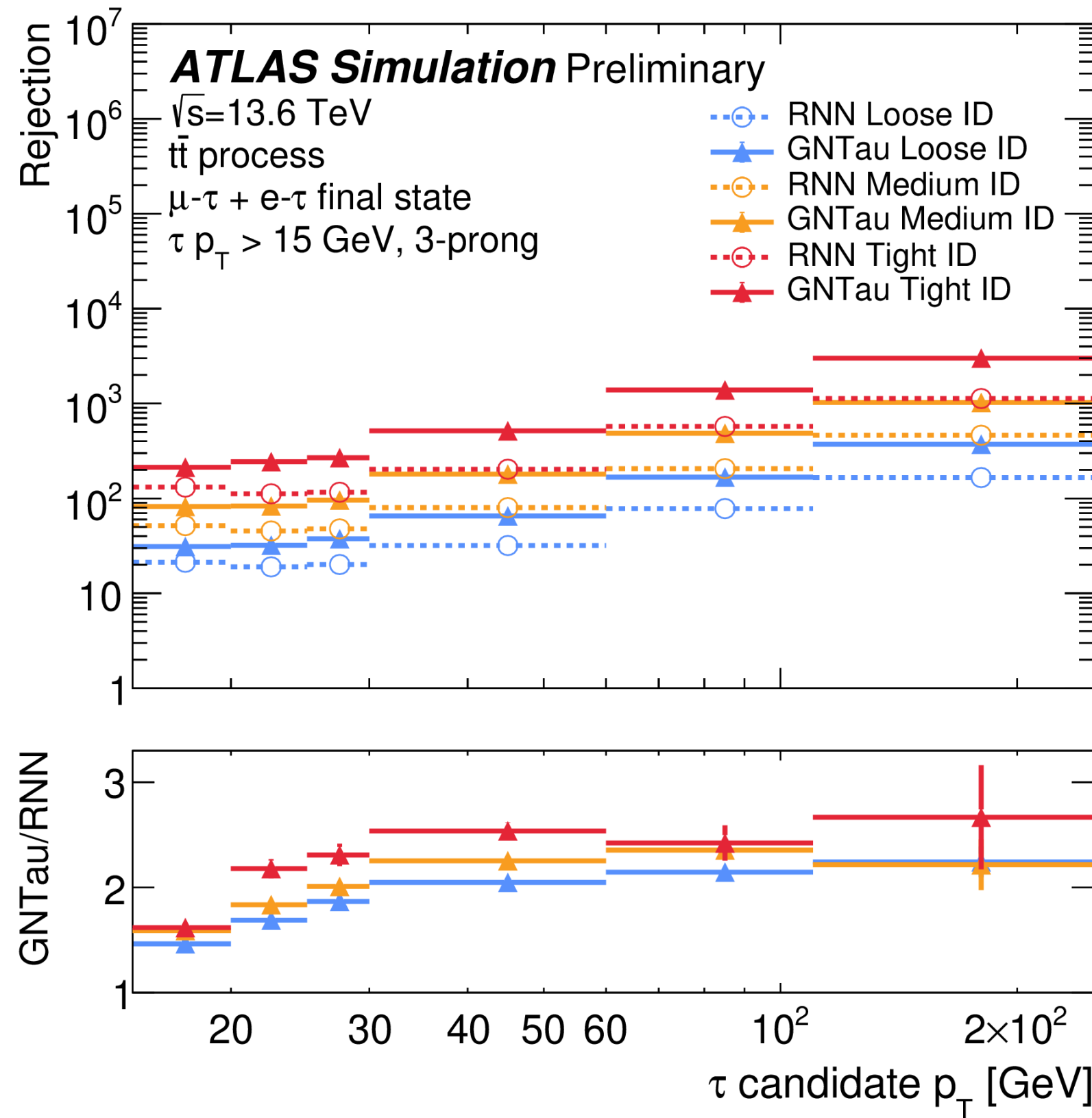
Improvements in background rejection per jet flavour: 1-prong

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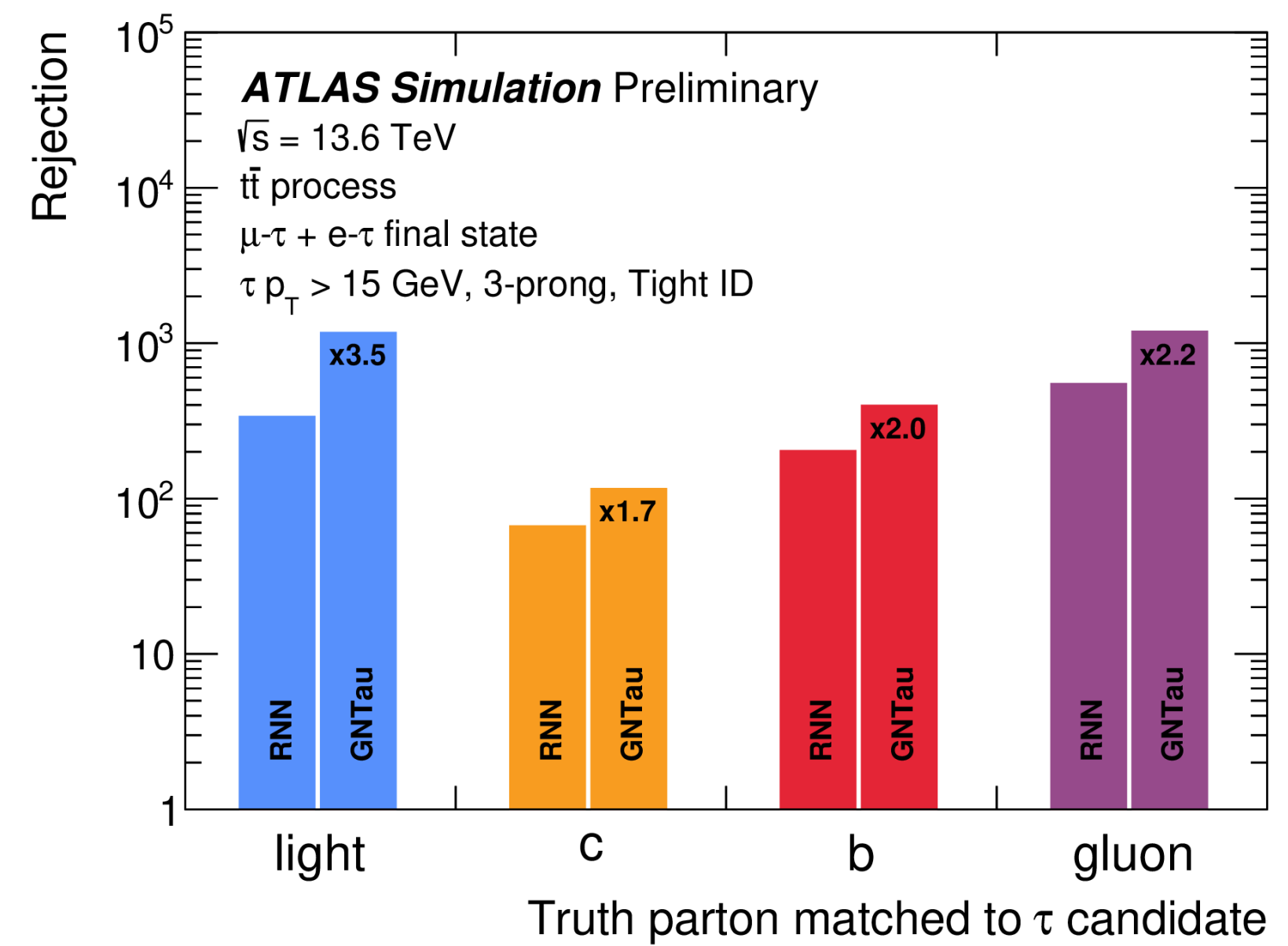
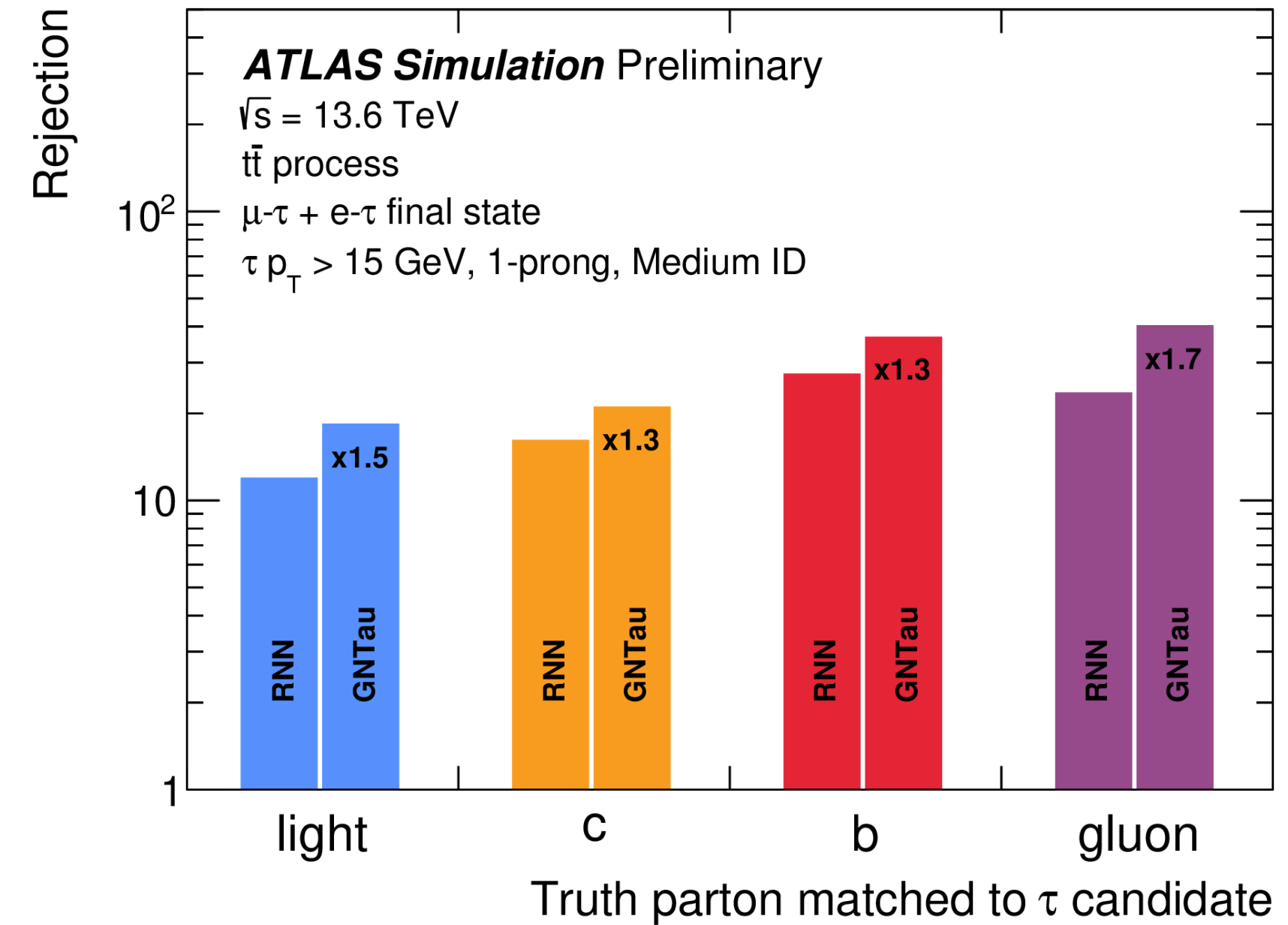
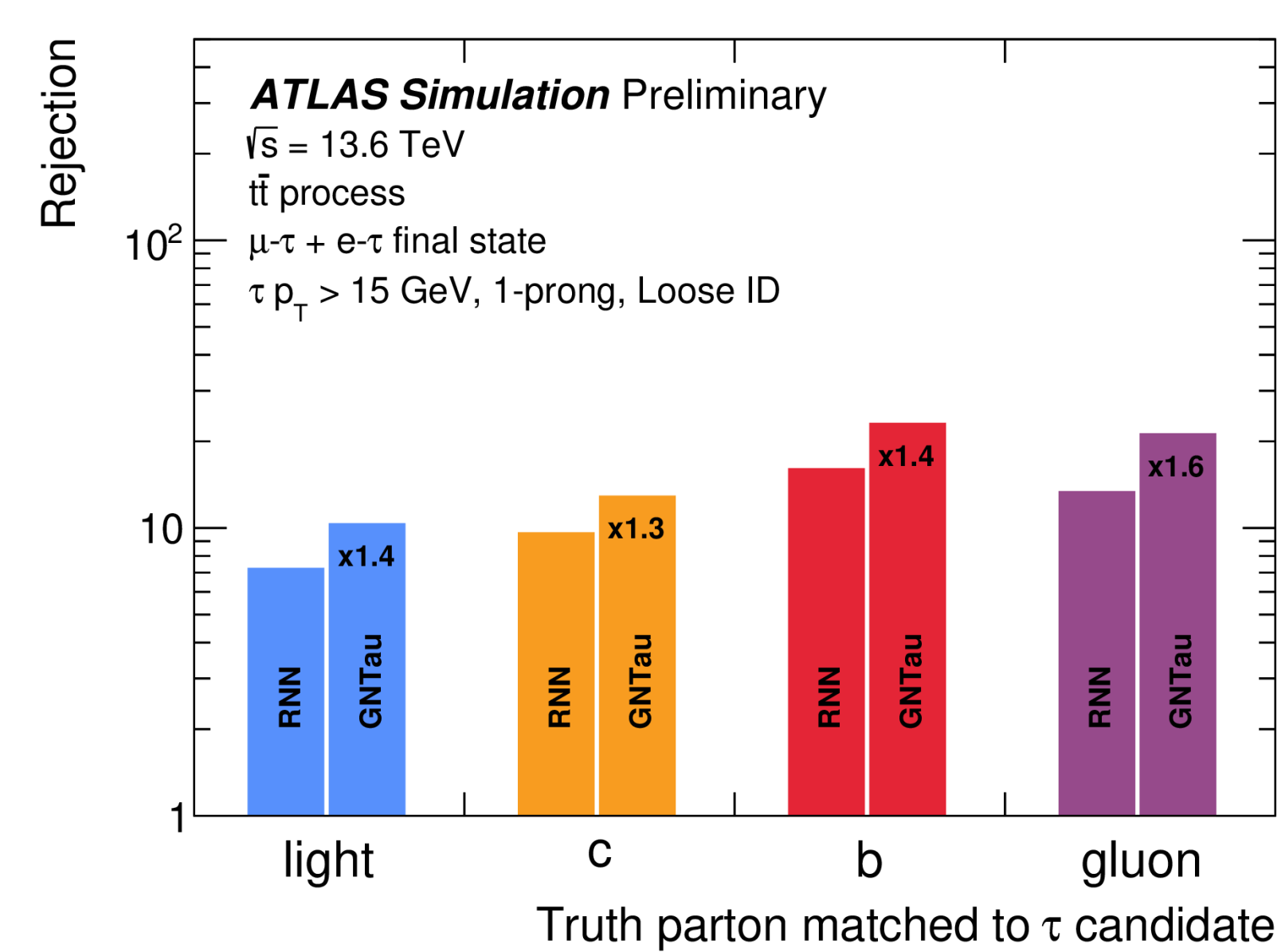
Improvements in background rejection: 3-prong

TAUP-2026-01



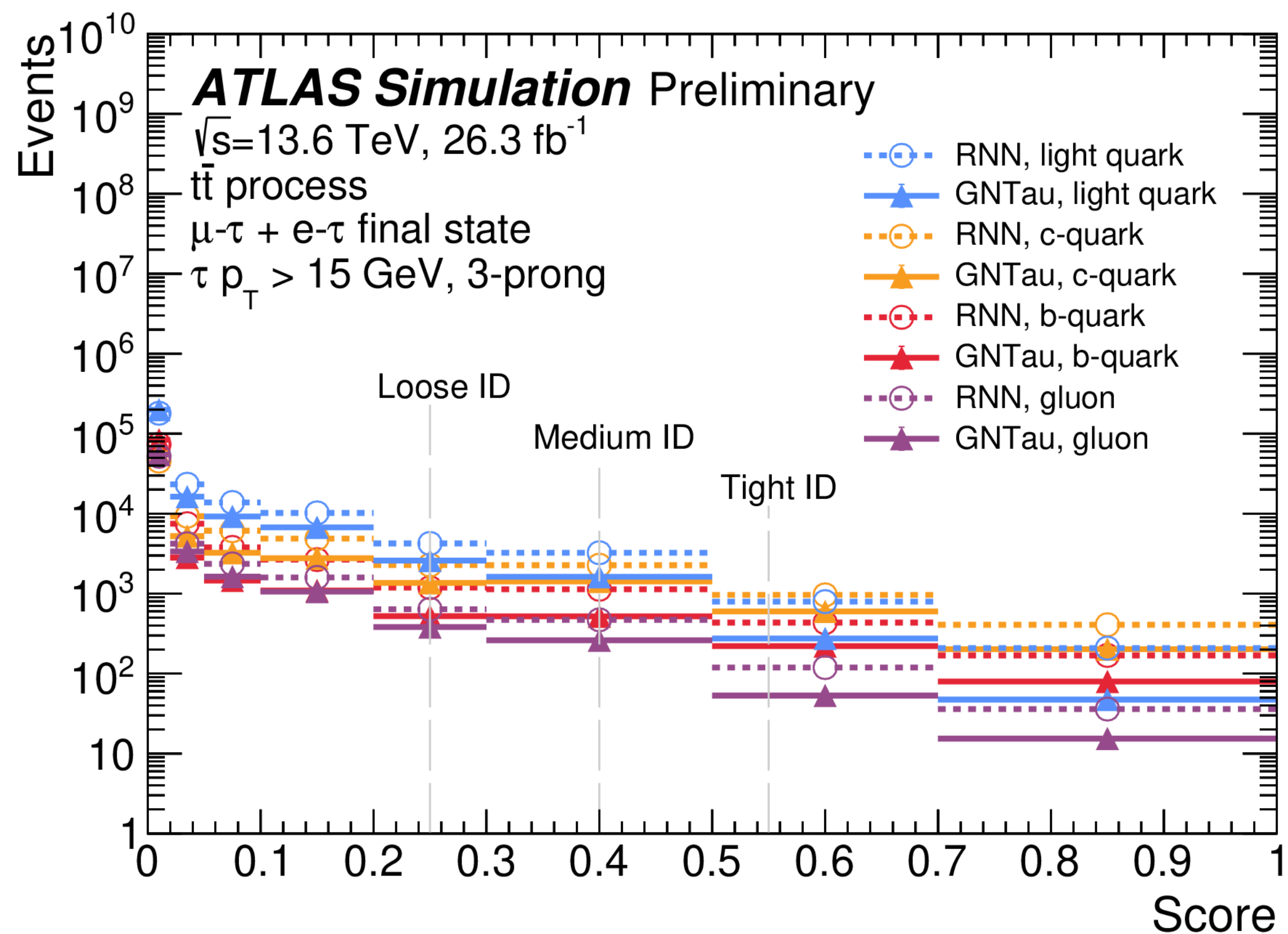
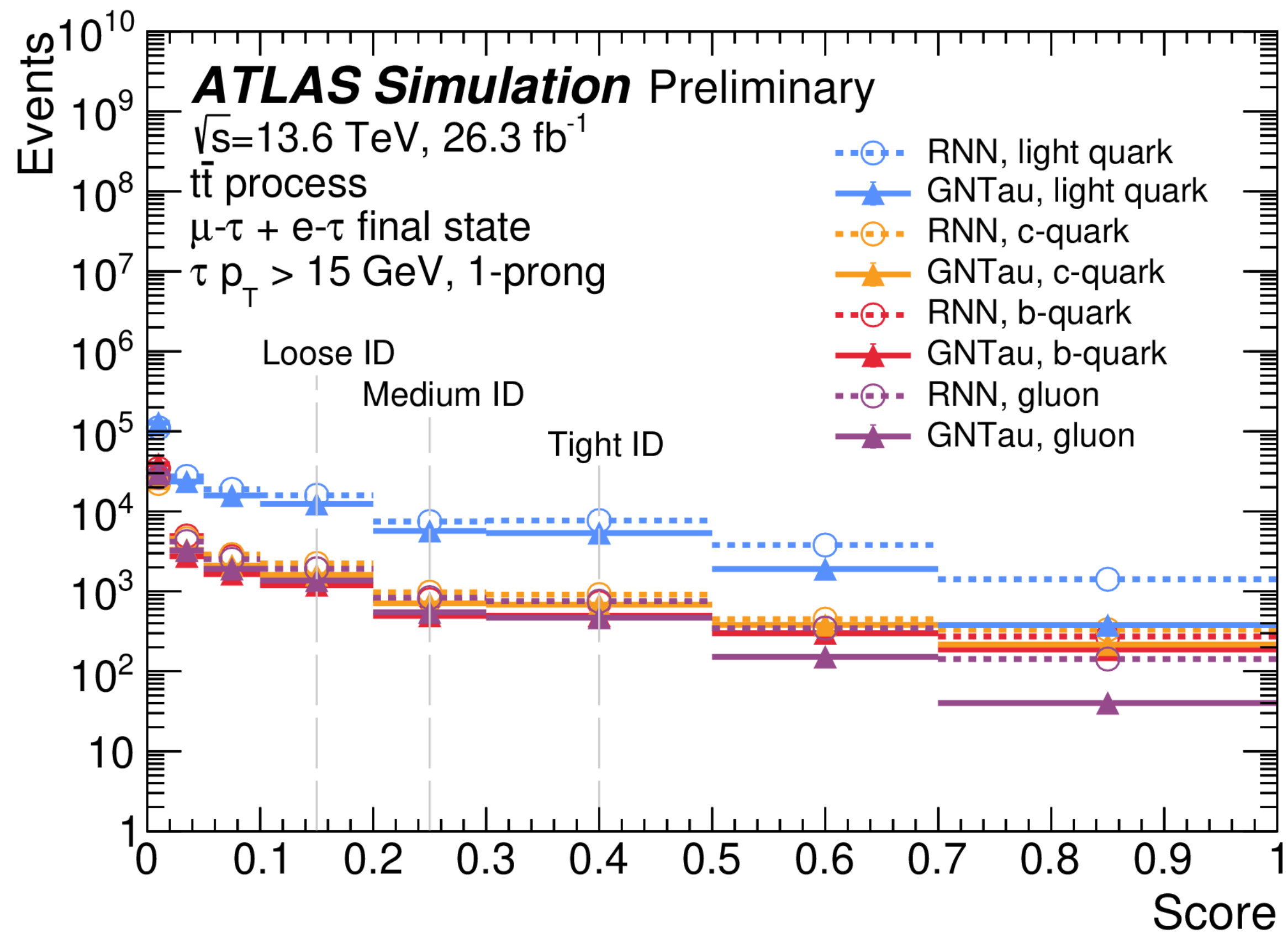
Improvements in background rejection per jet flavour: 3-prong

[TAUP-2026-01](#)



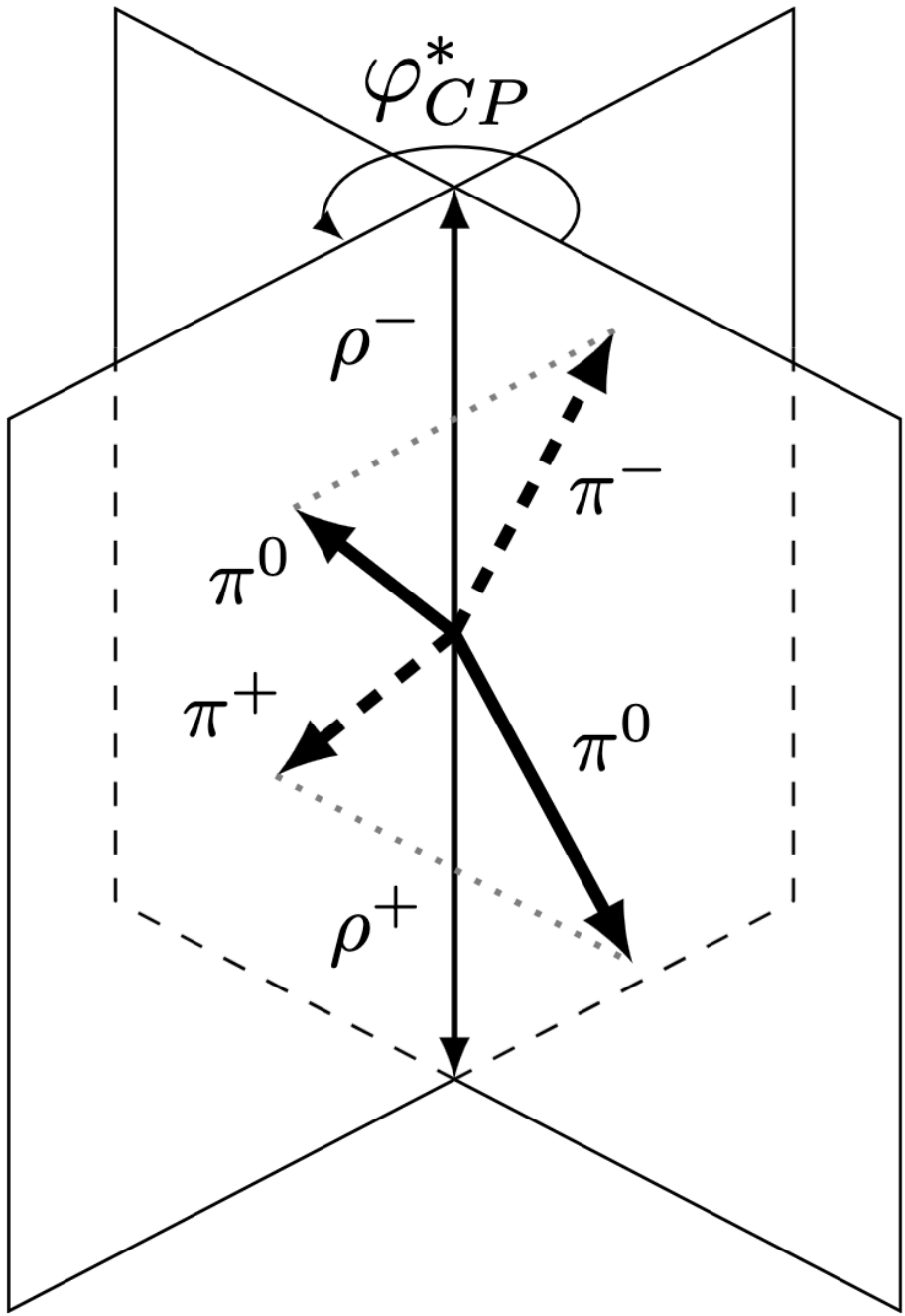
Improvements in background rejection, 1-prong and 3-prong

TAUP-2026-01



Hadronic tau decay mode classification

- Standard τ_{had} reconstruction only reconstructs the number of charged hadrons in the decay.
- Various physics analyses, such as [Eur. Phys. J. C 83 \(2023\) 563](#) rely on the identification of the τ_{had} decay mode.
- A DeepSet neural network is used to classify the decay mode of the τ_{had} .

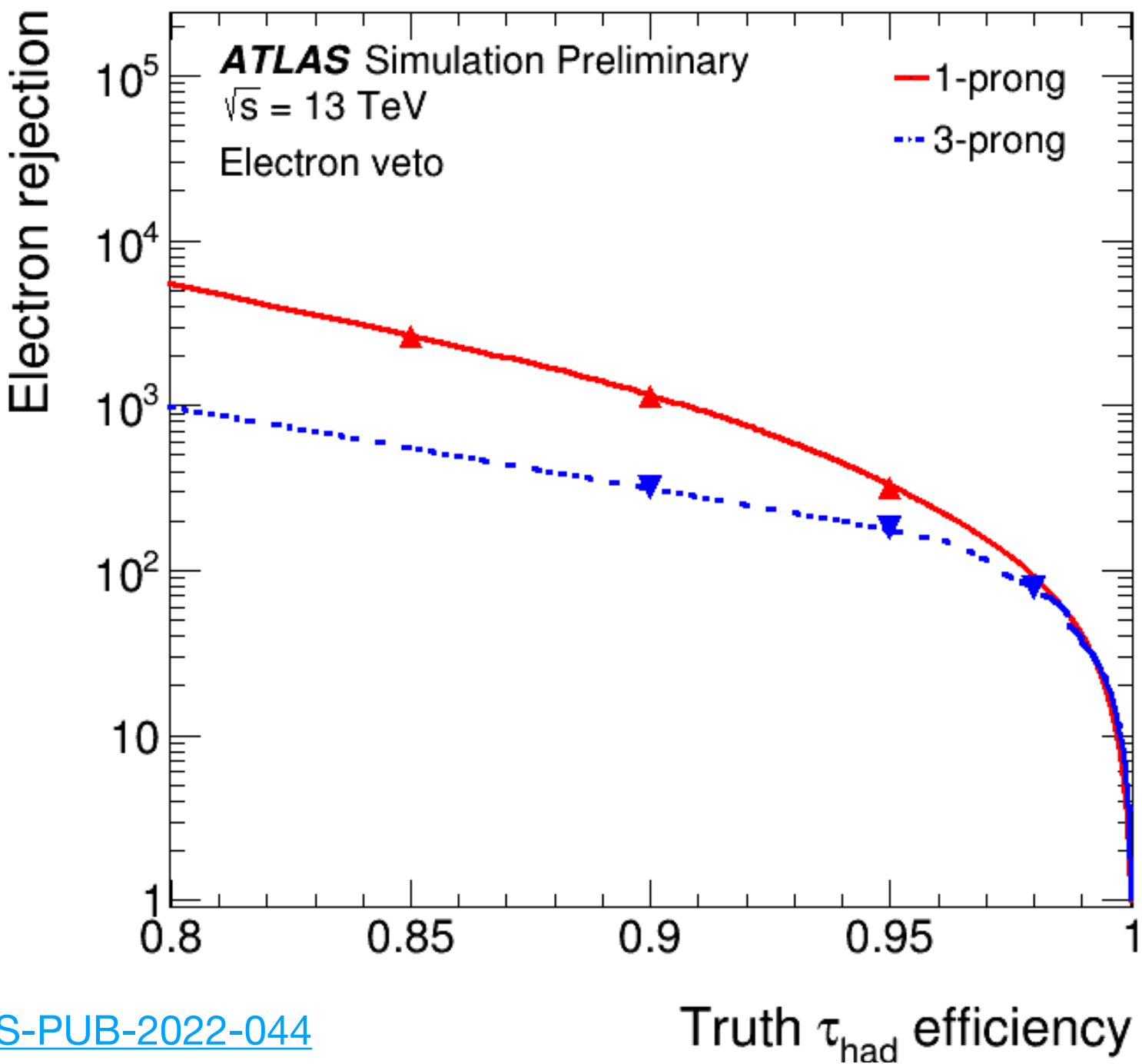


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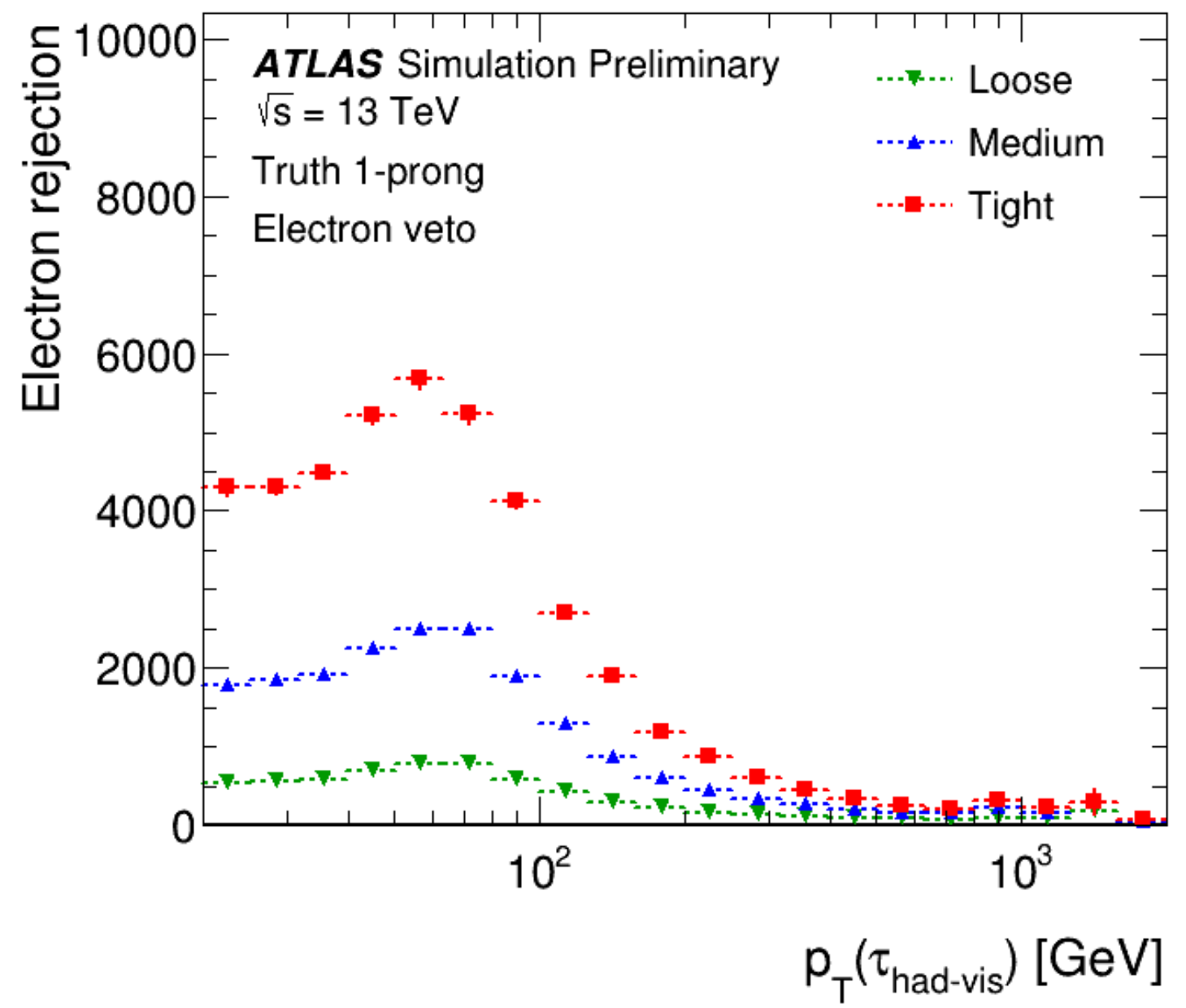
ATLAS Simulation Preliminary $\sqrt{s} = 13 \text{ TeV}$			Diagonal efficiency: 72.9% Medium τ_{had} identification			
BDT tau decay mode	3pXn	0.0	0.3	0.3	5.1	55.4
	3p0n	0.1	0.1	0.0	90.8	33.9
	1pXn	1.9	11.4	41.1	0.6	3.2
	1p1n	16.3	78.7	56.1	1.7	6.5
	1p0n	81.6	9.4	2.4	1.7	1.0
		1p0n	1p1n	1pXn	3p0n	3pXn
		Truth tau decay mode				

Hadronic tau electron-veto

- The RNN and GNTau algorithms provide rejection of quark and gluon jets that fake τ_{had} .
- A dedicated RNN provides discrimination for electrons faking τ_{had} candidates, using track and calorimeter information.
- Different networks are trained for 1-prong and 3-prong τ_{had} candidates.

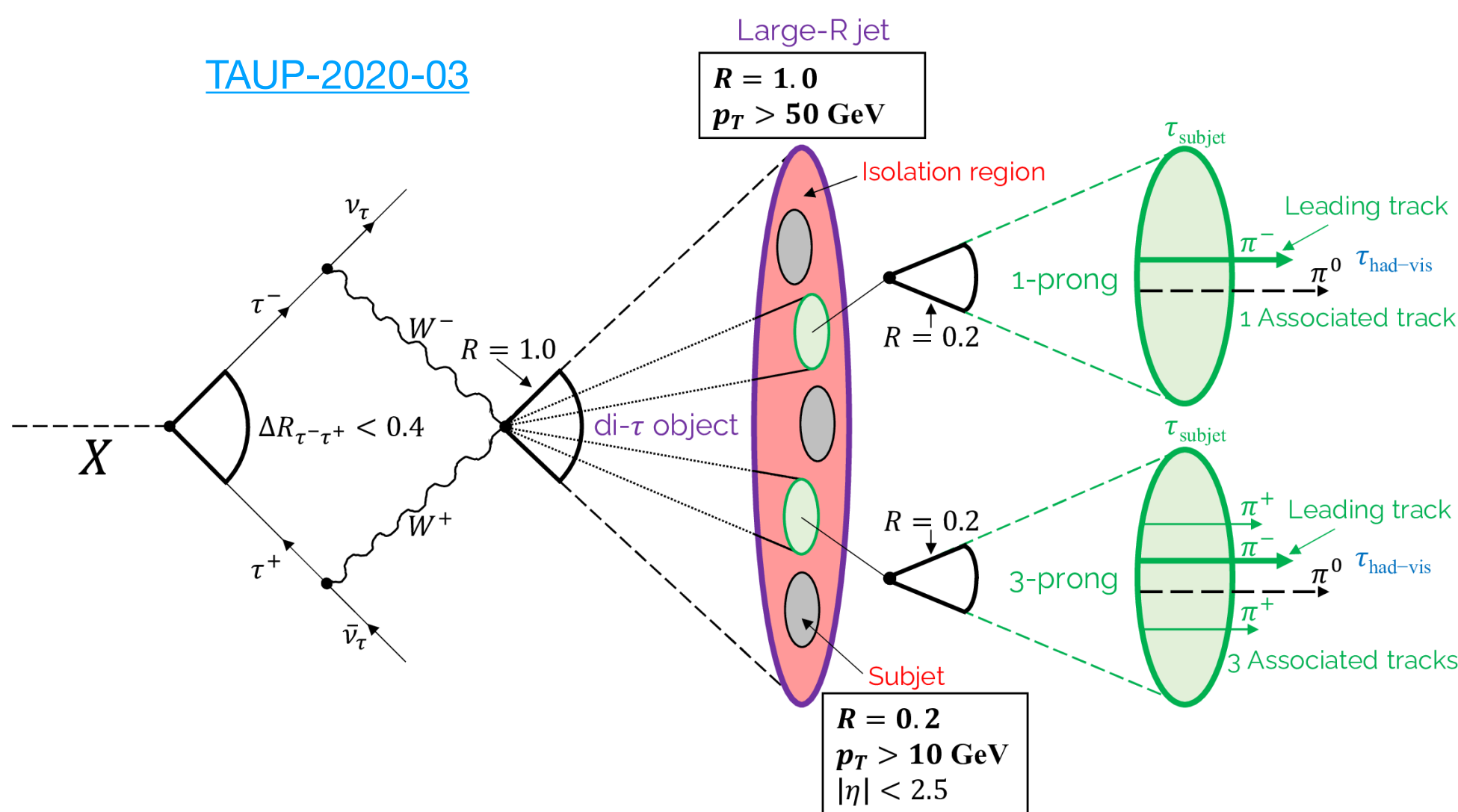


[ATL-PHYS-PUB-2022-044](#)



Di-tau taggers

- In the case of highly boosted $H \rightarrow \tau\tau$ or low mass $X \rightarrow \tau\tau$ events, the two τ_{had} jets can be collimated.
- Tracks can be grouped with the incorrect seed jet, leading to an incorrect reconstruction and identification.
- In the boosted regime, the di- τ_{had} object is reconstructed from a large-R jet ($R=0.1$) with either low (TAUP-2020-03) or high p_T (HIGP-2024-49), consisting of two $R = 0.2$ subjets.
- Dedicated neural networks are then used to distinguish the di- τ_{had} object from multi-jet backgrounds.



HIGP-2024-49

