Boosted $HH \rightarrow bb\tau\tau$

R&D of GN3X taggers with $\tau_{\rm lep}\tau_{\rm had}$ channel

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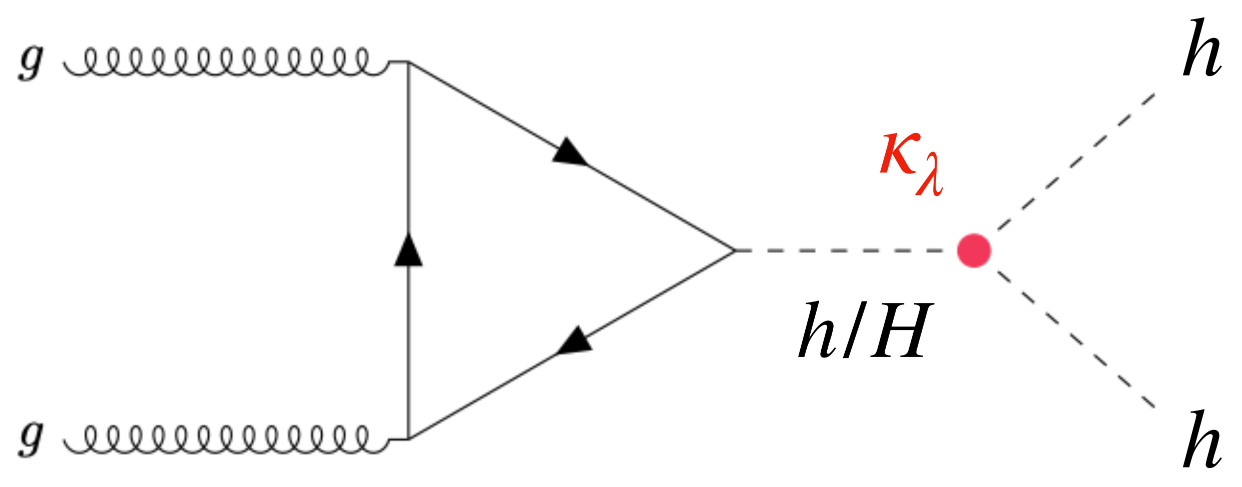
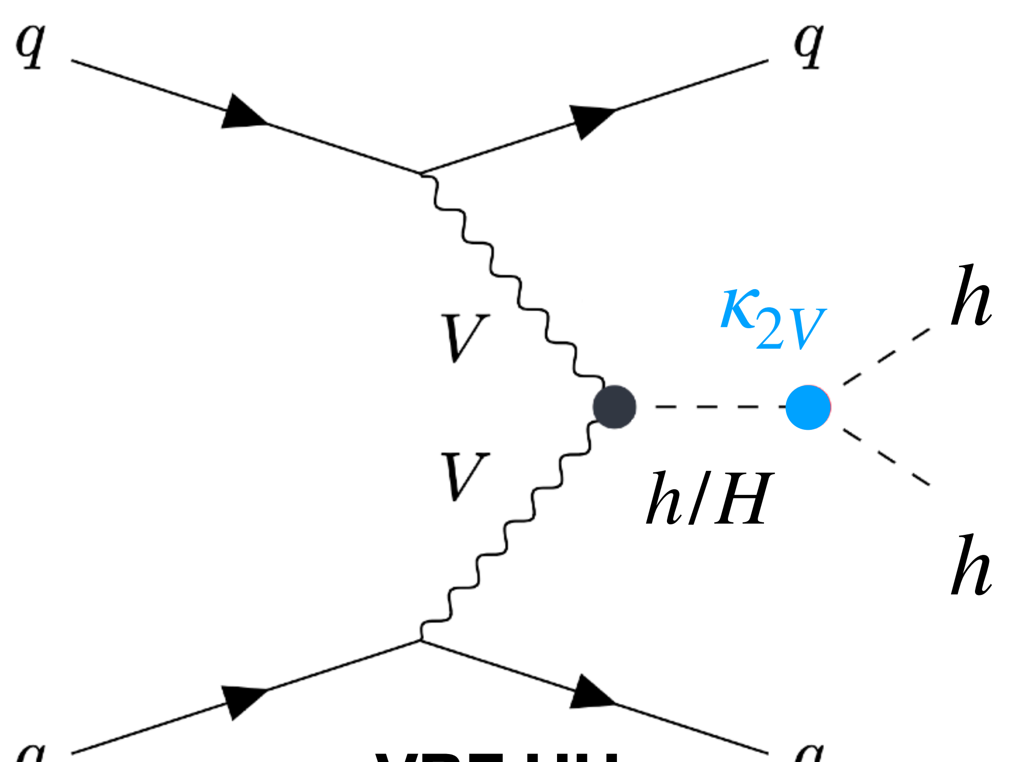
Motivation

non-resonant

- ggF HH : Probe the higgs potential through κ_λ
- VBF HH : Probe the structure of EWSB through κ_{2V}



ggF HH



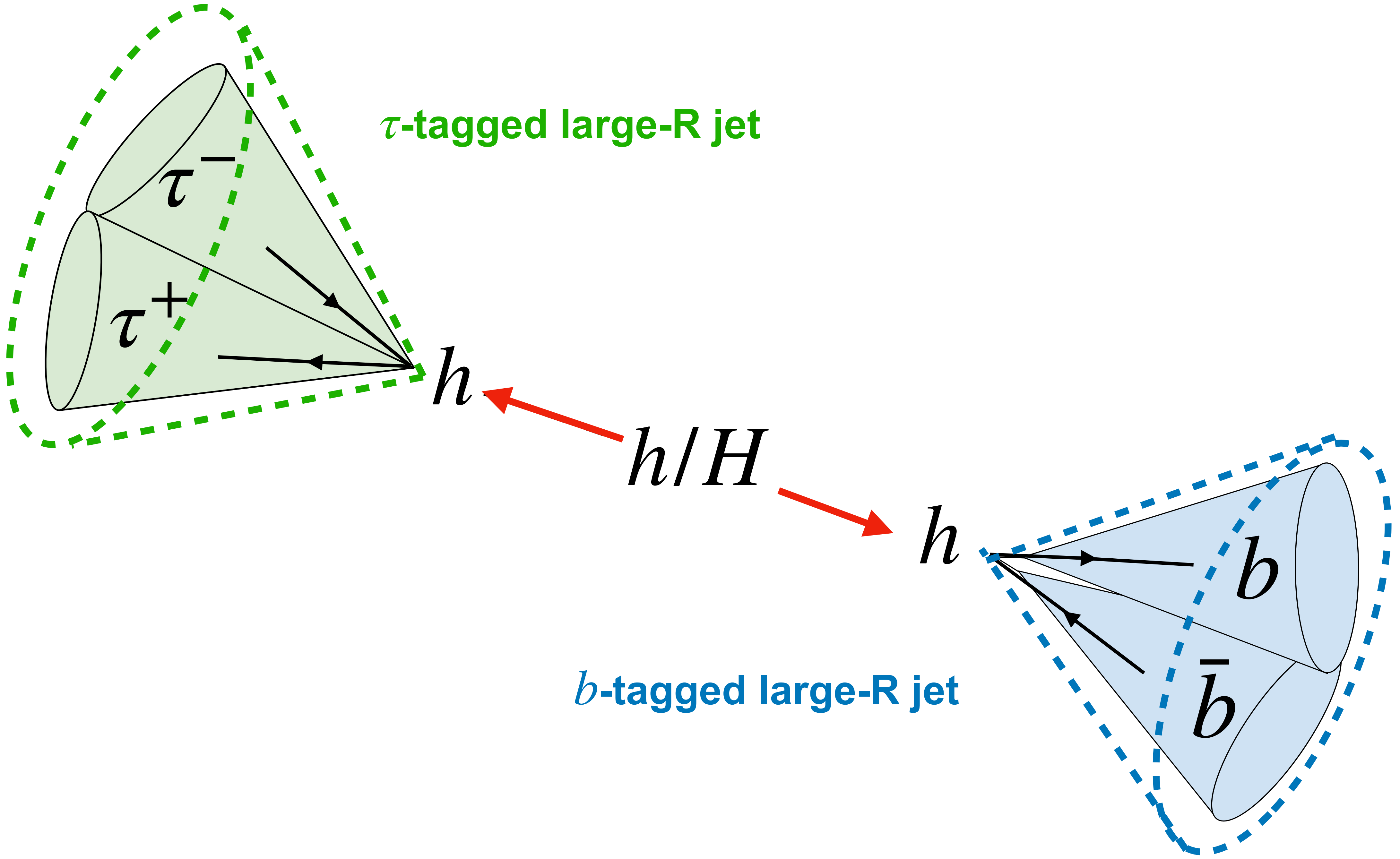
VBF HH

Resonant

- Search for Spin-0 boson : Probe the extended Higgs sectors and physics beyond standard model
  - ➡ ex. Two-Higgs-Doublet Models (2HDM) , Supersymmetry, Electroweak baryogenesis, ...

Analysis strategy for this round

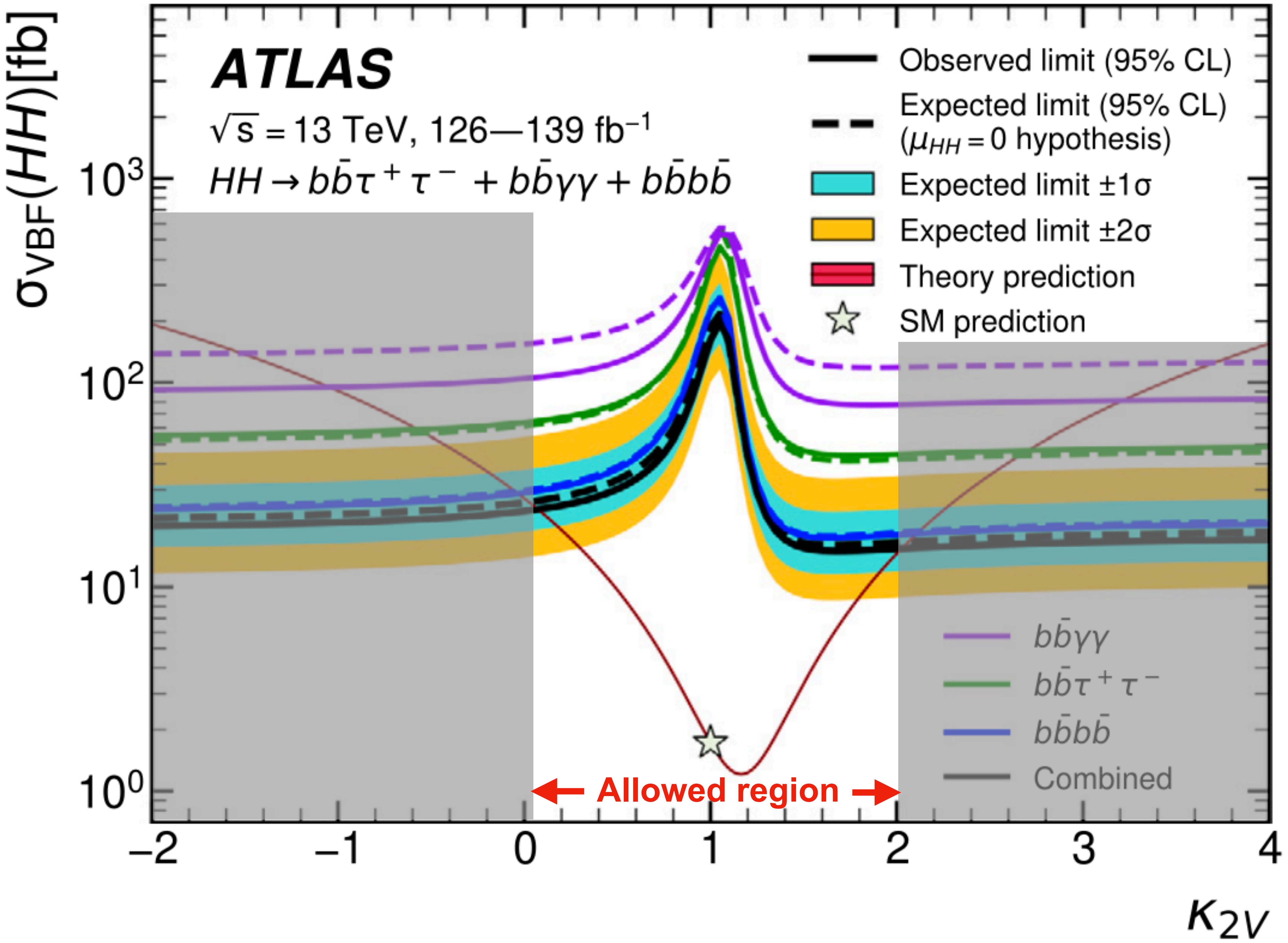
- Target : LHCP2027 (Jun 2027)
- Data : Run2 + partial Run3 (up to 2024) $\approx$ 300 fb^{-1}
- Event are reconstructed as two large-R jets.
- Tagging large-R jets using GN3X
  - ➡ Boosted $\tau\tau$ in the fully hadronic channel
- Main backgrounds are $Z \rightarrow \tau\tau$, ZH, ZZ, Multi-jets.

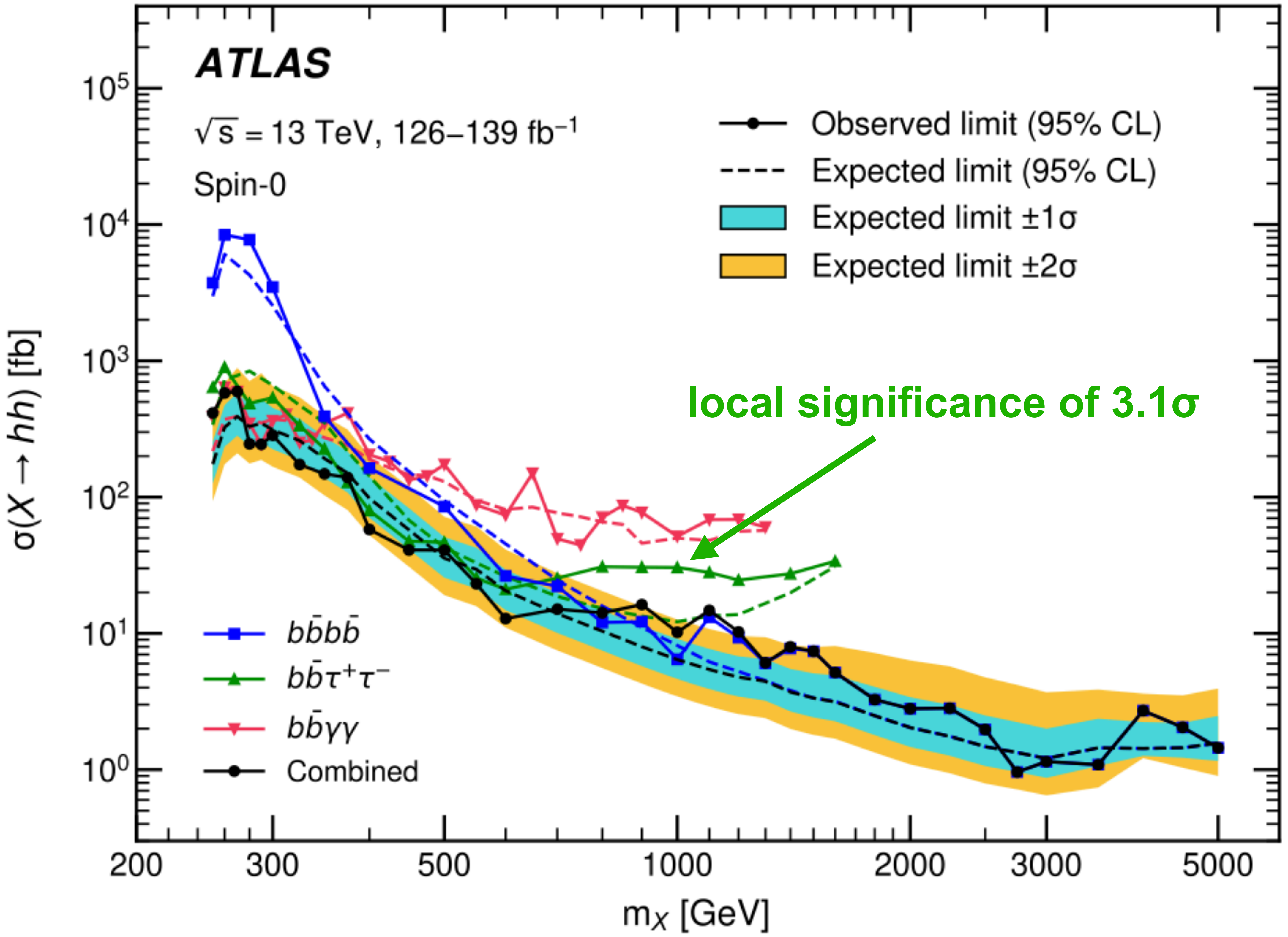


Di-Higgs Analysis in Run2

- Non-resonant : Constraint on κ_{2V} coupling $0.1 < \kappa_{2V} < 2.0$, using VBF process.
- Resonant : 95% CL upper limit on the $X \to hh$ production cross-section.
  - bbtautau at m_X=1 TeV : local significance of 3.1σ , global significance of 2.0σ.
  - bbbb at mX=1.1 TeV : local significance of 2.3σ, global significance of 0.4σ

➡ **Di-Higgs searches in the high mass region need to be improve for κ_{2V} and $X \to hh$.**





Preliminary sensitivity in this round

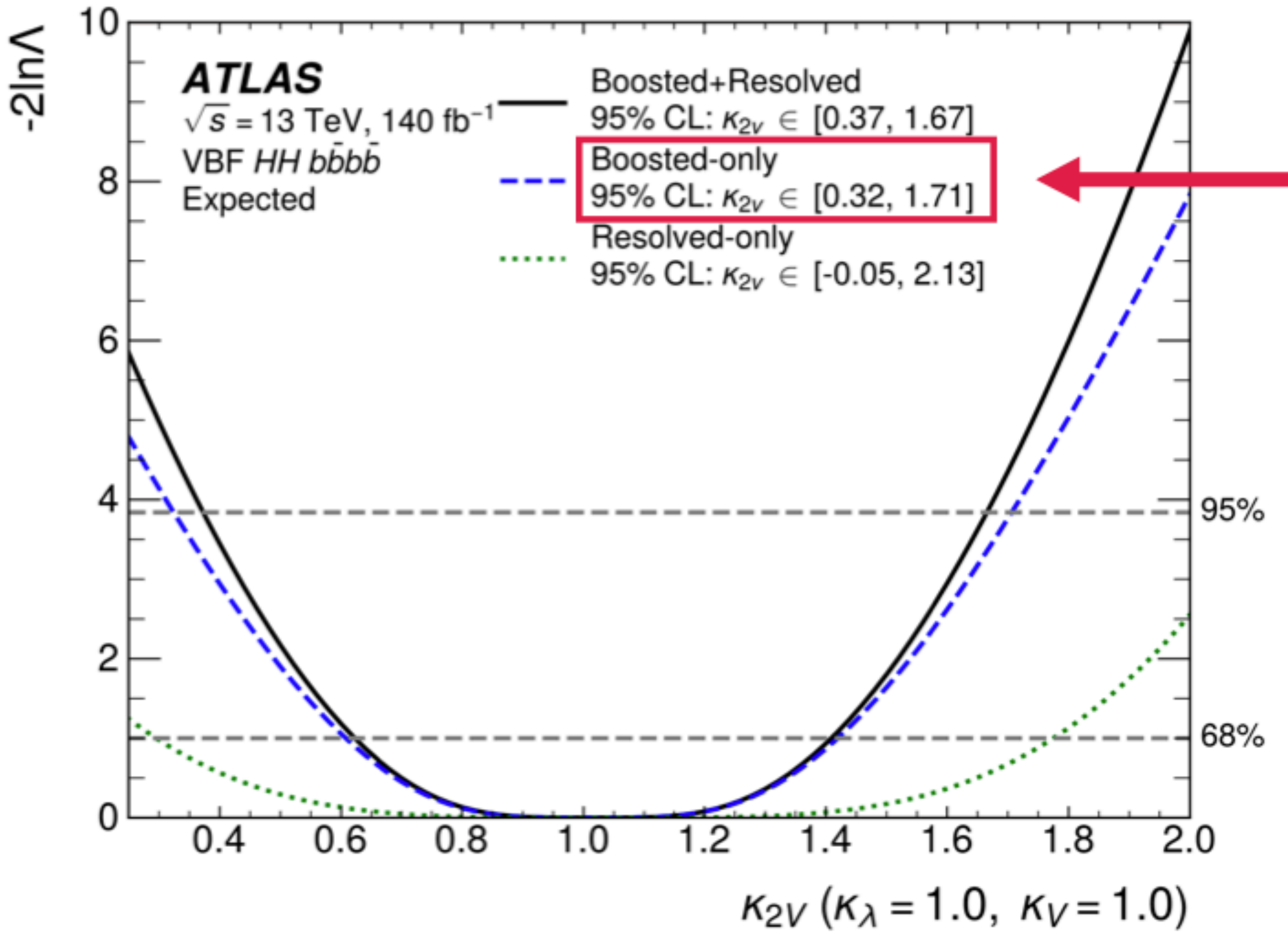
- Non-resonant : Constraint on κ_{2V} coupling : $0.31 < \kappa_{2V} < 1.54$
- Resonant : Constraint on $\sigma(X \to hh)$: $\lesssim 10^1$ fb
  - The resonant sensitivity can be further improved by optimizing the ML training.

➡ The boosted $bb\tau\tau$ provides sensitivity comparable to the boosted $bbbb$.

Refer to our group presentation (link)

Comparison with 4b

comparing with boosted HH->4b legacy Run 2 results (paper link)



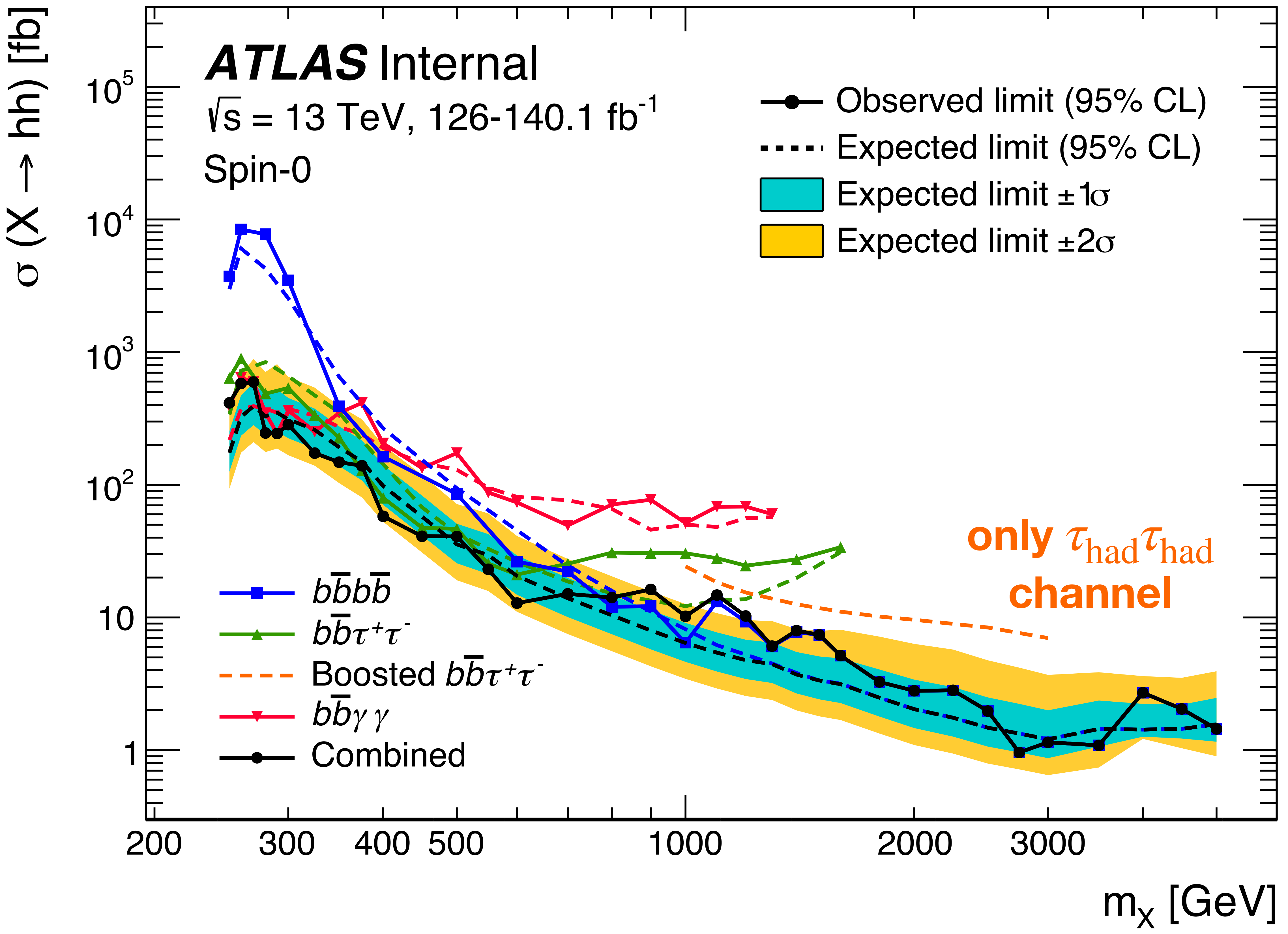
Boosted $bb\tau\tau$

From Run2 only fit:

$\kappa_{2V} \in [0.31 ; 1.54]$ (95% CL)

- Results from legacy Run 2 analysis
- 4b including systematics
- Typically not yet using GN#X taggers

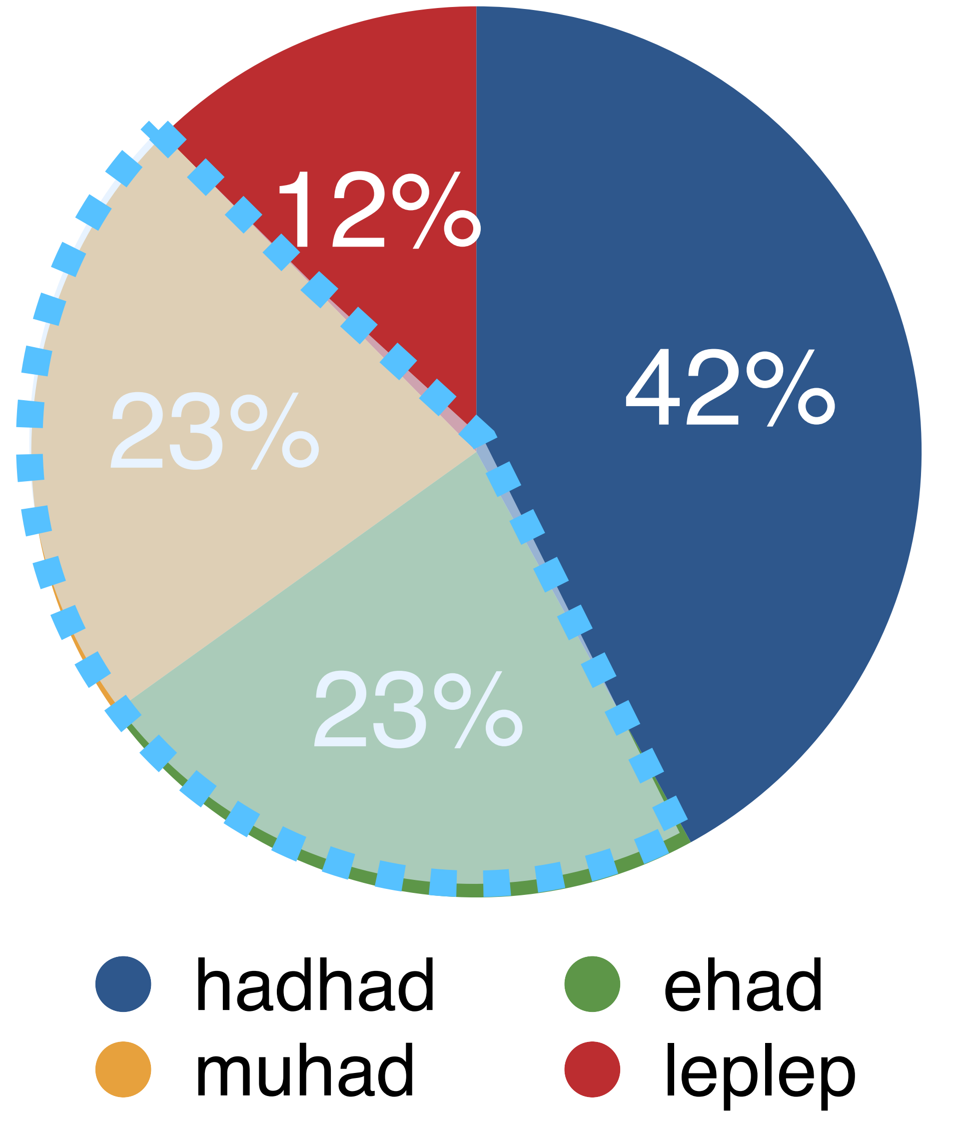
Yet our results are preliminary, so even if expecting improvements on the 4b side, should remain comparable



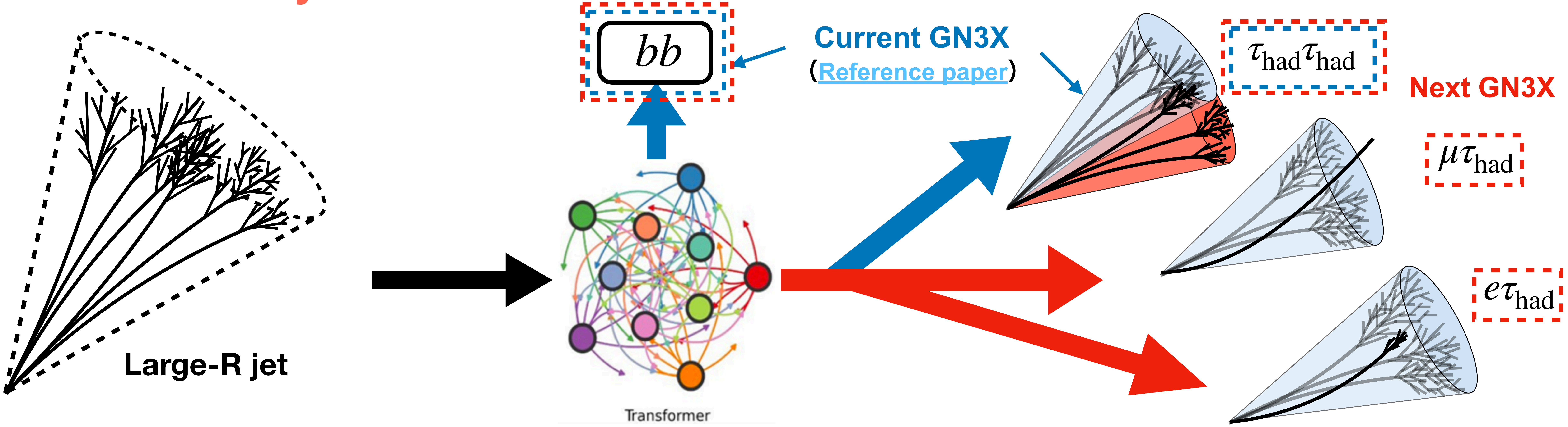
R&D of GN3X with $\tau_{lep}\tau_{had}$ in next round

- Current GN3X tagger targets only the $\tau_{had}\tau_{had}$ channel.
  - input variable did not include electrons and muons.
- The branching ratio of $\tau_{lep}\tau_{had}$ channel is ~46%
  - The signal yield could be increased by a **factor of ~2**.

➡ **R&D of GN3X with $\tau_{lep}\tau_{had}$ is important for increasing boosted $bb\tau\tau$ sensitivity.**



Branching ratio of $\tau\tau$ decay



Training setup

- New signal classes : $h \rightarrow \tau_e\tau_{\text{had}}$, $h \rightarrow \tau_\mu\tau_{\text{had}}$
- Update to the input variables :
  - Add electron and muon inputs.
  - Remove leptonID from the track input.
  - Include the muon p_T in the jet input.

➡ The transformer is trained to learn the relationship between leptons and hadrons.

Input variable

Jet Input	Description
p_T	Large-R jet transverse momentum including the muon p_T
η	Large-R jet pseudorapidity

Track Input	Description
q/p	Track charge divided by momentum (measure of curvature)
$d\eta$	Pseudorapidity of track relative to the large-R jet η
$d\phi$	Azimuthal angle of the track, relative to the large-R jet ϕ
d_0	Closest distance from track to primary vertex (PV) in the transverse plane
$z_0 \sin\theta$	Closest distance from track to PV in the longitudinal plane
$\sigma(q/p)$	Uncertainty on q/p
$\sigma(\theta)$	Uncertainty on track polar angle θ
$\sigma(\phi)$	Uncertainty on track azimuthal angle ϕ
$s(d_0)$	Lifetime signed transverse IP significance
$s(z_0 \sin\theta)$	Lifetime signed longitudinal IP significance
nPixHits	Number of pixel hits
nSCTHits	Number of silicon microstrip tracker (SCT) hits
nIBLHits	Number of innermost pixel layer (IBL) hits
nBLHits	Number of next-to-innermost pixel layer (B-layer) hits
nIBLShared	Number of shared IBL hits
nIBLSplit	Number of split IBL hits
nPixShared	Number of shared pixel hits
nPixSplit	Number of split pixel hits
nSCTShared	Number of shared SCT hits
~~leptonID~~	~~Identifier based on whether the track was used in the reconstruction of an electron/muon~~

UFO Input	Description
p_T	Transverse momentum of UFO constituent
energy	Energy of UFO constituent
$d\eta$	Pseudorapidity of UFO constituent relative to the large-R jet η
$d\phi$	Azimuthal angle of UFO constituent relative to the large-R jet ϕ

New variables

Electron Input	Description
p_T	Electron transverse momentum
$d\eta$	Pseudorapidity of electron relative to the large-R jet η
$d\phi$	Azimuthal angle of electron relative to the large-R jet ϕ
dR	Azimuthal angle of electron relative to the large-R jet R

Muon Input	Description
p_T	Muon transverse momentum
$d\eta$	Pseudorapidity of muon relative to the large-R jet η
$d\phi$	Azimuthal angle of muon relative to the large-R jet ϕ
dR	Azimuthal angle of muon relative to the large-R jet R

Input number of jets each class

Large-R jet truth-matched class	Source process	Training jets $[10^6]$
$H \rightarrow b\bar{b}$	ZH (flat-mass)	30
$H \rightarrow c\bar{c}$	ZH (flat-mass)	30
$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	ZH (flat-mass)	7
$H \rightarrow \tau_e\tau_{\text{had}}$	ZH (flat-mass)	4
$H \rightarrow \tau_\mu\tau_{\text{had}}$	ZH (flat-mass)	4
Top	$Z' \rightarrow tt$	35
$W(q,q')$	$W' \rightarrow WZ$	2
QCD	Multijet	60
Total		172

New class

Discriminant of $h \to \tau\tau$

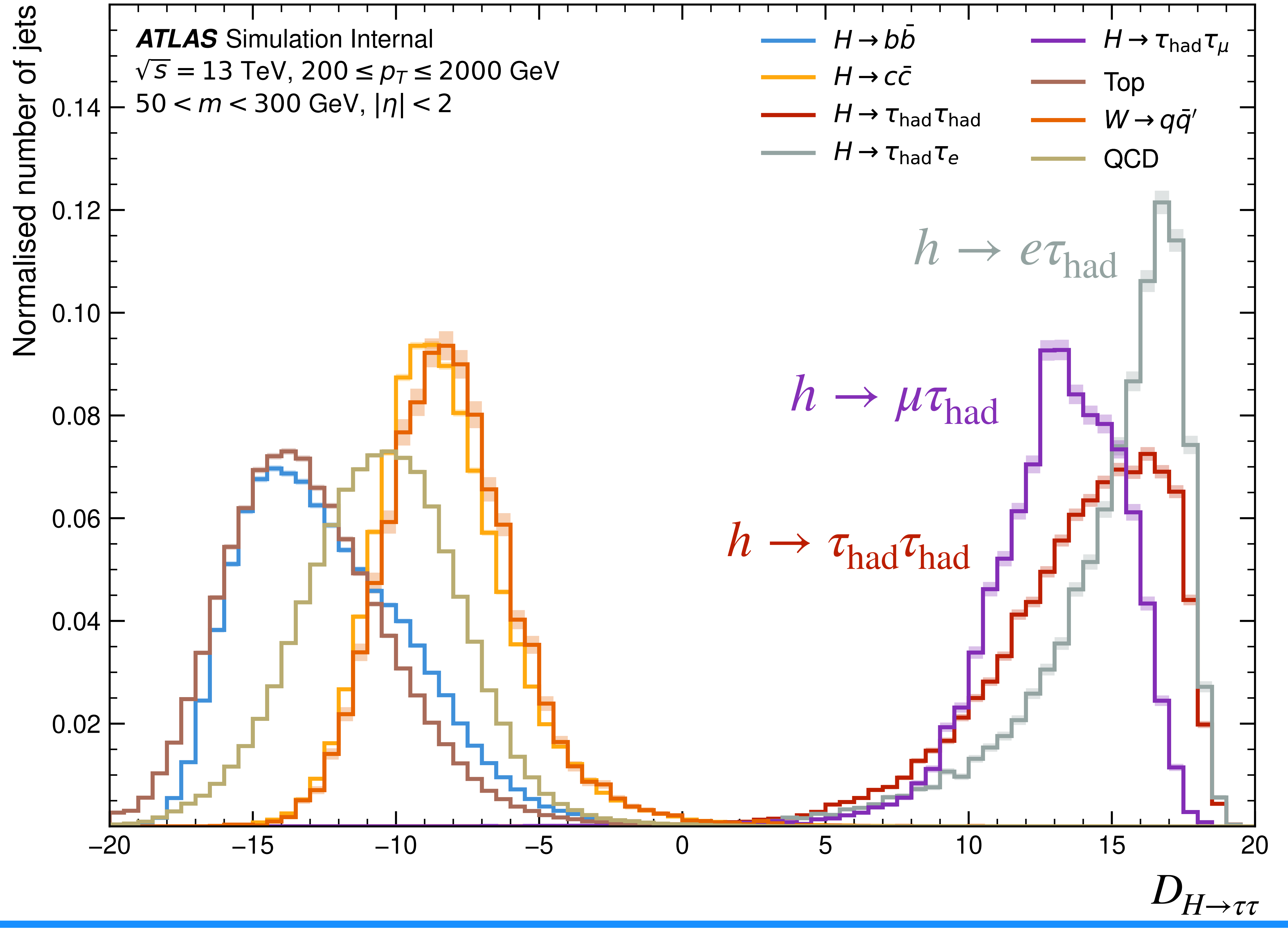
GN3X τ-tagger 3-class discriminant definition:

$$\boxed{D_{H\to\tau\tau} = \ln\left(\frac{P_{H\tau_{\rm had}\tau_{\rm had}} + P_{H\tau_e\tau_{\rm had}} + P_{H\tau_\mu\tau_{\rm had}}}{f_{Hbb}P_{Hbb} + f_{Hcc}P_{Hcc} + f_{\rm Top}P_{\rm Top} + f_{Wqq}P_{Wqq} + f_{\rm QCD}P_{\rm QCD}}\right)}$$

$$f_{Hcc} = f_{Hbb} = 0.02, \quad f_{Wqq} = 0.10, \quad f_{\rm Top} = 0.25, \quad f_{\rm QCD} = 0.55$$

- The P_X is output score of class X.
- $h \to \tau\tau$ discriminant is defined using 3 class $h \to \tau\tau$ score in the numerator.

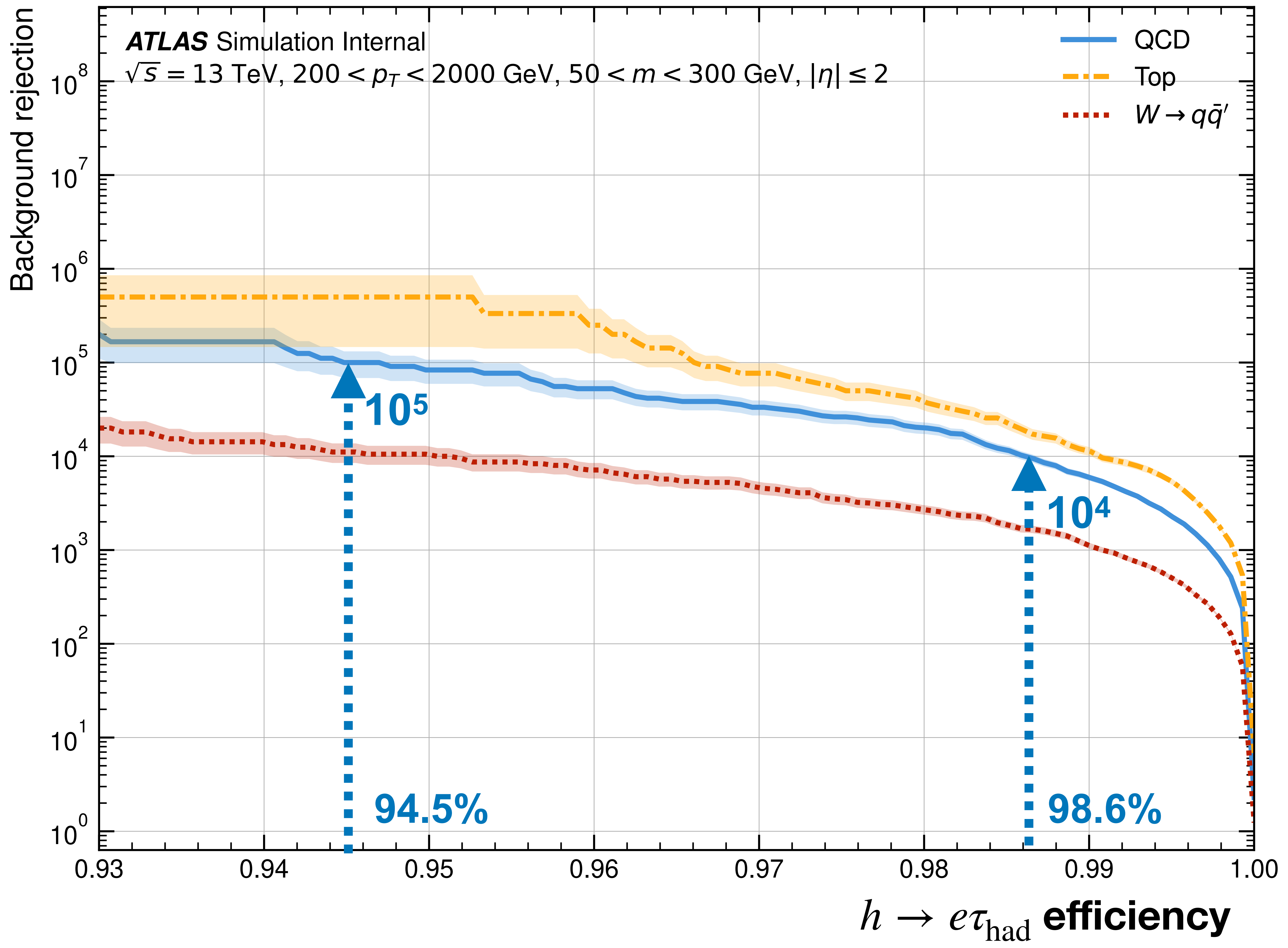
➡ $h \to \tau\tau$ discriminant clearly separates $h \to \tau\tau$ from $h \to bb/cc$ and other backgrounds.

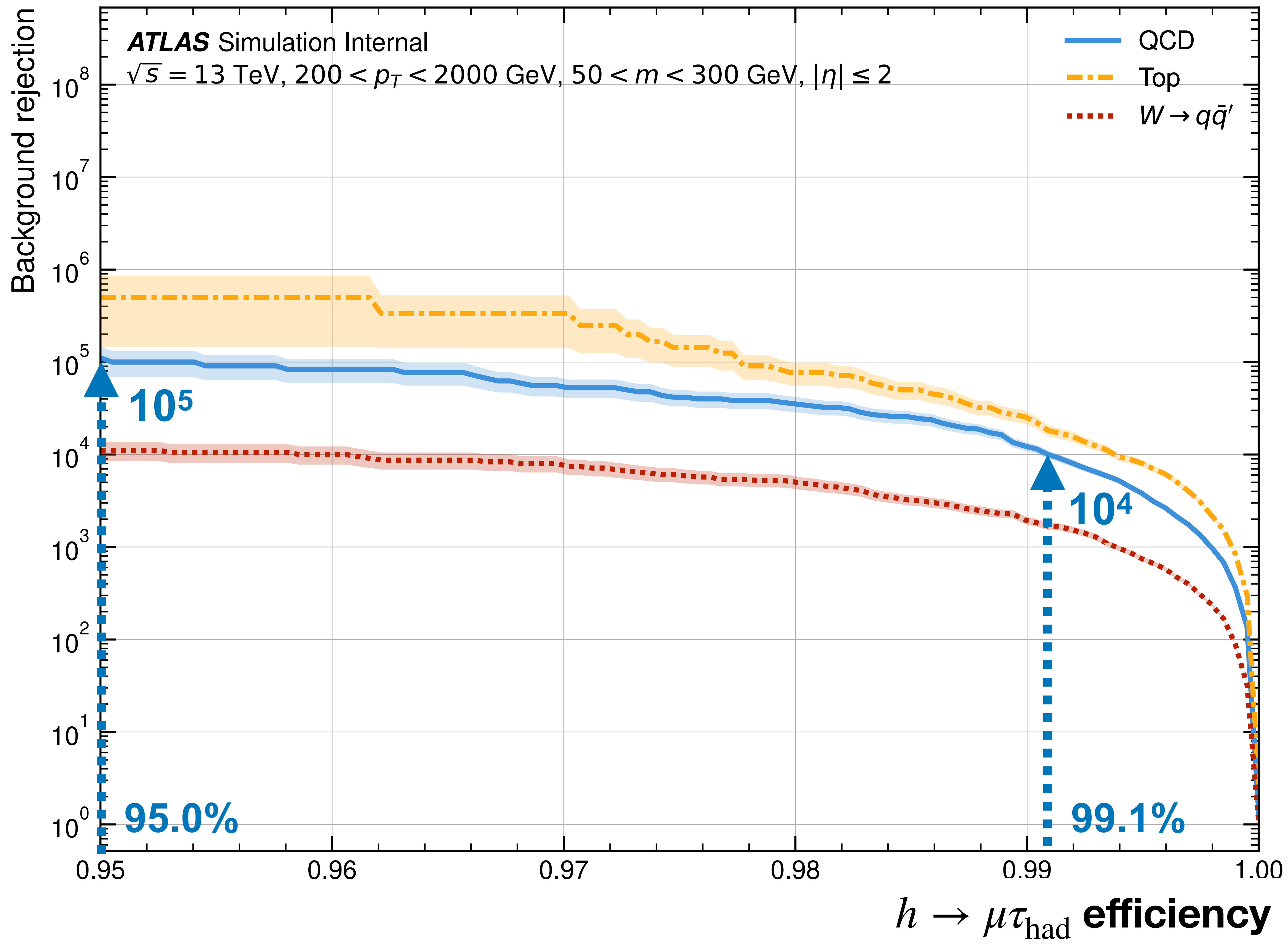


ROC curve : $h \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$

- $h \to e\tau_{\mathrm{had}}$: QCD background rejection of 10^5 at ~94.5% signal efficiency.
- $h \to \mu\tau_{\mathrm{had}}$: QCD background rejection of 10^5 at ~95% signal efficiency.

➡ The GN3X tagger with $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ achieves strong separation from background.





ROC curve : $h \to \tau_{\text{had}}\tau_{\text{had}}$

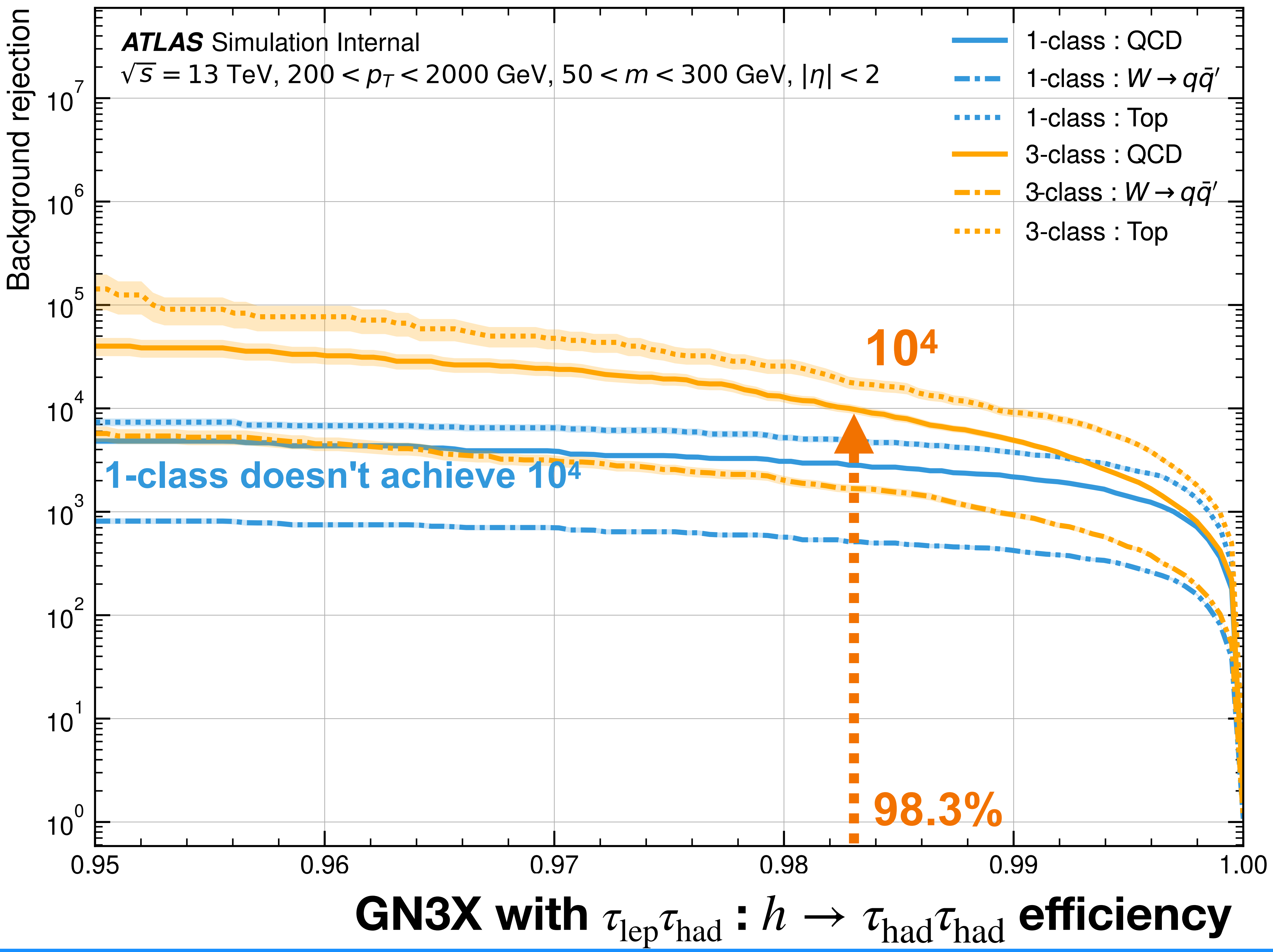
- $h \to \tau_{\text{had}}\tau_{\text{had}}$: QCD background rejection of 10^5 at ~98.3% efficiency using 3-class discriminant.

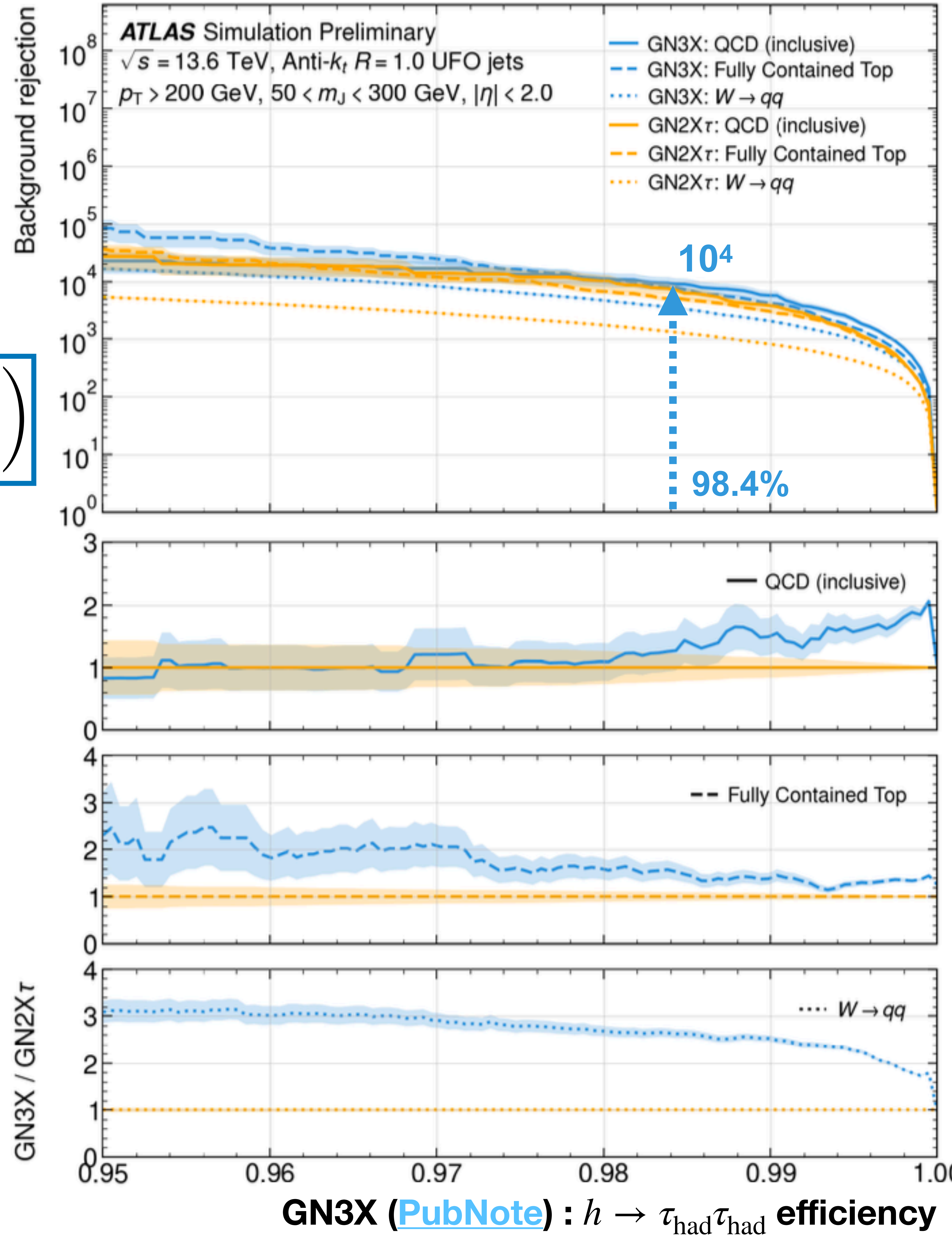
➡ GN3X with $\tau_{\text{lep}}\tau_{\text{had}}$ is comparable to the GN3X (PubNote).

GN3X τ-tagger 1-class discriminant definition:

$$D_{H\to\tau\tau} = \ln\left(\frac{P_{H\tau_{\text{had}}\tau_{\text{had}}}}{f_{Hbb}P_{Hbb} + f_{Hcc}P_{Hcc} + f_{H\tau_e\tau_{\text{had}}}P_{H\tau_e\tau_{\text{had}}} + f_{H\tau_\mu\tau_{\text{had}}}P_{H\tau_\mu\tau_{\text{had}}} + f_{\text{Top}}P_{\text{Top}} + f_{Wqq}P_{Wqq} + f_{\text{QCD}}P_{\text{QCD}}}\right)$$

$$f_{Hcc} = f_{Hbb} = f_{H\tau_e\tau_{\text{had}}} = f_{H\tau_\mu\tau_{\text{had}}} = 0.02, \quad f_{Wqq} = 0.10, \quad f_{\text{Top}} = 0.25, \quad f_{\text{QCD}} = 0.55$$





ROC curve : $h \rightarrow bb$

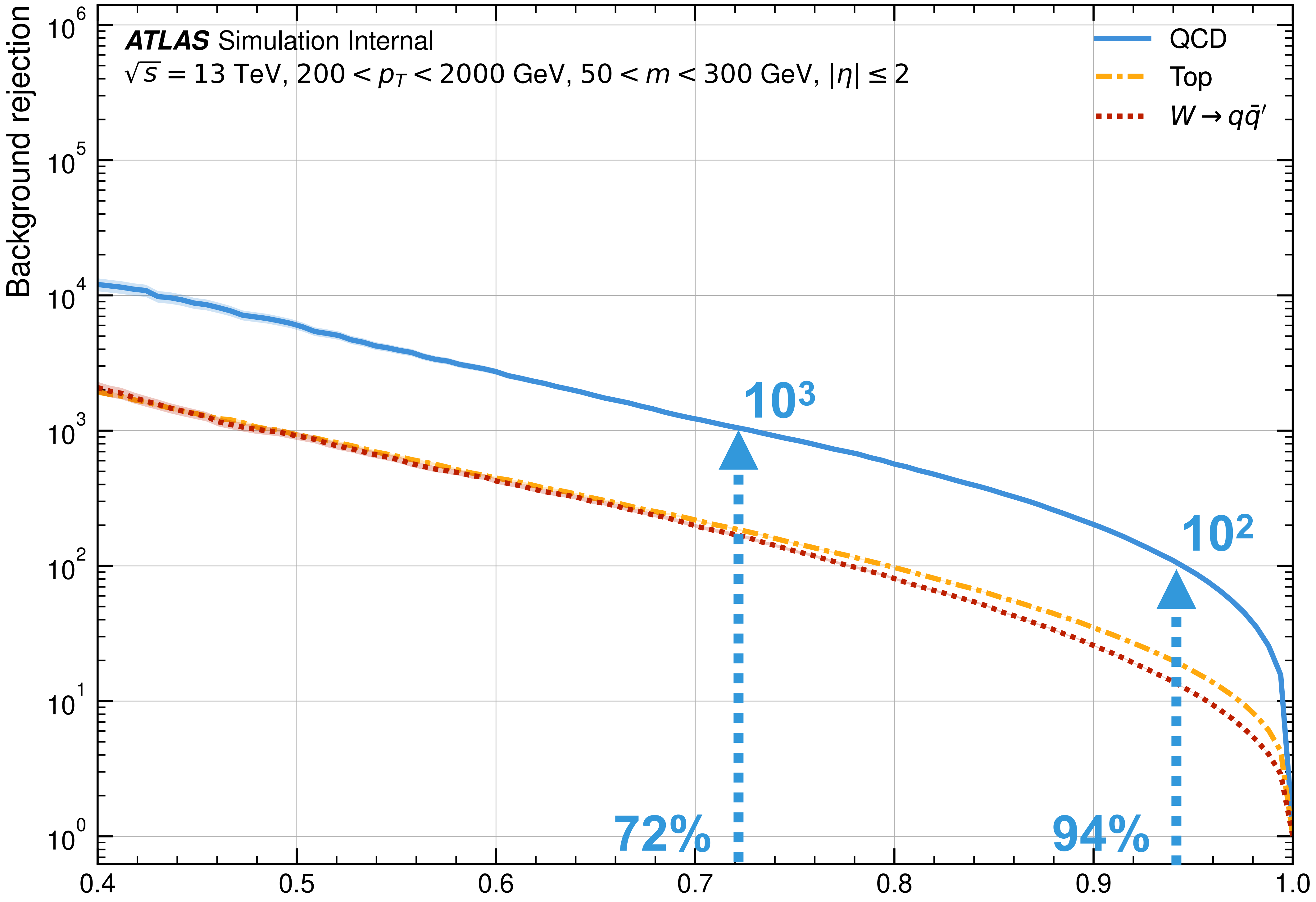
- $h \rightarrow bb$: QCD background rejection of 10^2 at ~94.0% efficiency.

➡ GN3X with $\tau_{\rm lep}\tau_{\rm had}$ show better performance to the GN3X (PubNote).

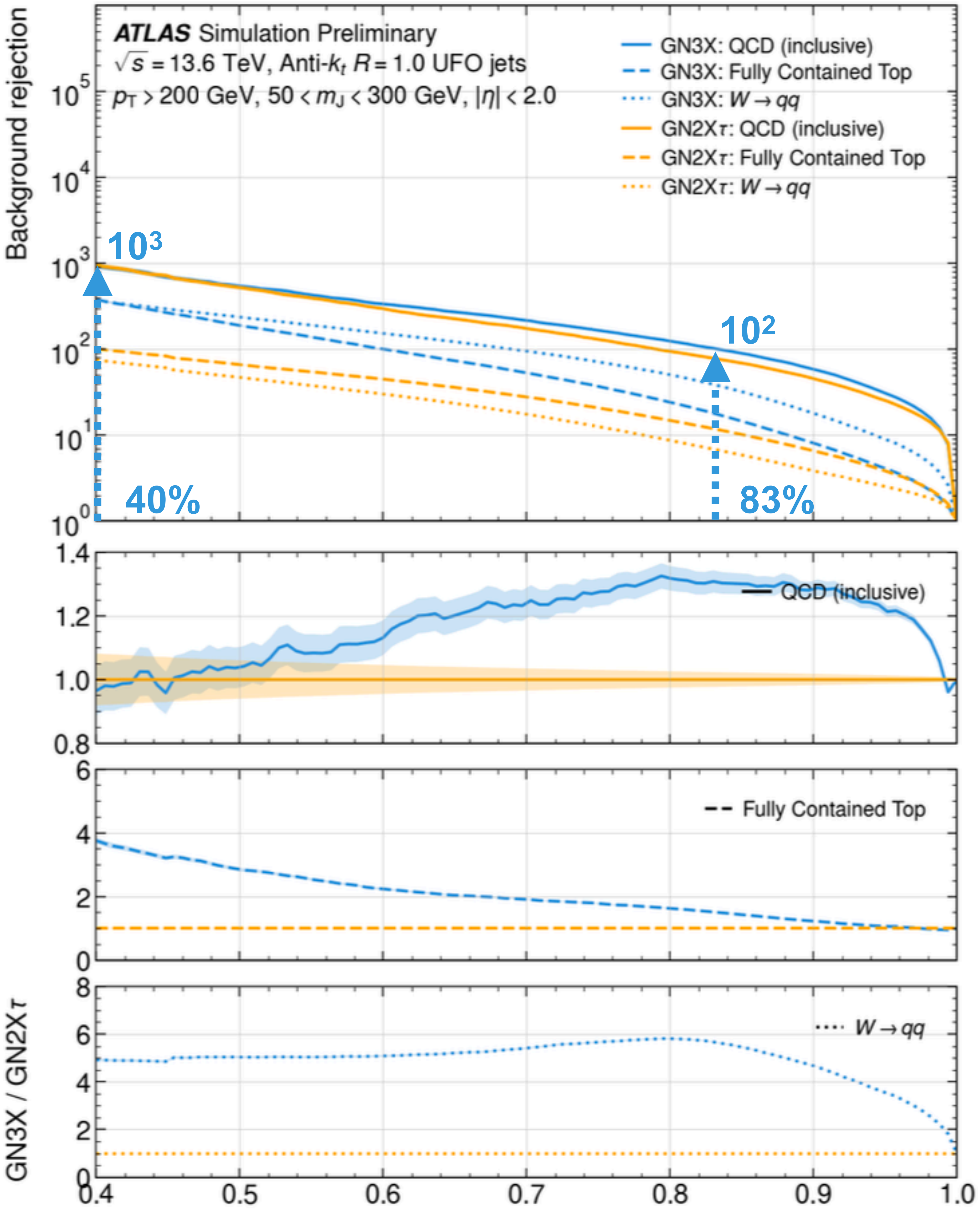
GN3X b-tagger 1-class discriminant definition:

$$D_{H\rightarrow bb} = \ln\left(\frac{P_{bb}}{f_{Hcc}P_{Hcc} + f_{H\tau_{\rm had}\tau_{\rm had}}P_{H\tau_{\rm had}\tau_{\rm had}} + f_{H\tau_e\tau_{\rm had}}P_{H\tau_e\tau_{\rm had}} + f_{H\tau_\mu\tau_{\rm had}}P_{H\tau_\mu\tau_{\rm had}} + f_{\rm Top}P_{\rm Top} + f_{Wqq}P_{Wqq} + f_{\rm QCD}P_{\rm QCD}}\right)$$

$$f_{Hcc} = f_{H\tau_{\rm had}\tau_{\rm had}} = f_{H\tau_e\tau_{\rm had}} = f_{H\tau_\mu\tau_{\rm had}} = 0.02, \quad f_{Wqq} = 0.10, \quad f_{\rm Top} = 0.25, \quad f_{\rm QCD} = 0.55$$



GN3X with $\tau_{\rm lep}\tau_{\rm had}$: $h \rightarrow bb$ efficiency

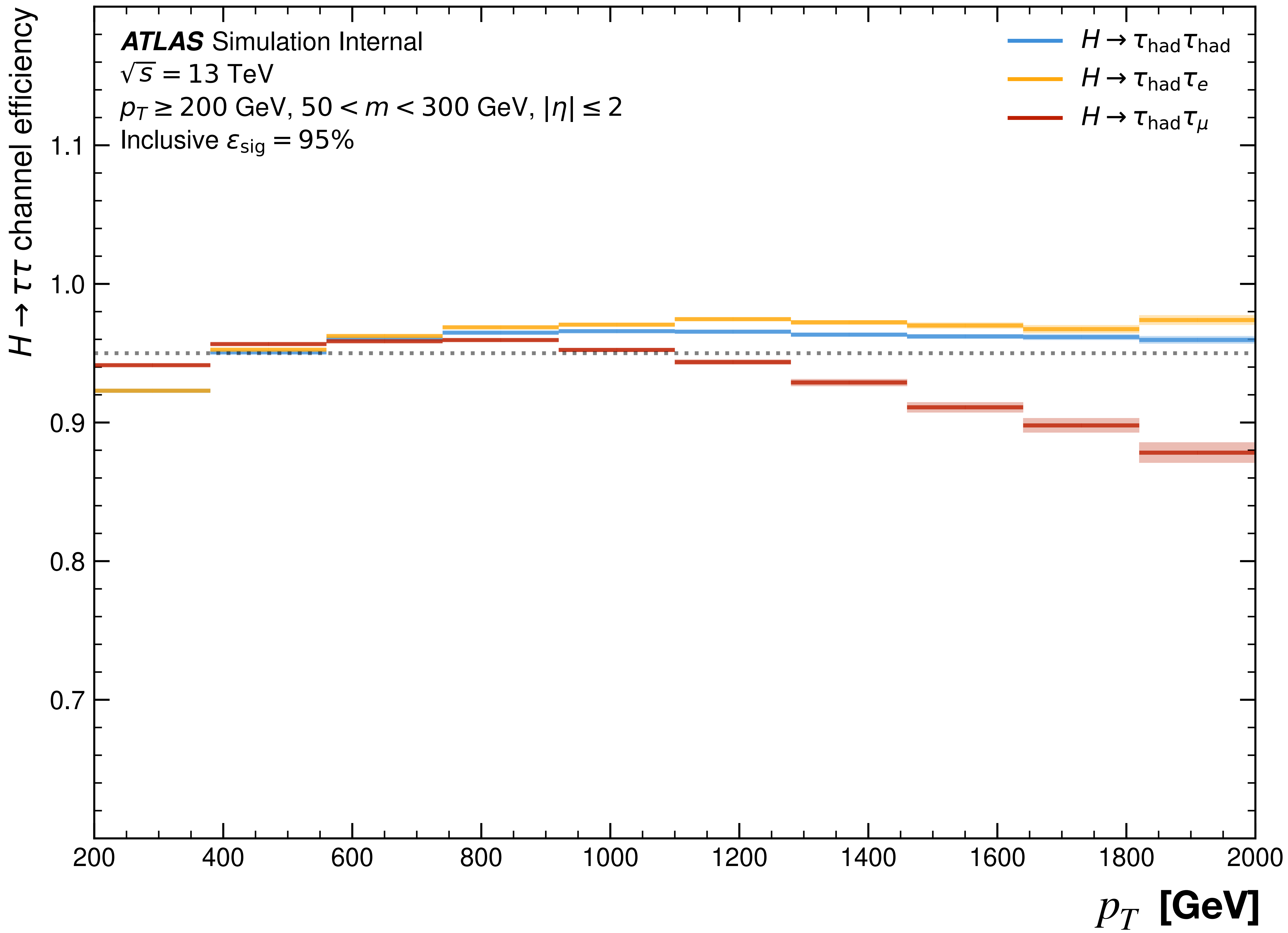


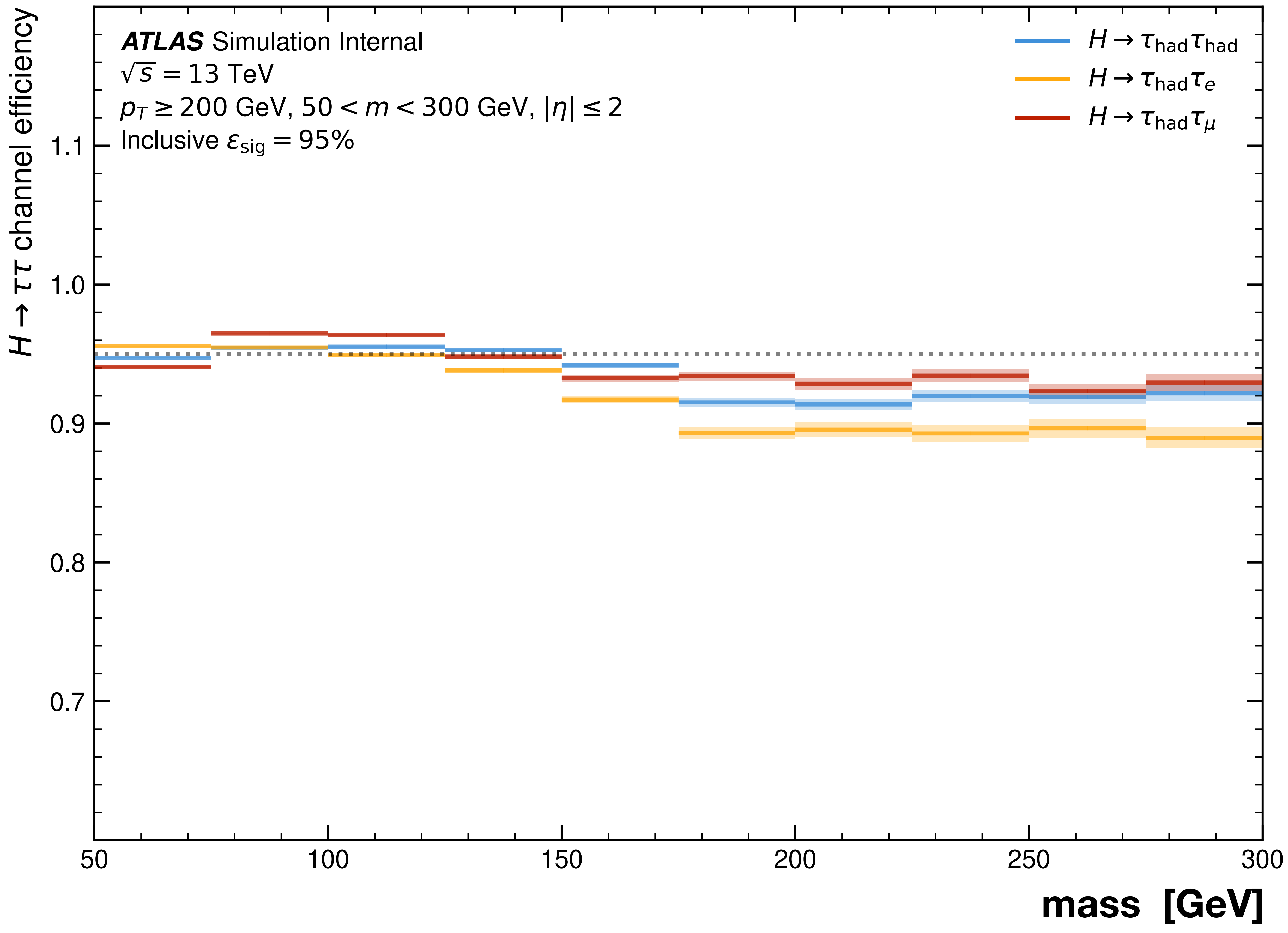
GN3X (PubNote) : $h \rightarrow bb$ efficiency

Efficiency : $h \to \tau\tau$

- $h \to \tau\tau$ efficiency in each channel as function of jet p_T and mass at the 95% WP.
- $h \to \mu\tau_{\text{had}}$ efficiency decreases in the high p_T region, but remains around ~90%.

➡ GN3X with $h \to \tau_{\text{lep}}\tau_{\text{had}}$ maintains a stable tagging efficiency.





Summary

- Motivation
  - ggF HH : Probe the higgs potential through κ_λ
  - VBF HH : Probe the structure of EWSB through κ_{2V}
  - Search for Spin-0 boson : Probe the extended Higgs sectors and physics beyond standard model
- R&D of GN3X with $\tau_{\text{lep}}\tau_{\text{had}}$ in next round
  - The branching ratio of $\tau_{\text{lep}}\tau_{\text{had}}$ channel is ~46%. The signal yield could be increased by a **factor of ~2**.
  - $h \to e\tau_{\text{had}}$: QCD background rejection of 10^5 at ~94.5% signal efficiency.
  - $h \to \mu\tau_{\text{had}}$: QCD background rejection of 10^5 at ~95% signal efficiency.
  - $h \to \tau_{\text{had}}\tau_{\text{had}}$: QCD background rejection of 10^5 at ~98.3% efficiency using 3-class discriminant.
  - $h \to bb$: QCD background rejection of 10^2 at ~94.0% efficiency.
  - GN3X with $h \to \tau_{\text{lep}}\tau_{\text{had}}$ maintains a stable tagging efficiency.
- Under investigation : which parameters contribute most to this performance.