UNIVERSITY OF BIRMINGHAM

ATLAS EXPERIMENT

Searches for new scalars and BSM physics with h^{125}

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on behalf of the ATLAS collaboration

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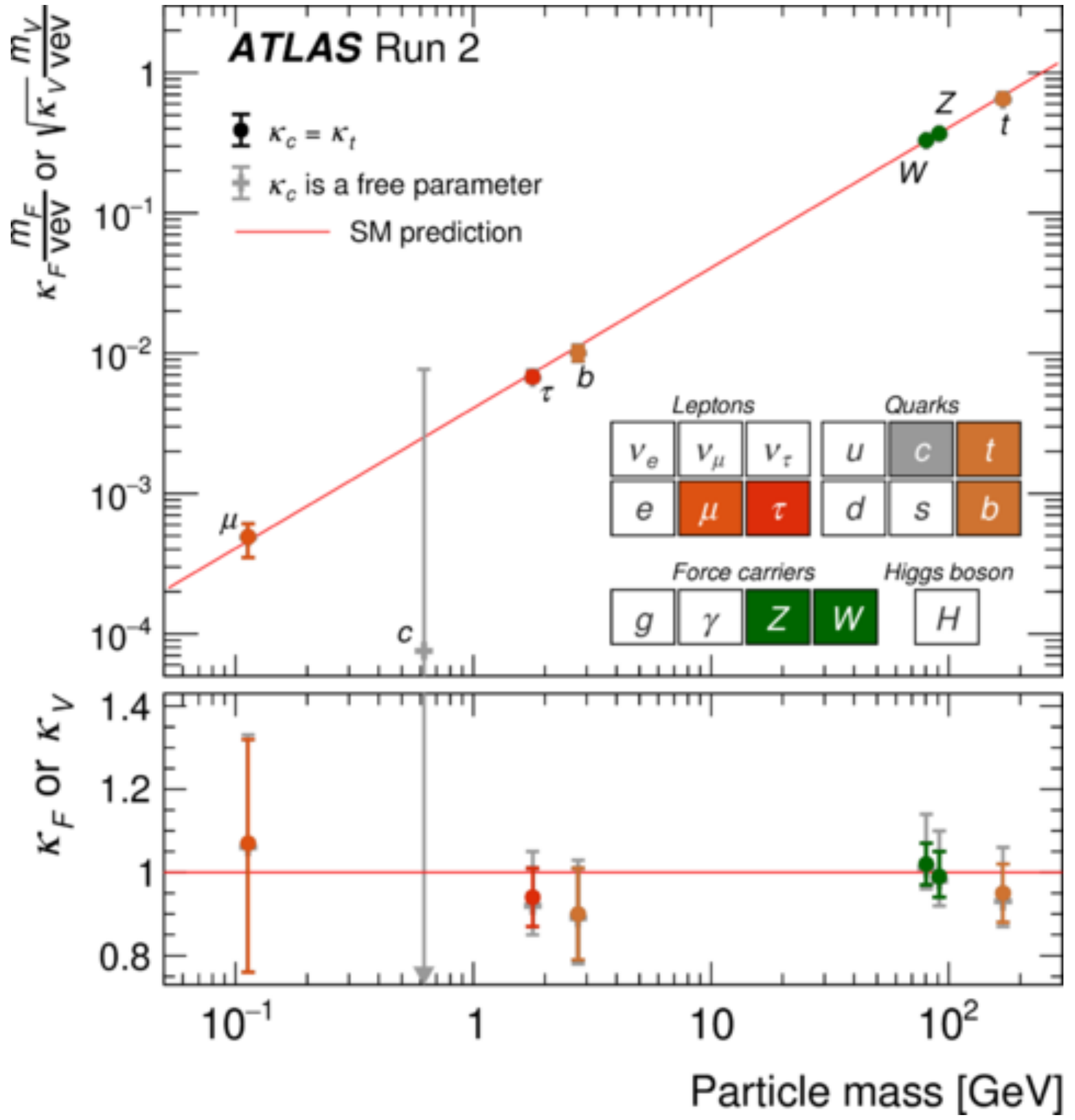
Introduction

Experimental facts

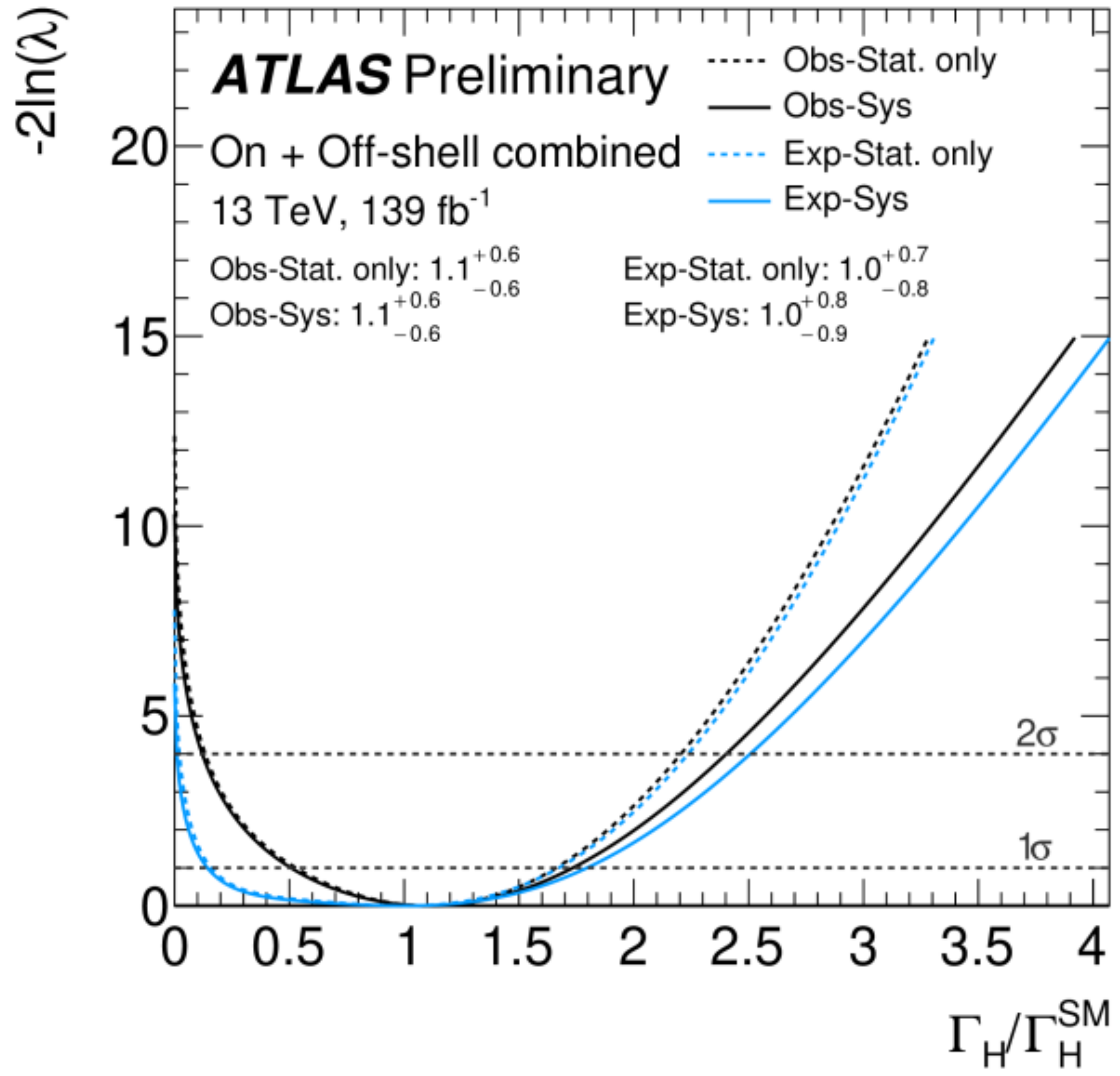
- We know fermion masses and we know there are three generations but why ?
- From neutrino oscillation experiments we know neutrinos have very small masses — how do they obtain their mass?

Higgs total width 4.5(+3.3 -2.5) MeV - ATLAS

Even a small coupling to another light state can open up additional sizeable decay modes.



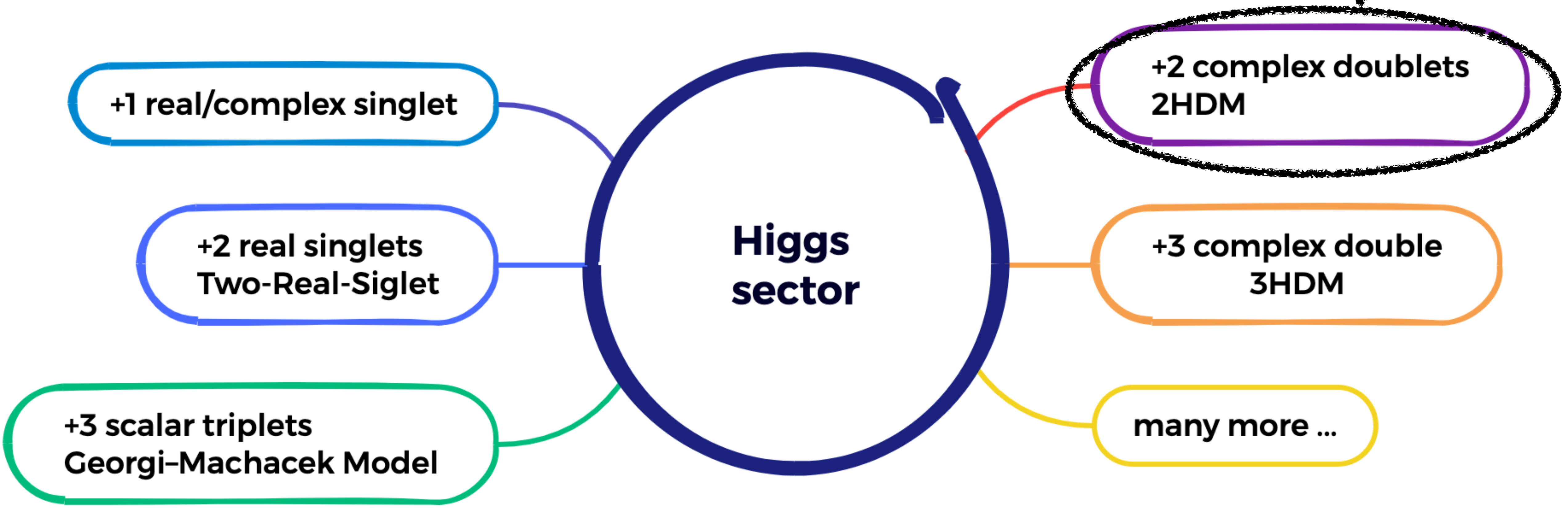
DOI: 10.1038/s41586-022-04893-w

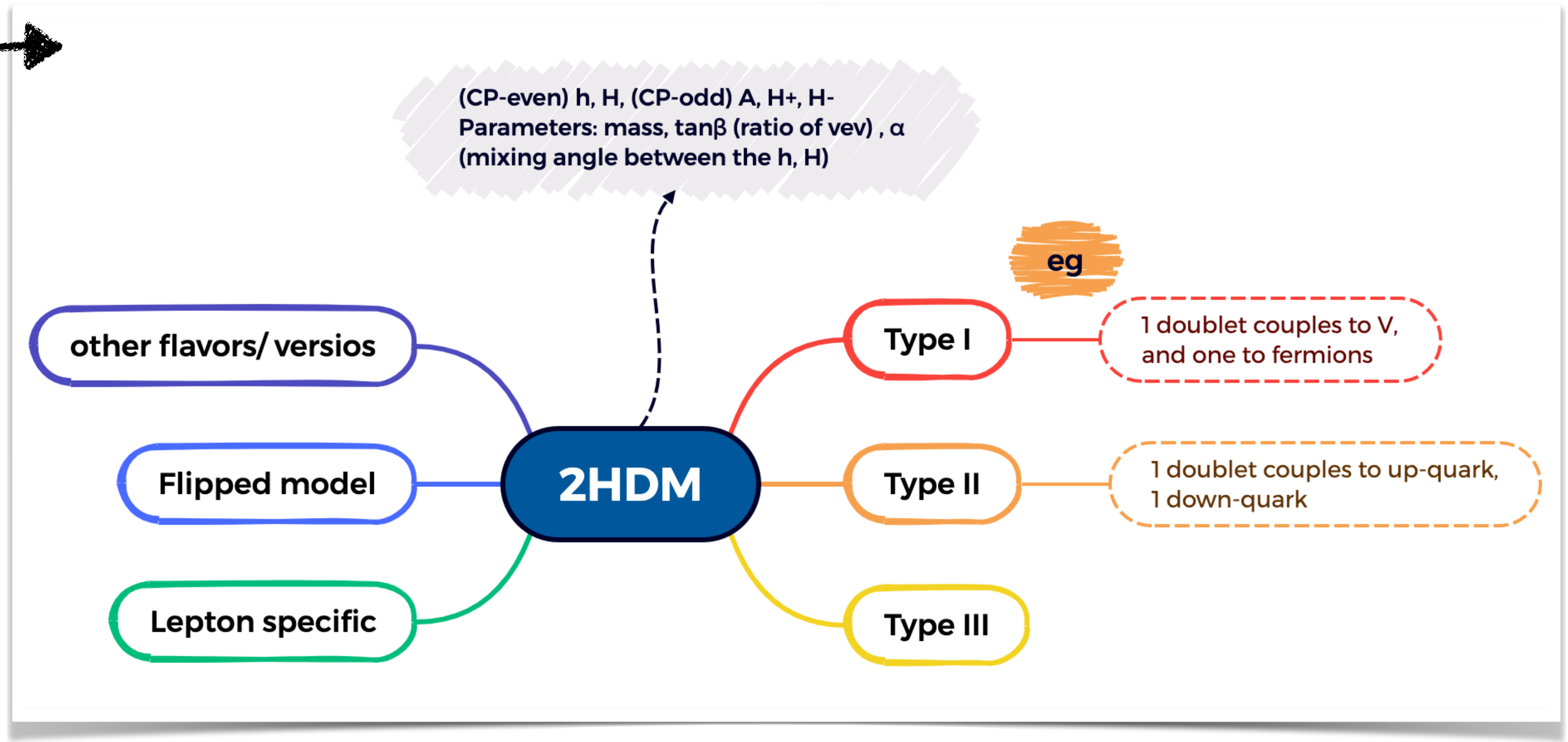


Phys. Lett. B 846 (2023) 138223

Models predicting new scalars and BSM h^{125} decays

To get new scalars we could extend the Higgs sector …



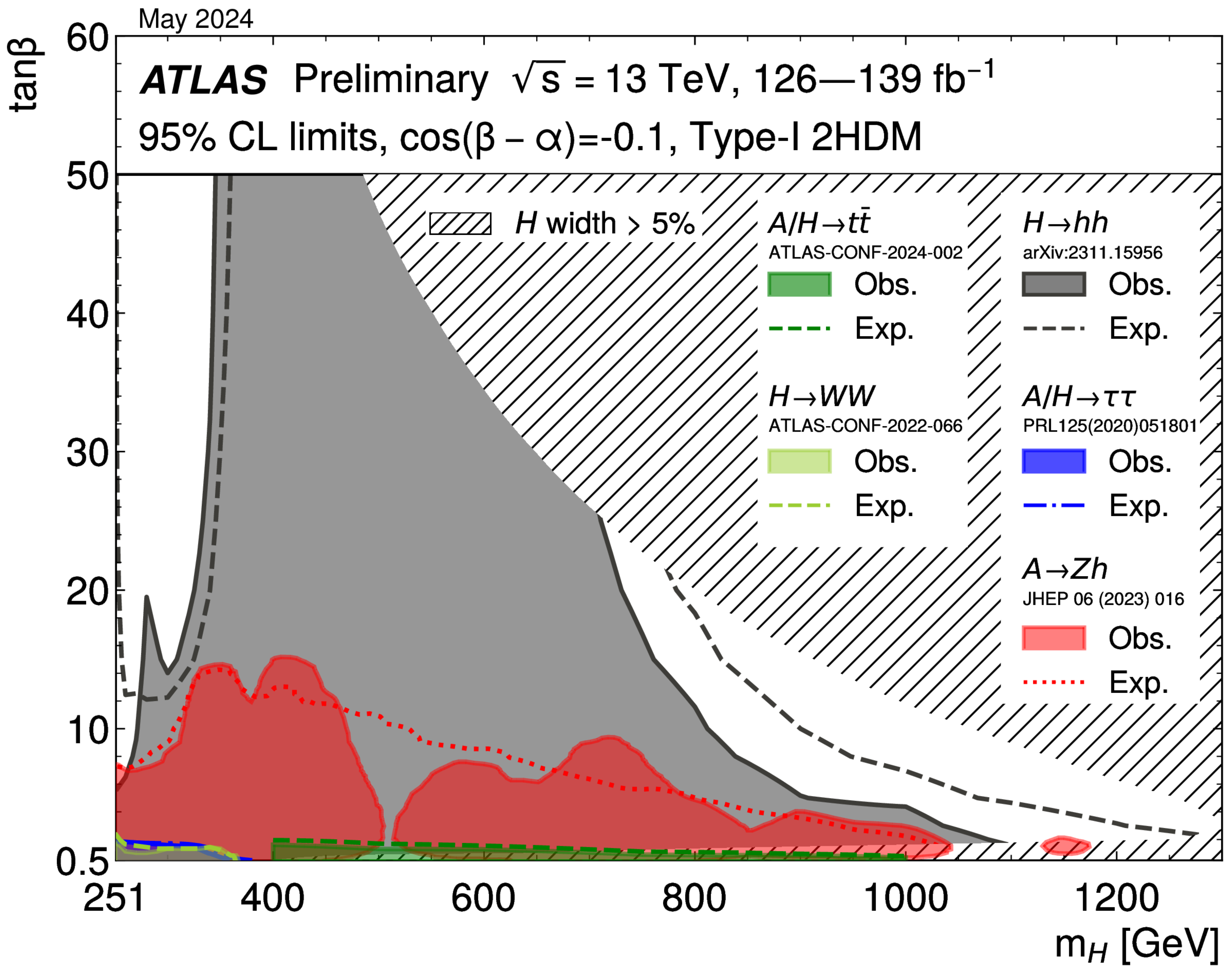


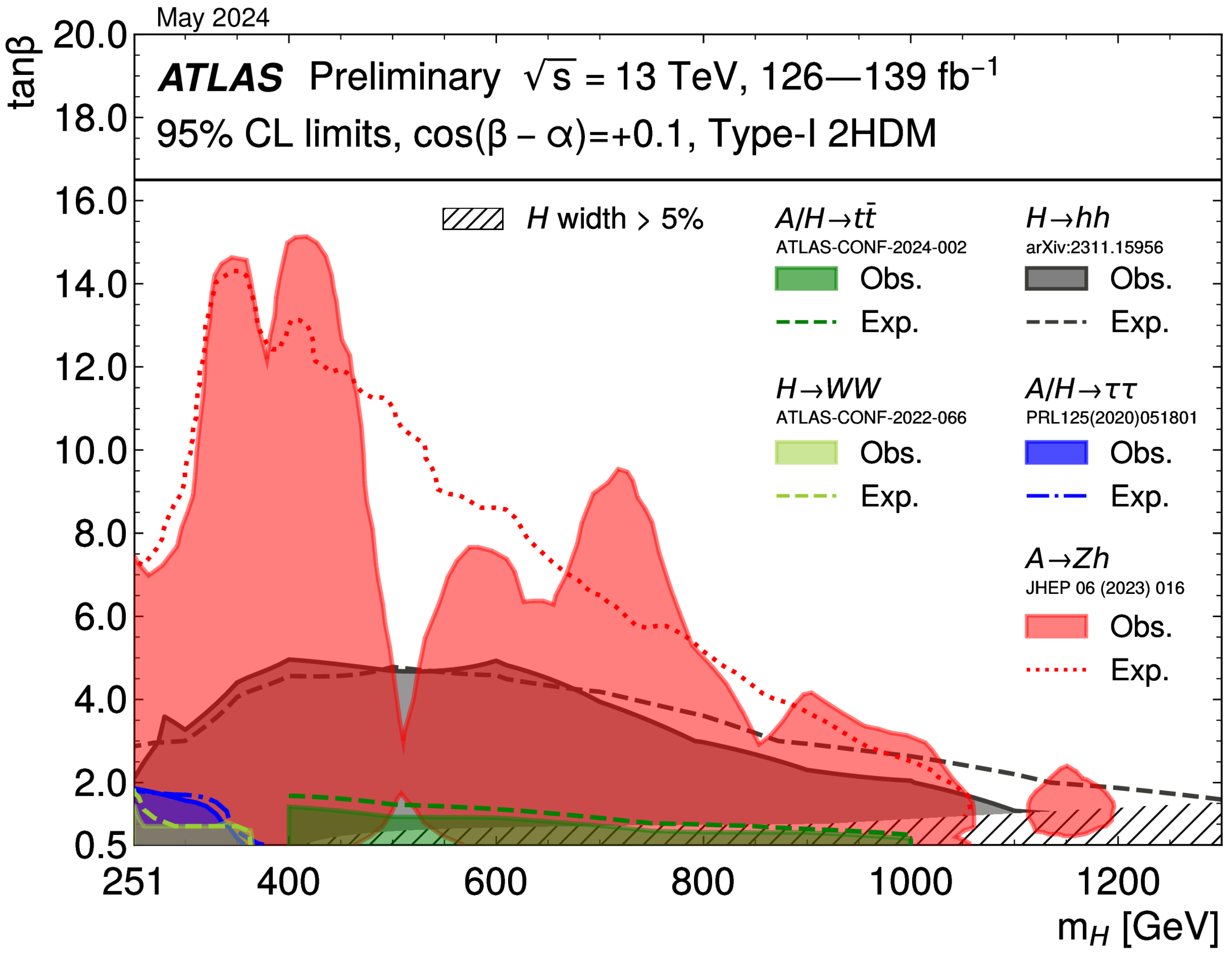
Constrained from

- Higgs and other SM Precision measurements
- Exotic searches
- BSM Higgs searches

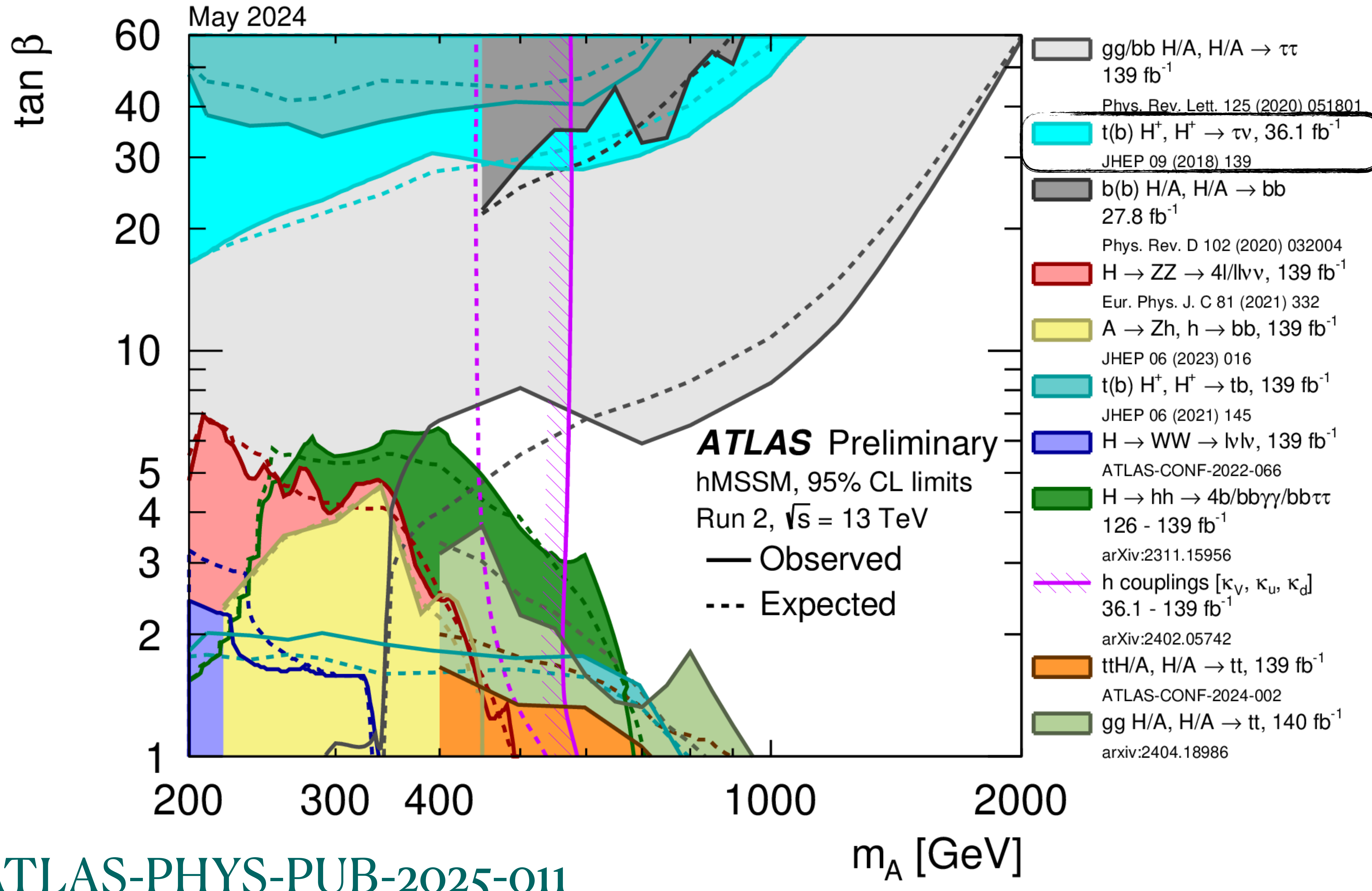
Higgs BSM searches :
Main focus: the experimental signature
Main design goal: cover as much as we can from the available phase-space, for a specific signature, but we are still quite **model-dependent**

Summary plots (2HDM-I)





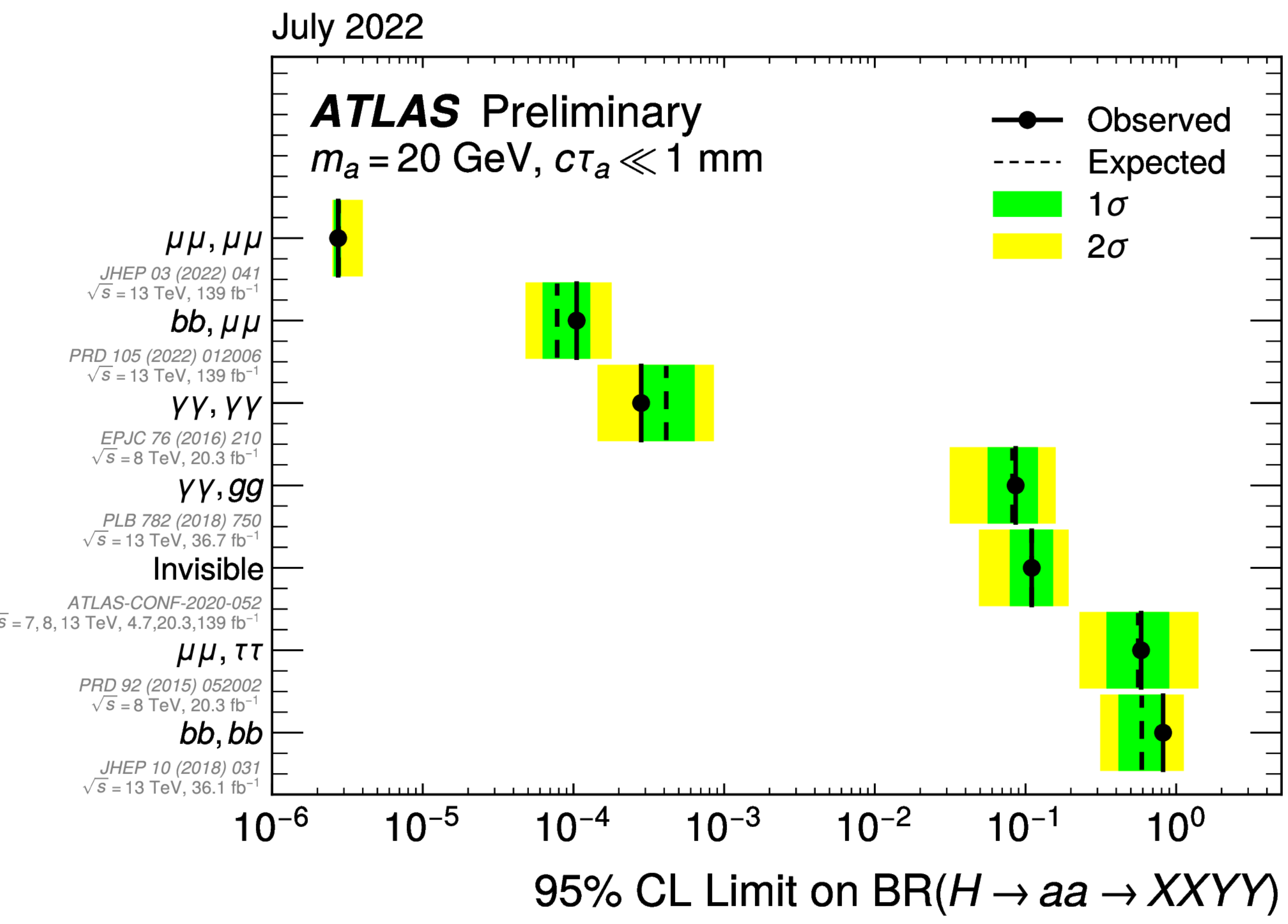
Summary plots (hMSSM)

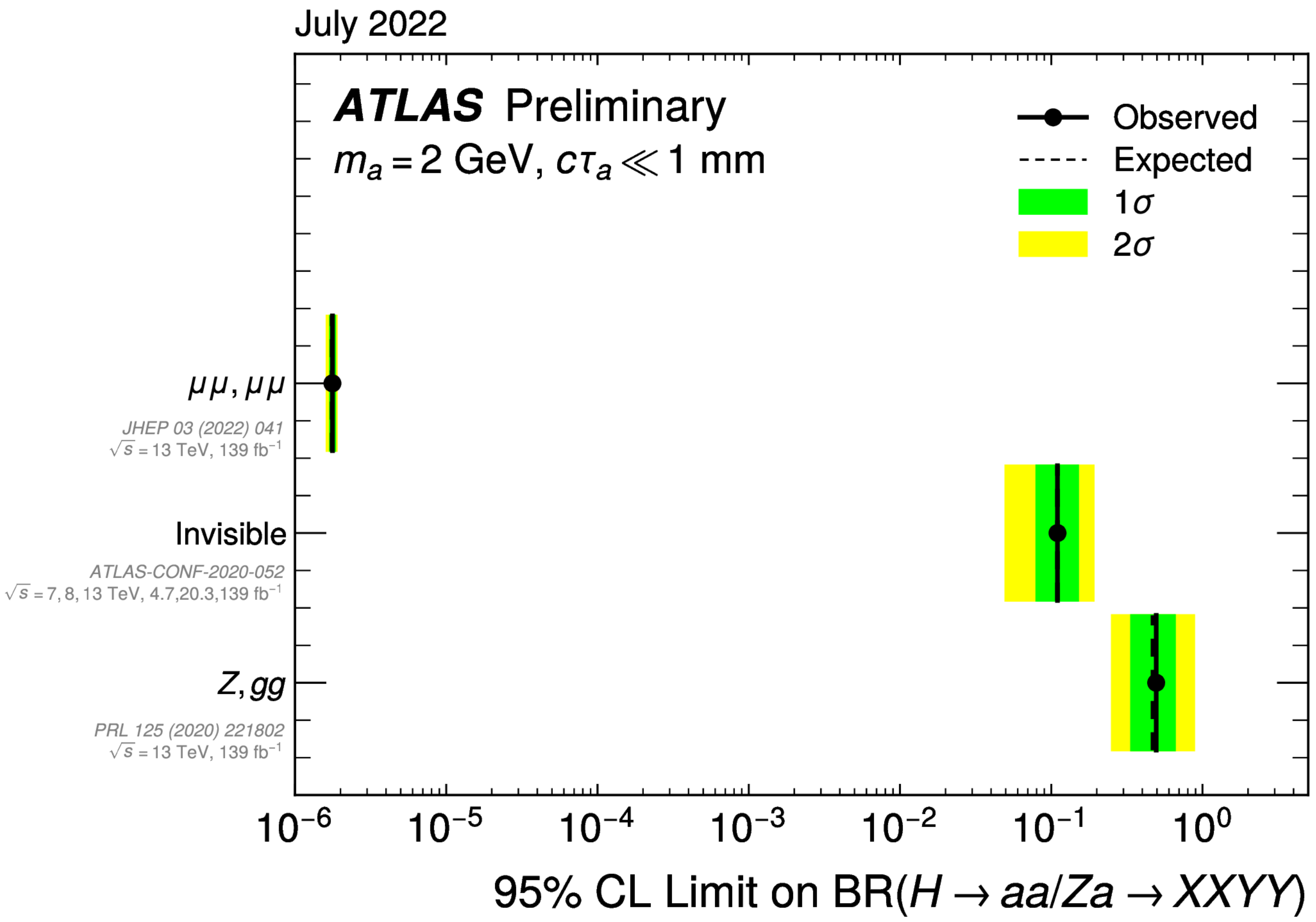


New full Run-2 results of this analysis in this talk

ATLAS-PHYS-PUB-2025-011

BSM Higgs Boson Decays- ATLAS

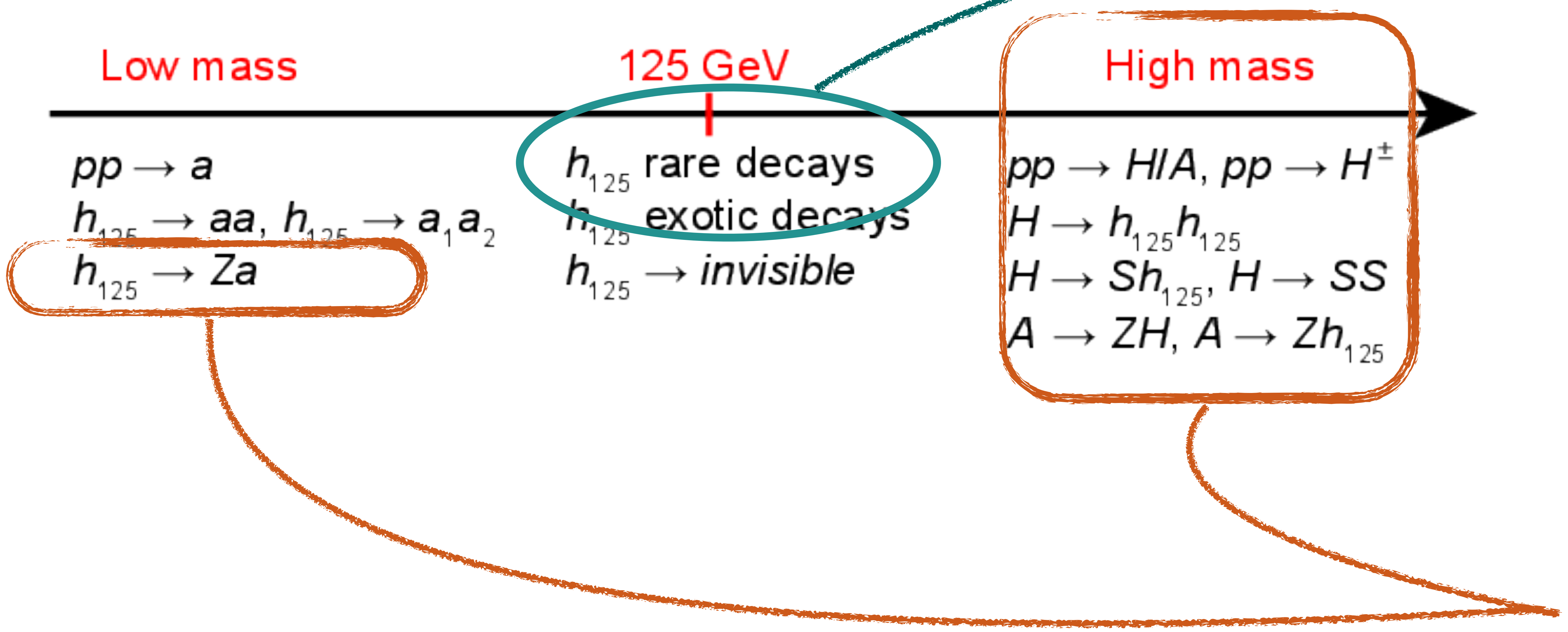




ATLAS-PHYS-PUB-2025-011

A quick recap of last year

- Summary of ATLAS searches for additional scalar and exotic Higgs decays
  [DOI: 10.1016/j.physrep.2024.09.002]



From [Huacheng Cai talk] in Higgs Hunting 2024

- $H \to \omega/K^* + \gamma$ [10.1016/j.physletb.2023.138292]
- $H \to D^*\gamma$ [10.1016/j.physletb.2024.138762]
- $H \to Z\gamma$ [10.1103/PhysRevLett.132.021803]

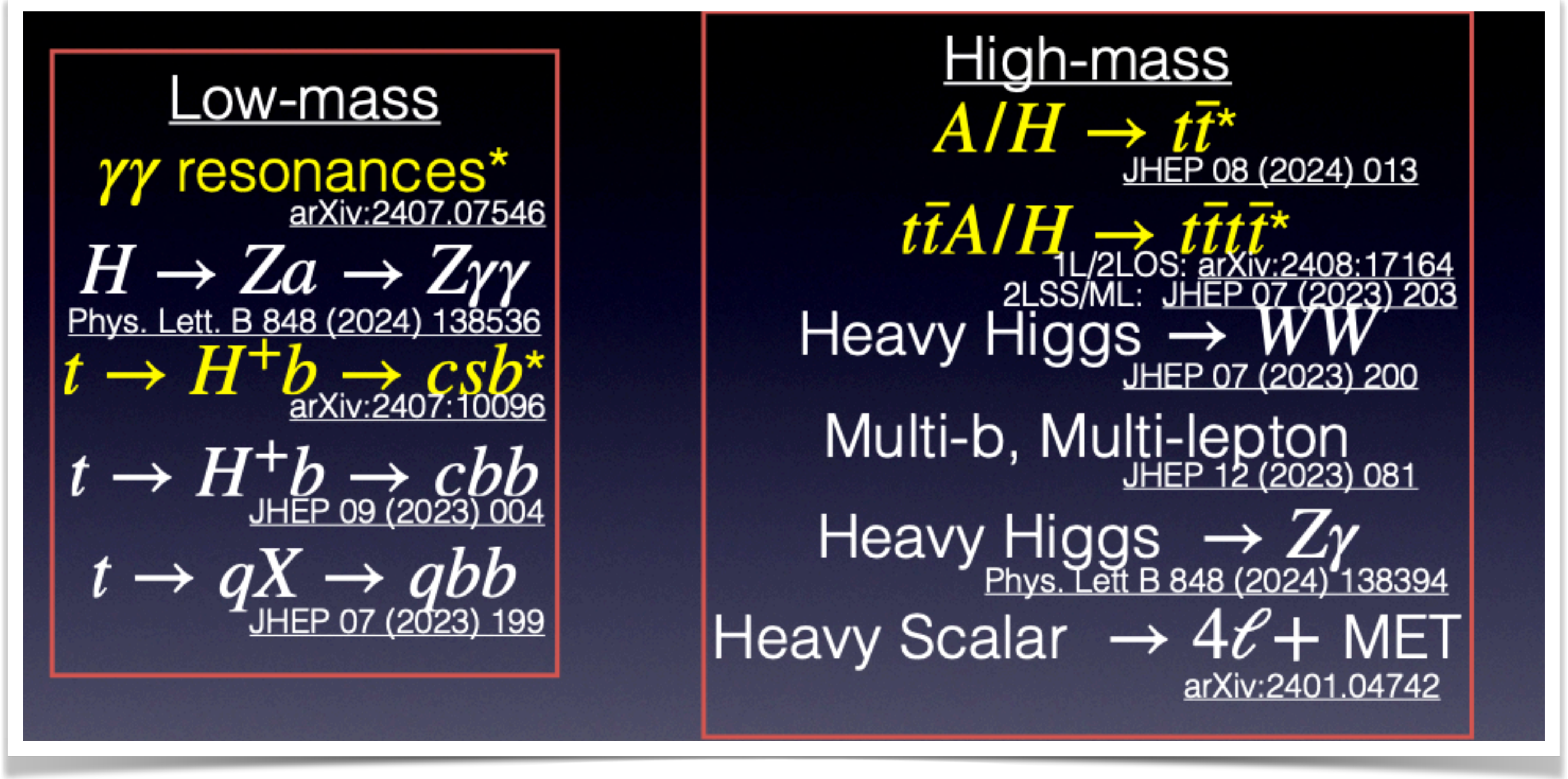
} Allowed by the SM but with extremely small BR

- $H \to b\bar{b}\tau^+\tau^-$ [arXiv:2407.01335]
- $H \to Z + \gamma\gamma$ [10.1016/j.physletb.2024.138536]

} Preferred by models introducing BSM light pseudoscalar (2HDM+s)

- $H \to e/\mu + \tau$ [10.1007/JHEP07(2023)166] → Search for Lepton-flavour-violating (LFV)

From [E.Varnes talk] in Higgs Hunting 2024



Latest ATLAS results

Light resonances
[0.5 - 60] GeV

- HZ, H→ αα →4b, 6b, arXiv:2507.01165
- H→aa→ γγττ, DOI: 10.1007/JHEP03(2025)190
- H→aa → ττττ, arXiv:2503.0563
- H→ Za→ llγγ and H → aa → 4γ, ATL-PHYS_PUB-2025-007
  long lived ALPS reinterpretation
- H→Za→lljets, DOI: 10.1016/j.physletb.2025.139671

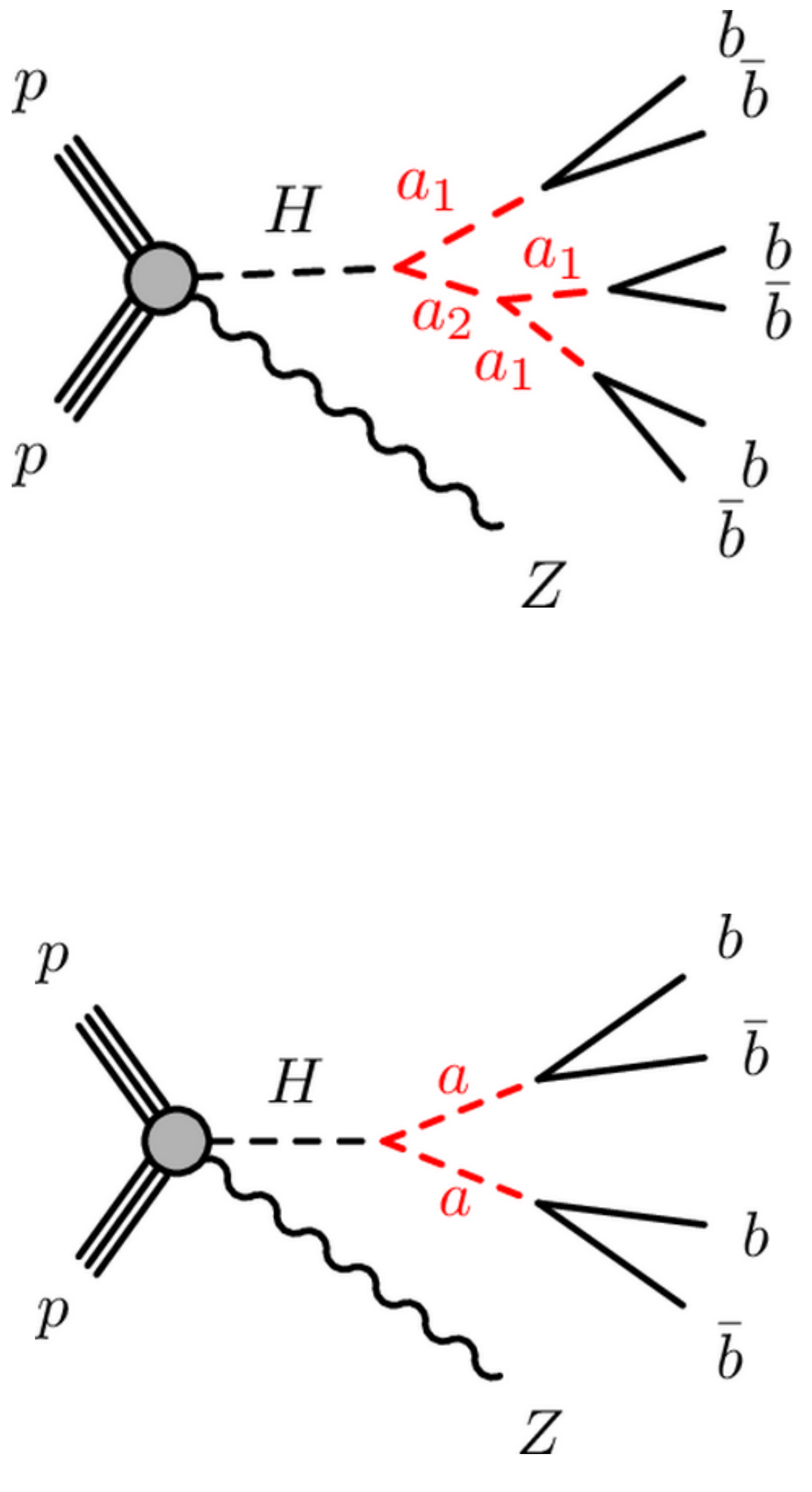
Searches exploring
higher mass ranges
30 GeV up to 3TeV

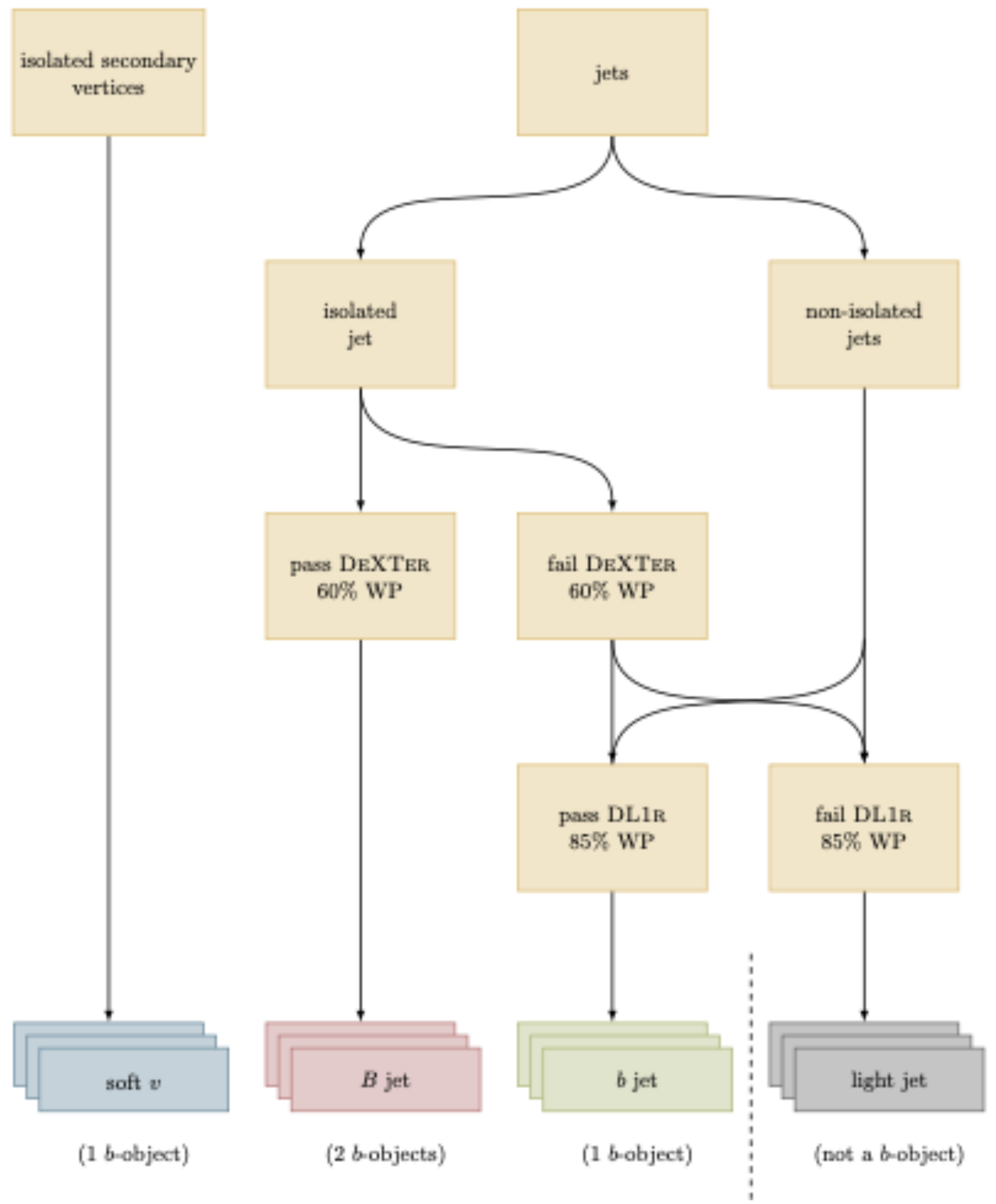
- S → XX → 4leptons, DOI:10.1016/j.physletb.2025.139472
- $H^{\pm}$ → WH , H →bb, DOI: 10.1007/JHEP02(2025)143
- $H^{\pm}$ → $\tau^{\pm}$ ν, DOI: 10.1103/PhysRevD.111.072006
- **Not in this talk**: Weakly-supervised anomaly detection in dijet final states , arXiv:2502.09770

H→aa → 4b, 6b

arXiv:2507.01165

- *ZH* production, the first exotic search
- Mass range: [12,60] GeV
- 4 and 6 *b*-quarks in the final state
- Z for triggering, both Z → ll and Z → νν (missing p_T) , defining two channels: 0, and 2 leptons
- Main backgrounds : Z+jets, ttbar, constrained by CR
- Improvement wrt partial Run 2 search: dedicated heavy-flavor reconstruction algorithms, DeXTer algorithm [ATL-PHYS-PUB-2022-042]
- Challenges:
  - (m_a < 20 GeV: decay products collimated with low p_T)
  - Correctly pair the jets to form a





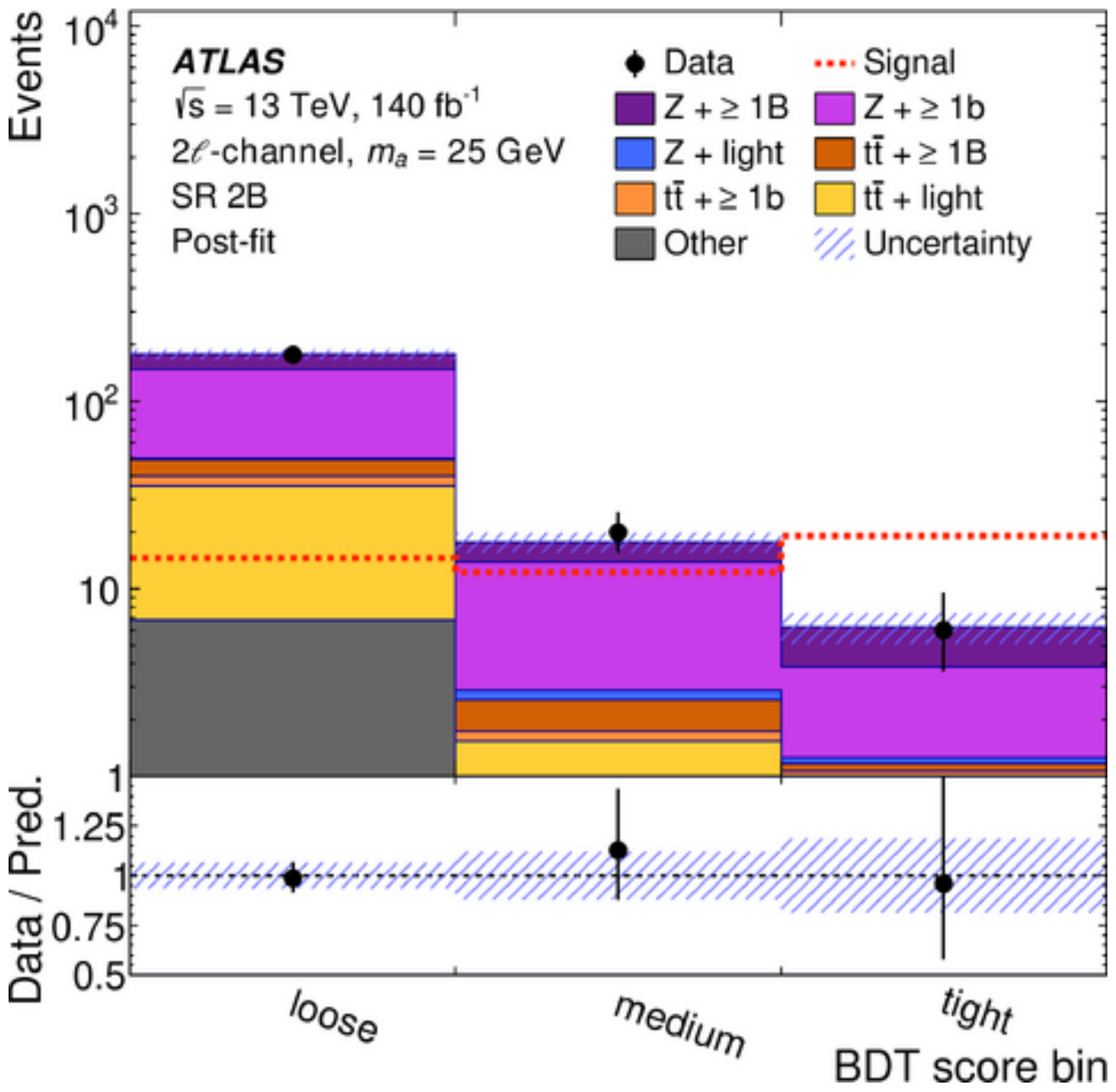
H→ aa → 4b, 6b

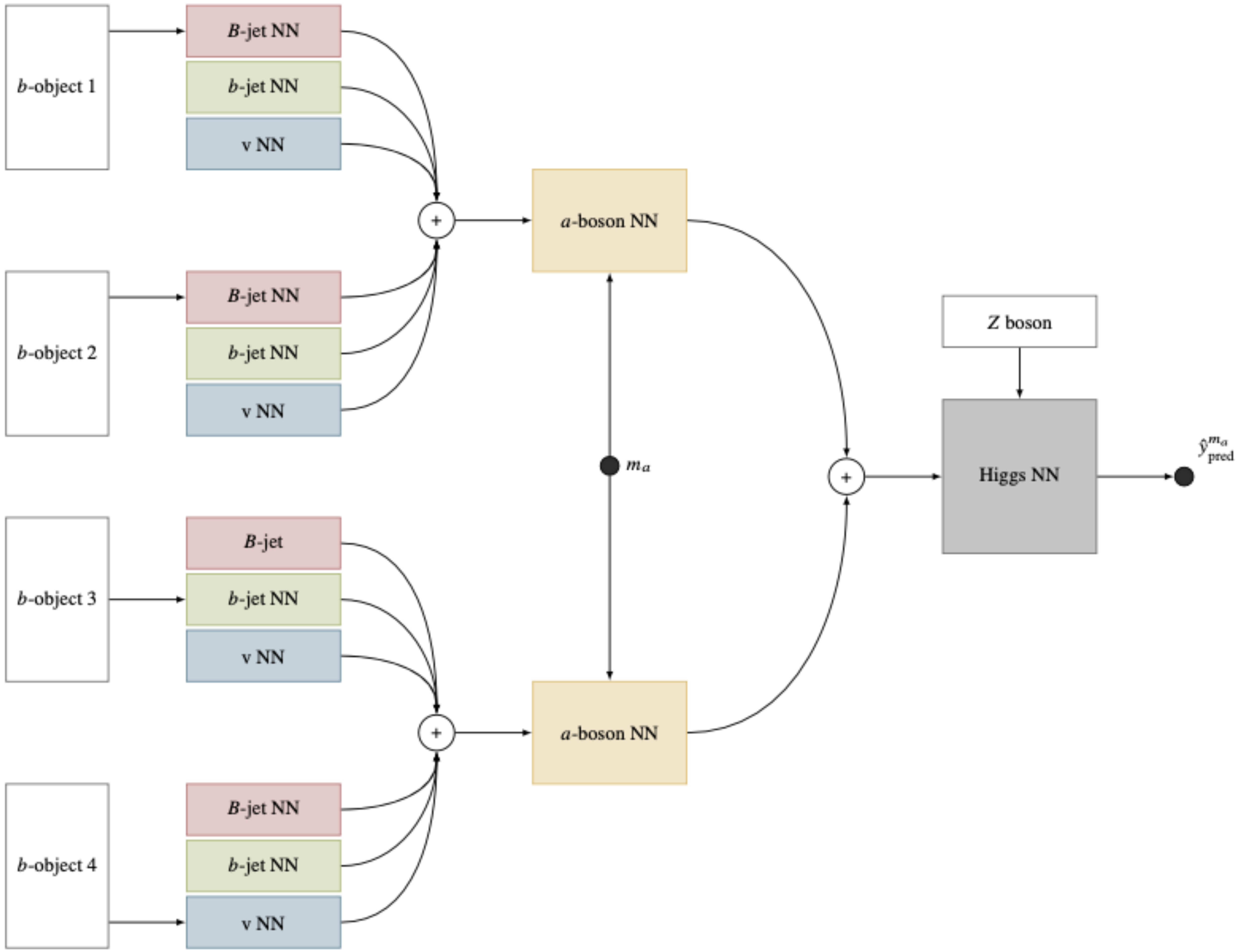
arXiv:2507.01165

The signal events are selected based on their conmpatibility with the Higgs boson hypothesis determined by a “quadruplet selection NN”

Signal to Bg discrimination: BDT

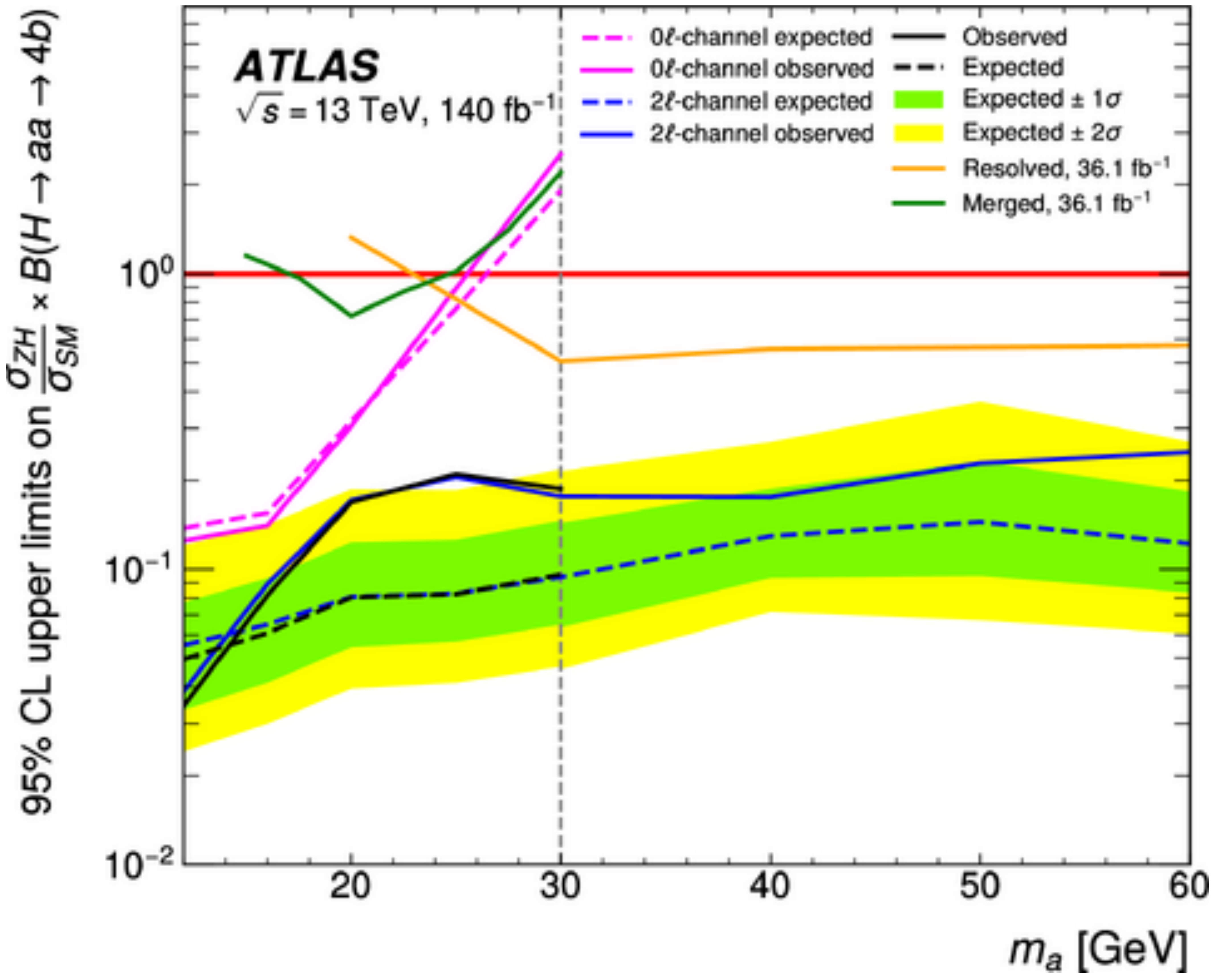
Main fit discriminant: BDT score

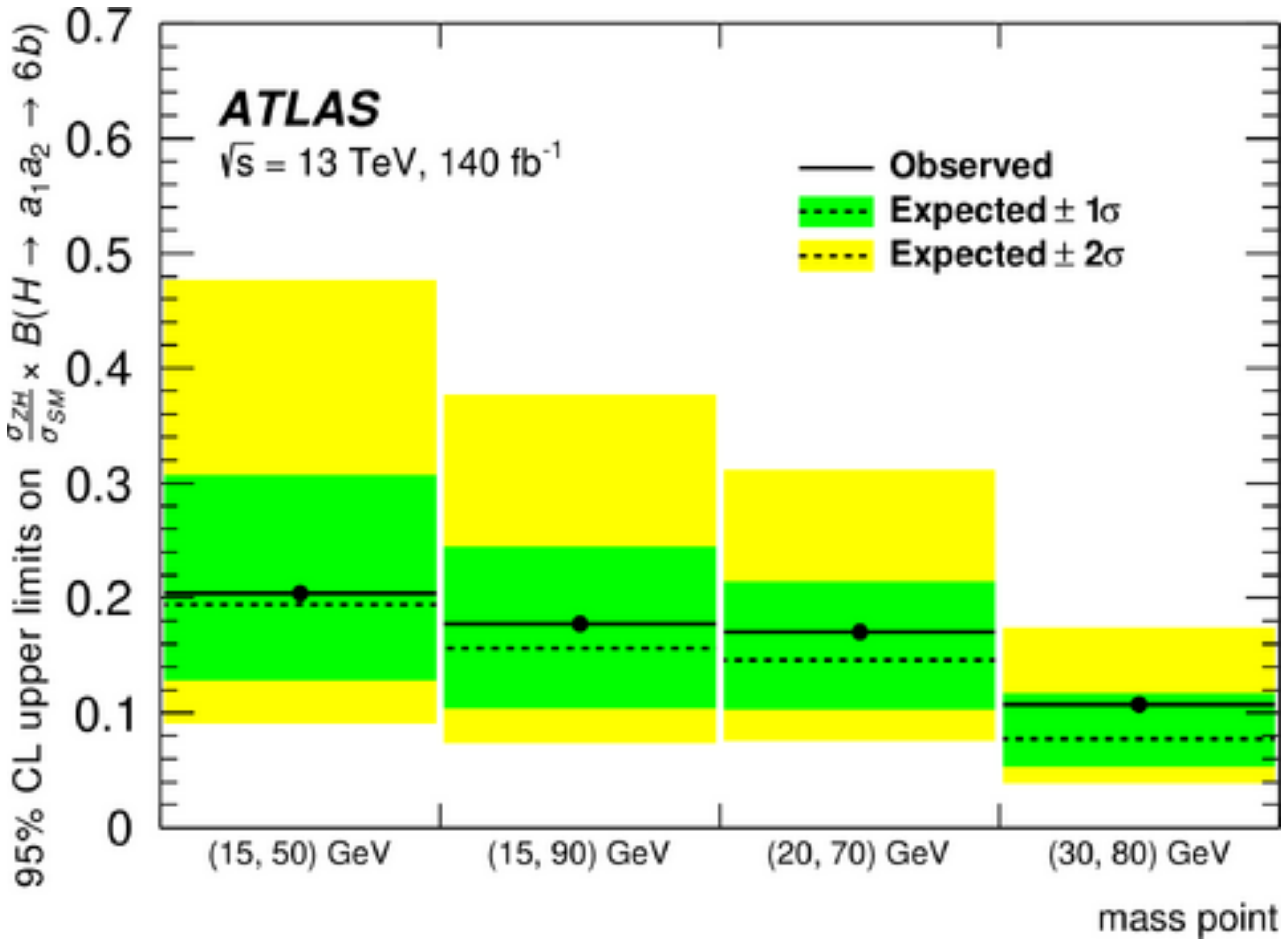




H→aa → 4b, 6b

arXiv:2507.01165

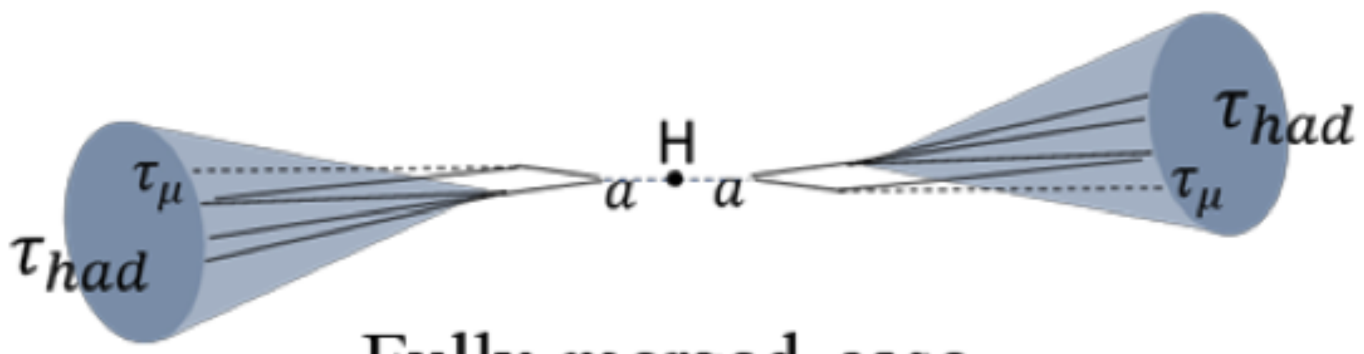




arXiv:2503.0563

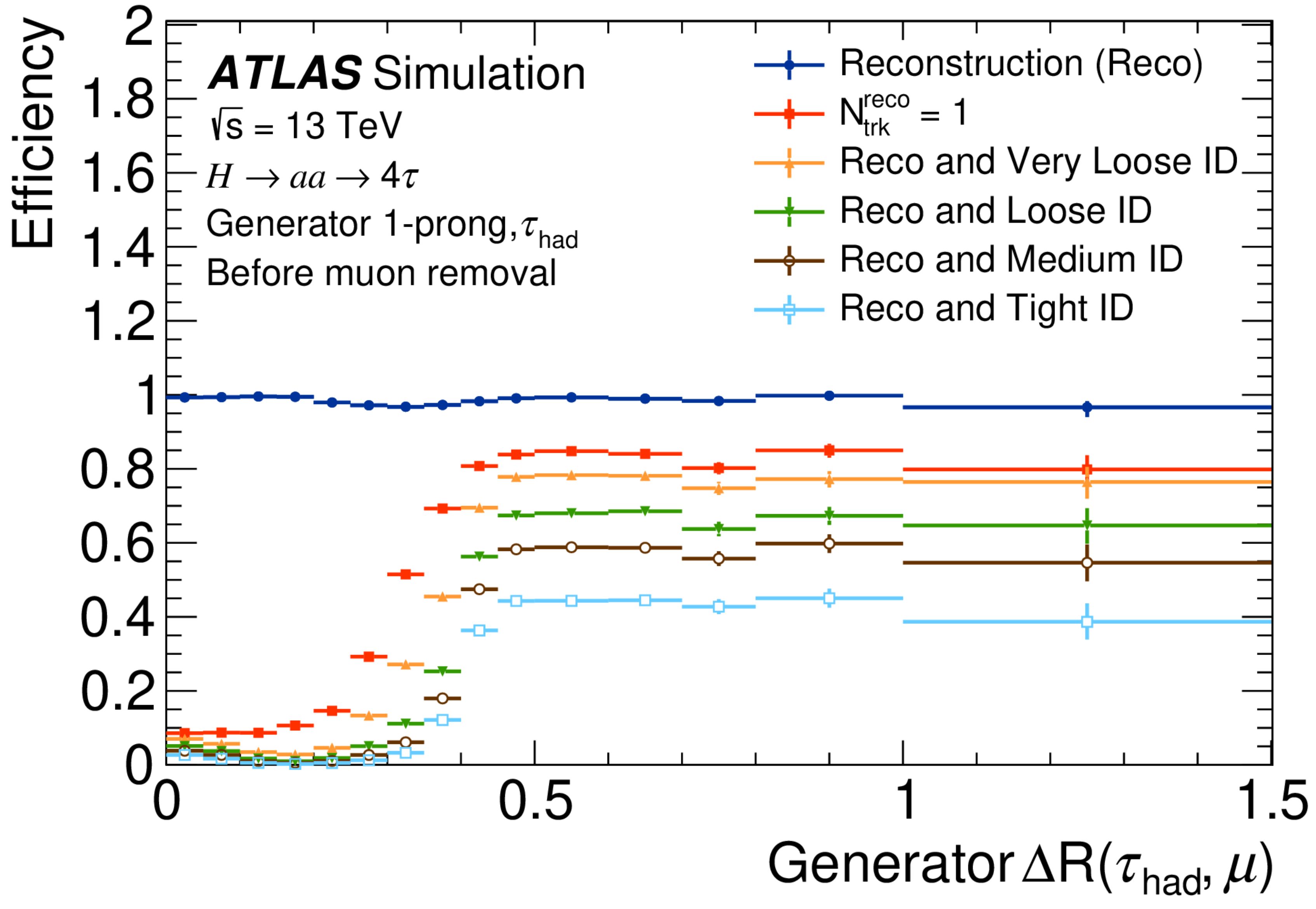
H→ aa → ττττ

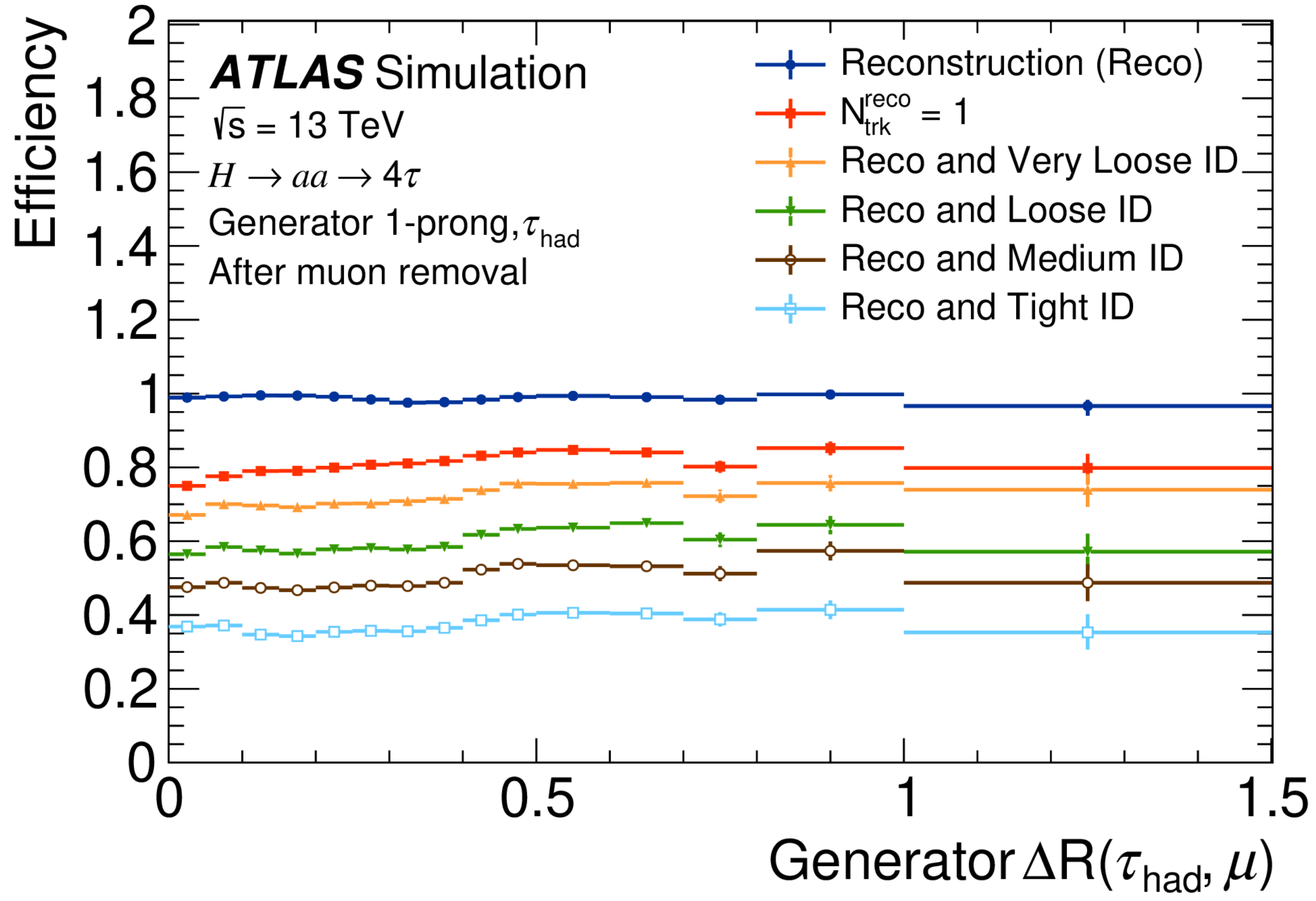
- a mass range [4,15] GeV
- $\tau^+\tau^- \rightarrow$ hadrons and μ (and neutrinos)
- Boosted a decays into merged di–τ



Fully merged case

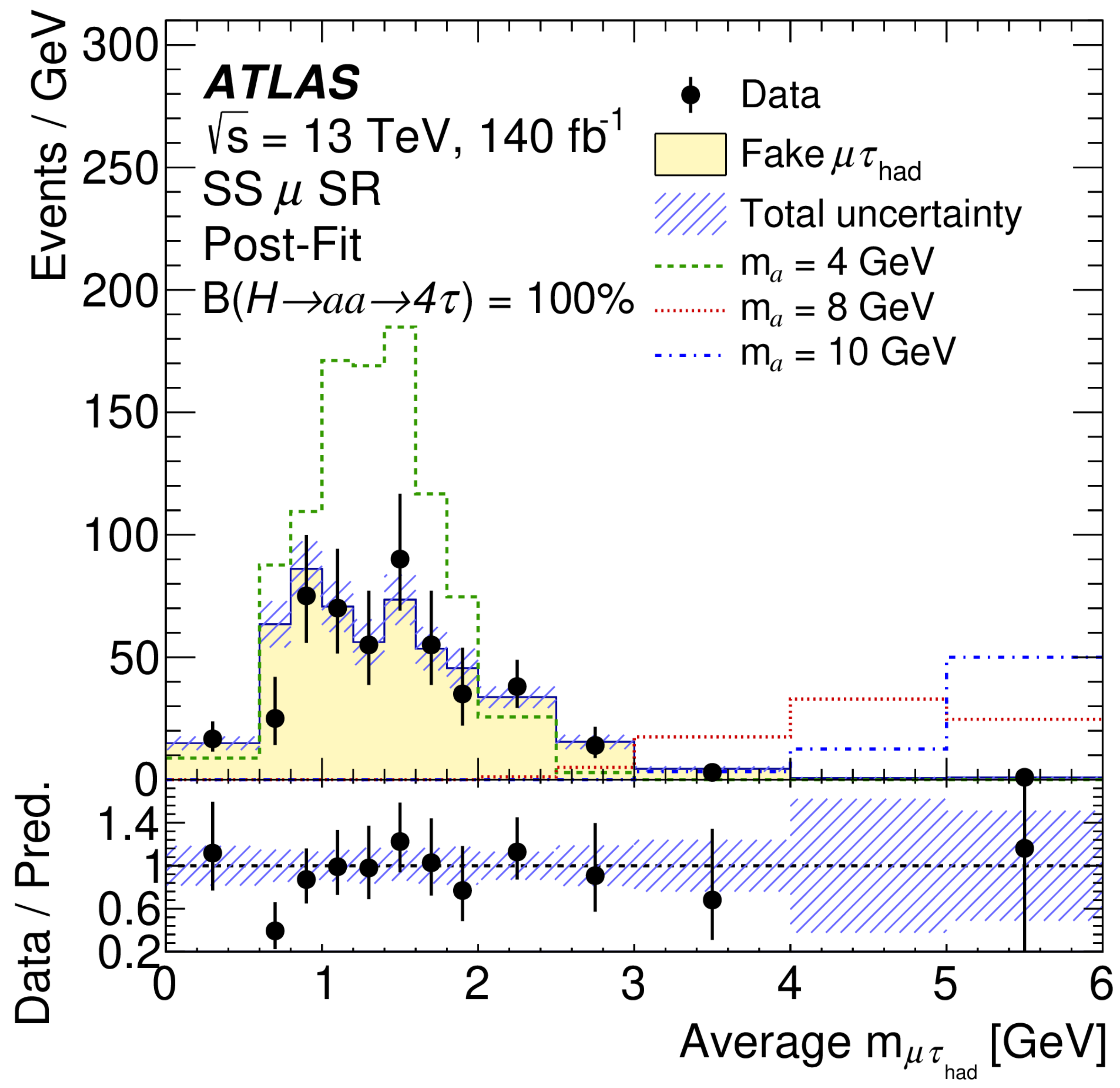
- Main challenge: identify the merged $\mu\tau_{had}$ object.
  - RNN for the hadronically decaying τ: reduced efficiency
  - μ removal technique: remove tracks and calo-clusters associated to the muon
- Main source of uncertainty : modelling of fake τ
- Statistically limited for higher masses

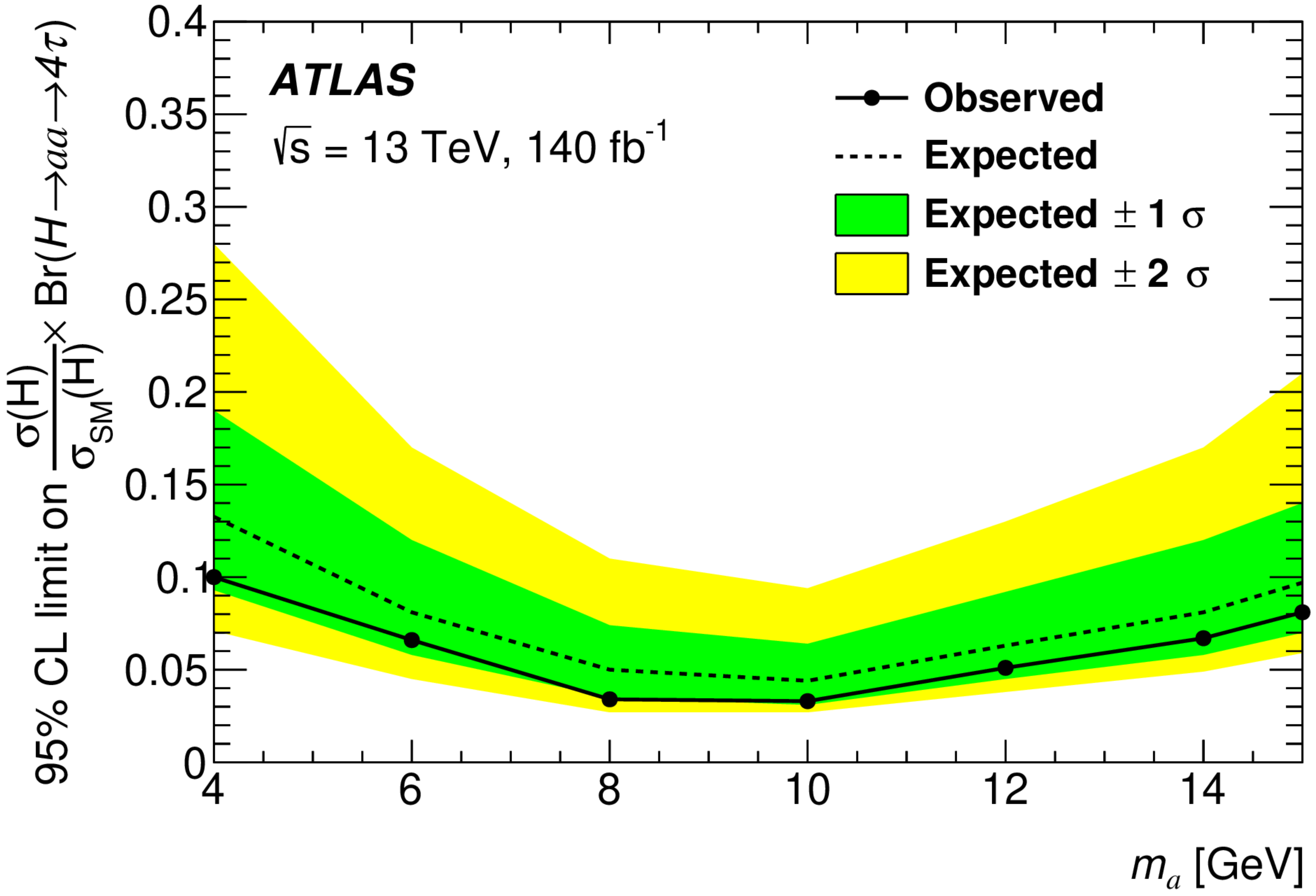




H→ aa → ττττ

arXiv:2503.0563



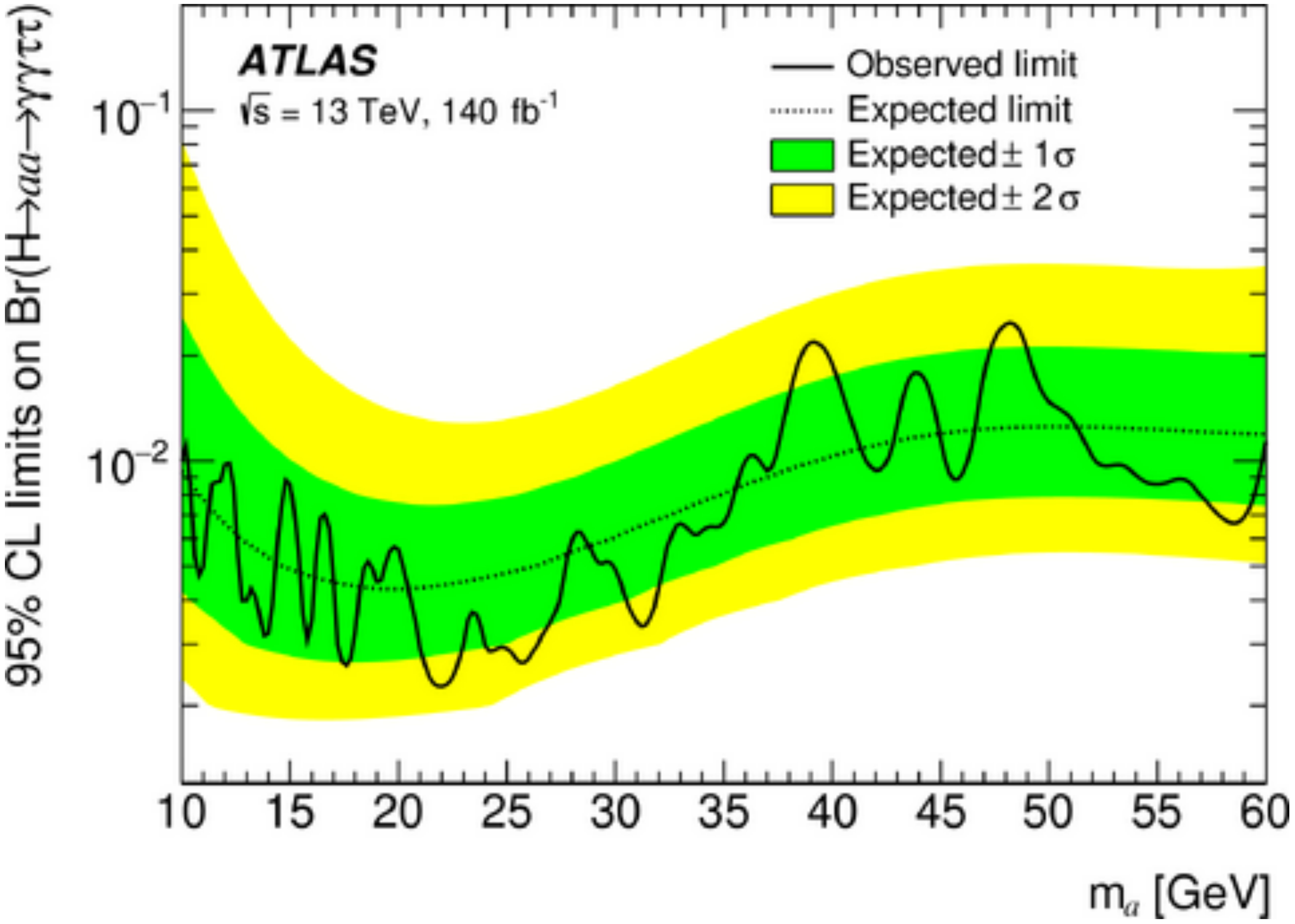


Main sources of systematic uncertainty in this search are the ones related to the modelling of the fake-τ background. Also statistically limited for higher masses

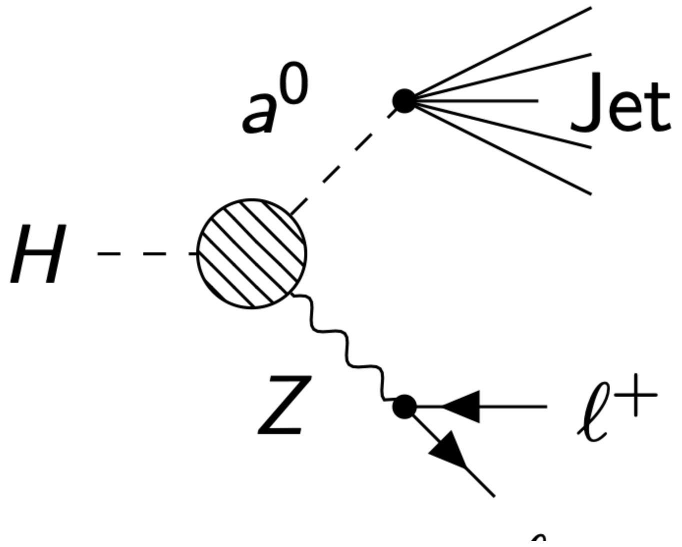
H→aa→ γγττ

DOI: 10.1007/JHEP03(2025)190

- First analysis to look at this decay channel
- ggF production mode only
- Use of diphoton triggers – main limitation thresholds at 20GeV
- Trained BDT to identified merged tau leptons
- Upper limits ranging from 0.2% to 2%, depending on the -boson mass hypothesis.

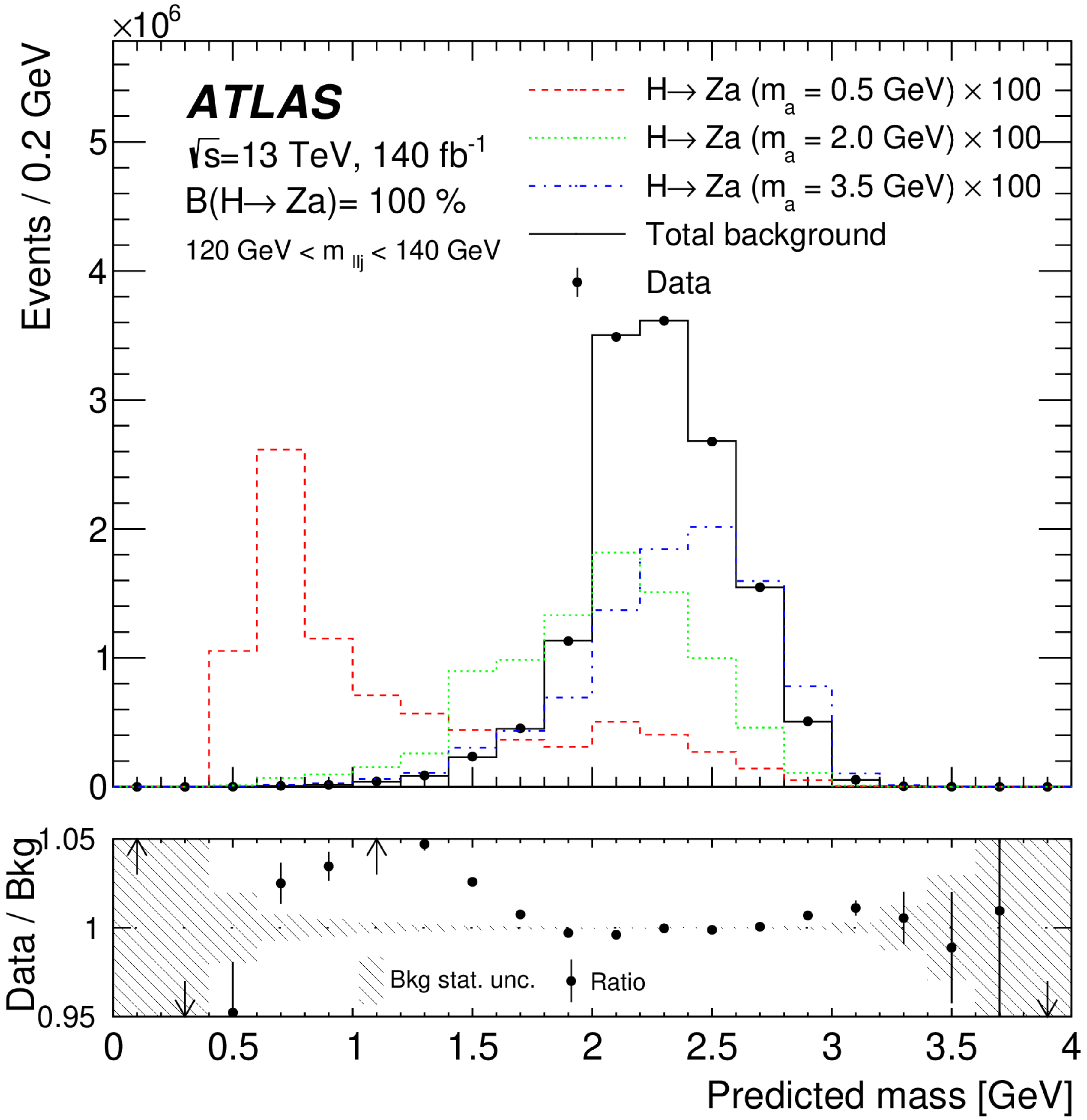


$H \to Za$, a hadronic decays

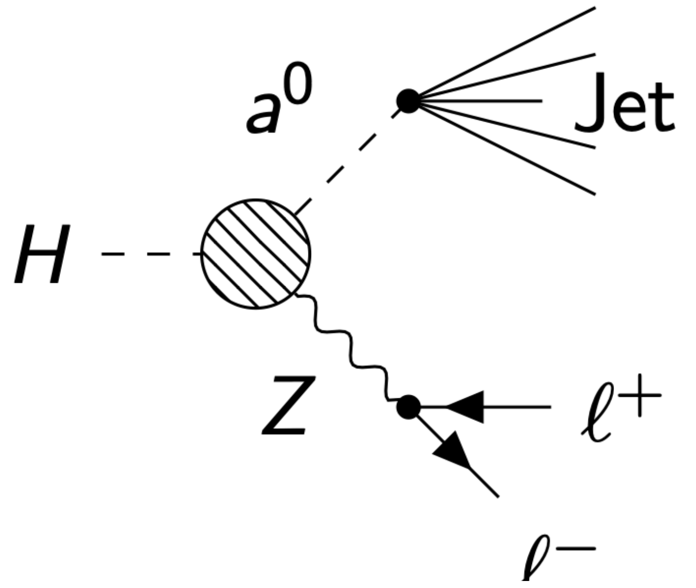


DOI: 10.1016/j.physletb.2025.139671

- Targeting extremely low masses for a [0.5,4] GeV, in many models a → hadrons significant
- Classification NN which uses reconstructed mass information in the training
- Main challenges :
    - Calorimeter resolution for low mass jets. **Solution**: predict the mass using regression NN



H → Za , a hadronic decays



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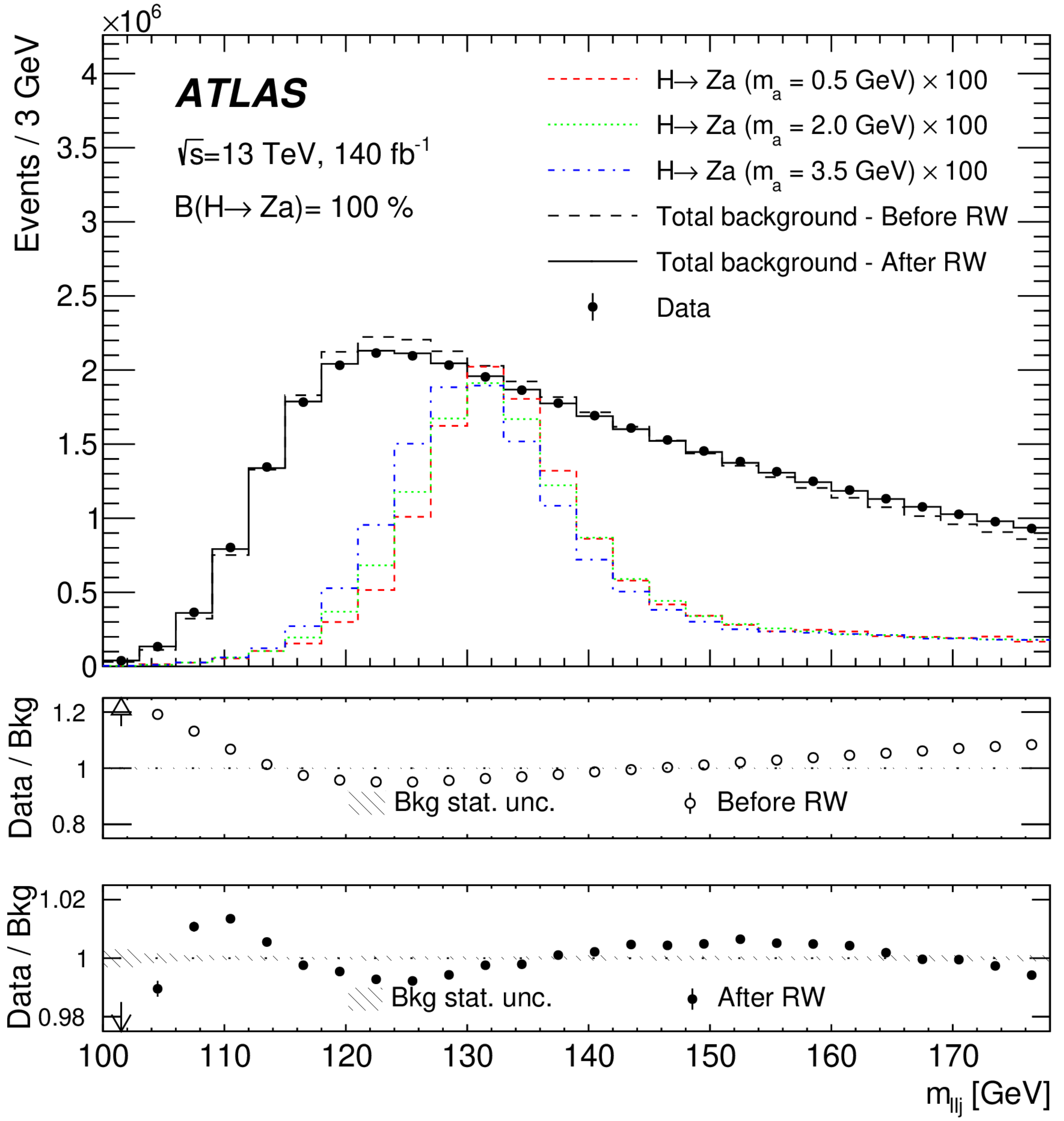
- Classification NN which uses reconstructed mass information in the training
- Main challenges :
  - Calorimeter resolution for low mass jets. **Solution**: predict the mass using regression NN
  - Simulation can't describe crucial jet substructure variables. **Solution**: re-weight distribution using NN



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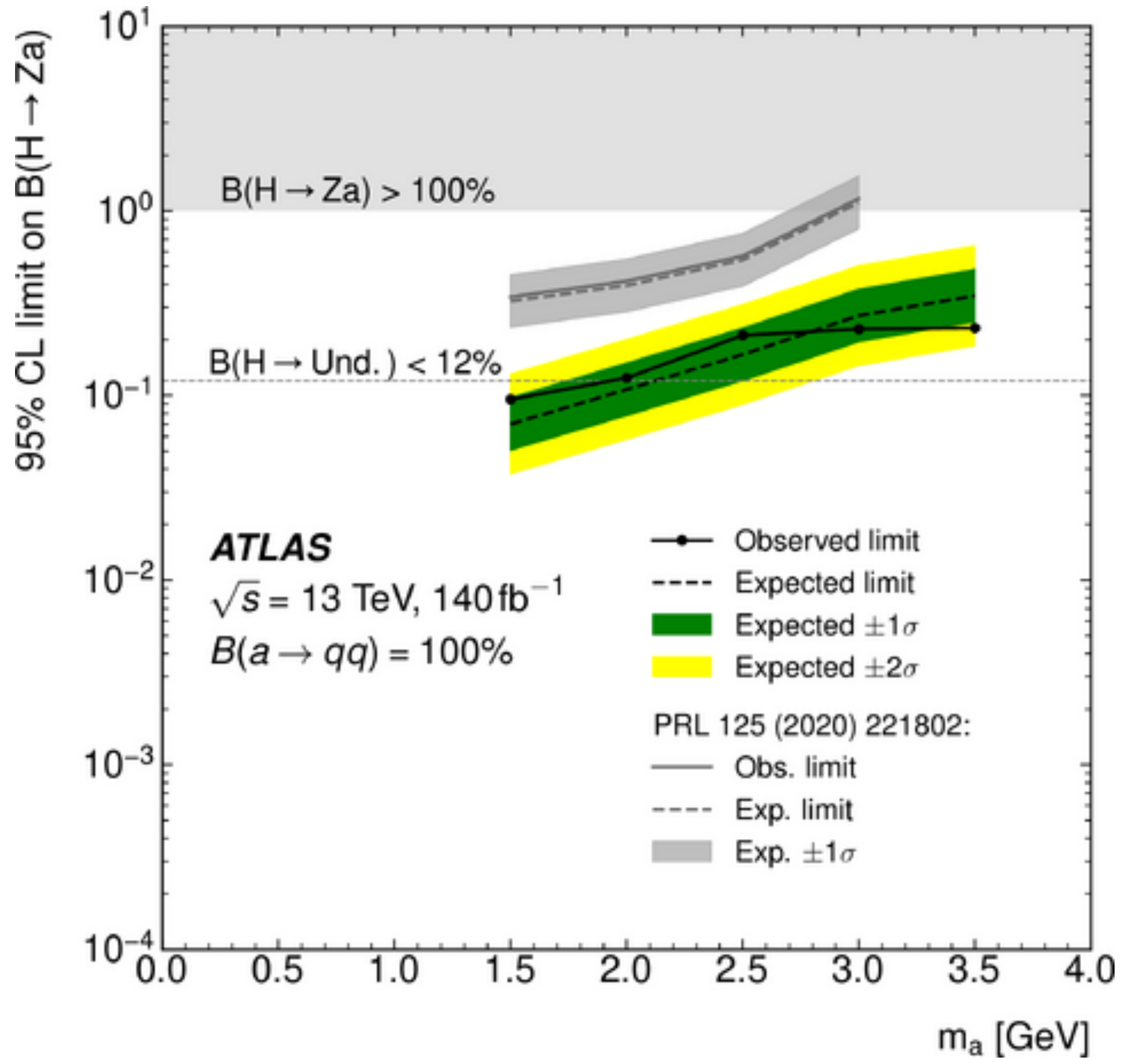
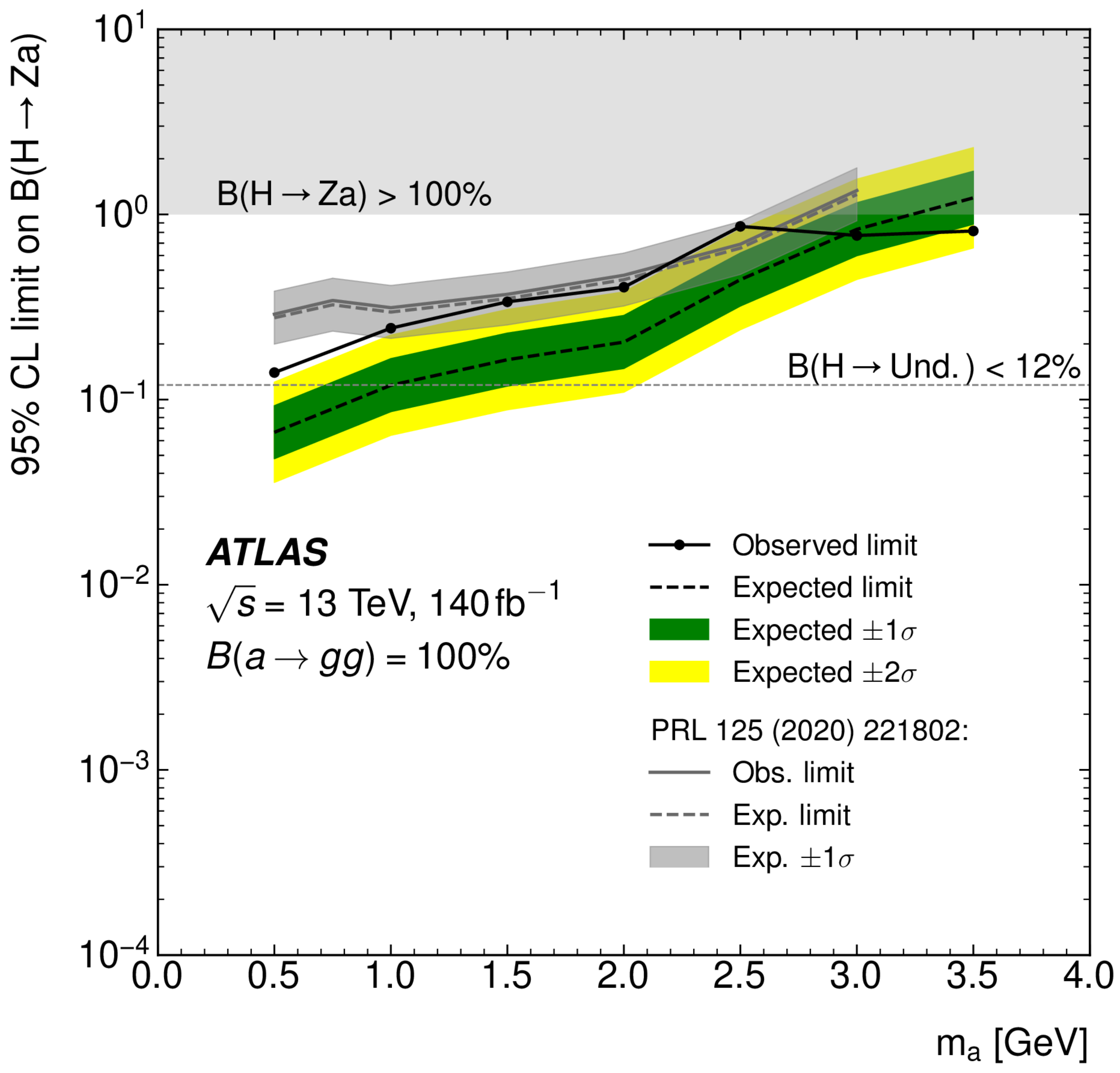
H → Za , a hadronic decays



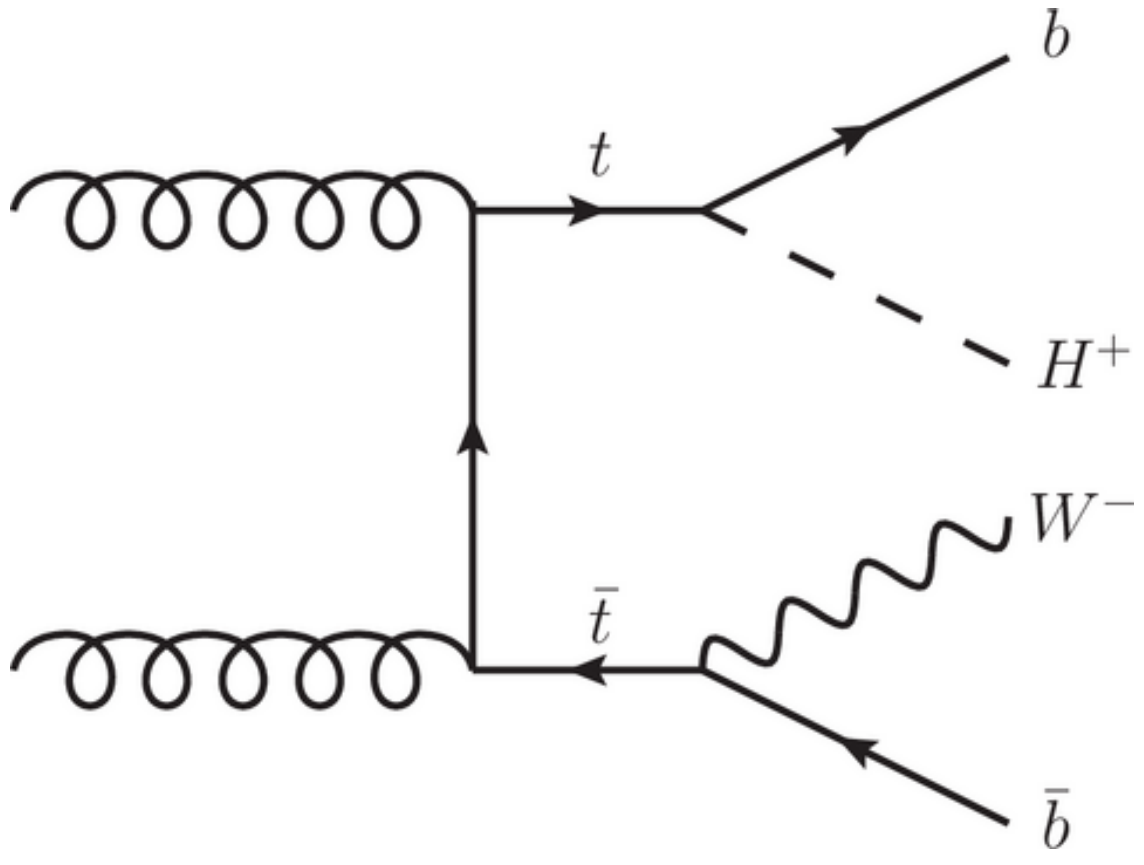


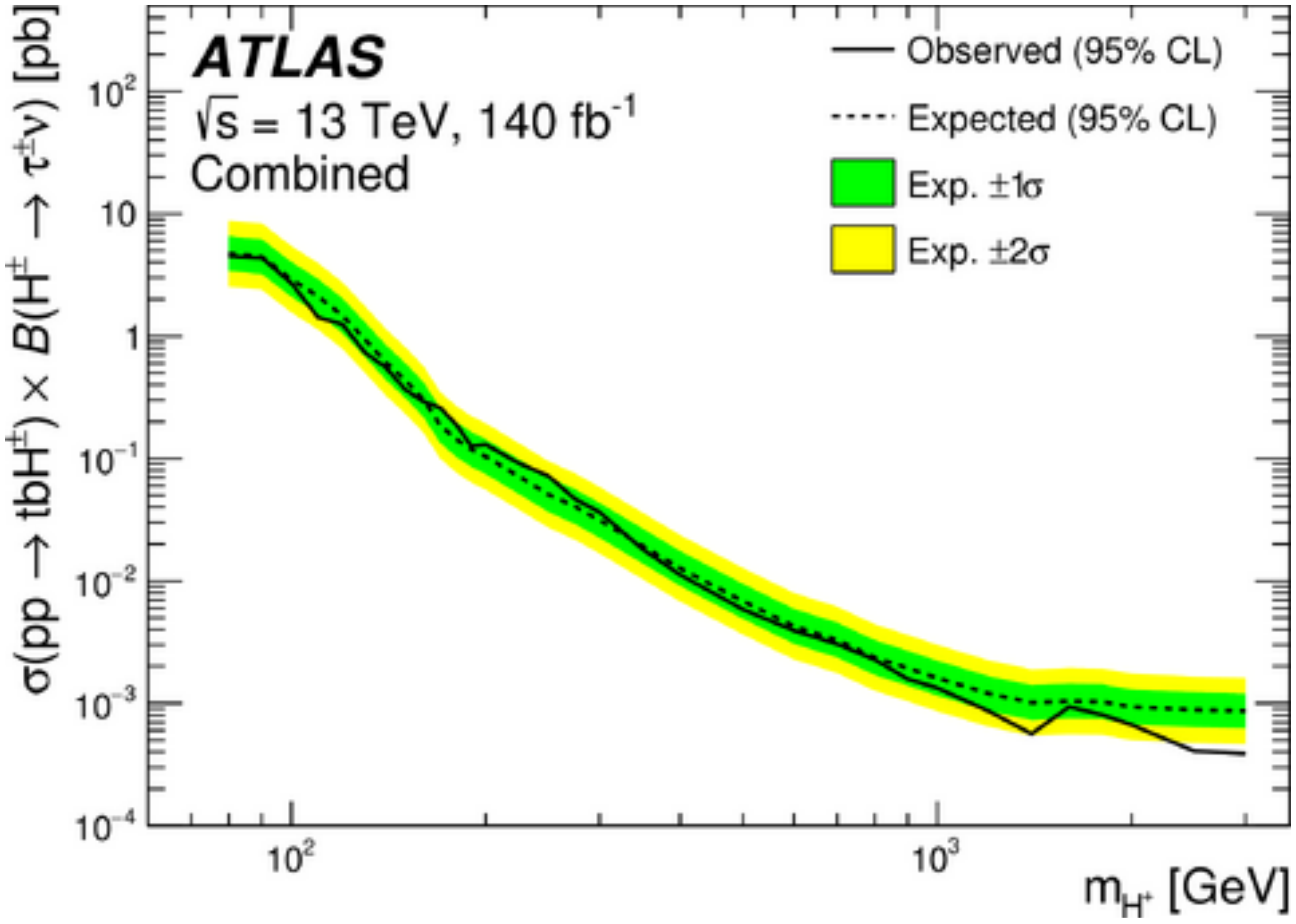
Factor of three limit improvement compared to previous Run-2 result for a → qq
Main limitation: ps signal modelling uncertainty, higher for the a → gg

$H^{\pm} \rightarrow \tau^{\pm} \nu$

DOI: 10.1103/PhysRevD.111.072006

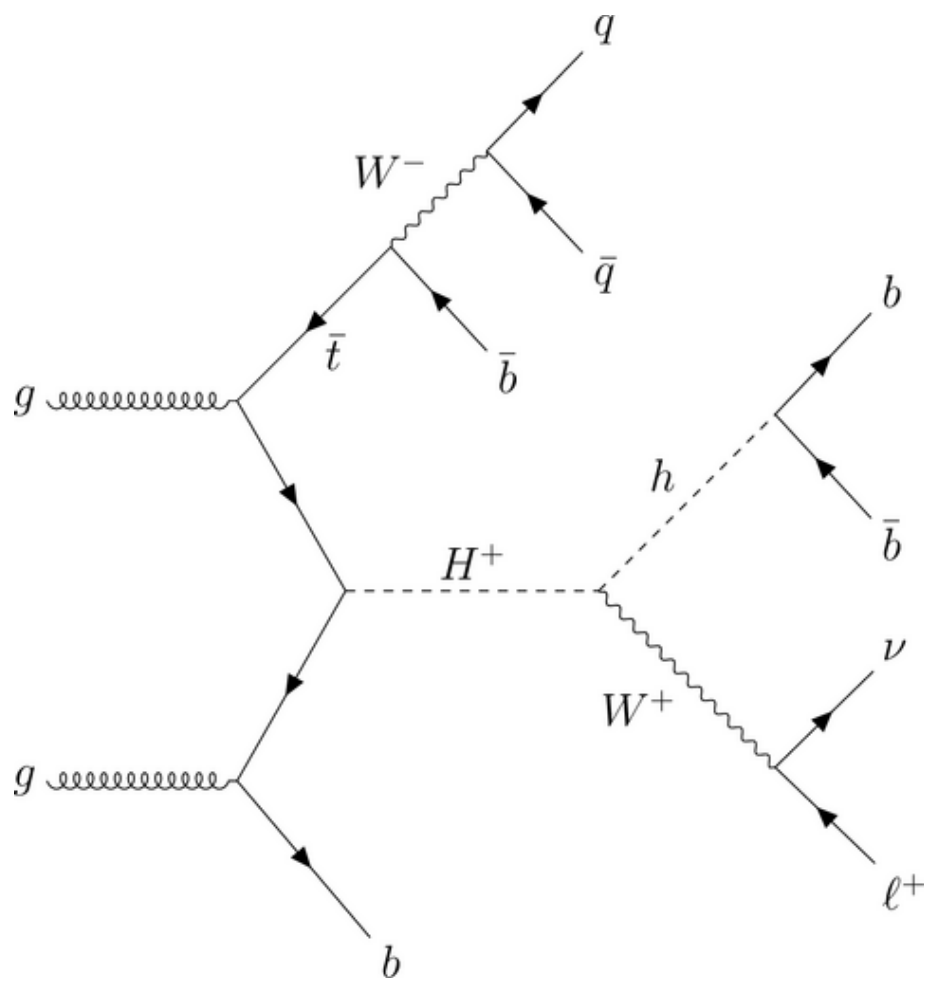
- Production through top quark decays and t-associate production
- Final states: τ+jets and τ+μ, τ+e
- Final discriminant: PNN , trained with the generator-level H^+ mass → classifiers for every mass hypothesis

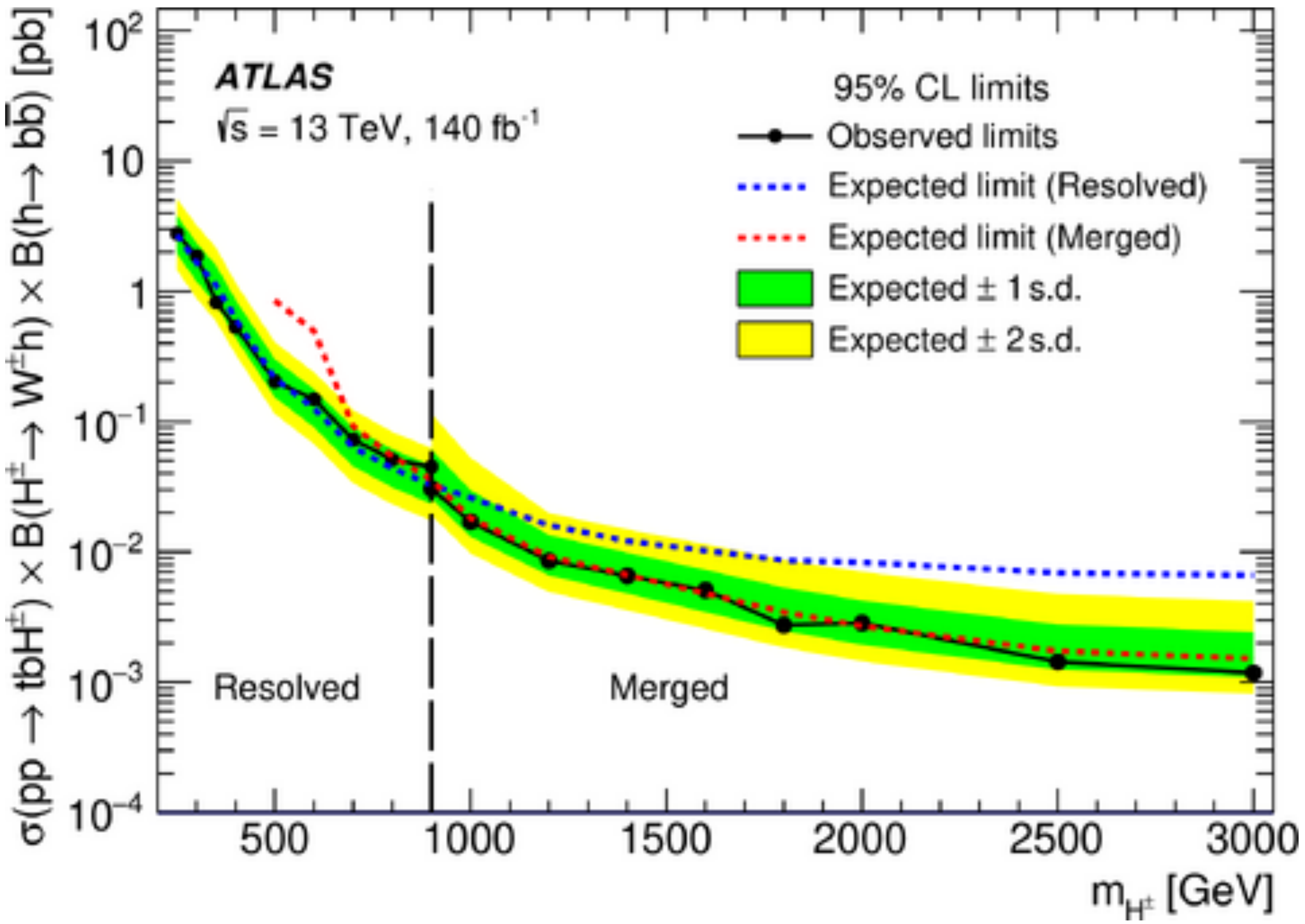




H± → WH , H →bb

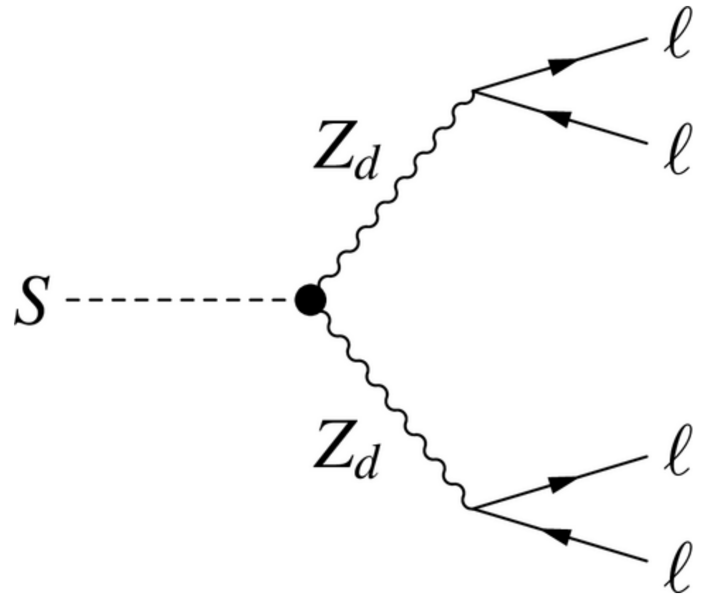
- Production in association with a top and a bottom quark,
- Resolve for low and boosted for high mass regime
- Charged H mass: [250 GeV, 3 TeV]
- Flavour and Higgs tagging are crucial
- NN to reconstruct boosted Higgs bosons (H →bb)
- Limits on $\sigma\,(pp \rightarrow tbH^{\pm}) \times \mathrm{B}\,(H^{\pm} \rightarrow W^{\pm}\mathrm{h}) \times \mathrm{B}(\mathrm{h} \rightarrow bb)$



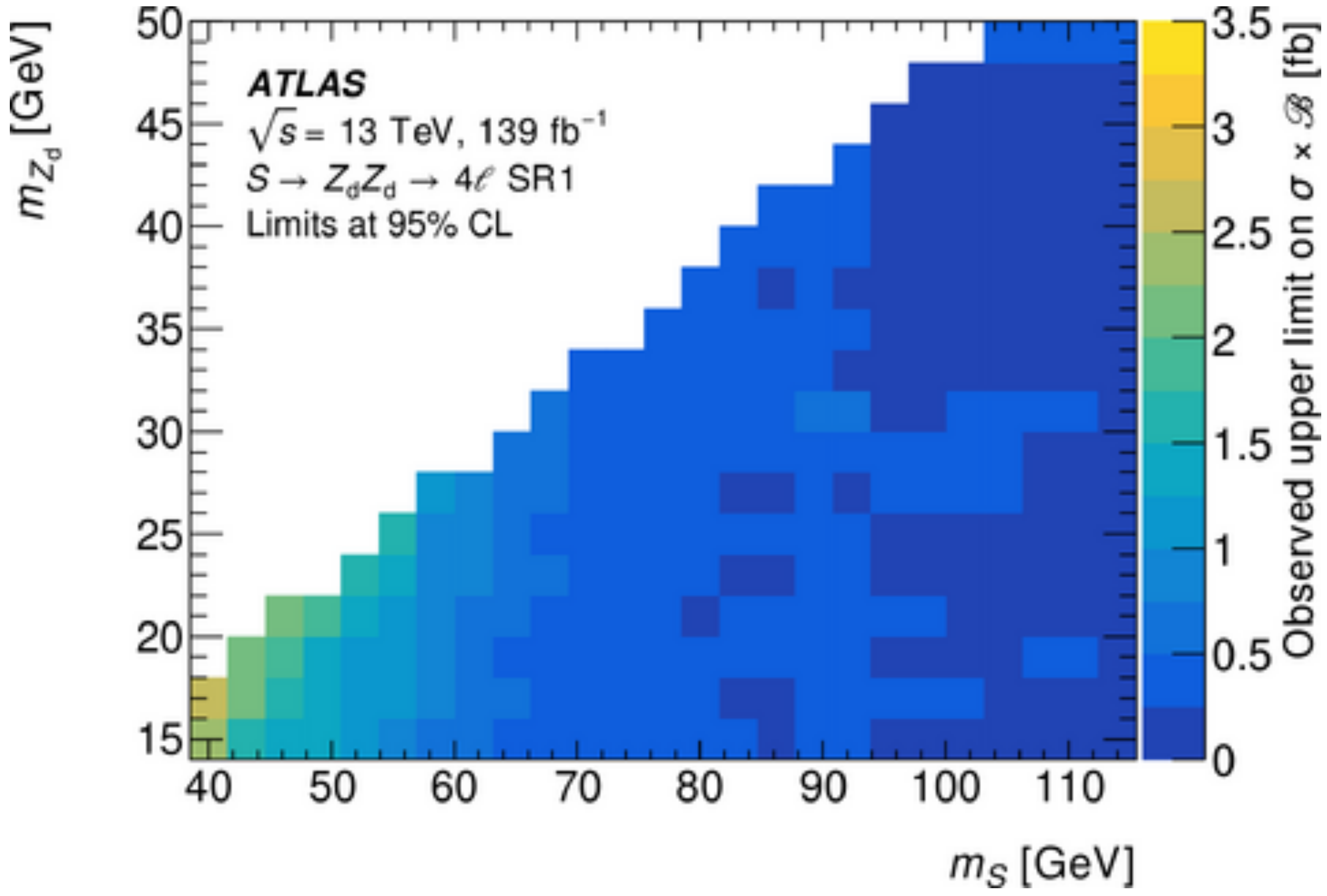


S → ZdZd→ 4leptons

DOI:10.1016/j.physletb.2025.139472



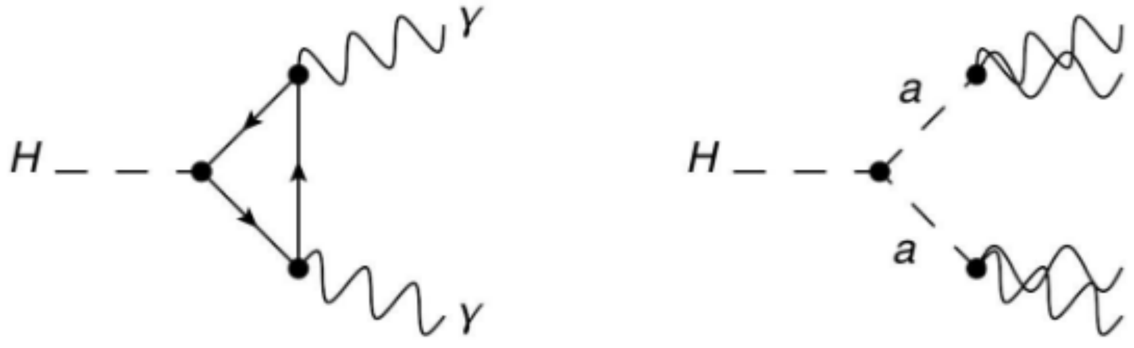
- Looking at Hidden Abelian Higgs Model (HAHM)
- Additional scalar *S* along with a new gauge boson Z_d or "dark photon"
- Same production mechanisms as SM Higgs
- Three final states: 4e,2e2μ,4μ
- BG Dominant: Non resonant SM ZZ*. WZ, VVV/VBS processes, H → ZZ → 4l, J/ψ and Υ, tt and Z+ jets
- No siginificant excess : set limits on $\sigma(gg \rightarrow S) \times B(S \rightarrow Z_d Z_d \rightarrow 4\ell)$

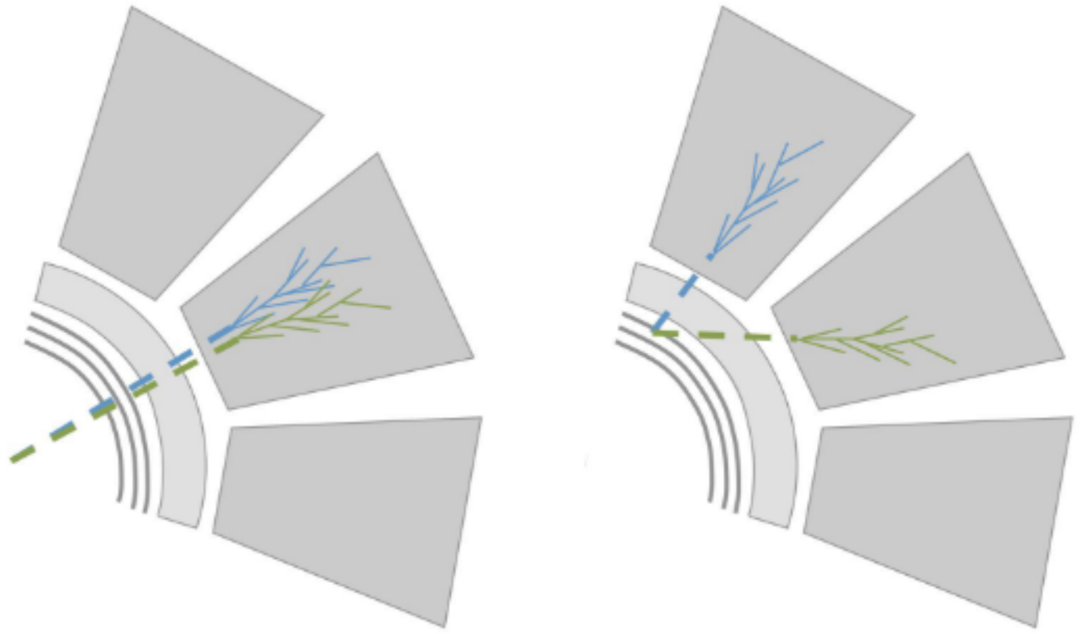


$H \rightarrow Za \rightarrow ll\gamma\gamma$ and $H \rightarrow aa \rightarrow 4\gamma$

ATL-PHYS_PUB-2025-007

- **Reinterpretation of previous searches**
- a: Axion-like particles (ALP)
- In many scenarios, the di-photon decay is the dominant
- For small $|C\gamma\gamma|/\Lambda$ ALPs long-lived
- Analysis that are re-interpreted:
  - H→Za – only promptly decaying (up to 33mm) (DOI: 10.1016/j.physletb.2024.138536)
  - H→aa – both prompt and long-lived provided (DOI: 10.1016/j.physletb.2024.138536)

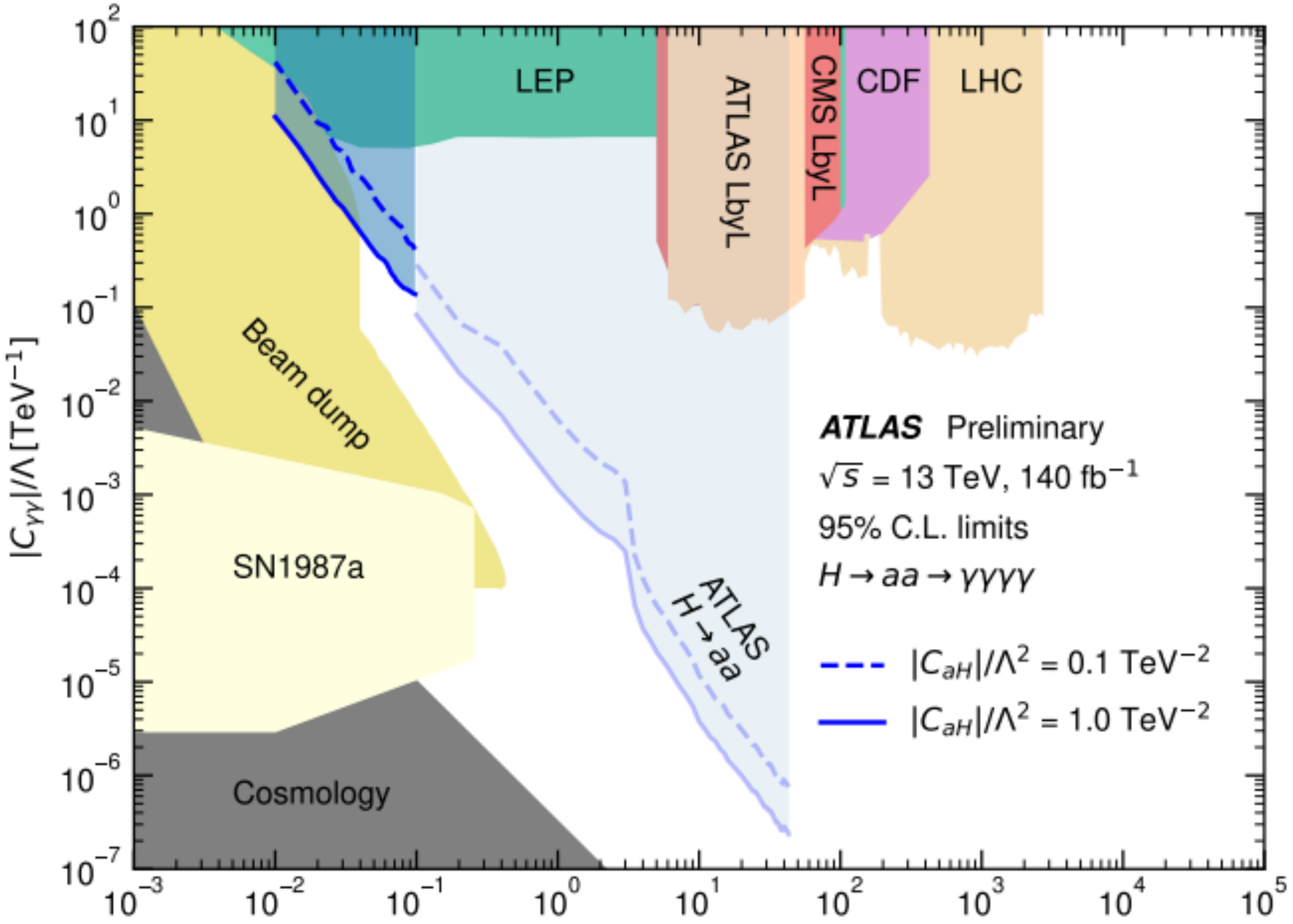


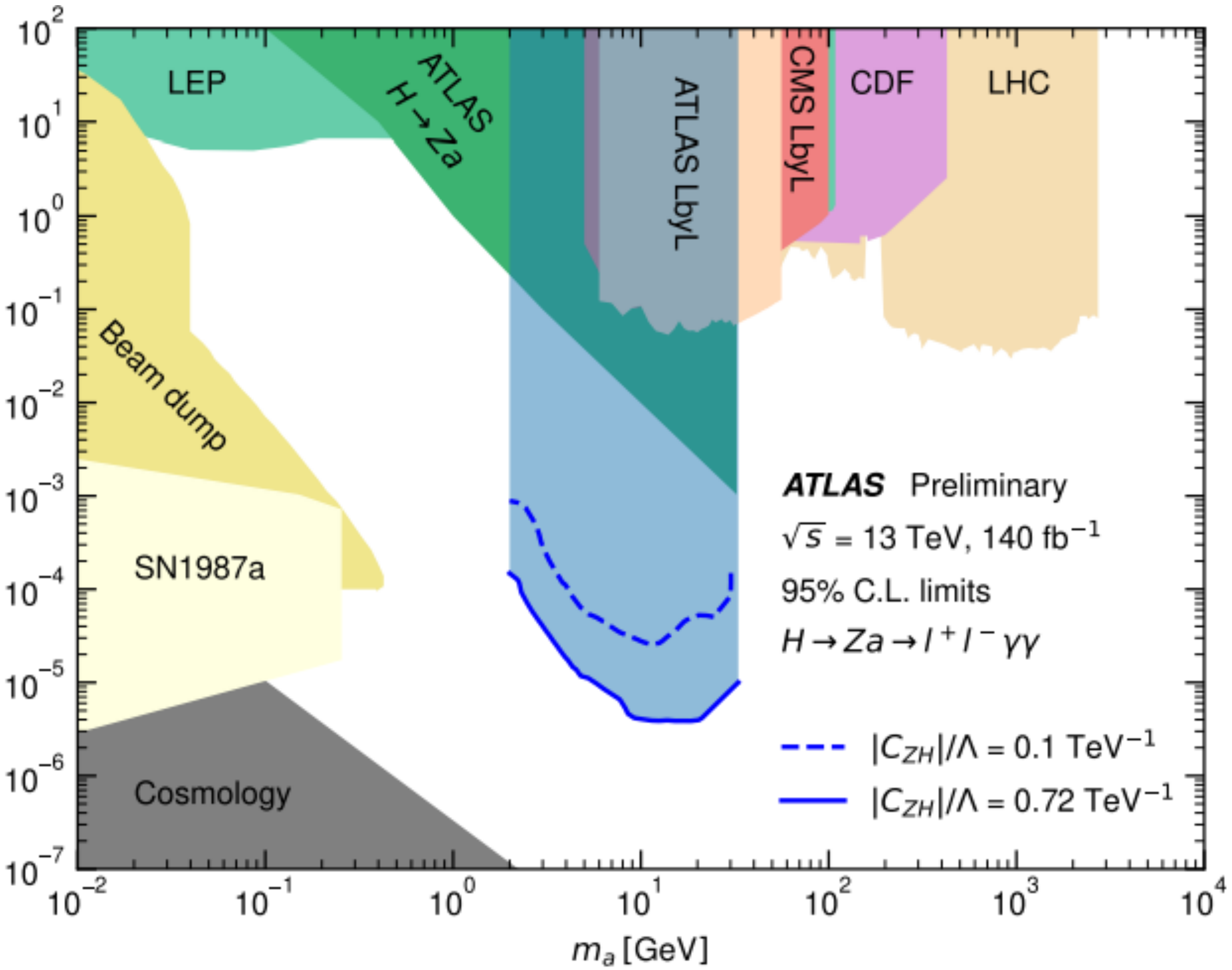


- Data and BG predictions from HEP data
- For H→Za corrected the photon ID efficiency by applying weights as functions of ALP dispacement
- H→aa : generator lvl simulated events in conjunction with efficiency maps

H→ Za → llγγ and H → aa → 4γ

ATL-PHYS_PUB-2025-007





Extended the H → aa → 4γ to lower mass points, and H→ Za by including long-lived particles

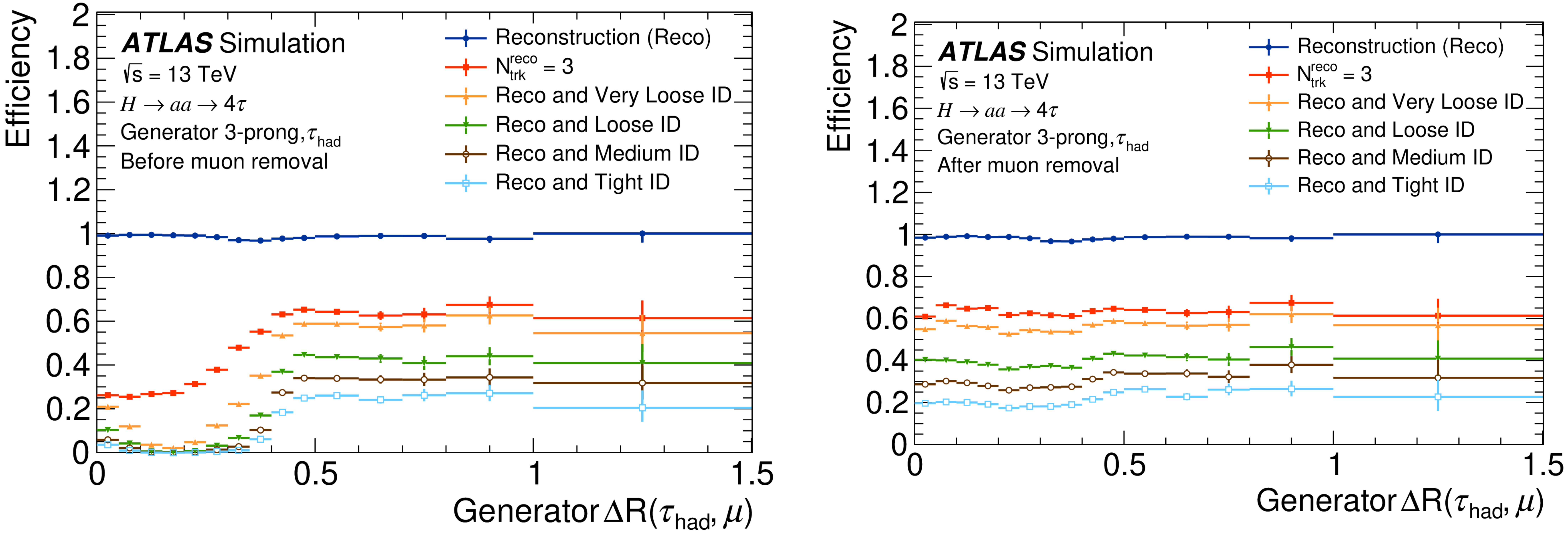
Summary

- Huge number of searches for additional Higgs bosons, exotic/rare decays, additional scalar
- BSM Higgs searches complement precision measurements of the Higgs and other SM and exotic particles
- They make an extensive use of Machine Learning techniques to solve many problems, e.g background modelling, object identification, pairing, etc.
- They have constrained the phase space of possible models considerably
- Reinterpretation of existing analysis has extended their reach, improving limits for ALP scenarios
- We have exciting years coming up for the BSM Higgs program, and many new searches that will use Run-3 data

Additional material

H→ aa → ττττ

arXiv:2503.0563

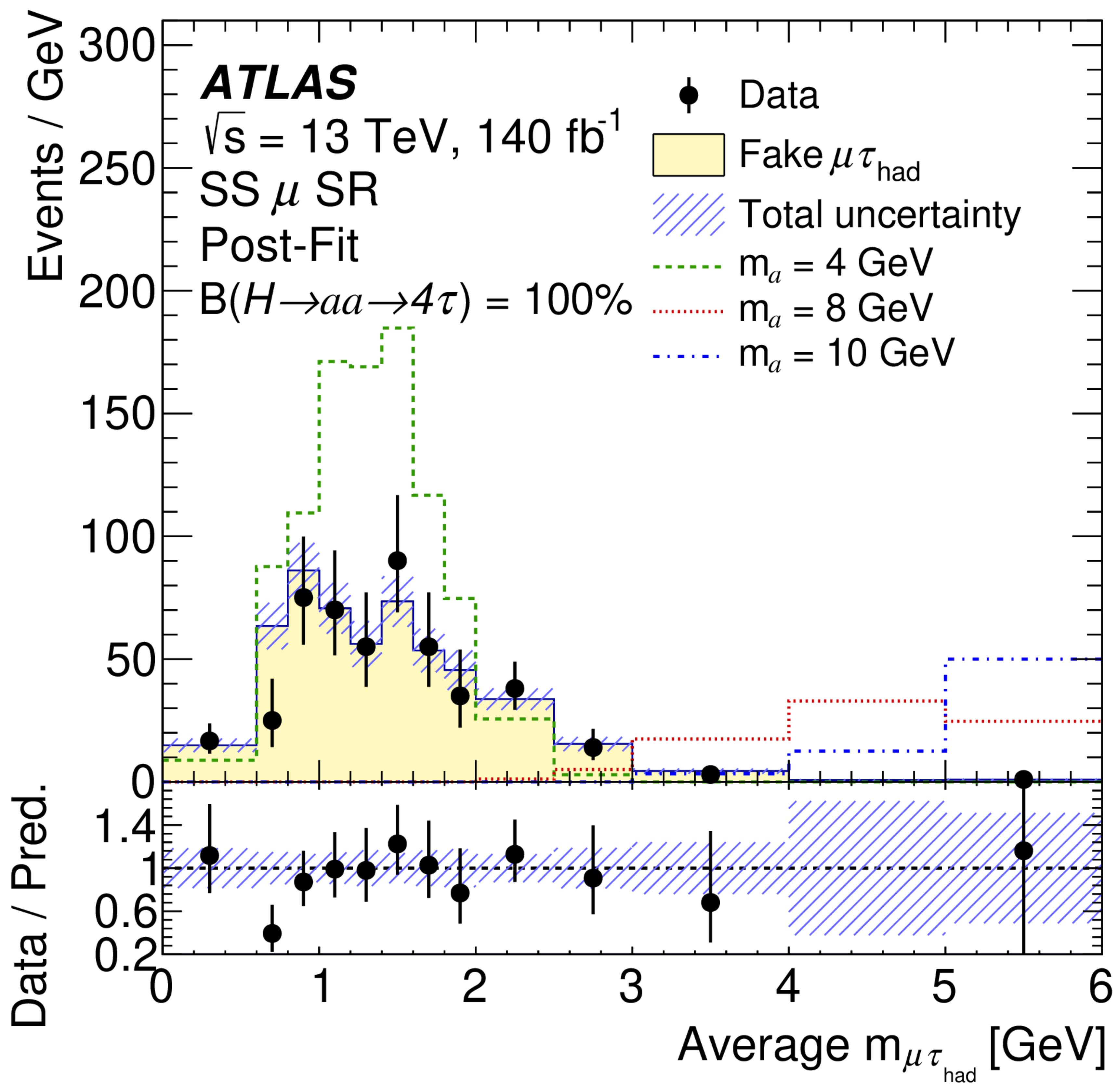


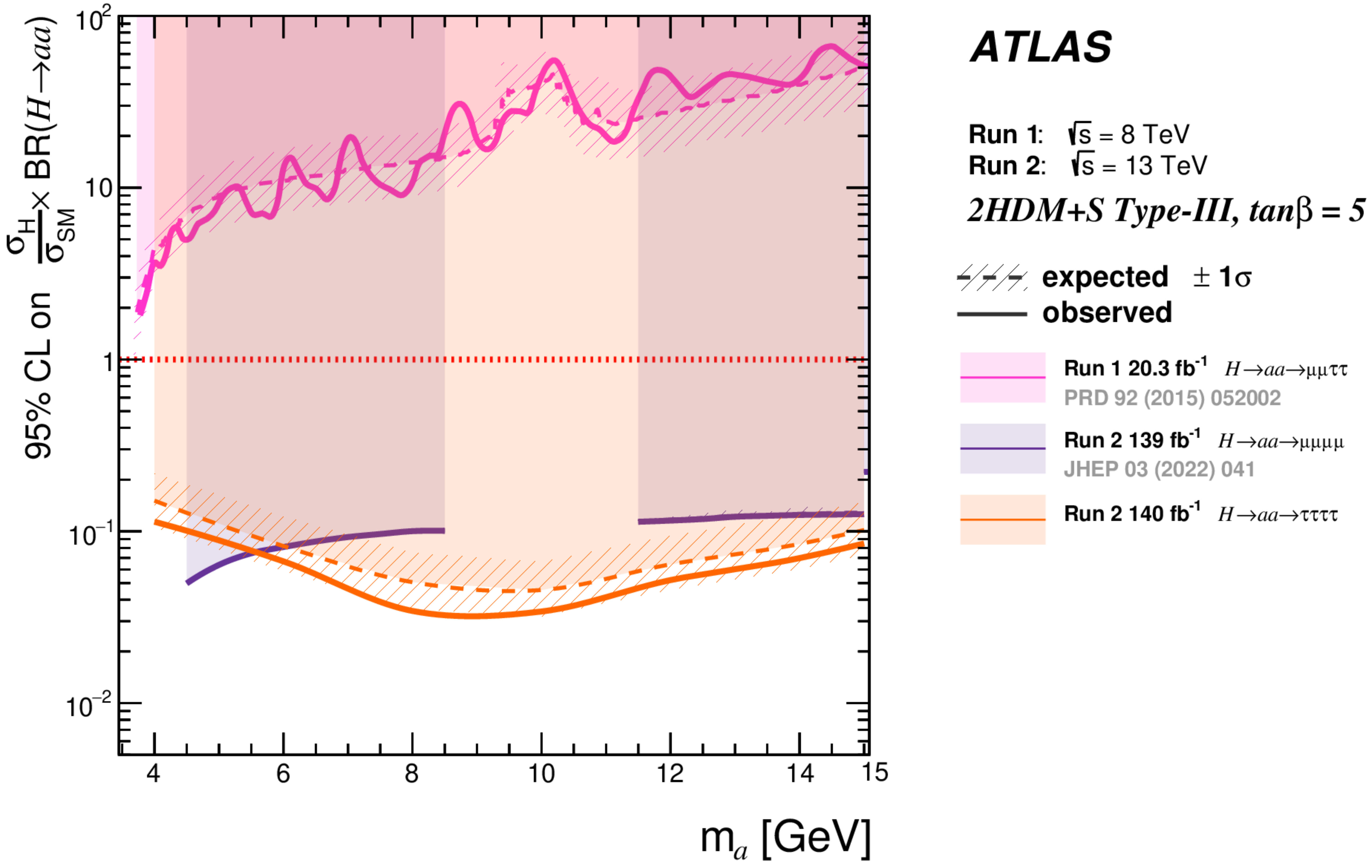
τ had reconstruction and RNN identification efficiency before and after the muon removal for generator-level 1-prong τ candidates for all working points as a function of generator-level $\Delta R(\tau, \mu)$.

More on the muon removal technique DOI: 10.1140/epjc/s10052-025-14012-4

H→ αα → ττττ

arXiv:2503.0563

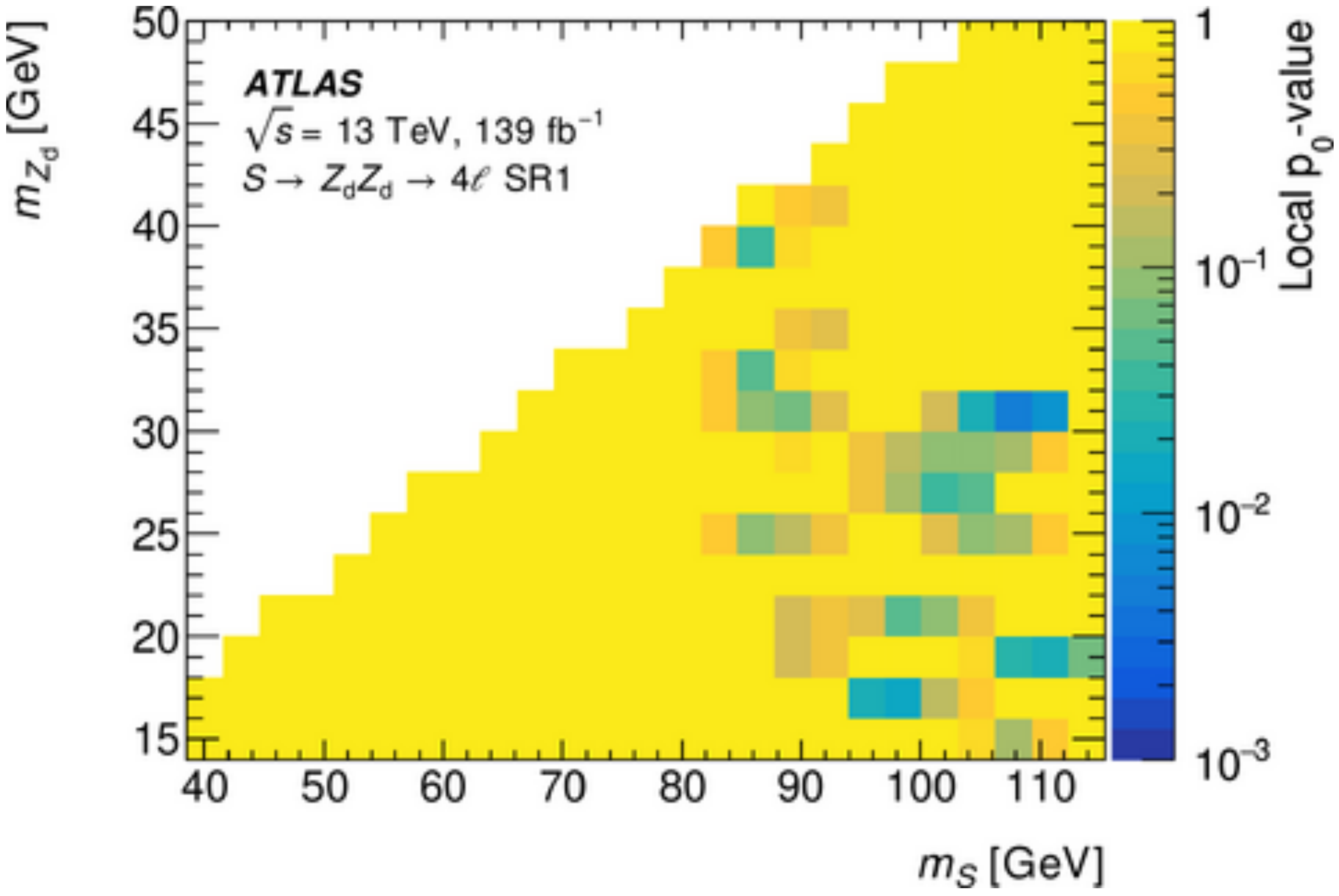




Main sources of systematic uncertainty in this search are the ones related to the modelling of the fake-τ background. Also statistically limited for higher masses

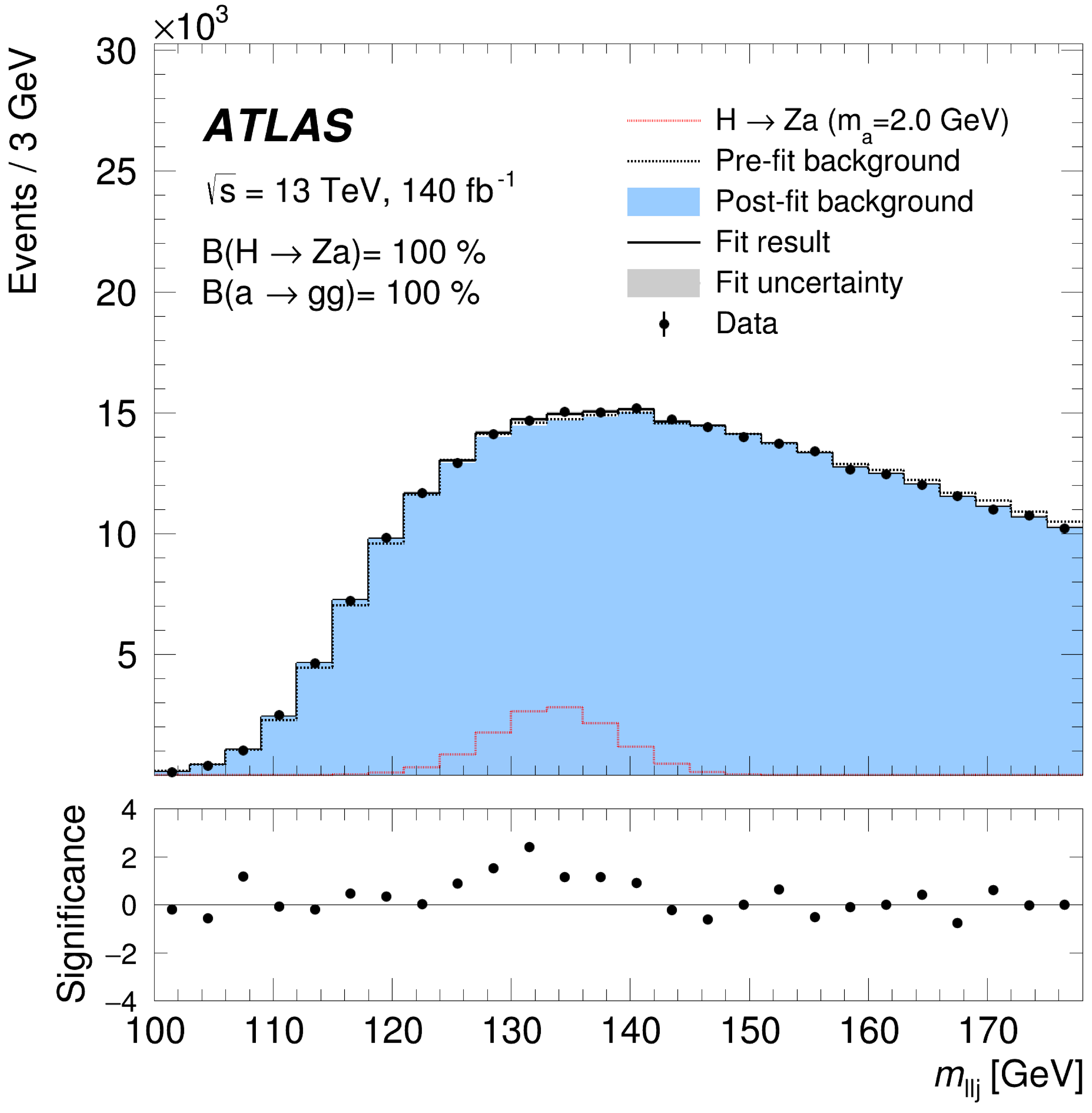
S → ZdZd→ 4leptons

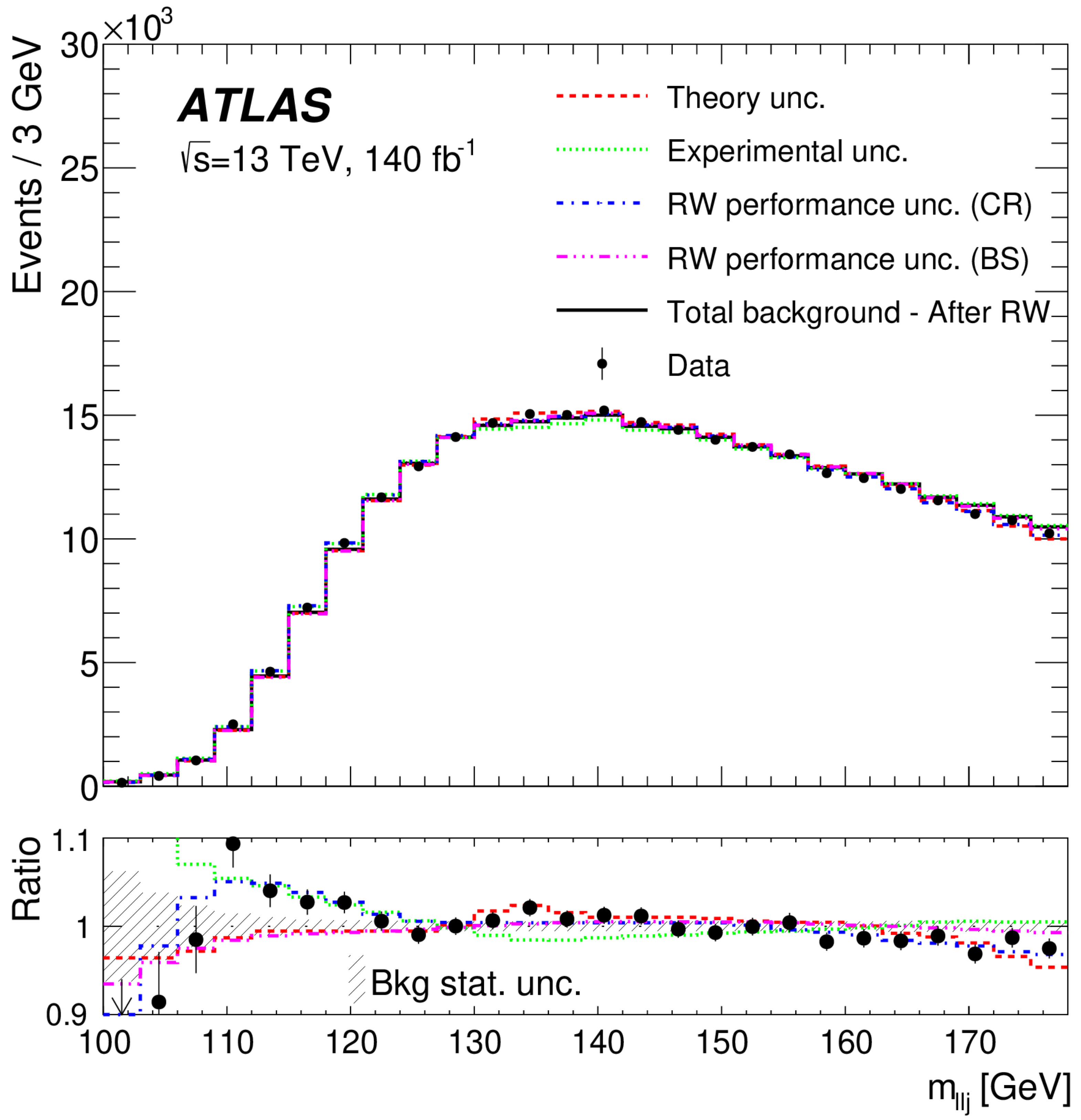
- Most significant excess found in at mS 110 GeV and mZd =30GeV with a local(global) significance of 2.7σ(1.6σ). limits σ(gg →S) ×B(S→Z_d Z_d →4ℓ)

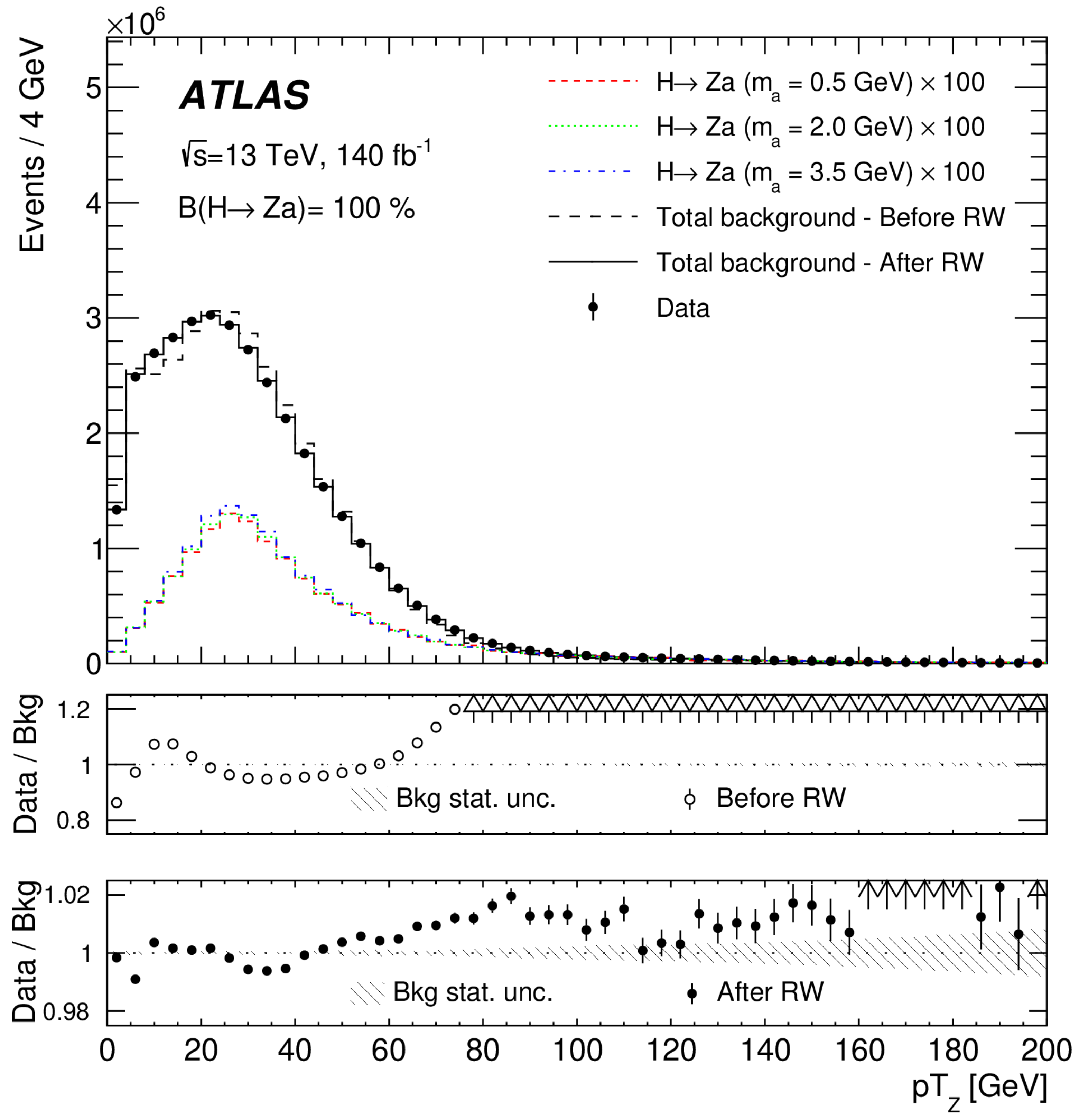


H → Za , a hadronic decays

DOI: 10.1016/j.physletb.2025.139671



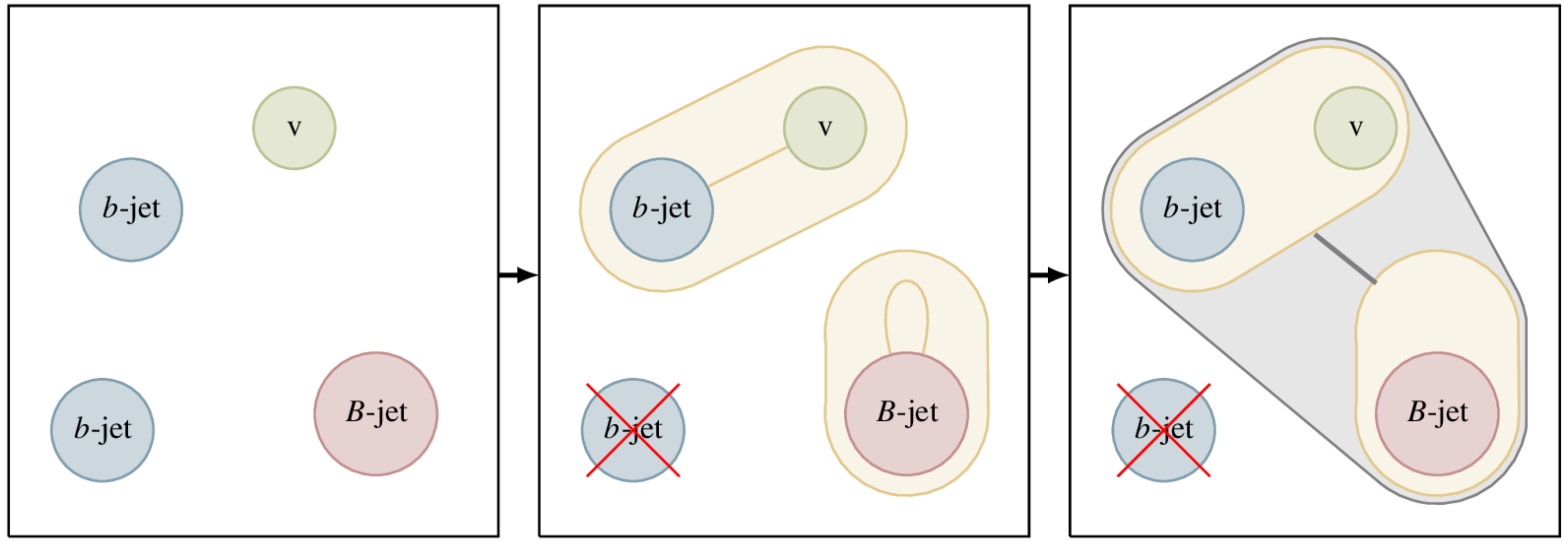




$H \rightarrow \alpha\alpha \rightarrow 4b, 6b$

arXiv:2507.01165

Schematic overview summarising the heavy-flavour algorithms used and the criteria used to define the b-objects



$H \rightarrow aa \rightarrow 4b, 6b$

arXiv:2507.01165

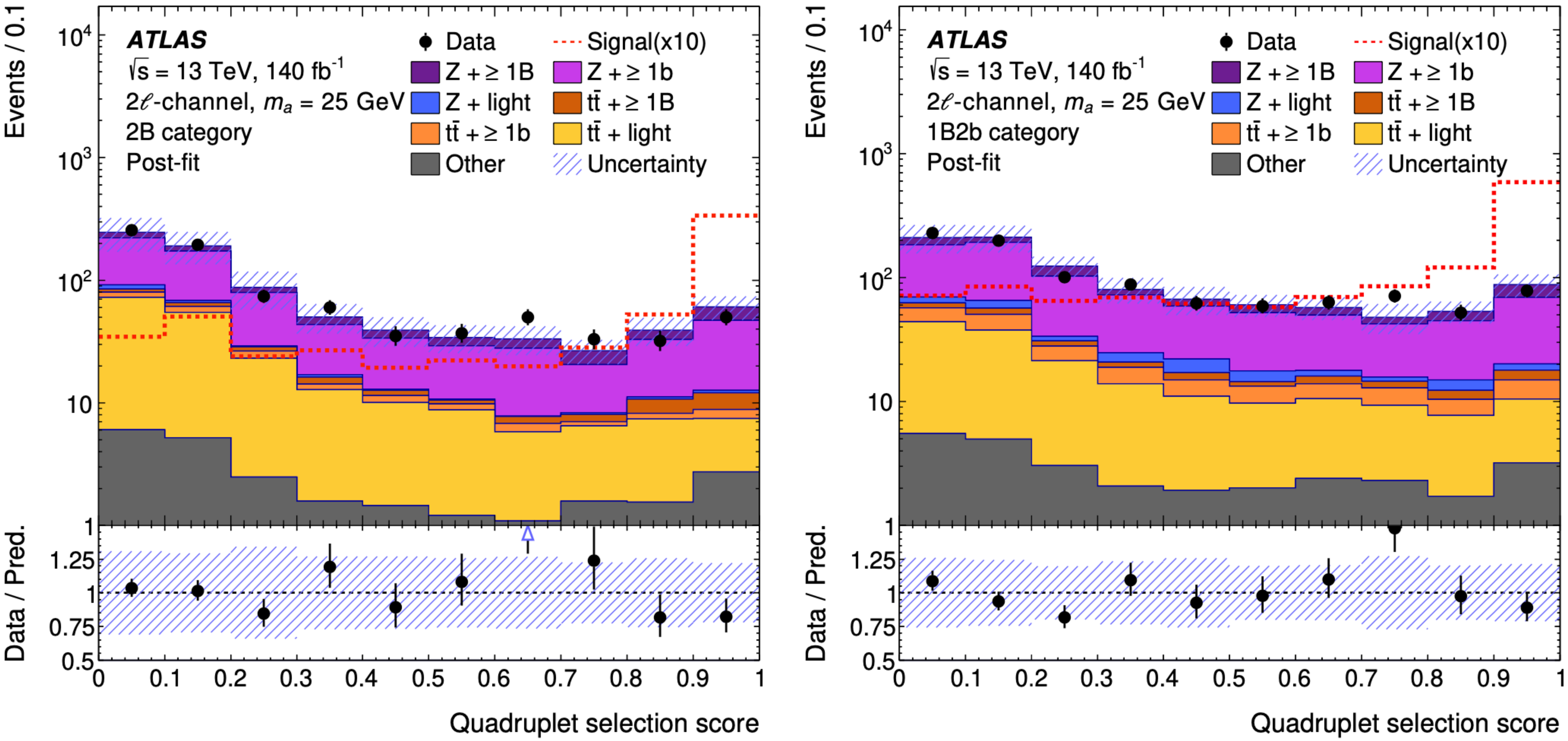
Table 2: Summary of the event selection, and signal and control region definitions, for the 0ℓ and 2ℓ channels.

Analysis channels	**0ℓ** $H \rightarrow 2a \rightarrow 4b$	**2ℓ** $H \rightarrow 2a/a_1a_2 \rightarrow 4b$	$H \rightarrow a_1a_2 \rightarrow 6b$
	Common selection		
Triggers	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	
Leptons	$p_{\mathrm{T}} > 7$ GeV	lead $p_{\mathrm{T}} > 27$ GeV, sublead $p_{\mathrm{T}} > 10$ GeV	
b-object multiplicity	$n_b = 2$, $n_B = 1$ or $n_B = 2$	$n_b + 2n_B + n_{\mathrm{v}} \geq 4$	
	Signal regions		
Leptons	0 leptons	2 SFOS leptons	2 SFOS leptons
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	–	–
Z boson selection	–	$\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV
Higgs boson selection	$\lvert m_{aa} - m_H \rvert < 50$ GeV	High quadruplet NN score	–
Multijet rejection	$\min \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, a \text{ cand.}) > 60°$	–	–
Categorization	$n_j, n_b, n_{B_t}, n_{B_l}$	Quadruplet NN prediction	$n_{\mathrm{v}}, n_b, n_{B_t}, n_{B_l}$
Binning	–	Loose, Medium, Tight BDT bins	Medium, Tight BDT bins

	Control regions		
Multijet	*ABCD method* $150 < m_{aa} - m_H < 250$ GeV $\min \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, a \text{ cand.}) < 30°$	–	–
Lost lepton		–	–
Signal veto	$\lvert m_{aa} - m_H \rvert > 50$ GeV		
Leptons	1 lepton, $p_{\mathrm{T}} > 27$ GeV, $\Delta R(\ell, B) > 0.8$		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss,eff}} > 150$ GeV		
Categorization	n_b, n_{B_t}, n_{B_l}		
Z+jets enriched			
Signal veto	$\lvert m_{aa} - m_H \rvert > 50$ GeV	Low quadruplet NN score	Loose BDT bins
Leptons	2 SFOS leptons, lead $p_{\mathrm{T}} > 27$ GeV	2 SFOS leptons	2 SFOS leptons
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV, $E_{\mathrm{T}}^{\mathrm{miss,eff}} > 30$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Z boson selection	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
Categorization	n_b, n_{B_t}, n_{B_l}	$n_{\mathrm{v}}, n_b, n_{B_t}, n_{B_l}$	$n_{\mathrm{v}}, n_b, n_{B_t}, n_{B_l}$
$t\bar{t}$ enriched	–		
Leptons		2 DFOS leptons	
Categorization		$n_{\mathrm{v}}, n_b, n_{B_t}, n_{B_l}$	

H→ $\alpha\alpha$ → 4b, 6b

arXiv:2507.01165



$H^{\pm} \to \tau^{\pm} \nu$

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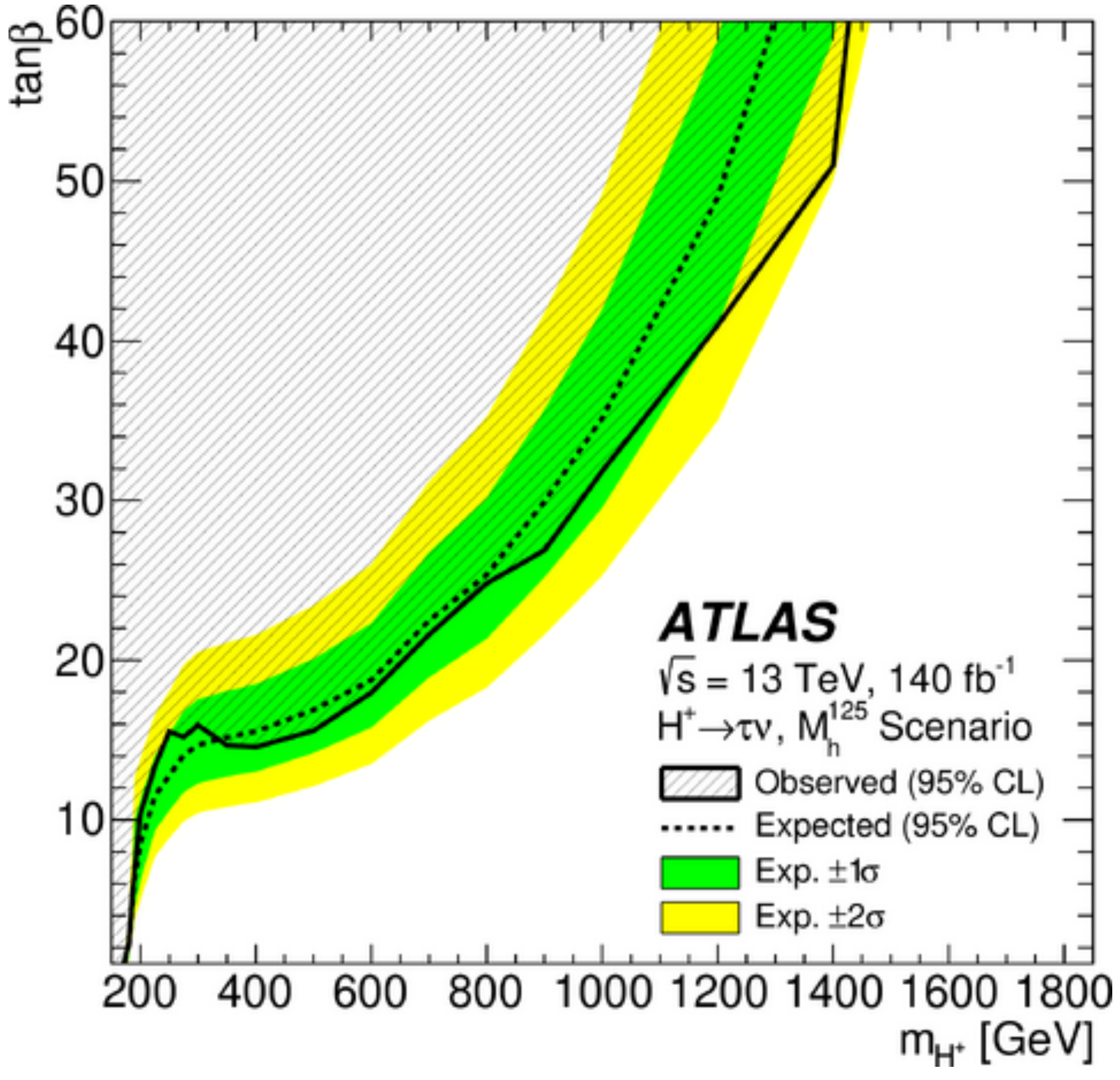

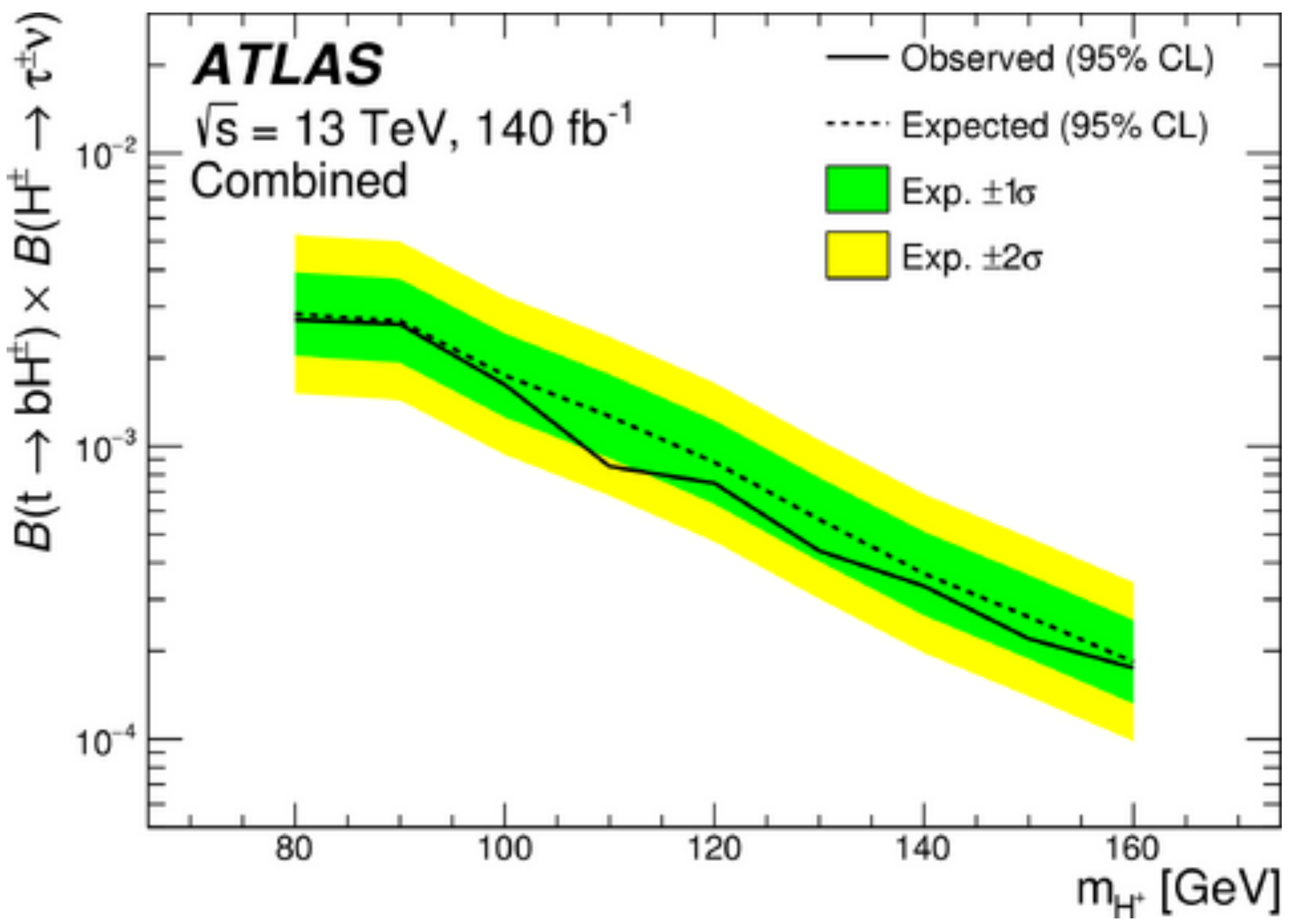

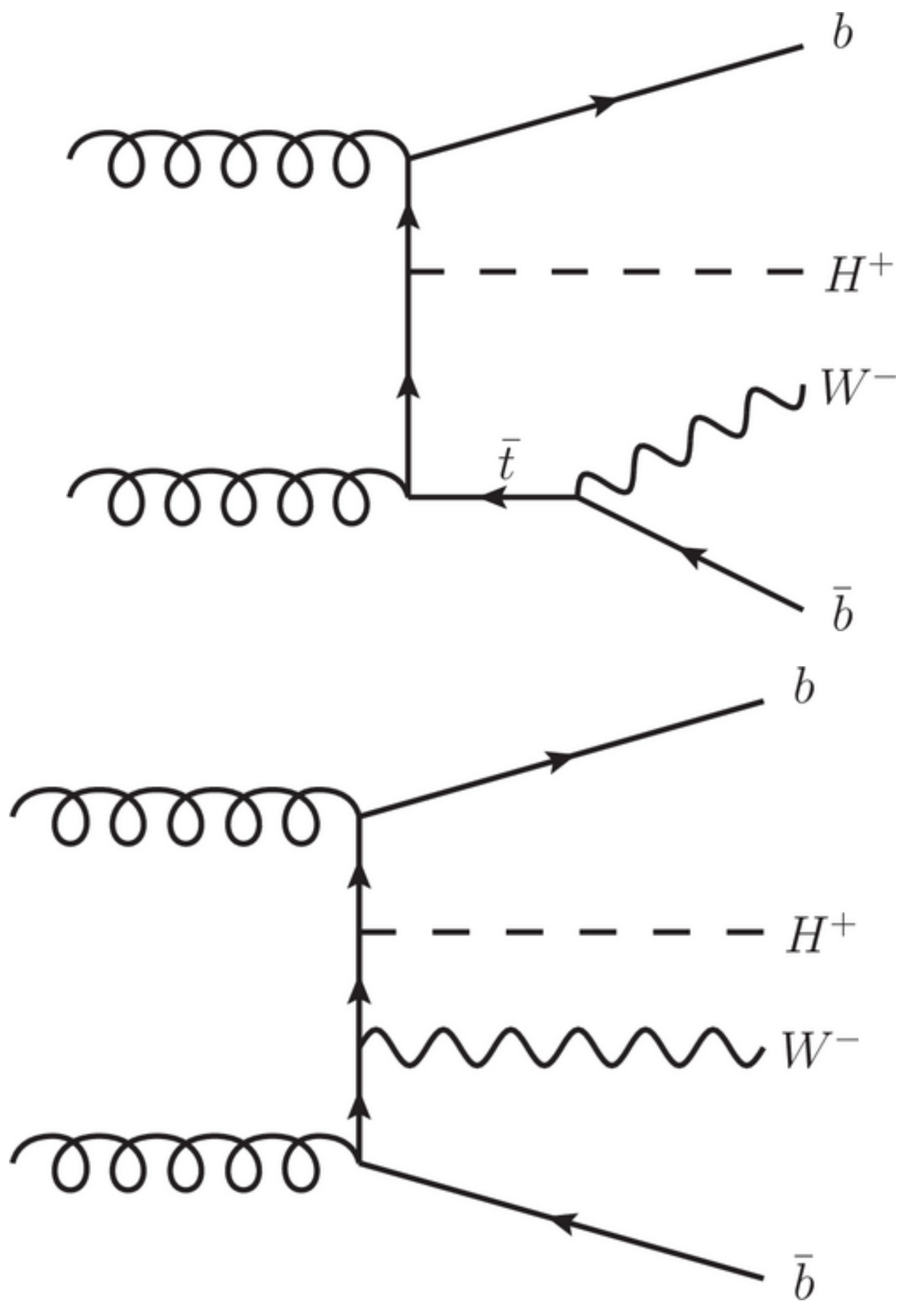

- At low mass, the sensitivity of the analysis is driven by the τ +lepton channel, while at high mass the τ +jets channel dominates
- Exclusion limits for $mH+ \leq 140$ GeV are not shown, as the hMSSM scenario is not valid in this range
- Limits plot stops at $\tan \beta = 60$, above that no reliable theoretical calculations exist