Searches for Heavy Resonances: New Scalars and BSM Higgs Decays with ATLAS Run 2 Data

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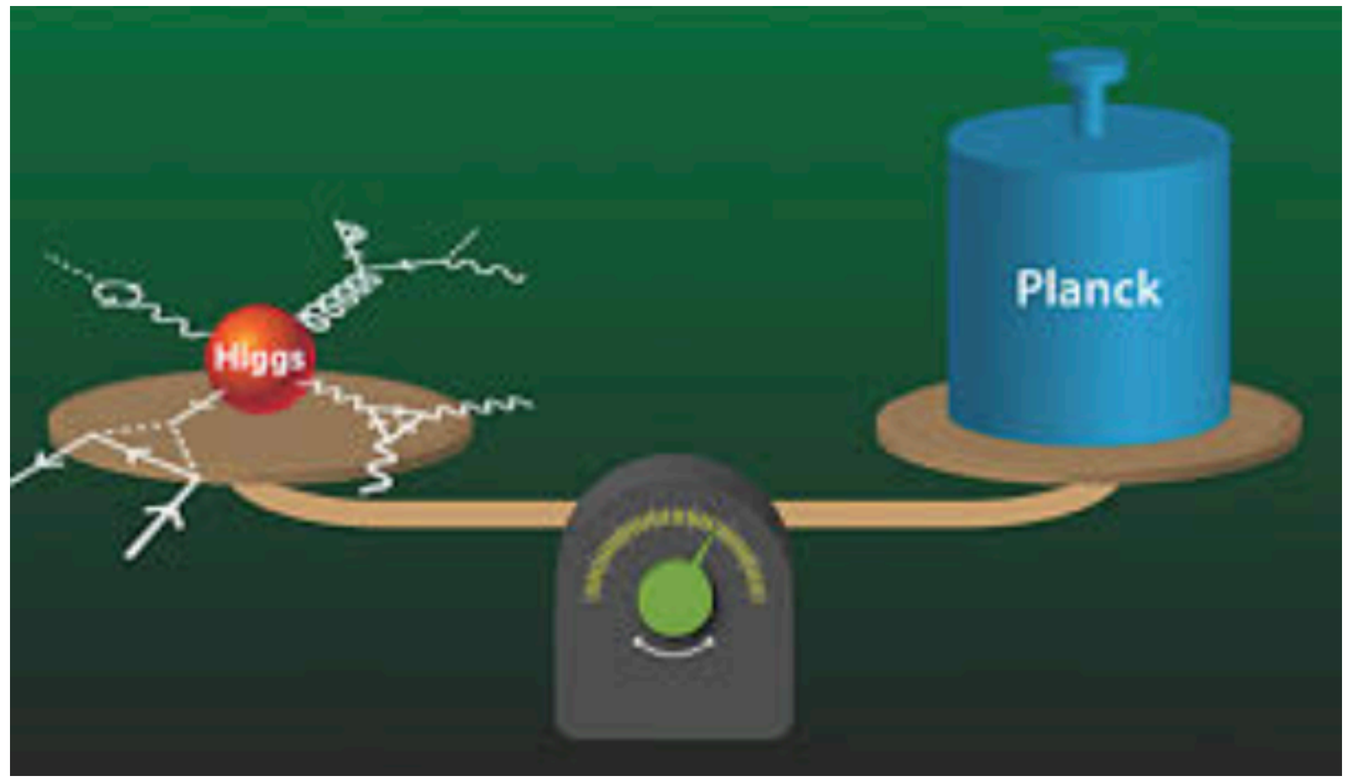
Why Go Beyond the Standard Model?

The **Standard Model (SM)** accurately describes known particles and interactions culminating in the 2012 discovery of the Higgs boson. However, there are some unanswered questions!





These gaps **motivate searches** for Beyond-the-Standard-Model (BSM) physics.

Extending the Higgs Sector – A Natural Next Step

Main Points:

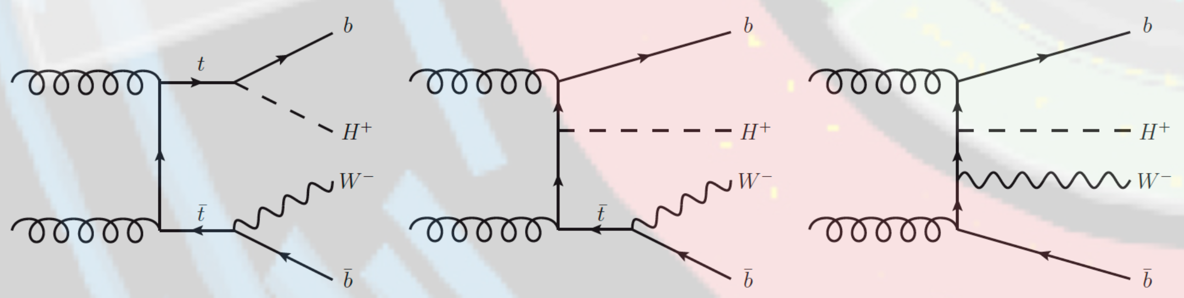
- Many BSM predict **extended Higgs sectors**, such as:
  - Two-Higgs-Doublet Models (2HDM)
  - Supersymmetry (MSSM, hMSSM)
  - Hidden Abelian Higgs Models (HAHM)
- These models imply new particles: Neutral heavy scalars (H), pseudoscalars (A), $H^{\pm}$(H^{++})
- New decay modes (e.g. $H^{\pm} \rightarrow W^{\pm}h$, $H^{+} \rightarrow \tau\nu$, $S \rightarrow Z_d Z_d \rightarrow 4\ell$) open **unique experimental windows** into BSM physics.

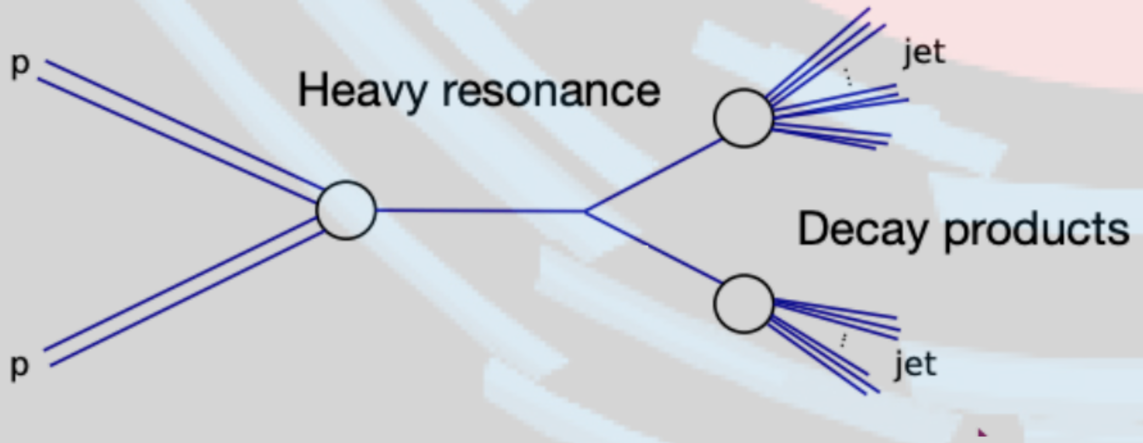
ATLAS searches

Full Run 2 dataset: **~140** fb^{-1} of pp collisions at **13 TeV**

This dataset allows us to probe:

- Rare decay channels like $H^{\pm} \to W^{\pm}h$
- New topologies (e.g., $S \to Z_d Z_d \to 4\ell$)
- **Model-independent searches** using anomaly detection in di-jets

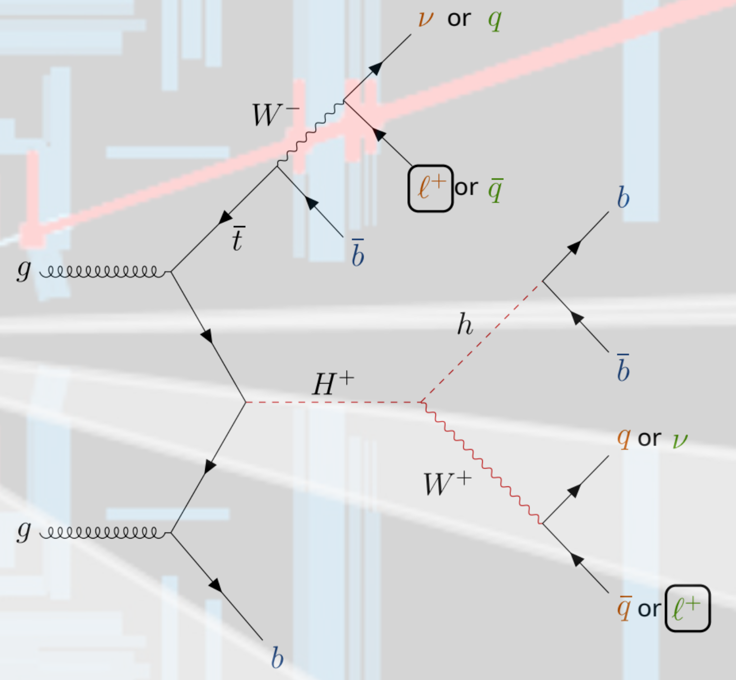




4 landmark ATLAS searches

scalar and resonance phenomenology.

- $H^{\pm} \to W^{\pm}h \to lbb$
- $H^{\pm} \to \tau^{\pm}\nu$
- $S \to Z_d Z_d \to 4l$
- dijet BSM heavy resonance searches



$H^{\pm} \to W^{\pm}h \to l\nu bb(q\bar{q}b\bar{b})$

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Target:

- Mass range from **250 GeV to 3 TeV**.

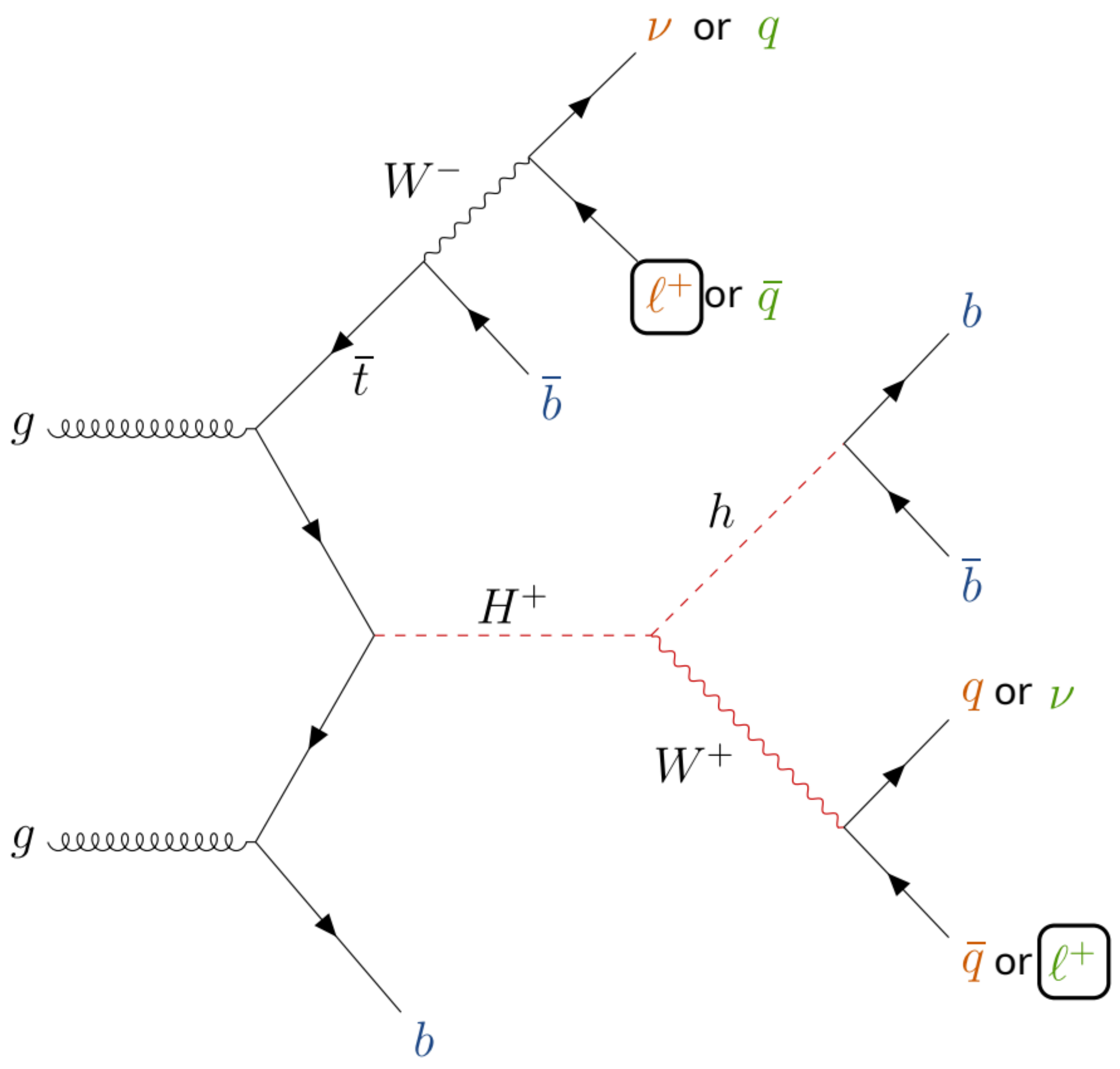
Method: Investigate events with 1 lepton, MET, and jets; search for resonances in *Wh invariant mass* spectrum.

Topologies:

- **Resolved**: Targets lower-mass $H^{\pm}$ decay products are small-radius jets.
- **Merged**: Targets high-mass $H^{\pm}$ boosted decays are as large-radius jets.

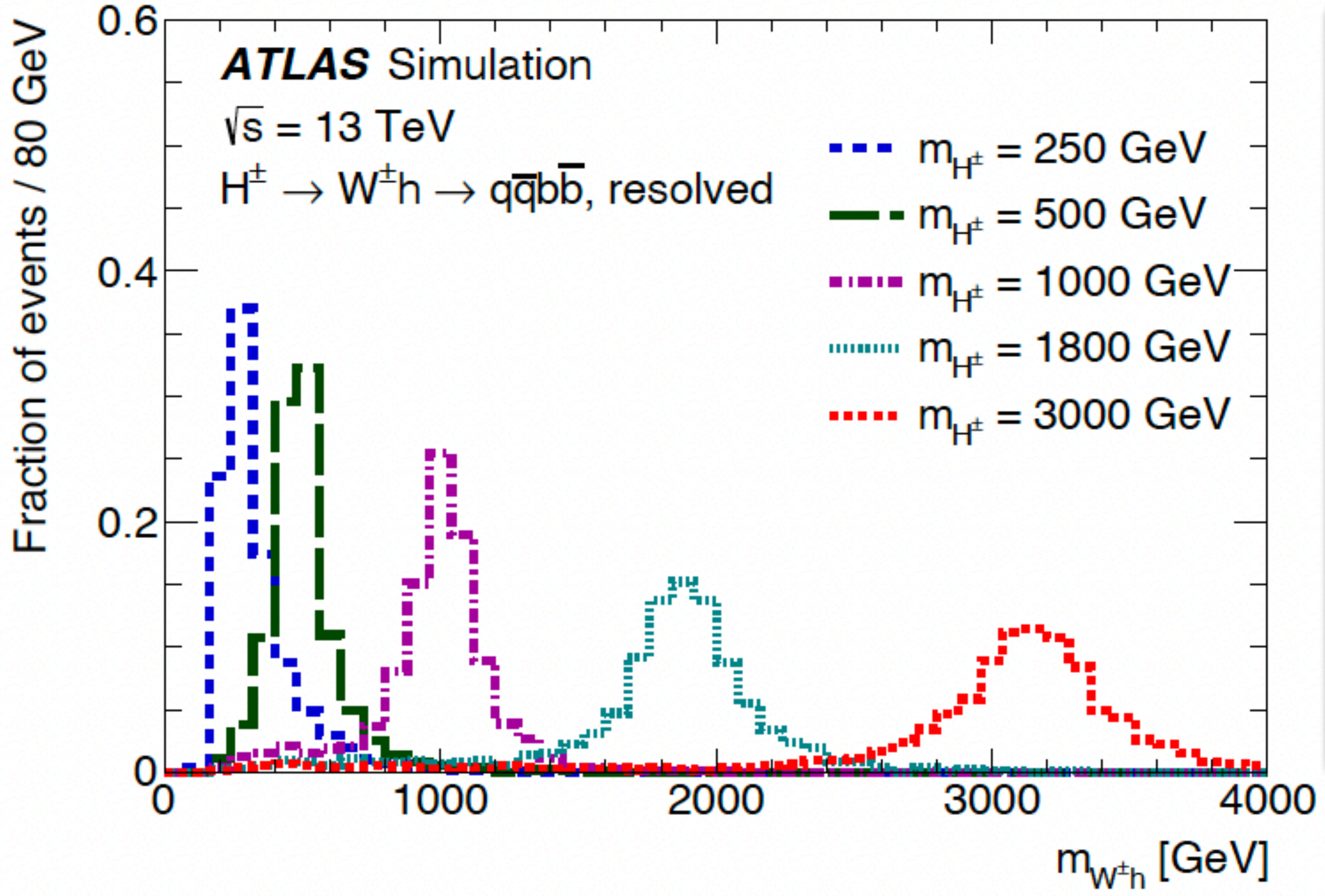
Reconstruction:

- **BDTs** for resolved events, **NNs** for merged events.
- Event classification based on kinematics of reconstructed leptonic top-quark mass(e.g., m_{top}^{lep}) to separate channels.

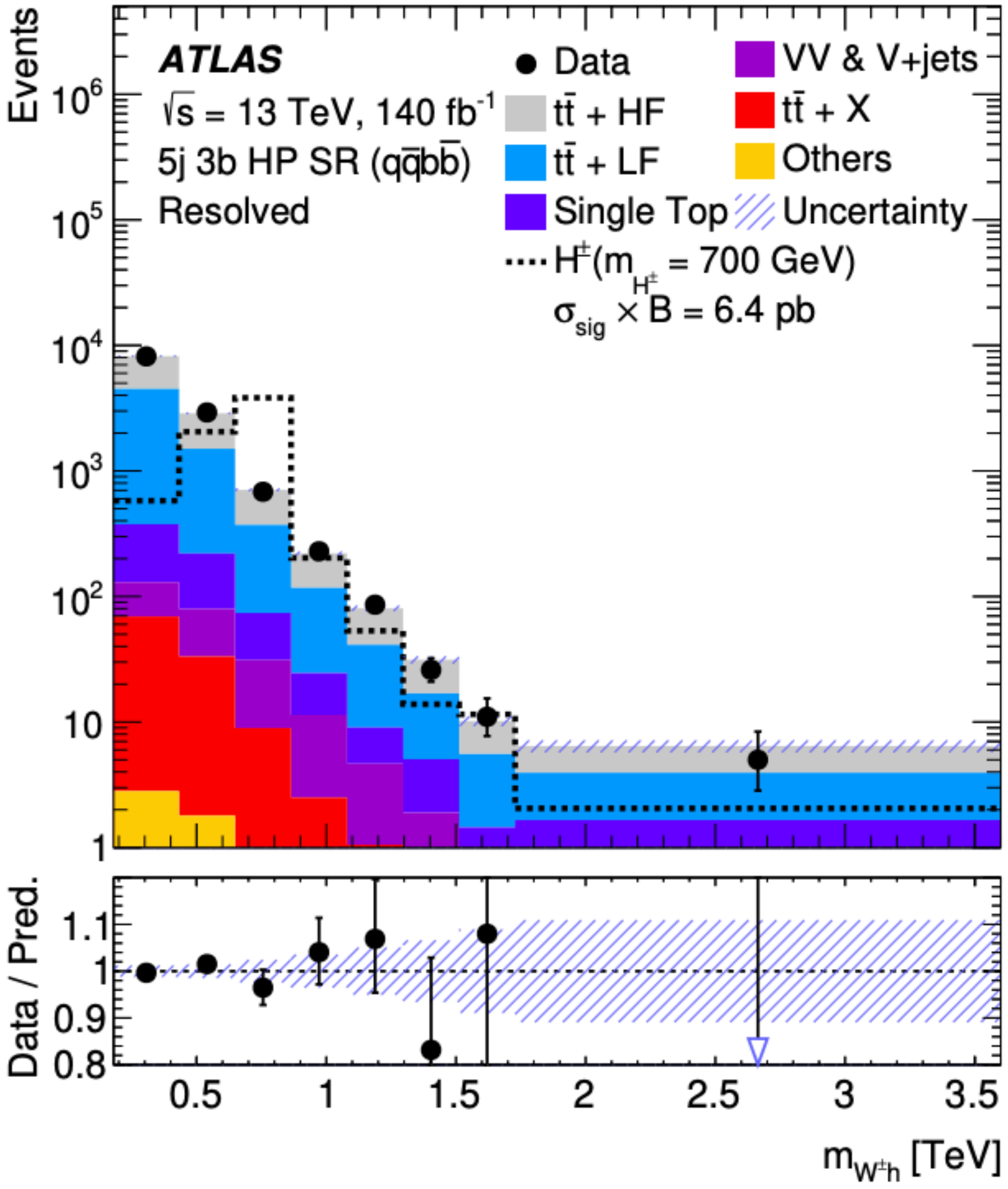


$H^{\pm} \rightarrow W^{\pm}h \rightarrow l\nu bb(q\bar{q}b\bar{b})$

- **Signal & Control Regions**:
  - Using BDT/NN output scores and event categories based on jet multiplicities and b-tag content.
  - Signal extracted via a simultaneous profile likelihood fit to the invariant mass m_{Wh} distributions.



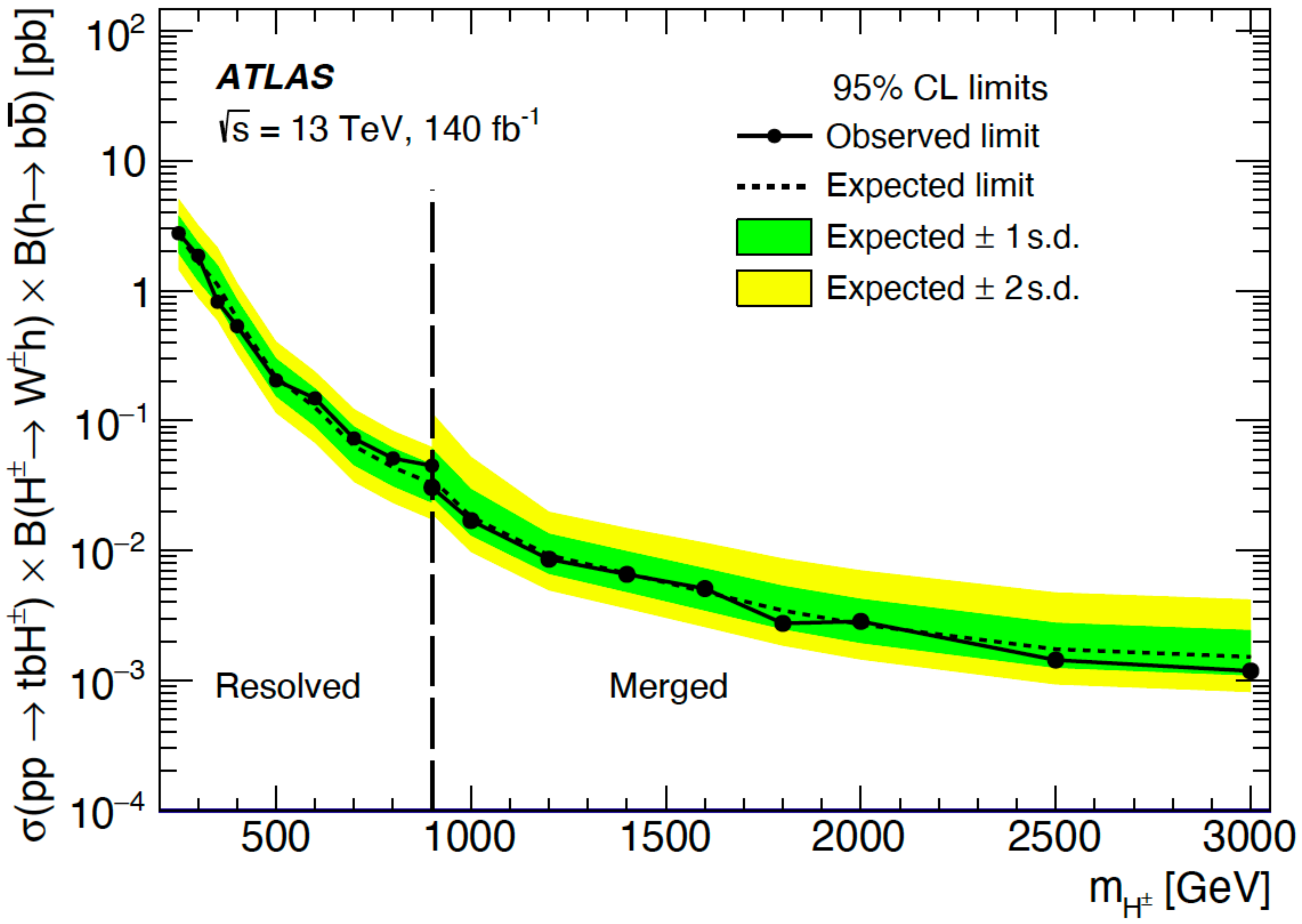
- Main backgrounds are $t\bar{t}$ +heavy-flavor, W/ Z+jets, and single top; minor from diboson and multijets.
- CRs help constrain key backgrounds.



$$H^{\pm} \rightarrow W^{\pm}h \rightarrow l\nu bb(q\bar{q}b\bar{b})$$

A **simultaneous binned maximum likelihood fit** is performed:

- Fit includes SRs and CRs across multiple event categories.



No significant excess observed above the SM prediction.

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

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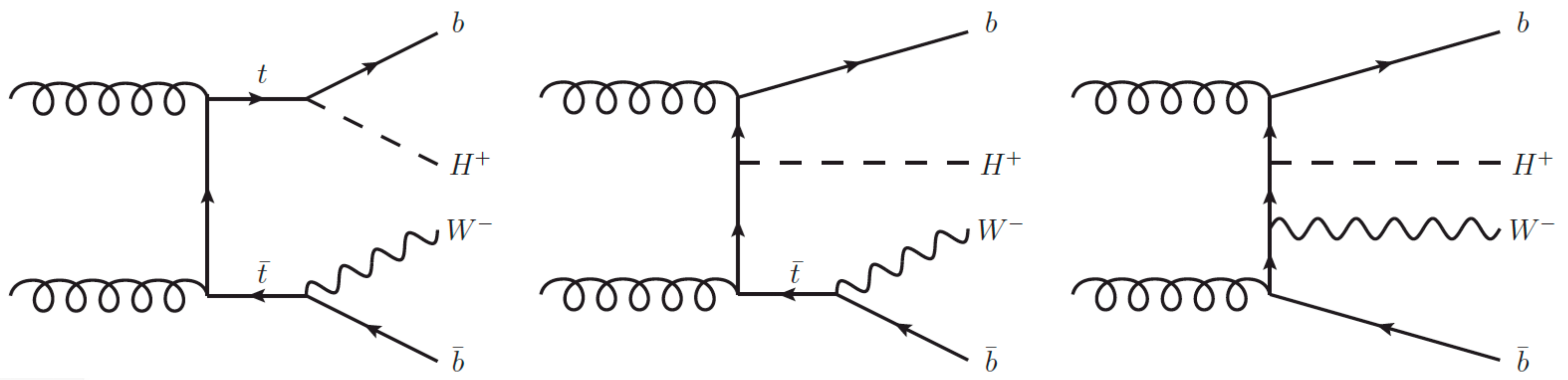


Mass Range Probed: 80 GeV $\leq m_{H^\pm} \leq$ 3000 GeV

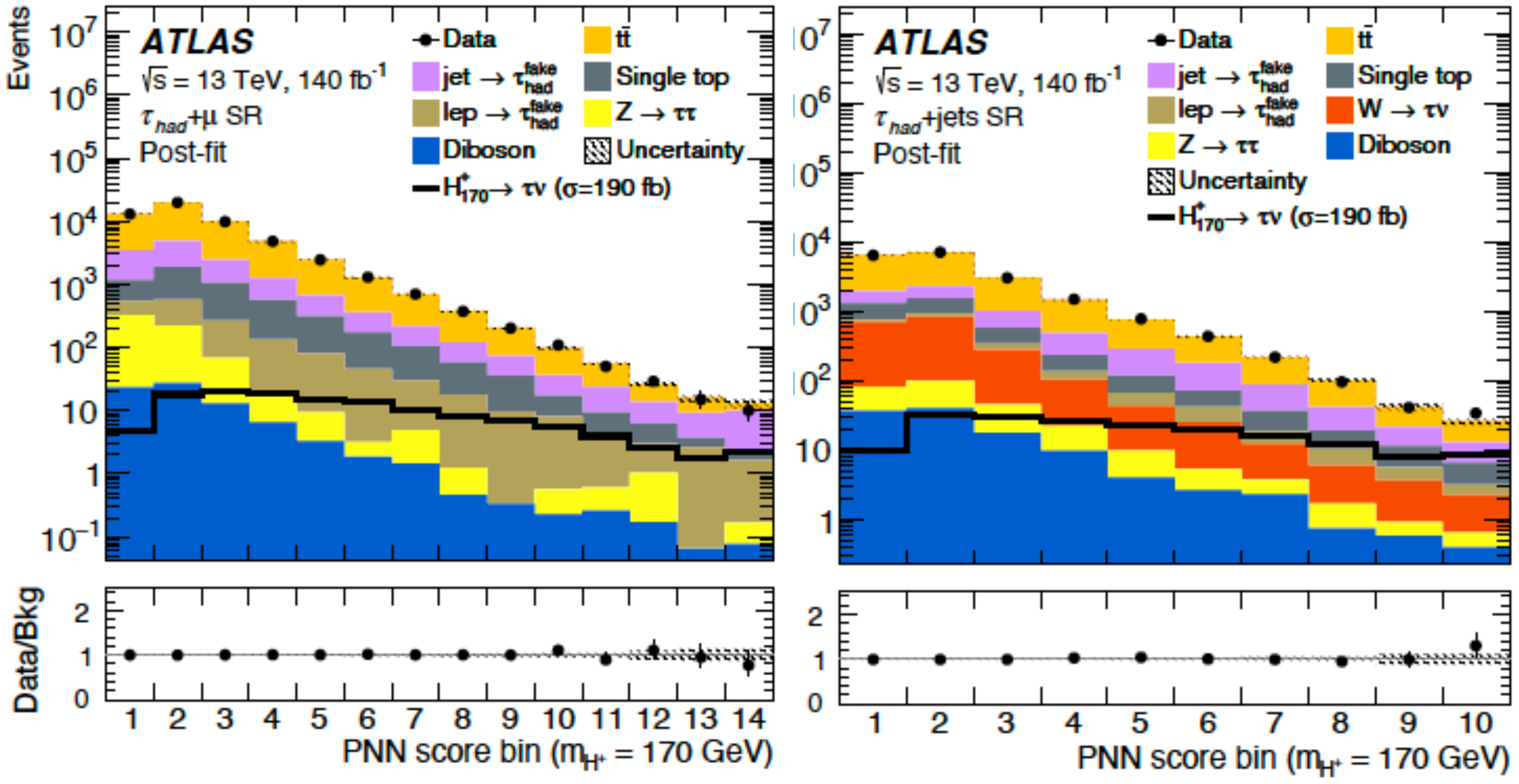
dominant in 2HDM for $m_{H^\pm} < m_t$

Channels:

- $\tau_{had} + jets$: most sensitive at high-mass, large $W \to q\bar{q}$
- $\tau_{had} + lept$ (e/μ): most sensitive at low mass, because of single lepton triggers

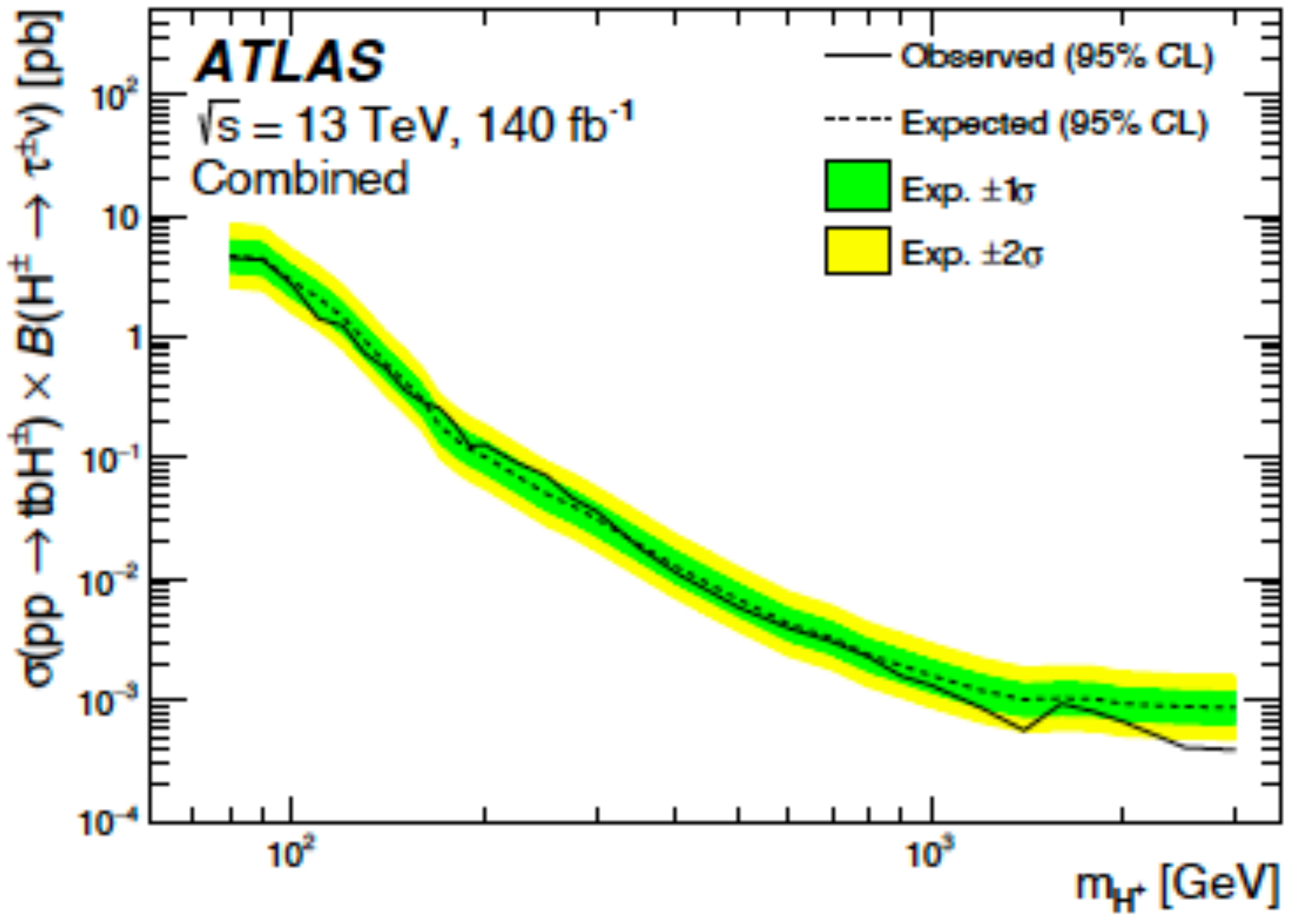
- **Key Features:**
  - Advanced object reconstruction using RNN and PNN
  - Using recurrent NN to identify τ_{had} and BDT to separate them from electrons.
  - Data-driven fake-τ estimation with fake factors
  - Multivariate analysis using mass-parameterized NN
- **CRs:** Defined to validate and correct background modeling
- Likelihood fit to PNN output

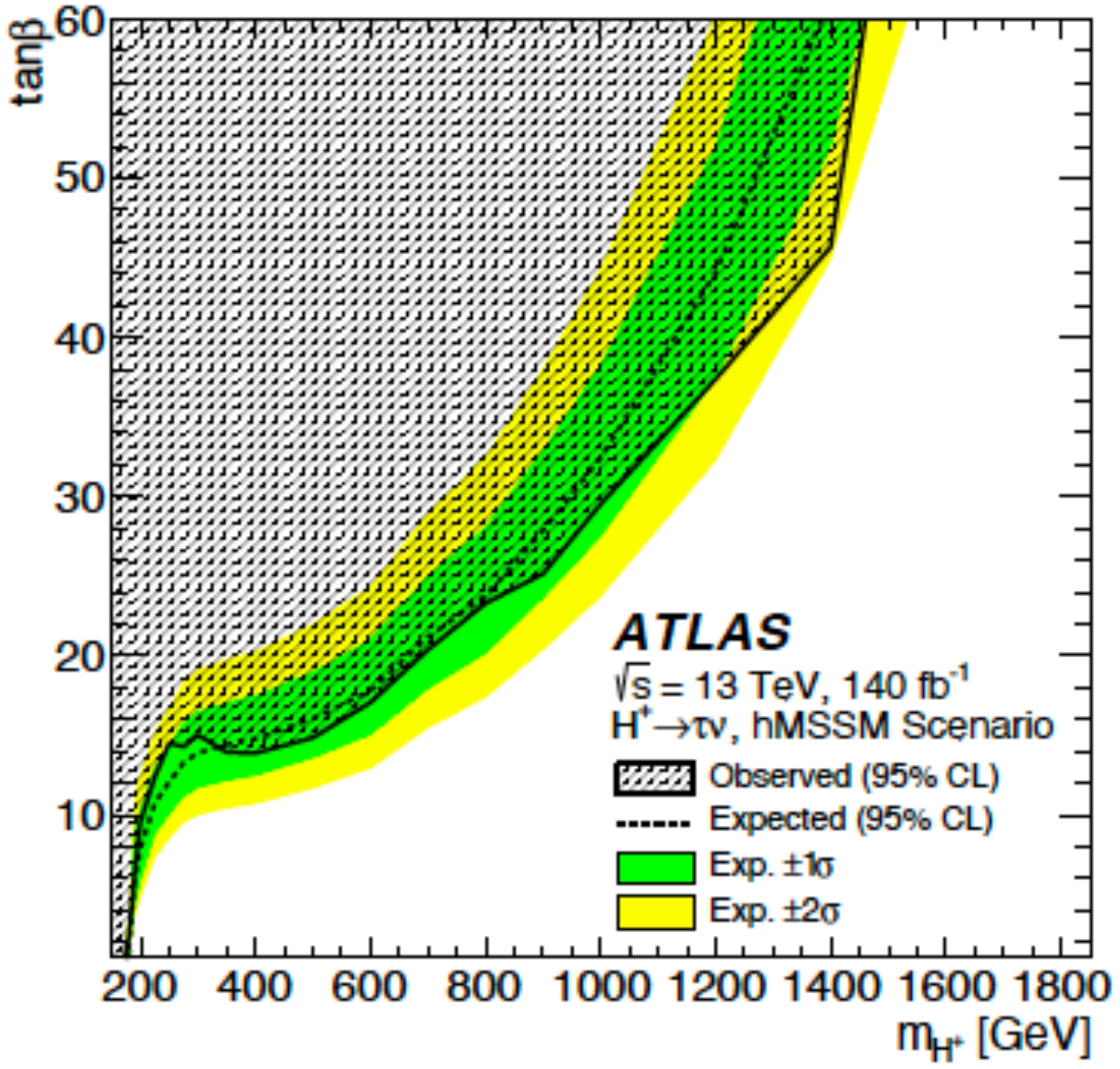
$m_{H^\pm} < m_t$



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

- $\sigma(pp \rightarrow tbH^{\pm}) \times BR(H^{\pm} \rightarrow \tau\nu)$
- $BR(t \rightarrow bH^{\pm}) \times BR(H^{\pm} \rightarrow \tau\nu)$ in the low mass range (60-180 GeV) assuming SM $t\bar{t}$
- $tan\beta$ vs $m_{H^{\pm}}$ in the hMSSM and MSSM with M_h^{125} scenario





Improvement by factor 2-4 with respect to previous analysis: better τ_{had} identification, fake τ_{had} background estimation

$S \rightarrow Z_d Z_d \rightarrow 4l$

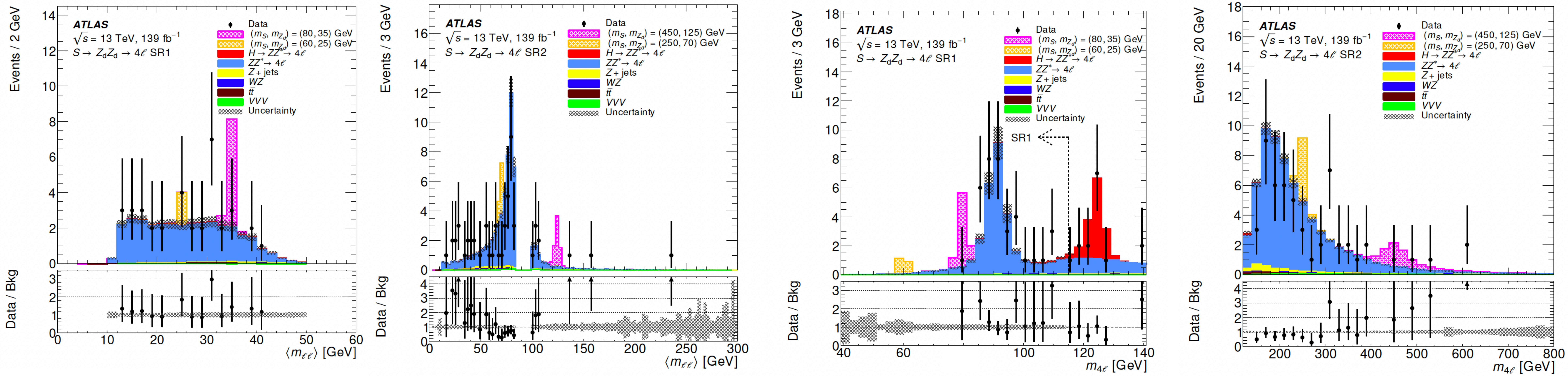
Phys. Lett. B 865 (2025) 139472

Physics goal: Search for a new scalar boson S (m_S: [30, 115] ∪ [130, 800] GeV)

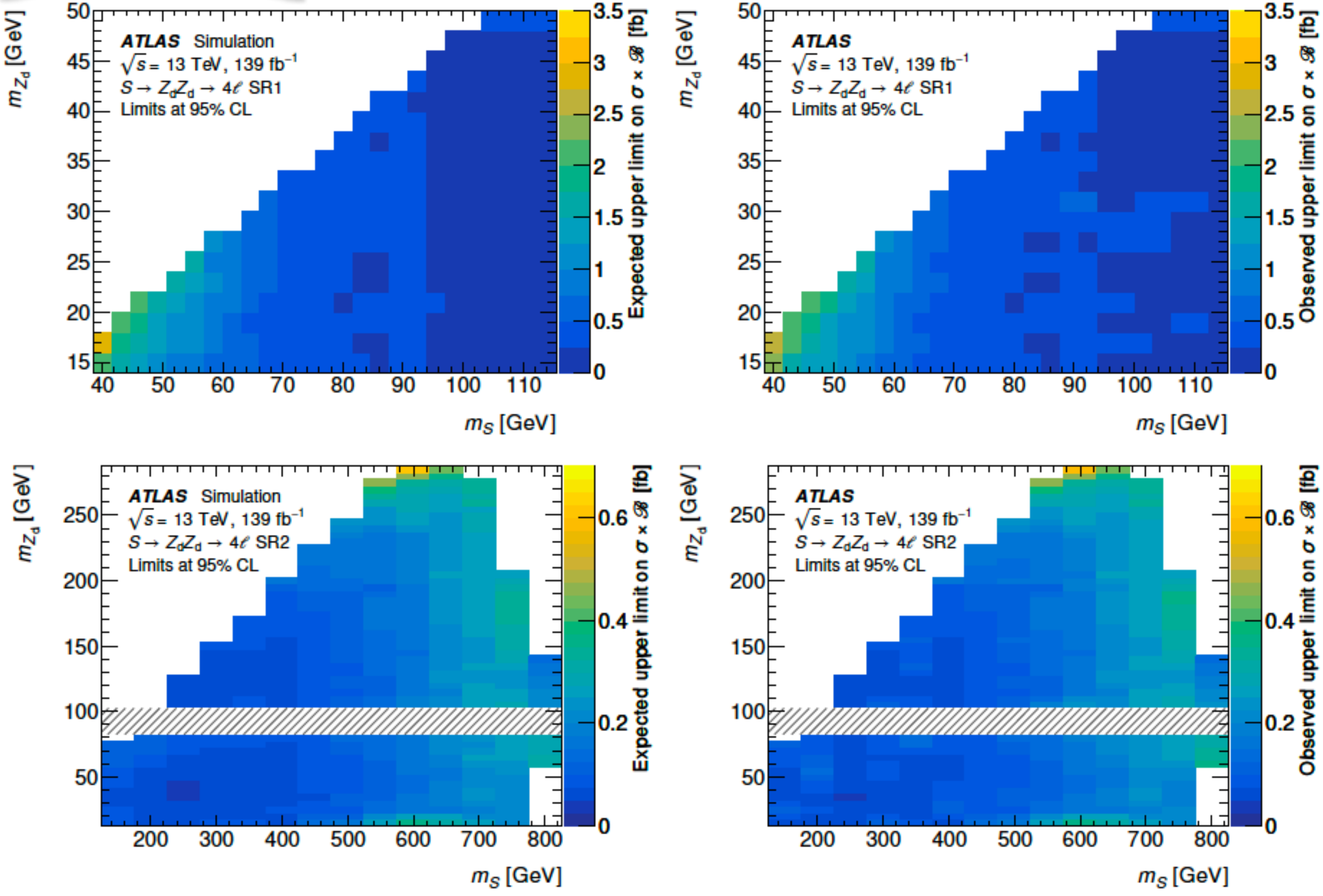
- decaying to a new spin-1 boson Z_d (on-shell [15,300] GeV)
- In the $4l$ final states : $4e$,4μ,$2e2\mu$

Motivation: Probe extensions of the SM, such as HAHM, which predict a "dark photon" Z_d.

- Main background: $ZZ^* \rightarrow 4l$, from the simulation
- Reducible background $(t\bar{t}, Z + j)$ from CRs (Data driven estimate)
- Two signal regions: $m_{4l} < 115$ GeV and $m_{4l} > 130$ GeV



$S \rightarrow Z_d Z_d \rightarrow 4l$



Profile likelihood fit in $\langle m_{\ell\ell} \rangle$ and $m_{4\ell}$

Set 95% CL upper limits on $\sigma(gg \rightarrow S) \times \mathcal{B}(S \rightarrow Z_d Z_d \rightarrow 4\ell)$

In the SR1 ($m_{4l} < 115$ GeV):

The limit range from 0.14-3.1 fb

In the SR2 ($m_{4l} > 130$ GeV):

From 0.05- 0.6 fb

Dijet BSM heavy resonance searches

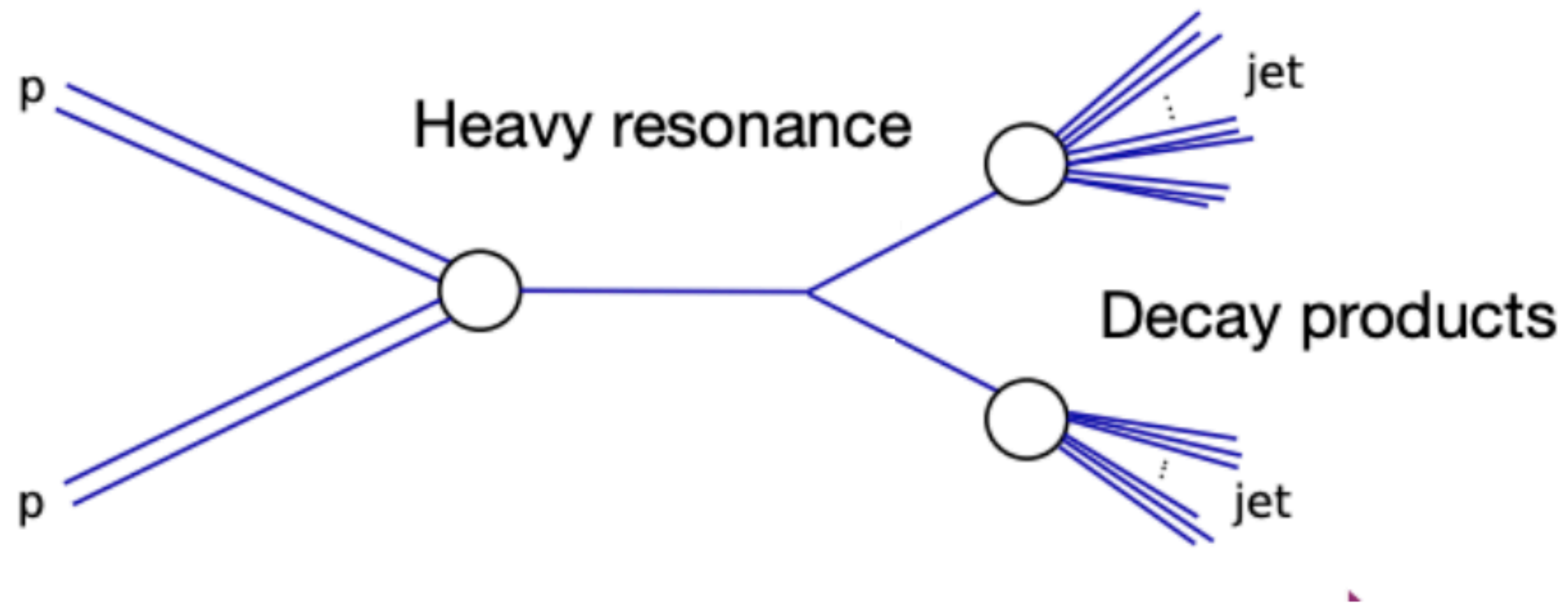
arxiv2502.09770

Anomaly Detection (AD) for Resonant New Physics

Objective: Search for new narrow-width resonances decaying into dijets without assuming specific new physics models

Motivation: Weakly supervised AD can reveal unexpected signals.

Target regime: dijet resonances in $2 < m_{jj} < 5.6 TeV$ using large-R(R=1) jets



Techniques Used:

- **CWoLa Paradigm**: Classification Without Labels
- **Weak Supervision**: Distinguish background from potential signal via ML.
- **Focus**: Events with high-pT, large-radius jets using jet mass and substructure variables

Dijet BSM heavy resonance searches

Methodology

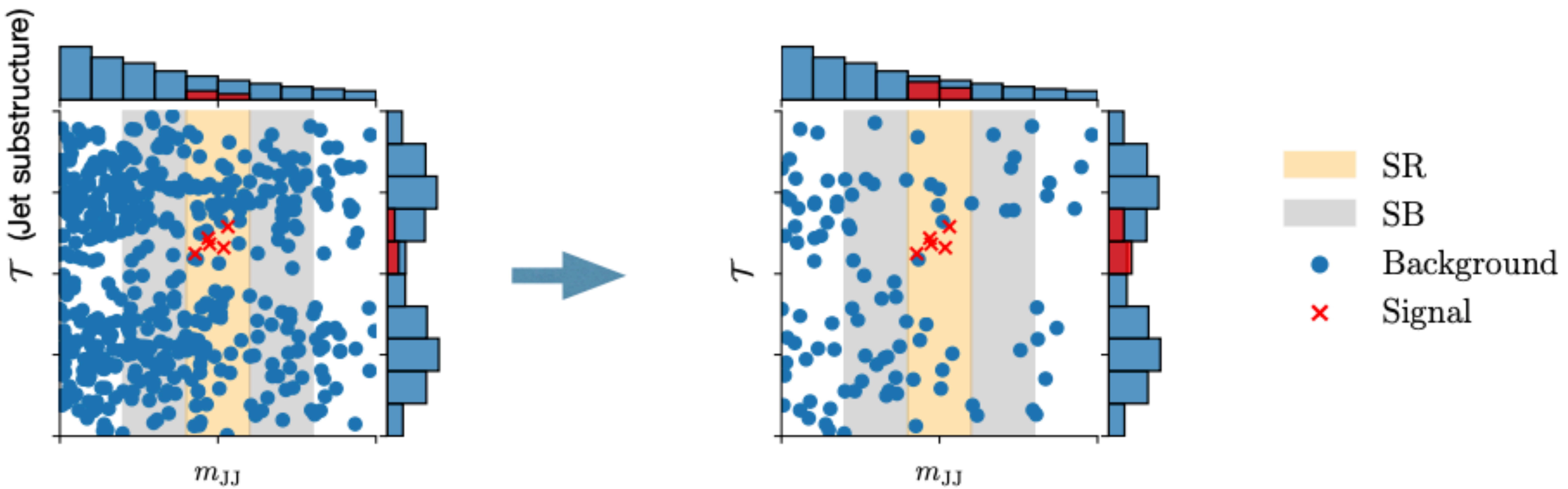
Title: Model-Agnostic ML Search Strategy

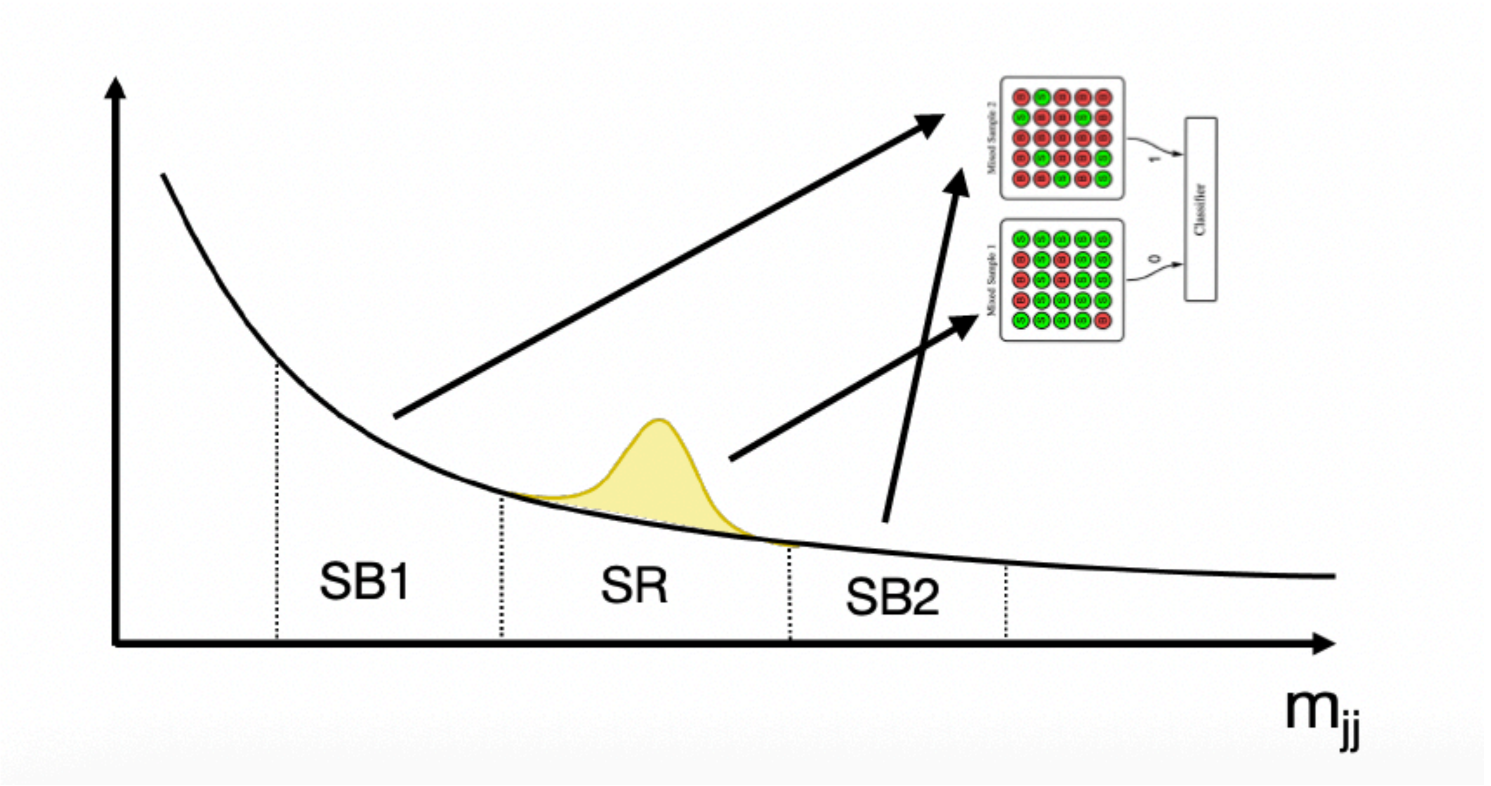
Background Estimation:

- **SALAD**: Simulation reweighting using sideband classifiers.
- **CURTAINs**: Morphing of sideband data using normalizing flows.

Search Strategy:

1. Define Signal Region (SR) and Sidebands (SB) in mJJ.
2. Train ML classifiers on SB to estimated background in SR.
3. Apply classifier cuts and scan for “bumps” in mJJ.

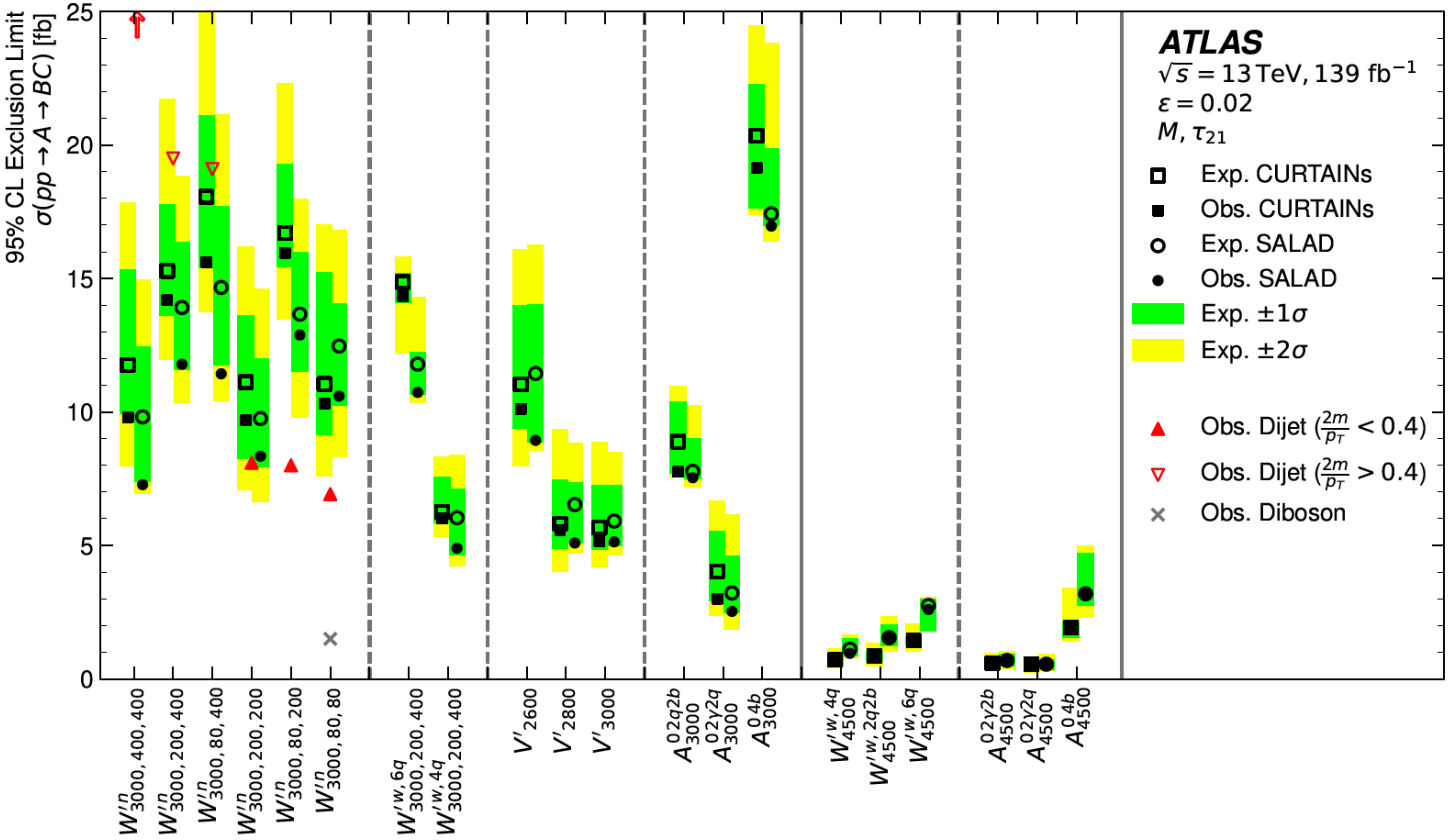




Dijet BSM heavy resonance searches

Results:

- No significant local excess observed.
- Maximum observed local significance ~1.3σ.
- Limits placed on benchmark BSM models (e.g., W', A0).



ATLAS Searches for Heavy Resonances – Summary

Explore Beyond Standard Model (BSM) physics via extended Higgs sectors (2HDM, MSSM, HAHM)

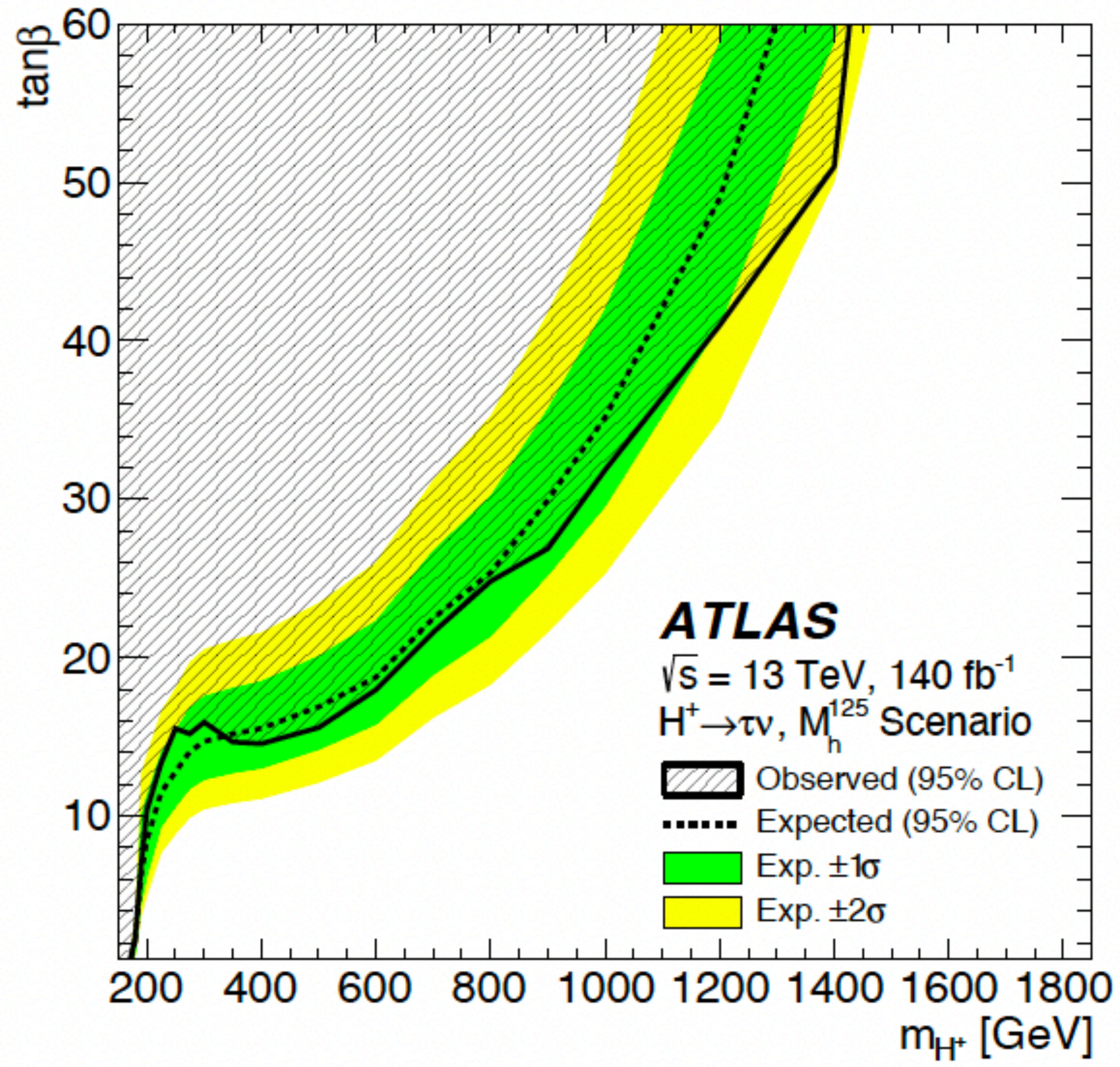
Search Channels and Key Results:

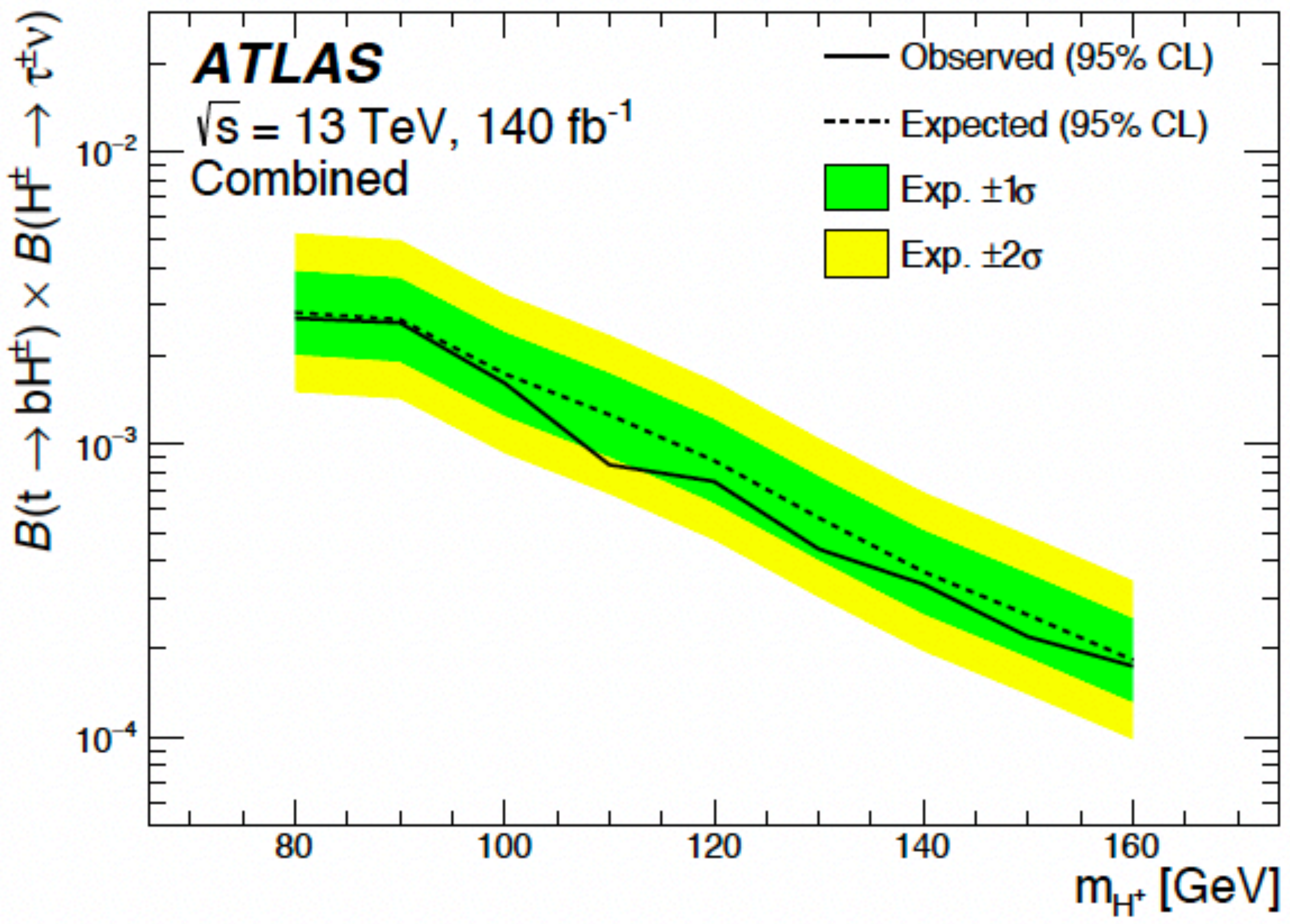
1. $H^{\pm} \rightarrow W^{\pm}h \rightarrow lbb$
   - Boosted object reconstruction (BDT/NN)
   - No excess; limits set in 2HDM parameter space
2. $H^{\pm} \rightarrow \tau^{\pm}\nu$
   - Full mass range explored with advanced τ ID (RNNs)
   - Significant sensitivity improvement (×2-4 wrt Run 1)
3. $S \rightarrow Z_d Z_d \rightarrow 4l$
   - Exotic Higgs decays to dark photons
   - No excess; strong model-independent limits
4. Model-Independent Dijet Resonances
   - Anomaly detection with ML (SALAD, CURTAINs)
   - No significant bump observed; generic BSM limits set

Thanks for your attention

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

Backup





- $BR(t \to bH^{\pm}) \times BR(H^{\pm} \to \tau\nu)$ in the low mass range (60-180 GeV) assuming SM $t\bar{t}$
- $tan\beta$ vs $m_{H^{\pm}}$ in the MSSM with M_h^{125} scenario

Backup

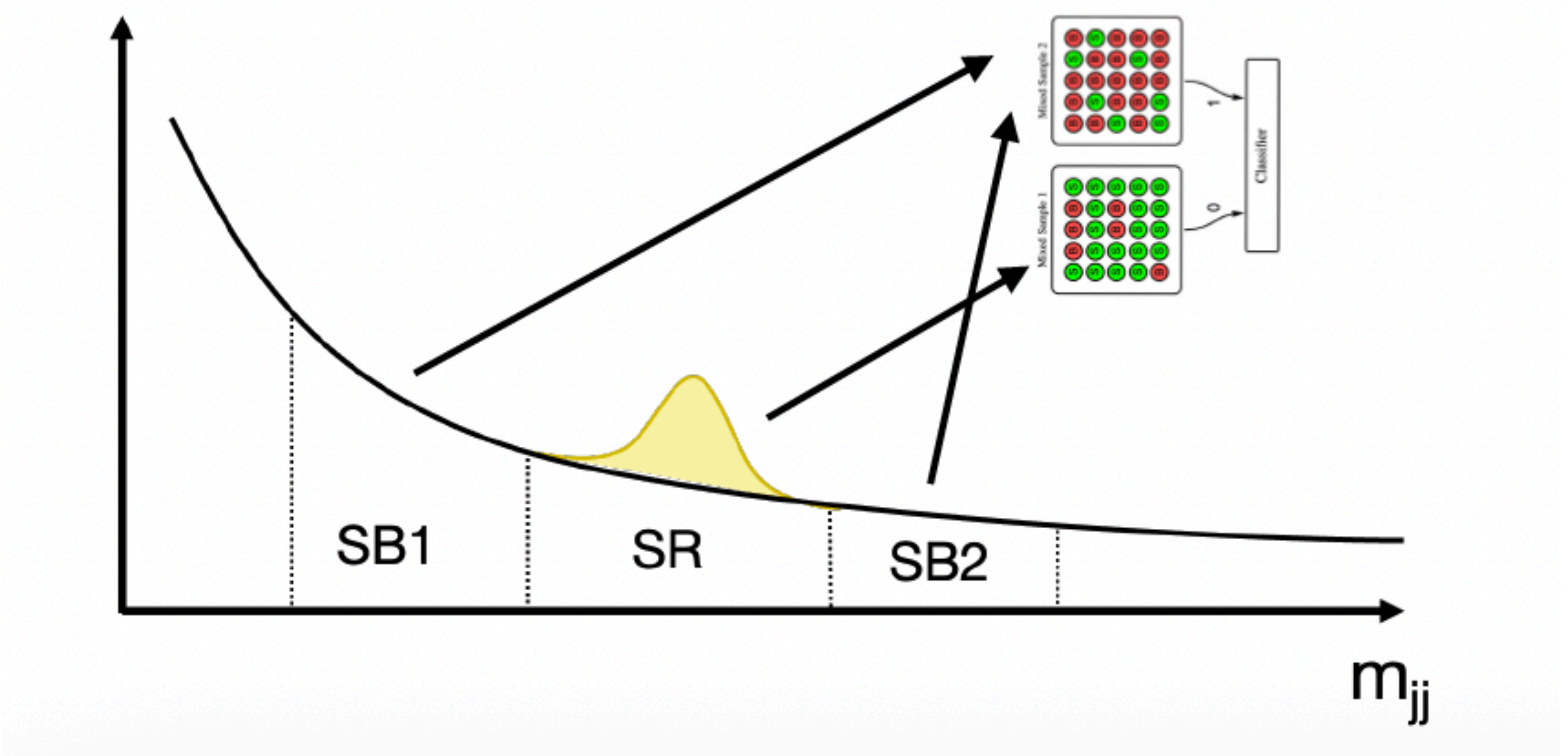
Classification w/o labels

Idea: train a classifier to distinguish two mixed samples with different S/B ratios

- Optimal classifier for sample 1 vs 2 = optimal for S vs B
- No per-event labels required

How to construct mixed samples for a resonant search?

- Original: SR & SBs (fully data-driven!)
- Recent: SR & ML-generated background template



Backup

Use SBs to correct MC to data (SALAD) OR train an invertible neural network (CURTAINS)
Interpolate to the signal region → get estimate of background in SR (template)

Final mass spectrum: CURTAINS

Seven signal regions analysed in a sliding window approach

- Background estimated using SBs

- No excess compared to background-only interpretation

→ largest deviation 1.3σ