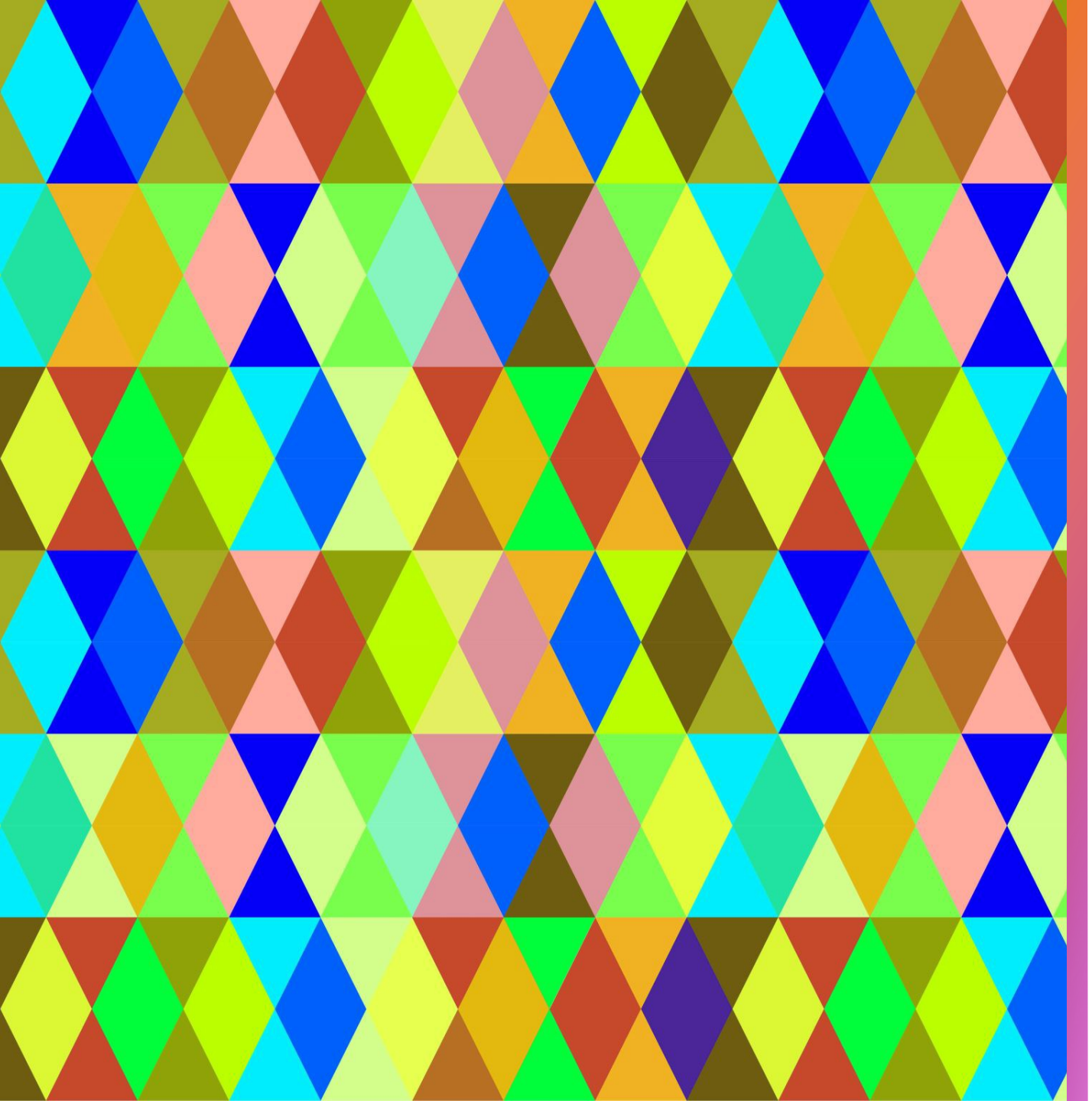


Searches for resonances decaying to pairs of heavy bosons in ATLAS

F. Conventi

on behalf of the ATLAS and CMS collaborations

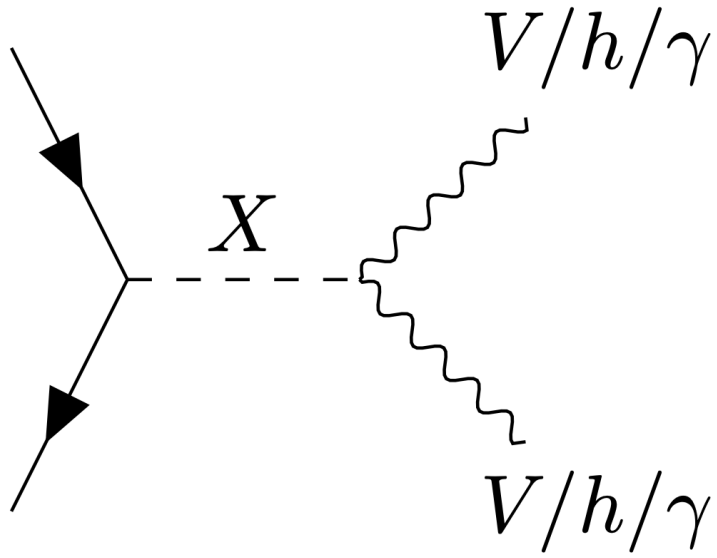
Lake Louise Winter Institute 2024

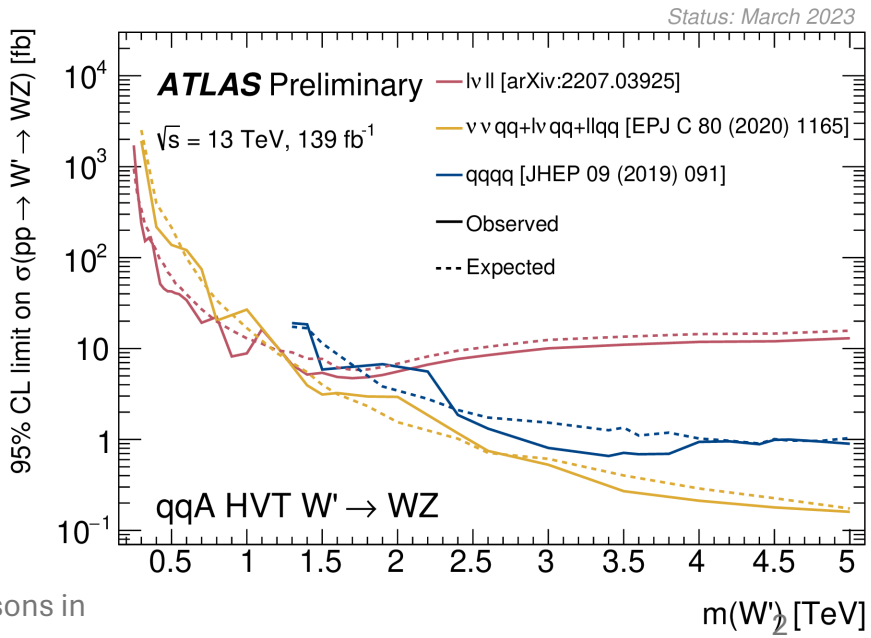
23/02/2024

Introduction

- Several scenarios for physics beyond the Standard Model include new particles decaying into pairs of bosons
- This can be due to eg. new Gauge symmetries or extensions to the Higgs sector, like the 2-Higgs Doublet Model, Supersymmetry or models introducing spin-2 gravitons.
- ATLAS present limits on 3 benchmark models for these models:
  - Neutral Spin-0: Randal-Sundrum Radion (Charged Spin-0: Georgi-Machacek)
  - Spin-1: Heavy vector triplet (HVT)
  - Spin-2: Randall-Sundrum Graviton

- The SM Higgs boson (in this talk denoted H) provides one (but not the only) promising potential to look for such new resonances
- A common challenge: The presence of very boosted particles in the final states – often only in parts of the searched signal parameter space





Several recent ATLAS studies on architecture comparisons for tagging

ATL-PHYS-PUB-2023-020

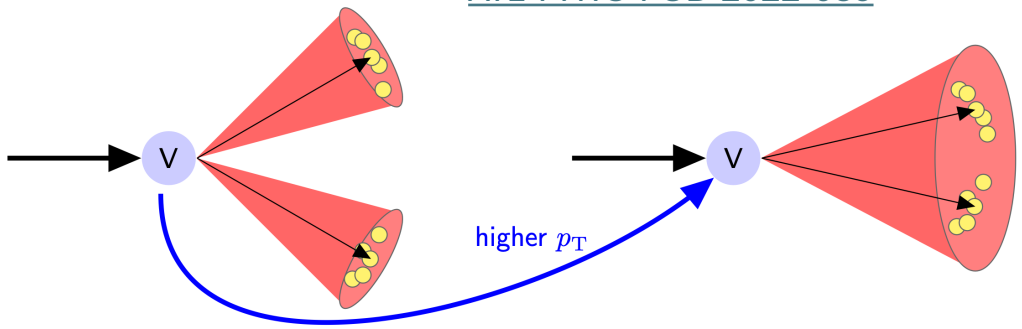
ATL-PHYS-PUB-2023-017

ATL-PHYS-PUB-2022-039

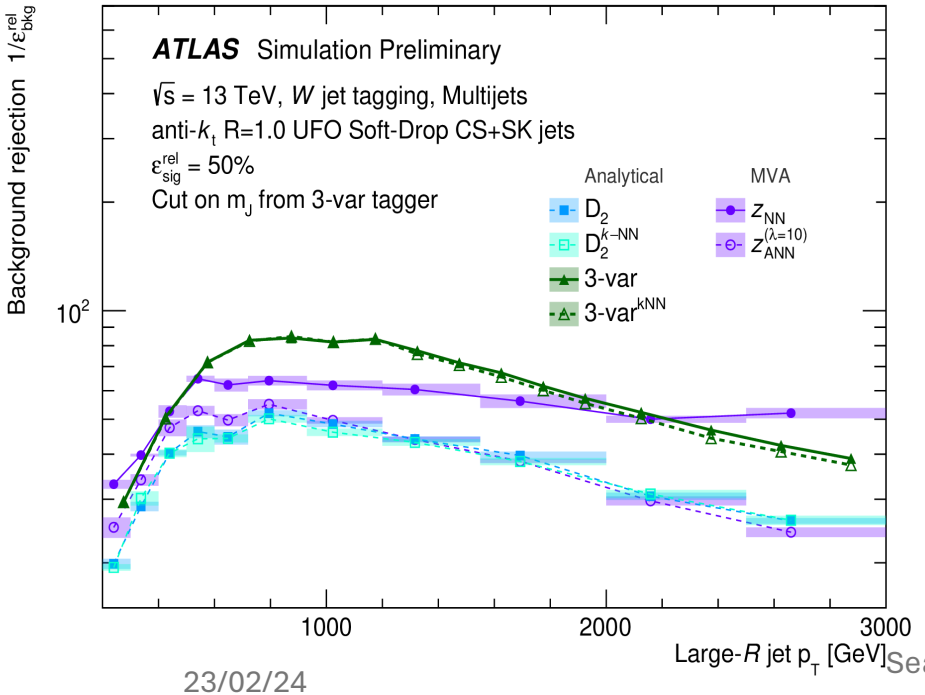
Boosted Bosons Reconstruction

When searching for new heavy resonance the boson pT often very high i.e. opening angle of decay products $\sim \frac{2m(V/h)}{p_{\mathrm{T}}(V/h)}$

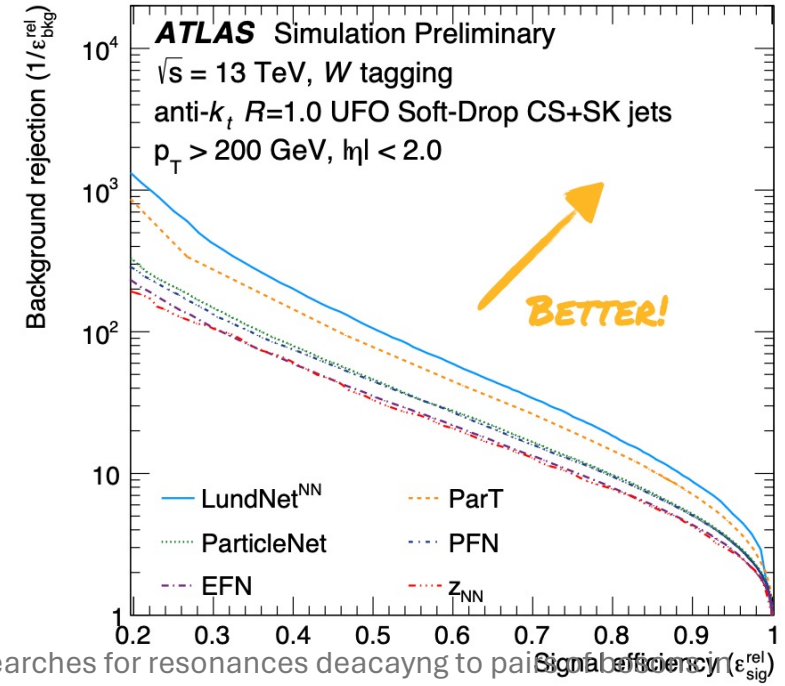
Machine-learning techniques to “tag” large-R jets as heavy bosons (W/Z/h/etc)



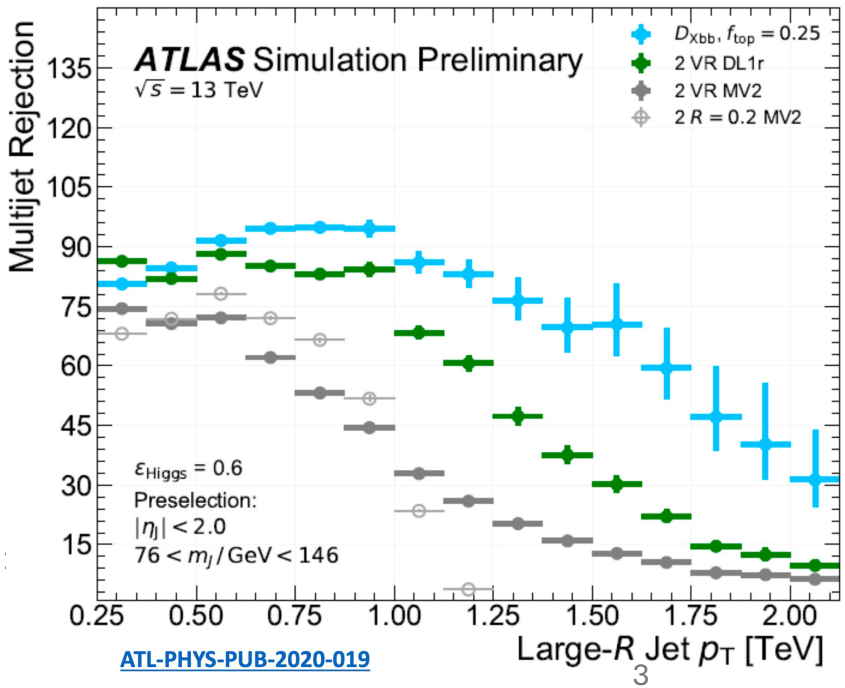
W/Z taggers *(high-level features)*



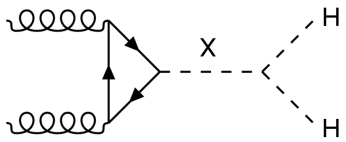
Costituents based W taggers



Higgs ($H \to bb$) Tagging



Resonant HH



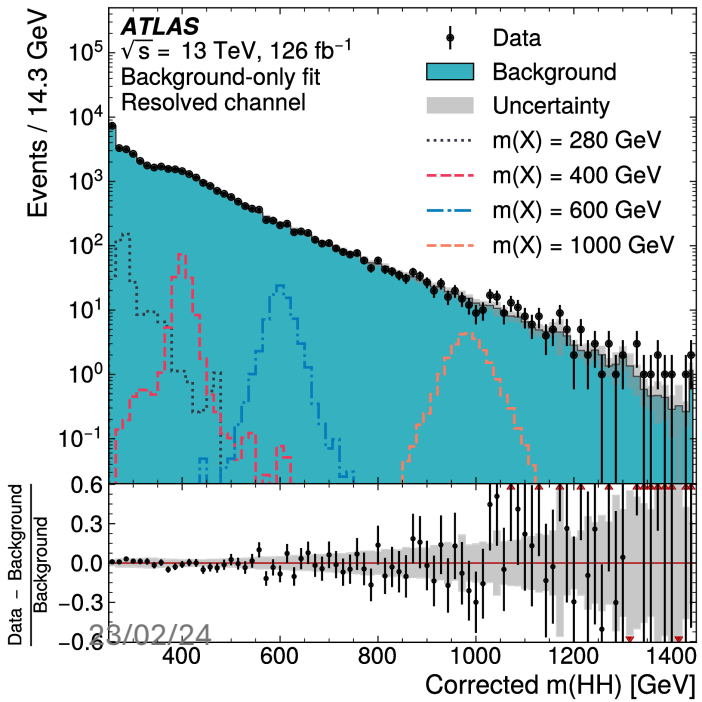
$X \to HH \to b\bar{b}b\bar{b}$

2 channels spanning 250 < mX < 5000 GeV:

Resolved: Four R=0.4 b-tagged jets, with BDT to pair them as Higgs candidates

Boosted: Two R=1.0 b-tagged jets (pT>250GeV)

Good agreement with SM small excess at 1.1 TeV
2.3σ for Spin-0 (2.5σ for Spin-2)



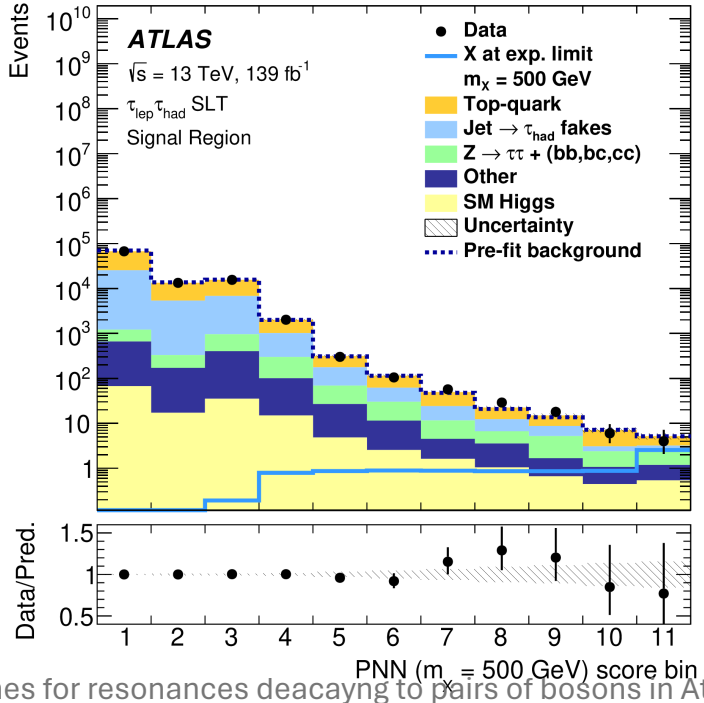
Phys. Rev. D 105 (2022) 092002

$X \to HH \to b\bar{b}\tau^+\tau^-$

2 channels spanning 250 < mX < 1600 GeV:

- **τhadτhad**: Two opposite-charge hadronic tau leptons, no electrons or muons (trigger) with leading τ pT >100-180 GeV
- **τlepτhad**: Exactly one electron (muon) and one hadronic tau with opposite charge

Final fit on **Parametrized NN**
largest deviation from SM combined local (global) excess at mX = 1 TeV, of 3.1 (2.0)σ

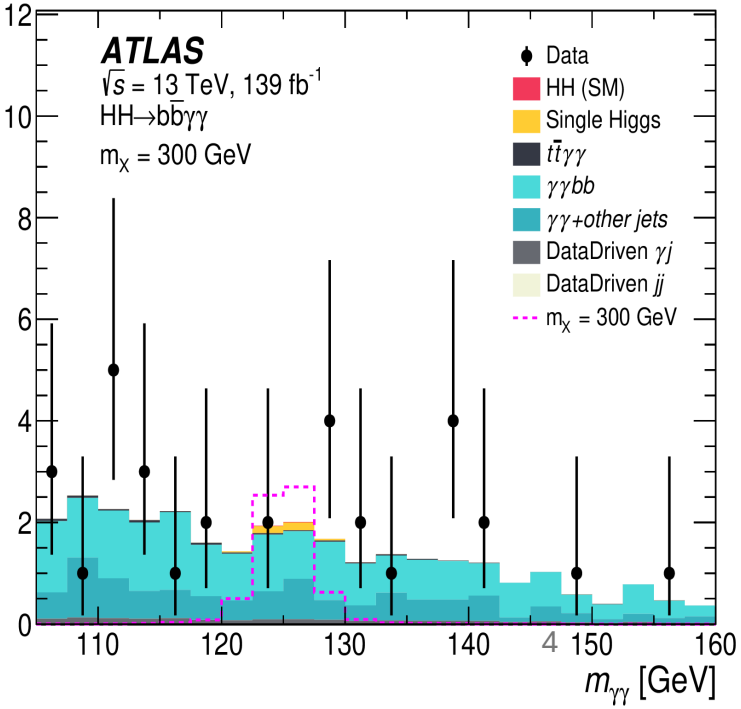


Phys. Rev. D 105 (2022) 092002
JHEP 11 (2020) 163 JHEP 07 (2023) 040
JHEP 07 (2023) 040 JHEP 11 (2020) 163

$X \to HH \to b\bar{b}\gamma\gamma$

Search 251 < mX < 1000 GeV
2 BDTs trained and combined to discriminate signal from non-resonant (continuum) and resonant (single Higgs) backgrounds respectively

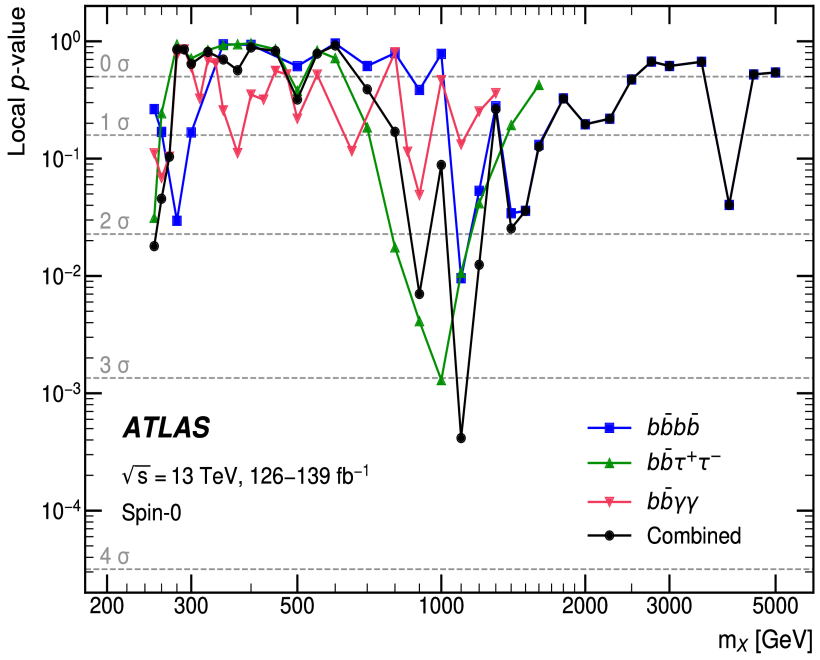
No significant excess observed

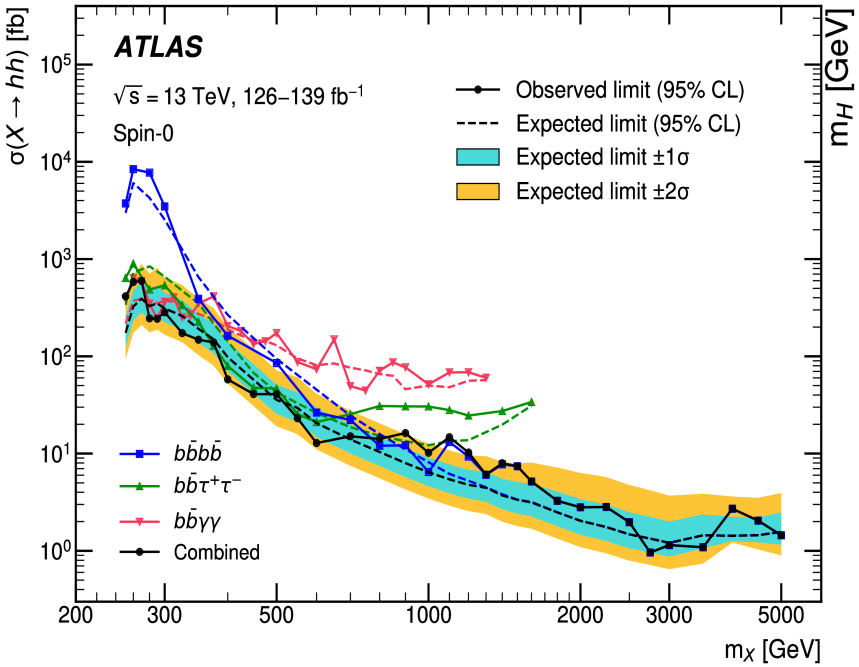


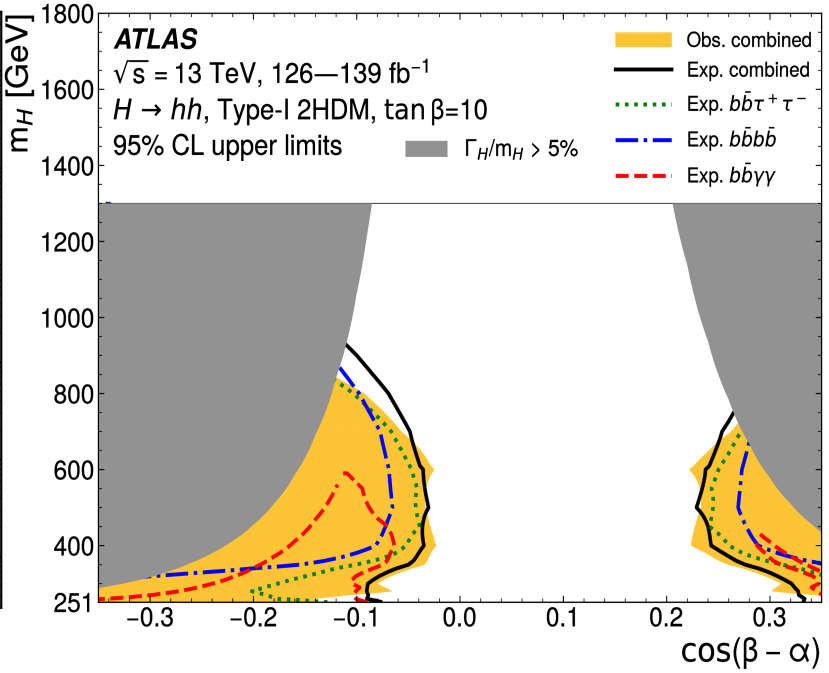
arXiv:2311.15956

Resonant HH: Combination

- Combined likelihood with inputs from all three HH resonant analyses
- No significant excess wrt SM. Largest combined deviation of 3.3 (2.1)σ at 1.1 TeV
- The limits are interpreted in the Type-I Two-Higgs-Doublet Model and the Minimimal Supersymmetric Standard Model, and constrain parameter space not previously excluded by other searches



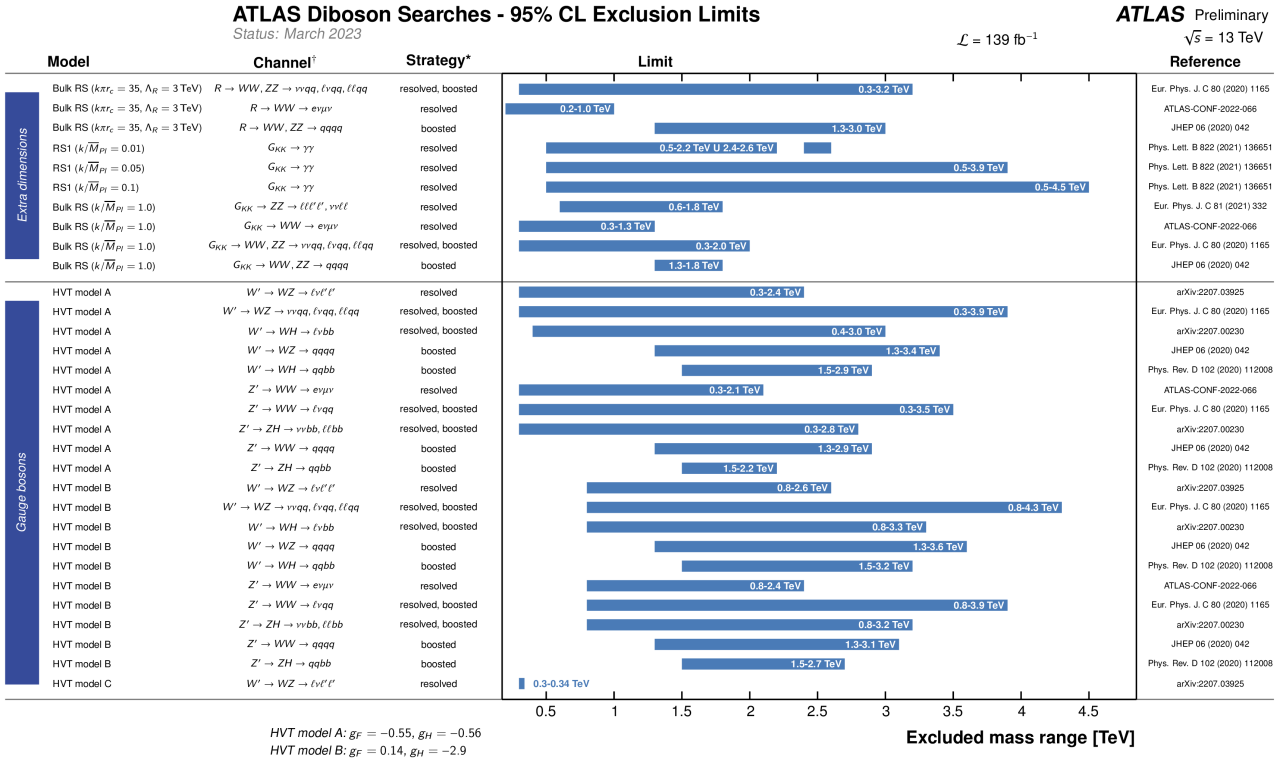


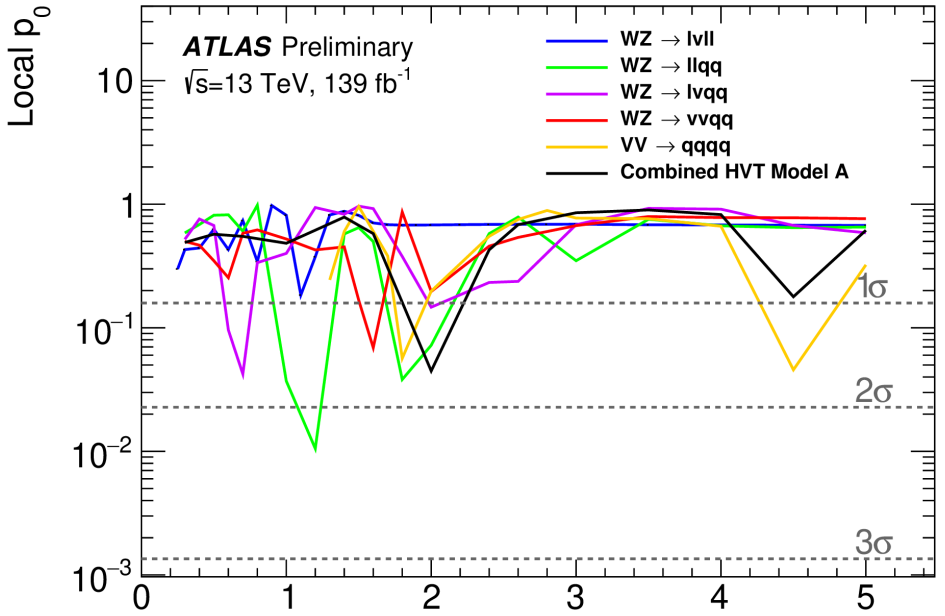


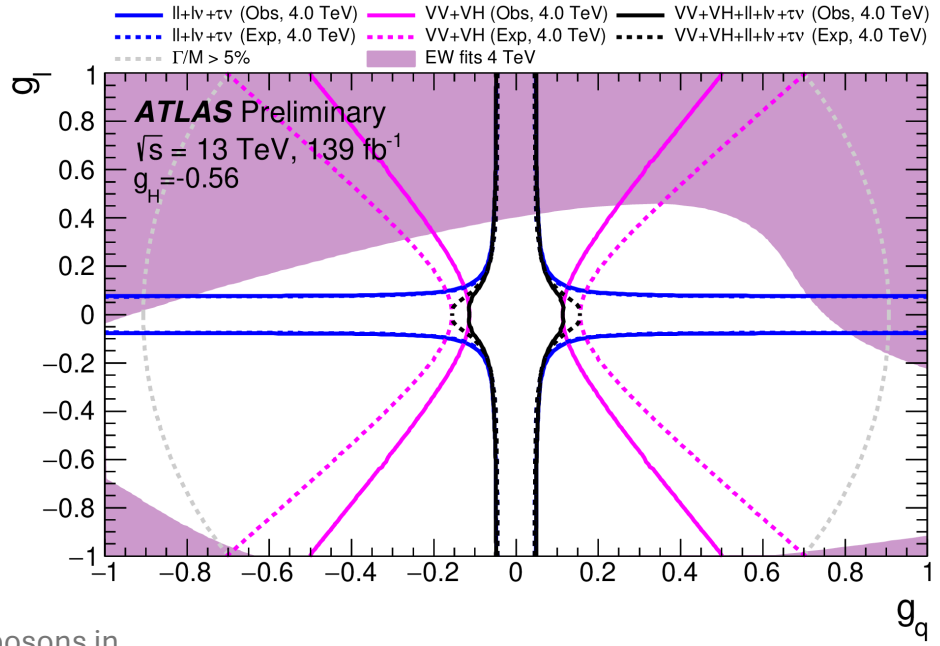
Heavy Resonance Combination

ATLAS published combination of all VV/Vh/lΓ resonance searches using full Run-2 dataset

- Check if local excesses coincide
- Strongest limits
- Limits directly on couplings of benchmark HVT model





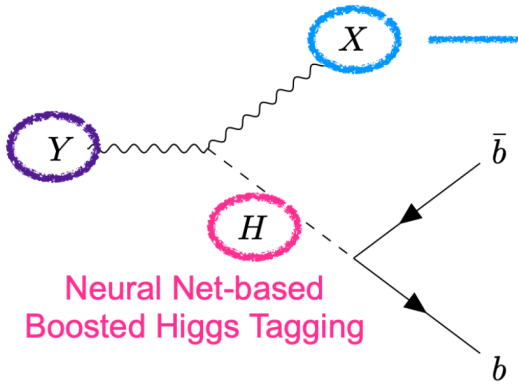


Anomaly detection in Y->XH

Phys. Rev. D 108, 052009

High (~1-6TeV) Y mass resulting in X and H boosted
Y reconstructed with two large-R jets

Resonant mass (bump hunt)



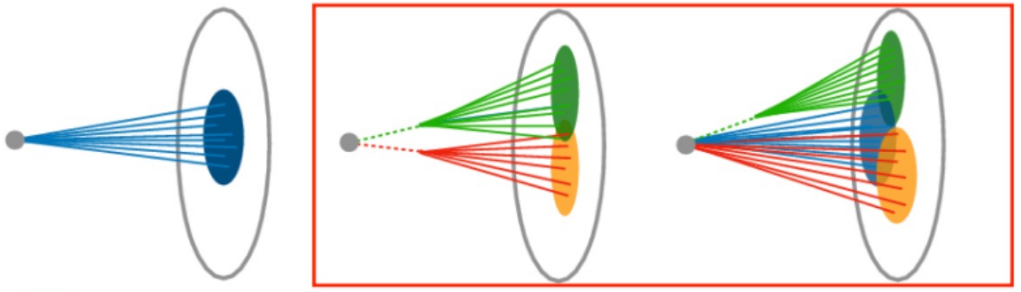
Neural Net-based Boosted Higgs Tagging

Anomaly Score

? Jet-level anomaly score given by a **variational recurrent neural network (VRNN):** Unsupervised training in data modeled as sequence of kt-ordered constituent 4-vectors.

H Candidate: Neural net-based tagging of boosted H→ bb topology. XbbTagger @60% WP + mass windowcut (75GeV < mH < 145GeV)

Define anomaly score (AS) per jet as a function of VRNN loss

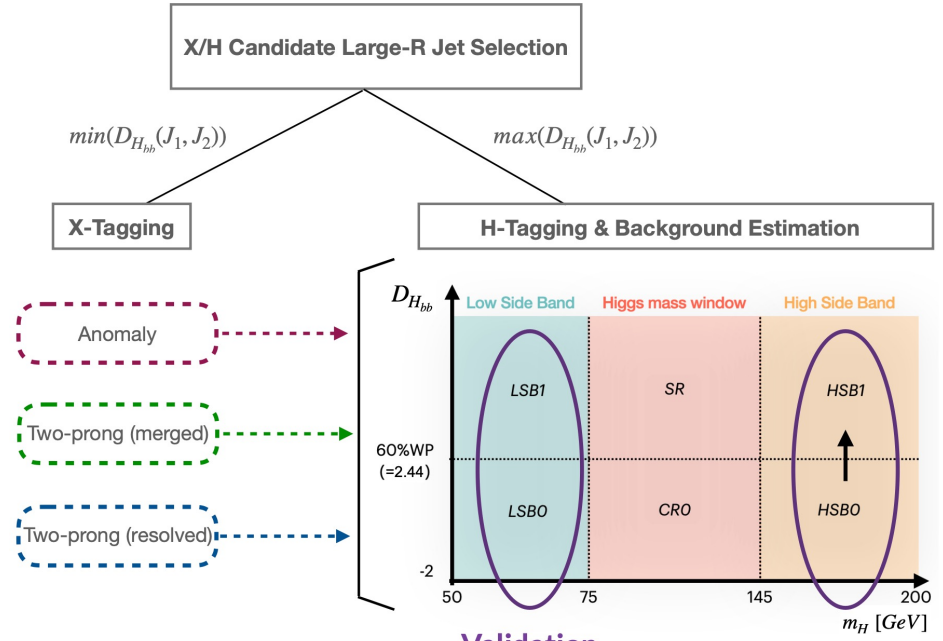


No substructure

2-prong

3-prong

high reco error



Validation Region

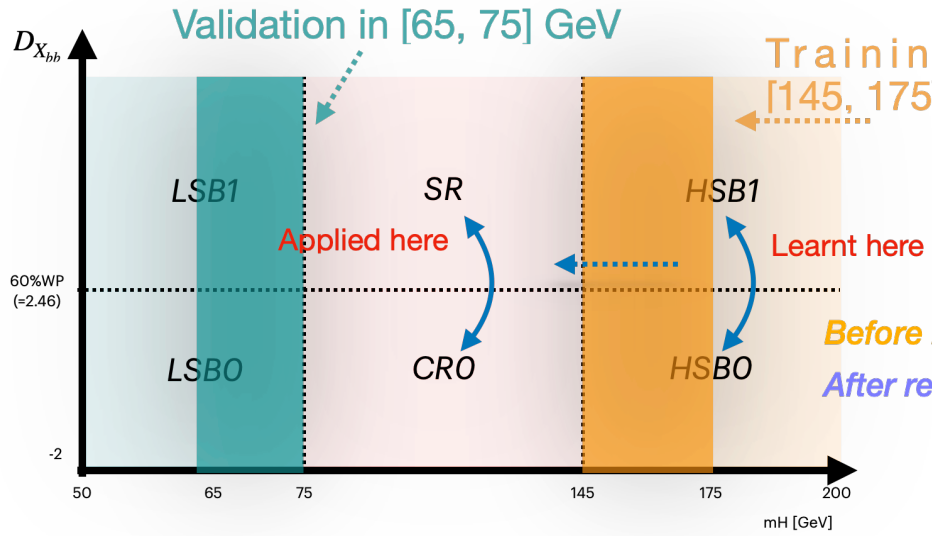
Control Region

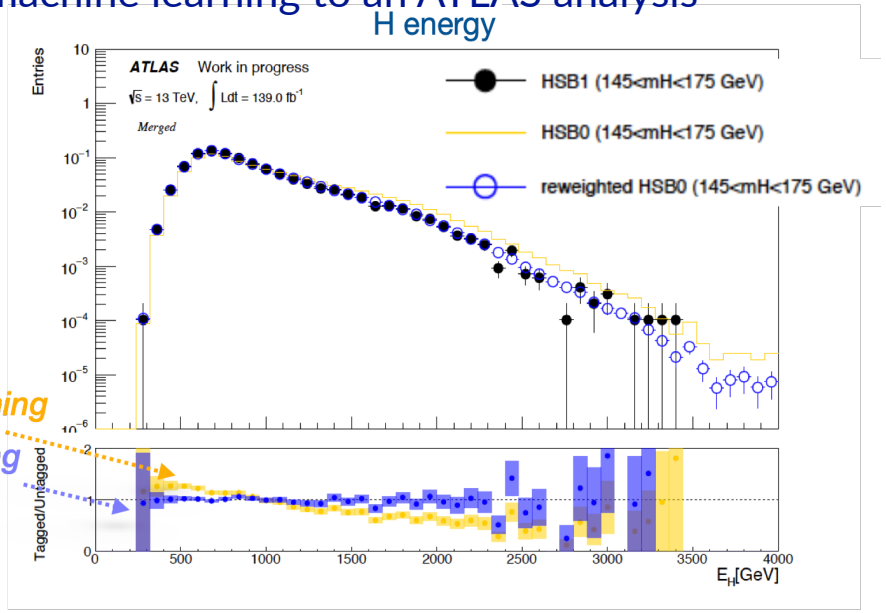
Anomaly detection in Y->XH

➡️ First application of fully unsupervised machine learning to an ATLAS analysis

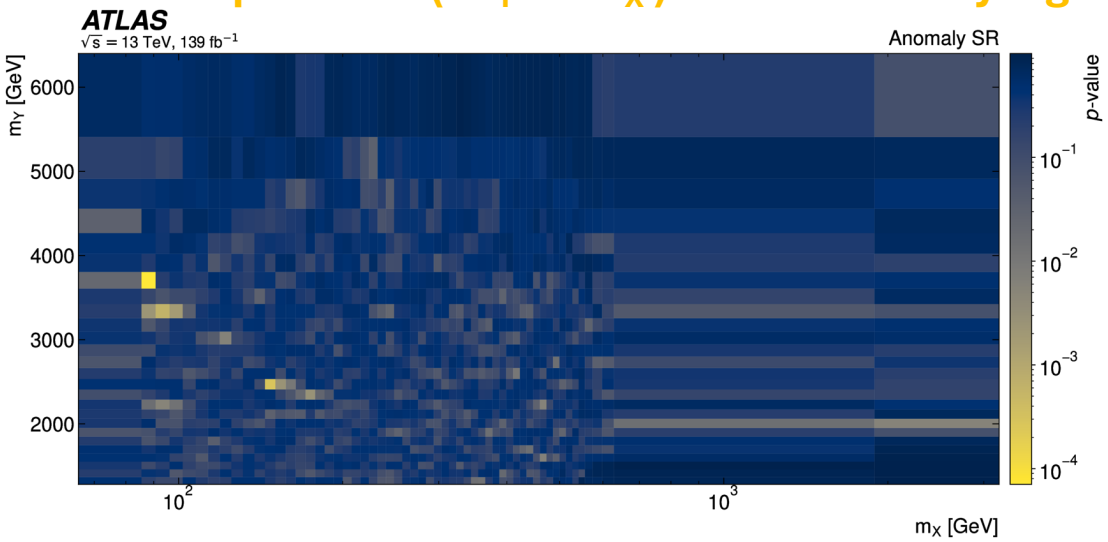
Background estimation:

DNN has been applied for estimating the likelihood ratio between two kinematic regions **and obtaining reweighting factor for the background estimation** in the signal region





Observed p-values (m_Y vs m_X) in the anomaly signal region

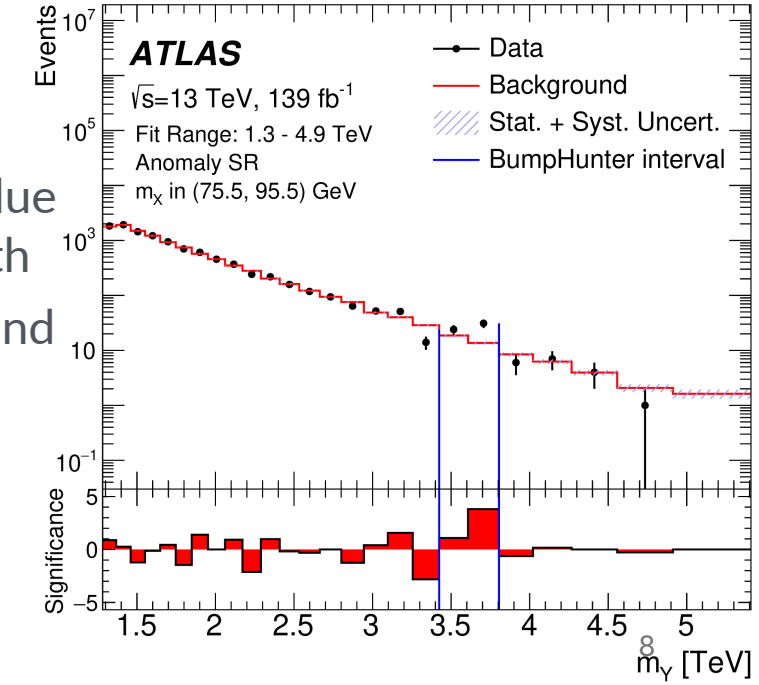


The lowest observed p-value corresponds to the bin with

$mY \in [3608, 3805]$ GeV and

$mX \in [75.5, 95.5]$ GeV

1.4σ global significance in BumpHunter

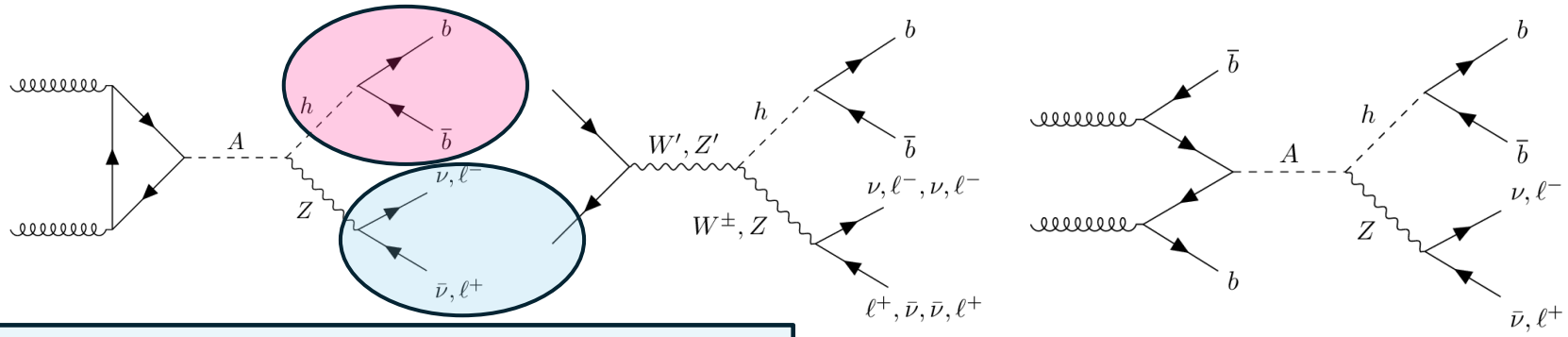


VH semileptonic resonances

JHEP 06 (2023) 016

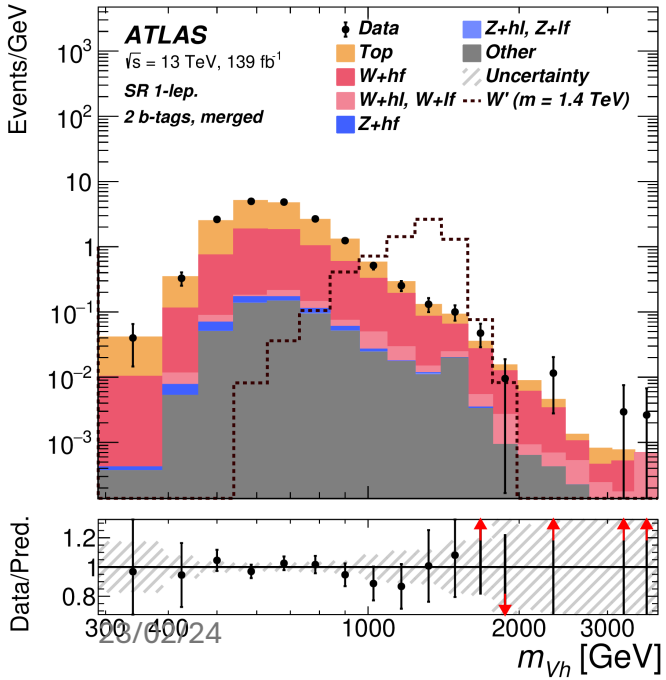
Recent search for V h → llbb/lvbb/vvbb

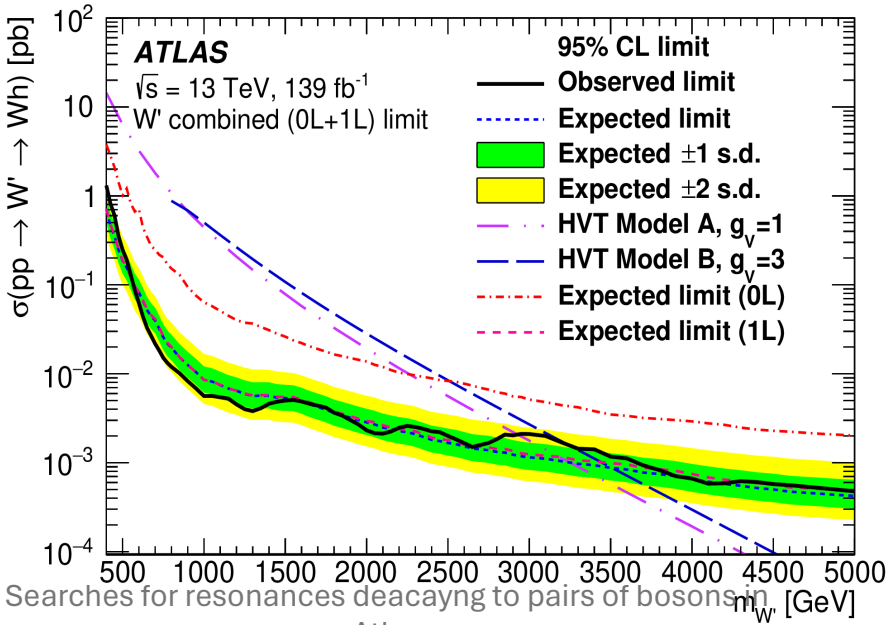
H candidate: Different reconstruction techniques for h → bb:
- 2 resolved R = 0.4 jets or 1 large R=1.0 jet
- 1,2 btag jets

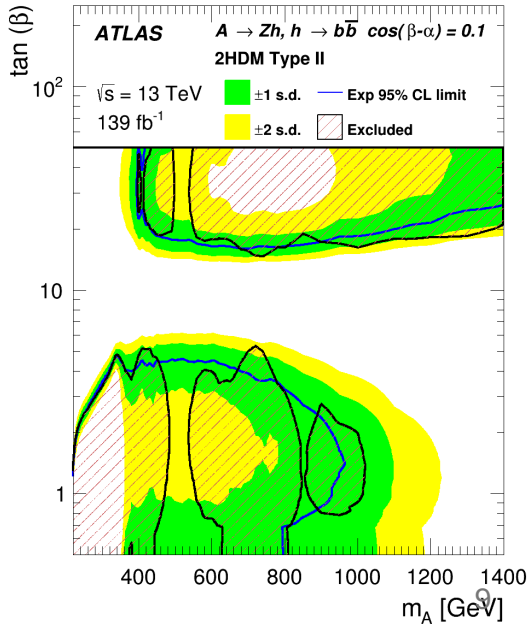


0,1,2 leptons: The search is conducted by examining the reconstructed invariant or transverse mass distributions of *Z*h or *Wh* candidates for evidence of a localised excess in the mass range from **220 GeV to 5 TeV.**

Results consistent with SM
- Limits on HVT model
- Limits on 2HDM model in inclusive and b b̄-associated



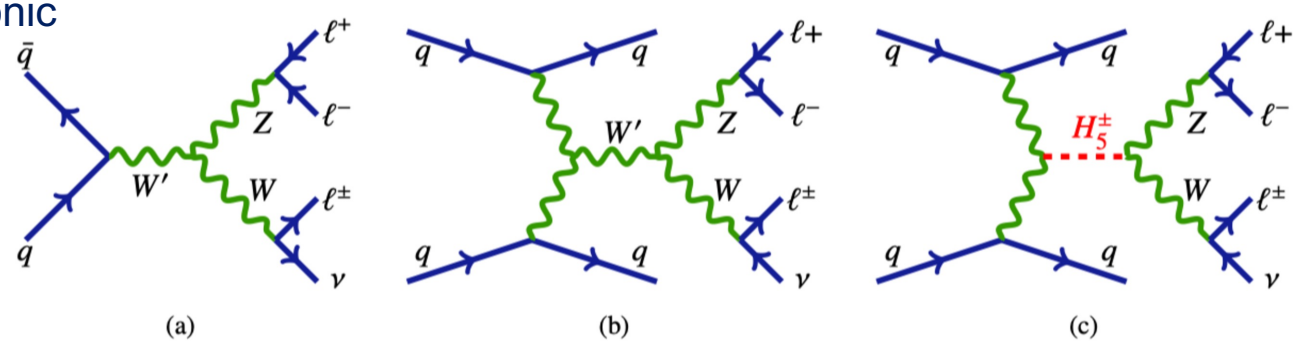




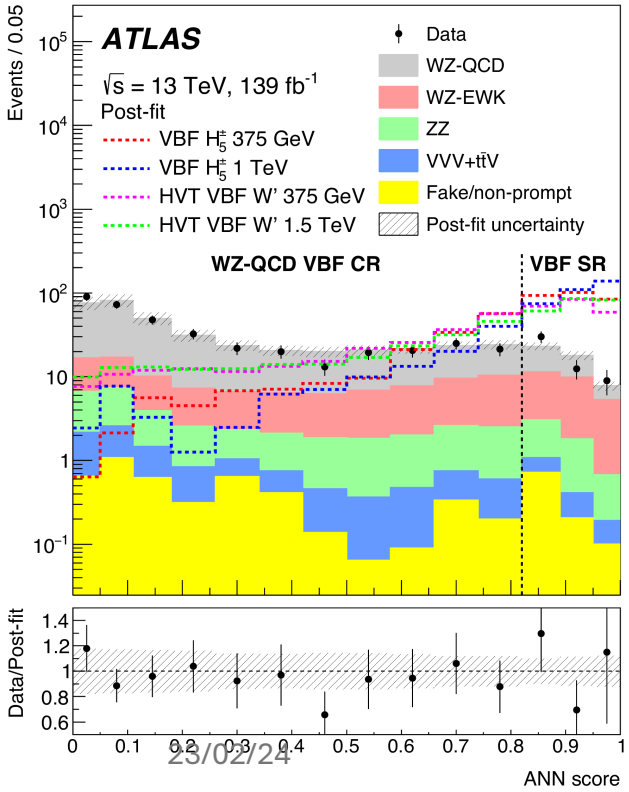
VV fully leptonic resonances

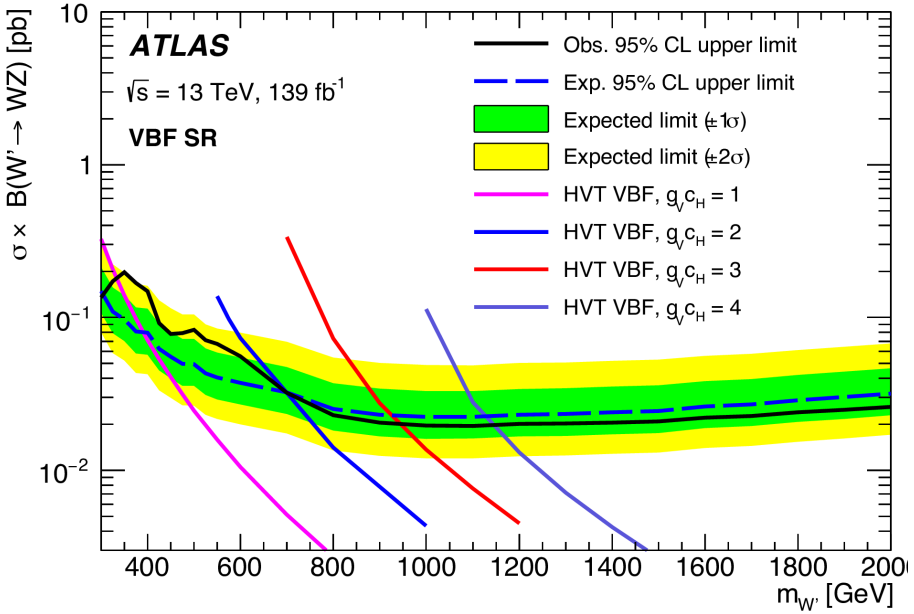
Eur. Phys. J. C 83 (2023) 633

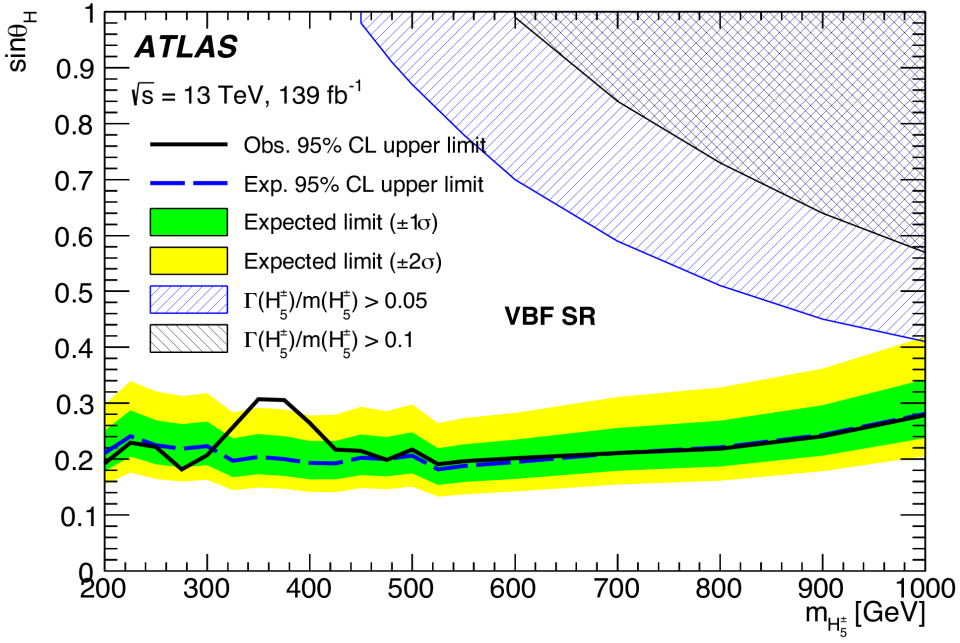
Complementary to fully-hadronic searches, searches with leptonic decays WZ → lvll
Very low-background, but also lower signal
- Can rely on good MC predictions
- Better constraints at mid-mass **300 GeV < m(X) < 1 TeV**



Analysis focused on VBF-produced signals
ANN to separate inclusive vs VBF production





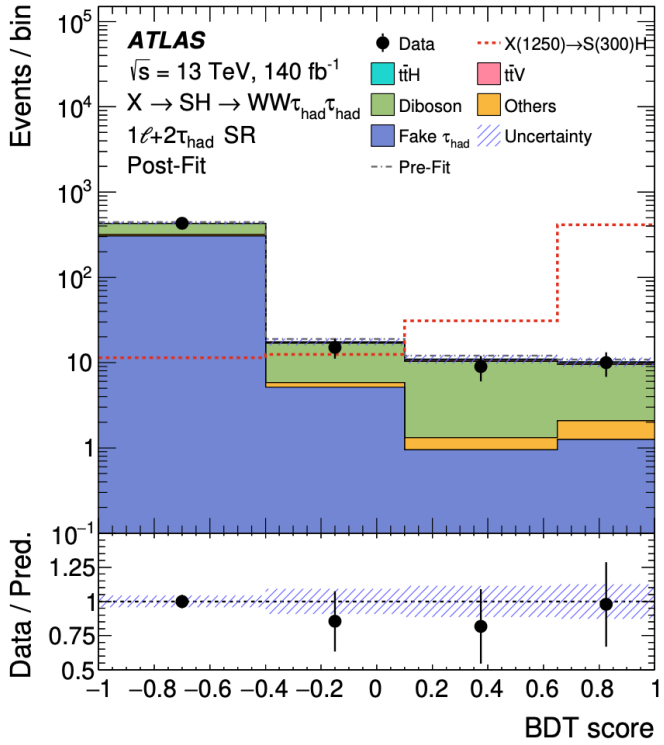


$X \rightarrow SH \rightarrow VV\tau^+\tau^-$

- Scans a window of **500 < m_X < 1500** GeV with **200< m_S <500GeV**
- Select **two opposite-sign τ_{had}** (pT>25 GeV, **Δ**R<2)

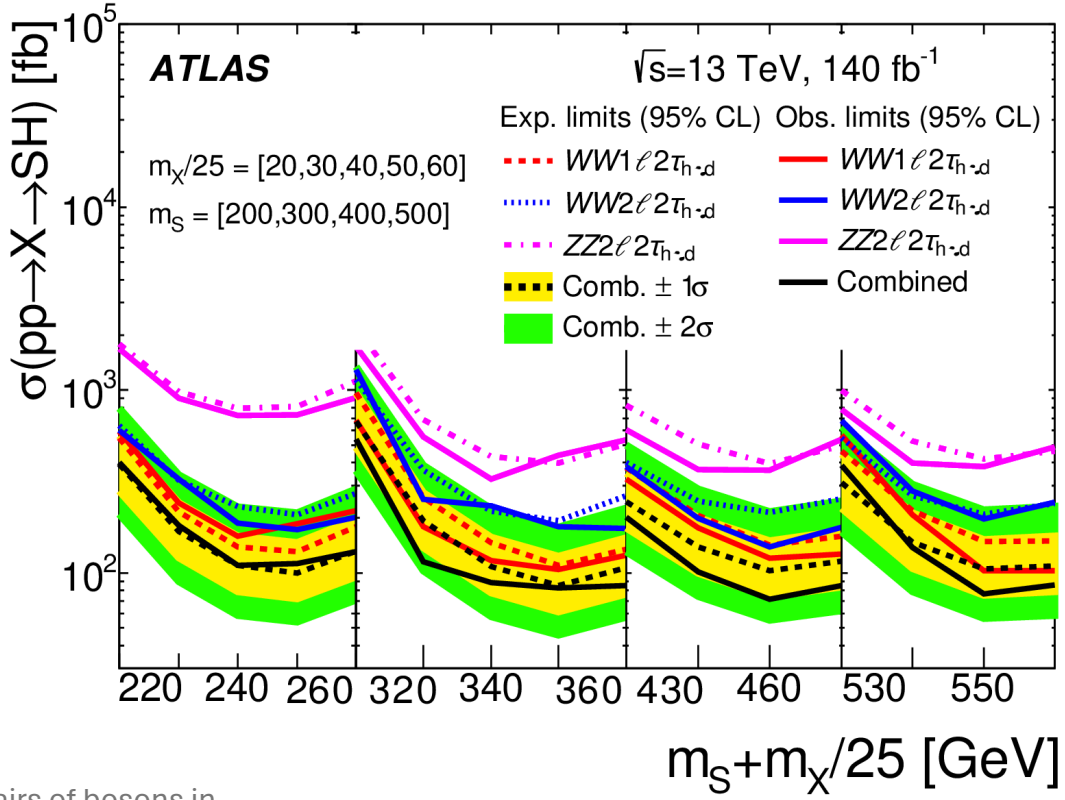
Signal-to background (dibosons, ttV, fake τ) discrimination with **parameterized BDT** (one per signal region and m_s hypothesis)

Three signal regions:
- **WW1l**: == 1 lepton *(main contribution to set limits)*
- **ZZ2l:** same-flavour OS leptons with mll in Z window
- **WW2l:** opposite-sign leptons, vetoed if same-flavour leptons in Z window



No significant excess observed in data to SM background expectation

Limits set through combining the 3 SRs obtained under assumption that branching ratios of S equal to those of SM Higgs

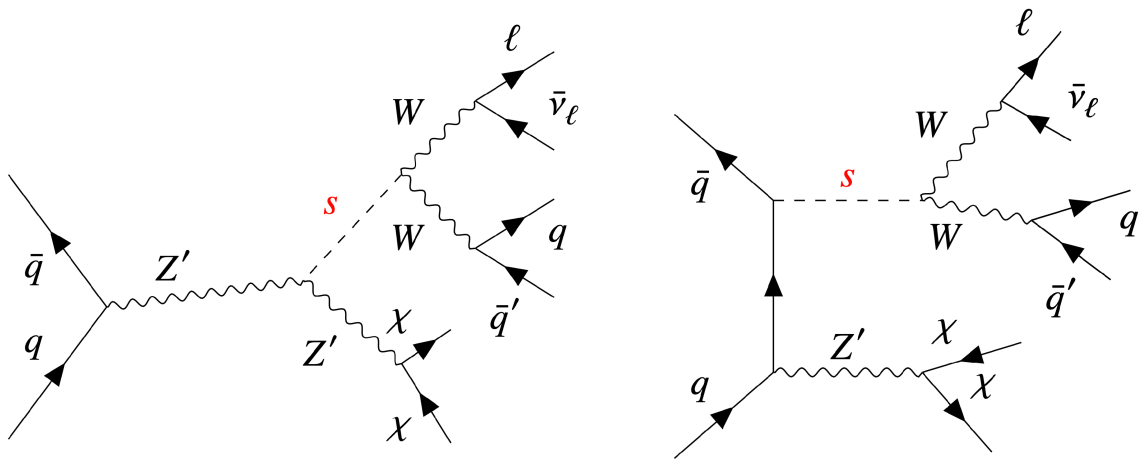


JHEP 07 (2023) 116

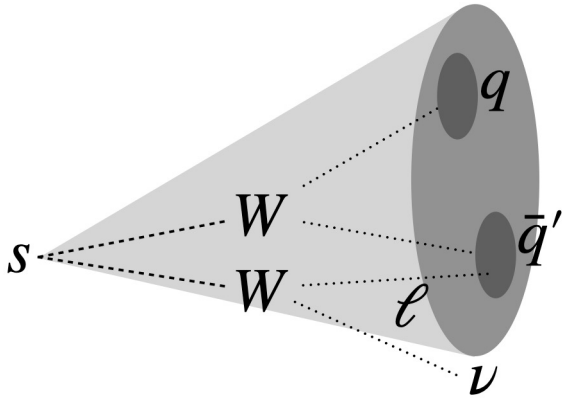
DM + dark Higgs → VV

Many DM searches at LHC rely on the $E_{T,miss}$ + X framework with WIMP-like particles recoiling again SM particles.
Also interest in **two-mediator models** with spin-1 **Z'** and **dark Higgs boson** decaying into *W+W–*

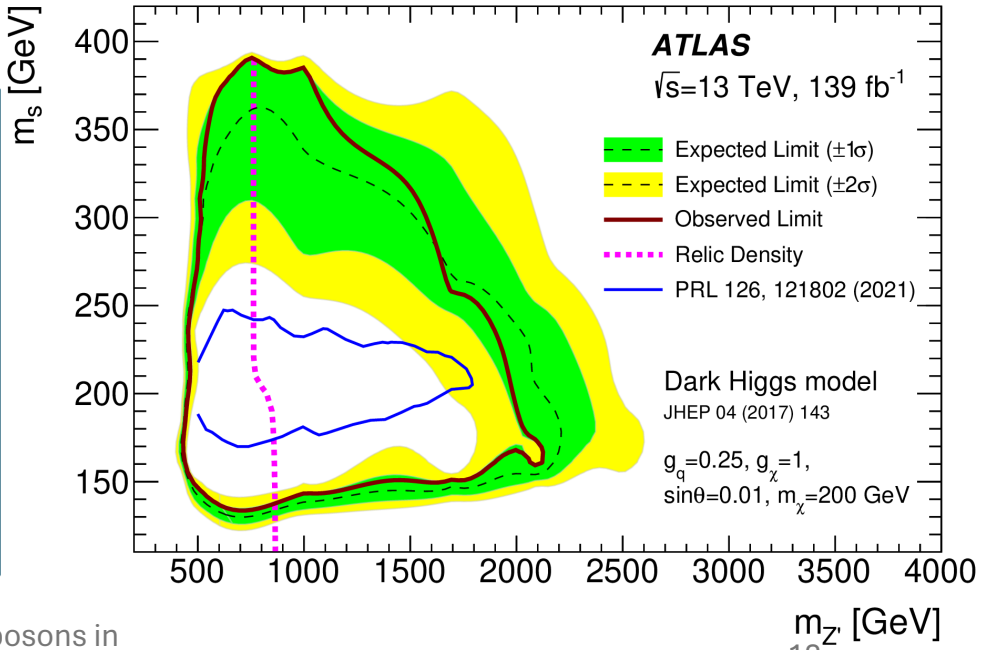
- s→VV dominates above m_s>160GeV



If the dark Higgs boson (s) is significantly boosted → reconstructed as a large-(R) jet and often leads to an overlap of the charged lepton ℓ and the large-(R) jet from the W→ $q\bar{q}'$ decay.



- **Dominant channels is lvqq**
- Data in agreement with SM predictions: no excesses
- Limits for scenarios with **dark Higgs boson masses ranging between 140 and 390 GeV are excluded** (rely on assumptions of DM mass and couplings)



Summary

- Atlas experiments have a very broad search programs for resonances decaying to pairs of bosons. The resonance masses in these searches **span in a large range** from O(200 GeV) < mX < O(5 TeV) with many different final states.
- Many of these analysis utilize state-of-the-art reconstruction techniques:
  - - **Boosted W/Z/h/t-tagging** is now common place
  - - Many **advanced machine-learning** techniques at play
- So far **no significant excesses** in data to SM expectation found, and we proceed to tightly exclude heavy resonance
- **These resonances remain a promising potential for future analyses** on Run 3 data, moreover EFTs provide framework to extend searches to tail effects of even heavier resonances

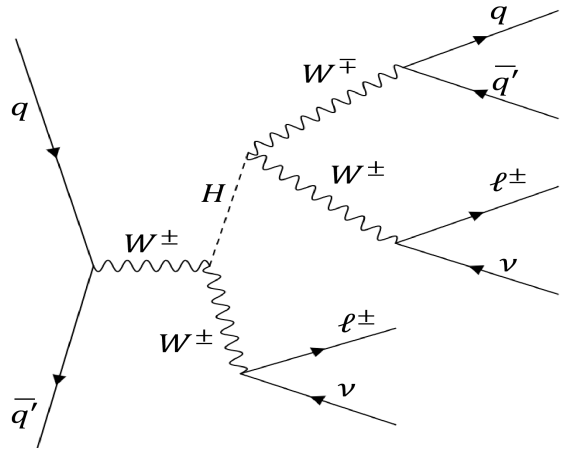
JHEP 07 (2023) 200

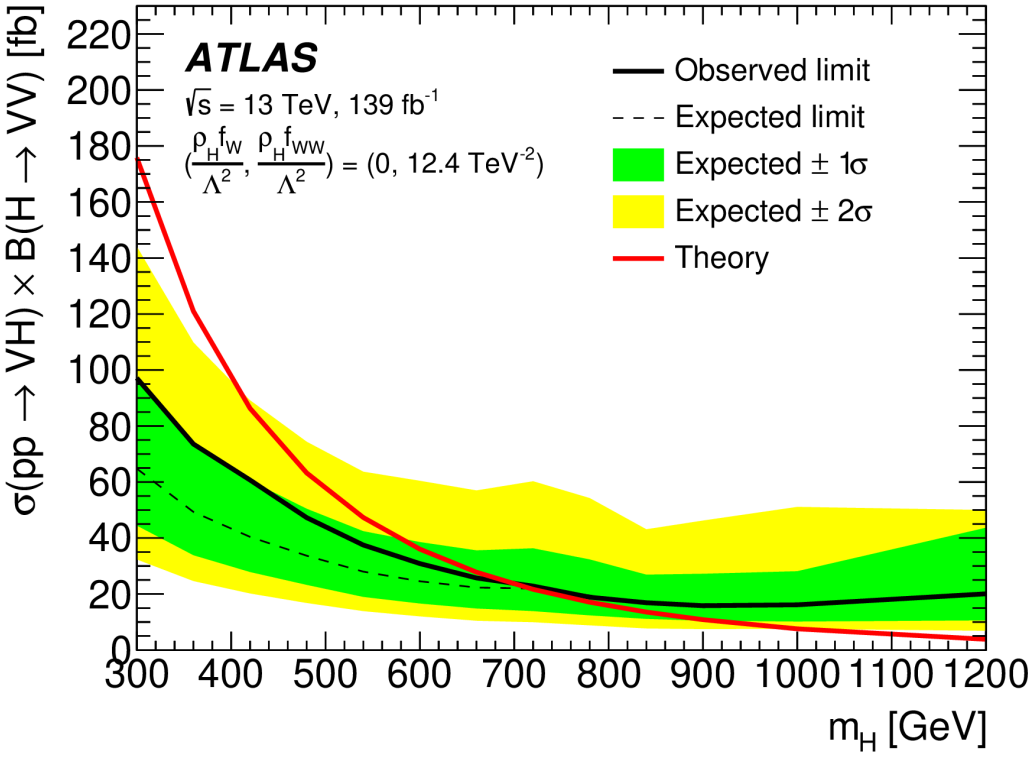
Generic Search for a Heavy Higgs boson (VH)

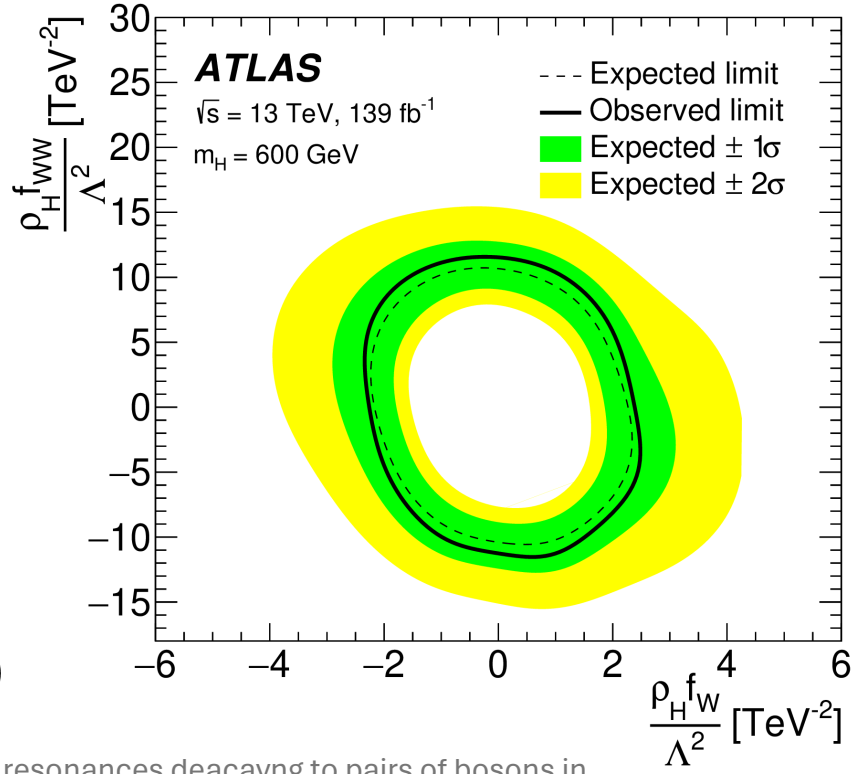
Search for heavy Higgs boson produced in VH channel with same-sign di-lepton final state

$W^{\pm}H \rightarrow W^{\pm}W^{\pm}W^{\pm} \rightarrow l^{\pm}\nu l^{\pm}\nu qq$ **(H not the SM Higgs *h*)**

- Highest signal sensitivity among other VH decay channels
- Sizeable Branching Fraction for $H \rightarrow W^{\pm}W^{\mp}$ decay





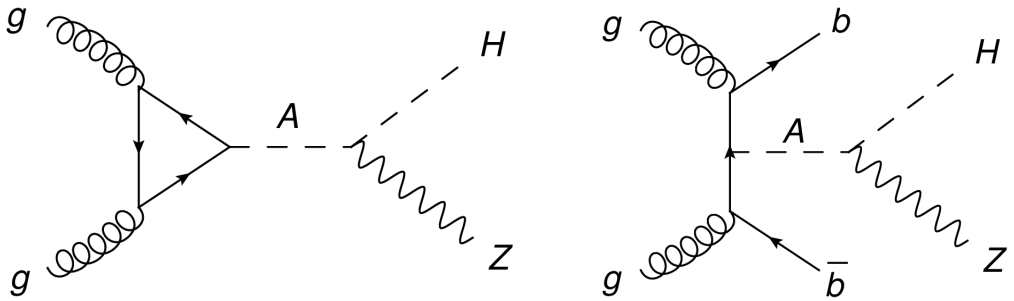


- **Upper limits** derived as a function of Heavy Higgs mass and coupling strengths to vector boson
- Exclusion Contours show **observed results are consistent** with the expected result within 1 sigma uncertainty

VH semileptonic resonances (mH !=125)

arXiv:2311.04033

Search for a heavy boson ***A*** *(*CP-odd Higgs) →***Z** + heavy CP-even boson ***H***



Heavy Higgs bosons *(A/H)* from the 2HDM
Mass range **400-1200 GeV for *A***, and **130-800 GeV for *H***
Decay of *A* to a BSM Higgs boson *H* and a *Z* boson
Z→2*l*or2*ν* and *H*→*tt* or *bb*,leading to ***lltt* and *vvbb* finalstates**

Main backgrounds: *ttZ* / *Z*+hf, *tt*
3 SR categories, based on number of leptons, jets, *b*-jets, MET, reconstructed *Z* and *H* boson masses:
❒ 1 *lltt* SR: 3*l*, ≥4 jets and 2 *b*-jets
❒ 2 *vvbb* SRs: 0*l*, MET, 2 *b*-jets and ≥3 *b*-jets

Final discriminant variables:
lltt SR: mass difference between *A* and *H*: $\Delta m = m(lltt) - m(tt)$
vvbb SRs: transverse mass of *A* $m_T(VH)$
No significant excess above SM observed
Mild excess observed in the *lltt* channel for
(m_A, m_H) = (650 GeV, 450 GeV) with local significance of **2.85σ**