Searches for resonances decaying to pairs of heavy bosons in ATLAS

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ATLAS EXPERIMENT

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Introduction

- ATLAS has a vast heavy resonances search program
  - ✓ Many theories predict the existence of such new particles: *Heavy Vector Triplet (HVT), Two-Higgs-Doublet Model (2HDM), Georgi-Machacek (GM), technicolor, etc.*
  - ✓ Often feature new heavy resonances decaying to SM bosons and fermions
  - ✓ Boosted decays are essential channels for these searches

- Jet substructure and jet performance crucial for various di-boson searches
  - ✓ Resonance with high masses require excellent V-tagging and H-tagging in boosted scenarios

- This talk:
  - ✓ Highlight few of the latest jet techniques
  - ✓ Recent results in the heavy di-boson search

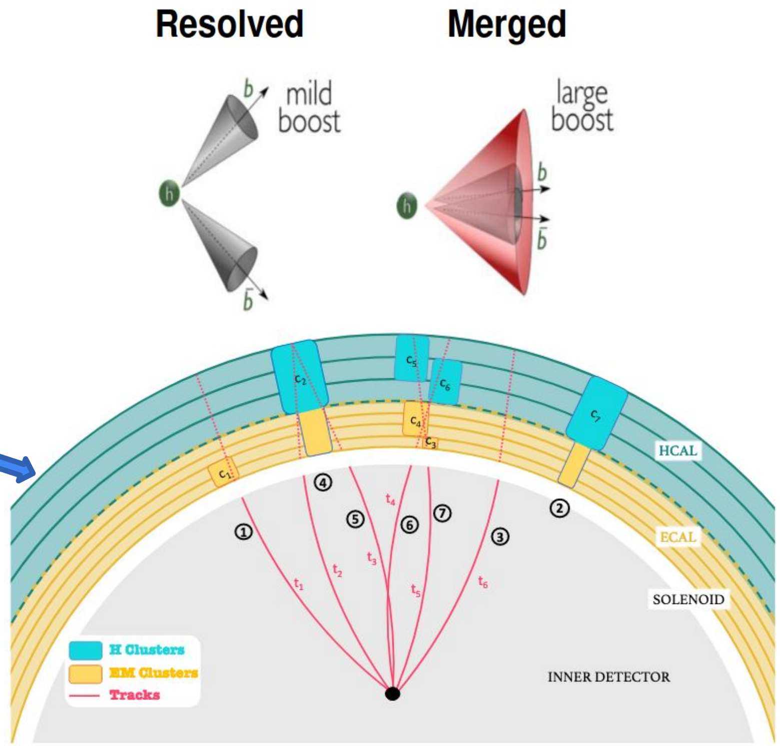
Jet substructure

➢ Boosted decay products are often reconstructed into single jets

➢ Calorimeter (calo) information is used to reconstruct the large radius jets

➢ Discuss **two techniques** used by ATLAS to improve the jet tagging performance for these topologies

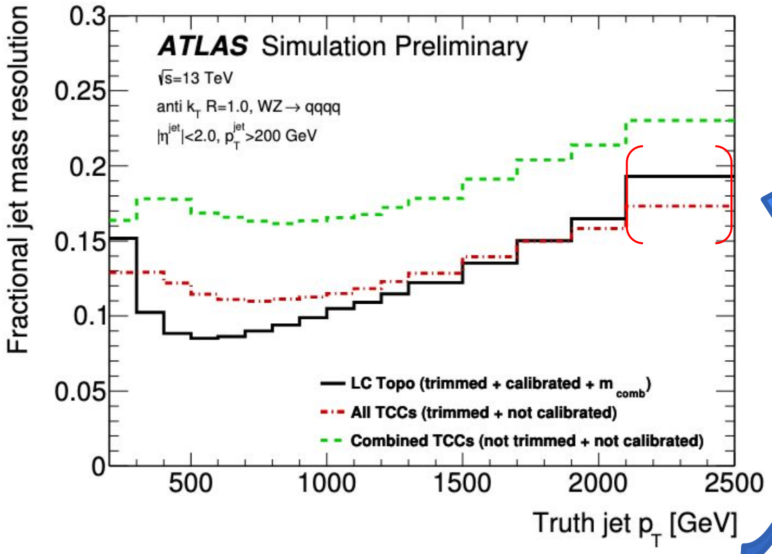
✓ **Track-Calo-Clusters** (TCC) and **W/Z Taggers**

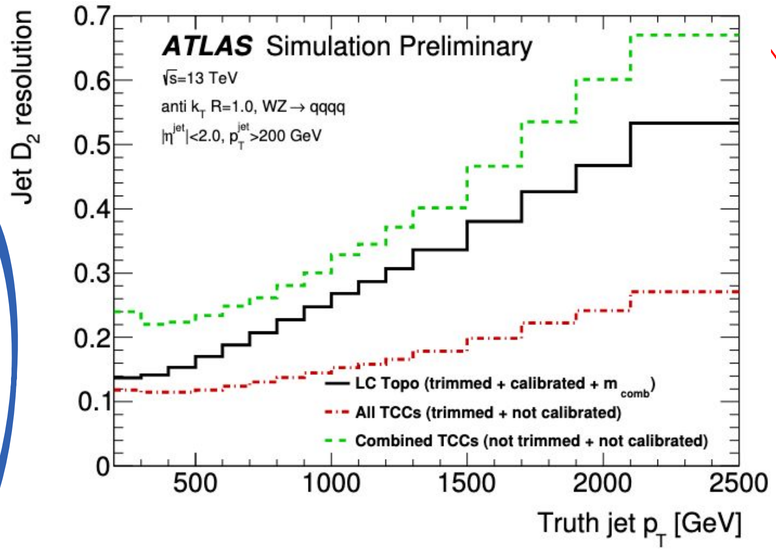


Track-Calo-Clusters (TCC)

ATL-PHYS-PUB-2017-15

- ➢ Jets constructed using **track** (eta and phi) and **calo-energy**
  - ✓ **Tracks** matched to **calo-clusters**



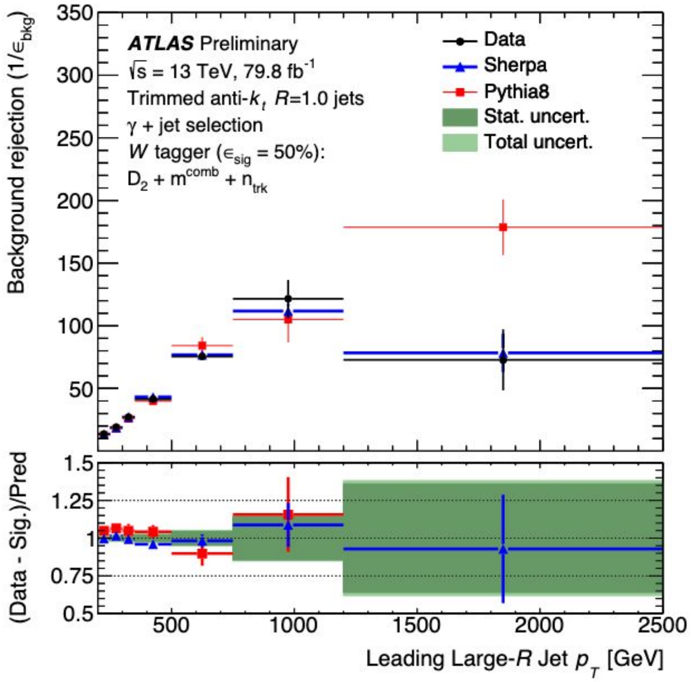


- ➢ At high momentum a nice **mass resolution** improvement seen
- ➢ Significant improvement on **D2** sub-structure which provided crucial separation between QCD jets and two body decays

W and Z Taggers

ATL-PHYS-PUB-2020-17

- W/Z bosons often used to probe the jet substructure of the **large R-jets**
- Cut based taggers used to identify the **W/Z** jets
  - ✓ Requirement on the jet mass window, and selection applied on energy correlation functions and associated tracks
- Performance of both taggers evaluated in **MC simulation** and **data**
  - ✓ Excellent background rejection and signal efficiency



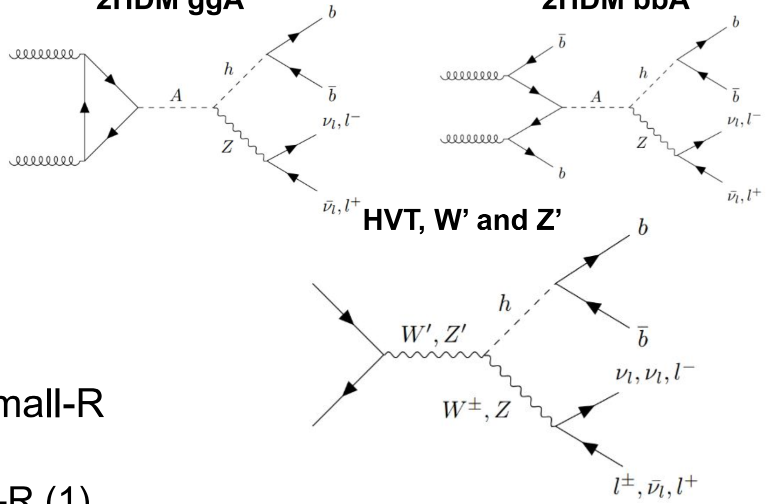
Measured background rejection in γ+jets events for the 50% W tagger

Search for heavy resonance decaying to VH semi-leptonic

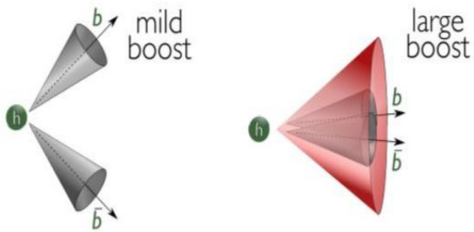
Analysis strategy

- ➢ **3 Channels targeting - ννbb, lνbb and llbb:**
  - ✓ **0 lepton**: 2HDM A, Z' and W'
  - ✓ **1 lepton**: W'
  - ✓ **2 leptons**: 2HDM A and Z'
- ➢ **2 event categories:**
  - ✓ **Resolved:** SM Higgs reconstructed by 2 small-R (0.4) calo jets
  - ✓ **Merged:** SM Higgs reconstructed by 1 large-R (1) TCC calo jets with at least one associated b-tagged Variable Radius (VR) track jet
- ➢ **b-tagging** - use the **70%** efficient Working Point (WP) of the Multivariate-based algorithm (**MV2c10**)

2HDM ggA **2HDM bbA** **HVT, W' and Z'**



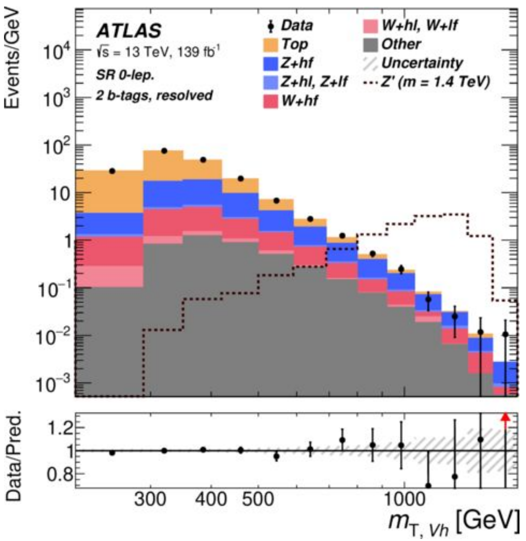
Resolved **Merged**



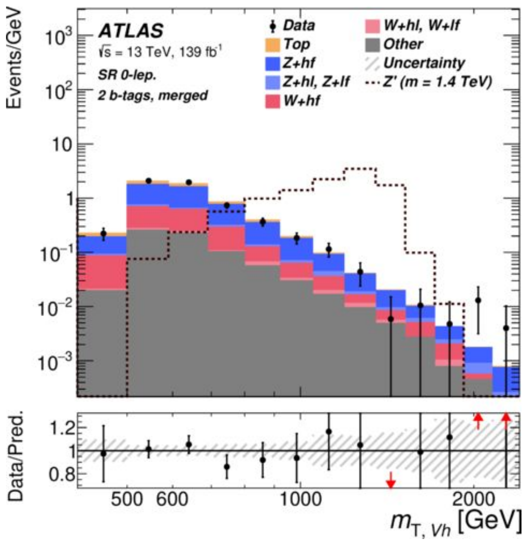
Event selection

- ➢ **Event selections are mostly the same as the previous publication except:**
  - ✓ New **MET** significance cut to suppress the **QCD** background in the **0-lepton** channel
  - ✓ **ΔR(l,h)** threshold for orthogonality to tt1L analysis
  - ✓ Changed sub-leading lepton **Pt** cut from **7 GeV** to **20 GeV** to suppress the **QCD** and **W+jets** backgrounds in the **2-lepton** channel

0-lepton - 2 b-tags resolved

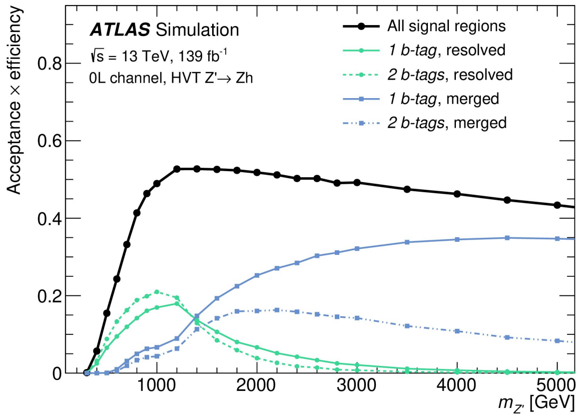


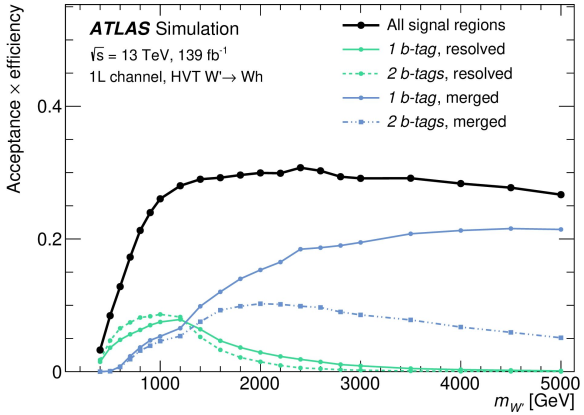
0-lepton - 2 b-tags merged



Acceptance x efficiency

- Various channels achieve good efficiency coverage over a wide range of resonance masses:
  - **0-lepton channel:**
    - ✓ High efficiency for high masses, from 1.2 TeV and above
  - **1-lepton channel:**
    - ✓ Acceptance times efficiency up to 30% in high masses
  - **2-lepton channel:**
    - ✓ High efficiency for low mass range (see backup)
- Acceptance x efficiecy range from **10** to **~55%** for most interesting masses





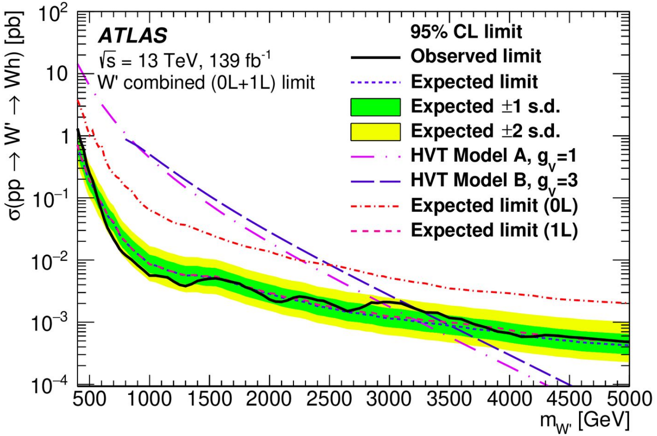
Results: 1D limits

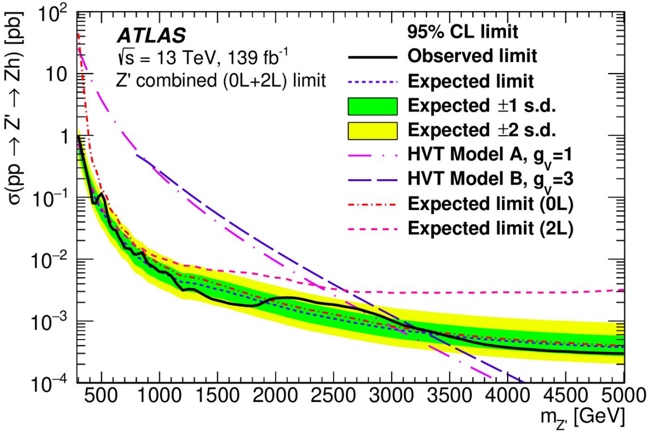
- ➢ 0L and 1L combined **W'** limits for the **HVT model**
  - ✓ Main contribution from 1L channel
  - ✓ Exclusions masses below:
    - ▪ **HVT model A**: 2.95 TeV
    - ▪ **HVT model B**: 3.15 TeV

- ➢ 0L and 2L combined **Z'** limits for the **HVT model**
  - ✓ Slight excesses observed around $m_{Z'}$ = 500 GeV (~2.1σ)

- ➢ Huge improvement in high masses, switching to **TCC large-R** and **VR track-jets**
  - ✓ Ranging from ~20% (< 2 TeV) up to 250% around 5 TeV

- ➢ **2HDM A limits results** can be found in the original paper: arXiv:2207.00230

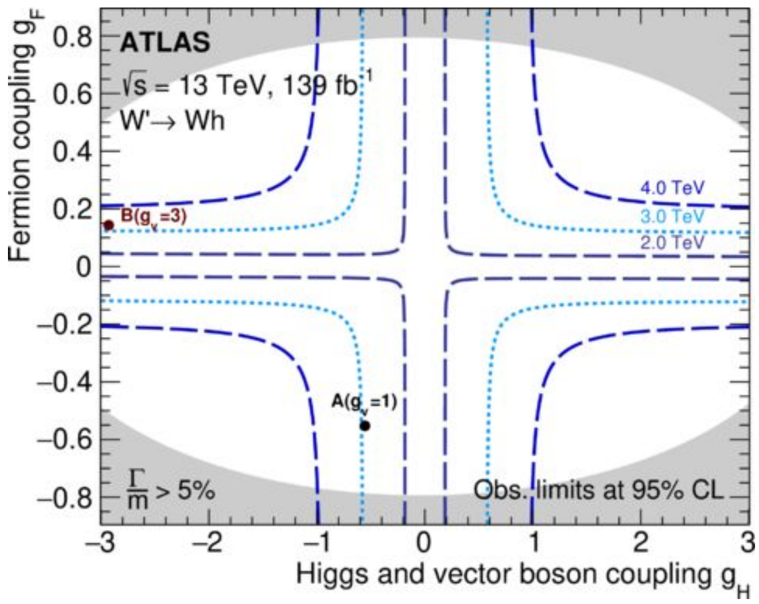




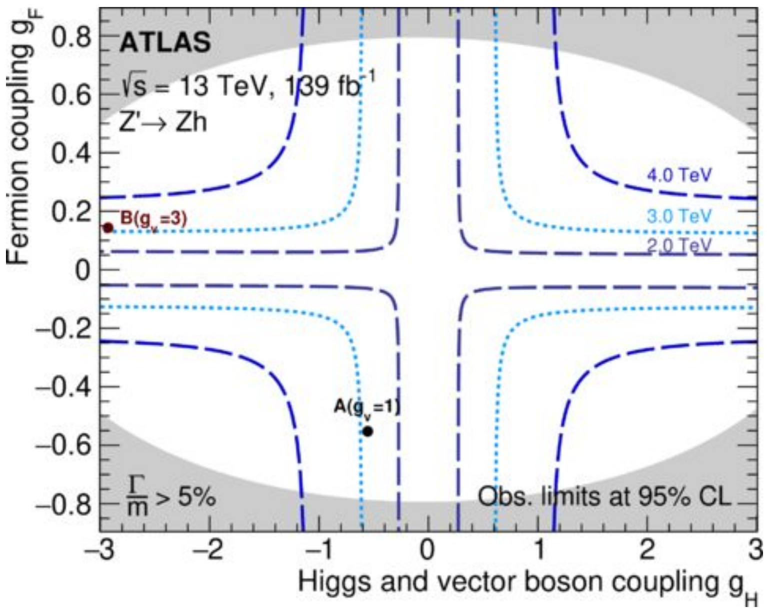
Results: HVT interpretation

- ✓ Exclusion contours in the **HVT parameter plane** **{gF,gH}**
- ✓ Constraints are **strongest** for large couplings and become **weaker** as couplings approach zero
- ✓ **Grey region** corresponds to the area of phase-space where the decay width is no longer negligible

W'



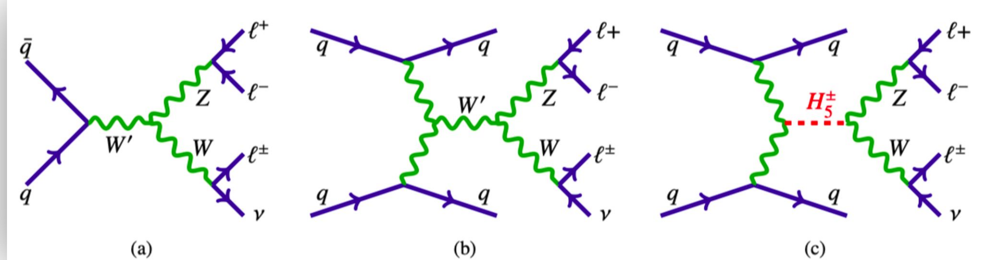
Z'



Analysis strategy

- Two production modes:
  - ✓ **Drell-Yan**
    - Uses cut-based
    - Interpreted in two benchmark models (HVT A and HVT B)
  - ✓ **Vector Boson Fusion:**
    - MVA Artificial Neural Network (ANN) was trained
    - Interpreted in **HVT C** and **Georgi - Machacek** (GM) models

- The final discriminant is the invariant mass of the **WZ** candidates, $\mathbf{m_{WZ}}$ is reconstructed from **3 leptons** and **missing transverse energy**



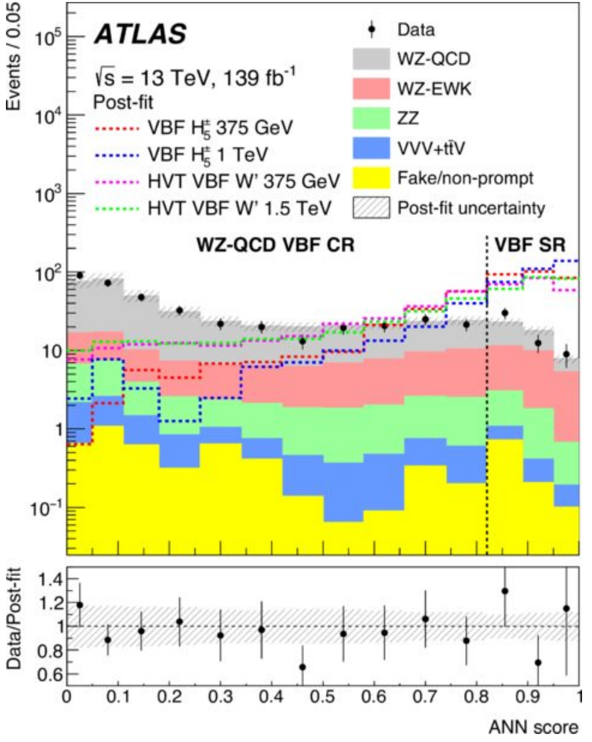
(a) HVT W' production via Drell-Yan, (b) HVT W' production via Vector Boson Fusion and (c) GM $H^{\pm}_{5}$ production via Vector Boson Fusion

- **Backgrounds:**
  - ✓ WZ production (QCD and EWK mediated production), ZZ, ttV, VVV, and non-prompt leptons (Z+jets, Zy, ttbar)

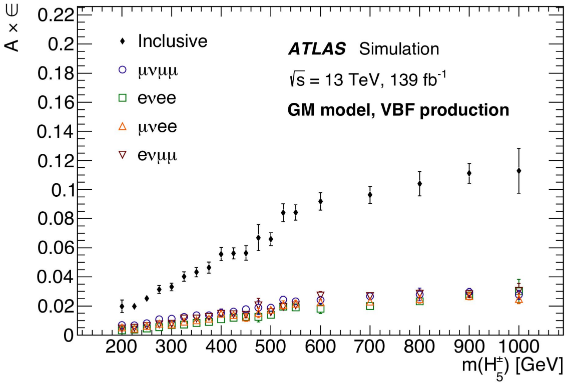
VBF Signal Selection

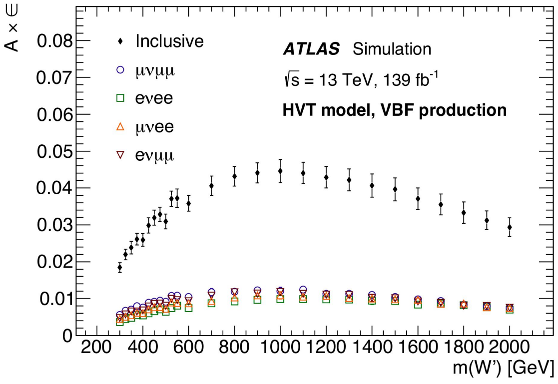
- ➢ **ANN VBF signal and control regions**
  - ✓ Signal region defined from one single training
  - ✓ Tested training one ANN per mass point, no significant improvement in the expected limits and was dropped

Training variables
m_{jj}, $\Delta\phi_{jj}$, η_W, $\eta_{\mathbf{Z}}$, η_{j1}, ζ_{Lep}, $E_{\mathrm{T}}^{\mathrm{miss}}$ H_T



➔ **A x ε after applying the ANN -based VBF selection for different channels**



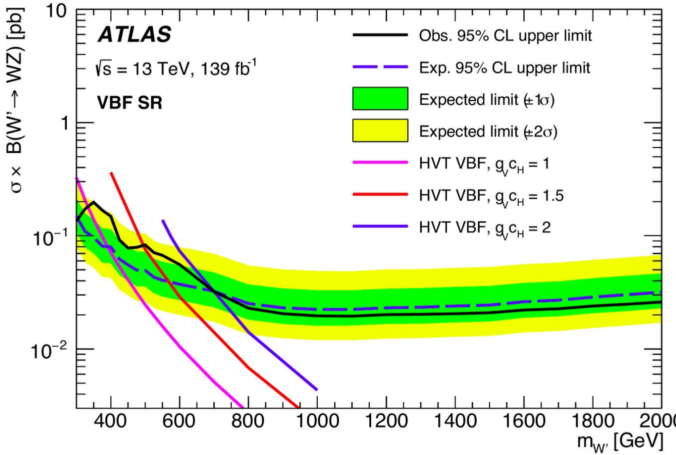


Results: limits

HVT W’ VBF production

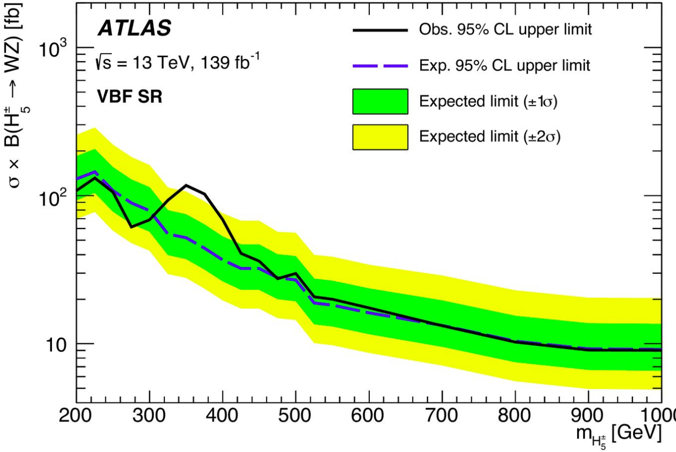
- Largest difference located around **375 GeV** with a local significance of **2.5σ**, while the Global significance is **1.7σ** (look elsewhere effect is considered up to **1.2 TeV**)

- Excluded masses:
  - ✓ HVT VBF ($g_V c_H$ = 1): **< 340 GeV**
  - ✓ HVT VBF ($g_V c_H$ = 1.5): **< 500 GeV**
  - ✓ HVT VBF ($g_V c_H$ = 2): **< 700 GeV**



GM H5 W’ VBF

- Excess around **375 GeV**
  - ✓ local significance **2.8σ**
  - ✓ Global significance **1.6σ**, taken into account the elsewhere effect up to **1 TeV**



Heavy resonances combination

ATLAS-CONF-2022-028

- Uses 9 published analyses during 2018-2022 for the heavy resonances combination
  - ✓ All channels are orthogonal (dropped some CRs, due to overlaps)
  - ✓ Cutting on leptons, jets and ET_{miss}
- **Types of resonances: VV , VH, ll**
  - ✓ **VV/VH fully hadronic** - largest branching ratio, but large background contamination, sensitive in high masses
  - ✓ **VV fully leptonic** - clean signature and sensitive in low masses
  - ✓ **VV semileptonic** - one/zero leptons with significant ET_{miss}, or two leptons, sensitive to different production mechanisms (ggF/VBF)
  - ✓ **VH semileptonic** - uses H-tagging for reconstructing higgs candidates
  - ✓ **Fully leptonic ll, lv** - very clean signature

Analysis	leptons	$E_{T_{miss}}$	jets	b-tags	Discr.
$WW/WZ \to qqqq$	0	Veto	$\geq$2J	-	m_{VV}
$WZ \to \nu\nu qq$	0	Yes	$\geq$1J	0	m_{VV}
$WZ \to \ell\nu qq$	1e, 1μ	Yes	$\geq$2j, $\geq$1J	0, 1, 2	m_{VV}
$WZ \to \ell\ell qq$	2e, 2μ	-	$\geq$2j, $\geq$1J	0	m_{VV}
$WZ \to \ell\nu\ell\ell$	3 $\subset$ (e, μ)	Yes	-	0	m_{VV}
$WH \to qqbb$	0	Veto	$\geq$2J	1, 2	m_{VH}
$ZH \to \nu\nu bb$	0	Yes	$\geq$2j, $\geq$1J	1, 2	m_{VH}
$WH \to \ell\nu bb$	1e, 1μ	Yes	$\geq$2j, $\geq$1J	1, 2	m_{VH}
$ZH \to \ell\ell bb$	2e, 2μ	Veto	$\geq$2j, $\geq$1J	1, 2	m_{VH}
$\ell\nu$	1e, 1μ	Yes	-	-	m_T
$\tau\nu$	1τ	Yes	-	-	m_T
$\ell\ell$	$\geq$2e, $\geq$2μ	-	-	-	$m_{\ell\ell}$

Results interpreted in terms of coupling constants

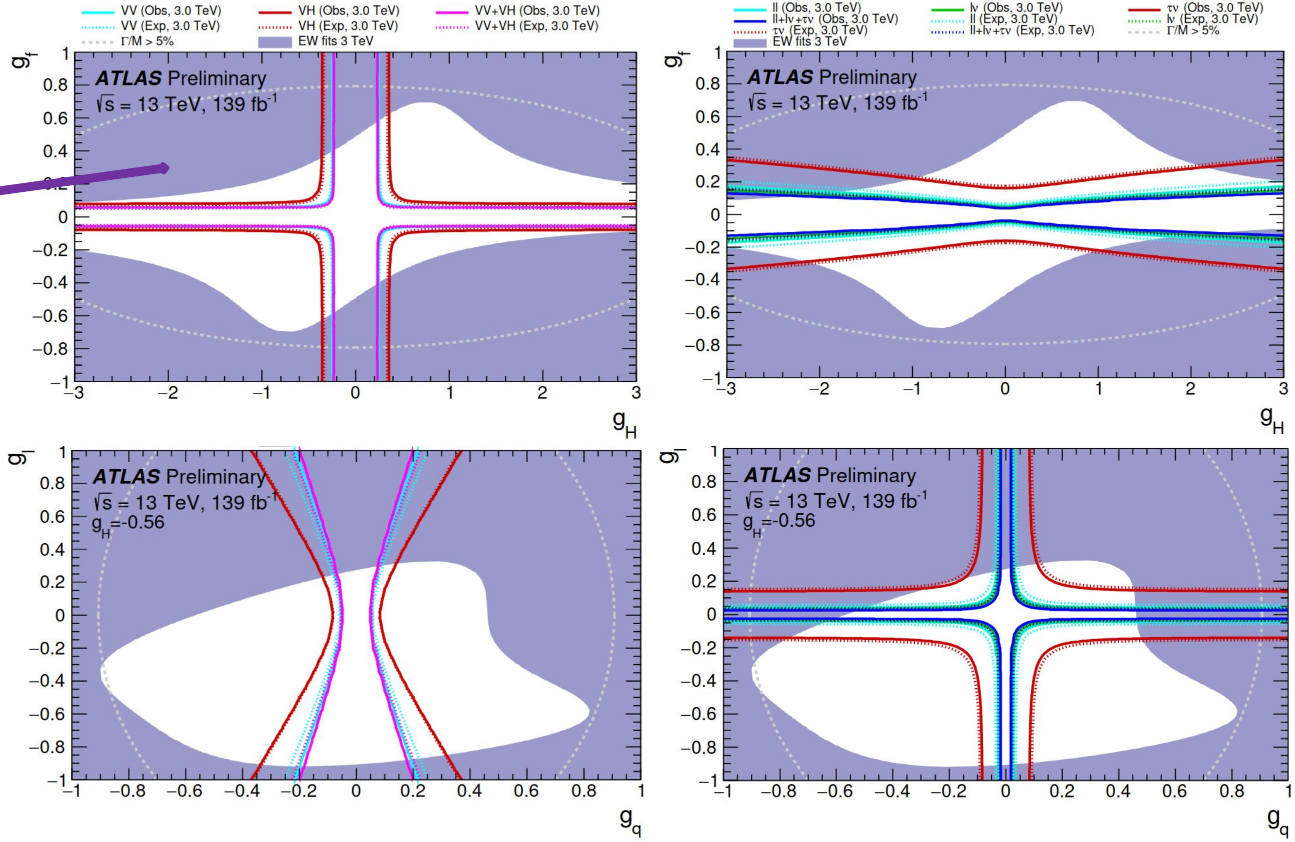
- Constraints on **heavy resonances** from precision EW measurement

- Combined results strengthen the constraints on the physics BSM, and permits the expression of constraints in terms of couplings to quarks, leptons and bosons.

- **Plots for other channels and masses can be found in the original conf. note**

Bosonic sub-combination

Leptonic sub-combination



Summary

- Many **BSM theories** predict new resonances that decay to boson pairs
  - ✓ Currently - no evidence of these resonances observed

- The Run-2 search for **semi-leptonic VH**
  - ✓ Huge improvement of the sensitivity at high masses due to the use of TCC large-R and VR track-jets
  - ✓ No evidence for heavy resonances, but 2-3x improved limits w.r.t previous iteration

- The Run-2 search for **fully leptonic WZ**
  - ✓ Excess around 375 GeV, with global significance of 1.7 for HVT VBF production

- **ATLAS combination** of 9 searches during 2018-2022, provides an extensive picture on the experimental limits of these resonances

- **ATLAS summary interpretation** of heavy Higgs boson searches in the Georgi-Macheck Model
  - ✓ Best limits have been obtained on $\sin(\theta_H)$ (more plots in the paper: ATL-PHYS-PUB-2022-008)

Backup

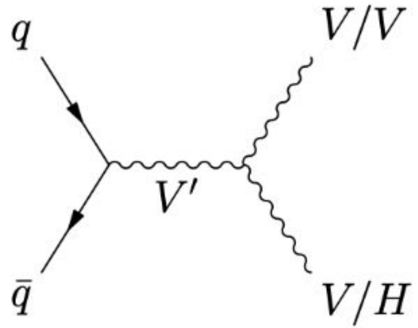
Theoretical models

➢ Heavy Vector Triplet Model (HVT)

- ✓ Used for the interpretation of the results showed in this talk
- ✓ Simplified model with an additional SU(2) field
- ✓ Lagrangian given as:

$$\mathcal{L}_W^{\text{int}} = -g_q \mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left(\mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right)$$

- ✓ Two new nearly degenerate heavy spin-1 resonances coupled to the SM particles (Z' and W')
- ✓ Models specified by coupling strengths of the new particles to SM fermions and bosons:
  - ✓ Model A
    - Weakly coupled with extended Gauge Symmetry
    - gv = 1, gH = - 0.56 and gf = - 0.55
  - ✓ Model B
    - Minimal Composite Higgs Model
    - gv = 3, gH = -2.9 and gf = 0.14
  - ✓ Model C
    - gH=1 gf = 0
- ✓ Extra theoretical models are introduced in the original papers



A x E - VH semi-leptonic

- Various channels achieve good efficiency coverage over a wide range of resonance masses:
  - **0 lepton channel:**
    - ✓ High efficiency for high masses, from 1.2 TeV and above
  - **1 lepton channel:**
    - ✓ Acceptance times efficiency up to 30% in high masses
  - **2 lepton channel:**
    - ✓ High efficiency for low mass range

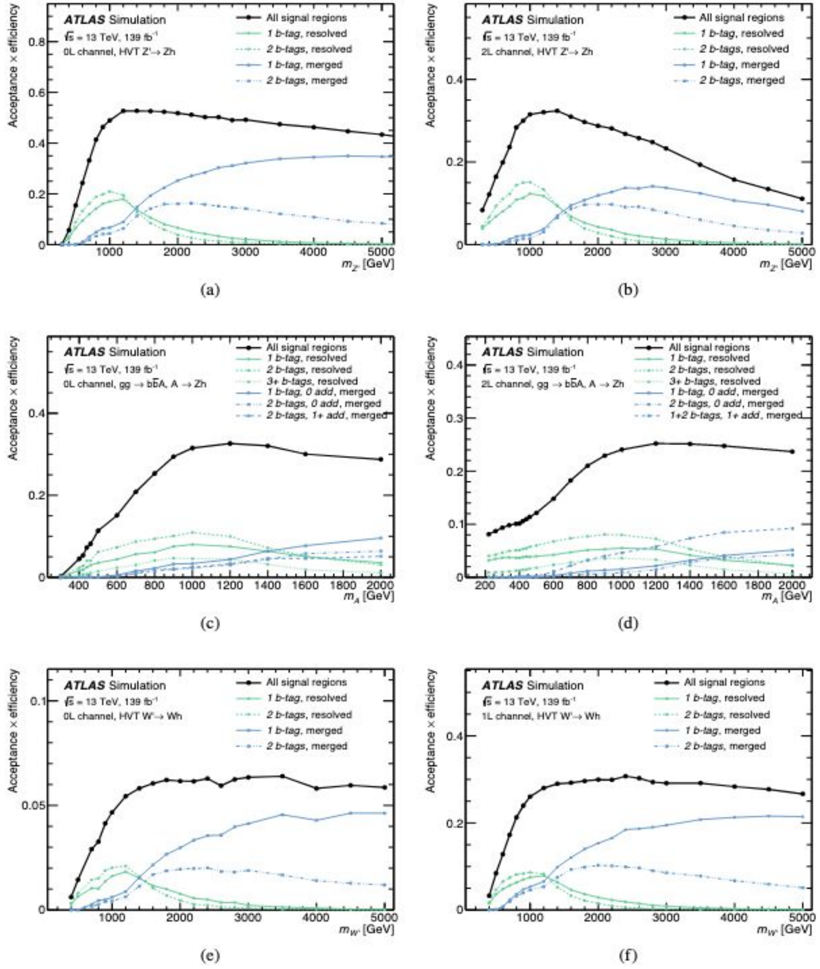
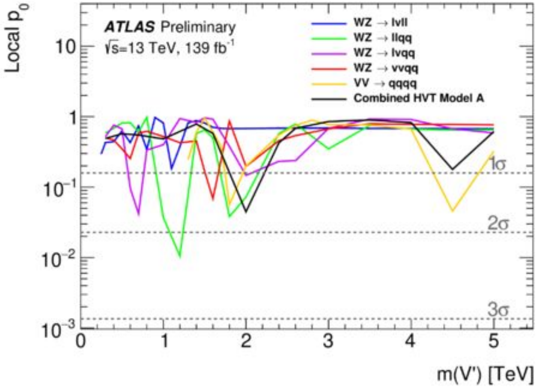
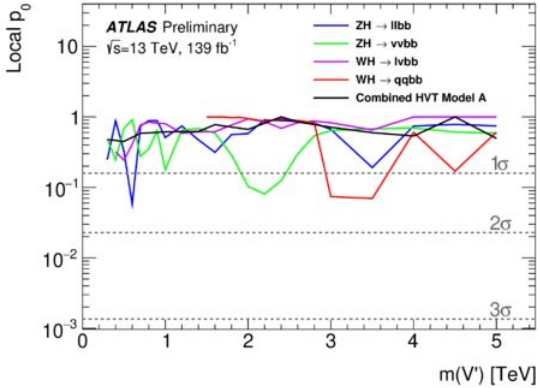
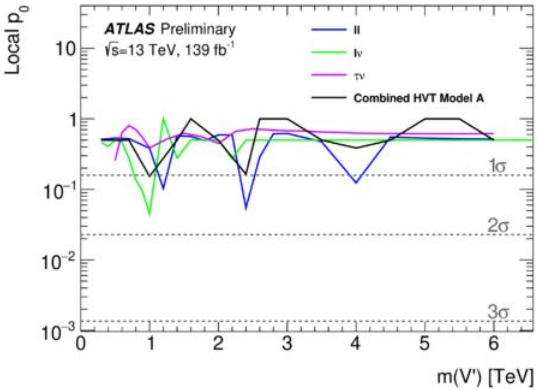


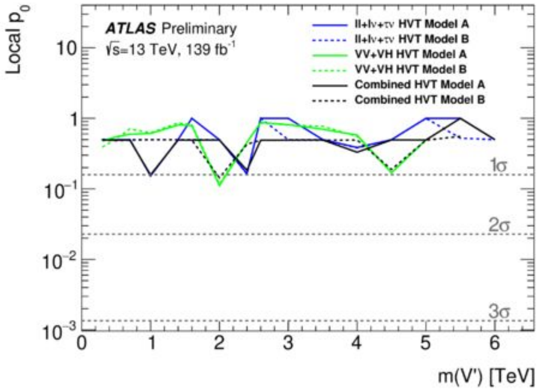
Figure 2: Product of acceptance and efficiency for (a) $Z' \to Zh \to \nu\bar{\nu}b\bar{b}/c\bar{c}$, (b) $Z' \to Zh \to \ell^+\ell^- b\bar{b}/c\bar{c}$, (c) $b\bar{b}A$ ($\to Zh \to \nu\bar{\nu}b\bar{b}$), (d) $b\bar{b}A$ ($\to Zh \to \ell^+\ell^- b\bar{b}$) and (e, f) $W' \to Wh \to \ell^\pm \nu b\bar{b}/c\bar{c}$ as a function of the resonance mass for the 0-lepton signal regions (a, c, e), the 2-lepton signal regions (b, d), and the 1-lepton signal regions (f).

p-value scan - Heavy resonances combination





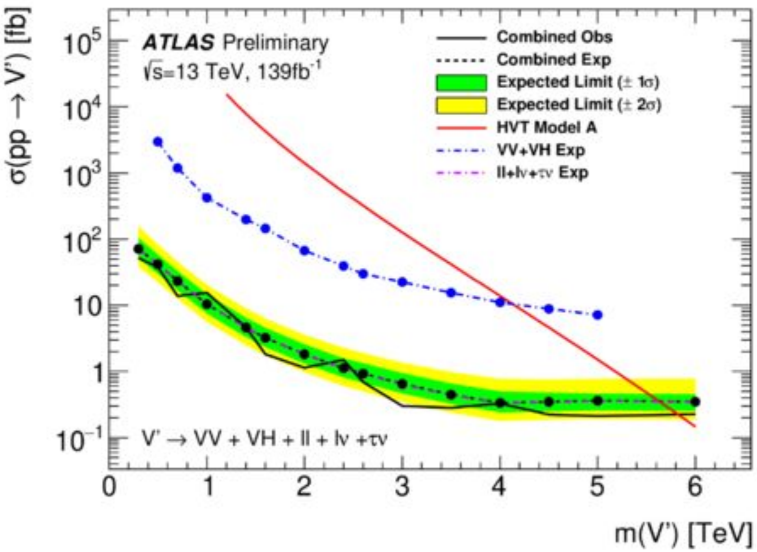




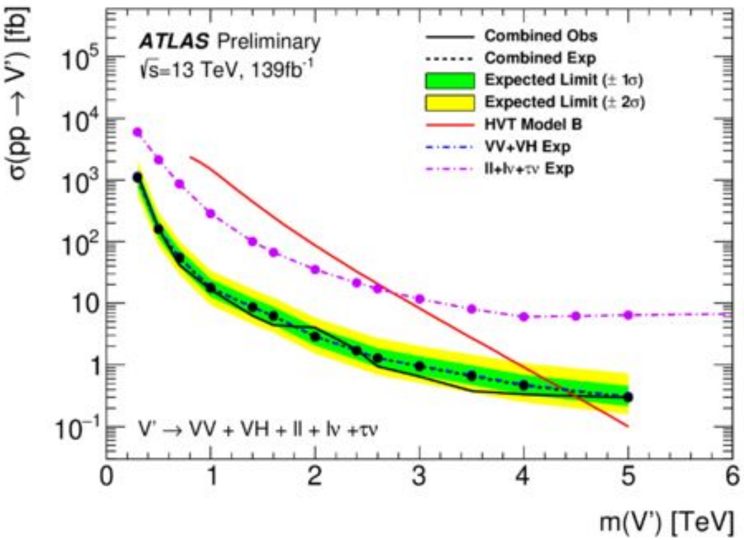
- scans for leptonic channel is extended up to 6 TeV (channels benefit from higher statistics!)
- the scan for the full combination is slightly coarser than the individual searches due to alignment of the tested pole masses

Exclusions limits - Heavy resonances combination

Weakly coupled HVT-A coupling



Strongly coupled HVT-B coupling



- HVT limits exclusions:
  - ✓ HVT model A: 5.8 TeV
  - ✓ HVT model B: 4.5 TeV