# Searches for resonances decaying to bosons in leptonic final states in ATLAS

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# Introduction

- Many Beyond the Standard Model Physics (BSM) predict new Gauge, Higgs and other Bosons (Graviton, Radion,...)
- Often decay into Standard Model Bosons:
  - WW, WZ, ZZ, WH, ZH, $\gamma\gamma$
- Simplified Benchmark Models
  - Heavy Vector Triplets (HVT) $W^{-\prime}$, $Z^{0\prime}$, $W^{+\prime}$
  - Georgi-Machacek Model (GM):

    Higgs quintuplet ($H_5^{++}$,$H_5^{+}$,$H_5^{0}$,$H_5^{-}$,$H_5^{--}$)
- Effective Field Theory (EFT)

# HVT benchmark models

- HVT Lagrangian — JHEP 09 (2014) 060
  - Simplified Model to bridge Theory & Data

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_f \mathcal{W}_\mu^a \bar{f}_k \gamma^\mu \frac{\sigma_a}{2} f_k - g_H \left( \mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.}. \right),$$

$$g_f = \frac{g^2}{g_V} c_f; \; g_H = g_V c_H$$

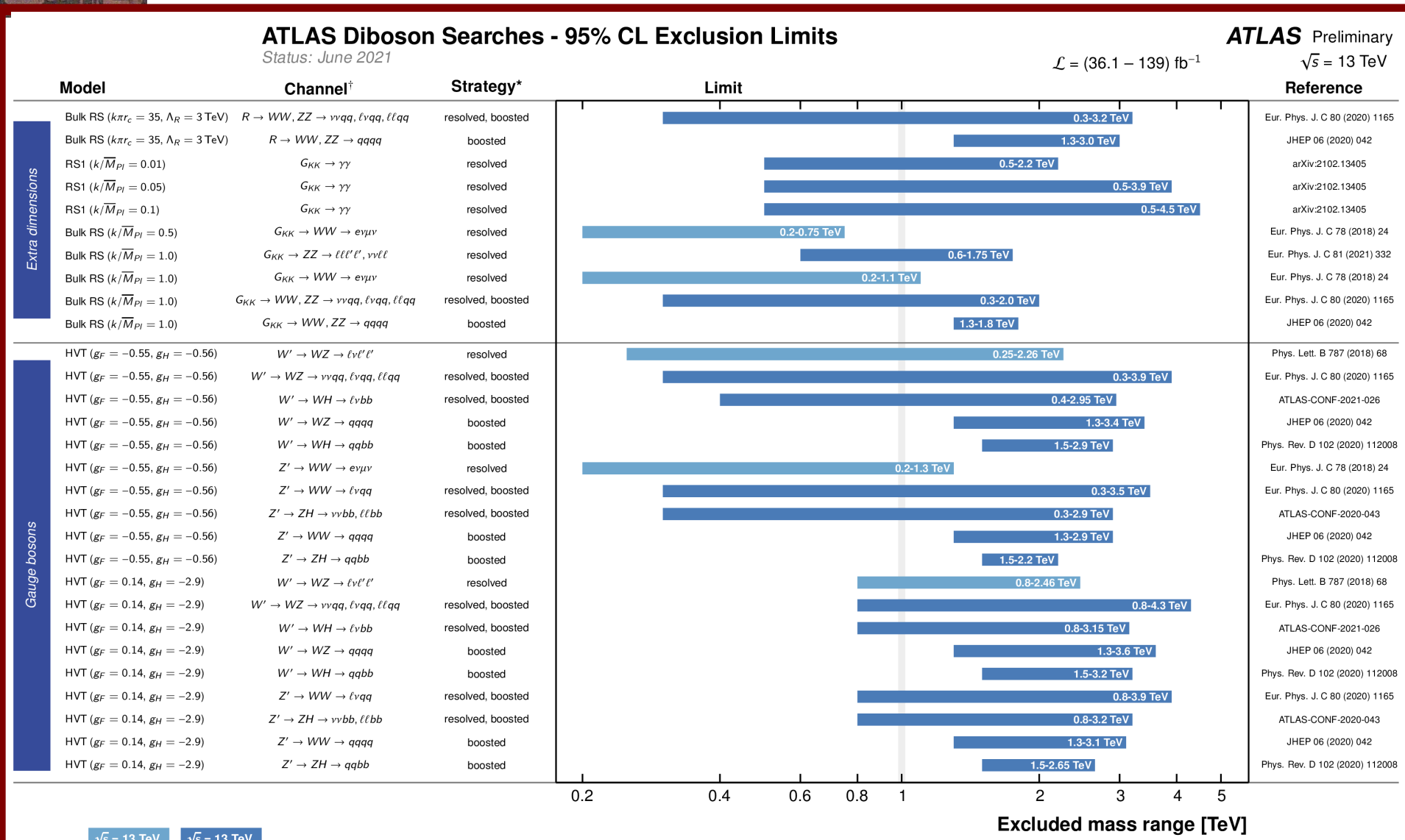
- Model A
  - Extended Gauge Symmetry (extra SU(2))
  - $g_v$ = 1 ($g_H$ = -0.56 and $g_f$ = -0.55) $c_f \sim c_H \sim 1$
- Model B
  - Minimal Composite Higgs Model
  - $g_v$ = 3 ($g_H$ = -2.9 and $g_f$ = 0.14)

# Leptonic final states

- Clear signature in pp collisions
- Provides a trigger signature
- Usually fewer backgrounds than other modes
- Leptonic di-boson signatures
  - $WW \rightarrow \ell\nu\ell\nu$, $WW \rightarrow \ell\nu qq$
  - $WZ \rightarrow \ell\nu\ell\ell$, $WZ \rightarrow \ell\nu qq$, $WZ \rightarrow qq\ell\ell$, $WZ \rightarrow qq\nu\nu$
  - $ZZ \rightarrow \ell\ell\nu\nu$, $ZZ \rightarrow \ell\ell\ell\ell$, $ZZ \rightarrow qq\ell\ell$, $ZZ \rightarrow qq\nu\nu$
  - $WH \rightarrow \ell\nu bb$
  - $ZH \rightarrow \ell\ell bb$

here usually $\ell$ = e, $\mu$

# Overview

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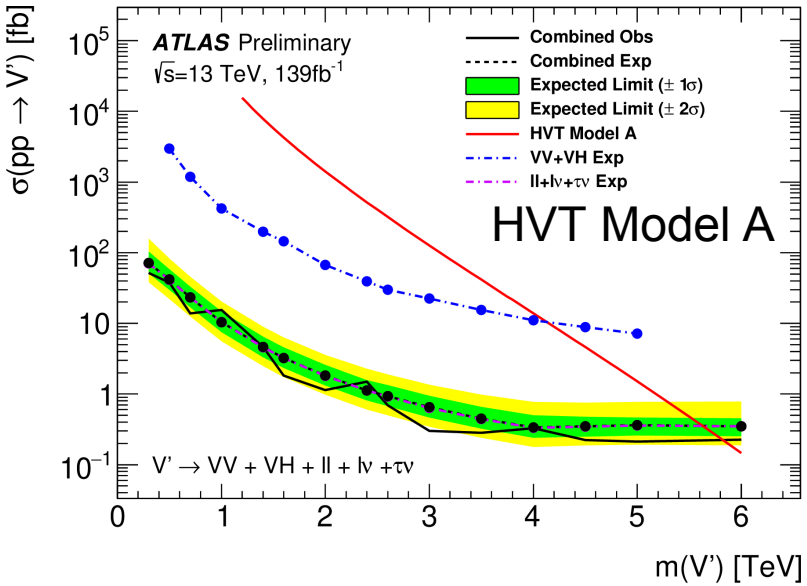
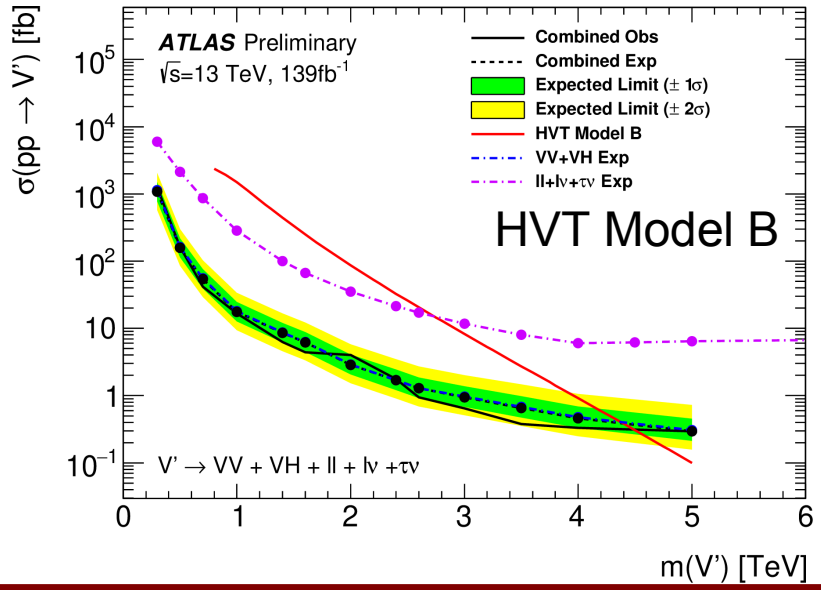
# Combination X → VV and X → VH

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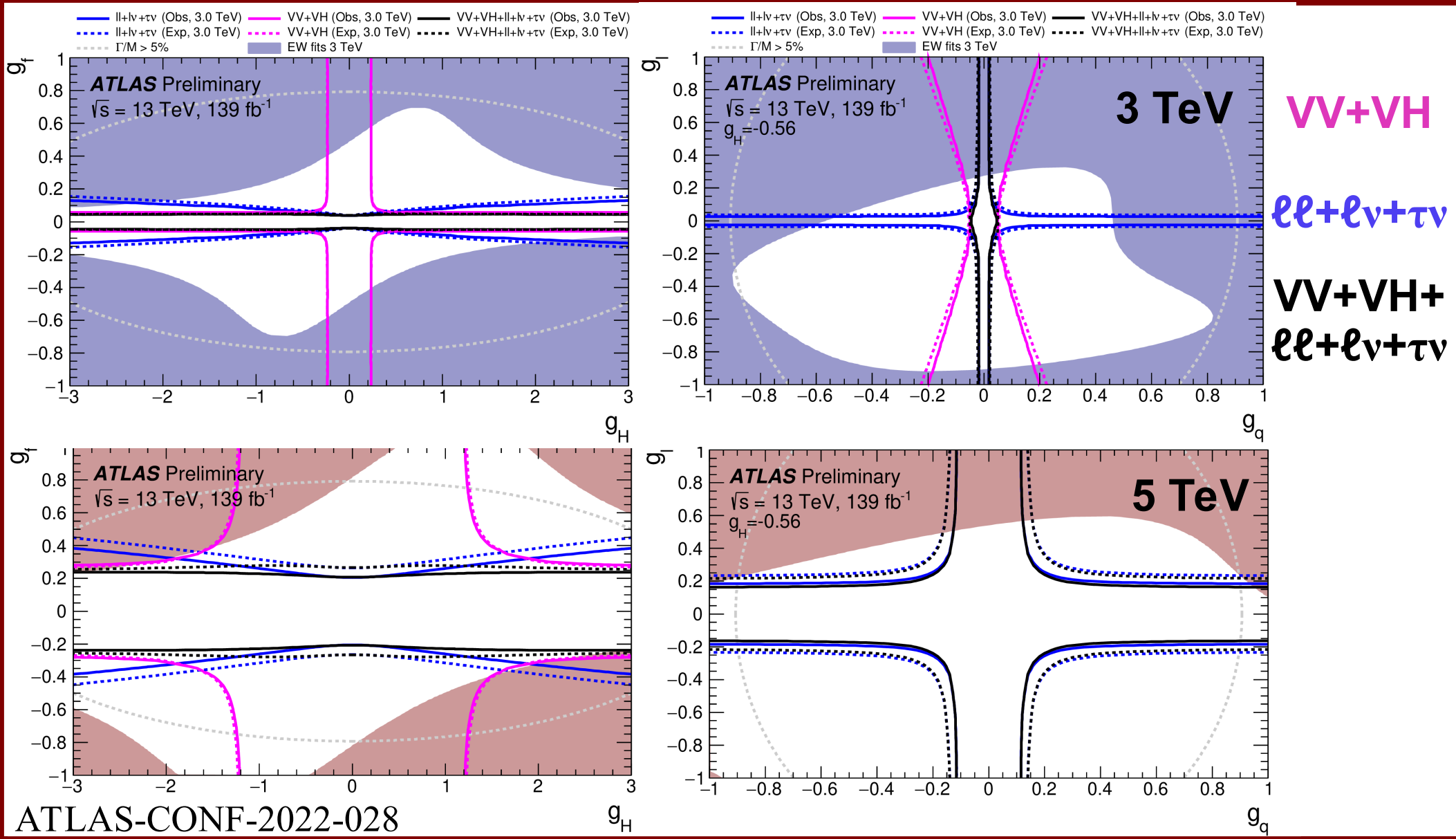
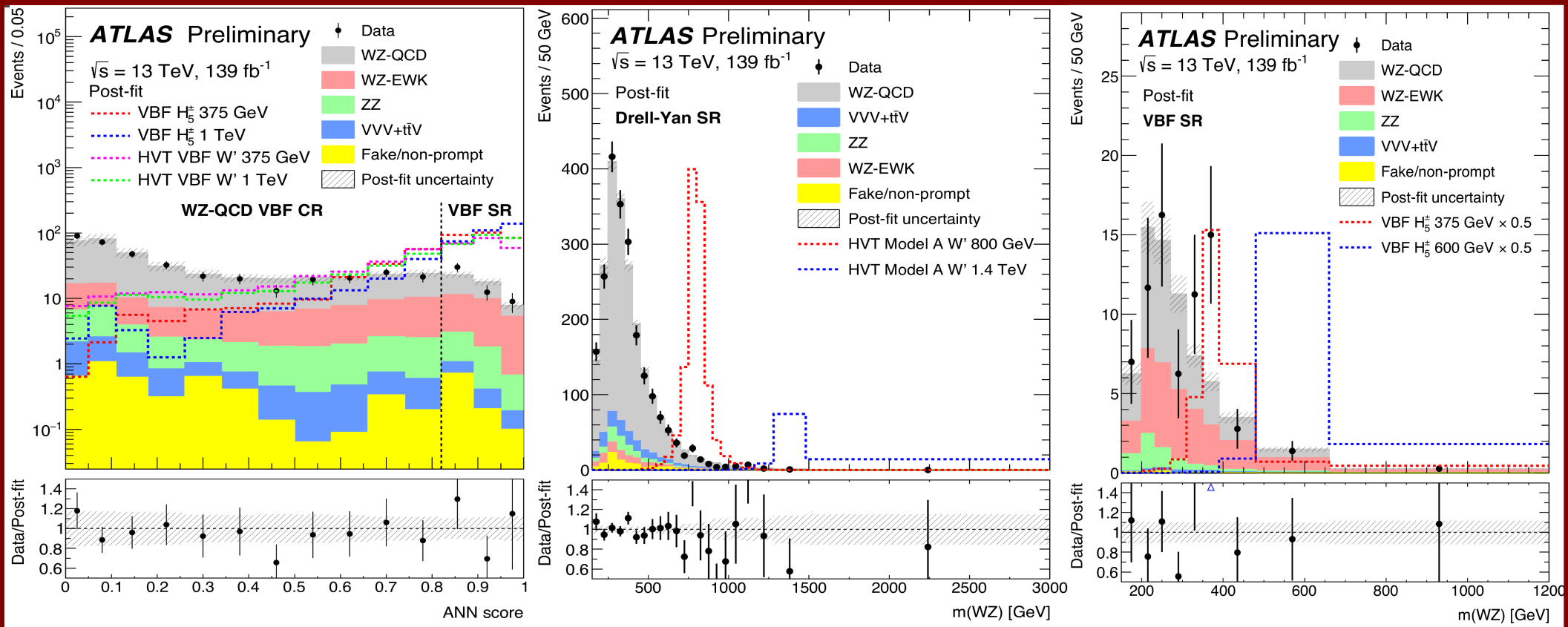
| Analysis | leptons | $E_{T_{miss}}$ | jets | b-tags | Discr. | Ref |
|---|---|---|---|---|---|---|
| $WW/WZ \to qqqq$ | 0 | Veto | ≥2J | - | $m_{VV}$ | [10] |
| $WZ \to \nu\nu qq$ | 0 | Yes | ≥1J | 0 | $m_{VV}$ | [11] |
| $WZ \to \ell\nu qq$ | 1e, 1$\mu$ | Yes | ≥2j, ≥1J | 0, 1, 2 | $m_{VV}$ | [11] |
| $WZ \to \ell\ell qq$ | 2e, 2$\mu$ | - | ≥2j, ≥1J | 0 | $m_{VV}$ | [11] |
| $WZ \to \ell\nu\ell\ell$ | 3 ⊂ (e, $\mu$) | Yes | - | 0 | $m_{VV}$ | [12] |
| $WH \to qqbb$ | 0 | Veto | ≥2J | 1, 2 | $m_{VH}$ | [13] |
| $ZH \to \nu\nu bb$ | 0 | Yes | ≥2j, ≥1J | 1, 2 | $m_{VH}$ | [15] |
| $WH \to \ell\nu bb$ | 1e, 1$\mu$ | Yes | ≥2j, ≥1J | 1, 2 | $m_{VH}$ | [14] |
| $ZH \to \ell\ell bb$ | 2e, 2$\mu$ | Veto | ≥2j, ≥1J | 1, 2 | $m_{VH}$ | [15] |
| $\ell\nu$ | 1e, 1$\mu$ | Yes | - | - | $m_T$ | [17] |
| $\tau\nu$ | 1$\tau$ | Yes | - | - | $m_T$ | [18] |
| $\ell\ell$ | ≥2e, ≥2$\mu$ | - | - | - | $m_{\ell\ell}$ | [16] |

- Limits set on
  - HVT model A: 5.8 TeV
  - HVT model B: 4.5 TeV
- Constraints on $g_f$ & also individual lepton $g_l$ & quark $g_q$ couplings

# Combination X → VV and X → VH



# $X \to WZ \to \ell\nu\ell'\ell'$




- 2 signal regions: Drell-Yan and Vector-Boson-Fusion
- Selected using Artificial NN and $p_T/m(WZ)$
- VBF Signal Region excess at 375 GeV < 1.6σ (2.8σ local)

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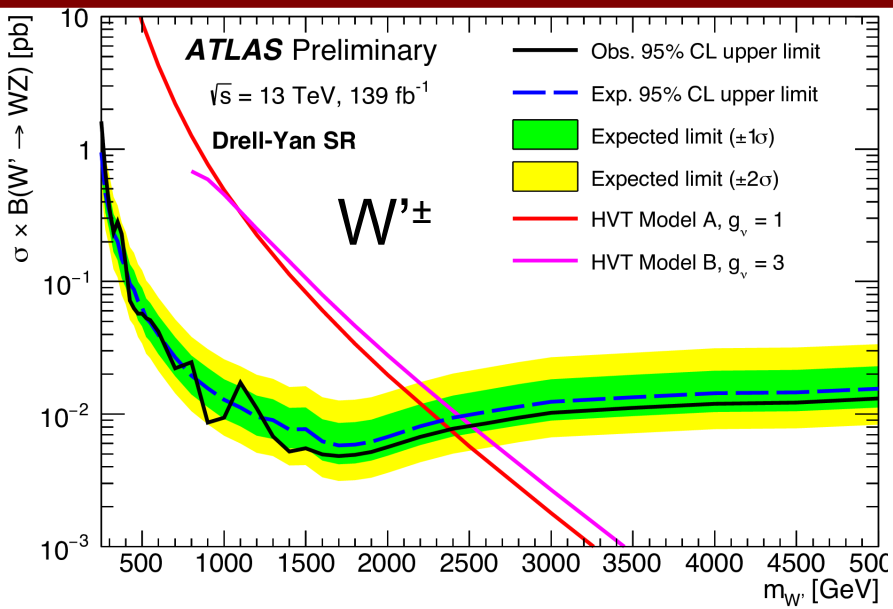
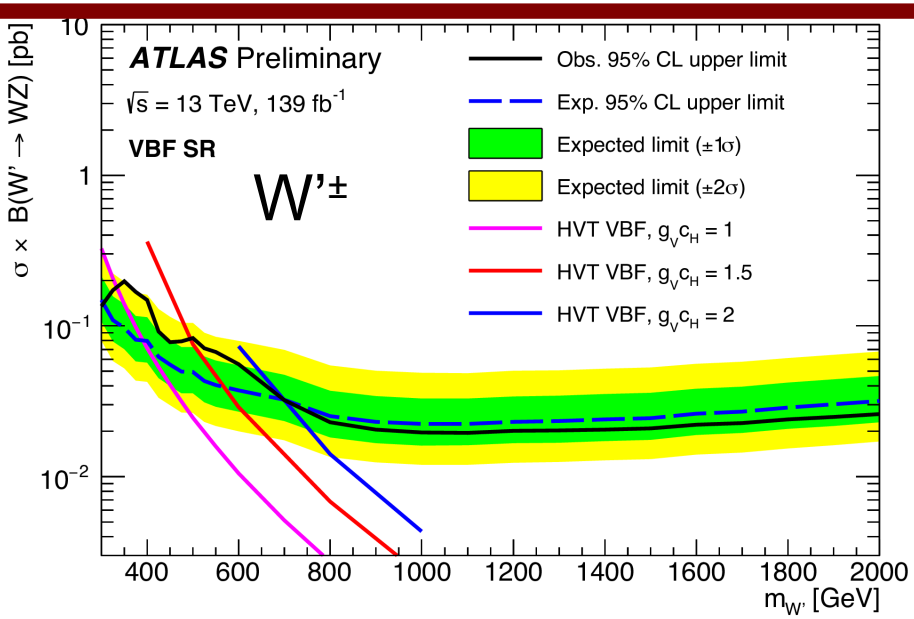
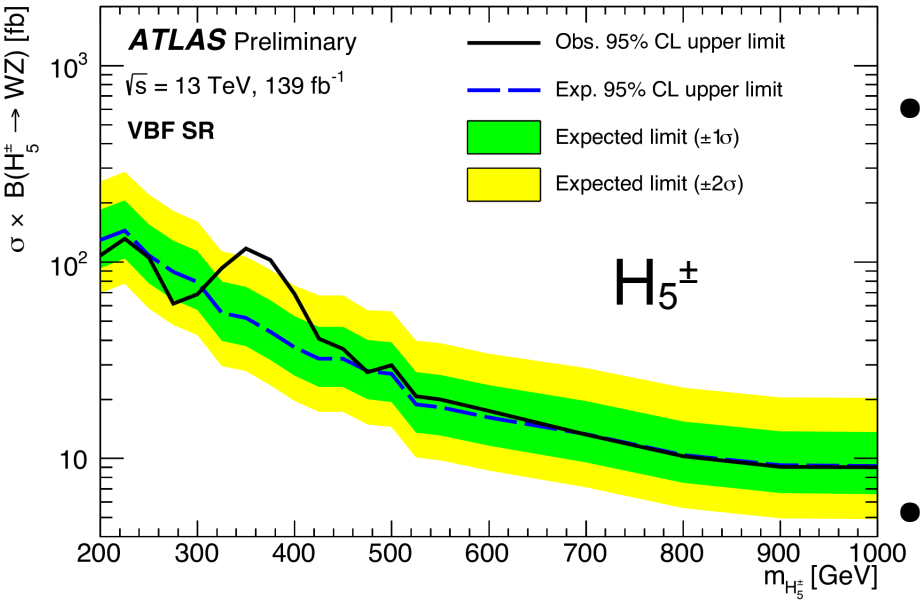
# X → WZ → ℓνℓ'ℓ'

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- Limits set on
  - HVT model A,B
  - Fermiophobic HVT model
  - GM model $H_5^{\pm}$
- Excess at 375 GeV < 2.8σ local

# WH → WWW → Xℓ±ℓ±

- Search for additional heavy Higgs Bosons **H**
- General formulation in Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \sum_{D=2} \mathcal{L}^{(D)} = \sum_{D=2} \sum_{i} \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

$$\mathcal{L}_{HWW}^{(4)} = \rho_H g m_W H W^{\mu} W_{\mu},$$

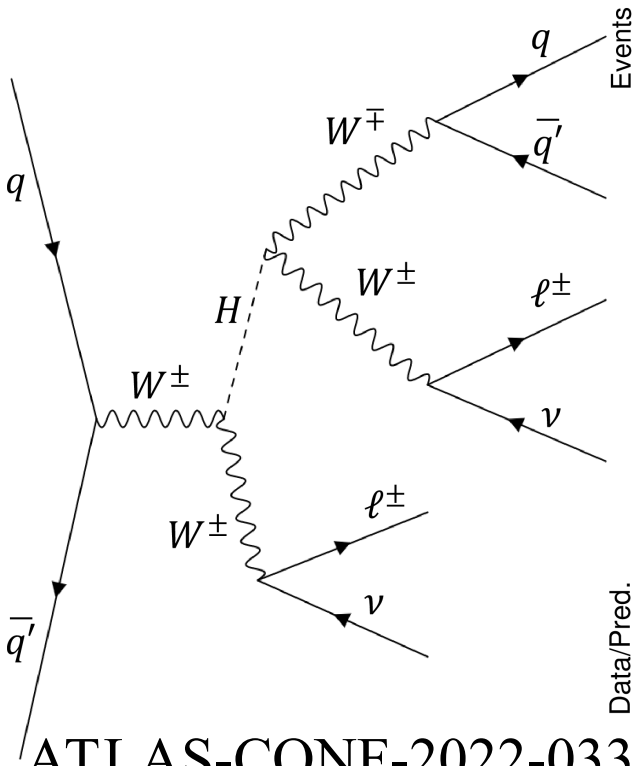
$$\mathcal{L}_{HWW}^{(6)} = \rho_H g m_W \frac{f_W}{2\Lambda^2} \left( W_{\mu\nu}^{+} W^{-\mu} \partial^{\nu} H + h.c. \right) - \rho_H g m_W \frac{f_{WW}}{\Lambda^2} W_{\mu\nu}^{+} W^{-\mu\nu} H,$$

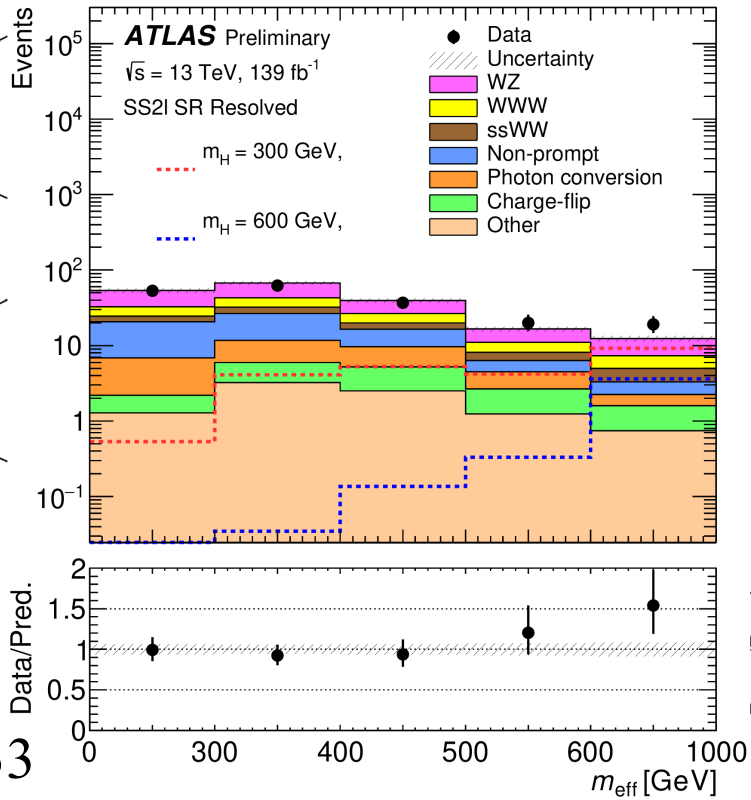
- Considers also dim-6 operators
  scale of new physics $\Lambda$, anomalous couplings $f_W$,$f_{WW}$
- Enhancement of HVV coupling at higher boson momenta possible

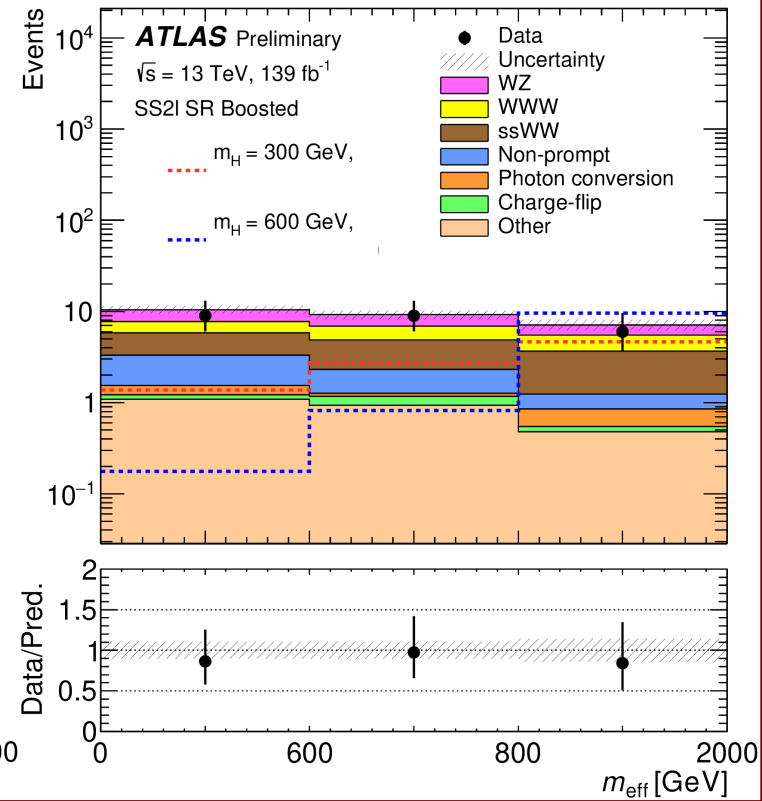
ATLAS-CONF-2022-033

# WH → WWW → Xℓ±ℓ±

- Utilise associated production & same sign dilepton signature
- Effective mass of ($\ell\nu q\bar{q}'$) system $m_{eff} = \Sigma\, p_T$, using $p_T$(lepton), $p_T$(jets) and missing transverse energy (MET)

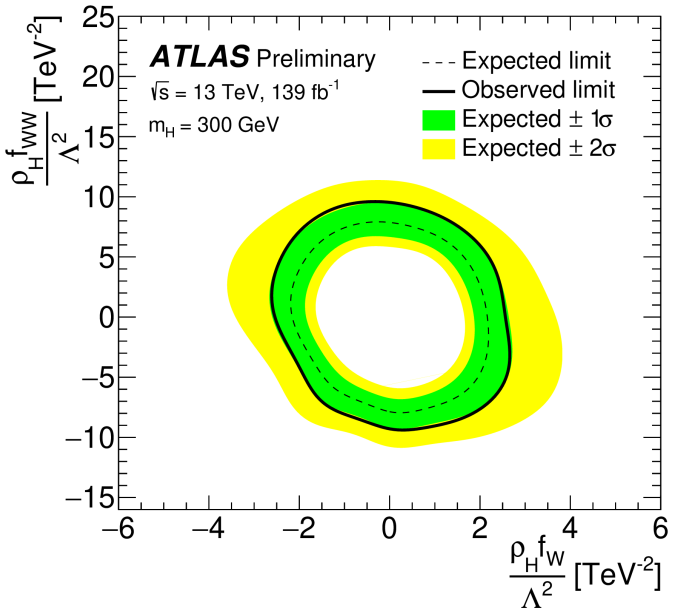


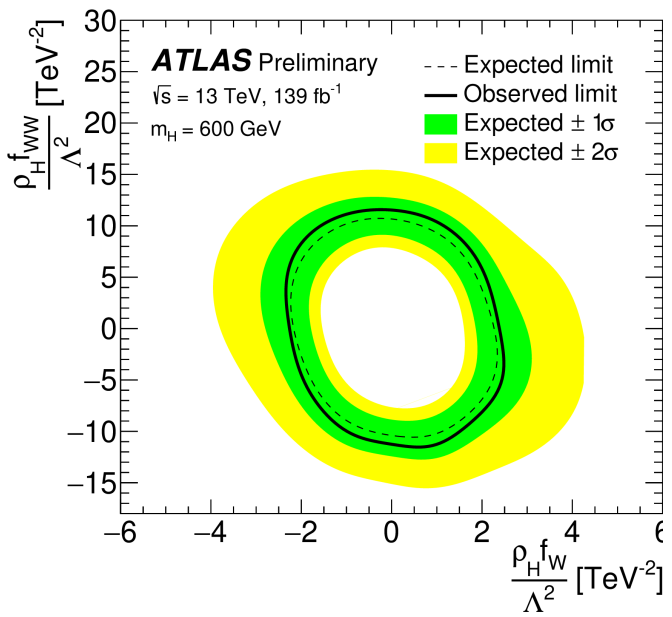



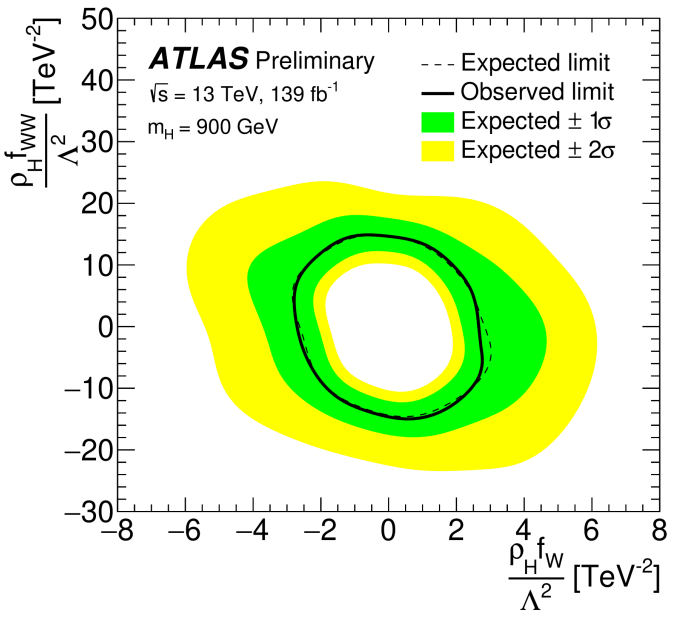




ATLAS-CONF-2022-033

# $WH \rightarrow WWW \rightarrow X\ell^{\pm}\ell^{\pm}$

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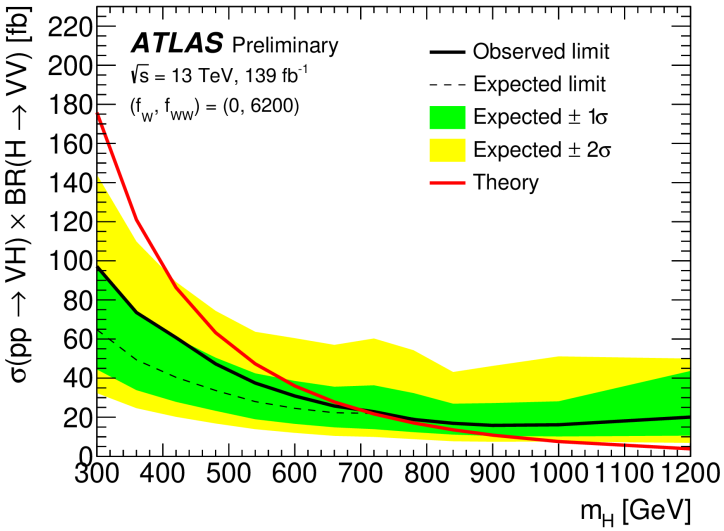


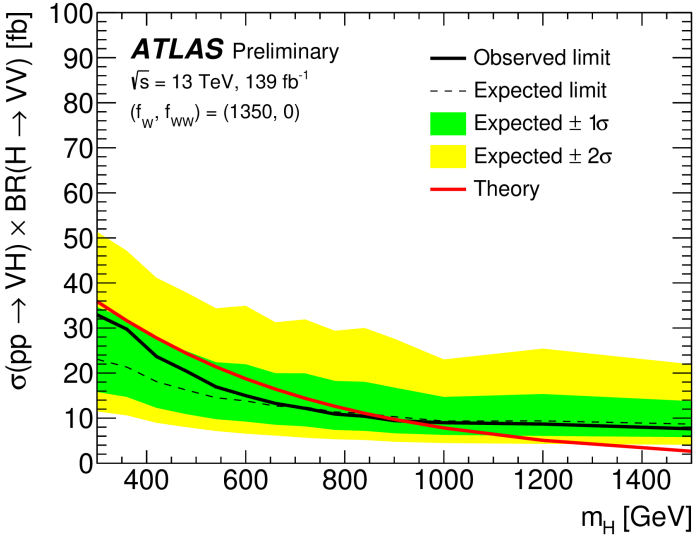

# Conclusion

- ATLAS continues exploring the energy frontier
- Probed BSM physics with multi-boson signatures
- Interpret in simplified models HVT, GM, EFT
- So far no deviation from the SM found

the search continues ….

# Bonus Slides

[10] ATLAS Collaboration, *Search for diboson resonances in hadronic final states in 139 $fb^{-1}$ of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, JHEP **09** (2019) 091, arXiv: 1906.08589 [hep-ex] (cit. on pp. 2, 6).

[11] ATLAS Collaboration, *Search for heavy diboson resonances in semileptonic final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Eur. Phys. J. C **80** (2020) 1165, arXiv: 2004.14636 [hep-ex] (cit. on pp. 2, 6).

[12] ATLAS Collaboration, *Search for Resonant $WZ \to \ell\nu\ell'\ell'$ Production in Proton-Proton Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, ATLAS-CONF-2022-005, 2022, URL: https://cds.cern.ch/record/2803929 (cit. on pp. 2, 6).

[13] ATLAS Collaboration, *Search for resonances decaying into a weak vector boson and a Higgs boson in the fully hadronic final state produced in proton−proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Phys. Rev. D **102** (2020) 112008, arXiv: 2007.05293 [hep-ex] (cit. on pp. 2, 6).

[14] ATLAS Collaboration, *Search for heavy resonances decaying into a W boson and a Higgs boson in final states with leptons and b-jets in 139 $fb^{-1}$ of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, ATLAS-CONF-2021-026, 2021, URL: https://cds.cern.ch/record/2773302 (cit. on pp. 2, 6).

[15] ATLAS Collaboration,
*Search for heavy resonances decaying into a Z boson and a Higgs boson in final states with leptons and b-jets in 139 $fb^{-1}$ of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*,
ATLAS-CONF-2020-043, 2020, URL: https://cds.cern.ch/record/2728053
(cit. on pp. 2, 6).

[16] ATLAS Collaboration, *Search for high-mass dilepton resonances using 139 $fb^{-1}$ of pp collision data collected at $\sqrt{s}$ =13 TeV with the ATLAS detector*, Phys. Lett. **B796** (2019) 68,
arXiv: 1903.06248 [hep-ex] (cit. on pp. 2, 6).

[17] ATLAS Collaboration, *Search for a heavy charged boson in events with a charged lepton and missing transverse momentum from pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*,
Phys. Rev. D **100** (2019) 052013, arXiv: 1906.05609 [hep-ex] (cit. on pp. 2, 6).

[18] ATLAS Collaboration, *Search for high-mass resonances in final states with a tau lepton and missing transverse momentum with the ATLAS detector*, ATLAS-CONF-2021-025, 2021,
URL: https://cds.cern.ch/record/2773301 (cit. on pp. 2, 6).

# Systematics: X → WZ → ℓνℓ'ℓ'

ATLAS-CONF-2022-005

| Source of uncertainty | $\Delta\mu/\mu$ [%] | |
|---|---|---|
| | Drell-Yan signal region $m(W') = 1100$ GeV | VBF signal region $m(H_5^{\pm}) = 375$ GeV |
| $WZ$-QCD+$ZZ$ normalization | 2 | 11 |
| $WZ$ background: parton shower | 6 | 1 |
| $WZ$ background: scale, PDF | 5 | 8 |
| Fake/non-prompt background | 3 | 1 |
| $ZZ$ background: scale, PDF | 0.2 | <0.1 |
| $VVV + t\bar{t}V$ modelling | 3 | 1 |
| Electron identification | 6 | 3 |
| Muon identification | 1 | 4 |
| Jet uncertainty | 0.8 | 16 |
| Flavour tagging | 0 | 1 |
| Missing transverse energy | 0.2 | 0.5 |
| MC statistical uncertainty | 10 | 5 |
| Luminosity | 2 | 8 |
| Pileup | 0.1 | 8 |
| Total systematic uncertainty | 16 | 22 |
| Data statistical uncertainty | 54 | 55 |
| Total | 56 | 59 |