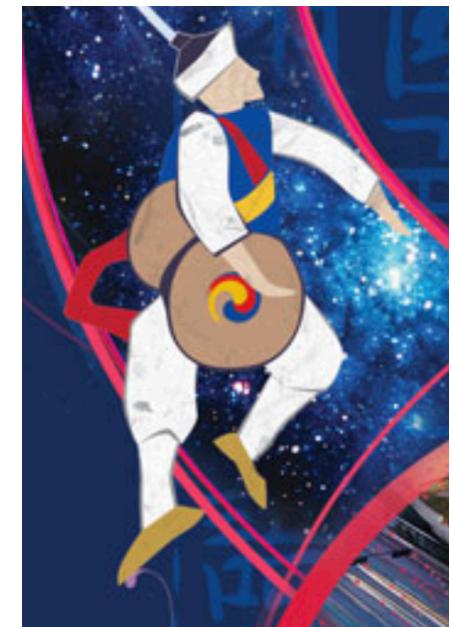


# Complementarity and combination of heavy resonance searches in bosonic and leptonic final states with ATLAS



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on behalf of ATLAS

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# Why search for heavy resonances?

Many SM extensions predict new resonances produced via different mechanisms (not all listed below!)

- **Spin 0**

- Extended Higgs sector (e.g. 2HDM, SUSY, baryogenesis)
- Warped extra dimensions (Randall-Sundrum)

- **Spin 1**

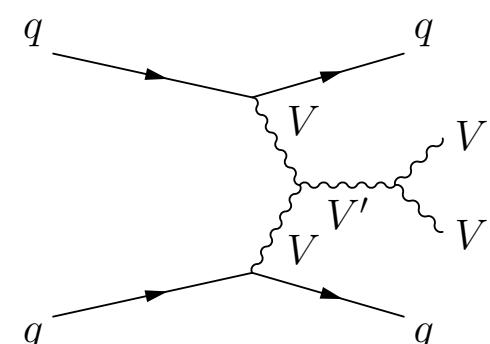
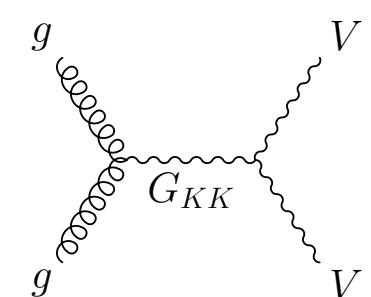
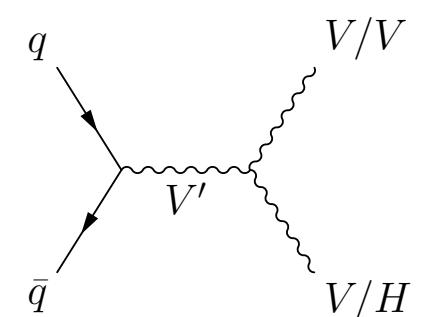
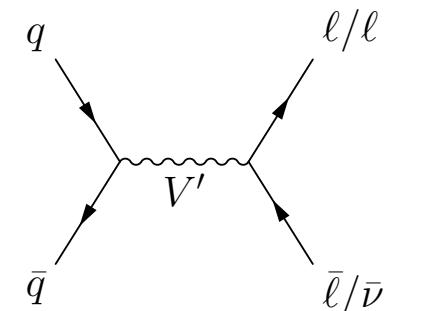
- Extra gauge symmetries  
(extended gauge model, heavy vector triplet)
- Dark matter mediators

- **Spin 2**

- Warped extra dimensions (RS)

- **Production mechanisms**

- Gluon-gluon fusion (ggF)
- Quark-antiquark annihilation (DY)
- Vector boson fusion (VBF)
- Associated production with bb or tt



# Models for interpretation

- **Heavy vector triplet (HVT) model** features triplet of colorless vector bosons  $V'$  ( $W'^+$ ,  $Z'$ ,  $W'^-$ )

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

- $g_q$  and  $g_\ell$ : Universal coupling strength of  $V'$  to quarks and leptons
- $g_H$ : Coupling strength of  $V'$  to Higgs field => to  $W$  and  $Z$

[arXiv:1402.4431](#)

- HVT model A

- Weakly coupled (e.g. extended gauge symmetry):  
 $g_H = -0.56$  and  $g_f = g_q = g_\ell = -0.55$

- HVT model B

- Strongly coupled (e.g. composite Higgs):  
 $g_H = -2.9$  and  $g_f = g_q = g_\ell = 0.14$

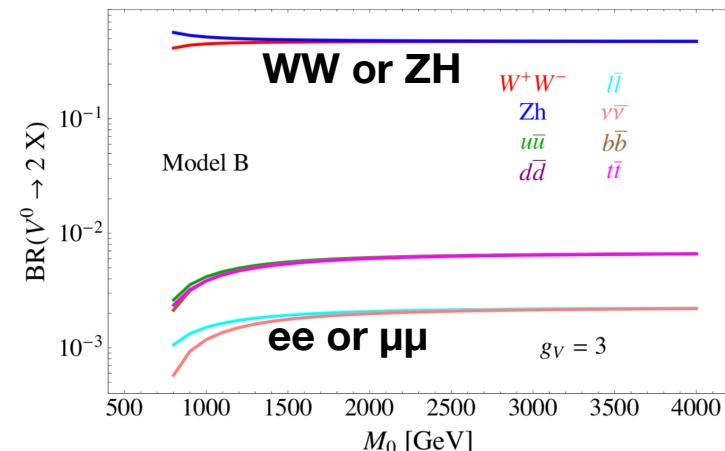
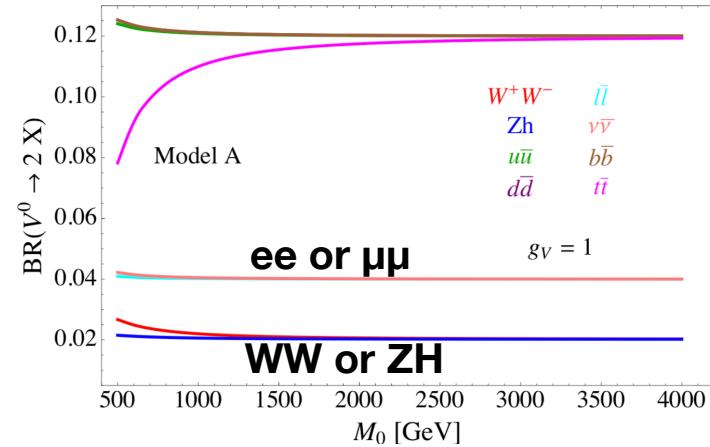
- HVT model C

- VBF only:  $g_H = 1$  and  $g_f = g_q = g_\ell = 0$

- **Randall-Sundrum** warped extra dimensions “bulk” model

- Empirical **heavy scalar** model

- Natural width negligible relative to experimental resolution



# How to search for heavy resonances?

Searches carried out in a wide variety of final states with different experimental signatures

## • quark-antiquark

- light q/g, b, t

## • lepton-antilepton

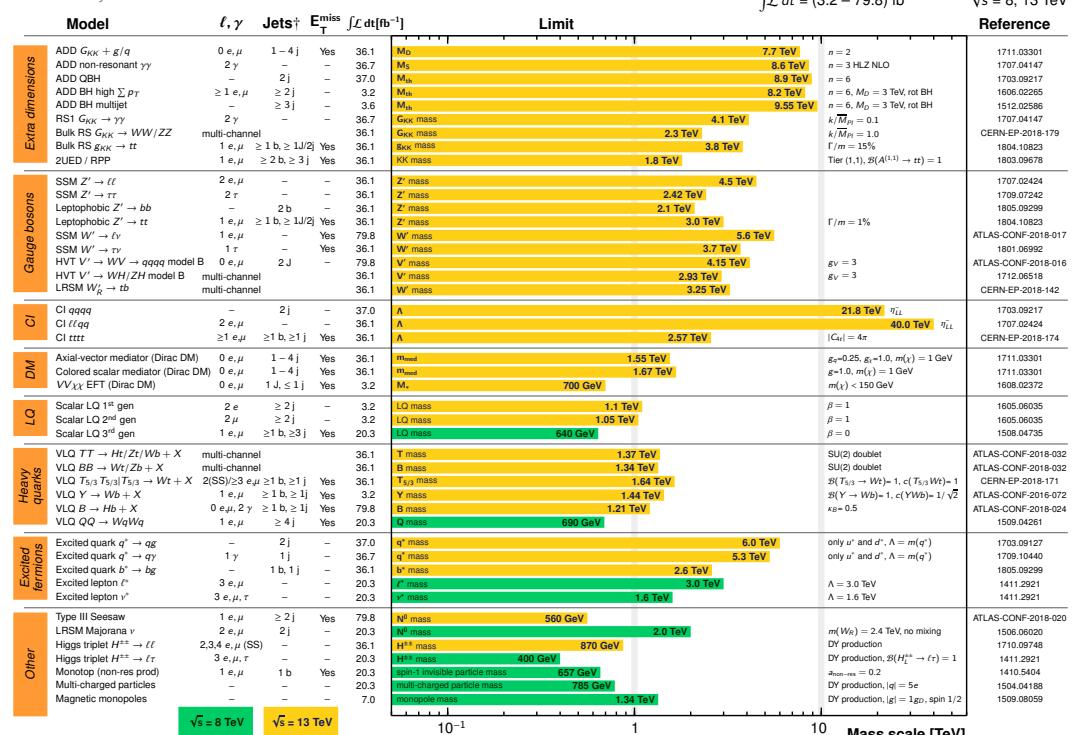
- l (e/ $\mu$ ),  $\tau$ ,  $\nu$

## • diboson ( $\gamma\gamma$ , $VV$ , $V\gamma$ , $VH$ , $HH$ , $H\gamma$ )

- $V$  (W / Z)  $\rightarrow$  qq, lv / qq, ll, vv
- H  $\rightarrow$  bb,  $\tau\tau$

ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2018



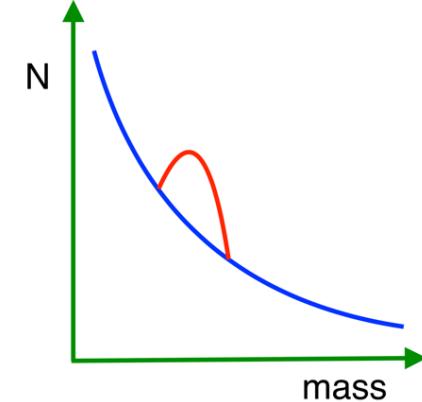
\*Only a selection of the available mass limits on new states or phenomena is shown.

<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter j (J).

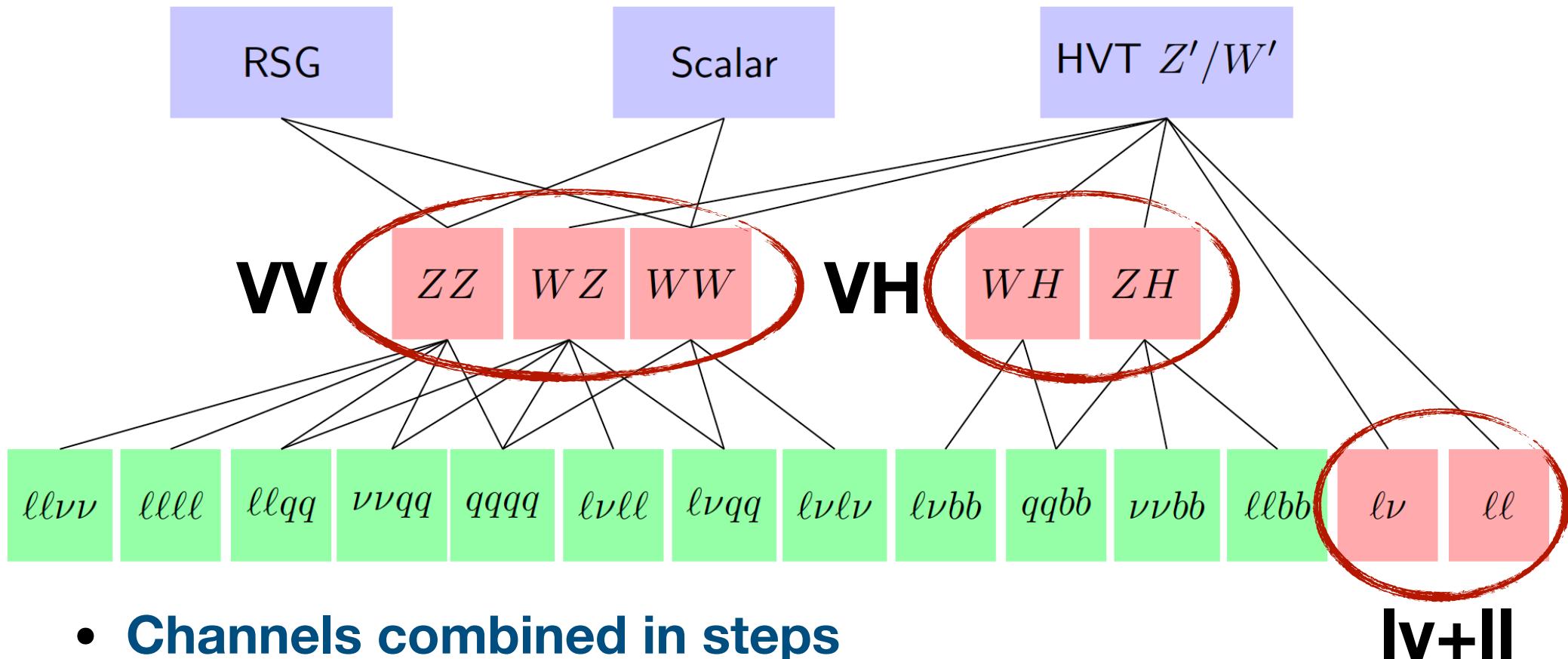
=> Improve sensitivity by combining different final states:  
here consider leptonic and bosonic signatures

## Observable

- Narrow resonance => Bump in mass distribution



# Bosonic & leptonic channels: VV, VH, lv, ll



- **Channels combined in steps**

- VV, VH, and lv+ll separately
- VV+VH
- VV+VH+lv+ll

**First time at the LHC!**

# Combination of results

- Orthogonality between channels guaranteed by selection on number of leptons, jets, b-tags, and selection on ETmiss
- Overlap between VV and VH analyses removed by vetoing Higgs boson candidates overlapping W or Z mass window

Channel	Diboson state	Leptons	Selection			VBF cat.
			$E_T^{\text{miss}}$	Jets	b-tags	
$qqqq$	$WW/WZ/ZZ$	0	veto	2J	–	–
$vvqq$	$WZ/ZZ$	0	yes	1J	–	yes
$\ell vqq$	$WW/WZ$	$1e, 1\mu$	yes	$2j, 1J$	–	yes
$\ell \ell qq$	$WZ/ZZ$	$2e, 2\mu$	–	$2j, 1J$	–	yes
$\ell \ell vv$	$ZZ$	$2e, 2\mu$	yes	–	0	yes
$\ell v \ell v$	$WW$	$1e+1\mu$	yes	–	0	yes
$\ell v \ell \ell$	$WZ$	$3e, 2e+1\mu, 1e+2\mu, 3\mu$	yes	–	0	yes
$\ell \ell \ell \ell$	$ZZ$	$4e, 2e+2\mu, 4\mu$	–	–	–	yes
$qqbb$	$WH/ZH$	0	veto	2J	$1, 2$	–
$vvbb$	$ZH$	0	yes	$2j, 1J$	$1, 2$	–
$\ell vbb$	$WH$	$1e, 1\mu$	yes	$2j, 1J$	$1, 2$	–
$\ell \ell bb$	$ZH$	$2e, 2\mu$	veto	$2j, 1J$	$1, 2$	–
$\ell v$	–	$1e, 1\mu$	yes	–	–	–
$\ell \ell$	–	$2e, 2\mu$	–	–	–	–

j=small-R jet, J=large-R jet

- HVT model for  $\ell v + ll$ : Require generator-level mass to be within mass window of  $W'/Z'$  pole to minimize effects of interference btw signal and dominant DY bkg

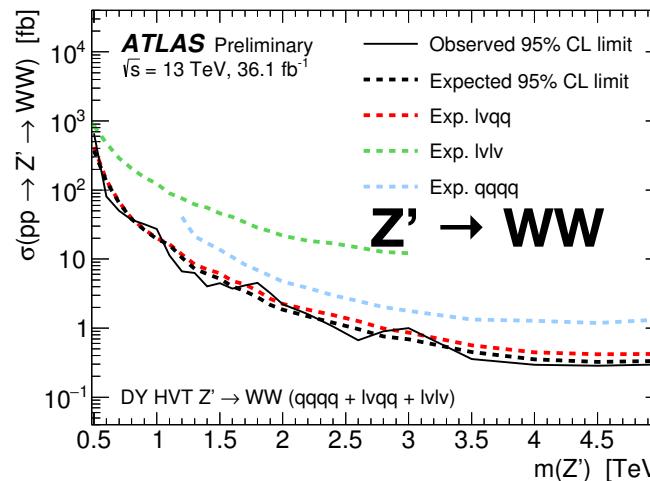
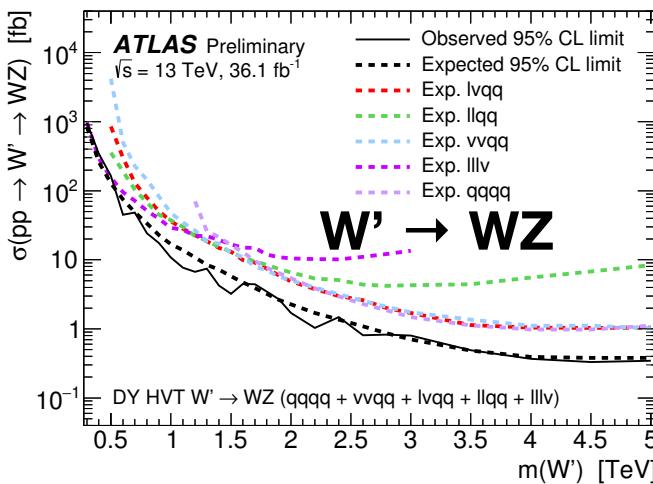
# Statistical analysis

- Channels combined with profile likelihood approach to yield
  - Cross section x BF limits vs. resonance mass
  - Exclusion contours in HVT coupling planes  $\{g_H, g_f\}$  or  $\{g_q, g_\ell\}$  for resonance masses of 3, 4, 5 TeV [VBF category not included here]
  - Exclude regions with CLs < 0.05
- Correlations of systematic uncertainties between channels taken into account
- Rely on asymptotic approximation
  - Cross section limits are too aggressive with this method by a factor growing with resonance mass (as determined with MC trials)
  - Worst case: factor of 1.20 at 2 TeV (1.55 at 5 TeV) for lv+ll combination
  - Effect is smaller for other combinations in this work
  - Impact in terms of mass limits is a few hundred GeV at most (lv+ll combination)
  - Full treatment with MC trials over coupling planes is computationally prohibitive

# Cross section limits

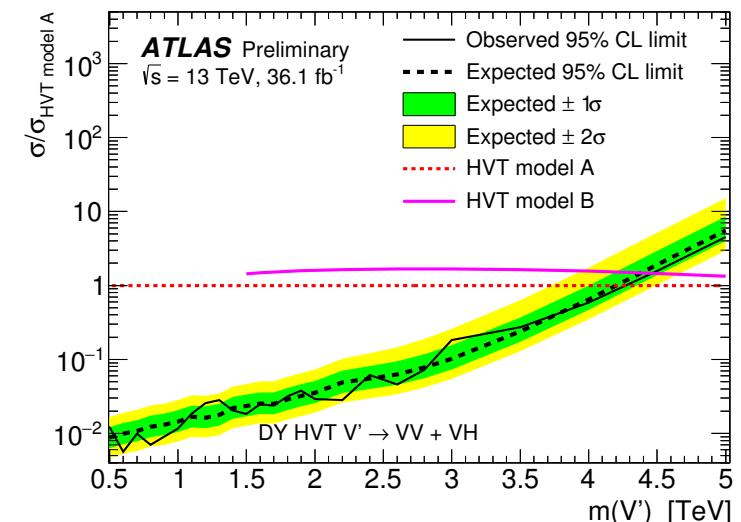
## Combination of bosonic channels

- Semileptonic final states have highest sensitivity over broadest mass range
- Fully leptonic (hadronic) final states contribute at lower (higher)  $V'$  mass



$V' \rightarrow VV \text{ or } VH$

- **VV combination:** Significant improvement relative to single best channel (lvqq)
- **VV+VH combination:** Further improvement in sensitivity



# Cross section limits

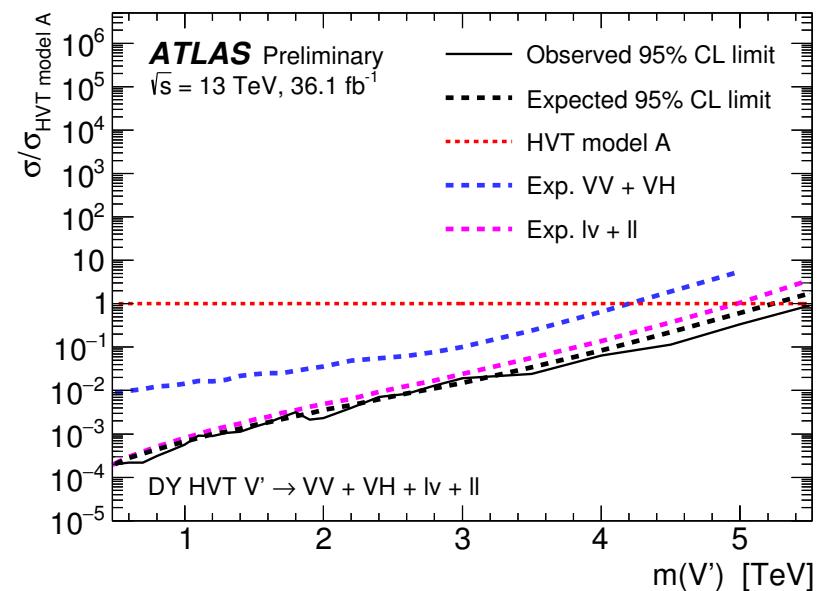
**Significant improvement going from best single VV analysis channel to VV, VV+VH, and VV+VH+lv+ll combinations**

Observed / expected lower mass limits in TeV for HVT model A

	lvqq	VV	VV+VH	lv+ll	VV+VH+lv+ll
W'	2.80 / 2.90	3.6 / 3.6			
Z'	2.75 / 2.85	2.9 / 3.1			
V'		3.7 / 3.7	4.3 / 4.3	5.0 / 5.0	5.5 / 5.3

## NOTE:

*Relative impact of bosonic and leptonic channels is model dependent, e.g. lv+ll does not improve sensitivity to model B beyond that of VV+VH combination due to low BF(V' → lv/ll) in model B*  
 Numbers above are for HVT model A



# Coupling constraints

Complementarity of bosonic & leptonic channels:

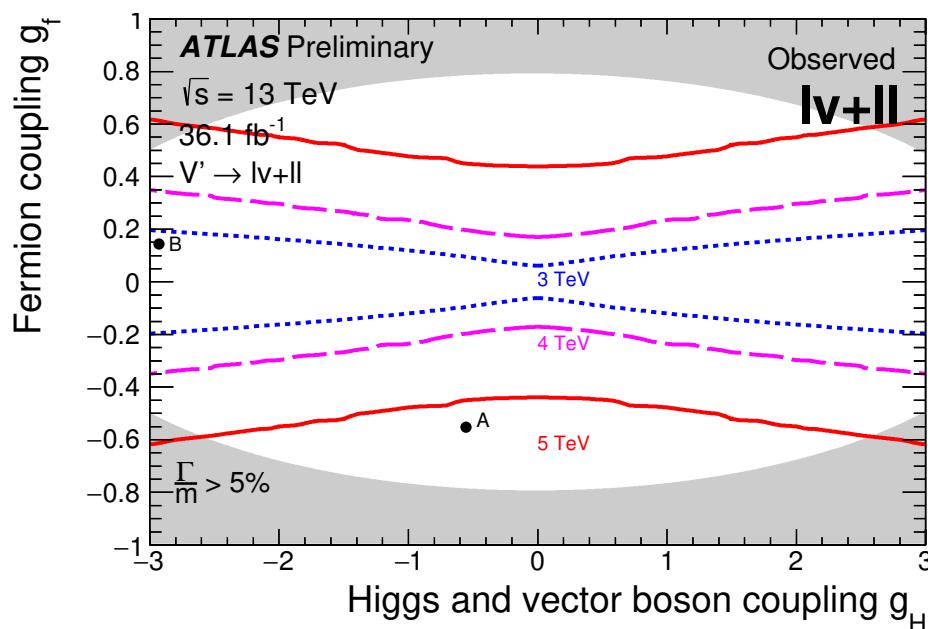
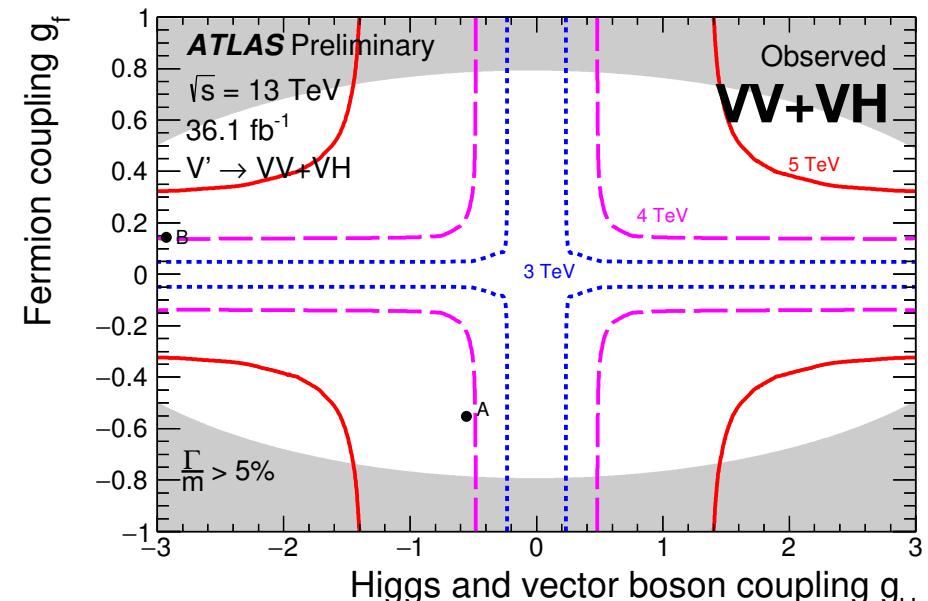
## Higgs and (universal) fermion couplings

- Coupling regions outside contours are excluded
- VV+VH combination excludes fermion coupling  $|g_f| > 0.05$  for resonance mass  $\leq 3$  TeV at sufficiently large  $|g_H|$

No exclusion at low  $|g_H|$  due to vanishing  $\text{BF}(V' \rightarrow \text{VV/VH})$  as  $|g_H| \rightarrow 0$

- ll+ll combination provides sensitivity to small  $|g_H|$

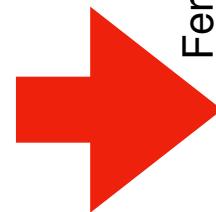
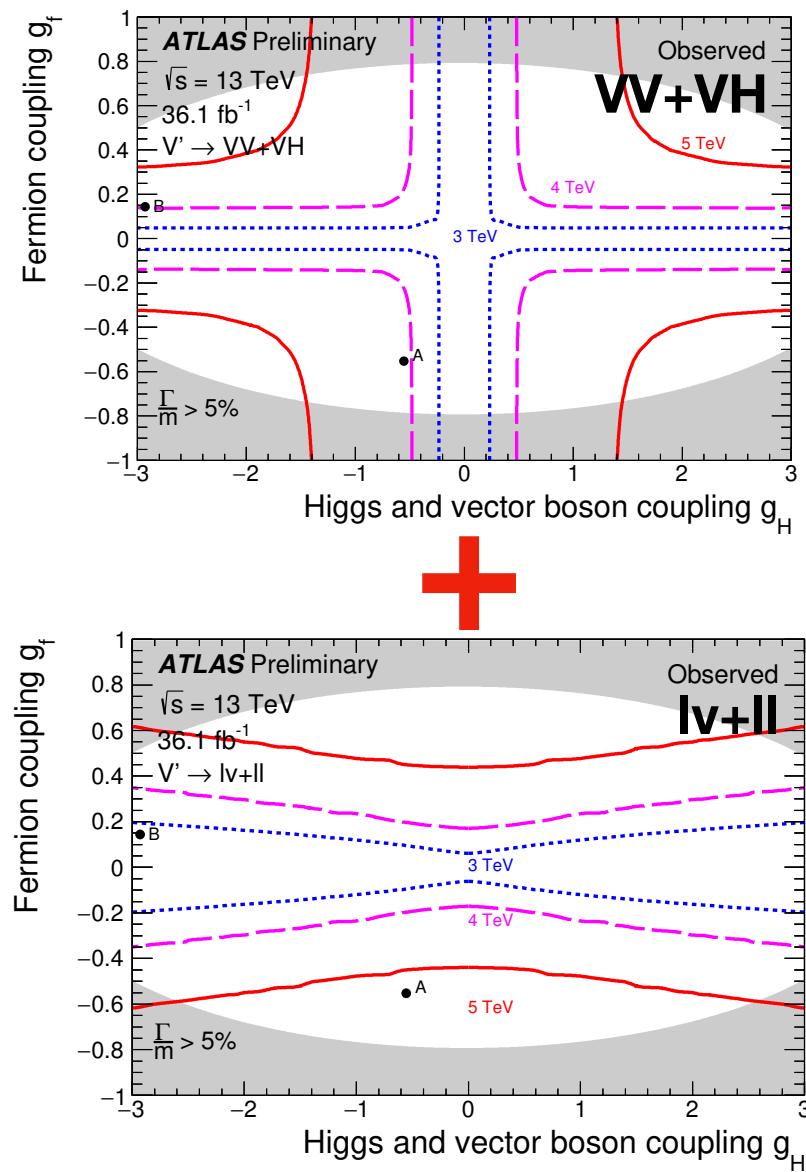
Lower  $\text{BF}(V' \rightarrow \text{VV/VH}) \Rightarrow$  higher  $\text{BF}(V' \rightarrow \text{ll+ll})$



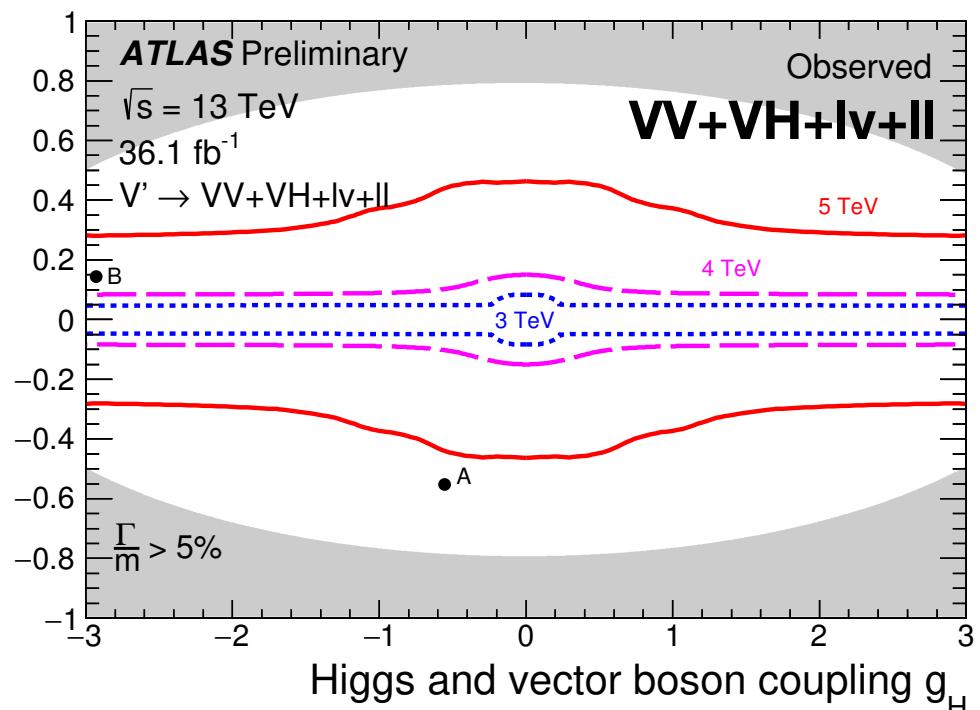
# Coupling constraints

Complementarity of bosonic & leptonic channels:

**Higgs and (universal) fermion couplings**



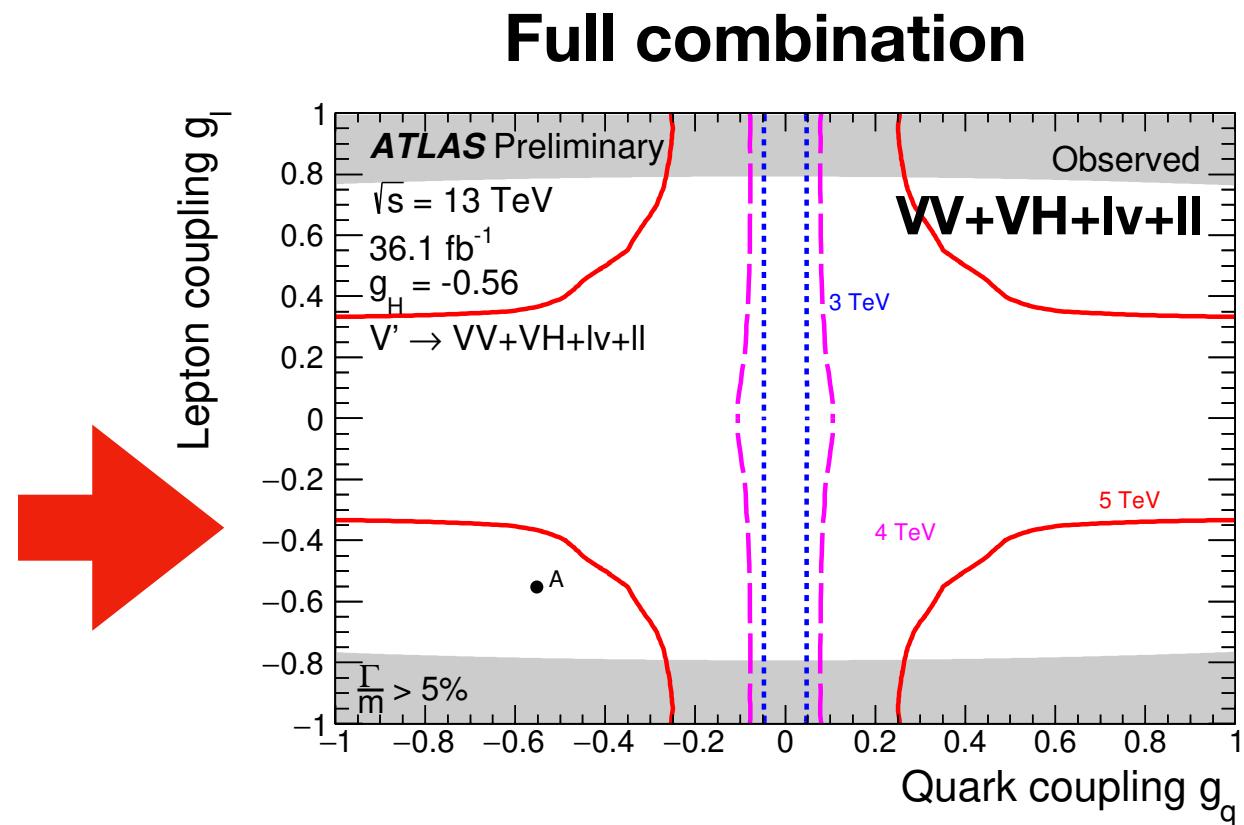
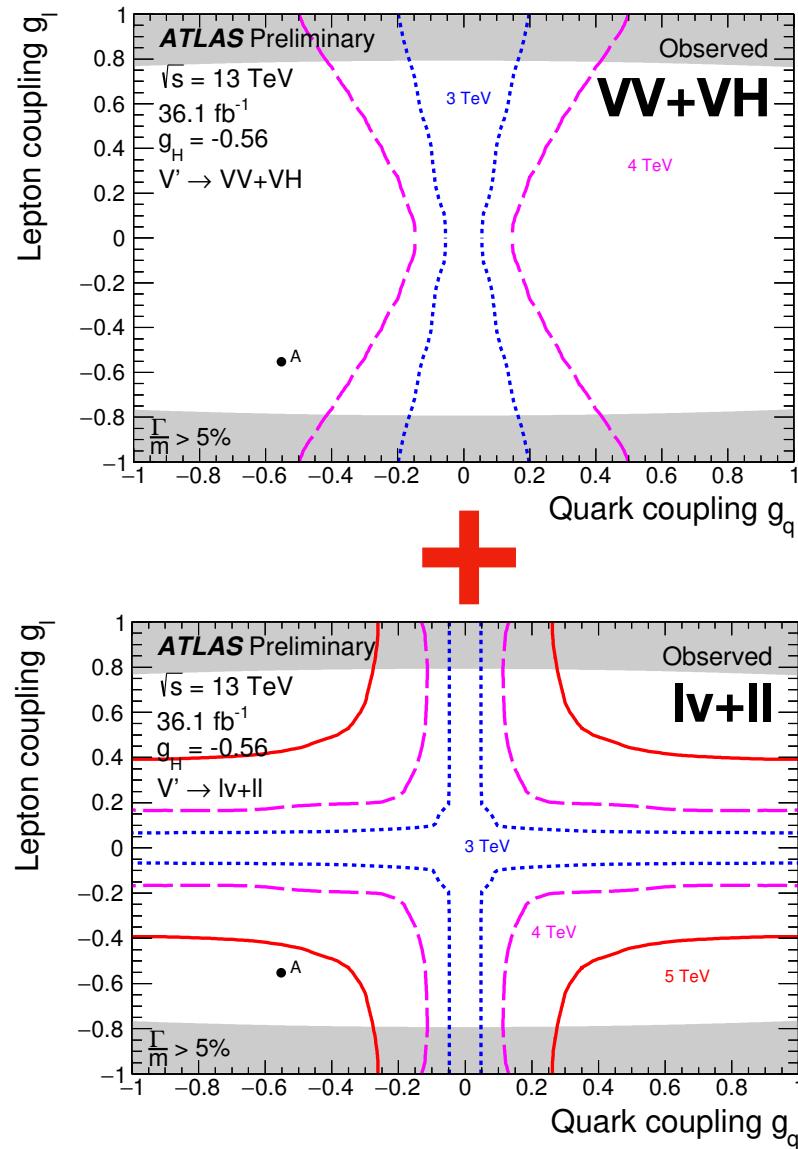
**Full combination**



# Coupling constraints

Complementarity of bosonic & leptonic channels:

**quark and lepton couplings for  $g_H = -0.56$**

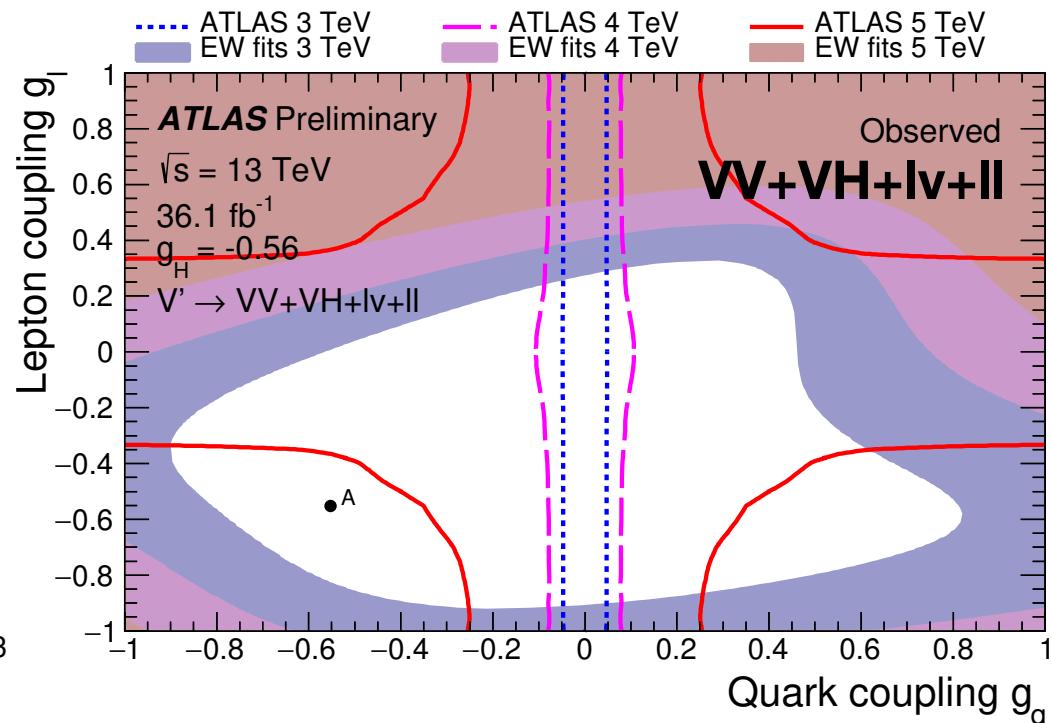
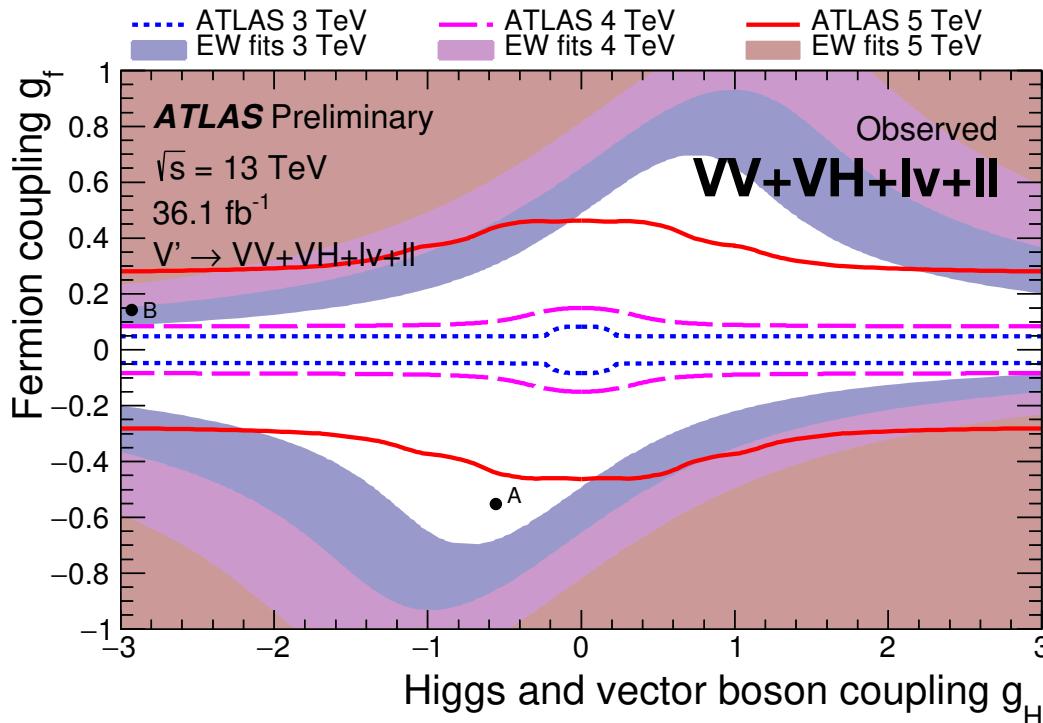


Strongest constraints from  $lv+ll$ , except at low  $|g_\ell|$   
 VV+VH complements constraint at low  $|g_\ell|$

# Coupling constraints

J. de Blas: update of arXiv:1005.3998

- Comparison with constraints from precision electroweak measurements:  
**Higgs and (universal) fermion couplings**      **quark and lepton couplings**



Constraints from  $VV+VH+l\nu+ll$  combination:

- Stronger than those from EW measurements in entire  $\{g_H, g_f\}$  plane
- Stronger than those from EW measurements in most of  $\{g_q, g_\ell\}$  plane, except at low  $|g_q|$  since  $V'$  production cross section vanishes as  $|g_q| \rightarrow 0$

# Summary

- Searches for heavy resonances in the VV, VH, lv, and ll decay modes are combined => improved sensitivity
  - First VV+VH+lv+ll combination performed at the LHC
- Constraints in terms of Higgs and fermion couplings show complementarity between bosonic and leptonic modes
- Full VV+VH+lv+ll combination provides stronger constraints than precision EW measurements in almost all coupling scenarios
- *Results are preliminary, finalized results will appear in CERN-EP-2018-179*

# **Extra material**

# References

- D. Pappadopulo, A. Thamm, R. Torre, and A. Wulzer,  
*Heavy Vector Triplets: Bridging Theory and Data*, **JHEP 09** (2014) 060, arXiv: [1402.4431 \[hep-ph\]](#).
- J. de Blas, J. M. Lizana, and M. Perez-Victoria, *Combining searches of  $Z'$  and  $W'$  bosons*,  
**JHEP 01** (2013) 166, arXiv: [1211.2229 \[hep-ph\]](#).
- ATLAS Collaboration, Search for diboson resonances with boson-tagged jets in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, **Phys. Lett. B 777** (2018) 91, arXiv: [1708.04445 \[hep-ex\]](#).
- ATLAS Collaboration, *Search for  $WW/WZ$  resonance production in  $l\bar{q}qq$  final states in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, **JHEP 03** (2018) 042, arXiv: [1710.07235 \[hep-ex\]](#).
- ATLAS Collaboration, Search for resonant  $WZ$  production in the fully leptonic final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, (2018), arXiv: [1806.01532 \[hep-ex\]](#).
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- ATLAS Collaboration, Searches for heavy  $ZZ$  and  $ZW$  resonances in the  $llqq$  and  $vvqq$  final states in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, **JHEP 03** (2018) 009, arXiv: [1708.09638 \[hep-ex\]](#).
- ATLAS Collaboration, Searches for heavy  $ZZ$  and  $ZW$  resonances in the  $llqq$  and  $vvqq$  final states in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, **JHEP 03** (2018) 009, arXiv: [1708.09638 \[hep-ex\]](#).

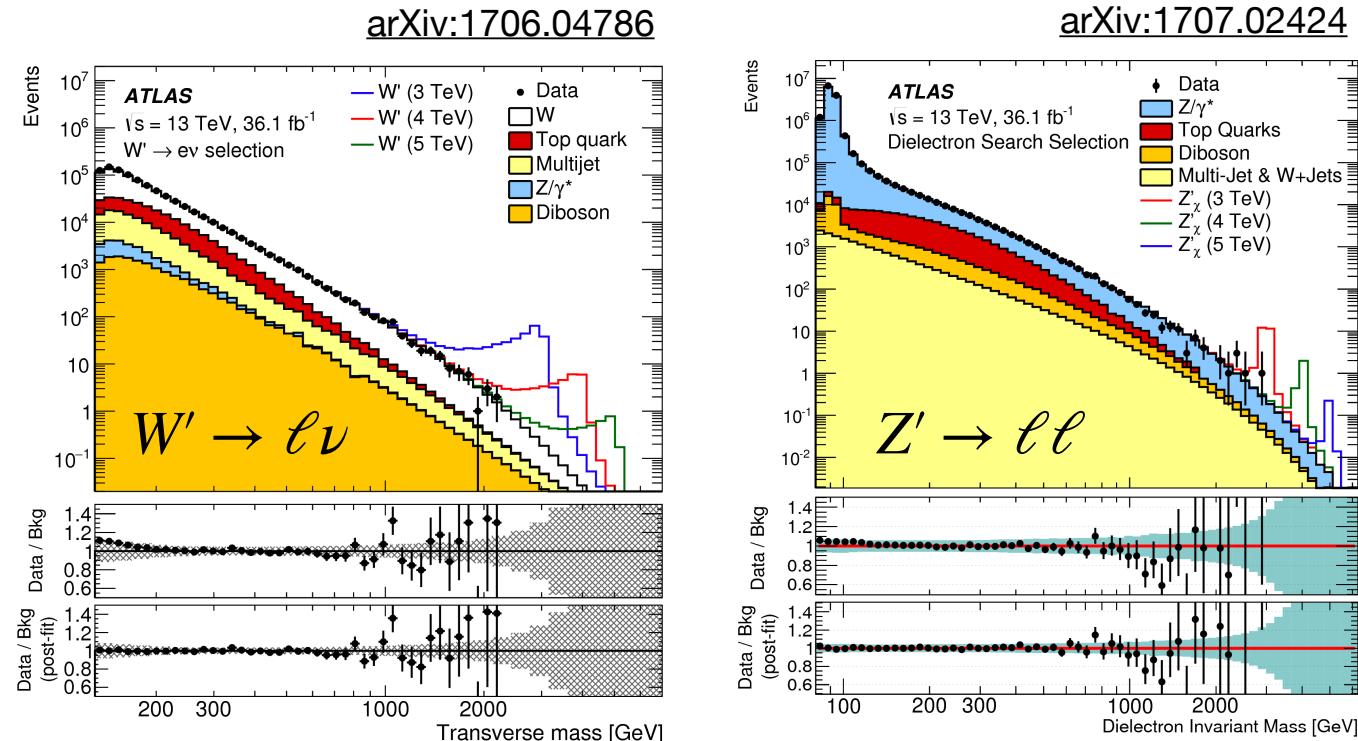
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- ATLAS Collaboration, Search for heavy ZZ resonances in the  $l^+l^-l^+l^-$  and  $l^+l^-vv^-$  final states using proton–proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, [Eur. Phys. J. C 78 \(2018\) 293](#), arXiv: [1712.06386 \[hep-ex\]](#).
- ATLAS Collaboration, Search for heavy resonances decaying to a W or Z boson and a Higgs boson in the qqbb final state in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, [Phys. Lett. B 774 \(2017\) 494](#), arXiv: [1707.06958 \[hep-ex\]](#).
- ATLAS Collaboration, Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b-jets in  $36\text{ fb}^{-1}$  of  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector, [JHEP 03 \(2018\) 174](#), arXiv: [1712.06518 \[hep-ex\]](#).
- ATLAS Collaboration, Search for a new heavy gauge boson resonance decaying into a lepton and missing transverse momentum in  $36\text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS experiment, [Eur. Phys. J. C 78 \(2018\) 401](#), arXiv: [1706.04786 \[hep-ex\]](#).
- ATLAS Collaboration, Search for new high-mass phenomena in the dilepton final state using  $36\text{ fb}^{-1}$  of proton–proton collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector, [JHEP 10 \(2017\) 182](#), arXiv: [1707.02424 \[hep-ex\]](#).
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# Leptonic final states: I $\nu$ and II

Interpretation for leptonic final state analyses modified w.r.t. publications<sup>#</sup> to minimize impact of interference between HVT  $W' \rightarrow l\nu$  ( $Z' \rightarrow ll$ ) signals and dominant charged-current (neutral-current) Drell-Yan background

- I $\nu$  (II) generator-level mass required to be within window around  $W'$  ( $Z'$ ) pole
- Width of mass window fixed so that difference between cross sections with and without interference is less than 15% in the HVT coupling range explored in combination



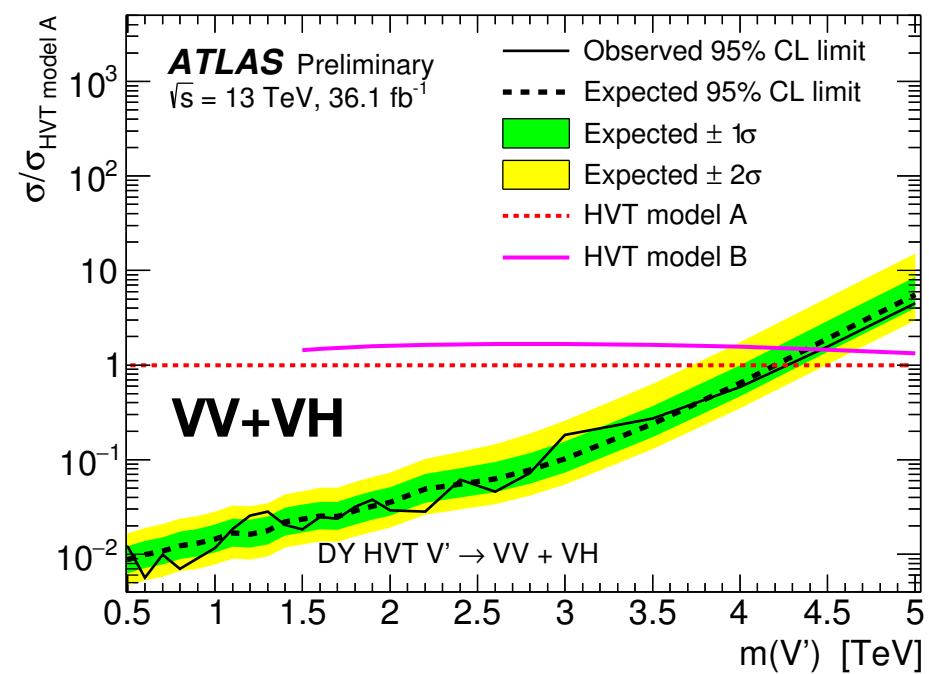
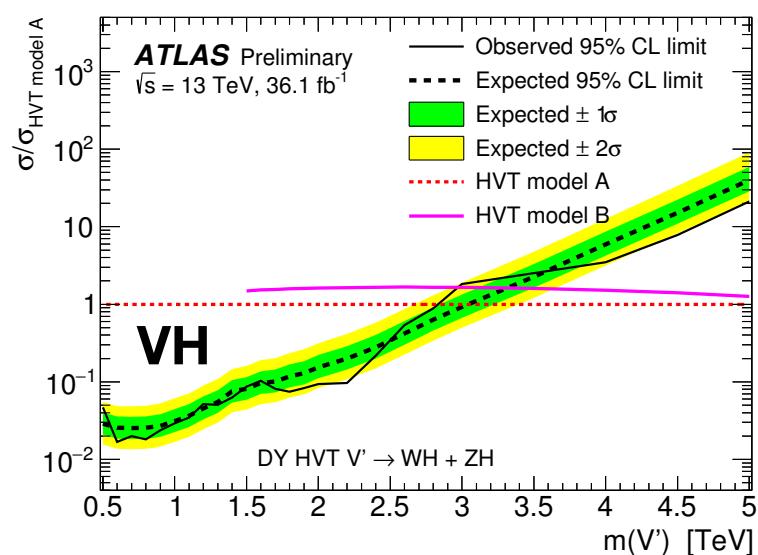
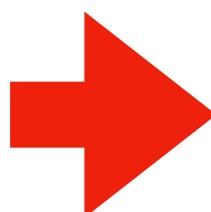
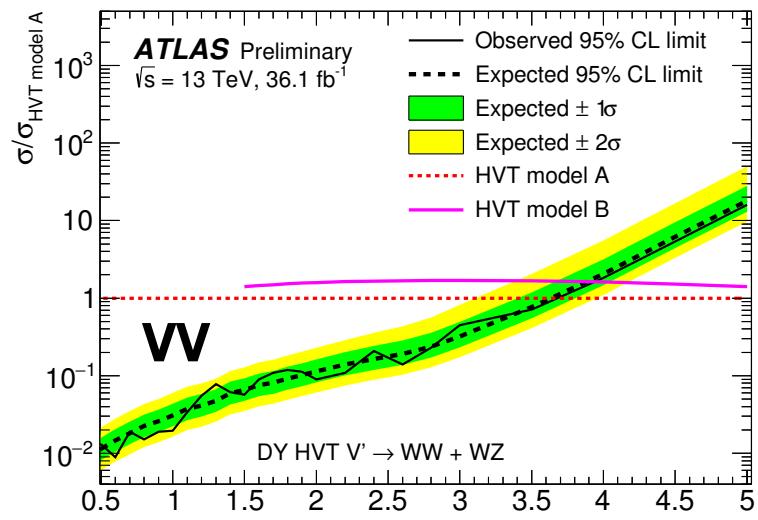
<sup>#</sup> Interference is accounted for in context of minimal  $Z'$  model

# Cross section limits

## Combination of VV and VH channels

- Obs [Exp]  $V'$  lower mass limit:

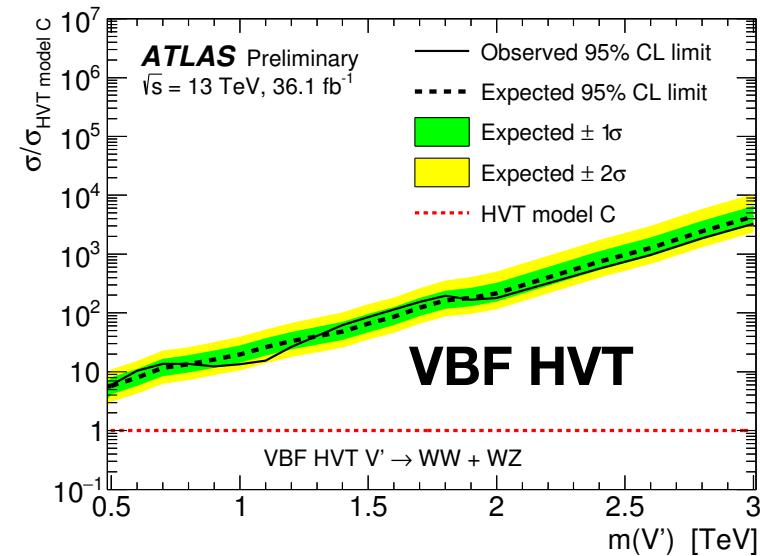
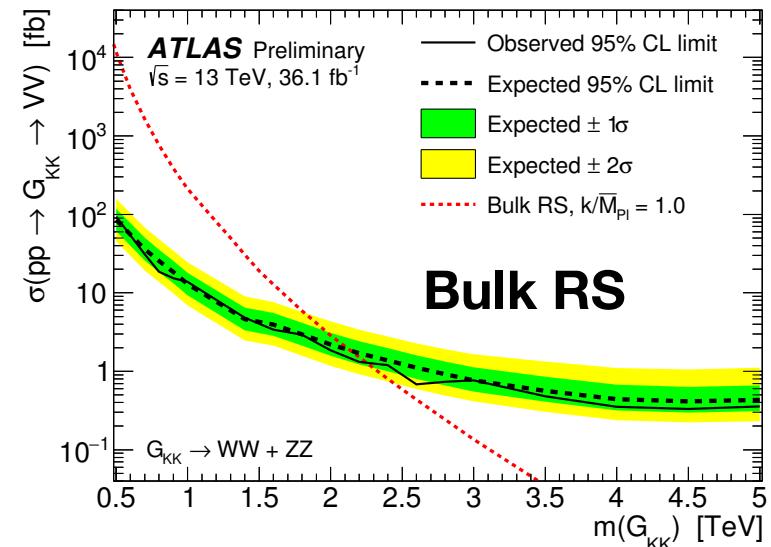
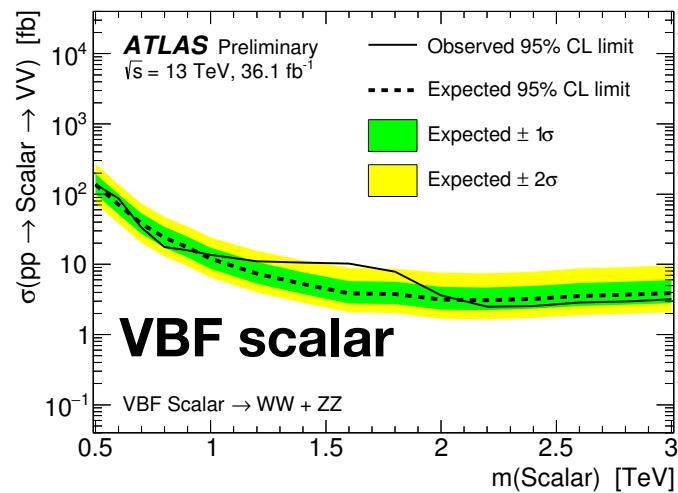
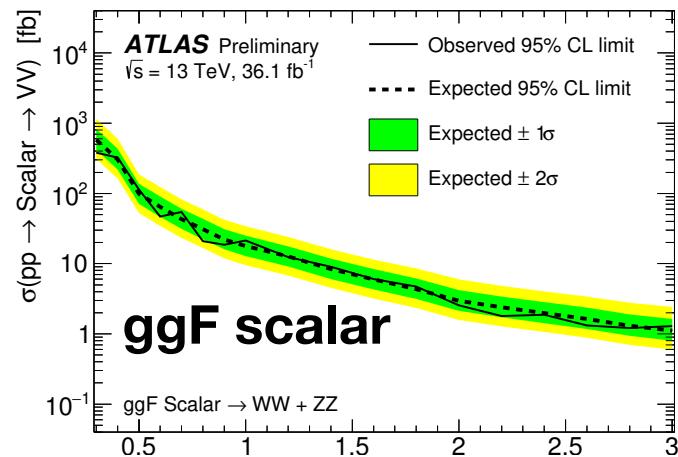
3.7 TeV [3.7 TeV] for VV  $\rightarrow$  4.3 TeV [4.3 TeV] for VV+VH



# Cross section limits

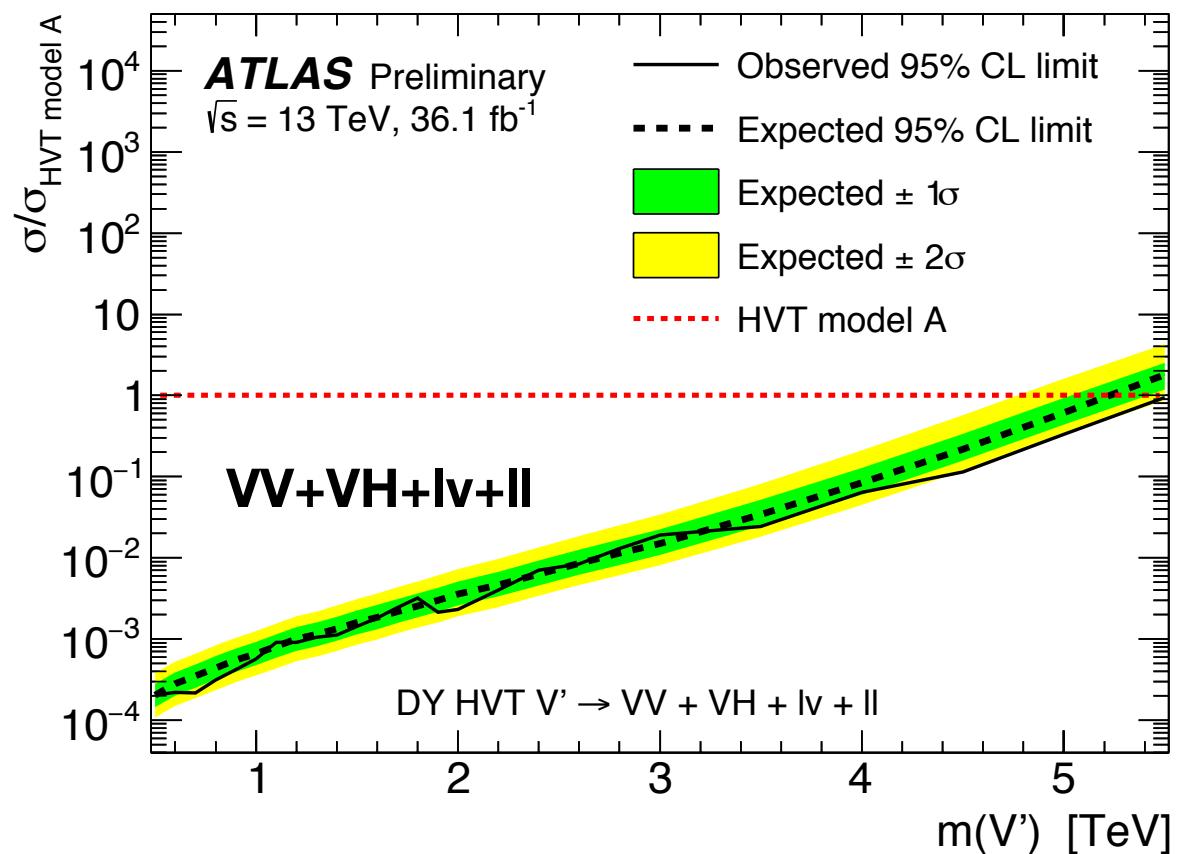
## Combination of bosonic channels

- Limits also obtained for ggF production of spin-0 and spin-2 resonances, as well as VBF production of spin-0 and spin-1 resonances (separately from DY)



# Cross section limits

Combination of bosonic and leptonic channels



# Coupling constraints

Constraints from precision electroweak measurements include:

- Z pole measurements from LEP
- LEP2 measurements
- Lower-energy experiments, CKM unitarity, alpha\_s
- Top-quark mass world average
- Higgs-boson mass world average

Update of analysis from <https://arxiv.org/abs/1005.3998>

# Acceptance x efficiency

