Search for Resonant and Non-Resonant VHH Production

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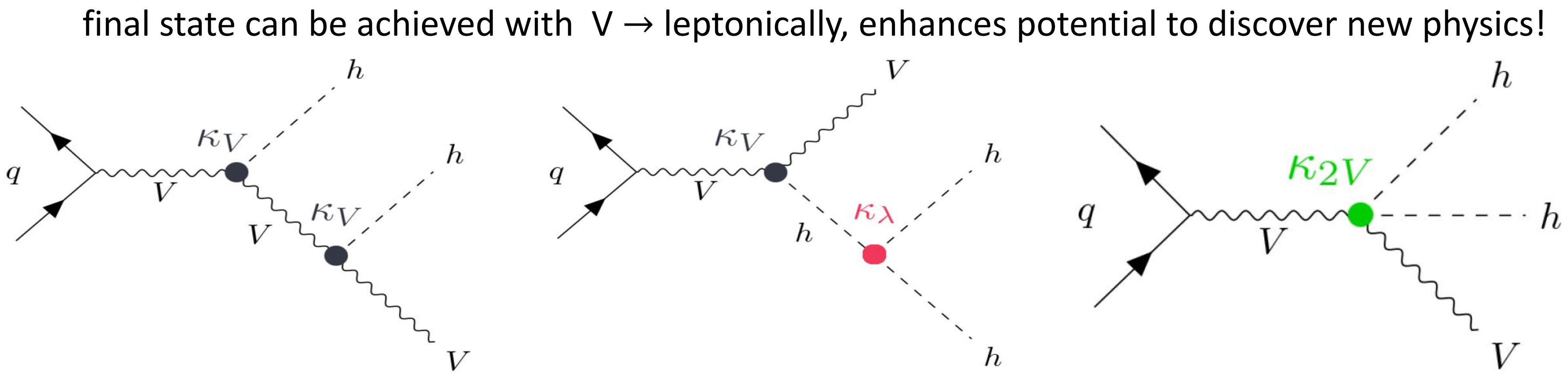
V*hh* Introduction

V*hh* is a very rare process in the SM, with a **production** cross-section at 13 TeV of < 1 fb.

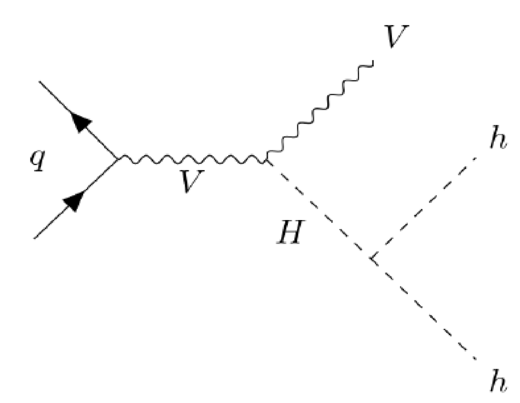
- First analysis targeting Vhh final-state!
- Sets initial V*hh* cross-sections limits with full Run-2 (139 fb^{-1}) dataset!
- Although a small expected cross-section: the corresponding SM background is low, and a clean-final state can be achieved with V → leptonically, enhances potential to discover new physics!



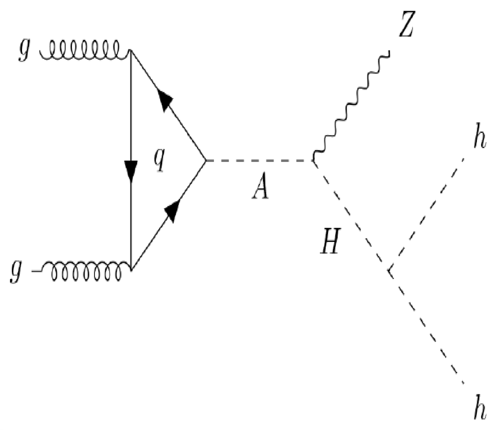
At LO, 3 different Standard Model (SM) Feynman diagrams can produce this final state.

Analysis also targets two resonant signal searches!

- **Heavy Narrow Resonance** (V → $lep.$ H → $hh \to b\bar{b}b\bar{b}$) **(left)**
- **Heavy Pseudo-scalar *AZH* Resonance** (A → ZH w/ Z → $ll/\nu\nu$ & H → $hh \to b\bar{b}b\bar{b}$) **(right)**



h: SM Higgs
H: Heavy-Scalar Higgs
A: neutral, heavy, CP-odd pseudo-scalar



Explores *wide range* of mass points!
Heavy Narrow Resonant H: m_H: 260-1000 GeV
Heavy Pseudo-scalar A→ZH: m_A: 360-800 GeV (both Narrow (NW) and Large-width (LW)), m_H: 260-400 GeV

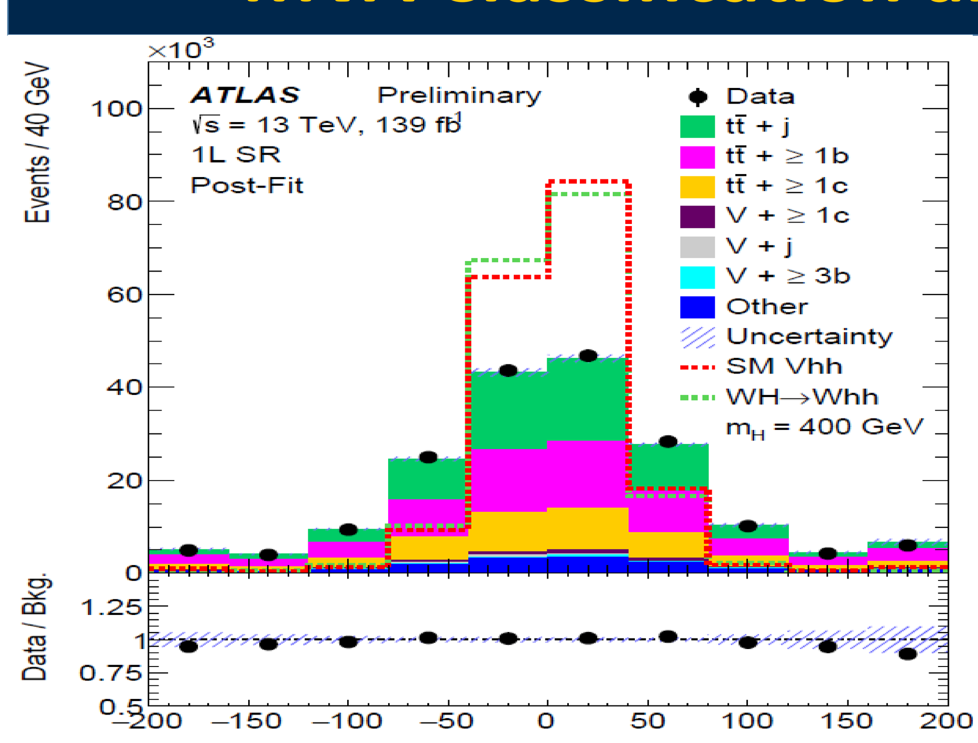
Event Selection

Targets final-state with V decaying leptonically and Higgs boson decaying to a pair of b quarks.

- Different lepton and E_T^{miss} requirements depending on the channel.
- Two main backgrounds ($t\bar{t}$, V+jets), constrained by dedicated $t\bar{t}$ & V+jets Control Region (CR).
- Remaining backgrounds are minor (<10%), and contributions are normalized to σ_{Theory}.

	Signal regions			Control regions	
	0L	1L (1L+/1L−)	2L	$t\bar{t}$	V + jets
Trigger	E_T^{miss}	single-lepton	single-lepton	single-lepton	single-photon
Lepton or photon	0 *loose* leptons	= 1 *tight* electron with $p_T > 27$ GeV OR 1 *medium* muon with $p_T > 25$ GeV, 0 additional *loose* leptons	= 2 *loose* leptons (e^+e^- or $\mu^+\mu^-$), ≥ 1 lepton with $p_T > 27$ GeV, 81 GeV $< m_{\ell\ell} <$ 101 GeV	= 2 *loose* leptons ($e^\pm\mu^\mp$), ≥ 1 lepton with $p_T > 27$ GeV	= 1 photon with $p_T > 150$ GeV, 0 *loose* leptons
p_T^{miss}	$E_T^{miss} > 150$ GeV, $S(E_T^{miss}) > 12$, $\lvert\Delta\phi(p_T^{miss}, h)\rvert > 1$	$E_T^{miss} > 30$ GeV	—	—	—
Jets	≥ 4 jets with $p_T > 20$ GeV and passing the 85% b-tagging WP				

MVA Classification and Fitting Strategy



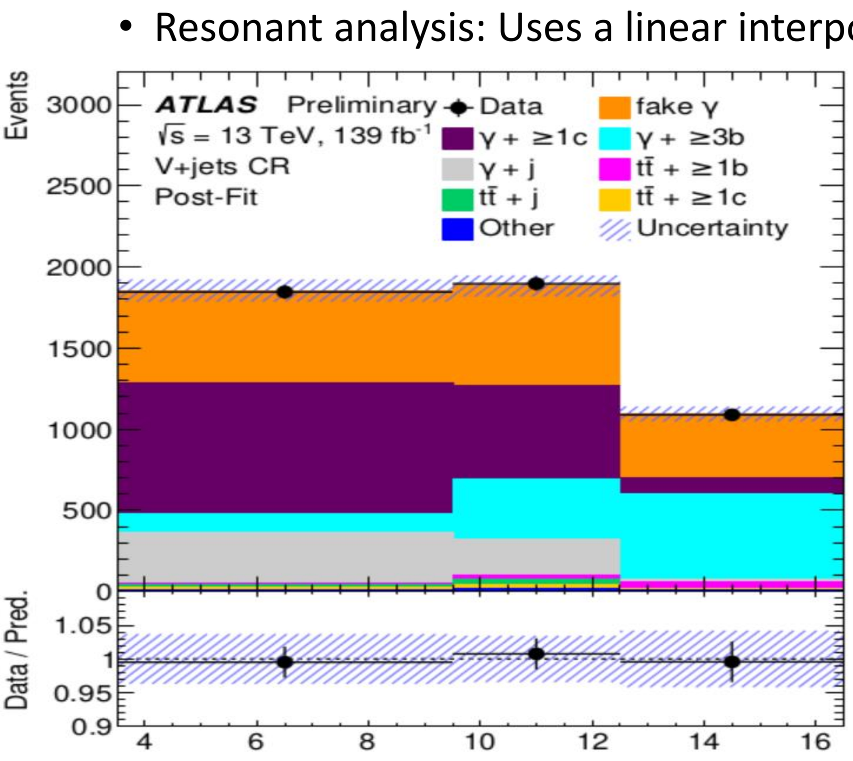
BDT's used to exploit kinematic differences between signal and background.

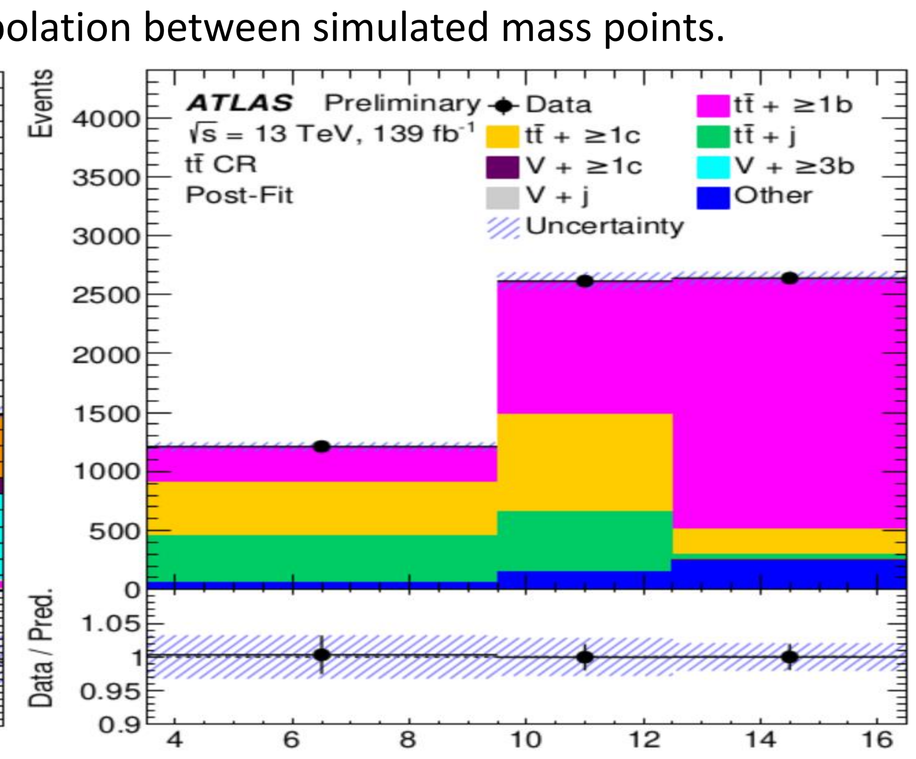
- 1 BDT used for each channel (0L, 1L, 2L) and each signal model (Vhh, VH, and A→ZH) (8 Total).
- 7 Common input variables used across all 8 BDT's:
  - $(m_{h_1} - m_2)$, $(m_{h_1} + m_{h_2})$, N_{jets}, Σ_{PC}, H_T^{Ex}, $m_{h_1}^{FSR}$, $m_{h_2}^{FSR}$

Example (1L) kinematic distribution of $m_{h_1} - m_{h_2}$ variable used in BDT training.

Simultaneous binned maximum likelihood fit for each signal model

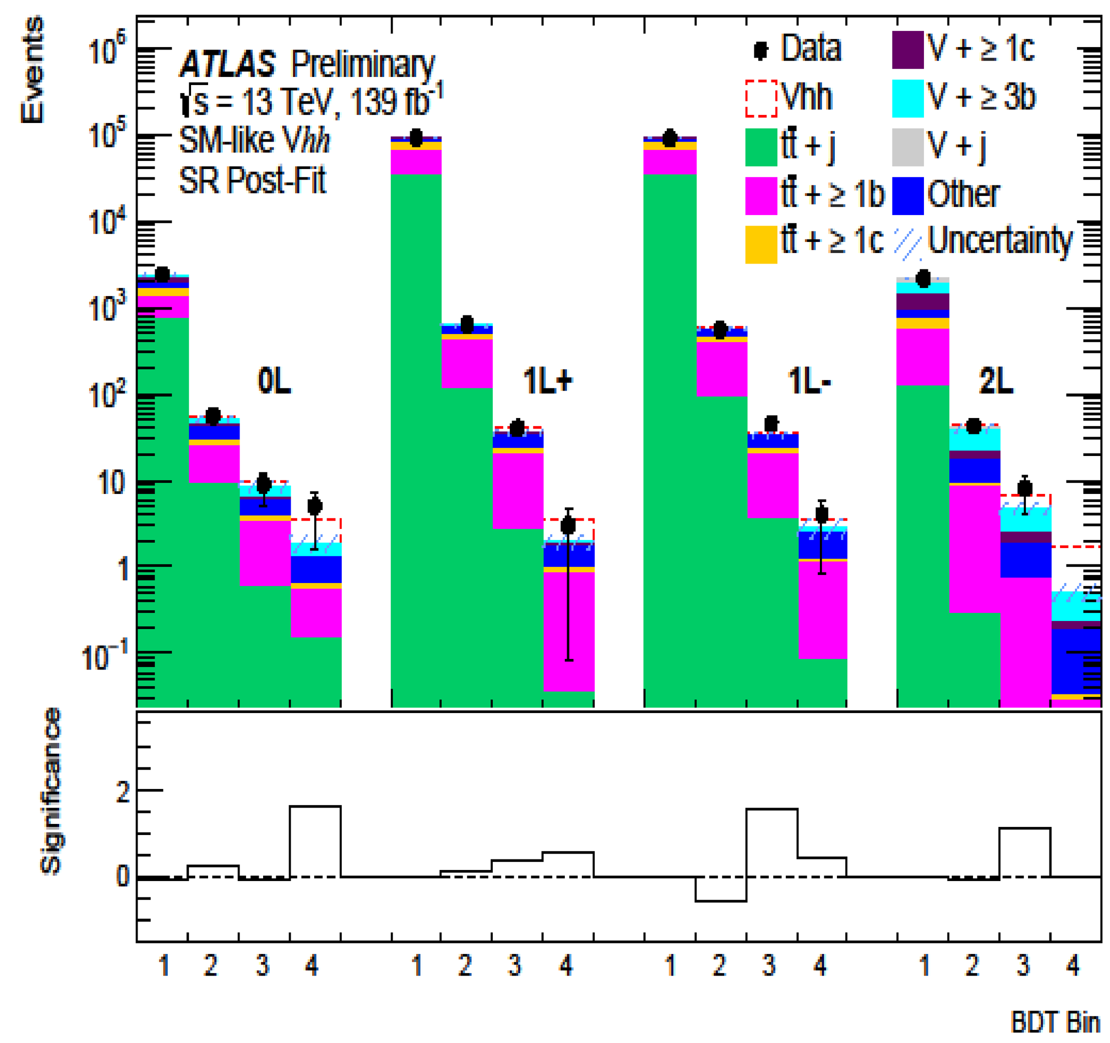
- Control Regions: Sum of the pseudo-continuous b-tagging scores distributions are fit to extract background.
- Signal Regions: output BDT distributions are fit to extract signal contribution.
- Resonant analysis: Applies mass window cuts prior to fitting BDT distributions.
- Resonant analysis: Uses a linear interpolation between simulated mass points.





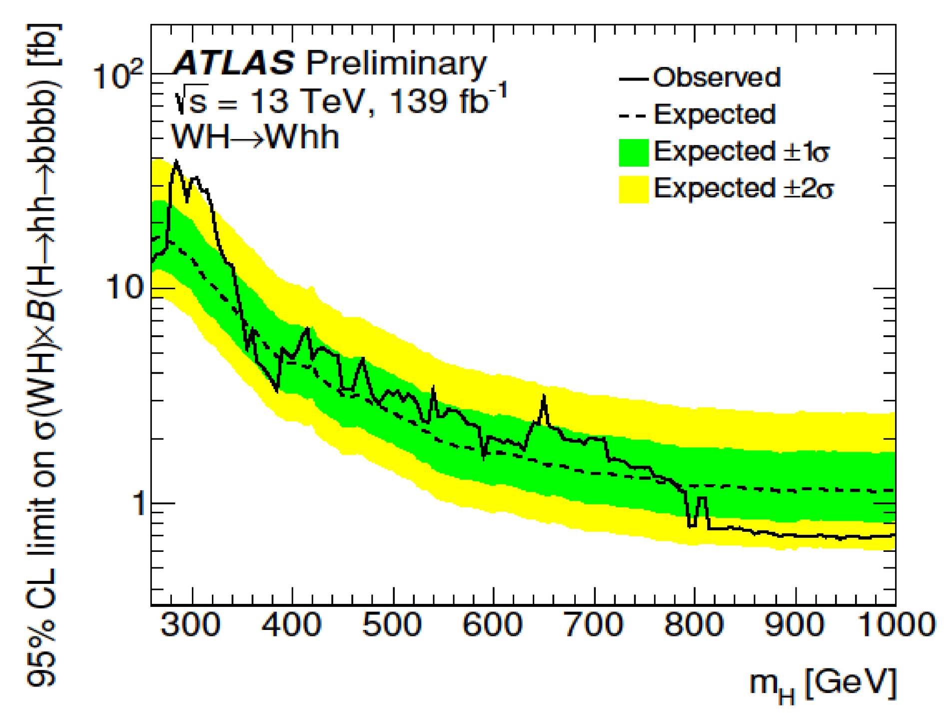
Background-only post-fit distributions of the sumer of the pseudo-continuous b-tagging scores of the four highest-score jets in the V+jets (**left**) and $t\bar{t}$ (**right**) CR's.

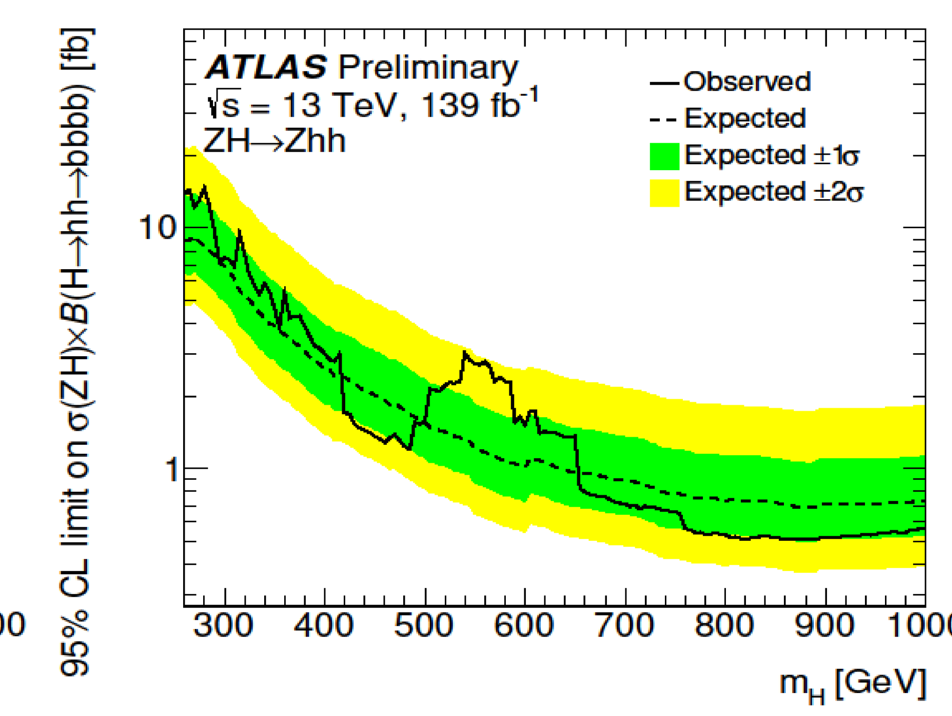
V*hh* Non-Resonant Search



Observed & (expected) 95% CL-interval constraints on hhh and hhVV couplings (expected):
-34.4 (-24.1) < κ_λ < 33.3 (22.9)
-8.6 (-5.7) < κ_{2V} < 10.0 (7.1)
An observed upper cross section limit of 183 times the Standard Model, compared with an expected limit of 87^{+41}_{-24} is set.
The weaker observed bounds compared with expectations are largely due to small excesses of data in the highest BDT bins

VH Limits



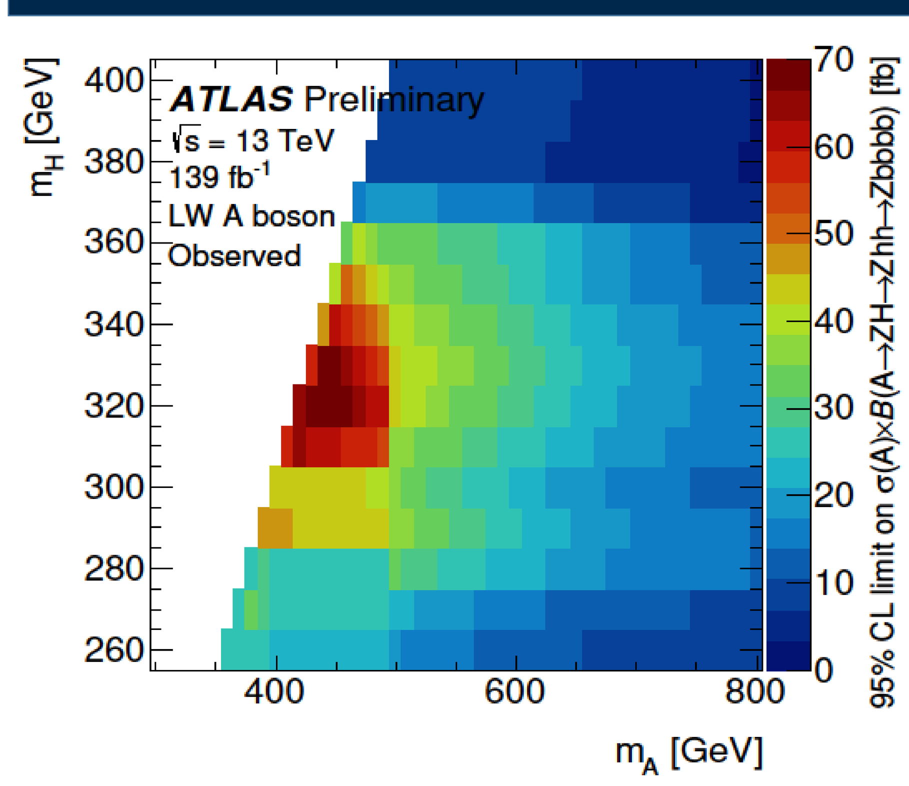


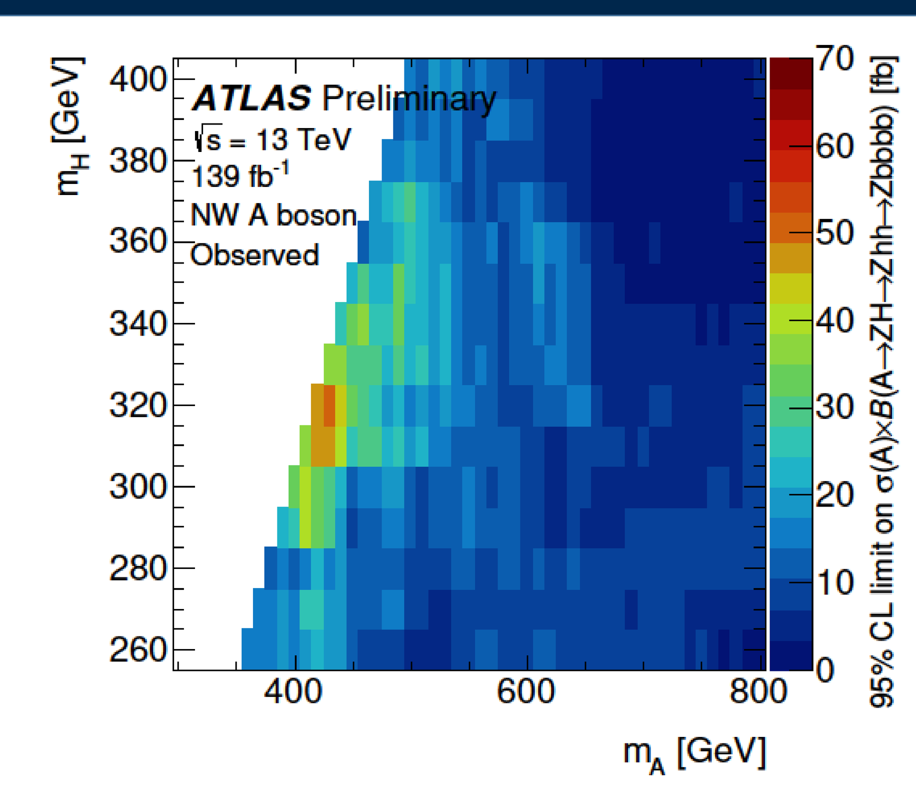
Observed (solid black curve) and expected (black dashed curve) 95% CL upper limits on production cross section for WH(*hh*) **(left)** and ZH(*hh*) **(right)**

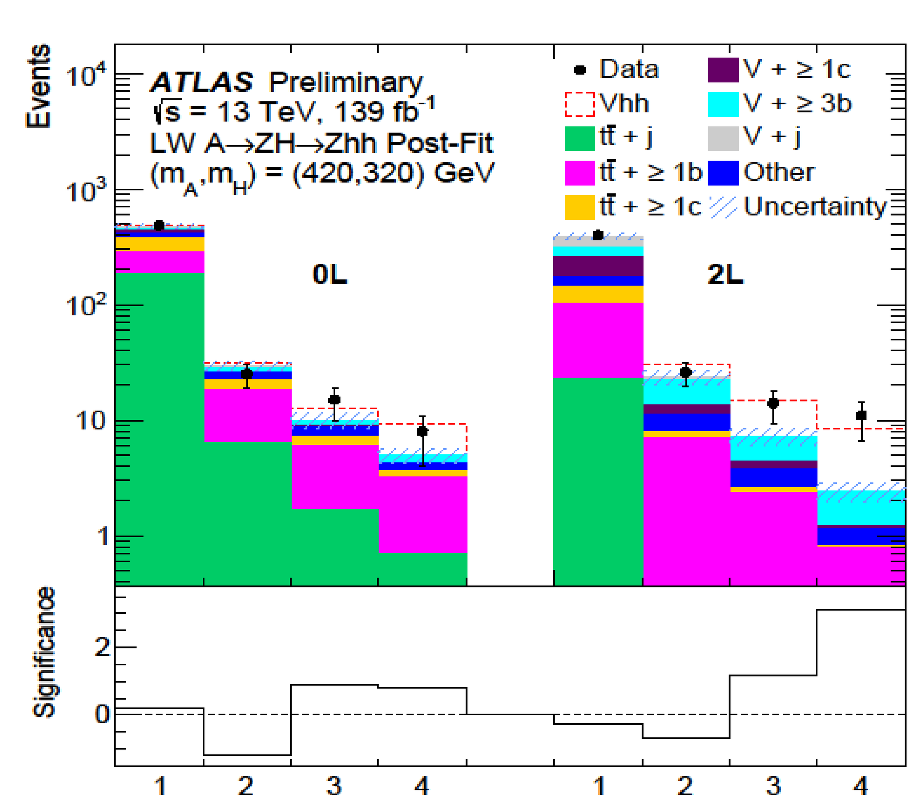
Slight excess observed in WH(*hh*) fits **(left)** at m_H = 315 GeV: local significance 2.5 with corresponding global significance 1.3.

Slight excess observed in ZH(*hh*) fits **(right)** at m_H = 550 GeV: local significance 2.7 with corresponding global significance 1.3.

A → ZH Search

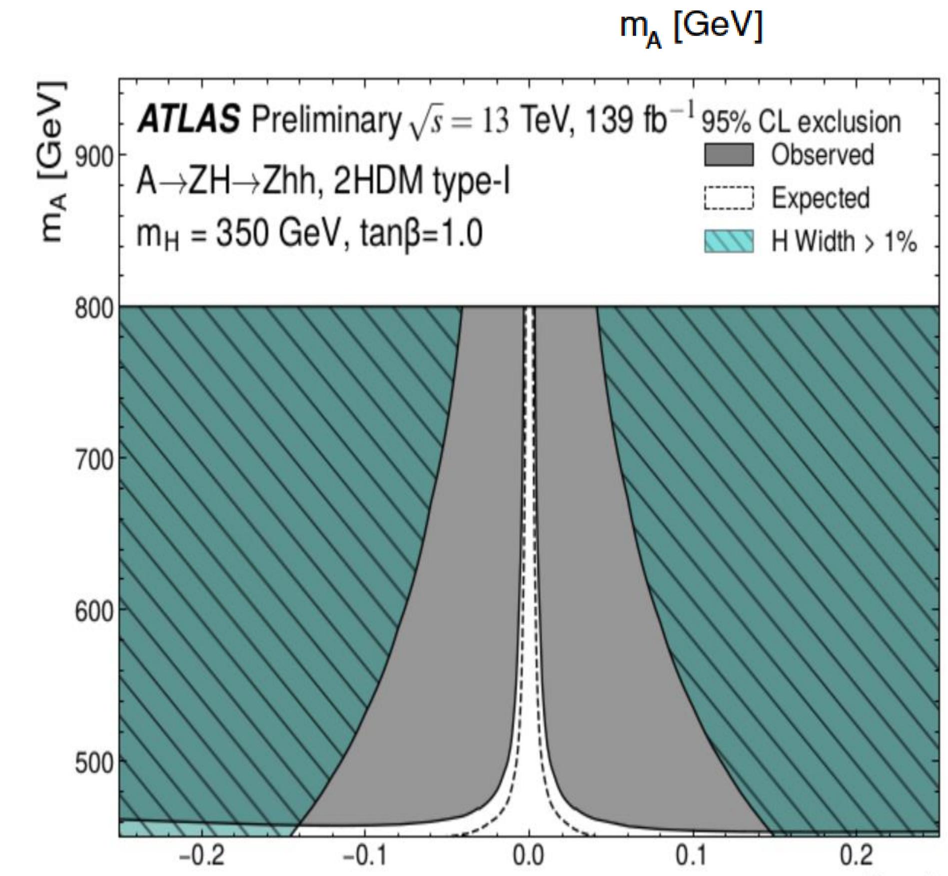






Highest obs. excess in NW A→ZH (**left**) fits at (m_A, m_H) = (420,320) GeV: local sig. 3.8 w/ corr. global sig. 2.8.

Highest obs. excess in LW A→ZH (**not shown**) fits at (m_A, m_H) = (800,300) GeV: local sig. 3.6 w/ corr. global sig. 1.6.



Type-1 2HDM upper limit interpretations on σ(A)xBr(A→ZH→Z*hh*→Zbbbb) . Shaded areas are 95% CL exclusion contours in $\cos(\beta-\alpha)$ - m_A plane for $\tan(\beta)$ = 1.0 & m_H = 350 GeV.