Search for Non Standard Model Higgs Boson

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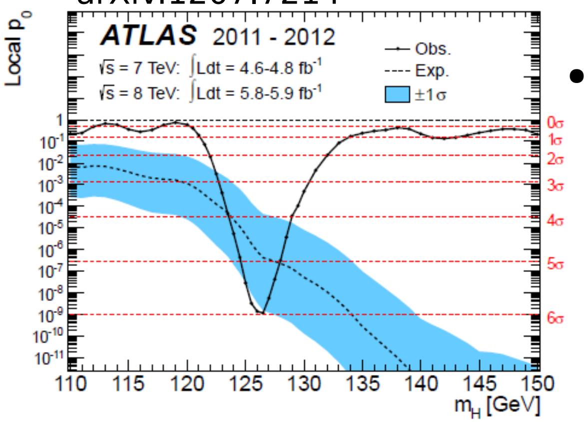
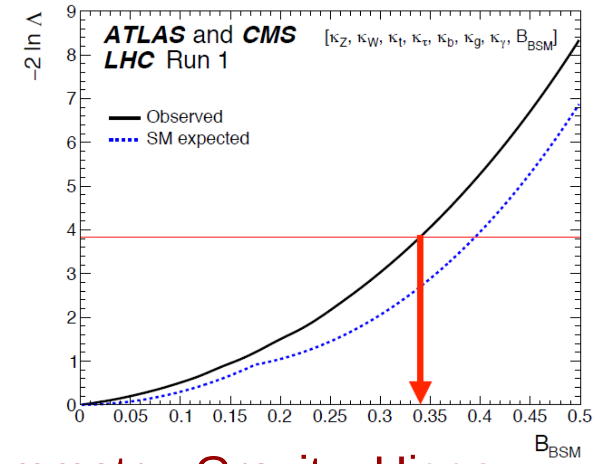
On behalf of the ATLAS Collaboration

Introduction and Motivation

arXiv:1207.7214



- Discovery of the Higgs (125 GeV) by ATLAS and CMS collaboration
  - great success of particle physics, especially Standard Model (SM)



- Hierarchy problem; Origin of dark matter, dark energy; Baryon Asymmetry; Gravity; Higgs br to Beyond Standard Model (BSM) particles of BR_{BSM} < 34% at 95% C.L.

!There is plenty of room for Higgs physics beyond the Standard Model.

Higgs BSM Searches

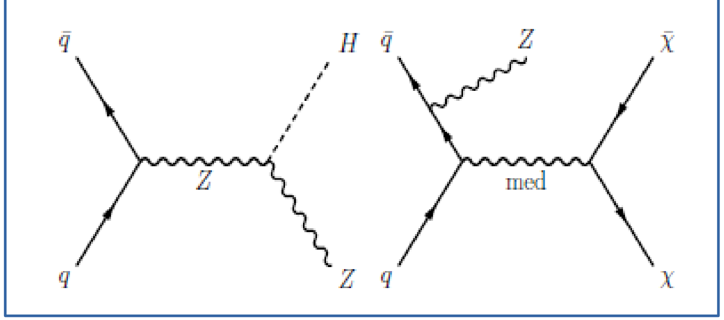
Deviations from the SM Higgs boson Properties (spin, couplings)

Additional Higgs-like scalars
-neutral or charged
-decays to SM particles or to H bosons
BSM Higgs decays and couplings
-new resonances
-long lived particles
-flavor violating couplings
-invisible decays

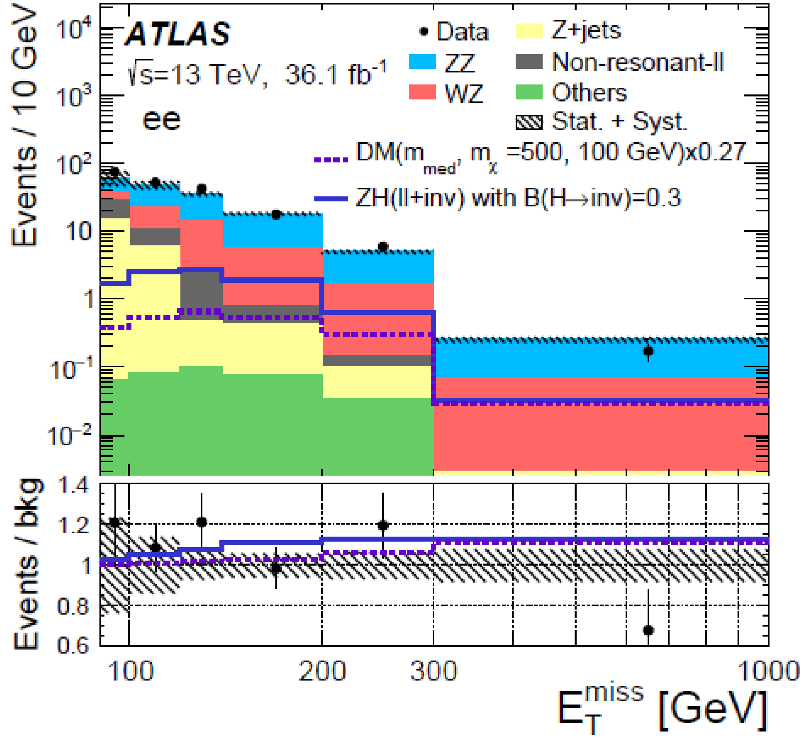
- Results presented use the full 2015+2016 (36.1 fb^{-1}) pp collision dataset at 13 TeV

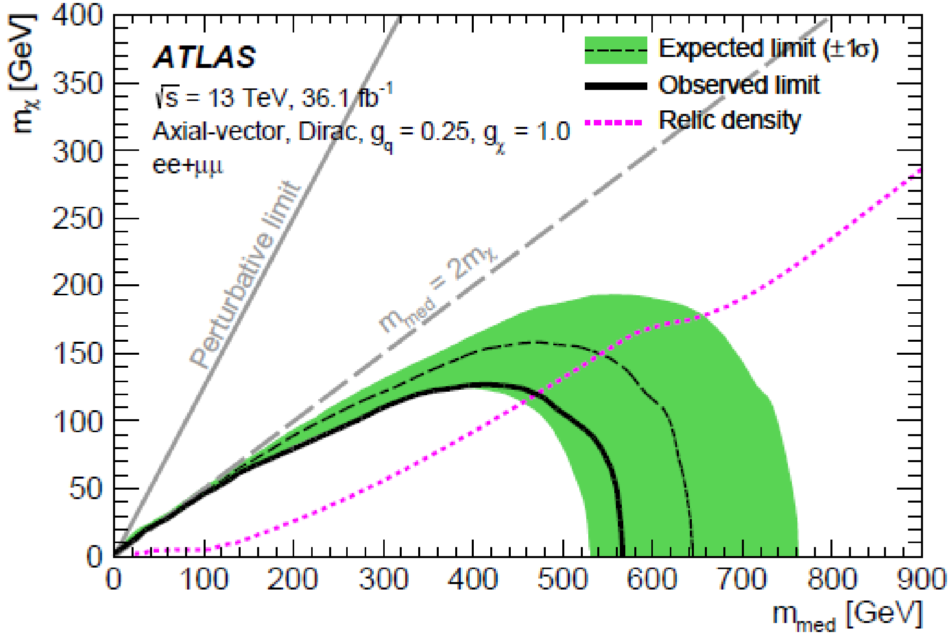
H → inv (arXiv:1708.09624)

- $B_{H\rightarrow inv}$ significantly above the SM value → strong indication for physics BSM, WIMPs.



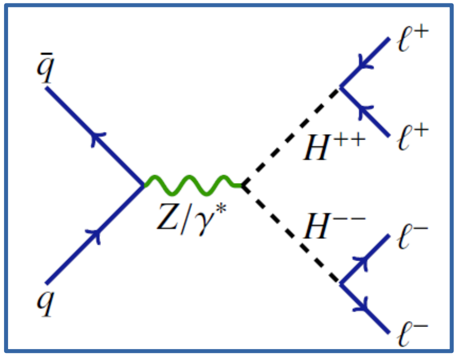
- The search focuses on ZH and WIMP pair production in a final state of $\ell\ell+E_T^{miss}$
  - pair of high-pT isolated e or m, large E_T^{miss} due to an invisible Higgs decay or a WIMP pair



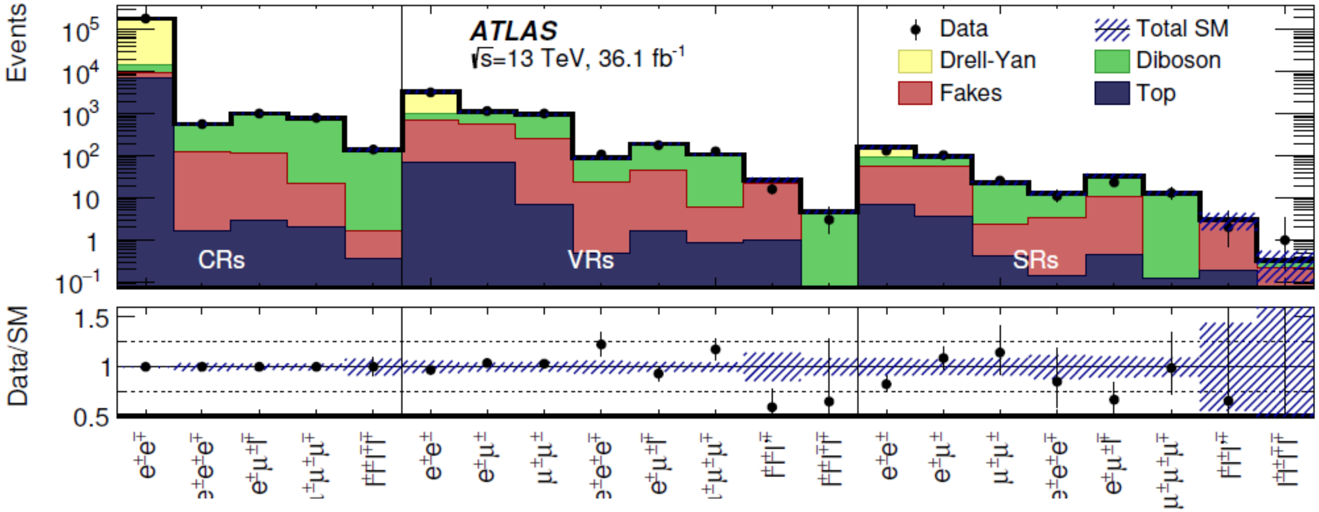


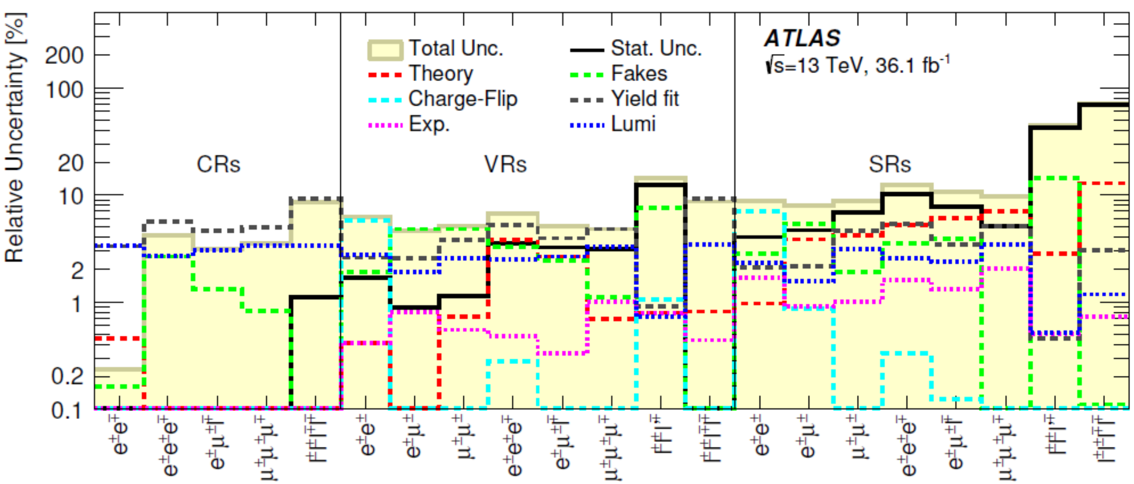
- Systematic uncertainties: evaluated for E_T^{miss} (used to constrain existence of new phenomena).
- No significant data excess above the expectation of the SM backgrounds
- m_{med} is excluded up to 560 GeV at the 95% CL for a light WIMP, WIMP mass m is excluded up to 130 GeV for m_{med} = 400 GeV.

$H^{\pm\pm} \to \ell^{\pm}\ \ell^{\pm}$ (arXiv:1710.09748)



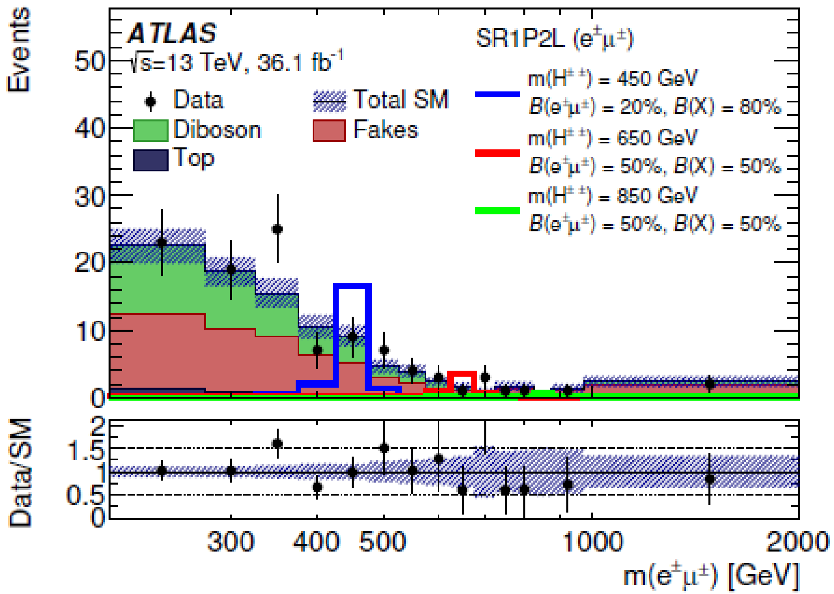
- Procedure: fitting the $\ell\ell$ mass spectra in several exclusive signal regions (two-, three-, and four-lepton further divided into unique flavour categories to increase the sensitivity).
  - \+ VR and CR defined using kinematic variables (pT, ΔM/M etc) and b-tagging

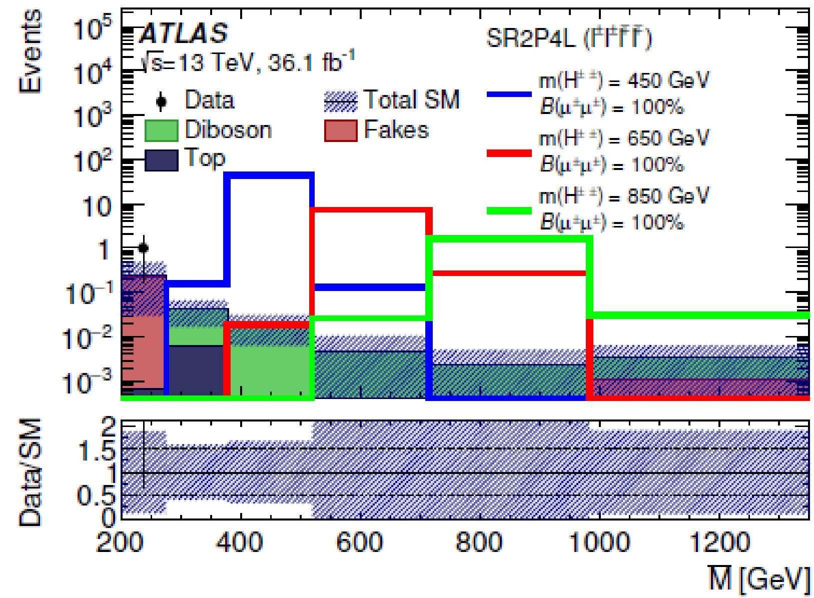


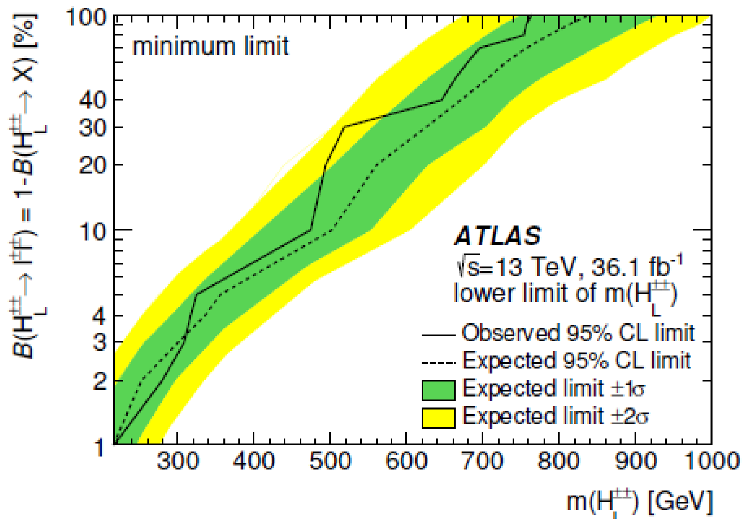


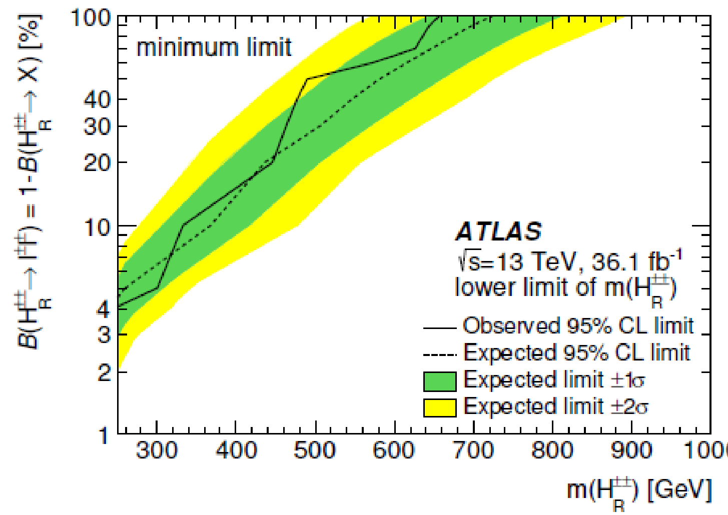
Backgrounds:

- Prompt; Electron charge misidentification (bremsstrahlung).
- Fake-lepton background is estimated using fake factor' method (data-driven approach).



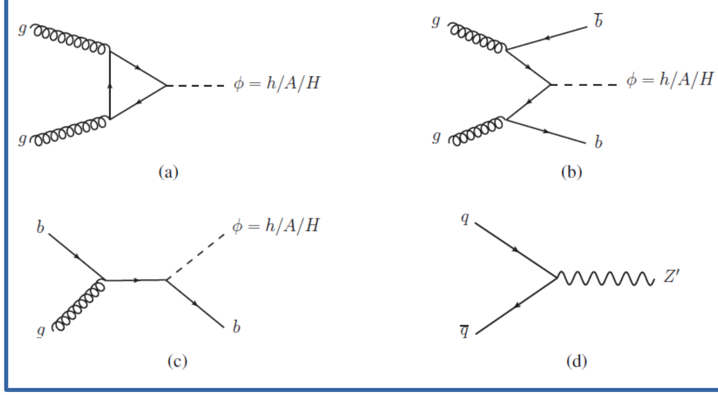






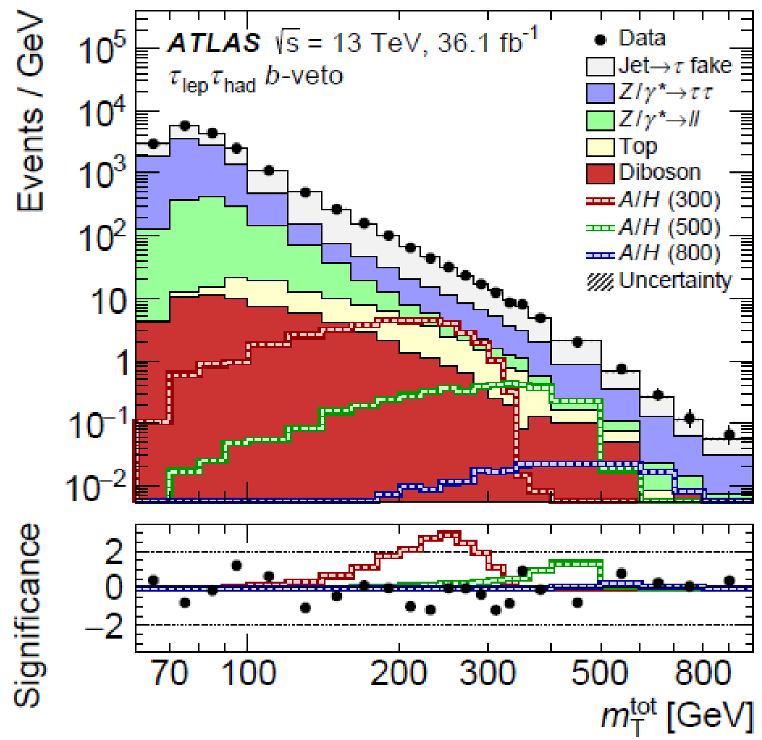
- No significant excess above the Standard Model prediction was found
  - 770-870 GeV $mH^{\pm\pm}_L$ for $B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = 100\%$ and >450 GeV for $B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) \geq 10\%$
  - 660-760 GeV $mH^{\pm\pm}_R$ for $B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = 100\%$ and >320 GeV for $B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) \geq 10\%$
- The observed limits are consistent with the expected limits.

h/A/H → ττ (arXiv:1709.07242)

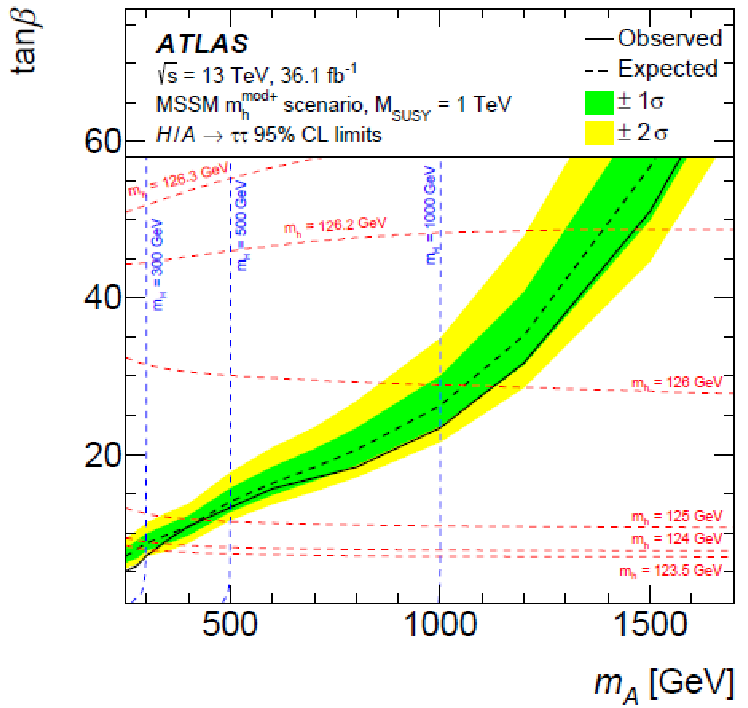


- Neutral MSSM Higgs bosons + high-mass Z' resonances in the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ decay
- Events categorization: b-tag /b-veto category (not used for the Z' search).
- **ττ** mass reconstruction: good separation S/B.
  - Reconstruction is challenging due to the presence of neutrinos from the τ_{lep}
  - Replaced by total transverse mass:

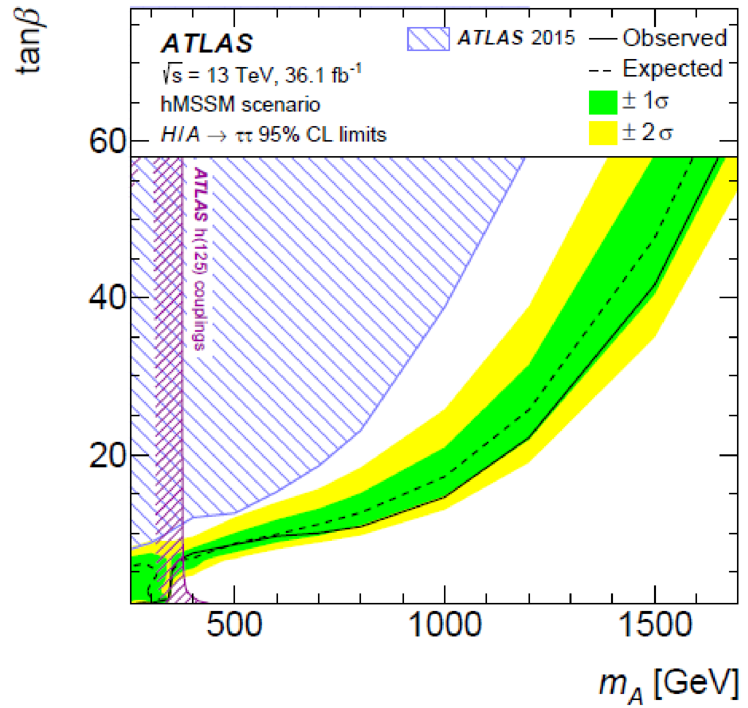
$$m_{\mathrm{T}}^{\mathrm{tot}} \equiv \sqrt{(p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T}}^{\tau_1} + \mathbf{p}_{\mathrm{T}}^{\tau_2} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$



- Background estimation
  - $\tau_{had}\tau_{had}$: dominant background multijet production, estimated using a data-driven technique; Z/γ* → ττ at high m_T^{tot} in the b-veto category, $t\bar{t}$ production in the b-tag category, + W(→ ℓν)+jets, single top-quark, diboson and Z/γ* → ℓℓ+jets, estimated using simulation.
  - $\tau_{lep}\tau_{had}$: $\tau_{had\text{-}vis}$ candidate originates from a jet, estimated using a data-driven technique.



(a) m_h^{mod+} scenario

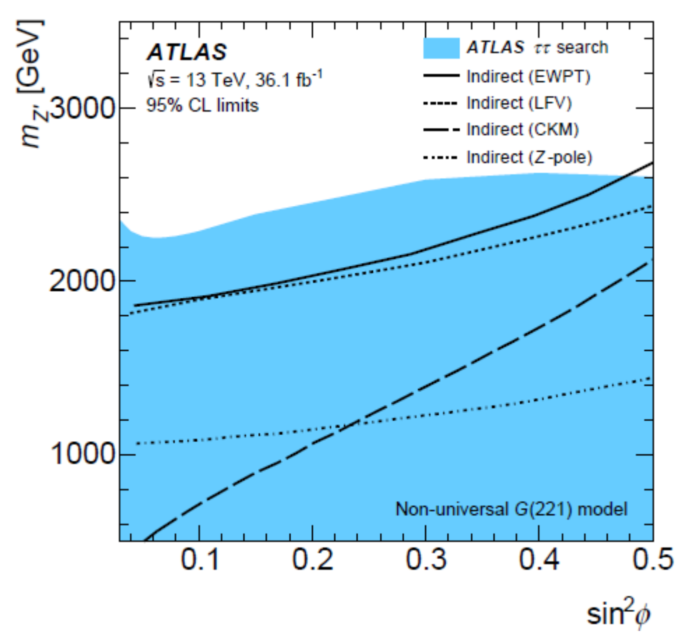


(b) hMSSM scenario

tanβ = ratio of the vacuum expectation values of the two Higgs doublets

non-universal G(221) model: SM SU(2) gauge group is split into one coupling to fermions of the first two generations and one coupling to third generation fermions.
Mixing between these groups described by $\sin^2\varphi$ ($\sin^2\varphi < 0.5$ corresponding to enhanced third generation couplings)

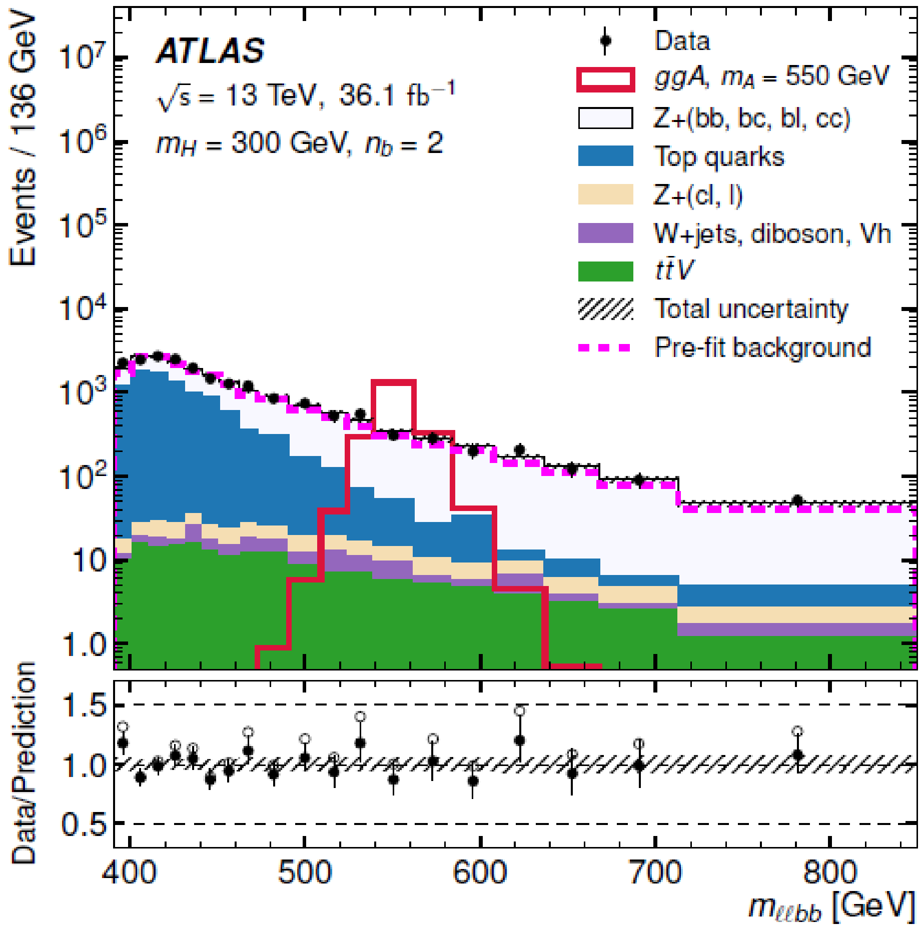
- No indication of an excess over the expected SM, upper limits σ at 95% CL:
  - 0.78–0.0058 pb for **ggF (b-associated) production (a)** of scalar bosons with masses of 0.2–2.25 TeV
  - 1.56–0.0072 pb for **Drell–Yan production of Z' bosons (d)** with masses of 0.2– 4 TeV.
- hMSSM scenario: *tanβ*> 1.0 for m_A = 0.25 TeV and *tanβ*> 42 for m_A = 1.5 TeV at 95% CL.
- mZ'_{NU} < 2.25–2.60 TeV excluded in the range 0.03 < $\sin^2\phi$ < 0.5 for non-universal G(221) model.

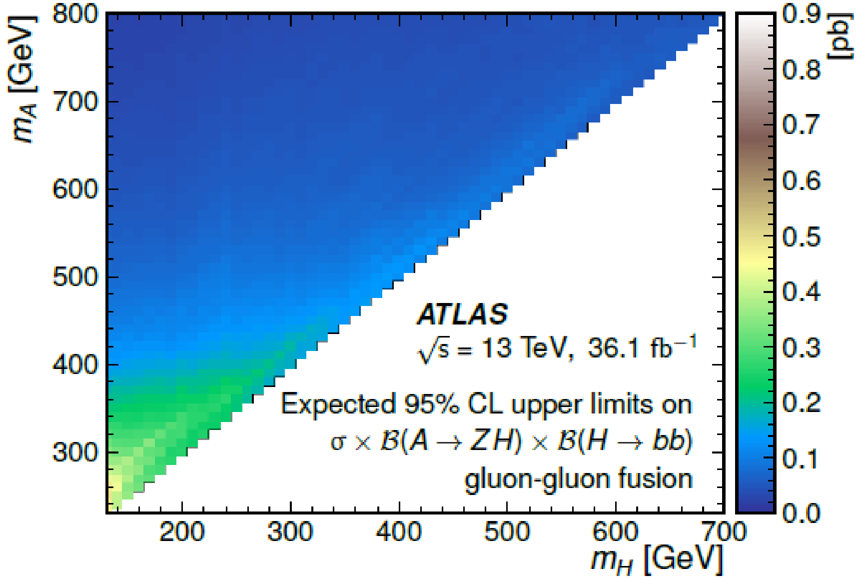


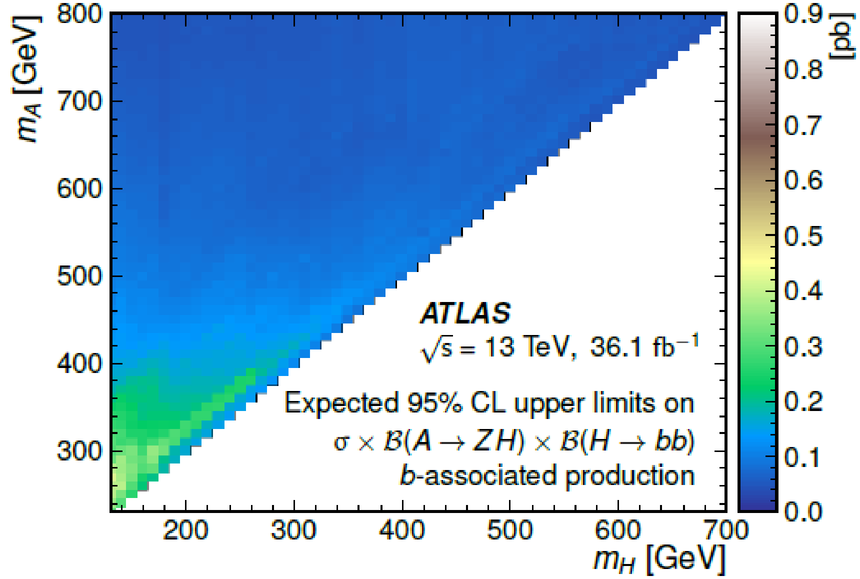
A → ZH → ℓℓbb (arXiv:1804.01126)

- Only Z → ℓℓ (e/μ) and H → bb, categorized by the presence of two or three b-tagged jets.
  - SR: use kinematic cuts on discriminating variables ($m_{\ell\ell}$, $E^t_{miss}/\sqrt{H_T}$ etc)
  - Top and Z+jets CR: constructed usng m_H and m_{bb}
- The results are interpreted in the context of the two-Higgs-doublet model.

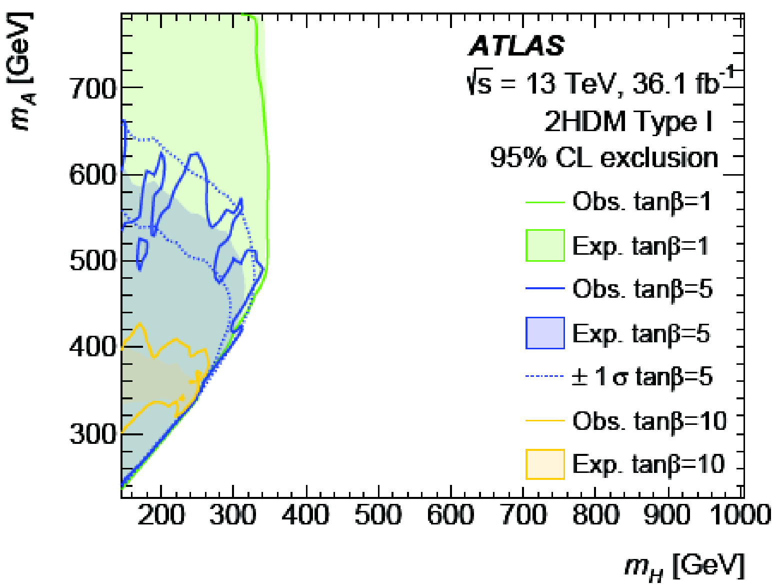
- The $m_{\ell\ell bb}$ distributions from different m_{bb} mass windows: scanned for potential excesses beyond the background expectations through signal-plus-background fits
  - steps of 10 GeV
  - m_A range 230–800 GeV
  - m_H range 130–700 GeV

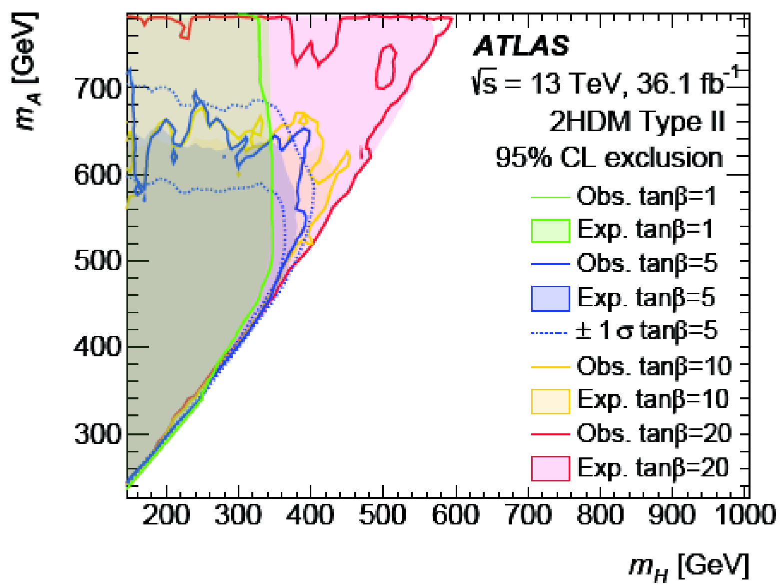






- No significant deviation from the SM.
- Constraints on the 2HDM.



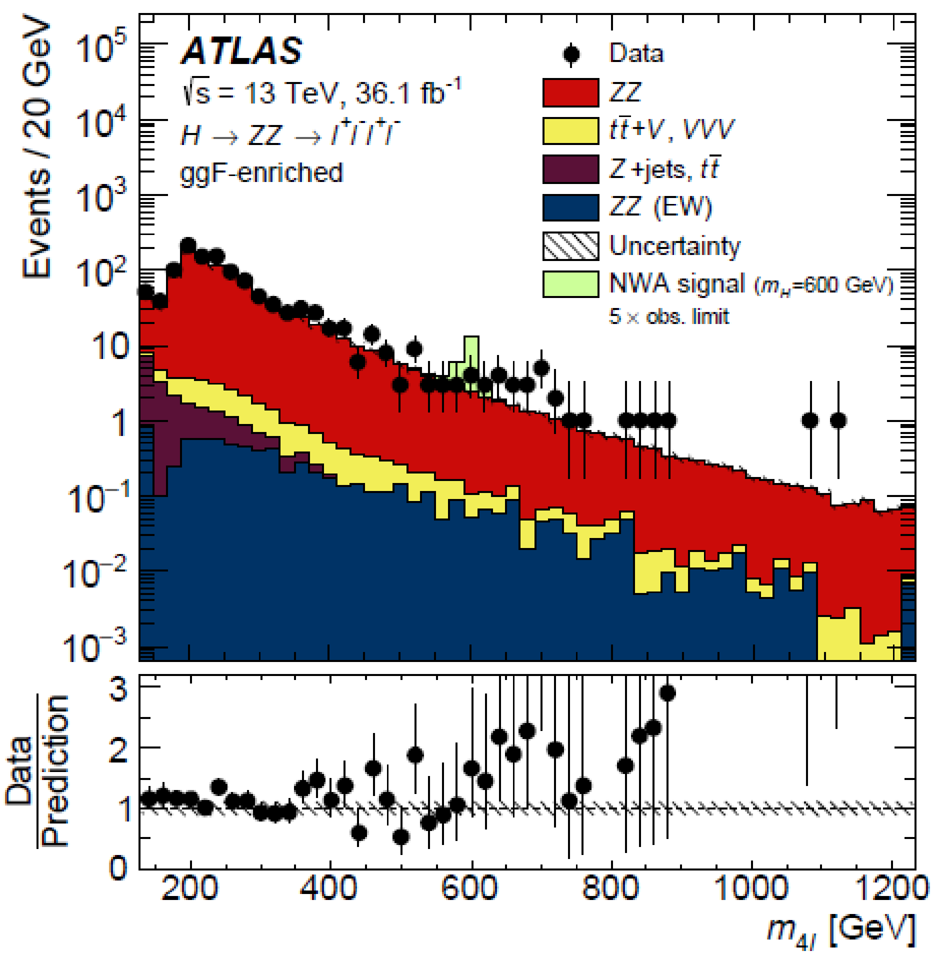


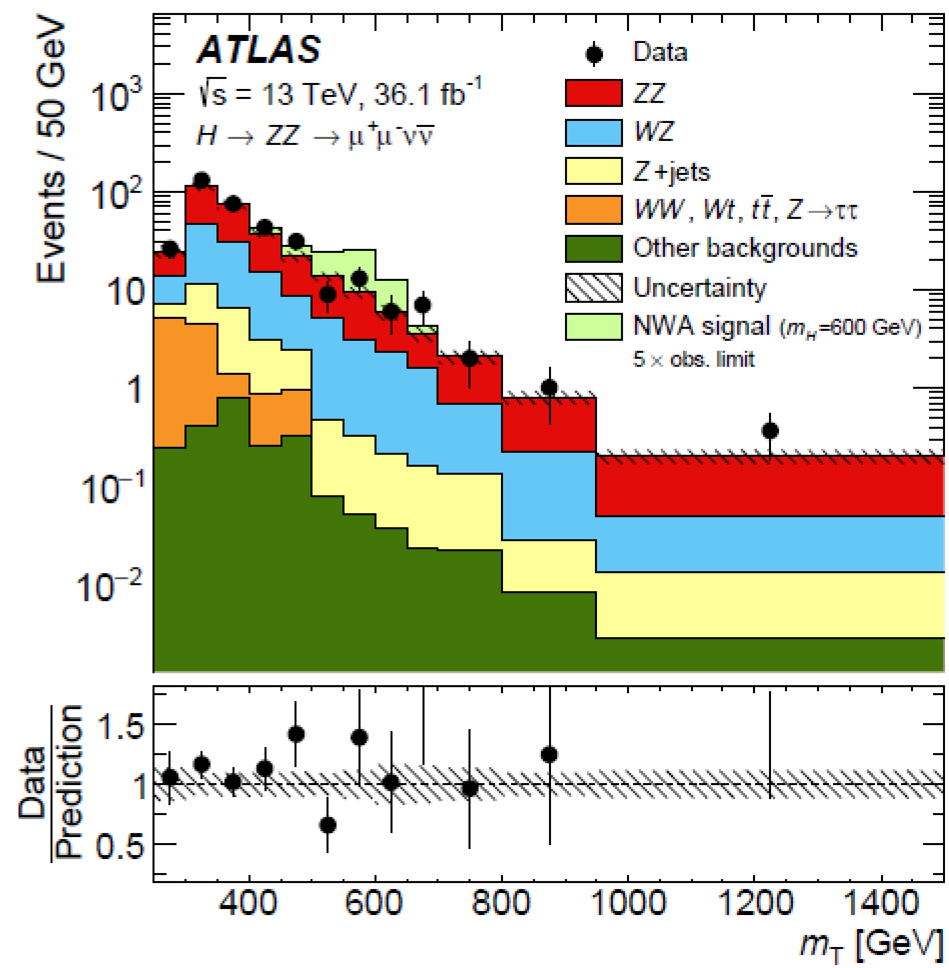
- Upper limits @ 95% CL for $\sigma \times B(A \to ZH) \times B(H \to bb)$ of 14–830 fb for ggF and 26–570 fb for b-associated production of a narrow A boson (130–700 GeV m_H, 230–800 GeV m_A).

ZZ resonances → $\ell^+\ell^-\ell^+\ell^-/\ell^+\ell^-\nu\bar{\nu}$ (arXiv:1712.06386)

- The results are interpreted in ggF and VBF production modes. Procedure: look for an excess in distributions of $m_{4\ell}$ ($\ell^+\ell^-\ell^+\ell^-$), m_T ($\ell^+\ell^-\nu\bar{\nu}$).

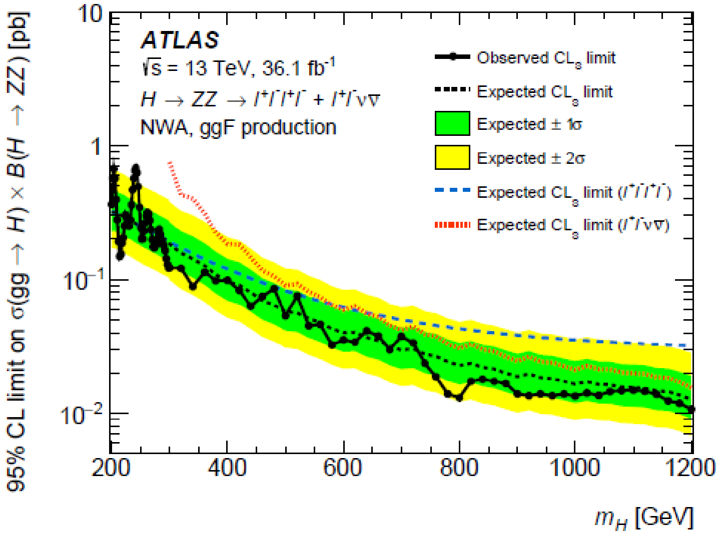
$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2},$$

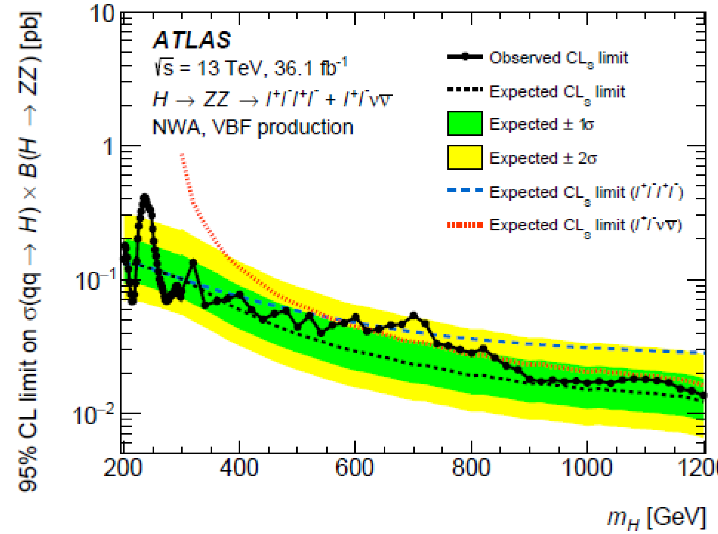




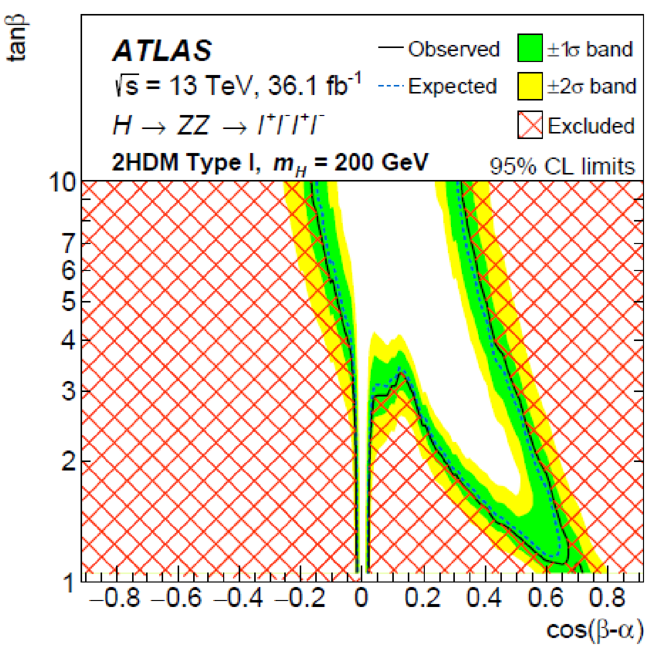
- Two excesses observed in the data for $m_{4\ell}$ 240 and 700 GeV (local significance of 3.6σ, global significance 2.2σ; using the NWA, 200 GeV< m_H < 1200 GeV using pseudo-experiments).
- Signal hypotheses: heavy Higgs boson (spin-0 resonance) under the narrow-width approximation (NWA); large-width assumption (LWA); the Randall–Sundrum (RS) model.

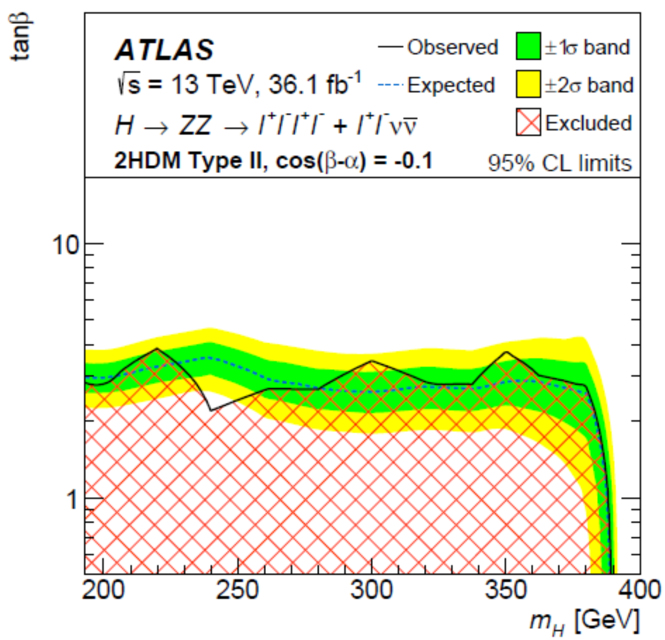
- 95% CL upper limits: 0.68 pb at m_H = 242 GeV to 11 fb at m_H = 1200 GeV for the ggF and from 0.41 pb at m_H = 236 GeV to 13 fb at m_H = 1200 GeV for the VBF.





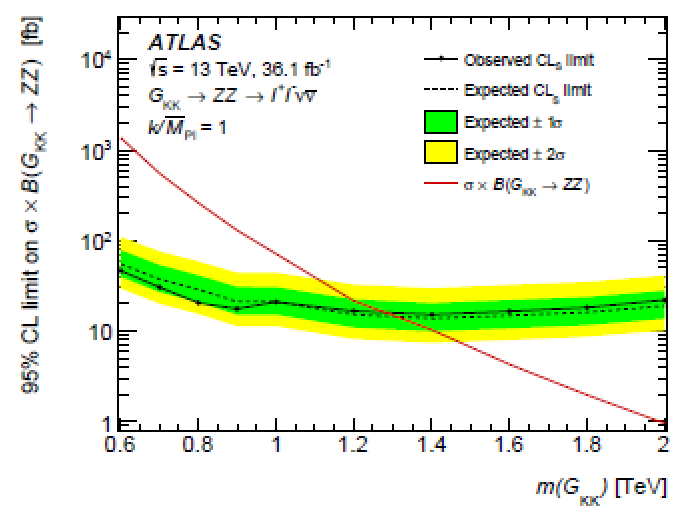
- The results: interpreted in the context of Type-I and Type-II two-Higgs-doublet models: tan β versus cos(β − α) (for m_H = 200 GeV) and tan β versus m_H planes.





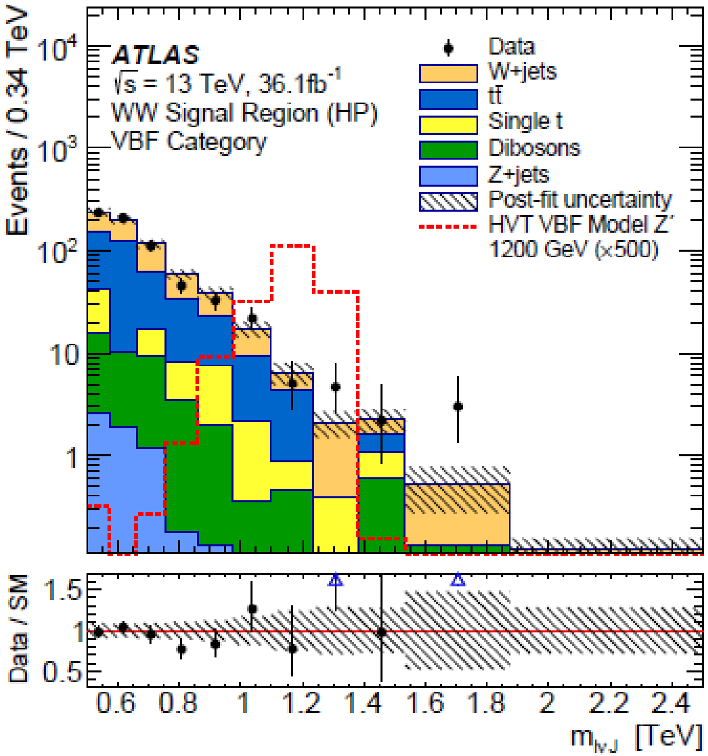
α: mixing angle between the two CP-even Higgs bosons

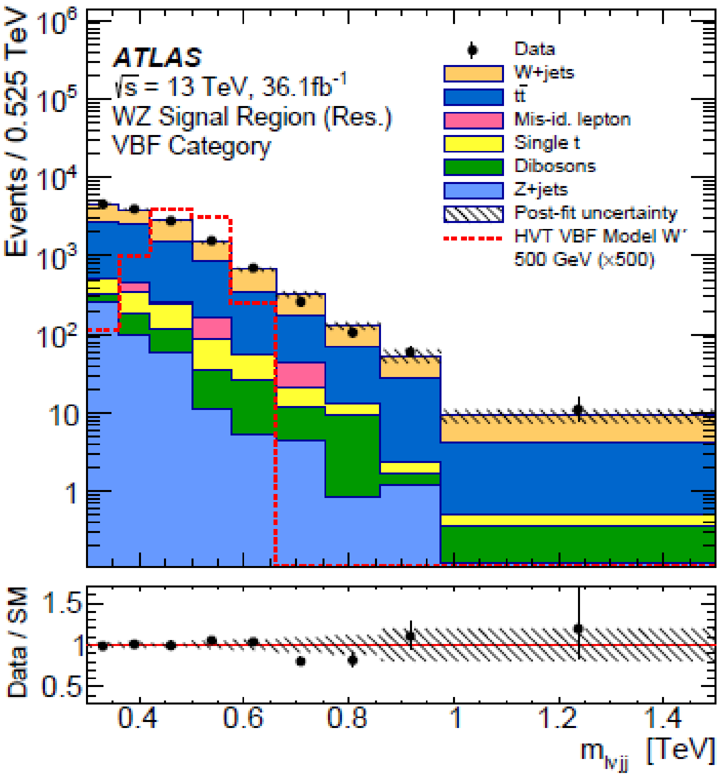
- Randall–Sundrum model with one warped extra dimension a graviton excitation spin-2 resonance with $m(G_{KK})$ < 1300 GeV is excluded at 95% CL.



WW/WZ→$\ell\ell$qq (arXiv:1710.07235)

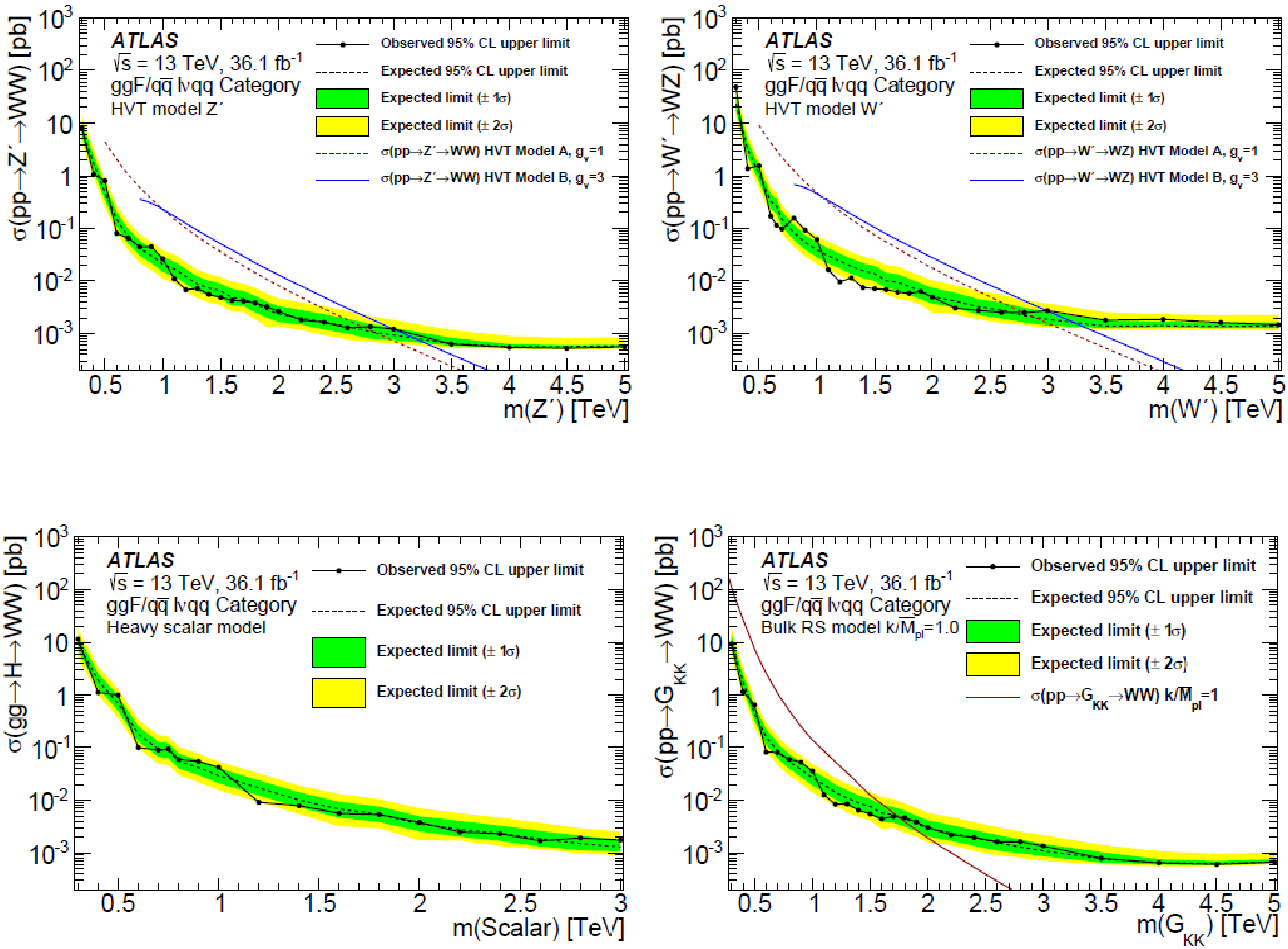
- Charged or neutral resonance (300-5000 GeV) → WZ or WW (W →lept, W=Z boson (V) → had); m($_{WV}$), is examined for localized excesses over the expected SM background.
  - VBF and ggF/$q\bar{q}$ categories separately
- The strategy for identification of resonances:
  - High-mass resonances, the opening angles between the quarks from V boson decays are small and both quarks can be identified as a single jet →$\ell\nu$J.
  - Low-mass resonances: resolved analysis → $\ell\nu$j j.





- Background estimation: Dominant: W+jets and $t\bar{t}$ events; + multijet production

- Signal models: heavy vector triplet (HVT) parameterization, bulk Randall–Sundrum (RS)



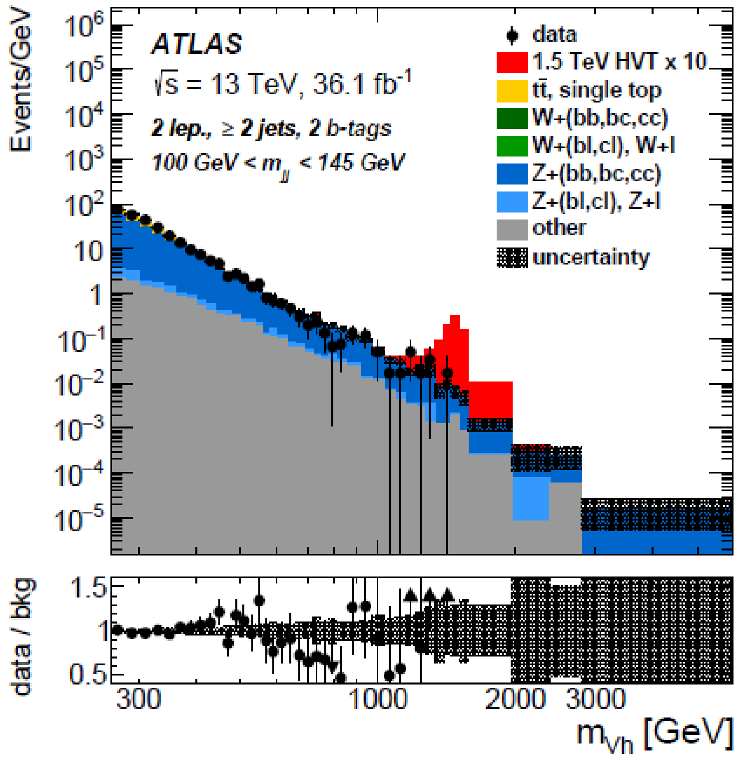
- Data are compatible with the SM
  - Z' → 2730-3000 GeV are excluded @ 95% CL in HVT parametrization
  - W' → 2800-2990 GeV.
- RSGKK signals with k= M_Pl = 1.0 produced via ggF are excluded at 95% CL below 1750 GeV

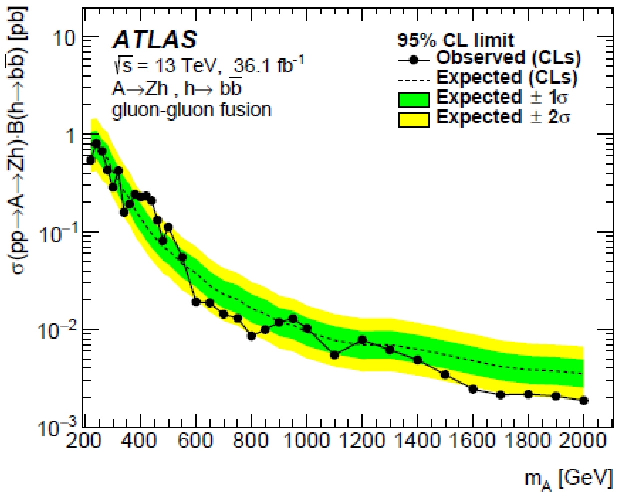
$W' \to W^{\pm}h \to \ell^{\pm}\nu b\bar{b}$; $Z'/A \to Zh \to \ell^{+}\ell^{-}b\bar{b}$; $Z'/A \to Zh \to \nu\bar{\nu}b\bar{b}$ (arXiv:1712.06518)

- The search performed by looking for a localised excess in the distribution of the reconstructed mass, the mass range : 220 GeV to 5 TeV
  - low p_T → decay products of the Higgs boson reconstructed as individual jets.
  - high p_T → decay products merge, reconstructed as a single jet.
- Two benchmark models are used in this analysis:
  - Model A, the branching fractions to fermions and gauge bosons are comparable
  - Model B, fermionic couplings suppressed, dynamical models (ex minimal composite Higgs)

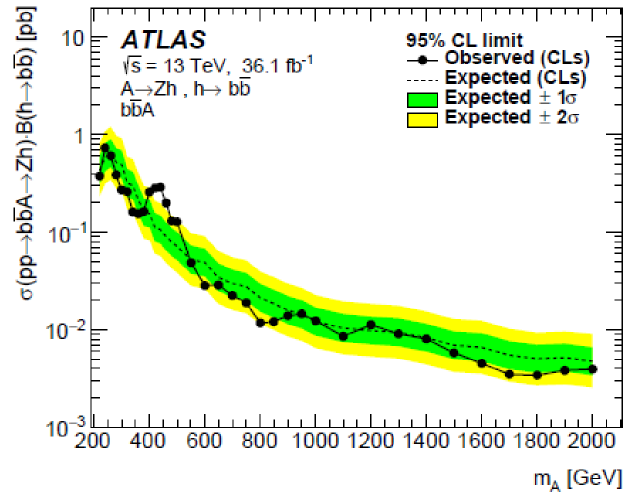
Background estimation

- 0-lepton: dominant background Z+jets and $t\bar{t}$ events; + W+jets.
- 1-lepton: $t\bar{t}$, single-top-quark and W+jets production.
- 2-lepton: Z+jets; + $t\bar{t}$ background.



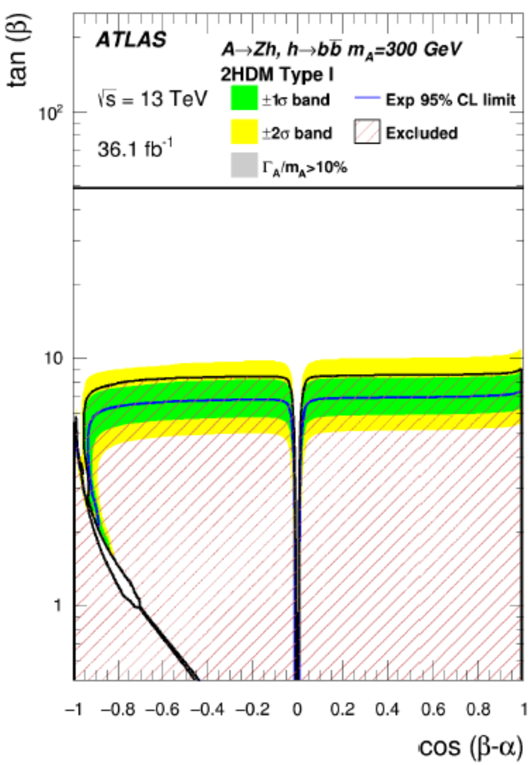


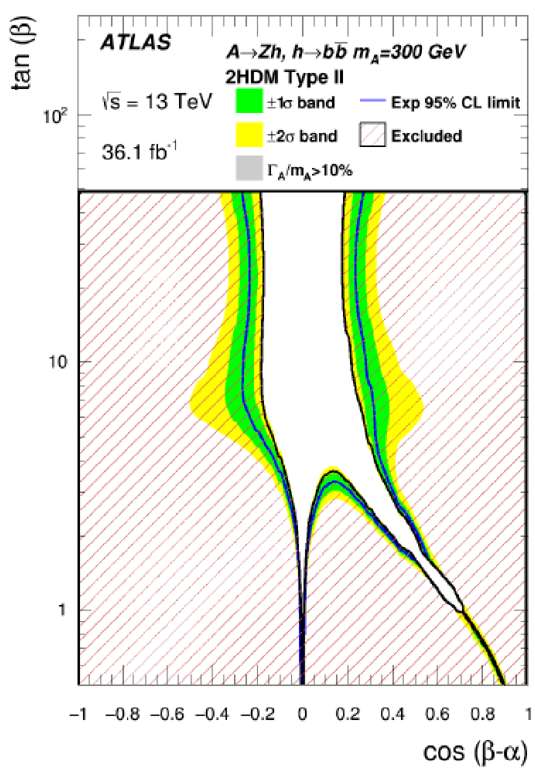
(a) Pure gluon–gluon fusion production



(b) Pure b-quark associated production

- No significant excess observed above the SM, upper limits are set.





- $m_{W'}$ < 2.67 TeV (2.82 TeV) and $m_{Z'}$ < 2.65 TeV (2.83 TeV) excluded for the benchmark HVT Model A (Model B); the combined HVT: 2.80 TeV (2.93 TeV).

α: mixing angle between the two CP-even Higgs bosons

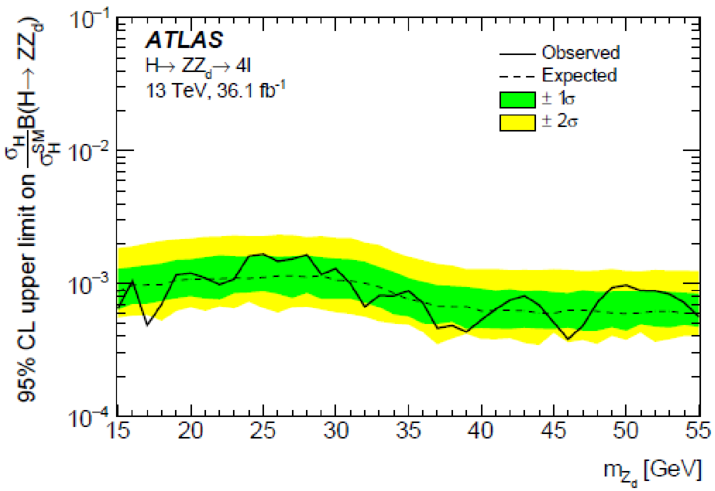
Conclusion and Future Prospects

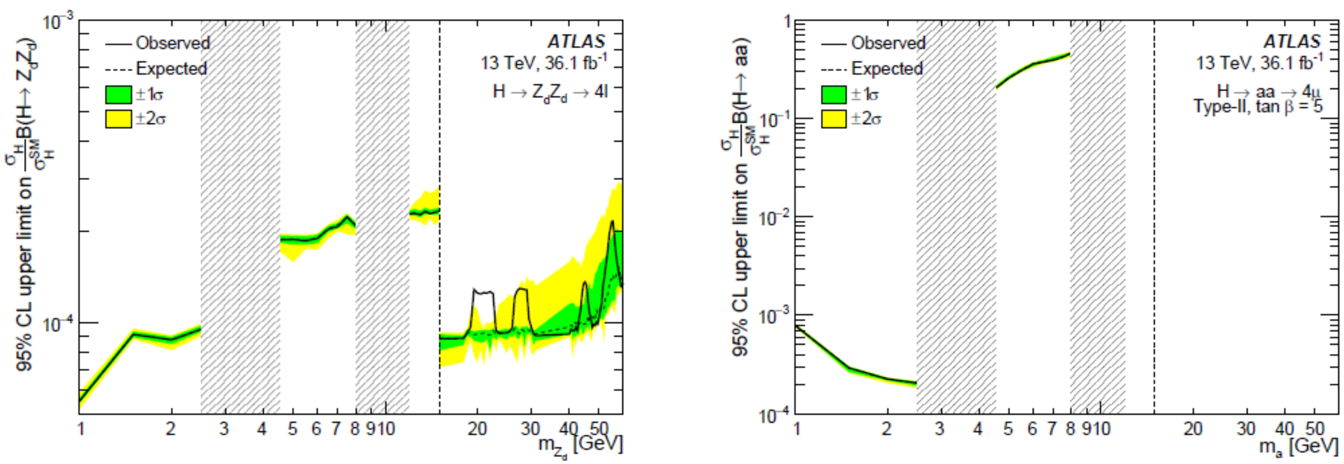
- ATLAS is very active in searching for BSM phenomena in the Higgs sector: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- No sign of additional Higgs boson seen in the LHC data.
- However, exclusion limits continue to improve and limit model phase space.
- Hope for the HBSM evidence in Run II (Total integrated luminosity for Run II ~ 150 fb^{-1}), and beyond at the HL-LHC (3000 fb^{-1}).
- More about non-Standard Model decays of the Higgs boson → Elliot Reynolds talk

Backup Slides

H → ZX/XX → 4ℓ (arXiv:1802.03388)

- Z = SM Z boson, X = possible new vector boson Z_d or a new pseudoscalar boson a; same-flavour decays of the new particle to pairs of e and μ are considered.
- Benchmark models that predict exotic decays to light beyond-the-Standard-Model (BSM) bosons:
  - higher mass range: the SM is extended with a dark-sector U(1) group ($U(1)_d$) → Z_d.
  - lower mass range: two Higgs doublets + additional singlet scalar field (2HDM+S) → a.



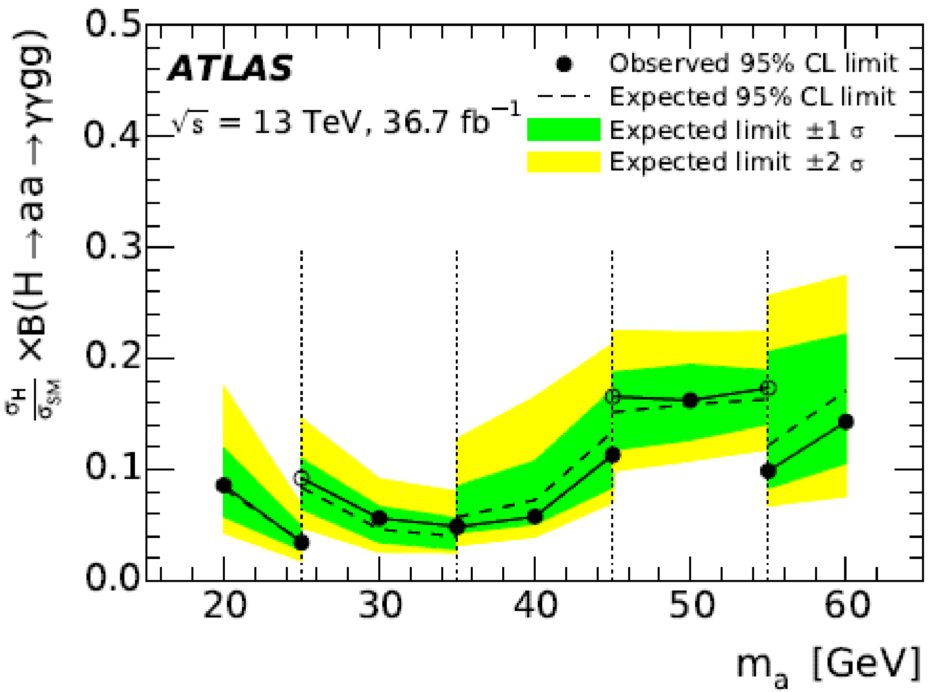


(a) $H \to Z_d Z_d$ (b) $H \to aa$

- The data are found to be globally consistent with SM background predictions.
- Upper limits H → ZZ_d, Z_dZ_d, and aa: $B(H\to ZZ_d) \approx 0.1\%$, $B(H\to Z_dZ_d) \approx 0.01\%$, and $B(H\to aa) \approx 1\%$ respectively (depending on mass range).

$H \rightarrow aa \rightarrow \gamma\gamma jj$ final state (arXiv:1803.11145)

- $20 < m_a < 60$ GeV + additional jet requirements to enhance VBF (excellent for probing fermion-suppressed coupling models).
- Background: $\gamma\gamma$+multi-jet (originating from isolated EM radiation or from jets). A data-driven estimation based on two-dimensional sidebands is used to predict the background yields.



- $H \rightarrow \gamma\gamma jj$ more sensitive to photon couplings with the new physics sector;
- $H \rightarrow \gamma\gamma\gamma\gamma$ more sensitive to scenarios with enhanced photon couplings.

- No significant excess of data is observed relative to the SM predictions.
- An upper limit of the production cross-section for pp → H x $B(H \rightarrow aa \rightarrow \gamma\gamma gg)$: 3.1 - 9.0 pb.

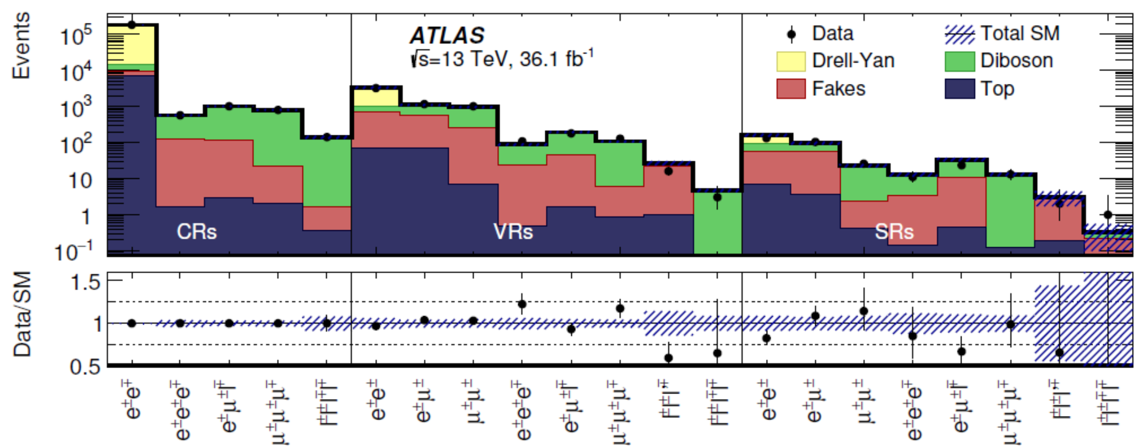
Search for doubly charged Higgs boson production in multi-lepton final states (link)

Physics process	Event generator	ME PDF set	Cross-section normalisation	Parton shower	Parton shower tune
Signal					
$H^{\pm\pm}$	Pythia 8.186 [34]	NNPDF2.3NLO [35]	NLO (see Table 2)	Pythia 8.186	A14 [36]
Drell–Yan					
$Z/\gamma^* \to ee/\tau\tau$	Powheg-Box v2 [37–39]	CT10 [40]	NNLO [41]	Pythia 8.186	AZNLO [42]
Top					
$t\bar{t}$	Powheg-Box v2	NNPDF3.0NLO [43]	NNLO [44]	Pythia 8.186	A14
Single top	Powheg-Box v2	CT10	NLO [45]	Pythia 6.428 [46]	Perugia 2012 [47]
$t\bar{t}W$, $t\bar{t}Z/\gamma^*$	MG5_aMC@NLO 2.2.2 [48]	NNPDF2.3NLO	NLO [49]	Pythia 8.186	A14
$t\bar{t}H$	MG5_aMC@NLO 2.3.2	NNPDF2.3NLO	NLO [49]	Pythia 8.186	A14
Diboson					
ZZ, WZ	Sherpa 2.2.1 [50]	NNPDF3.0NLO	NLO	Sherpa	Sherpa default
Other (inc. $W^\pm W^\pm$)	Sherpa 2.1.1	CT10	NLO	Sherpa	Sherpa default
Diboson Sys.					
ZZ, WZ	Powheg-Box v2	CT10NLO	NLO	Pythia 8.186	AZNLO

Selection for fake-enriched regions	
Muon channel	Electron channel
Single-muon trigger	Single-electron trigger
b-jet veto	b-jet veto
One muon and one jet	One electron
$p_T(\text{jet}) > 35$ GeV	Number of tight electrons < 2
$\Delta\phi(\mu, \text{jet}) > 2.7$	$m(ee) \notin [71.2, 111.2]$ GeV
$E_T^{\text{miss}} < 40$ GeV	$E_T^{\text{miss}} < 25$ GeV

- **Prompt light leptons are defined as leptons originating from Z, W, and H boson decays or leptons from decays if the has a prompt source (e.g. Z → ττ). MC events containing at least one non-prompt or fake selected tight or loose lepton are discarded to avoid an overlap with the data-driven fake background estimation.**
- **Electron charge misidentification caused predominantly by bremsstrahlung.**
- **The fake-lepton background is estimated with a data-driven approach, the so-called 'fake factor' method. The b-jet veto significantly reduces fake leptons from heavyflavour decays. The fake factor method provides an estimation of events with fake leptons in analysis regions by extrapolating the yields from the so-called 'side-band regions'. For each analysis region a corresponding side-band region is defined. It requires exactly the same selection and lepton multiplicity except that at least one lepton must fail to satisfy the tight identification criteria. The ratio of tight to loose leptons is measured in dedicated 'fake-enriched regions'. It is determined as a function of lepton flavour, pT, and , and referred to as the 'fake factor' (F(pT; ; flavour)).**

Region / Channel	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^\pm e^\mp$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$	
Mixed channel	-	$e^\pm \mu^\pm \ell^\mp$	$\ell^\pm \ell^\pm \ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm \ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm \ell^\mp \ell^\mp$
Muon channel	-	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$	
$m(e^\pm e^\pm)$ [GeV]	$[130, 2000]$	$[90, 200)$		$[130, 200)$	$[90, 200)$		$[200, \infty)$	$[200, \infty)$	
$m(\ell^\pm \ell^\pm)$ [GeV]	-	$[90, 200)$	$[60, 150)$	$[130, 200)$	$[90, 200)$	$[150, 200)$	$[200, \infty)$	$[200, \infty)$	$[200, \infty)$
$m(\mu^\pm \mu^\pm)$ [GeV]	-	$[60, 200)$		$[60, 200)$	$[60, 200)$		$[200, \infty)$	$[200, \infty)$	
b-jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-	-	✓	✓
$\Delta R(\ell^\pm, \ell^\pm) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_T(\ell^\pm \ell^\pm) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum \lvert p_T(\ell) \rvert > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M/\bar{M}$ requirement	-	-	-	-	-	-	-	-	✓



Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson (link)

Table 1: Event selection criteria in the $\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ search.

	Selection criteria
Two leptons	Two opposite-sign leptons, leading (subleading) $p_{\mathrm{T}} > 30$ (20) GeV
Third lepton veto	Veto events if any additional lepton with $p_{\mathrm{T}} > 7$ GeV
$m_{\ell\ell}$	$76 < m_{\ell\ell} < 106$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}} > 0.6$
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$	$\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) > 2.7$ radians
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} < 1.8$
Fractional p_{T} difference	$\left\lvert p_{\mathrm{T}}^{\ell\ell} - p_{\mathrm{T}}^{\mathrm{miss,jets}} \right\rvert / p_{\mathrm{T}}^{\ell\ell} < 0.2$
b-jets veto	$N(b\text{-jets}) = 0$ with b-jet $p_{\mathrm{T}} > 20$ GeV and $\lvert\eta\rvert < 2.5$

Final State	ee	$\mu\mu$
Observed Data	437	497
Signal		
$ZH \to \ell\ell + \mathrm{inv}$ ($B_{H\to\mathrm{inv}} = 30\%$)	$32 \pm 1 \pm 3$	$34 \pm 1 \pm 3$
DM ($m_{\mathrm{med}} = 500$ GeV, $m_\chi = 100$ GeV) $\times 0.27$	$10.8 \pm 0.3 \pm 0.8$	$11.1 \pm 0.3 \pm 0.8$
Backgrounds		
$qqZZ$	$212 \pm 3 \pm 15$	$221 \pm 3 \pm 17$
$ggZZ$	$18.9 \pm 0.3 \pm 11.2$	$19.3 \pm 0.3 \pm 11.4$
WZ	$106 \pm 2 \pm 6$	$113 \pm 3 \pm 5$
Z + jets	$30 \pm 1 \pm 28$	$37 \pm 1 \pm 19$
Non-resonant-$\ell\ell$	$30 \pm 4 \pm 2$	$33 \pm 4 \pm 2$
Others	$1.4 \pm 0.1 \pm 0.2$	$2.5 \pm 2.0 \pm 0.8$
Total Background	$399 \pm 6 \pm 34$	$426 \pm 6 \pm 28$

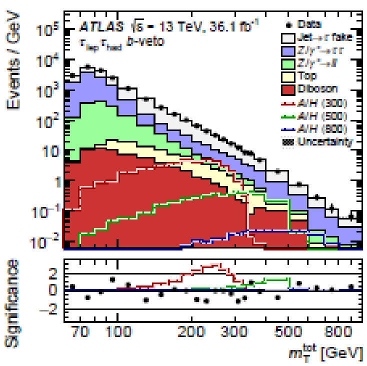
- Theoretical uncertainties: PDF choice, the perturbative calculation, and the parton shower modelling.
- Experimental uncertainties: luminosity, the momentum scale and resolution of leptons and jets, lepton reconstruction, selection eff.

Search for additional heavy neutral Higgs and gauge bosons in the ditau final state (link)

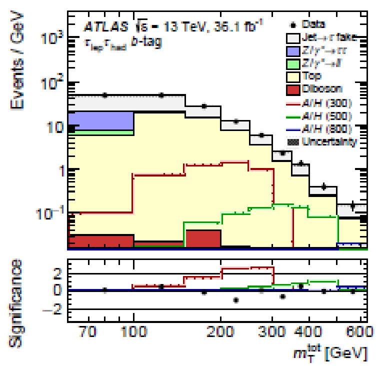
The dominant background contribution in the τhadτhad channel is from multijet production, which is estimated using a data-driven technique. Other important background contributions come from Z/γ* →ττ production at high m^{tot}_{T} in the b-veto category, tt production in the b-tag category, and to a lesser extent W(→lν) +jets, single top-quark, diboson and Z/γ*(→ll)+jets production. These contributions are estimated using simulation.
The dominant background contribution in the τlepτhad channel arises from processes where the τhad-vis candidate originates from a jet. This contribution is estimated using a data-driven technique.

Table 1: Definition of signal, control and fakes regions used in the $\tau_{had}\tau_{had}$ channel. The symbol τ_1 (τ_2) represents the leading (sub-leading) $\tau_{had\text{-}vis}$ candidate.

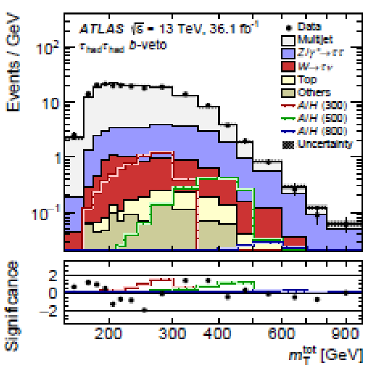
Region	Selection
SR	τ_1 (trigger, medium), τ_2 (loose), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_T^{\tau_1}, \mathbf{p}_T^{\tau_2})\rvert > 2.7$
CR-1	Pass SR except: τ_2 (fail loose)
DJ-FR	jet trigger, τ_1+τ_2 (no identification), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_T^{\tau_1}, \mathbf{p}_T^{\tau_2})\rvert > 2.7$, $p_T^{\tau_2}/p_T^{\tau_1} > 0.3$
W-FR	μ (trigger, isolated), τ_1 (no identification), $\lvert\Delta\phi(\mathbf{p}_T^{\mu}, \mathbf{p}_T^{\tau_1})\rvert > 2.4$, $m_T(\mathbf{p}_T^{\mu}, \mathbf{E}_T^{miss}) > 40$ GeV, b-veto category only
T-FR	Pass W-FR except: b-tag category only



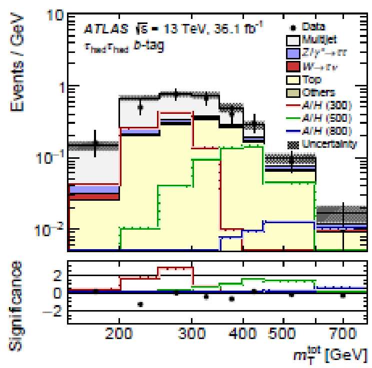
(a) $\tau_{lep}\tau_{had}$ b-veto category



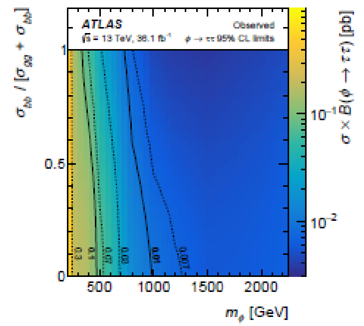
(b) $\tau_{lep}\tau_{had}$ b-tag category



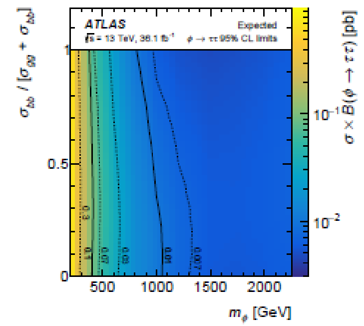
(c) $\tau_{had}\tau_{had}$ b-veto category



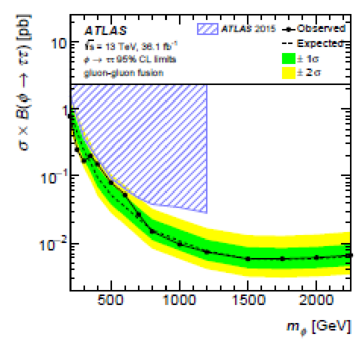
(d) $\tau_{had}\tau_{had}$ b-tag category



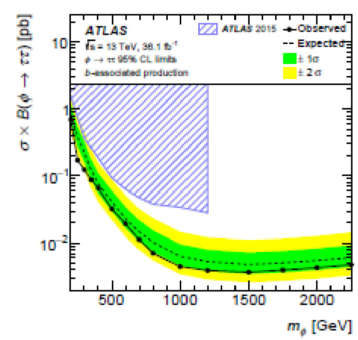
(a) Observed



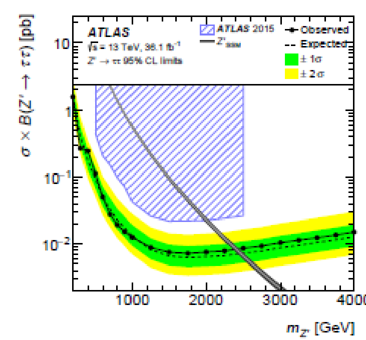
(b) Expected



(a) $\phi \to \tau\tau$ (gluon–gluon fusion production)



(b) $\phi \to \tau\tau$ (b-associated production)



(c) $Z' \to \tau\tau$

Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell$bb (**link**)

Table 1: Summary of the event selection for signal and control regions.

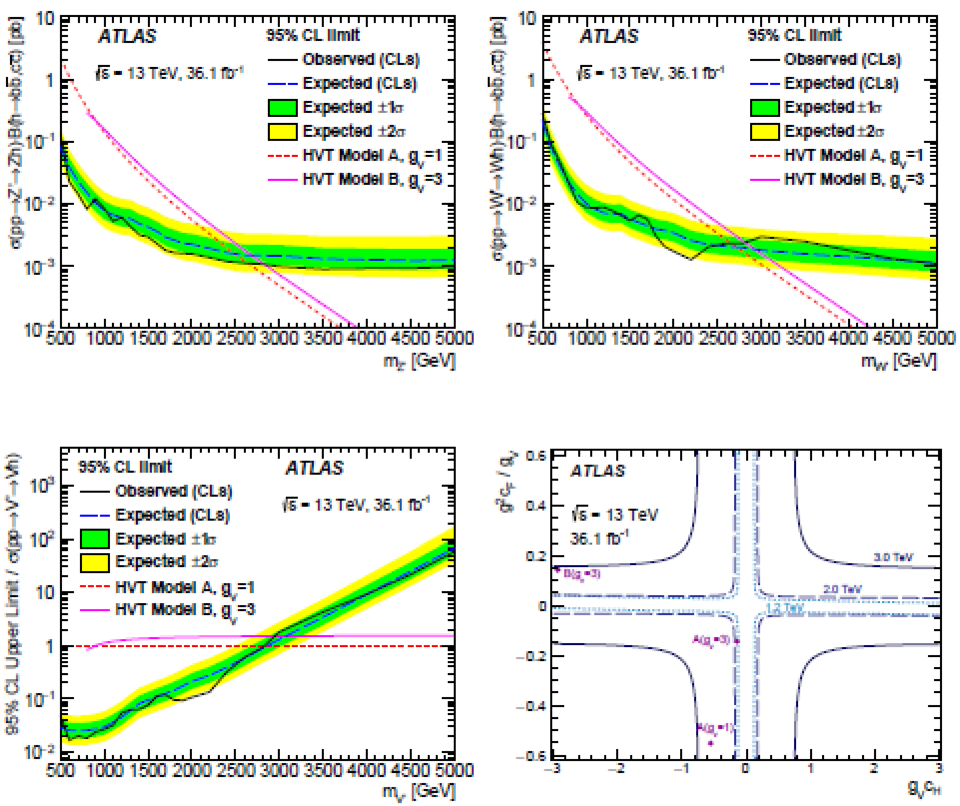
Single-electron or single-muon trigger		
Exactly 2 leptons (e or μ) (p_T > 7 GeV) with the leading one having p_T > 27 GeV		
Opposite electric charge for $\mu\mu$ or $e\mu$ pairs; 80 GeV < $m_{\ell\ell}$, $m_{e\mu}$ < 100 GeV, $\ell = e, \mu$		
At least 2 b-jets (p_T > 20 GeV) with one of them having p_T > 45 GeV		
$E_T^{miss}/\sqrt{H_T} < 3.5$ GeV$^{1/2}$, $\sqrt{\Sigma p_T^2}/m_{\ell\ell bb} > 0.4$		
	$n_b = 2$ category	$n_b \geq 3$ category
	Exactly 2 b-tagged jets	At least 3 b-tagged jets
Signal region	ee or $\mu\mu$ pair $0.85 \cdot m_H - 20$ GeV $< m_{bb} < m_H + 20$ GeV	ee or $\mu\mu$ pair $0.85 \cdot m_H - 25$ GeV $< m_{bb} < m_H + 50$ GeV
Top control region	$e\mu$ pair $0.85 \cdot m_H - 20$ GeV $< m_{bb} < m_H + 20$ GeV	$e\mu$ pair $0.85 \cdot m_H - 25$ GeV $< m_{bb} < m_H + 50$ GeV
Z+jets control region	ee or $\mu\mu$ pair $m_{bb} < 0.85 \cdot m_H - 20$ GeV or $m_{bb} > m_H + 20$ GeV	ee or $\mu\mu$ pair $m_{bb} < 0.85 \cdot m_H - 25$ GeV or $m_{bb} > m_H + 50$ GeV

Table 2: The effect of the most important sources of uncertainty on the signal-strength parameter at two example mass points of $(m_A, m_H) = (230, 130)$ GeV and $(m_A, m_H) = (700, 200)$ GeV for both the gluon–gluon fusion and b-associated production of a narrow-width A boson. The signal cross-sections are taken to be the expected median upper limits (see Section 8). JES and JER stand for jet energy scale and jet energy resolution, 'Sim. stat.' for simulation statistics, and 'Bkg. model.' for the background modelling.

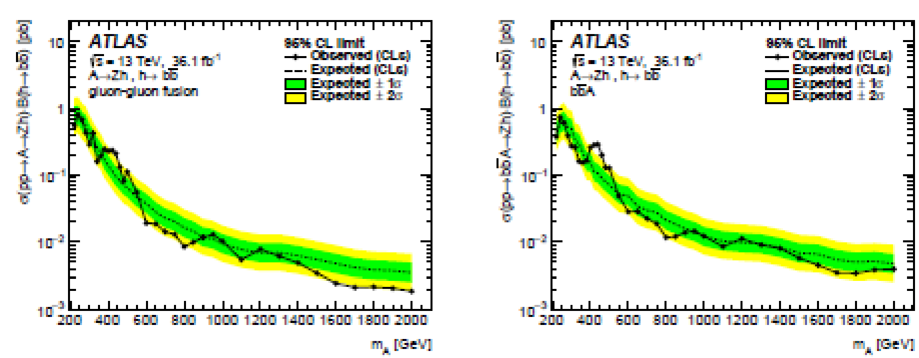
Gluon–gluon fusion production				b-associated production			
(230, 130) GeV		(700, 200) GeV		(230, 130) GeV		(700, 200) GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
Data stat.	32	Data stat.	49	Data stat.	35	Data stat.	46
Total syst.	36	Total syst.	22	Total syst.	38	Total syst.	26
Sim. stat.	22	Sim. stat.	10	Sim. stat.	26	Sim. stat.	12
Bkg. model.	16	Bkg. model.	10	b-tagging	14	Bkg. model.	11
JES/JER	12	Theory	9.1	JES/JER	11	b-tagging	10
b-tagging	9.9	b-tagging	8.5	Bkg. model.	9.8	Theory	6.8
Theory	7.5	Leptons	4.2	Theory	7.0	JES/JER	6.2

Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b-jets (link)

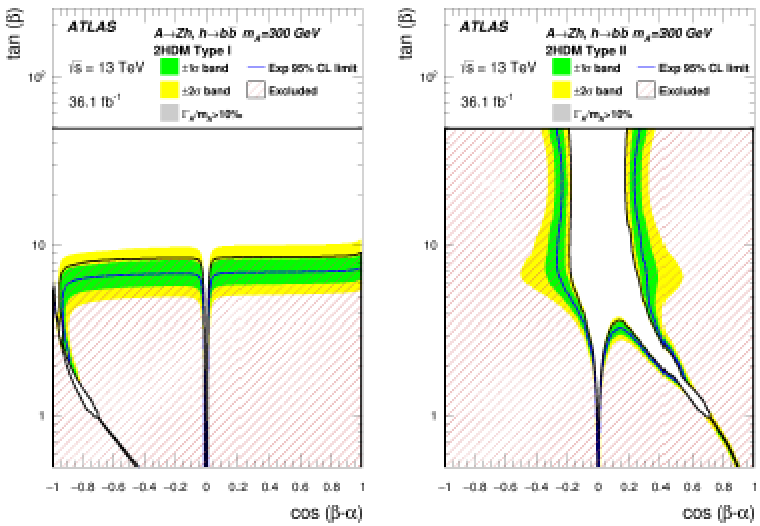
- The analyses target leptonic decays of the vector bosons and decays of the h boson into a b-quark pair: $W' \to W^{\pm}h \to \ell^{\pm}\nu b\bar{b}$, $Z'/A \to Zh \to \ell^{+}\ell^{-}b\bar{b}$, , $Z'/A \to Zh \to \nu\bar{\nu}b\bar{b}$
  - Two benchmark models are used in this analysis:
    - Model A, the branching fractions to fermions and gauge bosons are comparable
    - Model B, fermionic couplings are suppressed, as in strong dynamical models such as the minimal composite Higgs model.



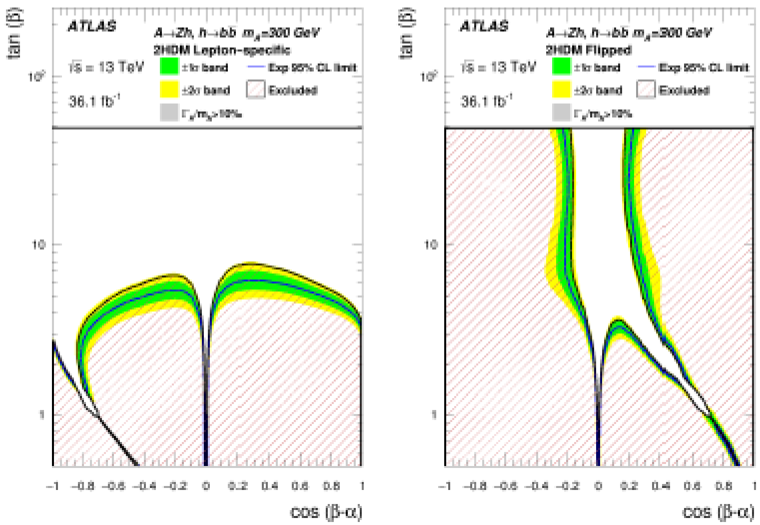
- The results from the A → Zh search are interpreted as exclusion limits on tan(β), and on cos(β-α); evaluated for the Type I, Type II, Lepton-specific, and Flipped 2HDMs. This search starts at the Zh threshold of approximately 220 GeV and goes up to 2 TeV.



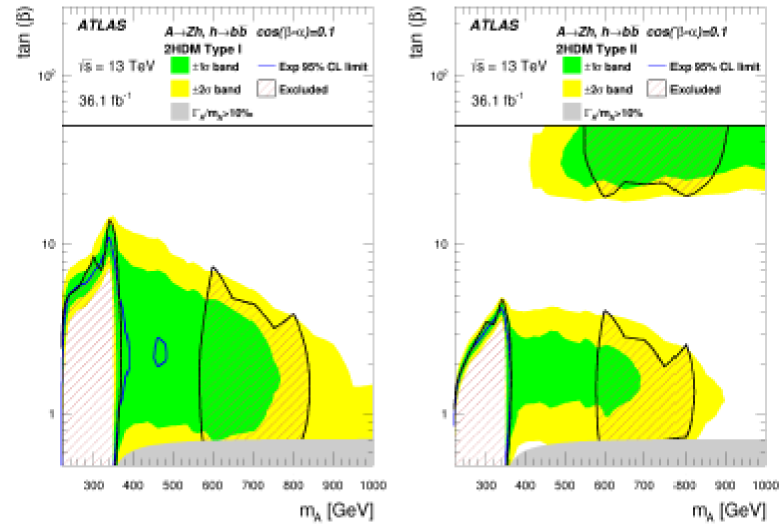
(a) Pure gluon–gluon fusion production (b) Pure b-quark associated production



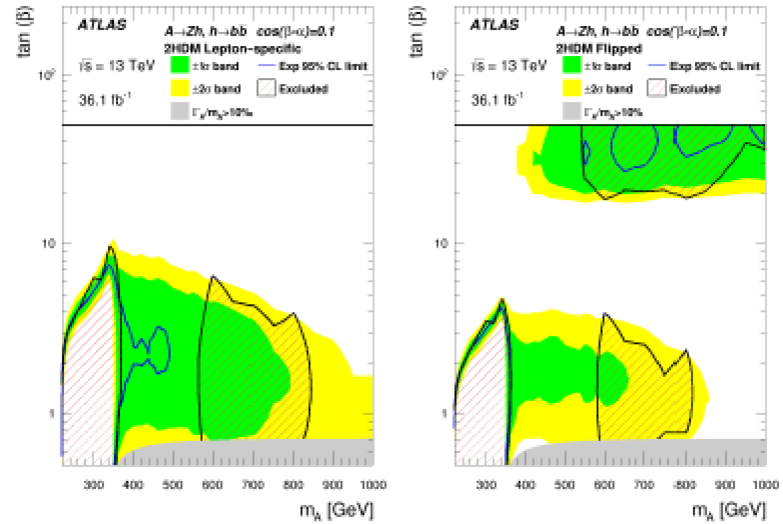
(a) 2HDM Type-I (b) 2HDM Type-II



(c) 2HDM Lepton-specific (d) 2HDM Flipped



(a) 2HDM Type-I (b) 2HDM Type-II



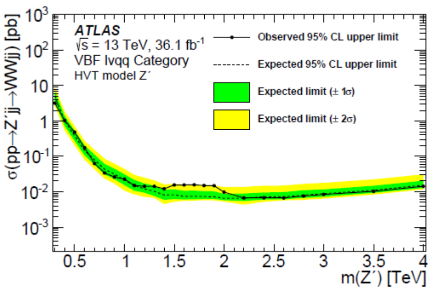
(c) 2HDM Lepton-specific (d) 2HDM Flipped

- No significant excess of events is observed above the SM predictions in all three channels.
- Upper limits are placed at the 95% CL on the cross-section times branching fraction, $(pp \rightarrow V' \rightarrow Vh)\ B(h \rightarrow b\bar{b}; c\bar{c})$, ranging between $1.1\text{x}10^{-3}$ and $2.8\text{x}10^{-3}$ pb for the W' boson and between $9.0\text{x}10^{-3}$ and $1.3\text{x}10^{-3}$ pb for the Z' boson in the mass range of 500 GeV to 5 TeV.
- The W' and Z' bosons with masses $m_{W'}$ < 2.67 TeV (2.82 TeV) and $m_{Z'}$ < 2.65 TeV (2.83 TeV) are excluded for the benchmark HVT Model A (Model B), while for the combined HVT search masses up to 2.80 TeV (2.93 TeV) are excluded.
- For an A boson, upper limits are placed on $(pp \rightarrow A \rightarrow Zh)\text{x}B(h \rightarrow b\bar{b})$ between $5.5\text{x}10^{-3}$ and $2.4\text{x}10^{-1}$ pb for gluon–gluon fusion production and between $3.4\text{x}10^{-3}$ and $7.3\text{x}10^{-1}$ pb for production with associated b-quarks in the mass range 220 GeV to 2 TeV.

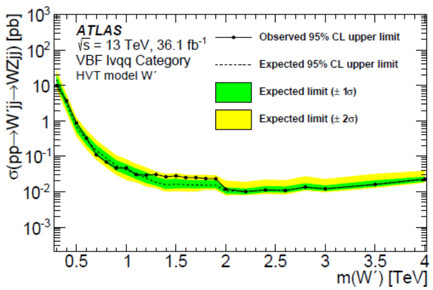
Search for WW=WZ resonance production in $\ell\ell$qq final states (link)

Table 1: Summary of the selection criteria used to define the merged WW and WZ signal regions (SR) and their corresponding W+jets control regions (W CR) and $t\bar{t}$ control regions ($t\bar{t}$ CR) in the high-purity (HP) and low-purity (LP) categories. The events are also categorized according to their production mechanism, the VBF selection is prioritized and the remaining events are assigned to the ggF/$q\bar{q}$ category.

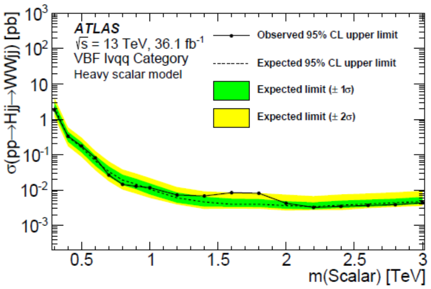
Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
Production category	VBF	$m^{\text{tag}}(j,j) > 770$ GeV and $\lvert\Delta\eta^{\text{tag}}(j,j)\rvert > 4.7$		
	ggF/$q\bar{q}$	Fails VBF selection		
$W \rightarrow \ell\nu$ selection	Num. of signal leptons	1		
	Num. of veto leptons	0		
	$E_{\text{T}}^{\text{miss}}$	> 100 GeV		
	$p_{\text{T}}(\ell\nu)$	> 200 GeV		
	$E_{\text{T}}^{\text{miss}}/p_{\text{T}}(e\nu)$	> 0.2		
$V \rightarrow J$ selection	Num. of large-R jets	≥ 1		
	D_2 eff. working point (%)	Pass 50 (80)	Pass 50 (80)	Pass 50 (80)
	Mass window Eff. working point (%)	Pass 50 (80)	Fail 80 (80)	Pass 50 (80)
Topology criteria	$p_{\text{T}}(\ell\nu)/m(WV)$ $p_{\text{T}}(J)/m(WV)$	> 0.3 for VBF and > 0.4 for ggF/$q\bar{q}$ category		
Num. of b-tagged jet	excluding b-tagged jets with $\Delta R(J,b) \leq 1.0$	0		≥ 1



(a)



(b)



(c)

Figure 6: The observed and expected cross-section upper limits at the 95% confidence level for WV production in the VBF category are presented as a function of the resonance mass. The dots in the observed limit curve represent the generated resonance mass values. Interpretations for (a) HVT Z', (b) HVT W' and (c) heavy scalar signals, H, produced via VBF are shown. The mass region greater than 1500 GeV is covered by two bins in $m(WV)$.

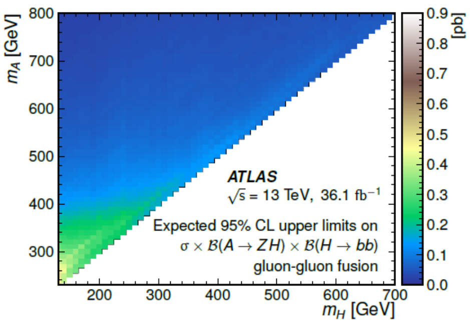
Table 5: Observed and expected excluded masses at the 95% confidence level for various signal hypotheses as extracted from the ggF/$q\bar{q}$ category.

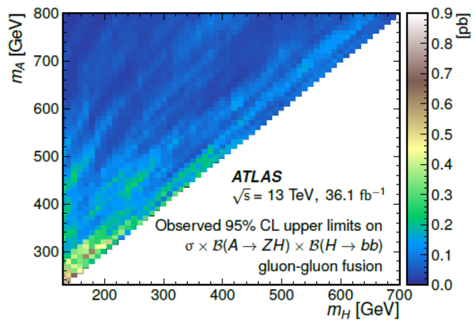
WW Selection			
Excluded Masses	HVT Model A	HVT Model B	RS G_{KK} $k/\bar{M}_{\text{Pl}} = 1.0$
Observed	<2750 GeV	<3000 GeV	<1750 GeV
Expected	<2850 GeV	<3150 GeV	<1750 GeV

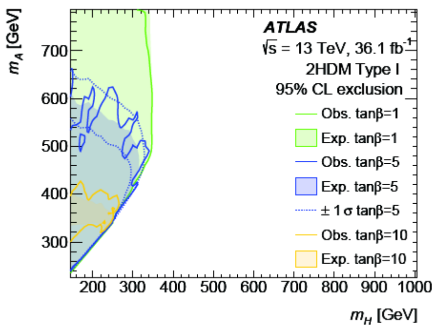
WZ Selection		
Excluded Masses	HVT Model A	HVT Model B
Observed	<2800 GeV	<3000 GeV
Expected	<2900 GeV	<3200 GeV

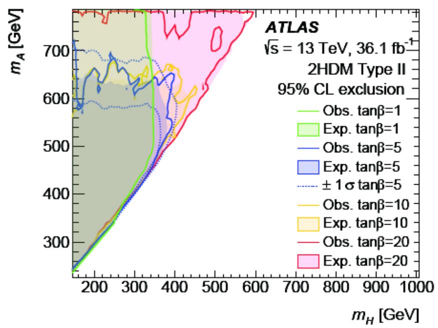
Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell bb$ (**link**)

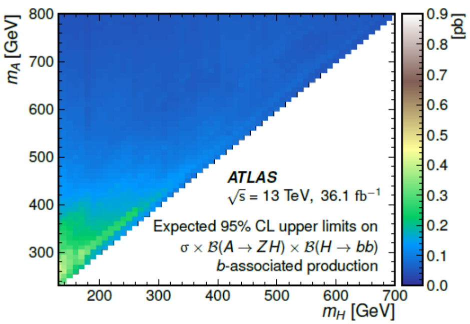
- This search targets A→ZH decays, only Z →ℓℓ (e/μ) and H→bb, categorized by the presence of two or three b-tagged jets.
- The results are interpreted in the context of the two-Higgs-doublet model.

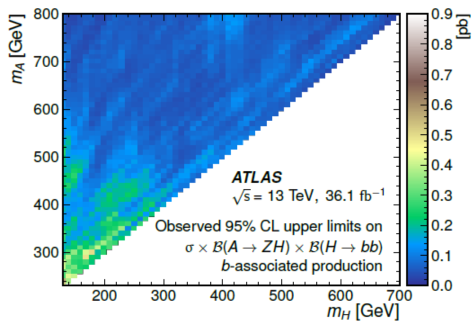


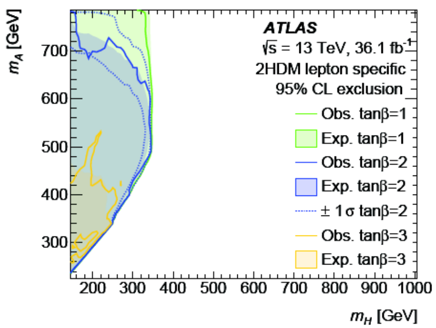


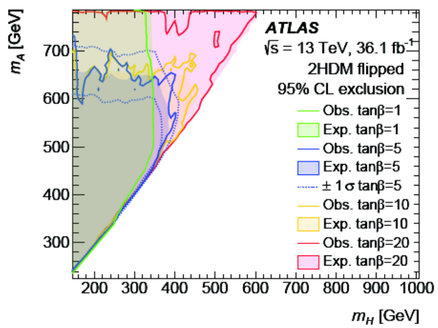








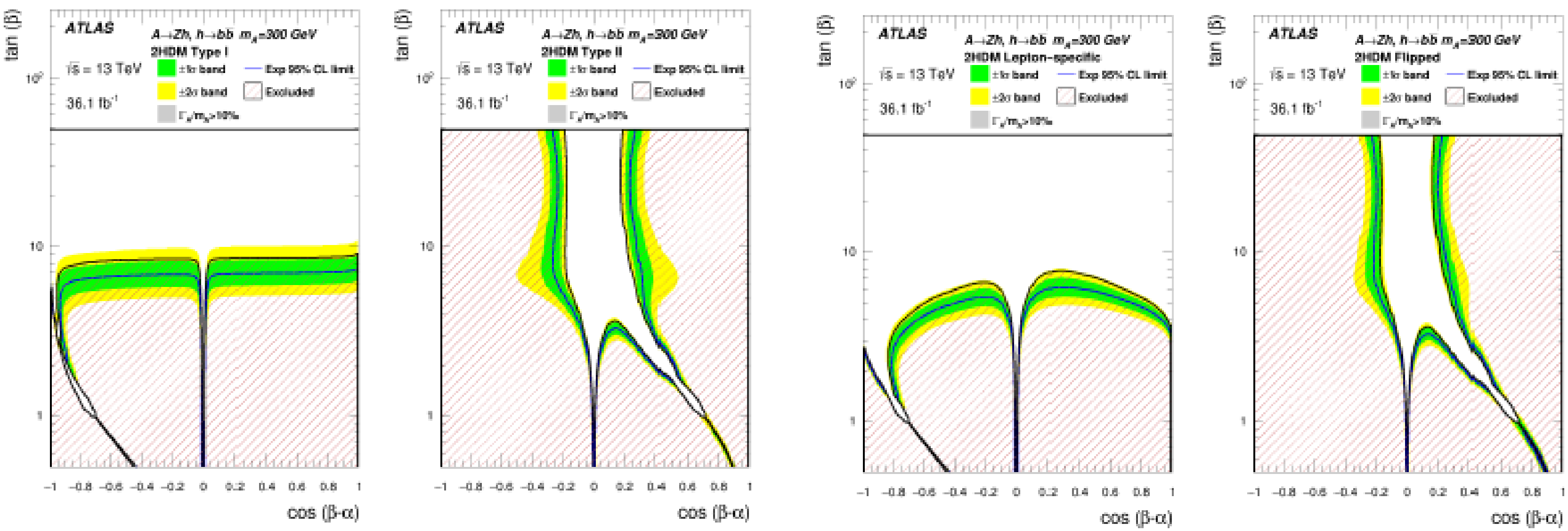




- No significant deviation from the SM background predictions are observed.
- Upper limits @ 95% CL for σ x B(A→ZH) x B(H→bb) of 14–830 fb for ggF and 26–570 fb for b-associated production of a narrow A boson (130–700 GeV m_H, 230–800 GeV m_A).
- Both production processes tightens the constraints on the 2HDM in the case of large mass splittings between its heavier neutral Higgs bosons.

Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b-jets (link)

- The analyses target lep decays of the vector bosons and decays of the h into a b-quark pair:
  - $W' \rightarrow W^{\pm}h \rightarrow \ell^{\pm}\nu b\bar{b}$, $Z'/A \rightarrow Zh \rightarrow \ell^{+}\ell^{-}b\bar{b}$, , $Z'/A \rightarrow Zh \rightarrow \nu\bar{\nu}b\bar{b}$
- Two benchmark models are used in this analysis:
  - Model A, the branching fractions to fermions and gauge bosons are comparable
  - Model B, fermionic couplings are suppressed, as in strong dynamical models (ex minimal composite Higgs)



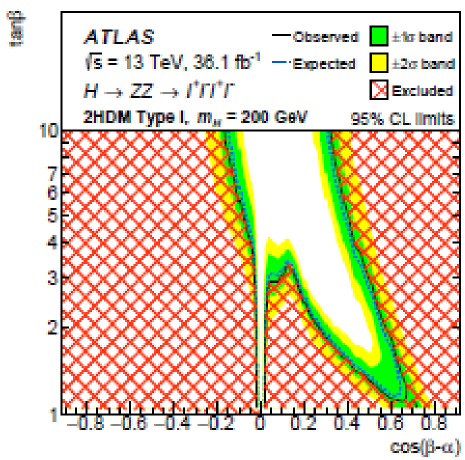
(a) 2HDM Type-I (b) 2HDM Type-II (c) 2HDM Lepton-specific (d) 2HDM Flipped

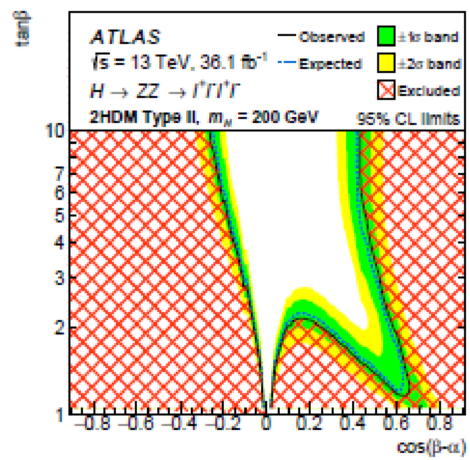
- No significant excess of events is observed above the SM in all three channels.
- Upper limits at the 95% CL ($pp \rightarrow V' \rightarrow Vh$) x $B(h \rightarrow b\bar{b}; c\bar{c})$: 1.1×10^{-3} - 2.8×10^{-3} pb for the W' boson; 9.0×10^{-3} - 1.3×10^{-3} pb for the Z', mass range 500 - 5 TeV.
- $m_{W'} < 2.67$ TeV (2.82 TeV) and $m_{Z'} < 2.65$ TeV (2.83 TeV) excluded for the benchmark HVT Model A (Model B); the combined HVT search masses up to 2.80 TeV (2.93 TeV) are excluded.
- Upper limits ($pp \rightarrow A \rightarrow Zh$)x$B(h \rightarrow b\bar{b})$: 5.5×10^{-3} - 2.4×10^{-1} pb for ggF production; 3.4×10^{-3} - 7.3×10^{-1} pb for production with associated b-quarks in the mass range 220 GeV to 2 TeV.

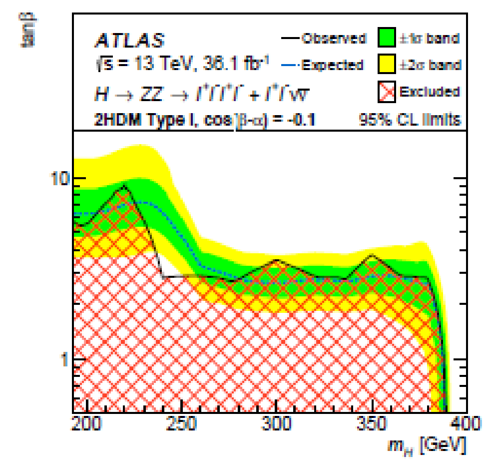
Search for heavy ZZ resonances in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states (link)

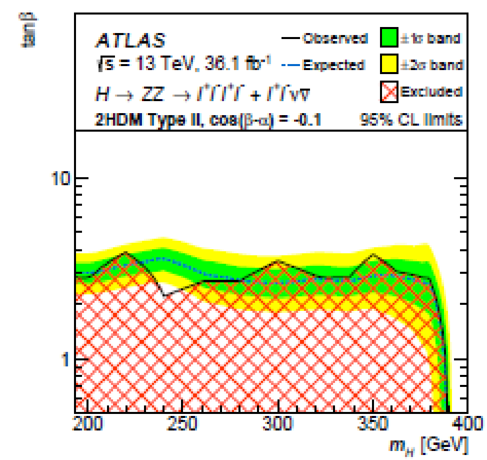
- The results are interpreted in ggF and VBF production modes. Procedure: look for an excess in distributions of m4ℓ ($\ell^+\ell^-\ell^+\ell^-$), m_T ($\ell^+\ell^-\nu\bar{\nu}$).
- Signal hypotheses: the ggF and VBF production of a heavy Higgs boson (spin-0 resonance) under the narrow-width approximation (NWA); large-width assumption (LWA) models; the Randall–Sundrum (RS) model.

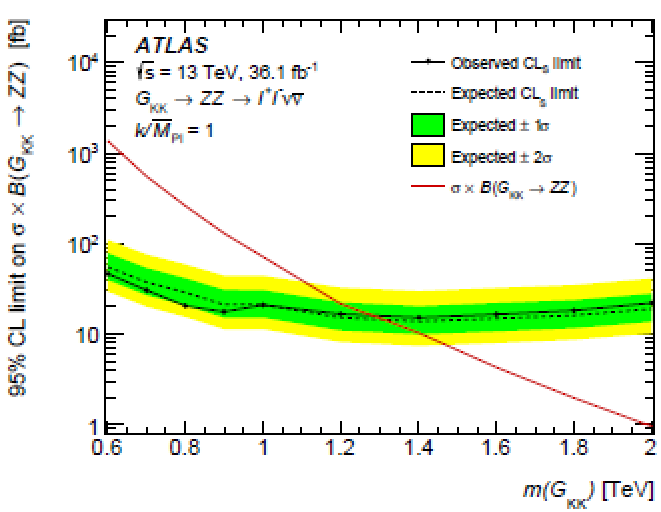
$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2},$$





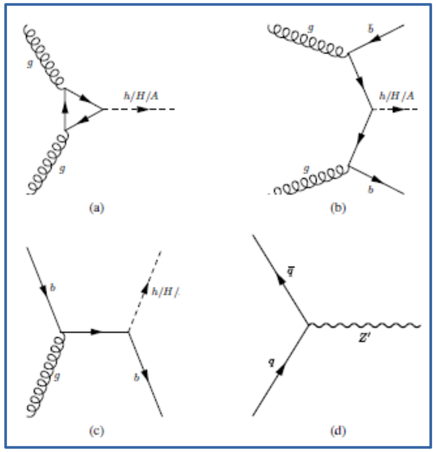




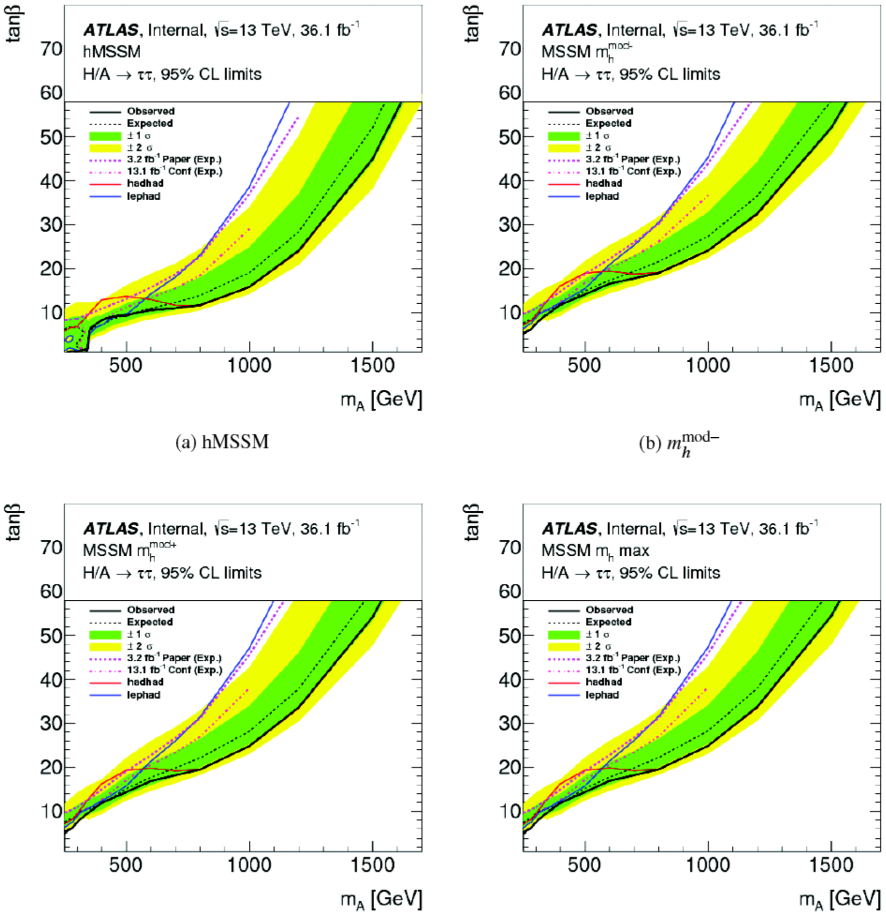


- Combining the two final states, 95% CL upper limits range from 0.68 pb at m_H = 242 GeV to 11 fb at m_H = 1200 GeV for the ggF and from 0.41 pb at m_H = 236 GeV to 13 fb at m_H = 1200 GeV for the VBF.
- The results: interpreted in the context of Type-I and Type-II two-Higgs-doublet models, with exclusion contours given in the tan β versus cos(β − α) (for m_H = 200 GeV) and tan β versus m_H planes.
- Randall–Sundrum model with one warped extra dimension a graviton excitation spin-2 resonance with $m(G_{KK})$ < 1300 GeV is excluded at 95% CL.

Search for Neutral MSSM Higgs bosons H/A and Z' decaying to $\tau_\ell \tau_h$ (link)



- Searches in the ditau channel: sensitive to sgoldstino-like scalars in supersymmetric models, hidden sector Z' models, to the anomalous -lepton dipole moments and higher order-gluon couplings
- The Sequential Standard Model (SSM) contains a single additional Z' boson with the same couplings as the SM Z boson.

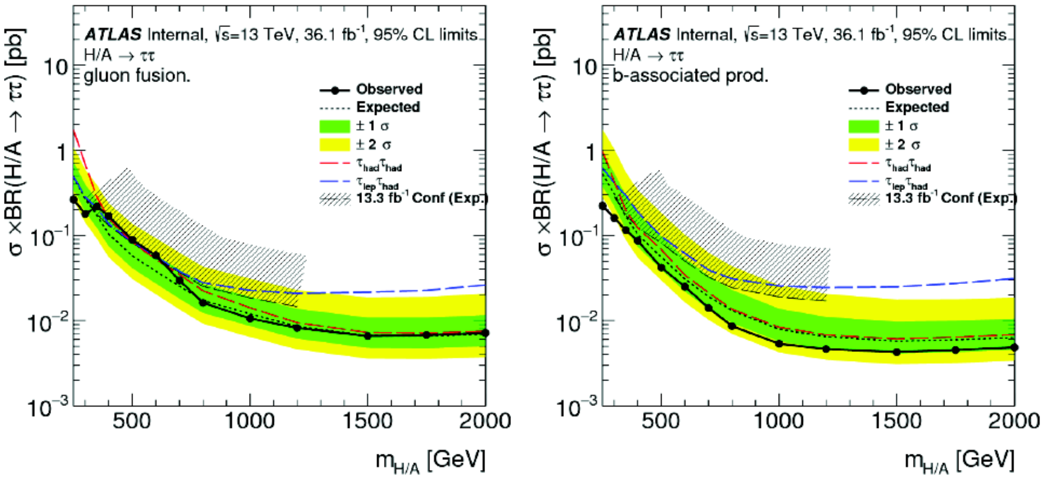


(a) hMSSM

(b) m_h^{mod-}

(c) m_h^{mod+}

(d) m_h^{max}



(a) $\tau\tau$, gluon-fusion

(b) $\tau\tau$, b-associated production

- The exclusion limits are calculated in dependence of m_H and the relative magnitude of the production processes (gluon fusion and b-associated production).