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BSM Higgs boson searches with ATLAS

Arnaud Ferrari

Higgs boson searches beyond the Standard Model with the ATLAS experiment

Arnaud Ferrari (Uppsala University)
on behalf of the ATLAS Collaboration

3rd ComHEP, Cali (Colombia), 3-7 December 2018

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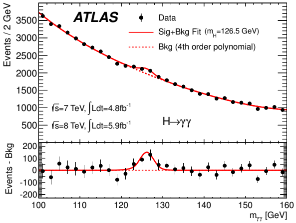
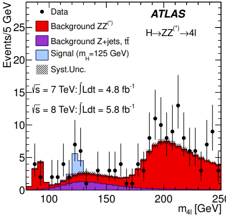
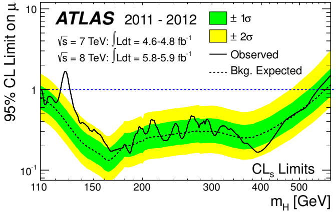
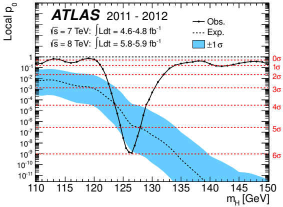
4 July 2012: Higgs-dependence day

Clear evidence for the production of a new neutral particle with a mass of 125 GeV, corresponding to a background fluctuation probability of 1.7×10^{-9} ($5.9\ \sigma$).





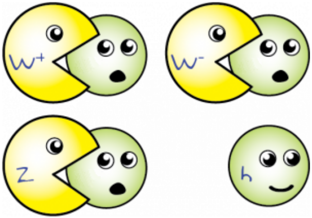




All plots from Phys. Lett. B716 (2012) 1-29

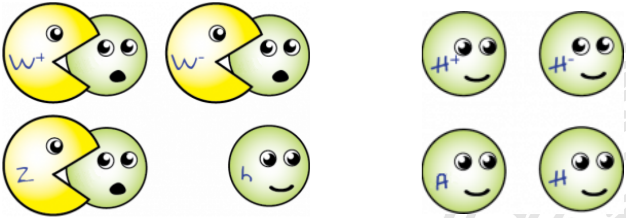
SM Higgs sector

After the discovery of **a** Higgs boson at 125 GeV, a major question is whether this is **the** scalar particle predicted by the Standard Model to break the electroweak symmetry...



BSM Higgs sector

After the discovery of **a** Higgs boson at 125 GeV, a major question is whether this is **the** scalar particle predicted by the Standard Model to break the electroweak symmetry...
or is it the first state of an extended Higgs sector?



Several BSM models predict an extended scalar sector, e.g. with two Higgs doublets (2HDM) or Higgs triplets, all containing neutral and charged Higgs bosons.

Two Higgs Doublet Models (2HDMs)

- Two Higgs doublets Φ_1 and Φ_2, with vevs v_1 and v_2, such that $\tan\beta = v_2/v_1$.

- Two CP-even Higgs bosons *h* and *H* (with a mixing angle α), one CP-odd Higgs boson *A*, two charged Higgs bosons $H^{\pm}$.

To avoid flavour-changing neutral currents, each group of fermions must couple to exactly one of the two doublets
$\Rightarrow$ four 2HDM types, depending on fermion couplings:

Model	up-type quarks	down-type quarks	charged leptons
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Alignment limit: $\cos(\beta - \alpha) \simeq 0 \Rightarrow h$ has SM-like couplings.

Minimal Supersymmetric Standard Model

The MSSM is the minimal extension of the Standard Model which realises Supersymmetry:

- It can provide dark matter candidates and grand unification;
- Super-partners have high masses (not observed $\Rightarrow$ SUSY softly broken);
- MSSM Higgs sector = type-II 2HDM.

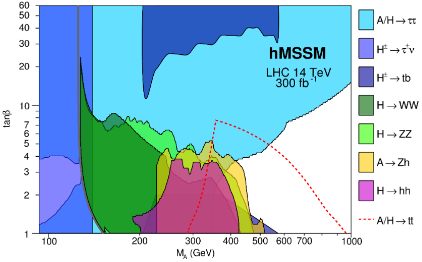
Tree-level predictions use one Higgs boson mass and tan β.

Various benchmark scenarios where SUSY parameters enter as radiative corrections:

- m_h^{max}: m_h is maximised for fixed tan β and large m_A.
- $m_h^{mod\pm}$: the top-squark mixing parameter is chosen so that m_h is close to 125 GeV.
- hMSSM: the measured value of m_h is used to predict the remaining Higgs boson masses and couplings, without explicit reference to soft SUSY-breaking parameters.

Minimal Supersymmetric Standard Model

Example of search projections in the hMSSM, taken from A. Djouadi, et al., JHEP06 (2015) 168:



In this talk:

- A/H→ττ ← JHEP01 (2018) 055
- H$^\pm$→τν ← JHEP09 (2018) 139
- H$^\pm$→tb ← JHEP11 (2018) 085
- H→WW, H→ZZ: PRD 98, 052008 (2018): VV combination. See also Refs. [9–14] therein.
- A→Zh ← JHEP03 (2018) 174
- H→hh ← ATLAS-CONF-2018-043: hh combination. See also Refs. [21–23] therein.

Disclaimer: most experimental results shown here are motivated by or interpreted in 2HDMs, but several other theories predict extended Higgs sectors, e.g. 2HDM+S, Higgs triplets, etc.

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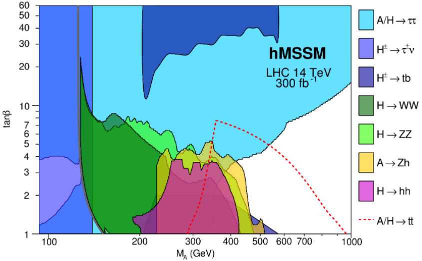

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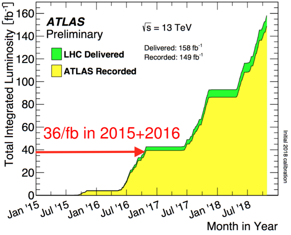
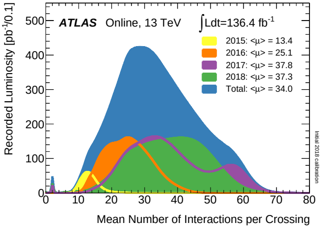
The Large Hadron Collider in one slide

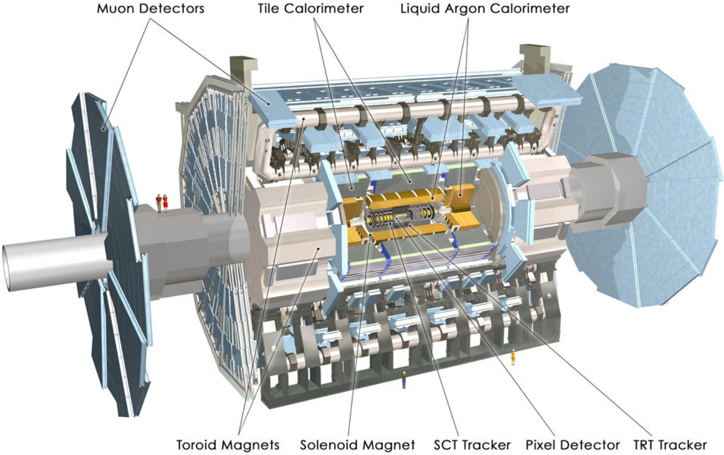
- Circumference = 27 km,
- Proton revolutions per second = 11245.5,
- Centre-of-mass energy:
  - 7 TeV in 2011;
  - 8 TeV in 2012;
  - 13 TeV in 2015-2018;
- Luminosity: 10^{34} cm^{-2}.s^{-1} (design), but achieved twice higher!

From https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2:





The ATLAS experiment in one slide



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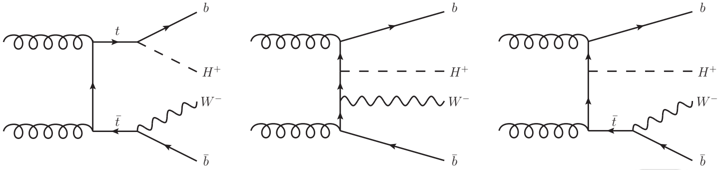
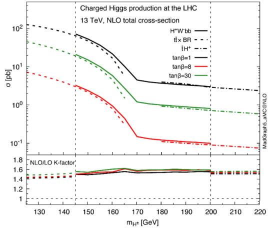
H^+ production and decays

Charged Higgs bosons are primarily produced in decays of (low-mass) or in association with (high-mass) a top quark:

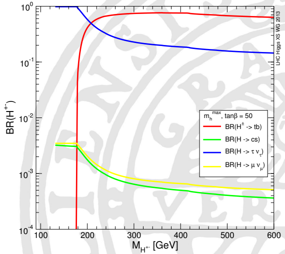


Theoretical predictions are now available in the region $m_{H^+} \simeq m_t$.



M. Zaro @ cHarged2018 (Uppsala).

$H^+ \to \tau\nu$ or $H^+ \to tb$ dominate.



From the LHC Higgs XS WG twiki page.

$H^+ \to \tau\nu$ – event selections

$pp \to bbWH^+ \to bb(jj)(\tau_{\text{had}}\nu)$

$\to$ *Sensitive at large m_{H^+}.*

1) E_T^{miss} trigger: efficiency from data, applied to simulation.

2) Select events with a τ_{had} and a hadronic top-quark decay:

- $\geq$1 τ object with $p_T^\tau > 40$ GeV,
- $\geq$3 jets with $p_T > 25$ GeV, including $\geq$1 b-tag,
- Electron and muon veto,
- $E_T^{\text{miss}} > 150$ GeV,
- $m_T = \sqrt{2p_T^\tau E_T^{\text{miss}} \cos \Delta\phi_{\tau,\text{miss}}} > 50$ GeV.

$pp \to bbWH^+ \to bb(\ell\nu)(\tau_{\text{had}}\nu)$

$\to$ *Sensitive at low/intermediate m_{H^+}.*

1) Single-lepton triggers.

2) Select events with a τ_{had} and a leptonic top-quark decay:

- =1 lepton (e/μ) with $p_T^\ell > 30$ GeV,
- =1 τ object with $p_T^\tau > 30$ GeV,
- Two opposite-sign channels: $e + \tau$ and $\mu + \tau$,
- $\geq$1 b-tagged jet with $p_T > 25$ GeV,
- $E_T^{\text{miss}} > 50$ GeV.

- Backgrounds with a true τ: simulation;
- Backgrounds with $e, \mu \to \tau$ fakes: simulation + data-driven corrections;
- Backgrounds with $j \to \tau$ fakes: data-driven fake-factor method.

A single-bin control region using $\ell + \tau$ selections but with an $e\mu$ pair is used to constrain the normalisation of the $t\bar{t}$ background.

$H^+ \to \tau\nu$ – analysis strategy

Multivariate discriminant:

- BDTs trained in 5 H^+ mass bins;
- Separate training for τ+jets and τ+lepton final states;
- Polarisation variable used for 1-prong τ objects when $m_{H^+} < 500$ GeV:

$$\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^\tau} \simeq 2\frac{p_T^{\tau\text{-track}}}{p_T^\tau} - 1$$

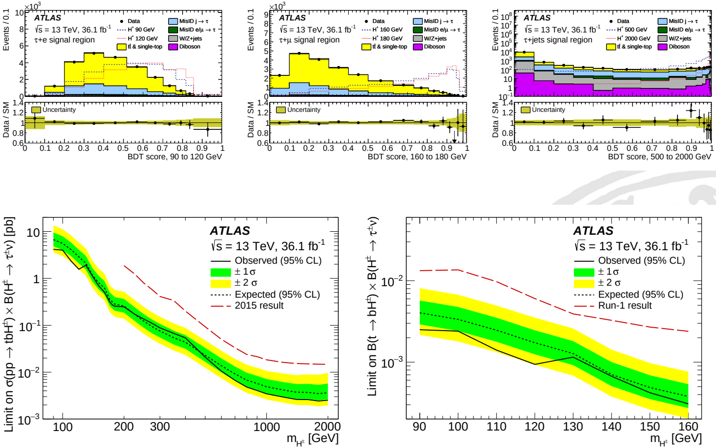
BDT input variable	$\tau_{\text{had-vis}}$+jets	$\tau_{\text{had-vis}}$+lepton
E_T^{miss}	✓	✓
p_T^τ	✓	✓
$p_T^{b\text{-jet}}$	✓	✓
p_T^ℓ		✓
$\Delta\phi_{\tau,\text{miss}}$	✓	✓
$\Delta\phi_{b\text{-jet},\text{miss}}$	✓	✓
$\Delta\phi_{\ell,\text{miss}}$		✓
$\Delta R_{\tau,\ell}$		✓
$\Delta R_{b\text{-jet},\ell}$		✓
$\Delta R_{b\text{-jet},\tau}$	✓	
Υ	✓	✓

BDT mass bins:

- 90–120 GeV;
- 130–160 GeV;
- 160–180 GeV;
- 200–400 GeV;
- 500–2000 GeV.

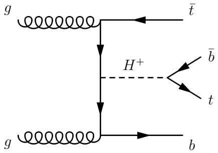
$H^+ \to \tau\nu$ – results

No statistically significant deviation from the SM predictions.
Exclusion limits obtained from a fit of the BDT distributions.

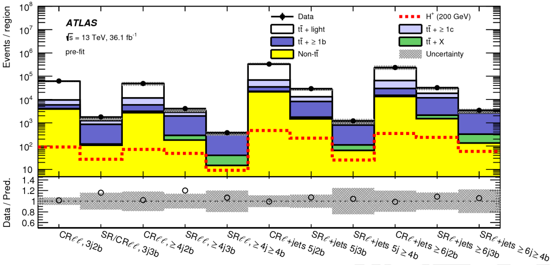


$H^+ \to tb$ – event selections

- At least one leptonic top-quark decay $\Rightarrow$ single-lepton triggers;
- Single- and di-lepton (OS) channels;
- Z-veto in *ee* and $\mu\mu$ channels;



Event categorisation in signal and control regions according to the number of jets and *b*-jets.



Single-lepton: CR 5j2b, SR 5j3b, SR 5j≥4b, CR ≥6j2b, SR ≥6j3b, SR ≥6j≥4b.
Di-lepton: CR 3j2b, CR/SR 3j3b, CR ≥4j2b, SR ≥4j3b, SR ≥4j≥4b.

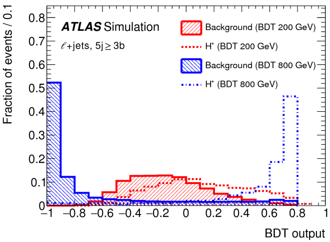
$H^+ \to tb$ – analysis strategy

The dominating background is $t\bar{t}$+jets ($\sigma = 832^{+46}_{-51}$ pb).

- Model = Powheg+Pythia8.
- Categorised according to the flavour of additional jets.
- $t\bar{t}+\geq$1b further split based on the number of jets matched to *b*-hadrons.
- Normalisation of $t\bar{t} + \geq$1c and $t\bar{t} + \geq$1b freely floating in the fit.

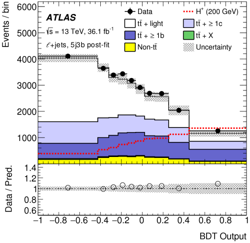
Multivariate technique (BDT) used to separate signal and background in the SRs. The BDT is trained:

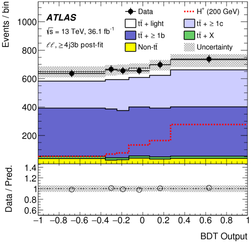
- separately for each m_{H^+} and SR,
- against all backgrounds for the single-lepton channel,
- against $t\bar{t}$ in the di-lepton channel.

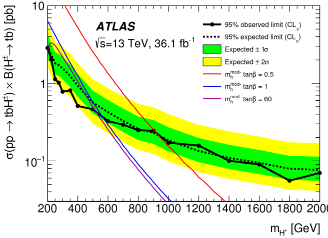


$H^+ \to tb$ – results

No statistically significant deviation from the SM predictions. Exclusion limits obtained from a fit of the BDT distributions in SRs and a single bin in CRs.





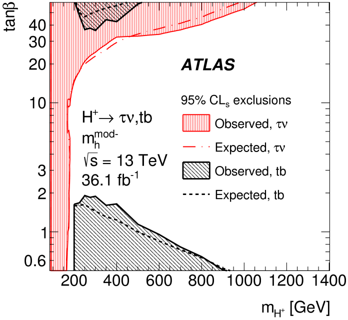


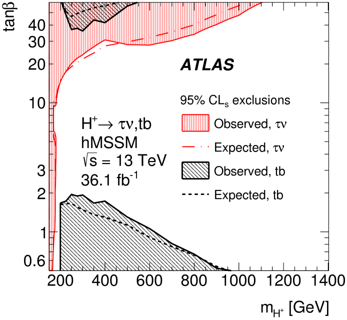
Systematics-dominated analysis:

Uncertainty Source	$\Delta\mu(H^+_{200})$ [pb]	$\Delta\mu(H^+_{800})$ [pb]
Jet flavour tagging	0.70	0.050
$t\bar{t}+\geq 1b$ modelling	0.65	0.008
Jet energy scale and resolution	0.44	0.031
$t\bar{t}$+light modelling	0.44	0.019
MC statistics	0.37	0.044
$t\bar{t}+\geq 1c$ modelling	0.36	0.032
Other background modelling	0.36	0.039
Luminosity	0.24	0.010
Jet-vertex assoc., pile-up modelling	0.10	0.006
Lepton, E_T^{miss}, ID, isol., trigger	0.08	0.003
H^+ modelling	0.03	0.006
Total systematic uncertainty	1.4	0.11
$t\bar{t}+\geq 1b$ normalisation	0.61	0.022
$t\bar{t}+\geq 1c$ normalisation	0.28	0.012
Total statistical uncertainty	0.69	0.050
Total uncertainty	1.5	0.12

Charged Higgs boson searches: summary

Projecting the $H^+ \to \tau\nu$ and $H^+ \to tb$ exclusion limits in the $(m_{H^+}; \tan\beta)$ plane of two MSSM scenarios illustrates the complementary of the two channels.





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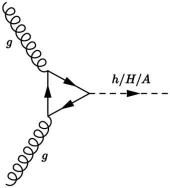
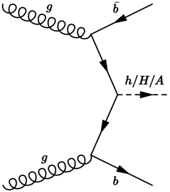
A/H production and decays

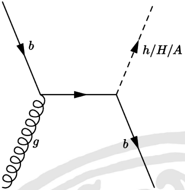
Heavy neutral Higgs bosons are produced via gluon-gluon fusion or *b*-associated production (enhanced at high tan β):



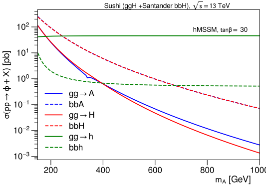
gg fusion

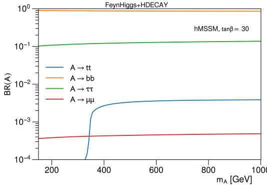


b-associated, 4FS



b-associated, 5FS



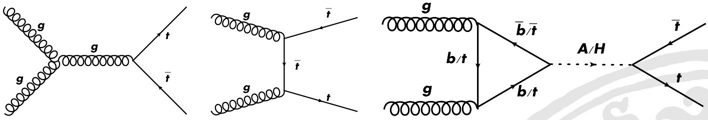


Decays to $b\bar{b}$ & $\tau\tau$ at high tan β, or to $t\bar{t}$ at low tan β.

G. Hamity, private communication

A few words about $A/H \to t\bar{t}$

Gluon-gluon fusion production of $A/H \to t\bar{t}$ is potentially the golden channel for $m_{A/H}$ above 350 GeV at low tan β, however the destructive interference of the signal and $t\bar{t}$ background must be taken into account $\to$ peak-and-dip structure, as illustrated in PRL 119 (2017) at 8 TeV.



$(b\bar{b}/t\bar{t}) + A/H \to t\bar{t}$ has:

- negligible interference with backgrounds :-)
- complicated final states :-(

ATLAS has no dedicated search for $(b\bar{b}/t\bar{t}) + A/H \to t\bar{t}$. Other searches for $t\bar{t} + X$ final states were re-interpreted in 2HDMs, e.g. ATLAS-CONF-2016-104 and arXiv:1807.11883.

$A/H \to \tau\tau$ – analysis strategy

- The couplings to b and τ are enhanced at large $\tan\beta$.
- Two production modes: gg fusion, b-associated.

Four categories: OS $[\tau_\ell\tau_h, \tau_h\tau_h] \otimes [0\ b, \geq 1\ b]$.

Event selection	$\tau_\ell\tau_h$ b-veto	$\tau_\ell\tau_h$ b-tag	$\tau_h\tau_h$ b-veto	$\tau_h\tau_h$ b-tag
Trigger	1 ℓ	1 ℓ	1 τ	1 τ
N_ℓ (p_T in GeV)	$\geq$1 (30)	$\geq$1 (30)	veto	veto
N_τ (p_T in GeV)	=1 (25)	=1 (25)	2 $(^{85}_{165}, 65)$	2 $(^{85}_{165}, 65)$
N_b (70% efficiency)	=0	$\geq$1	=0	$\geq$1
$\Delta\phi$ ($\ell\tau_h$ or $\tau_{h1}\tau_{h2}$)	> 2.4	> 2.4	> 2.7	> 2.7
$m_T(\ell, E_T^{miss})$ [GeV]	< 40	< 40	-	-
$m_{vis}(e, \tau_h)$ [GeV]	$\neq$ 80-110	$\neq$ 80-110	-	-

Discriminating variable:

$$m_T^{tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$

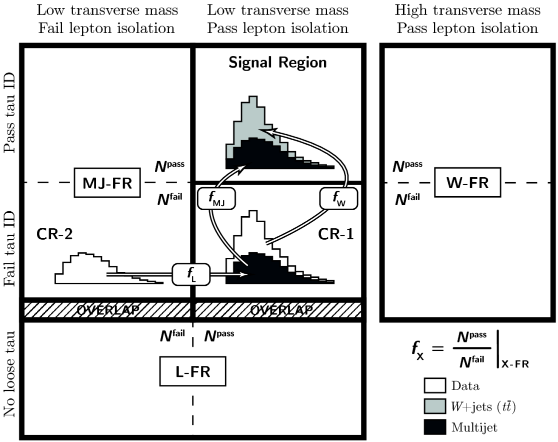
Background modelling

- simulation for backgrounds with true leptons and τ_h objects;
- data-driven fake-factor method for backgrounds with $j \to \tau_h$ (for $\tau_\ell\tau_h$ and multi-jet events in $\tau_h\tau_h$);
- fake-rate method for $j \to \tau_h$ in simulated backgrounds for $\tau_h\tau_h$.

$A/H \to \tau_\ell \tau_h$ – background

Background with a true τ_h estimated with simulation.

Background with $j \to \tau_h$ from a fake-factor method:



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$A/H \to \tau_h\tau_h$ – background

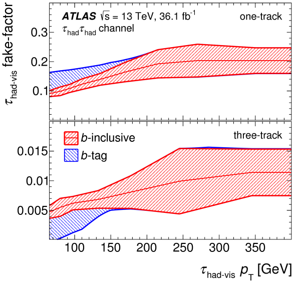
Simulated background processes → fake-rate method:

- $j \to \tau_h$ fake rates are measured with data in regions enriched with W+jets ($\mu\tau_h$ + 0b) or $t\bar{t}$ ($\mu\tau_h$ + $\geq$1b);
- $j \to \tau_h$ fake rates are applied as a weight to each τ_h candidate *in simulation* not matched to a true τ.

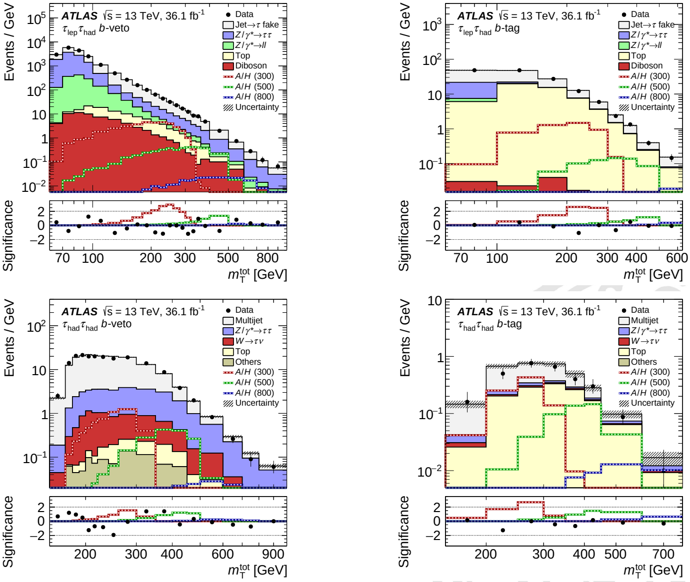
Multi-jet processes → fake-factor method:

$$N^{\rm SR}_{\rm multijet}(\nu;\mathbf{y}) = f_{\rm DJ}(\mathbf{y}) \cdot \left[N^{\rm CR-1}_{\rm data}(\nu;\mathbf{y}) - N^{\rm CR-1}_{\rm non-MJ}(\nu;\mathbf{y})\right]$$

- fake factors are measured in a dijet control region;
- fake factors are applied to data where the sub-leading τ_h fails the ID criteria (CR-1).



$A/H \to \tau\tau$ – results



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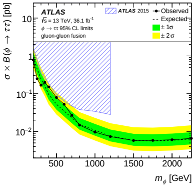
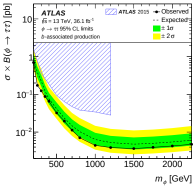
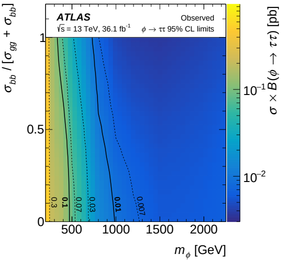
$A/H \to \tau\tau$ – exclusion limits

ggΦ limits



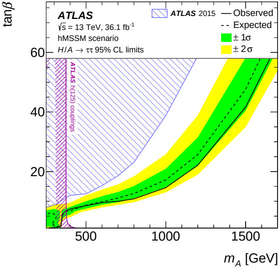
bbΦ limits





For masses of 0.2–2.25 TeV, model-independent limits are in the range 0.78–0.0058 pb (*gg* fusion) or 0.70–0.0037 pb (*b*-associated production).

hMSSM limits ⟶



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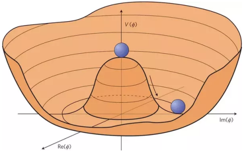
Reminder: the Higgs potential

After discovering the Higgs boson, the ultimate probe of the Standard Model is to fully measure the Higgs potential.



$$V(\Phi) = -\frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4 \overset{\Phi\to v+h}{=} \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

mass term $\frac{1}{2} m_h^2 h^2$

self-interaction terms

$\rightarrow v = \mu/\sqrt{\lambda} = 246$ GeV and $\lambda = m_h^2/(2v^2) = 0.13$ fully determine the shape of the Higgs potential.

$\rightarrow$ In order to further test the Standard Model, one must observe $h \rightarrow hh$ (and eventually $h \rightarrow hhh$ too).

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BSM Higgs boson searches with ATLAS

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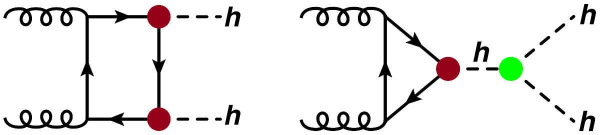
SM Higgs boson pair production

Gluon-gluon fusion:



Due to the destructive interference between the box and Higgs self-coupling diagrams, the SM Higgs boson pair production cross-section is very small, about one order of magnitude less than for single Higgs boson production.

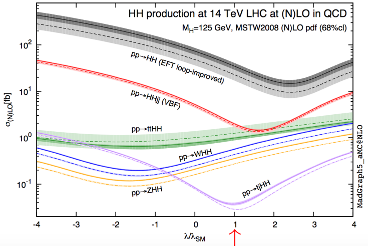
Other production modes: even smaller cross-sections...

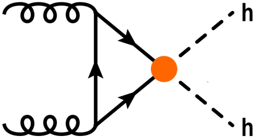
$\sqrt{s}$	8 TeV	13 TeV	14 TeV
ggF hh	10.2	33.4	39.6
VBF hh	0.46	1.62	1.95
$W/Z + hh$	0.36	0.86	0.98
$tt + hh$	0.17	0.77	0.95

$\sigma^{hh}_{\mathrm{NLO}}$ in fb (https://arxiv.org/abs/1610.07922)

BSM Higgs boson pair production

Enhancements of the *hh* production cross-section and modified kinematics (e.g. m_{hh}, p_T^h) may occur through variations of the Yukawa- or self-coupling, as well as new vertices.



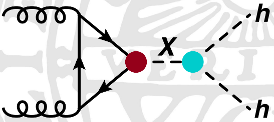


← Phys. Lett. B732 (2014) 142

(λ = Higgs self-coupling)

Resonant Higgs boson pair production:

- Randall-Sundrum graviton (spin-2): $G \to hh$
- 2HDM heavy Higgs boson (spin-0): $H \to hh$



Higgs boson pair decays

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0053%

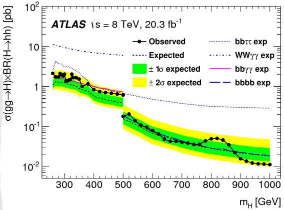
Many final states to explore...
In this talk:

- *bbbb*: arXiv:1804.06174
- $bb\gamma\gamma$: JHEP11 (2018) 040
- $bb\tau\tau$: Phys. Rev. Lett. 121, 191801
- Statistical combination: ATLAS-CONF-2018-043

Run-1 legacy:

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

Phys. Rev. D 92, 092004 (2015)



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$hh \to bbbb$

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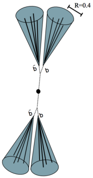
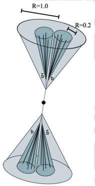
$hh \rightarrow bbbb$ – event categories

Two event topologies depending on the probed mass range:

- Non-resonant and resonant production of $hh \rightarrow bbbb$ with mass up to $\simeq$1 TeV: resolved topology.
- Resonant production of $hh \rightarrow bbbb$ with mass $\gtrsim$1 TeV: boosted topology.

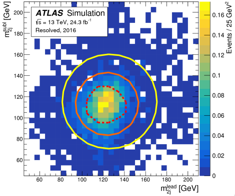


Topology/ Objects	Resolved (260-1400 GeV)	Boosted (800-3000 GeV)
Triggers and corresponding $\int Ldt$ (fb^{-1})	Combination of b-jet triggers 3.2+24.3	Single large-R jet trigger 36.1
N_{jets}	$\geq$4 jets, $R = 0.4$	$\geq$2 jets, $R = 1.0$
p_T cut	40 GeV	450 / 250 GeV
b-tagging	70% for all jets	70% on track-jets with $R = 0.2$
$N_{\text{b-jets}}$	4	2, 3, 4



$hh \to bbbb$ – resolved topology

Event selection:



- Use 4 jets with highest b-tagging scores.
- Selection and pairing of jets into Higgs boson candidates using ΔR_{jj}, m_{4j} and differences in m_{2j}.
- m_{4j}- and m_{2j}-dependent requirements on the p_T and mass of the Higgs boson candidates $\Rightarrow$ SR centered at (120 GeV; 110 GeV).
- Events where a three-jet-combination is compatible with a top-quark decay are vetoed to reduce the $t\bar{t}$ background contamination.

Background estimation:

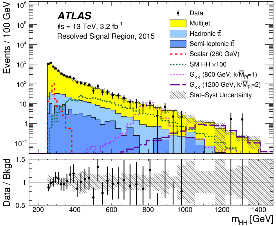
- Multi-jet sample: built with the nominal event selection, but $N_b = 2$: one h candidate from the two b-tagged jets, one from two non-b-tagged jets;
- Weights are derived by comparing $2b$+$2j$ and $4b$ samples in a sideband (SB) region, then applied to the $2b$+$2j$ sample of the SR;
- $t\bar{t}$ sample: simulated m_{4j} shape for fully-hadronic and semi-leptonic $t\bar{t}$;
- Normalisations of multi-jet events, fully-hadronic and semi-leptonic $t\bar{t}$ by a simultaneous fit of three background-enriched regions of the SB.

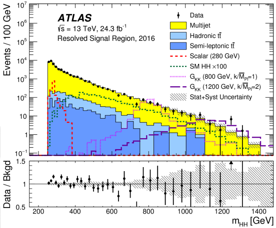
$hh \to bbbb$ – resolved topology

After the validation of backgrounds in control regions, no significant excess of events is found in the SR:

Sample	2015 SR	2016 SR	2015 CR	2016 CR
Multijet	866 ± 70	6750 ± 170	880 ± 71	7110 ± 180
$t\bar{t}$, hadronic	52 ± 35	259 ± 57	56 ± 37	276 ± 61
$t\bar{t}$, semileptonic	13.9 ± 6.5	123 ± 30	20 ± 9	168 ± 40
Total	930 ± 70	7130 ± 130	956 ± 50	7550 ± 130
Data	928	7430	969	7656
G_{KK} (800 GeV)	12.5 ± 1.9	89 ± 14		
Scalar (280 GeV)	24 ± 7.5	180 ± 57		
SM HH	0.607 ± 0.091	4.43 ± 0.66		

Largest local deviation at 280 GeV: it is 3.6σ for a narrow-width scalar resonance (global significance of 2.3σ).

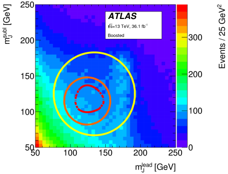




$hh \rightarrow bbbb$ – boosted topology

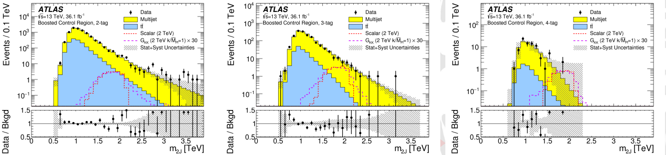
Event selection:

- The two large-R jets with highest p_T are used, with $|\Delta\eta_{JJ}| < 1.7$;
- ≥ 1 b-tagged track-jet per $J \Rightarrow 2, 3, 4$ b-tags;
- Requirements on the jet masses $\Rightarrow$ SR centered at (124 GeV; 115 GeV).



Background estimation:

- Multi-jet template from "lower-tagged" event selections (i.e. one of the large-R jet has no b-tagged track-jet and at least one failing b-tagging) + re-weight the kinematics of the non-b-tagged J to mimic a h candidate;
- Shape of the $t\bar{t}$ background from simulation;
- Normalisation of the backgrounds from binned likelihood fits of the leading large-R jet mass distribution in the sideband region.

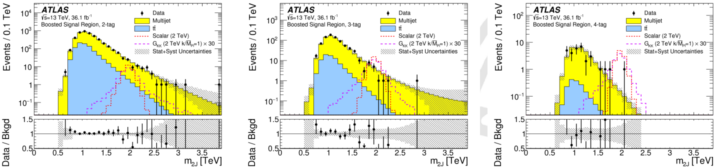


$hh \to bbbb$ – boosted topology

After the validation of backgrounds in control regions, no significant excess of events is found in the SR:

	Two-tag		Three-tag		Four-tag	
Multijet	3390	± 150	702	± 63	32.9	± 6.9
$t\bar{t}$	860	± 110	80	± 33	1.7	± 1.4
Total	4250	± 130	782	± 51	34.6	± 6.1
$G_{\rm KK}$ (2 TeV)	$0.97 \pm$	0.29	$1.23 \pm$	0.16	$0.40 \pm$	0.13
Scalar (2 TeV)	$28.2 \pm$	9.0	$35.0 \pm$	4.6	10.9	± 3.5
Data	4376		801		31	

Discriminant = m_{2J} after correction of the large-R jet momenta by m_h/m_J.



$hh \to bbbb$ – results

Statistical analysis:

- Combination of the resolved and boosted topologies in the range 800-1400 GeV, where they overlap.
- Simultaneous fit of m_{4j} in the 2015 and 2016 dataset for resolved topologies, and of m_{2J} in the 2, 3 and 4 *b*-tag regions for boosted topologies.

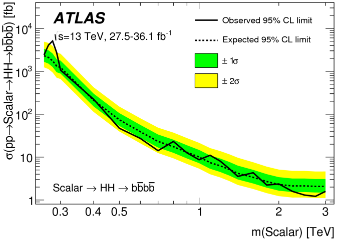
Non-resonant *hh* production:

Observed 95% CL upper limit on $\sigma_{hh} \times \mathrm{BR}(bbbb)$ at 147 fb.

In units of the SM prediction:

Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

Resonant *hh* production (2HDM interpretation):



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$$hh \to bb\gamma\gamma$$

$hh \to bb\gamma\gamma$ – event selections

Two photons

- Di-photon trigger with thresholds at 35 and 25 GeV;
- 2 photons with $E_T/m_{\gamma\gamma}$ above 0.35/0.25 & $m_{\gamma\gamma} \subset [105; 160]$ GeV.

Jet selection

- $\geq$2 central jets with $p_T > 25$ GeV, reject events with >2 *b*-tags (70%);
- 2-tag: exactly 2 *b*-jets (70%);
- 1-tag: fails 2-tag but has 1 *b*-jet (60%) + BDT to choose the second jet;
- 0-tag $\to$ data-driven estimates of the background shape.

Additional loose (tight) selection

- Optimised for 260–500 GeV & varied λ ($\geq$ 500 GeV & non-resonant);
- Leading jet $p_T > 40\,(100)$ GeV, sub-leading jet $p_T > 25\,(30)$ GeV;
- m_{jj} between 80 (90) and 140 GeV;
- $m_{\gamma\gamma}$ within 4.7 (4.3) GeV of m_h [resonant].

$hh \to bb\gamma\gamma$ – signal and background models

Non-resonant *hh* production

- Analysis strategy: fit the $m_{\gamma\gamma}$ distribution.
- Signal modelling: double-sided Crystal Ball function.
- Single Higgs boson production: simulation, double-sided Crystal Ball function.
- Continuum background modelling: fit to the data with a first-order exponential, which minimises the spurious signal*.

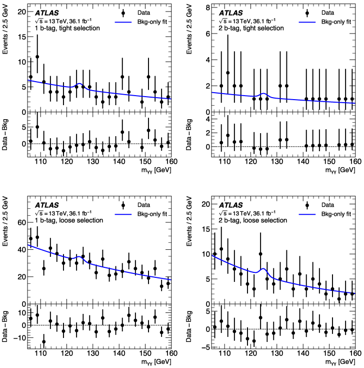
Resonant *hh* production

- Analysis strategy: rescale the dijet four-momentum by m_h/m_{jj} and fit the $m_{\gamma\gamma jj}$ distribution around m_X.
- Signal modelling: Gaussian core with exponential tails.
- Background modelling: fit to the data, with a functional form chosen to minimise the spurious signal $\to$ Novosibirsk (exponential) function for the loose (tight) event selection.

(*) Spurious signal: bias measured by fitting a signal+background model to a background-only sample.

$hh \to bb\gamma\gamma$ – results

Non-resonant *hh* production:

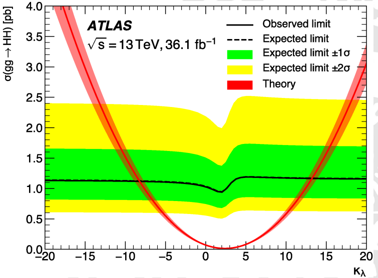


No significant excess.

Tight selection used to set 95% CL limits on the cross section for non-resonant production:

Observed	-1σ	Expected	$+1\sigma$
22	20	28	40

Loose selection used to set 95% CL limits on the Higgs self-coupling $\longrightarrow \longrightarrow \longrightarrow \longrightarrow$

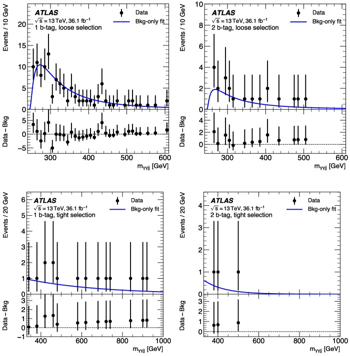


$(\kappa_\lambda = \lambda/\lambda_{SM})$

$\Longrightarrow -8.2 < \kappa_\lambda < 13.2$ @ 95% CL!

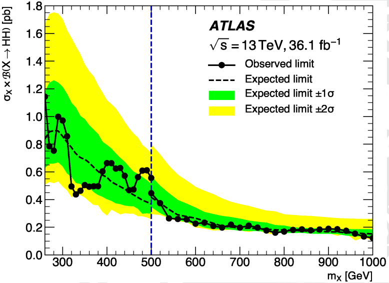
$hh \to bb\gamma\gamma$ – results

Resonant *hh* production:



Loose (tight) selection used up to (above) 500 GeV.

Observed 95% upper limits ranging from 1.14 to 0.12 pb.

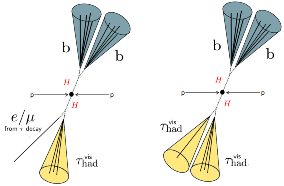


$hh \to bb\tau\tau$

$hh \to bb\tau\tau$ – event selections

Two sub-channels: $\tau_\ell\tau_h$ and $\tau_h\tau_h$ but three signal regions based on the trigger strategy:

- $\tau_\ell\tau_h$ channel:
  - Single-lepton trigger (SLT)
  - If !SLT, lepton-tau trigger (LTT)
- $\tau_h\tau_h$ channel:
  - Single- (STT) or di-τ (DTT) trigger



$\tau_\ell\tau_h$ selections:

- 1 lepton and 1 medium τ_h (OS)
- p_T^ℓ based on SLT/LTT thresholds
- $p_T^\tau > 20/30$ GeV
- $\geq$2 jets, $p_T^{j_{1(2)}} > 45$-80 (20) GeV*

$\tau_h\tau_h$ selections:

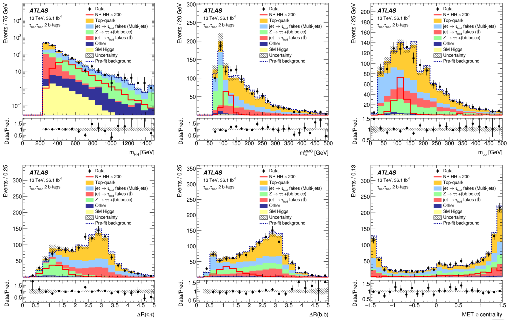
- 2 medium τ_h's (OS)
- $p_T^{\tau_{1(2)}} > 100$-180 (20) GeV for STT
- $p_T^{\tau_{1(2)}} > 40$ (30) GeV for DTT
- $\geq$2 jets, $p_T^{j_{1(2)}} > 45$-80 (20) GeV*

For all selected events, there must be 2 *b*-jets and the output of the Missing Mass Calculator must be $m_{\tau\tau}^{\rm MMC} > 60$ GeV.

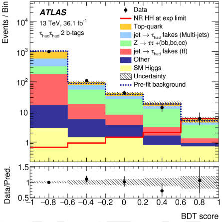
(*) $p_T^{j_1}$ is raised (45→80 GeV) when using LTT or DTT (level-1 trigger jet).

$hh \to bb\tau\tau$ – analysis strategy

BDTs to separate signal and background:



Variable	$\tau_{lep}\tau_{had}$ channel (SLT resonant)	$\tau_{lep}\tau_{had}$ channel (SLT non-resonant & LTT)	$\tau_{had}\tau_{had}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
E_T^{miss}	✓		
E_T^{miss} ϕ centrality	✓		✓
m_T^W	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_T(\text{lep}, \tau_{\text{had-vis}})$	✓		
Sub-leading b-jet p_T	✓		



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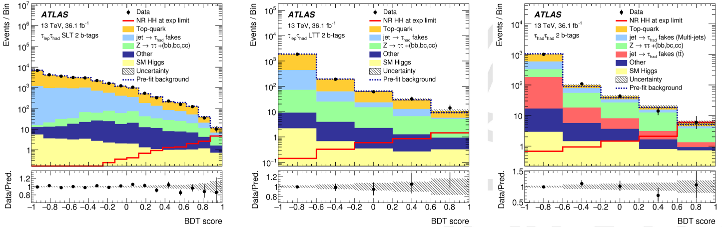
$hh \to bb\tau\tau$ – analysis strategy

Background estimation techniques:

- Top-quark background with true τ_hs: simulation + normalisation from data at low-BDT;
- Jet $\to$ fake τ_h:
  - $\tau_\ell\tau_h$: data-driven fake-factor method for all processes;
  - $\tau_h\tau_h$: fakes rates measured in data and applied to simulated $t\bar{t}$ + data-driven ABCD method for multi-jet events;
- $Z \to \tau\tau + bb/bc/cc$: simulation + normalisation from data;
- All other backgrounds: simulation.



$hh \to bb\tau\tau$ – results

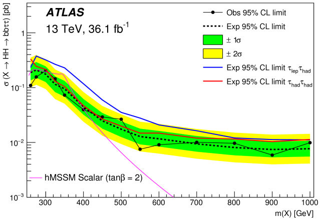
- Exclusion limits obtained from a fit of the BDT distributions in SRs and a single-bin $Z \to \mu\mu + bb$ region.
- Non-resonant *hh*: BDT separately trained for $\kappa_\lambda = 1$ (SM) and $\kappa_\lambda = 20$ (Higgs self-coupling scan).
- Resonant *hh*: BDT trained for every mass point, including the two neighbouring masses in the signal model.

Non-resonant *hh* production:

		Observed	-1σ	Expected	$+1\sigma$
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\mathrm{SM}}$	23.5	20.5	28.4	39.5
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\mathrm{SM}}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\mathrm{SM}}$	12.7	10.7	14.8	20.6

Most stringent limit on non-resonant hh at the LHC:
obs. (exp.): $12.7\,(14.8) \times \sigma^{hh}_{SM}$

Resonant *hh* production (2HDM interpretation):



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hh combination

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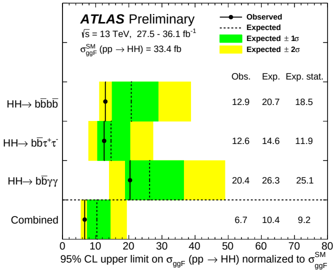
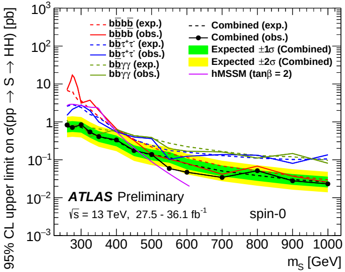
hh – statistical combination

Statistical combination of the 3 most sensitive channels:

Non-resonant *hh* production:



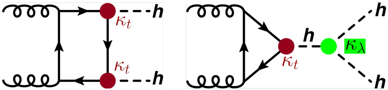
Resonant *hh* production:



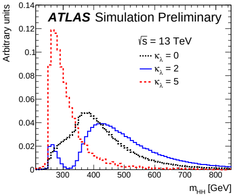
Non-resonant *hh* combined limit:

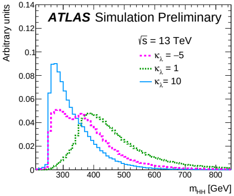
Observed (expected): $6.7\,(10.4) \times \sigma^{hh}_{\mathrm{SM}}$

hh – variation of the Higgs self-coupling



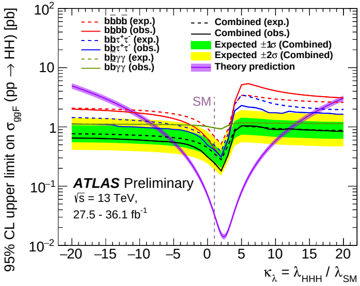
Variations of κ_λ affect the interference, hence m_{hh} and the signal acceptances.





With $\kappa_t = 1$, the Higgs self-coupling is observed (expected) to be constrained @ 95% CL to:

$$-5.0 < \kappa_\lambda < 12.1 \; (-5.8 < \kappa_\lambda < 12.0)$$



$H \to VV$ – summary of individual searches

There is a long list of searches for di-boson resonances in ATLAS, in both gluon-gluon fusion and VBF production modes. All of them provide an interpretation for $H \to VV$ and none of them found any significant deviation from the SM background predictions. See back-up slides for more details.

- $H \to ZZ \to 4\ell$ & $\ell\ell\nu\nu$: Eur. Phys. J. C 78 (2018) 293
- $H \to WW \to \ell\nu\ell\nu$: Eur. Phys. J. C 78 (2018) 24
- $H \to WW \to \ell\nu qq$: JHEP03 (2018) 042
- $H \to ZZ \to (\ell\ell/\nu\nu)qq$: JHEP03 (2018) 009
- $H \to VV \to qqqq$: Phys. Lett. B 777 (2017) 91 (*)

(*) The latest search for $VV \to qqqq$ resonances with 80/fb of data can be found in ATLAS-CONF-2018-016.

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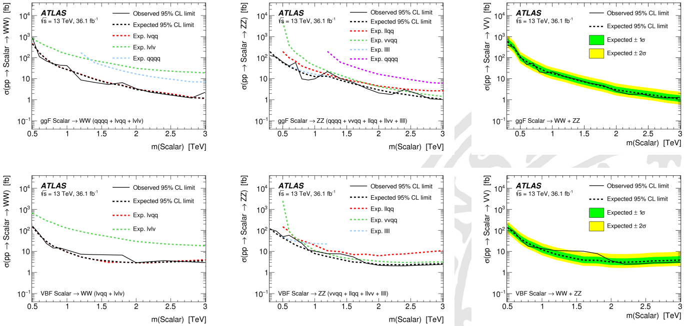
$H \to VV$ – combination

Statistical combinations of $H \to WW$, $H \to ZZ$ and $H \to WW + ZZ$ in an empirical heavy scalar model

$H \to WW$ | $H \to ZZ$ | $H \to VV$

ggF

VBF



The largest local excess is in the VBF $H \to WW + ZZ$ search, with a significance of 2.9σ for a mass of 1.6 TeV.

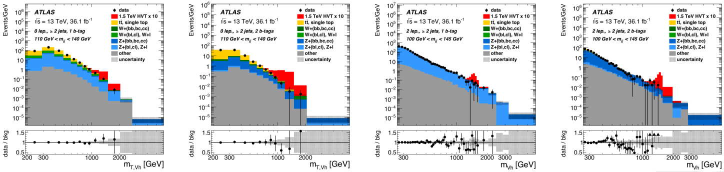
$A \to Zh$ – analysis flow

Search for *gg* fusion & *b*-associated production of $A \to Z(\ell\ell/\nu\nu)h(bb)$.

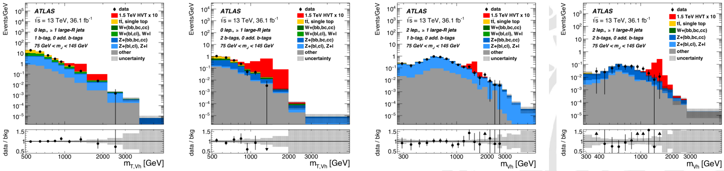
- $Z \to \ell\ell,\ \nu\nu \Rightarrow$ 0/2 leptons:
  - trigger = $E_{\mathrm{T}}^{\mathrm{miss}}$ or single-lepton;
  - discriminant = m_{Zh}^{T} or m_{Zh};
- $h \to bb \Rightarrow$ two categories:
  - resolved = two small-R jets: $m_{jj} = 110 - 140$ GeV (0ℓ) or $100 - 145$ GeV (2ℓ), 1 or 2 *b*-tags;
  - merged = one large-R jet: $m_{jj} = 75 - 145$ GeV, $\geq$1 associated track-jet;
- resolved events with >2 *b*-tags and merged events with additional *b*-tagged track-jets $\Rightarrow$ *bbA* mode;
- additional cuts are applied to reduce the SM backgrounds.

$A \to Zh$ – mass plots

Resolved, 0/2 leptons, 1 or 2 *b*-tags:



Merged, 0/2 leptons, no extra *b*-tag:



Disclaimer: a spin-1 Z’ boson (HVT) signal is shown in these plots...

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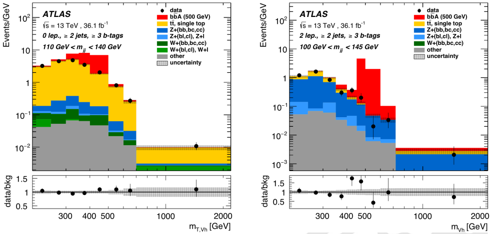
$A \rightarrow Zh$ – mass plots

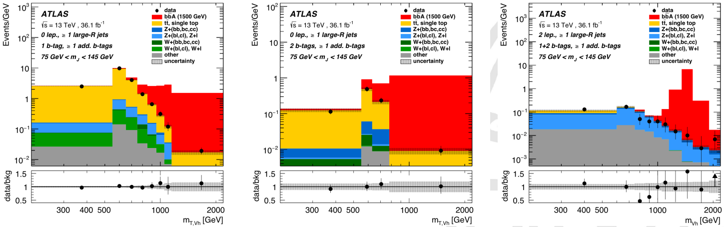
Probing the *bbA* mode:

Resolved ⇒



Merged

⇓



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BSM Higgs boson searches with ATLAS

Arnaud Ferrari

Introduction

Charged Higgs boson searches

Neutral Higgs boson decays to fermions

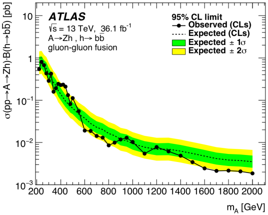
Higgs boson pair production

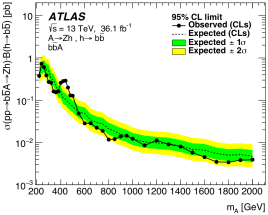
Neutral Higgs boson decays to VV/Vh

Conclusion

$A \to Zh$ – results

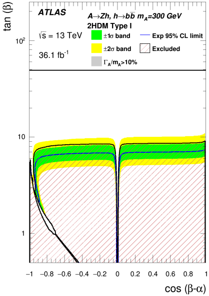
3.6σ excess at 440 GeV, mostly driven by the $\mu\mu$ channel with $\geq$3 b-tags (global excess of 2.4σ).

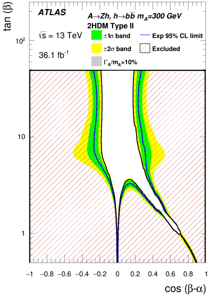




Exclusion contours for a type-I (II) 2HDM at $m_A = 300$ GeV $\longrightarrow$

Exclusion plots in the $(m_A; \tan\beta)$ plane for $\cos(\alpha-\beta) = 0.1$ in JHEP03 (2018) 174.





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Bonus: $A \to ZH$ – event selections

The mass degeneracy of A and H can be relaxed in e.g. 2HDM electroweak baryogenesis, motivating a search for $A \to Z(\ell\ell)H(bb)$ [Phys. Lett. B 783 (2018) 392].

Gluon-gluon fusion and bbA modes probed by defining two event categories: $2b$ and $\geq 3b$.

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; $80 \text{ GeV} < m_{\ell\ell},\ m_{e\mu} < 100$ GeV, $\ell = e,\ \mu$

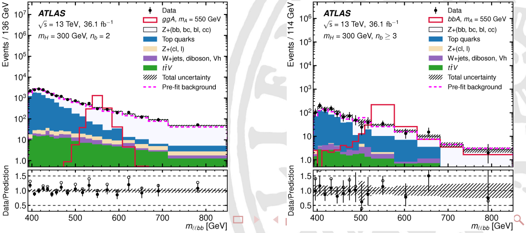
At least 2 b-jets ($p_T > 20$ GeV) with one of them having $p_T > 45$ GeV

$E_T^{miss}/\sqrt{H_T} < 3.5\ \text{GeV}^{1/2}$, $\sqrt{\Sigma p_T^2}/m_{\ell\ell bb} > 0.4$

	$n_b = 2$ category	$n_b \geq 3$ category
	Exactly 2 b-tagged jets	At least 3 b-tagged jets
Signal region	ee or $\mu\mu$ pair $0.85 \cdot m_H - 20\ \text{GeV} < m_{bb} < m_H + 20$ GeV	ee or $\mu\mu$ pair $0.85 \cdot m_H - 25\ \text{GeV} < m_{bb} < m_H + 50$ GeV

Discriminant: $m_{\ell\ell bb}$

Shown here for $m_A = 550$ GeV, $m_H = 300$ GeV.



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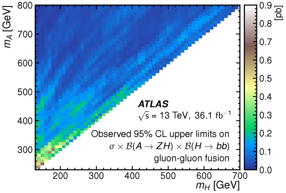
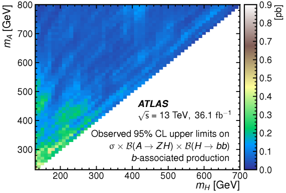
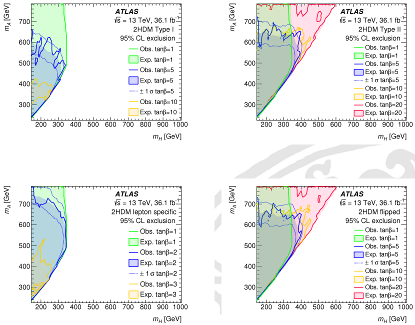
Bonus: $A \to ZH$ – results

Observed 95% CL model-independent limits:





2HDM interpretations:

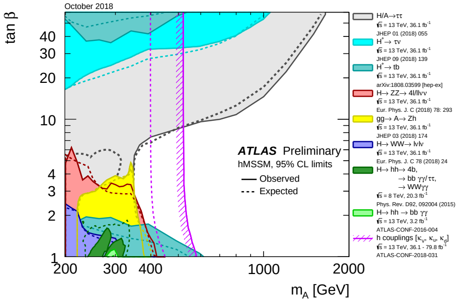


High tan $\beta \to$ ggF decreases, so the sensitivity is driven by *bbA* in type-II and flipped 2HDMs.

Conclusion

There is a plethora of searches for physics beyond the Standard Model in the Higgs sector at the LHC.

Only a small selection of results were presented here...



No significant excess has been observed so far.

The LHC has performed extremely well during the Run-2, we have about 140/fb of *pp* collision data at 13 TeV to analyse.

Thank you for your attention! Do you have any questions?

Sven Heinemeyer – Charged Higgs 2018 (Uppsala), 27.09.2018

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BSM Higgs boson searches with ATLAS

Arnaud Ferrari

BACK-UP SLIDES

More on $A/H \to t\bar{t}$

Gluon-gluon fusion $A/H \to t\bar{t}$ (8 TeV dataset)

Potentially the golden channel for $m_{A/H}$ above 350 GeV at low tan β... but the destructive interference between the signal and the $t\bar{t}$ background must be taken into account!

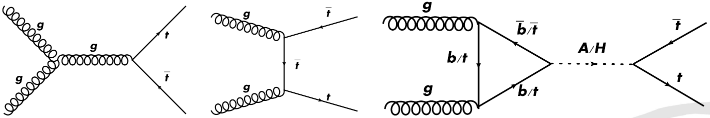
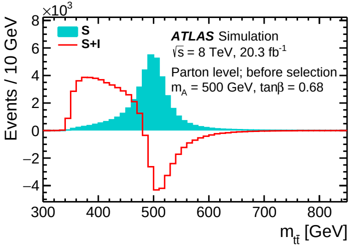


Diagram removal scheme: Madgraph was modified to remove the SM $t\bar{t}$ matrix element to yield only the signal+interference on an event-by-event basis.



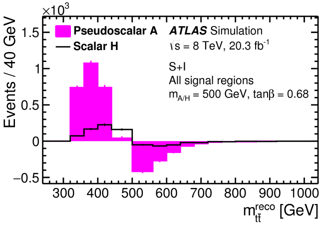
$\Rightarrow$ Search for a peak-and-dip structure.

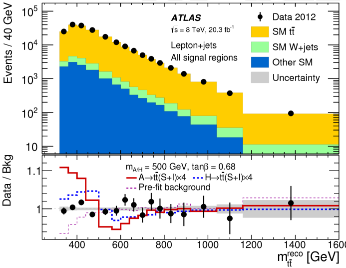
Gluon-gluon fusion $A/H \to t\bar{t}$ (8 TeV dataset)

Revisit the $t\bar{t}$ resonance search of JHEP08 (2015) 148:

- final states with e/μ + $\geq$4 jets (including $\geq$1 b-tag),
- $E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV,
- jet assignment via a kinematic fit (using m_W and m_t as constraints),
- three b-tagging categories depending on whether b-jets are coming from hadronic or semi-leptonic top-quark candidates;
- main backgrounds: $t\bar{t}$ (MC), multi-jet and W+jets events (data-driven).

Example of m_{tt} template for $S + I$:



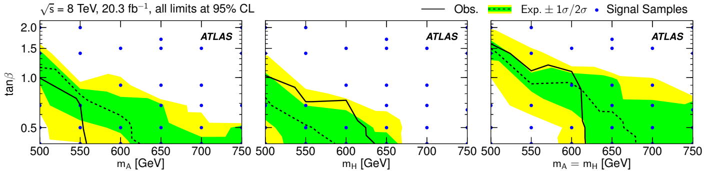


Gluon-gluon fusion $A/H \to t\bar{t}$ (8 TeV dataset)

The shape of the binned reconstructed m_{tt} distribution is parameterised as a function of the signal strength μ:

$$\mu S + \sqrt{\mu} I + B = \sqrt{\mu}(S + I) + (\mu - \sqrt{\mu})S + B$$

Limits were set as a function of $\tan\beta$ in a type-II 2HDM. Assume $\sin(\alpha - \beta) = 1$, $m_{12}^2 = m_A^2 \tan\beta/(1 + \tan^2\beta)$ and $m_h = 125$ GeV:



Blue points are for the generated samples. Upper limits at intermediate points are obtained from a linear triangular interpolation.

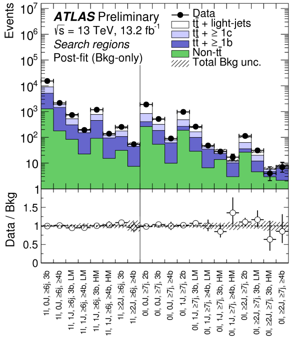
Correction factors K_S and K_B are applied to S and B to normalise their cross-sections to NNLO predictions. The correction factor for the interference term I is $\sqrt{K_S \times K_B}$.

$(b\bar{b}/t\bar{t}) + A/H \rightarrow t\bar{t}$ (13 TeV, 13.2/fb)

- negligible interference with backgrounds :-)
- complicated final states :-(

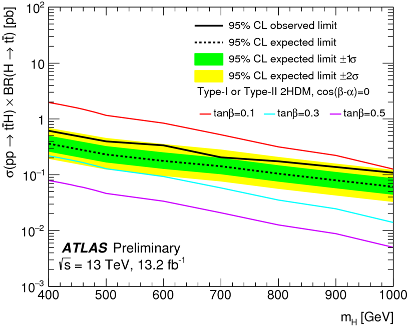
ATLAS has no dedicated search for $(b\bar{b}/t\bar{t}) + A/H \rightarrow t\bar{t}$. But the search for $t\bar{t}$ final states + heavy-flavour jets was re-interpreted as BSM Higgs searches.

- Lepton+jets selection.
- Split between search and validation regions based on #jets and #*b*-tags.
- Main background: $t\bar{t}$ + jets.
- Optimized for VLQ/4t but re-used for BSM Higgs interpretations.



$(b\bar{b}/t\bar{t}) + A/H \to t\bar{t}$ (13 TeV, 13.2/fb)

- $b\bar{b} + A/H(t\bar{t})$ not sensitive to 2HDM yet.
- $t\bar{t} + A/H(t\bar{t})$ can exclude very low $\tan\beta$ in 2HDM type-I/II.
- Limits on top-associated $H^+ \to tb$ less stringent than with the optimized search.



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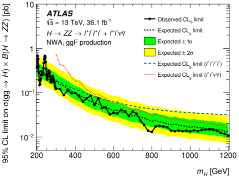
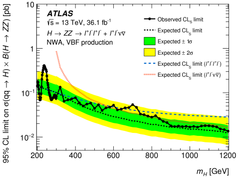
Individual $H \to VV$ searches

$H \to VV$ – summary of individual searches

- $H \to ZZ \to 4\ell$ & $\ell\ell\nu\nu$:

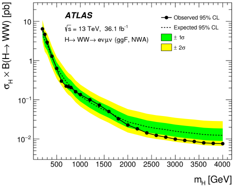


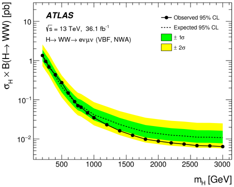


Two 3.6σ excesses:
- 240 GeV in $4e$ only (not covered by $\ell\ell\nu\nu$)
- 700 GeV in 4ℓ (excluded by $\ell\ell\nu\nu$)

$\Rightarrow$ 1.3σ global excess.

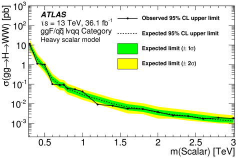
- High-mass $H \to WW \to e\nu\mu\nu$:

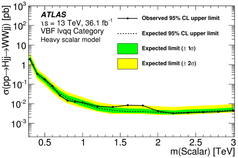




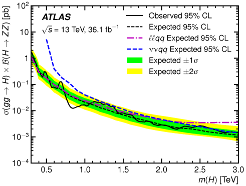
$H \to VV$ – summary of individual searches

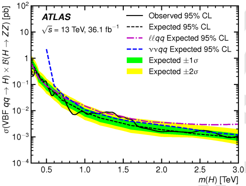
$H \to WW \to \ell\nu qq$



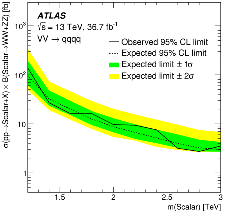


$H \to ZZ \to \ell\ell qq$
$H \to ZZ \to \nu\nu qq$





$H \to VV \to qqqq$
High-mass $\Rightarrow JJ$



No VBF category.

H^{++} searches

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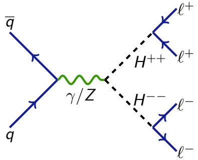
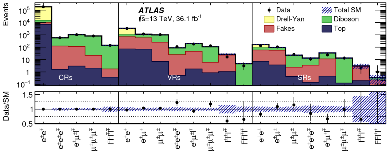
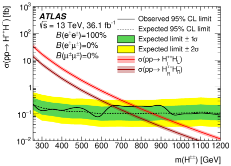
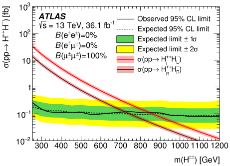
$H^{++}H^{--} \rightarrow \ell^+\ell^+\ell^-\ell^-$ (13 TeV, 36.1/fb)

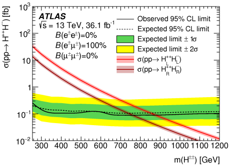
Pairs of doubly-charged Higgs bosons were searched for by ATLAS, in fully-leptonic channels. No deviation from the SM prediction was found: arXiv:1710.09748 [hep-ex].











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$H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^-$ (13 TeV, 36.1/fb)