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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

Higgs boson searches beyond the Standard Model with the ATLAS experiment

Arnaud Ferrari (Uppsala University)

Uppsala University, 22 November 2018





- 1 Introduction
- 2 Charged Higgs boson searches
- 3 Neutral Higgs boson decays to fermions
- 4 Higgs boson pair production
- 5 Neutral Higgs boson decays to VV/Vh
- 6 Conclusion



Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion

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- 2 Charged Higgs boson searches
- 3 Neutral Higgs boson decays to fermions
- 4 Higgs boson pair production
- 5 Neutral Higgs boson decays to VV/Vh
- 6 Conclusion





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} (5.9σ).

BSM Higgs
boson searches
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Arnaud Ferrari

Introduction

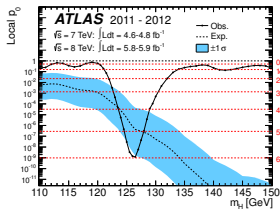
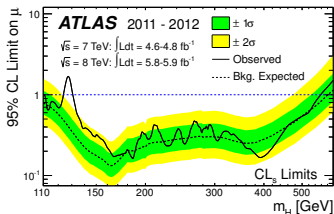
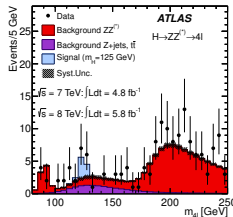
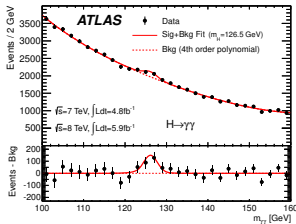
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boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion



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



Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

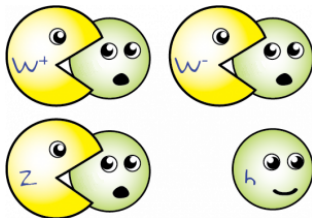
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Neutral Higgs
boson decays to
 VV/Vh

Conclusion

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...





Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

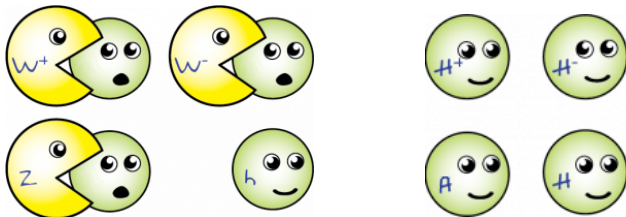
Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion

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.



Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV / Vh

Conclusion

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 $\tan \beta$.

Various benchmark scenarios where SUSY parameters enter as radiative corrections:



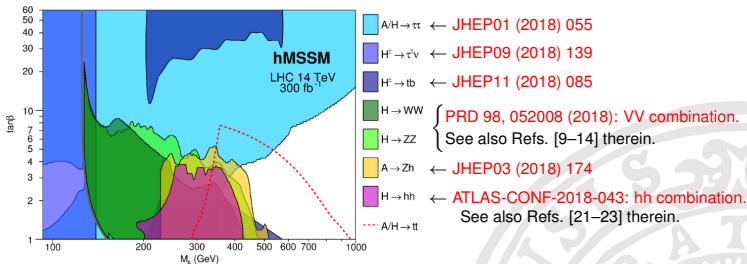
- m_h^{\max} : m_h is maximised for fixed $\tan \beta$ and large m_A .
- $m_h^{\text{mod}\pm}$: the top-squark mixing parameter is chosen so that m_h is close to 125 GeV.
- $h\text{MSSM}$: the measured value of m_h is used to predict the remaining Higgs boson masses and couplings, without explicit reference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



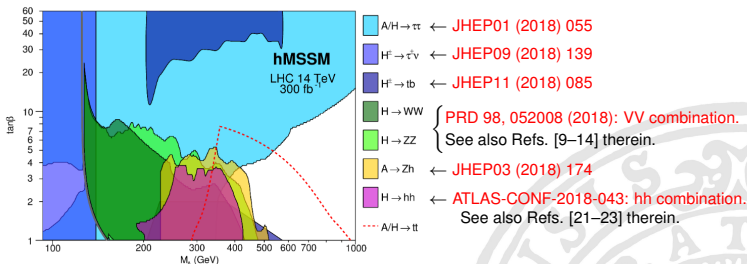
Disclaimer: most experimental results shown here are motivated by or interpreted in 2HDMs, but several other theories predict extended Higgs sectors, e.g. 2HDM+S, Higgs triplets, etc.



Minimal Supersymmetric Standard Model

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The Large Hadron Collider in one slide

BSM Higgs boson searches with ATLAS

Arnaud Ferrari

Introduction

Charged Higgs boson searches

Neutral Higgs boson decays to fermions

Higgs boson pair production

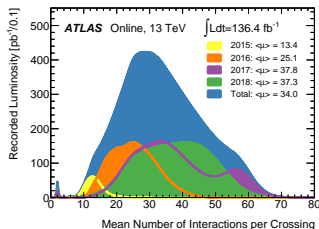
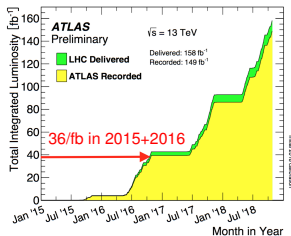
Neutral Higgs boson decays to VV/Vh

Conclusion



- 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: $10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$ (design), but achieved twice higher!

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





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The ATLAS experiment in one slide

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Introduction

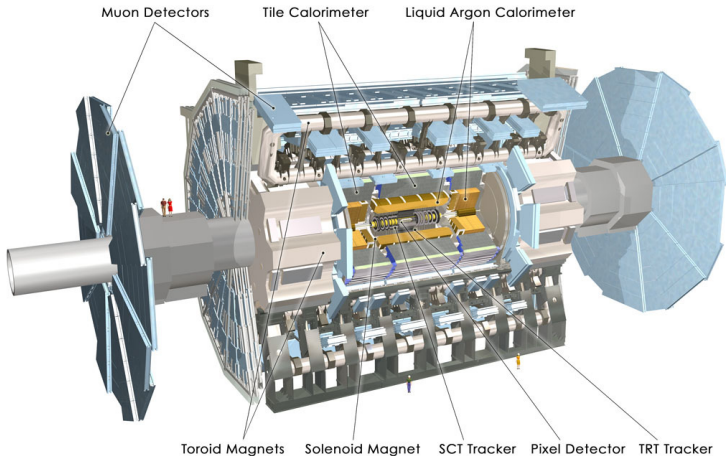
Charged Higgs
boson searches

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fermions

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production

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boson decays to
 VV/Vh

Conclusion





- 1 Introduction
- 2 Charged Higgs boson searches**
- 3 Neutral Higgs boson decays to fermions
- 4 Higgs boson pair production
- 5 Neutral Higgs boson decays to VV/Vh
- 6 Conclusion



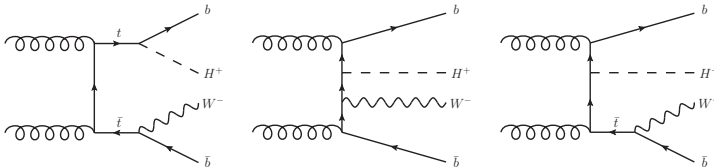


H^+ production and decays

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

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Arnaud Ferrari



Introduction

Charged Higgs boson searches

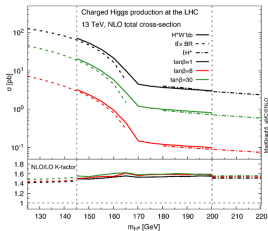
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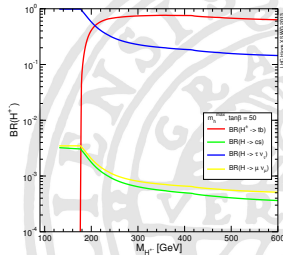
Conclusion

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



M. Zaro @ charged2018 (Uppsala).

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



From the LHC Higgs XS WG twiki page.





$H^+ \rightarrow \tau\nu$ – event selections

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

→ 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:

- ≥ 1 τ object with $p_T^\tau > 40$ GeV,
- ≥ 3 jets with $p_T > 25$ GeV, including ≥ 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.

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

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

→ 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 $\mu + \tau$,
- ≥ 1 b -tagged jet with $p_T > 25$ GeV,
- $E_T^{\text{miss}} > 50$ GeV.



$H^+ \rightarrow \tau\nu$ – 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:

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

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

BDT mass bins:

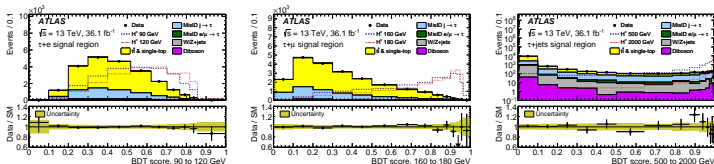
- 90–120 GeV;
- 130–160 GeV;
- 160–180 GeV;
- 200–400 GeV;
- 500–2000 GeV.

$H^+ \rightarrow \tau\nu$ – results

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

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Introduction

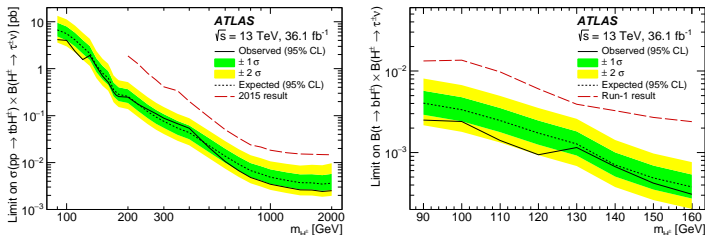
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

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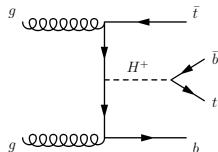
Conclusion



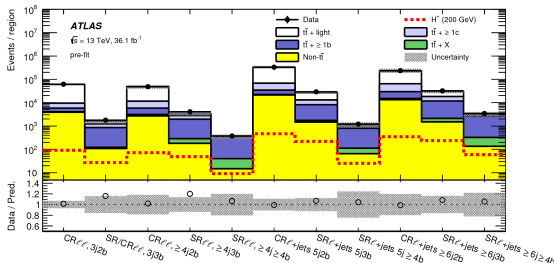


$H^+ \rightarrow tb$ – event selections

- At least one leptonic top-quark decay
⇒ **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 \geq 4b, CR \geq 6j2b, SR \geq 6j3b, SR \geq 6j \geq 4b.
 Di-lepton: CR 3j2b, CR/SR 3j3b, CR \geq 4j2b, SR \geq 4j3b, SR \geq 4j \geq 4b.



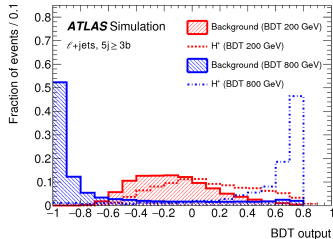
$H^+ \rightarrow tb$ – analysis strategy

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



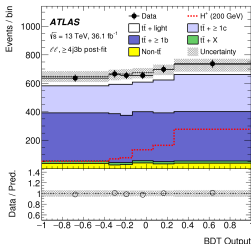
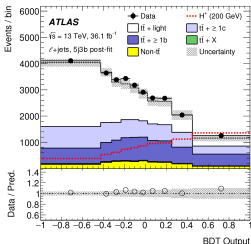


$H^+ \rightarrow tb$ – results

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.

BSM Higgs boson searches with ATLAS

Arnaud Ferrari



Introduction

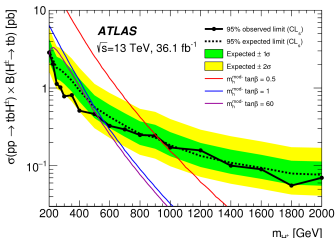
Charged Higgs boson searches

Neutral Higgs boson decays to fermions

Higgs boson pair production

Neutral Higgs boson decays to VV/Vh

Conclusion



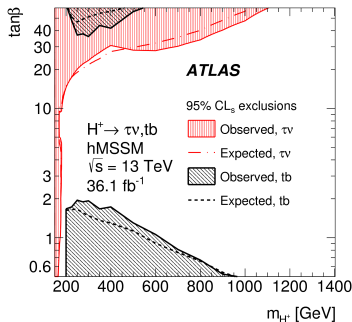
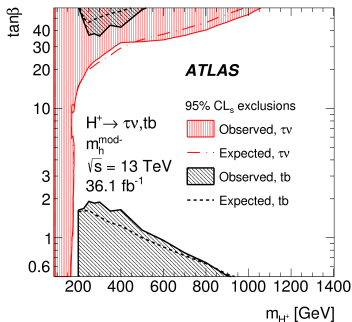
Systematics-dominated analysis:

Uncertainty Source	$\Delta\rho(H_{\tau\tau}^{\pm})$ [pb]	$\Delta\rho(H_{bb}^{\pm})$ [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
$H^+ \rightarrow \tau b$ 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_{τ}^{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
$t\bar{t} + > 1c$ 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 $H^+ \rightarrow \tau\nu$ and $H^+ \rightarrow tb$ exclusion limits in the $(m_{H^+}; \tan\beta)$ plane of two MSSM scenarios illustrates the complementary of the two channels.





- 1 Introduction
- 2 Charged Higgs boson searches
- 3 Neutral Higgs boson decays to fermions**
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- 5 Neutral Higgs boson decays to VV/Vh
- 6 Conclusion



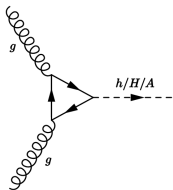


A/H production and decays

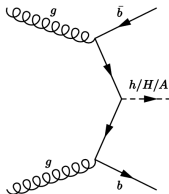
Heavy neutral Higgs bosons are produced via gluon-gluon fusion or b -associated production (enhanced at high $\tan\beta$):

BSM Higgs boson searches with ATLAS

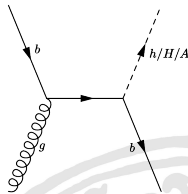
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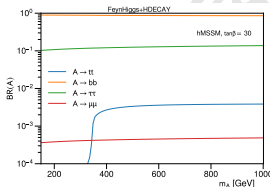
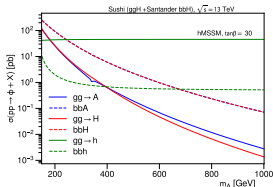
gg fusion



b -associated, 4FS



b -associated, 5FS



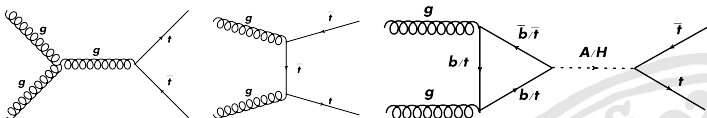
Decays to $b\bar{b}$ & $\tau\tau$ at high $\tan\beta$, or to $t\bar{t}$ at low $\tan\beta$.

G. Hamity, private communication



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

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



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

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

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



$A/H \rightarrow \tau\tau$ – 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	$\tau_\ell\tau_h$		$\tau_h\tau_h$	
	b -veto	b -tag	b -veto	b -tag
Trigger	$1\ \ell$	$1\ \ell$	$1\ \tau$	$1\ \tau$
N_ℓ (p_T in GeV)	≥ 1 (30)	≥ 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)	$= 0$	≥ 1	$= 0$	≥ 1
$\Delta\phi$ ($\ell\tau_h$ or $\tau_{h1}\tau_{h2}$)	> 2.4	> 2.4	> 2.7	> 2.7
$m_T(\ell, E_T^{\text{miss}})$ [GeV]	< 40	< 40	-	-
$m_{\text{vis}}(e, \tau_h)$ [GeV]	$\neq 80\text{-}110$	$\neq 80\text{-}110$	-	-

Discriminating variable:

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

Background modelling

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



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

Background with a true τ_h estimated with simulation.

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

BSM Higgs
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Introduction

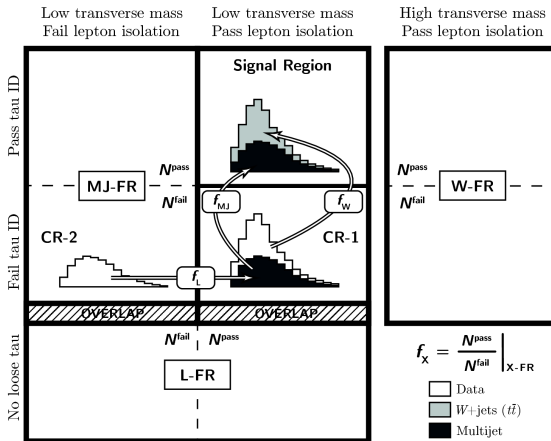
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boson searches

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$A/H \rightarrow \tau_h \tau_h - \text{background}$

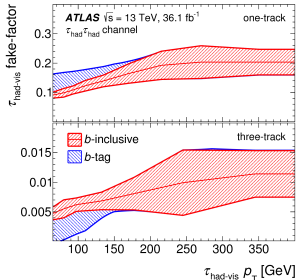
Simulated background processes \rightarrow fake-rate method:

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

Multi-jet processes \rightarrow fake-factor method:

$$N_{\text{multijet}}^{\text{SR}}(v; \mathbf{y}) = f_{\text{DJ}}(\mathbf{y}) \cdot [N_{\text{data}}^{\text{CR-1}}(v; \mathbf{y}) - N_{\text{non-MJ}}^{\text{CR-1}}(v; \mathbf{y})]$$

- 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).





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Introduction

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boson searches

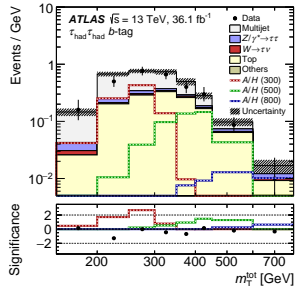
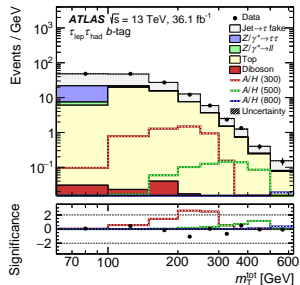
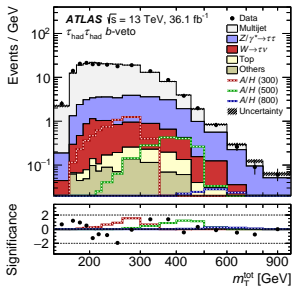
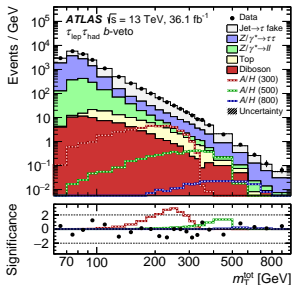
Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion

$A/H \rightarrow \tau\tau$ - results



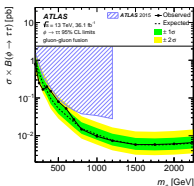


A/H → ττ – exclusion limits

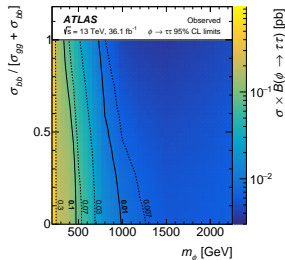
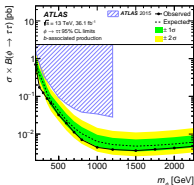
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boson searches
with ATLAS

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ggφ limits



bbφ limits



Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

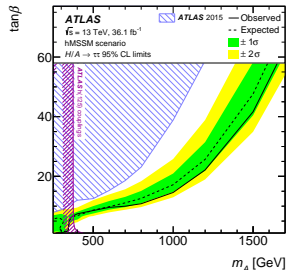
Higgs boson pair
production

Neutral Higgs
boson decays to
VV / Vh

Conclusion

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 →





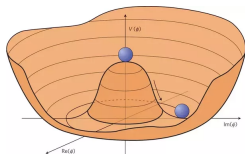
- 1 Introduction
- 2 Charged Higgs boson searches
- 3 Neutral Higgs boson decays to fermions
- 4 Higgs boson pair production**
- 5 Neutral Higgs boson decays to VV/Vh
- 6 Conclusion





Reminder: the Higgs potential

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



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

mass term

self-interaction terms

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



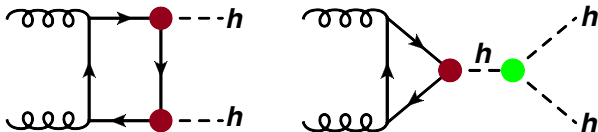
$\rightarrow v = \mu/\sqrt{\lambda} = 246 \text{ GeV}$ and $\lambda = m_h^2/(2v^2) = 0.13$ fully determine the shape of the Higgs potential.

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



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

σ_{NLO}^{hh} 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.

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boson searches
with ATLAS

Arnaud Ferrari

Introduction

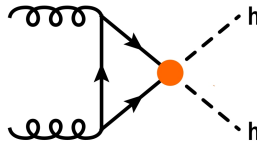
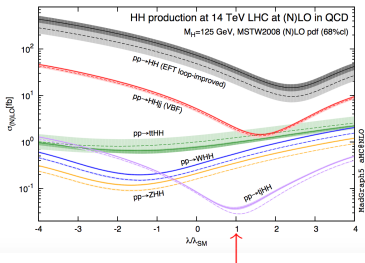
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

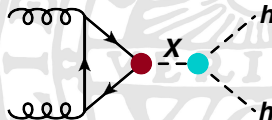
Conclusion



← Phys. Lett. B732 (2014) 142
(λ = Higgs self-coupling)

Resonant Higgs boson pair production:

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





Higgs boson pair decays

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	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.10%	0.029%	0.013%	0.0053%

Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion

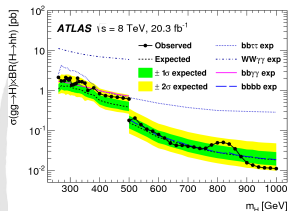
Run-1 legacy:

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)

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





**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

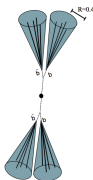
$$hh \rightarrow bbbb$$



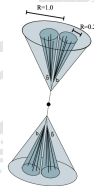
$hh \rightarrow bbbb$ – event categories

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 $\int L dt$ (fb^{-1})	Combination of b -jet triggers 3.2+24.3	Single large- R jet trigger 36.1
N_{jets}	≥ 4 jets, $R = 0.4$	≥ 2 jets, $R = 1.0$
p_T cut	40 GeV	450 / 250 GeV
b -tagging	70% for all jets	70% on track-jets with $R = 0.2$
$N_{b\text{-jets}}$	4	2, 3, 4

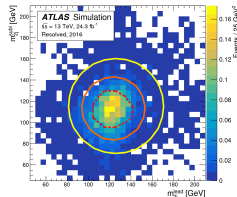




$hh \rightarrow bbbb$ – resolved topology

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.

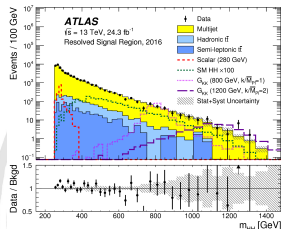
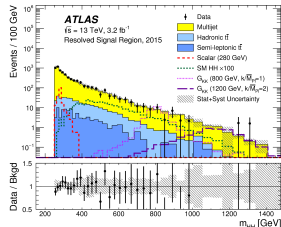


$hh \rightarrow bbbb$ – resolved topology

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

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

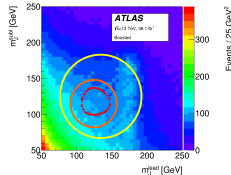




$hh \rightarrow bbbb$ – boosted topology

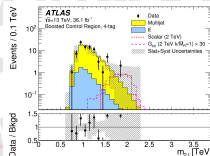
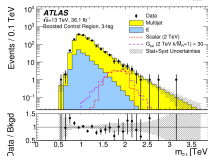
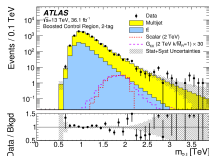
Event selection:

- 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.



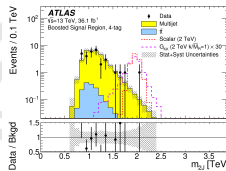
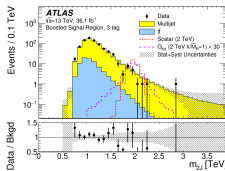
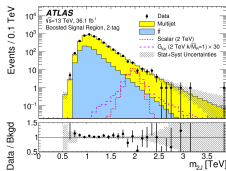


$hh \rightarrow bbbb$ – boosted topology

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 \pm 150	702 \pm 63	32.9 \pm 6.9
$t\bar{t}$	860 \pm 110	80 \pm 33	1.7 \pm 1.4
Total	4250 \pm 130	782 \pm 51	34.6 \pm 6.1
G_{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 \pm 3.5
Data	4376	801	31

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





$hh \rightarrow bbbb$ – 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.

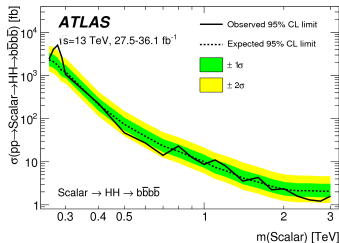
Non-resonant hh production:

Observed 95% CL upper limit on $\sigma_{hh} \times \text{BR}(bbbb)$ 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):





**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

$$hh \rightarrow bb\gamma\gamma$$



$hh \rightarrow bb\gamma\gamma$ – 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

- ≥ 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 \rightarrow data-driven estimates of the background shape.

Additional loose (tight) selection

- Optimised for 260–500 GeV & varied λ (≥ 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].



$hh \rightarrow bb\gamma\gamma$ – 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 \rightarrow Novosibirsk (exponential) function for the loose (tight) event selection.

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

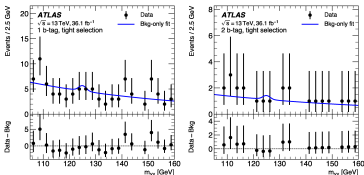


$hh \rightarrow bb\gamma\gamma$ – results

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Non-resonant hh production:



No significant excess.

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

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

Introduction

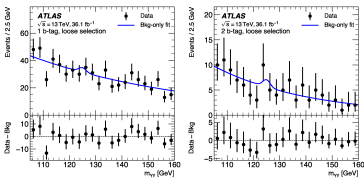
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

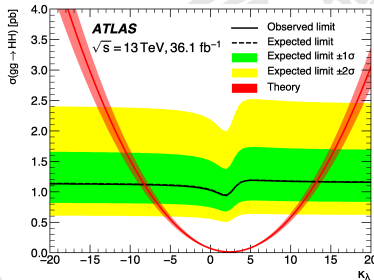
Neutral Higgs
boson decays to
 VV / Vh

Conclusion



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

$\Rightarrow -8.2 < \kappa_\lambda < 13.2 @ 95\% \text{ CL!}$

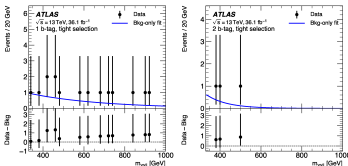
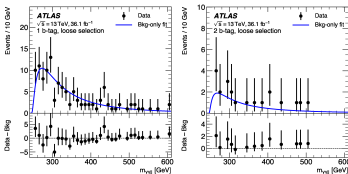


$(\kappa_\lambda = \lambda / \lambda_{\text{SM}})$



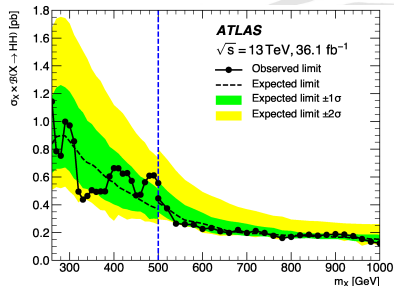
$hh \rightarrow bb\gamma\gamma$ – results

Resonant hh production:



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

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



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



**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

$$hh \rightarrow bb\tau\tau$$



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

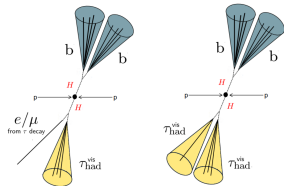
Two sub-channels: $\tau_\ell\tau_h$ and $\tau_h\tau_h$ but three signal regions based on the trigger strategy:

● $\tau_\ell\tau_h$ 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
- ≥ 2 jets, $p_T^{j(2)} > 45-80$ (20) GeV*

$\tau_h\tau_h$ selections:

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

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

(*) p_T^j is raised (45 \rightarrow 80 GeV) when using LTT or DTT (level-1 trigger jet).



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

BDTs to separate signal and background:

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Arnaud Ferrari

Introduction

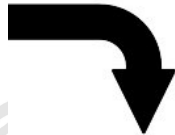
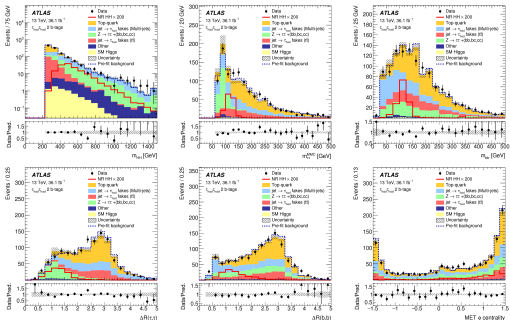
Charged Higgs boson searches

Neutral Higgs boson decays to fermions

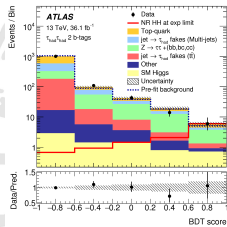
Higgs boson pair production

Neutral Higgs boson decays to VV/Vh

Conclusion



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_{MMC}	✓	✓	✓
$m_{\tau\tau}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau, \tau)$	✓	✓	✓
$\Delta R(b, b)$	✓	✓	✓
E_T^{miss}	✓	✓	✓
$E_T^{miss} \phi$ centrality	✓	✓	✓
m_T^W	✓	✓	✓
$\Delta\phi(H, H)$	✓	✓	✓
$\Delta p_T(lep, \tau_{had-vis})$	✓	✓	✓
Sub-leading b -jet p_T	✓	✓	✓

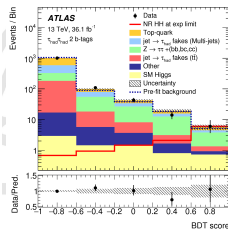
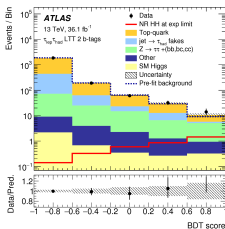
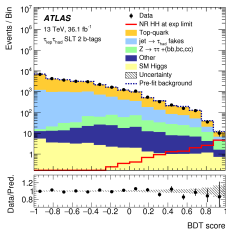




$hh \rightarrow bb\tau\tau$ – analysis strategy

Background estimation techniques:

- Top-quark background with true τ_h s: simulation + normalisation from data at low-BDT;
- Jet \rightarrow 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;
- $Z \rightarrow \tau\tau + bb/bc/cc$: simulation + normalisation from data;
- All other backgrounds: simulation.





$hh \rightarrow bb\tau\tau$ – results

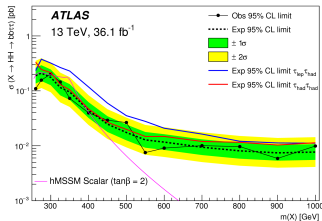
- Exclusion limits obtained from a **fit of the BDT distributions** in SRs and a single-bin $Z \rightarrow \mu\mu + bb$ region.
- **Non-resonant hh** : BDT separately trained for $\kappa_\lambda = 1$ (SM) and $\kappa_\lambda = 20$ (Higgs self-coupling scan).
- **Resonant hh** : BDT trained for every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

Non-resonant hh production:

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

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

Resonant hh production
(2HDM interpretation):





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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

hh combination



hh – statistical combination

Statistical combination of the 3 most sensitive channels:

Non-resonant *hh* production:

Resonant *hh* production:

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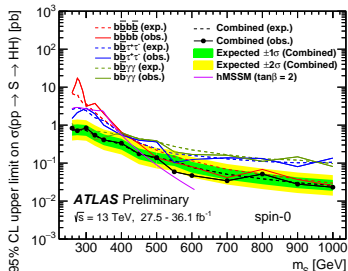
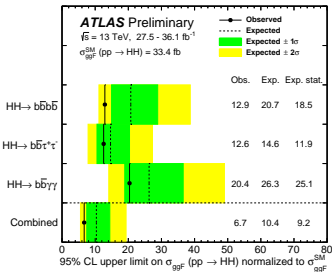
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
VV / *Vh*

Conclusion

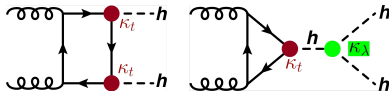


Non-resonant *hh* combined limit:

Observed (expected): $6.7 (10.4) \times \sigma_{\text{SM}}^{\text{hh}}$



hh – variation of the Higgs self-coupling



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

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Introduction

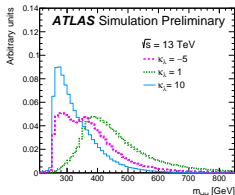
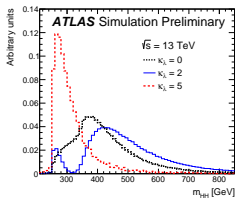
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

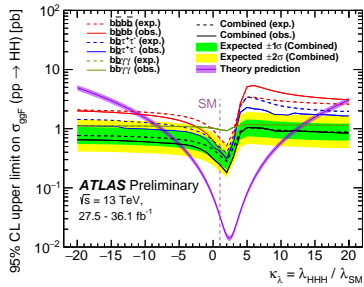
Neutral Higgs
boson decays to
 VV/Vh

Conclusion



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

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





- 1 Introduction
- 2 Charged Higgs boson searches
- 3 Neutral Higgs boson decays to fermions
- 4 Higgs boson pair production
- 5 Neutral Higgs boson decays to VV/Vh**
- 6 Conclusion



$H \rightarrow VV$ – 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 $H \rightarrow VV$** and none of them found any significant deviation from the SM background predictions. See back-up slides for more details.

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

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



$H \rightarrow VV$ – combination

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

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Introduction

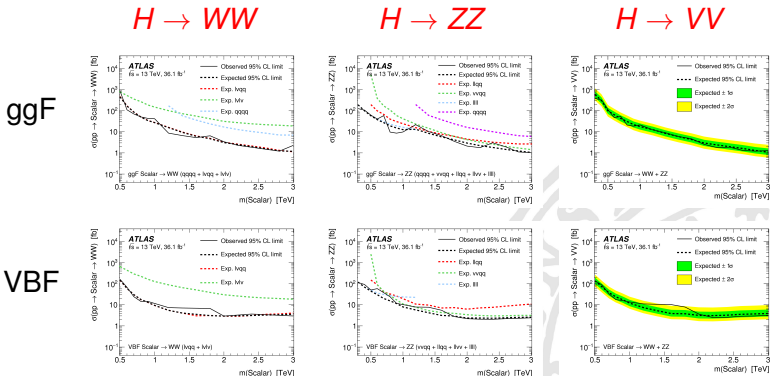
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion



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





$A \rightarrow Zh$ – analysis flow

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

- $Z \rightarrow \ell\ell, \nu\nu \Rightarrow 0/2$ leptons:
 - trigger = E_T^{miss} or single-lepton;
 - discriminant = m_{Zh}^T or m_{Zh} ;
- $h \rightarrow bb \Rightarrow$ 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,
 ≥ 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.

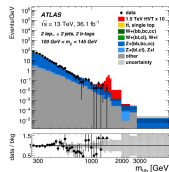
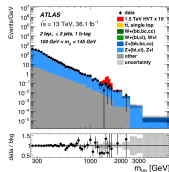
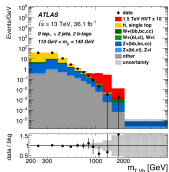
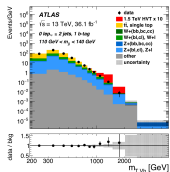


$A \rightarrow Zh$ – mass plots

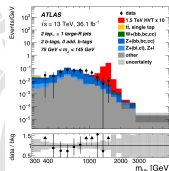
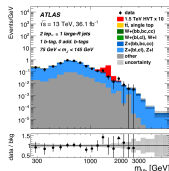
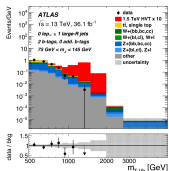
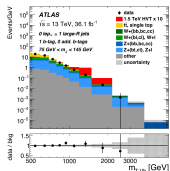
Resolved, 0/2 leptons, 1 or 2 b -tags:

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



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



$A \rightarrow Zh$ – mass plots

Probing the bbA mode:

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Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

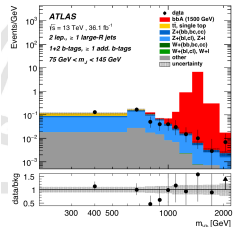
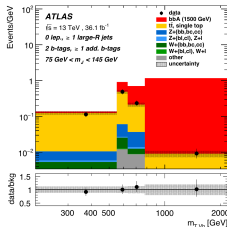
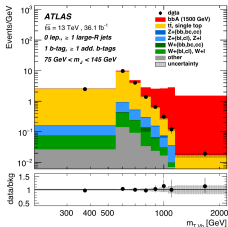
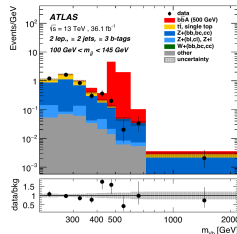
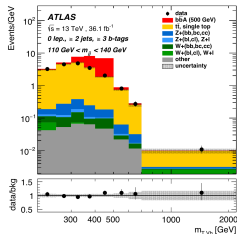
Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion

Resolved \Rightarrow

Merged



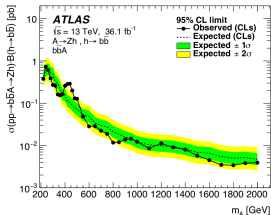
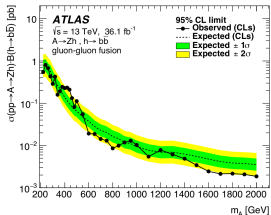


$A \rightarrow Zh$ – results

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

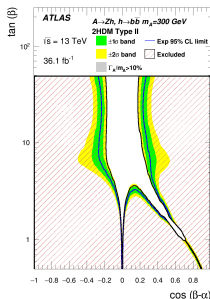
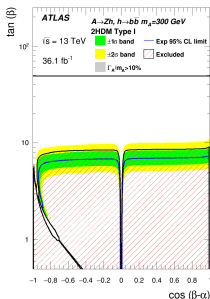
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Exclusion contours for a type-I (II) 2HDM at $m_A = 300 \text{ GeV} \rightarrow$

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





Bonus: $A \rightarrow ZH$ – event selections

The mass degeneracy of A and H can be relaxed in e.g. 2HDM electroweak baryogenesis, motivating a search for $A \rightarrow Z(\ell\ell)H(bb)$ [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

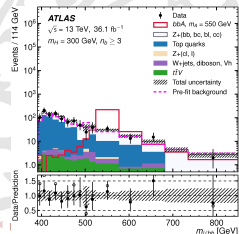
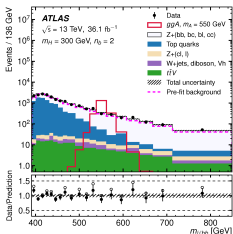
Exactly 2 leptons (e or μ) ($p_T > 7$ GeV) with the leading one having $p_T > 27$ GeV
Opposite electric charge for $\mu\mu$ or $e\mu$ pairs; $80 \text{ GeV} < m_{\ell\ell}, m_{e\mu} < 100$ GeV, $\ell = e, \mu$
At least 2 b -jets ($p_T > 20$ GeV) with one of them having $p_T > 45$ GeV

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

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

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

Shown here for
 $m_A = 550 \text{ GeV}$,
 $m_H = 300 \text{ GeV}$.





Bonus: $A \rightarrow ZH$ – results

Observed 95% CL
model-independent
limits:

2HDM interpretations:

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Introduction

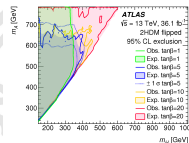
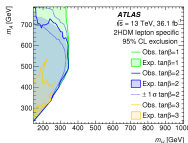
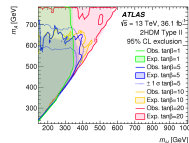
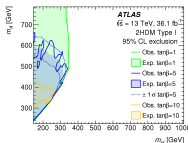
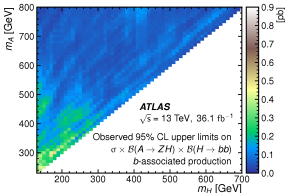
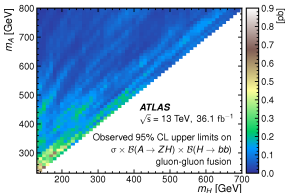
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion



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



- 1 Introduction
- 2 Charged Higgs boson searches
- 3 Neutral Higgs boson decays to fermions
- 4 Higgs boson pair production
- 5 Neutral Higgs boson decays to VV/Vh
- 6 Conclusion





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...

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Introduction

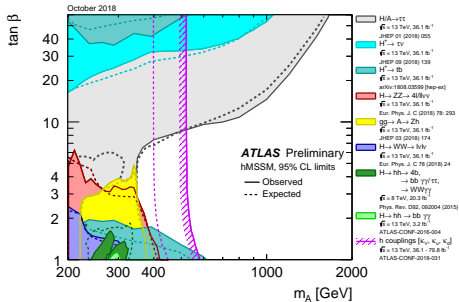
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boson searches

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fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion



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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Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion

BACK-UP SLIDES



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boson searches
with ATLAS**

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Introduction

Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV/Vh

Conclusion

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



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

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

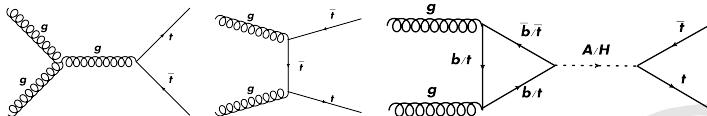
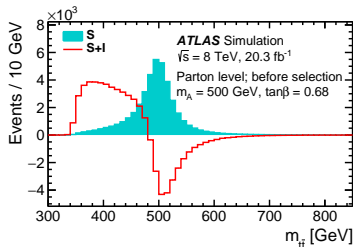


Diagram removal scheme:
Madgraph was modified to remove the SM $t\bar{t}$ matrix element to yield only the signal+interference on an event-by-event basis.

⇒ Search for a peak-and-dip structure.



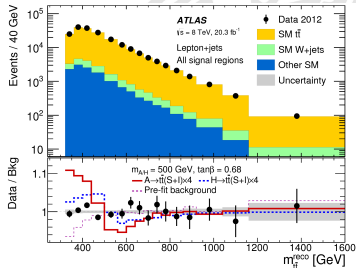
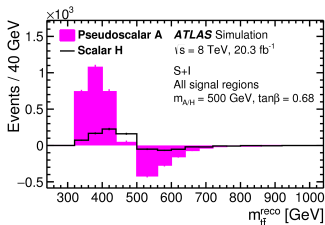


Gluon-gluon fusion $A/H \rightarrow t\bar{t}$ (8 TeV dataset)

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

- final states with $e/\mu + \geq 4$ jets (including ≥ 1 b -tag),
- $E_T^{\text{miss}} > 20$ GeV and $E_T^{\text{miss}} + m_T^W > 60$ 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 $S + I$:



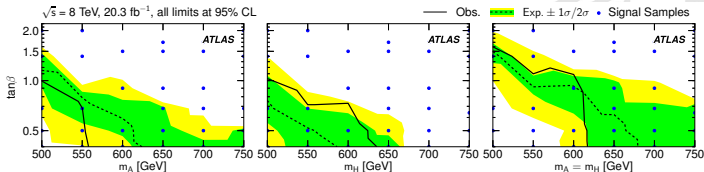


Gluon-gluon fusion $A/H \rightarrow t\bar{t}$ (8 TeV dataset)

The shape of the binned reconstructed $m_{t\bar{t}}$ 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 $\sqrt{K_S \times K_B}$.

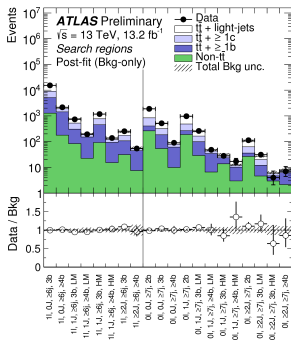


$(b\bar{b}/t\bar{t}) + A/H \rightarrow t\bar{t}$ (13 TeV, 13.2/fb)

- 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.

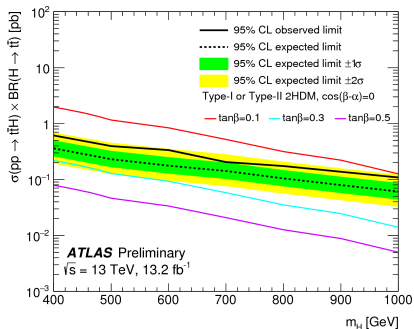
- Lepton+jets selection.
- Split between search and validation regions based on #jets and #b-tags.
- Main background: $t\bar{t}$ + jets.
- Optimized for VLQ/4t but re-used for BSM Higgs interpretations.





$(b\bar{b}/t\bar{t}) + A/H \rightarrow t\bar{t}$ (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 $H^+ \rightarrow tb$ less stringent than with the optimized search.





**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

Individual $H \rightarrow VV$
searches



$H \rightarrow VV$ – summary of individual searches

BSM Higgs
boson searches
with ATLAS

Arnaud Ferrari

Introduction

Charged Higgs
boson searches

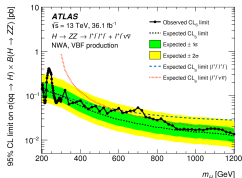
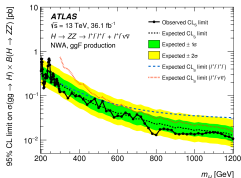
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boson decays to
 VV/Vh

Conclusion

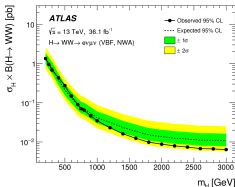
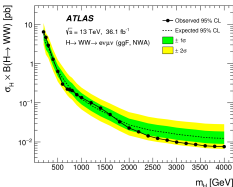
$H \rightarrow ZZ \rightarrow 4l$ & $ll\nu\nu$:



Two 3.6σ excesses:

- 240 GeV in $4e$ only (not covered by $ll\nu\nu$)
 - 700 GeV in $4l$ (excluded by $ll\nu\nu$)
- $\Rightarrow 1.3\sigma$ global excess.

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





$H \rightarrow VV$ – summary of individual searches

$H \rightarrow WW \rightarrow \ell\nu qq$

$H \rightarrow ZZ \rightarrow \ell\ell qq$

$H \rightarrow VV \rightarrow qqqq$

$H \rightarrow WW \rightarrow \ell\nu qq$

$H \rightarrow ZZ \rightarrow \nu\nu qq$

High-mass $\Rightarrow JJ$

BSM Higgs
boson searches
with ATLAS

Arnaud Ferrari

Introduction

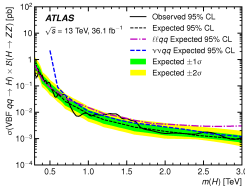
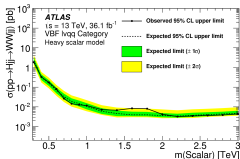
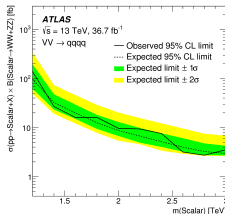
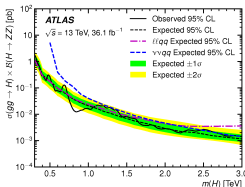
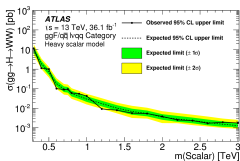
Charged Higgs
boson searches

Neutral Higgs
boson decays to
fermions

Higgs boson pair
production

Neutral Higgs
boson decays to
 VV / Vh

Conclusion



No VBF category.



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H^{++} searches



$H^{++}H^{--} \rightarrow \ell^+\ell^+\ell^-\ell^-$ (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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