Beyond-the-Standard Model Higgs Physics using the ATLAS Experiment

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Introduction

- A 125 GeV Higgs boson was observed by ATLAS and CMS.
  - This observed Higgs boson can easily fit into BSM Higgs models.
  - **Question:** Is it really the Standard Model (SM) Higgs boson?
- Many models beyond the Standard Model (SM) introduce a second Higgs doublet (Two Higgs Doublets Model (2HDM)).
  - five physical Higgs states: $H^{\pm}$, H^0, h^0, A (CP-Odd).

Higgs searches in ATLAS:

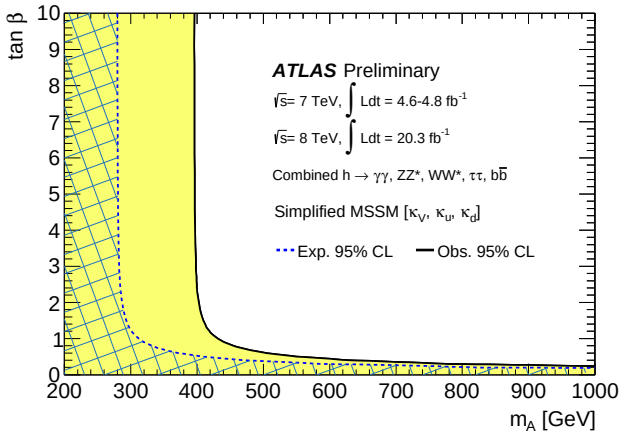
- Charged Higgs
- Neutral BSM Higgs
- NMSSM searches
- Higgs coupling interpretation

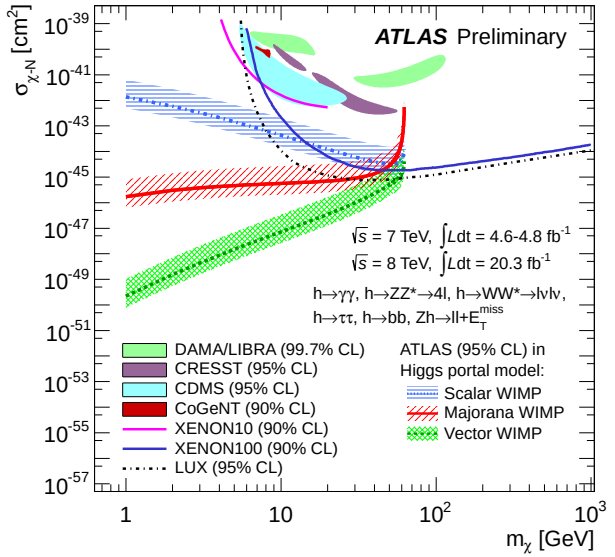
Detailed informations:
ATLAS public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Constraints on new phenomena from Higgs coupling

- Higgs mass dependence of coupling to particles is probed and interpreted in the context of different extensions to the SM.
- Constraints are set on:
  - Minimum Higgs compositeness models
  - Additional electroweak singlet
  - Two-Higgs-doublet models (I,II,III,IV)
  - Simplified MSSM (top right)
  - Higgs portal to dark matter (bottom right)
- No evidence for physics beyond the SM is observed.
- The mass dependence of the coupling is consistent with the predictions of the SM Higgs.

Results can be found in ATLAS-CONF-2014-010



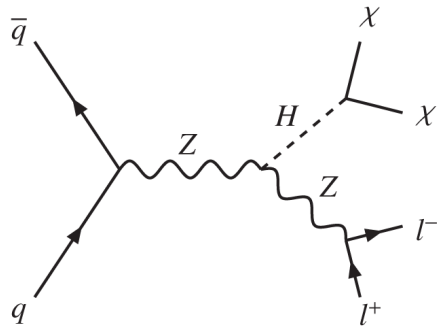


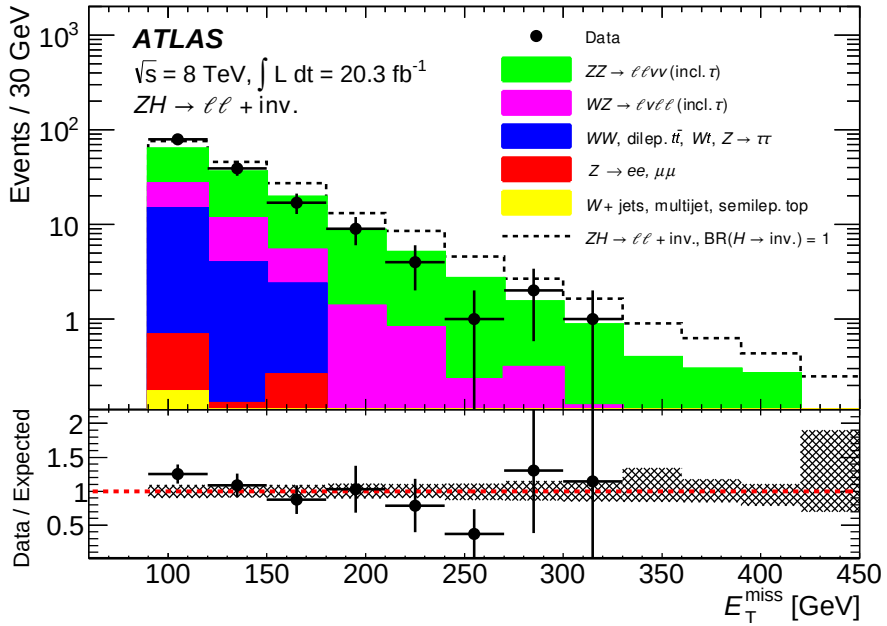
Neutral Higgs Searches

Invisible decay Higgs search: Analysis Overview

Search for invisible decay of a Higgs boson produced in association with a Z boson decaying into two leptons

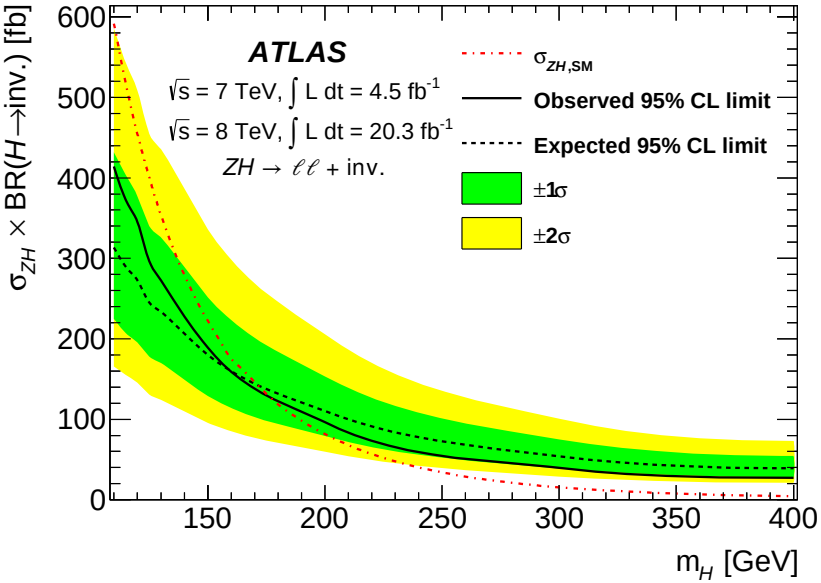
- Invisible decaying Higgs boson.
  - Allowed by some extensions of the SM: SUSY, extra dimension, Higgs portal dark matter.
- Dominant Background: SM ZZ and WZ production (MC).
- Other backgrounds:
  - WW, $t\bar{t}$, Wt, $Z \to \tau\tau$: using flavor symmetry.
  - Z production: ABCD Method.
  - Multijet: Matrix Method.
- E_T^{miss} is used as discriminating variable.

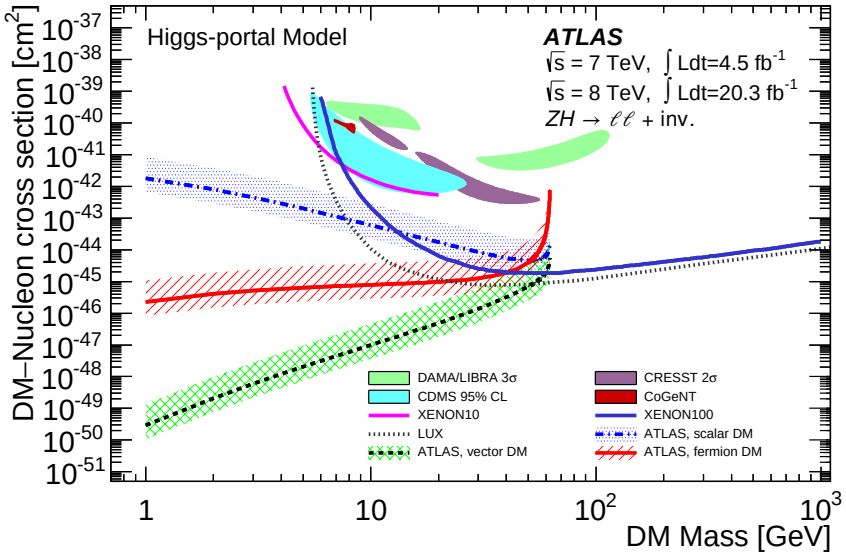




Results can be found in CERN-PH-EP-2013-210

Invisible decay Higgs search: Results



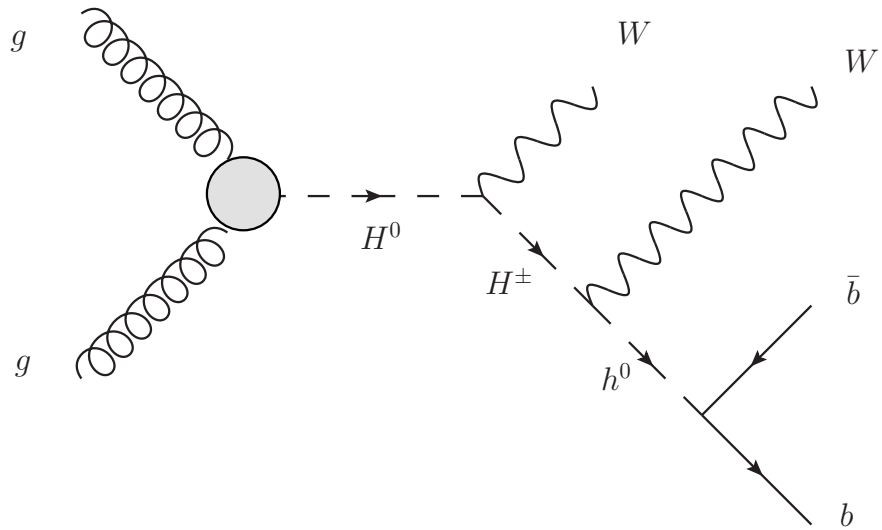


- Limits are set on the $\sigma_{ZH} \times BR(H \to inv.)$ in the mass range $110 < m_H < 400$ GeV.
  - For the currently observed Higgs an upper limit of 75% at 95% CL is set (SM production rate).
- Limits are interpreted in the context of the Higgs-portal dark matter scenario.
  - Limits on the dark-matter-nucleon scattering CS are derived.

Multi-Higgs-boson cascade in $W^+W^-b\bar{b}$: Analysis Overview

- **Search for BSM Higgs decay chain** including a heavy Higgs (H^0), intermediate charged Higgs ($H^\pm$) and light Higgs (h^0).
  - The light neutral Higgs (h^0) is assumed to have the mass of the currently observed Higgs $m_{h^0} = 125\,GeV$.

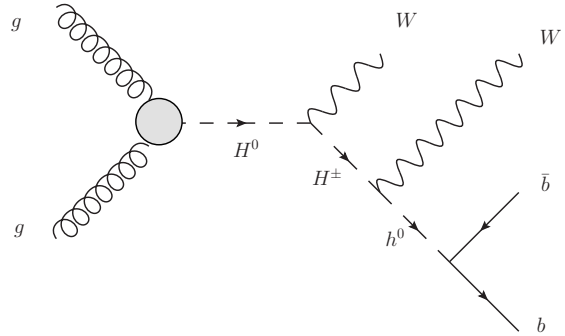
- **Final state:** $W^\pm W^\mp b\bar{b}$
  - Require one hadronically decaying W,
  - one leptonically decaying W.
- Boosted decision trees to separate signal from background.
  - **Main background** $t\bar{t}$.

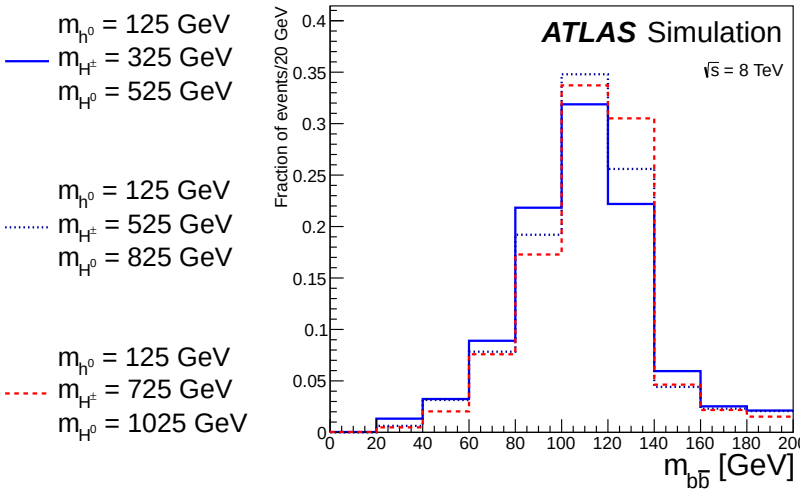


Results can be found in Phys. Rev. D 89, 032002 (2014)

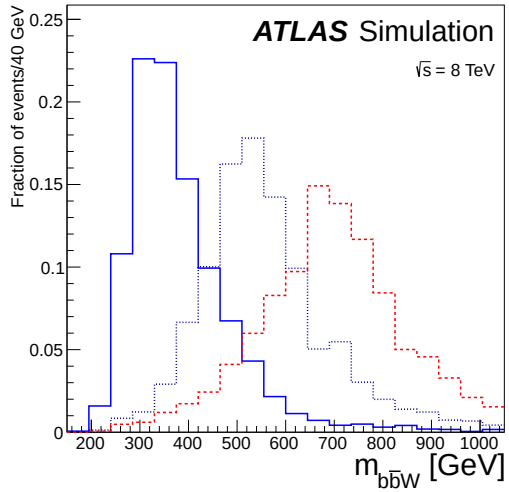
Multi-Higgs-boson cascade in $W^+W^-b\bar{b}$: Reconstruction

- **Higgs Boson cascade event reconstruction:**
  - Identify leptonic W.
  - Reconstruct the light Higgs h^0 from two b-jets.
  - Construct $H^\pm$ from h^0 and W which gives largest $m_{H^\pm}$.
  - Construct H^0 from $b\bar{b}WW$.

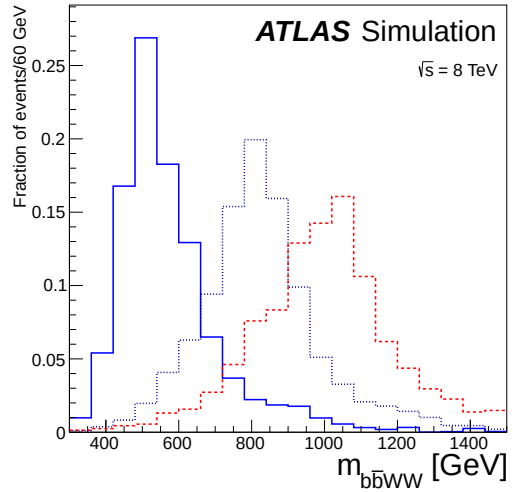




h^0

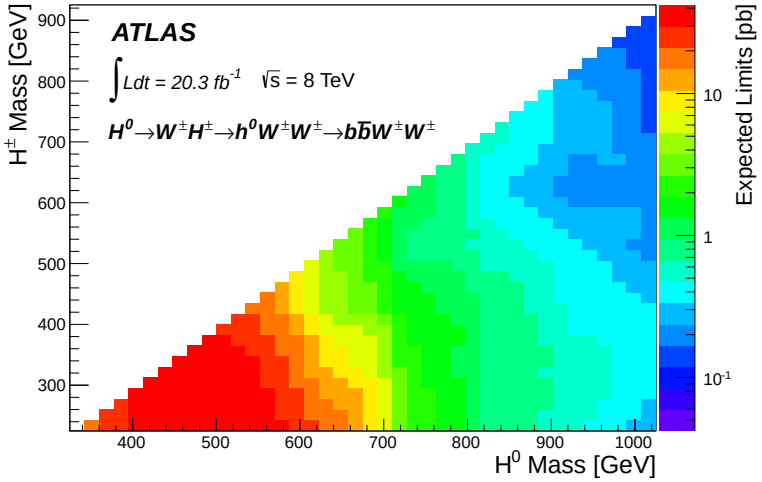


$H^\pm$

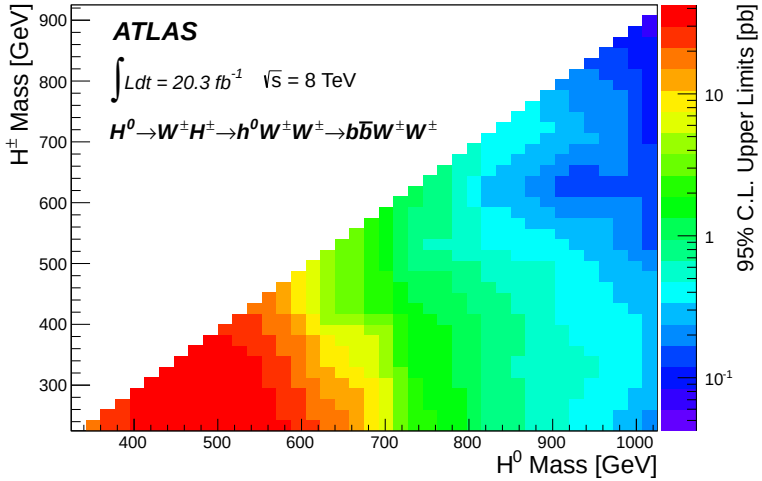


H^0

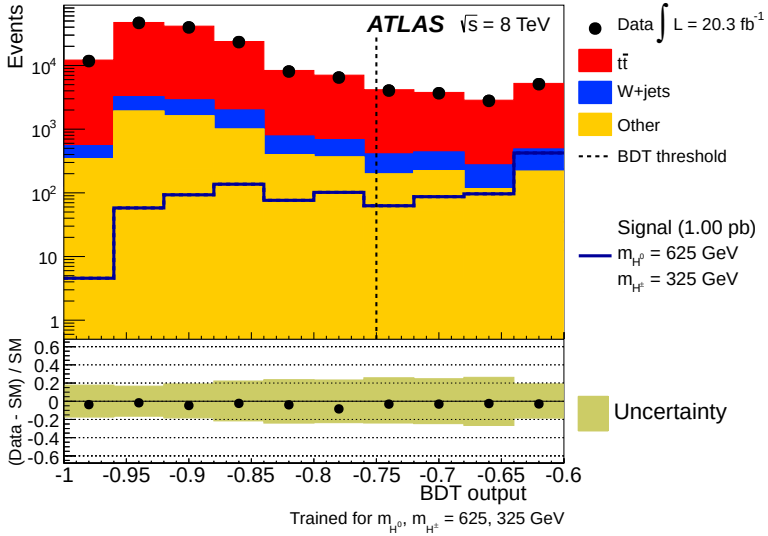
Multi-Higgs-boson cascade in $W^+W^-b\bar{b}$: Results



expected



observed

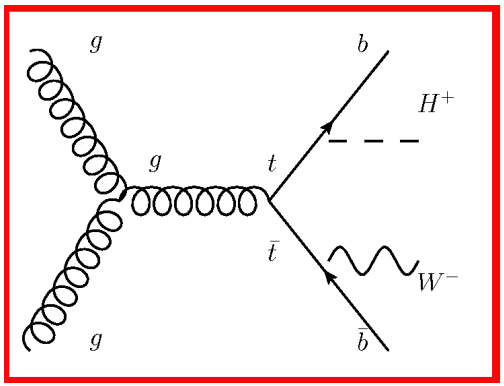


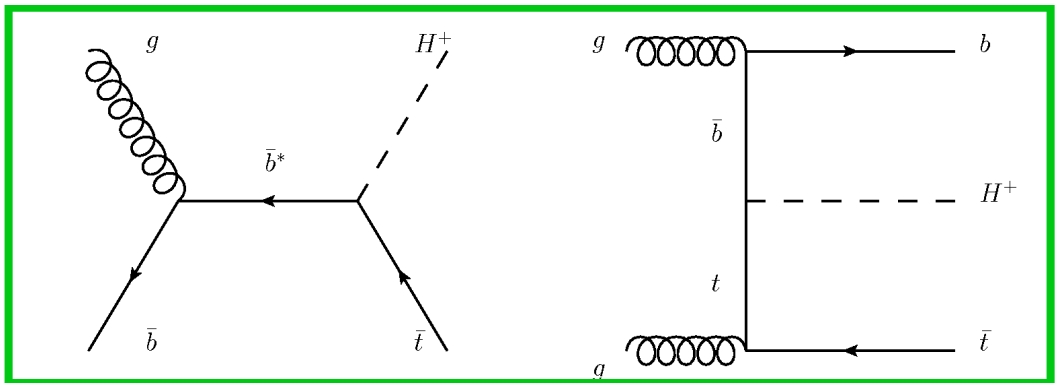
- No significant deviation from the SM was found.
- 95 % CL upper limits are set in the $H^0 - H^{\pm}$ plane.

Charged Higgs Searches

$H^+ \to \tau^+\nu$+jets: Analysis Overview

- Charged Higgs bosons (H^+) are predicted by many models with an extended Higgs sector.
- First limit on heavy charged Higgs bosons searches.
- **Search Strategy:**
  - light H^+ ($m_H^+ < m_{top}$)
  - heavy H^+ (associated production tH^+)

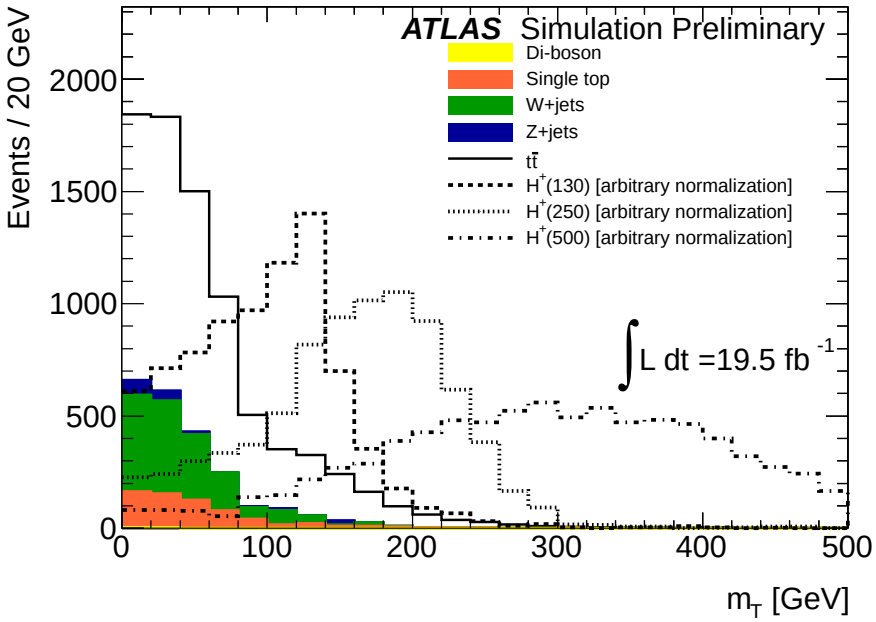




- **Search range:** 90 GeV - 160 GeV and 180 GeV - 600 GeV.
- Interpret in the context of $B(H^+ \to \tau\nu) = 1$, and hadronic decaying τ.

Results can be found in ATLAS-CONF-2013-090

$H^+ \to \tau^+\nu$+jets: Final State



- **Signal selection**
  - Fully hadronic state:
    - $W \to$ jets
    - hadronic τ
  - 4 (3) jets for light (heavy) H^+, at least one b-tagged jet.
  - Veto on other leptons.
  - $E_T^{miss} > 65(80)$ GeV
- **Discriminating Variable:**
  - $m_T = \sqrt{2p_T^\tau E_T^{miss}(1-\cos(\Delta\phi_{\tau,miss}))}$

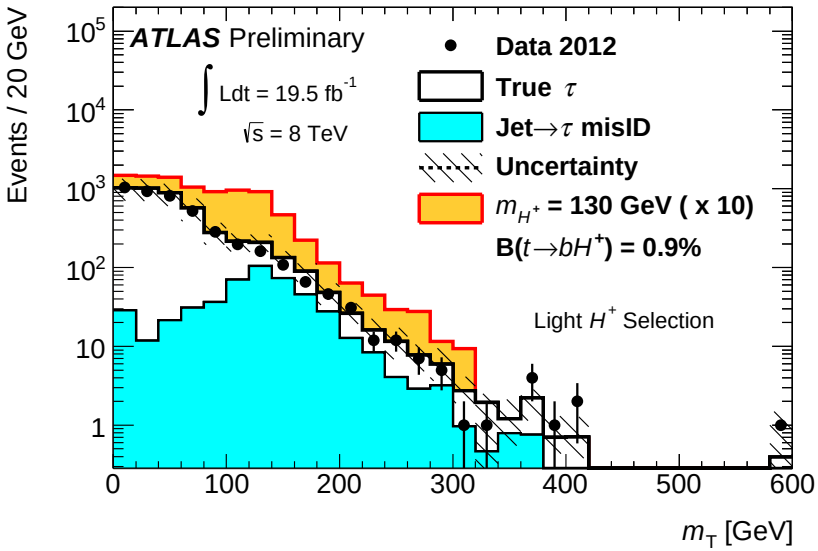
$$t\bar{t} \to [H^+ b][W^- \bar{b}] \to [(\tau^+ + \nu_\tau)b][q\bar{q}\bar{b}] \quad (1)$$

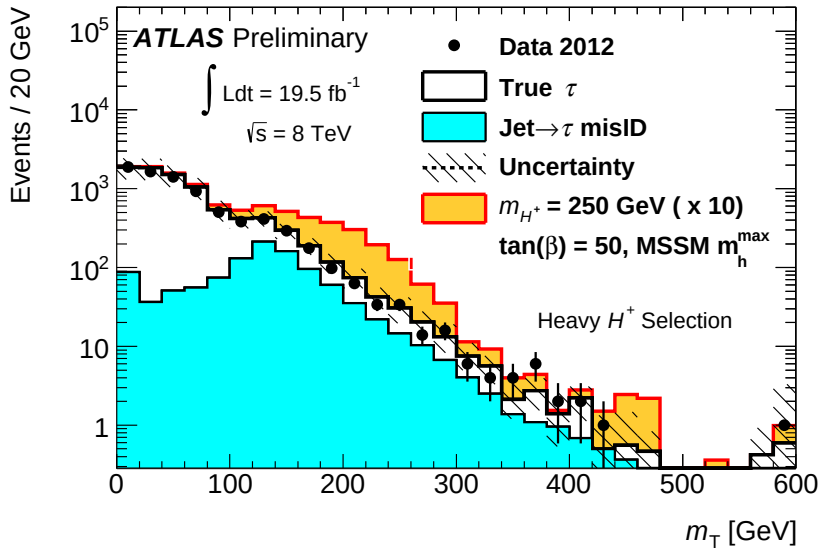
$$g\bar{b} \to [\bar{t}][H^+] \to [q\bar{q}\bar{b}][\tau^+ + \nu_\tau] \quad (2)$$

$$gg \to [\bar{t}b][H^+] \to [(q\bar{q}\bar{b})b][\tau^+ + \nu_\tau] \quad (3)$$

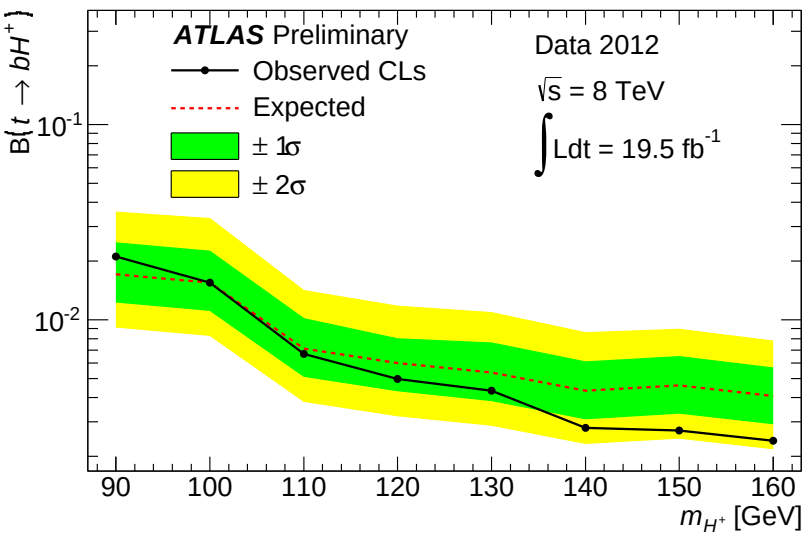
$H^+ \to \tau^+\nu$+jets: Background

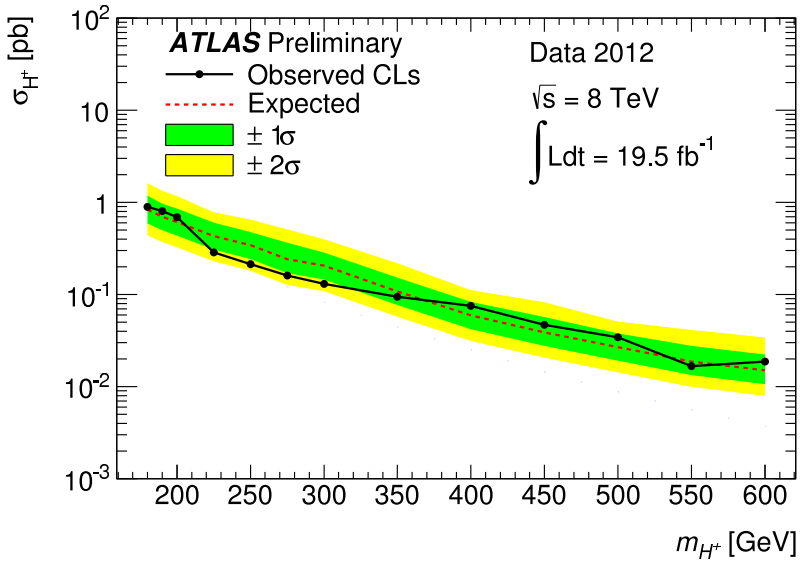
- **Backgrounds:** $t\bar{t}$, single top, W+jets, Z+jets, diboson and multi-jet.
- Backgrounds can be categorized according to the origin of the hadronically decaying τ candidate.
  - **Electron, muon, true τ reconstructed as τ candidate** $\to$ taken from simulation.
  - **Misidentified jets as τ candidates** $\to$ data-driven method that applies weights calculated from identification and misidentification efficiencies in data events (Matrix Method).





$H^+ \to \tau^+\nu$+jets: Results

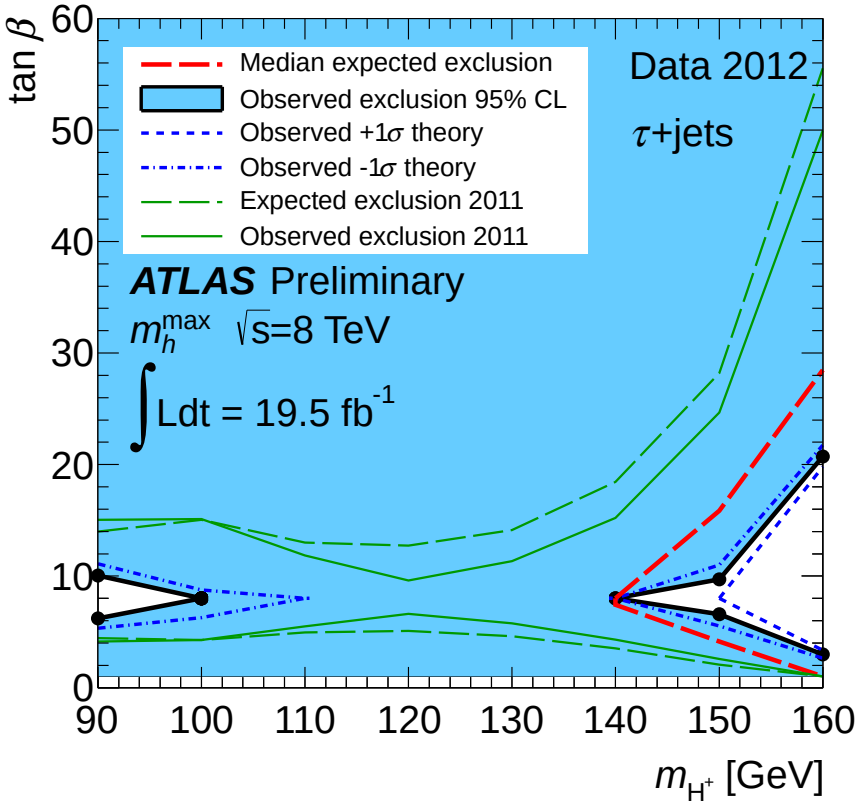


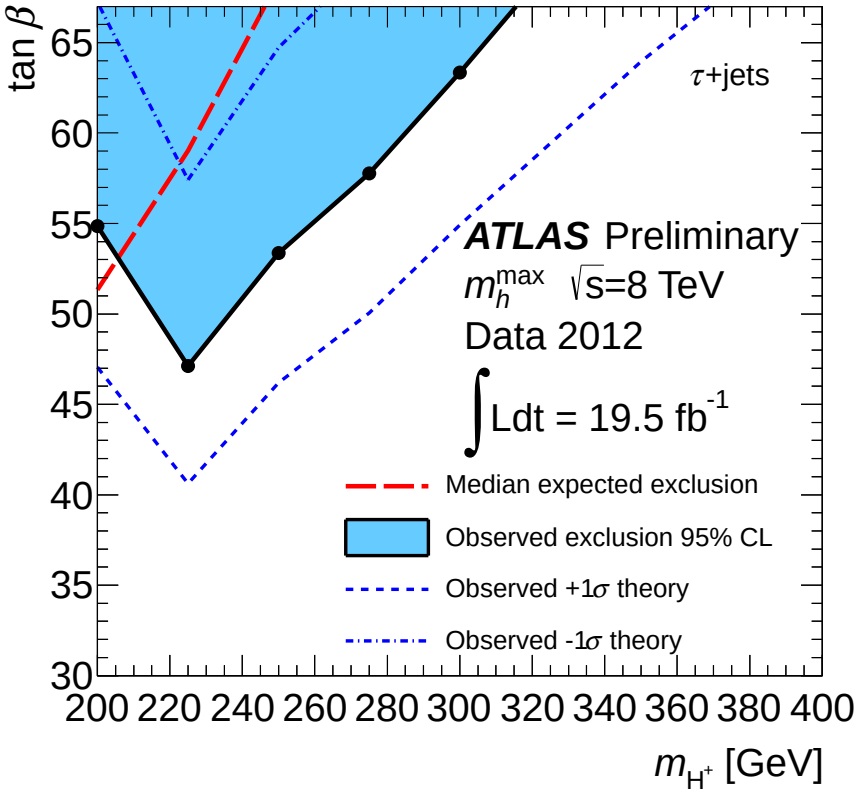


- 95% CL upper limits for light charged Higgs (left) and heavy charged Higgs (right).
  - (Left) Branching ratio of top to charged Higgs.
  - (Right) Production cross section $\times$ B($H^+ \to \tau\nu$).
  - Upper limits:
    - Light H^+: 90 GeV - 160 GeV, 0.24 - 2.1% on B($t \to H^+ b$).
    - Heavy H^+: 180 GeV - 600 GeV, 0.017 - 0.90 pb on the production CS ($\sigma(pp \to t(b)H^+)$).
- $\Rightarrow$ **No evidence for the existence of a charged Higgs boson.**

$H^+ \to \tau^+\nu$+jets: Results

Interpretation:





- In the m_h^{max} scenario of the MSSM:
  - Exclusion of $\tan\beta > 1$ between 100 GeV - 140 GeV.
  - Exclusion of $\tan\beta$ 47 - 63 in the range 200 - 300 GeV.

Conclusion

- Different analyses and interpretations have been presented:
  - Constraints on new phenomena from Higgs coupling.
  - Invisible decay Higgs search.
  - Multi-Higgs-boson cascade in $W^+W^-b\bar{b}$.
  - $H^+ \to \tau^+\nu$+jets.
- Limits on different models have been set.
- No evidence for physics beyond the Standard Model have been observed.

Outlook:

- With the LHC Run II next year more data at higher energies will be collected.
  - This will probe the currently observed Higgs boson further.
  - Higher mass ranges will be probed.
    - Further improvements on the limits are expected.

Backup

Invisible Higgs search: Events

Data Period	2011 (7 TeV)	2012 (8 TeV)
$ZZ \to \ell\ell\nu\nu$	$20.0 \pm 0.7 \pm 1.6$	$91 \pm 1 \pm 7$
$WZ \to \ell\nu\ell\ell$	$4.8 \pm 0.3 \pm 0.5$	$26 \pm 1 \pm 3$
Dileptonic $t\bar{t}$, Wt, WW, $Z \to \tau\tau$	$0.5 \pm 0.4 \pm 0.1$	$20 \pm 3 \pm 5$
$Z \to ee$, $Z \to \mu\mu$	$0.13 \pm 0.12 \pm 0.07$	$0.9 \pm 0.3 \pm 0.5$
W + jets, multijet, semileptonic top	$0.020 \pm 0.005 \pm 0.008$	$0.29 \pm 0.02 \pm 0.06$
Total background	$25.4 \pm 0.8 \pm 1.7$	$138 \pm 4 \pm 9$
Signal ($m_H = 125.5$ GeV, $\sigma_{\mathrm{SM}}(ZH)$, BR($H \to$ inv.) $= 1$)	$8.9 \pm 0.1 \pm 0.5$	$44 \pm 1 \pm 3$
Observed	28	152

TABLE I. Number of events observed in data and expected from the signal and from each background source for the 7 and 8 TeV data-taking periods. Uncertainties on the signal and background expectations are presented with statistical uncertainties first and systematic uncertainties second.

Invisible Higgs search: Event selection

- two leptons with $p_T > 20$ GeV
- jets with $p_T > 20$ GeV
- Overlap removal between overlapping objects
- Z window: $76 < m_{ll} < 106$ GeV
- $E_T^{miss} > 90$ GeV
- mis-reconstructed energy suppression: $\Delta\phi(E_T^{miss}, p_T^{miss}) < 0.2$
- momentum balance $Z - H$: $\Delta\phi(p_T^{ll}, E_T^{miss}) > 2.6$
- $\Delta\Phi(l, l) < 1.7$
- $|E_T^{miss} - p_T^{ll}|/p_T^{ll} < 0.2$
- no reconstruct jets with $p_T > 25$ GeV

Multi-Higgs-boson cascade in $W^+W^-b\bar{b}$: Events

TABLE I. Expected background contributions with their total (systematic and statistical) uncertainties and the observed number of events with exactly one lepton and at least four jets, and in the SPR region, which additionally requires at least two b-tagged jets. In the table, contributions from processes with light-flavor (LF) u, d, s quarks and heavy-flavor (HF) c, b quarks are distinguished.

Source	e/μ + ≥ 4 jets	SPR yields
$t\bar{t}$	$36.0^{+3.7}_{-3.8} \times 10^4$	$14.0^{+2.1}_{-2.0} \times 10^4$
W-boson + jets LF	$16.0^{+8.2}_{-8.3} \times 10^4$	$6.0^{+4.2}_{-4.1} \times 10^2$
W-boson + jets HF	$8.6^{+4.4}_{-4.4} \times 10^4$	$4.6^{+2.5}_{-2.4} \times 10^3$
Z-boson + jets LF	$26.0^{+6.3}_{-6.4} \times 10^3$	$11.0^{+8.3}_{-7.7} \times 10^1$
Z-boson + jets HF	$4.9^{+1.1}_{-1.0} \times 10^3$	$6.7^{+1.7}_{-1.6} \times 10^2$
Single top-quark	$16.0^{+2.0}_{-2.1} \times 10^3$	$46.0^{+7.6}_{-7.3} \times 10^2$
WW, WZ, ZZ	$26.0^{+5.4}_{-5.5} \times 10^2$	$6.9^{+1.9}_{-2.0} \times 10^1$
Fake leptons	$1.8^{+1.8}_{-1.8} \times 10^4$	$8.6^{+8.6}_{-8.6} \times 10^2$
Total	$68.0^{+14.0}_{-18.0} \times 10^4$	$15.1^{+2.2}_{-2.4} \times 10^4$
Observed	664876	151123

TABLE II. Details of the systematic uncertainties relative to the total expected background and the signal efficiency in the signal region for a Higgs-boson cascade signal with $m_{H^0}, m_{H^\pm} = 425, 225$ GeV. The signal region for this mass point is defined as the events that pass the BDT threshold for this mass sample. The positive and negative relative shifts have been averaged for compactness.

Uncertainty	Background Yields	Signal efficiency (%) $m_{H^0}=425$ GeV $m_{H^\pm}=225$ GeV
Jet vertex fraction	±1.6	±2.1
b-tagging efficiency	±8.8	±14
Jet energy scale	±3.9	±7
Jet energy resolution	±1.1	±11
Jet reconstruction efficiency	$\pm < 1.0$	$\pm < 1.0$
μ momentum	$\pm < 1.0$	$\pm < 1.0$
e energy	$\pm < 1.0$	$\pm < 1.0$
Lepton trigger efficiency	$\pm < 1.0$	±1.8
Lepton identification efficiency	±1.5	±2.1
Lepton reconstruction efficiency	$\pm < 1.0$	$\pm < 1.0$
W-boson + jets shape	$\pm < 1.0$	···
Quark/gluon radiation	$\pm < 1.0$	±2.8
$t\bar{t}$ modeling	±2.7	···
Background normalization	±5.5	···
Luminosity	±2.8	±2.8
Total uncertainty	±12	±20

- SPR: Signal pre region

Multi-Higgs-boson cascade in $W^+W^-b\bar{b}$: Events selection

- one triggered electron or muon with $p_T > 25$ GeV
- At least 4 jets with $p_T > 25$ GeV
  - at least 2 must be b-tagged
- MET and MTW requirement

$H^+ \to \tau^+\nu$+jets: Event Selection

- at least 4 (3) jets pass the p_{T}, η and JVF criteria as described in Sec. 3.2 for the light (heavy) signal selection,
- at least one of the selected jets must be b-tagged,
- exactly one hadronically decaying τ has $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ (this $\tau_{\mathrm{had-vis}}$ candidate must match to the τ object used in the trigger decision),
- there must be no additional hadronically decaying τ leptons with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, nor any muon or electron with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$,
- $E_{\mathrm{T}}^{\mathrm{miss}}$ >65 (80) GeV for the light (heavy) charged Higgs boson search,
- a requirement is placed on the quantity $\frac{E_{\mathrm{T}}^{\mathrm{miss}}}{0.5\cdot\sqrt{\sum p_T^{\mathrm{PV\ trk}}}}$ >13 (12) $\mathrm{GeV}^{1/2}$ in the light (heavy) H^+ search. Here $p_T^{\mathrm{PV\ trk}}$ is the transverse momentum of a track originating from the primary vertex and the sum is taken over all tracks from the PV.

$H^+ \to \tau^+\nu$+jets: Event Selection

m_{H^+} [GeV]	90	100	110	120	130	140	150	160
Efficiency (%)	0.72	0.76	0.85	0.92	1.02	1.19	1.19	1.18
m_{H^+} [GeV]	180	190	200	225	250	275	300	350
Efficiency (%)	1.78	1.88	2.00	2.31	2.75	2.93	3.15	3.60
m_{H^+} [GeV]	400	450	500	550	600			
Efficiency (%)	4.05	4.19	4.48	4.78	4.89			

Table 1: The signal selection efficiency, as determined from simulation, as a function of the charged Higgs boson mass.

	Light H^+	Heavy H^+
True $\tau_{\text{had-vis}}$	$4000 \pm 80 \pm 800$	$7400 \pm 100 \pm 1400$
Lepton $\to \tau_{\text{had-vis}}$	$40 \pm 4 \pm 10$	$80 \pm 10 \pm 20$
Multi-jet	$500 \pm 30 \pm 100$	$1000 \pm 40 \pm 200$
Σ SM	$4500 \pm 100 \pm 800$	$8500 \pm 100 \pm 1400$
Data	4230	7950
H^+	$500 \pm 10 \pm 100$	$100 \pm 2 \pm 20$
Signal + Background	$5000 \pm 100 \pm 800$	$8600 \pm 100 \pm 1400$

Table 8: Number of expected events after all selections cuts and comparison with 19.5 fb^{-1} of ATLAS data. The values shown for the H^+ signal correspond to $m_{H^+} = 130$ GeV and $B(H^+ \to \tau\nu) = 0.9\%$ for the light H^+ selection, and $m_{H^+} = 250$ GeV and $\tan\beta = 50$ in the MSSM m_h^{max} scenario [59] for the heavy H^+ selection. Both statistical and systematic uncertainties are shown, in that order.

$H^+ \to \tau^+\nu$+jets: Systematic Unc.

Variation	Shift up (%)	Shift down (%)	Shift up (%)	Shift down (%)
	Light H^+ event selection		Heavy H^+ event selection	
b jet (mis-)tag efficiency uncertainty	3.1	-3.4	2.9	-3.2
Jet energy scale uncertainties	3.7	-4.8	7.1	-6.8
JVF uncertainty	2.2	-1.9	2.2	-2.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties	0.4	0.3	-0.6	-0.2
$\tau_{\mathrm{had-vis}}$ e-veto uncertainty	0.02	-0.02	0.01	-0.01
$\tau_{\mathrm{had-vis}}$ energy scale uncertainty	3.6	-3.8	3.6	-3.8
$\tau_{\mathrm{had-vis}}$ identification uncertainty	3.8	-3.8	3.7	-3.7
Pile-up uncertainties	0.9	-1.5	2.6	-2.1

Table 3: The effect of each systematic uncertainty on the final event yield in events passing the light (left) and heavy (right) H^+ event selection, respectively. Effects are evaluated for background contributions estimated from simulation. Groups of related systematics are shown here added in quadrature, though they are treated as individual nuisance parameters in the statistical interpretation.

Source of uncertainty	Normalization uncertainty
Light $H^\pm$	
Generator model ($b\bar{b}W^\pm H^\pm$)	9%
Generator model ($b\bar{b}W^+W^-$)	9%
$t\bar{t}$ cross section uncertainty	10%
Jet production rate (SM and $H^\pm$)	11%
Heavy $H^\pm$	
Generator model ($H^\pm$)	2 – 9%
Generator model (SM)	8%
$t\bar{t}$ cross section uncertainty	10%
Jet production rate ($H^\pm$)	4.4 – 11%
Jet production rate (SM)	11%

Table 5: Systematic uncertainties arising from $t\bar{t}$ generator modeling, and from the jet production rate. The uncertainties are shown for the $t\bar{t}$ background and the charged Higgs boson signal, for the light and heavy charged Higgs boson selections.

$H^+ \to \tau^+\nu$+jets: Limit

m_{H^+} (GeV)	90	100	110	120	130	140	150	160
$B(t \to bH^+)$ (in %)	2.1	1.6	0.67	0.50	0.43	0.30	0.27	0.24
	(1.7)	(1.6)	(0.51)	(0.43)	(0.39)	(0.32)	(0.33)	(0.29)
m_{H^+} (GeV)	180	190	200	225	250	275	300	350
σ_{H^+} (in pb)	0.90	0.80	0.69	0.29	0.21	0.16	0.13	0.095
	(0.83)	(0.70)	(0.61)	(0.43)	(0.34)	(0.24)	(0.21)	(0.11)
m_{H^+} (GeV)	400	450	500	550	600			
σ_{H^+} (in pb)	0.075	0.047	0.034	0.017	0.019			
	(0.059)	(0.039)	(0.027)	(0.019)	(0.015)			

Table 10: Observed (Expected) limits, with $B(H^+ \to \tau\nu) = 100\%$, on $B(t \to bH^+)$ (in %) for $m_{H^+} = 90 - 160$ GeV, and on the production cross section (in pb) for $m_{H^+} = 180 - 600$ GeV, as a function of the charged Higgs boson mass.