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Searches for Higgs bosons beyond the Standard Model using the ATLAS experiment

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16 February 2015

Two-Higgs-Doublet Models in one slide

Rather than giving a catalogue of results, I focus on two recent analyses at $\sqrt{s} = 8$ TeV, with interpretations in CP-conserving Two-Higgs-Doublet Models (2HDMs):

- Five Higgs bosons: two CP-even (h and H), one CP-odd (A), two charged (H^+ and H^-).
- Seven free parameters: four Higgs boson masses, the ratio of vevs $\tan\beta$, the mixing angle α between h and H, the potential parameter m_{12}^2 that mixes the two Higgs doublets Φ_1 and Φ_2.
- Four Yukawa coupling arrangements:

	q_u	q_d	ℓ
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

(*) The MSSM Higgs sector is a type-II 2HDM.

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BSM Higgs boson searches in ATLAS

Arnaud Ferrari

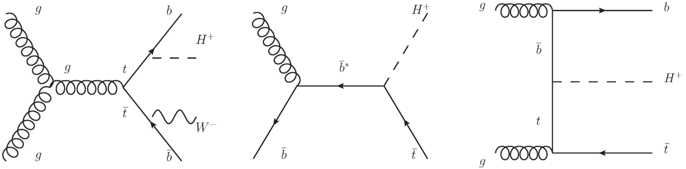
Outline

1. Search for $H^+ \to \tau\nu$ in ATLAS

2. Search for $A \to Zh$ in ATLAS

$H^+ \to \tau\nu$ in ATLAS (1)

Search for charged Higgs bosons produced in association with top quarks, in the mass ranges 80-160 GeV (light H^+) and 180-1000 GeV (heavy H^+). The decay $H^+ \to \tau\nu$ is significant for all mass points.



Search strategy for a light (heavy) H^+ boson:

- Use a $\tau_{\text{had}} + E_{\text{T}}^{\text{miss}}$ trigger,
- Exactly one τ_{had} with $p_{\text{T}}^{\tau} > 40$ GeV, no electron/muon of $p_{\text{T}} > 25$ GeV, at least 4 (3) jets with $p_{\text{T}} > 25$ GeV, including ≥ 1 b-tag;
- $\begin{cases} E_{\text{T}}^{\text{miss}} > 65\,(80)\ \text{GeV}; \\ E_{\text{T}}^{\text{miss}} / \sqrt{\sum p_{\text{T}}^{\text{PV trk}}} > 6.5\,(6.0)\ \text{GeV}^{1/2}. \end{cases}$

$H^+ \to \tau\nu$ in ATLAS (1)

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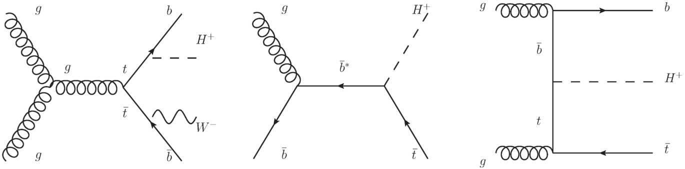

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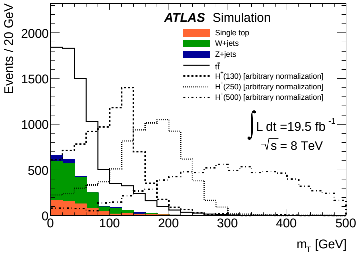
$H^+ \to \tau\nu$ in ATLAS (2)

In selected τ+jets events, the discriminating variable is the transverse mass, with a cut at 20 (40) GeV for the light (heavy) H^+ search:

$$m_T = \sqrt{2 p_T^\tau E_T^{miss} (1 - \cos \Delta\phi_{\tau_{had},miss})}.$$



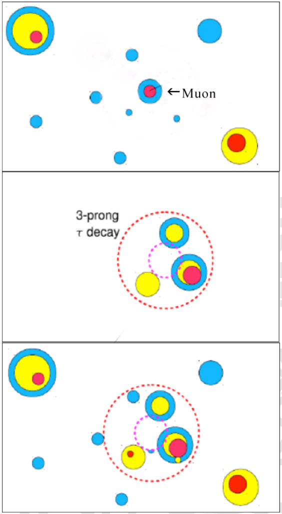
Background estimations → data-driven methods for 99% of the total background:

- True τ_{had}: embedding;
- Fake τ_{had} from jets: matrix method;
- Fake τ_{had} from electrons/muons: simulation with correction factors from data.

$H^+ \to \tau\nu$ in ATLAS (3)

Embedding

- Select a μ+jets sample in data, with looser cuts than the nominal event selection;
- Remove the muon signature and replace it with a simulated τ;
- Let τ decay with TAUOLA;
- Propagate the τ decay products through the full ATLAS detector simulation and reconstruction to get the background shape.
- Renormalise this background to account for trigger efficiencies, τ decay branching fractions, etc.



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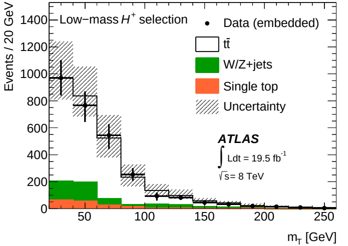
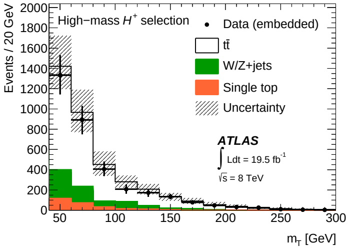
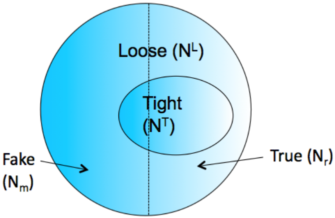




$H^+ \to \tau\nu$ in ATLAS (4)

Matrix method

- Select loose and tight samples in data, which differ only by the τ_{had} identification criteria;
- From simulation, determine the probability p_r of a *real* loose τ_{had} to fulfill the tight requirement;
- Using a W+jets control region in data, determine the probability p_m that a *fake* loose τ_{had} fulfills the tight requirement;
- In the loose sample, weight events as follows:
  - Loose but not tight τ_{had} $\to w = \frac{p_m p_r}{p_r - p_m}$,
  - Tight τ_{had} $\to w = \frac{p_m (p_r - 1)}{p_r - p_m}$.



$$\begin{pmatrix} N_{\rm T} \\ N_{\rm L} \end{pmatrix} = \begin{pmatrix} p_{\rm r} & p_{\rm m} \\ (1-p_{\rm r}) & (1-p_{\rm m}) \end{pmatrix} \times \begin{pmatrix} N_{\rm r} \\ N_{\rm m} \end{pmatrix}$$

$H^+ \to \tau\nu$ in ATLAS (4)

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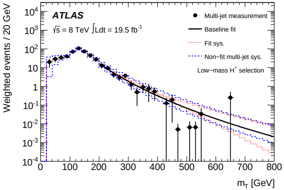
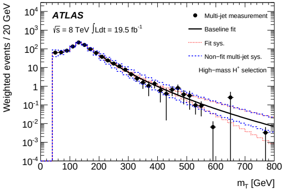
Multi-jet background from data-driven methods, with the results of fits using the power-log function:





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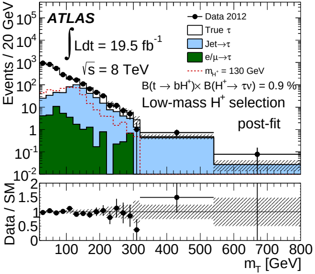
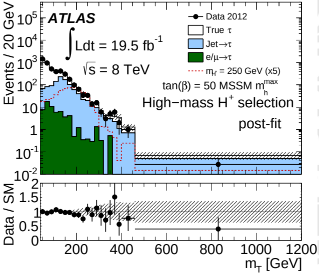
$H^+ \to \tau\nu$ in ATLAS (5)

Result: no statistically significant excess of data with respect to the SM predictions.

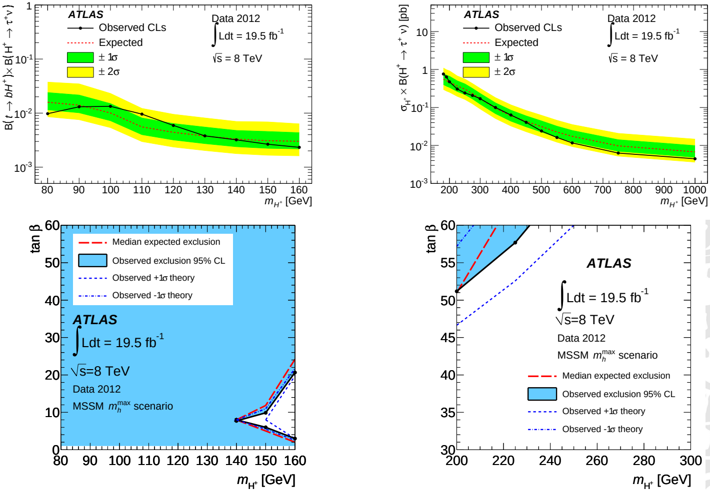
Sample	Low-mass H^+ selection	High-mass H^+ selection
True τ_{had} (embedding method)	$2800 \pm 60 \pm 500$	$3400 \pm 60 \pm 400$
Misidentified jet $\to \tau_{had}$	$490 \pm 9 \pm 80$	$990 \pm 15 \pm 160$
Misidentified $e \to \tau_{had}$	$15 \pm 3 \pm 6$	$20 \pm 2 \pm 9$
Misidentified $\mu \to \tau_{had}$	$18 \pm 3 \pm 8$	$37 \pm 5 \pm 8$
All SM backgrounds	$3300 \pm 60 \pm 500$	$4400 \pm 70 \pm 500$
Data	3244	4474
H^+ ($m_{H^+} = 130$ GeV)	$230 \pm 10 \pm 40$	
H^+ ($m_{H^+} = 250$ GeV)		$58 \pm 1 \pm 9$





$H^+ \to \tau\nu$ in ATLAS (6)

Limit plots + interpretation in the MSSM m_h^{max} scenario



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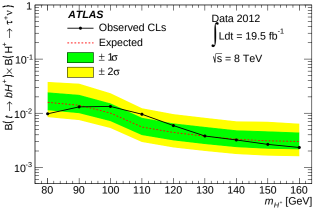
Search for $H^+ \to \tau\nu$ in ATLAS

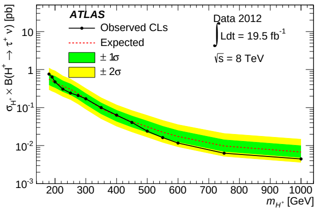
Search for $A \to Zh$ in ATLAS

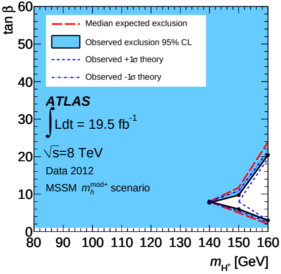
Back-up

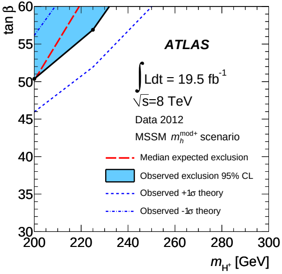
$H^+ \to \tau\nu$ in ATLAS (6)

Limit plots + interpretation in the MSSM m_h^{mod+} scenario



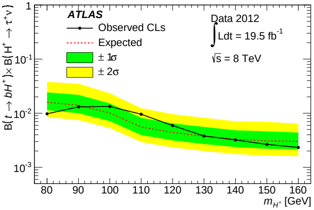


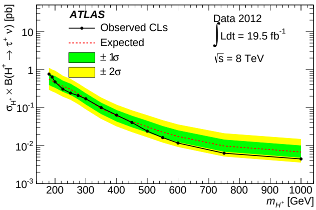


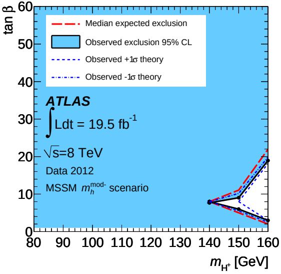


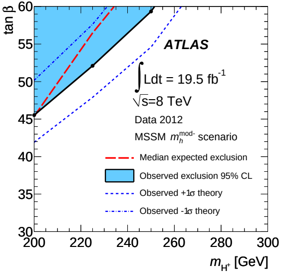
$H^+ \to \tau\nu$ in ATLAS (6)

Limit plots + interpretation in the MSSM m_h^{mod-} scenario









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Search for $A \to Zh$ in ATLAS

Back-up

$A \to Zh$ in ATLAS (1)

Search for a neutral CP-odd Higgs boson produced via gluon fusion, in the mass range 220-1000 GeV. The decay $A \to Zh$ ($m_h = 125$ GeV) is significant for part of the 2HDM parameter space, especially below the $t\bar{t}$ threshold.

* *Search strategy for $A \to Zh$, with $h \to \tau\tau$:*

- Reconstruct only $Z \to \ell\ell$ decays ($\ell = e, \mu$);
- Three channels: $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$, $\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$, $\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$;
- Missing Mass Calculator (MMC) to estimate $m_{\tau\tau}$;
- Reconstruct the A boson mass with:

$$m_A^{\text{rec}} = m_{\ell\ell\tau\tau} - m_{\ell\ell} - m_{\tau\tau} + m_Z + m_h.$$

* *Search strategy for $A \to Zh$, with $h \to b\bar{b}$:*

- Two channels: $\ell\ell bb$, $\nu\nu bb$;
- Scale each b-jet four-momentum by 125 GeV$/m_{bb}$;
- $A \to Zh \to \ell\ell bb \Rightarrow m_A^{\text{rec}} = m_{\ell\ell bb}$;
- $A \to Zh \to \nu\nu bb \Rightarrow$ reconstruct a transverse mass:

$$m_A^{\text{rec,T}} = \sqrt{(E_T^{bb} + E_T^{\text{miss}})^2 - (\vec{p}_T^{bb} + \vec{p}_T^{\text{miss}})^2}.$$

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$A \to Zh$ in ATLAS (2)

Backgrounds for $A \to Zh \to \ell\ell\tau_{had}\tau_{had}$, $\ell\ell\tau_{lep}\tau_{had}$:

- ZZ^*, SM Zh (with real objects) $\to$ simulation.
- Fake τ_{had} (and/or lepton) background, mostly from Z+jets $\to$ data-driven template method.

* Background shape from a template region = signal event selections, except that the opposite-sign $\tau\tau$ and/or τ_{had}-identification requirements fail.
* Region A (B) = Signal (template) region with inverted $m_{\tau\tau}$ requirements (i.e. less than 75 GeV or more than 175 GeV).
* Scale the template shape by the ratio N_A/N_B.

Backgrounds for $A \to Zh \to \ell\ell\tau_{lep}\tau_{lep}$:

- VV, VVV, $t\bar{t}Z$ (with real objects) $\to$ simulation.
- Fake lepton background (mostly for $\tau_{lep}\tau_{lep} \to e\mu$), from Z+jets: extrapolation from a control region in data with non-isolated lepton(s).

Backgrounds for $A \to Zh \to \ell\ell bb$, $\nu\nu bb$:

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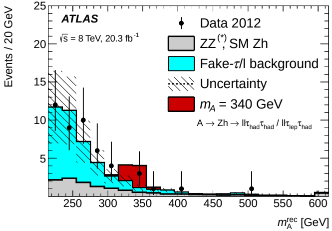
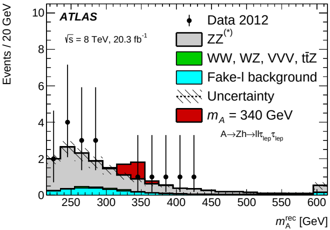
Back-up

$A \to Zh$ in ATLAS (3)

No statistically significant excess of data with respect to the SM predictions in the three channels with $h \to \tau\tau$.

	Expected Background	Data
$\ell\ell\tau_{\text{had}}\tau_{\text{had}}$	28 ± 6	29
$\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$	17 ± 4	18
$\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$ (SF)	9.5 ± 0.6	10
$\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$ (DF)	7.2 ± 0.7	7

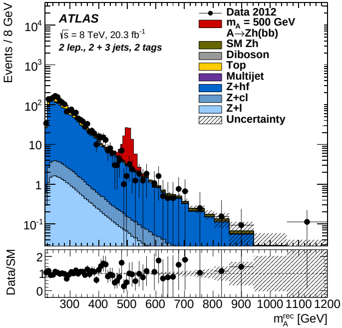


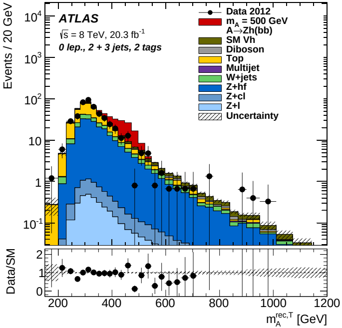


$A \to Zh$ in ATLAS (4)

No statistically significant excess of data with respect to the SM predictions in the two channels with $h \to b\bar{b}$.

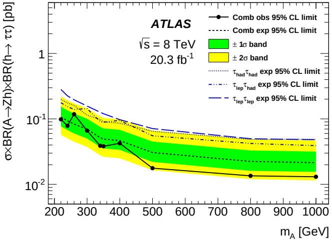
	$\ell\ell bb$	$\nu\nu bb$
Z+jets	1443 ± 60	225 ± 11
W+jets	–	55 ± 8
Top	317 ± 28	203 ± 15
Diboson	30 ± 5	10.8 ± 1.6
SM Zh, Wh	31.7 ± 1.8	22.5 ± 1.2
Multi-jet	20 ± 16	3.2 ± 3.1
Total background	1843 ± 34	521 ± 12
Data	1857	511

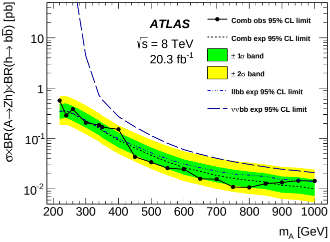




$A \to Zh$ in ATLAS (5)

Limit plots for $\sigma_{pp \to A} \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to \tau\tau / b\bar{b})$





The next slides show interpretations of these limits in CP-conversing 2HDMs, assuming:

- $m_h = 125$ GeV,
- $m_A = m_H = m_{H^\pm}$,
- $m_{12}^2 = m_A^2 \tan\beta/(1+\tan^2\beta)$.

$A \to Zh$ in ATLAS (5)

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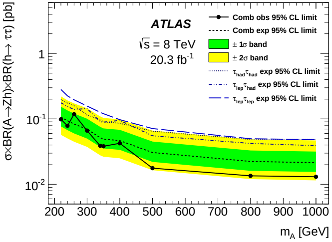
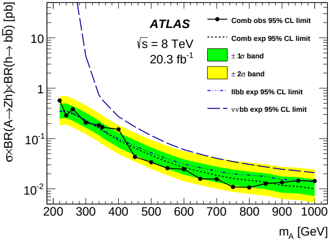
Search for $A \to Zh$ in ATLAS

Back-up

Limit plots for $\sigma_{pp\to A} \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to \tau\tau/b\bar{b})$

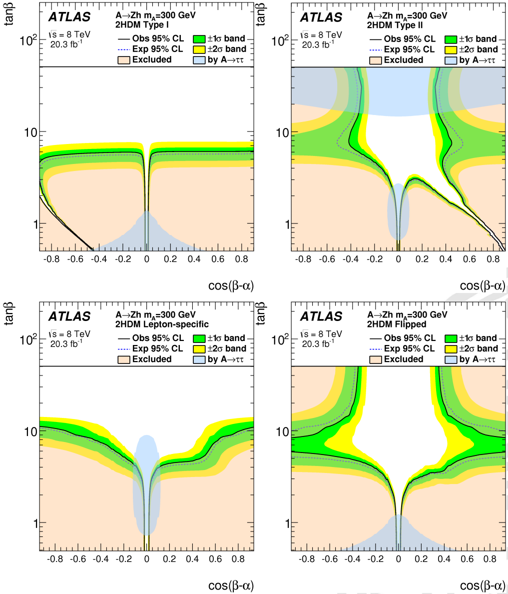




The next slides show interpretations of these limits in CP-conversing 2HDMs, assuming:

- $m_h = 125$ GeV,
- $m_A = m_H = m_{H^\pm}$,
- $m_{12}^2 = m_A^2 \tan\beta/(1+\tan^2\beta)$.

$A \to Zh$ in ATLAS (6a)



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BSM Higgs boson searches in ATLAS

Arnaud Ferrari

Search for $H^+ \to \tau\nu$ in ATLAS

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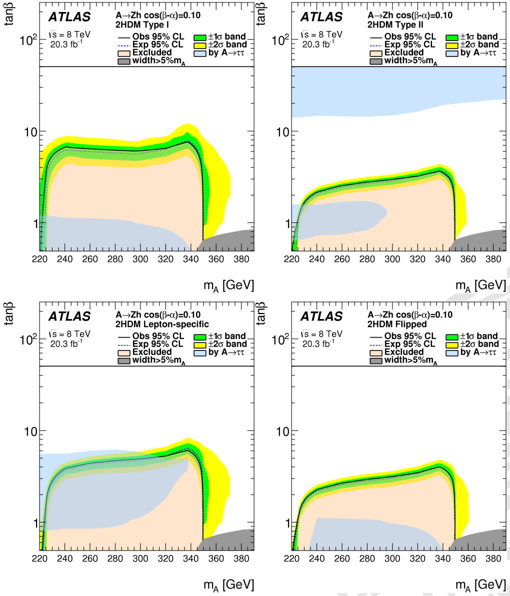
Back-up

$A \to Zh$ in ATLAS (6b)



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Conclusion

Two searches for BSM Higgs bosons were recently made public by ATLAS, based on the full 2012 dataset at 8 TeV:

- Search for a charged Higgs boson H^+ decaying into $\tau\nu$ in fully hadronic final states:
  - $\text{BR}(t \to bH^+) \times \text{BR}(H^+ \to \tau\nu) < 1.3 - 0.23\%$ for the mass range 80-160 GeV;
  - $\sigma_{t[b]H^+} \times \text{BR}(H^+ \to \tau\nu) < 760 - 4.5$ fb for the mass range 180-1000 GeV;
  - More details in http://arxiv.org/abs/1412.6663.
- Search for a CP-odd Higgs boson A decaying into Zh (five different final states):
  - $\sigma_A \times \text{BR}(A \to Zh) \times \text{BR}(h \to \tau\tau) < 98 - 13$ fb, $\sigma_A \times \text{BR}(A \to Zh) \times \text{BR}(h \to b\bar{b}) < 570 - 14$ fb, both for the mass range 220-1000 GeV;
  - Submitted to arXiv today! For more details, see also: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-06/

More (BSM) Higgs boson searches in ATLAS can be found here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

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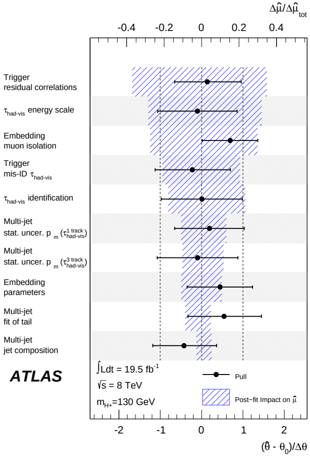
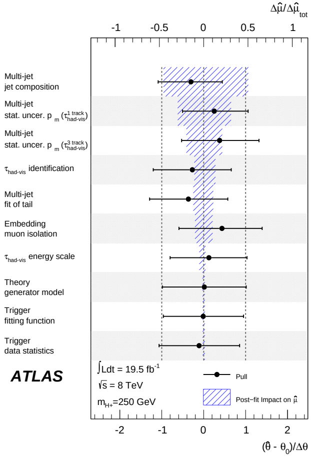
$H^+ \to \tau\nu$ – systematic uncertainties

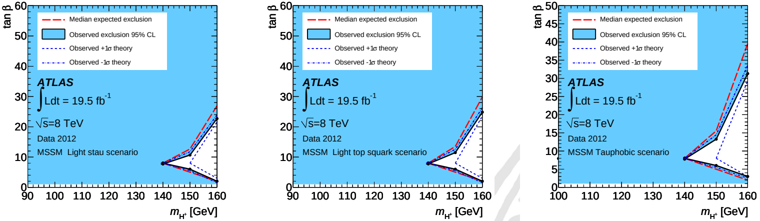
Impact of systematic uncertainties on the final observed limit, ordered (from top to bottom) by decreasing impact on the fitted signal strength parameter.





$H^+ \to \tau\nu$ – more MSSM interpretation plots

From left to right: light stau, light top squark, tauphobic MSSM scenarios. There is only a significant exclusion power for light H^+.



$A \to Zh \to \ell\ell\tau_{\text{had}}\tau_{\text{had}}$ – event selection

- Combination of single-lepton and di-lepton triggers;
- Exactly two opposite-sign leptons (ee or $\mu\mu$) and exactly two opposite-sign τ_{had} (loose τ-ID = 65% efficiency):
  - $p_{\text{T}} > 26$ (15) GeV for a leading (sub-leading) e,
  - $p_{\text{T}} > 25 - 36$ (10) GeV for a leading (sub-leading) μ,
  - $p_{\text{T}} > 35$ (20) GeV for a leading (sub-leading) τ_{had}.
- $80 < m_{\ell\ell}$ (GeV) < 100 & $75 < m_{\tau\tau}$ (GeV) < 175;
- $p_{\text{T}}(\ell\ell) > \begin{cases} 125 \text{ GeV if } m_A^{\text{rec}} > 400 \text{ GeV}, \\ 0.64 \times m_A^{\text{rec}} - 131 \text{ GeV otherwise.} \end{cases}$

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Search for $H^+ \to \tau\nu$ in ATLAS

Search for $A \to Zh$ in ATLAS

Back-up

$A \to Zh \to \ell\ell\tau_{\text{lep}}\tau_{\text{had}}$ – event selection

- Combination of single-lepton and di-lepton triggers;
- Exactly three leptons (eee, $ee\mu$, $e\mu\mu$, $\mu\mu\mu$) and exactly one τ_{had} (medium τ-ID = 55% efficiency):
  - $p_{\text{T}} > 26$ (15) GeV for a leading (remaining) e,
  - $p_{\text{T}} > 25 - 36$ (10) GeV for a leading (remaining) μ,
  - $p_{\text{T}} > 20$ GeV for τ_{had}.
- The same-flavour opposite-sign $\ell\ell$ pair with the smallest $|m_{\ell\ell} - m_Z|$ is assigned to Z, the remaining lepton is τ_{lep} and must be opposite-sign w.r.t. τ_{had};
- $80 < m_{\ell\ell}$ (GeV) < 100 & $75 < m_{\tau\tau}$ (GeV) < 175.

$A \to Zh \to \ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$ – event selection

- Combination of single-lepton and di-lepton triggers;
- At least four leptons with:
  - one same-flavour opposite-sign pair satisfying $80 < m_{\ell\ell}$ (GeV) < 100,
  - one same-flavour (SF) or different-flavour (DF) lepton pair with a MMC mass between 90 and 190 GeV,
  - $p_{\text{T}} > 20$ $(15, 10)$ GeV for the leading (second, third) lepton.
- Among all possible lepton quadruplets, pick the one that minimizes the sum of mass differences w.r.t. the *Z* and *h* bosons;
- Cuts to reduce the ZZ^* and *Z*+jets backgrounds:
  - m_h^{rec} outside the *Z* peak (80-100 GeV),
  - $E_{\text{T}}^{\text{miss}} > 30$ GeV,
  - $\Delta\phi(Z, \text{miss}) > \pi/2$,
  - $p_{\text{T}} > 15$ GeV for the highest-p_{T} lepton of the *h* boson.

$A \to Zh \to \ell\ell bb$ – event selection

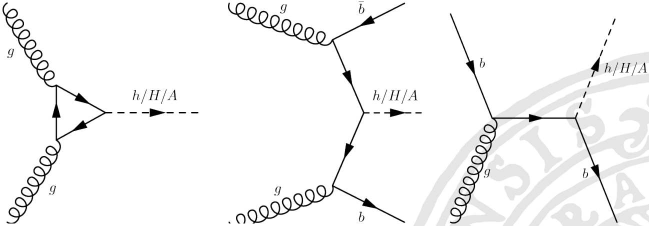
- Combination of single-lepton and di-lepton triggers;
- Exactly two same-flavour leptons with $p_T > 25$ GeV for one of them, $83 < m_{\ell\ell}$ (GeV) < 99;
- Exactly two b-jets with $p_T > 45$ (20) GeV for the leading (sub-leading) jet, $105 < m_{bb}$ (GeV) < 145;
- $E_T^{miss}/\sqrt{H_T} > 3.5$ GeV$^{1/2}$, with H_T the scalar sum of p_T of all leptons and jets;
- $p_T(\ell\ell) > 0.44 \times m_A^{rec} - 106$ GeV.

$A \to Zh \to \nu\nu bb$ – event selection

- E_T^{miss} trigger with a threshold at 80 GeV;
- $E_T^{miss} > 120$ GeV (energy-based) and $p_T^{miss} > 30$ GeV (track-based);
- No electron or muon with $p_T > 7$ GeV;
- Exactly two b-jets with $p_T > 45$ (20) GeV for the leading (sub-leading) jet, $105 < m_{bb}$ (GeV) < 145;
- Reject events fulfilling any of the following:
  - there is a jet with $|\eta| > 2.5$,
  - there are four or more jets,
  - one of the b-jets is the third highest-p_T jet.
- $H_T > 120$ (150) GeV, for events with two (three) jets;
- Requirements on ΔR_{bb} similar to the SM h boson search of JHEP 01 (2015) 069;
- $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss}) < \pi/2$, Min$[\Delta\phi(\vec{E}_T^{miss}, \text{jet})] > 1.5$, $\Delta\phi(\vec{E}_T^{miss}, bb) > 2.8$.

$h/H/A \to \tau\tau$ in ATLAS (1)

Search for MSSM neutral Higgs bosons produced through gluon-gluon fusion or in association with *b*-quarks (dominating at large tan β). At the decoupling limit, *A* and *H* have similar masses and *h* becomes identical to the SM Higgs boson. The decay $h/H/A \to \tau\tau$ is considered.



Search channels for $h/H/A$ bosons: $\tau_e\tau_\mu$ (6%), $\tau_e\tau_{\text{had}}$ (23%), $\tau_\mu\tau_{\text{had}}$ (23%), $\tau_{\text{had}}\tau_{\text{had}}$ (42%).

$h/H/A \to \tau\tau$ in ATLAS (2)

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Search for $A \to Zh$ in ATLAS

Back-up

Two mass reconstruction methods:

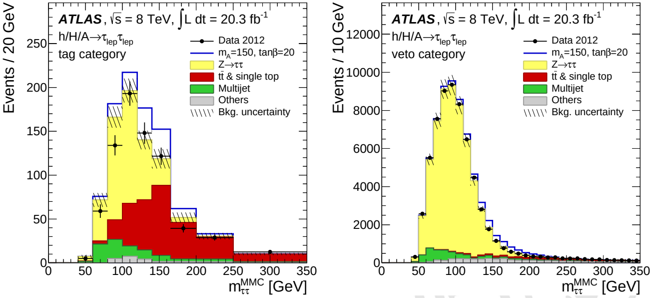
- Missing Mass Calculator:
  - assume that $E_{\mathrm{T}}^{\mathrm{miss}}$ only comes from the neutrinos from τ decays,
  - scan over the angles between the neutrinos and visible τ decay products,
  - weight each solution by probability density functions derived from simulations,
  - find the most likely value $m_{\tau\tau}^{\mathrm{MMC}}$.
- Total transverse mass:

$$m_{\mathrm{T}}^{\mathrm{total}} = \sqrt{m_{\mathrm{T}}^2(\tau_1, \tau_2) + m_{\mathrm{T}}^2(\tau_1, E_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}^2(\tau_2, E_{\mathrm{T}}^{\mathrm{miss}})},$$

with $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}1}p_{\mathrm{T}2}(1 - \cos\Delta\phi)}$.

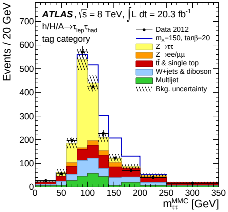
$h/H/A \to \tau_e \tau_\mu$ in ATLAS

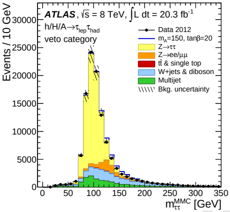
- Exactly one electron ($p_T > 15$ GeV) and one muon ($p_T > 10$ GeV), with opposite charges and isolation requirements;
- Events with at least one loose τ_{had} are vetoed;
- Two event categories: "tag" and "veto" based on the presence or absence of a *b*-jet;
- Kinematic requirements to reduce backgrounds with top quarks;
- *Z*+jets background estimated using embedding of simulated τs into data $Z/\gamma^* \to \mu\mu$ events;
- Multi-jet background estimated using an ABCD data-driven method, based on the charge product of $e\mu$ and isolation requirements.

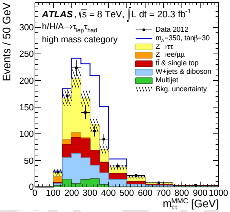


$h/H/A \to \tau_{\rm lep}\tau_{\rm had}$ in ATLAS

- Exactly one electron/muon ($p_{\rm T} > 26$ GeV) and one oppositely charged medium $\tau_{\rm had}$;
- Searches for $m_A < 200$ GeV:
  - Two categories, "tag" and "veto", based on the presence or absence of a b-jet,
  - Kinematic requirements to reduce backgrounds with top quarks in the tag category,
  - Kinematic requirements to reduce W+jets backgrounds in the veto category.
- Searches for $m_A \geq 200$ GeV:
  - Kinematic requirements to reduce mostly W+jets backgrounds,
  - $\tau_{\rm lep}$ and $\tau_{\rm had}$ well separated in ϕ and $p_{\rm T}$.
- Z+jets background $\to$ embedding;
- Multi-jet background $\to$ ABCD method, based on the charge product of $\tau_{\rm lep}\tau_{\rm had}$ and lepton isolation requirements;
- Fake $\tau_{\rm had}$ background estimated with simulation and renormalised after comparison in data control regions.

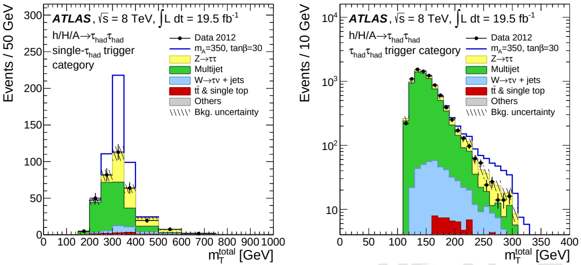






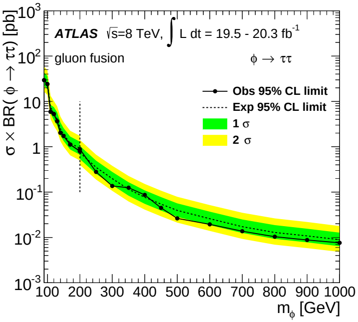
$h/H/A \to \tau_{had}\tau_{had}$ in ATLAS

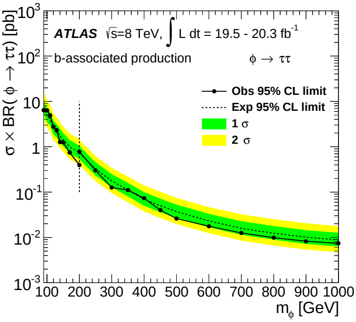
- At least two loose τ_{had} objects, the two with the highest p_T must have $p_T > 50$ GeV, opposite charges, and be back-to-back.
- Events with electrons and/or muons are vetoed;
- Two event categories:
  - single-τ_{had} trigger (STT) with at least one τ_{had} of $p_T > 150$ GeV,
  - di-τ_{had} trigger (DTT) with a leading τ_{had} of $p_T < 150$ GeV, both medium τ-ID, $E_T^{miss} > 10$ GeV, $H_T > 160$ GeV.
- m_T^{total} is the final discriminant, as the multi-jet background dominates:
  - STT: uses a control region where the second τ_{had} fails the τ-ID requirement + the measured probability of a jet faking τ_{had} in dijet events,
  - DTT: ABCD data-driven method, based on the charge product of $\tau_{had}\tau_{had}$ and E_T^{miss} requirement.



$h/H/A \to \tau\tau$ in ATLAS – limits (1)

Upper limits on the cross section of a scalar boson produced via gluon fusion (left) or in association with *b*-quarks (right) times the branching fraction into $\tau\tau$.

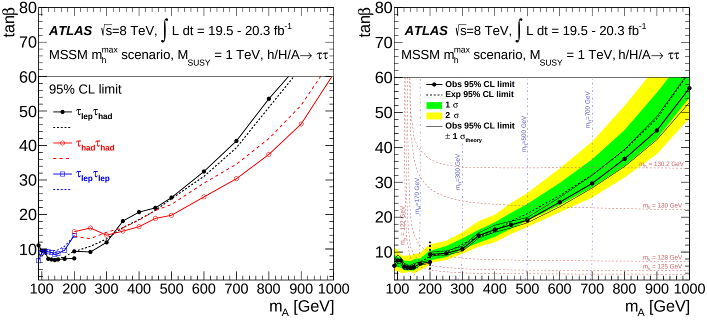




$h/H/A \to \tau\tau$ in ATLAS – limits (2)

Interpretation in the MSSM m_h^{max} scenario:

In the m_h^{max} scenario, the radiative corrections are chosen such that m_h is maximized for a given $\tan\beta$ and M_{SUSY}. For $M_{SUSY} = 1$ TeV, this results in $m_h \simeq 130$ GeV for large m_A and $\tan\beta$.



$h/H/A \to \tau\tau$ in ATLAS – limits (3)

Interpretation in the MSSM m_h^{mod+} and m_h^{mod-} scenarios:

The m_h^{mod+} and m_h^{mod-} scenarios are similar to the m_h^{max} scenario, apart from the fact that the choice of radiative corrections is such that the maximum light CP-even Higgs boson mass is about 126 GeV (the amount of mixing in the top squark sector is reduced compared to m_h^{max}). This choice increases the region of the parameter space compatible with the observed Higgs boson mass. The m_h^{mod+} and m_h^{mod-} scenarios only differ in the sign of a parameter.