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Search for BSM Higgs Bosons at the LHC

Arnaud Ferrari

Search for BSM Higgs Bosons at the Large Hadron Collider

Arnaud Ferrari†

† Department of Physics and Astronomy
Uppsala University, Sweden

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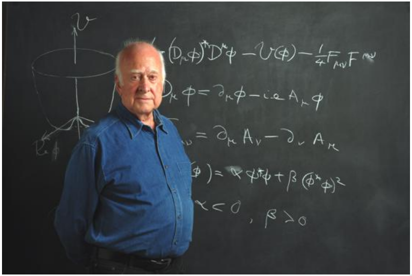
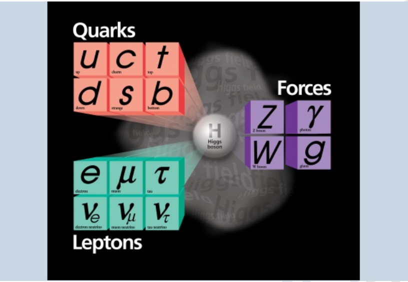
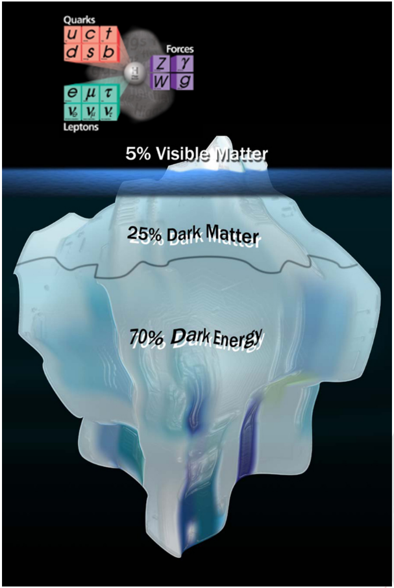
Outline

The end of a quest?





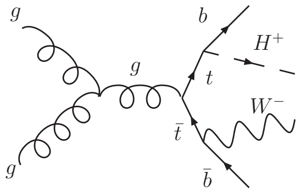
Or the beginning of a new quest?

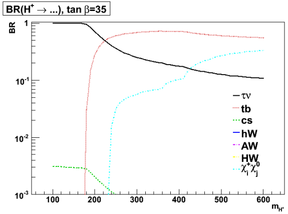


Can the Higgs sector give an indication of new physics, beyond the Standard Model?

Search for light charged Higgs bosons

With 2011 LHC data at 7 TeV, mostly sensitive to light charged Higgs bosons ($m_{H^+} < m_{top}$) produced in top quark decays.





m_h^{max} scenario of the MSSM

Search strategies: $\begin{cases} H^+ \to \tau_{had}\nu \text{ (dominant)}, \\ H^+ \to c\bar{s} \text{ at low } \tan\beta. \end{cases}$

Upper limits on $Br(t \to bH^+)$ are extracted assuming $Br(H^+ \to \tau\nu) = 100\%$ or $Br(H^+ \to c\bar{s}) = 100\%$.

$H^+ \to \tau\nu$: τ_{had}+jets channel (1) ATLAS

Search for $pp \to t\bar{t} \to b\bar{b}WH^+$ with:

- $W \to jj$,
- $H^+ \to \tau_{\text{had}}\nu$.

1. $\tau + E_T^{\text{miss}}$ trigger with thresholds of 29 and 35 GeV;
2. Exactly one τ jet having $p_T > 40$ GeV, matched to the trigger object;
3. At least four additional jets having $p_T > 20$ GeV, with at least one b-tag;
4. $E_T^{\text{miss}} > 65$ GeV and $\frac{E_T^{\text{miss}}}{0.5 \cdot \sqrt{\sum p_T}} > 13\ \text{GeV}^{1/2}$;
5. The jjb combination with the highest p_T^{jjb} must satisfy $m_{jjb} \in [120, 240]$ GeV.

Discriminating variable: $m_T = \sqrt{2 p_T^{\tau} E_T^{\text{miss}} (1 - \cos \Delta\phi_{\tau,\text{miss}})}$

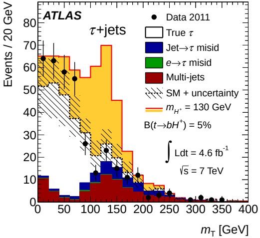
$H^+ \to \tau\nu$: τ_{had}+jets channel (2) ATLAS

Background with multi-jet events: m_T shape measured in a control region, event yield from a fit of E_T^{miss} in the signal region using simulation + a multi-jet template from data.

Electroweak background with fake τ jets:

* $e \to \tau_{\text{had}}$: simulations are corrected using scale factors.
* $j \to \tau_{\text{had}}$: misidentification probabilities are measured in W+jets events in data and then applied in simulations.

Background with true τ jets (embedding): select $t\bar{t}$-like μ+jets events in data + replace the muon by a simulated hadronic τ decay + normalize using simulation.



Sample	Event yield (τ+jets)
True τ (embedding method)	210 ± 10 ± 44
Misidentified jet $\to \tau$	36 ± 6 ± 10
Misidentified $e \to \tau$	3 ± 1 ± 1
Multi-jet processes	74 ± 3 ± 47
All SM backgrounds	330 ± 12 ± 65
Data	355
$t \to bH^+$ (130 GeV)	220 ± 6 ± 56
Signal+background	540 ± 13 ± 85

$H^+ \to \tau\nu$: ratio method (1) **ATLAS**

- While W bosons decay equally to all lepton families, H^+ mostly decays to $\tau \Rightarrow$ excess of events with τ_{had}.
- To cancel several systematic uncertainties in the analysis, event yield ratios are computed between $l + \tau_{\text{had}}$ and dilepton ($e\mu$) final states.

Event selections:

1. Single-lepton trigger (threshold of 20 or 22 GeV for electrons, 18 GeV for muons);
2. One lepton having E_T > 25 GeV (electron) or p_T > 25 GeV (muon), matched to the corresponding trigger object;
3. At least two jets having p_T > 20 GeV, with two b-tags;
4. Either exactly one τ jet with $p_T > 25$ GeV and no other lepton, or exactly one other lepton l' with E_T or p_T above 25 GeV and a different flavor than the trigger-lepton;
5. $E_T^{\text{miss}} > 40$ GeV.

$H^+ \to \tau\nu$: ratio method (2a) ATLAS

Background with fake leptons:

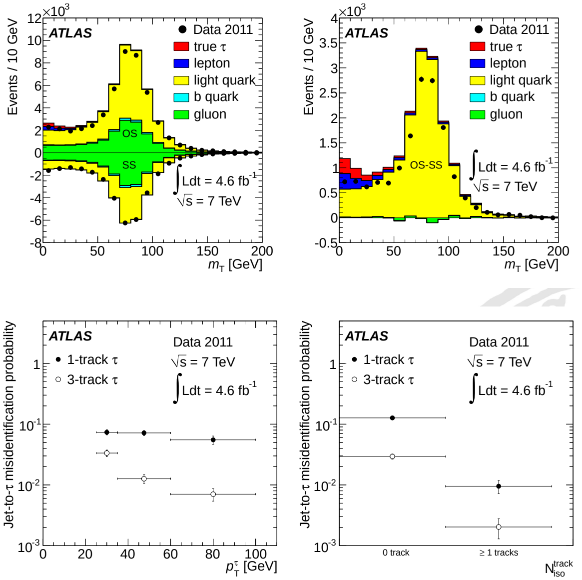
It is estimated using a data-driven method based on events containing tight or loose leptons:

$$N_f^T = \frac{f}{r - f}(rN^L - N^T).$$

Background with fake τ jets:

- $e \to \tau_{\text{had}}$: same as for τ_{had}+jets
- $j \to \tau_{\text{had}}$: data-driven method
  - Giving a negative weight to same-sign (SS) events cancels gluon and b-quark jet contributions, leaving only light quark jets misidentified as τ objects;
  - The fake rate of light quark jets to τ jets is derived from data using OS-SS W + >2 jets events, i.e. one lepton, one τ candidate, at least two jets with no b-tag, $E_T^{\text{miss}} > 40$ GeV, $m_T(l, \text{miss}) > 30$ GeV.

$H^+ \to \tau\nu$: ratio method (2b) **ATLAS**

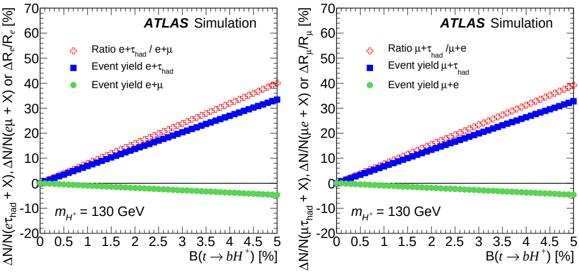


$H^+ \to \tau\nu$: ratio method (3) ATLAS

OS-SS event yield ratios are computed:

$$R_l = \frac{\mathcal{N}(bb + l\tau_{had} + E_T^{miss})}{\mathcal{N}(bb + ll' + E_T^{miss})}.$$

R_e in SM: 0.105 ± 0.012;
R_μ in SM: 0.166 ± 0.017;
Data: $R_e = 0.115 \pm 0.010$ (stat), $R_\mu = 0.165 \pm 0.015$ (stat)



Combination of electron- and muon-triggered channels: the fraction of dilepton events that fire both triggers is 42% in data.

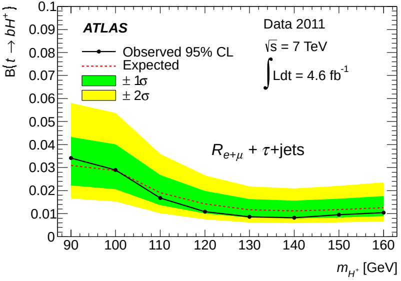
$$R_{e+\mu} = \frac{\mathcal{N}(e + \tau_{had}) + \mathcal{N}(\mu + \tau_{had})}{[\mathcal{N}(e + \mu) + \mathcal{N}_{OR}(\mu + e)]}$$

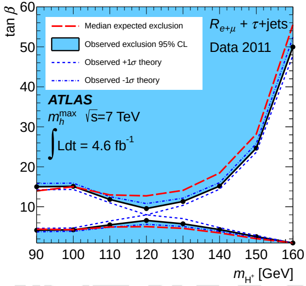
$H^+ \to \tau\nu$: limits

ATLAS

With the assumption $\mathrm{Br}(H^+ \to \tau\nu) = 100\%$, upper limits are set on the branching fraction $\mathrm{Br}(t \to bH^+)$.

The combined limit on $\mathrm{Br}(t \to bH^+) \times \mathrm{Br}(H^+ \to \tau\nu)$ is then interpreted in the $m_h^{\max}$ scenario of the MSSM.

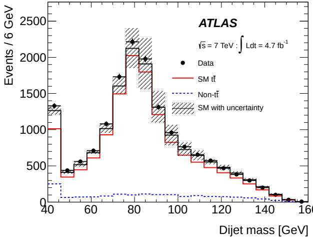


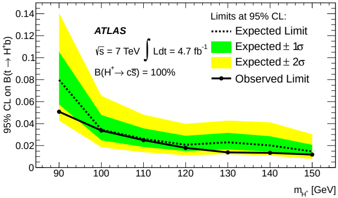


$H^+ \to c\bar{s}$ ATLAS

This decay has a significant branching fraction at low $\tan\beta$: search for $pp \to t\bar{t} \to b\bar{b}WH^+$ with $W \to \ell\nu$ and $H^+ \to c\bar{s}$.

- One electron (muon) with $p_T > 25$ (20) GeV, at least 4 jets (with 2 b-tags), and some requirements on $m_T(l, \text{miss})$ and E_T^{miss};
- $t\bar{t}$ is the dominant background;
- Kinematic fit on the top quark decay products: better mass resolution (see back-up slides);
- The di-jet mass is the discriminating variable.

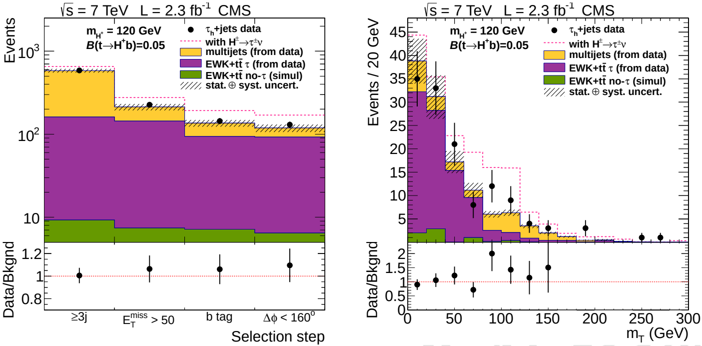




Overview of $H^+ \to \tau\nu$ searches in CMS (1a)

A first search for $H^+ \to \tau\nu$ used 2.3 fb^{-1} of data at 7 TeV:

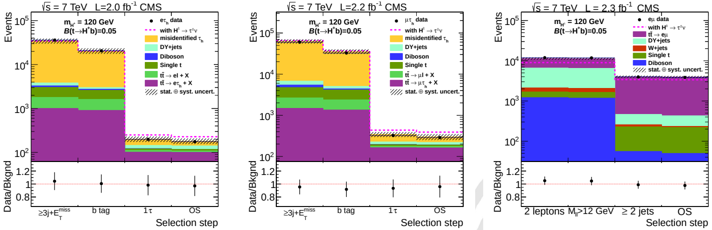
- $\tau_{\rm had}$+jets channel: fit of the m_T distribution:



Overview of $H^+ \to \tau\nu$ searches in CMS (1b)

A first search for $H^+ \to \tau\nu$ used 2.3 fb^{-1} of data at 7 TeV:

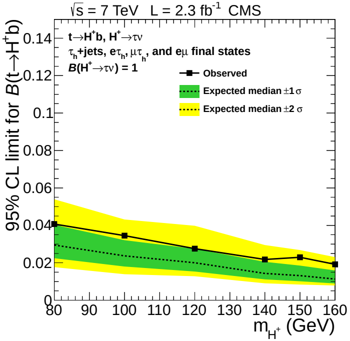
- $e + \tau_{\text{had}}$, $\mu + \tau_{\text{had}}$ and $e + \mu$ channels: cut-and-count analysis.

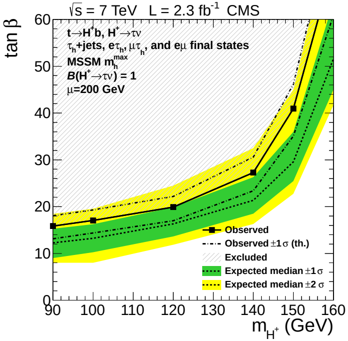


Overview of $H^+ \to \tau\nu$ searches in CMS (1c)

A first search for $H^+ \to \tau\nu$ used 2.3 fb^{-1} of data at 7 TeV:

- Combined limit on Br($t \to bH^+$) and interpretation in the $m_h^{\max}$ scenario.

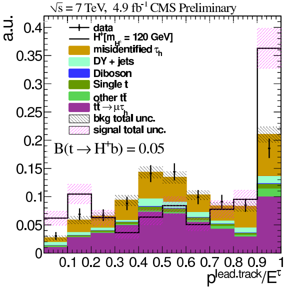


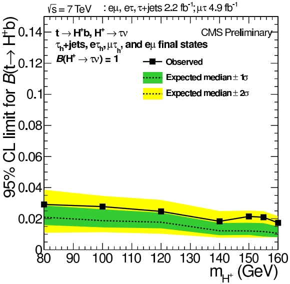


Overview of $H^+ \to \tau\nu$ searches in CMS (2)

The search for $H^+ \to \tau\nu$ was recently updated using 4.9 fb^{-1} of data at 7 TeV, in the $\mu + \tau_{\text{had}}$ channel only.

A shape analysis was done using the ratio $p_\tau^{\text{lead.track}}/E_\tau$ as the discriminating variable.





Combined with the $e + \tau_{\text{had}}$, $e + \mu$ and τ_{had}+jets analyses (2.3 fb^{-1}), it leads to new upper limits on Br($t \to bH^+$) in the 2-3% range.

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Search for BSM Higgs Bosons at the LHC

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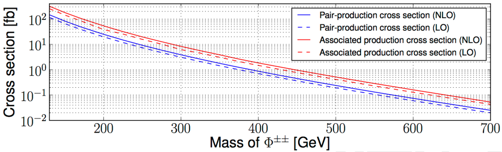
Production and decays of doubly charged Higgs bosons

Events with two like-sign leptons are rare in the SM but can be enhanced in several extensions of the SM. Doubly charged Higgs bosons $\phi^{\pm\pm}$ can be observed as a narrow resonance in sign-like dilepton mass distributions.

- $pp \to Z/\gamma^* \to \phi^{\pm\pm}\phi^{\mp\mp}$: 4 leptons
- $pp \to W^* \to \phi^{++}\phi^{-}$: 3 leptons

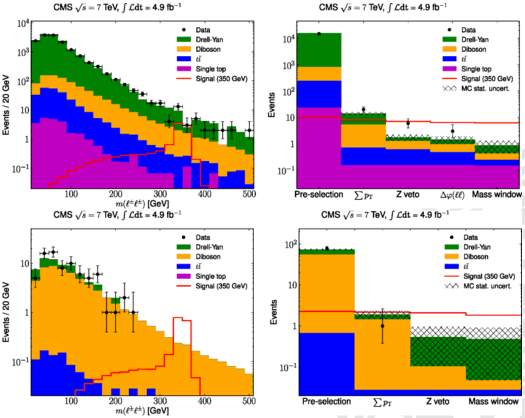


Cross sections with the assumption that $\phi^{\pm\pm}$ and $\phi^{\pm}$ are degenerate in mass.

Both ATLAS and CMS published results on the analysis of the full 2011 dataset at 7 TeV.

Doubly charged Higgs bosons in CMS (1)

Analysis of three-lepton ($\ell\ell\ell$ + $\ell\ell\tau_{\rm had}$) and four-lepton ($\ell\ell\ell\ell$ + $\ell\ell\ell\tau_{\rm had}$ + $\ell\ell\tau_{\rm had}\tau_{\rm had}$) final states:



The sign-like dilepton mass distributions are shown after pre-selection.

Doubly charged Higgs bosons in CMS (2)

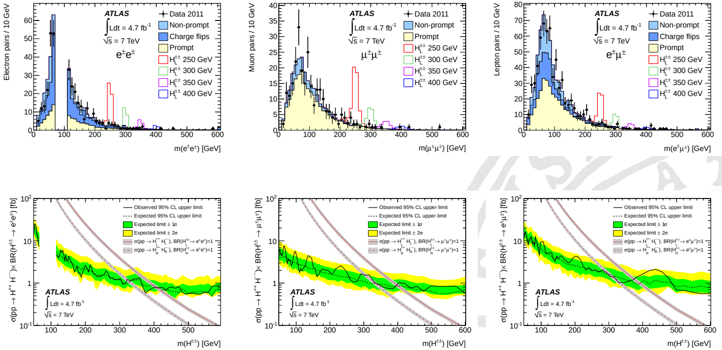
The data and the estimated background contributions are found to be in reasonable agreement for all final states... Limits on $\sigma \times B^2$ were derived as a function of $m_{\phi^{\pm\pm}}$ and then interpreted in different scenarios.

Benchmark point	Combined 95 % CL limit [GeV]	95 % CL limit for pair production only [GeV]
$\mathcal{B}(\Phi^{++} \to e^+e^+) = 100\ \%$	444	382
$\mathcal{B}(\Phi^{++} \to e^+\mu^+) = 100\ \%$	453	391
$\mathcal{B}(\Phi^{++} \to e^+\tau^+) = 100\ \%$	373	293
$\mathcal{B}(\Phi^{++} \to \mu^+\mu^+) = 100\ \%$	459	395
$\mathcal{B}(\Phi^{++} \to \mu^+\tau^+) = 100\ \%$	375	300
$\mathcal{B}(\Phi^{++} \to \tau^+\tau^+) = 100\ \%$	204	169
BP1	383	333
BP2	408	359
BP3	403	355
BP4	400	353

Benchmark point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

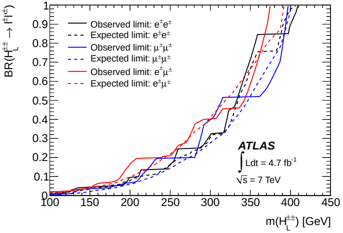
Doubly charged Higgs bosons in ATLAS (1)

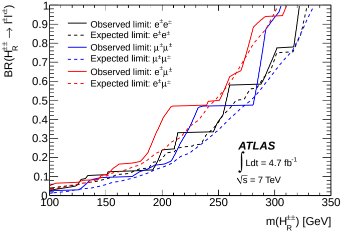
ATLAS has searched for pair-produced doubly-charged Higgs bosons only ($H_L^{\pm\pm}$ & $H_R^{\pm\pm}$, with different couplings to Z), by looking for resonances in $e^\pm e^\pm$, $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$ mass distributions $\rightarrow$ limits on $\sigma \times B^2$ vs $m_{H^{\pm\pm}}$.



Doubly charged Higgs bosons in ATLAS (2)

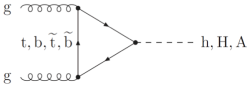
Limits are then interpreted in the (m,Br) plane, separately for $H_L^{\pm\pm}$ & $H_R^{\pm\pm}$ (different pair-production cross sections).





Production and decays of the MSSM neutral Higgs bosons $\phi = h, A, H$

- 2 main Production Processes:



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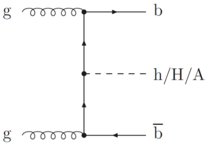

- Cross-section increases ~tan β²

With increasing tan β:

- Couplings to down-type fermions are enhanced for *A* and either *H* or *h*;
- Couplings to up-type fermions are suppressed for *A* and either *H* or *h*;
- Couplings to the SM vector bosons are absent for *A* and suppressed for either *H* or *h*.

Decays at high tan β: $b\bar{b}$ (90%), $\tau_{\rm lep}\tau_{\rm lep} + \tau_{\rm had}\tau_{\rm lep} + \tau_{\rm had}\tau_{\rm had}$ (10%), $\mu\mu$ (0.04% but clean signature, see back-up slides).

$h/A/H \to \tau\tau$: common aspects ATLAS

Missing Mass Calculator (MMC):

- Assume that E_T^{miss} only comes from neutrinos.
- Instead of using a collinear approximation, scan over the neutrino directions and pick the most likely value of $m_{\tau\tau}$, according to the probability density functions from simulated τ decays (see back-up slides).

$Z \to \tau\tau$ background - embedding: Detector signatures of muons from $Z \to \mu\mu$ in data are replaced by simulated τ decays, the event yield is normalized using simulation.

Multi-jet background - ABCD method:

- Two uncorrelated variables are chosen to define 4 regions in data: A (signal), B, C, D.
- After subtracting other processes in control regions, the multi-jet background in A is $n_A = n_B \times (n_C/n_D)$.

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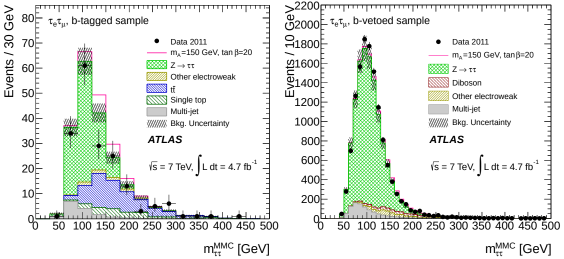
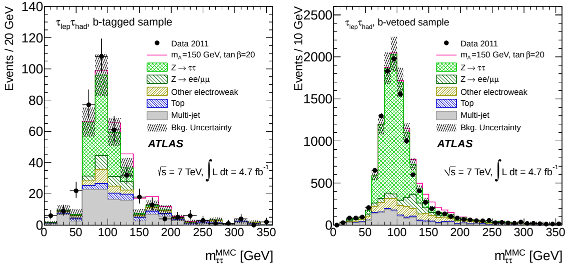
$h/A/H \to \tau\tau$: $e + \mu$ channel **ATLAS**

1. Single-lepton or electron+muon trigger;
2. Exactly one electron and one muon (with E_T/p_T on the plateau of the trigger curve) with $m_{e\mu} > 30$ GeV;
3. Split events according to flavor content:
   - b-tagged: one b-jet, $H_T = \sum_j E_T(j) < 100$ GeV $E_T^{\text{miss}} + p_T(e) + p_T(\mu) < 125$ GeV, $\Delta\phi_{e\mu} > 2.0$, $\sum_{e,\mu} \cos\Delta\phi_{l,\text{miss}} > -0.2$.
   - b-vetoed: no b-jet, $E_T^{\text{miss}} + p_T(e) + p_T(\mu) < 150$ GeV, $\Delta\phi_{e\mu} > 1.6$, $\sum_{e,\mu} \cos\Delta\phi_{l,\text{miss}} > -0.4$.
4. $t\bar{t}$ background estimated in a region with 2 b-tags.



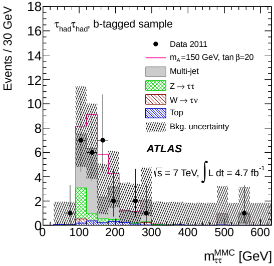
$h/A/H \to \tau\tau$: τ_{had}+lepton channel **ATLAS**

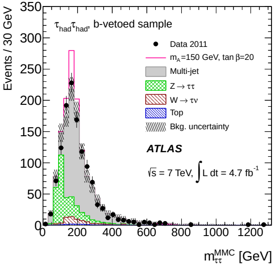
1. Single-lepton trigger + exactly one electron (muon) with p_T > 25 (20) GeV + one τ jet of opposite sign;
2. $m_T(l, \text{miss})$ < 30 GeV, then split events:
   - b-tagged: the highest-p_T jet is b-tagged, with a p_T between 20 and 50 GeV;
   - b-vetoed: the highest-p_T jet is not b-tagged and $E_T^{\text{miss}} > 20$ GeV;
3. $t\bar{t}$ background estimated in a region with 2 b-tags, W+jets background estimated in a high-m_T region.



$h/A/H \to \tau\tau$: $\tau_{had} + \tau_{had}$ channel **ATLAS**

1. Di-τ_{had} trigger with thresholds of 29 and 20 GeV + two opposite-sign τ jets with $p_T > 45/30$ GeV, with no electron or muon;
2. $E_T^{miss} > 25$ GeV, then split events:
   - b-tagged: the highest-p_T jet is b-tagged, with a p_T between 20 and 50 GeV;
   - b-vetoed: no jet or the highest-p_T jet is not b-tagged + $p_T(\tau_1)$ raised to 60 GeV;
3. $t\bar{t}$, W/Z+jets backgrounds mostly from simulation.





Search for BSM Higgs Bosons at the LHC

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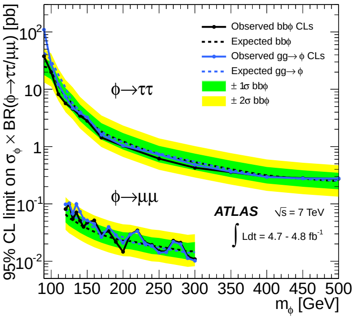
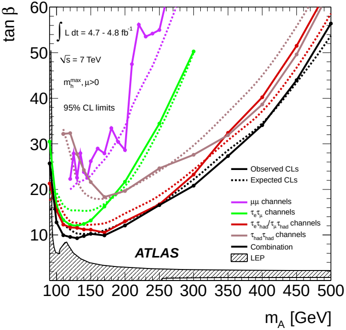
MSSM neutral Higgs bosons: limits **ATLAS**

The limits on the cross section for a single neutral Higgs boson times the branching fraction into τ and μ pairs can be interpreted in the $m_h^{\max}$ scenario of the MSSM.





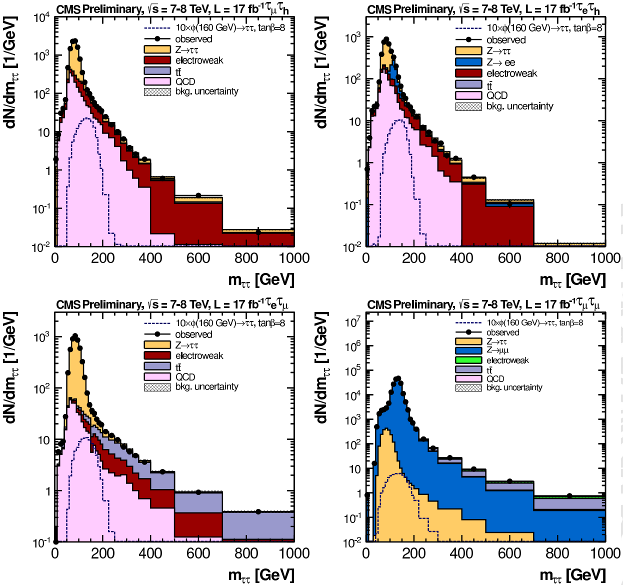
$h/A/H \to \tau\tau$ searches in CMS (1)

CMS has analysed 4.9+12.1=17 fb^{-1} of 2011+2012 data to search for MSSM neutral Higgs bosons:

- $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$, $e\mu$ and $\mu\mu$ final states;
- two event categories:
  - b-tagged: at least one b-jet with $p_T > 20$ GeV and not more than one jet with $p_T > 30$ GeV,
  - b-vetoed: no b-jet with $p_T > 20$ GeV;
- a maximum likelihood technique computes the di-τ mass that is the most compatible with the observed visible τ decay products and E_T^{miss}, with kinematic constraints;
- Background estimation using similar techniques as in ATLAS.

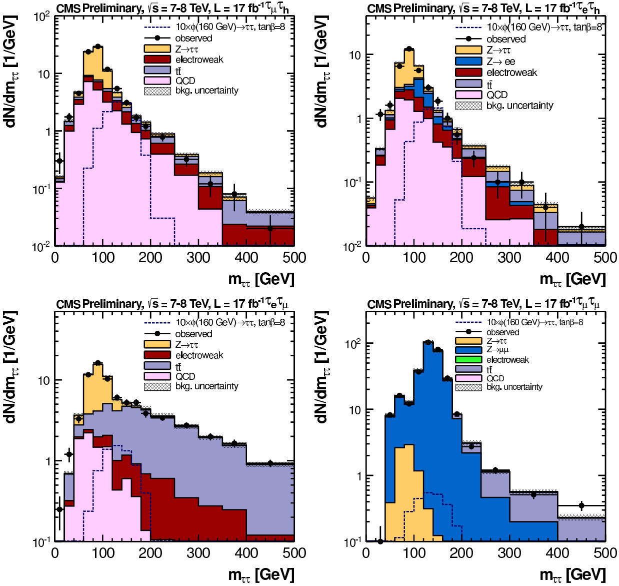
$h/A/H \to \tau\tau$ searches in CMS (2a)

Mass reconstruction in b-vetoed events:



$h/A/H \to \tau\tau$ searches in CMS (2b)

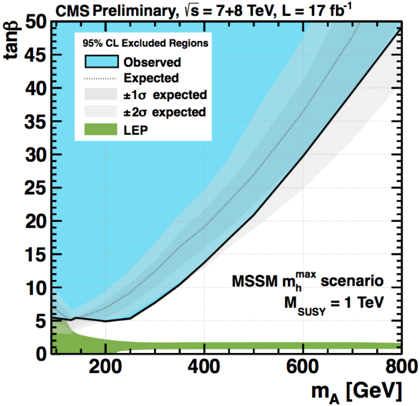
Mass reconstruction in b-tagged events:



$h/A/H \to \tau\tau$ searches in CMS (3)

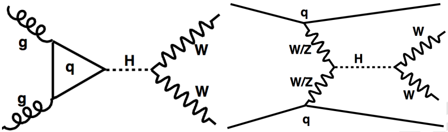
Limits in the $m_h^{\max}$ scenario:

- $M_{SUSY} = 1$ TeV
- $X_t = 2M_{SUSY}$
- $\mu = 200$ GeV
- $M_{\tilde{g}} = 800$ GeV
- $M_2 = 200$ GeV
- $M_1 = (5/3)M_2 \frac{\sin\theta_W}{\cos\theta_W}$
- $A_t = A_b$



2HDM $H \to WW \to e\nu\mu\nu$ in ATLAS (1)

Test of type-I and type-II 2HDM: assume h (125 GeV) is the light scalar and search for a second Higgs boson H decaying into WW (A does not decay to vector bosons and hence does not contribute).



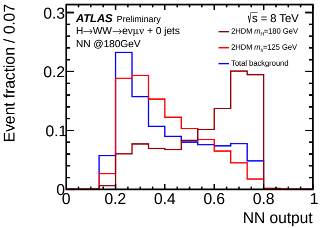
- exactly two OS leptons of different flavors, with $p_T(\ell_1/\ell_2) > 25/15$ GeV and $m_{\ell_1\ell_2} > 10$ GeV,
- $E_{T,rel}^{miss} > 25$ GeV,
- split events in two categories:
  - 0 jet + $\Delta\phi_{\ell_1,\ell_2} < 2.4$ + $m_{\ell_1\ell_2} < 75$ GeV,
  - 2 jets + no b-tag + $\eta(j_1)\eta(j_2) < 0$ + $m_{\ell_1\ell_2} < 80$ GeV + $m_T(\ell_1, \ell_2, E_T^{miss}) < 180$ GeV.

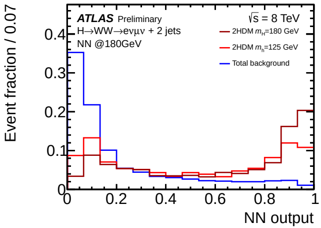
2HDM $H \rightarrow WW \rightarrow e\nu\mu\nu$ in ATLAS (2)

Signal = h and H.
Background = no Higgs.

Signal/background separation: kinematic variables (6 for 0-jet, 9 for 2-jets) are combined into one NN discriminant.

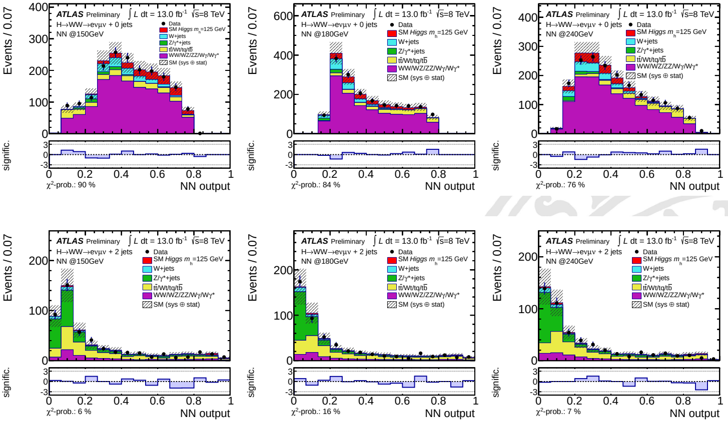
Training at three m_H points: 150, 180, 240 GeV. The modelling of the NN-discriminant was successfully checked in background-enriched regions.





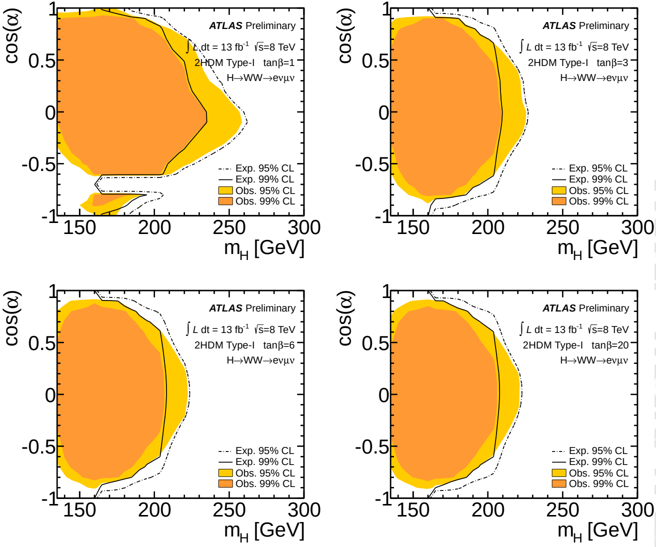
2HDM $H \to WW \to e\nu\mu\nu$ in ATLAS (3)

NN-discriminant distributions in the signal regions (top: 0-jet, bottom: 2-jets). Good agreement between data and SM predictions.



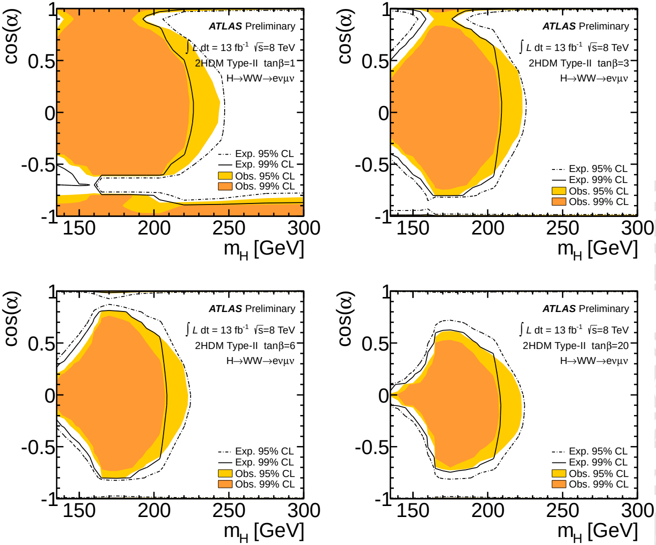
2HDM $H \to WW \to e\nu\mu\nu$ in ATLAS (4a)

Exclusion plots for type-I 2HDM:



2HDM $H \to WW \to e\nu\mu\nu$ in ATLAS (4b)

Exclusion plots for type-II 2HDM:



UPPSALA UNIVERSITET

Search for BSM Higgs Bosons at the LHC

Arnaud Ferrari

Conclusion and outlooks

- A Higgs-like boson was discovered at the LHC, but several BSM theories predict more Higgs bosons.
- New neutral and charged Higgs bosons have been searched for by ATLAS and CMS using 2011 LHC data (and sometimes a fraction of 2012 data).
- No significant excess of data with respect to the SM prediction was found...

Some references:

- H^+ searches in ATLAS: JHEP 1206 (2012) 039, arXiv:1212.3572, arXiv:1302.3694.
- H^+ searches in CMS: JHEP 1207 (2012) 143, CMS-PAS-HIG-12-052.
- $H^{\pm\pm}$ searches in ATLAS: Eur. Phys. J. C72 (2012) 2244.
- $H^{\pm\pm}$ searches in CMS: Eur. Phys. J. C72 (2012) 2189.
- MSSM $h/A/H$ searches in ATLAS: JHEP02 (2013) 095.
- MSSM $h/A/H$ searches in CMS: CMS-PAS-HIG-12-050.
- 2HDM h/H searches in ATLAS: ATLAS-CONF-2013-027.

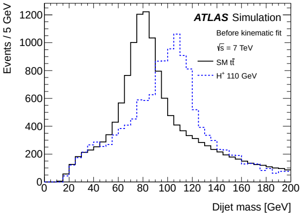
Back-up slides

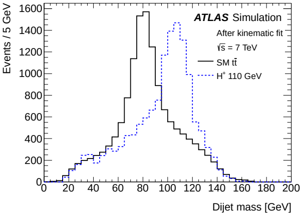
$H^+ \to c\bar{s}$: kinematic fit **ATLAS**

Among all jet combinations, the one with the smallest χ^2 value is selected as the best assignment:

$$\chi^2 = \sum_{i=\ell,4\text{jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{\text{SEJ},\text{fit}} - p_j^{\text{SEJ},\text{meas}})^2}{\sigma_{\text{SEJ}}^2} + \sum_{k=jjb,b\ell\nu} \frac{(M_k - m_{\text{T}})^2}{\Gamma_t^2} .$$

SEJ: vector sum of the energy of the remaining jets in the event

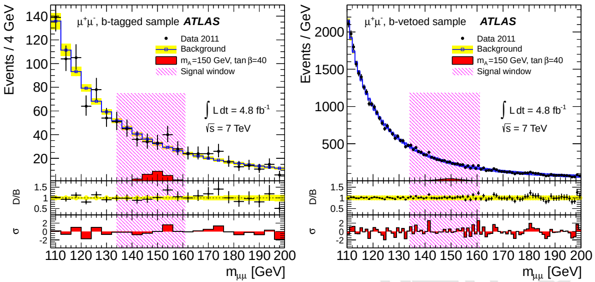




$h/A/H \to \mu\mu$ channel **ATLAS**

- At least one trigger-matched muon with $p_T > 20$ GeV and at least another muon with $p_T > 15$ GeV;
- The pair of highest-p_T oppositely charged muons has $m_{\mu\mu} > 70$ GeV;
- $E_T^{\text{miss}} < 40$ GeV.

A fit of the sidebands of the $m_{\mu\mu}$ distribution is performed to estimate SM backgrounds from data.



$h/A/H \to \tau\tau$ channel: MMC in one slide

The full reconstruction of the $h/A/H \to \tau\tau$ events requires solving equations with more unknowns than constraints.

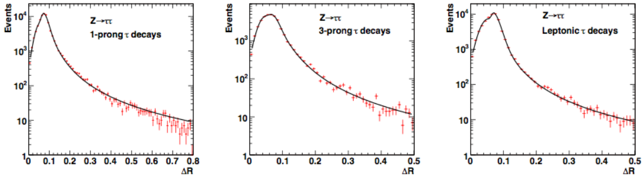
$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$

$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$

$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1}p_{\text{mis}_1}\cos\Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2}p_{\text{mis}_2}\cos\Delta\theta_{vm_2}$$

More information is available from the angular distance ΔR between the visible and missing τ decay products.



- An $m_{\tau\tau}$ distribution is produced by scanning a grid in $\phi_{\text{mis1}}, \phi_{\text{mis2}}$ and $m_{\text{mis},i}$ (only for leptonic τ decays);
- Each point gets a weight $\mathcal{P}(\Delta R_1, p_{\tau 1}) \times \mathcal{P}(\Delta R_2, p_{\tau 2})$;
- The most probable value of $m_{\tau\tau}$ is chosen.