Searches for additional Higgs bosons in the MSSM with the ATLAS detector

Alvaro Lopez Solis
On behalf of the ATLAS collaboration

DIS 2018 – Kobe - Japan
18th April 2018
Introduction

Discovery of a new scalar in 2012 at the LHC at $m_h = 125$ GeV.

- Masses, spin/parity and couplings compatible with the SM Higgs boson.

Possibility that there are more Higgs bosons → Still not ruled out by measurements.

In the MSSM, two Higgs doublets $\Phi_u = (\Phi^+, \Phi^0_u)$ and $\Phi_d = (\Phi^0_d, \Phi^-_d) \rightarrow 5$ mass eigenstates: h (SM Higgs), H, A, H⁺, H⁻.
**Run I legacy**

No new resonances were found during Run I. Main interpretation using hMSSM $\rightarrow$ Phenomenology approximately described by $\tan\beta$ and $m_A$.

In Run II, results are public with partial 2015+2016 dataset or full 2015+2016 luminosity (36.1 fb$^{-1}$)

Focusing on charged Higgs and A/H searches $\rightarrow$ High-mass searches/di-Higgs/Higgs couplings talks during the workshop.

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*Data good for physics = 36.1 fb$^{-1}$*
Charged Higgs searches: $H^{\pm} \rightarrow \tau \nu$

Final state with hadronic $\tau$'s and at least 3 jets from $tbH^+$ production (at least 1b-tagged) and $E_{T}^{\text{miss}}$.

- Main backgrounds are the $t\bar{t}$, jet $\rightarrow \tau$, $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$.
- Data-driven jet $\rightarrow \tau$ fake factors estimated on multijet enriched CRs.
- $e/\mu$ misidentification rate estimated on $Z \rightarrow ee$ events.
- Other backgrounds: shape from simulation and validated in data control regions.

Main uncertainties related to jet $\rightarrow \tau$ fake factors, jet energy scale and $tt$ parton shower model.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>True $\tau_{\text{had}}$</td>
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<tr>
<td>$t\bar{t}$ &amp; single-top-quark</td>
<td>$2880 \pm 770 \pm 25$</td>
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<td>$W \rightarrow \tau\nu$</td>
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<td>$Z \rightarrow \tau\tau$</td>
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<td>diboson ($WW, WZ, ZZ$)</td>
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<tr>
<td>Misidentified $e, \mu \rightarrow \tau_{\text{had-vis}}$</td>
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<tr>
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<td>All backgrounds</td>
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<td>$H^{+}$ (200 GeV), hMSSM $\tan \beta = 60$</td>
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<td>$7.5 \pm 0.6 \pm 0.05$</td>
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<td>Data</td>
<td>$4645$</td>
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$\mathcal{L} = 14.7$ fb$^{-1}$
Charged Higgs searches: $H^{+,-} \rightarrow \tau \nu$

Final state with hadronic $\tau$'s and at least 3 jets from tbH+ production (at least 1 b-tagged) and $E_{T\text{miss}}$

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$H^+ (200 \text{ GeV}), \text{hMSSM} \tan \beta = 60$

- 523 ± 86 ± 4

$H^+ (1000 \text{ GeV}), \text{hMSSM} \tan \beta = 60$

- 7.5 ± 0.6 ± 0.05

Data

4645

$\mathcal{L} = 14.7 \text{ fb}^{-1}$

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Charged Higgs searches: $H^{±} \rightarrow \tau \nu$

- Fits on SR $m_\tau$ distribution defined to get one medium ID hadronic $\tau$ plus $E_{T}^{miss}$ and b-jets.
- No BSM is observed $\Rightarrow$ Limits on cross-section

$m_T = \sqrt{2p_T^{\tau}E_{T}^{miss}(1 - \cos \Delta \phi_{\tau}, E_{T}^{miss})}$.
Charged Higgs searches: $H^{+,-} \rightarrow tb$

Similar production than $H \rightarrow \tau\nu \rightarrow$ Final state: 2 top-quark and 2-b-quarks

- At least 4 jets, at least two b-jets and 1 lepton.
- Main background is $t\bar{t}$: divided according to additional jet flavour.
- Profit of the high number of jets and b-jets in the signal.
- Define SRs and CRs depending of the $N_{bjet}$ and $N_{jet}$
- Trained BDTs for each simulated signal
- Dominated by $t\bar{t}$+1b modeling, normalization and b-tagging efficiency

Control regions

Signal regions

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>$\Delta\mu(H_{300}^{+})$</th>
<th>$\Delta\mu(H_{800}^{+})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ + 1b modelling</td>
<td>+0.53 -0.53</td>
<td>+0.07 -0.07</td>
</tr>
<tr>
<td>Jet flavour tagging</td>
<td>+0.30 -0.29</td>
<td>+0.07 -0.07</td>
</tr>
<tr>
<td>$t\bar{t}$ + 1c modelling</td>
<td>+0.23 -0.22</td>
<td>+0.03 -0.03</td>
</tr>
<tr>
<td>Background model statistics</td>
<td>+0.19 -0.19</td>
<td>+0.05 -0.05</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.18 -0.17</td>
<td>+0.03 -0.03</td>
</tr>
<tr>
<td>Jet+light modelling</td>
<td>+0.16 -0.16</td>
<td>+0.03 -0.03</td>
</tr>
<tr>
<td>Other background modelling</td>
<td>+0.15 -0.14</td>
<td>+0.03 -0.03</td>
</tr>
<tr>
<td>Jet-vertex association, pileup modelling</td>
<td>+0.12 -0.11</td>
<td>+0.01 -0.01</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.12 -0.12</td>
<td>+0.01 -0.01</td>
</tr>
<tr>
<td>Light lepton ($e, \mu$) ID, isolation, trigger</td>
<td>+0.01 -0.01</td>
<td>&lt;0.01 &lt;0.01</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+0.72 -0.79</td>
<td>+0.13 -0.11</td>
</tr>
<tr>
<td>$t\bar{t}$ + 1b normalisation</td>
<td>+0.36 -0.36</td>
<td>+0.03 -0.03</td>
</tr>
<tr>
<td>$t\bar{t}$ + 1c normalisation</td>
<td>+0.15 -0.14</td>
<td>+0.02 -0.02</td>
</tr>
<tr>
<td>Total statistical uncertainty</td>
<td>+0.44 -0.43</td>
<td>+0.08 -0.08</td>
</tr>
<tr>
<td>Total</td>
<td>+0.84 -0.90</td>
<td>+0.15 -0.13</td>
</tr>
</tbody>
</table>
Charged Higgs searches: $H^{+,-} \rightarrow tb$

- Simultaneous fit to all SRs and CRs distributions
- Discriminant variable in SRs: BDTs
- Discriminant variables in CRs: $H_T^{\text{had}}$

Post-fit $N_{\text{events}}$ for CRs and SRs

**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

**ATLAS**

- Observed limit (CLs)
- Expected limit (CLs)
- $\pm 1\sigma$
- $\pm 2\sigma$
- $m_{H^+}^{\text{mod.}}: \tan\beta = 0.5$
- $m_{H^+}^{\text{mod.}}: \tan\beta = 1$
- $m_{H^+}^{\text{mod.}}: \tan\beta = 60$

**ATLAS**

- $\sigma(pp\rightarrow tbH) \times \text{BR}(H \rightarrow tb)$ [pb]

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Neutral Higgs searches: $H/A \rightarrow \tau\tau$

Searching for two $\tau$'s in the final state. Two $\tau$ decays are triggered: $\tau$(lep)$\tau$(had) and $\tau$(had)$\tau$(had)

- $\tau$(had)$\tau$(had) selecting two jets passing $\tau$-ID criteria
- $\tau$(lep)$\tau$(had), 1 lepton +1 $\tau$-jet candidate back-to-back.
- b-veto and b-tag to enhance significant for each production mode.
- Main backgrounds come from misidentification of $\tau$ and $Z \rightarrow \tau\tau$
  - Jet $\rightarrow \tau$: fake factors depending on jet $p_T$ estimated on data CRs enriched with multijet events.
  - $\tau$(lep): $e/\mu \rightarrow \tau$ fakes coming mainly from $W$+jets, $tt$ and lepton+jets events.
  - Important experimental uncertainties.

$\mathcal{L} = 36.1$ fb$^{-1}$
Neutral Higgs searches: $H/A \rightarrow \tau\tau$

- Considering ggF and b-associated production: categories with no b-jet or with b-jet.
- No BSM excess is found
  - Discriminant variable is $m_{T_{\text{tot}}}$

\[ m_{T_{\text{tot}}} = \sqrt{(p_{T1}^\tau + p_{T2}^\tau + E_{T}^{\text{miss}})^2 - (p_{T1}^\tau + p_{T2}^\tau + E_{T}^{\text{miss}})^2} \]
Neutral Higgs searches: $A \to Zh$

Production via gluon-fusion or $bbA$. Considering the $Z \to \nu\nu, ll$ decays and $h \to bb$.

- The range of $m_A$ could provide boosted Higgs bosons $\rightarrow$ Both $b$-jets merged in a large one.
- Merged: searching for a large-$R$ (1.0) $b$-jet. Resolved: searching for two $R=0.4$ $b$-jets.
- $Z \to ll, \nu\nu$ : 2-leptons and 0-lepton categories.
- $bbA$ search: requiring one more small $b$-jet (merged and resolved categories + $\geq 1$ $b$-jet)
- Main uncertainties from jet energy estimation, large-$R$ jet mass calibration and $b$-tagging efficiency.

Resolved

Merged

$\mathcal{L} = 36.1$ fb$^{-1}$

Look at Jason Veatch talk for large-$R$ jet details.

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Neutral Higgs searches: $A \rightarrow Zh$

- Discriminant variables are $m_{TZh} (OL)$ and $m_{Zh} (2L)$
- Combined fits on all categories with 2 small b-jets (1 large-R b-jet) for ggF production
- Fit on additional categories for bbA production

\[ m_{T,Vh} = \sqrt{(E_T^h + E_{T,miss}^h)^2 - (\vec{p}_T^h + \vec{E}_{T,miss}^h)^2}, \]

\[ m_{Vh} = \sqrt{(E_h + E_{\ell+\ell^-})^2 - (\vec{p}_h + \vec{p}_{\ell+\ell^-})^2}, \]
Neutral Higgs searches: $A \rightarrow Zh$

3.6 $\sigma$ (local), 2.4 $\sigma$ (global) in dimuon category.

2HDM limits derived by combining bbA and ggF production.
Additional searches: high-mass searches

High mass: $X \rightarrow WW \rightarrow l\nu l\nu$

$\mathcal{L} = 36.1 \text{ fb}^{-1}$

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ATLAS

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ATLAS

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Summary plot of Run II results

Limits and reinterpretation of limits of the searches into the plane \([m_A, \tan \beta]\) in the hMSSM framework.

ATLAS Preliminary
hMSSM, 95% CL limits

- Observed
- Expected

Run II results

Presented in this talk
Reinterpretable on MSSM

See presentations from Yaquan Fang, Monica Trovatelli and Flavia de Almeida Dias
Summary plot of Run II results

Limits and reinterpretation of limits of the searches into the plane \([m_A, \tan\beta]\) in the hMSSM framework.

- **Run I results**
  - ATLAS Preliminary
  - hMSSM, 95% CL limits
    - Observed
    - Expected

- **Run II results**
  - ATLAS
  - hMSSM, 95% CL limits

- **Presented in this talk**
- **Reinterpretable on MSSM**

See presentations from **Yaquan Fang, Monica Trovatelli** and **Flavia de Almeida Dias**
Prospects for next LHC upgrades

Still a large region of the parameter space can be explored
Conclusions

- Presented a small selection of additional Higgs boson searches in ATLAS at 13 TeV.
  - Many other searches also have results interpretable in terms of an additional Higgs production
- By now, there are no significant excesses from additional Higgs bosons in ATLAS data.
- Results presented here correspond to an integrated luminosity of $36.1 \text{ fb}^{-1}$ collected during 2015+2016
- New techniques are being developed: jet color-flow, neural networks ...

Stay tuned for the 2017 results!!

Data good for physics = 43.8 fb$^{-1}$
Additional material
Charged Higgs phenomenology

Neutral heavy Higgses phenomenology

A.Djouadi et al. (arXiv:1307.5205)
The Higgs sector and the MSSM

- Assuming that:
  - Observed Higgs is the lightest one ($h$)
  - Only radiative corrections from top and stop are not negligible
  - All other SUSY heavy particles are heavy enough to neglect contributions on couplings

\[
M_S^2 = M_Z^2 \begin{pmatrix} c^2_\beta & -s_\beta c_\beta \\ -s_\beta c_\beta & s^2_\beta \end{pmatrix} + M_A^2 \begin{pmatrix} s^2_\beta & -s_\beta c_\beta \\ -s_\beta c_\beta & c^2_\beta \end{pmatrix} + \begin{pmatrix} \Delta M^2_{11} \\ \Delta M^2_{12} \\ \Delta M^2_{22} \end{pmatrix}
\]

Radiative corrections

\[
M_H^2 = \frac{(M_A^2 + M_Z^2 - M_h^2)(M_Z^2 c^2_\beta + M_A^2 s^2_\beta) - M_A^2 M_Z^2 c_\beta s_\beta}{M_Z^2 c^2_\beta + M_A^2 s^2_\beta - M_h^2}
\]

\[
\alpha = -\arctan \left( \frac{(M_Z^2 + M_A^2)c_\beta s_\beta}{M_Z^2 c^2_\beta + M_A^2 s^2_\beta - M_h^2} \right)
\]

<table>
<thead>
<tr>
<th>$g_{VV}$</th>
<th>$g_{uu}$</th>
<th>$g_{dd,\ell\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>0</td>
<td>cot $\beta$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\cos(\beta - \alpha)$</td>
<td>$\sin\alpha/\sin\beta$</td>
</tr>
<tr>
<td>$h$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\cos\alpha/\sin\beta$</td>
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With these assumptions, the MSSM Higgs sector can be approximately well-described by $\tan\beta$ and $m_A$. 

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H/A → τ(lep)τ(had) : jet bkg estimation

Region Selection

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<tbody>
<tr>
<td>SR</td>
<td>ℓ (trigger, isolated), τ_1 (medium), q(ℓ) × q(τ_1) &lt; 0,</td>
</tr>
<tr>
<td>CR-1</td>
<td>Pass SR except: τ_1 (very-loose, fail medium)</td>
</tr>
<tr>
<td>CR-2</td>
<td>Pass SR except: τ_1 (very-loose, fail medium), ℓ (fail isolation)</td>
</tr>
<tr>
<td>MJ-FR</td>
<td>Pass SR except: τ_1 (very-loose), ℓ (fail isolation)</td>
</tr>
<tr>
<td>W-FR</td>
<td>Pass SR except: 70 (60) &lt; m_T(p_T^ℓ, E_T^{miss}) &lt; 150 GeV in τ_eτ_had (τ_μτ_had) channel</td>
</tr>
<tr>
<td>CR-T</td>
<td>Pass SR except: m_T(p_T^ℓ, E_T^{miss}) &gt; 110 (100) GeV in the τ_eτ_had (τ_μτ_had) channel, b-tag category only</td>
</tr>
<tr>
<td>L-FR</td>
<td>ℓ (trigger, selected), jet (selected), no loose τ_had-vis, m_T(p_T^ℓ, E_T^{miss}) &lt; 30 GeV</td>
</tr>
</tbody>
</table>

Low transverse mass | Low transverse mass | High transverse mass
Fail lepton isolation | Pass lepton isolation | Pass lepton isolation

\[ f_X = \frac{N_{pass}}{N_{fail}} \]

Data | W+jets (t\bar{t}) | Multijet
**H/A → τ(had)τ(had) : jet → τ fake estimation**

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</tr>
<tr>
<td>CR-1</td>
<td>Pass SR except: (\tau_2) (fail loose)</td>
</tr>
<tr>
<td>DJ-FR</td>
<td>jet trigger, (\tau_1+\tau_2) (no identification), (q(\tau_1) \times q(\tau_2) &lt; 0,</td>
</tr>
<tr>
<td>W-FR</td>
<td>(\mu) (trigger, isolated), (\tau_1) (no identification), (</td>
</tr>
<tr>
<td>T-FR</td>
<td>Pass W-FR except: (b)-tag category only</td>
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![Graph showing \(\tau_{had-vis}\) fake-factor vs. \(p_T\) for ATLAS \(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\), one-track and three-track channels.](image-url)