Beyond the Standard Model Higgs Physics using the ATLAS detector

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On behalf of the ATLAS Collaboration

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Many search ongoing for extended Higgs sector at ATLAS

Almost all the searches uses a minimal extension of the Higgs sector like a Two Higgs Doublets Model (2HDM)

This leads to 5 physical Higgses: $H^\pm$, $H^0$, $h^0$, $A$ (CP-odd)

Two types considered:

- Type-I: all quarks couple to just one of the doublets
- Type-II: up-type-quarks and down-type-quarks couple to different doublets. (MSSM is an example)

One can easily accommodate the 125 GeV Higgs in those models
Overview of ATLAS BSM Higgs Searches

- **Charged Higgs:**
  \[ H^+ \rightarrow \tau^+\nu + \text{jets (updated)} \]
  \[ H^+ \rightarrow \overline{CS} \]
  Doubly charged Higgs

- **Neutral Higgs:**
  \[ H^0 \rightarrow \tau^+\tau^- \text{ and } \mu^+\mu^- \]
  \[ 2\text{HDM} \quad H^0 \rightarrow W^+W^- \]
  Invisible Higgs
  Fermiophobic \[ H^0 \rightarrow \gamma\gamma \]
  4\text{th} fermion generation

- **Next to Minimal:**
  NMSSM \[ a_1 \rightarrow \mu\mu \]
  NMSSM \[ h \rightarrow a_1a_1 \rightarrow 4\gamma \]

For More details:
**ATLAS PUBLIC RESULT**
Neutral Higgs Searches
• **Assumption**: “the Higgs” at 125 GeV is the light “h” → search for a heavier neutral H assuming a 2HDM

• **Production**: gluon fusion and vector boson fusion

• **Final state**: W decays leptonically, only considered electron-muon, missing energy

• **Strategy**: split into 0-jet and 2-jet channels

• **Discriminant variable**: neural network output (trained for different masses)
2HDM $H \rightarrow WW$: Limits

Exclusion limit set for type-I and II, for $\tan\beta = 1, 3, 6, 20, 50$
Search for: Neutral Higgs H/h/A decaying ττ/μμ assuming MSSM

Production: gluon-fusion and b-associated

General Strategy: split in b-tag and b-veto categories

At high tanβ BR to ττ ~ 10% and to μμ ~ 0.04%, final state considered: τₑτₑ, τₑτₕ, τₕτₕ, and μμ

Discriminant variable: di-τ invariant mass (likelihood based method), μμ channel – parametrized background fitted to data (invariant mass scan)

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MSSM $H \rightarrow \tau\tau/\mu\mu$ - Limits:

Expected and observed 95% CL limits on $\tan\beta$ as a function of $m_A$ (left), and on the production cross-section times BR for each production mechanism (right). Assuming gluon-fusion and b-associated production.
Charged Higgs Searches
H^+ → \tau^+\nu + \text{jets: Analysis Overview}

- NOTE: charge conjugated is implied
- First LHC search for Heavy charged Higgs!
- **Analysis Strategy:** Light and Heavy Higgs mass category to take advantage of production channels
- Assuming MSSM: high BR of H^+ to \tau^+ over wide range of parameter space
- **Goal** discovery of H^+ or put limits on:

\[ \text{Total BR}(t \rightarrow H^+ b) \times \sigma(\text{top assoc. prod.}) \times \text{BR}(H^+ \rightarrow \tau^+\nu) \]
$H^+ \rightarrow \tau^+ \nu + \text{jets}: \text{Signal final state}$

- **Analysis final state selections:**
  - Fully hadronic final state: only $W \rightarrow \text{jets}$ and hadronic $\tau$ considered
  - Veto on other leptons
  - 3 or 4 jets of which 1 btagged
  - High Missing Transverse Energy
  - Discriminating variable $m_T$

$m_T = \text{Transverse invariant mass of tau and Missing Transverse Energy}$
**H^+ → τ^+ν + jets: Background Model**

- Backgrounds: tt and single-top, W and Z + jets, dibosons, QCD multi-jet.
- **Background estimation divided in 2 categories:**
  - Real taus (and an additional lepton-fake taus) contribution → estimated via Simulation
  - Jet-fake taus → estimated via data-driven method: apply to data weights calculated from τ identification and misidentification efficiency
No evidence in data found for the existence of a charged Higgs boson.

Using 2012 full dataset expected and observed 95% CL upper limits are set for:

- Left – Branching ratio of top into charged higgs, assuming $\text{BR}(H^+ \rightarrow \tau^+\nu) = 1$ (light higgs search)
- Right – production cross-section $\times \text{BR}(H^+ \rightarrow \tau^+\nu)$ (heavy higgs search)
Interpretation in the context of the MSSM $m_h^{\text{max}}$ scenario of the limits on BR($t \rightarrow H^+ b$) for light $H^+$ (left) and production of heavy charged Higgs (right)
An update on the search for charged Higgs using the $\tau^+$+jet channel with 19.5 fb$^{-1}$ has been presented.

No evidence of charged Higgs is found.

Limits are set at 95% CL on:

- $\text{BR}(t \rightarrow bH^+)$ in a range of 0.2 - 2.1% for $90 < m_{H^+} < 160$ GeV
- $\sigma(\text{top assoc. prod.}) \times \text{BR}(H^+ \rightarrow \tau^+\nu)$ in a range of 0.01 – 0.9 pb for mass $180 < m_{H^+} < 600$ GeV

Many different searches for extended BSM Higgs sector with Atlas, however no evidence found.

Further analysis still in progress!!!
Additional Material
$H^\pm$ data driven jet-fake tau

\[ N^L = N^L_m + N^L_r; \]
\[ N^T = N^T_m + N^T_r, \]
\[ N^T_m = \frac{p_m}{(p_r - p_m)}(p_r \times N^L - N^T) \]
# H\(^{\pm}\) Systematics Table

<table>
<thead>
<tr>
<th>Variation</th>
<th>Detector effects</th>
<th>Shift Up (%)</th>
<th>Shift Down (%)</th>
<th>Shift Up (%)</th>
<th>Shift Down (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>light (H^{+}) event selection</td>
<td>heavy (H^{+}) event selection</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(b)–Jet (Mis-)Tag Efficiency Uncertainty</td>
<td>3.1</td>
<td>-3.4</td>
<td>2.9</td>
<td>-3.2</td>
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<tr>
<td>Jet Energy Scale Uncertainties</td>
<td>3.7</td>
<td>-4.8</td>
<td>7.1</td>
<td>-6.8</td>
<td></td>
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<tr>
<td>JVF Uncertainty</td>
<td>2.2</td>
<td>-1.9</td>
<td>2.2</td>
<td>-2.1</td>
<td></td>
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<tr>
<td>(E_{T}^{\text{miss}}) Uncertainties</td>
<td>-0.6</td>
<td>0.2</td>
<td>0.4</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>(\tau_{\text{had–vis}}) e-Veto Uncertainty</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.01</td>
<td>-0.01</td>
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<tr>
<td>(\tau_{\text{had–vis}}) Energy Scale Uncertainty</td>
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<td>-3.8</td>
<td>3.6</td>
<td>-3.8</td>
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<tr>
<td>(\tau_{\text{had–vis}}) ID Uncertainty</td>
<td>3.8</td>
<td>-3.8</td>
<td>3.7</td>
<td>-3.7</td>
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<tr>
<td>Pile-up Uncertainties</td>
<td>0.9</td>
<td>-1.5</td>
<td>2.6</td>
<td>-2.1</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Variation</th>
<th>Data-driven method</th>
<th>Shift (±%)</th>
<th>Shift (±%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>light (H^{+}) event selection</td>
<td>heavy (H^{+}) event selection</td>
<td></td>
</tr>
<tr>
<td>True (\tau_{\text{had–vis}}) Contamination</td>
<td>3.1</td>
<td>3.3</td>
<td></td>
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<tr>
<td>Jet Composition</td>
<td>10.1</td>
<td>9.8</td>
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<tr>
<td>Statistical Uncertainty on (p_{m})</td>
<td>16.3</td>
<td>13.9</td>
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<tr>
<td>Statistical Uncertainty on (p_{r})</td>
<td>6.7</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>(\tau_{\text{had–vis}}) e-Veto Uncertainty</td>
<td>3.5</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>(\tau_{\text{had–vis}}) ID Uncertainty</td>
<td>9.2</td>
<td>10.9</td>
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The compatibility with background is measured by $p_0$-values, probability that a background only hypothesis is as or more compatible with the result than that obtained from the maximum likelihood fit to data with the background+signal model.
# 2HDM $H \rightarrow WW$: NN variables

Table 2: Input variables used for the NNs in the 0-jet and 2-jet channels. The definitions of the variables use the terms *leading lepton* and *leading jet*, defined as the lepton/jet with the highest $p_T$.

<table>
<thead>
<tr>
<th>Variables used in the 0-jet channel and the 2-jet channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
</tr>
<tr>
<td>$m_T$ The transverse mass of the lepton-$E_T^{\text{miss}}$ system, as defined in Equation 2.</td>
</tr>
<tr>
<td>$m(\ell_1\ell_2)$ The invariant mass of the dilepton system.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables used in the 0-jet channel only</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(\ell_1\ell_2)$ The transverse momentum of the dilepton system.</td>
</tr>
<tr>
<td>$E_{T,\text{rel}}^{\text{miss}}$ The projection of the calorimeter-based missing transverse momentum.</td>
</tr>
<tr>
<td>$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables used in the 2-jet channel only</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(\ell_2)$ The transverse momentum of the second-leading lepton.</td>
</tr>
<tr>
<td>$p_T(j_1)$ The transverse momentum of the leading jet.</td>
</tr>
<tr>
<td>$m(j_1)$ The mass of the leading jet.</td>
</tr>
<tr>
<td>$\cos \theta(\ell_1,\ell_2)$ The cosine of the angle between the two charged leptons.</td>
</tr>
<tr>
<td>$m(j_1j_2)$ The invariant mass of the dijet system.</td>
</tr>
<tr>
<td>$p_T^{\text{tot}}$ The total transverse momentum, defined as the magnitude of the vector sum of the transverse momenta of the two jets, the two leptons and the missing transverse momentum: $p_T^{\text{tot}} =</td>
</tr>
</tbody>
</table>
MMC in MSSM $H \rightarrow \tau\tau$

- From 6 to 8 unknowns in the final state (depending on $\tau$ decays)
- Only 4 constraint
- Scan parameter space, calculate di-tau invariant mass and weight it by the tau decay likelihood distribution
- Most probable invariant mass used as estimator

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

\[ M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2} \sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2}p_{\text{mis}_2} \cos \Delta \theta_{\text{em}_2} \]
H$^+ \rightarrow c\bar{s}$ in $t\bar{t}$ events

- **Search for:** Light charged Higgs in top decays (as previously).
- **In MSSM for $\tan\beta < 1$** $\text{BR}(H^+ \rightarrow c\bar{s}) \sim 70\%$ for mass $\sim 110$ GeV
- **Final state:** $H^\pm \rightarrow 2\text{jets}$, and leptons from second top.
- **Selections:** $e/\mu$ and $\geq 4$ Jets (of which 2 b-tagged) High Missing Energy
- **Discriminant variable:** di-jet invariant mass. Using Kinematic fitter to fully reconstruct top decay.
- **Upper limits on BR($t \rightarrow bH^+$) are set.**