BSM Higgs Physics using the ATLAS Experiment

Searches for $H^+ \rightarrow \tau\nu$ and $A \rightarrow Zh$

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(CP-conserving) Two-Higgs-Doublet Models (2HDM)

- Higgs sector with two $Y=1$ isospin doublet scalar fields $\phi_1$ and $\phi_2$.
- If the potential is CP-conserving, there are five Higgs bosons: CP-even $h, H$; CP-odd $A$; and electrically charged $H^+, H^−$.
- Their masses are free parameters together with:
  - $m_{12}$, mixing parameter of $\phi_1$ and $\phi_2$ in the potential.
  - $\alpha$, the mixing angle between the scalar components.
  - $\beta$, the mixing angle between the charged components and between the pseudoscalar components. $\tan \beta$ is also the ratio of the VEVs.
- Four arrangements of the Yukawa couplings:
  - Type I: $\phi_2$ couples to all fermions,
  - Type II: $\phi_1$ couples to down-type fermions, $\phi_2$ couples to up-type fermions,
  - Lepton specific: $\phi_1$ couples to leptons, $\phi_2$ couples to quarks,
  - Flipped: Like Type II but leptons couple to $\phi_2$.
- If $\cos(\beta - \alpha) = 0$, $h$ has identical couplings to the SM Higgs boson.

The Higgs Sector of the Minimal Supersymmetric Standard Model (MSSM)

- Is a Type II 2HDM with two free parameters at tree-level.
- Benchmark scenarios are defined that keep the low number of parameters at higher orders [arXiv:hep-ph/0202167].

Presented here: Searches for $A \rightarrow Zh$ and $H^\pm \rightarrow \tau\nu$ with the 8 TeV dataset.
$A \rightarrow Zh$
A → Zh with Z → ℓℓ, h → ττ

- 2–4 leptons, including ℓℓ = ee or μμ pair
- 3 combinations of hadronic/leptonic tau decays:
  - $\ell\ell + \tau_{\text{had}}\tau_{\text{had}}$
    - "Loose" $\tau_{\text{had}}$ identification with 65% efficiency
    - Require large Z boost
    - Large "fake-$\tau_{\text{had}}$" background
    - shape & normalization from control regions
  - $\ell\ell + \tau_{\text{lep}}\tau_{\text{had}}$
    - "Medium" $\tau_{\text{had}}$ identification (55% efficiency)
    - Large "fake-$\tau_{\text{had}}/\ell$" background
    - shape & normalization from control regions
  - $\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$
    - Include low-$p_T$ leptons, forward muons and muons identified in the calorimeter
    - Large ZZ background if leptons assigned to the $h$ decay have the same flavor:
      - require $E_T^{\text{miss}}$ and $m_{\tau\tau}$ outside Z peak

- Require well-reconstructed Z and SM Higgs bosons
- $m_{\tau\tau}$ obtained with Missing Mass Calculator (MMC)

$\sigma \times BR = 50 \text{ pb}$

$\sigma \times BR = 50 \text{ pb}$

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

Alexander Madsen: Beyond-the-Standard Model Higgs Physics using the ATLAS Experiment - Phenomenology 2015
Two $b$-jets with invariant mass close to 125 GeV.

Their four-momenta are scaled with 125 GeV / $m_{bb}$.

$\ell\ell + bb$
- Require a well-reconstructed $Z$ boson
- Suppress $t\bar{t}$ by requiring a low $E_T^{\text{miss}} / \sqrt{H_T}$
- Suppress $Z$+jets by requiring large $Z$ boost
- Can reconstruct $m_A^{\text{rec}}$ with 2–3% resolution

$\nu\nu + bb$
- High $E_T^{\text{miss}}$ (calorimeter- and track-based)
- Well-separated, high-$p_T$ $b$-tagged jets
- Suppress $t\bar{t}$ by vetoing additional jets
- Multi-jet events suppressed with angular cuts on $E_T^{\text{miss}}$
- $m_A^{\text{rec},T} = \sqrt{(E_T^{bb} + E_T^{\text{miss}})^2 - (\vec{p}_T^{bb} + \vec{E}_T^{\text{miss}})^2}$

Simulated $Z$+jets, $W$+jets, $t\bar{t}$bar events reweighted to match data in control regions.

Shape and normalization of multi-jets events from control regions in data.
**$A \rightarrow Zh$ cross section limits**

- CLs upper limits are set on 
  \[ \sigma(gg \rightarrow A) \times \mathcal{B}(A \rightarrow Zh) \times \mathcal{B}(h \rightarrow bb/\tau\tau) : \]

- Limited by uncertainties on background cross sections, $\tau_{\text{had}}$ ID and energy scale, and on the fake $\ell/\tau_{\text{had}}$ background.

- Limited by systematic uncertainties on the jet energy scale, and on the $b$-tagging efficiency.

- Combined results are interpreted in the CP-conserving 2HDM
**A → Zh: 2HDM interpretations**

Assumptions:

\[ m_A = m_H = m_{H^\pm}, \]
\[ m_h = 125 \text{ GeV}, \]
\[ m_{12}^2 = m_A^2 \frac{\tan \beta}{1 + \tan^2 \beta} \]

This slide:
fix \( m_A = 300 \text{ GeV} \)

Blue areas show regions excluded by previous search for \( A \to \tau \tau \)
$A \rightarrow Zh$: 2HDM interpretations

Assumptions:

$m_A = m_H = m_{H^\pm}$,
$m_h = 125 \text{ GeV},$
$m_{12}^2 = m_A^2 \frac{\tan \beta}{1 + \tan^2 \beta}$

This slide:

fix $\cos(\beta - \alpha) = 0.1$

Blue areas show regions excluded by previous search for $A \rightarrow \tau \tau$
$H^\pm \rightarrow \tau \nu$
"Light $H^\pm$" production

Require at least four jets in the event

Select one hadronic tau decay, one $b$-tagged jet and $E_T^{\text{miss}}$

Reconstruct the transverse mass:

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

Using $\tau_{\text{had}} + E_T^{\text{miss}}$ trigger, simulated events corrected with efficiencies measured in data.

"Heavy $H^\pm$" production

Require at least three jets in the event

Increased $E_T^{\text{miss}}$ requirement

Graphical representation of the reactions:

- $H^+ \rightarrow \tau^+ \nu$
- $H^- \rightarrow \tau^- \bar{\nu}$

ATLAS event correction factors:

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ [GeV]</th>
<th>Trigger correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.7</td>
</tr>
<tr>
<td>150</td>
<td>0.75</td>
</tr>
<tr>
<td>200</td>
<td>0.8</td>
</tr>
<tr>
<td>250</td>
<td>0.85</td>
</tr>
<tr>
<td>300</td>
<td>0.9</td>
</tr>
</tbody>
</table>

- $\int_{Ld} = 19.5 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}$
- 1-track $\tau$
Backgrounds

**$tt$ background (embedding method)**

- Select events in data with a muon in place of the $\tau_{\text{had}}$, and relax cuts to avoid bias.
- Remove muon track and calorimeter deposits
- Replace muon with a simulated tau (with rescaled momentum to account for mass difference) and propagate it through the detector simulation.
- Re-reconstruct the hybrid event

**Multi-jet events with jet $\rightarrow \tau_{\text{had}}$ fakes**

- Estimated using a matrix method with fake rates measured in an event selection enriched with $W$+jets events
- For $m_T > 200$ GeV there are very few events and the expected event yield is obtained by fitting the $m_T$ distribution with a power-log function.

- The very small contribution from $e/\mu \rightarrow \tau_{\text{had}}$ fakes is the only background estimation that relies mainly on simulation.
**H^± → τν results**

**Low-mass signal selection:** Limits on $\mathcal{BR}(t \rightarrow bH^+) \times \mathcal{BR}(H^+ \rightarrow \tau\nu)$

![Low-mass H^+ selection](image)

**Main systematic uncertainties:**
- Trigger efficiency
- $\tau_{\text{had}}$ energy scale
- Embedding muon isolation

**Expected $\mathcal{BR} < 1.3 - 0.23\%$**

**High-mass signal selection:** Limits on $\sigma(pp \rightarrow \bar{t}H^+ + X) \times \mathcal{BR}(H^+ \rightarrow \tau\nu)$

![High-mass H^+ selection](image)

**Main systematic uncertainties:**
- Multi-jet background
- $\tau_{\text{had}}$ identification

**σ × BR < 0.76 pb – 4.5 fb**
\( H^\pm \rightarrow \tau \nu \): MSSM interpretations

\[ \int L dt = 19.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV} \]
Data 2012
MSSM \( m^\text{max}_{h} \) scenario

\[ \int L dt = 19.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV} \]
Data 2012
MSSM \( m^\text{mod+}_{h} \) scenario

\[ \int L dt = 19.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV} \]
Data 2012
MSSM \( m^\text{mod-}_{h} \) scenario
Other recent BSM Higgs results

- Higgs to invisible - Searches for SM Higgs boson decaying to Dark Matter
  - In association with a hadronically decaying vector boson
    [arXiv:1504.04324]
  - VBF production
    [ATLAS-CONF-2015-004]
  - $\mathcal{B}\mathcal{R}(H_{125} \rightarrow \text{ inv.}) < 29\%$

- $H^\pm \rightarrow W^\pm Z$ [arXiv:1503.04233]
  - Important in Higgs Triplet Models

- $Y_c$ coupling
  Higgs to $J/\Psi$: $\mathcal{B}\mathcal{R} < 1.5 \times 10^{-3}$, Higgs to $\Upsilon(1S, 2S, 3S)\gamma$:
  $\mathcal{B}\mathcal{R} < (1.3, 1.9, 1.3) \times 10^{-3}$

- Higgs pair production:
  $HH \rightarrow \gamma\gamma b\bar{b}$: $\sigma \times \mathcal{B}\mathcal{R} < 3.5$ pb
  (non-resonant < 1 pb)
Presented two recent ATLAS searches for BSM Higgs bosons

- **A → Zh**
  - With $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$, $\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$, $\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$, $\ell\ell bb$, $\nu\nu bb$ final states
  - Constraints on Type I, Type II, Lepton specific and Flipped 2HDMs

- **$H^+ \rightarrow \tau\nu$**
  - Considering $H^+$ masses below and above the top quark
  - Constraints on several MSSM scenarios

Analysis documentations

- **$H^+ \rightarrow \tau\nu$**: JHEP03 (2015) 088

More to come in Run 2...

- Very exciting time for searches!