Charged Higgs boson searches with the ATLAS detector

Arnaud Ferrari (Uppsala University) on behalf of the ATLAS collaboration

Higgs Couplings, SLAC, 9-12 November 2016
Introduction

After the discovery of a Higgs boson at 125 GeV, a major question is whether this is the scalar particle predicted by the Standard Model to break the electroweak symmetry...
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After the discovery of a Higgs boson at 125 GeV, a major question is whether this is the scalar particle predicted by the Standard Model to break the electroweak symmetry... or is it the first state of an extended Higgs sector?

Several BSM models predict an extended scalar sector, e.g. with two Higgs doublets (2HDM) or Higgs triplets, all containing charged Higgs bosons.
Introduction

Charged Higgs bosons are primarily produced in decays of (low-mass) or in association with (high-mass) a top quark:

- $m_{H^+} < m_{\text{top}}$
- $m_{H^+} > m_{\text{top}}, 5\text{FS}$
- $m_{H^+} > m_{\text{top}}, 4\text{FS}$

Short theory overview

- MSSM = type-II 2HDM;
- Tree-level charged Higgs sector determined by $m_A$ and $\tan \beta$;
- Several benchmark scenarios at NLO: $m_{h_{\text{max}}}$, $m_{h_{\text{mod}}}^\pm$, hMSSM...
- $H^+ \rightarrow \tau \nu$ and $tb$ dominate.
Outline

1 Run-1 legacy

2 Run-2 searches
   - $H^+ \rightarrow \tau \nu$
   - $H^+ \rightarrow tb$
Run-1 low-mass $H^+$ searches

$H^+ \rightarrow cs$
- Search in lepton+jets $t\bar{t}$ events (7 TeV, 4.7/fb);
- 95% C.L limits on $\text{Br}(t \rightarrow bH^+)$ in the range 1-5%, assuming that $\text{Br}(H^+ \rightarrow cs) = 100%$;

$H^+ \rightarrow \tau\nu$
- Most sensitive search in $\tau_{\text{had}}$+jets $t\bar{t}$ events (8 TeV, 19.5/fb);
- 95% C.L limits on $\text{Br}(t \rightarrow bH^+)$ in the range 0.2-1.3%, assuming that $\text{Br}(H^+ \rightarrow \tau\nu) = 100%$;
- Low-mass MSSM parameter space(s) almost excluded;
Run-1 high-mass $H^+$ searches

**VBF $H^+ \rightarrow WZ \rightarrow q\ell \ell$ events (8 TeV, 20.3/fb)**

- 95% C.L limits in the range 31-1020 fb for $200 \leq m_{H^+} (\text{GeV}) \leq 1000$;
- Interpretation: Georgi-Machacek Higgs Triplet Model;

**Top-quark associated $H^+ \rightarrow \tau \nu$ and $tb$ searches (8 TeV, 19.5-20.3/fb)**

- Analysis strategies similar to Run-2 searches (see upcoming slides);
- $H^+ \rightarrow \tau \nu$: 95% C.L limits of 4.5-760 fb for $180 \leq m_{H^+} (\text{GeV}) \leq 1000$ [JHEP03 (2015) 088];
- $H^+ \rightarrow tb$: broad excess of $\sim 2\sigma$ in the range $200 \leq m_{H^+} (\text{GeV}) \leq 600$, however not compatible with signal [JHEP03 (2016) 127].
Run-1 high-mass $H^+$ searches

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Physics objects

$H^+$ searches rely on excellent $\tau$- and $b$-jet identification. Both use anti-$k_t$ jets with $R = 0.4$ as seeds.

**$\tau$ objects**
- One or three prongs, narrow jet with an isolation annulus of $\Delta R = 0.2$;
- BDT-based ID: $\varepsilon = 55/40\%$ and jet rejection of $\mathcal{O}(10^2)$ for 1/3-prong taus.

**$b$-tagged jets**
- Impact parameters + secondary and tertiary vertices used for $b$-tagging;
- MVA-based ID: $\varepsilon = 70\%$ and $c$- or light-jet rejection of $10/400$.

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$H^+ \to \tau \nu$: event selection

Selection of $pp \to [b]tH^+ \to [b](bjj)(\tau_{\text{had}}\nu)$ topologies

1) $E_T^{\text{miss}}$ trigger: the efficiency is measured in data and then applied to simulated events.

2) Select events with hadronic $\tau$ and top-quark decays:
   - One $\tau$ object with $p_T^{\tau} > 40$ GeV,
   - $\geq 3$ jets with $p_T > 25$ GeV, including $\geq 1 b$-tag,
   - Electron and muon veto,
   - $E_T^{\text{miss}} > 150$ GeV.

3) Select events with the discriminant $m_T > 50$ GeV:

\[
m_T = \sqrt{2p_T^{\tau}E_T^{\text{miss}}\cos \Delta \phi_{\tau,\text{miss}}}
\]
$H^+ \rightarrow \tau \nu$: background modelling

- Backgrounds with a true $\tau$: simulation, with rescaling (validation) in control regions enriched in $W$+jets ($t\bar{t}$) events;
- Backgrounds with $e, \mu \rightarrow \tau$ fakes: simulation + data-driven corrections;
- Backgrounds with $j \rightarrow \tau$ fakes: data-driven method.

Fake factor (FF) method

- Anti-$\tau$ template in the signal region: fail $\tau$-ID + lower cut on the BDT;
- Simulated events with a true $\tau$ are subtracted from all anti-$\tau$ samples;
- FFs measured in a control region with 0 $b$-tag, $E_T^{\text{miss}} < 80$ GeV:

$$\text{FF} = \frac{N^\tau_{\text{CR}}}{N^{\text{anti-}\tau}_{\text{CR}}} \quad \Rightarrow$$

in bins of $p_T$ and $N_{\text{prong}}$;

$$N^\tau_{\text{SR, fakes}} = \sum_i N^{\text{anti-}\tau}_{\text{SR}}(i) \times \text{FF}(i)$$
**H**<sup>+</sup> → τν: systematic uncertainties

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Impact on the expected limit (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m&lt;sub&gt;H+&lt;/sub&gt; = 200 GeV</td>
</tr>
<tr>
<td>Experimental</td>
<td></td>
</tr>
<tr>
<td>luminosity</td>
<td>1.5</td>
</tr>
<tr>
<td>trigger</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>τ&lt;sub&gt;had-vis&lt;/sub&gt;</td>
<td>1.0</td>
</tr>
<tr>
<td>jet</td>
<td>3.0</td>
</tr>
<tr>
<td>E&lt;sub&gt;miss&lt;/sub&gt;</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Fake factors</td>
<td>0.8</td>
</tr>
<tr>
<td>Signal and background models</td>
<td>13.2</td>
</tr>
<tr>
<td>t̅t̅ modelling</td>
<td></td>
</tr>
<tr>
<td>H**+** signal modelling</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Low-mass: t̅t̅ modelling uncertainties dominate: cross section (6%), matrix element (MG5_MC@NLO vs Powheg), parton shower (Pythia vs Herwig), ISR/FSR.

High-mass: FF method uncertainties dominate: BDT score cut in the anti-τ sample, contamination of events with true τ, size of the control sample.

The high-mass search is dominated by statistical uncertainties.
**charged higgs boson searches with the atlas detector**

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Run-1 legacy

Run-2 searches

$H^+ \rightarrow \tau \nu$

$H^+ \rightarrow t\bar{b}$

**conclusion**

$H^+ \rightarrow \tau \nu$: results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>True $\tau_{had}$</td>
<td>2880 ± 770 ± 25</td>
</tr>
<tr>
<td>$t\bar{t}$ &amp; single-top-quark</td>
<td>265 ± 51 ± 18</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>43 ± 6.8 ± 7.6</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>13.8 ± 2.2 ± 1.7</td>
</tr>
<tr>
<td>diboson ($WW, WZ, ZZ$)</td>
<td></td>
</tr>
<tr>
<td>Misidentified $e, \mu \rightarrow \tau_{had-vis}$</td>
<td>126 ± 24 ± 6.5</td>
</tr>
<tr>
<td>Misidentified jet $\rightarrow \tau_{had-vis}$</td>
<td>1170 ± 110 ± 16</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>4500 ± 800 ± 36</td>
</tr>
<tr>
<td>$H^+ (200 \text{ GeV})$, hMSSM $\tan \beta = 60$</td>
<td>523 ± 86 ± 4</td>
</tr>
<tr>
<td>$H^+ (1000 \text{ GeV})$, hMSSM $\tan \beta = 60$</td>
<td>7.5 ± 0.6 ± 0.05</td>
</tr>
<tr>
<td>Data</td>
<td>4645</td>
</tr>
</tbody>
</table>

**2015 result**

$H^+ \rightarrow \tau \nu$, hMSSM scenario

- Observed exclusion
- Expected exclusion

$\sqrt{s} = 13 \text{ TeV}, 14.7 \text{ fb}^{-1}$

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$H^+ \rightarrow \tau \nu$, hMSSM scenario

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$H^+ \rightarrow tb$: analysis strategy

Selection of $pp \rightarrow [b]tH^+ \rightarrow [b](bjj)(bb\ell\nu)$ topologies

Event selection

- single-lepton trigger & one $e/\mu$ with $p_T > 25$ GeV;
- $\geq 4$ jets with $p_T > 25$ GeV, including $\geq 2$ $b$-tags;
- Split in signal and control regions based on the jet and $b$-jet multiplicities.

Simultaneous maximum likelihood fit to all regions:

$$H_T^{\text{had}} = \sum p_T^{\text{jets}} \text{ in CRs}$$

$$\Rightarrow \text{BDT output in the SRs}$$
**H^+ → tb**: background modelling and rejection

The dominating background is \(t\bar{t}+\text{jets}\) (\(\sigma = 832^{+46}_{-51}\) pb).

- **Model** = Powheg+Pythia6, split into light and heavy flavors based on additional jets:
  - \(t\bar{t} + \text{light-jets}, \ t\bar{t} + \geq 1c\)
    - reweighted to the NNLO prediction for \(p_{T}^{t}\) and \(p_{T}^{t}\),
  - \(t\bar{t} + \geq 1b\) event kinematics reweighted to the NLO Sherpa+OpenLoops predictions.
- **Normalisation** of \(t\bar{t} + \geq 1c\) and \(t\bar{t} + \geq 1b\) freely floating in the fit.

Multi-variate technique (BDT) used to separate signal and background in the SRs. The BDT is trained:

- separately for each \(m_{H^+}\) and SR,
- against \(t\bar{t} + \geq 1b\) events for \(m_{H^+} \leq 500\text{ GeV}\),
- against inclusive \(t\bar{t}\) for \(m_{H^+} > 500\text{ GeV}\).
$H^+ \rightarrow tb$: event yields

Pre-fit:
- Signal (300 GeV, 1 pb) shown both stacked and separately,
- Simulated yields below data in all categories.

Post-fit:
- Slightly negative signal at this mass,
- Good post-fit agreement in the SRs,
- Reduced uncertainties (constrained in CRs).
$H^+ \to tb$: post-fit CR distributions (300 GeV)
**Charged Higgs boson searches with the ATLAS detector**

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**Run-1 legacy**

**Run-2 searches**

\[ H^+ \rightarrow \tau \nu \]

\[ H^+ \rightarrow tb \]

**Conclusion**

\[ H^+ \rightarrow tb: \text{post-fit SR distributions (300 GeV)} \]
\( H^+ \rightarrow \tau \nu: \) systematic uncertainties

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>( \Delta \mu(H_{300}^+) )</th>
<th>( \Delta \mu(H_{800}^+) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{t}t + \geq 1b ) modelling</td>
<td>+0.53</td>
<td>+0.07</td>
</tr>
<tr>
<td>Jet flavour tagging</td>
<td>+0.30</td>
<td>+0.07</td>
</tr>
<tr>
<td>( \bar{t}t + \geq 1c ) modelling</td>
<td>+0.23</td>
<td>+0.03</td>
</tr>
<tr>
<td>Background model statistics</td>
<td>+0.19</td>
<td>+0.05</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.18</td>
<td>+0.03</td>
</tr>
<tr>
<td>( \bar{t}t ) + light modelling</td>
<td>+0.16</td>
<td>+0.03</td>
</tr>
<tr>
<td>Other background modelling</td>
<td>+0.15</td>
<td>+0.03</td>
</tr>
<tr>
<td>Jet-vertex association, pileup modelling</td>
<td>+0.12</td>
<td>+0.01</td>
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<tr>
<td>Light lepton ((e, \mu)) ID, isolation, trigger</td>
<td>+0.01</td>
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</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+0.72</td>
<td>+0.13</td>
</tr>
<tr>
<td>( \bar{t}t + \geq 1b ) normalisation</td>
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Largest instrumental uncertainties: \( b \)-tagging, jet energy scale and resolution.

**\( \bar{t}t \) background modelling uncertainties**

- Inclusive \( \bar{t}t \): same as \( H^+ \rightarrow \tau \nu \) (uncorrelated across categories).
- \( \bar{t}t + \text{light-jets} \& \geq 1c \): apply or not reweighting in \( p_t^{\bar{t}t} \) and \( p_t^{t} \).
- \( \bar{t}t + \geq 1c \): c-jets in matrix element vs parton shower.
- \( \bar{t}t + \geq 1b \): different scales, PDFs and shower recoil schemes in Sherpa+OpenLoops; matrix element; parton shower; multi-parton interactions.
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**Run-1 legacy**

**Run-2 searches**

**Conclusion**

### $H^+ \rightarrow tb$: systematic uncertainties

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- $t\bar{t}$ + light-jets & $\geq 1c$: apply or not reweighting in $p_T^{t\bar{t}}$ and $p_T^t$.
- $t\bar{t}$ + $\geq 1c$: $c$-jets in matrix element vs parton shower.
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Run-1 legacy

Run-2 searches

Conclusion

Post-fit event yields, $m_{H^+} = 300$ GeV

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Process} & \text{4j2b} & \text{4j \geq 3b} & \text{5j2b} & \geq \text{6j2b} \\
\hline
H_{3\ell}^+ & -240 \pm 210 & -120 \pm 110 & -250 \pm 220 & -170 \pm 150 \\
tH^+ \rightarrow \ell + \ell & 18500 \pm 7300 & 1860 \pm 670 & 18600 \pm 6800 & 14800 \pm 5600 \\
tH^+ \rightarrow b + b & 6500 \pm 1300 & 2310 \pm 450 & 6900 \pm 1200 & 8400 \pm 1300 \\
tH^+ \rightarrow b + \ell & 15800 \pm 7400 & 5010 \pm 710 & 8800 \pm 6400 & 55700 \pm 5300 \\
\text{Fakes} & 8100 \pm 2000 & 1330 \pm 500 & 3080 \pm 750 & 1360 \pm 310 \\
tH^+ \rightarrow W & 99 \pm 16 & 5.2 \pm 0.9 & 131 \pm 22 & 208 \pm 40 \\
tH^+ \rightarrow Z & 113 \pm 20 & 15.9 \pm 4.1 & 147 \pm 23 & 276 \pm 40 \\
\text{Single top} & 5400 \pm 1300 & 260 \pm 74 & 2950 \pm 830 & 1630 \pm 540 \\
\text{Other top} & 4400 \pm 1200 & 172 \pm 49 & 1540 \pm 460 & 670 \pm 200 \\
\text{Diboson} & 450 \pm 220 & 23 \pm 12 & 220 \pm 110 & 184 \pm 88 \\
W + \text{jets} & 6700 \pm 2200 & 250 \pm 110 & 2120 \pm 780 & 1140 \pm 440 \\
Z + \text{jets} & 1310 \pm 560 & 40 \pm 21 & 460 \pm 200 & 300 \pm 130 \\
tH^+ & 62.9 \pm 6.8 & 27.8 \pm 8.4 & 95.7 \pm 9.5 & 200 \pm 22 \\
tH & 0.5 \pm 2.7 & 5.1 \pm 1.5 & 8.1 \pm 2.3 & 9.9 \pm 2.3 \\
\text{Total} & 208400 \pm 86000 & 12010 \pm 750 & 125000 \pm 6800 & 84800 \pm 5400 \\
\text{Data} & 208329 & 11904 & 124688 & 84556 \\
\hline
\end{array}
\]

\[
\begin{align*}
\text{H}^+_{3\ell} & \rightarrow -170 \pm 150 \quad -25 \pm 21 \quad -300 \pm 180 \quad -62 \pm 53 \\
tH^+ \rightarrow \ell + \ell & \rightarrow 2300 \pm 720 \quad 68 \pm 21 \quad 2240 \pm 780 \quad 102 \pm 44 \\
tH^+ \rightarrow b + b & \rightarrow 3490 \pm 540 \quad 320 \pm 37 \quad 5580 \pm 640 \quad 1090 \pm 90 \\
tH^+ \rightarrow b + \ell & \rightarrow 3990 \pm 610 \quad 38 \pm 13 \quad 2940 \pm 550 \quad 40 \pm 21 \\
\text{Fakes} & \rightarrow 420 \pm 110 \quad 19.2 \pm 0.8 \quad 410 \pm 110 \quad 1.2 \pm 0.6 \\
tH^+ \rightarrow W & \rightarrow 9.5 \pm 1.7 \quad 0.2 \pm 0.1 \quad 23.6 \pm 4.7 \quad 1.4 \pm 0.4 \\
tH^+ \rightarrow Z & \rightarrow 28.0 \pm 5.7 \quad 4.7 \pm 1.3 \quad 68.8 \pm 9.8 \quad 18.5 \pm 3.5 \\
\text{Single top} & \rightarrow 202 \pm 64 \quad 5.9 \pm 3.1 \quad 173 \pm 71 \quad 16.5 \pm 9.5 \\
\text{Other top} & \rightarrow 94 \pm 26 \quad 6.5 \pm 2.2 \quad 71 \pm 22 \quad 8.7 \pm 2.3 \\
\text{Diboson} & \rightarrow 17.4 \pm 9.0 \quad 0.4 \pm 0.2 \quad 16.7 \pm 8.5 \quad 2.3 \pm 1.1 \\
W + \text{jets} & \rightarrow 164 \pm 81 \quad 2.1 \pm 0.9 \quad 97 \pm 43 \quad 8.2 \pm 3.6 \\
Z + \text{jets} & \rightarrow 30 \pm 24 \quad 0.7 \pm 0.3 \quad 17.5 \pm 7.7 \quad 1.6 \pm 0.7 \\
tH^+ & \rightarrow 49.6 \pm 5.2 \quad 11.0 \pm 1.6 \quad 122 \pm 13 \quad 46.4 \pm 6.2 \\
tH & \rightarrow 4.5 \pm 1.3 \quad 1.0 \pm 0.3 \quad 6.0 \pm 1.8 \quad 2.0 \pm 0.6 \\
\text{Total} & \rightarrow 10900 \pm 380 \quad 462 \pm 47 \quad 11800 \pm 600 \quad 1300 \pm 100 \\
\text{Data} & \rightarrow 10755 \quad 418 \quad 11561 \quad 1285 \\
\end{align*}
\]
Conclusion

ATLAS has conducted two searches for charged Higgs bosons based on Run-2 pp collision data at the LHC:

- $H^+ \to \tau \nu$: ATLAS-CONF-2016-088,
- $H^+ \to tb$: ATLAS-CONF-2016-089.

Unfortunately no significant excess, but improved exclusions with respect to Run-1 at high mass.

We already have three times more data to analyse, stay tuned for improved $H^+$ searches in a near future!

Disclaimer

I didn’t cover searches for *doubly* charged Higgs bosons in this talk... but have a look at the back-up slides!
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Thank you for your attention! Do you have any questions?
charged higgs boson searches with the ATLAS detector

arnaud ferrari

run-1 legacy

run-2 searches

conclusion

\(H^+ \rightarrow \tau \nu\): event display

This event has four jets (white and blue cones), including two \(b\)-tagged jets (blue cones), and one 3-prong \(\tau\) object (yellow cone). The red arrow displays the direction of the missing transverse momentum. The \(p_T\) of the \(\tau\) is 137 GeV. The \(p_T\) of the jets are: \(p_{T,1} = 175\) GeV (\(b\)-tagged), \(p_{T,2} = 169\) GeV, \(p_{T,3} = 124\) GeV (\(b\)-tagged), \(p_{T,4} = 33\) GeV. The missing transverse momentum amounts to 152 GeV and \(m_T = 162\) GeV.
Control region enriched in $W$+jets events (0 $b$-tag).

$m_h^{\text{mod}}$ interpretation:
**H^+ \rightarrow tb: BDT details**

- Highest jet $p_T$
- Mass of $bb\bar{b}b$ pair with minimum $\Delta R$
- $p_T$ of 5th jet, having $b$-tagged jets first followed by non-$b$-tagged jets
- Second Fox-Wolfram, moment calculated using jets and leptons
- Average $\Delta R$ of all $bb\bar{b}b$ pairs
- $\Delta R$ of the lepton and the $bb\bar{b}b$ pair with smallest $\Delta R$
- Mass of untagged jet pair with minimum $\Delta R$
- Scalar sum of $E_T$ calculated using all jets
- Mass of $bb\bar{b}b$ pair with maximum $p_T$
- Mass of $bb\bar{b}b$ pair with maximum mass
- Mass of jet triplet with maximum $p_T$
- Centrality, calculated using jets and leptons
$H^+ \rightarrow tb$: post-fit CR distributions (800 GeV)
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Run-1 legacy
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Conclusion

\[ H^+ \rightarrow tb : \text{post-fit SR distributions (800 GeV)} \]
Charged Higgs boson searches with the ATLAS detector

Arnaud Ferrari

Run-1 legacy

Run-2 searches

Conclusion

\[ H^{++} \rightarrow e^+ e^+ \] (ATLAS-CONF-2016-051)

The analysis considers only the electron channel.

Signal region = at least same-sign (SS) electron pair with \( m_{ee} \) above 300 GeV.

Two control regions:

- OSCR = 1 OS pair, 0 SS pair;
- DBCR = 1 OS pair (\( Z \)) + SS pairs (\( m_{ee} < 200 \) GeV).
Higgs Couplings, SLAC, 9-12 November 2016

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$H^{++} \rightarrow e^+ e^+$ (ATLAS-CONF-2016-051)

BumpHunter is used to look for excesses or deficits in the post-fit SR distribution.

Limits for $H_R^{\pm\pm}$ and $H_L^{\pm\pm}$ at 420 GeV and 570 GeV, assuming a 100% branching fraction to electrons.