Searches for singly charged Higgs bosons in ATLAS

Blake Burghgrave on behalf of the ATLAS Collaboration

2018-09-27
Analyses

- **Run 1 legacy analyses (short review)**
  - VBF $H^\pm \rightarrow W^\pm Z \rightarrow q\bar{q}\ell\ell$ (arxiv:1503.04233)
  - Light $H^\pm \rightarrow cs$ (arxiv:1302.3694)
  - Cascade $H \rightarrow WH^\pm \rightarrow WWh$ (arxiv:1312.1956)
  - $H^\pm \rightarrow \tau\nu$ (arxiv:1412.6663)
  - $H^\pm \rightarrow tb$ (arxiv:1512.03704)

- **New run 2 search results**
  - $H^\pm \rightarrow \tau\nu$ (arxiv:1807.07915 accepted by JHEP)
  - $H^\pm \rightarrow tb$ (arxiv:1808.03599 submitted to JHEP)
Assuming MSSM-like 2HDM, $\sigma(pp \to H^\pm)$ depends on $\tan \beta$ and $m_{H^\pm}$

- Current analyses use MG5, high-mass samples use 4FS @NLO, low-mass LO

- For comparison, $t\bar{t}$ is often the dominant background, $\sigma(pp \to t\bar{t})$ generally $\sim 3$ orders of magnitude higher for $m_{H^\pm} \lesssim m_t$. 

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ \tan \beta = 30 \]

\[ m_H \text{ [GeV]} \]

\[ \sigma_{pp \to H^\pm} \text{ [pb]} \]

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ m_H = 200 \text{ GeV} \]

\[ \tan \beta \]

\[ \text{Inclusive } t\bar{t} \text{ cross section [pb]} \]

- Preliminary

**ATLAS+CMS Preliminary**

Nov 2017

LHC HIGGS XS WG 2016

matched

4FS

5FS

\[ \sqrt{s} \text{ [TeV]} \]

\[ m_{H^\pm} \text{ [GeV]} \]

\[ \sigma(pp \to H^\pm) \text{ [pb]} \]

- Tevatron combined 1.96 TeV (L $\leq 8.8$ fb$^{-1}$)
- CMS dilepton+jets* 5.02 TeV (L = 27.4 pb$^{-1}$)
- ATLAS $t\bar{t}$ jets 7 TeV (L = 4.6 fb$^{-1}$)
- CMS $t\bar{t}$ 8 TeV (L = 20.3 fb$^{-1}$)
- CMS $t\bar{t}$ 8 TeV (L = 19.7 fb$^{-1}$)
- LHC combined $t\bar{t}$ jets 8 TeV (L $= 5.3 - 20.3$ fb$^{-1}$)
- ATLAS $t\bar{t}$ 13 TeV (L = 3.2 fb$^{-1}$)
- CMS $t\bar{t}$ 13 TeV (L = 2.2 fb$^{-1}$)
- ATLAS $t\bar{t}$ jets 13 TeV (L = 85 pb$^{-1}$)
- CMS $t\bar{t}$ jets 13 TeV (L = 2.53 fb$^{-1}$)

- NNLO+NNLL (pp)
- NNLO+NNLL (q$q$)
Run-1 VBF $H^\pm \rightarrow W^\pm Z \rightarrow qq\ell\ell$

- Looks for $H^\pm \rightarrow W^\pm Z$, produced via VBF
  - $W^\pm \rightarrow q\bar{q}'$
  - $Z \rightarrow e^+e^- / \mu^+\mu^-$
- No significant deviation from SM background, limits set (top right)

(arxiv:1503.04233)
Run-1 Light $H^{\pm} \rightarrow cs$

- Looks for light $H^{\pm}$ decaying to $cs$, expected for relatively low $\tan \beta$
- $H^{\pm}$ from $t\bar{t}$ decay, the other top-quark decays leptonically
- No significant deviation from SM predictions, limits set (above right) assuming $\mathcal{B}(H^{\pm} \rightarrow cs)=100\%$

(arxiv:1302.3694)
Run-1 Cascade $H \rightarrow WH^\pm \rightarrow WWh$

- Looks for $H^\pm \rightarrow W^\pm h$ as part of the above process
- Final state: 1 lepton, $\geq 4$ jets, significant $E^\text{miss}_T$
- No significant deviation from SM background found
- Expected and observed limits shown to the right

(\texttt{arxiv:1312.1956})
Run-1 $H^\pm \rightarrow \tau \nu$

- Run-1 $H^\pm \rightarrow \tau \nu$, $t \bar{b}$ associated, cut-based analysis, $\tau$+jets final state
- Model independent limits set (right)

(arxiv:1412.6663)
Run-1 $H^\pm \rightarrow tb$, $tb$ associated, BDT-based analysis

- Model independent limits set (right)

(arxiv:1512.03704)
$H^\pm \rightarrow \tau \nu$

- $H^\pm$ produced in association with a $b$ and $W$ (usually from a $t$ decay)

- Event selection:
  - 1 hadronically decaying $\tau$ (from the $H^\pm$)
  - Significant $E_T^{\text{miss}}$ (neutrinos)
  - At least 1 $b$ jet
  - $\tau$+jets: 2 additional jets from the $W$ decay, $E_T^{\text{miss}}$ trigger
  - $\tau$+lepton: $e$ or $\mu$ from the $W$ decay, lepton triggers

- Analysis considers 4 final states:
  - $\tau$+jets SR
  - $\tau$ + $e$ SR
  - $\tau$ + $\mu$ SR
  - $e$ + $\mu$ CR (mostly $t\bar{t}$)

- Considers 90 GeV $\leq m_{H^\pm} \leq$ 2000 GeV
  - Including the first look at the intermediate mass range, $m_{H^\pm} \approx m_t$
- \(\tau+\text{jets}\) use \(E_T^{\text{miss}}\) triggers, shown above
  - Trigger efficiency measured data
    - Select \(\tau+e\) events, using electron trigger
    - Measure \(E_T^{\text{miss}}\) trigger efficiency
  - Used to reweight MC, instead of using \(E_T^{\text{miss}}\) trigger from simulation
  - Shown with \(E_T^{\text{miss}}\) thresholds at 70/90/110 GeV (available triggers change throughout data taking)

- \(\tau+\text{lepton}\) uses single lepton triggers, using the lowest \(p_T^\ell\) available unprescaled trigger (up to 26 GeV by the end of 2016)
Dominant background is SM $t\bar{t}$
- Modeled well in dilepton $t\bar{t}$ control region, above

Next largest background is from misidentified jet $\rightarrow \tau$ fakes
- Modeled with data-driven fake factor approach
- Validated in b-veto region
- For more info, see: Marzieh’s talk
Analysis Strategy

- Multi-Variate Analysis using Boosted Decision Trees
  - FastBDT trained via a TMVA plugin
  - Signal binned in 5 mass ranges:
    - 90 to 120 GeV
    - 130 to 160 GeV (low mass 160 GeV)
    - 160 to 180 GeV (intermediate mass)
    - 200 to 400 GeV
    - 500 to 2000 GeV
  - Trained against dominant $t\bar{t}$ background
  - Data-driven jet $\rightarrow \tau$ fakes included in 500 to 2000 GeV for $\tau$+jets, $\Upsilon$ (sensitive to $\tau$ polarization) not included in this mass range
  - Background modeling and BDT training kept statistically independent via the k-fold method

<table>
<thead>
<tr>
<th>MVA input variable</th>
<th>$\tau$+jets</th>
<th>$\tau$+lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{miss}^T$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T^\tau$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_{b\text{-jet}}^T$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T^\ell$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta\phi_{\tau,\text{miss}}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta\phi_{b\text{-jet},\text{miss}}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell,\text{miss}}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta R_{\tau,\ell}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta R_{b\text{-jet},\ell}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta R_{b\text{-jet},\tau}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Upsilon = 2\frac{p_T^{\tau\text{-track}}}{p_T^\tau} - 1$</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- BDT score used as discriminating variable, fit with profile likelihood ratio
- Fitted regions: $\tau$+jets, $\tau + e$, $\tau + \mu$, and $(e\mu + \text{btag})$ single-bin CR for $t\bar{t}$
<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Impact on the expected limit (stat. only) in %</th>
<th>$m_{H^+} = 170$ GeV</th>
<th>$m_{H^+} = 1000$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>luminosity</td>
<td>2.9</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>trigger</td>
<td>1.3</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{had-vis}}$</td>
<td>14.6</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>jet</td>
<td>16.9</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>electron</td>
<td>10.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>muon</td>
<td>1.1</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>9.9</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>Fake-factor method</td>
<td>20.3</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>$\Upsilon$ modelling</td>
<td>0.8</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Signal and background models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$ modelling</td>
<td>6.3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>$W/Z+$jets modelling</td>
<td>1.1</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>cross-sections ($W/Z/VV/t$)</td>
<td>9.6</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>$H^+$ signal modelling</td>
<td>2.5</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>52.1</td>
<td>13.8</td>
<td></td>
</tr>
</tbody>
</table>

- From impact on the expected limit (stat. only) when adding a set of nuisance parameters
Results, $\tau + \text{jets}$

ATLAS

$\mathcal{L} = 13$ TeV, 36.1 fb$^{-1}$

$\tau + \text{jets}$ signal region

BDT score, 90 to 120 GeV

BDT score, 130 to 160 GeV

BDT score, 160 to 180 GeV

BDT score, 200 to 400 GeV

BDT score, 500 to 2000 GeV

Data $\tau \rightarrow \text{MisID j}$

$H \tau \rightarrow \text{MisID e/}$

$\ell \& \text{single-top}$

Diboson

Events / 0.1

Data / SM

Uncertainty
Results, $\tau + e$
Results, $\tau + \mu$

### BDT Score, 90 to 120 GeV
- Data τ → MisID j
- H τ → µ MisID e/
- τ + µ signal region

### BDT Score, 160 to 180 GeV
- Data τ → MisID j
- H τ → µ MisID e/
- τ + µ signal region

### BDT Score, 500 to 2000 GeV
- Data τ → MisID j
- H τ → µ MisID e/
- τ + µ signal region
Expected and observed limits for low mass (left) and the full mass range (top right)

- Low-mass compared to Run 1
  - $B(t \rightarrow bH^\pm) \times B(H^\pm \rightarrow \tau \nu)$ between 0.25% and 0.031% for 90 – 160 GeV
- Full range compared to 2015 paper (3.2 fb$^{-1}$)
- Exclusion from hMSSM interpretation
Run-2 $H^\pm \to tb$

- $H^\pm \to tb$ produced in association with $tb$
- Considers $200 \text{ GeV} \leq m_{H^\pm} \leq 2000 \text{ GeV}$
- $\ell\ell$ and $\ell +$ jets final states, single lepton triggers
Background Modeling

<table>
<thead>
<tr>
<th>Process</th>
<th>SR $5j3b$</th>
<th>SR $5j \geq 4b$</th>
<th>SR $\geq 6j3b$</th>
<th>SR $\geq 6j \geq 4b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t} + \geq 1b$</td>
<td>$450 \pm 60$</td>
<td>$74 \pm 12$</td>
<td>$650 \pm 90$</td>
<td>$106 \pm 14$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1c$</td>
<td>$310 \pm 70$</td>
<td>$28 \pm 12$</td>
<td>$510 \pm 110$</td>
<td>$18 \pm 8$</td>
</tr>
<tr>
<td>$t\bar{t} + \text{light}$</td>
<td>$310 \pm 40$</td>
<td>$4.9 \pm 3.1$</td>
<td>$380 \pm 60$</td>
<td>$7 \pm 4$</td>
</tr>
<tr>
<td>Fakes</td>
<td>$20 \pm 100$</td>
<td>$3 \pm 4$</td>
<td>$50 \pm 60$</td>
<td>$(0.0 \pm 2.3) \times 10^{-3}$</td>
</tr>
<tr>
<td>$t\bar{t}W$</td>
<td>$1.14 \pm 0.21$</td>
<td>$0.048 \pm 0.029$</td>
<td>$3.3 \pm 0.6$</td>
<td>$0.16 \pm 0.07$</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>$3.0 \pm 0.6$</td>
<td>$1.02 \pm 0.23$</td>
<td>$8.4 \pm 1.3$</td>
<td>$1.5 \pm 0.4$</td>
</tr>
<tr>
<td>Single top $Wt$</td>
<td>$25 \pm 8$</td>
<td>$0.6 \pm 0.5$</td>
<td>$23 \pm 8$</td>
<td>$3.0 \pm 2.1$</td>
</tr>
<tr>
<td>Other top</td>
<td>$0.90 \pm 0.22$</td>
<td>$0.25 \pm 0.21$</td>
<td>$1.17 \pm 0.30$</td>
<td>$0.37 \pm 0.17$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$1.4 \pm 0.8$</td>
<td>$0.013 \pm 0.022$</td>
<td>$1.6 \pm 1.0$</td>
<td>$0.00 \pm 0.08$</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>$31 \pm 19$</td>
<td>$4 \pm 4$</td>
<td>$13 \pm 6$</td>
<td>$1.2 \pm 0.7$</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>$4.3 \pm 1.7$</td>
<td>$0.01 \pm 0.15$</td>
<td>$4.4 \pm 1.9$</td>
<td>$1.3 \pm 0.7$</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$6.4 \pm 0.7$</td>
<td>$2.4 \pm 0.5$</td>
<td>$18.3 \pm 2.2$</td>
<td>$3.6 \pm 0.6$</td>
</tr>
<tr>
<td>$tH$</td>
<td>$0.39 \pm 0.08$</td>
<td>$0.078 \pm 0.024$</td>
<td>$0.34 \pm 0.07$</td>
<td>$0.11 \pm 0.04$</td>
</tr>
<tr>
<td>Total</td>
<td>$1150 \pm 120$</td>
<td>$118 \pm 13$</td>
<td>$1650 \pm 90$</td>
<td>$139 \pm 13$</td>
</tr>
<tr>
<td>Data</td>
<td>$1258$</td>
<td>$105$</td>
<td>$1765$</td>
<td>$132$</td>
</tr>
<tr>
<td>$H^+ (200 \text{ GeV})$</td>
<td>$36 \pm 4$</td>
<td>$5.6 \pm 0.9$</td>
<td>$36 \pm 6$</td>
<td>$9.5 \pm 1.5$</td>
</tr>
<tr>
<td>$H^+ (800 \text{ GeV})$</td>
<td>$76 \pm 14$</td>
<td>$24 \pm 5$</td>
<td>$192 \pm 34$</td>
<td>$79 \pm 16$</td>
</tr>
</tbody>
</table>

- Background is mostly $t\bar{t}$, divided into several categories
  - $t\bar{t} + \geq 1b$, further subdivided:
    - Exactly 2 jets matched to $b$-hadrons ($t\bar{t} + b\bar{b}$)
    - Exactly 1 jet matched to a $b$-hadron ($t\bar{t} + b$)
    - At least one jet matched to two or more $b$-hadrons ($t\bar{t} + B$)
    - Other events ($t\bar{t} + \geq 3b$)
    - $t\bar{t} + b$ (MPI/FSR) for multi-parton interactions or final state radiation
  - $t\bar{t} + \geq 1c$
  - $t\bar{t} + \text{light}$, if the event contains other additional jets
- Non-prompt leptons in $\ell + \text{jets}$ are modeled with a data-driven matrix method
  - Use sample with enhanced non-prompt leptons (use loose selection)
  - Weight events by efficiencies for prompt and non-prompt leptons to pass default tight selection
Split into different SRs/CRs based on number of jets and $b$-tags

- $\ell\ell \ 3j3b$ is a SR for $m_{H^\pm} < 1$ TeV, CR for $m_{H^\pm} \geq 1$ TeV

Separate BDT trained in each SR and for each signal mass hypothesis

- Trained against all backgrounds for $\ell +$ jets
  - $5j3b$ and $5j \geq 4b$ trained together to increase training statistics
- Trained against $\tilde{t}\tilde{t}$ for $\ell\ell$
• Important variable at low mass is $D = \frac{P_{H^+}(x)}{(P_{H^+}(x) + P_{\bar{t}t}(x))}$ (above)
  • $P_{H^+}(x)$ and $P_{\bar{t}t}(x)$ are probability density functions for $x$ under signal and background hypotheses, where $x$ is $E_T^{\text{miss}}$ and final state particle four-momenta

• Other variables are mainly the $m$, $E$, and $p_T$ of different combinations of final state particles, and $\Delta m$, $\Delta E$, and $\Delta p_T$ between different particle systems
  • Exact combination depends on final state and mass range
  • Too long to go over here, but full table in backup
### Systematics

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>$\Delta \mu(H_{200}^+) [\text{pb}]$</th>
<th>$\Delta \mu(H_{800}^+) [\text{pb}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet flavour tagging</td>
<td>0.70</td>
<td>0.050</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ modelling</td>
<td>0.65</td>
<td>0.008</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>0.44</td>
<td>0.031</td>
</tr>
<tr>
<td>$t\bar{t} + \text{light}$ modelling</td>
<td>0.44</td>
<td>0.019</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.37</td>
<td>0.044</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1c$ modelling</td>
<td>0.36</td>
<td>0.032</td>
</tr>
<tr>
<td>Other background modelling</td>
<td>0.36</td>
<td>0.039</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.24</td>
<td>0.010</td>
</tr>
<tr>
<td>Jet-vertex assoc., pile-up modelling</td>
<td>0.10</td>
<td>0.006</td>
</tr>
<tr>
<td>Lepton, $E_{T}^{\text{miss}}$, ID, isol., trigger</td>
<td>0.08</td>
<td>0.003</td>
</tr>
<tr>
<td>$H^+$ modelling</td>
<td>0.03</td>
<td>0.006</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>1.4</td>
<td>0.11</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ normalisation</td>
<td>0.61</td>
<td>0.022</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1c$ normalisation</td>
<td>0.28</td>
<td>0.012</td>
</tr>
<tr>
<td><strong>Total statistical uncertainty</strong></td>
<td>0.69</td>
<td>0.050</td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td>1.5</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- Uncertainty in terms of effect on $\mu = \sigma(pp \rightarrow tbH^+) \times B(H^+ \rightarrow tb) [\text{pb}]$
Results, $\ell + \text{jets}, \ m_{H^\pm} = 200$ GeV
Results, $\ell\ell$, $m_{H^\pm} = 200$ GeV
Model independent limits

Exclusion from $m_{h^{mod-}}$ and hMSSM interpretations
Reviewed ATLAS Run-1 $H^\pm$ searches

New ATLAS searches for $H^\pm$, recently submitted for publication

$H^\pm \rightarrow \tau\nu$ (arxiv:1807.07915 accepted by JHEP)
- $tb$ associated production, $\tau+$jets or $\tau+$lepton final state
- Sensitive over a wide mass range and at high $\tan\beta$
  - Includes first look at intermediate mass range, $m_{H^\pm} \approx m_t$

$H^\pm \rightarrow tb$ (arxiv:1808.03599 submitted to JHEP)
- $tb$ associated production, $\ell+$jets or $\ell\ell$ final state
- Sensitive at high mass and high or low $\tan\beta$

No evidence of $H^\pm$, limits set on $\sigma \times B$ and interpreted in benchmark scenarios
Backup...
$H^\pm \rightarrow \tau\nu$ fake-factor method

- jet $\rightarrow \tau$ fakes are a significant background
- Modeled with a data-driven fake-factor method
  - FF measured in CRs with fakes from Multi-Jet (QCD) and $W+$jets events
  - Define anti-$\tau$ as objects failing $\tau$-ID but passing a looser ID
  - $FF = \frac{N_{\text{fake-}\tau}}{N_{\text{anti-}\tau}}$, binned in $p_\tau^T$ and $N_{\text{tracks}}$
  - Using FF: $N_{\text{fake-}\tau} = FF \times N_{\text{anti-}\tau}$
- $\alpha$QCD approach is used to apply FFs in SRs and CRs
  - Weighted average of FFs from QCD/$W+$jets CRs
  - Relative weights from template fit on $\tau$-ID BDT scores or jet width of 1-prong or 3-prong anti-$\tau$
### $H^\pm \to tb$ BDT Variables

**$\ell + j$-jets channel**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(j_1)$</td>
<td>Leading jet transverse momentum</td>
</tr>
<tr>
<td>$m(b\text{-pair}$ min$)$</td>
<td>Invariant mass of pair of b-tagged jets with smallest $\Delta R$</td>
</tr>
<tr>
<td>$R_{bT}$</td>
<td>Transverse momentum of fifth jet</td>
</tr>
<tr>
<td>$\Delta R(b\text{-pair})$</td>
<td>Second Fox-Wolfram moment [110] calculated using all jets and leptons</td>
</tr>
<tr>
<td>$\Delta R(\ell, b\text{-pair})$</td>
<td>Average $\Delta R$ between all b-tagged jets in the event</td>
</tr>
<tr>
<td>$m(\ell, b\text{-pair}$ min$)$</td>
<td>Invariant mass of the non-b-tagged jet-pair with minimum $\Delta R$</td>
</tr>
<tr>
<td>$R_{\ell, b}$</td>
<td>Scalar sum of all jets transverse momenta</td>
</tr>
<tr>
<td>$m(b\text{-pair}$ max$)$</td>
<td>Invariant mass of the b-tagged jet pair with maximum transverse momentum</td>
</tr>
<tr>
<td>$m_{\text{max}}(b\text{-pair})$</td>
<td>Largest invariant mass of any two b-tagged jets</td>
</tr>
<tr>
<td>$m_{\text{mix}}(b\text{-pair})$</td>
<td>Largest invariant mass of any three jets</td>
</tr>
<tr>
<td>$D$</td>
<td>Kinematic discriminant based on mass templates (for $m_{H^\pm} \leq 300$ GeV)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel, $m \leq 600$ GeV</th>
<th>$3j$-b</th>
<th>$\geq 4j$-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(\ell, b)$</td>
<td>$E_{\ell, b}$</td>
<td>$\Delta m(\ell, b)$</td>
</tr>
<tr>
<td>$\Delta m(j_1, j_2)$</td>
<td>$E_{j_1}$</td>
<td>$\Delta m(j_1, j_2, j_3)$</td>
</tr>
<tr>
<td>$p_T(j_1)$</td>
<td>$E_{j_1}$</td>
<td>$\Delta m(j_1, j_2, j_3)$</td>
</tr>
</tbody>
</table>

- **BDT trained on different variables depending on mass and final state**
- **Almost all are ($\Delta$) $p_T$, $E$, or $m$ of combinations of particles in the final state.**
- **Low-mass variable $D$ needs some explanation...**
Kinematic Discriminant $D$

- $D = P_{H^+}(x)/(P_{H^+}(x) + P_{\bar{t}\bar{t}}(x))$
- $P_{H^+}(x)$ and $P_{\bar{t}\bar{t}}(x)$ are probability density functions for $x$ under signal and background hypotheses
- $x$ is $E_T^{\text{miss}}$ and four-momentum of $e, \mu$, and jets
- $P_{H^+}(x)$ defined as the product of probability density functions for:
  - the mass of the semileptonically decaying top quark, $m_{b\ell\ell\nu}$
  - the mass of the hadronically decaying $W$ boson, $m_{q_1 q_2}$
  - the difference between the masses of the hadronically decaying top quark and the hadronically decaying $W$ boson, $m_{b_h q_1 q_2} - m_{q_1 q_2}$
  - the difference between the mass of the charged Higgs boson and the mass of the leptonically or hadronically decaying top quark, $m_{b_H+b\ell\ell\nu} - m_{b\ell\ell\nu}$ or $m_{b_H+b\ell q_1 q_2} - m_{b\ell q_1 q_2}$, depending on whether or not the top quark from the charged Higgs boson decays leptonically or hadronically

Where:

- $q_1$ and $q_2$ are quarks from the hadronic $W$ decay
- $\ell$ and $\nu$ are from the leptonic $W$ decay
- $b_h$ is the $b$-quark from the hadronic top quark decay
- $b_\ell$ is the $b$ quark from the leptonic top quark decay
- $b_H$ is the $b$-quark from the $H^+$ decay
Results, $\ell+$jets, $m_{H^\pm} = 300$ GeV

[Graphs showing data and predictions for $\ell+$jets events with different uncertainties and BDT output.]
Results, $\ell\ell$, $m_{H^\pm} = 300$ GeV

**ATLAS**

$\ell\ell$, 3j3b post-fit

$\ell\ell$, 4j3b post-fit

$\ell\ell$, $\geq 4j$3b post-fit

Events / bin

Data / Pred.

ATLAS

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$\ell\ell$, 3j3b post-fit

$\ell\ell$, 4j3b post-fit

$\ell\ell$, $\geq 4j$3b post-fit

BDT Output

0.6

0.8

1

1.2

1.4

Data / Pred.

Events / bin

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BDT Output

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1.4

Data / Pred.
Results, $\ell+\text{jets}, \; m_{H\pm} = 800 \text{ GeV}$

![Graphs showing data and predictions for $\ell+\text{jets}$ events with different jet and b-quark combinations.](image)

- ATLAS
- $\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$
- $\ell+\text{jets}, 5\text{j}3\text{b}$ post-fit
- $\ell+\text{jets}, \geq 6\text{j}3\text{b}$ post-fit
- $\ell+\text{jets}, \geq 6\text{j}4\text{b}$ post-fit
- Data and predictions for $H'$ at 800 GeV
- Comparison of observed data with predictions for different signal categories (if + light, if + 1c, if + 1b, if + X, non-t, uncertainty)

Events / bin

- Data / Pred.

33 / 26
Results, $\ell\ell$, $m_{H^\pm} = 800$ GeV