Searches for additional charged Higgs bosons in the MSSM

Lluïsa-Maria Mir
for the ATLAS Collaboration

ICHEP2018 Seoul
XXXIX International Conference on high energy physics
Many BSM models include extended Higgs sector with at least one pair of charged Higgs bosons (2HDM, Higgs triplets…)

- Single- (double-) resonant top contribution dominates at large (low) H$^+$ mass
- Interference becomes most relevant in the intermediate region

In 2HDM the decay is controlled by two parameters (besides mass)
- $\tan\beta$: ratio of v.e.v. of two Higgs doublets
- $\alpha$: mixing angle between two CP-even Higgs bosons
✓ At high masses $H^+$ to $tb$ dominates in decoupling and alignment limits
✓ For $H^+$ lighter than top-quark the decay to $\tau\nu$ dominates
✓ Present $H^+ \rightarrow \tau\nu$ and $H^+ \rightarrow tb$ searches with 2015-2016 data (36.1 fb$^{-1}$)
✓ Signal generated with (4FS) MG5_aMC + Pythia8
  ➢ Normalisation from Santander-matched 4FS & 5FS total cross-section
  ➢ Zero-width approximation used
H$^+ \rightarrow \tau v$ event selection

✓ $\tau_{\text{had}} + \text{jets}$:

- $E_T^\text{miss}$ trigger (70, 90, 110 GeV)
- $\geq 1$ $\tau_{\text{had}}$ $p_T > 40$ GeV + 0 lepton (e,$\mu$) $p_T > 20$ GeV
- $\geq 3$ jets ($\geq 1$ b-tag) $p_T > 25$ GeV
- $E_T^\text{miss} > 150$ GeV, $m_T > 50$ GeV

✓ $\tau_{\text{had}} + \text{lepton (e,$\mu$)}$:

- Single lepton triggers
- $\tau_{\text{had}} + \text{lepton}$ opposite sign $p_T > 30$ GeV each
- $\geq 1$ b-tag jet $p_T > 25$ GeV
- $E_T^\text{miss} > 50$ GeV

Final state:

```
  b            τ_{\text{had}}
  H^+ --> V    ν
  W^- --> q, l^- q', ν
  b
```
H⁺ → τν background modelling

- Backgrounds with prompt $\tau_{\text{had}}$:
  - $W → \tau\nu$ and $tt$ : modelled with MC
    - Control region (CR) with $\tau_{\text{had}}$+lepton selection but with e-μ pair to normalise $tt$
- Backgrounds with fake $\tau_{\text{had}}$:
  - Electron misidentified as $\tau_{\text{had}}$: estimated with MC, validated with $Z → e^+e^-$ CR
    - One electron, one $\tau_{\text{had}}$, muon and b-jet vetoes, and $40 < m_{\ell\tau} < 140$ GeV
  - Jet misidentified as $\tau_{\text{had}}$: estimated with data-driven fake-factor (FF) method:
    - Extract FF ($FF= N_{\text{pass}}/N_{\text{fail}}$) from two orthogonal control regions:
      - Multi-jet CR: $\tau_{\text{had}}$+jets selection with b-jet veto and $E_T^{\text{miss}} < 80$ GeV
      - $W$+jets CR: $\tau_{\text{had}}$+lepton selection with b-jet veto, no $E_T^{\text{miss}}$ requirement and $60 < m_{\tau(l, E_T^{\text{miss}})} < 160$ GeV
H$^+ \rightarrow \tau v$ analysis strategy

- Search in the 90 - 2000 GeV mass range

- $m(H^+) \sim m(t)$ region included for the first time

- Use multivariate techniques (BDTs) to separate S/B
  - Separately for $\tau_{\text{had}} + \text{jets}$ and $\tau_{\text{had}} + \text{lepton}$ channels and 1 or 3 tracks
  - $\tau_{\text{had}}$ polarization important at low mass
  - $E_{T}^{\text{miss}}, p_T(\tau_{\text{had}})$ and $\Delta\phi_{\tau,\text{miss}} (m_T)$ important at high mass

- Fit to BDT output in three SRs and number of events in $tt$ CR
✓ No significant excess above background-only hypothesis at any mass
✓ Example of post-fit plot in the 130 to 160 GeV τ+μ signal region
H^+ → \tau\nu limits

**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- Observed (CLs)
- \( \pm 1 \sigma \)
- \( \pm 2 \sigma \)
- Expected (CLs)
- Run-1 result

**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- Observed exclusion
- Expected exclusion

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**ATL-HIGG-2016-11**

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ICHEP'18, L.I.M. Mir
Single lepton triggers

Di-lepton:
- Exactly two OS leptons (ee/eμ/μμ), leading $p_T > 27$ GeV, sub-leading $p_T > 10$ GeV
- ee/μμ: $m_\ell\ell > 15$ GeV excluding $83 < m_\ell\ell < 99$ GeV
- $\geq 3$ jets ($\geq 2$ b-tags) $p_T > 25$ GeV

Lepton+jets:
- Exactly one lepton $p_T > 27$ GeV
- $\geq 5$ jets ($\geq 3$ b-tags) $p_T > 25$ GeV
- Veto di-lepton selection

Divide selected sample into signal/control regions according to jet/b-tag multiplicities

<table>
<thead>
<tr>
<th></th>
<th>2 b-tags</th>
<th>3 b-tags</th>
<th>$\geq 4$ b-tags</th>
<th>2 b-tags</th>
<th>3 b-tags</th>
<th>$\geq 4$ b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 jets</td>
<td>CR</td>
<td>SR/CR</td>
<td>SR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq 4$ jets</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 jets</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq 6$ jets</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\( tt \) is the largest background

- Modelled with Powheg + Pythia8
- Subdivided into \( tt \) + light flavor, \( tt + \geq 1b \) and \( tt + \geq 1c \)
- Modelling improved by sequential re-weighting of \( tt + \geq 1b \) to Sherpa + OpenLoops
  1. Reweight \( p_T \) of \( tt \) system
  2. Reweight \( p_T \) of top quark
  3. Reweight \( p_T \) of HF quark (if only one) or \( \Delta R \) of HF quarks and \( p_T \) of di-jet system (if more)

- Number of events with high leading jet \( p_T \) overestimated in simulation \( \Rightarrow \) re-weighting function for leading jet \( p_T \) by comparing simulation/data

Other backgrounds

- \( tt + V/H \)
- Single top, di-boson, tH, tV, W/Z + jets, QCD multi-jets
- W/Z + HF corrected using data-driven methods
- Multi-jets modelled using
  - Matrix method (lepton+jets)
  - Monte Carlo (di-lepton)
Search in the **200 - 2000 GeV** mass range

Signal fraction very small even in the most sensitive regions

- Use multivariate techniques (BDTs) to separate S/B in the SRs
- Lepton+jets BDT includes a kinematic discriminant \( D = \frac{P(H^+)}{P(H^+)+P(tt)} \) that reflects compatibility of event with \( H^+ \rightarrow tb \) and \( tt \) hypotheses

BDTs trained separately at each mass and SR

Simultaneous fit to BDT output distributions in SRs and number of events in CRs

\( tt + \geq 1b \) and \( tt + \geq 1c \) allowed to vary freely
H^+ \rightarrow tb fit results

- No significant excess above background-only hypothesis at any mass
- Example of post-fit plots for the 200 GeV mass hypothesis
H^+ → tb limits

ATLAS Preliminary

\[ \sigma(pp \to H^+ \to \bar{t}b) \times BR(H^+ \to \bar{t}b) \text{[pb]} \]

\[ \sqrt{s}=13 \text{ TeV, 36.1 fb}^{-1} \]

\[ m_{h^0}^{\text{mod}} \tan\beta = 0.5 \]

\[ m_{h^0}^{\text{mod}} \tan\beta = 1 \]

\[ m_{h^0}^{\text{mod}} \tan\beta = 60 \]

95% observed limit (CL_s)
95% expected limit (CL_s)

Expected ± 1σ
Expected ± 2σ

ATLAS Preliminary
$H^+ \rightarrow \tau\nu, tb$

$H^+ \rightarrow \tau\nu, tb$

$H^+ \rightarrow \tau\nu, tb$

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$H^+ \rightarrow \tau\nu, tb$

$H^+ \rightarrow \tau\nu, tb$
✓ ATLAS performed searches for heavy charged bosons in the $H^+ \rightarrow \tau \nu$ and $H^+ \rightarrow t\bar{b}$ decays using 36 fb$^{-1}$ of Run2 data

✓ No excess with respect to SM predictions observed
  - Improved exclusions
  - New final states and extended mass range w.r.t. previous searches

✓ Other ATLAS charged Higgs results:
  - $H^+ \rightarrow W^+ Z (l^+\nu l^-\bar{l}^-)$ in *Searches for new phenomena in leptonic final states using the ATLAS detector* by Borut Kersevan on *Beyond the SM* session on July 6th
### H⁺ → τν object reconstruction

#### Electrons
- Loose (tight) LH in τ+jets(lepton)
- Calorimeter and track isolation
- |η| < 2.4 excluding (1.37,1.52)

#### Muons
- Loose (tight) LH in τ+jets(lepton)
- Calorimeter and track isolation
- |η| < 2.5

#### Jets
- AntiKt4EMtopo
- p_T > 25 GeV
- |η| < 2.5

#### b-jets
- MV2C10 algorithm
- Uses impact parameter + secondary/tertiary vertices
- 70% efficient
- 13, 56 and 380 rejection factors (c, taus, light/gluon)

#### Taus
- Seeded by antiKt jets with E_T > 10 GeV and 1 or 3 tracks in ΔR =0.2
- |η| < 2.3 excluding (1.37,1.52)
- Identification BDT 75 (60)% efficient for 1(3) prongs and 30-80 (200-1000) rejection factors
- Likelihood-based veto 95% efficient with 20-200 rejection factors for electrons depending on η
<table>
<thead>
<tr>
<th>Electrons</th>
<th>Muons</th>
<th>Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight LH</td>
<td>Medium LH</td>
<td>AntiKt4EMtopo</td>
</tr>
<tr>
<td>Calorimeter and track isolation</td>
<td>Calorimeter and track isolation</td>
<td>p_T &gt; 25 GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.4$ excluding (1.37,1.52)</td>
</tr>
</tbody>
</table>

**b-jets**
- MV2C10 algorithm
- Uses impact parameter + secondary/tertiary vertices
- 70% efficient
- 13, 56 and 380 rejection factors (c, taus, light/gluon)
- Multiple points for $m(H^+) < 300$ GeV ($p_T < 250$ GeV) in lepton+jets
### $H^+ \rightarrow \tau v$ BDT variables

<table>
<thead>
<tr>
<th>BDT input variable</th>
<th>$\tau_{\text{had-vis} + \text{jets}}$</th>
<th>$\tau_{\text{had-vis} + \text{lepton}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T^{b\text{-jet}}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T^{\ell}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T$</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta \phi_{\tau, \text{miss}}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta \phi_{b\text{-jet, miss}}$</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>$\gamma$</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- **Important at low mass**
- **Important at high mass**
### $H^+ \rightarrow tb$ single lepton BDT variables

#### $\ell + \text{jets}$ 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>$m(b\text{-pair}^{\Delta R_{\text{min}}})$</td>
<td>Invariant mass of pair of $b$-tagged jets with smallest $\Delta R$</td>
</tr>
<tr>
<td>$p_T(j_5)$</td>
<td>Transverse momentum of fifth jet</td>
</tr>
<tr>
<td>$H_2$</td>
<td>Second Fox-Wolfram moment $[120]$ calculated using all jets and leptons</td>
</tr>
<tr>
<td>$\Delta R_{\text{avg}}(b\text{-pair})$</td>
<td>Average $\Delta R$ between all $b$-tagged jet pairs in the event</td>
</tr>
<tr>
<td>$\Delta R(\ell, b\text{-pair}^{\Delta R_{\text{min}}})$</td>
<td>$\Delta R$ between the lepton and the $b$-tagged jet pair with smallest $\Delta R$</td>
</tr>
<tr>
<td>$m(u\text{-pair}^{\Delta R_{\text{min}}})$</td>
<td>Invariant mass of the non-$b$-tagged jet-pair with minimum $\Delta R$</td>
</tr>
<tr>
<td>$H_T^{\text{jets}}$</td>
<td>Scalar sum of all jets transverse momenta</td>
</tr>
<tr>
<td>$m(b\text{-pair}^{P_T_{\text{max}}})$</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>Maximal $b$-tagged jet pair invariant mass</td>
</tr>
<tr>
<td>$m^{\text{max}}(j\text{-triplet})$</td>
<td>Maximal jet triplet invariant mass</td>
</tr>
<tr>
<td>$D$</td>
<td>Kinematic discriminant based on mass templates (for $m_{H^+} \leq 300$ GeV)</td>
</tr>
</tbody>
</table>

- Important at low mass
- Important at high mass
### $H^+ \rightarrow tb$ di-lepton BDT variables

<table>
<thead>
<tr>
<th>$\ell\ell$ channel, $m \leq 600$ GeV</th>
<th>3j3b</th>
<th>$\geq 4j3b$</th>
<th>$\geq 4j4b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(j, b)_{PT}^{max}$</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta E(j_3, \ell_2)$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$E(j_3)$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta m(j_1 + j_2, j_1 + j_3 + \ell_2 + E_T^{miss})$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R(j_2, j_1 + \ell_2 + E_T^{miss})$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T(b_1)$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$p_T((\ell, b)_{\Delta \eta}^{max})$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m((\ell, b)_{\Delta \phi}^{min})$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta E(b_1, \ell_1 + E_T^{miss})$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta m(j_2 + j_3, j_1 + \ell_1 + \ell_2)$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta m(\ell_1 + j_3 + E_T^{miss}, j_1 + j_2 + \ell_2)$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta p_T(j_1, j_3)$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$m_{min}^{b}$ (b-pair)</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$m_{min}^{(\ell, b)}$</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T(b_2 + \ell_1 + \ell_2 + E_T^{miss})$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R(\ell_2, j_2 + j_3 + \ell_1 + E_T^{miss})$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_T^{all}$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
### $H^+ \rightarrow t\bar{b}$ di-lepton BDT variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\ell\ell$ channel, $m &gt; 600$ GeV</th>
<th>$3j3b$</th>
<th>$\geq 4j3b$</th>
<th>$\geq 4j\geq 4b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T((\ell, b)\Delta\eta_{\text{min}})$</td>
<td>$p_T$ of the pair of lepton and $b$-tagged jet with smallest $\Delta\eta$</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$\Delta p_T(j_1, j_3)$</td>
<td>$p_T$ difference between leading and third jets</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$\Delta m(j_2 + \ell_1 + E_{T\text{miss}}, j_1 + j_3 + \ell_1)$</td>
<td>Inv. mass difference between $j_2 + \ell_1 + E_{T\text{miss}}$ and $j_1 + j_3 + \ell_1$</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$p_T((\ell, b)\Delta R_{\text{min}})$</td>
<td>$p_T$ of the pair of lepton and $b$-tagged jet with smallest $\Delta R$</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$m(\text{j-pair}\Delta\eta_{\text{min}})$</td>
<td>Inv. mass of the jet pair with smallest $\Delta\eta$</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$\Delta p_T(j_1, j_2 + E_{T\text{miss}})$</td>
<td>$p_T$ difference between leading jet and $j_2 + E_{T\text{miss}}$</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$p_T(j_1 + j_2 + j_3 + \ell_1)$</td>
<td>$p_T$ of $j_1 + j_2 + j_3 + \ell_1$</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$\Delta E(\ell_1 + E_{T\text{miss}}, j_1 + j_2)$</td>
<td>Energy difference between $\ell_1 + E_{T\text{miss}}$ and $j_1 + j_2$</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$E(j_1)$</td>
<td>Energy of the leading jet</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{max}}(\text{j-pair})$</td>
<td>Maximum $p_T$ of any jet pair</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$m(b_1 + b_2 + \ell_1 + \ell_2 + E_{T\text{miss}})$</td>
<td>Inv. mass of $b_1 + b_2 + \ell_1 + \ell_2 + E_{T\text{miss}}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$p_T((\ell, b)\Delta\eta_{\text{min}})$</td>
<td>$p_T$ of the lepton-$b$-jet pair with smallest separation in $\eta$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$\Delta p_T(\ell_1, u_1 + b_2 + E_{T\text{miss}})$</td>
<td>$p_T$ difference between subleading lepton and $u_1 + b_2 + E_{T\text{miss}}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$\Delta p_T(\ell_2, u_1 + b_1 + E_{T\text{miss}})$</td>
<td>$p_T$ difference between subleading lepton and $u_1 + b_1 + E_{T\text{miss}}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$\Delta p_T(\ell_2, \ell_1 + E_{T\text{miss}})$</td>
<td>$p_T$ difference between subleading lepton and $\ell_1 + E_{T\text{miss}}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$\Delta p_T(j_1, j_3 + \ell_1 + E_{T\text{miss}})$</td>
<td>$p_T$ difference between leading jet and $j_3 + \ell_1 + E_{T\text{miss}}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$\Delta E(\ell_1, j_2 + E_{T\text{miss}})$</td>
<td>Energy difference between leading lepton and $j_2 + E_{T\text{miss}}$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$m_{\text{min}}(b\text{-pair})$</td>
<td>Smallest invariant mass of any $b$-tagged jet pair</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$H_T^{\text{all}}$</td>
<td>Scalar sum of all jets and leptons transverse momenta</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>

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$p_T((\ell, b)\Delta\eta_{\text{min}})$ represents the $p_T$ of the pair of lepton and $b$-tagged jet with the smallest $\Delta\eta$ between them. $\Delta p_T(j_1, j_3)$ denotes the $p_T$ difference between the leading and third jets. $\Delta m(j_2 + \ell_1 + E_{T\text{miss}}, j_1 + j_3 + \ell_1)$ signifies the invariant mass difference between $j_2 + \ell_1 + E_{T\text{miss}}$ and $j_1 + j_3 + \ell_1$. $p_T((\ell, b)\Delta R_{\text{min}})$ indicates the $p_T$ of the pair of lepton and $b$-tagged jet with the smallest $\Delta R$. $m(\text{j-pair}\Delta\eta_{\text{min}})$ refers to the invariant mass of the jet pair with the smallest $\Delta\eta$. $\Delta p_T(j_1, j_2 + E_{T\text{miss}})$ is the $p_T$ difference between the leading jet and $j_2 + E_{T\text{miss}}$. $p_T(j_1 + j_2 + j_3 + \ell_1)$ represents the $p_T$ of the sum of the first three jets and the leptons. $\Delta E(\ell_1 + E_{T\text{miss}}, j_1 + j_2)$ is the energy difference between $\ell_1 + E_{T\text{miss}}$ and $j_1 + j_2$. $E(j_1)$ is the energy of the leading jet. $p_T^{\text{max}}(\text{j-pair})$ is the maximum $p_T$ of any jet pair. $m(b_1 + b_2 + \ell_1 + \ell_2 + E_{T\text{miss}})$ is the invariant mass of $b_1 + b_2 + \ell_1 + \ell_2 + E_{T\text{miss}}$. $p_T((\ell, b)\Delta\eta_{\text{min}})$ represents the $p_T$ of the lepton-$b$-jet pair with the smallest separation in $\eta$. $\Delta p_T(\ell_1, u_1 + b_2 + E_{T\text{miss}})$ indicates the $p_T$ difference between the subleading lepton and $u_1 + b_2 + E_{T\text{miss}}$. $\Delta p_T(\ell_2, u_1 + b_1 + E_{T\text{miss}})$ is the $p_T$ difference between the subleading lepton and $u_1 + b_1 + E_{T\text{miss}}$. $\Delta p_T(\ell_2, \ell_1 + E_{T\text{miss}})$ denotes the $p_T$ difference between the subleading lepton and $\ell_1 + E_{T\text{miss}}$. $\Delta p_T(j_1, j_3 + \ell_1 + E_{T\text{miss}})$ represents the $p_T$ difference between the leading jet and $j_3 + \ell_1 + E_{T\text{miss}}$. $\Delta E(\ell_1, j_2 + E_{T\text{miss}})$ is the energy difference between the leading lepton and $j_2 + E_{T\text{miss}}$. $m_{\text{min}}(b\text{-pair})$ is the smallest invariant mass of any $b$-tagged jet pair. $H_T^{\text{all}}$ is the scalar sum of all jets and leptons transverse momenta.
H^+ → tb background modelling (II)

✓ *tt* systematic uncertainties:
  - Inclusive cross section (including μ_F, μ_R, PDF, α_S, m_t) 6%
  - Generator: Powheg + Pythia8 vs 5FS SherpaOL
  - PS and hadronisation: Powheg + Pythia8 vs Powheg + Herwig7
  - ISR/FSR: Vary μ_R, μ_F, hdamp and A14 eigentune

✓ *tt* + ≥ 1b systematic uncertainties:
  - *tt* + ≥ 3b cross section (difference between 4FS and various 5FS predictions) 50%
  - Powheg + Pythia8 vs 4FS SherpaOL (5FS inclusive *tt* vs 4FS *tt* + *bb* predictions)
  - Reweighting:
    - Varying scale choices
    - Varying PDF sets (MSTW and NNPDF)
    - UE and PS with alternative sets of tuned parameters
    - 50% due to *tt* + b from MPI/FSR absence in SherpaOL

✓ *tt* + ≥ 1c systematic uncertainties:
  - Powheg + Pythia8 vs MG5_aMC + Herwig++ (4FS inclusive *tt* vs 3FS *tt* + *cc* in ME)
  - Leading jet p_T reweighting (comparison with no reweighting + 15% normalisation p_T > 400 GeV)
Consider a left-right symmetric model with additional triplet and doubly charged Higgs bosons

- BR depends on mass and v.e.v. of triplet
- $36.1 \text{ fb}^{-1} @13 \text{ TeV}, \ 250 \leq m(H^{±±}) \leq 1300 \text{ GeV}$
- Fit $m(l^±l^±)$ if 2 or 3 leptons or $M=0.5 \times (m^{++}+m^{--})$ if four leptons