Search for doubly charged Higgs using Tau leptons with ATLAS at $\sqrt{s} = 13$ TeV

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Why search for doubly charged Higgs?

• Doubly charged Higgs bosons can arise in various BSM theories
  • Left-right symmetric models, Higgs triplet models, little Higgs model, type-II seesaw models, ...
  • Closely related to generation mechanism of neutrino mass.
  • Hint for the existence of supersymmetry.
  • Can decay to a pair of same-sign leptons which are rare in SM.

Feynman diagrams for several doubly charged Higgs production channel. arXiv:1105.1379v1
Previous study by ATLAS on $H^{\pm \pm} \to l^{\pm} l'^{\pm}$

• Used pp data sample with Integrated luminosity 36.1 fb$^{-1}$ collected in 2015 and 2016 by the ATLAS detector at the LHC at $\sqrt{s}=13$ TeV

• Only pair production via the Drell–Yan process was considered

• Total assumed branching ratio of $H^{\pm \pm}$ is $B(H^{\pm \pm} \to l^{\pm} l'^{\pm}) + B(H^{\pm \pm} \to X) = 100\%$, while “X” does not enter any of the SRs. Only $e$ and $\mu$ were considered.

• Partial decay width of $H^{\pm \pm}$ to leptons is given by:

\[
\Gamma(H^{\pm \pm} \to l^{\pm} l'^{\pm}) = \frac{1}{1+\delta_{l,l'}} \frac{|\bar{h}_{l,l'}|^2 m_{H^{\pm \pm}}}{16\pi}, \quad \bar{h}_{l,l'} = \begin{cases} 2h_{l,l'} & l = l' \\ h_{l,l'} & l \neq l' \end{cases}
\]

• Masses studied: $200 \leq m_{H^{\pm \pm}} \leq 1300$ GeV
Previous study by ATLAS on $H^{±±} \rightarrow l^{±}l'^{±}$

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- Partial decay width of $H^{±±}$ to leptons is given by:

$$\Gamma(H^{±±} \rightarrow l^{±}l'^{±}) = \frac{1}{1+\delta_{ll'}} |\tilde{h}_{ll'}|^2 \frac{m_{H^{±±}}}{16\pi}, \quad \tilde{h}_{ll'} = \begin{cases} 2h_{ll'} & l = l' \\ h_{ll'} & l \neq l' \end{cases}$$

- Masses studied: $200 \leq m_{H^{±±}} \leq 1300$ GeV

Branching ratios of $H^{±±}$ into different final states vs. mass of $H^{±±}$ for $\nu_\Delta = 1$ GeV, $h_{ll} = 0.01$. arXiv:1105.1379v1
Previous study by ATLAS on $H^{\pm\pm} \rightarrow l^\pm l'^\pm$

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Branching ratios of $H^{\pm\pm}$ into different final states vs. vacuum expectation value. arXiv:1611.09594v2
Lower-limit plots on $H_L^{±±}$ and $H_R^{±±}$ mass

What’s next??
Add tau to the analysis!

• Excellent probe to new physics due to heavy mass (larger coupling to the SM Higgs)
• Based on the lower limits on $H^{\pm\pm}$, it’s likely that tau appears in the decay products
• Only interested in hadronic decay modes of tau
What am I working on..

• Add hadronically decaying taus to the current analysis framework (TNAnalysis)
• Apply selections on the ntuples (Sherpa 2.2.1 $Z \rightarrow \tau\tau$ and data taken from 2015 to 2017)
  • $p_T \geq 30$ GeV
  • Trigger matching
    (HLT_tau35_medium1_tracktwo_tau25_medium1_tracktwo)
  • Truth info matching (only for MC)
• Use data-driven method to perform charge flip rate estimation
Charge flip for tau

- Types of charge flip for electrons
  - Stiff tracks (high $p_T \to$ straighter tracks)
  - Trident events

- Assume Poissonian distribution for expected number of charge flipped events $\lambda$

\[
P(N_{SS}; \lambda) = \frac{\lambda^{N_{SS}}e^{-\lambda}}{N_{SS}!}
\]

where $\lambda$ is a function of the charge flip probability $\epsilon(p_T, \eta) = f(\eta) \cdot \sigma(p_T)$. Require $f(\eta)$ to be normalized.

- The expected number of charge flipped events:

\[
\lambda_{i,j} = \epsilon_i (1 - \epsilon_j) N_{AS}^{ij} + (1 - \epsilon_i) \epsilon_j N_{AS}^{ij}
\]

- Maximum likelihood method

\[
L(\lambda; N_{SS}) = \prod_{N_{SS}} P(N_{SS}; \lambda) = \prod_{N_{SS}} \frac{\lambda^{N_{SS}}e^{-\lambda}}{N_{SS}!}
\]
$Z \rightarrow \tau\tau$ mass spectrum of MC
$Z \rightarrow \tau\tau$ mass spectrum of data

![Mass spectra for $Z \rightarrow \tau\tau$ with data from ATLAS.](image)
Current results on charge-flip rate for MC without prongness

\[ \epsilon(p_T, \eta) = f(\eta) \cdot \sigma(p_T) \]

\[ \eta = f(\eta) \cdot \sigma(p_T) \]

\[ \text{Charge-flip rates for taus} \]

\[ \text{Sherpa 2.2.1 Z\rightarrow tautau} \]
Closure test on the charge-flip rate of taus

\[ Z \rightarrow \tau \tau \text{ peak} \]

\[ \text{Events} = 13 \text{ TeV}, 79.8 \text{ fb}^{-1} \]

\[ \text{Charge-flip rates closure test} \]

\[ Z \rightarrow \text{ee peak} \]

\[ \text{(OC data, SC data)} \]

\[ \text{ATLAS} \]

\[ \text{MC, AS} \]

\[ \text{Pred. from AS} \]

\[ \epsilon_i (1 - \epsilon_j) N_{AS}^{ij} + (1 - \epsilon_i) \epsilon_j N_{AS}^{ij} \]

\[ Z \rightarrow \tau \tau \text{ peak} \]

\[ Z \rightarrow \text{ee peak} \]

\[ \text{MC/pred} \]

\[ \text{Mass (GeV)} \]

\[ \text{Events / GeV} \]

\[ \times 10^6 \]

\[ \times 10^3 \]

\[ \text{arXiv: 1710.09748v1} \]
What about charge-flip rate including prongness?

• Still working on it...

• Challenges
  • Two times more parameters to minimize
    • $\epsilon(p_T, \eta, \text{prongness}) = f(\eta) \cdot \sigma(p_T) \cdot Y(\text{prongness})$
  • The current minimization method need to be modified as normalization requirement on $\eta$ does not seem to work well if we have $\eta_{1\text{-prong}}$ and $\eta_{3\text{-prong}}$
Future plans

• Perform charge-flip rate on 1-prong and 3-prong taus.
• Data have huge background. More studies on the background is required.
Backup slides
Previous $H^{++} + H^{--} \rightarrow l^+l^+l^-l^-$ analysis

- **Selection:**
  - $e$ and $\mu$
  - 2-, 3-, and 4-lepton final states
  - b-jet veto
  - Z veto on 1P3L & 2P4L
  - $\Delta R$, $p_T$ cuts

- **Signal regions**
  - 1P2L, 1P3L, 2P4L

- **Control regions**
  - Opposite-charge control region
  - Diboson control region
  - Diboson in 4$l$ region

- **Validation regions**
  - Same-charge validation region
  - 3$l$ validation region
  - 4$l$ validation region
Relative uncertainties in the total background yield estimation
Summary of the results from previous study

<table>
<thead>
<tr>
<th>Branching ratio assumption</th>
<th>Type of $H^{\pm\pm}$</th>
<th>Lower limit for mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Br(H^{\pm\pm} \rightarrow l^{\pm\pm}) = 100%$</td>
<td>$H_L^{\pm\pm}$</td>
<td>Vary between 770 and 870 GeV</td>
</tr>
<tr>
<td>$Br(H^{\pm\pm} \rightarrow l^{\pm\pm}) = 10%$</td>
<td>$H_L^{\pm\pm}$</td>
<td>450 GeV</td>
</tr>
<tr>
<td>$Br(H^{\pm\pm} \rightarrow l^{\pm\pm}) = 100%$</td>
<td>$H_R^{\pm\pm}$</td>
<td>Vary between 660 and 760 GeV</td>
</tr>
<tr>
<td>$Br(H^{\pm\pm} \rightarrow l^{\pm\pm}) = 10%$</td>
<td>$H_R^{\pm\pm}$</td>
<td>320 GeV</td>
</tr>
</tbody>
</table>
Charge-flip rate for electrons

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

\[ P(\rho_T, \eta) = \sigma(\rho_T) \times f(\eta) \]

Data
Sherpa 2.2.1 \( Z \to \text{ ee} \)

\[ \text{Data/MC} \]

\[ p_T [\text{GeV}] \]

\[ \eta \]

arXiv: 1710.09748v1