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

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MPI, 2019
Why search for doubly charged Higgs?

- Standard Model Higgs Boson is a spinless neutral particle with a vacuum expectation value $\nu_0$
- Neutrino oscillation $\rightarrow$ Neutrino must have mass $\rightarrow$ Origin??
- Doubly charged Higgs bosons can be introduced to explain the origin of neutrino mass!
- Can decay to a pair of same-sign leptons
  - violation of lepton flavour by two units

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

• 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.
• Masses studied: $200 \leq m_{H^{±±}} \leq 1300$ GeV
• Only $e$ and $\mu$ were considered.
• No significant excess was observed, but lower mass limits were presented (450 GeV for $B(H^{±±} \rightarrow l^{±}l'^{±}) = 10\%$).
• Only thing that has not been done is hadronic decay of $\tau$ (leptonic decay of $\tau$ is reconstructed as $e$ or $\mu$).
Backgrounds of same-charge hadronic tau

**Prompt**
Same-charge taus from SM processes: diboson ($W^\pm W^\pm / ZZ / WZ$) and $t\bar{t} X$ processes ($t\bar{t} W$, $t\bar{t} Z$, and $t\bar{t} H$)

**Non-prompt**
Real taus from non-prompt decays, e.g. from heavy flavored mesons
Jets mis-reconstructed as taus

**Charge-flip**
Oppositely charged leptons with charge of tau misidentified: $Z/\gamma^*, t\bar{t}, tW, W^\pm W^\mp$

Narrow jet with 1 or 3 prongs (charged particles)

Can be distinguished, but there is some chance of mis-reconstruction.
Backgrounds

**Prompt**

Same-charge taus from SM processes: diboson ($W^\pm W^\mp ZZ/WZ$) and $t\bar{t}X$ processes ($t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$)

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Narrow jet with 1 or 3 prongs (charged particles)

What I work on!
Hadronic tau charge-flip background studies

- Using three methods to perform charge-flip rate study of tau for MC and data.
- What we want at the end?
  - **scale factor**: ratio of the charge-flip rate between MC and data
  - apply the scale factor to the simulated events to compensate for the differences
- **Data-drive** and **tag-and-probe** method
  - used in previous charge-flip study on electron for MC and data.
  - not working for tau data due to heavily contaminated background
- **Template fit** method
  - a new method designed for studying the hadronic tau charge-flip rate of data

<table>
<thead>
<tr>
<th>Type</th>
<th>Method</th>
<th>Samples</th>
<th>Channel</th>
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<tbody>
<tr>
<td>MC</td>
<td>Data-driven</td>
<td>Ztautau</td>
<td>Ditau ((\tau_{had}\tau_{had}))</td>
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<tr>
<td></td>
<td></td>
<td>ttbar</td>
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<tr>
<td>Data</td>
<td>Template fit</td>
<td>2015-2017</td>
<td>muTau ((\tau_{\mu}\tau_{had}))</td>
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</tbody>
</table>
Data-driven method

• 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 \( \epsilon(p_T, \eta) = f(\eta) \cdot \sigma(p_T) \).

• The expected number of charge flipped events:

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

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<tr>
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<tr>
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<tr>
<td><strong>ttbar sample</strong></td>
</tr>
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<td><strong>Ztautau sample</strong></td>
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</tbody>
</table>
Charge-flip rate for MC estimated by data-driven method

\[ \delta(p_T, \eta) = f(\eta) \cdot \sigma(p_T) \]
Tag-and-probe method

- Estimate the charge flip rate using following decay
  \[ Z/t\bar{t} \rightarrow \tau\tau \rightarrow \tau_{had}\tau_{\mu} \]
- Muon charge (the tag) is assumed to be reliably reconstructed to estimate the charge flip rate of tau (the probe)
  \[ \epsilon_{\tau_{had}} = \frac{N_{SS}}{N_{AS}} \]
- \( \epsilon_{\tau_{had}} \) depends only on \( p_T \) or \( \eta \) due to consideration of statistics

### Selections

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<th>Baseline</th>
<th>Single muon trigger:</th>
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<td>One muon and one tau (BDT medium working point). Electron veto</td>
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<td>Muon: ( p_T &gt; 30 ) GeV, ( z0\sin\theta &lt; 0.5 ), ( d0\text{sig} &lt; 3.0 )</td>
<td></td>
</tr>
<tr>
<td>Tau: ( p_T &gt; 30 ) GeV, truth matched</td>
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</tr>
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<td>No extra cuts for MC samples</td>
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</table>
Charge-flip rate from tag-and-probe method

Weak dependence on $p_T$

Big error bar due to large error in same sign fill:

$AS_{pt} = 1538 \pm 95$

$SS_{pt} = -6.37 \pm 11.19$
Comparison of charge-flip rate $\epsilon_{\tau_{\text{had}}}(\eta)$ between 1-prong and 3-prong

**Diagram:**
- **ttbar**
  - ATLAS work in progress
  - $\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$
  - MC charge-flip rate fit
  - 3-Prong
  - 1-Prong

- **Ztautau**
  - ATLAS work in progress
  - $\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$
  - MC charge-flip rate fit
  - 3-Prong
  - 1-Prong
Difficulties in studying hadronic tau charge-flip rate for data illustrated using ttbar control region

Inclusive: no truth matching of taus and muons

Truth matched: taus and muons are matched to their origin

MC plot shows that the number of true SS muon tau events is very small. The SS data are heavily contaminated by fake taus
Ztautau control region has worse statistics

More events in ttbar in comparing to Z control region

Inclusive: no truth matching of tau and muon

Truth matched: taus and muons are matched to their origin

MC plot shows that the number of true SS muon tau events are very small. The SS data are heavily contaminated by fake taus.

Z control region truth matched SS muTau (selections in backup slides)
Template fit method

• Choose to use ttbar sample and muTau ($\tau_\mu \tau_{had}$) channel to build the templates due the highest statistics it has

• $\epsilon_{\tau_{had}}$ depends only on $\eta$

• Using muTau channel means that tau is always assumed to be the one with wrong charge, just like the tag-and-probe

$$\left(N_{\text{data}}^{\text{AS}}(\eta)\right)_{\text{signal}} \times \epsilon_{\text{had}}(\eta) = \left(N_{\text{data}}^{\text{SS}}(\eta)\right)_{\text{signal}}$$

• The compositions of AS and SS raw data can be separate to two parts

$$N_{\text{data}}^{\text{AS}}(\eta_i) = N_{\text{signal}}^{\text{AS}}(\eta_i) + N_{\text{bck}}^{\text{AS}}(\eta_i)$$

$$N_{\text{data}}^{\text{SS}}(\eta_i) = N_{\text{signal}}^{\text{SS}}(\eta_i) + N_{\text{bck}}^{\text{SS}}(\eta_i)$$

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Template fit method

• Four templates are required:
  • $TMPL(N_{signal}^{AS})$ comes from $N_{truth \ MC}^{AS}$
  • $TMPL(N_{bck}^{AS})$ comes from $N_{inc.\ MC}^{AS} - N_{truth \ MC}^{AS}$
  • $TMPL(N_{signal}^{SS})$ comes from $N_{truth \ MC}^{SS}$
  • $TMPL(N_{bck}^{SS})$ comes from $N_{inc.\ MC}^{SS} - N_{truth \ MC}^{SS}$

• Need to find optimum values for the parameter $a$, $b$, $c$, $d$:

$$N_{data}^{AS}(\eta_i) = a \cdot TMPL\left(N_{signal}^{AS}(\eta_i)\right) + b \cdot TMPL\left(N_{bck}^{AS}(\eta_i)\right)$$

$$N_{data}^{SS}(\eta_i) = c \cdot TMPL\left(N_{signal}^{SS}(\eta_i)\right) + d \cdot TMPL\left(N_{bck}^{SS}(\eta_i)\right)$$

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<td>Best fit value</td>
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<td>1.377 ± 0.070</td>
<td>1.364 ± 1.862</td>
<td>1.223 ± 0.078</td>
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• The charge flip rate is

$$\epsilon_{had}(\eta_i) = \frac{c \cdot TMPL\left(N_{signal}^{SS}(\eta_i)\right)}{a \cdot TMPL\left(N_{signal}^{AS}(\eta_i)\right)}$$
Template fit method

• Four templates are required:
  • $TMPL(N_{signal}^{AS})$ comes from $N_{truth\ MC}^{AS}$
  • $TMPL(N_{bck}^{AS})$ comes from $N_{inc\ MC}^{AS} - N_{truth\ MC}^{AS}$
  • $TMPL(N_{signal}^{SS})$ comes from $N_{truth\ MC}^{SS}$
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$$\epsilon_{had}(\eta_i) = \frac{c \cdot TMPL(N_{signal}^{SS}(\eta_i))}{a \cdot TMPL(N_{signal}^{AS}(\eta_i))}$$
Charge flip rate for data and scale factor
Conclusion and current status

• The ATLAS detector at LHC is currently used to search for doubly charged Higgs bosons using same-charge hadronic tau channel.

• Charge-flip rate of hadronic tau $\epsilon_{had}$ for MC and data have been studied.

• $\epsilon_{had}$ depends weakly on $p_T$ and strongly on $\eta$.

• The charge-flip background is not a dominant background. Only 0.5 – 2% for $|\eta|$ ranging from 0 to 2.5.

• The scale factor is derived to be around 2 ± 0.5.

• Currently study the cause of charge-flip rate using event display
Backup slides
Why search for doubly charged Higgs?

- Doubly charged Higgs bosons can arise in various BSM theories
  - Left-right symmetric models, little Higgs model, type-II seesaw models, ...
- Appear in $SU(2)_L$ triplet for almost all the models studied
  \[
  \Delta = \begin{pmatrix}
  H^+ / \sqrt{2} & H^{++} \\
  H^0 = \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta) & -H^+ / \sqrt{2}
  \end{pmatrix}
  \]
- The Yukawa interaction term
  \[-Y_\nu \bar{L}_i \sigma_2 \Delta L + h.c.
  \]
  and the neutrinos acquire a Majorana mass
  \[M_\nu = \sqrt{2}Y_\nu v_\Delta \approx Y_\nu \frac{\mu v_0^2}{M_\Delta^2}\]
- Can decay to a pair of same-sign leptons which are rare in SM
  - Signal violation of lepton flavour by two units

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

- 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 $B(H^{\pm\pm} \rightarrow l^\pm l'^\pm) + B(H^{\pm\pm} \rightarrow X) = 100\%$, 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:

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

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

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

• 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

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• Masses studied: $200 \leq m_{H^{\pm\pm}} \leq 1300$ GeV

$$|\tilde{y}_{ll'}|^2 = 2|m_{\nu|^2}/v^2$$

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

ATLAS
$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$
lower limit of m($H^{\pm \pm}$)

- Observed 95% CL limit
- Expected 95% CL limit
- Expected limit $\pm 1\sigma$
- Expected limit $\pm 2\sigma$

$m(H^{\pm \pm})$ [GeV]

arXiv: 1710.09748v1
Closure test for the MC charge flip rate
**Tag-and-probe method**

**Selections**

<table>
<thead>
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<th>Single muon trigger:</th>
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<tbody>
<tr>
<td>HLT_mu20_iloose + HLT_mu50 (2015)</td>
</tr>
<tr>
<td>HLTMuon26_iVarMedium + HLT_mu50 (2016-2017)</td>
</tr>
</tbody>
</table>

**One muon and one tau. Electron veto**

**Muon:**
- $p_T > 30$ GeV, medium $wp$, FixedCutTightTrackOnly, $z_0 \sin \theta < 0.5$, $d_0 \sigma < 3.0$

**Tau:**
- $p_T > 30$ GeV, medium $wp$, isoTau, hadronic tau

**Ttbar sample**
- At least one $b$-jet

**Ztautau**
- No extra cuts for MC samples

Estimate the charge flip rate using the following decay:

$$Z \to \gamma \phi \tau \to \gamma \phi \tau \mu$$

Muon charge (the tag) is assumed to be reliably reconstructed to estimate the charge flip rate of tau (the probe):

$$\epsilon_{\tau} = \frac{N_{\text{SS} \tau}}{N_{\text{AS} \tau}}$$
1D charge-flip rate with prongness from ttbar
## Tau Charge-flip rate for data

- Use recommended selections for Z and ttbar control regions

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<td>Muon: ( p_T &gt; 30 \text{ GeV} ), medium ( \text{wp} ), FixedCutTightTrackOnly, z0sintheta &lt; 0.5, d0sig &lt; 3.0</td>
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</tr>
<tr>
<td><strong>Z control region</strong></td>
</tr>
<tr>
<td>( m_T(\mu, E_T^{\text{miss}}) = \sqrt{2p_T(\mu)E_T^{\text{miss}}(1 - \cos \Delta \Phi(\mu, E_T^{\text{miss}}))} &lt; 50 \text{ GeV} )</td>
</tr>
<tr>
<td>( \cos \Delta \Phi(\mu, E_T^{\text{miss}}) + \cos \Delta \Phi(\tau, E_T^{\text{miss}}) &gt; 0.5 )</td>
</tr>
<tr>
<td><strong>ttbar control region</strong></td>
</tr>
<tr>
<td>Tau: ( p_T &gt; 50 \text{ GeV} ), muon: ( p_T &gt; 50 \text{ GeV} )</td>
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<tr>
<td>At least one b-jet</td>
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</table>
Why choose mu tau channel for template fit

\[ m_{\mu\tau} = 700 \text{ GeV} \]

DTT

SMT

\[ \int L \, dt = 79.8 \text{ fb}^{-1}; \sqrt{s} = 13 \text{ TeV} \]
Attempts to reduce the background

• A lot of efforts were spent on studying the correlations and distributions of tau and jet kinematic variables, but it seems that the BDT has already done a good job with selecting events with same topology.

No significant difference. It is not easy to reduce fake tau SS background.
Template fit method

• Perform fitting in Mathematica 11.1
• The models generally have the form:
  \[
  \frac{(ax + b)}{ef(x)}
  \]
  or
  \[
  \frac{(ax + b)}{ef(x)} + \text{Gaussian}(x)
  \]
where \( f(x) \) is a polynomial of \( x \)
Template fit method

- Need to find optimum values for the parameter $a, b, c, d$:

  $$N_{\text{data}}^{AS}(\eta_i) = a \cdot TMPL \left( N_{\text{signal}}^{AS}(\eta_i) \right) + b \cdot TMPL \left( N_{\text{bck}}^{AS}(\eta_i) \right)$$

  $$N_{\text{data}}^{SS}(\eta_i) = c \cdot TMPL \left( N_{\text{signal}}^{SS}(\eta_i) \right) + d \cdot TMPL \left( N_{\text{bck}}^{SS}(\eta_i) \right)$$
Our group

<table>
<thead>
<tr>
<th>Members</th>
</tr>
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<tbody>
<tr>
<td>Jozef Stefan Institute</td>
</tr>
<tr>
<td>Miha Muskinja</td>
</tr>
<tr>
<td>Tadej Novak</td>
</tr>
<tr>
<td>Andrej Gorišek</td>
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<td>Borut Kerševan</td>
</tr>
<tr>
<td>Marko Mikuž</td>
</tr>
<tr>
<td>The University Of Melbourne</td>
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<tr>
<td>Federico Scutti</td>
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<td>Frank Zhang</td>
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<tr>
<td>Lund University</td>
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<td>Tadej Novak</td>
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<tr>
<td>Doubly Charged Higgs</td>
<td>Katja Mankinen, Federico Scutti</td>
</tr>
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<td>Same-Sign Heavy Neutrino (2015+2016)</td>
<td>Miha Muskinja, Giulia Ucchielli</td>
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<td>Heavy Lepton Multiplet</td>
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https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/SameSignClusterRun2