Collider Studies of Higgs Triplet Model

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A. G. Akeroyd and CC:
PRD 80, 113010 (2009) (0909.4419 [hep-ph])

A. G. Akeroyd, CC, and N. Gaur:
JHEP 11, 005 (2010) (1009.2780 [hep-ph])
Outline

• Motivation
• Higgs Triplet Model (HTM)
• Properties of charged Higgs bosons ($H^{±±}$ and $H^±$)
• Production and signature of $H^{±±}$ at hadron colliders
• Summary
Physics Beyond SM

• Theoretical considerations suggest new physics:
  • Naturalness (fine-tuning or hierarchy problem)
  • Cosmological constant problem
  • Origin of CP violation and Baryon Asymmetry of Universe (BAU)
  • Flavor problem and GUT’s
Physics Beyond SM

• Theoretical considerations suggest new physics:
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  • Cosmological constant problem
  • Origin of CP violation and Baryon Asymmetry of Universe (BAU)
  • Flavor problem and GUT’s

• Experimental evidence demands physics beyond the SM:
  • Terrestrial: neutrino oscillation phenomena
  • Celestial: dark matter (DM) and dark energy (DE)
Neutrino Mass Data

• Cosmic and astronomical observations: $\Sigma m_\nu \leq 1 \text{ eV}$. Seljak 2004

• Solar and atmospheric neutrino experiments give:
  \[
  \Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{eV}^2, \quad |\Delta m_{31}^2| \simeq 2.5 \times 10^{-3} \text{eV}^2, \\
  \sin^2 2\theta_{12} \simeq 0.8, \quad \sin^2 \theta_{23} = 0.5, \quad \sin^2 2\theta_{13} \simeq 0, 
  \]
  Maltoni, Schwetz, Tortola, Valle 2004

• Normal hierarchy (NH): $\Delta m_{31}^2 > 0 \Rightarrow m_3 > m_2 > m_1$.

• Inverted hierarchy (IH): $\Delta m_{31}^2 < 0 \Rightarrow m_2 > m_1 > m_3$. 
Masses of most particles in SM are given through the VEV of the Higgs boson:

- EW gauge bosons: Higgs mechanism
- Quarks and charged leptons: Yukawa couplings with Higgs boson
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What is the mechanism responsible for neutrino masses?
- Same as others ⇒ Yukawa couplings $\leq 10^{-11}$ ⇒ fine-tuning
- Explore possibilities beyond SM
**Seesaw Mechanism**

- SM neutrinos are naturally much lighter than their charged partners and of *Majorana* nature.

- Achieve seesaw while:
  - keeping the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$.
  - adding at most one type of new particles to the spectrum.

Minkowski 1977; Gell-Mann, Ramond, Slansky 1979; Yanagida 1979; Glashow 1980; Mohapatra, Senjanovic 1980
Introduce a triplet Higgs field $\Delta (1,3,2)$:

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

with gauge invariant potential ($m^2 < 0$, $M_{\Delta}^2 > 0$ and $\mu > 0$):

$$\mathcal{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - m^2 (\Phi^\dagger \Phi) - \lambda (\Phi^\dagger \Phi)^2 + \text{Tr}(D_\mu \Delta)^\dagger (D^\mu \Delta) - M_{\Delta}^2 \text{Tr}(\Delta^\dagger \Delta) - \frac{\mu}{\sqrt{2}} (\Phi^T i\sigma_2 \Delta^\dagger \Phi)$$

$$-\lambda_1 (\Phi^\dagger \Phi) \text{Tr}\Delta^\dagger \Delta + \lambda_2 (\text{Tr}\Delta^\dagger \Delta)^2 + \lambda_3 \text{Tr}(\Delta^\dagger \Delta)^2 + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi$$

$$-h_{ij} \psi_i^T L C i\sigma_2 \Delta \psi_j L + \text{h.c.}$$

Triplet VEV and Majorana neutrino mass

$$\langle \delta^0 \rangle = \frac{v\Delta}{\sqrt{2}} , \quad v\Delta = \frac{\mu v_0^2}{\sqrt{2}M_{\Delta}^2} , \quad M_\nu = \sqrt{2}h v\Delta$$

Konetschny, Kummer 1977; Schechter, Valle 1980; Cheng, Li 1980; Gelmini, Roncadelli 1981
The HTM has 7 Higgs bosons: $H^{±±}$, $H^±$, $H^0$, $A^0$, and $h^0$.

$H^{±±}$ is purely triplet $δ^{±±}$, a very unique feature.

Higgs boson masses as a function of the $μ$ parameter.

( e.g., $ν_Δ = 1$ GeV, $λ = 0.566$, $λ_1 = 0$, $λ_{2,3} = 1$, $λ_4 = 0, -1$ )
Constraints on $v_{\Delta}$

• Based on realistic neutrino masses, perturbation is allowed for $v_{\Delta} \geq 1$ eV.

• Non-zero Higgs triplet VEV leads to

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} \neq 1$$

Current $\rho^{\exp} \approx 1.0004^{+0.0008}_{-0.0004}$ requires that $v_{\Delta} \leq$ a few GeV.

PDG 2008; Abada et al 2007
• Both $H^{±±}$ and $H^±$ can decay dominantly into leptonic final states, more desirable at hadron colliders.

• Concentrate on small $v_\Delta$ scheme ($< 10^{-4}$ GeV) and assume $M_{H^{±±}} = M_{H^±}$ for simplicity.
Searches at Tevatron

• Smoking gun of the model: production of doubly-charged Higgs boson that then decays into like-sign lepton pairs.
• CDF and D0 at Tevatron started first searches in 2003.
• In the searches, D0 has assumed
  • $q\bar{q} \rightarrow \gamma^*/Z \rightarrow H^{++} H^{--}$ is the only significant production channel
  • $H^{\pm\pm}$ decays into like-sign muon pairs at 100% rate.
• Left panel: look for two same-sign $\mu^+\mu^-$.
• Left panel: look for two same-sign $\mu^+\mu^+$.
• Right panel: look for two same-sign $\mu^+\mu^+$ and one $\mu^\mp$.

Results

2.6$\sigma$ excess at 150 GeV?

Open histogram expected for $m_{H^{\pm\pm}} = 140$ GeV

D0 2008
D0 concludes that $m_{H^{±±}} \geq 150$ GeV, based on

$p\bar{p} \rightarrow H^{++} (\rightarrow \mu^+ \mu^+) H^{--} (\rightarrow \mu^- \mu^-)$

D0 2008
• D0 concludes that $m_{H^{±±}} \geq 150$ GeV, based on

$$pp \rightarrow H^{++}(\rightarrow \mu^+ \mu^+)H^{--}(\rightarrow \mu^- \mu^-)$$

• However, they have overlooked:
  (A) one important mechanism, and (B) other final states.
**H^{±±} Production**

- $\sigma_{H^{±±}H^{±±}}$ is a function of $m_{H^{±±}}$ and independent of $h_{ij}$.
  
  *Barger et al 1982; Gunion et al 1989; Huitu et al 1997*

- $\sigma_{H^{±±}H^±}$ is a function of $m_{H^{±±}}$ and $m_{H^±}$.
  
  *Gunion 1998, Dion et. al 1999*

- If $m_{H^{±±}} \sim m_{H^±}$, then $\sigma_{H^{±±}H^±}$ and $\sigma_{H^{++}H^{--}}$ are about same order of magnitude
  
  $\Rightarrow$ equally important!

$$ (\partial^\mu H^{--}) H^{++} (gW_{3\mu} + g' B_\mu) + \text{h.c.} $$

$$ ig \left[ (\partial^\mu H^{++}) H^- - (\partial^\mu H^{--}) H^+ \right] W^\mu + \text{h.c.} $$
\( M_{H^{\pm \pm}} = M_{H^{\pm}} \) and \( K = 1.25 \) (LHC) or 1.3 (Tevatron)
• $M_{H^{±±}} = M_{H^{±}}$ and $K = 1.25$ (LHC) or 1.3 (Tevatron)

\[
R \equiv \frac{\sigma(p\bar{p}, pp \rightarrow H^{++}H^-) + \sigma(p\bar{p}, pp \rightarrow H^{--}H^+)}{\sigma(p\bar{p}, pp \rightarrow H^{++}H^-)}
\]
**Multi-Lepton Channels**

- 4-lepton final states are clear channels from pair production of doubly-charged Higgs boson.
- 3-lepton final states with two same-signs and the other opposite-sign have a higher production rate and are best for discovery.

> del Aguila, Aguilar-Saavedra 2009

- Consider only light charged leptons ($\ell = e, \mu$), because $\tau$ is more difficult to identify as it often decays hadronically.
- D0 has only looked for $\mu^+ \mu^+ \mu^-$, whereas there are totally six light 3-lepton channels:

$$e^\pm e^\pm e^\mp, e^\pm e^\pm \mu^\pm, e^\pm \mu^\pm e^\mp, e^\pm \mu^\pm \mu^\mp, \mu^\pm \mu^\pm e^\mp, \text{ and } \mu^\pm \mu^\pm \mu^\mp$$
Tri-Lepton Cross Section

- Define reduced (normalized) cross section through
  \[ \sigma_{\ell\ell\ell} = \hat{\sigma}_{\ell\ell\ell} \times \sigma(pp \rightarrow H^{++}H^{--}) \]

- Reduced cross sections of the six channels are (for LHC):
  \[
  \begin{align*}
  \hat{\sigma}_{\ell\ell\ell} &= B_{ee} [B_{ee} + 2(B_{e\mu} + B_{e\tau}) + 1.8B_{e\nu}] , \\
  \hat{\sigma}_{ee\mu} &= B_{ee} [2(B_{\mu\mu} + B_{e\mu} + B_{\mu\tau}) + 1.8B_{\mu\nu}] , \\
  \hat{\sigma}_{e\mu\ell} &= B_{e\mu} [B_{e\mu} + 2(B_{ee} + B_{e\tau}) + 1.8B_{e\nu}] , \\
  \hat{\sigma}_{e\mu\mu} &= B_{e\mu} [B_{e\mu} + 2(B_{e\mu} + B_{e\nu}) + 1.8B_{e\nu}] , \\
  \hat{\sigma}_{\mu\ell\ell} &= B_{\mu\mu} [2(B_{ee} + B_{e\mu} + B_{e\tau}) + 1.8B_{e\nu}] , \\
  \hat{\sigma}_{\mu\mu\mu} &= B_{\mu\mu} [B_{\mu\mu} + 2(B_{e\mu} + B_{\mu\tau}) + 1.8B_{\mu\nu}]
  \end{align*}
  \]

- Additional contribution to these processes than CDF and D0 considerations, 1.2 for Tevatron

- First two of same sign and last one of opposite sign
With or without the single production at LHC, assuming zero Majorana phases and NH:
• Reduced cross section as a function of lightest neutrino mass at LHC, assuming zero Majorana phases:

RESULTS

![Graphs showing reduced cross section as a function of lightest neutrino mass for normal and inverted hierarchies.](image)
Effects of Majorana Phases

- Reduced cross sections for $m_0 = 0.2$ eV.
Expected number of tri-lepton events being produced at hadron colliders for different masses of doubly-charged Higgs boson under certain integrated luminosities:

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>$m_{H^{\pm\pm}}$ (GeV)</th>
<th>$\sigma_{\ell\ell\ell}$ (fb)</th>
<th>$N_{\ell\ell\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>10</td>
<td>150</td>
<td>$\sim 20$</td>
<td>$\sim 200$</td>
</tr>
<tr>
<td>LHC</td>
<td>10</td>
<td>150</td>
<td>$\sim 200$</td>
<td>$\sim 2000$</td>
</tr>
<tr>
<td>LHC</td>
<td>10</td>
<td>250</td>
<td>$\sim 30$</td>
<td>$\sim 3000$</td>
</tr>
</tbody>
</table>
**Number of Events**

- Expected number of tri-lepton events being produced at hadron colliders for different masses of doubly-charged Higgs boson under certain integrated luminosities:

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<th>$N_{\ell\ell\ell}$</th>
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<tr>
<td>Tevatron</td>
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<td>150</td>
<td>$\sim$ 20</td>
<td>$\sim$ 200</td>
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<td>10</td>
<td>150</td>
<td>$\sim$ 200</td>
<td>$\sim$ 2000</td>
</tr>
<tr>
<td>LHC</td>
<td>100</td>
<td>250</td>
<td>$\sim$ 30</td>
<td>$\sim$ 3000</td>
</tr>
</tbody>
</table>

- What are the prospects after imposing cuts and comparing to backgrounds?
A search for 3 leptons and more (≥3 leptons) will improve the discovery prospects and have more sensitivity to the doubly-charged Higgs boson.

- Impose universal cuts, include detection efficiency, and compare with the 4-lepton search.
Event Generation

- Implement model in CalcHEP to generate signal events.
- Pass results to Pythia via the LHE interface.
- Include ISR/FSR in Pythia.
- Generate background events in Pythia.
- Use ATLFAST for simple detector simulations (jet construction, particle ID, etc).
**Pre-Selection Cuts**

- Exactly four leptons with two for each charge sign (for $4\ell$); 3 or more leptons of different signs (for $\geq 3\ell$).
- Each lepton has $|p_T| > 5$ GeV and $|\eta| < 2.5$.
- At least two of the leptons have $|p_T| > 30$ GeV.
- Opposite-sign dilepton invariant mass $> 20$ GeV.
After imposing pre-selection cuts for CM energy = 14 TeV and $L = 10 \text{ fb}^{-1}$. 
Opposite-sign (left) and same-sign (right) dilepton invariant mass distributions.
4-Lepton Signature

- Only pair production mechanism contributes to this.
- For definiteness, take $BR(H^{±±} \rightarrow ℓ^{±} ℓ^{±}) = BR(H^{±} \rightarrow ℓ^{±} ν) = 100\%$
- $H_T = \text{total transverse energy of leptons, including missing } E_T \text{ from neutrinos.}$

<table>
<thead>
<tr>
<th>Cut</th>
<th>Backgrounds</th>
<th>Signal ($M_{H^{±±}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$WZ$</td>
<td>$ZZ$</td>
</tr>
<tr>
<td>Pre-selection</td>
<td>0.2</td>
<td>130.5</td>
</tr>
<tr>
<td>$</td>
<td>m_{ℓ^+ℓ^-} - m_Z</td>
<td>&gt; 10 \text{ GeV}$</td>
</tr>
<tr>
<td>$H_T &gt; 300 \text{ GeV}$</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>$H_T &gt; 500 \text{ GeV}$</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>$S$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Background and signal events surviving the cuts for exactly 4-lepton final states. For these numbers we have taken $ℓ = 10 \text{ fb}^{-1}$ and $\sqrt{s} = 14 \text{ TeV}$. 
≥3-Leptons Signature

• Both production mechanisms contribute.
• Same assumptions and cuts imposed.
• Increased significance

\[ S = \sqrt{2 \left[ (s + b) \log \left( 1 + \frac{s}{b} \right) - s \right]} \]

<table>
<thead>
<tr>
<th>Cuts ↓</th>
<th>WZ</th>
<th>WWW</th>
<th>ZZ</th>
<th>tt</th>
<th>Zbb</th>
<th>Ztt</th>
<th>Wtt</th>
<th>Signal ( (M_{H^{\pm \pm}}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-selection</td>
<td>591.7</td>
<td>3.5</td>
<td>203.6</td>
<td>159.9</td>
<td>57.7</td>
<td>212.5</td>
<td>9.7</td>
<td>1570.4</td>
</tr>
<tr>
<td>(</td>
<td>m_\ell^+ \ell^- - m_Z</td>
<td>&gt; 10 \text{ GeV}</td>
<td>50.9</td>
<td>2.7</td>
<td>12.1</td>
<td>113.2</td>
<td>0.9</td>
<td>33.4</td>
</tr>
<tr>
<td>( H_T &gt; 300 \text{ GeV}</td>
<td>7.5</td>
<td>1.1</td>
<td>1.6</td>
<td>8.9</td>
<td>0</td>
<td>17</td>
<td>3.4</td>
<td>1351.1</td>
</tr>
<tr>
<td>( H_T &gt; 500 \text{ GeV}</td>
<td>1.7</td>
<td>0.3</td>
<td>0.4</td>
<td>0.9</td>
<td>0</td>
<td>3.2</td>
<td>0.6</td>
<td>796.2</td>
</tr>
<tr>
<td>( S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>77.4</td>
</tr>
</tbody>
</table>

Table 5. Background and Signal events surviving the cuts for at least 3 leptons in the final state. We have taken \( \mathcal{L} = 10 \text{ fb}^{-1} \) and \( \sqrt{s} = 14 \text{ TeV} \).
Discovery potential for $H^{±±}$ at the LHC through the $\geq 3\ell$ mode is better than the $4\ell$ mode.
SUMMARY

• HTM is motivated by neutrino masses and involves only a few model parameters in the Higgs sector, rendering the model relatively predictive and interesting at LHC.

• Distinctive features of the model:
  • doubly-charged Higgs boson;
  • possibly dominant like-sign dilepton decays;
  • possible lepton flavor violating processes.

• We include an important production channel for $H^{±±}$ that has been ignored by the experimentalists at Tevatron.

• We propose the $\geq 3 \ell$ signature for the search of $H^{±±}$, and have performed detailed simulations for LHC.