Abstract:
Ongoing searches for doubly charged Higgs bosons ($H^{\pm\pm}$) at the Tevatron assume that $H^{\pm\pm}$ are produced in pairs via $q\bar{q} \rightarrow H^{++}H^{--}$. We show that single $H^{\pm\pm}$ production via $q\bar{q} \rightarrow H^{\pm\pm}H^{\mp}$ can be comparable in size and consider its impact on present and future searches at Hadron Colliders.

• **Imminent start of Large Hadron Collider (LHC)**

• **Neutrino mass and mixing**

• **TeV scale mechanisms for neutrino mass generation**

• **Higgs Triplet Model** and **Left-Right Symmetric Model**

• **$H_{L}^{±±}$$** phenomenology at hadron colliders
Large Hadron Collider (LHC) due to commence operation in summer 2007

- Proton-Proton collisions at $\sqrt{s} = 14$ TeV
- Highest energy collider ever built
- ATLAS and CMS optimized for Higgs boson search
- New Physics discovery potential up to TeV scale
Strong evidence for neutrino masses and mixings from both terrestrial and celestial sources

Mixing angles are being probed by oscillation experiments:

i) Atmospheric angle almost maximal: $\sin^2 \theta_{23} \sim 1$

ii) Solar angle close to maximal: $\sin^2 \theta_{12} \sim 0.8$

iii) Reactor angle not measured: $\sin^2 \theta_{13} < 0.16$

$\theta_{23}$ and $\theta_{12}$ much larger than mixing angles in the quark sector
Oscillation experiments also sensitive to neutrino mass differences:

i) $\Delta M_{atm}^2 \sim 10^{-3} eV^2 (= M)$

ii) $\Delta M_{sol}^2 \sim 10^{-5} eV^2 (= m)$

Much lighter than other fermion masses ($m_e = 0.5$ MeV)

Three possibilities:

1) Hierarchical $\sim (0, m, M)$.

2) Inverted hierarchical $\sim (M, M + m, 0)$

3) Quasi-degenerate $\sim (M, M, M)$
Future measurements of Neutrino parameters

Present and Future neutrino experiments (e.g. T2K, MINOS, OPERA)

i) Measure $\Delta m^2$, $\theta_{12}$, $\theta_{23}$ with higher precision

ii) Possible first measurement of $\theta_{13}$, CP Phase

Mechanism of mass and mixing?

Models which can be probed at the Tevatron/LHC are of immediate phenomenological interest
Many models for neutrino mass generation!

Models with a specific signature at High Energy Colliders (Tevatron/LHC) are phenomenologically appealing

$H_L^{\pm\pm}$ with coupling to $W, Z$ and leptons

Two such models are:

i) Higgs Triplet Model (HTM) \cite{Gelmini/Roncadelli 80}

ii) Left-Right Symmetric Model (LR Model) \cite{Mohapatra/Senjanovic 80}
SM Lagrangian with one $SU(2)_L \ I = 1, \ Y = 2$ Higgs triplet

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

Higgs potential:

$$V = m^2(\Phi^\dagger\Phi) + \lambda_1(\Phi^\dagger\Phi)^2 + M^2 \text{Tr}(\Delta^\dagger\Delta)$$

$$+ \lambda_i \text{ (quartic terms)} + \frac{1}{\sqrt{2}} \mu(\Phi^T i\tau_2 \Delta^\dagger\Phi) + h.c$$

Triplet vacuum expectation value:

$$< H^0 > = v_L \sim \mu/M \ (1\text{eV} < v_L < 8\text{GeV})$$
Higgs boson spectrum

The HTM has 7 Higgs bosons:

\[ H^{\pm\pm}, H^\pm, H^0, A^0, h^0 \]

In general \( H^\pm, H^0, A^0 \) eigenstates are mixtures of doublet and triplet fields.

However, mixing \( \sim v_L/v \) and \( v_L << v \):

i) \( h^0 \) is *SM Higgs boson* (essentially \( I = 1/2 \) doublet)

ii) \( H^{\pm\pm} \) *purely triplet* and \( H^\pm, H^0, A^0 \) essentially *triplet*
Higgs boson masses

Close to degenerate with splittings caused by $\lambda_5$

$$m_{H^{\pm \pm}}^2 \approx M^2 + 2\frac{(\lambda_4 - \lambda_5)}{g^2} M_W^2$$

$$m_{H^\pm}^2 \approx m_{H^{\pm \pm}}^2 + 2\frac{\lambda_5}{g^2} M_W^2 \quad m_{H^0, A^0}^2 \approx m_{H^\pm}^2 + 2\frac{\lambda_5}{g^2} M_W^2$$

For $\lambda_5 > 0$ ($\lambda_5 < 0$):

$$m_{H^{\pm \pm}} < m_{H^\pm} < m_{H^0, A^0} \quad (m_{H^{\pm \pm}} > m_{H^\pm} > m_{H^0, A^0})$$

For $H^{\pm \pm}$ in range at LHC require $M < 1$ TeV.
Neutrino mass in Higgs Triplet Model (HTM)

No right handed neutrino:

Neutrino mass from triplet-lepton-lepton coupling ($h_{ij}$):

$$h_{ij} \left[ \sqrt{2} \bar{l}_i^c P_L l_j H_L^{++} + (\bar{l}_i^c P_L \nu_j + \bar{l}_j^c P_L \nu_i) H_L^+ - \sqrt{2} \bar{\nu}_i^c P_L \nu_j H_L^0 \right]$$

Light neutrinos receive a Majorana mass:

$$\mathcal{M}_\nu \sim v_L h_{ij}$$

$$h_{ij} = \frac{1}{\sqrt{2} v_L} V_{\text{MNS}} \text{diag}(m_1, m_2, m_3) V_{\text{MNS}}^T$$
Left-Right Symmetric Model can provide low-energy seesaw mechanism

Main differences with SM:

i) Introduce new gauge group $SU(2)_R$

ii) Right Handed fermions in doublets $(u_R, d_R), (\nu_R, l_R)$

iii) Existence of $\nu_R$ is required by gauge symmetry

iv) New (heavy) gauge bosons $W^\pm_R, Z_R$

v) Extended Higgs sector for symmetry breaking

$SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L} \rightarrow SU(2)_L \otimes U(1)_Y \rightarrow U(1)_Q$
1) Arbitrary hypercharge $Y$ has been replaced by theoretically attractive $B - L$

2) Parity conservation of weak interactions i.e. $\psi_L \rightarrow \psi_R$ symmetry restored at energies $> v_R$ and broken spontaneously

3) Low energy seesaw mechanism for neutrino mass can be implemented with appropriate choice of Higgs representations (Isospin $I=1$ Triplets) Mohapatra/Senjanovic 80

4) New particles (Higgs bosons, heavy RH neutrinos, gauge bosons) at $v_R$ scale possibly accessible to LHC
Higgs boson content

**bidoublet**: \( \phi = \begin{pmatrix} \phi_1^0 \\ \phi_1^- \\ \phi_2^- \\ \phi_2^0 \end{pmatrix} : \langle \phi_1^0 \rangle = \kappa_1, \langle \phi_2^0 \rangle = \kappa_2 \)

\[ \kappa_1^2 + \kappa_2^2 = \kappa^2 = 246^2 \text{GeV}^2 \]

**triplets**: \( \Delta_{L,R} = \begin{pmatrix} H_{L,R}^+ / \sqrt{2} & H_{L,R}^{++} \\ \sqrt{2} H_{L,R}^0 & -H_{L,R}^+ / \sqrt{2} \end{pmatrix} \)

\[ \langle H_{L,R}^0 \rangle = \nu_{L,R} \]

20 d.o.f give 14 physical scalars (6 neutral, 4 charged, 4 doubly charged) and 6 goldstone bosons
Neutrino mass in LR Symmetric Model

Right handed neutrino required by \( SU(2)_L \otimes SU(2)_R \otimes U(1) \)

Majorana neutrino mass obtained via seesaw mechanism:

\[
M_\nu = \begin{pmatrix} h_L v_L & M_D \\ M_D^T & h_R v_R \end{pmatrix}, \quad M_D = \frac{1}{\sqrt{2}}(h_l \kappa_1 + \tilde{h}_l \kappa_2)
\]

If \( h_L = h_R = h = \mathcal{O}(1), v_R = 1 \text{ TeV}, v_L = 0, M_D \sim \text{MeV} \)

\[
M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix},
\]

\( \rightarrow \) obtain neutrino mass \( (M_D^2/M_R) \) of eV scale
Summary

- **HTM**: Majorana mass for light neutrinos $\nu_L$ (No $\nu_R$).
- **LR symmetric model**: Majorana mass for $\nu_L$ via seesaw mechanism ($\nu_R$ needed)
- Both models can have $H_L^{\pm \pm}$ with mass $< 1$ TeV.

Phenomenology of $H_L^{\pm \pm}$ at Hadron Colliders
Summary of $H^{\pm\pm}$ searches

Searches at LEP, HERA, Tevatron:

![Graph showing exclusions and couplings for $H^{\pm\pm}$](image_url)
Production of $H_L^{\pm\pm}$ at Tevatron

First searches at a Hadron collider in 2003

CDF, D0

- $\sigma_{H^{++}H^{--}}$ is a simple function of $M_{H^{\pm\pm}}$
- $\sigma_{H^{++}H^{--}}$ has no dependence on $h_{ij}$
- $H^{\pm\pm}$ decays via $h_{ij}$ to same charge $ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$
Search strategy

Many possible searches!

From pair produced $H^{++}H^{--}$ one can select:

2 leptons ($2l$), 3 leptons ($3l$), and 4 leptons ($4l$)

Signal yield $S_{2l} > S_{3l} > S_{4l}$, Background $B_{2l} > B_{3l} > B_{4l}$

For discovery want to maximize $S/B$

Current status of Tevatron searches:

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<th>$\mu\mu$</th>
<th>$e\tau$</th>
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<td>&lt; 113 GeV</td>
<td>&lt; 136 GeV</td>
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<td>$4l$</td>
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<td>&lt; 114 GeV</td>
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Tevatron search for $p\bar{p} \rightarrow H^{++} H^{--}, H^{\pm\pm} \rightarrow e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$

Mass limits assume $\text{BR}(H^{\pm\pm} \rightarrow l_i^\pm l_j^\pm) = 100\%$ in a given channel.

Strongest mass limits for any Higgs boson! CDF 03
Tevatron search for $p\bar{p} \rightarrow H^{++} H^{--}$, $H^{\pm\pm} \rightarrow e^{\pm}\tau^{\mp}, \mu^{\pm}\tau^{\mp}$

$3l$ and $4l$ searches give essentially same mass limit

CDF 06
Any additional production mechanisms for $H^{\pm\pm}$?

For $H_{L}^{\pm\pm}$ one can exploit the vertex $W^{\pm}H_{L}^{\pm\pm}H_{L}^{\mp}$

Dion 98, Gunion 98

- Not possible at $e^{+}e^{-}$ colliders
- $H_{L}^{\pm} \to l^{\pm}\nu$ decay expected
Impact of $H_L^\pm \pm H_L^\mp$

Current searches are already sensitive to $qq' \rightarrow H_L^\pm \pm H_L^\mp$!

- **2l search:** *sensitive* to $H_L^\pm \pm H_L^\mp$ irrespective of $H_L^\pm$ decay
- **3l search:** *sensitive* to $H_L^\pm \pm H_L^\mp$ if $H_L^\pm \rightarrow l^\pm \nu$
- **4l search:** *insensitive* to $H_L^\pm \pm H_L^\mp$

Define inclusive single $H_L^\pm \pm$ cross-section for 2l,3l search:

$$\sigma_{H^\pm \pm} = \sigma(p\bar{p} \rightarrow H_L^++H_L^-) + \sigma(p\bar{p} \rightarrow H_L^\pm \pm H_L^\mp)$$

Akeroyd, Aoki 05
Inclusive single $H_L^{\pm\pm}$ production at Tevatron

$$\sigma_{H^{\pm\pm}} = \sigma(p\bar{p} \rightarrow H_L^{++} H_L^{--}) + 2\sigma(p\bar{p} \rightarrow H_L^{++} H_L^{--})$$

Increases search potential of Tevatron in $2l,3l$ channels  

Akeroyd,Aoki 05
Inclusive single $H_{L}^{±±}$ production at LHC

Discovery up to $M_{H^{±±}} < 1$ TeV for luminosity $=300$ fb$^{-1}$

Precision studies possible if light $M_{H^{±±}} (< 250$ GeV) found at Tevatron
Decay branching ratios of $H^{\pm\pm}$

Mass limits assume $\text{BR}(H^{\pm\pm} \rightarrow l_i l_j) = 100\%$ for specific $i, j$

Actual $\text{BR}(H^{\pm\pm} \rightarrow l_i l_j)$ depends on relative values of $h_{ij}$

LR Model: $h_{ij}$ arbitrary. No prediction for BRs

HTM: $h_{ij}$ directly related to neutrino mass matrix

$$h_{ij} = \frac{1}{\sqrt{2}v_L} V_{\text{MNS}} \text{diag}(m_1, m_2, m_3) V_{\text{MNS}}^T$$

Prediction for $\text{BR}(H^{\pm\pm} \rightarrow l_i l_j)$ depends on which neutrino mass hierarchy is realized!
Inclusive single $\sigma(p\bar{p} \rightarrow H_L^{\pm\pm} + X \rightarrow e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm)$

Normal neutrino mass hierarchy: $\sigma_{\mu\mu} >> \sigma_{ee}, \sigma_{e\mu}$
Inclusive single $\sigma(p\bar{p} \to H_L^{\pm\pm} + X \to e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm)$

Inverted neutrino mass hierarchy: $\sigma_{ee} > \sigma_{\mu\mu} >> \sigma_{e\mu}$
Quasi-degenerate neutrinos: $\sigma_{\mu\mu} \sim \sigma_{ee} \gg \sigma_{e\mu}$
Summary of $H^{\pm\pm}$ discovery prospects at Hadron colliders

- Tevatron searches are ongoing:
  - $0.24 \text{ fb}^{-1}/0.35 \text{ fb}^{-1}$ used ($> 1 \text{ fb}^{-1}$ accumulated)
- Tevatron can discover $H^{\pm\pm}$ up to 250 GeV in $ee, e\mu, \mu\mu$ channels (smaller masses in $e\tau, e\mu, \tau\tau$)
- HTM gives predictions for $H^{\pm\pm} \rightarrow l_i l_j$ which are sensitive to the neutrino mass hierarchy
- LHC has i) discovery capability up to 1 TeV or ii) precision measurements of $H^{\pm\pm} \rightarrow l_i l_j$ if $H^{\pm\pm}$ discovered at Tevatron
Conclusions

- Higgs triplets can generate neutrino mass via triplet vev
- Arise in HTM and LR symmetric model
- $H_L^{\pm\pm} \rightarrow l^\pm l^\pm$ distinctive signal
- Produced at Hadron Colliders via $q\bar{q} \rightarrow H_L^{++}H_L^{--}$
- Inclusion of $qq' \rightarrow H_L^{\pm\pm}H_L^{\mp\mp}$ increases cross-section
- Tevatron have shown interest in including $qq' \rightarrow H_L^{\pm\pm}H_L^{\mp\mp}$ in future searches