Doubly Charged Higgs Bosons at Hadron Colliders

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Abstract:

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

A.A and Mayumi Aoki (KEK), Phys. Rev. D72 (2005) 035011

Seminar at National Tsing Hua Univeristy, 12 October 2006

Outline

- 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
- $H_L^{\pm\pm}$ phenomenology at hadron colliders

Large Hadron Collider

LHC (CERN) 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

Neutrino Mass and Mixing

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: $\sin^2\theta_{13} < 0.16$

θ_{23} and θ_{12} much larger than mixing angles in the quark sector

Neutrino Mass

Oscillation experiments also sensitive to neutrino mass differences:

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

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

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 Δm^2, θ_{12}, θ_{23} with higher precision

ii) Possible first measurement of θ_{13}, CP Phase

Mechanism of mass and mixing?

Models which can be probed at the Tevatron/LHC

are of *immediate phenomenological interest*

TeV scale models of neutrino mass generation

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) Gelmini/Roncadelli 80

ii) Left-Right Symmetric Model (LR Model) Mohapatra/Senjanov

Higgs Triplet Model (HTM)

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:

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

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

Triplet vacuum expectation value:

$$< H^0 >= v_L \sim \mu/M \quad (1eV < v_L < 8GeV)$$

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 λ_5

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

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

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

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

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:

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

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

Left-Right Symmetric Model

Left-Right Symmetric Model Pati/Salam 74

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), (ν_R, l_R)

iii) Existence of ν_R is required by gauge symmetry

iv) New (heavy) gauge bosons $W_R^{\pm}, Z_R$

v) Extended Higgs sector for symmetry breaking

$$SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L} \to SU(2)_L \otimes U(1)_Y \to U(1)_Q$$

Virtues of LR model?

1) Arbitrary hypercharge Y has been replaced by theoretically attractive $B-L$

2) Parity conservation of weak interactions i.e. $\psi_L \to \psi_R$ 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 $: \phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} : <\phi_1^0> = \kappa_1, <\phi_2^0> = \kappa_2$

$$\kappa_1^2 + \kappa_2^2 = \kappa^2 = 246^2 GeV^2$$

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

$$< H_{L,R}^0 > = v_{L,R}$$

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:

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

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

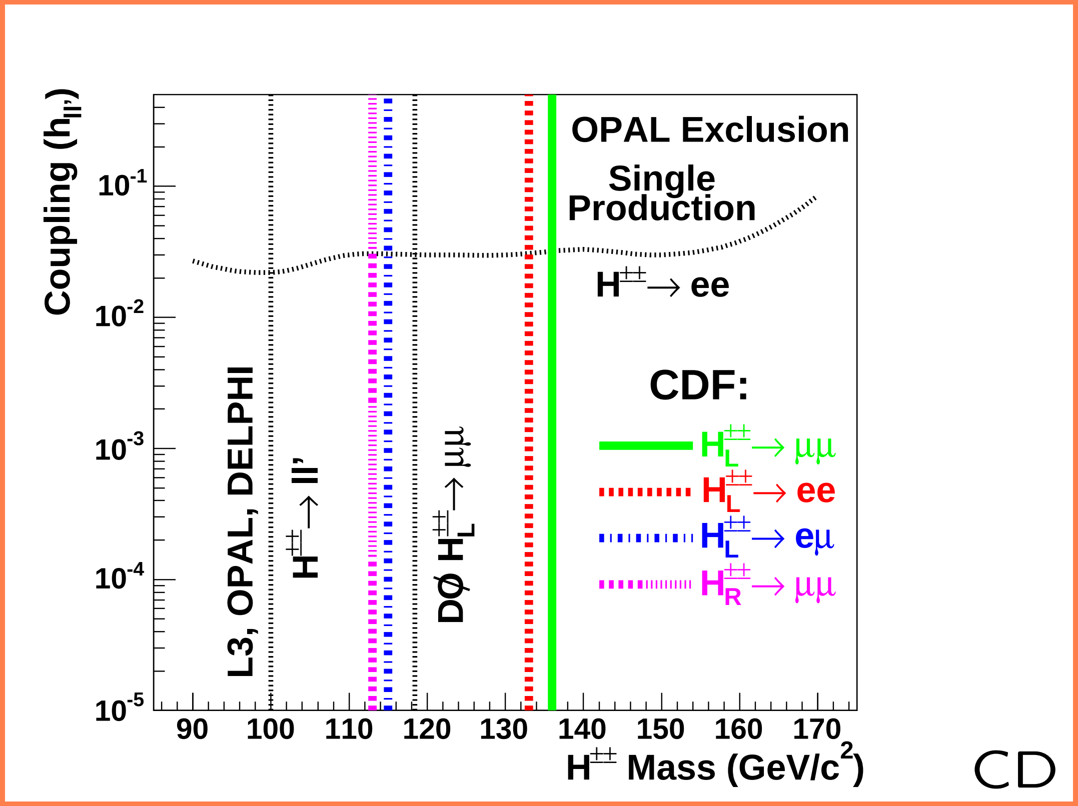
Summary

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

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

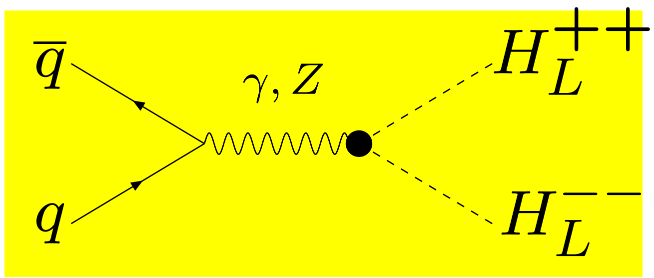
Summary of $H^{\pm\pm}$ searches

Searches at LEP, HERA, Tevatron:



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 $B_{2l} > B_{3l} > B_{4l}$

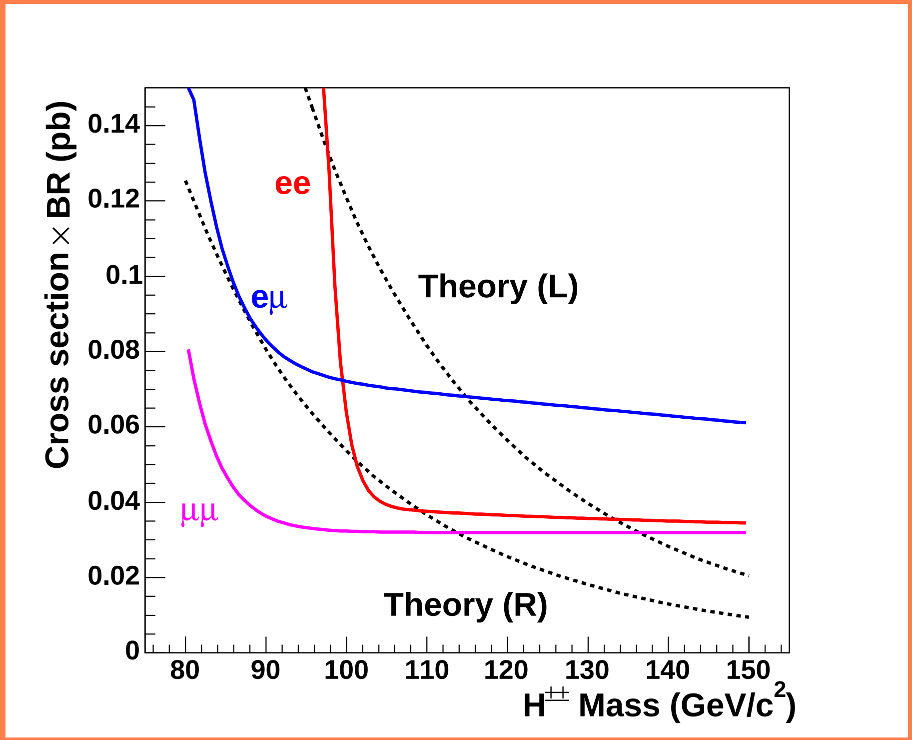
For discovery want to maximize S/B

Current status of Tevatron searches:

	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$
2l	< 133 GeV	< 113 GeV	< 136 GeV	x	x
3l				< 114 GeV	< 112 GeV
4l				< 114 GeV	< 112 GeV

Tevatron search for $p\overline{p} \rightarrow H^{++}H^{--}$, $H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$

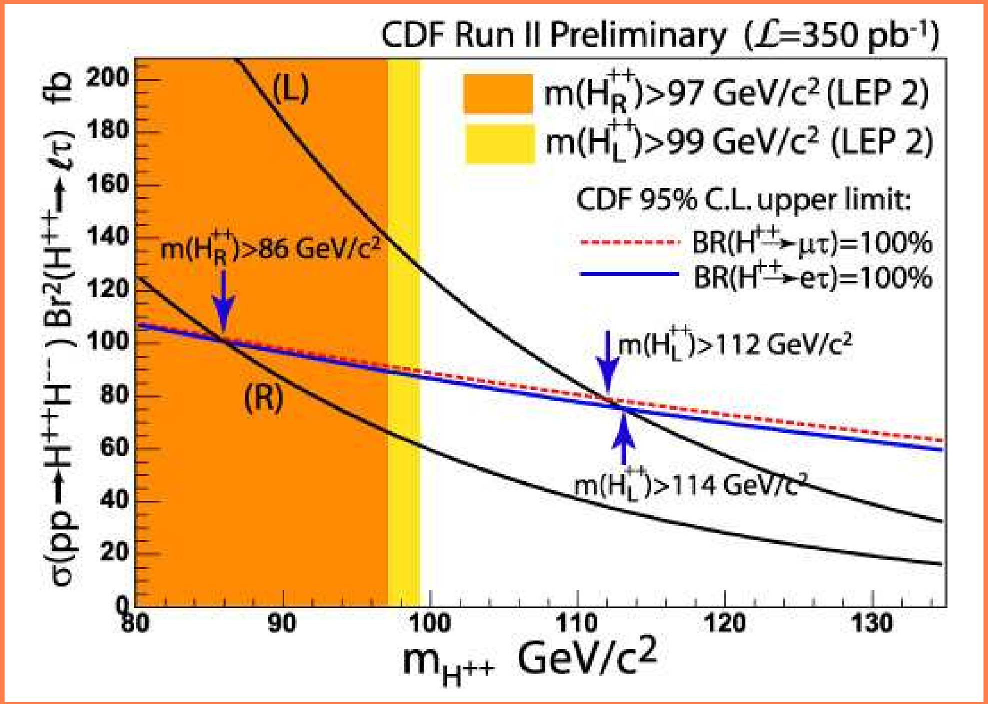
Mass limits assume BR$(H^{\pm\pm} \rightarrow l_i^{\pm} l_j^{\pm}) = 100\%$ in a given channel.



Strongest mass limits for any Higgs boson! CDF 03

Tevatron search for $p\bar{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to e^{\pm}\tau^{\pm}, \mu^{\pm}\tau^{\pm}$

$3l$ and $4l$ searches give essentially same mass limit CDF 06

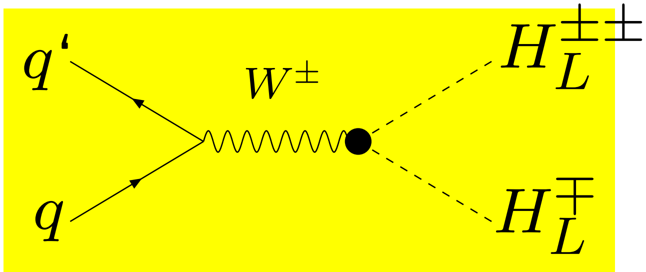


Single $H^{\pm\pm}$ production via $qq' \to H^{\pm\pm}H^{\mp}$

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 $qq' \to H_L^{\pm\pm} H_L^{\mp}$!

- $2l$ 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 $H_L^{\pm} \to l^{\pm}\nu$
- $4l$ search: *insensitive* to $H_L^{\pm\pm} H_L^{\mp}$

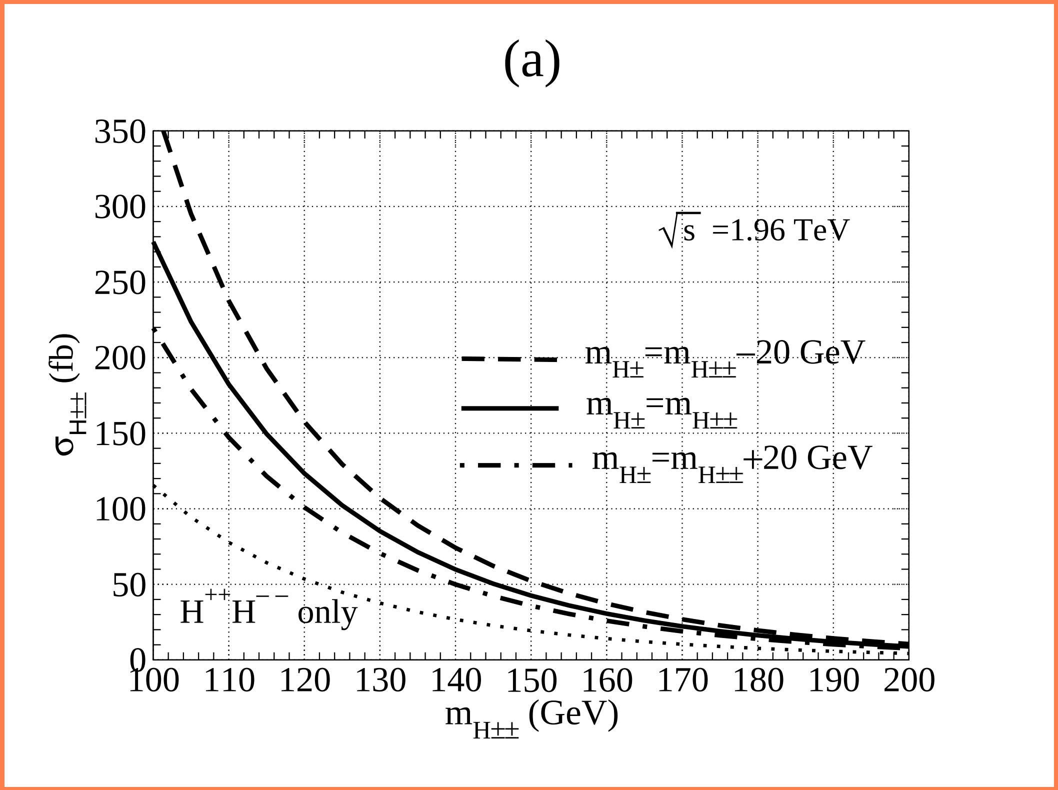
Define inclusive single $H_L^{\pm\pm}$ cross-section for $2l$,$3l$ search:

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

Akeroyd,Aoki 05

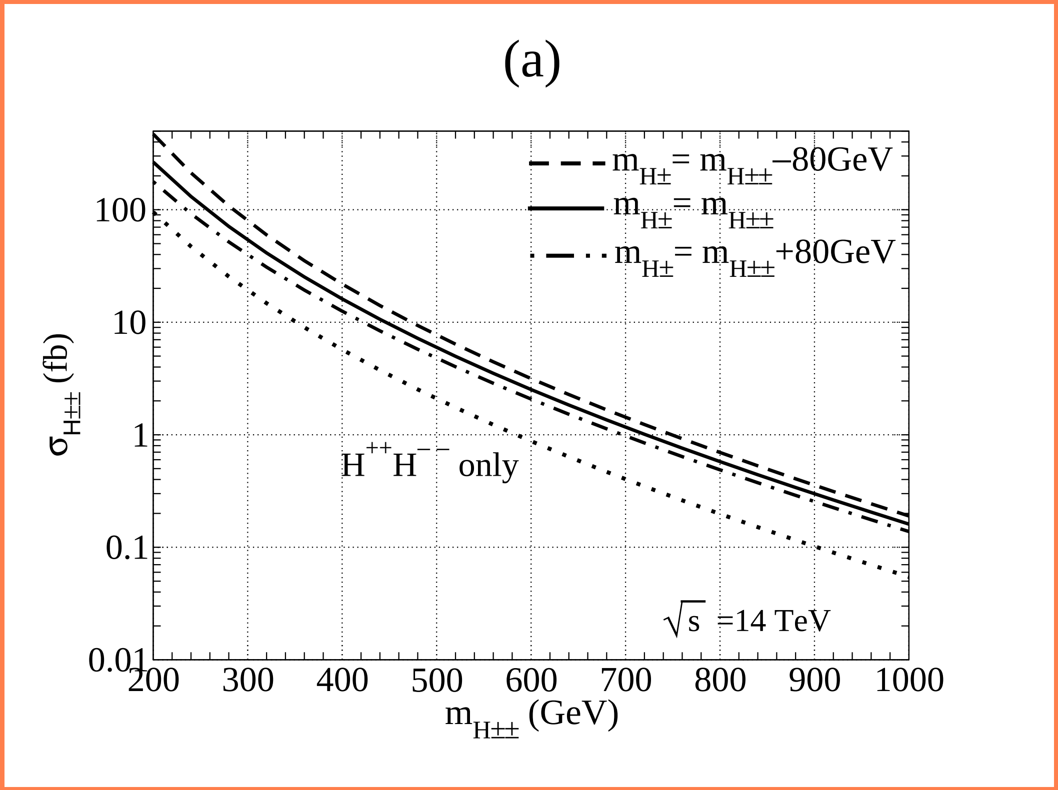
Inclusive single $H_L^{\pm\pm}$ production at Tevatron

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



Increases search potential of Tevatron in $2l$,$3l$ channels Akeroyd,Aoki 05

Inclusive single $H_L^{\pm\pm}$ production at LHC



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

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

Decay branching ratios of $H^{\pm\pm}$

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

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

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

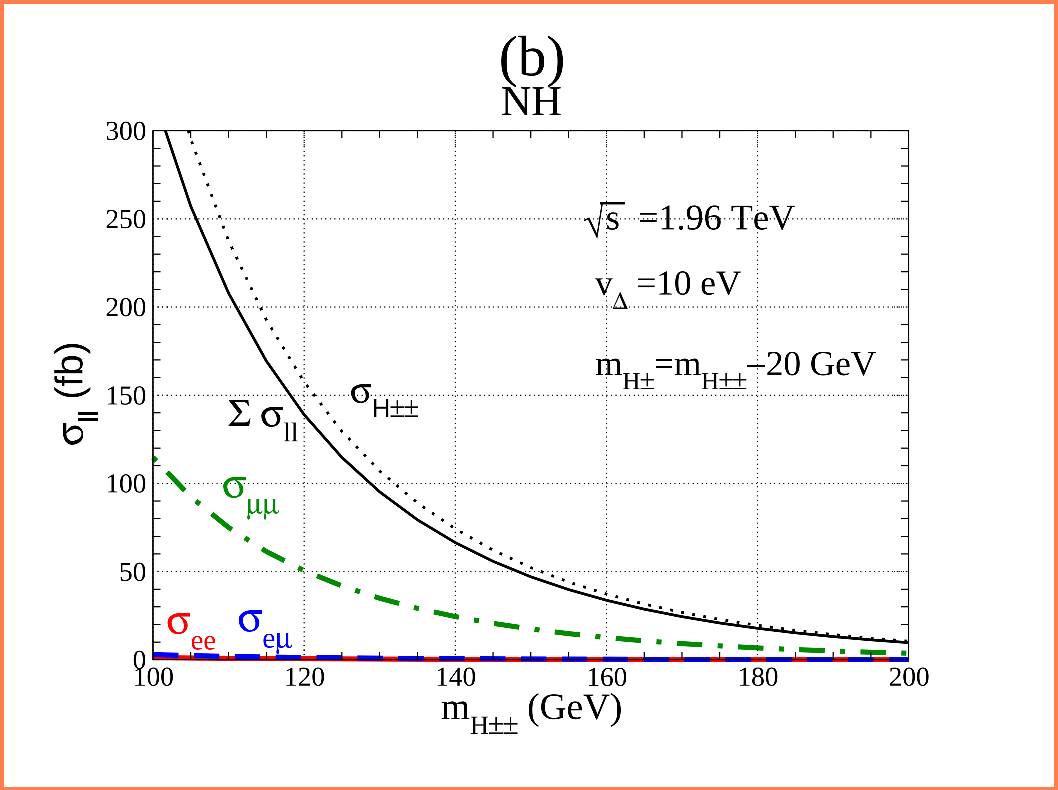
HTM: h_{ij} directly related to neutrino mass matrix

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

Prediction for BR($H^{\pm\pm} \to l_i l_j$) depends on which neutrino mass hierarchy is realized!

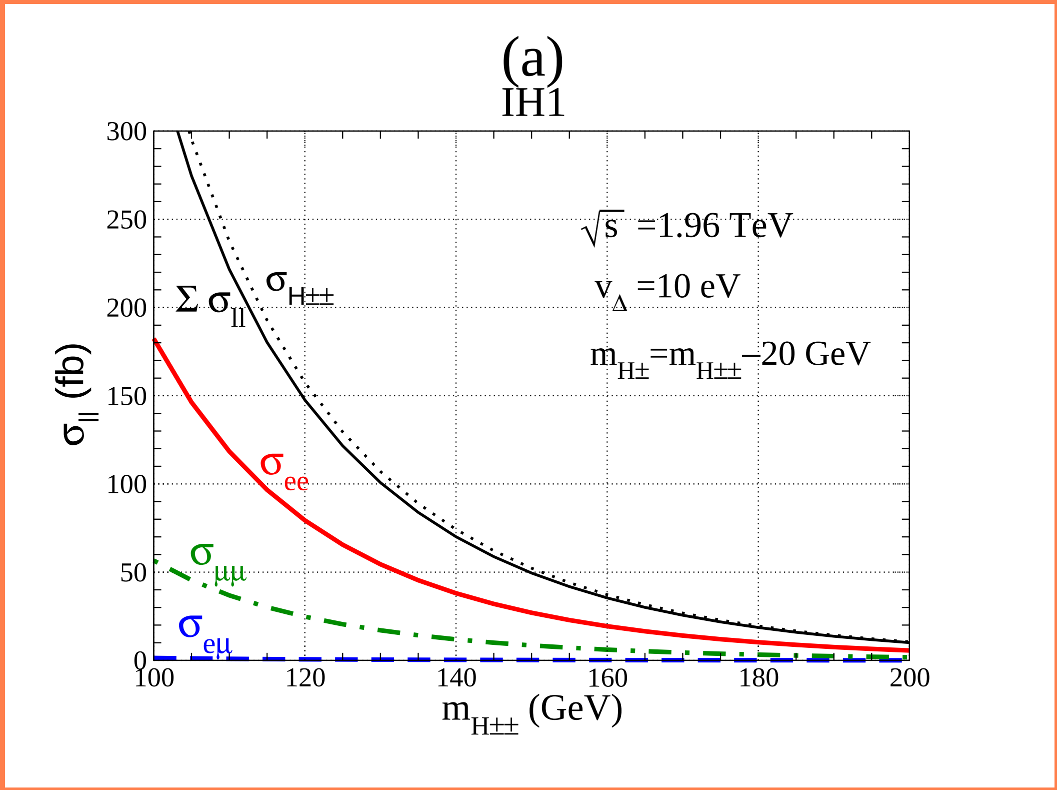
Inclusive single $\sigma(p\bar{p} \to H_L^{\pm\pm} + X \to e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm)$

Normal neutrino mass hierarchy: $\sigma_{\mu\mu} >> \sigma_{ee}, \sigma_{e\mu}$



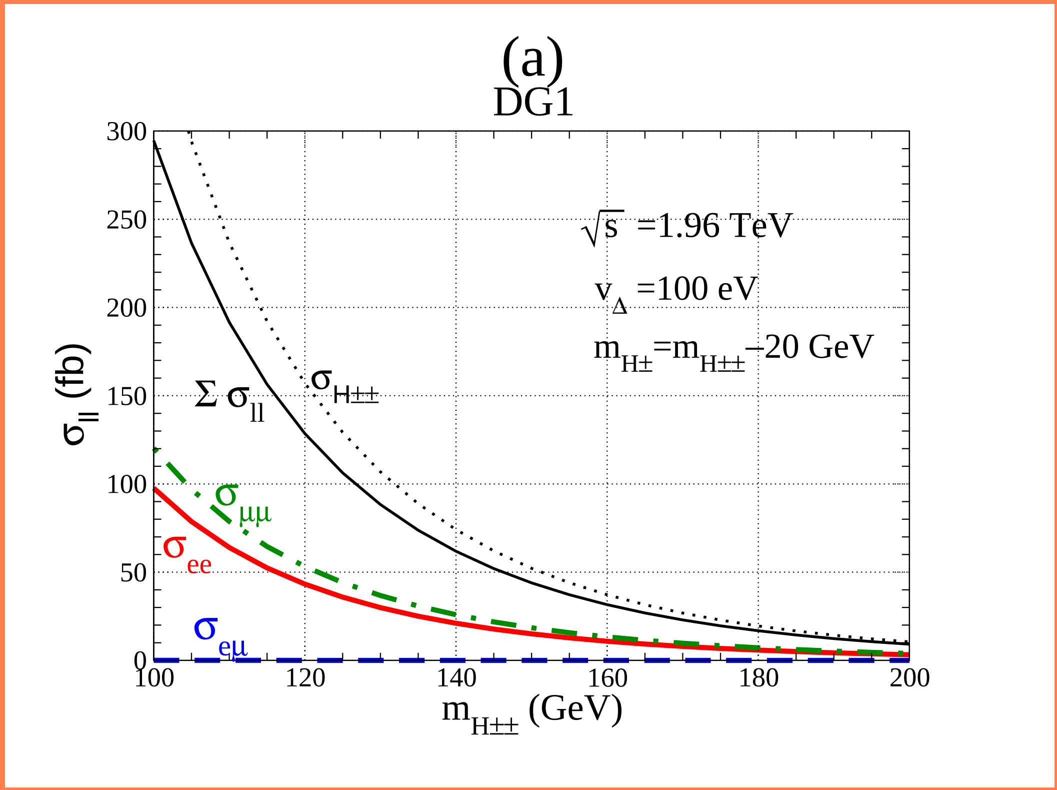
Inclusive single $\sigma(p\bar{p} \to H_L^{\pm\pm} + X \to e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm)$

Inverted neutrino mass hierarchy: $\sigma_{ee} > \sigma_{\mu\mu} >> \sigma_{e\mu}$



Inclusive single $\sigma(p\bar{p} \to H_L^{\pm\pm} + X \to e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm})$

Quasi-degenerate neutrinos: $\sigma_{\mu\mu} \sim \sigma_{ee} >> \sigma_{e\mu}$



Summary of $H^{\pm\pm}$ discovery propspects at Hadron collider

- Tevatron searches are ongoing:

0.24 fb^{-1}/0.35 fb^{-1} used ($>$ 1 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 $H^{\pm\pm} \to l_i l_j$ which are sensitive to the neutrino mass hierarchy

- LHC has i) discovery capability up to 1 TeV or ii) precision measurements of $H^{\pm\pm} \to l_i l_j$ if $H^{\pm\pm}$ discovered at Tevatron

Conclusions

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