Doubly Charged Higgs Bosons at Hadron Colliders

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- Higgs Triplet Model (HTM) and doubly charged scalars ($H^{\pm\pm}$)
- Leptonic decay channels $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$
- Production of $H^{\pm\pm}$ at hadron colliders
- Searches for $H^{\pm\pm}$ at Tevatron and at LHC

Collaborators: Mayumi Aoki (Kanazawa), Hiroaki Sugiyama (Ritsumeikan), Cheng-Wei Chiang (Nat.Cent.Univ),

Naveen Gaur (Delhi): Phys.Rev.D72,035011 (2005), Phys.Rev.D77,075010 (2008), JHEP1011,005 (2010)

IOP Meeting, University of Glasgow, 05 April 2011

Higgs Triplet Model (HTM)

SM Lagrangian with one $SU(2)_L$ $I = 1, Y = 2$ Higgs triplet

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

Higgs potential invariant under $SU(2)_L \otimes U(1)_Y$: $m^2 < 0$, $M_\Delta^2 > 0$

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

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

Triplet vacuum expectation value:

$$\boxed{< \delta^0 >= v_\Delta \sim \mu v^2/M_\Delta^2} \quad (v_\Delta < 5 \ GeV \text{ to keep } \rho \sim 1)$$

Neutrino mass in Higgs Triplet Model (HTM)

No additonal (heavy) neutrinos: $\mathcal{L} = h_{ij}\psi_{iL}^T C i\tau_2 \Delta \psi_{jL} + h.c$

$\psi_{iL}^T = (\nu_i, \ell_i);\ i = e, \mu, \tau$

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

$$h_{ij}\left[\sqrt{2}\,\bar{\ell}_i^c P_L \ell_j \delta^{++} + (\bar{\ell}_i^c P_L \nu_j + \bar{\ell}_j^c P_L \nu_i)\delta^{+} - \sqrt{2}\,\bar{\nu}_i^c P_L \nu_j \delta^0\right] + h.c$$

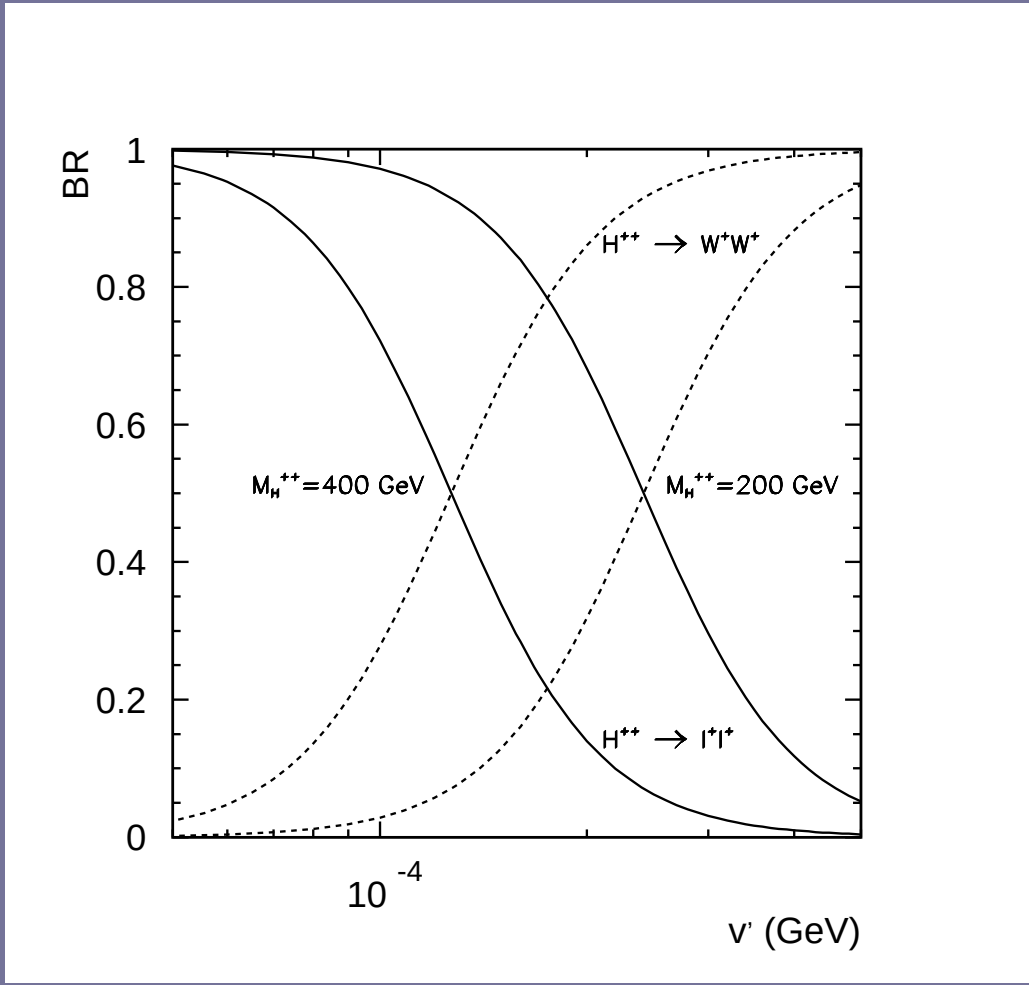
Light neutrinos receive a Majorana mass: $\mathcal{M}_{ij}^{\nu} \sim v_\Delta h_{ij}$

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

($V_{\text{PMNS}} = V_\ell^\dagger V_\nu$; take $V_\ell = I$ and $V_\nu = V_{\text{PMNS}}$)

BR($H^{\pm\pm} \to W^{\pm}W^{\pm}$) and BR($H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$) against triplet vev

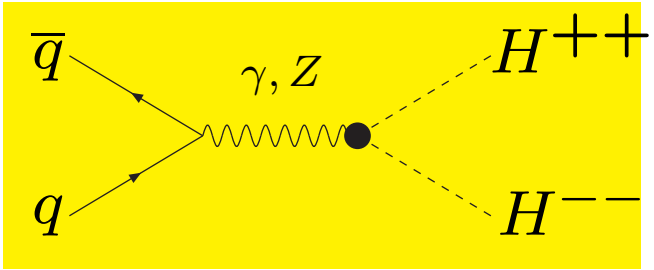
Han 07, Asaka/Hikasa 94



Production of $H^{\pm\pm}$ at Hadron Colliders

First searches at a Hadron collider in 2003 CDF,D0

$$\mathcal{L} = i\left[\left(\partial^{\mu} H^{--}\right) H^{++}\right]\left(gW_{3\mu} + g' B_{\mu}\right) + h.c$$



- $\sigma_{H^{++}H^{--}}$ is a simple function of $m_{H^{\pm\pm}}$ Barger 82, Gunion 89, Raidal 96
- $\sigma_{H^{++}H^{--}}$ has no dependence on Yukawa coupling h_{ij}

Strategy of most recent search by Tevatron

- $H^{\pm\pm}$ decays via h_{ij} to *same charge* $ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$
- Four leptons $(\ell^+\ell^+\ell^-\ell^-)$ from pair production of $H^{++}H^{--}$
- For $H^{\pm\pm} \to e^\pm e^\pm$,$e^\pm\mu^\pm$,$\mu^\pm\mu^\pm$, sufficient to search for

three leptons of high momentum with two leptons

having the same charge

$\to$ Six distinct signatures

$e^\pm e^\pm e^\mp$, $e^\pm e^\pm \mu^\mp$, $e^\pm \mu^\pm e^\mp$, $e^\pm \mu^\pm \mu^\mp$, $\mu^\pm \mu^\pm e^\mp$ and $\mu^\pm \mu^\pm \mu^\mp$

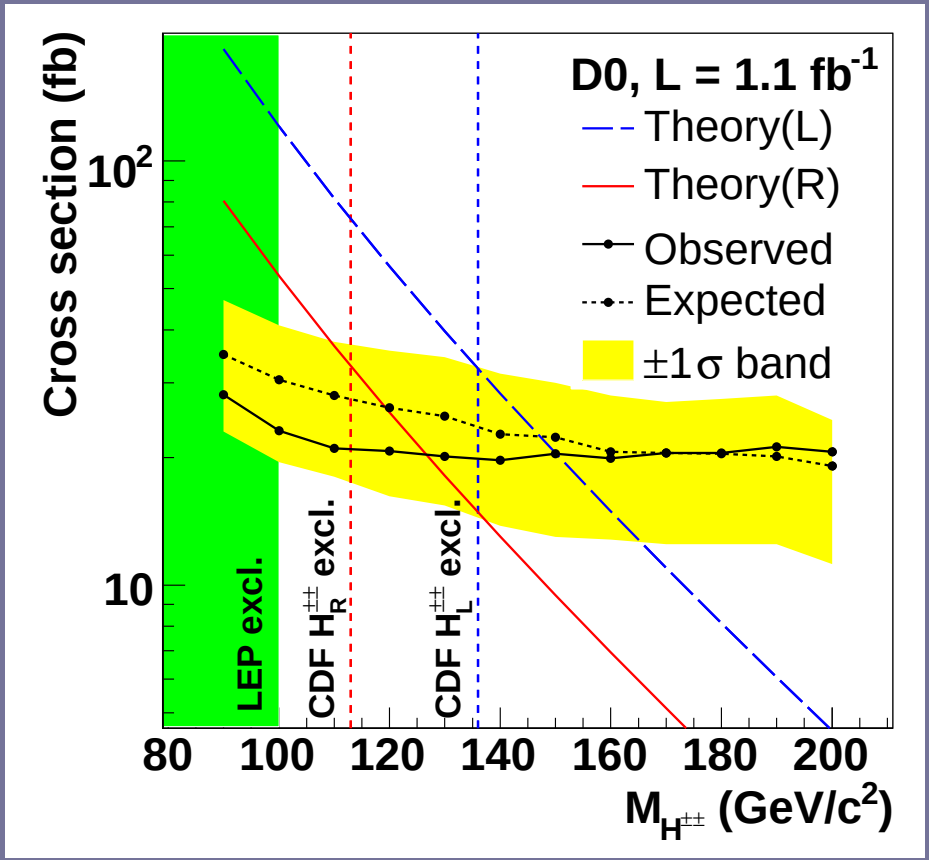
- Only $\mu^\pm\mu^\pm\mu^\mp$ has been searched for (1.1 fb^{-1} of data)
- Tevatron currently has 7 fb^{-1}, and expects 9 $\to$ 12 fb^{-1}

Tevatron search (D0, 2007) for $p\overline{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$

Selection	Preselection S1	Isolation S2	$\Delta\phi < 2.5$ S3	Like sign S4	Third muon S5
$Z/\gamma^* \to \mu^+\mu^-$	69181 ± 4642	58264 ± 3910	4936 ± 333	5.3 ± 1.6	< 0.01
Multijet	4492 ± 120	194 ± 18	18 ± 2	6.3 ± 0.8	0.2 ± 0.1
$Z/\gamma^* \to \tau^+\tau^-$	328 ± 25	269 ± 21	20 ± 3	< 0.01	< 0.01
$t\bar{t}$	38 ± 3	20 ± 1	14 ± 1	0.03 ± 0.01	< 0.01
WW	40 ± 3	34 ± 2	20 ± 1	< 0.01	< 0.01
WZ	19 ± 1	16 ± 1	11 ± 1	2.95 ± 0.20	1.62 ± 0.11
ZZ	10 ± 1	9 ± 1	5 ± 1	0.63 ± 0.05	0.47 ± 0.03
Total background	74108 ± 4644	58806 ± 3910	5024 ± 333	15.2 ± 1.8	2.3 ± 0.2
$M_{H^{\pm\pm}} = 140$ GeV	20.5 ± 2.7	18.5 ± 2.4	16.3 ± 2.1	11.6 ± 1.5	10.1 ± 1.3
Data	72974	58763	4558	16	3

Signal is defined as $\mu^+\mu^+\mu^-$ or $\mu^-\mu^-\mu^+$

Tevatron search (D0, 2007) for $p\overline{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$



Mass limit $m_{H^{\pm\pm}} > 150$ GeV, assuming BR($H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$) = 100%

Current status of Tevatron searches

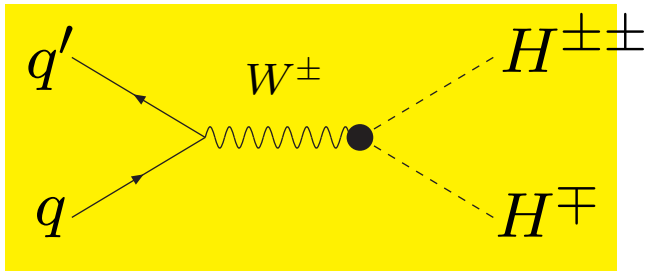
	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
2l	$>$ 133 GeV	$>$ 113 GeV	$>$ 136 GeV	x	x	x
3l			$>$ 150 GeV	$>$ 114 GeV	$>$ 112 GeV	
4l				$>$ 114 GeV	$>$ 112 GeV	

- $>$ 150 GeV limit uses 1.1 fb^{-1}
- Other limits use 0.24 fb^{-1} or 0.35 fb^{-1}
- Run II has accumulated $\sim$ 7 fb^{-1}
- Expect up to 12 fb^{-1} by 2011
- Sensitivity to $m_{H^{\pm\pm}} \sim 250$ GeV in $ee, e\mu, \mu\mu$ channels

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

Tevatron search assumes $q\overline{q} \to \gamma, Z \to H^{++}H^{--}$, but...

$$\mathcal{L} = ig\left[\left(\partial^{\mu}H^{+}\right)H^{--} - \left(\partial^{\mu}H^{--}\right)H^{+}\right]W_{\mu}^{+} + h.c..$$



- $\sigma_{H^{\pm\pm}H^{\mp}}$ is a function of $m_{H^{\pm\pm}}$ and $m_{H^{\pm}}$ Barger 82, Dion 98
- Similar magnitude to $\sigma(p\overline{p} \to H^{++}H^{--})$ for $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$

Impact of $qq' \to H^{\pm\pm}H^{\mp}$

Tevatron search is already sensitive to $qq' \to H^{\pm\pm}H^{\mp}$!

- $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ search is sensitive to $H^{\pm\pm}H^{\mp}$ for $H^{\pm} \to \ell^{\pm}\nu$

$\to$ Define inclusive cross section for $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ search:

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

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- Enables larger values of $m_{H^{\pm\pm}}$ to be probed in $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ channels
- Not yet included in searches at the Tevatron

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

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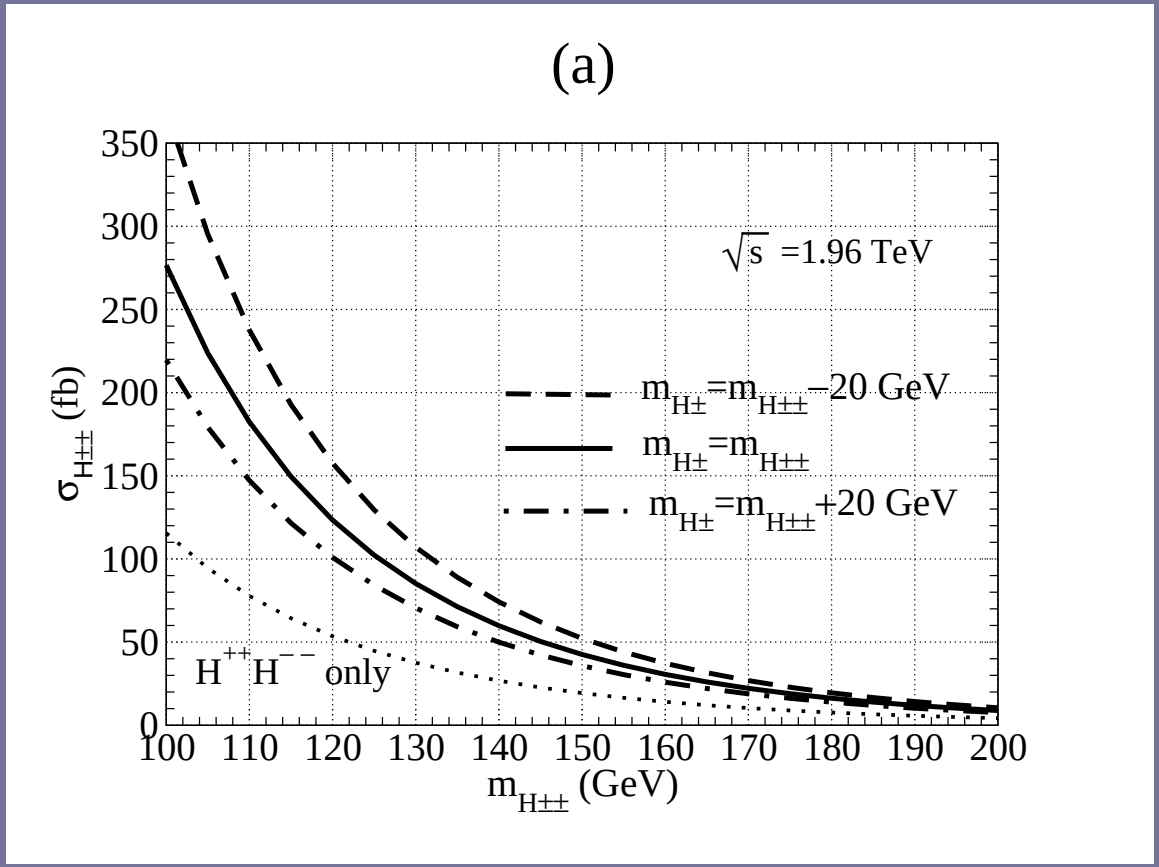
$$\sigma_{H^{\pm\pm}} = \sigma(p\overline{p} \to H^{++}H^{--}) + 2\sigma(p\overline{p} \to H^{++}H^{-})$$



Summary for $qq' \to H^{\pm\pm}H^{\mp}$

- $\sigma(qq' \to H^{\pm\pm}H^{\mp})$ can be as large as $\sigma(q\overline{q} \to H^{++}H^{--})$
- Can enhance the discovery potential for $H^{\pm\pm}$ in 3ℓ search channels
- Now receiving attention as a main production mechanism for $H^{\pm\pm}$
- First simulated at LHC in 2008 Han et al, Del Aguila et al
- Not included in Pythia (frequently used by experimentalists)
- Hopefully Tevatron will include it in next search for $H^{\pm\pm}$

March 2011: First search for $H^{\pm\pm}$ at LHC by CMS

- Included both $qq' \to H^{\pm\pm}H^{\mp}$ and $q\overline{q} \to H^{++}H^{--}$
- Performed both 3ℓ and 4ℓ searches
- Some limits already better than at the Tevatron

	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
Tevatron	$>$ 133 GeV	$>$ 113 GeV	$>$ 150 GeV	$>$ 114 GeV	$>$ 112 GeV	x
LHC	$>$ 144 GeV	$>$ 154 GeV	$>$ 156 GeV	$>$ 106 GeV	$>$ 106 GeV	x

Conclusions

- Higgs Triplet Model generates tree-level neutrino mass
- $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ a distinctive signal with fairly low backgrounds
- $H^{\pm\pm}$ produced via $pp \to H^{++}H^{--}$ and $pp \to H^{\pm\pm}H^{\mp}$
- $pp \to H^{\pm\pm}H^{\mp}$ has recently started to get recognition
- Tevatron searches have used only a fraction of the data
- LHC searches have already started
- Very promising future for $H^{\pm\pm}$ searches