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 $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$
- Production of $H^{\pm\pm}$ at hadron colliders
- Searches for $H^{\pm\pm}$ at Tevatron and simulations at LHC

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Naveen Gaur (Delhi): Phys.Rev.D72,035011 (2005), Phys.Rev.D77,075010 (2008), arXiv:1009.2780 (JHEP)

Seminar at RAL, 02 November 2010

Charged Higgs Bosons (Scalars)

The Higgs boson (1964) of the Standard Model is a spinless, neutral particle with a vacuum expectation value.

Still undiscovered If exists, how many Higgs bosons?

Classify Higgs bosons by their electric charge

- Neutral: h^0 (SM 1967), H^0,A^0 (2HDM 1973, MSSM 1980...)
- Singly Charged: $H^{\pm}$ (2HDM, MSSM..)
- Doubly Charged: $H^{\pm\pm}$ (this talk)

These three types have received considerable theoretical/experimental attention

(Order of priority: neutral $>$ singly charged $>$ doubly charged)

Models with Doubly Charged Higgs Bosons, $H^{\pm\pm}$

Motivation $\rightarrow$ neutrino mass generation

Scalar triplets (isospin $I = 1$) and scalar singlets ($I = 0$)

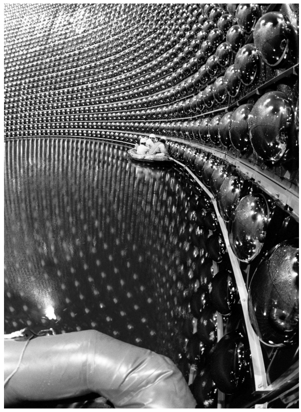
- Higgs Triplet Model: $I = 1, Y = 2$ (tree-level mass for ν)
- LR Symmetric Model: $I = 1, Y = 2$ (tree-level mass for ν)
- Zee-Babu Model: $I = 0, Y = 4$ (radiative mass for ν)

All of these models are in textbooks ("classic models")

I will discuss the Higgs Triplet Model

Konetschny/Kummer 77, Schechter/Valle 80, Cheng/Li 80

Neutrino Mass and Mixing



Strong evidence for neutrino masses and mixings from both terrestrial and celestial sources

$$V_{\rm MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Mixing angles are being probed by oscillation experiments:

i) *Atmospheric angle* is close to maximal: $\sin^2\theta_{23} \sim 0.5$

ii) *Solar angle* is sizeable, but not maximal: $\sin^2\theta_{12} \sim 0.3$

iii) *Reactor angle* is not measured: $\sin^2\theta_{13} < 0.03$

iv) Mass differences small: $\Delta M^2_{atm} \sim 10^{-3} eV^2$, $\Delta M^2_{sol} \sim 10^{-5} eV^2$

Higgs Triplet Model can accommodate these values

Large Hadron Collider

- LHC (at CERN) is colliding protons at $\sqrt{s} = 7$ TeV

- From 2013(?) it will operate at $\sqrt{s} = 14$ TeV
- Highest energy collider ever built
- Search for Higgs bosons of high (highest?) priority
- Detectors ATLAS and CMS optimised for Higgs boson search
- Fermilab Tevatron ($\sqrt{s} = 2$ TeV) is still operating
- An era of intense competition until year 2014?
- A great time to study the phenomenology of Higgs bosons

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: $<\delta^0> = v_\Delta \sim \mu v^2/M_\Delta^2$

($v_\Delta < 5$ GeV to keep $\rho = (M_Z^2 \cos^2\theta_W)/M_W^2 \sim 1$)

Neutrino mass in Higgs Triplet Model (HTM)

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

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

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

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

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

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

(m_i=neutrino masses; $V_{\mathrm{PMNS}} = V^\dagger_\ell V_\nu$; take $V_\ell = I$ and $V_\nu = V_{\mathrm{PMNS}}$)

Decay channels for $H^{\pm\pm}$ and $H^{\pm}$

Decays of $H^{\pm\pm}$:

- $\Gamma(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim |h_{ij}|^2$; $\Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm}) \sim v_{\Delta}^2$
- In HTM: $h_{ij}v_{\Delta} \sim \mathcal{M}_{ij}^{\nu}$

$\Gamma(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) > \Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm})$ for $v_{\Delta} < 10^{-4}$ GeV

- $H^{\pm\pm} \to H^{\pm}W^{*}$ suppressed if $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$

Tevatron searches have only been performed for $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

Decays of $H^{\pm}$:

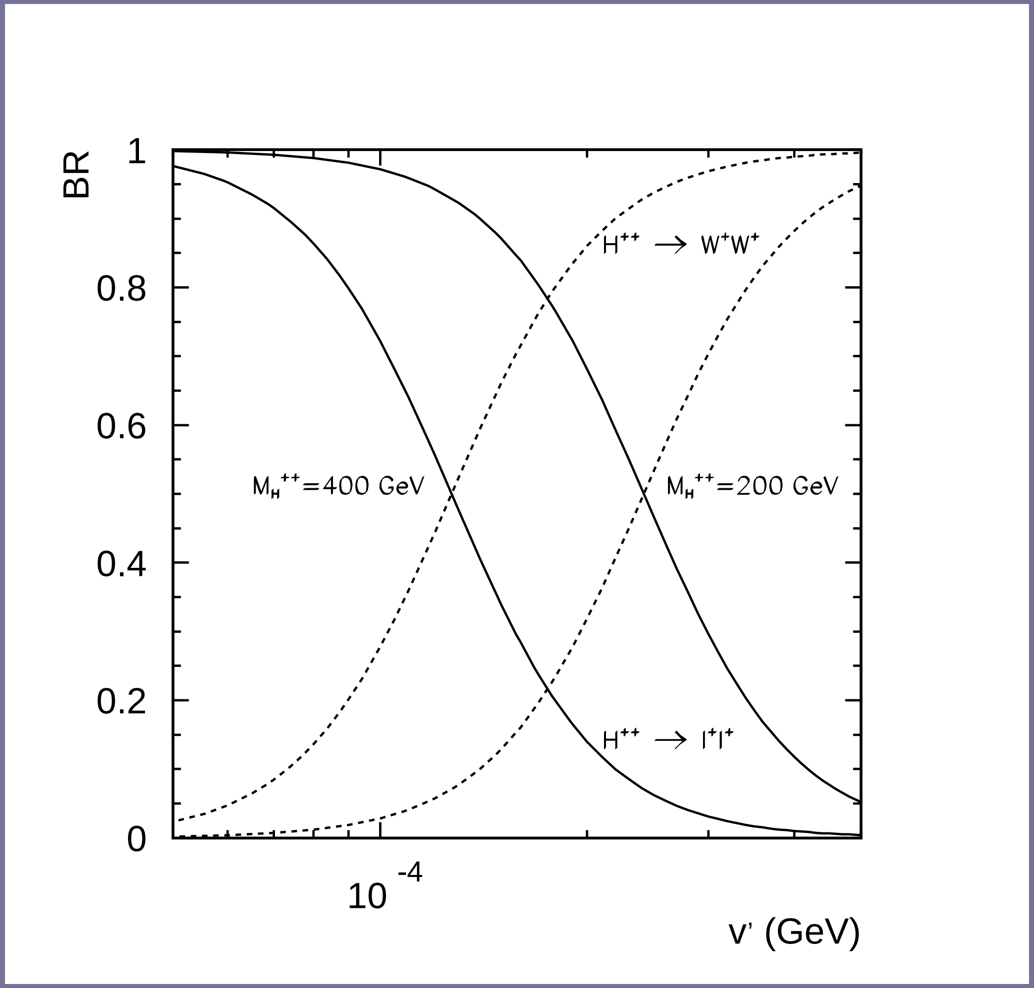
- $\Gamma(H^{\pm} \to \ell_i^{\pm}\nu) > \Gamma(H^{\pm} \to W^{\pm}Z, tb)$ for $v_{\Delta} < 10^{-4}$ GeV

If $h_{ij} > h_{electron}$ then $v_{\Delta} < 10^{-4}$ GeV

$\to$ leptonic decays $H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$ and $H^{\pm} \to \ell_i^{\pm}\nu$ dominate

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



Branching ratios of $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

$\mathrm{BR}(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})$ determined by h_{ij}

$$\Gamma(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim \frac{m_{H^{\pm\pm}}}{8\pi}|h_{ij}|^2$$

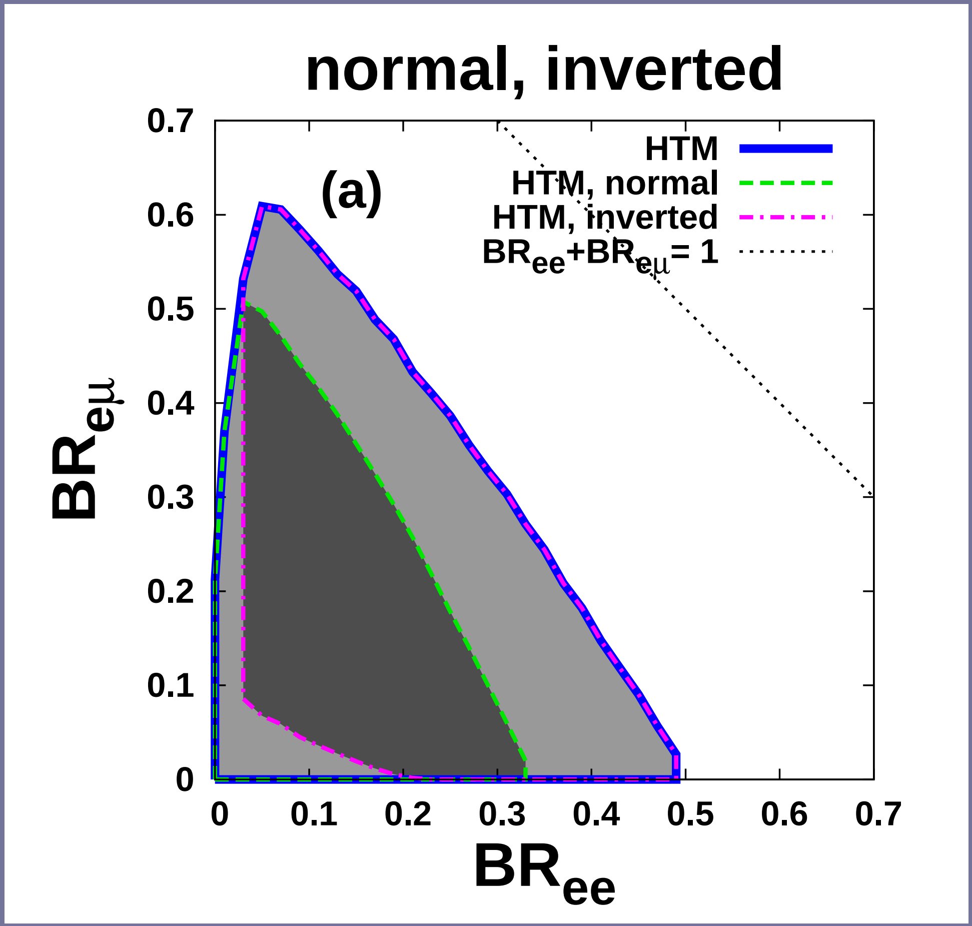
In HTM h_{ij} is directly related to neutrino mass matrix

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

Prediction for $\mathrm{BR}(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})$ determined by: Chun,Lee,Park 03

- Neutrino mass matrix parameters (masses, angles, phases)
- Neutrino mass hierarchy: normal $(m_3 > m_2 > m_1)$ or inverted

HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}e^{\pm}$),BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$)]



White region is ruled out by neutrino oscillation data

AGA/Aoki/Sugiyama 07

Limits on h_{ij}

Presence of $H^{\pm\pm}$ would lead to lepton-flavour-violating decays

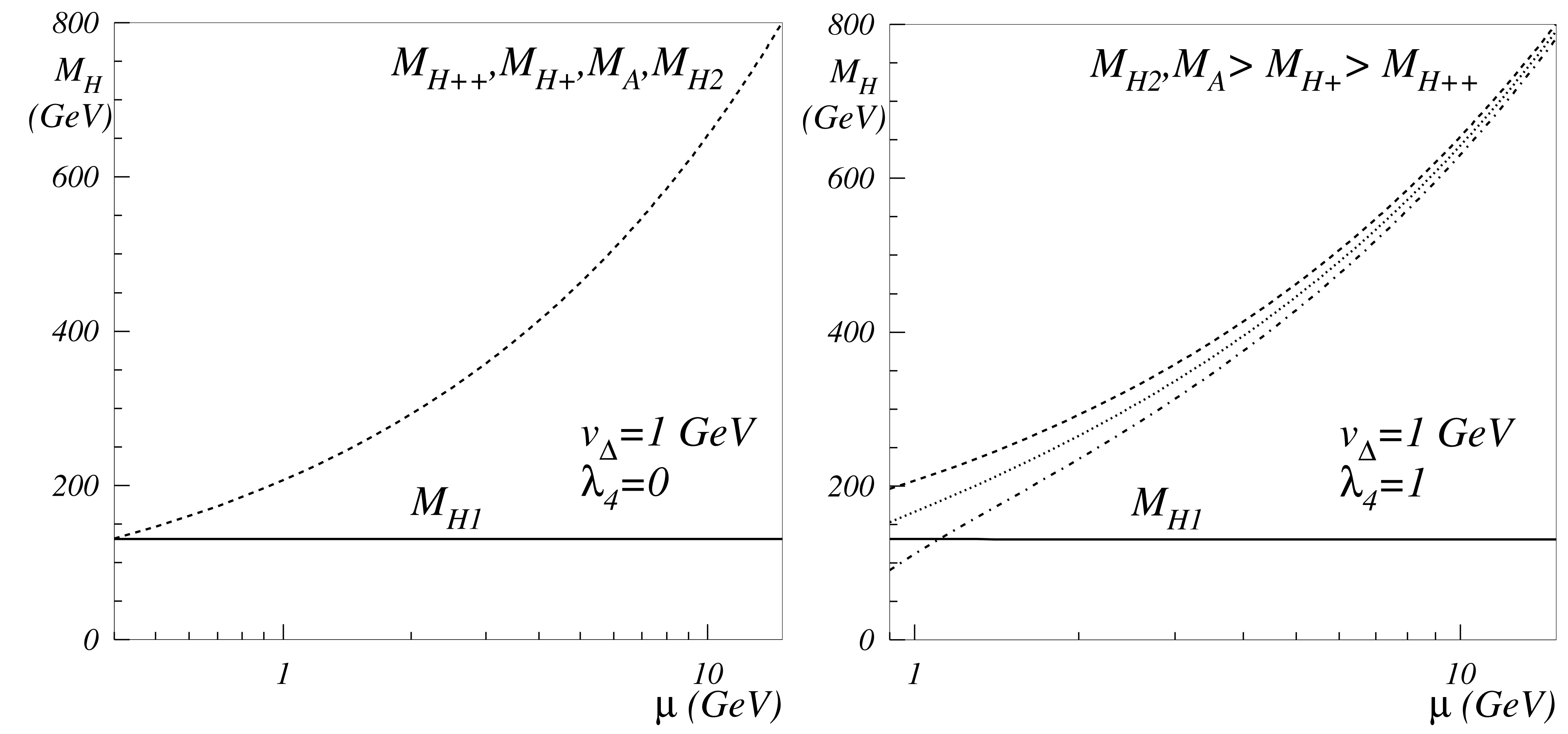
Many limits exist for h_{ij} (assuming $m_{H^{\pm\pm}} < 1$ TeV): Cuypers/Davidson 98

- BR($\mu \to eee$) $< 10^{-12} \to |h_{\mu e} h_{ee}| < 10^{-7}$ 1988; no forthcoming experiment
- BR($\tau \to \ell_i \ell_j \ell_k$) $< 10^{-8} \to |h_{\tau i} h_{jk}| < 10^{-4}$ Limits from ongoing B factories
- BR($\mu \to e\gamma$) $< 10^{-11} \to \sum_i |h_{\mu i} h_{ei}| < 10^{-6}$ sensitivity to BR$\sim 10^{-13}$ from 2011

All constraints can be respected with $|h_{ij}| < 10^{-2}$ or 10^{-3}

These decays provide valuable probes of virtual effects of $H^{\pm\pm}$

Masses of the Higgs bosons in the HTM as a function of μ ($\sim v_\triangle M_\triangle^2/v^2$)



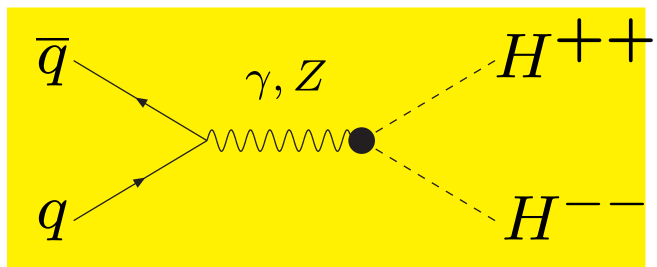
The triplet scalars tend to be degenerate, and $H^{\pm\pm}$ is the lightest for $\lambda_4 > 0$

Production of $H^{\pm\pm}$ at Hadron Colliders (Tevatron and LHC)

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 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

$\rightarrow$ 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 $\mu^\pm \mu^\pm \mu^\mp$

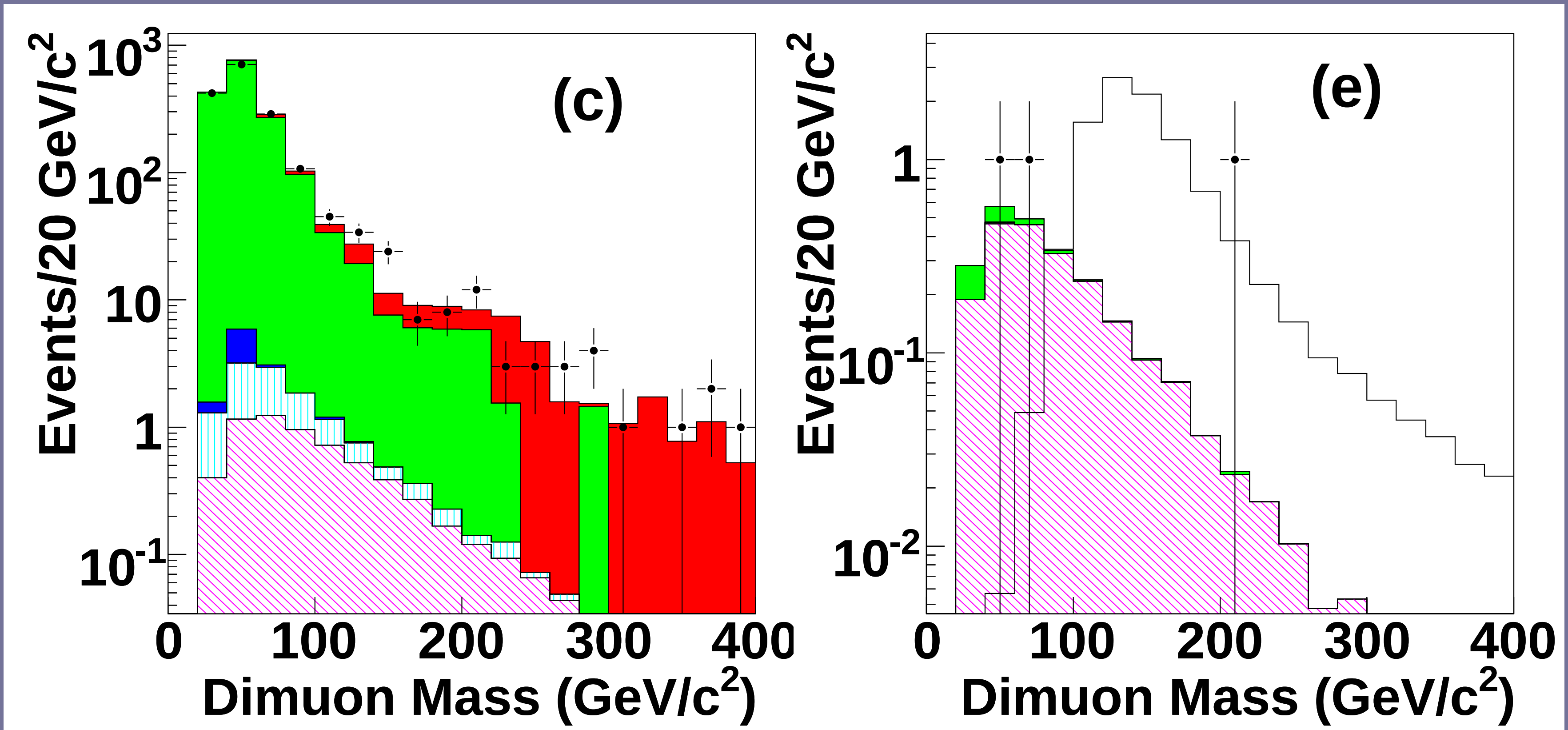
- Only $\mu^\pm\mu^\pm\mu^\mp$ has been searched for (1.1 fb^{-1} of data)
- Tevatron currently has 7 fb^{-1}, and expects $9 \to 12$ fb^{-1}

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 $\mu^-\mu^-\mu^+$

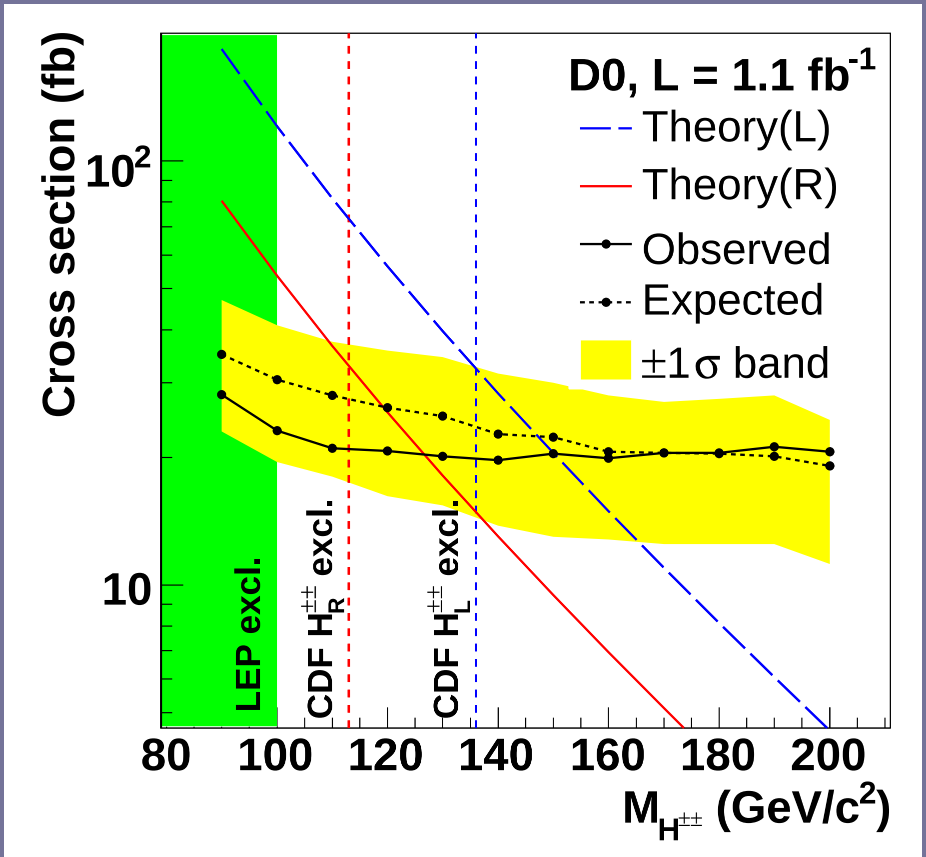
Tevatron search (D0, 2007) for $p\bar{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$



Two same-sign $\mu^{\pm}\mu^{\pm}$ after cuts S1 and S4

Two same-sign $\mu^{\pm}\mu^{\pm}$ and third $\mu^{\mp}$

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 for BR$(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) = 100\%$

Current status of Tevatron searches

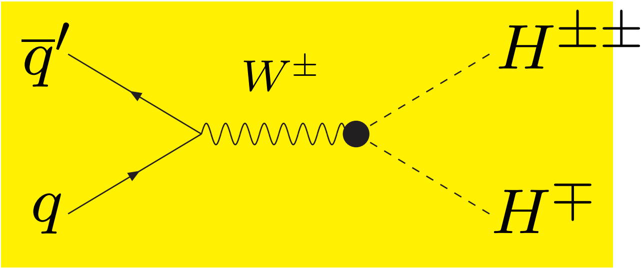
	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
2l	$>$ 133 GeV	$>$ 113 GeV	$>$ 136 GeV	x	x	x
3l			$>$ 150 GeV	$>$ 114 GeV	$>$ 112 GeV	
4l				$>$ 114 GeV	$>$ 112 GeV	

- $>$ 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 $q\overline{q}' \to H^{\pm\pm}H^{\mp}$

Ongoing searches assume $q\overline{q} \to \gamma, Z \to H^{++}H^{--}$, 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 $q\overline{q}' \to H^{\pm\pm}H^{\mp}$

Current searches are already sensitive to $q\overline{q}' \to H^{\pm\pm}H^{\mp}$!

- $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ 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:

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

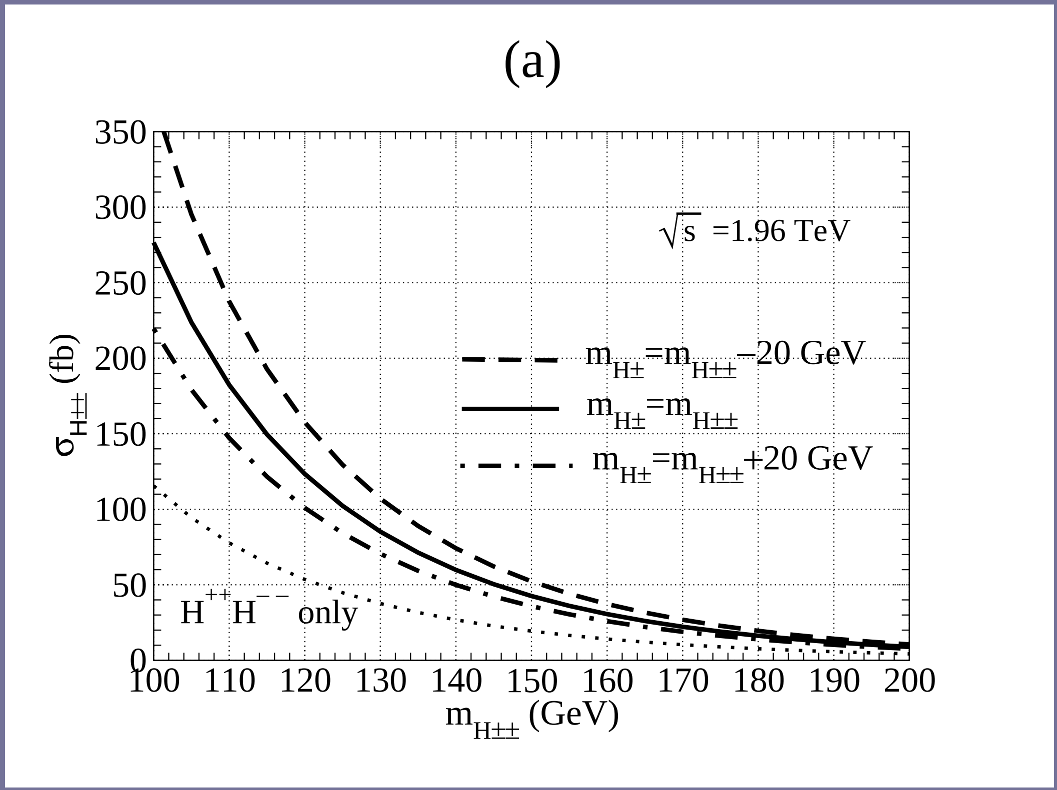
AGA, Aoki 05

- 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

AGA, Aoki 05

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



Mass limit $m_{H^{\pm\pm}} > 150$ GeV at Tevatron would strengthen to $m_{H^{\pm\pm}} > 180$ GeV

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

- $\sigma(q\overline{q}' \to H^{\pm\pm}H^{\mp})$ can be as large as $\sigma(q\overline{q} \to H^{++}H^{--})$
- Enhances the discovery potential for $H^{\pm\pm}$ in 3ℓ search channels, and strengthens the lower limit on $m_{H^{\pm\pm}}$
- Now receiving attention as a main production mechanism for $H^{\pm\pm}$
- Recently simulated at LHC Han et al 08, Del Aguila et al 08
- Not included in Pythia (frequently used by experimentalists)
- Convince Tevatron to include it in next search for $H^{\pm\pm}$?

Light $H^{\pm\pm}$ and decay $H^{\pm\pm} \to \ell^\pm \ell^\pm$ at LHC

Sizeable Event Numbers for $H^{\pm\pm}$:

$m_{H^{\pm\pm}}$ (GeV)	N_{pair} (30 fb^{-1})	N_{pair} (300 fb^{-1})	$N_{incl-sing}$ (300 fb^{-1})
200	3000	30000	84000
300	600	6000	16800
400	180	1800	5000

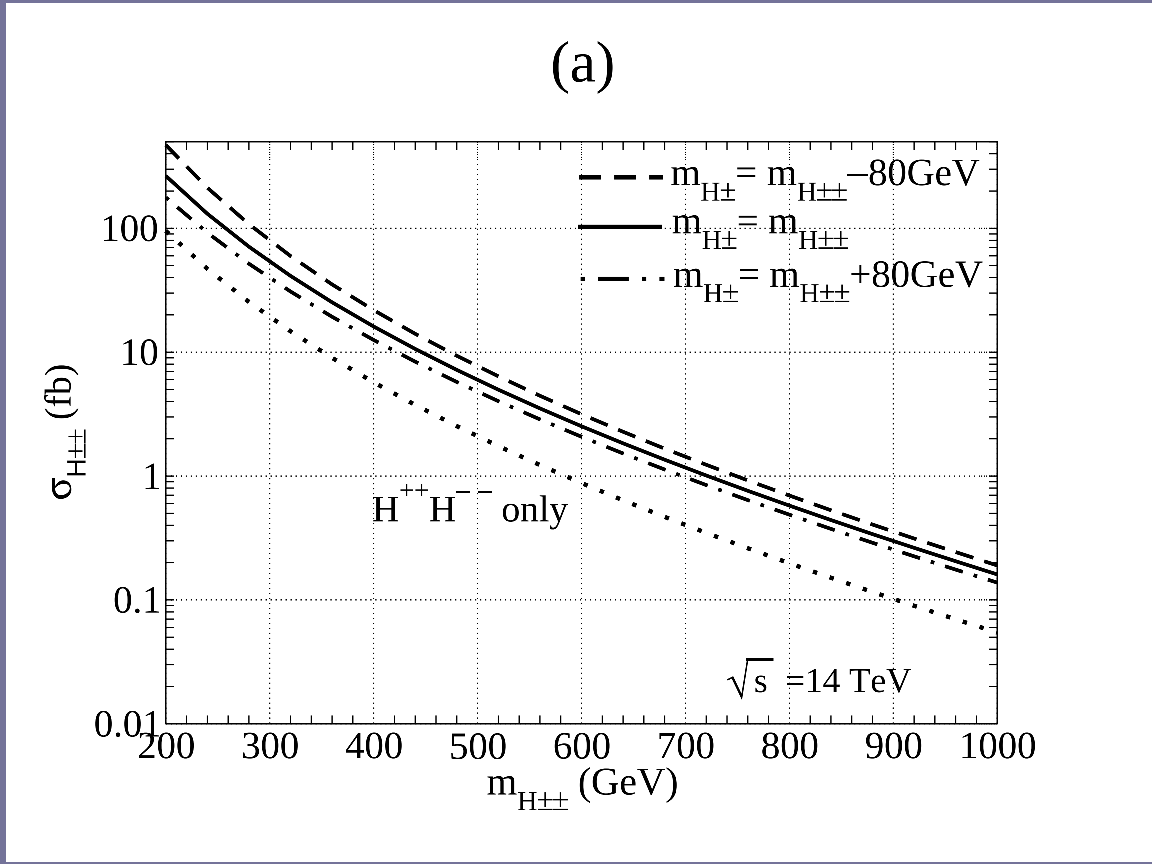
Simulations by Azuelos et al 05, Hebbeker et al 06, Hektor et al 07, Han et al 07

- Discovery for $m_{H^{\pm\pm}} < 400$ GeV with 1 fb^{-1}
- Precise measurements of BR$(H^{\pm\pm} \to \ell^\pm \ell^\pm)$ possible for $\ell = e, \mu$
- Sensitivity to BR$(H^{\pm\pm} \to \ell^\pm \ell^\pm) \sim 1\%$ for $\ell = e, \mu$

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

AGA,Aoki 05

$$\sigma_{H^{\pm\pm}} = \sigma(pp \to H^{++}H^{--}) + \sigma(pp \to H^{++}H^{-}) + \sigma(pp \to H^{--}H^{+})$$



Optimising discovery potential of $H^{\pm\pm}$ at LHC

$\rightarrow$ Signature which is sensitive to both production mechanisms

$q\bar{q} \rightarrow H^{++}H^{--}$ and $qq' \rightarrow H^{\pm\pm}H^{\mp}$

4ℓ signature: only $H^{++}H^{--}$ contributes

- CMS (2007): $\mu^+\mu^+\mu^-\mu^-$
- ATLAS (2005): 4ℓ $(\ell = e, \mu)$

3ℓ $(\ell^{\pm}\ell^{\pm}\ell^{\mp})$ signature: both $H^{++}H^{--}$ and $H^{\pm\pm}H^{\mp}$ contribute

- Del Aguila/Aguilar-Saavedra 2008: exactly 3ℓ $(\ell = e, \mu)$

Additional leptons vetoed $\rightarrow$ lose contribution from $q\bar{q} \rightarrow H^{++}H^{--}$

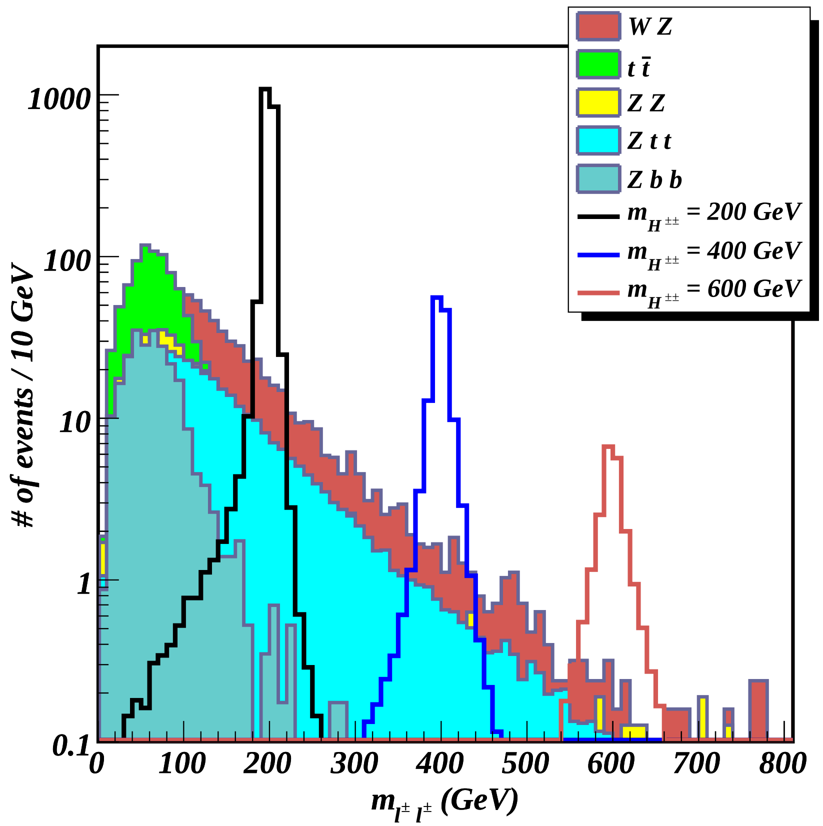
- AGA,Chiang,Gaur 2010: $\geq 3\ell$ $(\ell = e, \mu)$ (as done at Tevatron)

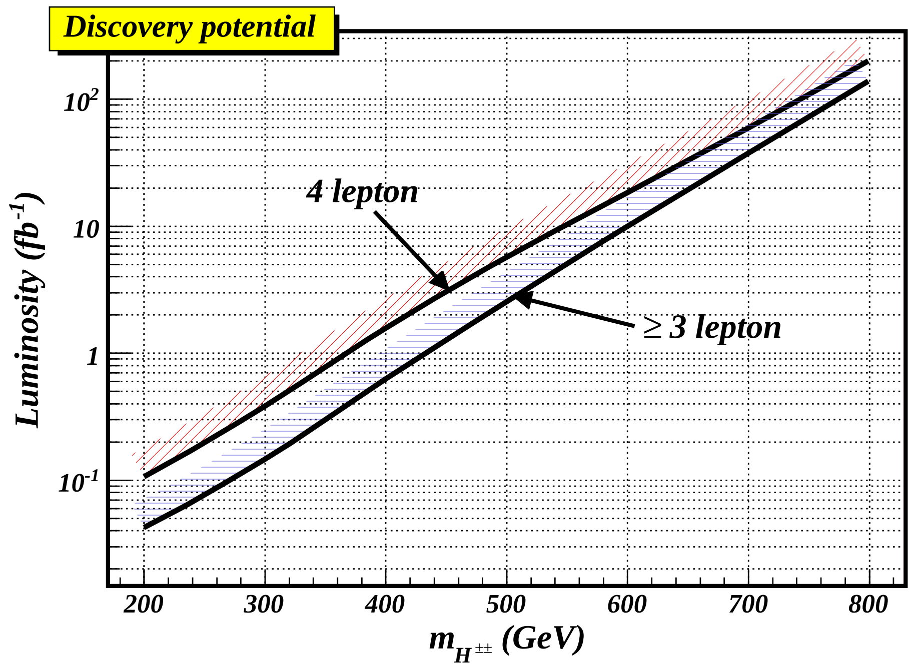
Signal and background for $\geq 3\ell$ ($\ell = e, \mu$) signature AGA,Chiang,Gaur 1

	Backgrounds							Signal ($M_{H^{\pm\pm}}$)	
Cuts ⇓	WZ	WWW	ZZ	$t\bar{t}$	Zbb	Ztt	Wtt	200	600
Pre-selection	591.7	3.5	203.6	159.9	57.7	212.5	9.7	1570.4	17.6
$\lvert m_{\ell^+\ell^-} - m_Z \rvert > 10$ GeV	50.9	2.7	12.1	113.2	0.9	33.4	7.4	1397.8	17.3
$H_T > 300$ GeV	7.5	1.1	1.6	8.9	0	17	3.4	1351.1	17.3
$H_T > 500$ GeV	1.7	0.3	0.4	0.9	0	3.2	0.6	796.2	17.3
$\mathcal{S}$								77.4	5

- Background and Signal events surviving the cuts for at least 3 leptons ($\ell = e, \mu$) in the final state
- Assume BR$(H^{\pm\pm} \to \ell^\pm \ell^\pm)$ = BR$(H^{\pm\pm} \to \ell^\pm \nu) = 100\%$
- $\mathcal{L} = 10$ fb^{-1} and $\sqrt{s} = 14$ TeV
- H_T is the total transverse energy of the ($\geq 3\ell$) leptons (defined to include missing E_T from $H^\pm \to \ell^\pm \nu$)

$\geq 3\ell$ signature from $pp \to H^{++}H^{--}$ and $pp \to H^{\pm\pm}H^{\mp}$, with $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ $(\ell = e, \mu)$





Left panel: Same-sign dilepton invariant mass distribution before Z veto and H_T cuts

Right panel: Integrated luminosity required for 5σ discovery in $\geq 3\ell$ and 4ℓ channels

Possible future topics?

Encourage CMS/ATLAS to simulate $\geq 3\ell$ $(\ell = e, \mu)$ signature in order to improve sensitivity to $m_{H^{\pm\pm}}$

- Compare discovery potential of Tevatron and low energy run ($\sqrt{s} = 7$ TeV) of LHC
- Exclusive final states (e.g. $e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$)
- Decay channels $H^{\pm\pm} \to e^{\pm}\tau^{\pm}, \mu^{\pm}\tau^{\pm}, \tau^{\pm}\tau^{\pm}$ might be dominant
- After discovery: separate the contributions from $q\overline{q} \to H^{++}H^{--}$ and $q\overline{q}' \to H^{\pm\pm}H^{\mp}$

Conclusions

- Doubly charged Higgs bosons appear in various models of neutrino mass generation
- Higgs Triplet Model generates neutrino mass $h_{ij} v_{\Delta}$
- $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ a distinctive signal with BRs determined by h_{ij}
- $H^{\pm\pm}$ produced via $pp \to H^{++}H^{--}$ and $pp \to H^{\pm\pm}H^{\mp}$
- Three-lepton signal $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ optimal channel for detection
- Much to simulate in the phenomenology of $H^{\pm\pm}$

Higgs boson spectrum

The HTM has 7 Higgs bosons: $H^{\pm\pm}, H^{\pm}, H^0, A^0, h^0$

- $H^{\pm\pm}$ is *purely triplet*: $H^{\pm\pm} \equiv \delta^{\pm\pm}$
- $H^{\pm}, H^0, A^0, h^0$ are mixtures of doublet (ϕ) and triplet (δ) fields
- Mixing $\sim v_{\Delta}/v$ and small ($v_{\Delta}/v < 0.03$)
- h^0 plays role of *SM Higgs boson* (essentially $I = 1/2$ doublet)
- $H^{\pm}, H^0, A^0$ are *dominantly* composed of triplet fields
- Masses of $H^{\pm\pm}, H^{\pm}, H^0, A^0$ close to degenerate $\sim M_{\Delta}$
- For $H^{\pm\pm}$, $H^{\pm}$ in range at LHC require $M_{\Delta} < 1$ TeV