Charged Higgs Bosons in extended (non-SUSY) Higgs Models

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- Four versions (I,I',II,II') of the Two Higgs Doublet Model
- Differences in the phenomenology of charged Higgs bosons ($H^{\pm}$)
- Search channels yet to be simulated in Models I,I',II'
- Higgs Triplet Model (HTM) and doubly charged scalars ($H^{\pm\pm}$)
- Production of $H^{\pm\pm}$ at hadron colliders
- Searches for $H^{\pm\pm}$ at Tevatron and simulations at LHC

cHarged 2010, Uppsala University, Sweden, 27-30 Sep 2010

The four versions of the Two Higgs Doublet Model (2HDM)

Four versions of 2HDM with natural flavour conservation

(no FCNCs induced by scalars at tree-level)

- All four models I,I',II,II' have the same scalar potential
- The models have different couplings to fermions
- Couplings $H^{\pm} \to f\overline{f} \sim \tan\beta$ or $1/\tan\beta$ ($\tan\beta = v_2/v_1$).

The four versions of the Two Higgs Doublet Model (2HDM)

- Type II is structure found in MSSM
- Much attention given to $H^{\pm}$ of Type II
- I will discuss some distinctive phenomenology of $H^{\pm}$ in Types I, I' and II'
- I will not discuss "inert 2HDM" (see talks at this workshop)
- Convenient program for phenomenology is "Two-Higgs-Doublet Model Calculator" (2HDMC) Eriksson/Rathsman/Stal arXiv:0902.0851

Fermionic couplings of $H^{\pm}$ in the four versions of the 2HDM

First detailed study of $H^{\pm}$ phenomenology in Barger/Hewett/Phillips 90

$$\mathcal{L}_{H^\pm} = -\left\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\,(m_u X P_L + m_d Y P_R)\,d\,H^+ + \frac{\sqrt{2}m_\ell}{v} Z \overline{\nu_L}\ell_R H^+ + H.c.\right\}$$

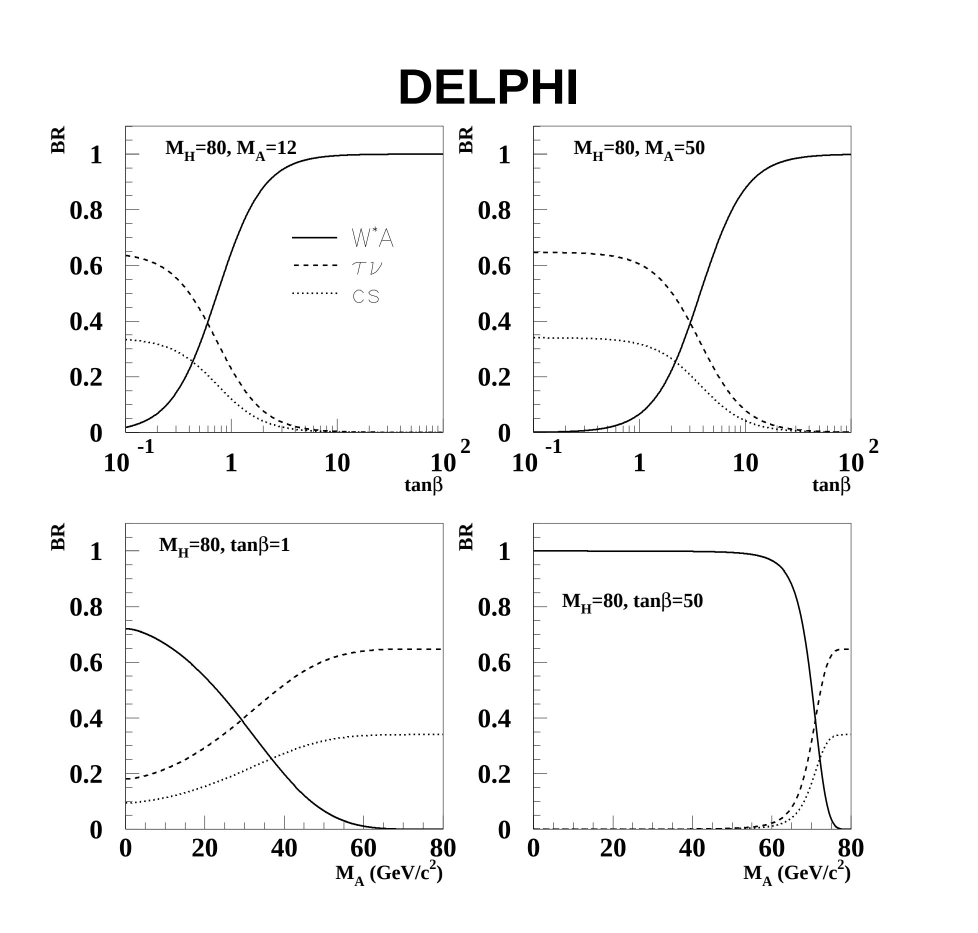
	X	Y	Z
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type I'	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type II'	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Main points of $H^{\pm}$ phenomenology in 2HDM (Model I)

- Phenomenology has been studied quite thoroughly (included in the Higgs Hunters Guide 1990)
- Branching ratios for fermionic decays are independent of $\tan\beta$: $H^{\pm} \to \tau\nu \sim 70\%$, $H^{\pm} \to cs \sim 30\%$ for $m_{H^{\pm}} < m_t + m_b$
- Coupling to all fermions ($1/\tan\beta$) is very small for $\tan\beta >> 1$ ("fermiophobic")
- $H^{\pm}$ can avoid constraints from flavour physics (e.g. $b \to s\gamma$) and so could be light
- Other decays (if open) such as $H^{\pm} \to A^0 W^*$ can be dominant

Branching ratios of $H^{\pm}$ of 2HDM (Type I)

AGA 98, Borzumati/Djouadi 98



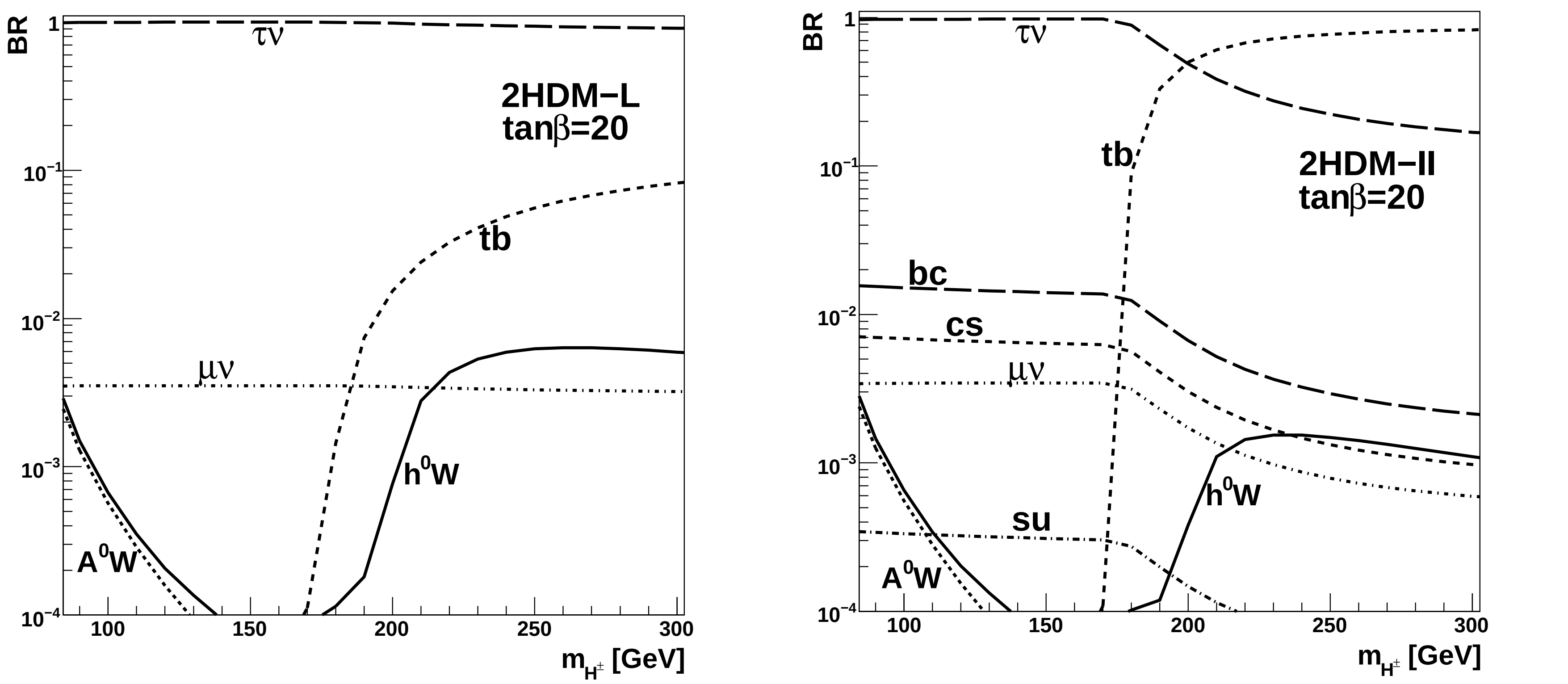
Searches for $e^+e^- \to H^+H^-$, $H^\pm \to A^0 W^*$ by DELPHI (2004) and OPAL (2008)

Main points of $H^{\pm}$ phenomenology in 2HDM (Model I')

- Received very little attention until 2009 Barger 90, AGA/Stirling 95, Park 06
- Suppressed couplings to quarks $(1/\tan\beta)$
- $H^{\pm}$ can avoid constraints from flavour physics and be light, and have sizeable coupling to leptons $(\tan\beta)$
- Production processes that rely on couplings to quarks will be ineffective
- Large branching ratio $H^{\pm} \to \tau\nu$ even for $m_{H^{\pm}} > m_t + m_b$

Comparison of branching ratios of $H^{\pm}$ in 2HDM (Models I' and II)

Logan/Maclennan 09: see also Aoki et al 09, Su et al 09, Goh et al 09

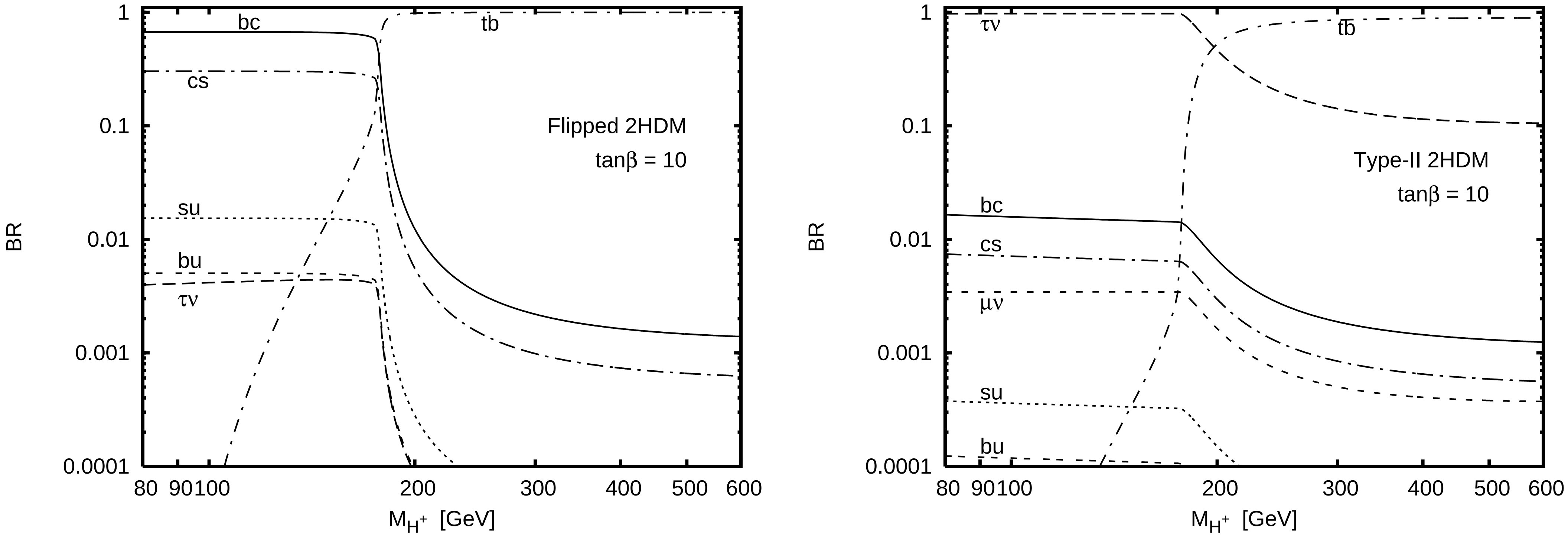


Main points of phenomenology of $H^{\pm}$ in 2HDM (Model II')

- Received very little attention until 2009
- Like Model II, $H^{\pm}$ can contribute sizeably to low-energy processes like $b \to s\gamma$
- $m_{H^{\pm}} < 300$ GeV would require some additional New Physics to cancel $H^{\pm}$ contribution to $b \to s\gamma$
- Main distinctive feature is sizeable branching ratio for $H^{\pm} \to cb$ for $m_{H^{\pm}} < m_t + m_b$

Comparison of branching ratios of $H^{\pm}$ in 2HDM (Models II' and II)

Logan/Maclennan 10; see also Aoki et al 09



Distinctive signatures of $H^\pm$ which have not been simulated

At LHC:

• Model I,II Decay $H^\pm \to A^0 W^\pm$ (from various production channels)

Kanemura/Moretti/Mukai/Santos/Yagyu 09

• Model I' $\tau\tau\tau\nu$ (other production channels suppressed) Aoki et al 09

$q\overline{q} \to H^\pm A^0 / H^\pm H^0$; $H^\pm \to \tau^\pm \nu, A^0/H^0 \to \tau^+\tau^-$

• Model II' $H^\pm \to cb$ in decay of top quark AGA 95, Logan/Maclennan 10

$q\overline{q} \to t\overline{t}$; $t \to Wb$, t$\to H^\pm b$; $H^\pm \to cb$

Doubly Charged Higgs bosons $H^{\pm\pm}$

TeV scale models of neutrino mass generation

Many models for neutrino mass generation!

Models with a signature accessible to High Energy Colliders (Tevatron/LHC) are phenomenologically appealing

One such model is: Higgs Triplet Model (HTM)

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

Distinctive signature:

Doubly charged Higgs boson: $H^{\pm\pm}$

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 $\rho \sim 1)$

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}):

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

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 $V_{\nu} = V_{\text{PMNS}}$)

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

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

- $\Gamma(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim |h_{ij}|^2$; $\Gamma(\mathrm{H}^{\pm\pm} \to W^{\pm}W^{\pm}) \sim v_{\Delta}^2$
- 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 $H^{\pm}$:

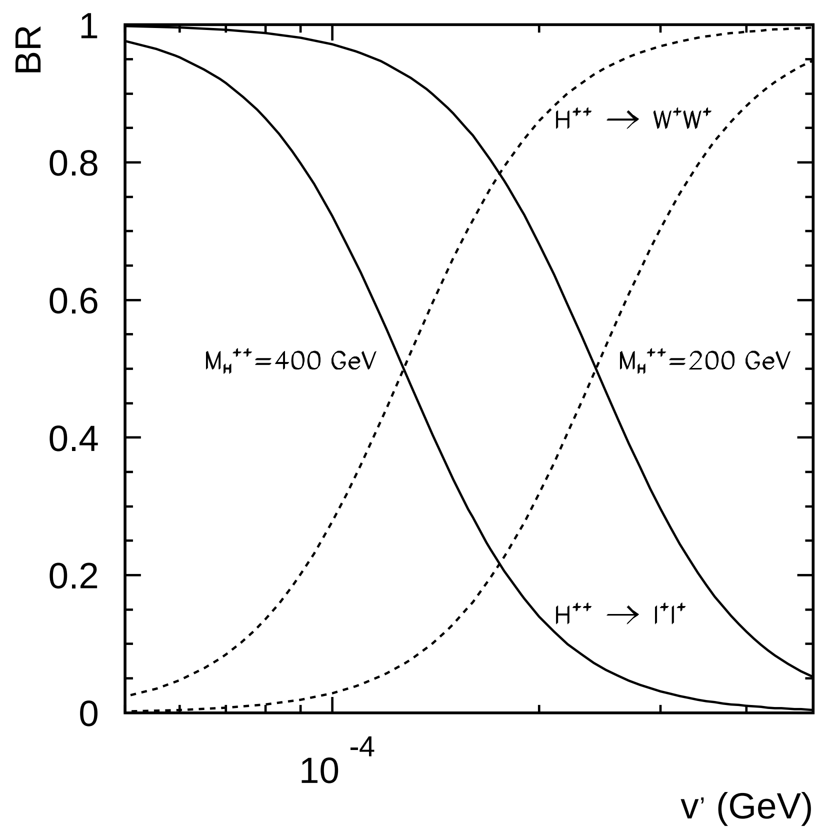
- $\Gamma(\mathrm{H}^{\pm} \to \ell_i^{\pm}\nu) > \Gamma(H^{\pm} \to W^{\pm}Z, tb)$ for $v_{\Delta} < 10^{-4}$ GeV

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 $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

BR$(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})$ depends on relative values of h_{ij}

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

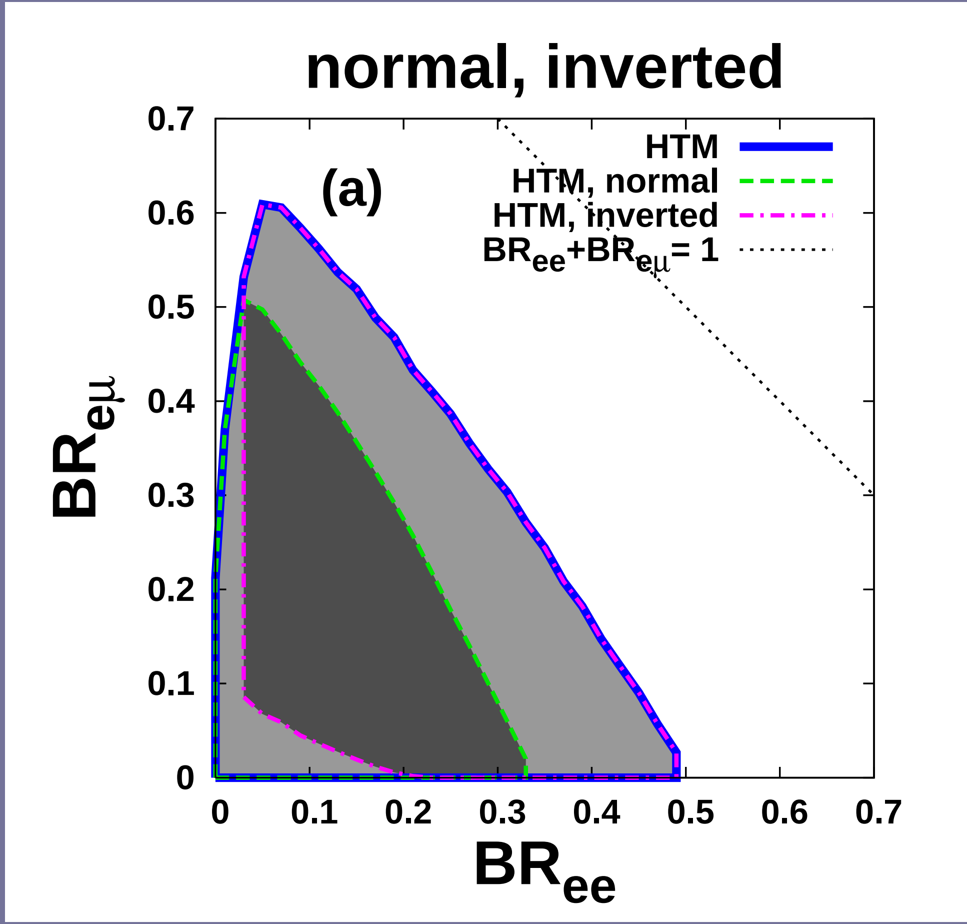
In HTM h_{ij} is directly related to neutrino mass matrix

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

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

- Neutrino mass hierarchy (normal, inverted)
- Neutrino mass matrix parameters (masses, angles, phases)

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

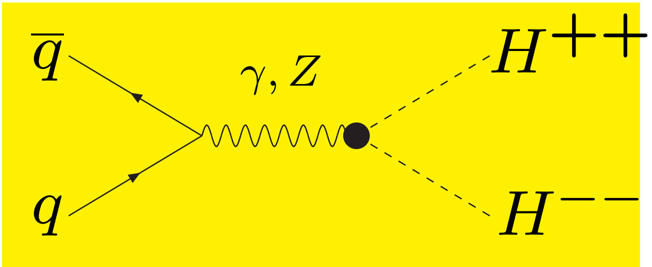
Production of $H^{\pm\pm}$ at Hadron Colliders

(Tevatron and LHC)

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

First searches at a Hadron collider in 2003 CDF,D0

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



- $\sigma_{H^{++}H^{--}}$ 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

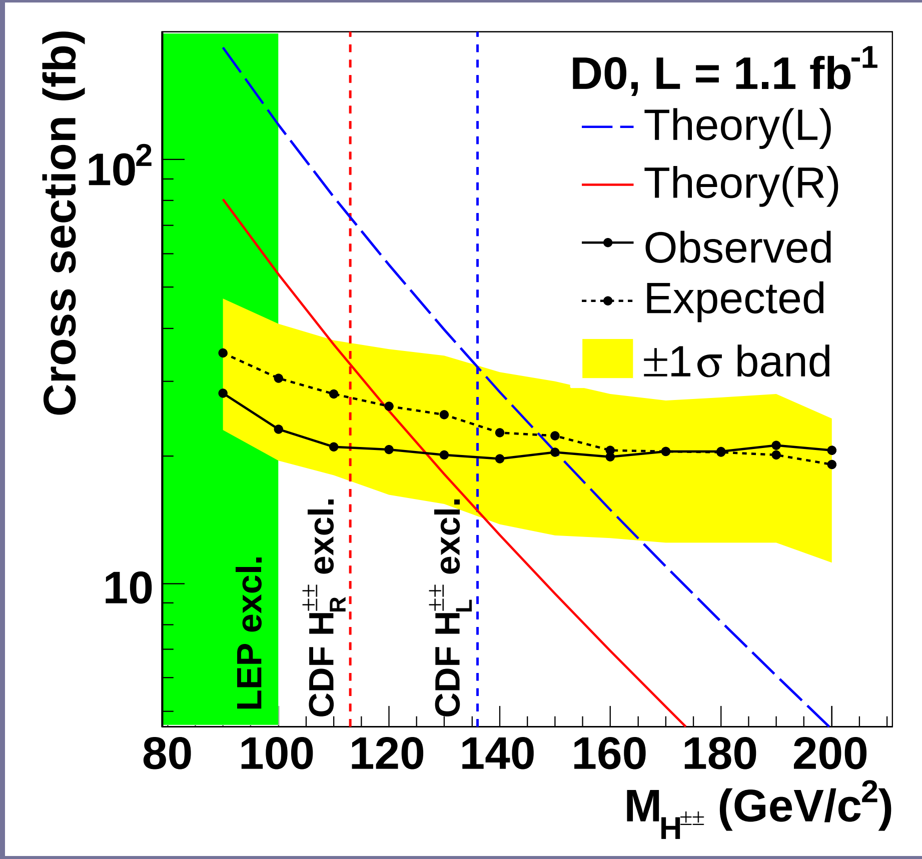
having the same charge

→ 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 $\mu^\pm \mu^\pm \mu^\mp$

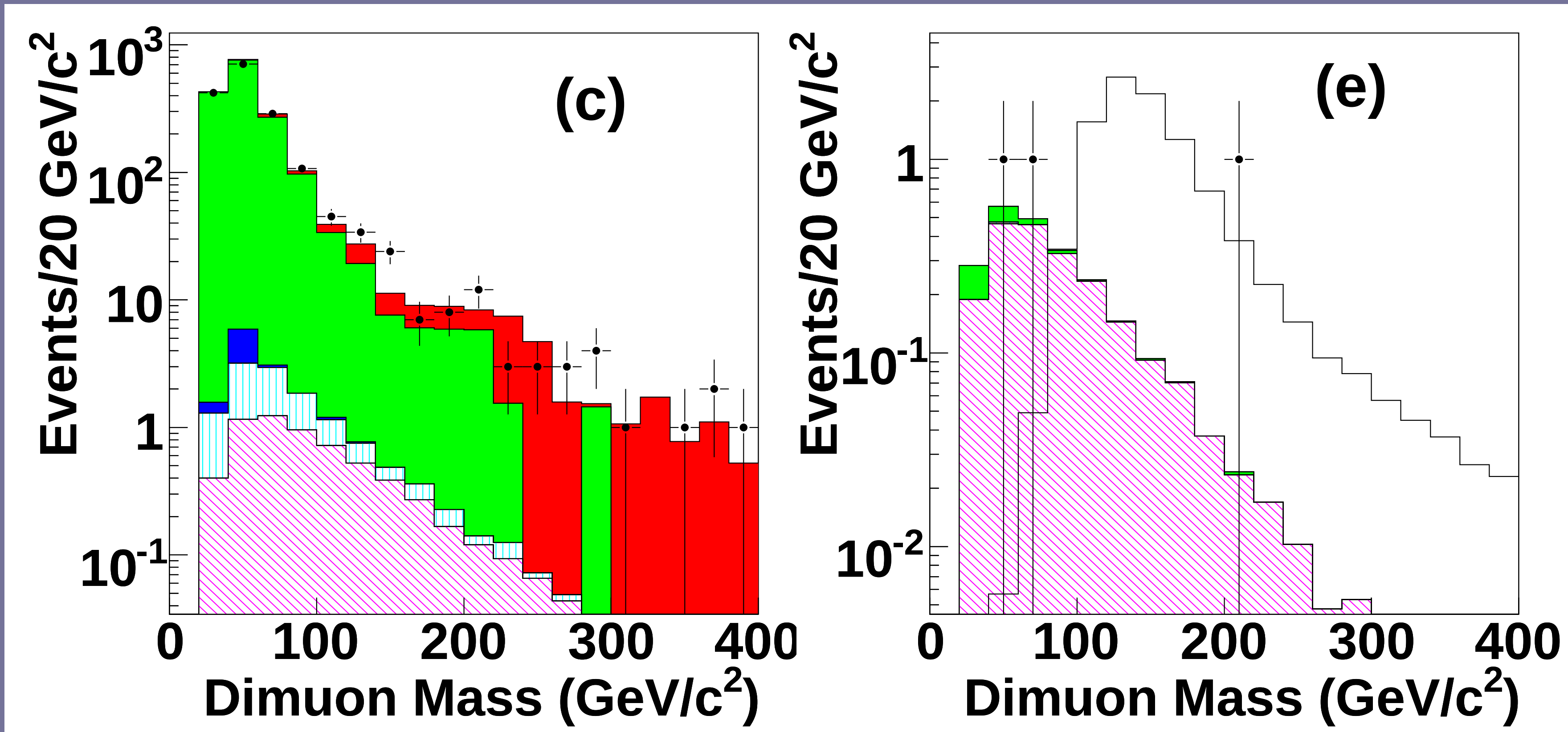
- Only $\mu^\pm\mu^\pm\mu^\mp$ has been searched for (1.1 fb^{-1} of data)
- Tevatron currently has 7 fb^{-1}, and expects $9 \to 12$ fb^{-1}

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



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

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



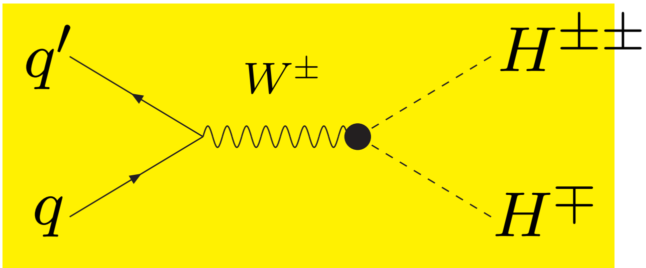
Two same-sign $\mu^{\pm}\mu^{\pm}$

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

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

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

Current searches are 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:

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

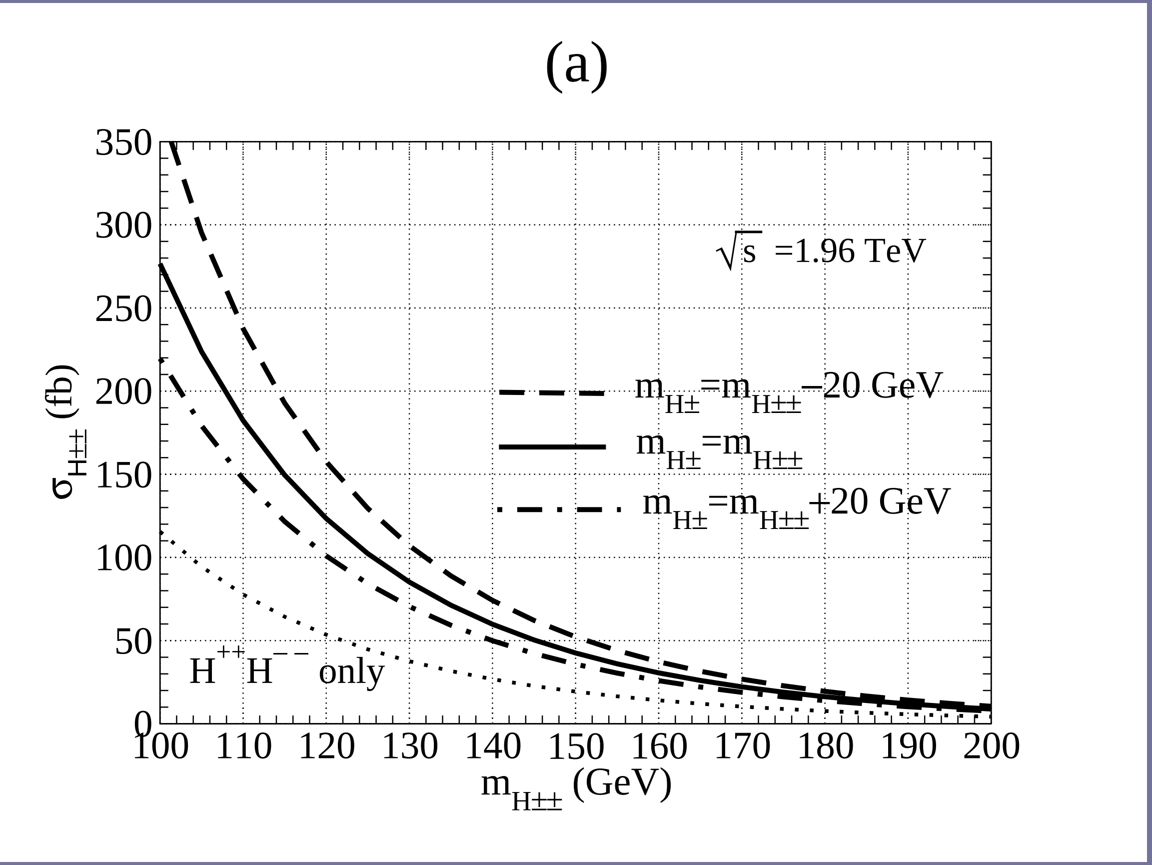
AGA, Aoki 05

- 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

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



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
- (Best?) Production process for $H^{\pm}$ of HTM at hadron colliders
- Now receiving attention as a main production mechanism for $H^{\pm\pm}$
- Recently simulated at LHC Han 08, Del Aguila 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

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 $\ell = e, \mu$

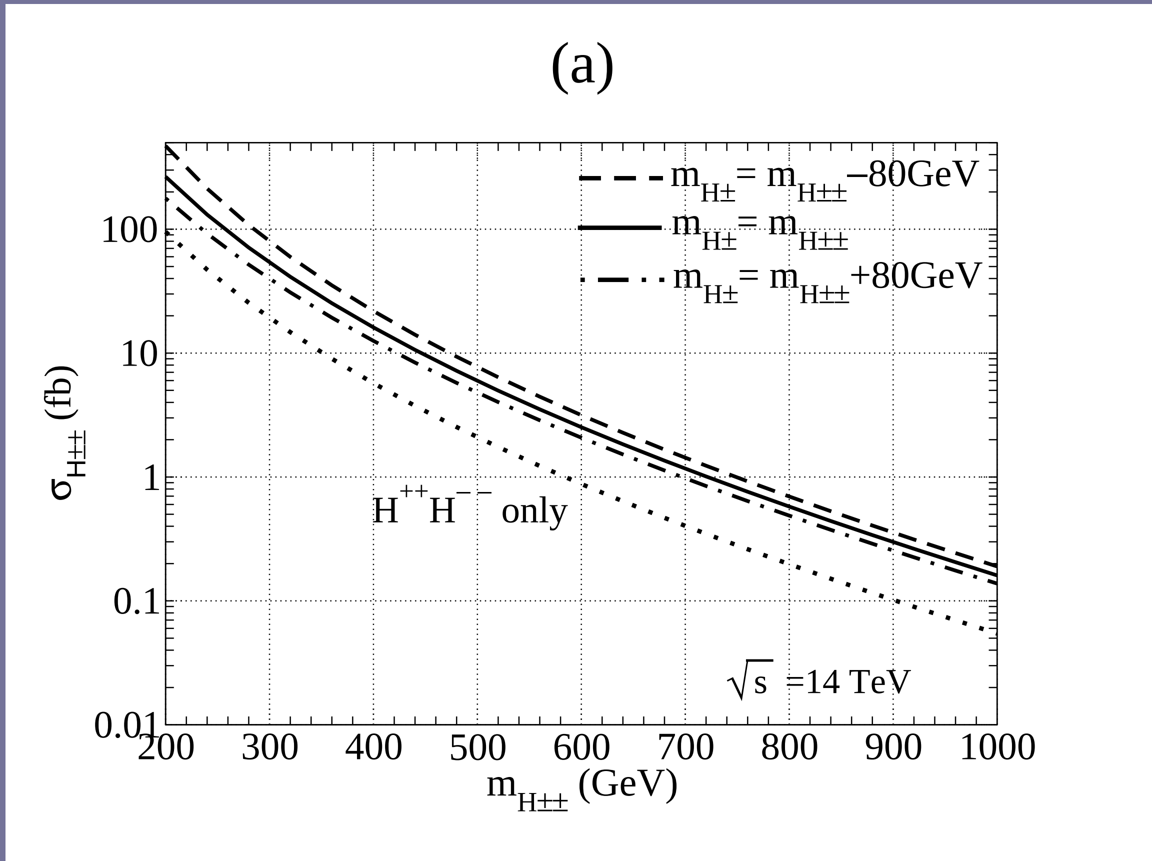
Large Event Numbers for $H^{\pm\pm}$:

$m_{H^{\pm\pm}}$ (GeV)	N_{pair} (30 fb^{-1})	N_{pair} (300 fb^{-1})	N_{incl} (300 fb^{-1})
200	1500	15000	42000
300	300	3000	8400
400	90	900	2500

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

AGA,Aoki 05

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



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

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

$q\overline{q} \longrightarrow H^{++}H^{--}$ and $qq' \longrightarrow H^{\pm\pm}H^{\mp}$

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: $H^{\pm\pm}H^{\mp}$ contributes

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

$\longrightarrow$ probes larger values of $m_{H^{\pm\pm}}$ (extra leptons vetoed)

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

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 $H^{\pm\pm} \to e^{\pm}\tau^{\pm}, \mu^{\pm}\tau^{\pm}, \tau^{\pm}\tau^{\pm}$
- After discovery: separate the contributions from

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

Conclusions

- Four different versions of the Two Higgs Doublet Model
- Phenomenology of $H^{\pm}$ differs in each model
- Some search channels yet to be simulated
- $H^{\pm\pm}$ arises in some models of neutrino mass generation

(e.g. Higgs Triplet Model)

- $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ is a distinctive signature
- $H^{\pm\pm}$ 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 $H^{\pm\pm}$

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

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

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

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

- $\text{BR}(\mu \to eee) < 10^{-12} \to |h_{\mu e} h_{ee}| < 10^{-7}$ 1988; no forthcoming experiment
- $\text{BR}(\tau \to \ell_i \ell_j \ell_k) < 10^{-8} \to |h_{\tau i} h_{jk}| < 10^{-4}$ Limits from ongoing B factories
- $\text{BR}(\mu \to e\gamma) < 10^{-11} \to \sum_i |h_{\mu i} h_{ei}| < 10^{-6}$ sensitivity to BR$\sim 10^{-13}$ from 2010

All constraints can be respected with suitably chosen h_{ij}

Provide valuable probes of virtual effects of $H^{\pm\pm}$