Phenomenology of 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 the Large Hadron Collider

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Electrically Charged Higgs Bosons (Scalars)

The Higgs boson of the Standard Model is a spinless, neutral particle with a vacuum expectation value ($v =$ 246 GeV, $m_f = h_f v$)

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, twice the charge of $e^{\pm}$)

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 (recently $I = 3/2$ and $I = 1/2$ studied)

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

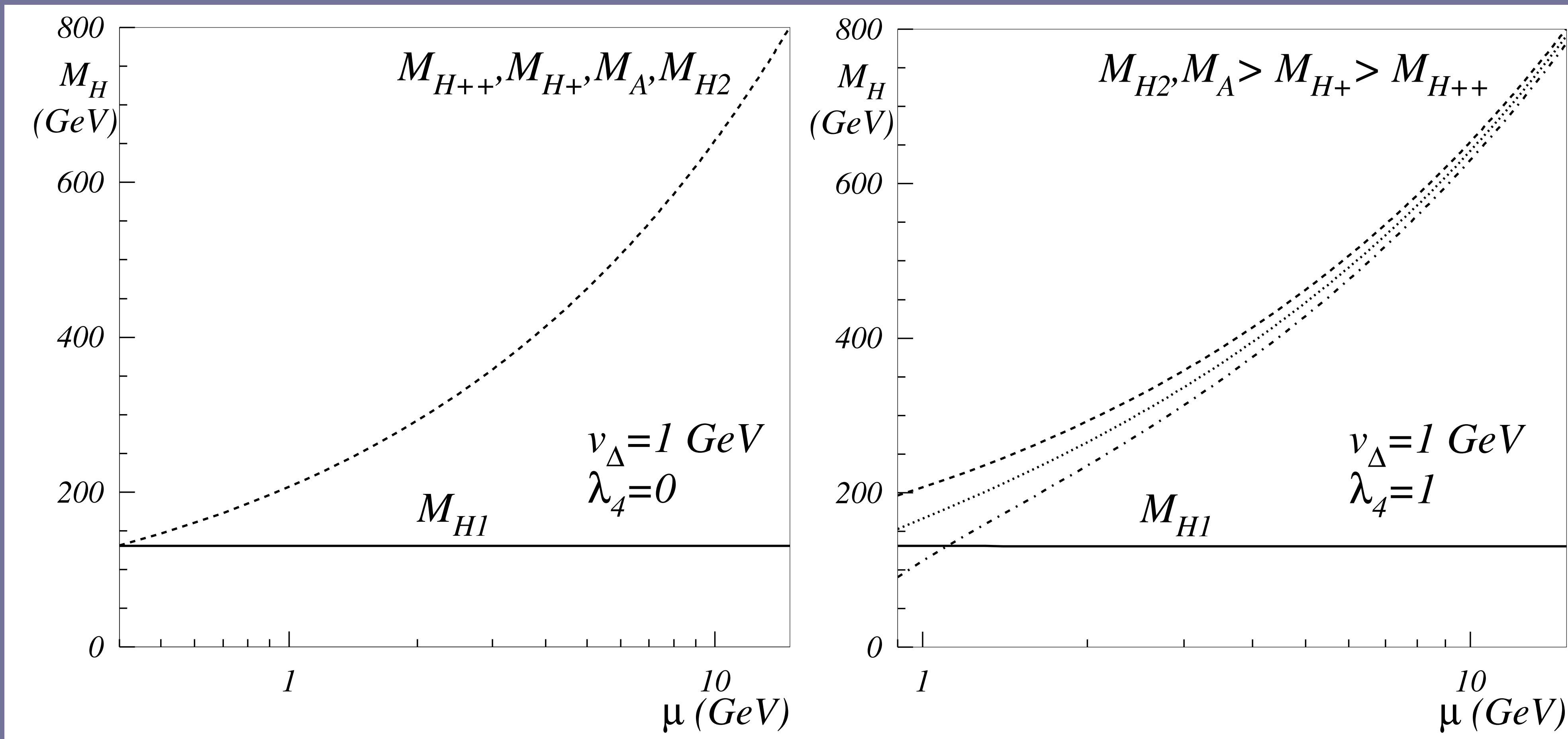
($v_\Delta \lesssim 5$ GeV to keep $\rho = (M_Z^2 \cos^2\theta_W)/M_W^2 \sim 1$); Δ has $L\# = 2$ and so $\mu(\Phi^T i\tau_2\Delta^\dagger\Phi)$ violates lepton number

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

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 $\lambda_4 > 0$ AGA/Chiang 10

Neutrino mass in Higgs Triplet Model (HTM)

No additional (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 Yukawa coupling, h_{ij} (complex and symmetric):

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

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

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

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

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

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

- In HTM: $h_{ij}v_\Delta \sim \mathcal{M}^\nu_{ij}$ (neutrino mass matrix)
- $\Gamma(H^{\pm\pm} \to \ell^\pm_i \ell^\pm_j) \sim |h_{ij}|^2 \sim 1/v^2_\Delta$; $\Gamma(H^{\pm\pm} \to W^\pm W^\pm) \sim v^2_\Delta$

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

Tevatron/LHC Searches have only been performed for $H^{\pm\pm} \to \ell^\pm \ell^\pm$

Decays of $H^{\pm}$:

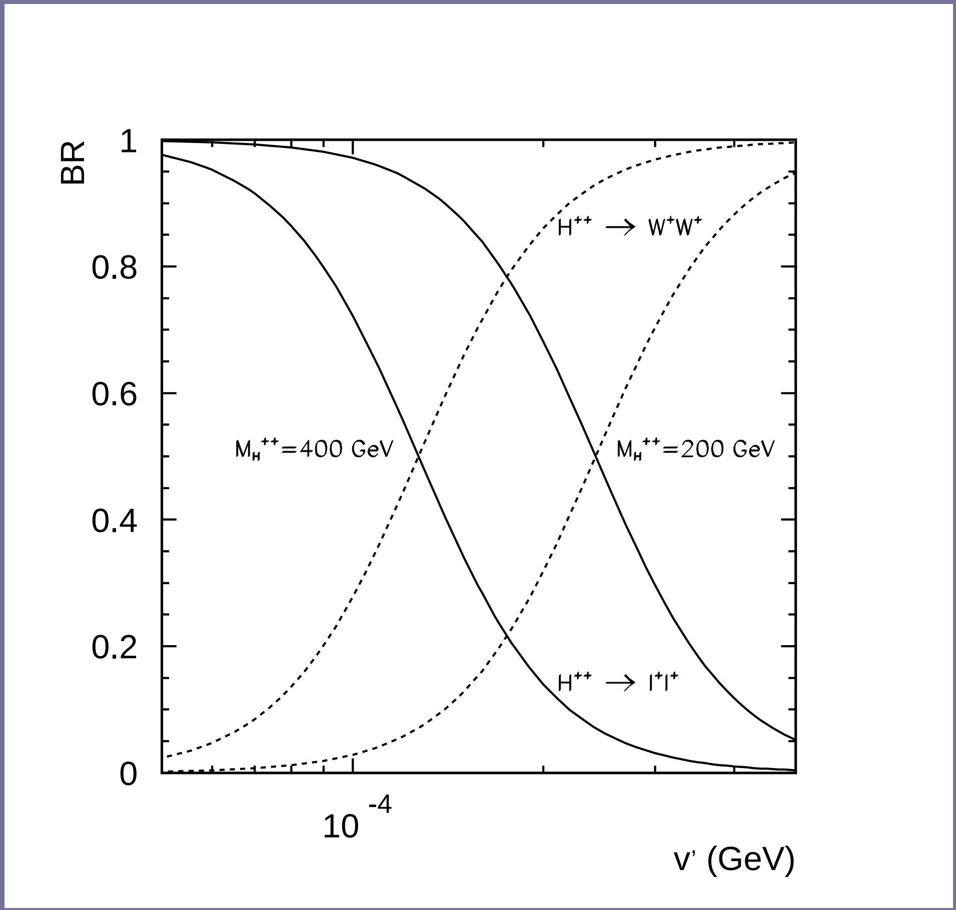
- $\Gamma(H^\pm \to \ell^\pm_i \nu) > \Gamma(H^\pm \to W^\pm Z, tb)$ for $v_\Delta < 10^{-4}$ GeV

Notably, if $h_{ij} > h_{electron}$ then necessarily $v_\Delta < 10^{-4}$ GeV

$\to$ leptonic decays $H^{\pm\pm} \to \ell^\pm_i \ell^\pm_j$ and $H^\pm \to \ell^\pm_i \nu$ dominate

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

Han 07, Asaka/Hikasa 94



I will only discuss the phenomenology of $H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$ (not $H^{\pm\pm} \to W^{\pm}W^{\pm}$), assuming $v_\Delta < 10^{-4}$ GeV

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

BR($H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$) determined by h_{ij} (six decays $ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$)

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

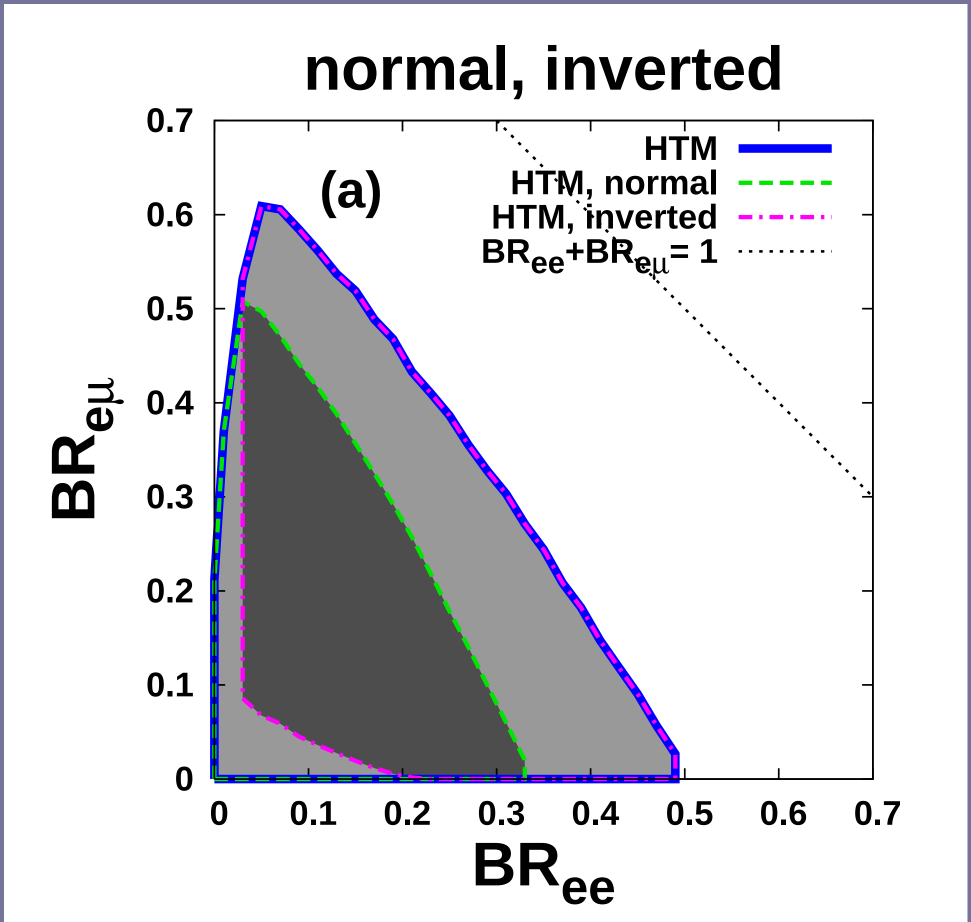
In HTM h_{ij} is directly related to the neutrino mass matrix

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

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

- Neutrino mass 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

- $\mathrm{BR}(\mu \to eee) < 10^{-12} \to |h_{\mu e} h_{ee}| < 10^{-7}$ 1988; no forthcoming experiment
- $\mathrm{BR}(\tau \to \ell_i \ell_j \ell_k) < 10^{-8} \to |h_{\tau i} h_{jk}| < 10^{-4}$ Limits from ongoing B factories
- $\mathrm{BR}(\mu \to e\gamma) < 10^{-11} \to \sum_i |h_{\mu i} h_{ei}| < 10^{-6}$ sensitivity to BR$\sim 10^{-13}$ from 2012

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

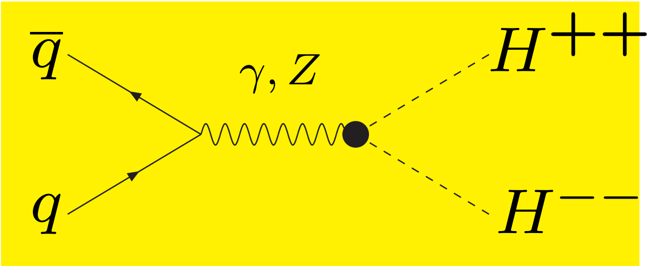
These decays provide valuable probes of virtual effects of $H^{\pm\pm}$

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

Pair production of $H^{\pm\pm}$ at Hadron Colliders

First searches at a hadron collider in 2003 Tevatron: CDF,D0

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

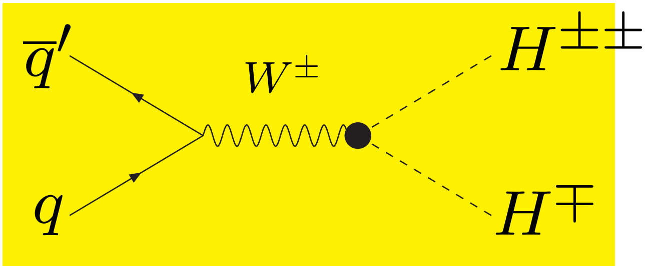


- $\sigma_{H^{++}H^{--}}$ is a simple function of $m_{H^{\pm\pm}}$ Barger 82, Gunion 89, Raidal 96
- $\sigma_{H^{++}H^{--}}$ has no dependence on h_{ij}

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

A mechanism not included in the Tevatron searches

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

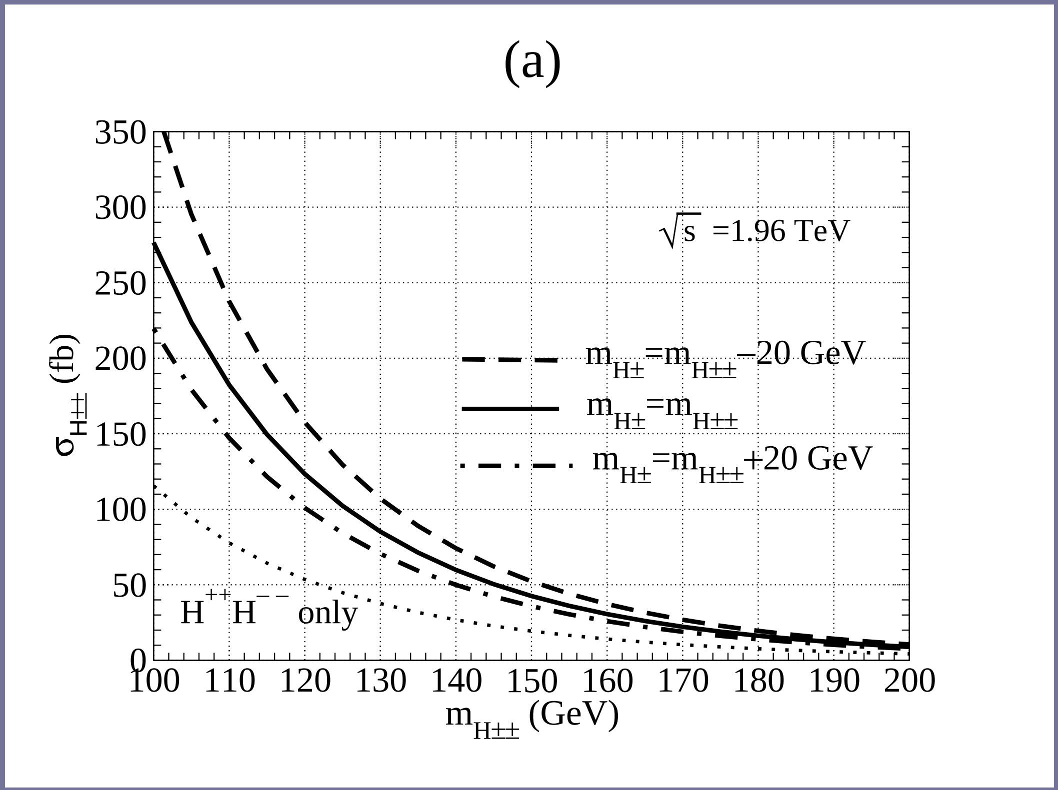


- $\sigma_{H^{\pm\pm}H^{\mp}}$ is a function of $m_{H^{\pm\pm}}$ and $m_{H^\pm}$ Barger 82, Dion 98
- Similar magnitude to $\sigma(p\overline{p} \to H^{++}H^{--})$ for $m_{H^{\pm\pm}} \sim m_{H^\pm}$

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

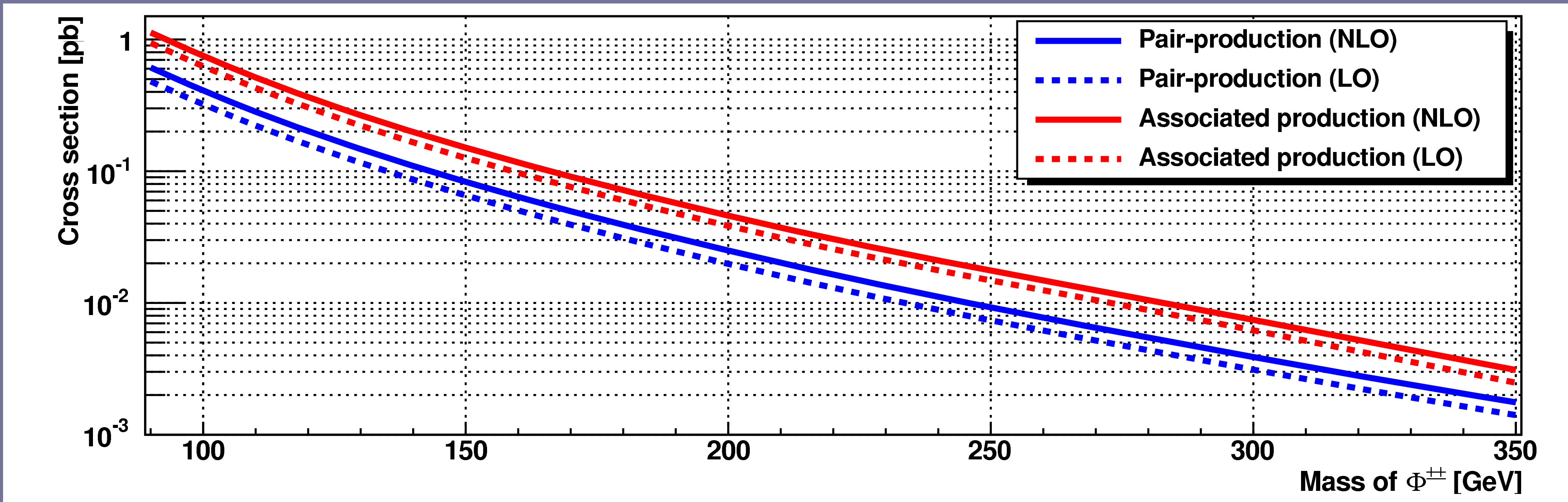
AGA,Aoki 05

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



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

LHC cross sections at $\sqrt{s} = 7$ TeV for $q\bar{q} \to H^{++}H^{--}$ and $q\bar{q}' \to H^{\pm\pm}H^{\mp}$



$\sigma(q\bar{q}' \to H^{\pm\pm}H^{\mp}) > \sigma(q\bar{q} \to H^{++}H^{--})$ for $m_{H^{\pm}} = m_{H^{\pm\pm}}$ and so should be included in searches

Importance of $q\overline{q}' \to H^{\pm\pm}H^{\mp}$

- $\sigma(q\overline{q}' \to H^{\pm\pm}H^{\mp})$ can be as large as $\sigma(q\overline{q} \to H^{++}H^{--})$
- Increases the sensitivity to $m_{H^{\pm\pm}}$ in 2ℓ and 3ℓ search channels, thus enhancing the discovery potential for $H^{\pm\pm}$ AGA,Aoki 05
- Received almost no theoretical attention from 1982 to 2005
- Not included in event generator Pythia, unlike $q\overline{q} \to H^{++}H^{--}$
- In AGA/Chiang/Gaur 10 we created a CalcHEP file to generate events for $q\overline{q}' \to H^{\pm\pm}H^{\mp}$, which can then be used as input for Pythia
- This enabled the CMS collaboration to carry out a search for $q\overline{q}' \to H^{\pm\pm}H^{\mp}$

Strategy of search for $H^{\pm\pm}$ by CMS collaboration (LHC)

- $H^{\pm\pm}$ decays via h_{ij} to *same charge* $ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$
- In the HTM, BR($H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$) depends mainly on

i) neutrino mass m_1 and ii) Majorana phases ϕ_1 and ϕ_2

- Define four benchmark points for BR($H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$)

	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
BP1 (normal hierarchy)	0	0.01	0.3	0.01	0.38	0.3
BP2 (inverted hierarchy)	0.50	0	0.125	0	0.25	0.125
BP3 (degenerate neutrinos)	1/3	0	1/3	0	0	1/3
BP4 (equal branching ratios)	1/6	1/6	1/6	1/6	1/6	1/6

Search strategy for $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ and $H^{\pm} \to \ell^{\pm}\nu$ at LHC

CMS search for $H^{\pm\pm}$ is the first one to include both production mechanisms $q\overline{q} \to H^{++}H^{--}$ and $qq' \to H^{\pm\pm}H^{\mp}$ (CMS PAS HIG-11-007)

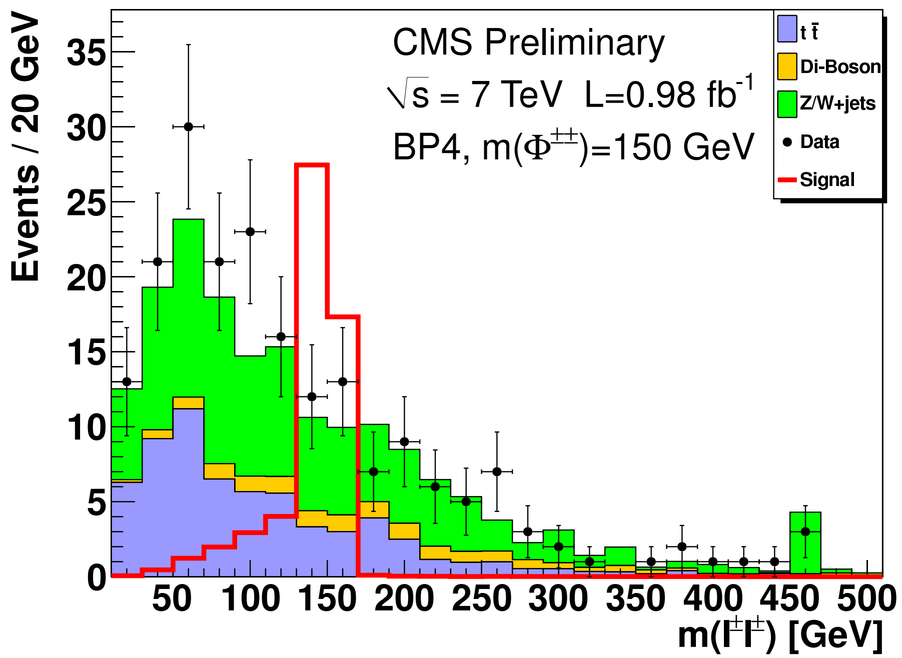
i) 4ℓ signature ($\ell^{+}\ell^{+}\ell^{-}\ell^{-}$):

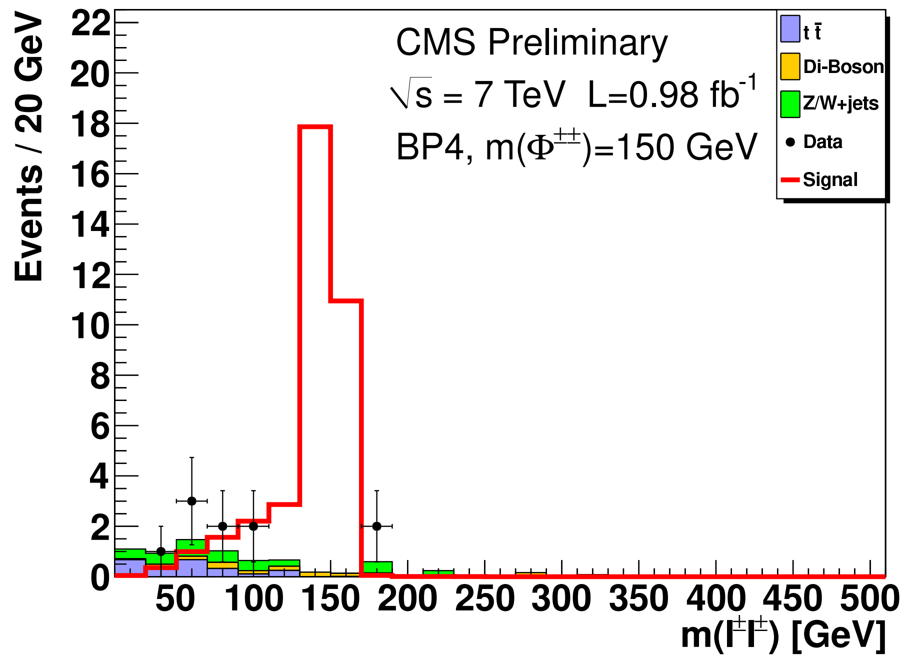
- Backgrounds are negligible after all selection cuts
- Only $H^{++}H^{--}$ contributes to the signal

ii) 3ℓ signature ($\ell^{\pm}\ell^{\pm}\ell^{\mp}$):

- $H^{\pm\pm}H^{\mp}$ contributes to the signal (assume $m_{H^{\pm}} = m_{H^{\pm\pm}}$)
- $H^{++}H^{--}$ contributes if one lepton is missed

LHC (CMS collaboration) search for 3ℓ signature

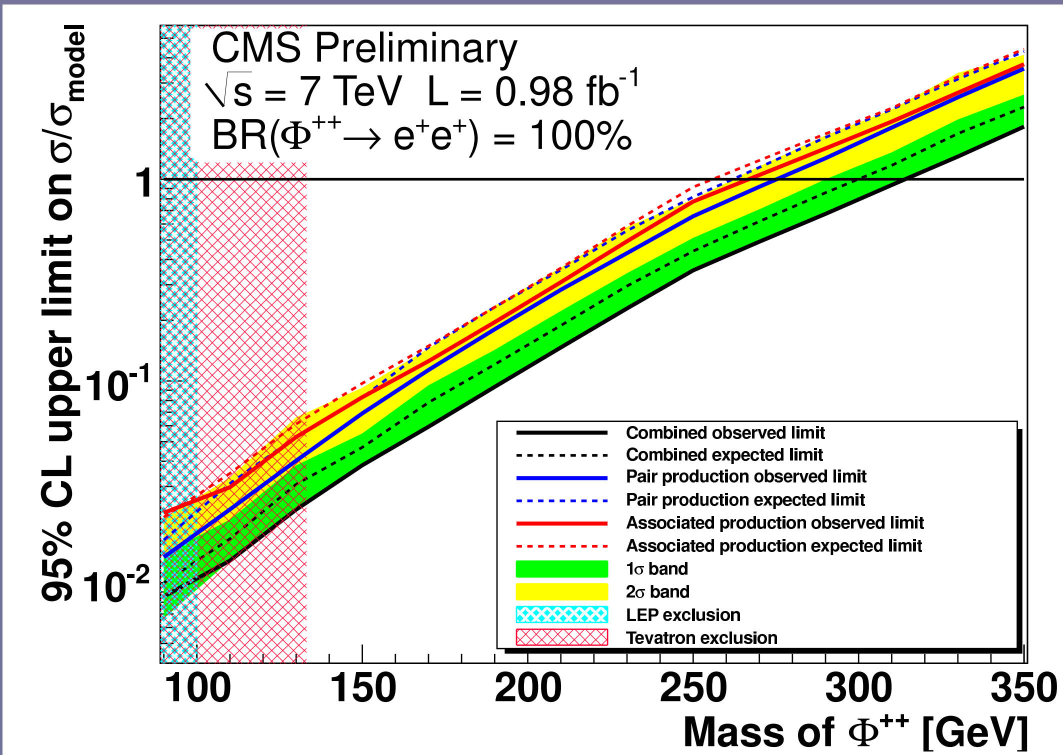


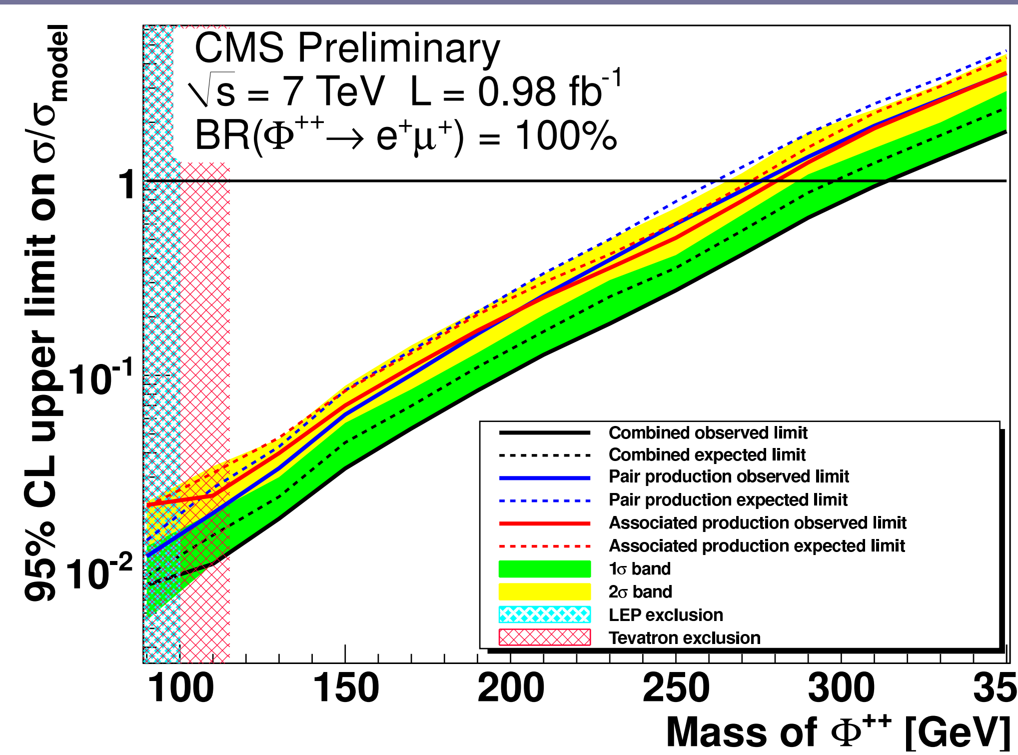


After pre-selection cuts (signal for BP4)

After all selection cuts (signal for BP4)

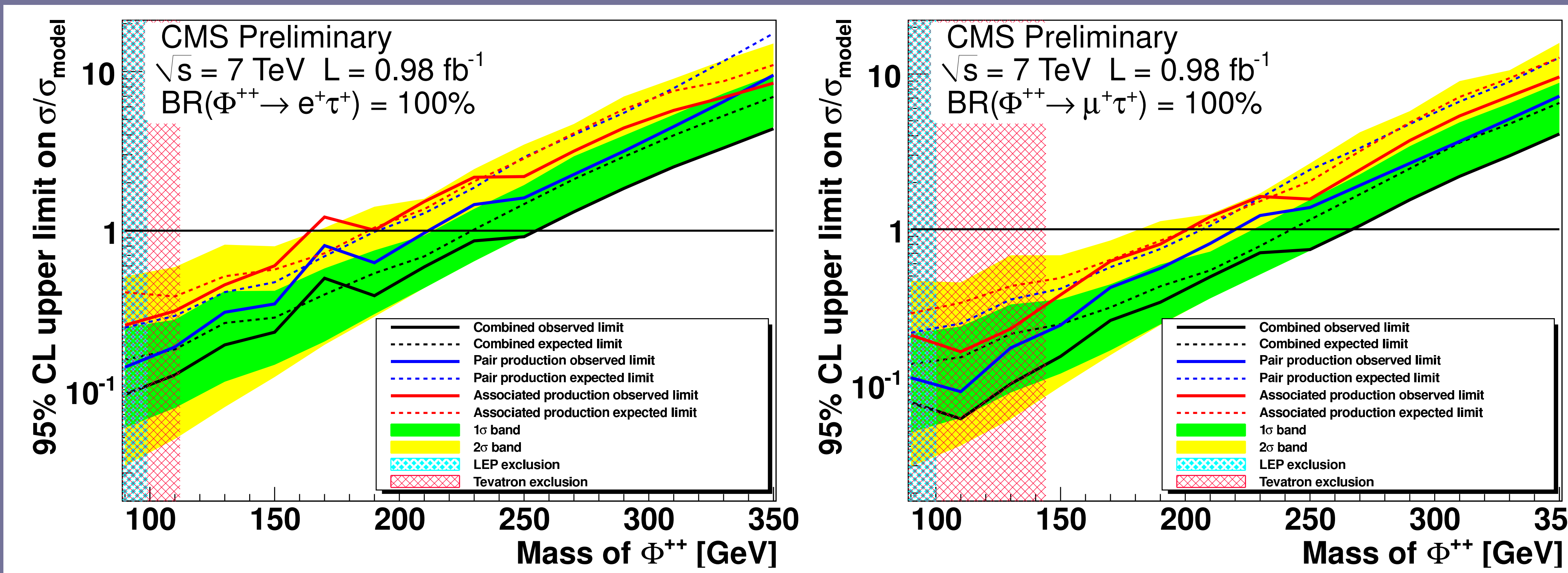
Excluded cross sections from 3ℓ and 4ℓ search: ee and $e\mu$ channels





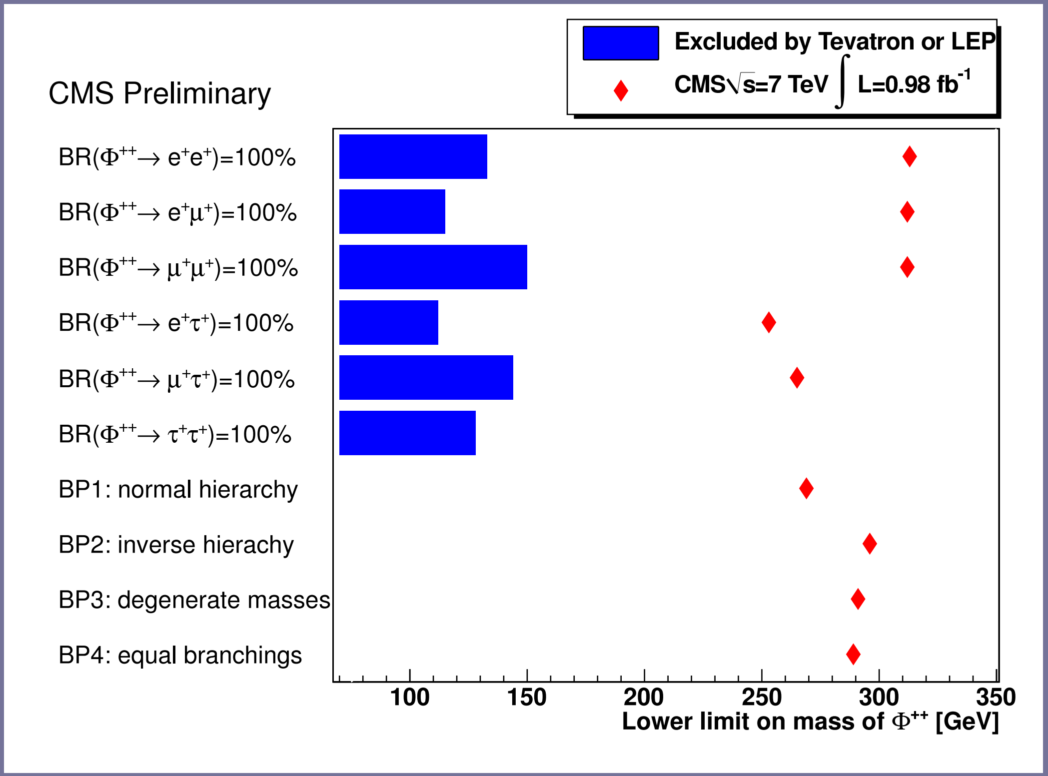
3ℓ (red) and 4ℓ (blue) have very similar sensitivity to $m_{H^{\pm\pm}}$. When combined, give stronger limit on $m_{H^{\pm\pm}}$.

Excluded cross sections from 3ℓ and 4ℓ search: $e\tau$ and $\mu\tau$ channels



4ℓ search (blue) has greater sensitivity to $m_{H^{\pm\pm}}$ than 3ℓ search

Mass limits on $m_{H^{\pm\pm}}$ from CMS search for $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$



Mass limit $m_{H^{\pm\pm}} > 300$ GeV for BR$(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = 100\%$ for $\ell = e, \mu$

Recent ATLAS search for $H^{\pm\pm} \to \mu^\pm\mu^\pm$ arXiv:1201.1091

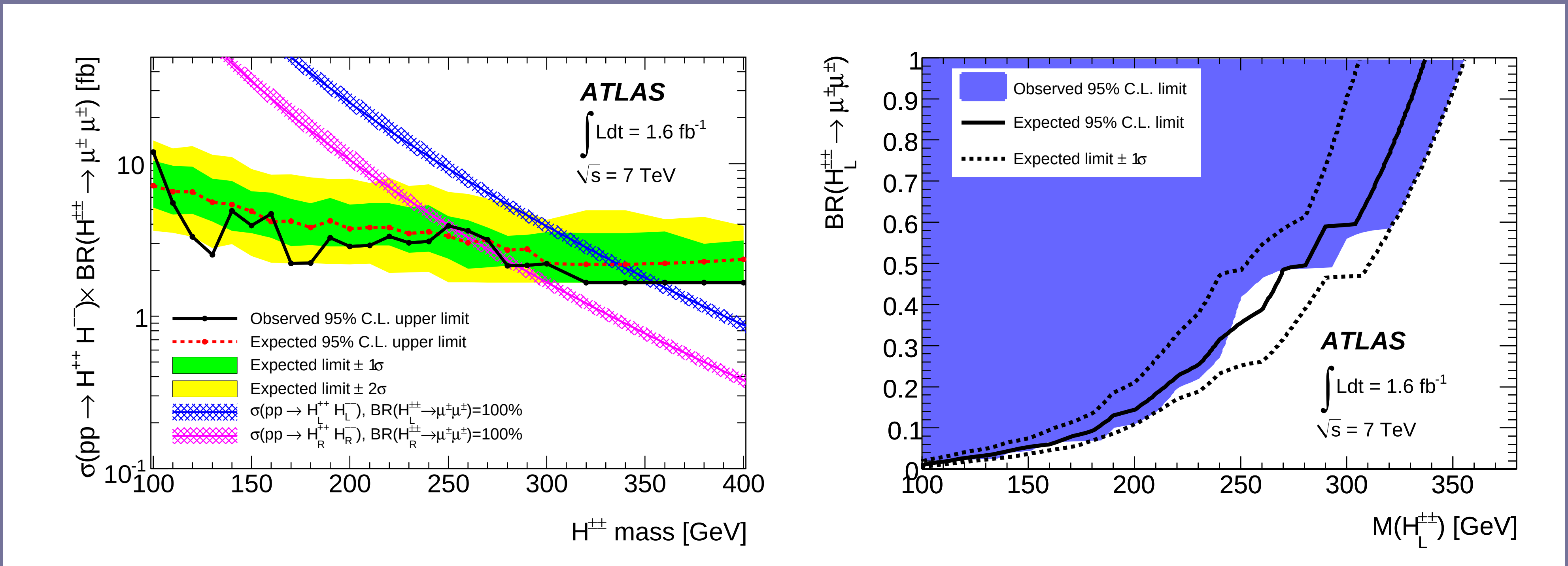
ATLAS has performed three searches for $q\overline{q} \to H^{++}H^{--}$

- Search in arXiv:1201.1091 is only performed for $H^{\pm\pm} \to \mu^\pm\mu^\pm$
- Uses 1.6 fb^{-1} of integrated luminosity (CMS used 0.98 fb^{-1})
- Signal is defined as two same-signed $(\mu^\pm\mu^\pm)$
- Differs from CMS search strategy ($\ell^\pm\ell^\pm\ell^\mp$ and $\ell^+\ell^+\ell^-\ell^-$)
- Number of signal events is linear (not quadratic)

in BR($H^{\pm\pm} \to \mu^\pm\mu^\pm$)$\to$ can probe smaller values of BR

- Current search does not include $q\overline{q}' \to H^{\pm\pm}H^{\mp}$

ATLAS search for $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$ with 1.6 fb^{-1} (CMS used 0.98 fb^{-1})



Limit $m_{H^{\pm\pm}} > 355$ GeV; stronger than CMS bound for $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$ ($m_{H^{\pm\pm}} > 313$ GeV)

Status of searches for $H^{\pm\pm}$ at LHC

The CMS collboration has performed the first search (July 2011) for $H^{\pm\pm}$ at the LHC (CMS PAS HIG-11-007)

- Used $0.98 fb^{-1}$ at $\sqrt{s} = 7$ TeV
- Both 4ℓ and 3ℓ signatures studied
- All six decay channels investigated: $ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$
- For the first time $\overline{q}q' \to H^{\pm\pm}H^{\mp}$ included in search for $H^{\pm\pm}$
- ATLAS (Aug/Oct/Nov 2011) have searched for 2ℓ, 3ℓ, 4ℓ
- Have not yet included $\overline{q}q' \to H^{\pm\pm}H^{\mp}$ in the 2ℓ and 3ℓ searches

Case of non-degeneracy of triplet scalars

$$m_{H^{\pm\pm}} < m_{H^{\pm}} < m_{H^0,A^0}$$

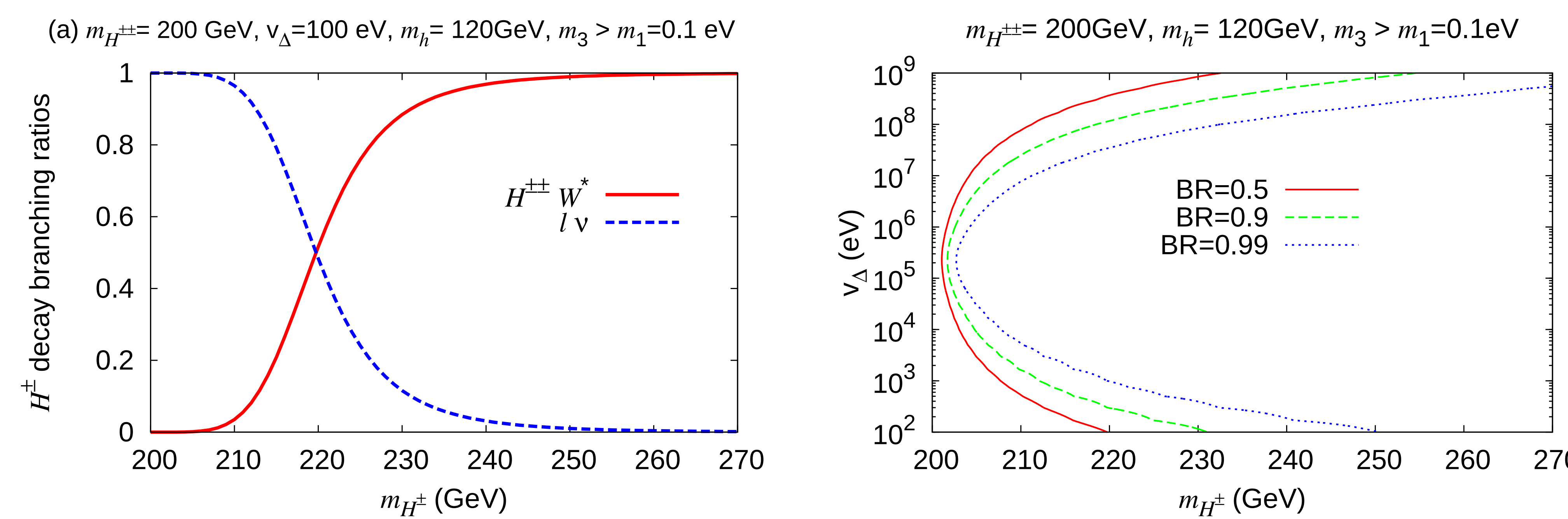
Case of non-degeneracy of triplet scalars

The ongoing CMS searches assume $\boxed{m_{H^{\pm\pm}} = m_{H^\pm} = m_{H^0,A^0}}$

This is only true if $\lambda_4 = 0$ in scalar potential term $\lambda_4\ H^\dagger \Delta \Delta^\dagger H$

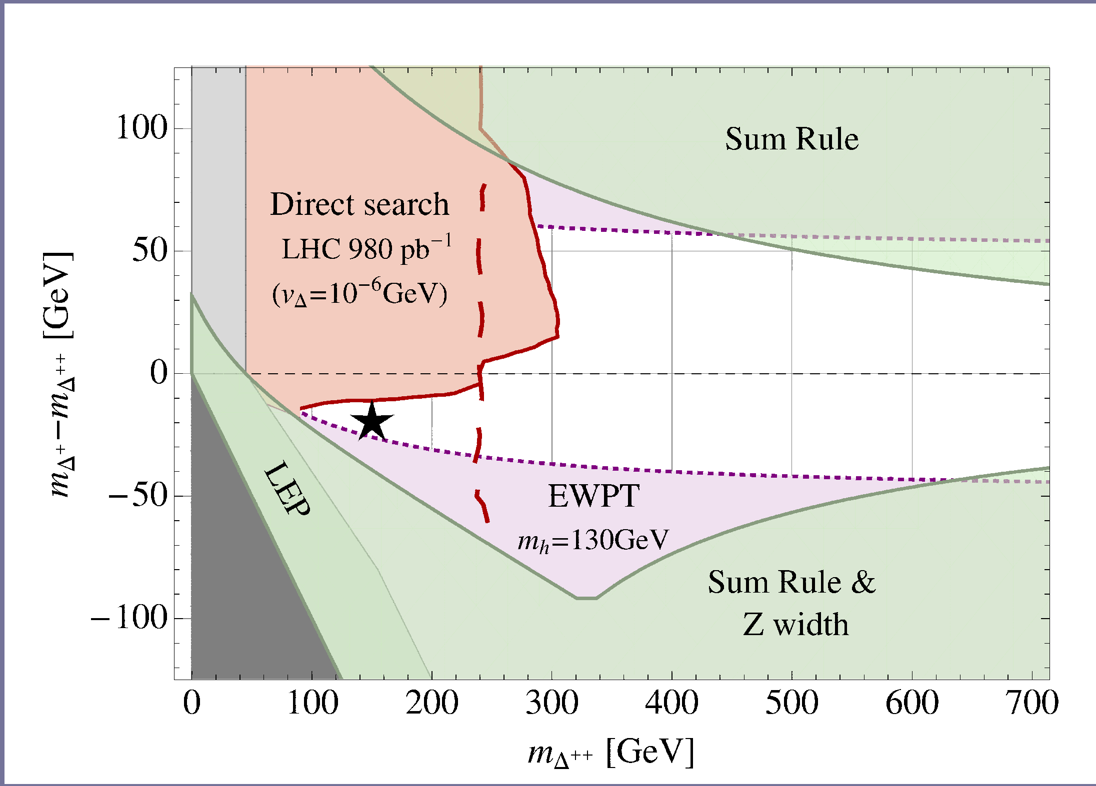
- For $\lambda_4 > 0$ one has $m_{H^{\pm\pm}} < m_{H^\pm} < m_{H^0,A^0}$
- The decay $H^\pm \to H^{\pm\pm} W^*$ would be open, and can have a large branching ratio even for $m_{H^\pm} - m_{H^{\pm\pm}} << m_W$
- $q'\overline{q} \to W^* \to H^{\pm\pm} H^\mp$ then leads to $\boxed{H^{++} H^{--} W^*}$ AGA/Sugiyama 11
- Would increase sensitivity to $m_{H^{\pm\pm}}$ in 4ℓ searches

BR($H^{\pm} \to H^{\pm\pm}W^*$) as a function of ($m_{H^{\pm}} - m_{H^{\pm\pm}}$) and v_{Δ} AGA/Sugiyama 11



Large parameter space for BR($H^{\pm} \to H^{\pm\pm}W^*$) > 50%

CMS sensitivity (with 0.98 fb^{-1}) to $m_{H^{\pm\pm}}$ in $\ell^+\ell^+\ell^-\ell^-$ channel as function of $m_{H^\pm} - m_{H^{\pm\pm}}$



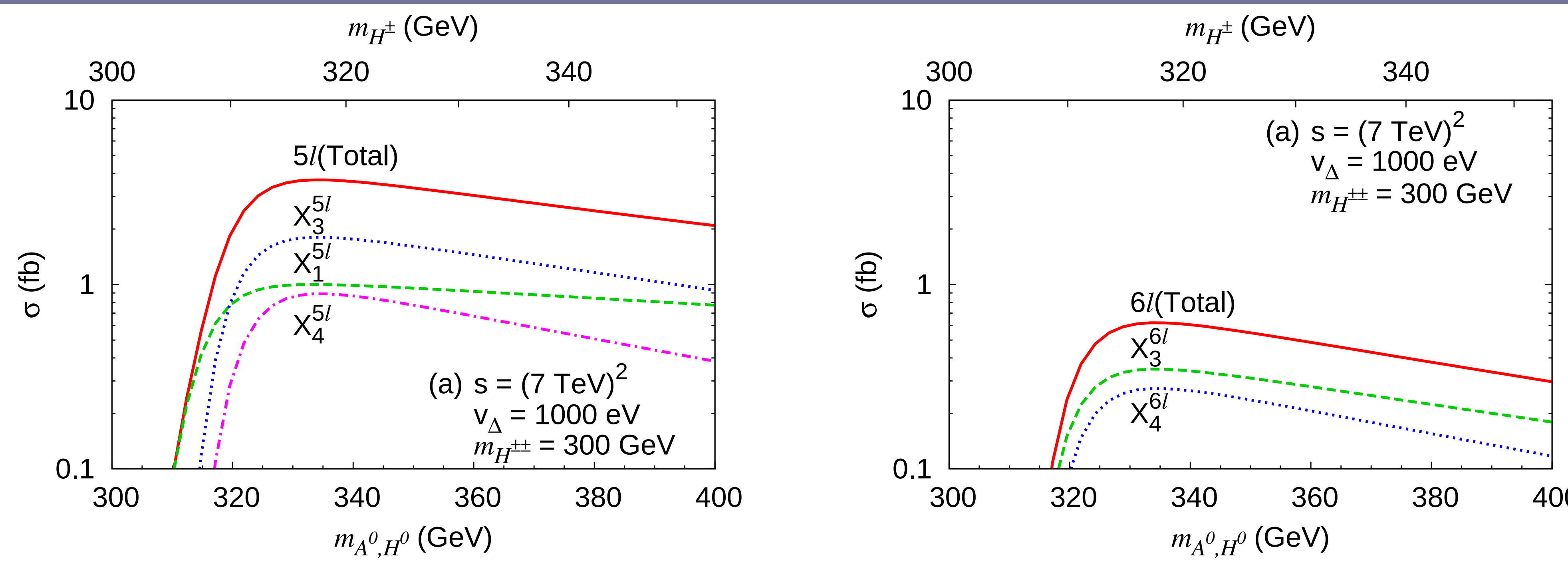
$\bar{q}q' \to H^{\pm\pm}H^{\mp}$ with $H^{\pm} \to H^{\pm\pm}W^*$ increases sensitivity to $m_{H^{\pm\pm}}$ by as much as 50 GeV Senjanovic et al 11

Five-lepton/six-lepton signals and detection of H^0 and A^0

Several cascade decays involving neutral triplet scalars

- $\mathrm{BR}(A^0 \to H^\pm W^*)$ and $\mathrm{BR}(H^0 \to H^\pm W^*)$ can also be $\sim 100\%$
- $q'\bar{q} \to W^* \to H^\pm H^0, H^\pm A^0$ leads to $H^{++}H^{--}W^*W^*W^*$
- $q\bar{q} \to Z^* \to H^0 A^0$ leads to $H^{++}H^{--}W^*W^*W^*W^*$
- $W^* \to \ell\nu$ $(\ell = e, \mu)$ of particular interest
- Leads to 5ℓ and 6ℓ signatures with negligible background
- Would enable detection of H^0 and A^0 AGA/Moretti/Sugiyama 12
- No search yet for 5ℓ and 6ℓ signatures

Cross sections for 5-lepton and 6-lepton signatures at LHC with $\sqrt{s} = 7$ TeV



Maximum of 4 fb for 5ℓ and 0.6 fb for 6ℓ AGA/Moretti/Sugiyama 12

Conclusions

- Doubly charged Higgs bosons appear in the Higgs Triplet Model of neutrino mass generation
- Neutrino mass generated at tree-level as $h_{ij}v_\Delta$
- $H^{\pm\pm} \longrightarrow \ell^\pm\ell^\pm$ is a distinctive signal
- Multi-lepton signals $(2\ell \rightarrow 6\ell)$ from $q\overline{q} \longrightarrow H^{++}H^{--}$ / $q'\overline{q} \longrightarrow H^{\pm\pm}H^{\mp}$
- Searches $(2\ell \rightarrow 4\ell)$ are ongoing, with sensitivity $m_{H^{\pm\pm}} <$ 300 GeV
- The HTM also predicts a SM-like Higgs boson in most of the parameter space of the scalar potential
- A large parameter space of the model will be probed at the LHC