Phenomenology of the Higgs Triplet Model at the LHC

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- Higgs Triplet Model (HTM) and doubly charged scalars ($H^{\pm\pm}$)
- The decay channel $H_1 \to \gamma\gamma$ and contribution from $H^{\pm\pm}$
- 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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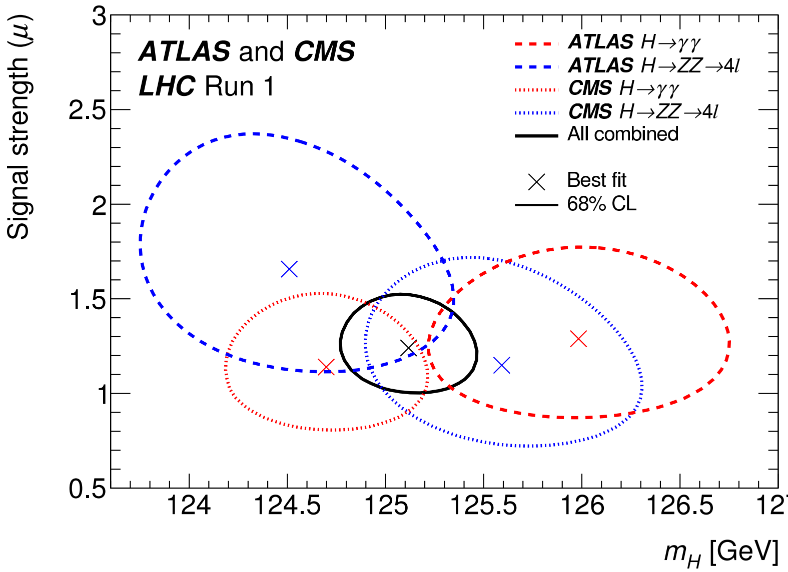
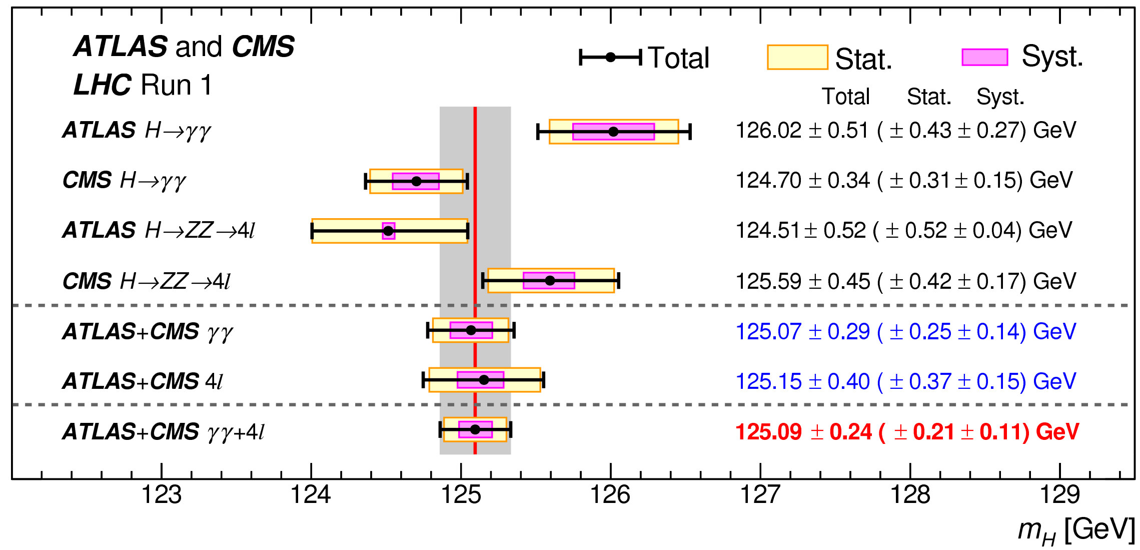
Seminar at IPMU Kashiwa 29 July 2015 (based on work from 2005 $\to$ 2013)

CERN Large Hadron Collider

- LHC is now colliding protons at $\sqrt{s} = 13$ TeV
- It will collect up to $\sim 300\text{fb}^{-1}$
- $\sim 5\text{fb}^{-1}$ at $\sqrt{s} = 7$ TeV; $\sim 20\text{fb}^{-1}$ at $\sqrt{s} = 8$ TeV
- Futher study of the 125 GeV Higgs boson
- LHC will search for new physics particles
- Extra Higgs bosons, SUSY particles, dark matter..

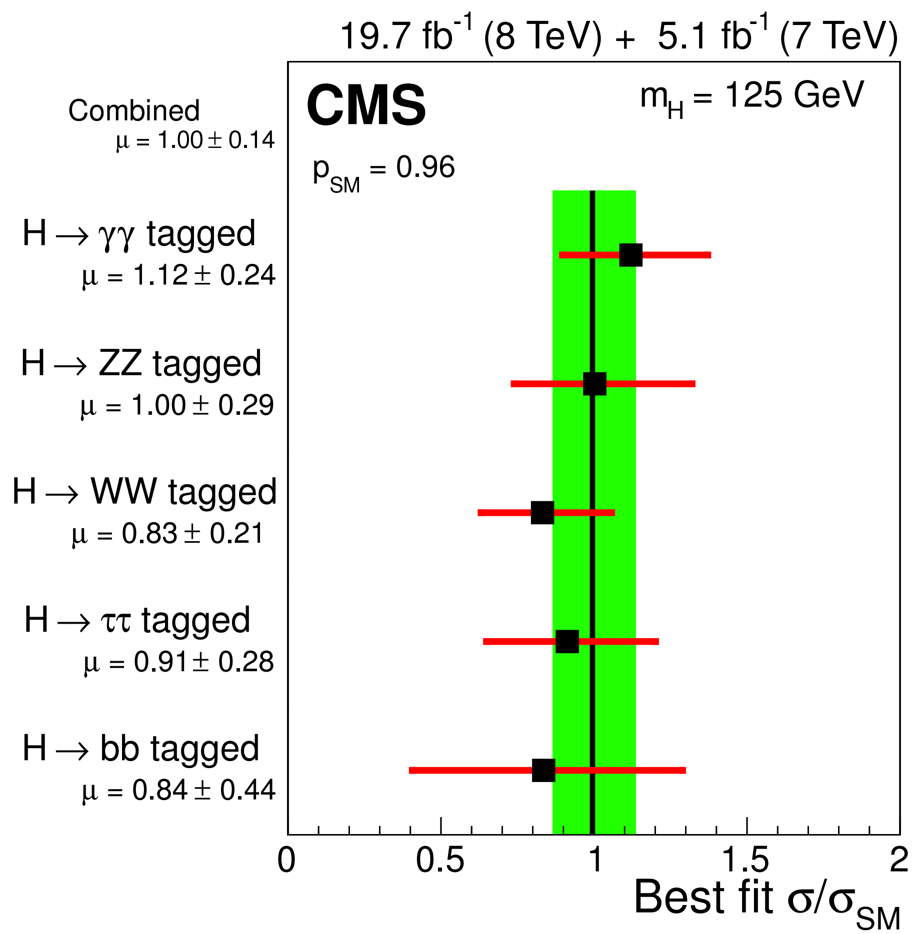
Discovery of a SM-like Higgs boson by ATLAS and CMS





- Clear signals in $H \to \gamma\gamma$ and $H \to ZZ^* \to \ell\ell\ell\ell$ channels
- Some evidence of $H \to b\bar{b}, \tau\tau, WW^*$
- Branching ratios in agreement with SM Higgs boson

Measured signal strengths relative to SM Higgs boson



Reasons to consider a non-minimal Higgs sector

- Neutrino mass (the motivation for the Higgs Triplet Model)
- (Scalar) Dark matter
- CP violation
- Supersymmetry
- A general non-minimal Higgs sector has additional neutral scalars H^0,A^0 and/or electrically charged scalars $H^{\pm}$, $H^{\pm\pm}$,...
- LHC searches for additional scalars of high priority now

Additional motivation for electrically charged scalars ($H^{\pm}$)

- A neutral scalar (spin=0) has been found at the LHC
- There might exist charged scalars, $H^{\pm}$,$H^{\pm\pm}$
- Classify elementary particles by their electric charge and spin

	Spin 0	Spin 1/2	Spin 1
Neutral Charged	h^0 ($H^{\pm}$,$H^{\pm\pm}$)?	ν_e, ν_μ, ν_τ $e^{\pm}, \mu^{\pm}, \tau^{\pm}, u, d, s, c, b, t$	γ,Z,g $W^{\pm}$

Why not charged, spin 0 particles $H^{\pm}$, $H^{\pm\pm}$?

The Higgs Triplet Model, HTM

Motivation → neutrino mass generation

- An isospin scalar doublet and an isopin scalar triplet $I = 1$
- Tree-level mass for neutrinos ("Type II seesaw mechanism")
- This model is in the textbooks ("a classic model")

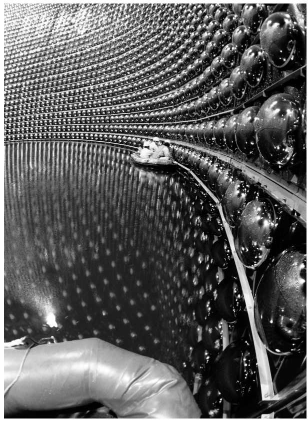
and is usually called the Higgs Triplet Model (Doublet-Triplet Model)

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

- Predicts a "Doubly Charged Higgs Boson", $H^{\pm\pm}$

(twice the electric charge of $e^{\pm}$), and a singly charged $H^{\pm}$

Neutrino Mass and Mixing



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

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

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) *Third angle* has recently been measured: $\sin^2 2\theta_{13} \sim 0.09$

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

Higgs Triplet Model (HTM)

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

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

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

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

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

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

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: $\mathcal{M}_{ij}^{\nu} \sim v_\Delta h_{ij}$

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

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

Higgs boson spectrum

The HTM has 7 Higgs bosons: $H^{\pm\pm}, H^{\pm}, A^0, H_2, H_1$

- $H^{\pm\pm}$ is *purely triplet*: $H^{\pm\pm} \equiv \delta^{\pm\pm}$
- $H^{\pm}, A^0, H_2, H_1$ are mixtures of doublet (ϕ) and triplet (δ) fields
- Mixing $\sim v_\Delta/v$ and small ($v_\Delta/v < 0.03$)
- H_1 plays role of *SM Higgs boson* (essentially $I = 1/2$ doublet)
- $H^{\pm}, H_2, A^0$ are *dominantly* composed of triplet fields
- Masses of $H^{\pm\pm}, H^{\pm}, H_2, A^0$ close to degenerate $\sim M_\Delta$
- For $H^{\pm\pm}$, $H^{\pm}$ in range at LHC require $M_\Delta < 1$ TeV

Scalar masses in terms of the input parameters

$$m_{H_1}^2 = \frac{\lambda}{2} v^2 \quad \text{(as in the SM)}$$

$$m_{H^{\pm\pm}}^2 = M_\Delta^2 + \frac{\lambda_1}{2} v^2 + \lambda_2 v_\Delta^2$$

$$m_{H^\pm}^2 = M_\Delta^2 + (\frac{\lambda_1}{2} + \frac{\lambda_4}{4}) v^2 + (\lambda_2 + \sqrt{2}\lambda_3) v_\Delta^2$$

$$m_{H_2}^2 = M_\Delta^2 + (\frac{\lambda_1}{2} + \frac{\lambda_4}{2}) v^2 + 3(\lambda_2 + \lambda_3) v_\Delta^2$$

$$m_{A^0}^2 = M_\Delta^2 + (\frac{\lambda_1}{2} + \frac{\lambda_4}{2}) v^2 + (\lambda_2 + \lambda_3) v_\Delta^2$$

Terms proportional to v_Δ^2 are negligible; $\lambda_4 \neq 0$ causes splitting among $m_{H^{\pm\pm}}, m_{H^\pm}, m_{H_2}, m_{A^0}$

Couplings of H_1 to fermions and bosons in the HTM

H_1 (lightest CP-even scalar) is essentially SM-like in most of the parameter space: $H_1 = \cos\alpha\ h^0\ +\ \sin\alpha\Delta^0$ AGA/Chiang 10

$$g_{H_1 t\bar{t}} = \cos\alpha/\cos\beta'$$

$$g_{H_1 b\bar{b}} = \cos\alpha/\cos\beta'$$

$$g_{H_1 WW} = \cos\alpha + 2\sin\alpha v_\Delta/v$$

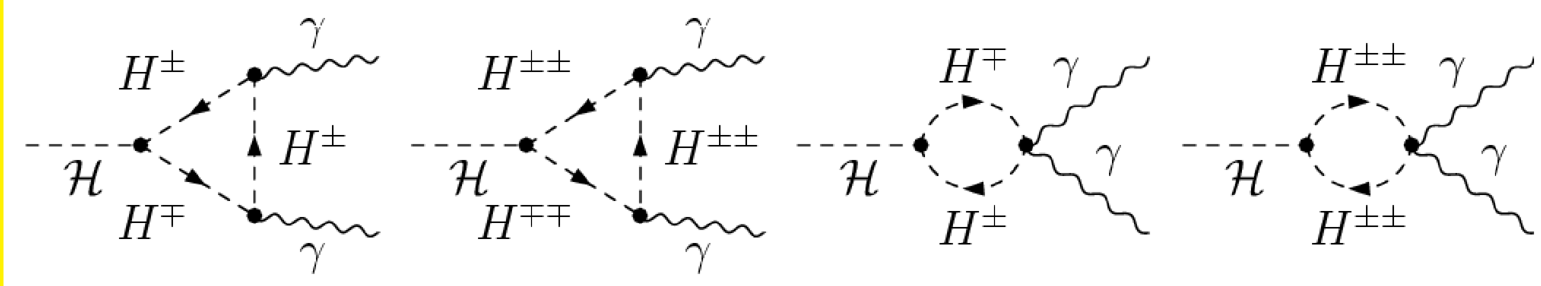
$$g_{H_1 ZZ} = \cos\alpha + 4\sin\alpha v_\Delta/v$$

One has $\cos\alpha \sim \sqrt{(1-4v_\Delta^2/v^2)} \sim 1$ and $\cos\beta' = \sqrt{(1-2v_\Delta^2/v^2)} \sim 1$

Ongoing searches for SM Higgs apply to H_1 of the HTM

Contribution of $H^{\pm\pm}$ and $H^{\pm}$ to $H_1 \to \gamma\gamma$ Arhrib 11; Kanemura 12

$H_1 \to \gamma\gamma$ is a loop-induced process $\to$ sensitive to charged scalars



SM diagrams are mediated by W and charged fermions, which interfere destructively

• $H^{\pm\pm}$ loop contribution has an enhancement factor of 4 relative to $H^{\pm}$ loop due to its electric charge

$$\Gamma(H_1 \to \gamma\gamma) = \frac{G_F \alpha^2 m_{H_1}^3}{128\sqrt{2}\pi^3} \Big| \sum_f N_c Q_f^2 g_{H_1 ff} A_{1/2}^{H_1}(\tau_f) + g_{H_1 WW} A_1^{H_1}(\tau_W) + \tilde{g}_{H_1 H^\pm H^\mp} A_0^{H_1}(\tau_{H^\pm}) + 4\tilde{g}_{H_1 H^{\pm\pm} H^{\mp\mp}} A_0^{H_1}(\tau_{H^{\pm\pm}}) \Big|^2$$

where $\tau_i = m_{H_1}^2/4m_i^2$ and scalar trilinear couplings are:

$$\tilde{g}_{H_1 H^{++} H^{--}} \sim \frac{m_W}{g m_{H^{\pm\pm}}^2} \lambda_1 v \quad (\text{and } m_{H^{\pm\pm}}^2 = M_\Delta^2 + \frac{\lambda_1 v^2}{2})$$

$$\tilde{g}_{H_1 H^{+} H^{-}} \sim \frac{m_W}{g m_{H^{\pm}}^2} (\lambda_1 + \frac{\lambda_4}{2}) v$$

Magnitude of scalar-loop contributions

- Coupling $\tilde{g}_{H_1 H^{++} H^{--}}$ depends on λ_1 only
- Main theoretical constraint on λ_i comes from stability of scalar potential, e.g.

$$\lambda_1 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} > 0$$

- Only positive λ_1 considered in previous studies Arhrib 11,Kanemura 12
- λ_1 could be negative AGA/Moretti 12

Definition of $R_{\gamma\gamma}$

LHC searches constrain $\text{BR}(H \to \gamma\gamma)_{model}/\text{BR}(H \to \gamma\gamma)_{SM}$ where the model has exactly SM production cross section (dominant contribution from $gg \to H$)

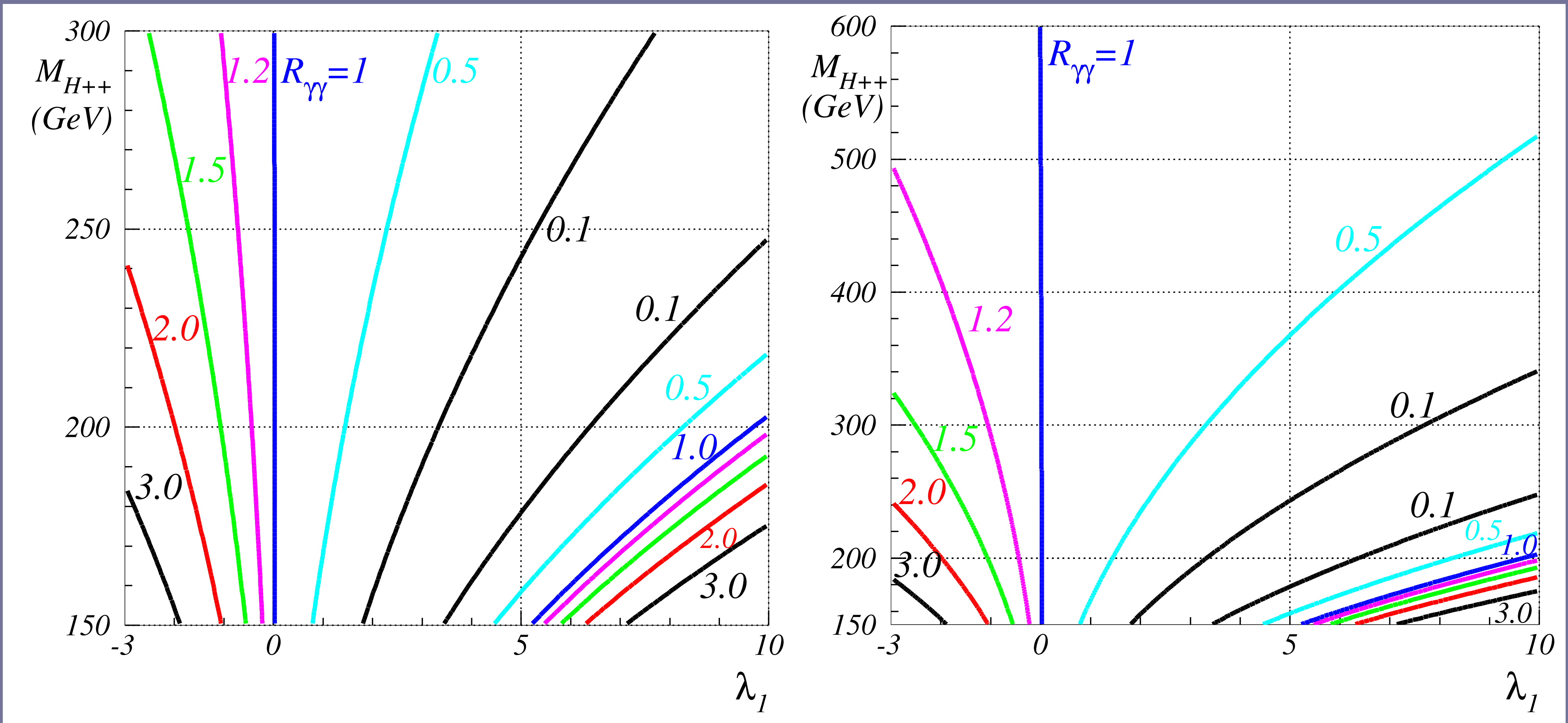
- $\Gamma(H_1 \to gg)/\Gamma(H_1 \to gg) \sim \cos^2\alpha \sim 1$; $VVH \sim \cos\alpha \sim 1$

We define:

$$R_{\gamma\gamma} = \frac{(\Gamma(H_1 \to gg) \times \text{BR}(H_1 \to \gamma\gamma))^{HTM}}{(\Gamma(H \to gg) \times \text{BR}(H \to \gamma\gamma))^{SM}}$$

- ATLAS: $R_{\gamma\gamma} = 1.17 \pm 0.27$; CMS: $R_{\gamma\gamma} = 1.14 \pm 0.25$

The ratio $R_{\gamma\gamma}$ in the plane $[\lambda_1, m_{H^{\pm\pm}}]$ for 150 GeV $< m_{H^{\pm\pm}} <$ 600 GeV, with $m_{H_1} \sim 125$ GeV



AGA/Moretti 12 | ATLAS: $R_{\gamma\gamma} = 1.17 \pm 0.27$ | CMS: $R_{\gamma\gamma} = 1.14 \pm 0.25$ | (between green and cyan)

Constraints on $[\lambda_1, m_{H^{\pm\pm}}]$ from $H_1 \to \gamma\gamma$

- Ongoing searches for $H_1 \to \gamma\gamma$ probe $[\lambda_1, m_{H^{\pm\pm}}]$
- Two lines correspond to $R_{\gamma\gamma} = 1$

i) $\lambda_1 = 0$ and ii) destructive interference of $H^{\pm\pm}$ with SM loops

- For $\lambda_1 > 0$, sizeable parameter space for $R_{\gamma\gamma} << 1$

$\rightarrow$ this region is now disfavoured

- Two surviving regions between green ($R_{\gamma\gamma} < 1.5$)

and cyan ($R_{\gamma\gamma} > 0.5$)

Phenomenology of charged scalars in the HTM

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

Neutrino mass in Higgs Triplet Model (HTM)

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

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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: $\mathcal{M}_{ij}^{\nu} \sim v_\Delta h_{ij}$

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

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

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)
- $\Gamma(H^{\pm\pm} \to \ell_i^\pm \ell_j^\pm) \sim |h_{ij}|^2 \sim 1/v_\Delta^2$; $\Gamma(H^{\pm\pm} \to W^\pm W^\pm) \sim v_\Delta^2$

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

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

Decays of $H^{\pm}$:

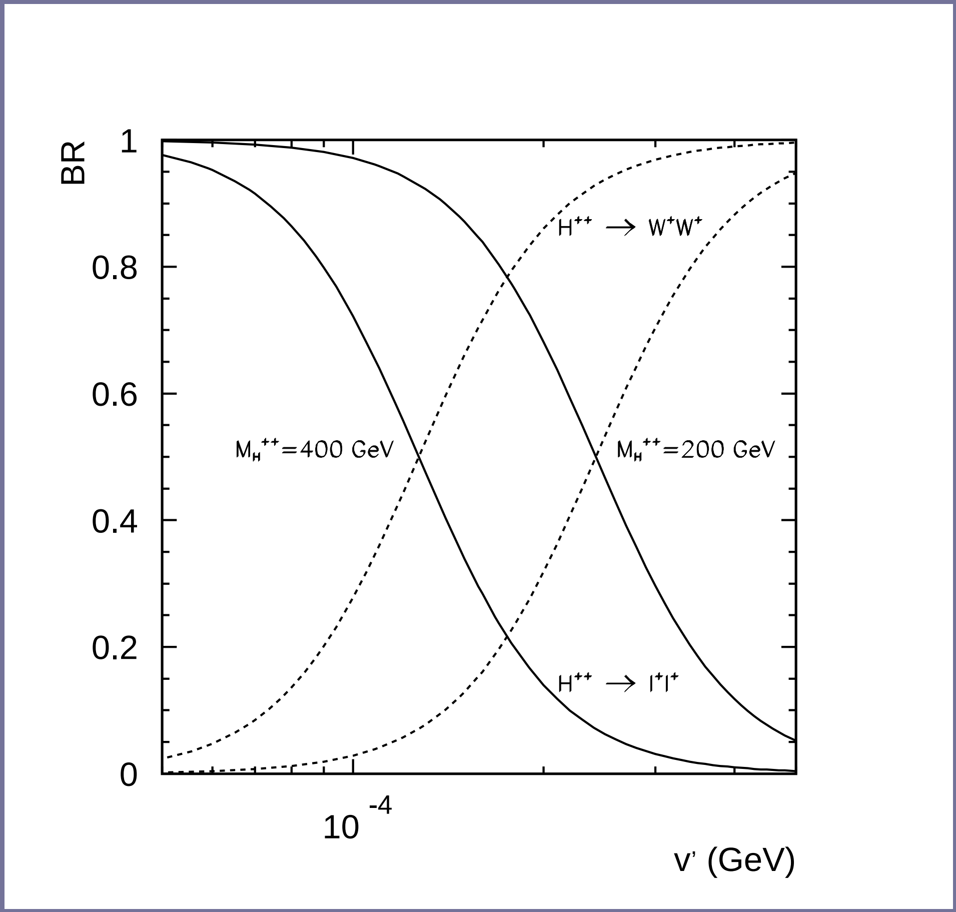
- $\Gamma(H^\pm \to \ell_i^\pm \nu) > \Gamma(H^\pm \to W^\pm Z, tb)$ for $v_\Delta < 10^{-4}$ GeV

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

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

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

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

Explicit expressions for h_{ij}

All h_{ij} are functions of nine parameters:

$$h_{ee} = \frac{1}{\sqrt{2}v_\Delta}(m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\varphi_1} + m_3 s_{13}^2 e^{-2i\delta} e^{i\varphi_2})$$

Five parameters are experimentally constrained:

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\text{eV}^2\,, \quad |\Delta m_{31}^2| \equiv |m_3^2 - m_1^2| \simeq 2.7 \times 10^{-3}\text{eV}^2\,,$$
$$\sin^2 2\theta_{12} \simeq 0.86\,, \qquad \sin^2 2\theta_{23} \simeq 1\,, \qquad \sin^2 2\theta_{13} \simeq 0.09\,.$$

Main uncertainty in h_{ij} comes from:

- Absolute mass of lightest neutrino: $0 < m_0 < 1eV$
- Majorana phases $0 < \phi_1, \phi_2 < 2\pi$

These three parameters are unconstrained by neutrino oscillation data

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

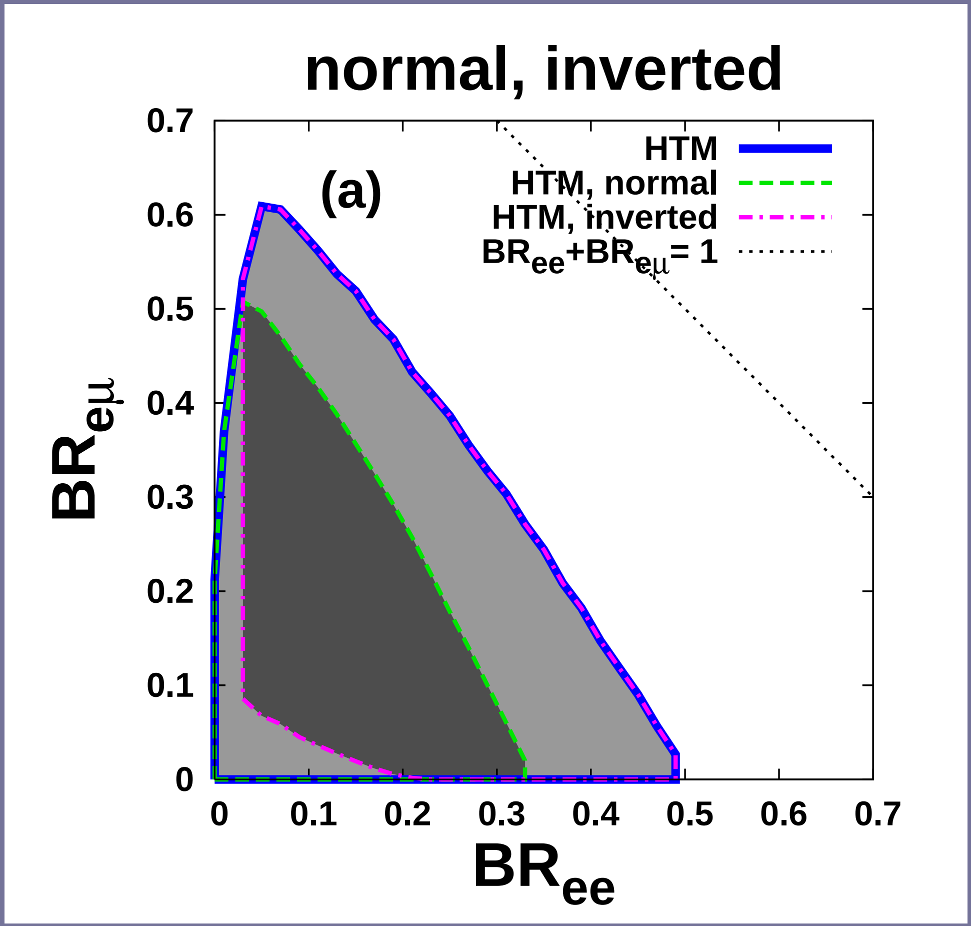
BR($H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$)

- Determined by h_{ij} (six distinct decays $ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$)
- Main uncertainty in BR from m_0, ϕ_1,and ϕ_2

BR($H^{\pm} \to \ell_i^{\pm}\nu_j$)

- Determined by $\sum_j h_{ij}$ (three distinct decays $e\nu, \mu\nu, \tau\nu$)
- Dependence on ϕ_1 and ϕ_2 drops out when sum over ν_j
- Main uncertainty in BR from m_0 only

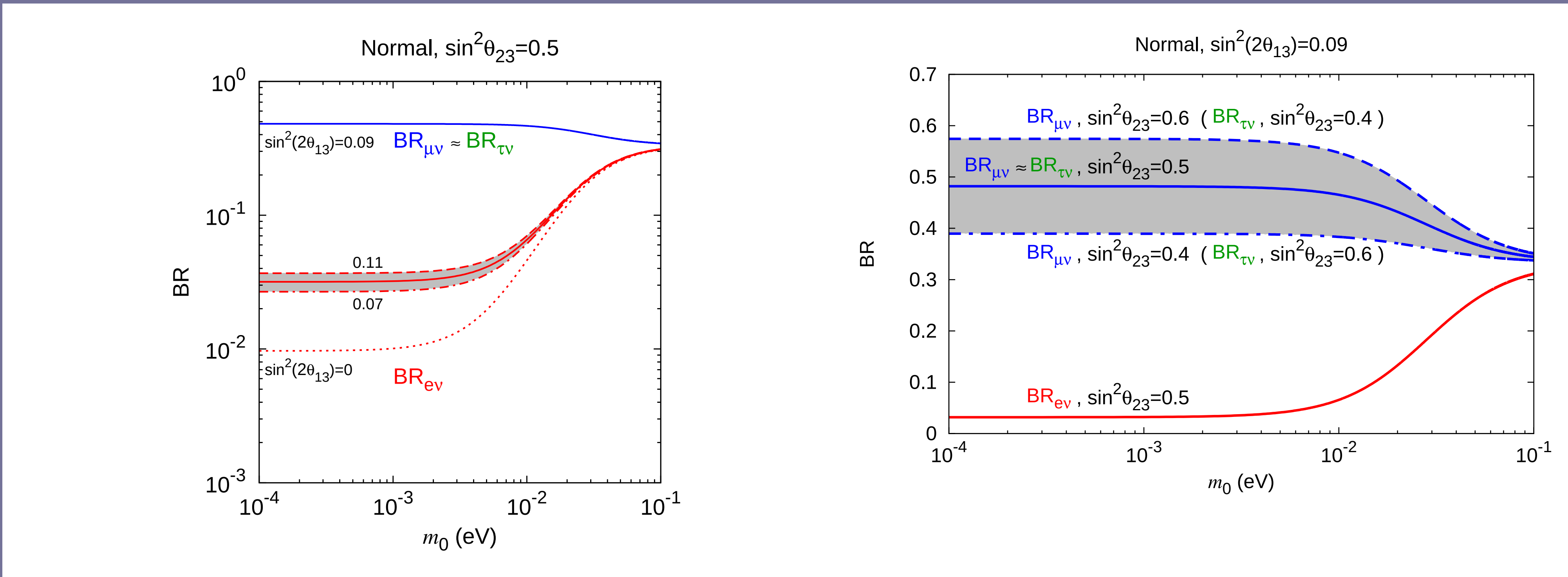
HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}e^{\pm}$),BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$)]



White region is ruled out by neutrino oscillation data

AGA/Aoki/Sugiyama 07

BR($H^\pm \to \ell^\pm \nu$) as a function of lightest neutrino mass m_0



Strong dependence on m_0 with uncertainty from $\sin\theta_{13}$ and $\sin\theta_{23}$

Han 08, AGA/Sugiyama/Moretti 13

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 B factories
- BR$(\mu \to e\gamma) < 10^{-12} \to \sum_i |h_{\mu i} h_{ei}| < 10^{-7}$ sensitivity to BR$\sim 10^{-13}$ from MEG

All constraints can be respected with $|h_{ij}| < 10^{-3}$ or 10^{-4}

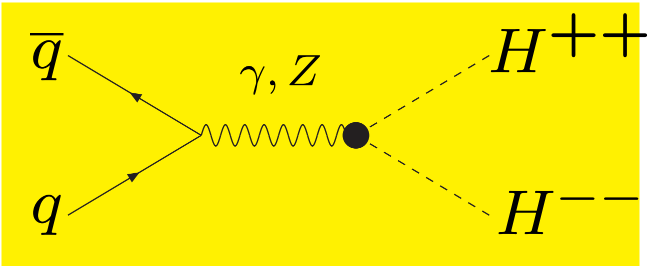
These decays provide valuable probes of virtual effects of $H^{\pm\pm}$

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

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

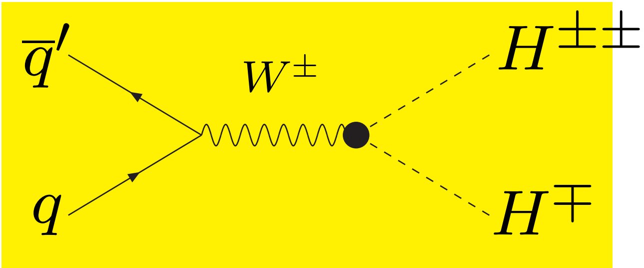


- $\sigma_{H^{++}H^{--}}$ is a simple function of $m_{H^{\pm\pm}}$ Barger 82, Gunion 89, Raidal 96
- $\sigma_{H^{++}H^{--}}$ has no dependence on h_{ij}

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

A mechanism not included in the Tevatron searches

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

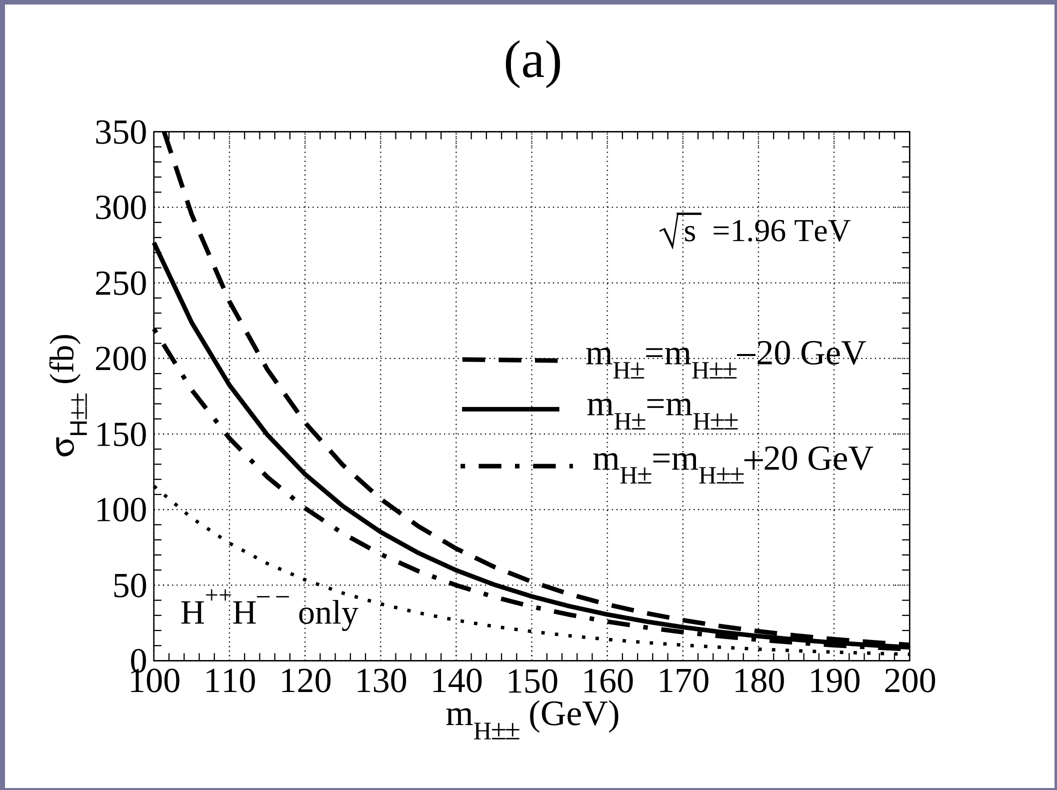


- $\sigma_{H^{\pm\pm}H^{\mp}}$ is a function of $m_{H^{\pm\pm}}$ and $m_{H^{\pm}}$ Barger 82, Dion 98
- Similar magnitude to $\sigma(p\overline{p} \to H^{++}H^{--})$ for $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$

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

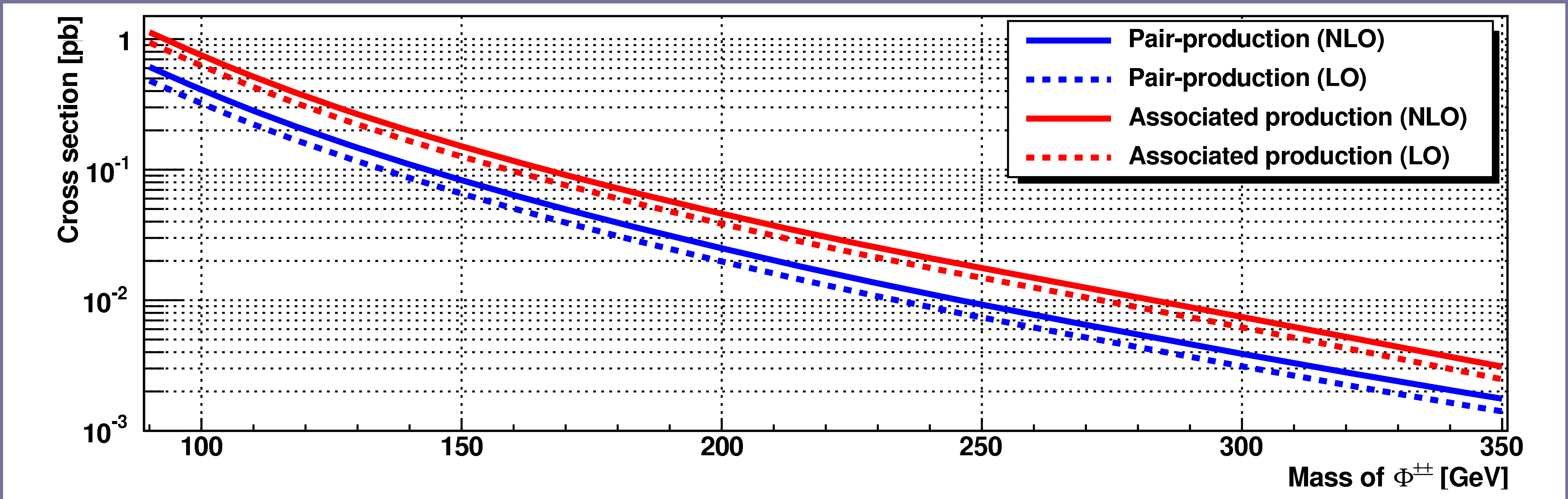
AGA,Aoki 05

Search was sensitive to $\ell^+\ell^+$ and $\ell^-\ell^-$: $\sigma_{H^{\pm\pm}} = \sigma(p\overline{p} \to H^{++}H^{--}) + 2\sigma(p\overline{p} \to H^{++}H^{-})$



Old mass limit $m_{H^{\pm\pm}} > 136$ GeV at Tevatron would strengthen to $m_{H^{\pm\pm}} > 160$ 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 $q\overline{q}' \longrightarrow H^{\pm\pm}H^{\mp}$

- $\sigma(q\overline{q}' \longrightarrow H^{\pm\pm}H^{\mp})$ can be as large as $\sigma(q\overline{q} \longrightarrow H^{++}H^{--})$
- Increases the sensitivity to $m_{H^{\pm\pm}}$ in $\ell^{\pm}\ell^{\pm}$ and $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ 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 $q\overline{q} \longrightarrow H^{++}H^{--}$
- In AGA/Chiang/Gaur 10 we created a CalcHEP file to generate events for $q\overline{q}' \longrightarrow H^{\pm\pm}H^{\mp}$, which can then be used as input for Pythia
- This enabled the CMS collaboration to carry out a search for $q\overline{q}' \longrightarrow H^{\pm\pm}H^{\mp}$

Ongoing searches for $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ at the LHC with $\sqrt{s} = 7/8$ TeV

1) CMS: Eur. Phys. J. C72 (2012) 2189 (1207.2666)

2) ATLAS: JHEP03 (2015) 041 (1412.0237)

(No search yet for $H^{\pm\pm} \to W^{\pm}W^{\pm}$)

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

- For $v_\Delta < 0.1$ MeV, $H^{\pm\pm}$ decays via h_{ij} to *same charge* $ee, \mu\mu, \tau\tau, e\mu, e$
- In the HTM, BR($H^{\pm\pm} \to \ell^\pm \ell^\pm$) depends mainly on

i) lightest neutrino mass m_1 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

Results also presented for BR($H^{\pm\pm} \to \ell^\pm \ell^\pm$) $= 100\%$

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

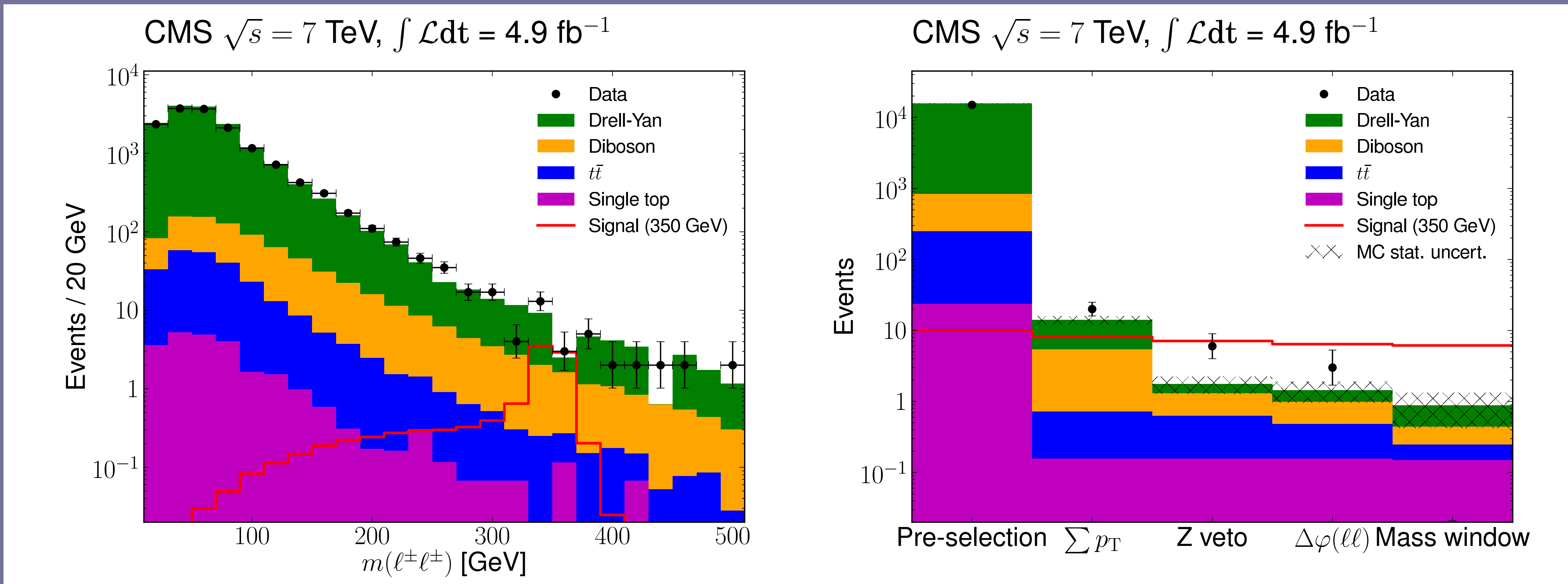
i) 4ℓ signature ($\ell^{+}\ell^{+}\ell^{-}\ell^{-}$):

- 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

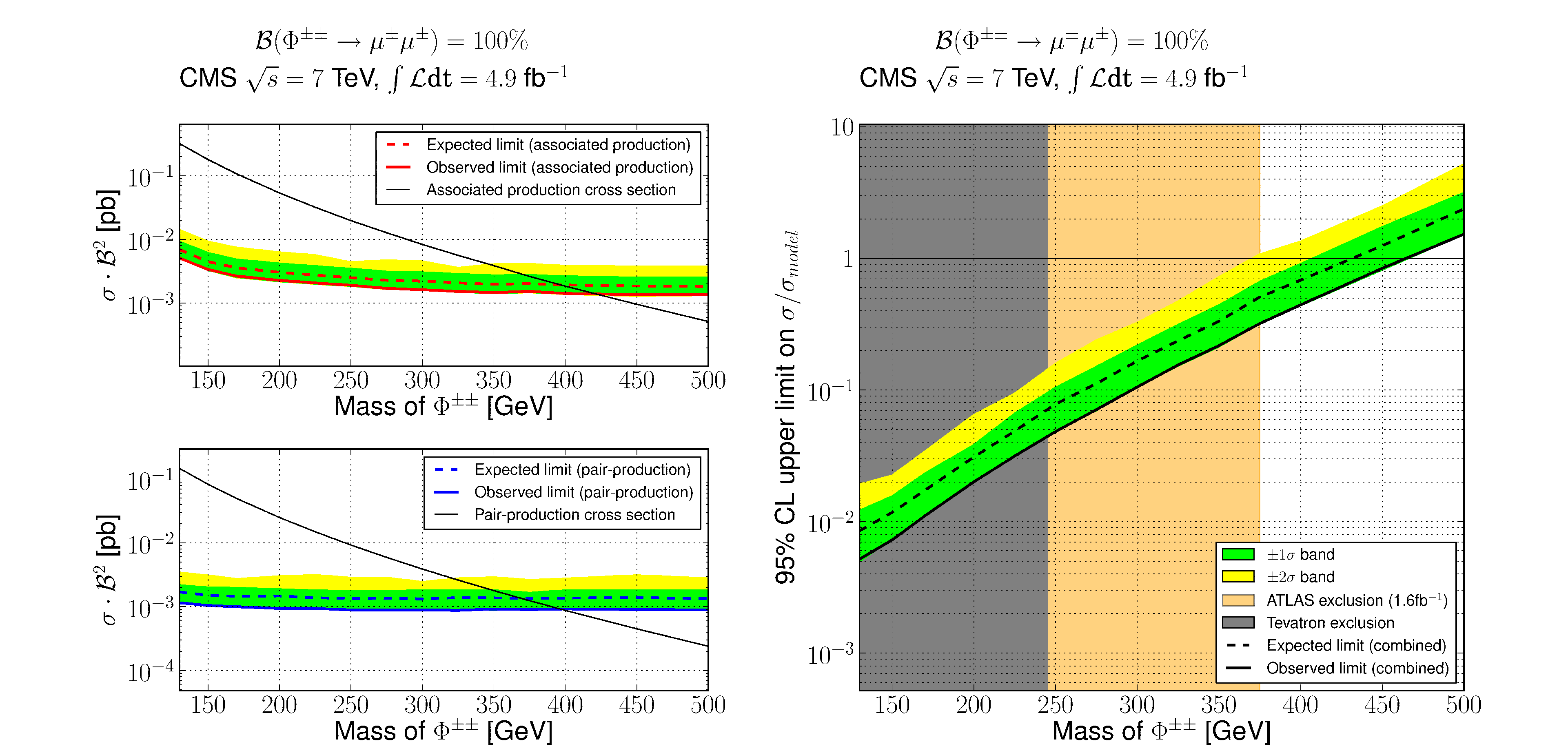
LHC (CMS collaboration) search for 3ℓ signature



After pre-selection cuts (signal for BP4)

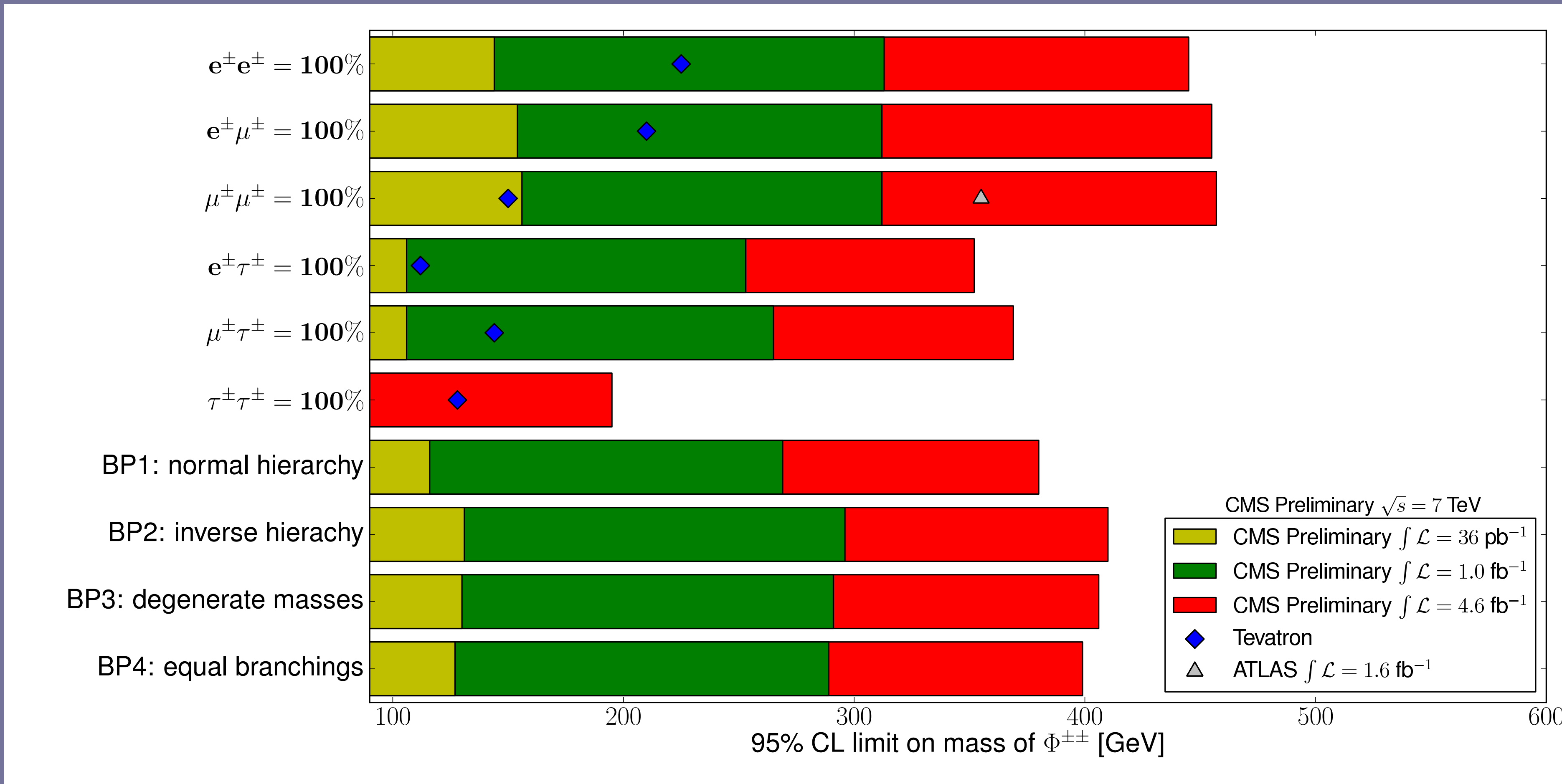
After all selection cuts (signal for BP4)

Excluded cross sections from 3ℓ and 4ℓ search: $\ell = \mu$ channel



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

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



Mass limit $m_{H^{\pm\pm}} > 400$ GeV for benchmark points in HTM

ATLAS search for $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

- ATLAS has performed a search for $q\overline{q} \to H^{++}H^{--}$
- 20.8 fb^{-1} and $\sqrt{s} = 8$ TeV arXiv:1412.0237
- Signal is defined as two same-signed leptons

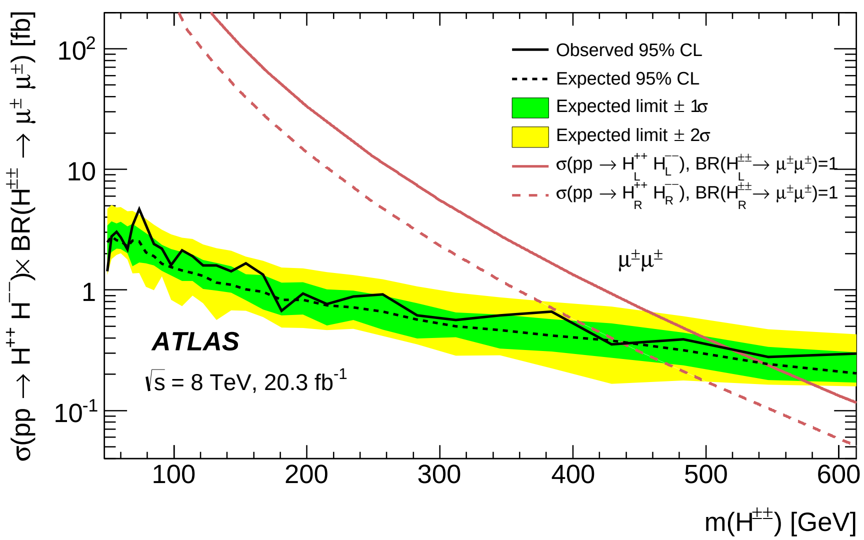
$e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$ (i.e. not requiring 3 or 4 leptons)

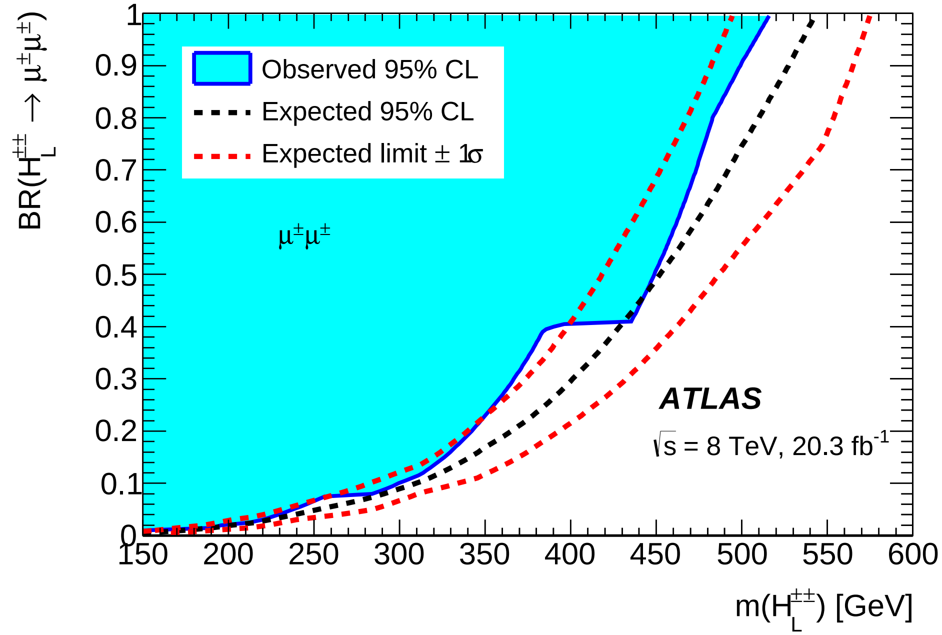
- Number of signal events is linear (not quadratic)

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 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV





$m_{H^{\pm\pm}} > 516$ GeV for BR$(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) = 100\%$

$m_{H^{\pm\pm}} < 300$ GeV possible for BR$(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) < 10\%$

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

Both CMS and ATLAS have both performed a search for $H^{\pm\pm}$

- CMS used $4.9 fb^{-1}$ at $\sqrt{s} = 7$ TeV
- Both 4ℓ and 3ℓ signatures were 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 a search for $H^{\pm\pm}$
- ATLAS have searched for $ee, e\mu, \mu\mu$ with $20.3 fb^{-1}$ (2ℓ search)
- Have not yet included $\overline{q}q' \to H^{\pm\pm}H^{\mp}$ (would strengthen limits)

The decay $H^{\pm\pm} \to W^{\pm}W^{\pm}$

- So far have only considered $v_{\Delta} < 0.1$ MeV for which BR($H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$) dominates
- BR($H^{\pm\pm} \to W^{\pm}W^{\pm}$) dominates for $v_{\Delta} > 0.1$ MeV
- No dedicated LHC search for $H^{\pm\pm} \to W^{\pm}W^{\pm}$
- Some simulations of discovery prospects Chiang/Nomura/Tsumura 12
- Kanemura/Yagyu/Yokoya 14 derive limit $m_{H^{\pm\pm}} > 84$ GeV by applying LHC search results for $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ to decay channel $H^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell^{\pm}\nu\ell^{\pm}\nu$.

The decay $H^{\pm\pm} \to H^{\pm} W^*$

- So far we have assumed degeneracy $m_{H^{\pm\pm}} = m_{H^{\pm}} = m_{H^0,A^0}$, which is realised for $\lambda_4 = 0$
- For $\lambda_4 < 0$ one has $m_{H^{\pm\pm}} > m_{H^{\pm}} > m_{H^0,A^0}$
- $H^{\pm\pm} \to H^{\pm} W^*$ Godbole et al 98 can dominate over $H^{\pm\pm} \to W^{\pm} W^{\pm}$ and $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$, and depends on $\delta m = m_{H^{\pm\pm}} - m_{H^{\pm}}$
- No LHC search for $H^{\pm\pm} \to H^{\pm} W^*$ (simulation Han/Ding/Liao 15)
- A light $H^{\pm\pm}$ with $m_{H^{\pm\pm}} < 150$ GeV is possible if $H^{\pm\pm} \to W^{\pm} W^{\pm}$ and/or $H^{\pm\pm} \to H^{\pm} W^*$ dominate

Conclusions

- The discovered SM-like Higgs boson could belong to a non-minimal Higgs sector
- Doubly charged Higgs bosons $H^{\pm\pm}$ appear in the Higgs Triplet Model of neutrino mass generation
- LHC searches are being carried out for $pp \to H^{++}H^{--}$ and $pp \to H^{\pm\pm}H^{\mp}$ with decay $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ and $H^{\pm} \to \ell^{\pm}\nu$
- Masses $m_{H^{\pm\pm}}$ up to 500 GeV are being probed
- A light $H^{\pm\pm}$ with $m_{H^{\pm\pm}} < 150$ GeV possible if $H^{\pm\pm} \to W^{\pm}W^{\pm}$ and/or $H^{\pm\pm} \to H^{\pm}W^{*}$ dominate (No LHC searches)