Enhancement of $H \to \gamma\gamma$ in the Higgs Triplet Model

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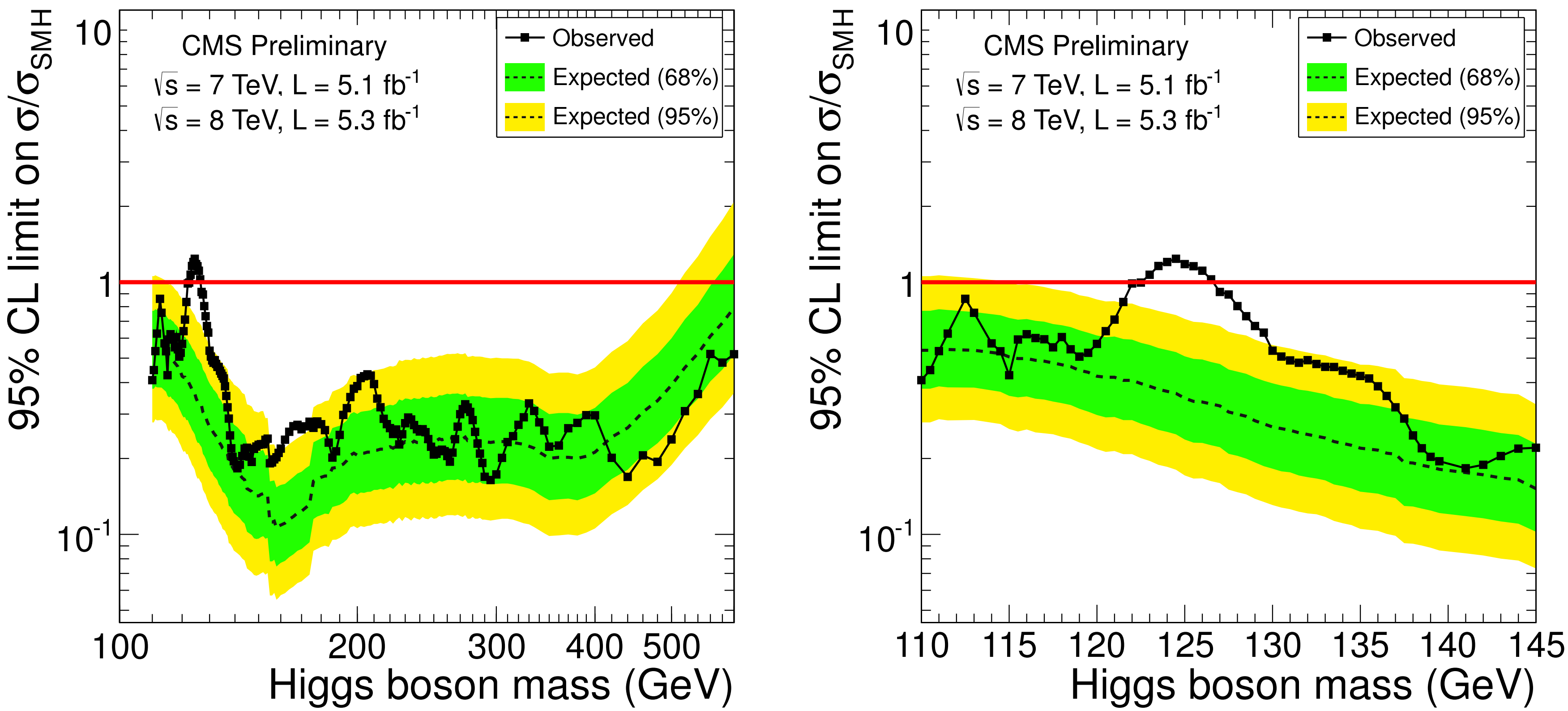
- Evidence for a Higgs boson with mass ~ 125 GeV
- Is it the SM Higgs boson, or from a non-minimal Higgs sector?
- BR($H \to \gamma\gamma$) might be larger than that for the SM Higgs boson
- Higgs Triplet Model (HTM) and doubly charged scalars ($H^{\pm\pm}$)
- $H_1 \to \gamma\gamma$ and (possible) enhancement from virtual $H^{\pm\pm}$

Collaborator: Stefano Moretti (Soton, UK), Phys. Rev. D86, 035015 (arXiv:1206.0535)

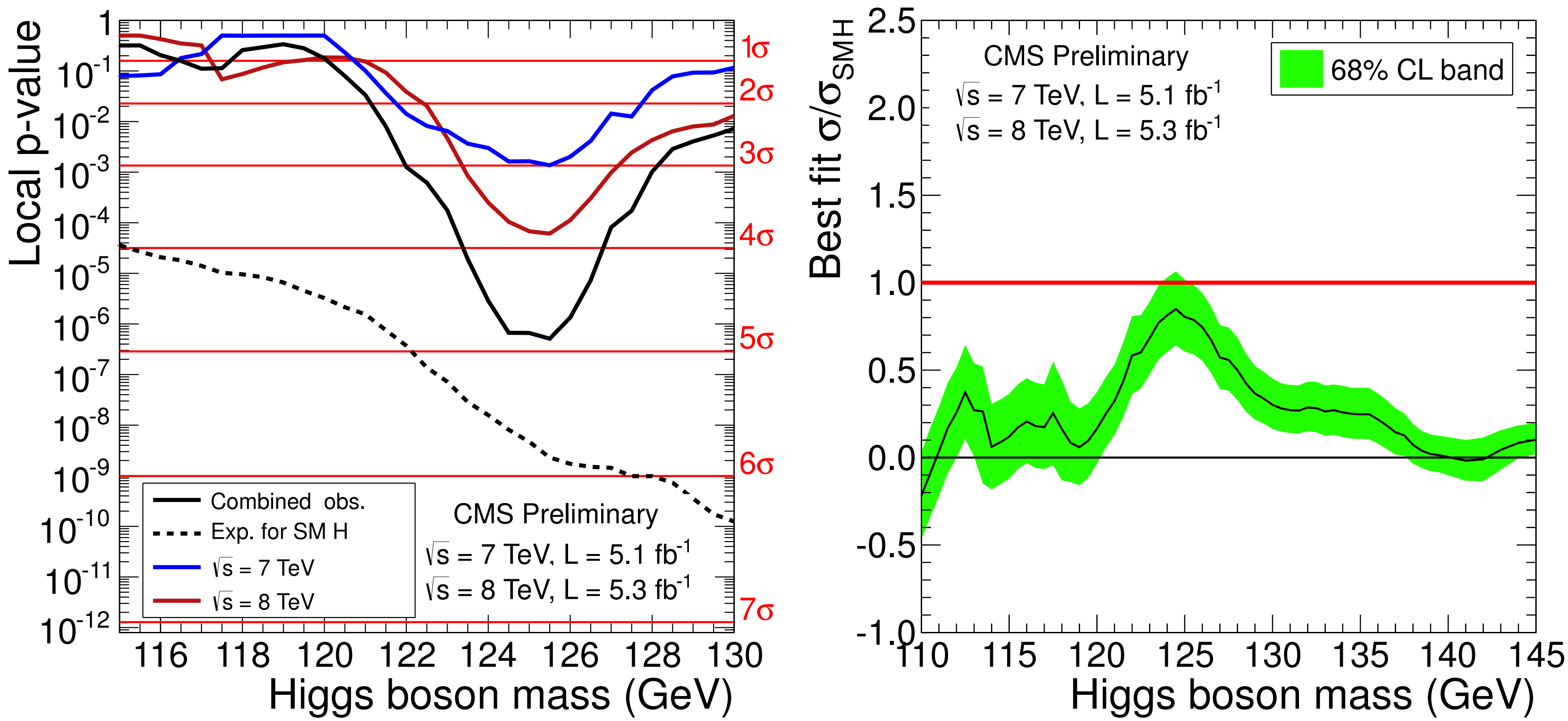
NExT meeting, RHUL, London, November 14, 2012

Search for the SM Higgs boson by ATLAS and CMS



The whole mass range of m_H is excluded except for $m_H \sim 125$ GeV

Statistical significance of the signal (with mass 125 GeV)



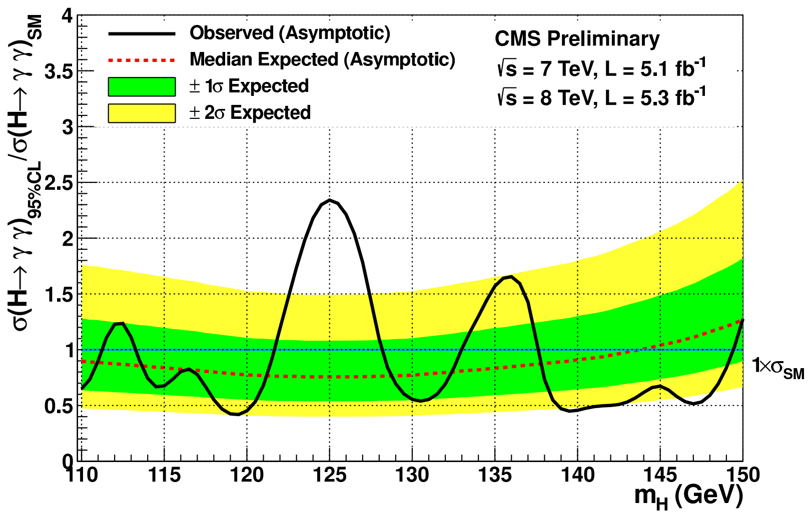
From combining searches for $H \to \gamma\gamma, ZZ, WW, bb, \tau^+\tau^-$ (ATLAS has similar results)

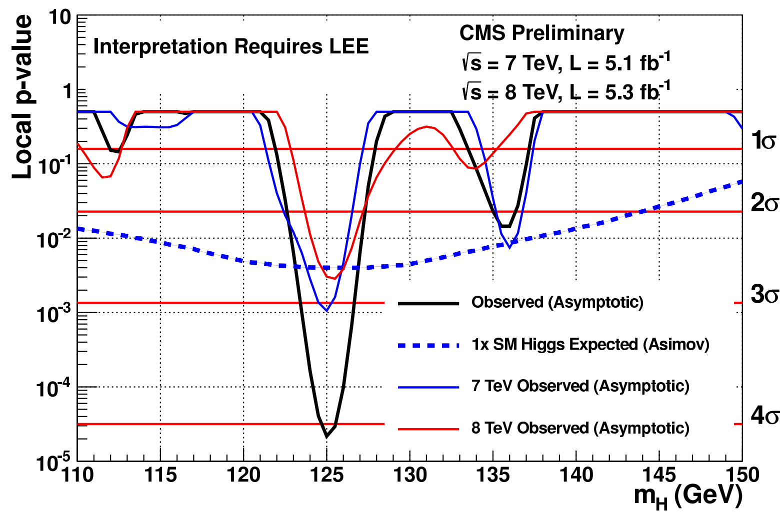
July 04: Evidence of the Higgs Boson with mass $\sim$ 125 GeV

- Compelling evidence for a neutral boson $m_H \sim 125$ GeV
- ATLAS 5.9σ and CMS 4.9σ (combining 7 and 8 TeV data)
- Strongest signal in channels $H \to \gamma\gamma$ and $H \to ZZ$
- Some evidence for $H \to WW$; none yet for $H \to \tau^+\tau^-$
- Hint of $H \to bb$ from Tevatron (LHC sensitivity still inferior)
- Event numbers consistent (within errors) with the signal expected for SM Higgs boson

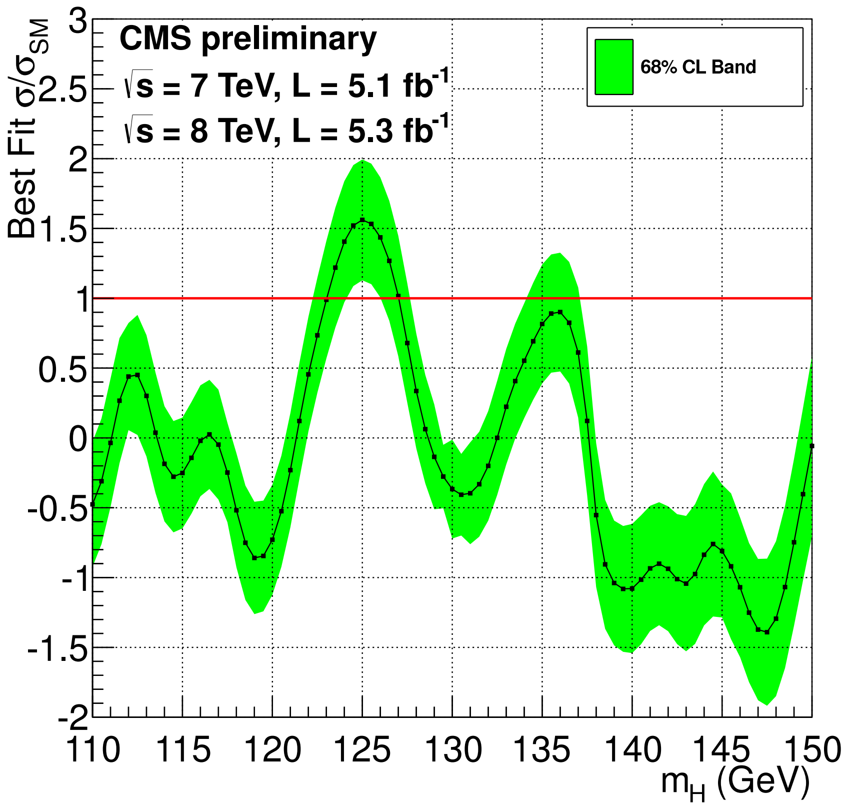
Strongest signal from $H \to \gamma\gamma$

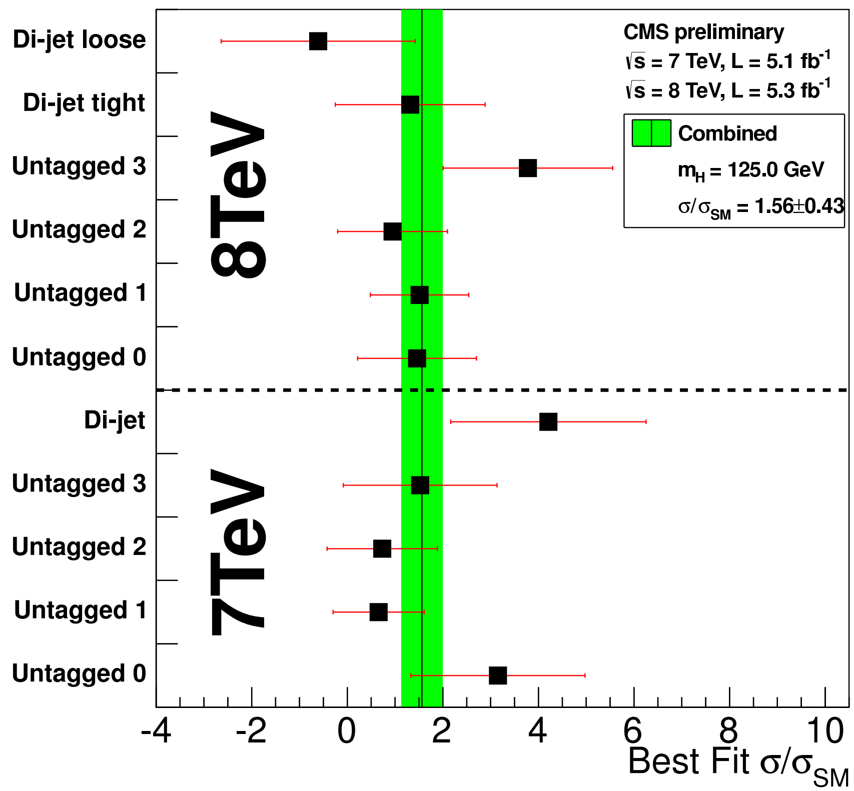
- Search is mainly sensitive to $gg \to H \to \gamma\gamma$
- Subdominant contributions from $pp \to WH, ZH, Hjj, Ht\bar{t}$
- ATLAS: local significance of excess at $\sim$ 125 GeV is 4.5σ
- CMS: local significance of excess at $\sim$ 125 GeV is 4.1σ





Hint of an enhanced BR($H \to \gamma\gamma$) with $m_H \sim 125$ GeV?





Hint of an enhanced BR($H \to \gamma\gamma$) with $m_H \sim$ 125 GeV?

- ATLAS: $\sigma_{\gamma\gamma}/\sigma_{SM} = 1.9 \pm 0.5$
- CMS: $\sigma_{\gamma\gamma}/\sigma_{SM} = 1.56 \pm 0.43$
- Average of the above searches for $H \to \gamma\gamma$ gives Raidal et al 12:

$$\text{BR}(H \to \gamma\gamma)_{obs}/\text{BR}(H \to \gamma\gamma)_{SM} = 1.6 \pm 0.3$$

- Future data (30 fb^{-1} by Dec 2012, and 13/14 TeV run) will greatly reduce the error
- $\sigma_{\gamma\gamma}/\sigma_{SM} > 1$ would suggest a non-minimal Higgs sector

Reasons to consider a non-minimal Higgs sector

- Neutrino mass
- (Scalar) Dark matter
- CP violation
- Supersymmetry
- Such models predict additional neutral scalars H^0, A^0

as well as electrically charged scalars $H^{\pm}$

- Searches for additional scalars of high priority now

The Higgs Triplet Model, HTM

Motivation → neutrino mass generation

- Non-minimal Higgs sector with scalar triplet of isospin $I = 1$
- Tree-level mass for ν ("Type II seesaw mechanism")
- This model is in the textbooks ("a classic model")

In this talk I will discuss the Higgs 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 $e^{\pm}$)

Higgs Triplet Model (HTM)

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

$$T = (T_1, T_2, T_3); \quad \Delta = \mathbf{T}.\mathbf{t} = T_1 t_1 + T_2 t_2 + T_3 t_3 = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

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

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

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

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

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

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

$$m^2_{H_1} = \frac{\lambda}{2}v^2 \quad \text{(as in the SM,} \sim 125\text{GeV)}$$

$$m^2_{H^{\pm\pm}} = M^2_{\Delta} + \frac{\lambda_1}{2}v^2 + \lambda_2 v^2_{\Delta}$$

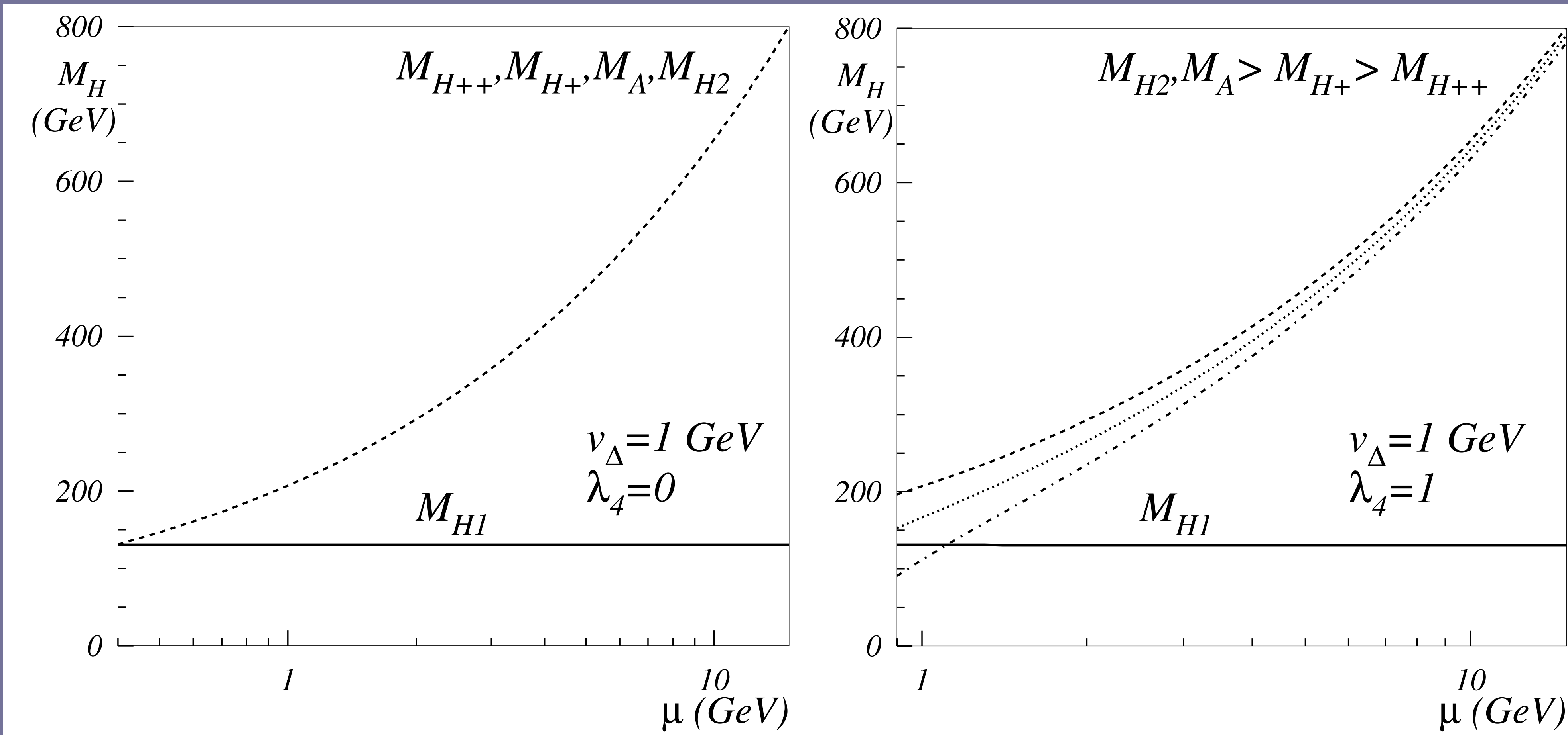
$$m^2_{H^{\pm}} = M^2_{\Delta} + (\frac{\lambda_1}{2} + \frac{\lambda_4}{4})v^2 + (\lambda_2 + \sqrt{2}\lambda_3)v^2_{\Delta}$$

$$m^2_{H_2} = M^2_{\Delta} + (\frac{\lambda_1}{2} + \frac{\lambda_4}{2})v^2 + 3(\lambda_2 + \lambda_3)v^2_{\Delta}$$

$$m^2_{A^0} = M^2_{\Delta} + (\frac{\lambda_1}{2} + \frac{\lambda_4}{2})v^2 + (\lambda_2 + \lambda_3)v^2_{\Delta}$$

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

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



Triplet scalars close to degenerate, and $H^{\pm\pm}$ is the lightest of them for $\lambda_4 > 0$

AGA/Chiang

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: $H_1 = \cos\alpha \; h^0 \; + \; \sin\alpha \Delta^0$

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

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

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

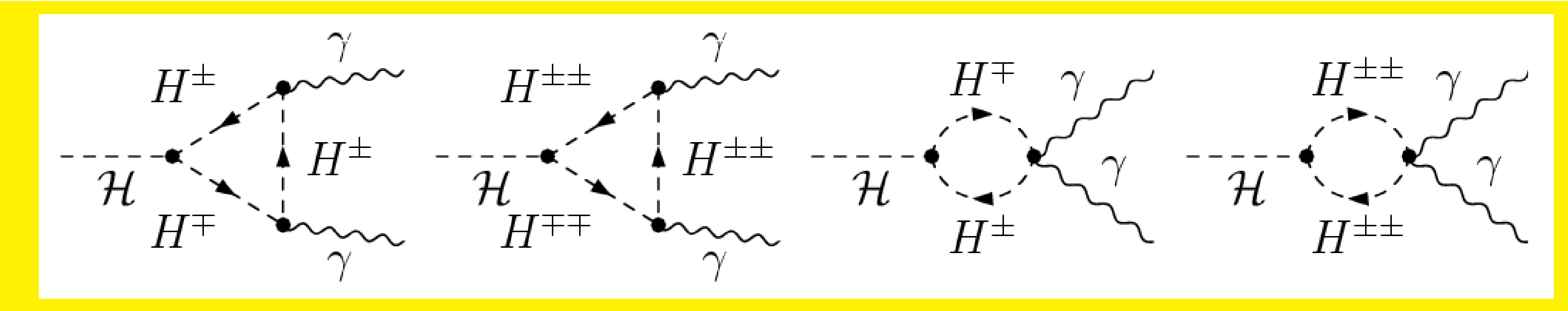
$$g_{H_1 ZZ} = \cos\alpha + 4\sin\alpha v_\Delta / v$$

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:

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

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

(where λ_1 and λ_4 appear in scalar potential as $\lambda_1 \ (H^\dagger H)\mathrm{Tr}\Delta^\dagger\Delta + \ \lambda_4 \ H^\dagger \Delta\Delta^\dagger H$)

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

Case of $\lambda_1 < 0$ and constructive interference of $H^{\pm\pm}$ and W

- Arhrib 11 considered $0 < \lambda_1 < 10$ (Destructive interference)

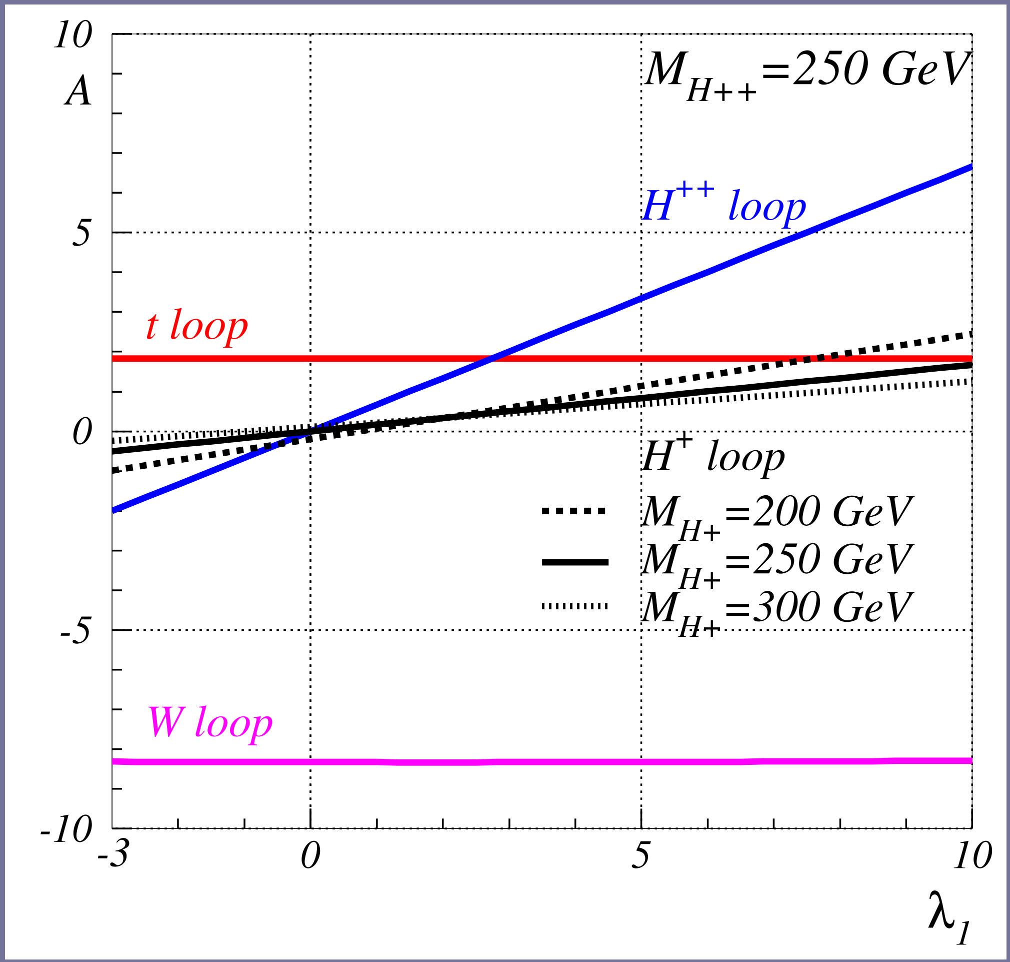
$\rightarrow$ discussed enhancements/suppressions of $\mathrm{BR}(H_1 \rightarrow \gamma\gamma)$

- Kanemura 12 considered $\lambda_1 > 0$

$\rightarrow$ discussed suppression of $\mathrm{BR}(H_1 \rightarrow \gamma\gamma)$

- For sufficiently positive λ_2, λ_3, the range $-3 < \lambda_1 < 0$ can be considered (Constructive interference) AGA/Moretti 12
- Varying λ_2, λ_3 has negligible effect on $m_{H^{\pm\pm}}$ and $\tilde{g}_{H_1 H^{++} H^{--}}$

Amplitudes of the contributions to $H_1 \to \gamma\gamma$ from $W, t, H^{\pm\pm}$ and $H^{\pm}$



$H^{\pm\pm}$ constructive (destructive) with W loop for $\lambda_1 < 0$ ($\lambda_1 > 0$)

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

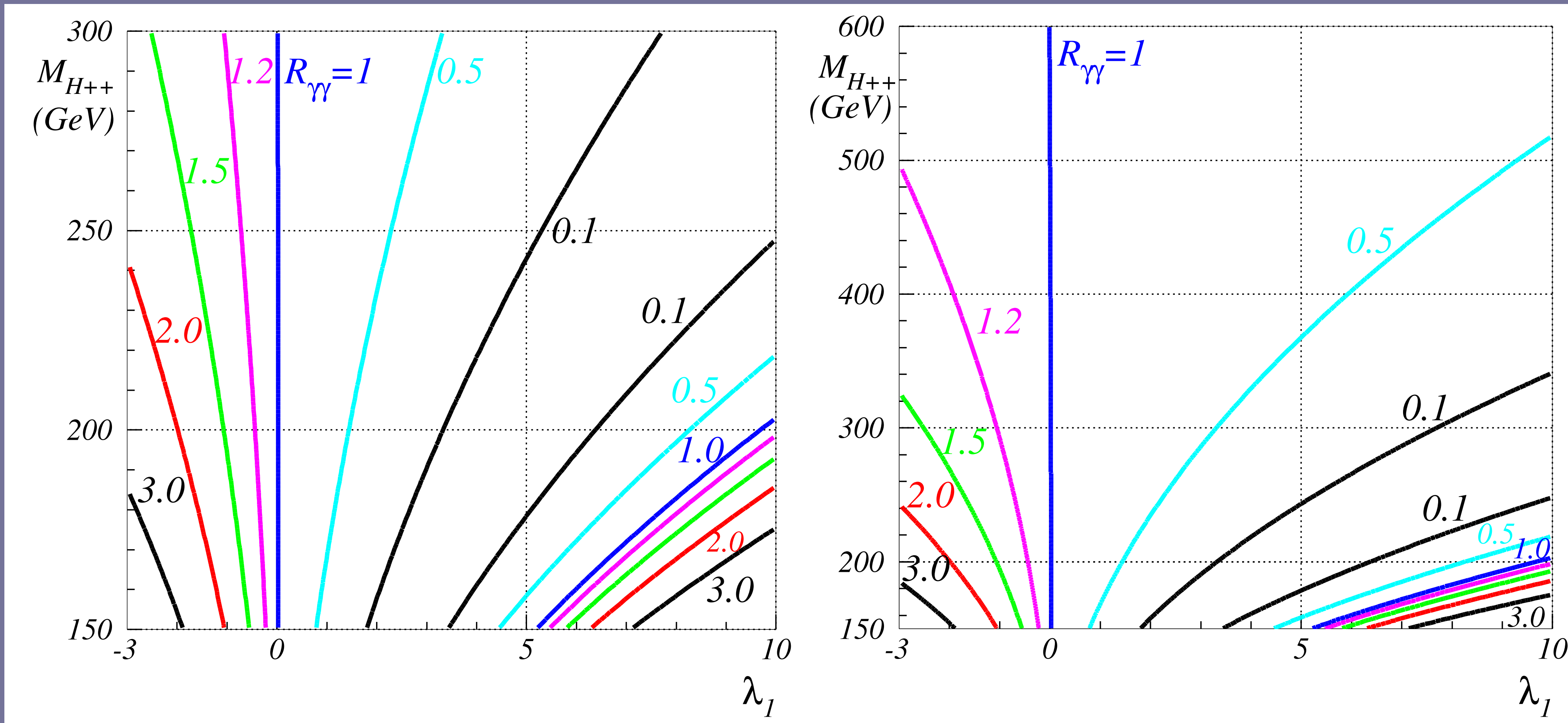
(dominant contribution from $gg \to H$)

We define:

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

- $R_{\gamma\gamma} = 1.6 \pm 0.3$ for $m_H = 125$ GeV Raidal et al 12
- $\Gamma(H_1 \to gg)/\Gamma(H_1 \to gg) \sim \cos^2\alpha \sim 1$; $VVH \sim \cos\alpha \sim 1$

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



$R_{\gamma\gamma} > 1$ for $\lambda_1 < 0$

AGA/Moretti 12

LHC measurement: $R_{\gamma\gamma} = 1.6 \pm 0.3$

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

- Ongoing searches for $H_1 \to \gamma\gamma$ probe $[\lambda_1, m_{H^{\pm\pm}}]$
- For $\lambda_1 > 0$, sizeable parameter space for $R_{\gamma\gamma} < 1$

$\rightarrow$ this region is now disfavoured due to $R_{\gamma\gamma} \sim 1.6 \pm 0.3$

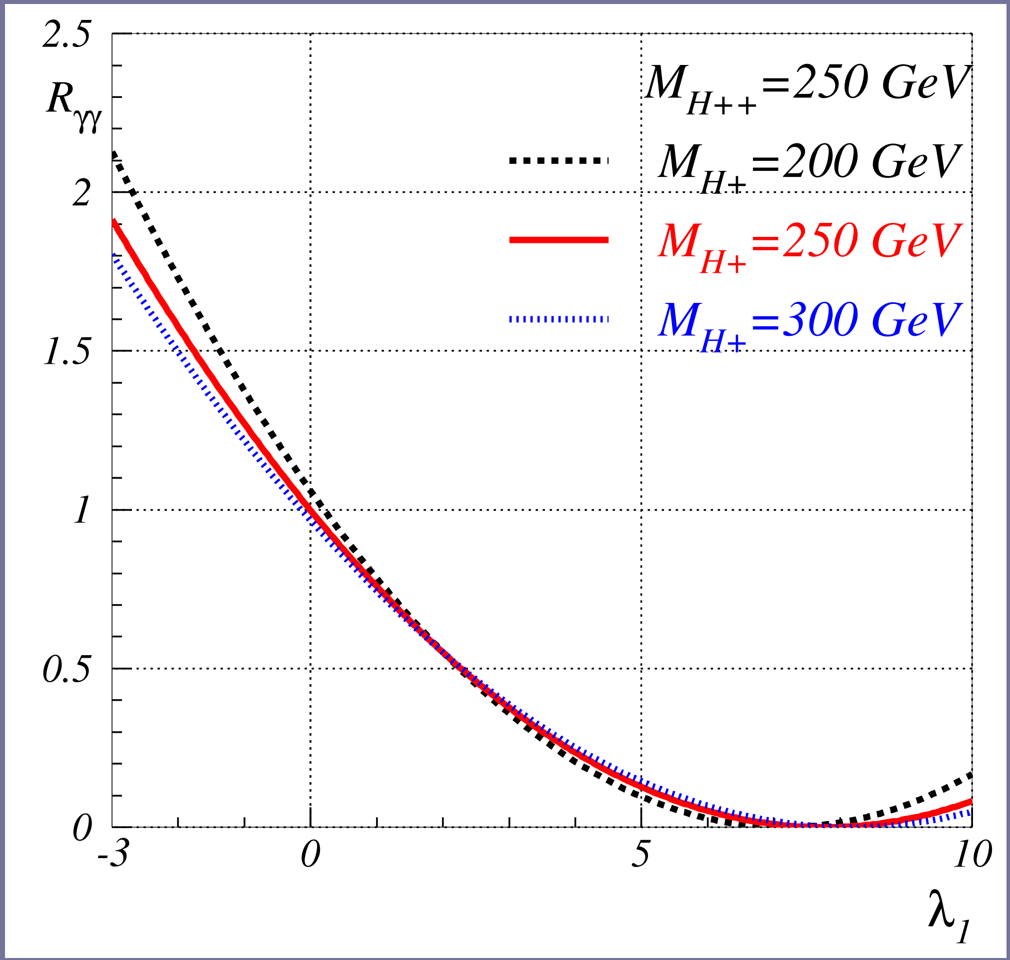
- For $\lambda_1 > 0$ and < 0 a parameter space for $R_{\gamma\gamma} > 1$

If preference for $R_{\gamma\gamma} > 1$ strengthens then

i) large positive λ_1 and $m_{H^{\pm\pm}} < 200$ GeV Arhrib 11, or

ii) small negative λ_1 and $m_{H^{\pm\pm}} < 400$ GeV AGA/Moretti 12

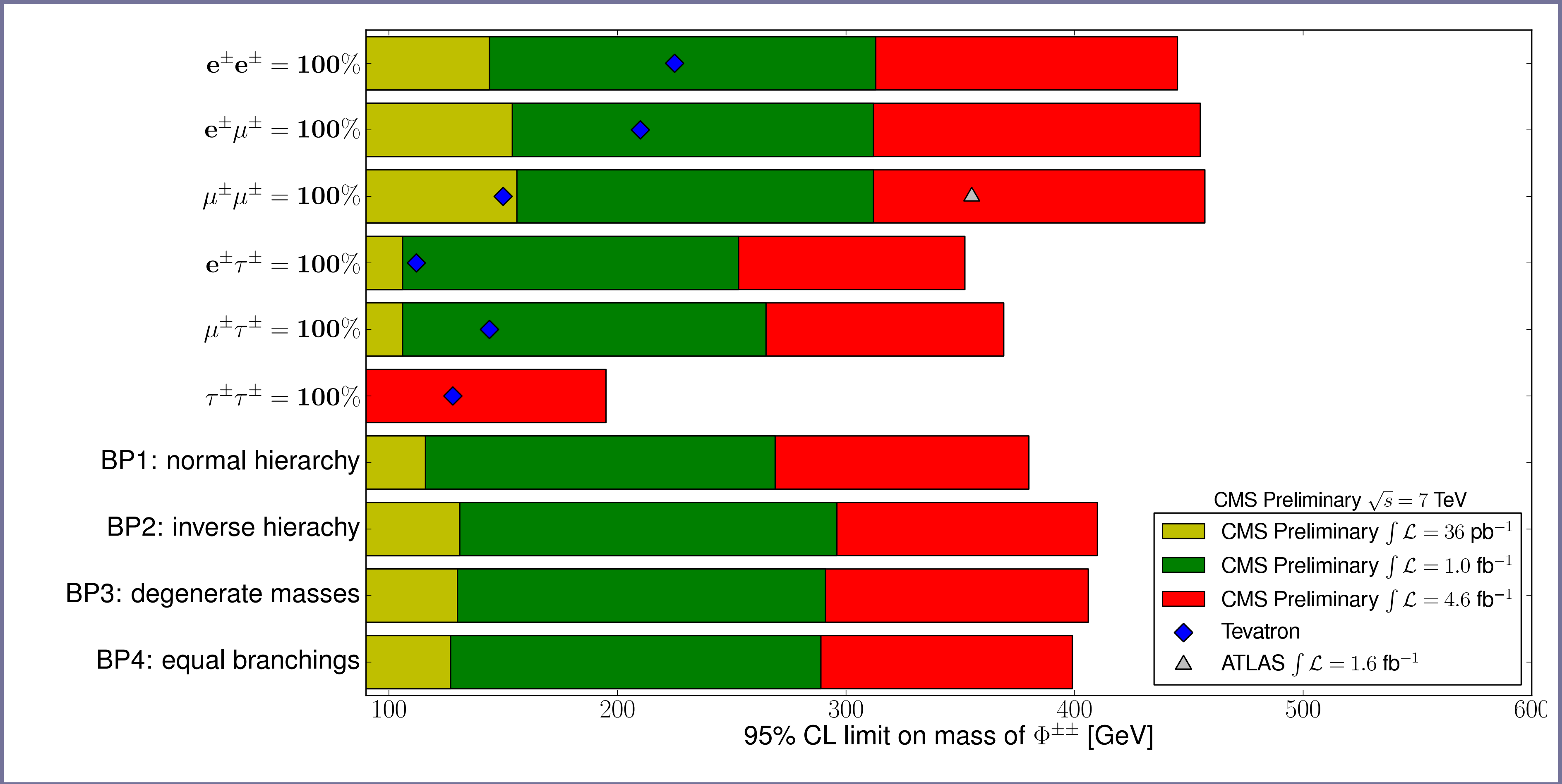
Magnitude of contribution of $H^{\pm}$ loop to $R_{\gamma\gamma}$ for several $m_{H^{\pm}}$



Contribution of $H^{\pm}$ for $m_{H^{\pm}} \neq m_{H^{\pm\pm}}$ can give $\pm 10\%$ effect

AGA/Moretti 12

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

Impact of mass limit on $m_{H^{\pm\pm}}$ on $H_1 \to \gamma\gamma$

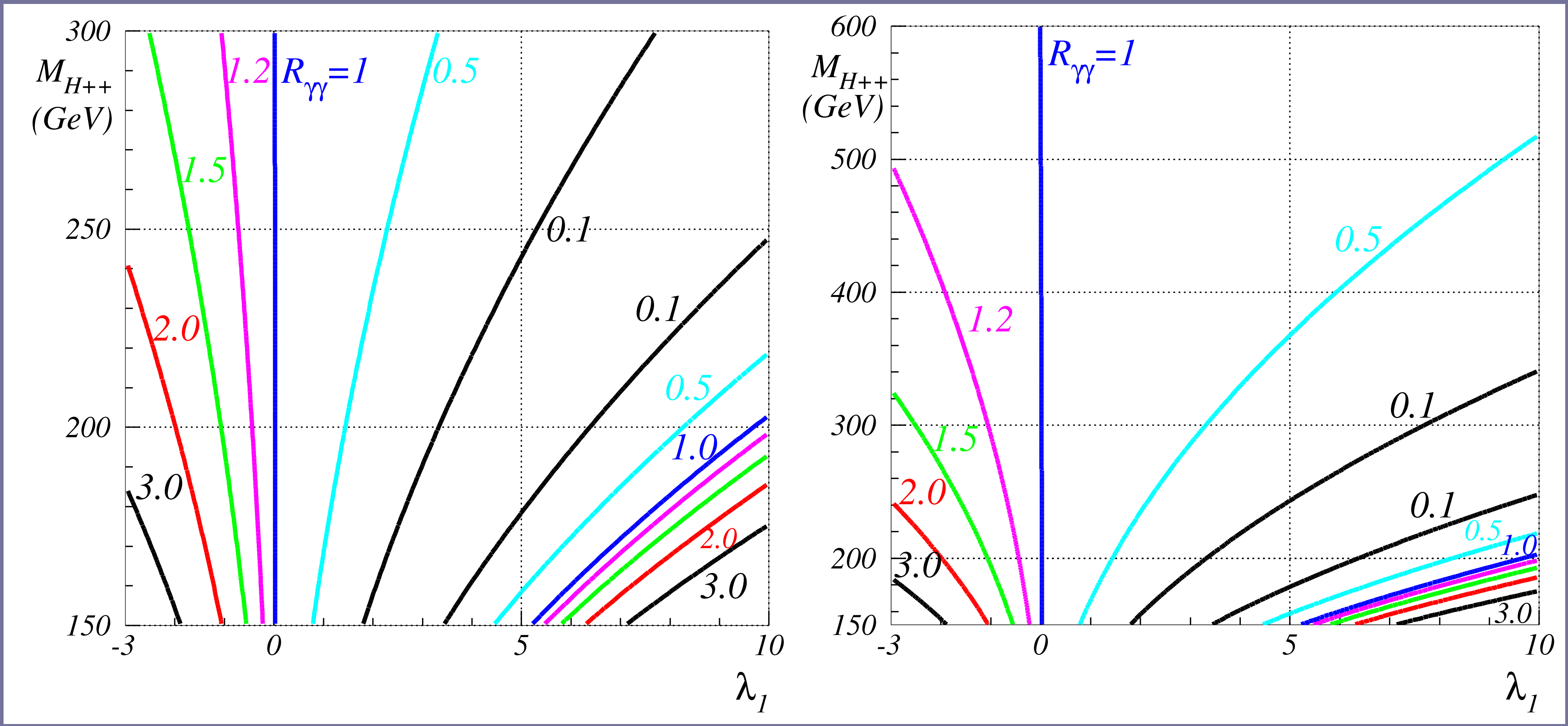
- Limit of $m_{H^{\pm\pm}} > 400$ GeV in benchmark points in HTM
- Applies to case of $\sum \mathrm{BR}(\mathrm{H}^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) \sim 1$ (for $v_\Delta < 0.1$ MeV)
- Limit weakened for points where $\mathrm{BR}(H^{\pm\pm} \to \tau^{\pm}\tau^{\pm})$ large

$H^{\pm\pm} \to W^{\pm}W^{\pm}$ dominates for $v_\Delta > 0.1$ MeV

- No searches for $H^{\pm\pm} \to W^{\pm}W^{\pm}$, but could be readily done
- $m_{H^{\pm\pm}}$ as light as 150 GeV allowed (simulation in Chiang/Nomura/Tsumura 12)
- For $m_{H^{\pm\pm}} = 150(400)$ GeV: $R_{\gamma\gamma} = 4.5, 3.1, 1.9\,(1.3, 1.2, 1.1)$

for $\lambda_1 = -3, -2, -1$

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



$R_{\gamma\gamma} > 1$ for $\lambda_1 < 0$

AGA/Moretti 12

LHC measurement: $R_{\gamma\gamma} = 1.6 \pm 0.3$

Conclusions

- Evidence for a Higgs boson in channels $H \to \gamma\gamma / H \to ZZ$
- Could be the first scalar of a non-minimal Higgs sector
- Doubly charged Higgs bosons appear in the Higgs Triplet

Model of neutrino mass generation $(m^{\nu}_{ij} = h_{ij} v_{\Delta})$

- $H^{\pm\pm}$ would contribute to (and could enhance) $H \to \gamma\gamma$
- $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ or $H^{\pm\pm} \to W^{\pm}W^{\pm}$ is a distinctive signal
- Multi-lepton signals $(2\ell \to 6\ell)$ from $q\overline{q} \to H^{++}H^{--}$ / $q'\overline{q} \to H^{\pm\pm}H^{\mp}$
- HTM has rich phenomenology at the LHC if $m_{H^{\pm\pm}} < 1$ TeV

Back up slides

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 $H^{\pm}$:

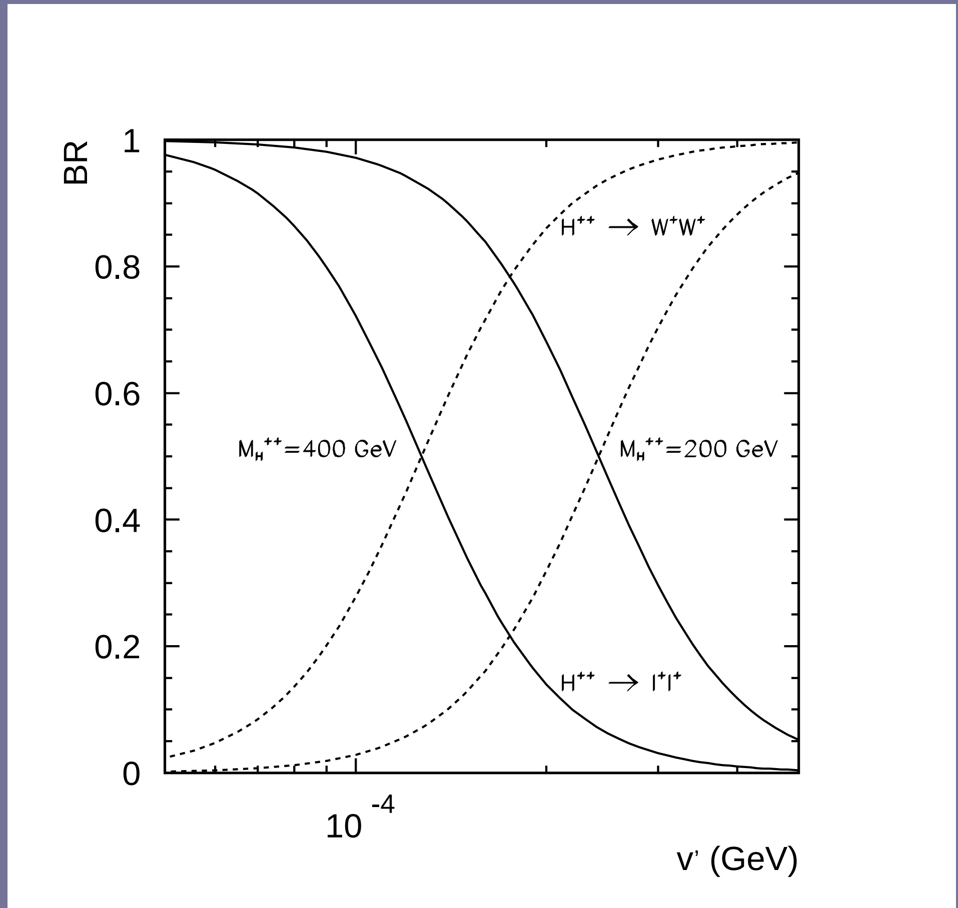
- $\Gamma(H^{\pm} \to \ell_i^{\pm} \nu) > \Gamma(H^{\pm} \to W^{\pm} Z, tb)$ for $v_{\Delta} < 10^{-4}$ GeV

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

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

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

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

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:

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\text{eV}^2, \quad |\Delta m_{31}^2| \equiv |m_3^2 - m_1^2| \simeq 2.7 \times 10^{-3}\text{eV}^2,$$
$$\sin^2 2\theta_{12} \simeq 0.86, \qquad \sin^2 2\theta_{23} \simeq 1, \qquad \sin^2 2\theta_{13} \lesssim 0.13.$$

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 $H^{\pm}$

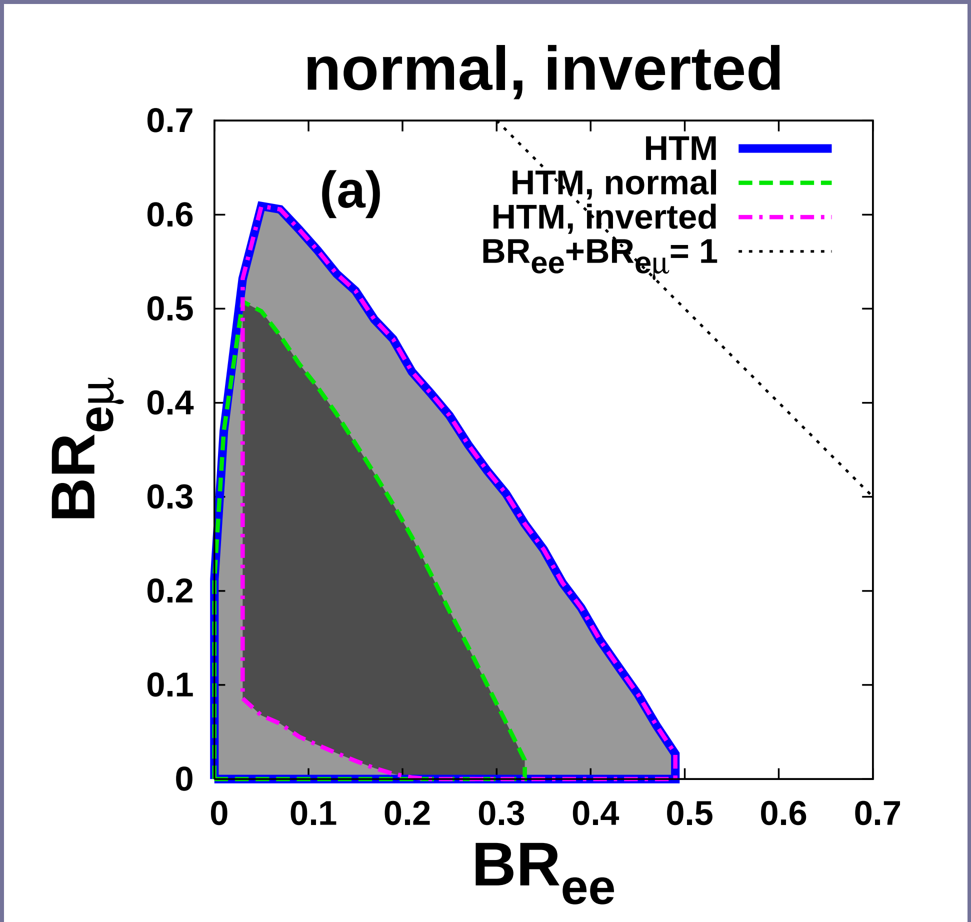
BR($H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$)

- 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

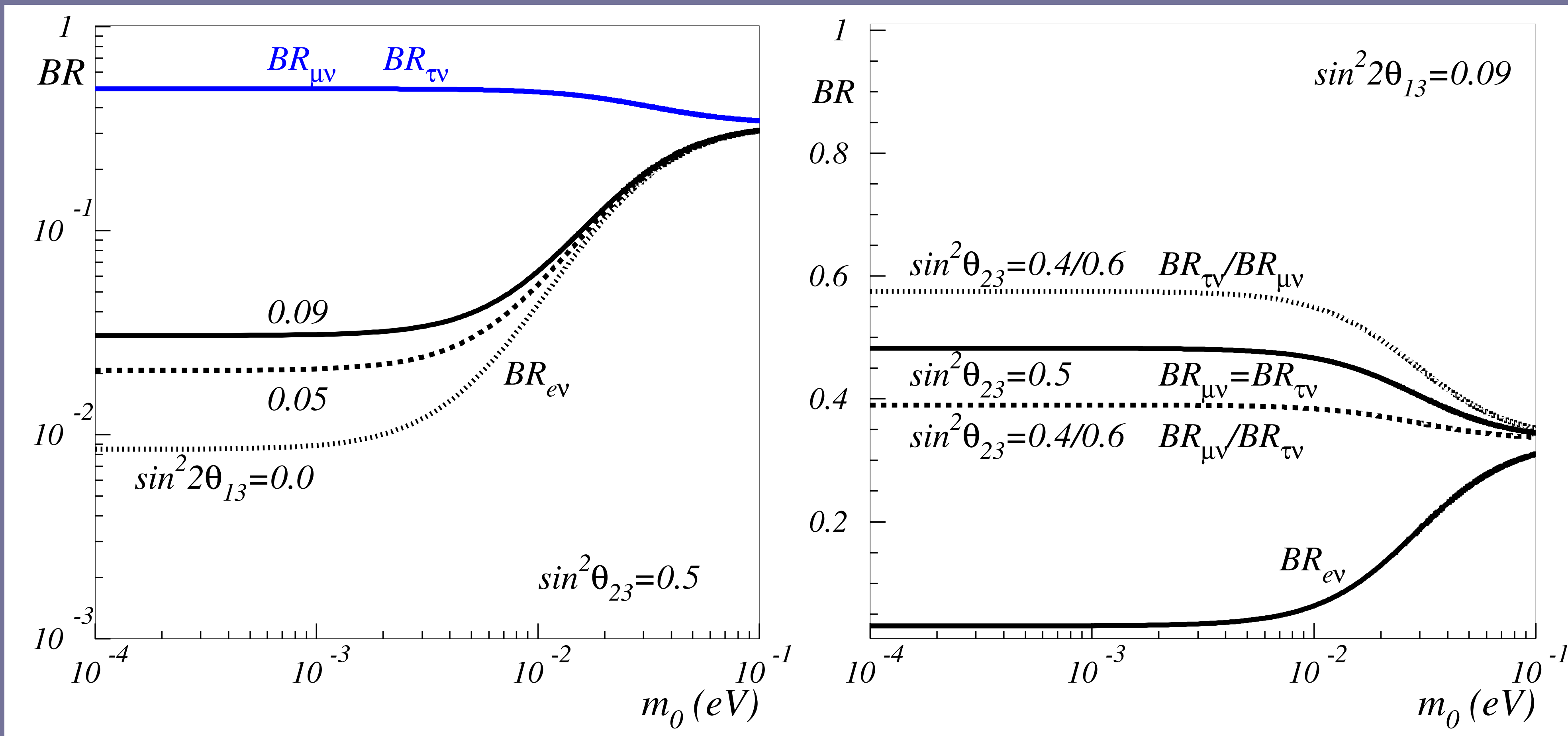
HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}e^{\pm}$),BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$)]



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



Fairly sharp prediction with uncertainty from $\sin\theta_{13}$ and $\sin\theta_{23}$

Han 08, AGA/Sugiyama 12

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 2012

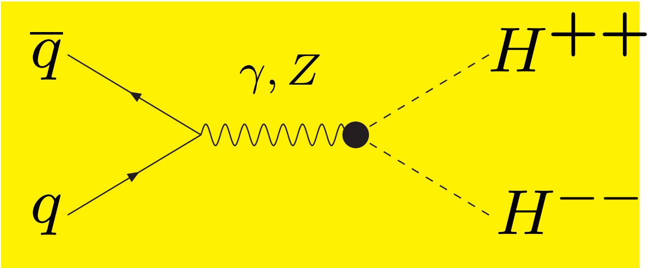
All constraints can be respected with $|h_{ij}| < 10^{-2}$ or 10^{-3}

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

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

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

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

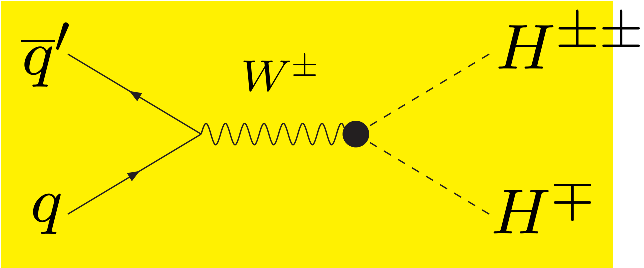


- $\sigma_{H^{++}H^{--}}$ is a simple function of $m_{H^{\pm\pm}}$ Barger 82, Gunion 89, Raidal 96
- $\sigma_{H^{++}H^{--}}$ has no dependence on h_{ij}

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

A mechanism not included in the Tevatron searches

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

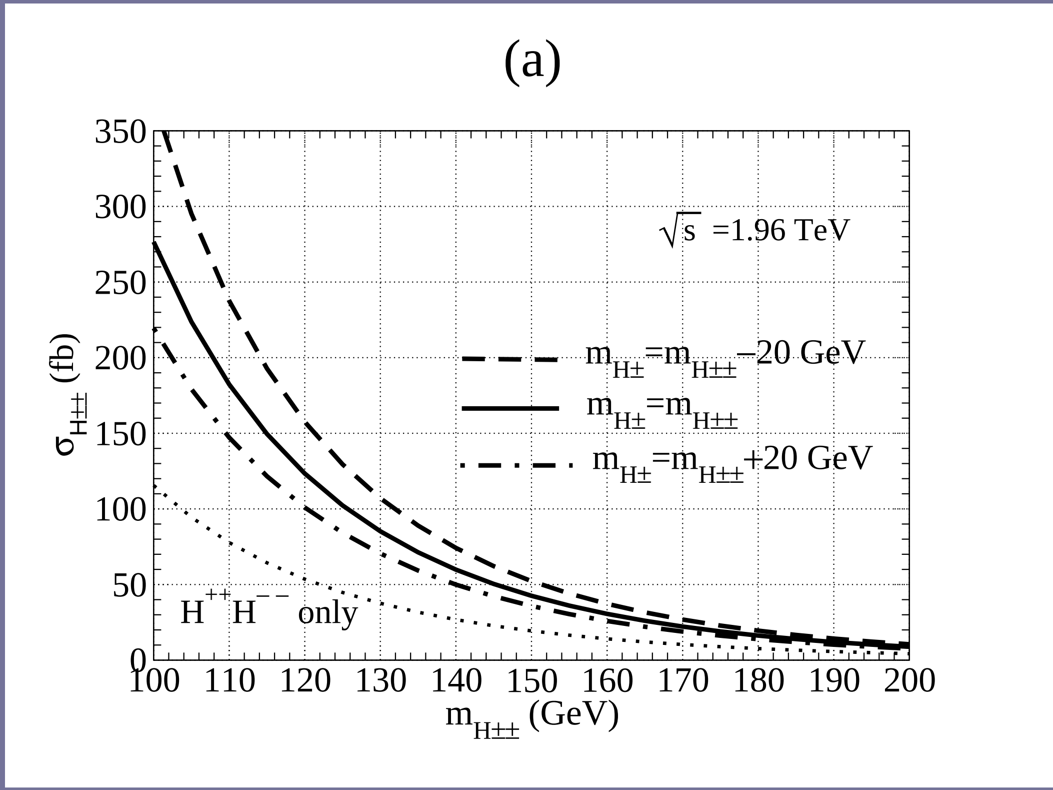


- $\sigma_{H^{\pm\pm}H^{\mp}}$ is a function of $m_{H^{\pm\pm}}$ and $m_{H^{\pm}}$ Barger 82, Dion 98
- Similar magnitude to $\sigma(p\overline{p} \to H^{++}H^{--})$ for $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$

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

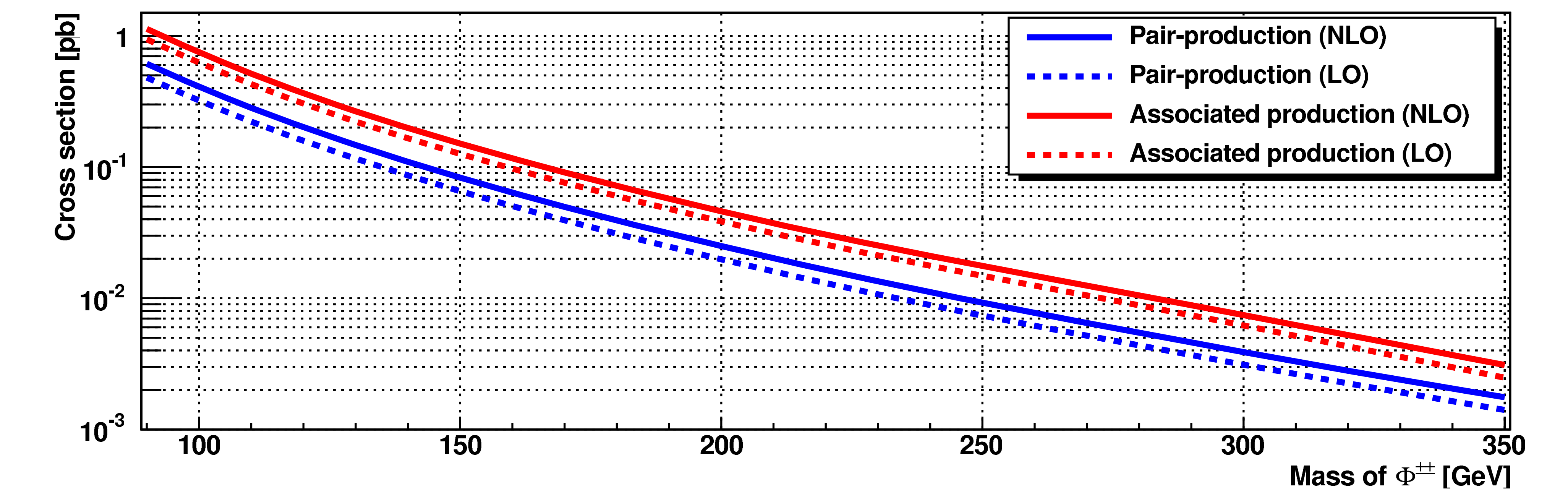
AGA,Aoki 05

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

- $\sigma(q\overline{q}' \to H^{\pm\pm}H^{\mp})$ can be as large as $\sigma(q\overline{q} \to H^{++}H^{--})$
- Increases the sensitivity to $m_{H^{\pm\pm}}$ in $\ell^{\pm}\ell^{\pm}$ 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 $q\overline{q} \to H^{++}H^{--}$
- 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)

- 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%