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

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- Observation of a Higgs boson with mass ~ 125 GeV at the LHC

- Is it the minimal SM Higgs boson or from a non-minimal Higgs sector?

- BR($H \to \gamma\gamma$) might be higher than that of the SM Higgs boson

- Higgs Triplet Model (HTM) and singly/doubly charged scalars ($H^{\pm}/H^{\pm\pm}$)

- The decay channel $H_1 \to \gamma\gamma$ and enhancement from virtual $H^{\pm}/H^{\pm\pm}$

Charged 2012, Uppsala, 8-11 October 2012

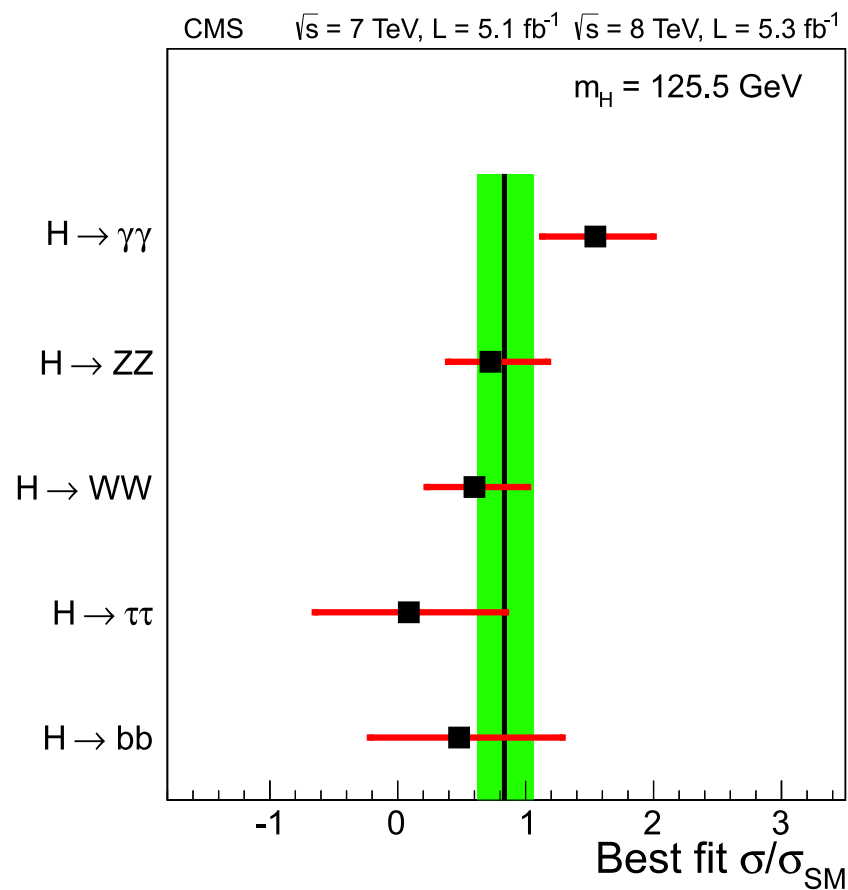## LHC evidence of a Higgs Boson with mass ~ 125 GeV

- Compelling evidence for a neutral boson $m_H \sim 125$ GeV

- ATLAS 5.9σ and CMS 5σ (combining 7 and 8 TeV data)

- Strongest signal in channels $\boxed{H \to \gamma\gamma \text{ and } H \to ZZ}$

- Some evidence for $H \to WW$: no evidence yet for $H \to \tau^+\tau^-$

- Hint of $H \to bb$ from Tevatron via WH, ZH (LHC sensitivity still inferior)

- Event numbers consistent (within errors) with the signal

expected for the SM Higgs boson

Strongest LHC signal from $H \to \gamma\gamma$
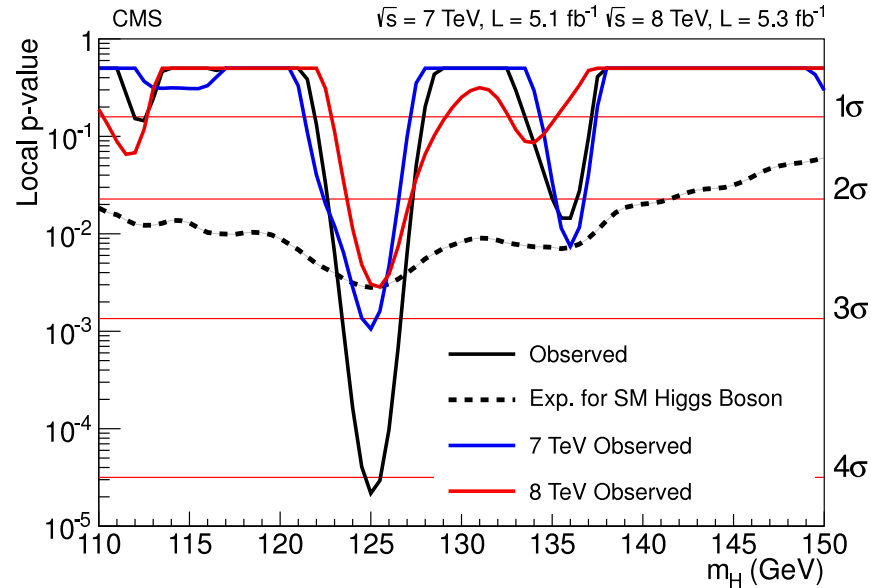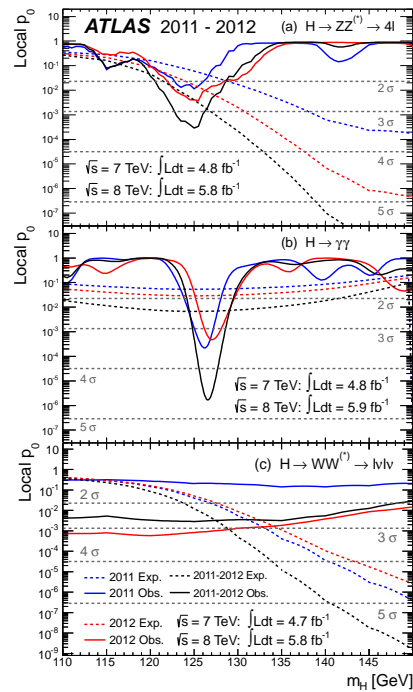
- Search is mainly sensitive to $gg \to H \to \gamma\gamma$

- Subdominant contributions from $pp \to WH, ZH, Hjj, Ht\bar{t}$

- ATLAS: local significance of excess at ~ 125 GeV is 4.5σ

- CMS: local significance of excess at ~ 125 GeV is 4.1σ

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

ATLAS 2011 - 2012 — m_H = 126.0 GeV

W,Z H $\to$ bb
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.7 fb^{-1}

H $\to$ $\tau\tau$
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.6-4.7 fb^{-1}

H $\to$ WW$^{(*)}$ $\to$ lνlν
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int$Ldt = 5.8 fb^{-1}

H $\to$ $\gamma\gamma$
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int$Ldt = 5.9 fb^{-1}

H $\to$ ZZ$^{(*)}$ $\to$ 4l
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int$Ldt = 5.8 fb^{-1}

Combined
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.6 - 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int$Ldt = 5.8 - 5.9 fb^{-1}
$\mu = 1.4 \pm 0.3$

Signal strength (μ)

CMS $\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}

m_H = 125.5 GeV

H $\to$ $\gamma\gamma$

H $\to$ ZZ

H $\to$ WW

H $\to$ $\tau\tau$

H $\to$ bb

Best fit σ/σ_{SM}
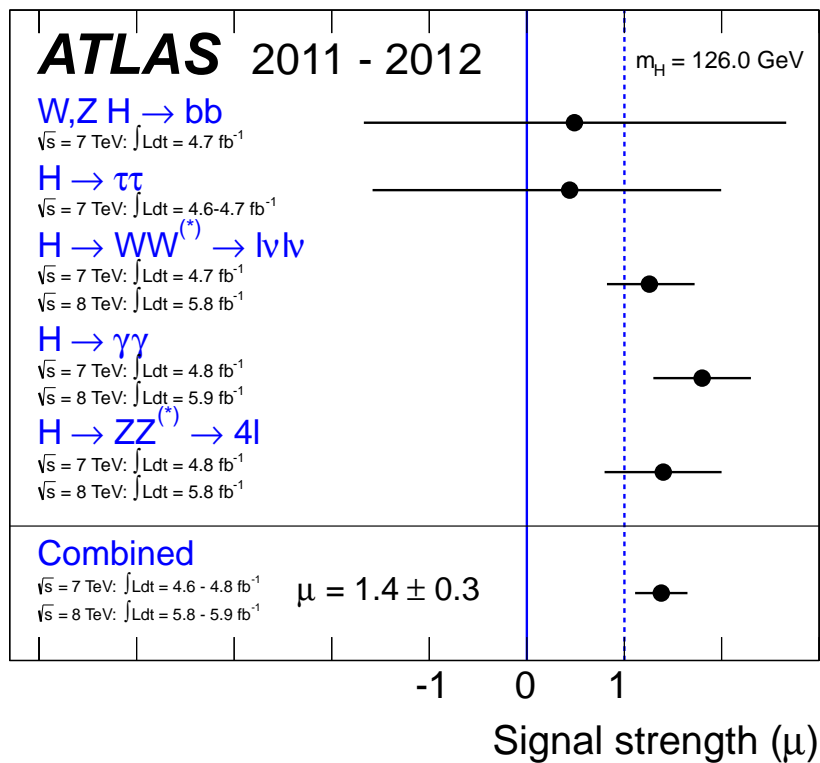
Hint of an enhanced $BR(H \to \gamma\gamma)$ with $m_H \sim 125$ GeV?

- 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 :

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

- Error in $\sigma_{\gamma\gamma}/\sigma_{SM}$ will be reduced in 8 TeV run and 13 TeV run

- $\sigma_{\gamma\gamma}/\sigma_{SM} > 1$ explained by a non-minimal Higgs sector

The Higgs Triplet Model, HTM

Motivation $\rightarrow$ 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 $e^{\pm}$): rather obvious way to enhance $H \rightarrow \gamma\gamma$!

Higgs Triplet Model (HTM)

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

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

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

$(v_\Delta \lesssim 5 \text{ GeV to keep } \rho = (M_Z^2 \cos^2 \theta_W)/M_W^2 \sim 1)$; 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: $H^{\pm\pm}, H^{\pm}, A^0, H_2, H_1$

- $H^{\pm\pm}$ 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

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

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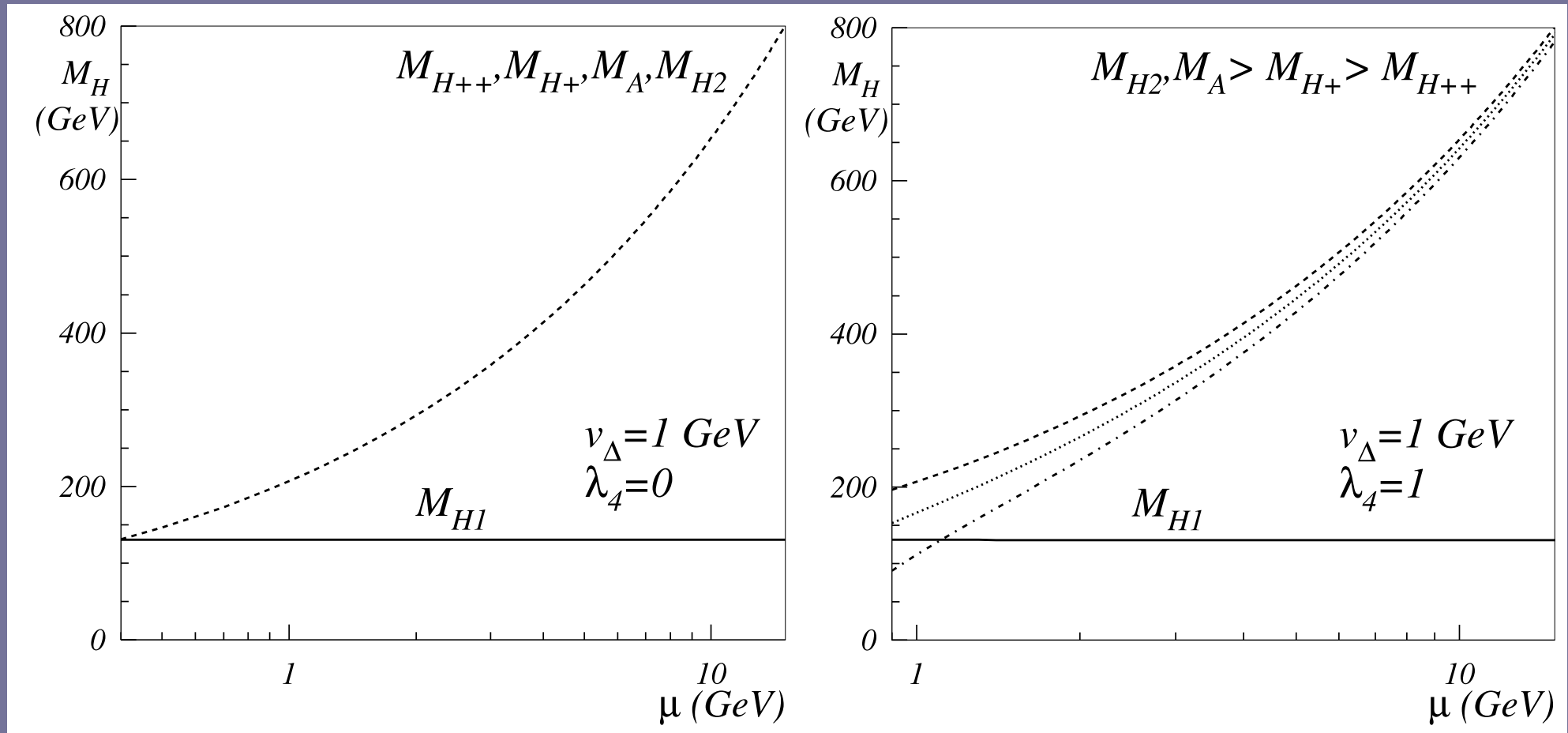
$$m_{H^\pm}^2 = M_\Delta^2 + \left(\frac{\lambda_1}{2} + \frac{\lambda_4}{4}\right) v^2 + (\lambda_2 + \sqrt{2}\lambda_3) v_\Delta^2$$

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

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

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

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

Left panel:
M_H (GeV)
$M_{H++}, M_{H+}, M_A, M_{H2}$
$v_\Delta = 1\ GeV$
$\lambda_4 = 0$
M_{H1}
$\mu\ (GeV)$

Right panel:
M_H (GeV)
$M_{H2}, M_A > M_{H+} > M_{H++}$
$v_\Delta = 1\ GeV$
$\lambda_4 = 1$
M_{H1}
$\mu\ (GeV)$

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

Akeroyd/Chia

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

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

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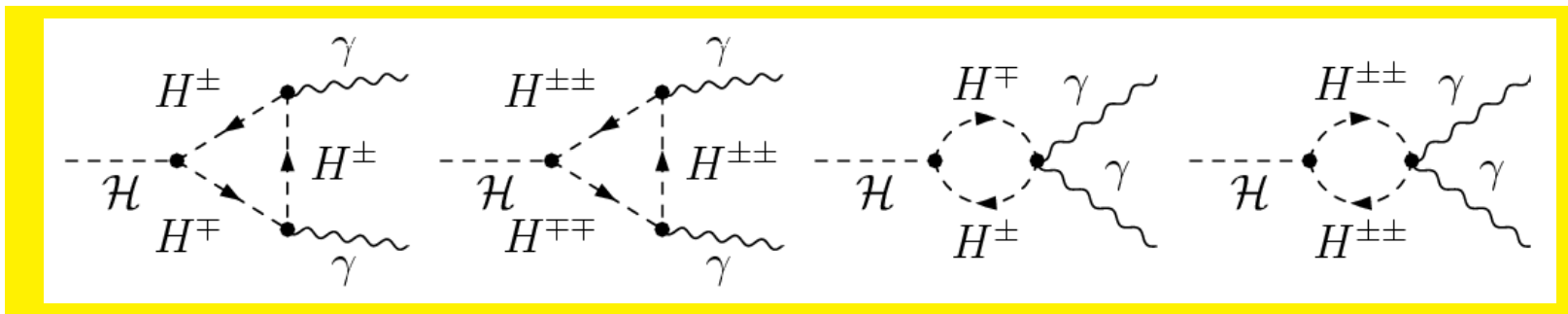
$$g_{H_1 WW} = \cos\alpha + 2\sin\alpha v_\Delta / v$$

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

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

$H_1 \to \gamma\gamma$ 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:

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

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

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

Magnitude of scalar-loop contributions

- Coupling $\tilde{g}_{H_1 H^{++} H^{--}}$ depends on λ_1 only

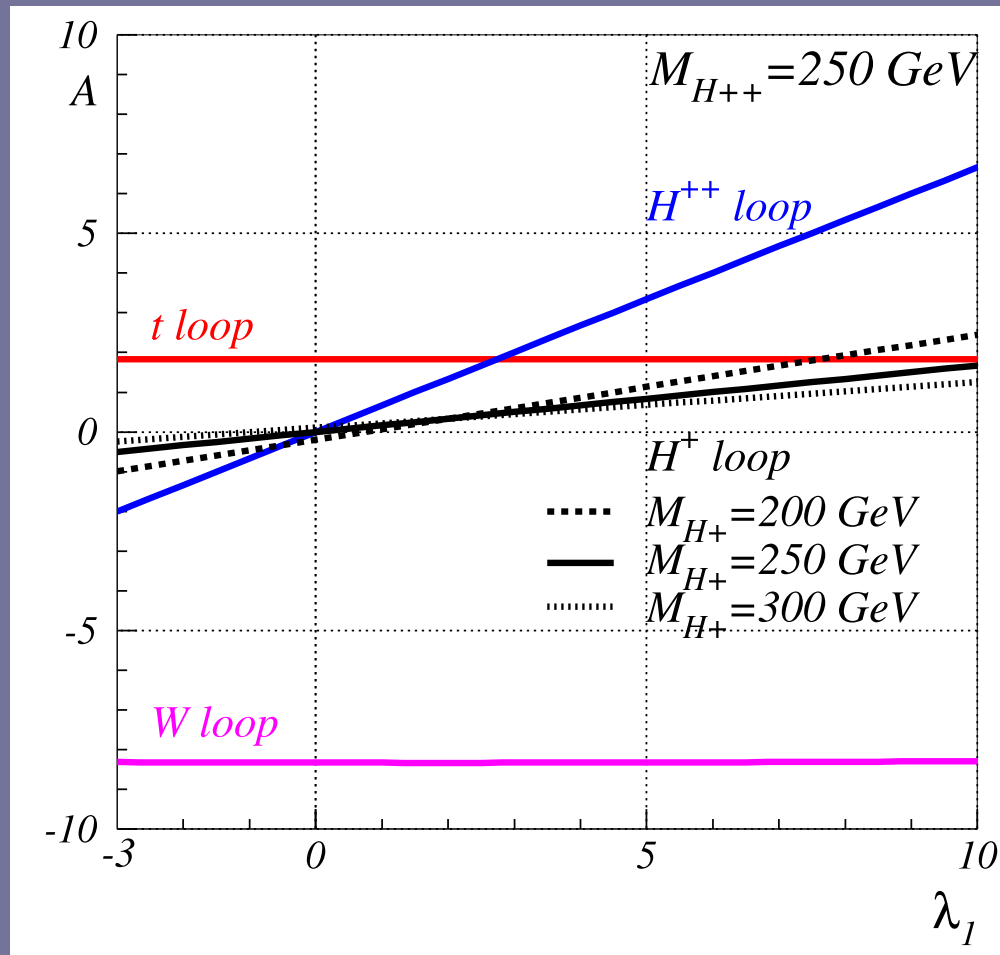- Main theoretical constraint on λ_i comes from stability of scalar potential, e.g.

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

- Only positive λ_1 considered in previous studies Arhrib 11,Kanemura 12

- λ_1 could be negative Akeroyd/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 $BR(H_1 \rightarrow \gamma\gamma)$

- Kanemura 12 considered $\lambda_1 > 0$

$\rightarrow$ discussed suppression of $BR(H_1 \rightarrow \gamma\gamma)$

- For sufficiently positive λ_2, λ_3, the range $-3 < \lambda_1 < 0$

can be considered (Constructive interference) Akeroyd/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 $H^{\pm}$

$M_{H++}=250\ GeV$

$H^{++}\ loop$

$t\ loop$

$H^{+}\ loop$
$M_{H+}=200\ GeV$
$M_{H+}=250\ GeV$
$M_{H+}=300\ GeV$

$W\ loop$

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

Akeroyd/Moretti 12

Definition of $R_{\gamma\gamma}$

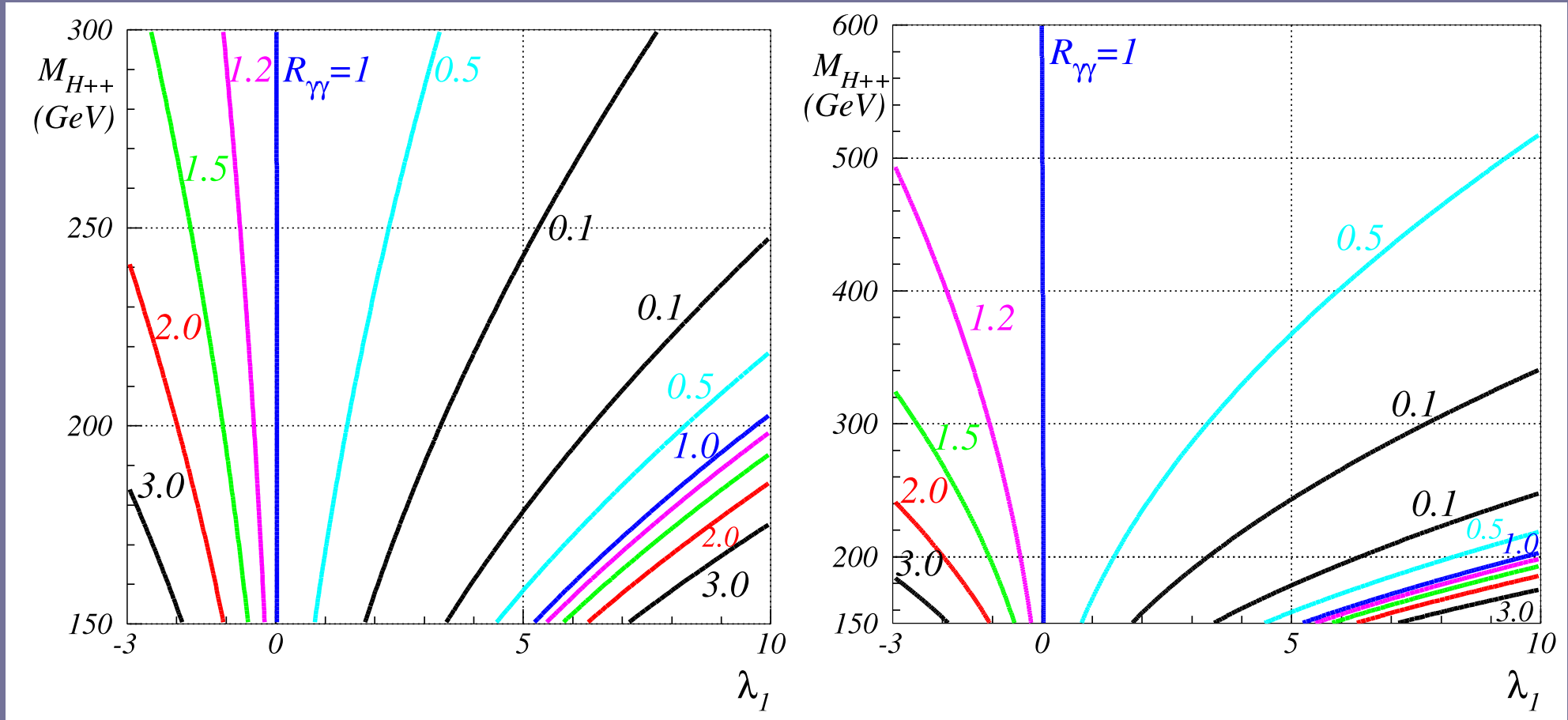LHC searches constrain $\mathrm{BR}(H \to \gamma\gamma)_{model}/\mathrm{BR}(H \to \gamma\gamma)_{SM}$

where the model has exactly SM production cross section

(dominant contribution from $gg \to H$)

We define:

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

- $R_{\gamma\gamma} = 1.6 \pm 0.3$ 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 $150\,\mathrm{GeV} < m_{H^{\pm\pm}} < 600$ GeV, with $m_{H_1} \sim 125$ GeV

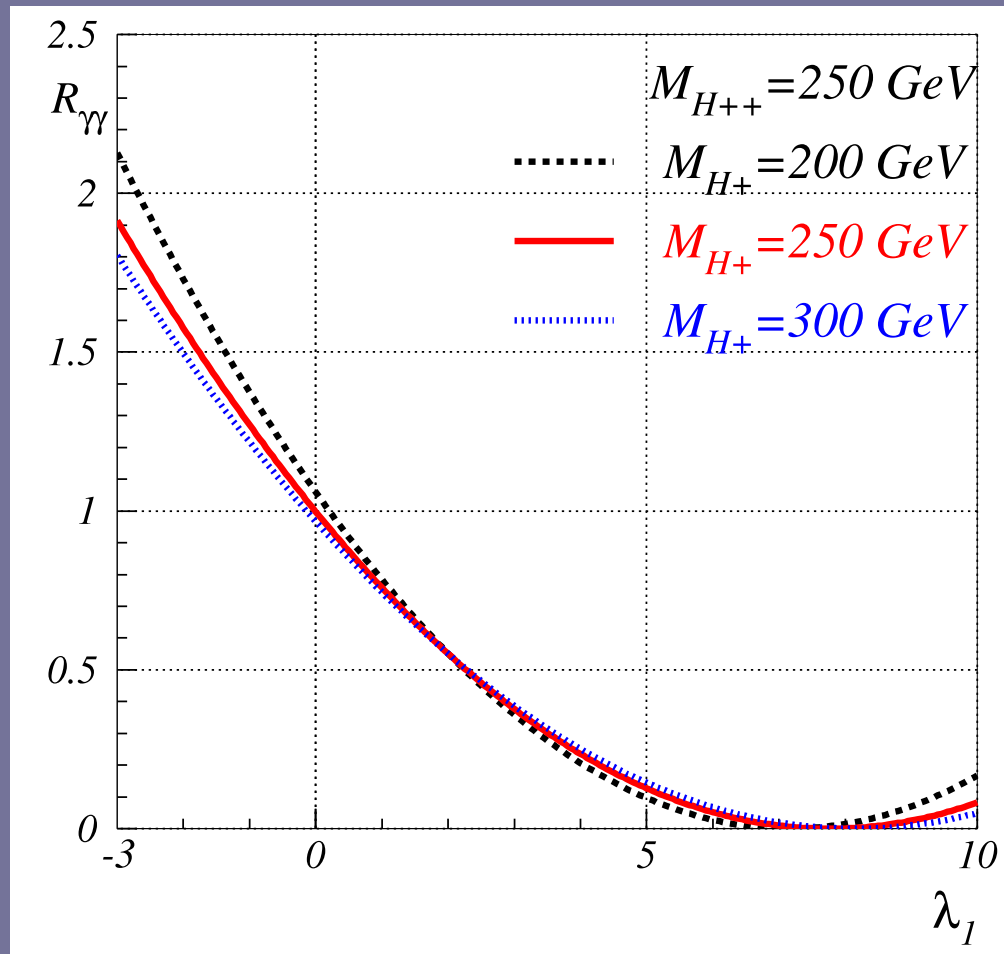$R_{\gamma\gamma} > 1$ for $\lambda_1 < 0$ Akeroyd/Moretti 12   LHC measurement: $R_{\gamma\gamma} = 1.6 \pm 0.3$

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

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

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

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

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

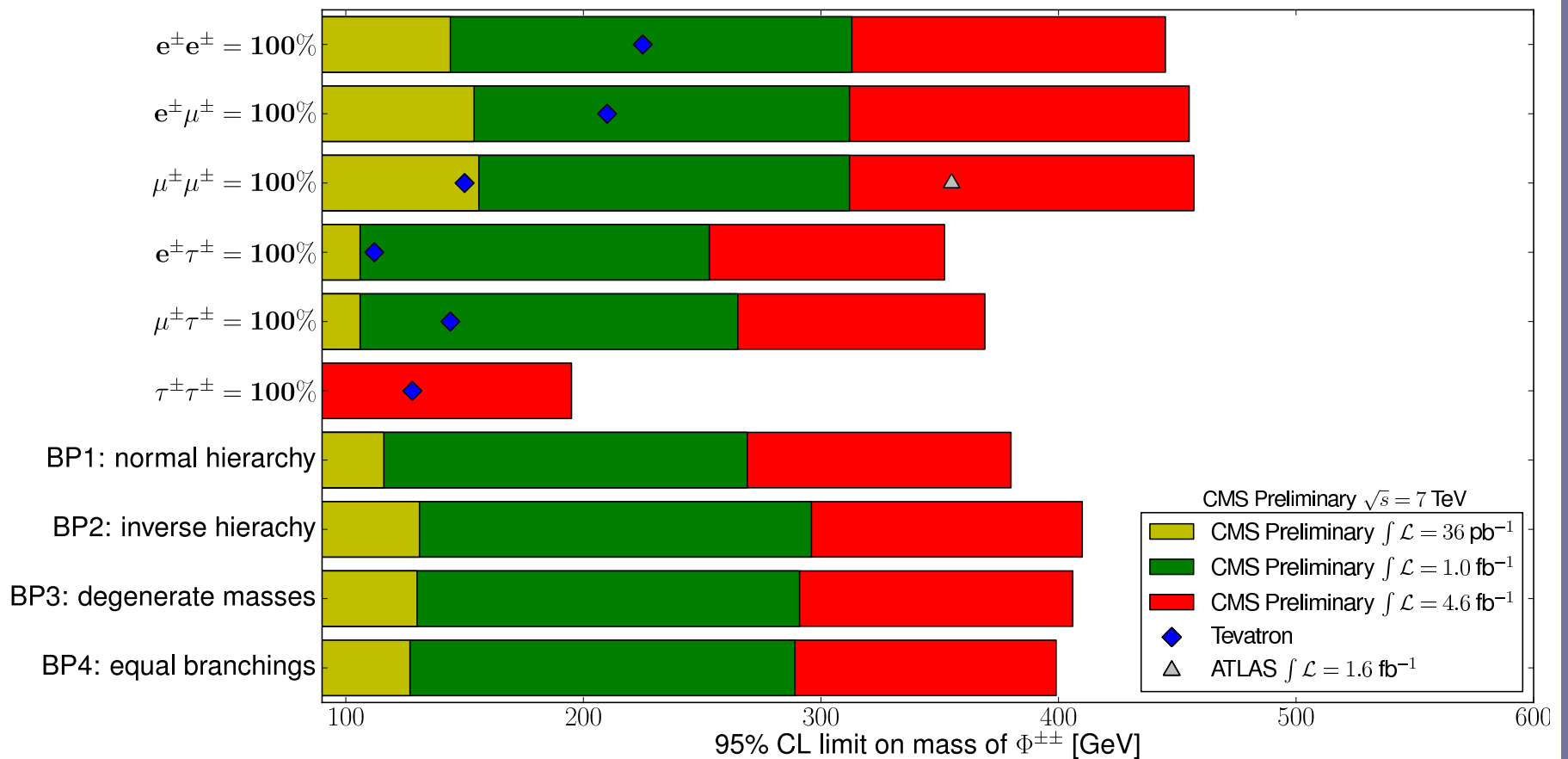ii) small negative λ_1 and $m_{H^{\pm\pm}} < 400$ GeV Akeroyd/Moretti 12

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

$R_{\gamma\gamma}$

$M_{H++}=250\ GeV$

$\cdots\cdots$ $M_{H+}=200\ GeV$

—— $M_{H+}=250\ GeV$

$\cdots\cdots$ $M_{H+}=300\ GeV$

λ_1

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

Akeroyd/Moretti 12

Mass limits on $m_{H^{\pm\pm}}$ from CMS/ATLAS searches 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 $\sum \mathrm{BR}(\mathrm{H}^{\pm\pm} \to \ell^\pm \ell^\pm) \sim 1$ (i.e. $v_\Delta < 0.1$ MeV)
- Limit weakened for points where $\mathrm{BR}(H^{\pm\pm} \to \tau^\pm \tau^\pm)$ large

However, $H^{\pm\pm} \to W^\pm W^\pm$ 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 $\lambda_1 = -3, -2, -1$

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

- Future data might prefer $\mathrm{BR}(H \to \gamma\gamma)$ higher than SM prediction

- Doubly charged Higgs bosons appear in the HTM Model of neutrino mass generation

- $H^{\pm\pm}$ 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

- HTM has rich phenomenology at the LHC if $m_{H^{\pm\pm}} < 1$ TeV

- `HTMDecay.f` code available for public use