# Revisiting $h \to \gamma\gamma$ and $h \to Z\gamma$ in the Higgs Triplet Model

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Based on PRD84'2011 & JHEP1204' 2012

# *Outline*

- *Introduction*
- *Motivations*
- $h \rightarrow \gamma\gamma$ *and* $h \rightarrow Z\gamma$ *in the Higgs Triplet Model (HTM)*
- *Summary & Conclusions*

# Brief Introduction.......

- On 4th July 2012: after many years of investigations, a new boson was discovered by ATLAS and CMS at CERN. [ATLAS PLB716'12 ; CMS PLB716'12]
- Both ATLAS and CMS reported a clear excess in the two photon channel and in the ZZ* channel.
  The discovery is also confirmed, with less significance in W W* channel and also by Tevatron $W H \rightarrow l \nu bb$ results.

- From 4-lepton and diphoton channels, both ATLAS and CMS updated their studies on spin and parity:

CP-even spin 0 state $J^P = 0^+$ seems to be favored, while CP-odd $0^-$ and spin $2^+$ hypotheses excluded [ATLAS-CONF-2012-169 ; CMS-PAS-HIG-12-041]

# $h \rightarrow \gamma\gamma$ : ATLAS & CMS updates

- The best-fit signal strength for a SM Higgs boson mass hypothesis @ 125 - 126 GeV is:

- $\sigma^{CMS} / \sigma_{SM} = 0.78 \pm 0.27$, -- Multivariate analysis (MV A) -- @ $m_{H} = 125.4 \pm 0.5$ (stat.) $\pm 0.6$ (syst.) GeV
- $\sigma^{CMS} / \sigma_{SM} = 1.11 \pm 0.31$ -- cut – based analysis -- @ $m_{H} = 124.5$ GeV

- $\sigma^{ATLAS} / \sigma_{SM} = 1.65 \pm 0.24$ (stat) $+ 0.25 - 0.18$ (syst) @ $m_{H} = 126.8 \pm 0.2$ (stat) $\pm 0.7$ (syst) GeV.

$$\sigma^{Combined} / \sigma_{SM} = 1.18 \pm 0.16$$

[ATLAS-CONF-2013-012, CMS-PAS-HIG-13-005]

# $h \to Z\ \gamma$ @ ATLAS & CMS

- $h \to \gamma\ Z \to \gamma\, l^+ l^-$ has also a clean and reconstructible signal at LHC.
- Provide some complementary information on the Higgs properties such as the mass, spin, parity.
- $h \to \gamma\ \gamma$ and $h \to \gamma\, Z$ should be correlated to some extent.
- Upper limits on signal strength with $m_H$ @ 125 GeV :
  - $\sigma^{CMS} / \sigma_{SM} < 13.5$
  - $\sigma^{ATLAS} / \sigma_{SM} < 37$

[ATLAS-CONF-2013-009 ; CMS-PAS-HIG-13-006]

(*Type II see-saw Model*)

# *Higgs Triplet Model*

# Motivations……

- Neutrino masses: Type I , II , III seesaw models; Hybrid seesaw (I+III) ; Left-Right symmetric models (I+II)

[Minkowski'77, Mohapatra, Senjanovic ´'79,Yanagida'79, Glashow'79, Gell-Mann, Ramond, Slansky'79]; [Magg, Wetterich'80,Lazarides, Shafi, Wetterich '81, Mohapatra]; [Foot, Lew, He, Joshi'89]; [Ma'98,B. Bajc and G. Senjanovic ´'06, Fileviez Pérez'07]; [Mohapatra, Pati'75, Senjanovic ´, Mohapatra'75]

- Real triplet with $v_t$ = **0** Could be a candidate for dark matter

M. Cirelli, N. Fornengo and A. Strumia, NPB 753(2006);
M. Cirelli et al NPB 787(2007) ;
F. Perez, Pavel et al. Phys.Rev. D79 (2009).

# Motivations....

$$\mathcal{L}_{Yukawa} \supset -Y_\nu L^T C \otimes i\sigma^2 \Delta L + h.c. \Rightarrow m_\nu = Y_\nu v_\Delta$$

$$V(\Delta, H) = M^2_\Delta Tr(\Delta^\dagger \Delta) + \mu (H^T i \tau^2 \Delta^\dagger H),$$

$$\Rightarrow \text{Seesaw Relation} : m_\nu = Y_\nu \mu v^2_d / M^2_\Delta$$

- If $m_\nu \approx 1 eV$, with $Y_\nu \approx 1$, then $M_\Delta \approx \mu \approx 10^{14-15}$ GeV.
  $\Rightarrow$ Not testable @ the LHC
- If $m_\nu \approx 1$ eV, and $M_\Delta \approx 1$ TeV, then $Y_\nu \mu \approx 10^{-8}$ GeV.

- Small $\mu$ can be viewed as soft breaking term of lepton number.

# Higgs Triplet Model (HTM)

- It consists of standard Higgs weak doublet $H$ and a scalar field $\Delta$ transforming as a triplet under $SU(2)_L$, with $Y_\Delta = 2$:
  $H \sim (1, 2, 1)$ and $\Delta \sim (1, 3, 2)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$H^\dagger = (\phi^+, \phi^0) \quad \text{and} \quad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

- $\mathcal{L} = (D_\mu H)^\dagger (D_\mu H) + Tr\,(D_\mu \Delta)^\dagger (D_\mu \Delta) - V(H, \Delta) + \mathcal{L}_{yukawa}$

The most general renormalizable Higgs potential:

- $V = M^2_\Delta\, Tr\,(\Delta^\dagger \Delta) - m^2_H H^\dagger H + \lambda/4 (H^\dagger H)^2 + \lambda_1 (H^\dagger H)\, Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr\,(\Delta^\dagger \Delta))^2 + \lambda_3 Tr\,(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H + \mu\, H^T i \tau^2 \Delta^\dagger H.$

# Higgs Triplet Model (HTM)

- After EWSB, $<\Delta^o> = v_t$ & $<\phi^o> = v_d$
- Minimization of the Higgs Potential yields:

$$\mathrm{M}_W^2 = \frac{g^2(\upsilon_d^2 + 2\upsilon_t^2)}{4}, \mathrm{M}_Z^2 = \frac{g^2(\upsilon_d^2 + 4\upsilon_t^2)}{4\cos^2\theta_W}$$

- Higgs Spectrum:

  - ✓ 2 CP even $h$ and $H$: mixtures of $\phi$ and $\Delta$
  - ✓ 1 CP odd $A$: dominated by triplet
  - ✓ a pair of charged $H^{\pm}$: dominated by triplet
  - ✓ a pair of doubly charged $H^{\pm\pm}$: purely triplet. .

- 7 Independents parameters : 5 masses, $\mu$ and $v_t$.

# HTM: Constraint on $v_t$

- *Modified form of the* ρ *parameter :*

$$\rho_0 = M_w^2 / c_w^2 M_z^2 \simeq 1 - 2v_t^2 / v_d^2 \approx 1 + \delta\rho$$

- *At the* 2σ *level,* $\rho_0 = 1.0004\ _{-0.0011}^{+0.0029}$, *one gets an upper bound :* $v_t \leq 5$ *GeV.*

- 1*-loop analysis is done: Similar conclusions.*

[S. Kanemura, K.Yagyu PRD85'2012]

# HTM: BFB Constraints

$$\lambda > 0 \;\;\&\;\; \lambda_2 + \lambda_3 > 0 \;\;\&\;\; \lambda_2 + \frac{\lambda_3}{2} > 0$$

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

$$\&\;\; \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} > 0 \;\;\&\;\; \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} > 0$$

# HTM: Perturbative Unitarity Constraints

$$|\lambda_1 + \lambda_4| \leq \kappa\pi$$

$$|\lambda_1| \leq \kappa\pi$$

$$|2\lambda_1 + 3\lambda_4| \leq 2\kappa\pi$$

$$|\lambda| \leq 2\kappa\pi$$

$$|\lambda_2| \leq \frac{\kappa}{2}\pi$$

$$|\lambda_2 + \lambda_3| \leq \frac{\kappa}{2}\pi$$

$$|\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}\,| \leq 4\kappa\pi$$

$$|3\lambda + 16\lambda_2 + 12\lambda_3 \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}\,| \leq 4\kappa\pi$$

$$|2\lambda_1 - \lambda_4| \leq 2\kappa\pi$$

$$|2\lambda_2 - \lambda_3| \leq \kappa\pi$$

# HTM: Unitarity & BFB Constraints

$$0 \leq \lambda \leq \frac{2}{3}\kappa\pi$$

$$\lambda_2 + \lambda_3 \geq 0 \ \ \& \ \ \lambda_2 + \frac{\lambda_3}{2} \geq 0$$

$$\lambda_2 + 2\lambda_3 \leq \frac{\kappa}{2}\pi$$

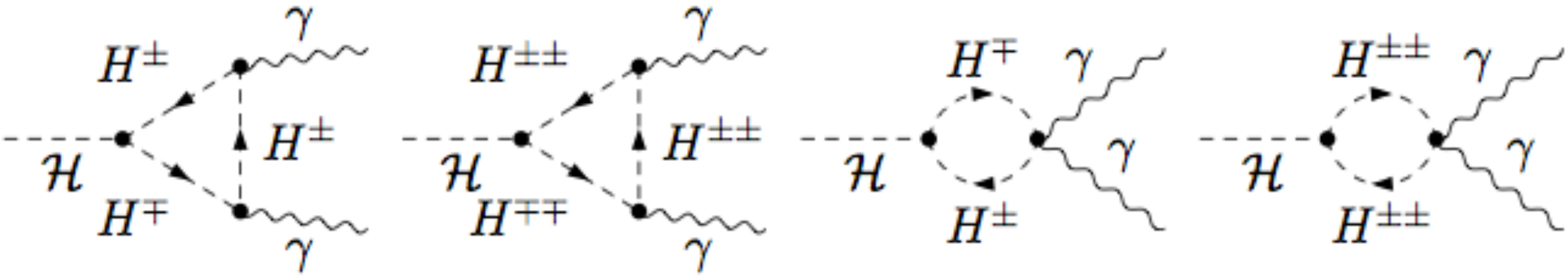
$$4\lambda_2 + 3\lambda_3 \leq \frac{\kappa}{2}\pi$$

$$2\lambda_2 - \lambda_3 \leq \kappa\pi$$

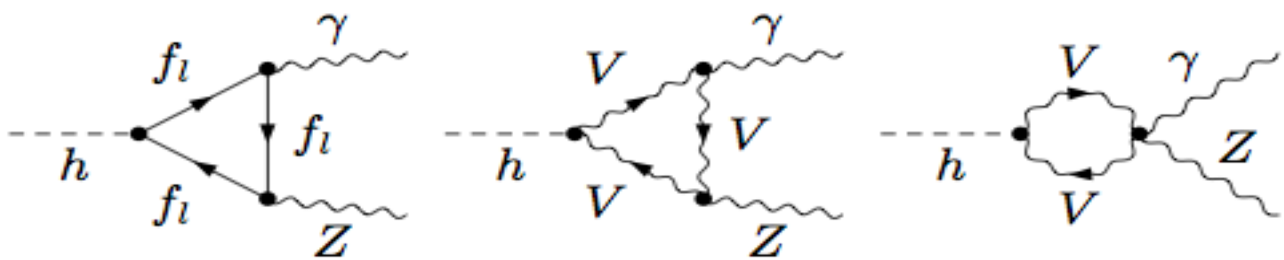
$$|\lambda_4| \leq \min \sqrt{(\lambda \pm 2\kappa\pi)(\lambda_2 + 2\lambda_3 \pm \frac{\kappa}{2}\pi)}$$

$$|2\lambda_1 + \lambda_4| \leq \sqrt{2(\lambda - \frac{2}{3}\kappa\pi)(4\lambda_2 + 3\lambda_3 - \frac{\kappa}{2}\pi)}$$

# $Higgs \rightarrow \gamma\ \gamma$ & $Higgs \rightarrow Z\ \gamma$




*Charged Higgs Triplet loop contributions*




*SM contributions*

# $h \to \gamma\gamma$ amplitude

$$\Gamma(h^0 \to \gamma\gamma) = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \Bigg| \sum_f N_c Q_f^2 g_{hff} A_{1/2}(\tau_f) + g_{hWW} A_1(\tau_W)$$

$$- \frac{M_W}{g} \Big( \frac{g_{hH^\pm H^\mp}}{m_{H^\pm}^2} A_0(\tau_{H^\pm}) + 4 \frac{g_{hH^{\pm\pm} H^{\mp\mp}}}{m_{H^{\pm\pm}}^2} A_0(\tau_{H^{\pm\pm}}) \Big) \Bigg|^2$$

with

$$g_{h^0 H^{++} H^{--}} = -2(\lambda_2 v_\Delta s_\alpha + \lambda_1 v_d c_\alpha) \approx -\lambda_1 v_d + \ldots$$

$$g_{h^0 H^+ H^-} = -\frac{1}{2}(2\lambda_1 + \lambda_4) v_d + \ldots$$

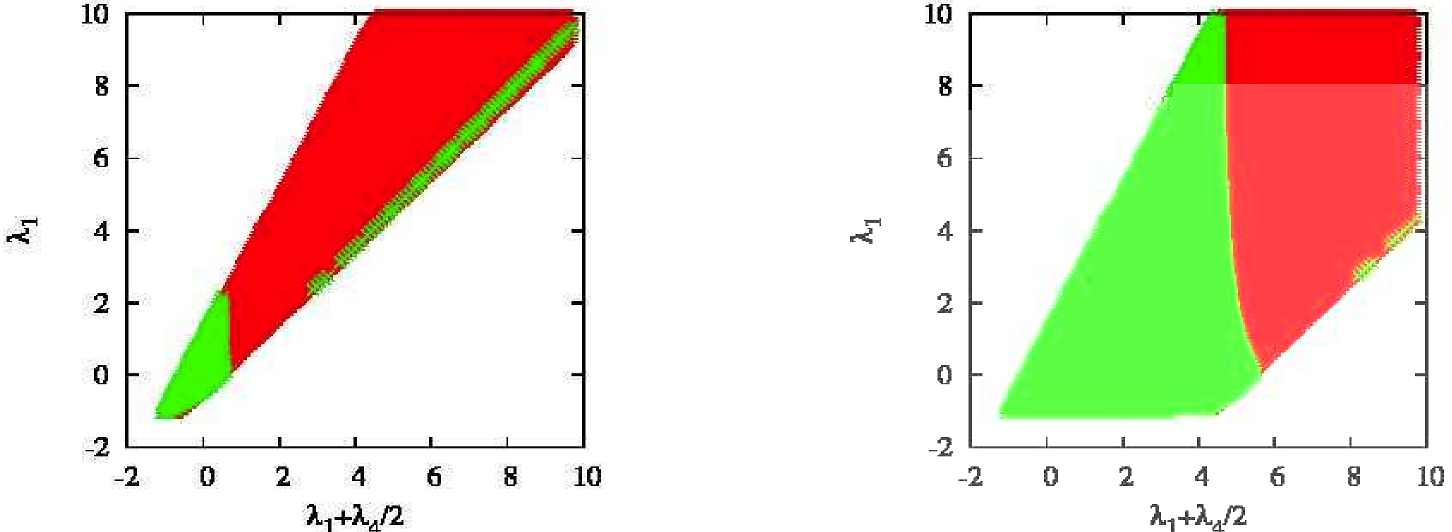
# $Higgs \rightarrow \gamma\,\gamma$

- To look for any excess in this decay channel and compare with LHC results, we define:

$$R_{\gamma\gamma} = (\sigma(h \rightarrow gg) \times Br(h \rightarrow \gamma\,\gamma))_{HTM} / (\sigma(h \rightarrow gg) \times Br(h \rightarrow \gamma\,\gamma))_{SM}$$

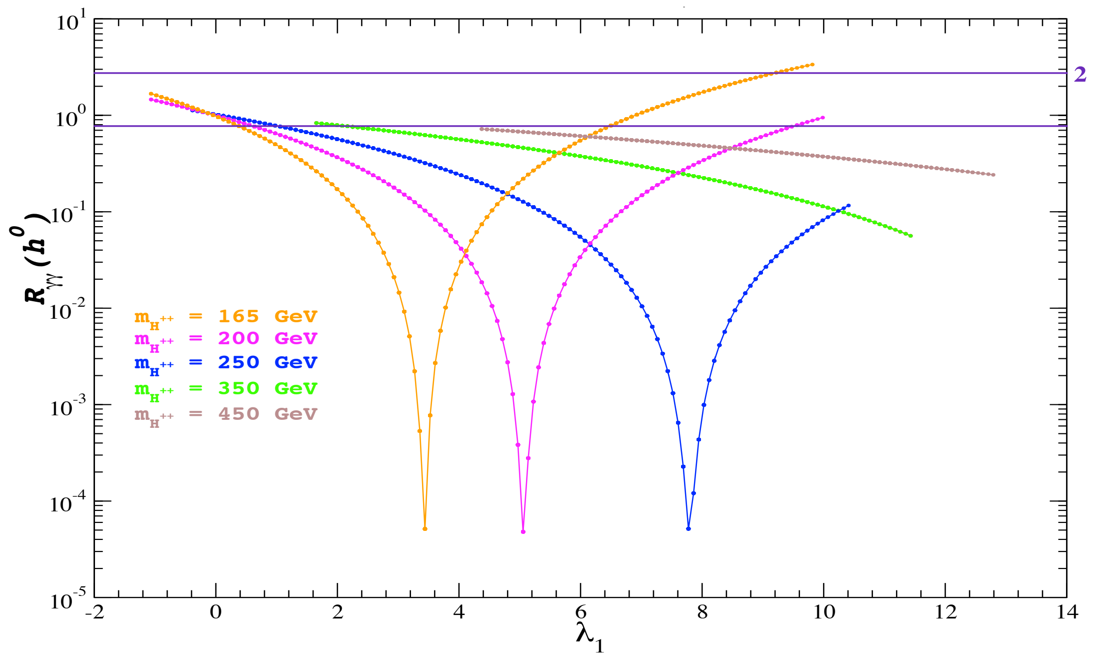
$$\begin{aligned} g_{h^0 H^{++} H^{--}} &= -\{2\lambda_2 v_t s_\alpha + \lambda_1 v_d c_\alpha\} \\ g_{h^0 H^{+} H^{-}} &= -\frac{1}{2}\Big\{\{4v_t(\lambda_2+\lambda_3)c^2_{\beta'} + 2v_t\lambda_1 s^2_{\beta'} - \sqrt{2}\lambda_4 v_d c_{\beta'} s_{\beta'}\}s_\alpha \\ &\quad + \{\lambda\, v_d s^2_{\beta'} + (2\lambda_1+\lambda_4)v_d c^2_{\beta'} + (4\mu - \sqrt{2}\lambda_4 v_t)c_{\beta'} s_{\beta'}\}c_\alpha \Big\} \end{aligned}$$

# at sign of $\lambda_1$ is prefered by constraints?



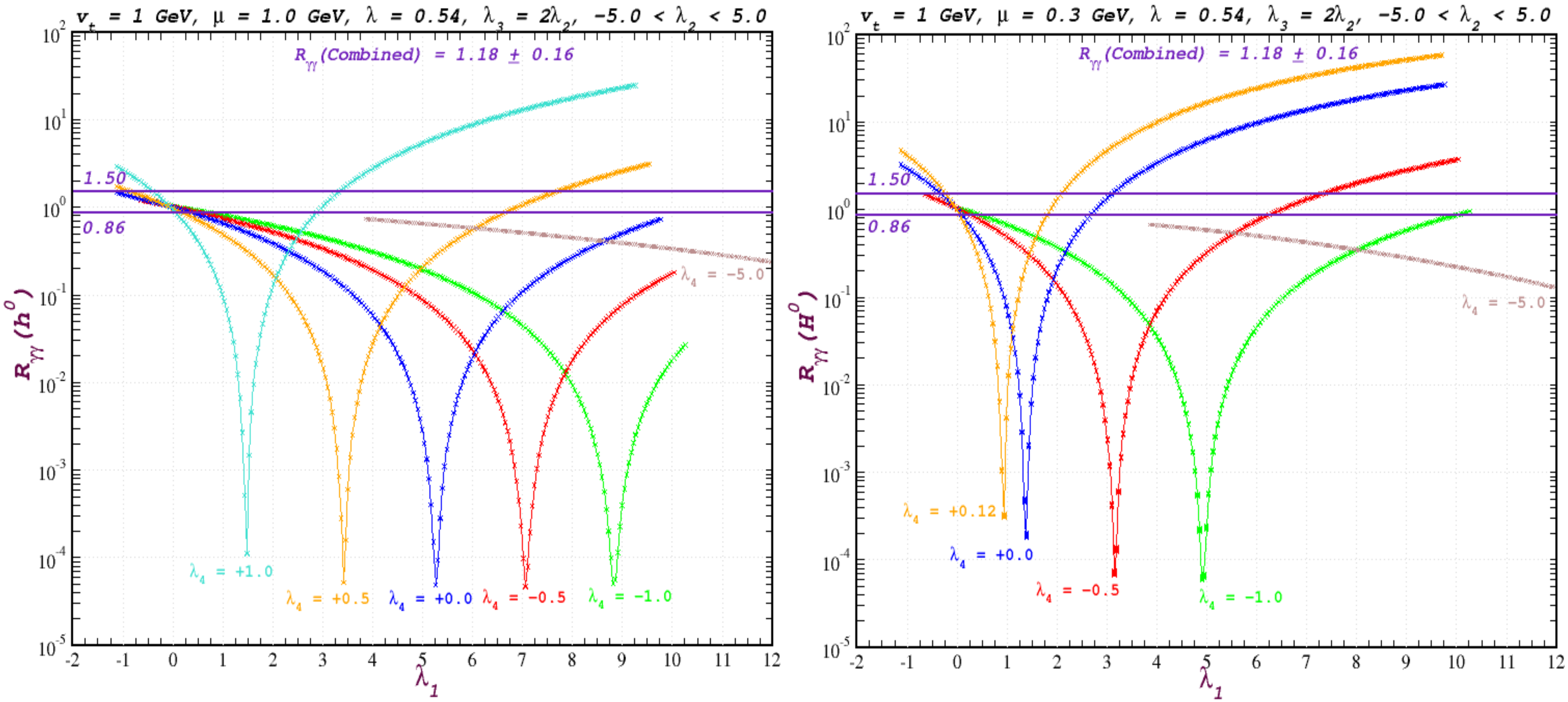

(a) $\mu = 1$ GeV , (b) $\mu = 8$ GeV

It is possible to have both $hH^{\pm\pm}H^{\mp\mp} \approx -\lambda_1 v_d$ and $hH^{\pm}H^{\mp} \approx -(2\lambda_1 + \lambda_4)v_d > 0$ and then $H^{\pm\pm}$ and $H^{\pm}$ contribute constructively with W loops.




$\lambda_3 = 2\lambda_2 = 0.2$, $m_h = 126$ GeV

$$R_{\gamma\gamma} = \frac{\sigma(gg\to h)\times Br(h\to\gamma\gamma)}{\sigma^{SM}(gg\to h)\times Br^{SM}(h\to\gamma\gamma)}$$

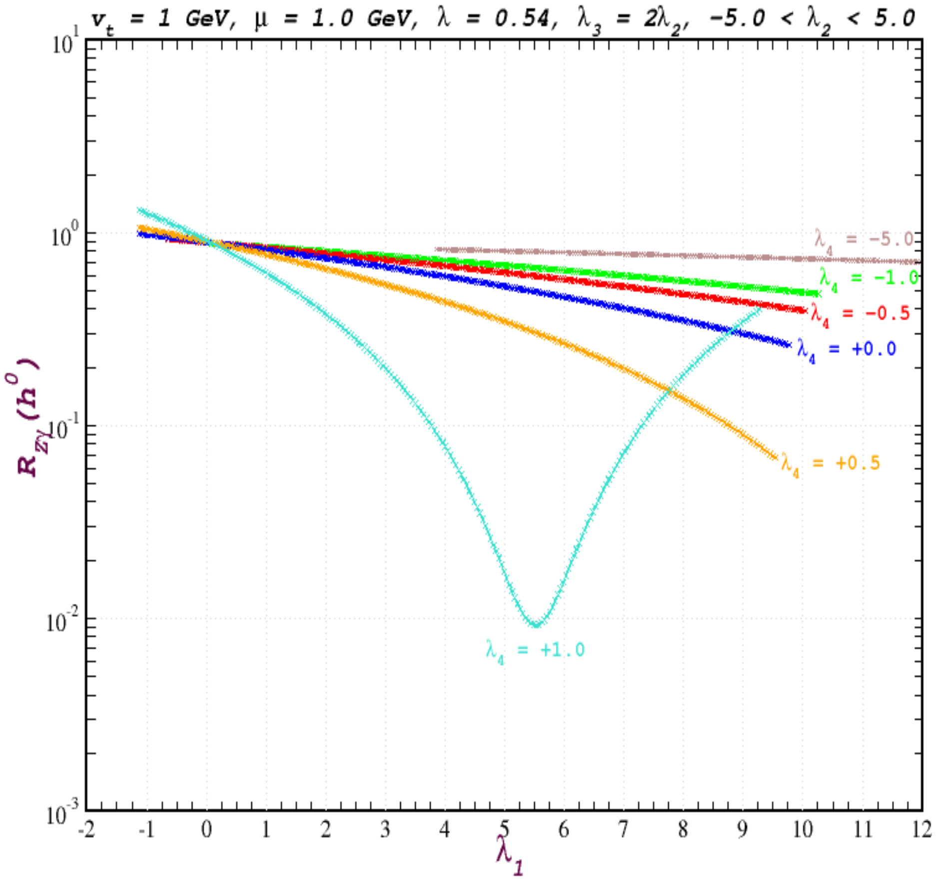


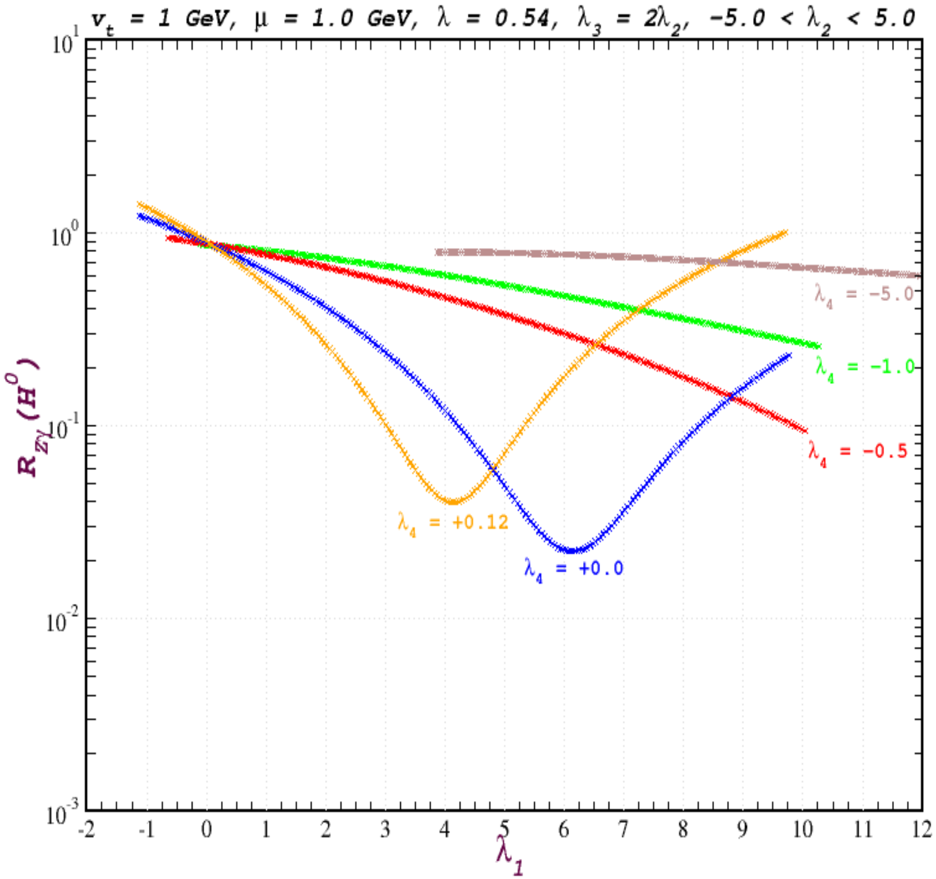

$R_{\gamma\gamma}$ *as a function of* $\lambda_1$ for various values of $\lambda_4$.

*Left* : $\mu = 1\,GeV$, $h^0$ *is SM – like with* $m_{h^0} = 125\text{-}126\,GeV$.

*Right* : $\mu = 0.3\,GeV$, $H^0$ *is SM – like*, with $m_{H^0} = 125\text{-}126\,GeV$.

$\lambda_3 = 2\lambda_2$, with $-2 < \lambda_2 < 2$ and $\upsilon_t = 1\,GeV$.



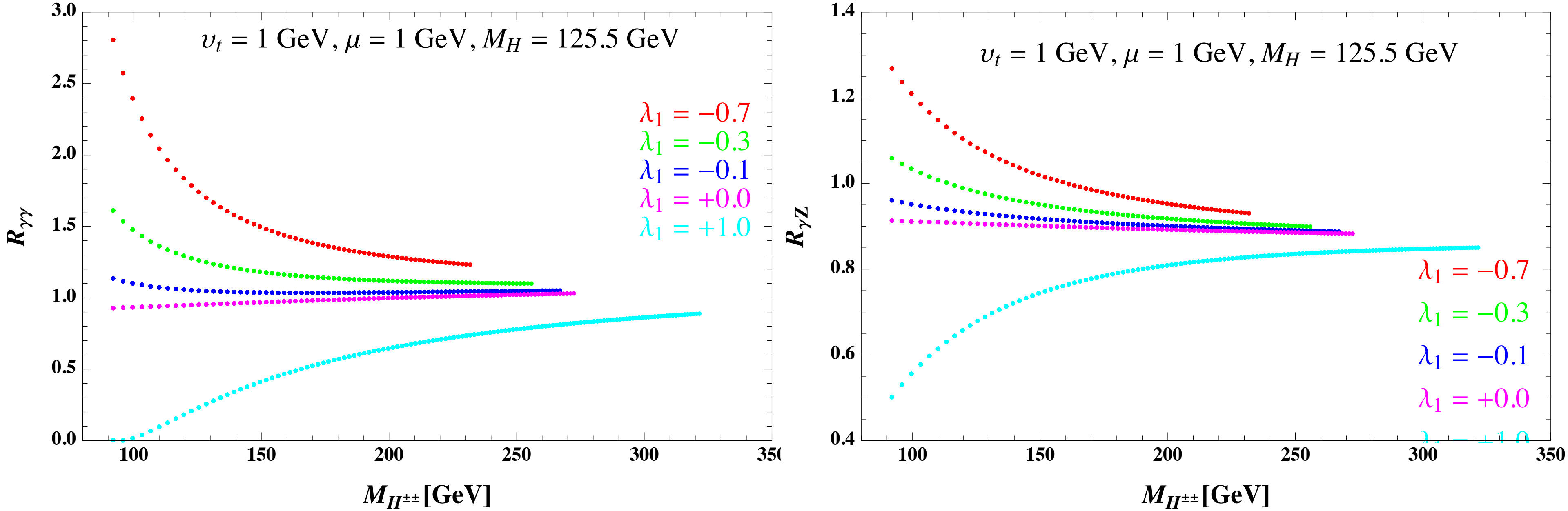




$R_{Z\gamma}$ *as a function of* $\lambda_1$ for var*ious values of* $\lambda_4$.

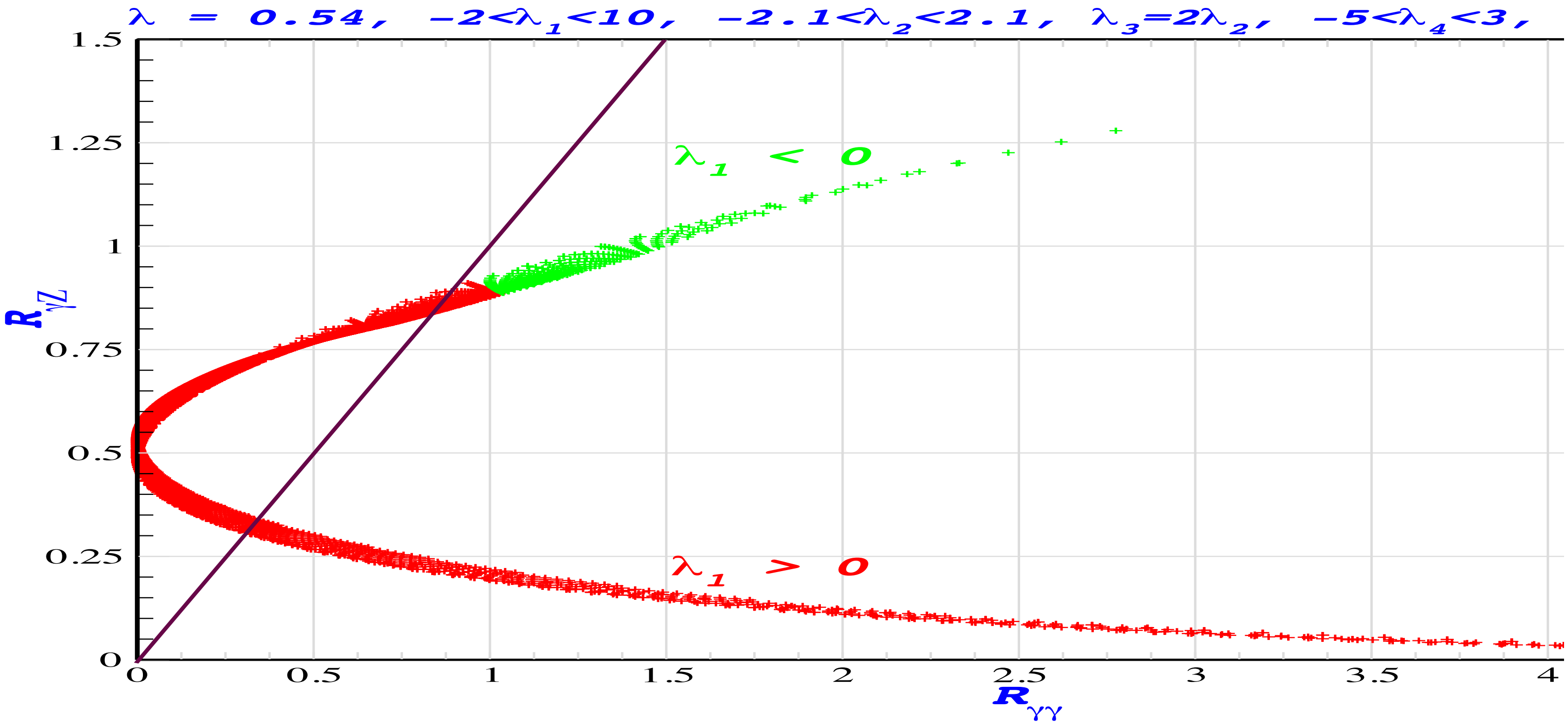
*Left* : $\mu = 1\,GeV$, $h^0$ *is SM – like with* $m_{h^0} = 125\text{-}126\,GeV$.

*Right* : $\mu = 0.3\,GeV$, $H^0$ *is SM – like*, with $m_{H^0} = 125\text{-}126\,GeV$.

$\lambda_3 = 2\lambda_2$, with $-2 < \lambda_2 < 2$ and $\upsilon_t = 1\,GeV$.




$R_{\gamma\gamma}$ and $R_{Z\gamma}$ *as a function of* $m_{H^{++}}$ *for* var*ious values of* $\lambda_1$.




*Correlation between $R_{z\gamma}$ and $R_{\gamma\gamma}$*

# Summary & Conclusions

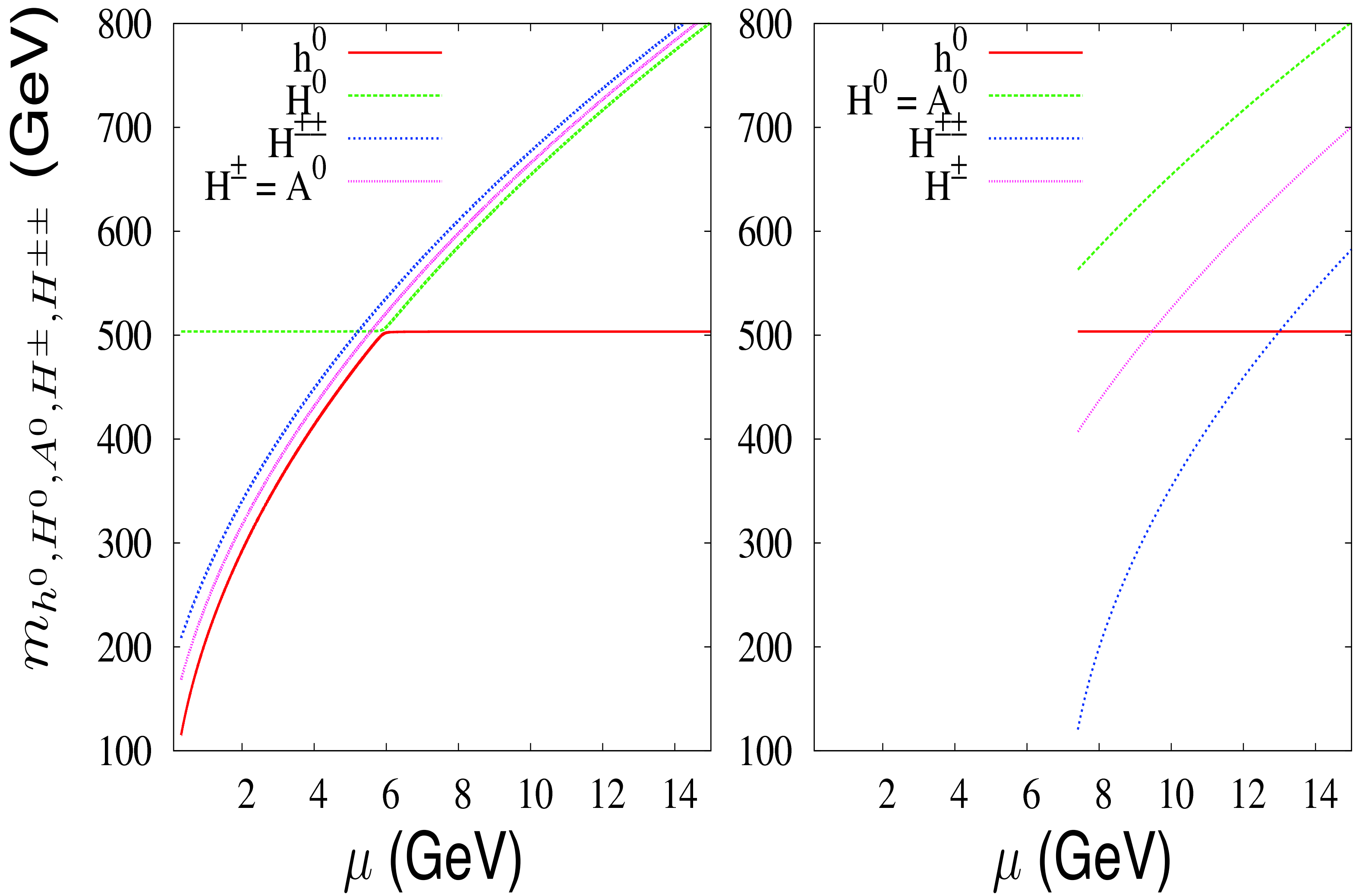
- Higgs Triplet Model (HTM) is consistent with 125 GeV higgs, it can fit the data even much better than SM

- We derive the full set of tree level perturbative unitarity and boundedness from below constraints for HTM.

- $h \rightarrow \gamma\gamma$ is very sensitive to charged particles and can be used to set limits on the parameter space of the model.

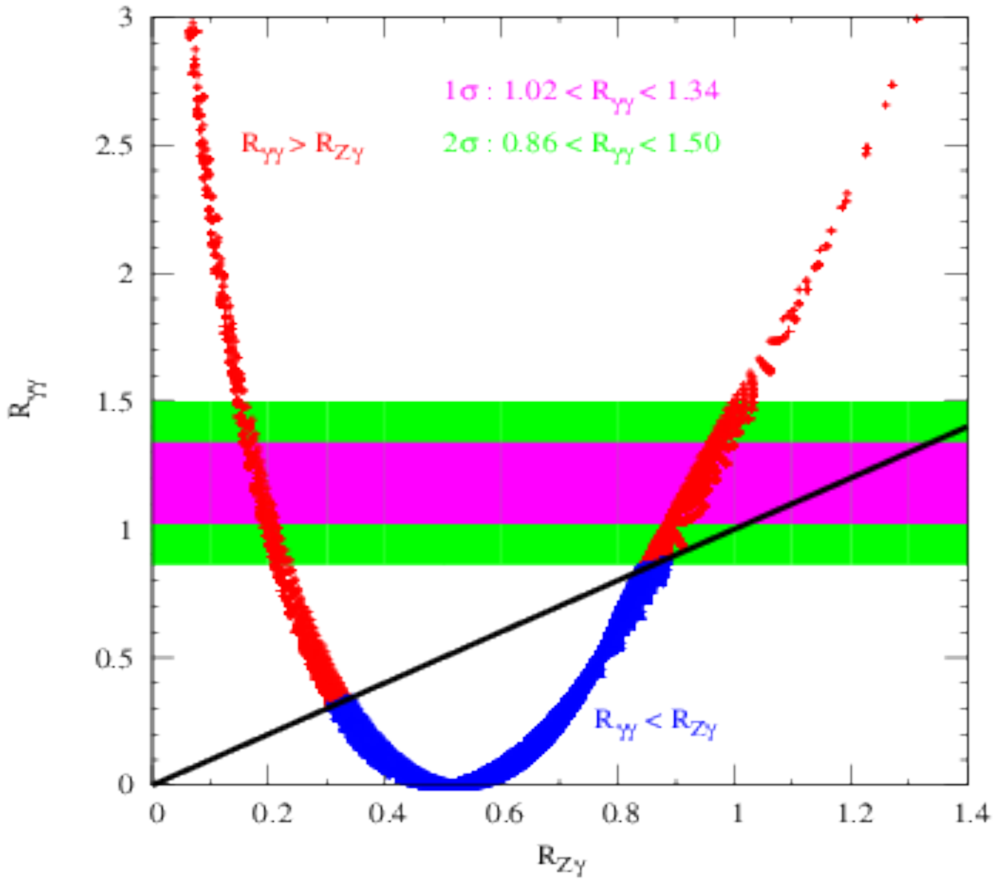
- $h \rightarrow \gamma\gamma$ and $h \rightarrow Z\gamma$ can be correlated or anti-correlated both in HTM .
- Unitarity on the SM-like Higgs is ≤ 700 GeV, while the other states $H^\pm$, $H^0$, $H^{\pm\pm}$ is very large (≈ 90 TeV).

THANK YOU

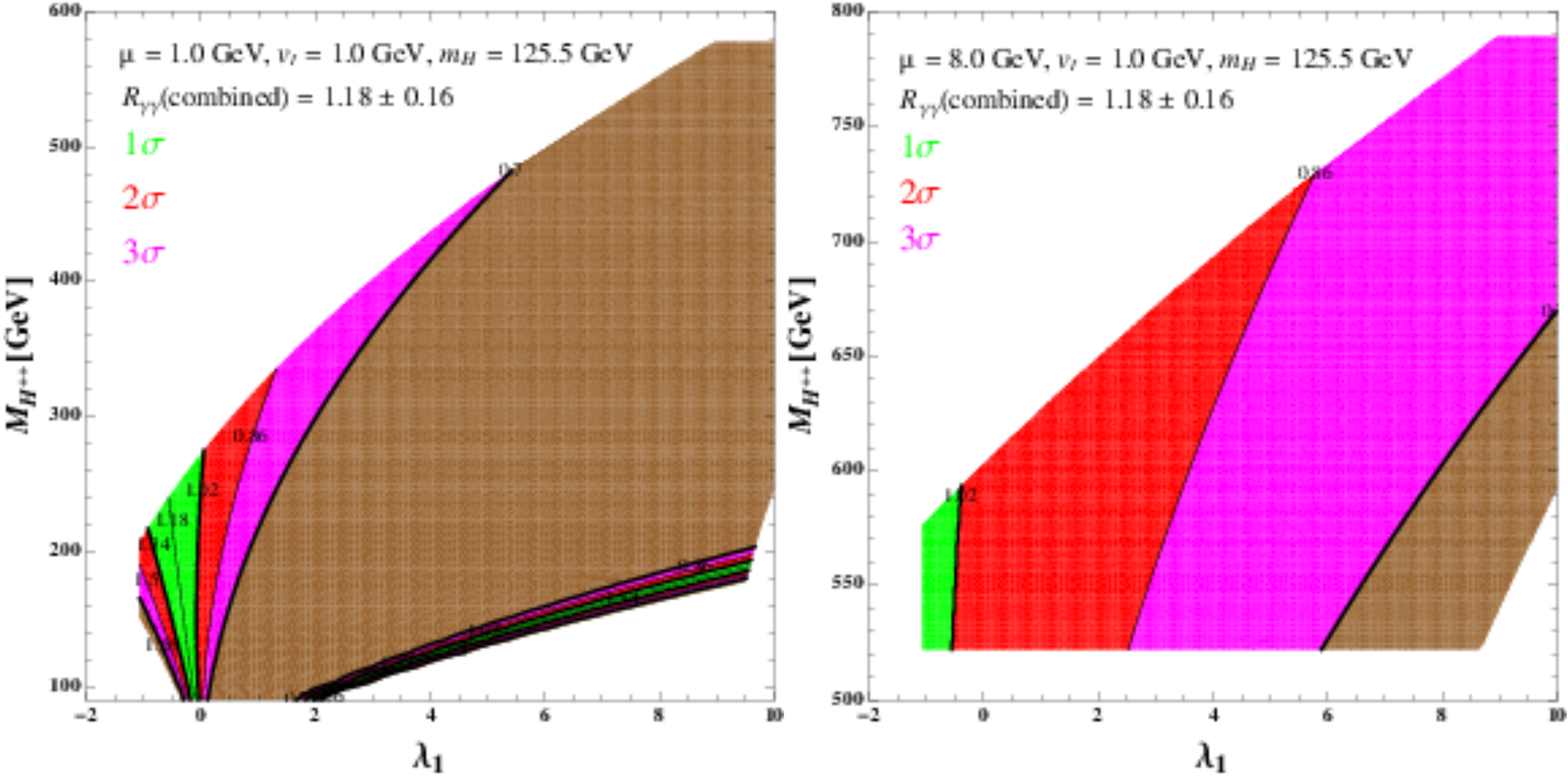



Higgs boson masses as a function of $\mu$ with $v_t = 1$ GeV, $\lambda = 8\pi/3$, $\lambda_1 = 0.5$,

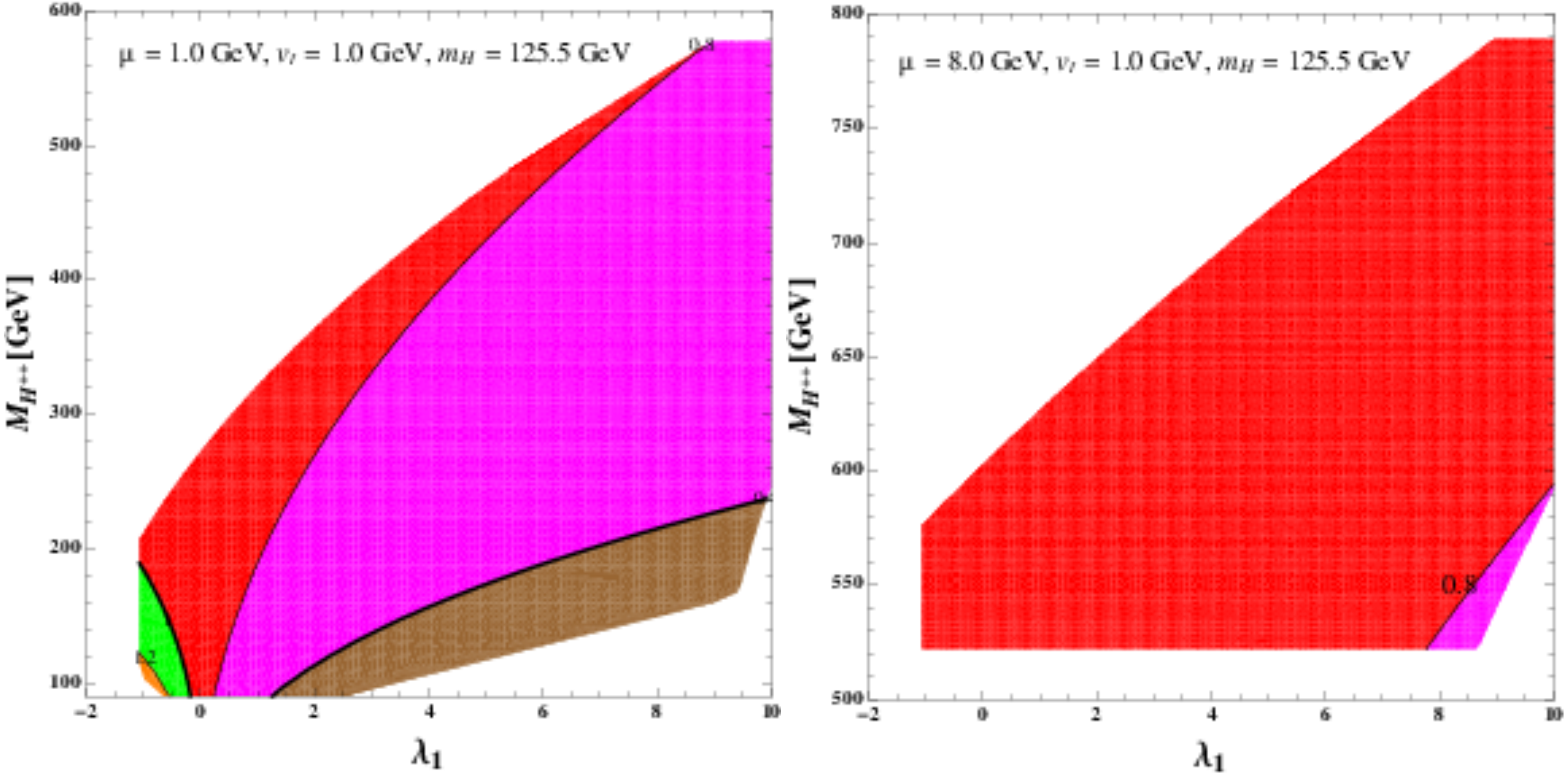
$\lambda_2 = \lambda_3 = 0.1$, $\lambda_4 = -1$ (left) and $\lambda_4 = 10$ (right)



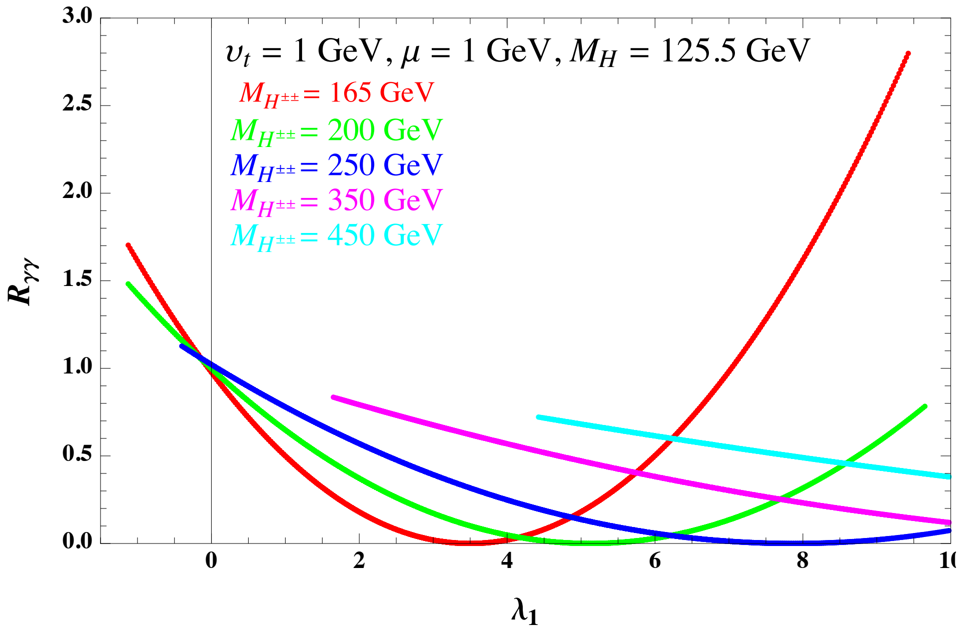

*Correlation between* $R_{\gamma\gamma}$ *and* $R_{\gamma\gamma}$ with *the range* @ $1\sigma$ *and* $2\sigma$ *of the combined* values of $R_{\gamma\gamma}$

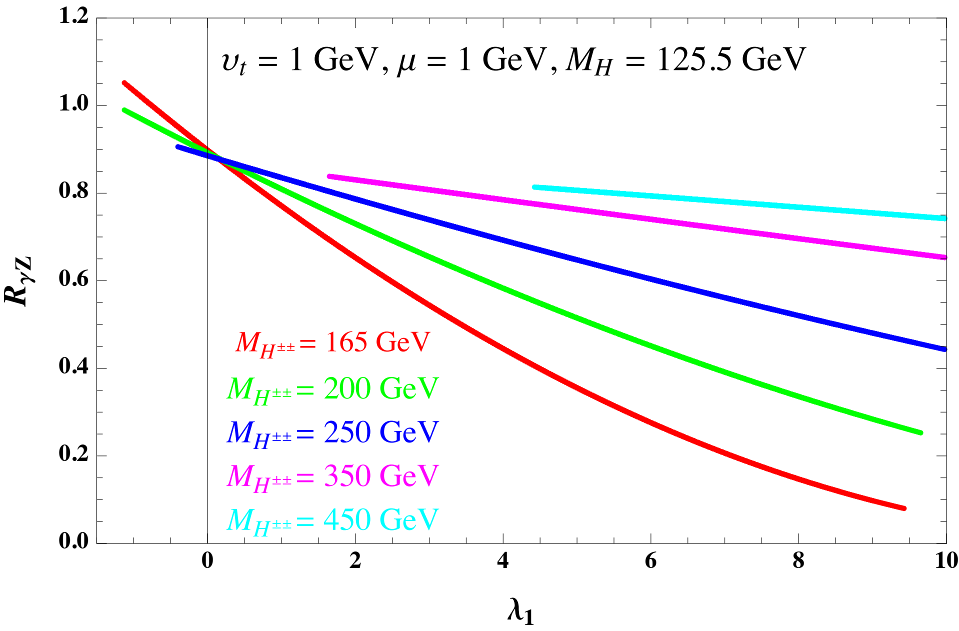



*Scatter plot* in $[\lambda_1, M_{H^{++}}]$ *plane showing* $R_{\gamma\gamma}$.




*Scatter plot* in $[\lambda_1, M_{H^{++}}]$ *plane showing* $R_{Z\gamma}$.




$R_{\gamma\gamma}$ and $R_{Z\gamma}$ *as a function of* $\lambda_1$ *for* various *values of* $m_{H^{++}}$

# Higgs masses

$$M_{H^{\pm\pm}}^2 = \frac{\sqrt{2}\mu v_d^2 - \lambda_4 v_d^2 v_t - 2\lambda_3 v_t^3}{2v_t}$$

$$M_{H^{\pm}}^2 = \frac{v^2[2\sqrt{2}\mu - \lambda_4 v_t]}{4v_t}$$

$$M_{A^0}^2 = \frac{\mu(v_d^2 + 4v_t^2)}{\sqrt{2}v_t}$$

$$M_{H^0}^2 = \frac{1}{2}[A + C + \sqrt{(A-C)^2 + 4B^2}]$$

$$M_{h^0}^2 = \frac{1}{2}[A + C - \sqrt{(A-C)^2 + 4B^2}]$$

$v_t \ll v_d$

$\epsilon = v_t/v_d$

$$M_{H^{\pm\pm}}^2 \simeq \frac{\mu v_d}{\sqrt{2}\epsilon} - \frac{\lambda_4 v_d^2}{2} + \mathcal{O}(\epsilon^2)$$

$$M_{H^{\pm}}^2 \simeq \frac{\mu v_d}{\sqrt{2}\epsilon} + \sqrt{2}\mu v_d \epsilon - \frac{\lambda_4 v_d^2}{4} + \mathcal{O}(\epsilon^2)$$

$$M_{A^0}^2 \simeq \frac{\mu v_d}{\sqrt{2}\epsilon} + 2\sqrt{2}\mu v_d \epsilon + \mathcal{O}(\epsilon^2)$$

$$M_{H^0}^2 \simeq \frac{\mu v_d}{\sqrt{2}\epsilon} + 2\sqrt{2}\mu v_d \epsilon + \mathcal{O}(\epsilon^2)$$

$$M_{h^0}^2 \simeq \frac{\lambda v_d^2}{2} - 2\sqrt{2}\mu v_d \epsilon + \mathcal{O}(\epsilon^2)$$

with

$$A = \frac{\lambda}{2} v_d^2$$

$$B = v_d[-\sqrt{2}\mu + (\lambda_1 + \lambda_4)v_t]$$

$$C = \frac{\sqrt{2}\mu v_d^2 + 4(\lambda_2 + \lambda_3)v_t^3}{2v_t}$$

$$M_\Delta^2 = \frac{2\mu v_d^2 - \sqrt{2}(\lambda_1 + \lambda_4)v_d^2 v_t - 2\sqrt{2}(\lambda_2 + \lambda_3)v_t^3}{2\sqrt{2}v_t}$$