Two inert scalars doublet model: status in $h \to \gamma\gamma, \gamma Z$

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2 Motivation

- ATLAS and CMS reported a little deviation in the $R_{\gamma\gamma}$

Ratio	ATLAS		CMS	
$R_{\gamma\gamma}$	$1.17^{+0.27}_{-0.27}$	[1]	$1.14^{+0.26}_{-0.23}$	[2]
$R_{\gamma Z}$	< 11	[3]	< 9.5	[4]

- Is there room for new physics in $R_{\gamma\gamma}$?
- We study the impact of the Two Inert Higgs Doublets on the processes $h \to \gamma\gamma, \gamma Z$. We found that when considering the more precise available experimental data for $h \to \gamma\gamma$ and the correlation between both channels, the enhancement for $h \to \gamma Z$ can not be larger than twice the standard model prediction.
- Work based in *Two inert scalar doublet model and* $h \to \gamma\gamma, \gamma Z$ *at LHC*, E. C. F. S. Fortes, A. C. Machado, J. Montaño, and V. Pleitez. arXiv:1408.0780 [hep-ph]

3 Experimental references

- $R_{\gamma\gamma}$

[1] G. Aad *et al.* [ATLAS Collaboration], *Measurement of Higgs boson production in the diphoton decay channel in* pp *collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, arXiv:1408.7084 [hep-ex].

[2] V. Khachatryan *et al.* [CMS Collaboration], *Observation of the diphoton decay of the Higgs boson and measurement of its properties*, arXiv:1407.0558 [hep-ex].

- $R_{\gamma Z}$

[3] G. Aad *et al.* [ATLAS Collaboration], *Search for Higgs boson decays to a photon and a Z boson in pp collisions at* $\sqrt{s}$*=7 and 8 TeV with the ATLAS detector*, Phys. Lett. B **732**, 8 (2014) , arXiv:1402.3051 [hep-ex].

[4] S. Chatrchyan *et al.* [CMS Collaboration], *Search for a Higgs boson decaying into a Z and a photon in pp collisions at* $\sqrt{s}$ *= 7 and 8 TeV*, Phys. Lett. B **726**, 587 (2013), arXiv:1307.5515 [hep-ex].

4 The IDMS$_3$

- Model explained in detailed in the talk *Scalar Dark Matter Candidates in Two Inert Higgs Doublet Model*, by A. C. B. Machado

- Mass eigenstates and the scalar potencial

$$S = \begin{pmatrix} h_1^+ \\ \frac{1}{\sqrt{2}}(v_{SM} + h_1^0 + iA_1^0) \end{pmatrix},$$

$$D = -\left[\begin{pmatrix} h_2^+ \\ \frac{1}{\sqrt{2}}(h_2^0 + iA_2^0) \end{pmatrix}, \begin{pmatrix} h_3^+ \\ \frac{1}{\sqrt{2}}(h_3^0 + iA_3^0) \end{pmatrix}\right],$$

$$\begin{aligned} V(h_i) &= 3\lambda_4 v^2 h_1^\dagger h_1 + \mu_d^2(h_2^\dagger h_2 + h_3^\dagger h_3) + \lambda_1(h_2^\dagger h_2 + h_3^\dagger h_3)^2 \\ &+ \lambda_2(h_2^\dagger h_3 - h_3^\dagger h_2)^2 + \lambda_3[(h_2^\dagger h_3 + h_3^\dagger h_2)^2 + (h_2^\dagger h_2 - h_3^\dagger h_3)^2] \\ &+ \lambda_4(h_1^\dagger h_1)^2 + \lambda_5 h_1^\dagger h_1(h_2^\dagger h_2 + h_3^\dagger h_3) + \lambda_6[|h_1^\dagger h_2|^2 + |h_1^\dagger h_3|^2] \\ &+ \{\lambda_7[(h_1^\dagger h_2)^2 + (h_3^\dagger h_1)^2] + \lambda_8[h_1^\dagger h_2(h_2^\dagger h_3 + h_3^\dagger h_2) \\ &+ h_1^\dagger h_3(h_3^\dagger h_3 - h_2^\dagger h_2)] + H.c.\}. \end{aligned}$$

5 Forbidden DM decays into $\gamma\gamma$ and γZ

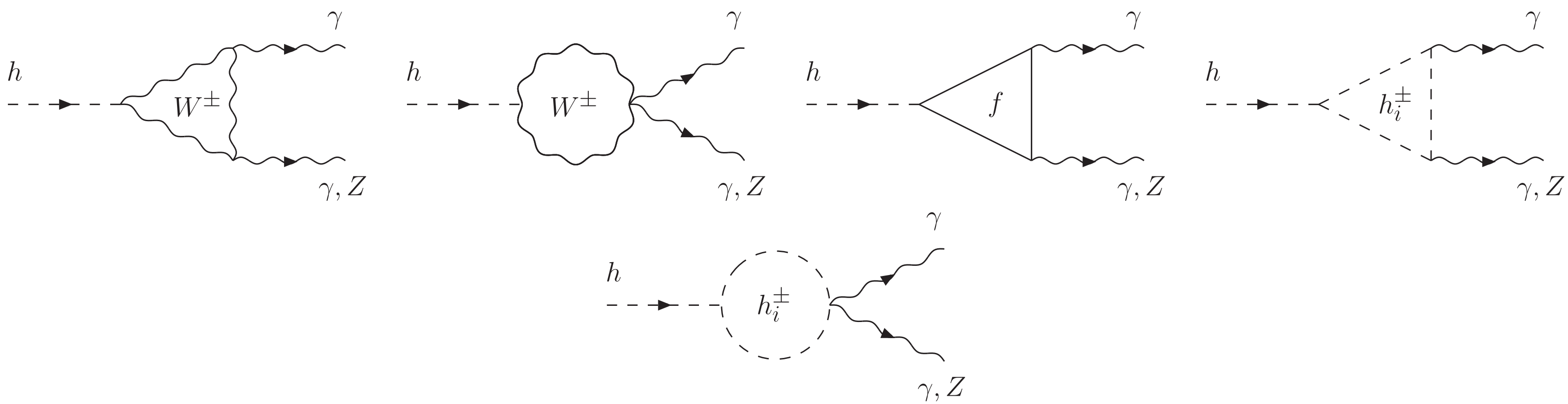
- The S_3 symmetry and the vacuum alignment forbid $H^0_{2,3} \to \gamma\gamma, \gamma Z$ through loops of new charged spin-0 content.

- Such prohibition occurs in different ways for the candidates H^0_2 and H^0_3.

- For H^0_2, the S_3 symmetry forbids the existence of $H^0_2 h^+_2 h^-_2$ and $H^0_2 h^+_3 h^-_3$.

- For H^0_3, the S_3 symmetry provides opposite signs for $+H^0_3 h^+_2 h^-_2$ and $-H^0_3 h^+_3 h^-_3$, this cancel out each other loop contribution if $m_{h^+_2} = m_{h^+_3}$. In the non degenerate case, those decays do not occur if $\lambda_8 = 0$, as we considered in arXiv:1407.4749.

6 Decays $h \to \gamma\gamma, \gamma Z$ new spin-0 contribution



- New couplings: $hH_i^+H_i^-$, $\gamma H_i^+H_i^-$, $ZH_i^+H_i^-$, $\gamma\gamma H_i^+H_i^-$, and $\gamma Z H_i^+H_i^-$, $i = 2, 3$.

$$\mathcal{L}_{Gauge} = igs_W \left(\partial_\mu h_i^- h_i^+ - \partial_\mu h_i^+ h_i^-\right) A^\mu + igc_W \left(\frac{1-t_W^2}{2}\right) \left(\partial_\mu h_i^- h_i^+ - \partial_\mu h_i^+ h_i^-\right) Z^\mu$$

$$+g^2 s_W^2 h_i^- h_i^+ A^\mu A_\mu + g^2 c_W^2 \left(\frac{1-t_W^2}{2}\right)^2 h_i^- h_i^+ Z^\mu Z_\mu$$

$$+2g^2 c_W s_W \left(\frac{1-t_W^2}{2}\right) h_i^- h_i^+ A^\mu Z_\mu \, ,$$

$$\mathcal{L}_{Scalars} = -\frac{\lambda_5 v_{SM}}{2} h \left(h_2^- h_2^+ + h_3^- h_3^+\right) .$$

7 $h \to \gamma\gamma$ **new spin-0 contribution**

- Width decay

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_{i=1}^{9} N_C^{f_i} Q_{f_i}^2 A_{1/2}^{\gamma\gamma} + A_1^{\gamma\gamma} + \sum_{i=2}^{3} \frac{\lambda_5 v_{SM}^2}{2m_{h_i^+}^2} A_0^{\gamma\gamma} \right|^2 ,$$

form factors $A_{\text{Spin}}^{\gamma\gamma}(\tau_i)$, with $\tau_i \equiv m_h^2/4m_i^2$.

- Spin-0 contribution: $A_0^{\gamma\gamma} \equiv -[\tau - f(\tau)]\tau^{-2}$,

$$f(\tau) \equiv \begin{cases} \arcsin^2 \sqrt{\tau} & , \quad \tau \leq 1 \\ -\frac{1}{4}\left(\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right)^2 & , \quad \tau > 1. \end{cases}$$

We follow the notation of Djouadi, from Phys. Rept. **457**, 1 (2008) [hep-ph/0503172] and Phys. Rept. **459**, 1 (2008) [hep-ph/0503173].

8 $h \to \gamma Z$ new spin-0 contribution

- Width decay

$$\Gamma(h \to \gamma Z) = \frac{G_F^2 m_W^2 \alpha m_h^3}{64\pi^4}\left(1 - \frac{m_Z^2}{m_H^2}\right)^3$$

$$\times \left| \sum_{i=1}^{9} \frac{N_C^{f_i} Q_{f_i} 2 g_V^{f_i}}{c_W} A_{1/2}^{\gamma Z} + A_1^{\gamma Z} + \sum_{i=2}^{3} \frac{\lambda_5 v_{SM}^2 v_{h^\pm}}{2 m_{h_i^+}^2} A_0^{\gamma Z} \right|^2 ,$$

form factors $A_{\text{Spin}}^{\gamma Z}(\tau_i, \lambda_i)$, with $\tau_i \equiv 4m_i^2/m_h^2$, $\lambda_i \equiv 4m_i^2/m_Z^2$, $v_{h^\pm} \equiv c_W(1 - t_W^2)$.

- Spin-0 contribution: $A_0^{\gamma Z} \equiv -I_1,$

$$I_1 \equiv \frac{\tau\lambda}{2(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}\left[f(\tau^{-1}) - f(\lambda^{-1})\right] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}\left[g(\tau^{-1}) - g(\lambda^{-1})\right],$$

$$g(\tau) \equiv \begin{cases} \sqrt{\tau^{-1}-1}\,\arcsin\sqrt{\tau} & , \quad \tau \le 1 \\ \frac{\sqrt{1-\tau^{-1}}}{2}\left(\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right) & , \quad \tau > 1, \end{cases}$$

here $g(\tau)$ with $\tau_i \equiv m_h^2/4m_i^2$ as in $f(\tau)$.

9 Correspondence between the Passarino-Veltman scalar functions and the analytical solutions

- Processes performed in FeynCalc and functions checked with LoopTools

$$f\left(\frac{M^2}{4m^2}\right) = -\frac{M^2}{2}C_0(0,0,M^2,m^2,m^2,m^2)\,,$$

$$\begin{aligned} f\left(\frac{M_1^2}{4m^2}\right) - f\left(\frac{M_2^2}{4m^2}\right) &= -\frac{M_1^2 - M_2^2}{2}C_0(0,M_1^2,M_2^2,m^2,m^2,m^2) \\ &= -\frac{M_1^2 C_0(0,0,M_1^2,m^2,m^2,m^2) - M_2^2 C_0(0,0,M_2^2,m^2,m^2,m^2)}{2}\,, \end{aligned}$$

$$g\left(\frac{M_1^2}{4m^2}\right) - g\left(\frac{M_2^2}{4m^2}\right) = -\frac{1}{2}\left[B(M_1^2,m^2,m^2) - B(M_2^2,m^2,m^2)\right].$$

10 The ratios $R_{\gamma\gamma}$ and $R_{\gamma Z}$

- IDMS_3 gives rise to couplings between the new charged scalars and SM Higgs boson, and also with vector gauge bosons.

- There are no modifications to the existing SM couplings,

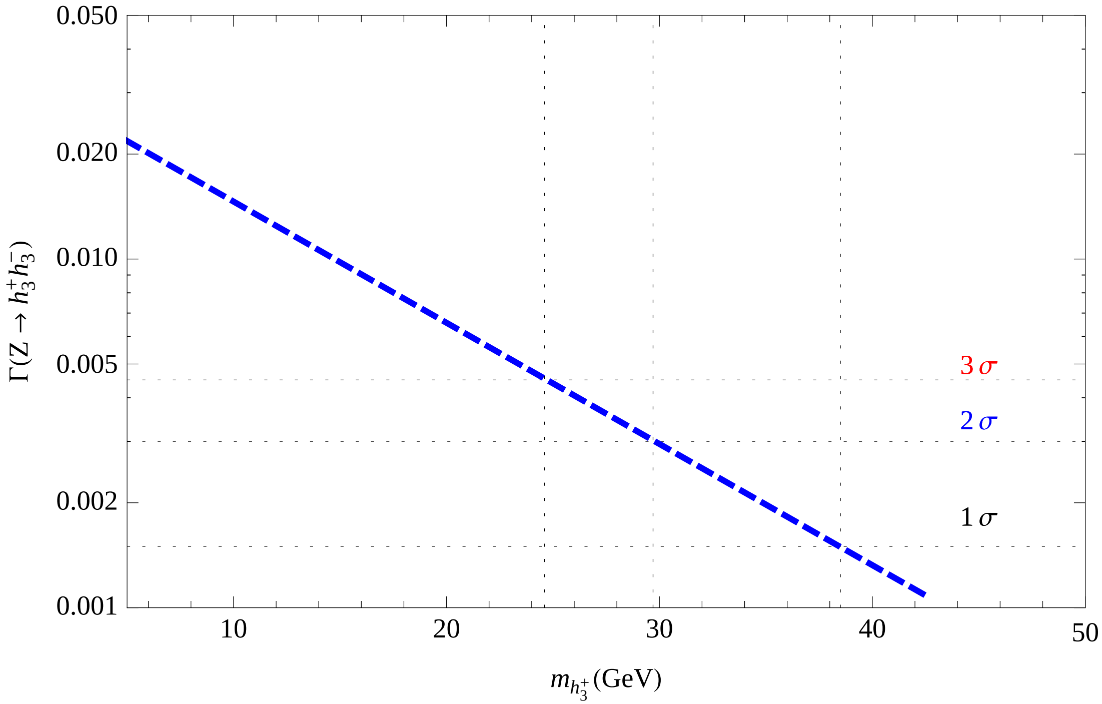
- For $h \to \gamma\gamma, \gamma Z$ only new scalar contribution is added to the existing ones, therefore, $V \equiv \gamma, Z$,

$$
\begin{aligned}
R_{\gamma V} &\equiv \frac{\sigma(pp \to gg \to h \to \gamma V)^{\text{IDMS3}}}{\sigma(pp \to gg \to h \to \gamma V)^{\text{SM}}} \\
&\overset{\text{NWA}}{\simeq} \frac{\Gamma(h \to \gamma V)^{\text{IDMS3}}}{\Gamma(h \to \gamma V)^{\text{SM}}} ,
\end{aligned}
$$

where $\Gamma_h^{\text{IDMS3}} \simeq \Gamma_h^{\text{SM}}$, because in our scenarios for the new neutral scalar the masses forbid invisible decays of the SM-Higgs.

11 Charged scalar mass limit

- $\Gamma(Z \to h_3^+ h_3^-)$ invisible decay as function of the charged scalar h_3^+ mass

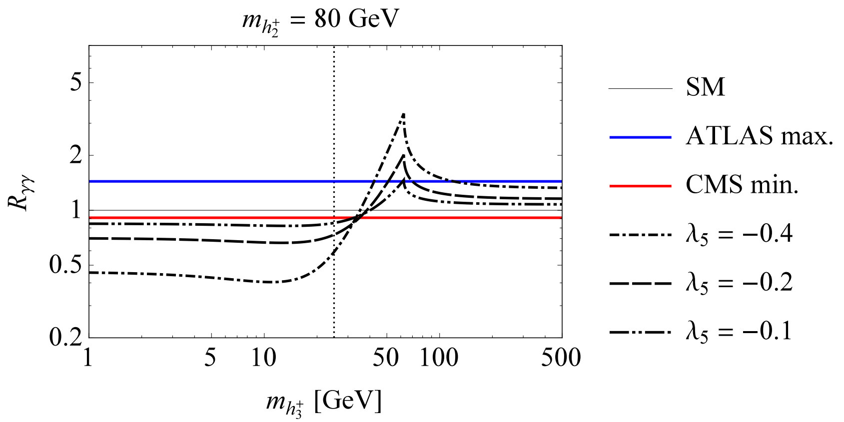


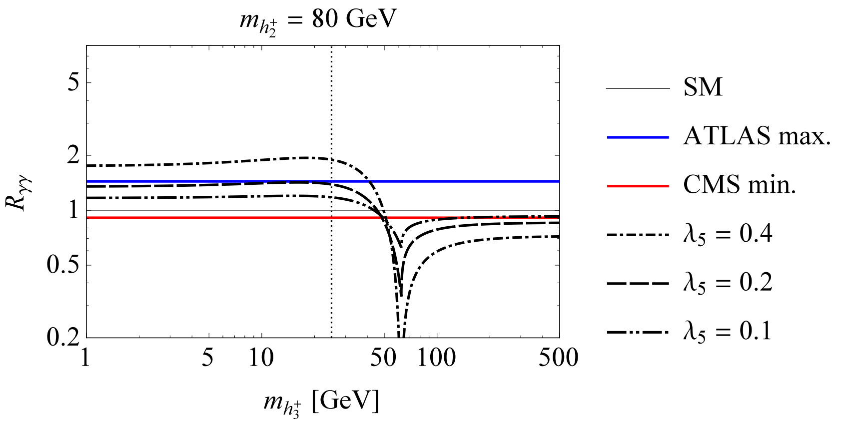
Allowed limit $m_{h_3^+} > 25$ GeV

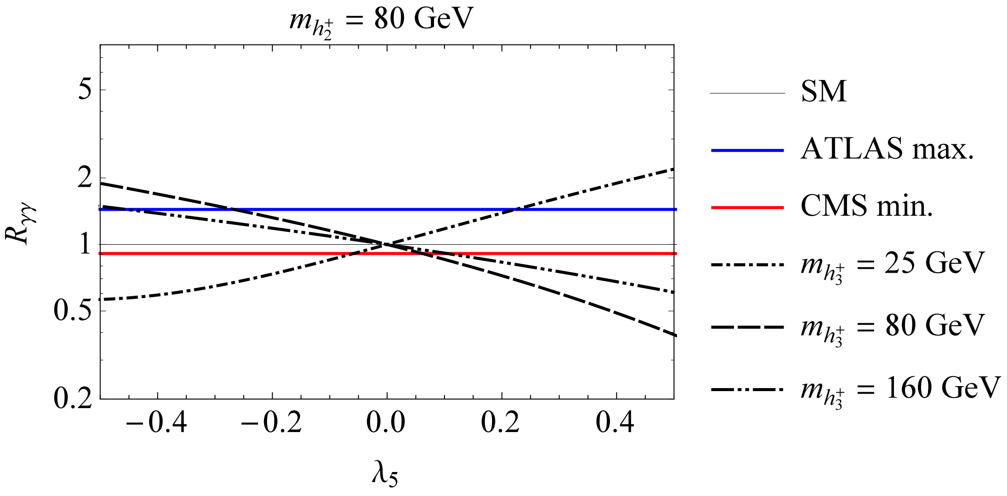
12 $R_{\gamma\gamma}$

- $R_{\gamma\gamma}^{\text{ATLAS max.}} = 1.17 + 0.27 = 1.44$ and $R_{\gamma\gamma}^{\text{CMS min.}} = 1.14 - 0.23 = 0.91$

- $m_{h_2^+} = 80$ GeV, $m_{h_3^+} > m_h/2$ and $\lambda_5 \in [-0.5, 0)$ favours an enhancement.



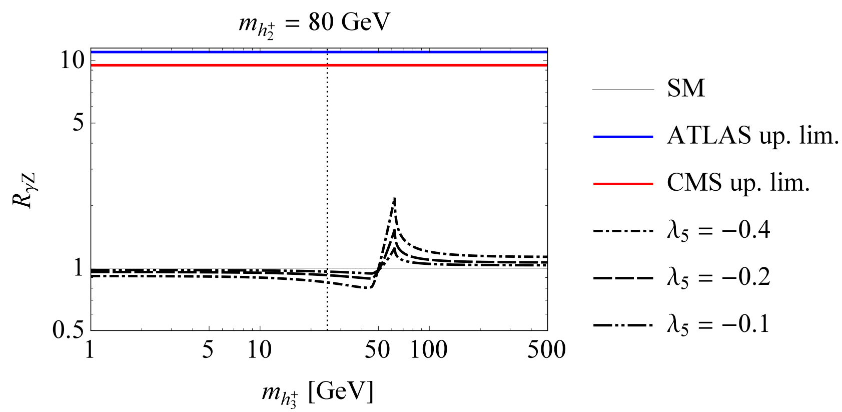


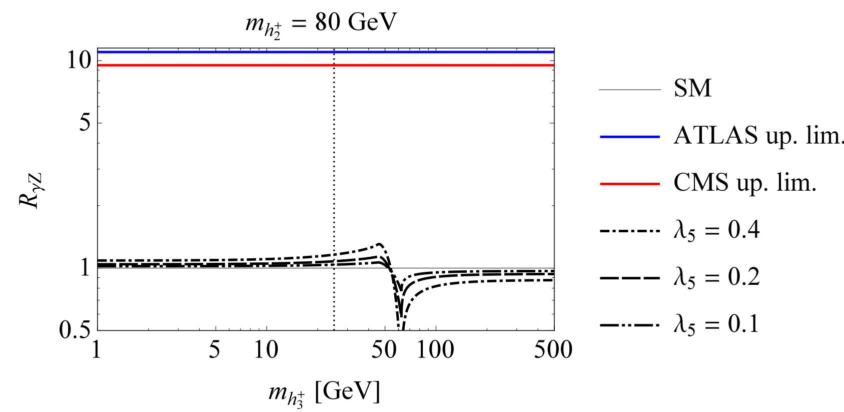


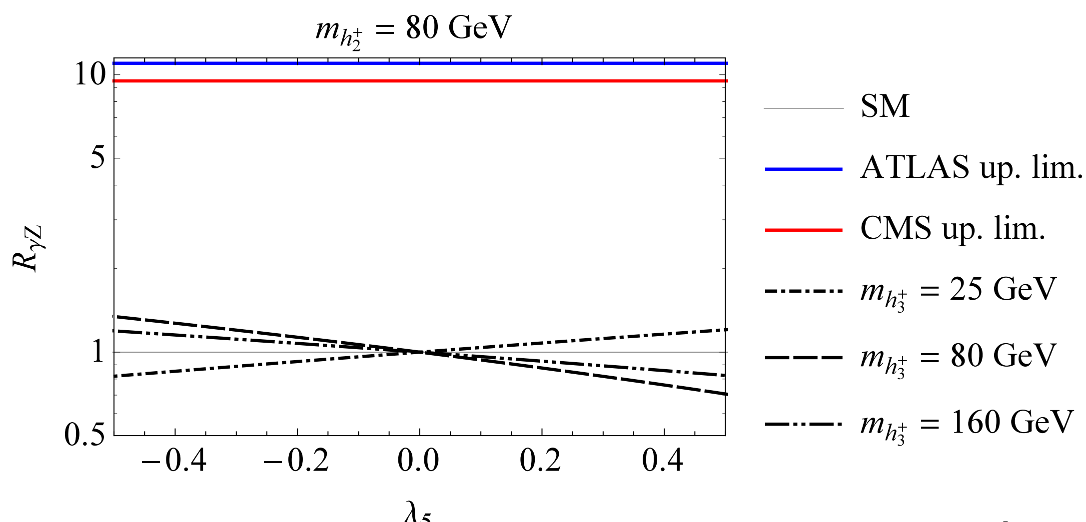
13 $R_{\gamma Z}$

- $R_{\gamma Z}^{\text{ATLAS up.lim.}} < 1.9$ and $R_{\gamma Z}^{\text{CMS up.lim.}} < 9.5$

- $m_{h_2^+} = 80$ GeV, $m_{h_3^+} > m_h/2$ and $\lambda_5 \in [-0.5, 0)$ favours an enhancement as in $R_{\gamma\gamma}$

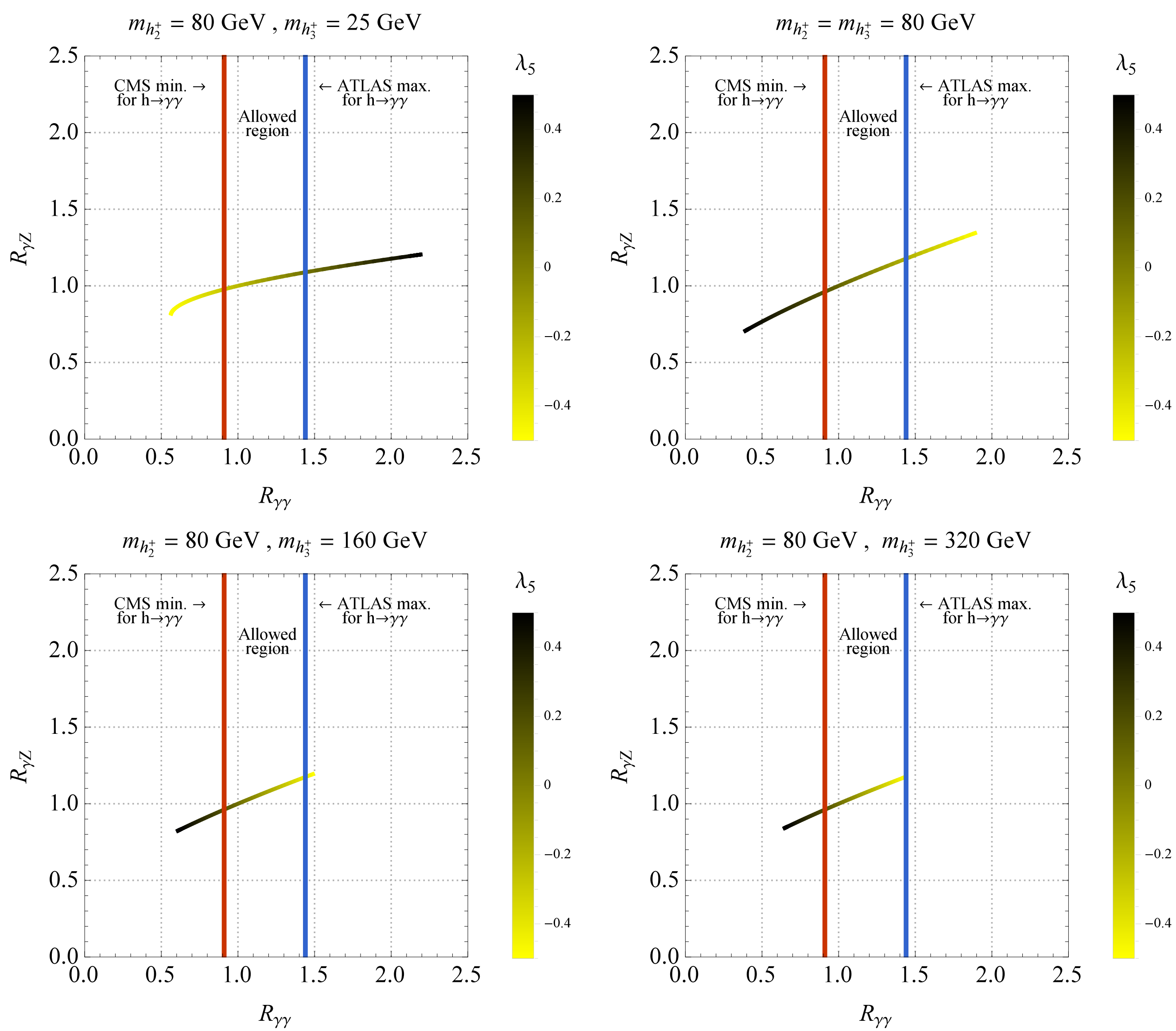






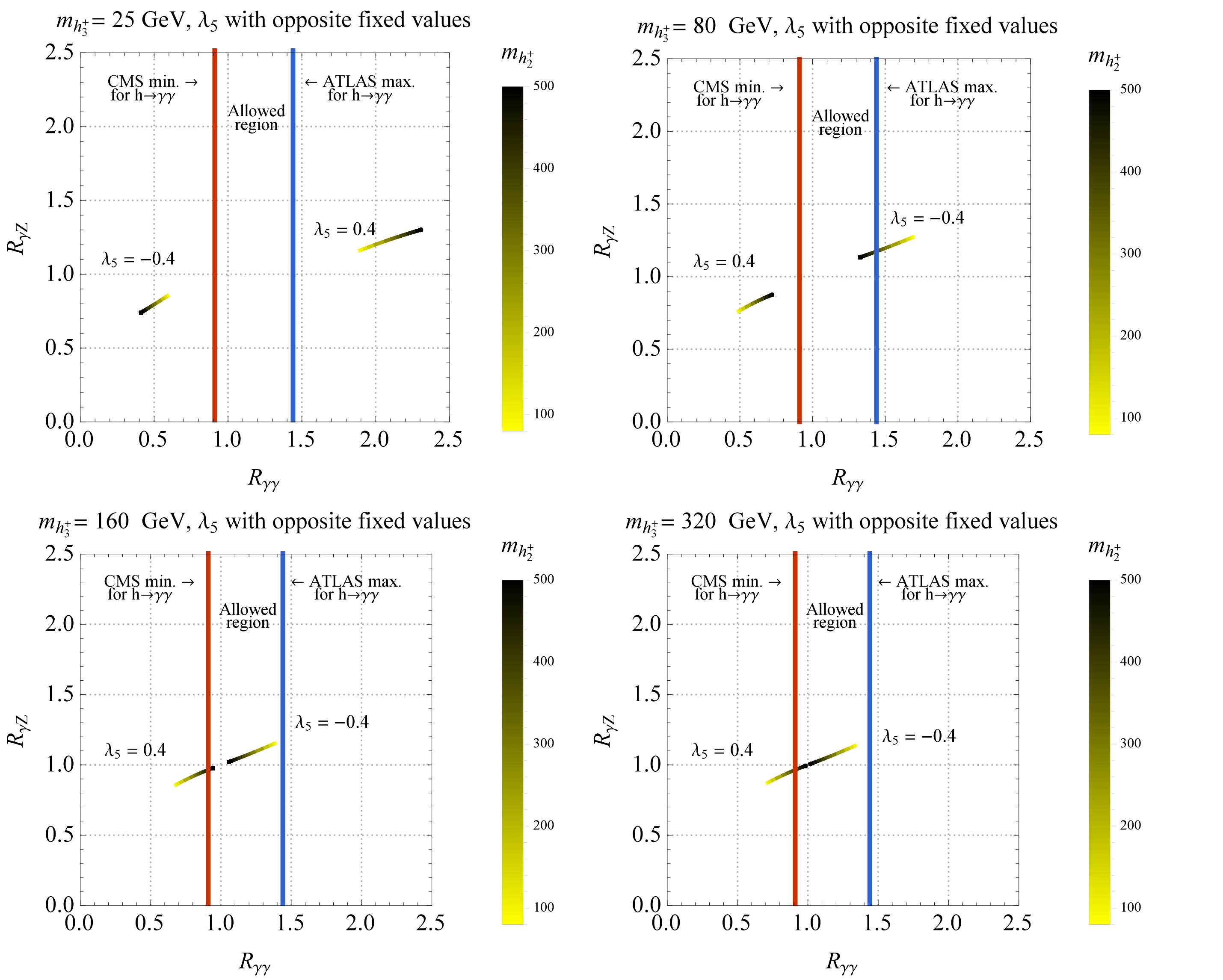
14 Correlation between $R_{\gamma\gamma}$ and $R_{\gamma Z}$

- As function of $\lambda_5 \in [-0.5, 0.5]$, $m_{h_2^+} = 80$ GeV, and various values of $m_{h_3^+}$



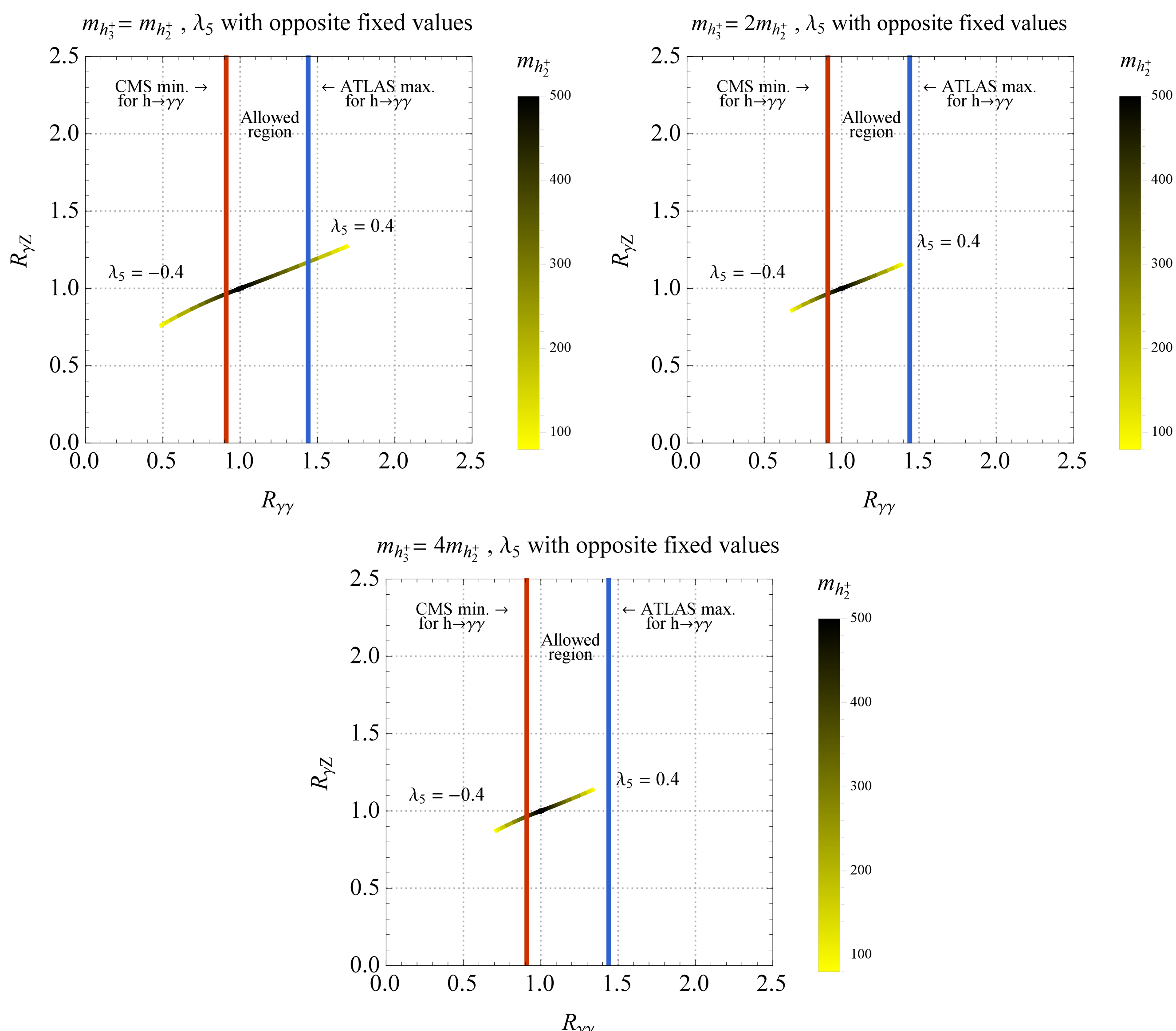
15 Correlation between $R_{\gamma\gamma}$ and $R_{\gamma Z}$

- As function of $m_{h_2^+} \in [80, 500]$ GeV, $\lambda_5 = \pm 0.4$, and various values of $m_{h_3^+}$



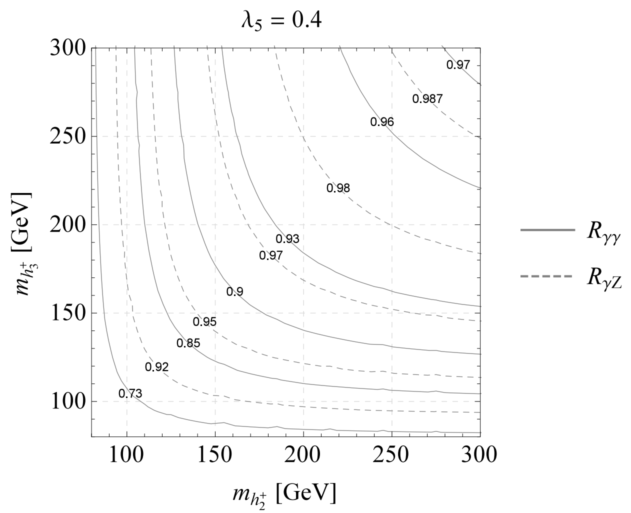
16 Correlation between $R_{\gamma\gamma}$ and $R_{\gamma Z}$

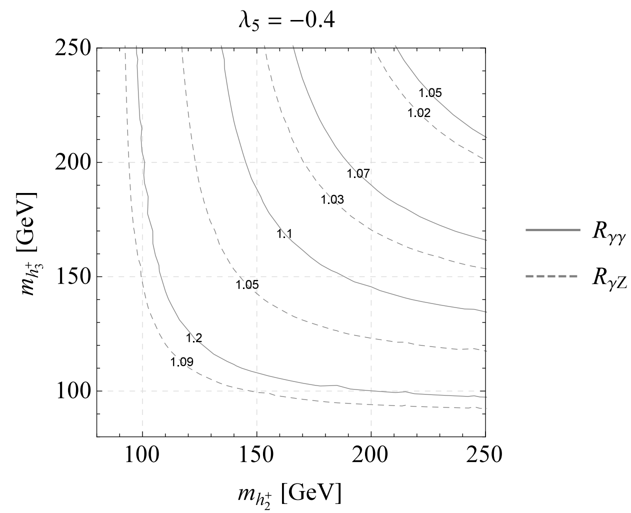
- As function of $m_{h_2^+} \in [80, 500]$ GeV, $\lambda_5 = \pm 0.4$, in cases of $m_{h_3^+} \propto m_{h_2^+}$



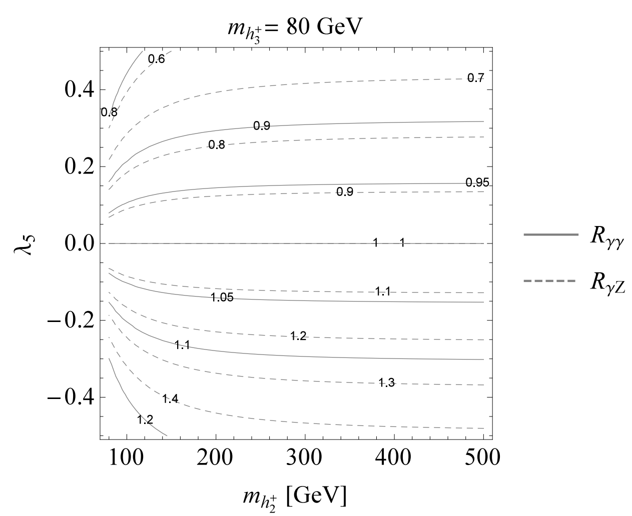
17 $R_{\gamma\gamma}$ and $R_{\gamma Z}$

- As function of $m_{h^+_{2,3}} \geq 80$ GeV with $\lambda_5 = \pm 0.4$





- As function of $m_{h^+_2} \geq 80$ and $\lambda_5 \in [-0.5, 0.5]$ with $m_{h^+_3} = 80$ GeV



18 Conclusions

- In this work we have considered the SM-like Higgs scalar decaying in $\gamma\gamma$ and γZ in the context of the IDMS$_3$ model.
- The two charged scalars $h_2^+,\ h_3^+$ of our model could explain the enhancement of the $R_{\gamma\gamma}$.
- The signal of the λ_5 parameter is the most responsible for this positive or negative enhancement.
- $-0.5 < \lambda_5 < 0$ favours an enhancement for the $R_{\gamma\gamma}$.
- The correlation between $R_{\gamma\gamma}$ and $R_{\gamma Z}$ suggests that the latter process is less sensitive to the common parameters λ_5 and $m_{h_3^+}$. Otherwise, if future results show that a deviation up to one order of magnitude for the photon and Z channel is possible compared to SM prediction, it could be due to new physics effects or an invitation to revisit the status of the SM.