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Impact of $H \to Z\gamma$ on Two-Higgs Doublet Models

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Outline

- Motivation
- The general two Higgs doublet model
- Loop calculations
- Reappraisal of the wrong sign Yukawa coupling in Type II 2HDM
- Implications of LHC@8TeV and predictions of LHC@14TeV for the C2HDM
- Conclusions

Collaborators: J. P. Silva, D. Fontes, arXiv:1406.6080 [PRD90 (2014) 015021] and arXiv:1408.2534

Motivation

- Check if the Higgs-like particle found at the LHC with a mass around 125 GeV is the SM Higgs boson
- Find out what is the space left for new Physics in the Higgs sector after the 8 TeV run at the LHC
- Deviations from the SM are expected to occur even before new particles are found due to their contributions to loops
- These deviations are potentially larger, in relative terms, in processes that are absent at tree level and only occur in the SM at one-loop order
- While $h \to \gamma\gamma$ has already been measured at LHC, there is only an upper limit for $h \to Z\gamma$. So this process will be a very important check of the SM and extensions in the next LHC run
- Therefore we perform a complete evaluation of the $h \to Z\gamma$ process in the general C2HDM

The potential for the general C2HDM

- We consider a model with two Higgs doublets, ϕ_1 and ϕ_2, with the Z_2 symmetry $\phi_1 \to \phi_1, \phi_2 \to -\phi_2$ violated softly.

$$
\begin{aligned}
V_H =& m_{11}^2 |\phi_1|^2 + m_{22}^2 |\phi_2|^2 - m_{12}^2\, \phi_1^\dagger \phi_2 - (m_{12}^2)^*\, \phi_2^\dagger \phi_1 \\
&+ \frac{\lambda_1}{2} |\phi_1|^4 + \frac{\lambda_2}{2} |\phi_2|^4 + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 \left(\phi_1^\dagger \phi_2\right) \left(\phi_2^\dagger \phi_1\right) \\
&+ \frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \frac{\lambda_5^*}{2} (\phi_2^\dagger \phi_1)^2 .
\end{aligned}
$$

- Hermiticity implies that all couplings are real, except m_{12}^2 and λ_5. If $\arg(\lambda_5) \neq 2 \arg(m_{12}^2)$, then the phases cannot be removed. This is known as the complex two Higgs doublet model, C2HDM

- If $\arg(\lambda_5) = 2 \arg(m_{12}^2)$, then we can choose a basis where m_{12}^2 and λ_5 become real and, if the vacuum expectation values (vev) of ϕ_1 and ϕ_2 are also real, we talk about the real 2HDM

- The potential has 9 independent parameters. We trade these for v and for the 8 input parameters β, $m_{H^\pm}$, α_1, α_2, α_3, m_1, m_2, $\mathrm{Re}(m_{12}^2)$

Couplings in the real 2HDM and C2HDM

- The relevant couplings are defined in the Lagrangian

$$\mathcal{L}_Y = -\left(\sqrt{2}G_\mu\right)^{1/2} m_f\, \bar{\psi}\,(a + ib\gamma_5)\,\psi\, h,$$

$$\mathcal{L}_{hH^+H^-} = \lambda\, v\, hH^+H^-,$$

$$\mathcal{L}_{hVV} = C\left[g\, m_W W^+_\mu W^{\mu -} + \frac{g}{2c_W} m_Z Z_\mu Z^\mu\right] h,$$

where a, b, and C are real, $c_W = \cos\theta_W$, and θ_W is the Weinberg angle. In the limit, $a = C = 1$, and $b = \lambda = 0$, we obtain the SM

- In the real 2HDM we have

$$C = \sin(\beta - \alpha), \quad \lambda = -\frac{2m^2_{H^\pm}}{v^2}(g_1 + g_2 + g_3) \quad \text{with}$$

$$g_1 = \sin(\beta - \alpha)\left(1 - \frac{m_h^2}{2m^2_{H^\pm}}\right), \quad g_2 = \frac{\cos(\beta + \alpha)}{\sin(2\beta)}\frac{m_h^2}{m^2_{H^\pm}},$$

$$g_3 = -\frac{2\cos(\beta + \alpha)}{\sin^2(2\beta)}\frac{m^2_{12}}{m^2_{H^\pm}}.$$

Couplings in the C2HDM · · ·

- In the C2HDM we have

$$C = c_\beta R_{11} + s_\beta R_{12}$$
$$-\lambda = c_\beta \left[s_\beta^2 \lambda_{145} + c_\beta^2 \lambda_3 \right] R_{11} + s_\beta \left[c_\beta^2 \lambda_{245} + s_\beta^2 \lambda_3 \right] R_{12} + s_\beta c_\beta \, \mathrm{Im}(\lambda_5)\, R_{13}$$

- Here $\lambda_{145} = \lambda_1 - \lambda_4 - \mathrm{Re}(\lambda_5)$ and $\lambda_{245} = \lambda_2 - \lambda_4 - \mathrm{Re}(\lambda_5)$ with $R_{11} = c_1 c_2, R_{12} = s_1 c_2, R_{13} = s_2$

- For fermions in the C2HDM

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$
Down	$\frac{R_{12}}{s_\beta} + i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - i s_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - i s_\beta \frac{R_{13}}{c_\beta}\gamma_5$
Leptons	$\frac{R_{12}}{s_\beta} + i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - i s_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - i s_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + i c_\beta \frac{R_{13}}{s_\beta}\gamma_5$

- In the 2HDM: $R_{11} \to -\sin\alpha, \quad R_{12} \to \cos\alpha, \quad R_{13} \to 0$

Amplitudes for $h \to \gamma\gamma$ and $h \to Z\gamma$

- We write the general form for the amplitudes ($V = Z, \gamma; i = F, W, H^\pm$)

$$M_i^{V\gamma} \equiv \frac{e^2 g}{m_W} \frac{1}{16\pi^2} \left[(q_1 \cdot q_2\, \epsilon_1 \cdot \epsilon_2 - q_1 \cdot \epsilon_2\, q_2 \cdot \epsilon_1)\, X_i^{V\gamma} + \epsilon_{\mu\nu\alpha\beta}\, q_1^\mu q_2^\nu \epsilon_1^\alpha \epsilon_2^\beta\, Y_i^{V\gamma} \right]$$

- We do not write the results for $i = W$ as they are the SM value $\times\ C$

- For fermion loops

$$X_F^{\gamma\gamma} = -\sum_f \frac{4a\, Q_f^2\, m_f^2}{m_h^2} \left[\left(4m_f^2 - m_h^2\right) C_0(0, 0, m_h^2, m_f^2, m_f^2, m_f^2) + 2 \right]$$

$$Y_F^{\gamma\gamma} = \sum_f 4b\, Q_f^2\, m_f^2\ C_0(0, 0, m_h^2, m_f^2, m_f^2, m_f^2)$$

$$X_F^{Z\gamma} = -\sum_f N_c^f \frac{4a\, g_V^f\, Q_f\, m_f^2}{s_W c_W} \left[\frac{2m_Z^2}{(m_h^2 - m_Z^2)^2} \Delta B_0(m_f^2) \right.$$
$$\left. + \frac{1}{m_h^2 - m_Z^2} \left[\left(4m_f^2 - m_h^2 + m_Z^2\right) C_0(m_Z^2, 0, m_h^2, m_f^2, m_f^2, m_f^2) + 2 \right] \right]$$

Amplitudes for $h \to \gamma\gamma$ and $h \to Z\gamma \cdots$

$$Y_F^{Z\gamma} = \sum_f N_c^f \frac{4b\, g_V^f\, Q_f\, m_f^2}{s_W c_W} C_0(m_Z^2, 0, m_h^2, m_f^2, m_f^2, m_f^2)\,.$$

where $\Delta B_0(m^2) \equiv B_0(m_h^2, m^2, m^2) - B_0(m_Z^2, m^2, m^2)$ **Finite!**

- For Charged Higgs loops

$$X_H^{\gamma\gamma} = -\frac{4\lambda m_W v}{g m_h^2}\left[2m_{H^\pm}^2 C_0(0,0,m_h^2, m_{H^\pm}^2, m_{H^\pm}^2, m_{H^\pm}^2) + 1\right]$$

$$X_{H^\pm}^{Z\gamma} = -\frac{1}{\tan\theta_W}\frac{\lambda v^2(1-\tan^2\theta_W)}{m_h^2 - m_Z^2}\left[\frac{m_Z^2}{m_h^2 - m_Z^2}\Delta B_0(m_\pm^2) + \left(2m_\pm^2 C_0(m_Z^2, 0, m_h^2, , m_\pm^2, m_\pm^2, m_\pm^2) + 1\right)\right]$$

- We have compared with all known results and the numerical evaluation was done using `LoopTools`

Widths for $h \to \gamma\gamma$ and $h \to Z\gamma$

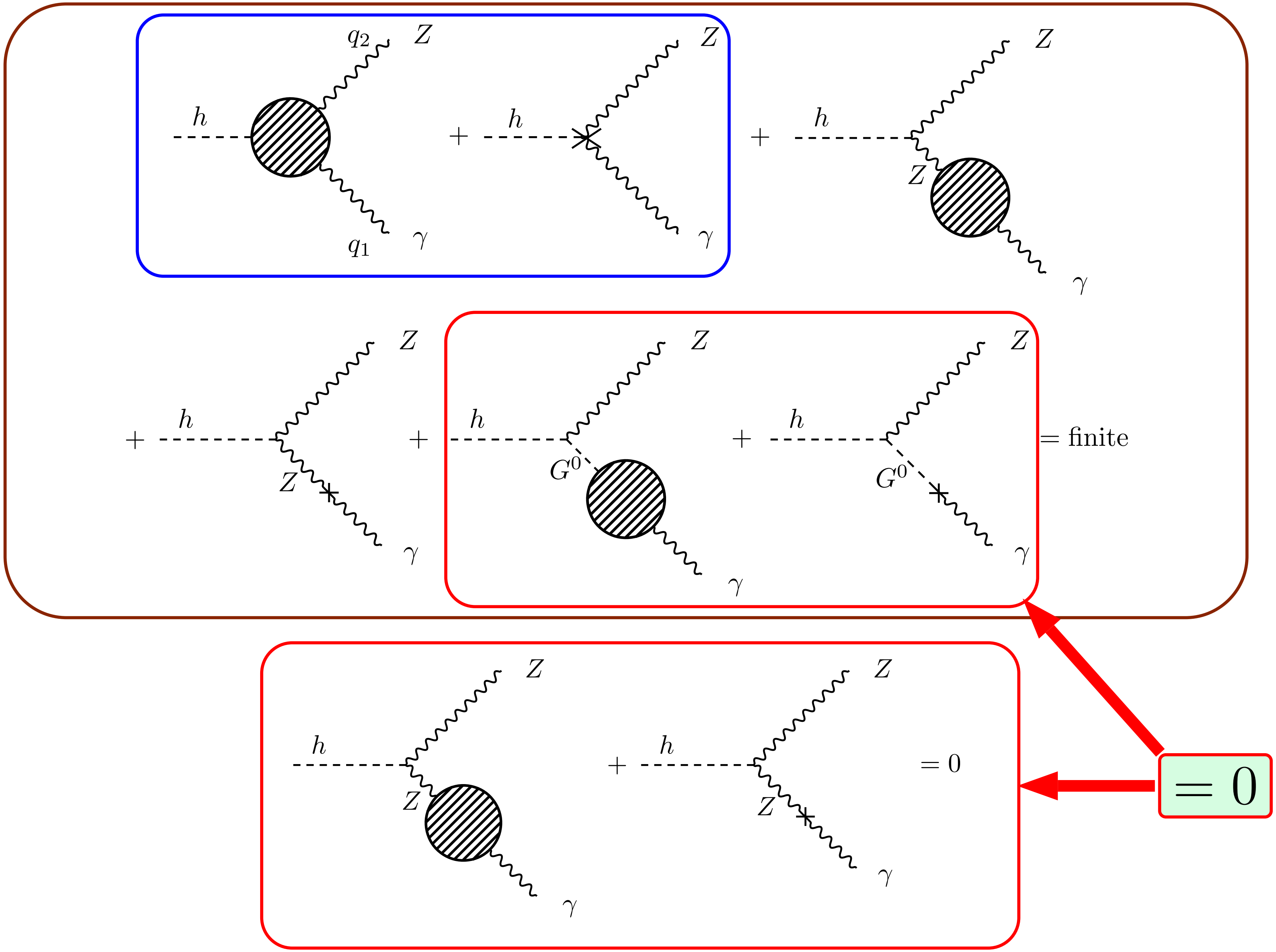
- We get for the widths

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left(|X_F^{\gamma\gamma} + X_W^{\gamma\gamma} + X_H^{\gamma\gamma}|^2 + |Y_F^{\gamma\gamma}|^2 \right)$$

$$\Gamma(h \to Z\gamma) = \frac{G_F \alpha^2 m_h^3}{64\sqrt{2}\pi^3} \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 \left(|X_F^{Z\gamma} + X_W^{Z\gamma} + X_H^{Z\gamma}|^2 + |Y_F^{Z\gamma}|^2 \right)$$

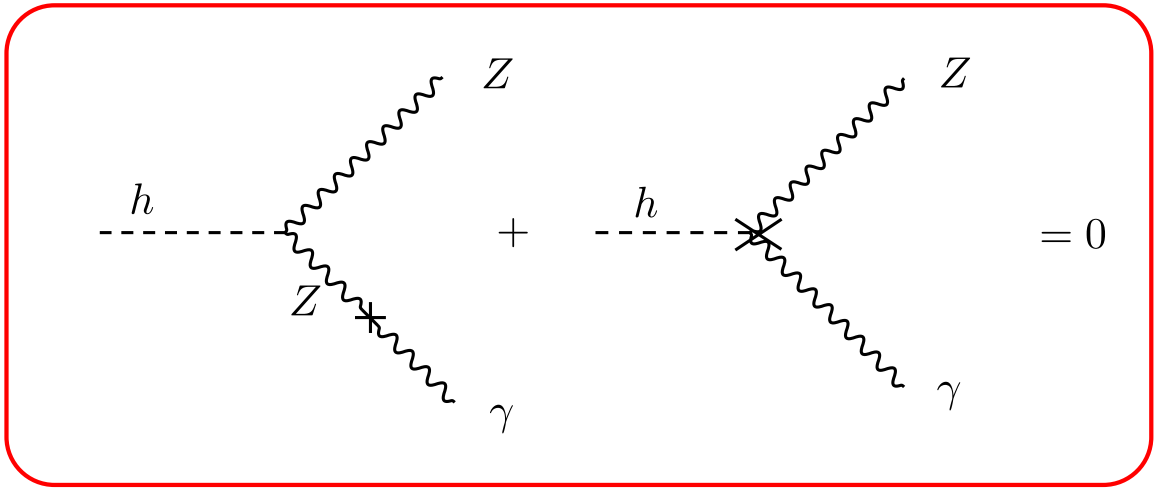
- Important points
  - All results finite and gauge invariant (verified with `FeynCalc`)
  - No interference between the scalar and pseudoscalar components of the Higgs boson even in the case of the decay $h \to Z\gamma$
  - In principle large values for $h \to Z\gamma$ (and also $h \to \gamma\gamma$) can be obtained due to the new contributions in the loops
  - We will show how the current limits on $h \to WW, ZZ$ put constraints on this possibility.

On-shell renormalization of the $h \to Z\gamma$ three point function

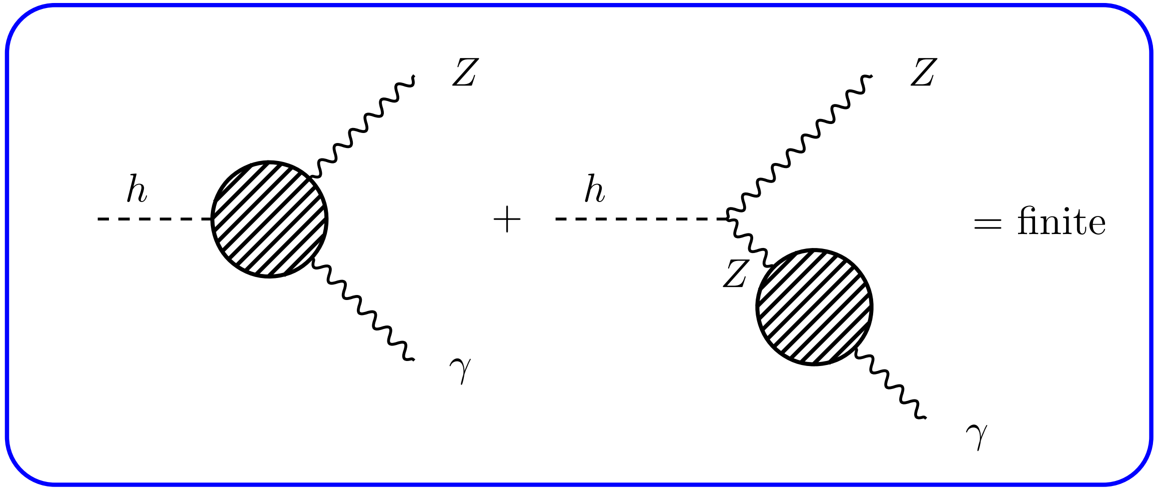


On-shell renormalization of the $h \to Z\gamma$ three point function $\cdots$

- However one can show that



- So we can also have



Simulation Procedure

- We generate points in parameter space with $m_1 = 125$ GeV, the angles $\alpha, \alpha_{1,2,3}$ within the usual intervals, $1 \leq \tan\beta \leq 30$, $m_1 \leq m_2 \leq 900\,\text{GeV}$, $-(900\,\text{GeV})^2 \leq m_{12}^2 \leq (900\,\text{GeV})^2$, and $340\,(100)\,\text{GeV} \leq m_{H^\pm} \leq 900\,\text{GeV}$ (T2, Fli) or (T1, LS)

- Finally for each final state f, we compute the ratio of rates

$$\mu_f = \underbrace{\frac{\sigma^{\text{2HDM}}(pp \to h)}{\sigma^{\text{SM}}(pp \to h)}}_{\mathbf{R_P}} \underbrace{\frac{\Gamma^{\text{2HDM}}[h \to f]}{\Gamma^{\text{SM}}[h \to f]}}_{\mathbf{R_D}} \underbrace{\frac{\Gamma^{\text{SM}}[h \to \text{all}]}{\Gamma^{\text{2HDM}}[h \to \text{all}]}}_{\mathbf{R_{TW}}}$$

- We then compare with the experimental results from ICHEP2014

channel	ATLAS	CMS
$\mu_{\gamma\gamma}$	$1.57^{+0.33}_{-0.28}$	1.13 ± 0.24
μ_{WW}	$1.00^{+0.32}_{-0.29}$	0.83 ± 0.21
μ_{ZZ}	$1.44^{+0.40}_{-0.35}$	1.00 ± 0.29
$\mu_{\tau^+\tau^-}$	$1.4^{+0.5}_{-0.4}$	0.91 ± 0.27
$\mu_{b\bar{b}}$	$0.2^{+0.7}_{-0.6}$	0.93 ± 0.49

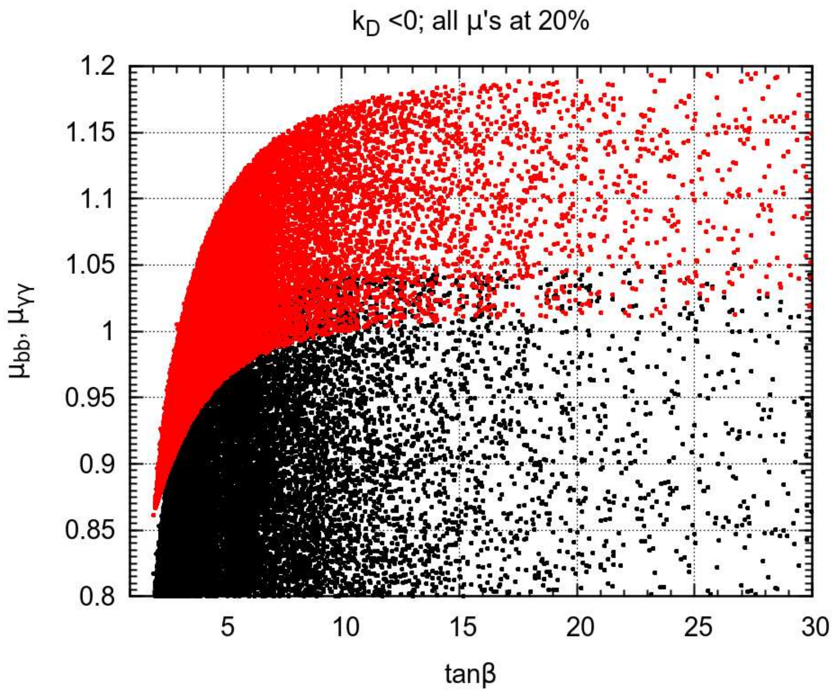
The wrong sign $hb\bar{b}$ coupling in the 2HDM

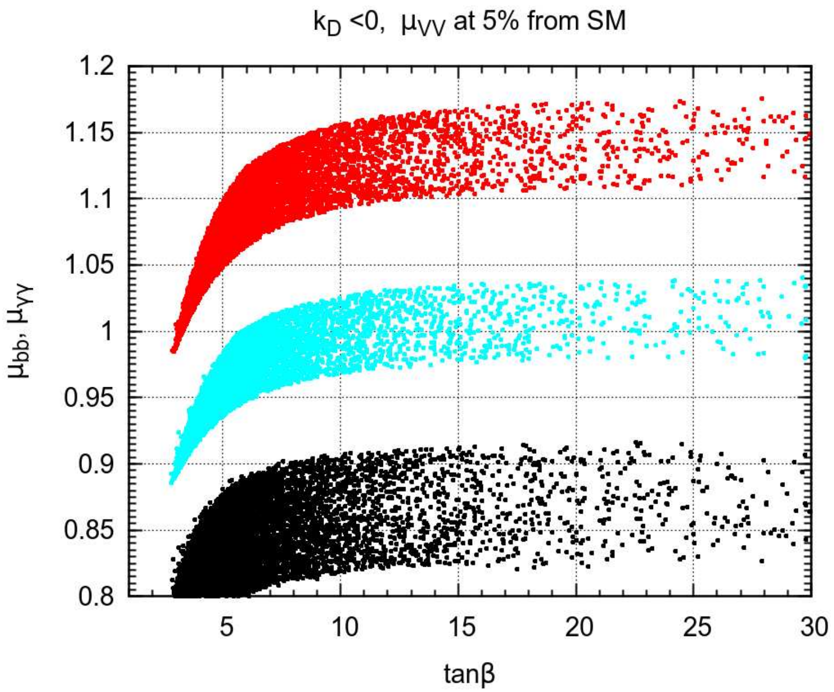
- In Type II 2HDM the coupling to down type quarks relative to the SM

$$k_D = -\frac{\sin\alpha}{\cos\beta}$$

can be negative ($k_D = 1$ in the SM)

- Ferreira et al. showed that a measurement of $\mu_{\gamma\gamma}$ at 5% could exclude this possibility (PRD89(2014)115003)





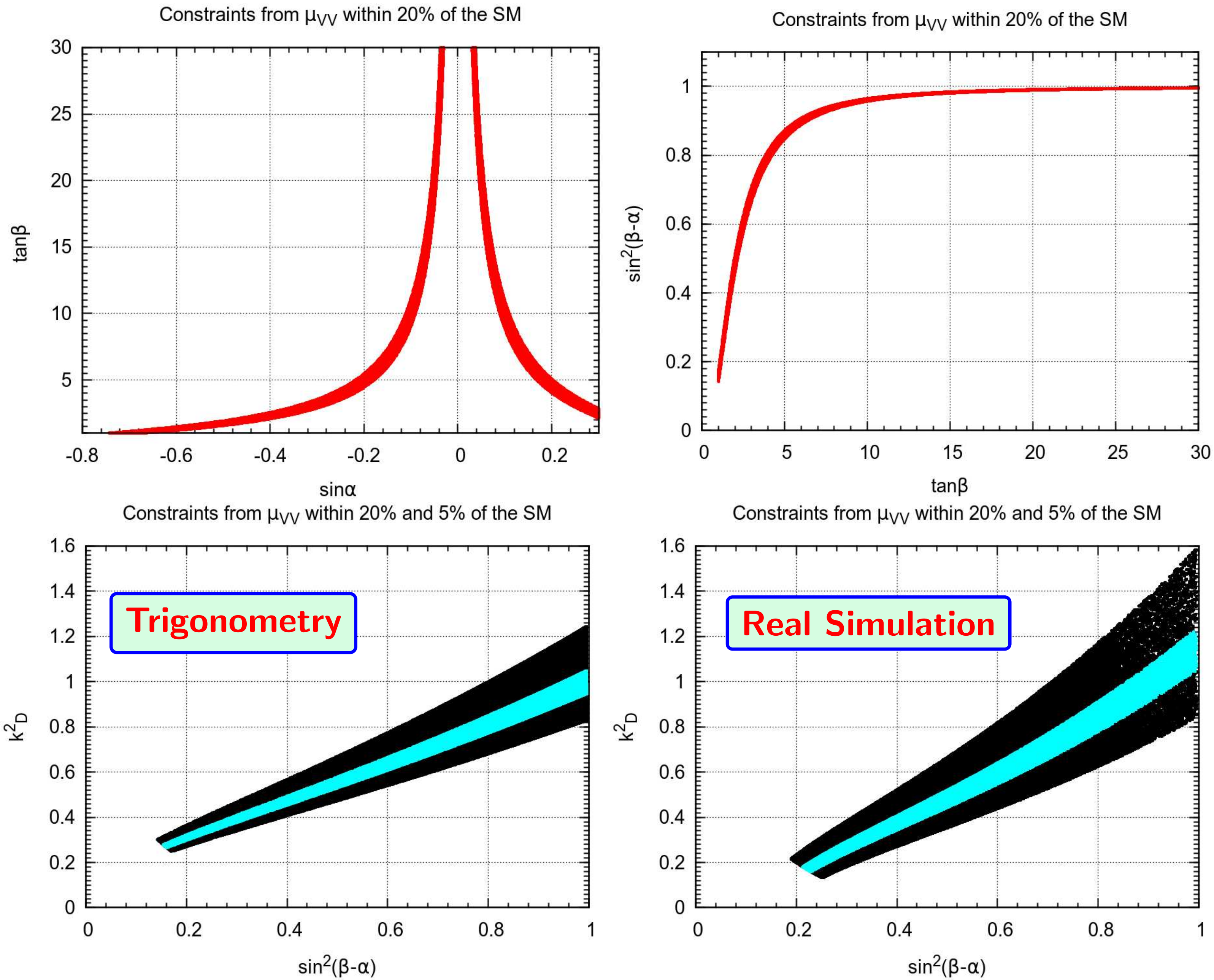
Independence of $\mu_{\gamma\gamma}$ on the QCD corrections to R_P

- While we reproduced their result for $\mu_{\gamma\gamma}$, our result for $\mu_{b\bar{b}}$ was larger
- We understood that this was due to a different version of HIGLU to calculate the NNLO corrections to the production, leading to a different production ratio R_P
- But the question then arose, how could we be in agreement on $\mu_{\gamma\gamma}$ while having different production ratio R_P?
- The key to understand this is *trigonometry*. Let us make the bold assumption that all the production is gluon fusion with top loop and that $h \to b\bar{b}$ is the only Higgs decay. Then

$$\mu_{VV} = k_U^2 \times k_V^2 \times \frac{1}{k_D^2} = \frac{k_U^2}{k_D^2} \sin^2(\beta - \alpha)$$

- Now we vary $\alpha \in [-\pi/2, \pi/2]$ and $\tan\beta \in [1, 30]$ and require $0.8 \leq \mu_{VV} \leq 1.2$. The results are extremely similar to what Ferreira et al. obtained with the full model

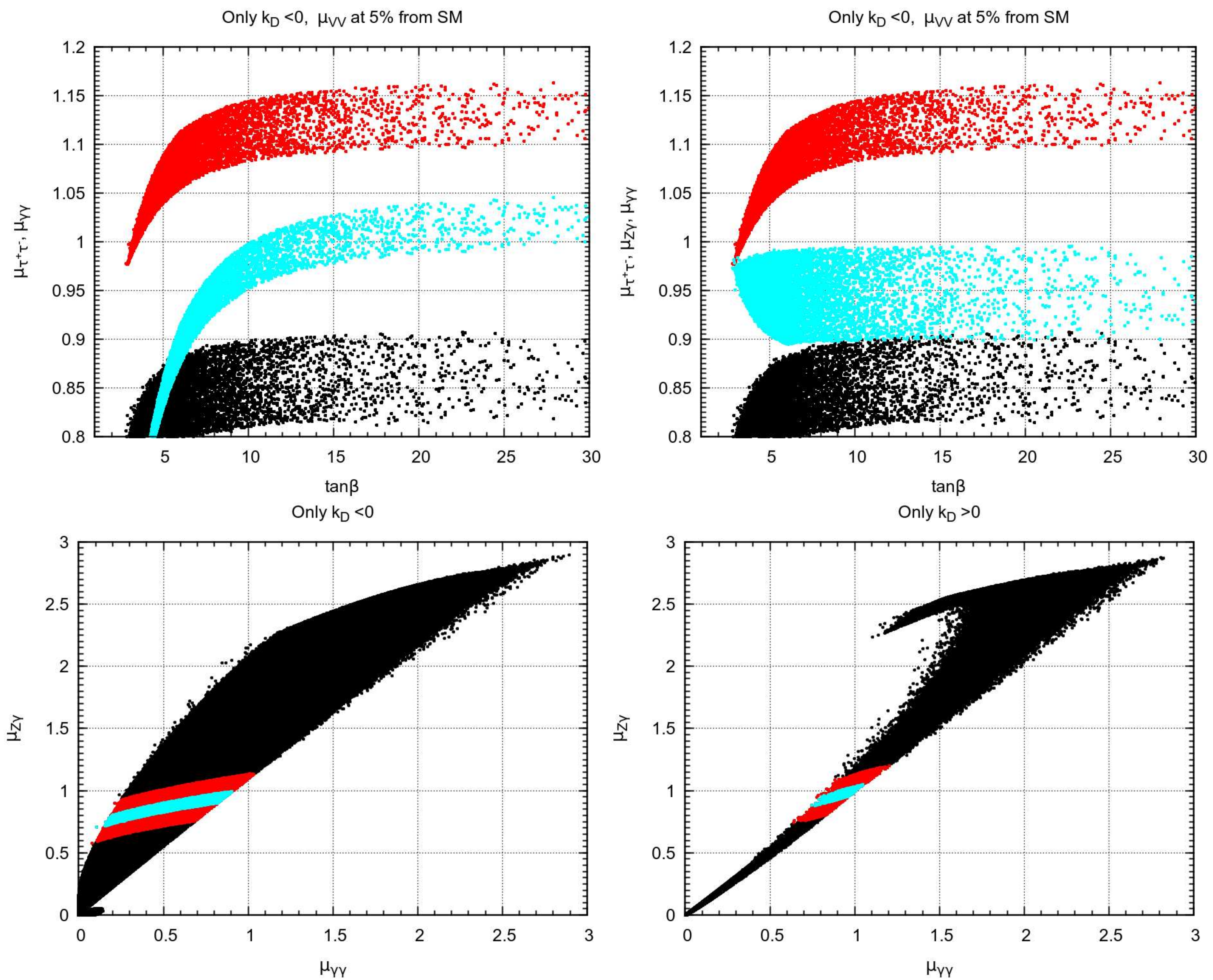
Trigonometry implications



Independence of $\mu_{\gamma\gamma}$ on the QCD corrections to R_P

- For each $\tan\beta$, $k_V^2 = \sin^2(\beta-\alpha)$ is almost fixed
- If we wish to keep $\mu_{VV} = R_P\, k_V^2\, R_{TW}$ constant and close to one then $R_P R_{TW} \simeq constant$
- An increase in R_P implies a decrease in R_{TW} that goes as $1/k_D^2$
- This implies an increase in k_D^2 and therefore in the decays $h\to b\bar{b}$ and $h\to\tau^-\tau^+$
- Finally, $\mu_{\gamma\gamma} = R_P\, k_{\gamma\gamma}^2\, R_{TW}$. As the effective coupling $k_{\gamma\gamma}$ is determined mainly by the W diagrams and the coupling k_V and this is fixed by trigonometry and μ_{VV} we obtain that $\mu_{\gamma\gamma}$ is independent of the production because $R_P R_{TW} \simeq constant$
- In conclusion $\mu_{\gamma\gamma}$ (and $\mu_{Z\gamma}$) do not depend on the details of the production. In particular, as stated by Ferreira et al., a measurement of $\mu_{\gamma\gamma}$ at 5% could decide about the wrong sign k_D coupling. The same is not true for $\mu_{Z\gamma}$, because its value can be very close to one

Predictions for the LHC@14TeV run for the Type II 2HDM



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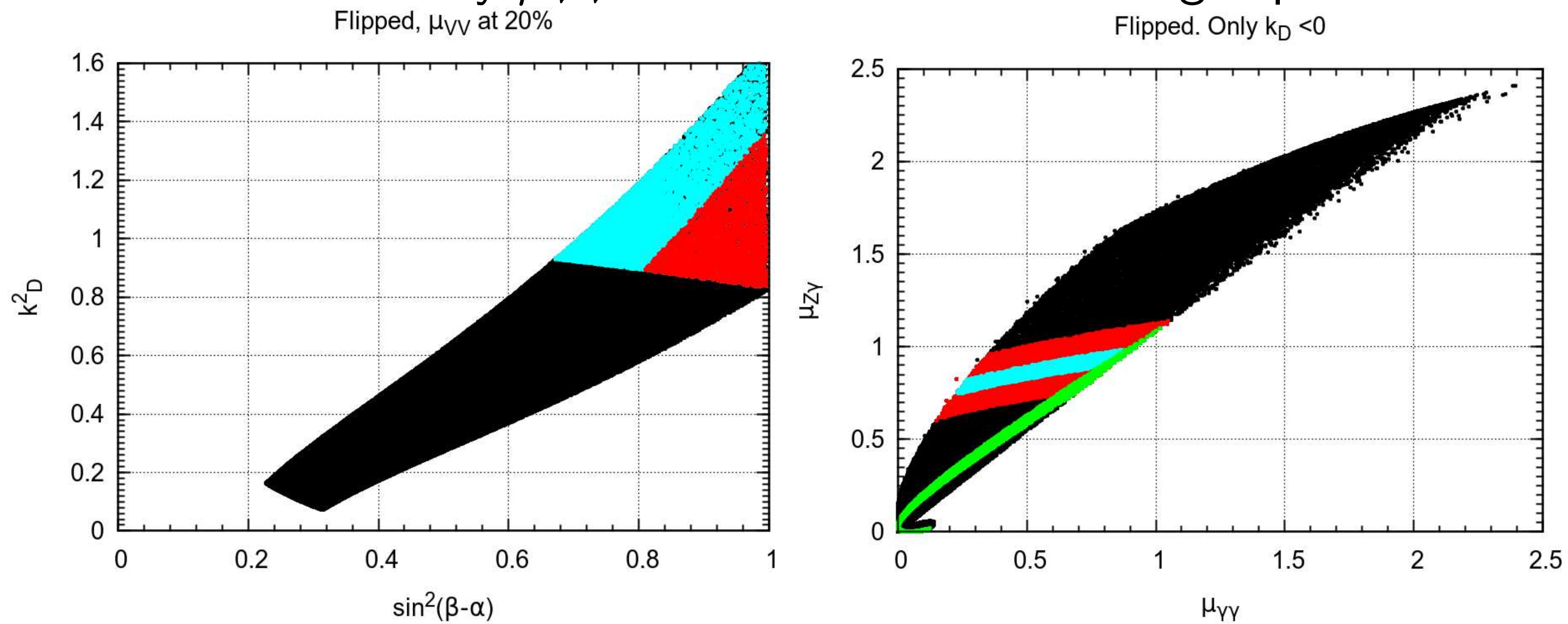
Predictions for the LHC@14TeV run for the Flipped 2HDM

- In the Flipped 2HDM coincides with the Type II except that leptons couple to the Higgs proportionally to k_U instead of k_D,

$$\frac{\mu_{\tau^+\tau^-}}{\mu_{VV}} = \frac{k_U^2}{\sin^2(\beta - \alpha)}$$

therefore the $\mu_{\tau^+\tau^-}$ has a larger impact as shown on the left panel

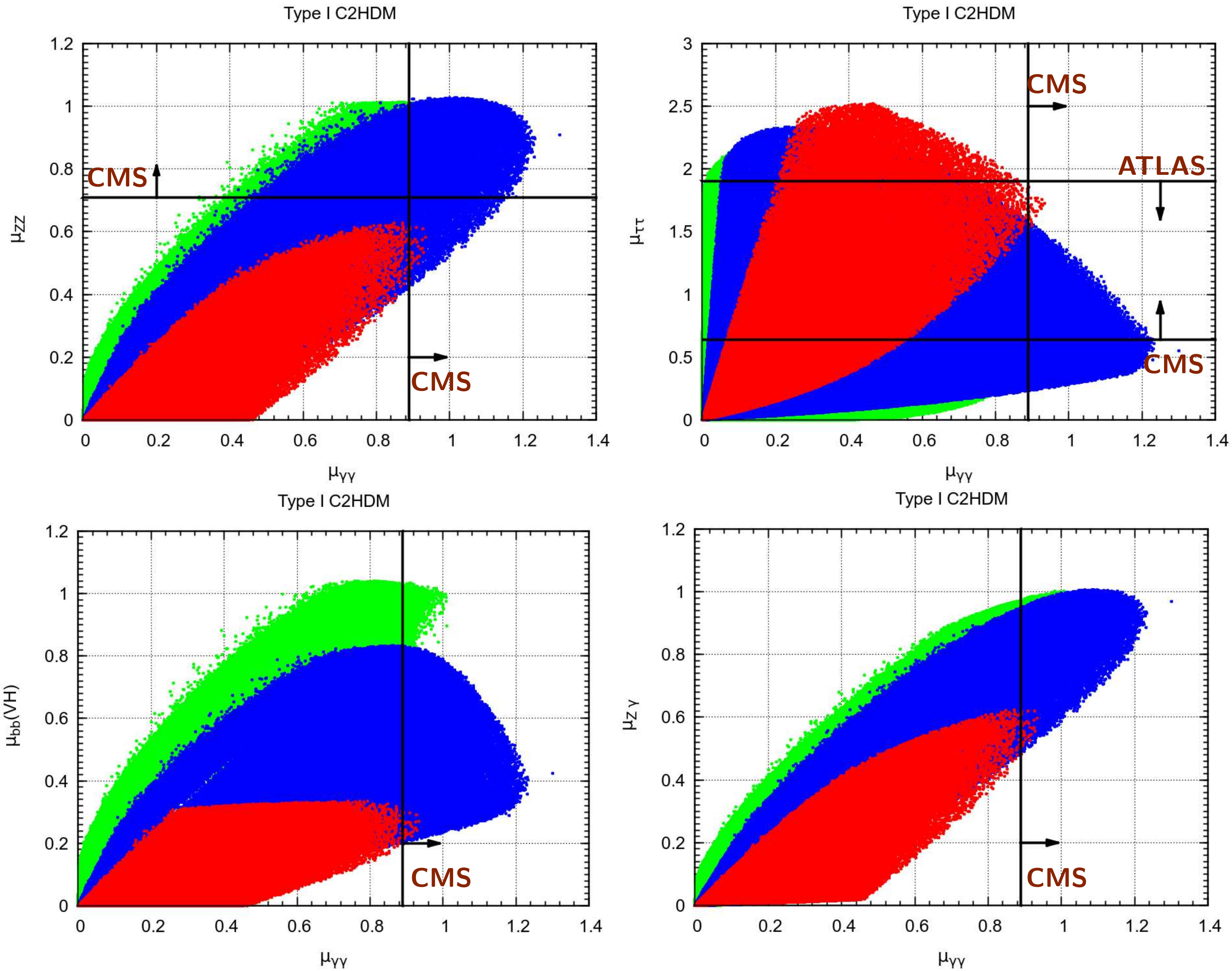
- However, this does not change the conclusions on $\gamma\gamma$ and $Z\gamma$, as those are determined by μ_{VV}. This is shown on the right panel



Setup for the C2HDM

- We simulate points as described before. We considered all the different variants of the C2HDM, Type I, Type II, Flipped and Lepton Specific.
- As $s_2 = 0$ ($|s_2| = 1$) corresponds to the Higgs h_1 being a pure scalar (pseudoscalar), in the following figures we separate three regions of s_2
  - $|s_2| < 0.1$ (green)
  - $0.45 < |s_2| < 0.55$ (blue)
  - $|s_2| > 0.85$ (red)
- In some figures the 1-σ LHC limits are superimposed
- For some figures we show what remains after requiring μ_{VV} at 20% (red) or 5% (cyan)

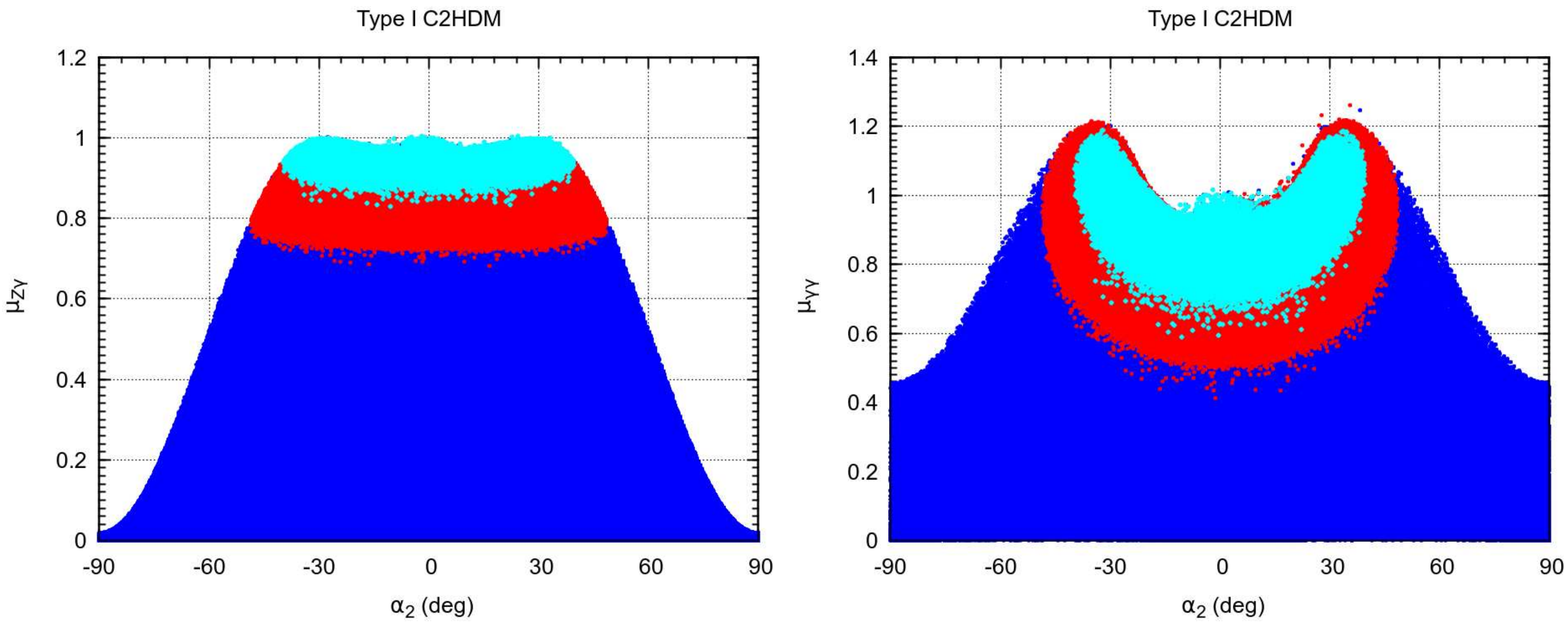
Results for Type I C2HDM



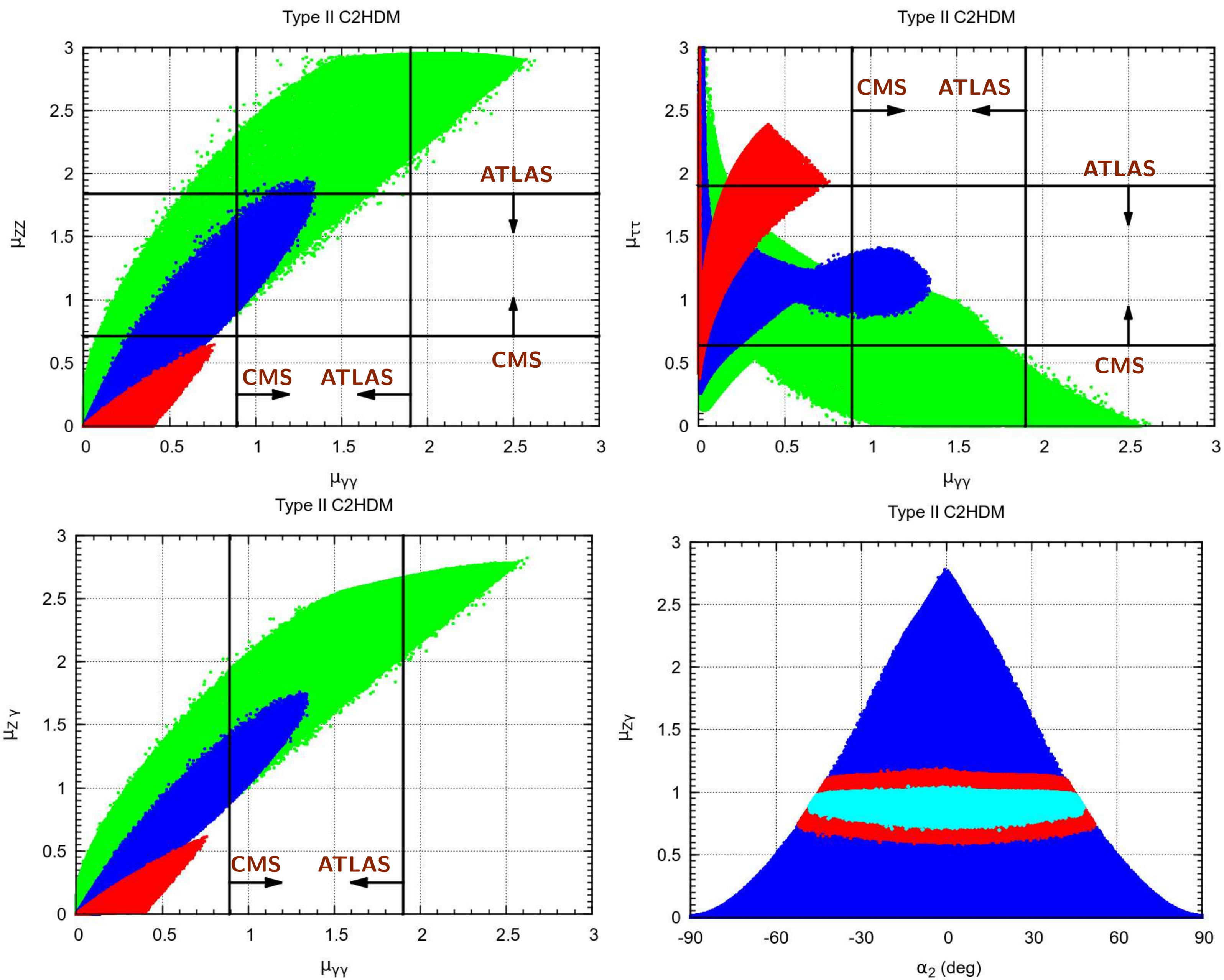
Results for Type I C2HDM ...

- μ_{VV} puts an upper limit on α_2. This is shown in the next plots, where we can see that $|\alpha_2| < 50^\circ$. In red (cyan) is shown the constraint on μ_{VV} at 20% (5%)

- Notice also that if $\mu_{\gamma\gamma}$ is measured around 1.2 (compatible with ATLAS), that would mean that $\alpha_2 \neq 0$, and a Type I C2HDM would be needed to explain the data

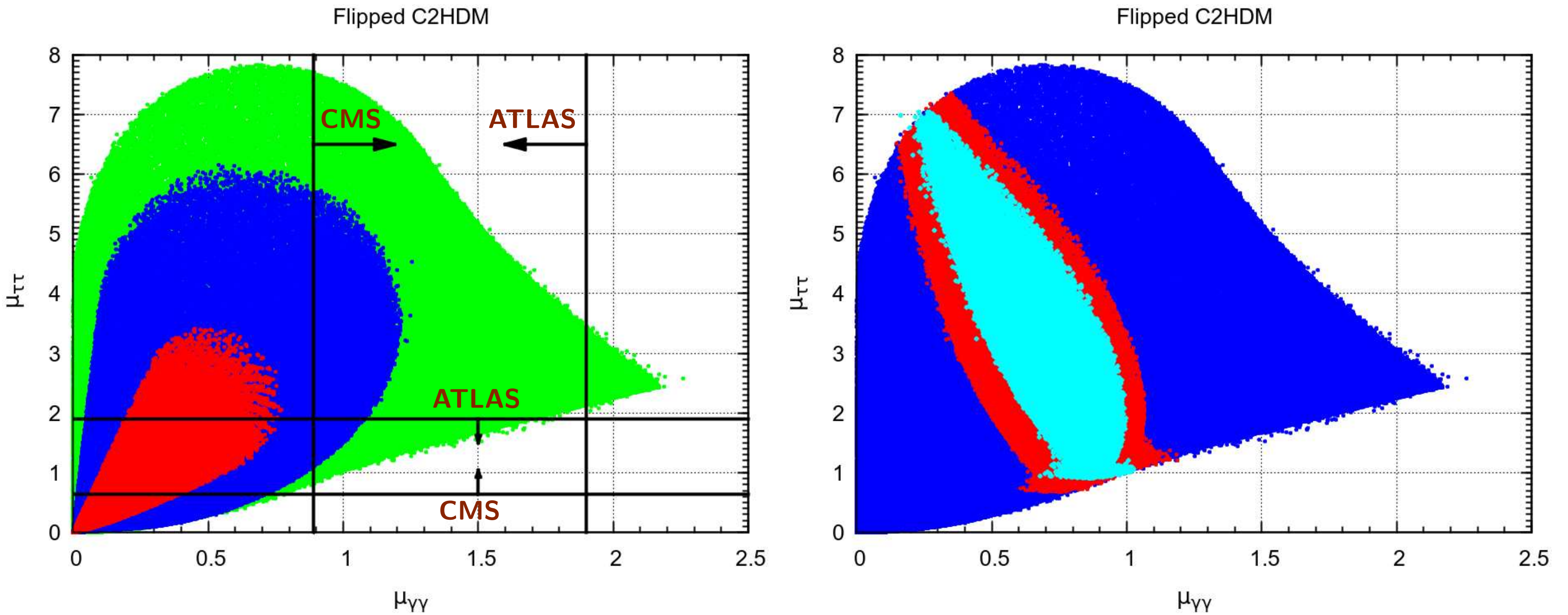


Results for Type II C2HDM



Results for Flipped C2HDM

- In the Flipped C2HDM the $\mu_{\tau^+\tau^-}$ can be very large.
- On the left panel we show the current 1-σ limits from LHC
- On the right panel, we show that even with μ_{VV} at 5% (cyan) $\mu_{\tau^+\tau^-}$ could be as large as 7. Therefore better limits on $\mu_{\tau^+\tau^-}$ are crucial
- A pure pseudoscalar, $|s_2| = 1$, in Flipped C2HDM is excluded at 1-σ

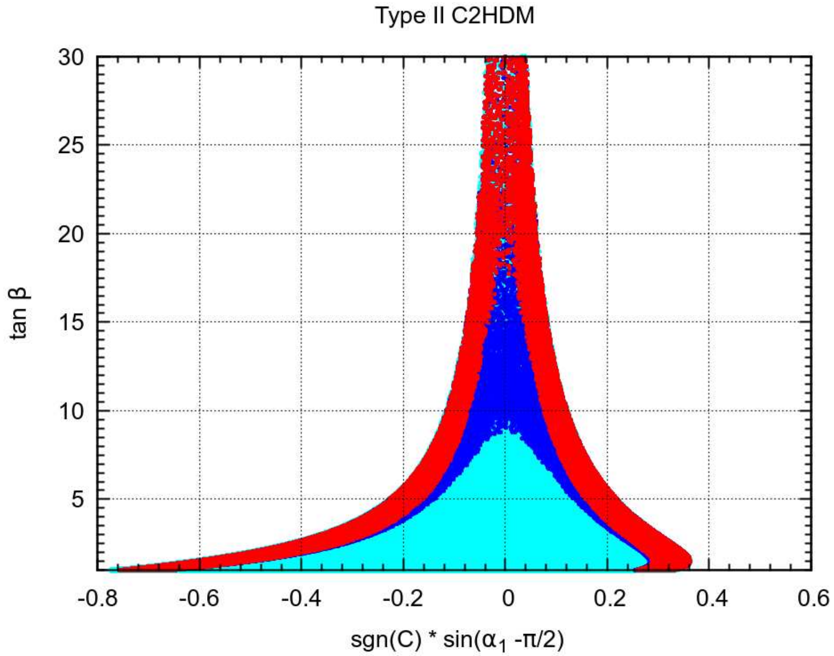


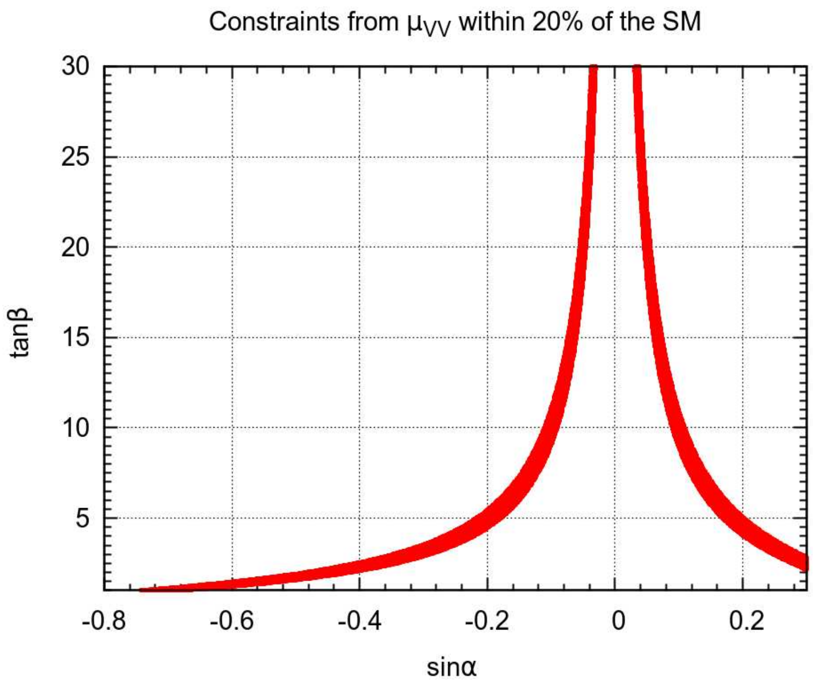
The importance of trigonometry in the C2HDM

- As in the real 2HDM trigonometry has a strong influence on the parameters

- On left panel we assume μ_{VV} at 20% and plot in the x-axis sgn$(C)\sin(\alpha_1 - \pi/2)$ that reduces to $\sin\alpha$ in the 2HDM limit. In cyan all points, in blue $|s_2|, |s_3| < 0.1$ and in red in blue $|s_2|, |s_3| < 0.05$.

- This should be compared with the result in the real 2HDM





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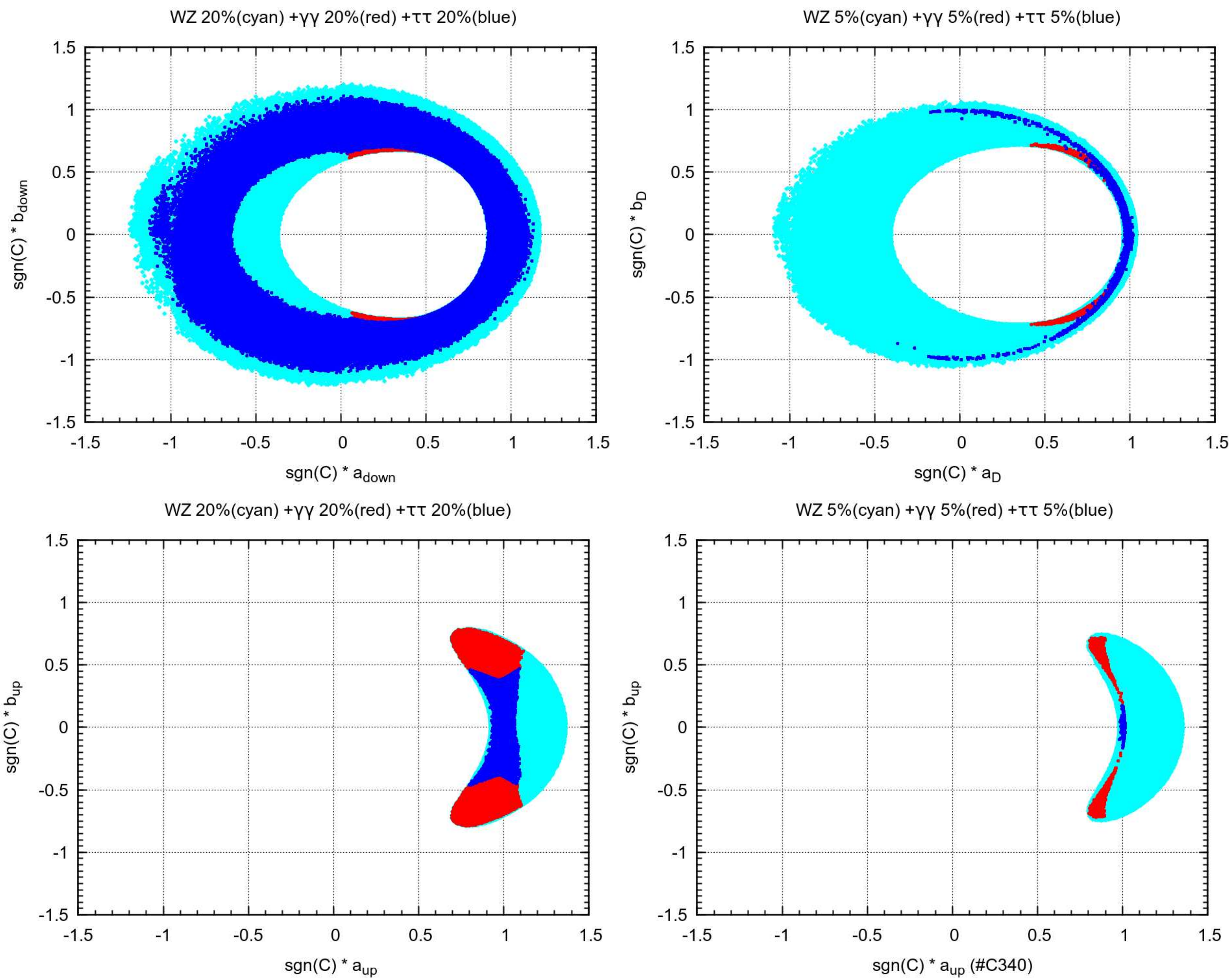
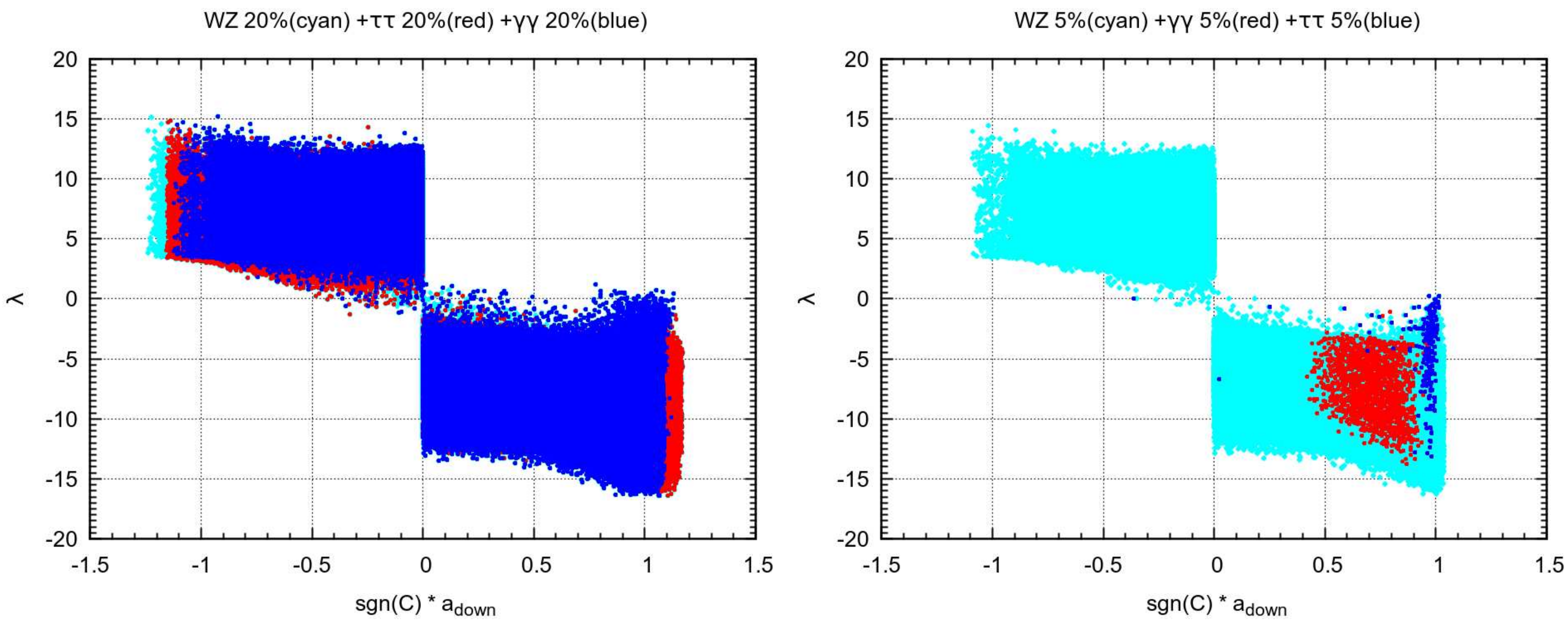
Fermion Couplings in the C2HDM (Type II)



Charged Higgs Couplings in the C2HDM

- In the 2HDM wrong sign solutions exist only with $k_D \sim -1$ This requires a large hH^+H^- coupling λ.
- We show the equivalent situation in the C2HDM. Left (right) panel for μ's at 20% (5%)
- Now we have a continuous region, but it remains true that sgn$(C)a_D \sim -1$ requires a large value of λ



Conclusions

- We have done a full calculation of the decay of a mixed scalar/pseudoscalar boson in $Z\gamma$ (also $\gamma\gamma$) in the full C2HDM
- In the particular case of the real 2HDM, we analyzed the wrong sign $hb\bar{b}$ Yukawa coupling. We showed that while the results for $\mu_{\tau^+\tau^-}$ and $\mu_{b\bar{b}}$ are sensitive to the details of the production, $\mu_{\gamma\gamma}$ and $\mu_{Z\gamma}$ are not. We agree with the claim of Ferreira et al., that a measurement of $\mu_{\gamma\gamma}$ at 5% would exclude (or confirm) this possibility
- We have performed a full update of the bounds on all types of C2HDM from LHC@8TeV and the outlook for LHC@14TeV, for all decay channels of interest
- In all types a large pseudoscalar component is already disfavoured at 1-σ. In the Flipped case we can have $\mu_{\tau^+\tau^-} \sim 7$, so a better measurement is crucial
- Concerning the wrong sign solutions, we found that we have more room, due to the existence of the pseudoscalar couplings, but that the general situation is similar to the 2HDM. However, even measurements at 5% would not exclude points with $\text{sgn}(C)a_D < 0$