The CP-conserving 2HDM after the 8 TeV run

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We confront the most common CP-conserving 2HDM with the LHC data analysed so far while taking into account all previously available experimental data. A special allowed corner of the parameter space is analysed - the so-called wrong-sign scenario where the Higgs coupling to down-type quarks changes sign relative to the Standard Model while the coupling to the massive vector bosons does not.

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1. Introduction

The end of the 8 TeV run at the Large Hadron Collider (LHC) has confirmed the existence of a Higgs boson [1, 2] that very much resembles the one predicted by the Standard Model (SM). Furthermore there are no hints of extra scalars in the data analysed so far. As many of the extension of the SM, the two-Higgs doublet model (2HDM) is being cornered into a SM-like region except for a few regions of the parameter space.

The 2HDM is an extension of the SM where one extra doublet is added to the particle content while keeping the SM symmetries. It appears in the literature in a variety of versions that depend mainly on the extra symmetries imposed on the Lagrangian and on how the $SU(2) \times U(1)$ symmetry is broken to $U(1)$. In this work we will focus on the CP-conserving 2HDM with a Z_2 discrete symmetry, softly broken in the potential by a dimension two term.

We will show the allowed parameter space of the model after the LHC 8 TeV run with all theoretical and experimental constraints taken into account. We will then study a region of the parameter space where the lightest CP-even Higgs (considered to be the SM-like Higgs throughout the paper) coupling to the down-type quarks changes sign relative to the SM.

2. The allowed parameter space of the 2HDM

The most general 2HDMs give rise to couplings corresponding to tree-level Higgs-mediated flavour-changing neutral currents (FCNCs), in clear disagreement with experimental data. A simple and natural way to avoid tree-level FCNCs is to impose a Z_2 symmetry on the scalar doublets, $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$, and a corresponding symmetry on the quark fields. This leads to the well known four Yukawa model types I, II, Flipped (F) (or Y) and Lepton Specific (LS) (or X). The different Yukawa types are built such that only ϕ_2 couples to all fermions (type I), or ϕ_2 couples to up-type quarks and ϕ_1 couples to down-type quarks and leptons (type II), or ϕ_2 couples to up-type quarks and to leptons and ϕ_1 couples to down-type quarks (type F) or finally ϕ_2 couples to all quarks and ϕ_1 couples to leptons (type LS). See [3] for a comprehensive review on the 2HDM.

The scalar potential in a softly broken Z_2 symmetric 2HDM can be written as

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] ,$$

where Φ_i, $i = 1, 2$ are complex SU(2) doublets. We will focus on a specific realisation of the 2HDM, the usual 7-parameter CP-conserving potential where the potential parameters and the VEVs are all real. In this model we choose as free parameters, the four masses, the rotation angle in the CP-even sector, α, the ratio of the vacuum expectation values, $\tan\beta = v_2/v_1$, and the soft breaking parameter m_{12}^2. By convention, we take $0 \leq \beta \leq \pi/2$ and $-\pi/2 \leq \alpha \leq \pi/2$.

The 2HDM parameters are chosen such that electric charge is conserved while neutral Higgs fields acquire real vacuum expectation values. Note that the existence of a tree-level scalar potential minimum that breaks the electroweak symmetry but preserves both the electric charge and CP symmetries, ensures that no additional tree-level potential minimum that spontaneously breaks the

electric charge and/or CP symmetry can exist [4]. Further, we force the CP-conserving minimum to be the global one [5].

In order to find the 2HDM parameter space that is still allowed after the 8 TeV run we have used ScannerS [6] interfaced with SusHi [7] and HDECAY [8, 9] for Higgs production and decays, cross-checked with HIGLU [10] and 2HDMC [11]. The remaining Higgs production cross sections were taken from [12]. All collider data was taken into account with HiggsBounds [13] and HiggsSignals [14]. The remaining constraints (see [15]), theoretical, electroweak precision and B-physics constraints are coded in ScannerS.

We have performed a scan in the 2HDM parameter space in the following range: $m_h = 125.9\,\text{GeV}$, $m_h + 5\,\text{GeV} < m_H$, $m_A < 1\,\text{TeV}$, $100\,\text{GeV} < m_{H^\pm} < 1\,\text{TeV}$, $1 < \tan\beta < 30$, $|\alpha| < \pi/2$ and $-(50\,\text{GeV})^2 < m_{12}^2 < (500\,\text{GeV})^2$. In figure 1 we present the allowed parameter space af-
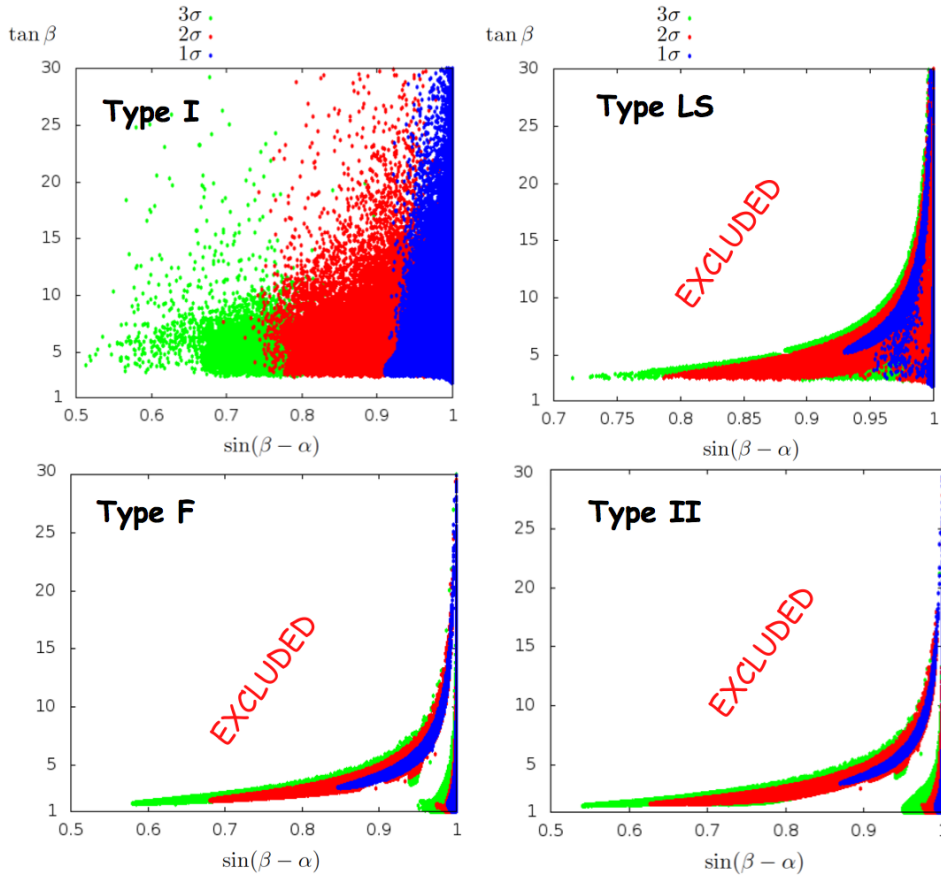

Figure 1: Allowed parameter space for models I, LS, F and II after the 8 TeV run.

ter the 8 TeV run at 1σ, 2σ and 3σ with all experimental and theoretical constraints taken into account. There are some interesting features worth mentioning. First, the bounds on $\sin(\beta - \alpha)$ range from about 0.5 in type II to about 0.7 in type LS at 3σ. Second, that large values of $\tan\beta$ require $\sin(\beta - \alpha)$ close to 1 except for the type I model. Note that although the Higgs couplings to quarks are equal in types I and LS, the couplings to leptons are different. As a result, the measurement of $pp \to h \to \tau^+\tau^-$ affects considerably more the parameter space of type LS than that

of type I [16]. Finally, it is clear from the figure that in models type II and Flipped, the allowed points are centred around two lines. The line on the right corresponds to the SM-like limit, that is $\sin(\beta - \alpha) = 1$. In this limit, the lightest Higgs couplings to gauge bosons and to fermions are the SM ones. The line on the left corresponds to the limit $\sin(\beta + \alpha) = 1$. In type II and with our conventions, it corresponds to the limit where the Higgs coupling to down-type quarks changes sign relative to the SM while couplings to up-type quarks and massive gauge bosons are the same. This is called the wrong-sign limit [17] (see also [18, 19] . Note that this limit is imposed only at tree-level.

3. The wrong-sign scenario

We will now analyse the wrong-sign scenario in the light of the next run of the LHC. This scenario was first discussed in [20]. Let us start by defining $\kappa_i^2 = \Gamma^{\text{2HDM}}(h \to i)/\Gamma^{\text{SM}}(h \to i)$ which means that at tree-level κ_i is just the ratio of couplings $\kappa_i = g^{\text{2HDM}}/g^{\text{SM}}$. In the SM-like limit, $\kappa_{W(Z)} = \sin(\beta - \alpha) = 1$, implies $\kappa_U = \kappa_D = \kappa_L = 1$, that is, the lightest Higgs couplings to up-type quarks (U), down-type quarks (D) and leptons (L), are the SM ones. The wrong-sign scenario can be defined as either $\kappa_D \kappa_W < 0$ or $\kappa_U \kappa_W < 0$ (κ_L never plays a major role in the interference terms). We can further have $\kappa_D \kappa_U < 0$, in which case both κ_g and κ_γ can be affected or $\kappa_D \kappa_U > 0$ meaning that only κ_γ can be affected. The wrong sign scenario is obtained in type II and F with

$$\sin(\beta + \alpha) = 1 \Rightarrow \kappa_D = -1 \,(\kappa_U = 1); \quad \sin(\beta - \alpha) = \frac{\tan^2 \beta - 1}{\tan^2 \beta + 1} \Rightarrow \kappa_W > 0 \,(\tan \beta > 1). \quad (3.1)$$

As the constraints from B-physics and from the R_b measurements force $\tan \beta$ to be above $O(1)$ we will focus on the case $\kappa_D = -1$. We will now discuss this scenario for the type II model (very similar to the type F case).

Will the LHC be able to probe the wrong-sign scenario? We define the signal strength as

$$\mu_f^h = \frac{\sigma \, \text{BR}(h \to f)}{\sigma^{\text{SM}} \, \text{BR}^{\text{SM}}(h \to f)} \quad (3.2)$$

where σ is the Higgs production cross section and $\text{BR}(h \to f)$ is the branching ratio of the decay into some given final state f; σ^{SM} and $\text{BR}^{\text{SM}}(h \to f)$ are the expected values for the same quantities in the SM. We will not separate different LHC initial state production mechanisms and instead sum over all production mechanisms in computing the cross section.

As a rough approximation of the precision with current data we require that the LHC's μ_f^h for the final states $f = WW$, ZZ, $b\bar{b}$, $\gamma\gamma$ and $\tau^+\tau^-$ are each consistent with unity within 20%. In order to understand how an increase in precision will affect the wrong-sign scenario we then require that all the μ_f^h are within 10% or 5% of the SM prediction. We now have to answer the following questions. First, why isn't this scenario excluded yet? Second, will it be probed at the LHC with high energy and high luminosity?

In the limit $\sin(\beta + \alpha) \to 1$, $\kappa_D \to -1$ which implies that the main Higgs production mode, gluon-gluon fusion, is enhanced. The quark initiated modes are not modified relative to the SM because there are no interference terms (at LO). VBF and associated production do not suffer any significant change because $\sin(\beta - \alpha) \approx \sin(\beta + \alpha)$ for $\tan \beta \gg 1$. Therefore the scenario

could in principle be probed at the production level in $gg \to h$ due to the interference between top and bottom loops. However, the uncertainties in the gluon fusion process advise not to use this production process to distinguish between the two scenarios [17, 19].

Regarding the Higgs decays, it is clear that there is no difference between the two scenarios in the decay to fermions. Again, because $\sin(\beta - \alpha) \approx \sin(\beta + \alpha)$ for $\tan\beta \gg 1$, taking $\tan\beta = 8$ the ratio of the wrong sign $\Gamma(h \to WW(ZZ))$ decay width to the respective SM width is 0.94, which corresponds to a negligible effect in μ_{WW}^h due to the already discussed Higgs production cross section enhancement. Therefore, we have to turn into the decays where the interference between the different loop contributions occur, that is $h \to \gamma\gamma$ and $h \to gg$. In figure 2 we present κ_γ (left) and
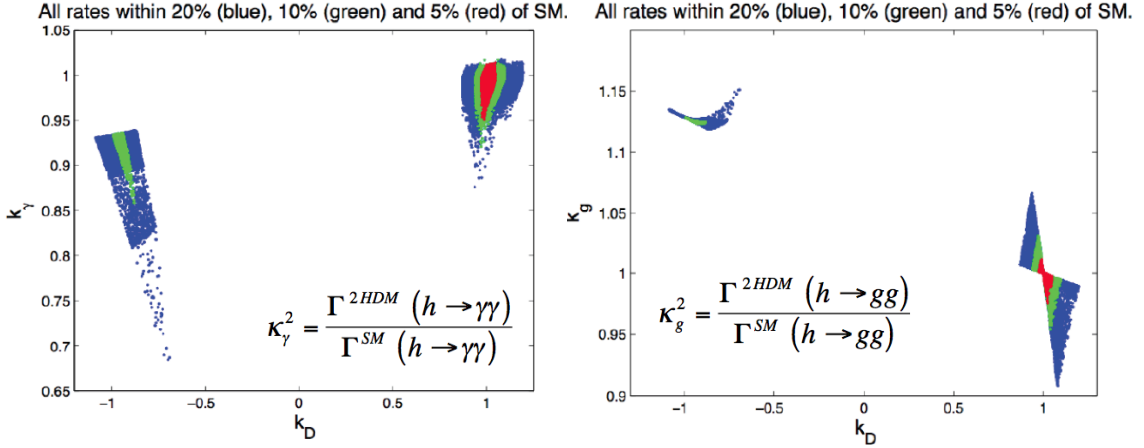

Figure 2: Left panel: κ_γ as a function of κ_D; right panel: κ_g as a function of κ_D

κ_g (right) as a function of κ_D in type II with all rates within 20% (blue), 10% (green) and 5% (red) of the SM values. While it is understandable that a measurement of κ_g could probe the wrong-sign scenario, the same is not true for κ_γ. In fact, the decay $h \to \gamma\gamma$ has not only the top and bottom loop contributions but also the W and charged-Higgs ones. Neglecting the charged-Higgs contribution, a change in the sign of κ_D amounts to about a 1% difference in the width. Therefore it is the charged Higgs loop that is responsible for the more substantial reduction in $\Gamma(h \to \gamma\gamma)$. This effect is due to the nondecoupling of the charged Higgs loop. As shown in [17] the charged-Higgs contribution to $\Gamma(h \to \gamma\gamma)$ in the $\kappa_D < 0$ case is approximately constant and always sufficiently significant as to eventually be observable at the LHC. However, the constraints coming from tree-level unitarity imply that the result is only perturbatively reliable for $m_{H^\pm} \sim 650$ GeV.

According to Table 1-20 of Ref. [21], the expected errors for κ_g based on fittings are 6–8% for $L = 300$ fb^{-1} and 3–5% for $L = 3000$ fb^{-1} (for 14 TeV). The predicted accuracy for κ_γ is 5–7% for an integrated luminosity of $L = 300$ fb^{-1} and 2–5% for $L = 3000$ fb^{-1}. Therefore there are good chances to probe the wrong-sign scenario in the 14 TeV LHC run. Also with the predicted accuracy for the International Linear Collider [22, 23] the scenario could not only be probed by a measurement of κ_g and κ_γ but also in the process $e^+e^- \to Zh(\to b\bar{b})$. Finally one should mention that a thorough study of this scenario has to take into account the 2HDM electroweak corrections, some of which are already available [24, 25].

References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].

[3] J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, *The Higgs Hunter's Guide* (Westview Press, Boulder, CO, 2000); G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher and J.P. Silva, Phys. Rept. **516**, 1 (2012).

[4] P.M. Ferreira, R. Santos and A. Barroso, Phys. Lett. B **603** (2004) 219 [Erratum-ibid. B **629** (2005) 114].

[5] A. Barroso, P. M. Ferreira, I. P. Ivanov and R. Santos, JHEP **1306** (2013) 045.

[6] R. Coimbra, M. O. P. Sampaio and R. Santos, Eur. Phys. J. C **73** (2013) 2428.

[7] R. V. Harlander, S. Liebler and H. Mantler, Computer Physics Communications **184** (2013) 1605.

[8] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. **108** (1998) 56.

[9] R. Harlander, M. Mühlleitner, J. Rathsman, M. Spira and O. Stål, arXiv:1312.5571 [hep-ph].

[10] M. Spira, arXiv:hep-ph/9510347.

[11] D. Eriksson, J. Rathsman and O. Stål, Comput. Phys. Commun. **181** (2010) 189.

[12] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

[13] P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein and K. E. Williams, Eur. Phys. J. C **74** (2014) 2693.

[14] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak and G. Weiglein, Eur. Phys. J. C **74** (2014) 2711.

[15] A. Barroso, P. M. Ferreira, R. Santos, M. Sher and J. P. Silva, arXiv:1304.5225 [hep-ph].

[16] A. Arhrib, C. -W. Chiang, D. K. Ghosh and R. Santos, Phys. Rev. D **85** (2012) 115003 [arXiv:1112.5527 [hep-ph]].

[17] P. M. Ferreira, J. F. Gunion, H. E. Haber and R. Santos, Phys. Rev. D **89** (2014) 115003.

[18] B. Dumont, J. F. Gunion, Y. Jiang and S. Kraml, arXiv:1405.3584 [hep-ph].

[19] D. Fontes, J. C. Romão and J. P. Silva, arXiv:1406.6080 [hep-ph].

[20] I. F. Ginzburg, M. Krawczyk and P. Osland, In *2nd ECFA/DESY Study 1998-2001* 1705-1733 [hep-ph/0101208].

[21] S. Dawson, A. Gritsan, H. Logan, J. Qian, C. Tully, R. Van Kooten *et al.*, arXiv:1310.8361 [hep-ex].

[22] H. Ono and A. Miyamoto, Eur. Phys. J. C **73** (2013) 2343.

[23] D.M. Asner, T. Barklow, C. Calancha, K. Fujii, N. Graf, H.E. Haber, A. Ishikawa, S. Kanemura *et al.*, arXiv:1310.0763 [hep-ph].

[24] D. Lopez-Val and J. Sola, Phys. Rev. D **81** (2010) 033003; D. Lopez-Val, T. Plehn and M. Rauch, JHEP **1310** (2013) 134.

[25] S. Kanemura, M. Kikuchi and K. Yagyu, Phys. Lett. B **731** (2014) 27.