THE WRONG SIGN LIMIT IN THE 2HDM

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ABSTRACT

A sign change in the Higgs couplings to fermions and massive gauge bosons is still allowed in the framework of two-Higgs doublet models (2HDM). In this work we discuss the possible sign changes in the Higgs couplings to fermions and gauge bosons, while reviewing the status of the 8-parameter CP-conserving 2HDM after the Large Hadron Collider 8 TeV run.

PRESENTED AT

The Second Annual Conference
on Large Hadron Collider Physics
Columbia University, New York, U.S.A
June 2-7, 2014
1 Introduction

The ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) have finally confirmed the existence of a Higgs boson. The measurements of the couplings to the fermions and gauge bosons have shown no major deviations from the Standard Model (SM) predictions. Also, because no other scalars were found, the parameter space of most extensions of the SM is becoming heavily constrained. Such is the case of the model where an extra doublet is added to the SM content, known as the two-Higgs doublet model (2HDM).

We will show that the parameter space of the 2HDM is indeed constrained to be close to the SM predictions as to reproduce the experimental results obtained at the LHC at the end of the 8 TeV run. There are however some interesting regions of parameter space where the Higgs couplings to fermions or gauge bosons change sign relative to the SM Higgs couplings. Whenever this sign change is measurable, given enough experimental precision, we call it wrong sign scenario [3]. This scenario was first studied in [4] and more recently in [5, 6].

2 The model

The 2HDM is built by simply adding a complex scalar doublet to the SM field content. In its most general form, the 2HDM Yukawa Lagrangian gives rise to tree-level Higgs-mediated flavour-changing neutral currents (FCNCs), in disagreement with experimental data. There is however a simple way to avoid these tree-level FCNCs which is to impose a $Z_2$ symmetry on the two scalar doublets, $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$. By imposing a corresponding discrete symmetry on the fermion fields one is able to construct four independent Yukawa types. A scan in this space was performed with ScannerS [10] with the parameters in the following ranges: $m_h = 125.9$ GeV, $m_h + 5$ GeV $< m_H$, $m_A < 1$ TeV, $100$ GeV $< m_{H^\pm} < 1$ TeV, $1 < \tan \beta < 50$, $|\alpha| < \pi/2$ and $-(900$ GeV$)^2 < m_{12}^2 < (900$ GeV$)^2$. ScannerS is interfaced with SushI [11] and HDECAY [12, 13] for Higgs production and decays, cross-checked with HIGLU [14] and 2HDMC [15]. The remaining Higgs production cross sections were taken from [16]. Collider data was taken into account with HiggsBounds [17] and HiggsSignals [18]. The remaining constraints (see [19]), theoretical, electroweak precision and B-physics constraints are coded in ScannerS.

We define

$$\kappa_i^2 = \frac{\Gamma_{2HDM}^{h \rightarrow i}}{\Gamma_{SM}^{h \rightarrow i}}$$

(2)

3 Results and discussion

In this section we present the parameter space of the 2HDM that is still allowed after the 8 TeV run for the different Yukawa types. A scan in this space was performed with ScannerS [10] with the parameters in the following ranges: $m_h = 125.9$ GeV, $m_h + 5$ GeV $< m_H$, $m_A < 1$ TeV, $100$ GeV $< m_{H^\pm} < 1$ TeV, $1 < \tan \beta < 50$, $|\alpha| < \pi/2$ and $-(900$ GeV$)^2 < m_{12}^2 < (900$ GeV$)^2$. ScannerS is interfaced with SushI [11] and HDECAY [12, 13] for Higgs production and decays, cross-checked with HIGLU [14] and 2HDMC [15]. The remaining Higgs production cross sections were taken from [16]. Collider data was taken into account with HiggsBounds [17] and HiggsSignals [18]. The remaining constraints (see [19]), theoretical, electroweak precision and B-physics constraints are coded in ScannerS.

We define

$$\kappa_i^2 = \frac{\Gamma_{2HDM}^{h \rightarrow i}}{\Gamma_{SM}^{h \rightarrow i}}$$

(2)
which at tree-level is just the ratio of the couplings \[ \kappa_i = \frac{g_i^{2HDM}}{g_i^{SM}}. \] We will also use the standard definition of signal strength

\[ \mu_f = \frac{\sigma \text{BR}(h \to f)}{\sigma^{SM} \text{BR}^{SM}(h \to f)} \quad (3) \]

where \( \sigma \) is the Higgs production cross section and \( \text{BR}(h \to f) \) is the branching ratio of the decay into some given final state \( f \); \( \sigma^{SM} \) and \( \text{BR}^{SM}(h \to f) \) 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.

![Figure 1: tan β as a function of \( \kappa_V = \sin(\beta - \alpha) \) for the type II model. Left panel: allowed parameter space taking into account all theoretical constraints and all experimental data including all data from the LHC’s 8 TeV run analysed so far at 1 (blue), 2 (red) and 3σ (green); right panel: same as left panel except for the LHC constraints, where instead we ask that all measured rates (\( \mu_{VV}, \mu_{\gamma\gamma} \) and \( \mu_{\tau^+\tau^-} \)) are within 5 (red), 10 (blue) and 20% (black) of the SM predictions.](image)

In the left panel of figure 1 we present the allowed parameter space of the type II CP-conserving 2HDM after the 8 TeV run at 1, 2 and 3σ with all experimental and theoretical constraints taken into account. The most striking feature in the plot is that there are two distinct regions that come together for \( \tan \beta \) close to \( \approx 17 \). The region on the the right corresponds to the the SM-like or alignment 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 region on the left is centred around the line \( \sin(\beta + \alpha) = 1 \). 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 remain the same. In fact, when \( \sin(\beta + \alpha) = 1 \), one obtains \( \kappa_D = -1 \) in type II, \( \kappa_V \kappa_D < 0 \), which was called the wrong sign limit in [3] (a limit imposed at tree-level). The most important point to note here is that the two limits can be distinguished experimentally. In fact, the alignment limit is already squeezed into values of \( \sin(\beta - \alpha) \) extremely close to 1 even at 3σ. On the contrary, the wrong sign limit spans a much larger region of \( \sin(\beta - \alpha) \), which at 3σ goes from about 0.52 to 1. The reason for the two regions meeting at large \( \tan \beta \) is that because \( \sin(\beta - \alpha) - \sin(\beta + \alpha) = \left( \tan^2 \beta - 1 \right)/\left( \tan^2 \beta + 1 \right) \), \( \sin(\beta - \alpha) \approx \sin(\beta + \alpha) \) for large \( \tan \beta \). The shape of these lines is primarily determined by the LHC constraints on \( \mu_{VV} \).

In the right panel we present \( \tan \beta \) as a function of \( \kappa_V = \sin(\beta - \alpha) \) with the same theoretical and experimental constraints except that the LHC present constraints on the measured Higgs rates are replaced by asking that all measured rates for the final states \( f = WW, ZZ, \gamma\gamma \) and \( \tau^+\tau^- \), are within 5 (red), 10 (blue) and 20% (black) of the SM predictions. Both the alignment limit and the wrong sign limit are
still present. As expected, the two regions shrink and the alignment limit is now almost a straight line for \( \sin(\beta - \alpha) = 1 \). However, two interesting features emerge. First, a measurement of the rates at 5% will exclude the wrong sign scenario as discussed in [3]. Second, large tan \( \beta \) values are excluded for the wrong sign scenario at 10% in type II. This is due to the bound imposed on \( \mu_{\tau^+ \tau^-} \) and it is ultimately a consequence of the large values of the \((gg + bb) \to h\) production cross section in the wrong sign limit as compared to the SM (there is no significant change in the \( h \to \tau^+ \tau^- \) branching ratios).

**Figure 2:** Left panel: \( \kappa_g \) as a function of \( \kappa_D \). Right panel: \( \kappa_\gamma \) as a function of \( \kappa_U \) where the upper region corresponds to the alignment limit while the lower one corresponds to the wrong sign limit.

When \( \kappa_V = \sin(\beta - \alpha) = 1 \), \( \kappa_U = \kappa_D = \kappa_L = 1 \), that is, the lightest Higgs couplings to up-type quarks (\( U \)), down-type quarks (\( D \)) and leptons (\( L \)), are the SM ones. The particular wrong sign scenario we are discussing, which occurs for \( \tan \beta > 1 \), is defined as \( \kappa_D \kappa_V < 0 \) and \( \kappa_D \kappa_U < 0 \).

In the wrong sign limit, the Higgs production cross section via gluon fusion is enhanced due to the sign change in \( \kappa_D \). The other modes that are different in the two limits (at LO) are the ones involving \( \kappa_V \), that is VBF and associated \( Vh \) production. As previously discussed, this difference vanishes for large \( \tan \beta \). Concerning the Higgs decays, 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 small effect in \( \mu_{VV} \). A difference could however appear for small values of \( \tan \beta \). Finally, the decays \( h \to \gamma \gamma \) and \( h \to gg \) could present a meaningful difference between the two limits due to the interference between the different loop contributions.

In figure 2 we present \( \kappa_\gamma \) as a function of \( \kappa_D \) (left) and \( \kappa_\gamma \) as a function of \( \kappa_U \) in type II with all rates within 20% (blue), 10% (green) and 5% (red) of the SM values. As a change in sign in \( \kappa_D \) leads to \( \kappa_\gamma \approx 1.13 \), it is expected that a precise measurement of \( \kappa_\gamma \) could exclude in the future the wrong sign scenario (\( \kappa_\gamma \) is extracted indirectly since there is no direct measurement of \( h \to gg \)). Regarding \( \kappa_\gamma \), shown on the right plot, one can see two distinct regions: the upper region is the alignment limit and the lower region is the wrong sign limit where \( \kappa_D = -1 \). The change of the \( \kappa_D \) sign in the SM amplitude amounts to only a 1% difference in \( \Gamma(h \to \gamma \gamma) \) relative to the respective SM width. Therefore the larger difference seen in the left panel of figure 2 has to come from the charged Higgs contribution. As was shown in [3] this 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. One should note however that the constraints coming from tree-level unitarity imply that the result is only perturbatively reliable for \( m_{H^\pm} \lesssim 650 \text{ GeV} \).

In order to understand if these differences can indeed be measured at the LHC we refer to table 1-20 of Ref. [20]. It is shown that the expected errors for \( \kappa_\gamma \) based on fittings are 6–8% for \( L = 300 \text{ fb}^{-1} \) and 3–5% for \( L = 3000 \text{ fb}^{-1} \) (for 14 TeV). The predicted accuracy for \( \kappa_\gamma \) is 5–7% for an integrated luminosity of \( L = 300 \text{ fb}^{-1} \) and 2–5% for \( L = 3000 \text{ fb}^{-1} \). In view of the plots in figure 2 it is clear that there are good chances of
probing the wrong-sign scenario in the 14 TeV LHC run. With the predicted accuracy for the International Linear Collider [21, 22] the wrong sign limit could not only be probed by a measurement of $\kappa_g$ and $\kappa_\gamma$ but also in the process $e^+ e^- \to Zh (\to b\bar{b})$. Finally one should note that a thorough study of this scenario has to take into account the 2HDM electroweak corrections, some of which are already available [23, 24].

Finally, in figure 3 we present $\tan \beta$ as a function of $\kappa_V = \sin (\beta - \alpha)$ for type I (left) and type LS (right) for the allowed parameter space taking into account all theoretical constraints and all experimental data. For type LS only the coupling to leptons changes sign and this change plays no role in the analysis. Let us recall that $\sin (\beta - \alpha) \approx \sin (\beta + \alpha)$ only for large $\tan \beta$. Therefore, the two curves on the right plot are close to the lines $\sin (\beta - \alpha) = 1$ (right) and $\sin (\beta + \alpha) = 1$ (left). Clearly the two curves can be distinguished, given enough precision, except for high values of $\tan \beta$. In conclusion, for (some) low values of $\tan \beta$ the symmetric limit can be probed at the next LHC run with very high luminosity, at least for type LS. The situation is not as clear for type I because the two regions are superimposed until $\sin (\beta - \alpha)$ is almost 1.

ACKNOWLEDGEMENTS

PMF, RG and RS are supported by FCT under contracts PTDC/FIS/117951/2010 and PEst-OE/FIS/UI0618/2011. RG is also supported by a FCT Grant SFRH/BPD/47348/2008. MS is supported by a FCT Grant SFRH/BPD/-69971/2010. JFG is supported in part by U.S. DOE grant DE-SC-000999. HEH is support in part by U.S. DOE grant DE-FG02-04ER41286.
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