Two-Higgs-Doublet Models with CP violation *

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Abstract

We consider the Two-Higgs-Doublet Model and determine the range of parameters for which CP violation and Flavor Changing Neutral Current effects are naturally small. It corresponds to small values of the mass parameter $m_{12}^2$, describing soft $(\phi_1, \phi_2)$ mixing in the potential. We discuss how, in this approach, some Higgs bosons can be heavy, with mass of the order of 1 TeV.

The possibility that at the Tevatron, LHC and an $e^+e^-$ Linear Collider, only one Higgs boson will be found, with properties indistinguishable from those in the Standard Model (SM), we define as the SM-like scenario. While this scenario can be obtained with large $\mu^2 \sim \text{Re} m_{12}^2$ parameter, in which case there is decoupling, we here discuss the opposite case of small $\mu^2$, without decoupling.

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1 Introduction

We consider the following Two-Higgs-Doublet Model (2HDM) potential, with quartic and quadratic terms separated [1, 2, 3, 4, 5]:

\[
V = \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) \\
+ \frac{1}{2} \left[ \lambda_5 (\phi_1^\dagger \phi_2)^2 + \text{h.c.} \right] + \left\{ \lambda_6 (\phi_1^\dagger \phi_1) + \lambda_7 (\phi_2^\dagger \phi_2) \right\} (\phi_1^\dagger \phi_2) + \text{h.c.} \\
- \left\{ m_{11}^2 (\phi_1^\dagger \phi_1) + \left[ m_{12}^2 (\phi_1^\dagger \phi_2) + \text{h.c.} \right] + m_{22}^2 (\phi_2^\dagger \phi_2) \right\}.
\]

(1)

As is well known, both CP violation in the Higgs sector and flavor-changing neutral currents (FCNC) can be suppressed by imposing a $Z_2$ symmetry [6]. This requires symmetry of the potential under ($\phi_1 \to -\phi_1$, $\phi_2 \to \phi_2$) (or vice versa), which implies $\lambda_6 = \lambda_7 = m_{12}^2 = 0$. We shall allow soft violation of this symmetry, i.e., we take $\lambda_6 = \lambda_7 = 0$, but allow $m_{12}^2 \neq 0$ [3, 5].

A simple discussion can be given for this case, in which $\text{Im} m_{12}^2 \neq 0$ signals CP violation.

2 CP violation

We shall now consider the simpler case of $\lambda_6 = \lambda_7 = 0$, and parametrize the minimum of the potential (or vacuum) as

\[
\phi_1 = \left[ \begin{array}{c} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{array} \right], \quad \phi_2 = \left[ \begin{array}{c} 0 \\ \frac{1}{\sqrt{2}} v_2 e^{i\xi} \end{array} \right].
\]

(2)

Naively, the phase $\xi$ violates CP, but it can be removed by a global phase transformation on the field $\phi_2$, together with the phases of $\lambda_5$, $m_{12}^2$ and the fermion fields [3, 4]. It is convenient to define

\[
\mu^2 = \text{Re}(m_{12}^2 e^{i\xi}) \frac{v^2}{v_1 v_2}.
\]

(3)

The phase $\xi$ can be found from the equation

\[
\text{Im}(m_{12}^2 e^{i\xi}) = \text{Im}(\lambda_5 e^{2i\xi}) v_1 v_2.
\]

(4)

Making use of the rephasing invariance [3, 4], we put $\xi = 0$. With this choice, eq. (3) becomes a constraint for the relation of $\text{Im}(m_{12}^2)$ to $\text{Im} \lambda_5$.

The neutral sector has a mass squared matrix of the form

\[
\mathcal{M}^2 = \begin{pmatrix}
M_{11}^2 & M_{12}^2 & -\frac{1}{2} \text{Im} \lambda_5 v^2 \sin \beta \\
M_{12}^2 & M_{22}^2 & -\frac{1}{2} \text{Im} \lambda_5 v^2 \cos \beta \\
-\frac{1}{2} \text{Im} \lambda_5 v^2 \sin \beta & -\frac{1}{2} \text{Im} \lambda_5 v^2 \cos \beta & M_{33}^2
\end{pmatrix}
\]

(5)

where $M_{11}^2$, $M_{12}^2$, $M_{22}^2$ and $M_{33}^2$ are the same as in the CP-conserving case. When $\text{Im} \lambda_5 = 0$, there is no CP violation, the matrix (5) is block diagonal, and the physical states are $h$, $H$ and $A$. When $\text{Im} \lambda_5 \neq 0$, all three neutral Higgs states mix; we denote them by $h_1$, $h_2$ and $h_3$. 

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The mass-squared matrix may be diagonalized via a rotation matrix, defined by
\[ R \mathcal{M}^2 R^T = \text{diag}(M_1^2, M_2^2, M_3^2). \] (6)

In the limit of weak $CP$ violation, the masses for $h_1$, $h_2$ and $h_3$ will deviate from those of $h$, $H$ and $A$ by terms quadratic in $\text{Im} \lambda_5$.

3 Decoupling or no decoupling?

We shall here consider the scenario of weak (or no) $CP$ violation and large masses of Higgs particles except one, namely $M_{h_1} \sim M_h$. Let us discuss how large masses $M_A$ (close to $M_{h_3}$) and $M_{H\pm}$ arise in such a case. The potential (5) (but with $\lambda_6 = \lambda_7 = 0$) gives
\[ M_A^2 = \frac{1}{2}\mu^2 - \text{Re} \lambda_5 v^2 \quad \text{and} \quad M_{H\pm}^2 = \frac{1}{2}[\mu^2 - (\lambda_4 + \text{Re} \lambda_5) v^2]. \] (7)

There are two rather distinct mechanisms for obtaining large mass $M_A^2$ and $M_{H\pm}^2$: either (i) $\mu^2$ is large (this is extensively discussed by Haber as the decoupling scenario) [2, 5], or (ii) $\mu^2$ is small, whereas $|\text{Re} \lambda_5|$ is “large” [4, 5]. In the latter case, there are obvious upper bounds (from perturbativity and positivity) on how large $|\text{Re} \lambda_5|$ can be. Decoupling properties of the Two-Higgs-Doublet Model were studied in [9].

In this model, with weak (or no) $CP$ violation, one can realize a Standard-Model-Like Scenario:

- There is a light Higgs boson with couplings to the up (e.g. $t$) and down (e.g. $b$) type quarks, and to $W$ and $Z$, like in the Standard Model,
\[ |g_i| \approx |g_{SM}^i| \quad (i = W, Z, \text{down, up}). \] (8)

- The other Higgs bosons are heavy, $\mathcal{O}(1 \text{ TeV})$.

Within the Two-Higgs-Doublet Model, this scenario can be realized in two distinct ways. They are [3]:

- Solutions A. All basic couplings are approximately the same as in the SM, up to an overall sign.
- Solutions B. Like Solutions A, except that the couplings to either up- or down-type quarks have opposite signs of those in the SM. This case cannot be realized in the decoupling scenario.
4 Model II. Observables

Let us now be more specific, and consider the so-called Model II for Yukawa couplings, where masses of down- and up-type quarks originate from couplings to $\phi_1$ and $\phi_2$, respectively. We denote by $\chi^h_u$, $\chi^h_i$ and $\chi^h_d$ the ratios of the Higgs couplings to $W$ and $Z$ ($V$) and to up and down-type quarks, with respect to those of the Standard Model. In particular, for the Yukawa couplings these ratios can be expressed via elements of the rotational matrix $R$ of eq. (6) as

$$\chi^h_u = \frac{1}{\sin \beta}[R_{i2} - i\gamma_5 \cos \beta R_{i3}], \quad \chi^h_i = \frac{1}{\cos \beta}[R_{i1} - i\gamma_5 \sin \beta R_{i3}],$$

(9)

where $R_{i3}$ is proportional to $\text{Im} \lambda_5$. Note that in accordance with eq. (9), the CP violation induced by Higgs exchange in $t\bar{t}$ production [10] provides information on $\text{Im} \lambda_5$.

Furthermore, these relative couplings satisfy a pattern relation [4, 8]:

$$(\chi^h_u + \chi^h_d) \chi^h_V = 1 + \chi^h_u \chi^h_d.$$  

(10)

In the CP-conserving case, even with all basic couplings being the same (up to a sign) as in the SM (8), loop-induced transition rates, like $h \rightarrow \gamma\gamma$, may differ from the SM prediction. This is due to the different behaviors of the trilinear Higgs coupling $hH^+H^-$ for small and large $\mu$. In fact, the ratio of this coupling to its SM value can be written as

$$\chi^h_{H^\pm} \equiv -\frac{v g_{hH^+H^-}}{2M^2_{H^\pm}} = \left(1 - \frac{M^2_h}{2M^2_{H^\pm}}\right) \chi^h_V + \frac{M^2_h - \frac{1}{2}\mu^2}{2M^2_{H^\pm}}(\chi^h_u + \chi^h_d).$$

(11)

Thus, if $\mu^2 \sim M^2_{H^\pm}$, there is no effect in $\Gamma_{\gamma\gamma}$, whereas if $\mu^2 < M^2_{H^\pm}$ there is a difference of several per cent, as illustrated in Fig. 1 (left panel) for the case of Solutions A [4]. Non-decoupling effects in the 2HDM were studied for other processes in [11, 12].

These deviations from unity are large enough that the form of the 2HDM potential (large or small $\mu$) can be tested at a $\gamma\gamma$ Collider [13].

Also, the loop-induced couplings to two gluons may differ from those of the SM-value, but this occurs only for Solutions B. This effect is also illustrated in Fig. 1 (right panel).

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Figure 1: Ratios of the Higgs boson decay widths in the SM-like 2HDM (II) and the SM as functions of $M_h$. Left panel: $h \rightarrow \gamma\gamma$ decay widths, solutions A, for $M_{H^\pm} = 800$ GeV and $\mu/\sqrt{2} = xM_{H^\pm}$. Right panel: $h \rightarrow gg$, solutions B.

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