TWO-HIGGS-DOUBLET MODELS WITH CP VIOLATION*

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Abstract

We consider the Two-Higgs-Doublet Model (2HDM) 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 terms 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 $\mu^2 \sim \operatorname{Re} m_{12}^2$ parameter, in which case there is decoupling, we here discuss the opposite case of small μ^2, without decoupling.

1 Introduction

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

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

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 [5]. 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 $m_{12}^2 \neq 0$ [2, 4, 6]. A simple discussion can be given for this case, in which $\operatorname{Im} m_{12}^2 \neq 0$ signals CP violation.

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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

$$\phi_1 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}}\, v_1 \end{bmatrix}, \quad \phi_2 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}}\, v_2\, e^{i\xi} \end{bmatrix}. \tag{2}$$

Naively, the phase ξ violates CP, but it can be removed by a global phase transformation on the field ϕ_2, together with the phases of λ_5, m_{12}^2 and the fermion fields [2]. It is convenient to define

$$\mu^2 = \mathrm{Re}(m_{12}^2 e^{i\xi}) \frac{v^2}{v_1 v_2}. \tag{3}$$

The phase ξ can be found from the equation

$$\mathrm{Im}(m_{12}^2\, e^{i\xi}) = \mathrm{Im}(\lambda_5\, e^{2i\xi}) v_1 v_2. \tag{4}$$

Making use of the rephasing invariance [2, 7], we put $\xi = 0$. With this choice, eq. (4) becomes a constraint for the relation of $\mathrm{Im}(m_{12}^2)$ to $\mathrm{Im}\,\lambda_5$.

The neutral sector has a mass squared matrix of the form

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 & -\frac{1}{2}\,\mathrm{Im}\,\lambda_5 \sin\beta \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 & -\frac{1}{2}\,\mathrm{Im}\,\lambda_5 \cos\beta \\ -\frac{1}{2}\,\mathrm{Im}\,\lambda_5 \sin\beta & -\frac{1}{2}\,\mathrm{Im}\,\lambda_5 \cos\beta & \mathcal{M}_{33}^2 \end{pmatrix} \tag{5}$$

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

The mass-squared matrix may be diagonalized via a rotation matrix, defined by

$$R\,\mathcal{M}^2\,R^{\mathrm{T}} = \mathrm{diag}(M_1^2, M_2^2, M_3^2). \tag{6}$$

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

3 Decoupling or no decoupling?

We shall here consider the scenario of weak (or no) CP violation and large M_A^2 and $M_{H^\pm}$. The potential (1) (but with $\lambda_6 = \lambda_7 = 0$) gives

$$M_A^2 = \tfrac{1}{2}\mu^2 - \mathrm{Re}\,\lambda_5 v^2 \quad \text{and} \quad M_{H^\pm}^2 = \tfrac{1}{2}[\mu^2 - (\lambda_4 + \mathrm{Re}\,\lambda_5)v^2]. \tag{7}$$

There are two rather distinct mechanisms for obtaining large masses M_A^2 and $M_{H^\pm}^2$: either *(i)* μ^2 is large (this is extensively discussed by Haber as *the decoupling scenario*) [1, 4], or *(ii)* μ^2 is small, whereas $|\,\mathrm{Re}\,\lambda_5|$ is "large" [3, 4]. In the latter case, there are obvious upper bounds (from perturbativity and positivity) on how large $|\,\mathrm{Re}\,\lambda_5|$ can be.

In this model, 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,*

$$|g_i| \approx |g_i^{\rm SM}| \quad (i = W, Z, \mathit{down}, \mathit{up}). \tag{8}$$

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

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 Experimental consequences

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 ϕ_1 and ϕ_2, respectively. We denote by χ_V^h, χ_u^h and χ_d^h 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

$$\chi_u^{h_i} = \frac{1}{\sin\beta}[R_{i2} - i\gamma_5 \cos\beta R_{i3}], \qquad \chi_d^{h_i} = \frac{1}{\cos\beta}[R_{i1} - i\gamma_5 \sin\beta R_{i3}], \tag{9}$$

where R_{i3} is proportional to $\mathrm{Im}\,\lambda_5$. Note that in accordance with eq. (9), the CP violation induced by Higgs exchange in $t\bar{t}$ production [8] provides information on $\mathrm{Im}\,\lambda_5$.

Furthermore, these relative couplings satisfy a *pattern relation* [3]:

$$(\chi_u^{h_i} + \chi_d^{h_i})\chi_V^{h_i} = 1 + \chi_u^{h_i}\chi_d^{h_i}. \tag{10}$$

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

$$\chi_{H^\pm}^h \equiv -\frac{v g_{hH^+H^-}}{2M_{H^\pm}^2} = \left(1 - \frac{M_h^2}{2M_{H^\pm}^2}\right)\chi_V^h + \frac{M_h^2 - \mu^2}{2M_{H^\pm}^2}(\chi_u^h + \chi_d^h). \tag{11}$$

Thus, if $\mu^2 \sim M_{H_\pm}^2$, there is no effect in $\Gamma_{\gamma\gamma}$, whereas if $\mu^2 < M_{H_\pm}^2$ there is a difference of several %, as illustrated in Fig. 1 (left panel) for the case of Solutions A [3] (see also [9]).

These deviations from unity are large enough that the form of the 2HDM potential (large or small μ) can be tested at a $\gamma\gamma$ Collider [10].

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).

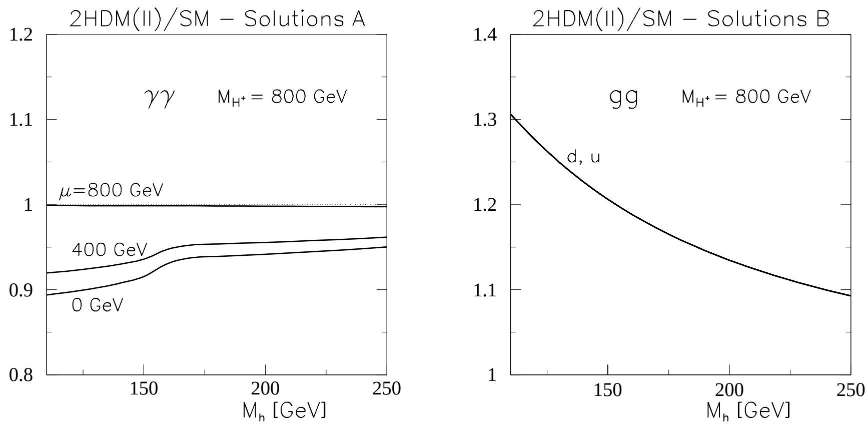

Figure 1: Ratios of the Higgs boson decay widths in the SM-like 2HDM (II) and the SM as functions of M_h for mass of charged Higgs boson equal to 800 GeV. *Left panel*: $h \to \gamma\gamma$ decay widths, solutions A, various values of μ. *Right panel*: $h \to gg$, solutions B.

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