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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 (ϕ_1, ϕ_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 $\mu^2 \sim \mathrm{Re}\, m_{12}^2$ parameter, in which case there is decoupling, we here discuss the opposite case of small μ^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]:

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

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 [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, 7]. A simple discussion can be given for this case, in which $\operatorname{Im} m_{12}^2 \neq 0$ 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

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

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 [3, 8]. It is convenient to define

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

The phase ξ can be found from the equation

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

Making use of the rephasing invariance [3, 8], we put $\xi = 0$. With this choice, eq. (4) becomes a constraint for the relation of $\operatorname{Im}(m_{12}^2)$ to $\operatorname{Im}\lambda_5$.

The neutral sector has a mass squared matrix of the form

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

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 $\operatorname{Im}\lambda_5 = 0$, there is no CP violation, the matrix (5) is block diagonal, and the physical states are h, H and A. When $\operatorname{Im}\lambda_5 \neq 0$, all three neutral Higgs states mix; we denote them by 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 for h_1, h_2 and h_3 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 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 (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 mass M_A^2 and $M_{H^\pm}^2$: either *(i)* μ^2 is large (this is extensively discussed by Haber as *the decoupling scenario*) [2, 5], or *(ii)* μ^2 is small, whereas $|\,\mathrm{Re}\,\lambda_5|$ is "large" [4, 5]. In the latter case, there are obvious upper bounds (from perturbativity and positivity) on how large $|\,\mathrm{Re}\,\lambda_5|$ 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,*

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

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

Within the Two-Higgs-Doublet Model, this scenario can be realized in two distinct ways. They are [4]:

- 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 ϕ_1 and ϕ_2, respectively. We denote by $\chi_V^{h_i}$, $\chi_u^{h_i}$ and $\chi_d^{h_i}$ 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 [10] provides information on $\mathrm{Im}\,\lambda_5$.

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

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

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 $h \to \gamma\gamma$, 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, the ratio of this coupling to its SM value can be written as

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

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 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 μ) 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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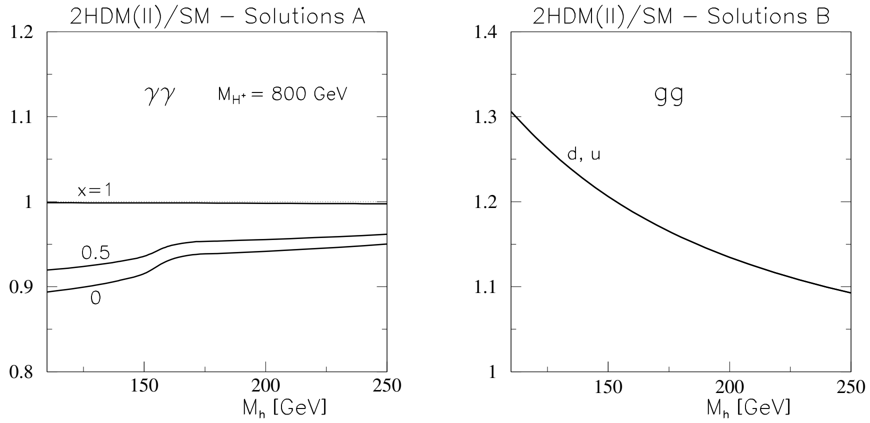

Figure 1: Ratios of the Higgs boson decay widths in the SM-like 2HDM (II) and the SM as functions of M_h. *Left panel*: $h \to \gamma\gamma$ decay widths, solutions A, for $M_{H^\pm} = 800$ GeV and $\mu/\sqrt{2} = xM_{H^\pm}$. *Right panel*: $h \to gg$, solutions B.

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