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CP violation and the H-A lineshape

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Abstract.

In two-Higgs doublet models (and particularly in the MSSM) the CP-even (H) and CP-odd (A) neutral scalars are nearly degenerate in mass, and their s-channel production would lead to nearly overlapping resonances. CP-violating effects may connect these two Higgs bosons, giving origin to one-loop particle mixing, which, due to their mass proximity, can be resonantly enhanced, altering their lineshape significantly. We show that, in general, the effect of such a CP-violating mixing cannot be mimicked by (or be re-absorbed into) a simple redefinition of the H and A masses in the context of a CP-conserving model. Specifically, the effects of the CP-mixing are such that, either the mass-splitting of the H and A bosons lies outside the range allowed by the theory in the absence of CP-mixing, and/or the detailed energy dependence of the produced lineshape is clearly different from the one obtained by redefining the masses, but not allowing any mixing.

1. Introduction

In the two-Higgs doublet models [1] and in most SUSY scenarios [2] the extended scalar sector contains five physical fields: a couple of charged Higgs bosons ($H^{\pm}$), a CP-odd scalar A, and two CP-even scalars h (the lightest, which is to be identified with the SM Higgs) and H. It is expected that their discovery and subsequenet study of their fundamental physical properties should be of central importance in the next decades. In addition to the LHC, where their primary discovery might take place, further detailed studies of their characteristics have been proposed in recent years, most notably in the context of muon-[3] and photon colliders [4].

A very characteristic feature of the the H-A system is that the masses m_H and m_A of these two particles are nearly degenerate. Specifically, their tree-level mass eigenvalues are related by [5]

$$m_H^2 = \frac{1}{2}\left[M_Z^2 + m_A^2 + \sqrt{(M_Z^2+m_A^2)^2 - 4m_A^2 M_Z^2\cos^2 2\beta}\right]\,. \tag{1}$$

In the decoupling limit, $M_A \gg M_Z$, we have that

$$m_H^2 \approx m_A^2 + M_Z^2 \sin^2 2\beta, \tag{2}$$

which, for $\tan\beta \geq 2$ (and thus $\cos^2 2\beta \approx 1$), implies that $m_H \approx m_A$. In general, the inclussion of radiative corrections is known to modify significantly the above tree-level relation, mainly due to the large Yukawa coupling of the top-quark, but does *not* lift the mass degeneracy, especially in the parameter space region where $m_A > 2M_Z$ and $\tan\beta \geq 2$ [6]. Therefore, the high-resolution scanning of the lineshape of the H-A system is expected to reveal two relatively closely spaced, or even superimposed, resonances [3].

Evidently, if the CP symmetry is exact, the H cannot mix with the A, at any given order. However, in the presence of a CP-violating interactions [7, 8] the H can mix with the A already at one-loop level, giving rise to a non-vanishing mixing self-energy $\Pi_{HA}(s)$. Such mixing, in turn, can be measured through the study of appropriate CP-odd observables, for example left-right asymmetries. As has been explained in [9] the CP-violating amplitude is particularly enhanced near resonace, if the two mixing particles are nearly degenerate, a condition which is naturally fullfilled in the H-A system. Furthermore, the mixing between H and A has an additional profound effect for the two masses: the near degeneracy of the two particles is lifted, and the pole masses move further apart [10]; as a result, the originally overlapping resonances of the CP-invariant theory tend to be separated.

In [11] we have explored the possibility of detecting the presence of CP-mixing between H and A through the detailed study of the cross-section of the s-channel process $\mu^+\mu^- \to A^*, H^* \to f\bar{f}$ as function of the center-of-mass energy. Although the lineshape is a CP-even quantity, there are certain characteristics that signal the presence of a CP-violating mixing. Due to the facts reviewed above, when studying the lineshape of the H-A system, one may envisage two, physically very different, scenarios. In the first one, the CP symmetry is exact, with the position of resonances determined by Eq.(2) plus its radiative corrections; the relative position between the two resonance will then specify $\tan\beta$. In the second scenario, CP is violated, resulting in mixing at one-loop level between CP-even and CP-odd states wich translates into a non-vanishing off-shell transition amplitude $\Pi_{HA}(s)$. Then, for the same mass splitting δm as in the previous case, one may not reach the same conclusion for the value of $\tan\beta$, because one could have started out with the two masses almost degenerate, corresponding to a different value for $\tan\beta$ (lower or higher depending on the value of the μ parameter), and the observed separation between m_H and m_A may be due to the lifting of the degeneracy produced by the presence of the aforementioned $\Pi_{HA}(s)$.

2. Results

We have studied the lineshape of the process $\mu^+\mu^- \to A^*, H^* \to f\bar{f}$, assuming the presence of CP-violating one-loop mixing between H and A, induced by the Yukawa couplings to the top and bottom squarks [8]. The kinematic regime considerd is $m_A > 2M_Z$ and $\tan\beta \geq 2$; the rotation angle of the scalar top and bottom quarks are equal to $\pi/4$, and we assume universal squarks soft masses ($\tilde{M}_Q = \tilde{M}_t = \tilde{M}_b = M_0 = 0.5$ TeV) and trilinear couplings ($A_t = A_b = A$ with $|A| = 1$). Finally $m_{H^\pm}$ has been fixed at the value of 0.4571 TeV.

The result of our analysis may be summarized as follows [11]: In the cases when the CP-breaking phases are sizeable ($\phi = 90°$, not shown), one can always clearly distinguish between the CP-invariant and CP-beaking scenarios, either because the mass splitting in the latter case is just too big for being due to CP-invariant radiative corrections only, or because of the different energy dependence of the cross section. For smaller values of the CP-breaking phases (say $\phi = 30°$, see Fig.1), one can still distinguish between the CP-invariant and CP-breaking case only when $\tan\beta$ is small; when $\tan\beta > 10$ one cannot tell the two cases apart simply by studying the lineshape. Thus, in general we conclude that either the mass-splitting of the H and A Higgs boson, in a CP-mixing scenario, cannot be accounted for in absence of CP-mixing, and/or the detailed energy dependence of the line-shape allows to discriminate between both scenarios.

We therefore believe that the experimental determination of the H-A line-shape, in conjunction with CP-odd asymmetries and other suitable observables, may provide valuable information for settling the issue regarding CP-mixing effects in two-Higgs doublet models. It would be interesting to extend this analysis to the more complicated case of the LHC, taking into account the variable gluon virtualities, in the spirit of [12].

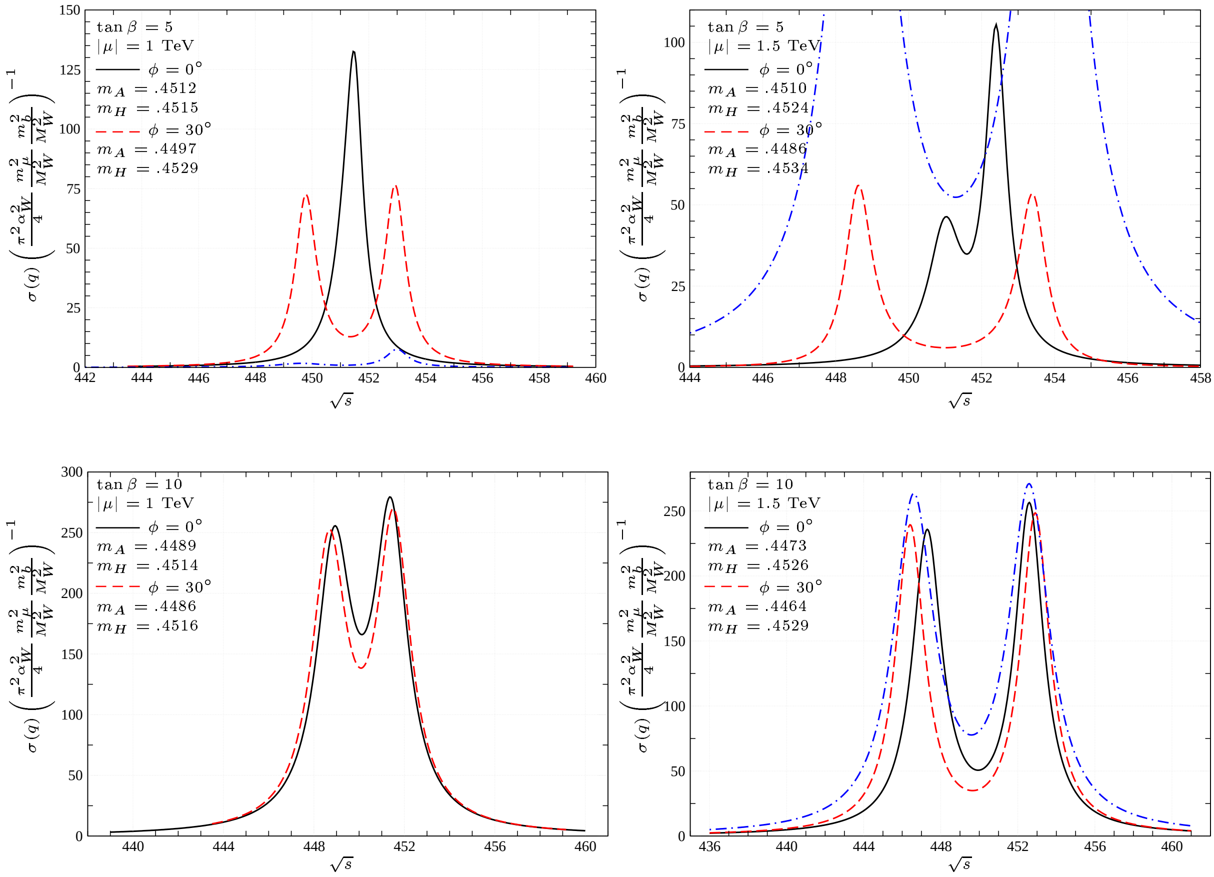

Figure 1. *The H-A lineshape for different values of $|\mu|$, $\tan\beta$ and ϕ. The black continuous curves correspond to the CP-invariant limit of the theory ($\phi = 0°$), the red dashed to the case where CP-breaking phases have been switched on (with $\phi = 30°$). Finally, the dashed-dotted blue curve, when present, corresponds to the CP-invariant limit of the theory re-calculated for a different value of $\tan\beta$ to accommodate the mass-splitting observed in the CP-breaking case.*

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References

[1] T. D. Lee, Phys. Rev. D **8**, 1226 (1973); G. C. Branco and M. N. Rebelo, Phys. Lett. B **160**, 117 (1985); J. Liu and L. Wolfenstein, Nucl. Phys. B **289**, 1 (1987); S. Weinberg, Phys. Rev. D **42**, 860 (1990).
[2] H. P. Nilles, Phys. Rept. **110** (1984) 1; H. E. Haber and G. L. Kane, Phys. Rept. **117** (1985) 75.
[3] V. D. Barger, M. S. Berger, J. F. Gunion and T. Han, Phys. Rept. **286**, 1 (1997).
[4] I. F. Ginzburg, M. Krawczyk and P. Osland, arXiv:hep-ph/0101331; S. Y. Choi, J. Kalinowski, Y. Liao and P. M. Zerwas, Eur. Phys. J. C **40**, 555 (2005).
[5] H. E. Haber, arXiv:hep-ph/9707213.
[6] See, *e.g.*, G.L. Kane, C. Kolda, L. Roszkowski and J.D. Wells, Phys. Rev. **D49**, 6173 (1994).
[7] J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez and J. W. F. Valle, Phys. Lett. B **187**, 303 (1987); J. Bernabeu, J. G. Korner, A. Pilaftsis and K. Schilcher, Phys. Rev. Lett. **71**, 2695 (1993).
[8] A. Pilaftsis, Phys. Lett. B **435**, 88 (1998)
[9] A. Pilaftsis, Nucl. Phys. B **504**, 61 (1997).
[10] M. Carena, J. R. Ellis, A. Pilaftsis and C. E. Wagner, Nucl. Phys. B **625**, 345 (2002).
[11] J. Bernabeu, D. Binosi and J. Papavassiliou, JHEP **0609**, 023 (2006).
[12] R. M. Godbole, D. J. Miller and M. M. Muhlleitner, arXiv:0708.0458 [hep-ph].

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