RESONANT CP VIOLATION IN HIGGS PRODUCTION,
MIXING AND DECAY

APOSTOLOS PILAFTSIS
Max-Planck-Institute für Physik, Föhringer Ring 6, 80805 Munich, Germany

ABSTRACT

CP violation induced by resonant transitions of a scalar to a pseudoscalar intermediate state is analyzed within a gauge-invariant resummation approach based on the pinch technique. Necessary conditions governing the resonant enhancement of CP violation in transition amplitudes are derived. The results of this study are then applied to describe the indirect mixing of a CP-even Higgs scalar, $H$, with a CP-odd Higgs particle, $A$, in two-Higgs doublet models. CP violation through $HA$ mixing in high-energy $pp$, $e^+e^-$ and $\mu^+\mu^-$ scatterings are estimated to be very large for a natural choice of kinematic parameters. Low-energy constraints originating from experimental upper bounds on the neutron electric dipole model are implemented in this analysis.

1. Introduction

CP asymmetries induced by finite widths of unstable particles have received much attention over the last few years. In many new-physics scenarios of the Standard Model (SM) with extended fermionic and/or Higgs sector, CP-violating effects may arise from the interference of the top-quark width with that of a new up-type quark $t'$ or from interference width effects between the $W$ boson and a new $H^+$ scalar in the partially integrated top decay rate.

Recently, resonant CP-violating transitions of a CP-even Higgs scalar, $H$, into a CP-odd Higgs particle, $A$, are studied within the context of two-Higgs doublet models. The size of CP violation has been estimated to be fairly large, i.e., of order one for some choice of kinematic parameters. Here, we shall show that these CP-violating phenomena have dynamical features very similar to those of the $K^0\bar{K}^0$ system.

The talk is organized as follows: We first derive the necessary conditions for resonantly enhanced CP violation and so demonstrate explicitly that this CP violation induced by $HA$ mixing has common features with the CP-violating phenomenon through indirect mixing in the kaon system in Section 2. Bounds from electric dipole moments (EDM’s) of the neutron and electron are discussed in Section 3. In Section 4, models with non-vanishing $HA$ mixing are considered and the physics potential

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to observe resonant CP violation through such a mixing at future $pp$, $e^+e^-$ or $\mu^+\mu^-$
machines is briefly discussed. Our conclusions are drawn in Section 5.

2. Necessary conditions for resonant CP violation

To deduce the necessary conditions under which CP violation can be resonantly
enhanced in the $HA$ system, we shall perform our analysis in a $K^0\bar{K}^0$-like basis. To
this end, the relation between the $K^0\bar{K}^0$ and $HA$ bases may be given by the following
transformations:

$$iA = \frac{1}{\sqrt{2}} (K^0 - \bar{K}^0),$$
$$H = \frac{1}{\sqrt{2}} (K^0 + \bar{K}^0),$$

(1)

where $\bar{K}^0$ is the Hermitian and CP-conjugate state of $K^0$. Expressing the effective
Hamiltonian $\mathcal{H}(s)$ in the $K^0\bar{K}^0$ basis, we get

$$(K^{0*}, \bar{K}^{0*}) \mathcal{H} \left( \begin{array}{c} K^0 \\ \bar{K}^0 \end{array} \right) =$$

$$\frac{1}{2} \left[ \begin{array}{cc} M_H^2 + M_A^2 - \hat{\Pi}^{HH} - \hat{\Pi}^{AA} & M_H^2 - M_A^2 - \hat{\Pi}^{HH} + \hat{\Pi}^{AA} + 2i\hat{\Pi}^{AH} \\ M_H^2 - M_A^2 - \hat{\Pi}^{HH} + \hat{\Pi}^{AA} - 2i\hat{\Pi}^{AH} & M_H^2 + M_A^2 - \hat{\Pi}^{HH} - \hat{\Pi}^{AA} \end{array} \right],$$

(2)

where the hat on the $HH$, $AA$ and $HA$ self-energies has two meanings. First, it
denotes that the diagonal self-energies are renormalized in some natural scheme, e.g.,
on-shell renormalization scheme, whereas the CP-violating $HA$ vacuum amplitudes
are ultra-violet (UV) finite in our models and do not require renormalization. Second,
the symbol hat indicates that the self-energies are evaluated within a gauge-invariant
resummation based on the PT. It is now easy to observe that $\tilde{\mathcal{H}}$ in Eq. (2) possesses
all known properties of the kaon system. In particular, CPT demands

$$\tilde{\mathcal{H}}_{11}(s) = \tilde{\mathcal{H}}_{22}(s),$$

(3)

which is valid in Eq. (2), while CP invariance is reassured only if

$$\tilde{\mathcal{H}}_{12}(s) = \tilde{\mathcal{H}}_{21}(s).$$

(4)

The latter can only be true if $\hat{\Pi}^{AH}(s) = 0$. Consequently, the presence of a non-zero
$HA$ mixing leads to CP violation in the effective Hamiltonian $\tilde{\mathcal{H}}(s)$. In particular, it
is known that the basic parameter measuring CP violation through indirect mixing
in the kaon system is given by

$$\left| \frac{q}{p} \right|^2 = \left| \frac{\mathcal{H}_{21}}{\mathcal{H}_{12}} \right|^2 = \left\{ \frac{[M_H^2 - M_A^2 - 2\Im(\hat{\Pi}^{HA})]^2 + [\Im(\hat{\Pi}^{HH} - \hat{\Pi}^{AA}) + 2\Re(\hat{\Pi}^{HA})]^2}{[M_H^2 - M_A^2 + 2\Im(\hat{\Pi}^{HA})]^2 + [\Im(\hat{\Pi}^{HH} - \hat{\Pi}^{AA}) - 2\Re(\hat{\Pi}^{HA})]^2} \right\}^{1/2}. $$

(5)
It will prove useful to consider the following two cases:

(i) The HA mixing occurs at the tree level or is induced radiatively after integrating out heavy degrees of freedom, i.e., $\Re\hat{\Pi}^{HA} \neq 0$ and it is UV safe. We also assume $\Im m\hat{\Pi}^{HA} = 0$. Then, for $M_H \approx M_A$, the CP-violating mixing parameter behaves as

$$\left| \frac{q}{p} \right|^2 \sim \left| \frac{\Im m(\hat{\Pi}^{HH} - \hat{\Pi}^{AA}) + 2\Re \hat{\Pi}^{HA}}{\Im m(\hat{\Pi}^{HH} - \hat{\Pi}^{AA}) - 2\Re \hat{\Pi}^{HA}} \right|.$$  

Clearly, for $\Im m(\hat{\Pi}^{HH} - \hat{\Pi}^{AA}) \sim \pm \frac{1}{2} \Re \hat{\Pi}^{HA}$,

$$\left| \frac{q}{p} \right| \text{ takes either very small or very large values, yielding resonant enhancement of CP violation.}$$

(ii) Another interesting case arises when $\Im m\hat{\Pi}^{HA} \neq 0$ and $\Re\hat{\Pi}^{HA} = 0$. For small width differences, $\Im m\hat{\Pi}^{HH} \approx \Im m\hat{\Pi}^{AA}$, we have

$$\left| \frac{q}{p} \right|^2 \sim \left| \frac{M_H^2 - M_A^2 - 2\Im m\hat{\Pi}^{HA}}{M_H^2 - M_A^2 + 2\Im m\hat{\Pi}^{HA}} \right|,$$

giving rise to the condition for resonant CP violation

$$M_H^2 - M_A^2 \sim \pm \frac{1}{2} \Im m\hat{\Pi}^{HA}.$$  

It is now important to remark that for maximal CP violation, i.e., of order unity, $|q/p|$ should either vanish or tend to infinity. This implies that either $\hat{H}_{12} = 0$ or $\hat{H}_{21} = 0$, but not both. This limiting case reflects the fact that the two (no-free) particles, $H$ and $A$, are exactly degenerate, i.e., $\Gamma_H = \Gamma_A$ and $\Gamma_H = \Gamma_A$, where $\Gamma_{H,A}^2 - i\Gamma_{H,A}\Gamma_{H,A}$ are the two complex pole-mass eigenvalues of the effective Hamiltonian $\hat{H}(s)$ in Eq. (2).

3. Constraints from electric dipole moments

The presence of a HA operator may also contribute to other low-energy CP-violating observables. CP-violating quantities sensitive to HA terms is the EDM of the neutron and the electron. The one-loop contribution of the HA mixing to the EDM may be estimated by

$$d_q/e \approx -Q_q \frac{\alpha_w}{4\pi} \frac{m_f}{M^2} \frac{m_f^2}{M_W^2} \xi_{HA} \ln \left( \frac{m_f^2}{M^2} \right),$$

with $M = (M_H + M_A)/2$, $Q_q$ denoting the fractional charge of the quark

$$\xi_{HA} = \chi_A^{\dagger} \chi_H \frac{\hat{\Pi}^{HA}(M^2)}{M^2}.$$
The experimental upper bound on the EDM of the neutron is \( (d_n/e) < 1.1 \times 10^{-25} \) cm, at 95% of confidence level (CL). However, taking the typical values of \( m_d = 10 \) MeV and \( M_W \approx M \approx 100 \) GeV, Eq. (11) gives \( (d_n/e) < 3.1 \times 10^{-30} \) cm, far beyond the above experimental bound. The prediction for the EDM of electron is less restrictive. On the other hand, the two-loop Barr-Zee (BZ) mechanism shown in Fig. 1 may have a significant contribution to the EDM, leading to tighter bounds on the HA mixing parameter \( \xi_{HA} \). In general, the theoretic prediction for the EDM is enhanced by a factor \( \alpha_{em}(M_W^2/m_d^2) \approx 10^6 \), with \( \alpha_{em} = 1/137 \). A recent analysis of constraints from the electron and neutron EDM’s may be found in Ref. 11 for the two-Higgs doublet model with maximal CP violation, in which the Weinberg’s unitarity bound is almost saturated. The authors find that the bounds on the neutron EDM may be evaded if the mass difference, \( \Delta M \), between \( A \) and \( H \) is sufficiently small, viz.

\[
\frac{\Delta M}{M} \approx \left( \frac{\hat{\Pi}^{HA}}{M^2} \right) < 0.10, \ 0.13, \ 0.24,
\]

for \( M = 200, \ 400, \ 600 \) GeV, respectively. Since we always have \( \hat{\Pi}^{HA}/M^2 < 0.1 \) in our two-Higgs doublet models, the EDM limits in Eq. (12) are therefore satisfied. For large tan \( \beta \) values, far way from the parametric point of maximal CP violation, the above EDM limits will be much weaker. However, our resonant CP-violating phenomena through particle mixing can still be very large as soon as the necessary conditions (7) and/or (9) are fulfilled.

4. CP violation through HA mixing at high-energy colliders

The most ideal place to look for resonant CP-violating HA transitions is at \( e^+e^- \) and, most interestingly, at muon colliders. In general, there are many observables suggested at high-energy colliders that may be formed to project out different CP/T-noninvariant contributions. All the CP-violating observables, however, may fall into two categories, depending on whether they are even or odd under naive CPT transformations. Our quantitative analysis of HA mixing phenom-
ena will rely on CP-violating quantities sensitive to CP- and CPT-odd observables of the form, $\langle \vec{s}_t \vec{k}_t \rangle$ or $(\vec{s}\bar{t} \vec{k}\bar{t})$, where $\vec{s}_t$ and $\vec{k}_t$ are respectively the spin and the three-momentum of the top-quark in the $t\bar{t}$ centre of mass (c.m.) system. For definiteness, assuming that having longitudinally polarized muon beams will be feasible without much loss of luminosity, we shall consider the CP asymmetry:

$$A_{CP}^{(\mu)} = \frac{\sigma(\mu_L^+ \mu_L^- \to f\bar{f}) - \sigma(\mu_R^+ \mu_R^- \to f\bar{f})}{\sigma(\mu_L^+ \mu_L^- \to f\bar{f}) + \sigma(\mu_R^+ \mu_R^- \to f\bar{f})}.$$  \hspace{1cm} (13)

If one is able to tag on the final fermion pair $f\bar{f}$ (e.g., $\tau^+\tau^-$, $b\bar{b}$, or $t\bar{t}$), $A_{CP}^{(\mu)}$ is then a genuine observable of CP violation, because the helicity states $\mu_L^+ \mu_L^-$ transform into $\mu_R^+ \mu_R^-$ under CP in the c.m. system. Similarly, at $e^+e^-$ or $p\bar{p}$ machines, one can define the CP asymmetry:

$$A_{CP}^{(e)} = \frac{\sigma(e^- e^+ \to f_Lf_L X) - \sigma(e^- e^+ \to f_Rf_R X)}{\sigma(e^- e^+ \to f_Lf_L X) + \sigma(e^- e^+ \to f_Rf_R X)},$$  \hspace{1cm} (14)

and an analogous observable $A_{CP}^{(p)}$. In Eq. (14), the chirality of fermions, such as the top quark, may not be directly observed. However, the decay characteristics of a left-handed top quark differ substantially from those of its right-handed component, giving rise to distinct angular-momentum distributions and energy asymmetries of the produced charged leptons and jets.

A CP-conserving two-Higgs doublet model predicts three physical Higgs scalars, from which two are CP even and one is CP odd. To break the CP invariance of the Higgs sector, one may have to introduce soft D-symmetry breaking terms in the Higgs potential, which violate CP as well. In this way, one does not spoil the desirable property of the imposed D symmetry, i.e., flavour-changing neutral currents are induced beyond tree level. Another alternative is to break CP invariance radiatively after integrating out heavy degrees of freedom which do not respect CP. As such, one may think of heavy Majorana fermions, such as heavy Majorana neutrinos or neutralinos in supersymmetric models. Here, we adopt the former realization and fix the three heavy neutrino masses to be $m_1 = 0.5$ TeV, $m_2 = 1$ TeV and $m_3 = 1.5$ TeV. In the two-Higgs doublet model with broken D symmetry, the tree-level $HA$ or $hA$ mixings, $\Pi^{HA}$ and $\Pi^{hA}$, are considered to be small phenomenological parameters in compliance with the constraint of Eq. (12). For the top quark mass, we use $m_t = 170$ GeV close to its experimental mean value.

For simplicity, we shall assume that only one CP-even Higgs particle, $H$ say, has a mass quite close to $A$, i.e., $M_H - M_A \ll M_H, M_A$, while the other CP-even Higgs, $h$, is much lighter than $H, A$, and vice versa. Clearly, $h$ will effectively decouple from the mixing system, having negligible contributions to both cross section and CP asymmetry at c.m. energies $s \approx M_H, M_A$. This is also the main reason accounting for the fact that CP violation through $HZ (G^0H)$ mixing has been found to be small as
only couples to the longitudinal component of the $Z$ boson, the massless would-be Goldstone $G^0$. To give an estimate, in the two-Higgs model with heavy Majorana neutrinos, we find that $\mathcal{A}_{\text{CP}}^{(\mu)} \approx 2 \times 10^{-2}$ for $M_H = 500$ GeV, while the production cross-section is $\sigma \approx 1$ fb. It is therefore unlikely to observe $HZ$-mixing effects, even if one assumes a high integrated luminosity of 50 fb$^{-1}$, designed for $e^+e^-$ and $\mu^+\mu^-$ colliders. For our illustrations, we also take the ratio of the vacuum expectation values of the two Higgs doublets $\tan \beta = 2$ and $\tan \theta = 1$, which relates the weak with the mass eigenstates for the CP-conserving Higgs particles, $H$ and $h$. In this scheme, the heaviest CP-even Higgs, $H$, has a significant coupling to fermions, whereas the squared of the $HWW$- and $HZZ$-couplings has strength 1/10 of that of the respective SM couplings. For $M_A > 2M_Z$, such a scheme is motivated by the MSSM and leads to nearly degenerate $H$ and $A$ scalars, i.e., $M_H \approx M_A$. Nevertheless, we shall not consider here that $M_H$ is very strongly correlated with $M_A$.

We shall now focus our attention on the resonant transition amplitudes $\mu_L^+\mu_L^- \rightarrow H^*, A^* \rightarrow f \bar{f}$. A straightforward calculation of the CP asymmetry gives

$$\mathcal{A}_{\text{CP}}^{(\mu)}(s) \approx \frac{2 \hat{\Pi}^{AH} (\beta_f \Im(\hat{\Pi}^{AA}) - \Im(\hat{\Pi}^{HH}))}{\beta_f [(s - M_A^2)^2 + (\Im(\hat{\Pi}^{AA}))^2] + (s - M_H^2)^2 + (\Im(\hat{\Pi}^{HH}))^2},$$

where $\beta_f = (1 - 4m_f^2/s)$ with $r_f = \lambda_1 f / \chi_A^f$. The analytic result of $\mathcal{A}_{\text{CP}}^{(\mu)}(s)$ in Eq. (15) reduces to the qualitative estimate presented in Ref. [4], if finite mass effects of the asymptotic states are neglected. Refinements of including high-order $(\hat{\Pi}^{AH})^2$ terms in the CP-conserving part of the CP asymmetry and other model-dependent details inherent to the two-Higgs doublet model may be found in Ref. [5].

Assuming that tuning the collider c.m. energy to the mass of $H$ or $h$ is possible, i.e., $\sqrt{s} = M_H$ or $M_h$, we analyze the following two reactions:

(a) $\mu_L^+\mu_L^- \rightarrow h^*, A^* \rightarrow b \bar{b}$, with $M_A = 170$ GeV,

(b) $\mu_L^+\mu_L^- \rightarrow H^*, A^* \rightarrow t \bar{t}$, with $M_A = 400$ GeV.

As has been discussed in Section 2, CP violation becomes maximal when the necessary condition (1) for $M_H \approx M_A$ is met. In Fig. 2(a), we show how $|A_{\text{CP}}|$ varies as a function of the parameter $x_A = \Im(\hat{\Pi}^{HA})/\Im(\hat{\Pi}^{HH} - \hat{\Pi}^{AA})$ or $\Im(\hat{\Pi}^{hA})/\Im(\hat{\Pi}^{HH} - \hat{\Pi}^{AA})$. We consider the kinematic region for resonantly enhanced CP violation, i.e., $M_A = M_h$ ($M_H$) for the reaction (a) (reaction (b)). We find that CP-violating effects could become very large, if the parameter $x_A$ was tuned to the value $x_A = 1$ for the process (a) and $x_A = 3$ for the process (b).

At future next linear $e^+e^-$ colliders (NLC), Higgs bosons can copiously be produced either via the Bjorken process for c.m. energies up to 0.5 TeV or through $WW$ fusion at higher energies. The most convenient way is to study CP violation in the kinematic range of the Higgs production and decay Therefore, we shall be
interested in the observable
\[ \mathcal{A}_{CP}(s) = \frac{d\sigma(e^- e^+ \to f_L \bar{f}_L X)/d\hat{s}}{d\sigma(e^- e^+ \to f_R \bar{f}_R X)/d\hat{s}} - \frac{d\sigma(e^- e^+ \to f_R \bar{f}_R X)/d\hat{s}}{d\sigma(e^- e^+ \to f_L \bar{f}_L X)/d\hat{s}}, \]  
where \( \hat{s} \) is the invariant mass energy of the produced final fermions \( f \). As final states,
we may take bottom or top quarks. Since $A$ does not couple to $WW$ or $ZZ$, the CP asymmetry $A_{CP}^{(e)}$ in Eq. (16) takes the simple form

$$A_{CP}^{(e)} \approx - \frac{2\hat{\Pi}^{AH}(\hat{s}) \Im m\hat{\Pi}^{AA}(\hat{s})}{(\hat{s} - M_A^2)^2 + (\Im m\hat{\Pi}^{AA}(\hat{s}))^2 + (\hat{\Pi}^{AH}(\hat{s}))^2}. \quad (17)$$

Since the destructive term, $\Im m\hat{\Pi}^{HH}$, is absent in Eq. (17), CP violation may become even larger, i.e., of order unity for specific values of the parameter $x_A$. Indeed, we see from Fig. 2(b) that $A^{(e)} \approx 1$, if $x_A = 0.07 \ (3)$ for the reaction with longitudinally polarized $b \ (t)$ quarks in the final state. In Ref. it has been estimated numerically that $A_{CP}^{(e)} < 15\%$ for Higgs masses $M_H < 600 \text{ GeV}$ and cross sections $\sigma(e^-e^+ \rightarrow H^*(h^*), A^* \rightarrow t\bar{t}X) \approx 10 - 100 \text{ fb}$ for c.m. energy of 2 TeV. Such CP-violating effects have good chances to be detected at the NLC.

At the LHC, the respective CP asymmetry $A_{CP}^{(p)}(\hat{s})$ may be obtained from Eq. (17), for Higgs particles that have a production mechanism similar to that at the NLC. If the Higgs is produced via gluon fusion, one has to use the analytic expression of $A_{CP}^{(p)}(\hat{s})$ in Eq. (15). Unless CP violation is resonantly amplified, i.e., of order one, the chances to detect CP-violating phenomena on the Higgs-resonance line after removing the contributing background appear to be quite limited at the LHC. It is therefore worth stressing that a large CP-violating signal at the Higgs-boson peak will certainly point towards the existence of an almost degenerate $H_A$ mixing system.

5. Conclusions

CP-violating phenomena can be significantly enhanced through the mixing of two resonant particles that behave differently under CP. In particular, the underlying mechanism for large CP violation induced by resonant $H_A$ transitions has been studied carefully on a rigorous field-theoretic basis and its connection with the $K^0\bar{K}^0$ system has been clarified in Section 2. Possible constraints resulting from experimental bounds on the neutron EDM are briefly discussed in Section 3. In Section 4, the size of CP-violation in the production, mixing and decay of a Higgs particle at planned high-energy machines, such as the LHC, NLC and/or muon collider, has been estimated. Since high order $\varepsilon'$-type effects are generally suppressed near the resonant region, possible large CP-violating phenomena can naturally be accounted for by the mixing mechanism presented in this talk.

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