CP violation of Extended Higgs sector and Its impact on

\[ D^0 \to \mu^+\mu^- \text{ decay} \]

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Abstract

We study the impact of the CP violation of the extra Higgs sector on \(D^0\) decay. The CP even and CP odd neutral Higgs mixing of the two Higgs doublet model is studied and we show how the CP violating effect of the mixing may lead to the longitudinal muon polarization asymmetry of \(D^0 \to \mu^+\mu^-\). The asymmetry of the short-distance contribution is sensitive to the CP violating phase of the extended Higgs sector.
Higgs sector is currently investigated by LHC. In this talk, we study the extended Higgs sector which may solve one of the questions of the origin of the flavor. In the standard model, all the masses of the quarks and leptons come from a single vacuum expectation value of Higgs, \( m_q = y_q v, m_l = y_l v \). In the extended Higgs sector with two Higgs doublets, the mass hierarchy of the 3rd generation comes from the ratio of the two vacuum expectation values of the two Higgs doublets. In Ref.\[1\], the origin of the large weak isospin breaking is explained in the context of the two Higgs doublet model. In this case, the extra Higgs which couples with the bottom quark and tau lepton has a small vacuum expectation value. The strength of the Yukawa coupling of the Higgs to down type quarks and charged leptons is much larger than the corresponding couplings of the standard model Higgs. One may probe the large strength of the Yukawa couplings of the extra Higgs by using the bottom quark and \( \tau \) lepton system.

I. TWO HIGGS DOUBLET MODEL WITH LARGE \( \tan \beta \)

In the scenario, the origin of the mass hierarchy of the bottom quark, top quark, and \( \tau \) lepton is the ratio of the vacuum expectation values of the two Higgs doublets. In contrast to the standard model where the hierarchical Yukawa couplings to bottom and top quarks are assumed, the Yukawa coupling of the bottom quark to the extra Higgs is the same order as that of the top quark in the scenario \[1\]. With the large ratio of the vacuum expectation values \( \tan \beta = \frac{v_2}{v_1} \approx 40 \), the ratio of the Yukawa couplings becomes,

\[
\frac{y_b v_1}{y_t v_2} = \frac{m_b}{m_t} \rightarrow \frac{y_b}{y_t} = \frac{m_b}{m_t} \tan \beta = 1.
\]

The strength of Yukawa couplings of the extra Higgs \( (\Phi_1) \) to bottom quark and \( \tau \) lepton are much larger than that of the standard model Higgs,

\[
y_b = 3y_\tau \simeq y_t \text{ SM}.
\]

The large strength of Yukawa couplings implies the bottom quark and tau lepton probe the extended Higgs sector. One can write the Yukawa couplings explicitly as\[2\],

\[
\mathcal{L}_Y = \frac{H_2}{v} \left[ \tan \beta (\bar{e}_i \gamma_5 e^{-i\gamma^\theta A_H} m_i \bar{e}_i + \bar{d}_i \gamma_5 e^{-i\gamma^\theta A_H} m_i \bar{d}_i) \right] \\
+ \frac{H_3}{v} \left[ \tan \beta (\bar{e}_i e^{-i\gamma^\theta A_H} m_i \bar{e}_i + \bar{d}_i e^{-i\gamma^\theta A_H} m_i \bar{d}_i) \right].
\]

(3)
One can see $\tan \beta$ enhancement of the Yukawa couplings.

A. Higgs potential leading to large $\tan \beta$ with CP violation

In the two Higgs doublet model with the softly broken $Z_2$ symmetry, the Higgs potential can naturally lead to the large $\tan \beta$, as shown in [1]. There the smaller Higgs vacuum expectation value is proportional to the mass parameter of the softly broken $Z_2$ symmetry,

$$\Phi_1 \to -\Phi_1, \Phi_2 \to \Phi_2.$$ 

The source of CP violation of the Higgs sector is a quartic coupling and the Higgs potential is given in [2],

$$V_{\text{tree}} = \sum_{i=1,2} \left( m_i^2 \Phi_i^\dagger \Phi_i + \frac{\lambda_i}{2} (\Phi_i^\dagger \Phi_i)^2 \right) - m_3^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2} \lambda_5 [e^{i\theta_5} (\Phi_2^\dagger \Phi_1)^2 + e^{-i\theta_5} (\Phi_1^\dagger \Phi_2)^2].$$

where $m_3^2$ is the soft breaking parameter for $Z_2$ symmetry. The origin of the CP violation of the vacuum expectation value of Higgs is a CP violating phase $\theta_5$ of the Higgs potential. The vacuum expectation values of the Higgs can be parameterized by the three order parameters.

$$\langle \Phi_1 \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \cos \beta \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin \beta \end{pmatrix} e^{-i\theta_5}.$$ 

(4)

When $\tan \beta$ is very large, the Higgs fields can be written as,

$$\Phi_1 = -\sin \beta \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix} + \cos \beta \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix},$$

$$\tilde{\Phi}_2 = e^{i\theta_5} \begin{pmatrix} \sin \beta \left( \frac{v+h}{\sqrt{2}} \right) \\ 0 \end{pmatrix} + \cos \beta \begin{pmatrix} \frac{H-iA}{\sqrt{2}} \\ -H^- \end{pmatrix},$$

where CP eigenstates of the neutral Higgs $(H, A)$ are not mass eigenstates and are related to the mass eigenstates $(H_2, H_3)$ as,

$$H = \cos \theta_{AH} H_3 + \sin \theta_{AH} H_2,$$

$$A = \cos \theta_{AH} H_2 - \sin \theta_{AH} H_3.$$ 

(5)
The mixing angle ($\theta_{AH}$) of CP even (H) and CP odd (A) Higgs bosons becomes,

$$\theta_{AH} = \theta_5 + \frac{\theta'}{2},$$
$$= \arctan \left[ \frac{M_{H_3}^2}{M_{H_2}^2} \tan \frac{\theta_5}{2} \right]. \quad (6)$$

For the fixed ratio of the masses of the two eigenstates, the mixing angle $\theta_{AH}$ can be large. For details, see figure.12 of [2].

II. IMPACT OF CP VIOLATION OF THE NEUTRAL HIGGS SECTOR ON RARE $D^0$ DECAY

In this section, we argue how the CP violation of the neutral Higgs boson may have some impact on a $D^0$ decay. At first sight, the impact of CP violation of the neutral Higgs on $D^0$ decays is small and is not relevant, since the neutral Higgs bosons with the small vacuum expectation value is coupled to the down quark and charged lepton. The coupling to the up quark sector is suppressed. However in $D^0$ FCNC decay such as $D^0 \rightarrow \mu^+\mu^-$, the situation is different from the expectation. In the tree level Feynman diagram, the FCNC $D^0$ decay is forbidden, since this model respects condition for the natural flavor conservation. Therefore the decay occurs through one loop diagrams where the down type quarks in the loop diagrams contribute to the process, as shown in Fig.1. Since the down quarks and the extra neutral Higgs couplings are large, one may expect that there is large contribution due to the new physics interaction.

The decay amplitudes of $D^0 \rightarrow \mu^+\mu^-$ can be generically parameterized as,

$$M(D^0 \rightarrow \mu^+\mu^-) \sim (a\bar{u}\gamma_5 v + i\bar{b}u\bar{v}).$$
The longitudinal muon polarization asymmetry can be written as,

\[ P_L = \frac{2\text{Im}(ab^*)}{|a|^2 + |b|^2(1 - \frac{4m_\mu^2}{M_D^2})}. \] (7)

In the present model, the amplitudes \(a\) and \(b\) are given as,

\[ a = \frac{m_b^2}{4s_W^2M_W^2}m_\mu \left[ 1 + \frac{V_{cs}V_{us}m_s^2}{V_{cb}V_{ub}m_b^2}e^{i\phi_3} \right. \]

\[- \left. \frac{i}{2} \left\{ \left( \frac{M_W^2}{M_2^2} + \frac{M_2^2}{M_3^2} \right) + e^{2i\theta_{AH}} \left( \frac{M_W^2}{M_2^2} - \frac{M_2^2}{M_3^2} \right) \right\} \right], \]

\[ b = -\frac{m_b^2}{4s_W^2M_W^2}m_\mu \left[ \left( \frac{M_W^2}{M_2^2} + \frac{M_2^2}{M_3^2} \right) - e^{2i\theta_{AH}} \left( \frac{M_W^2}{M_2^2} - \frac{M_2^2}{M_3^2} \right) \right]. \] (8)

where \( r = \frac{M_3^2}{M_4^2} \tan^2 \beta \log \frac{M_4^2}{M_3^2}. \) The terms proportional to \( r \) are new physics contribution. In the standard model, only a pseudoscalar term denoted by the term proportional to \( a \) is generated and it leads to vanishing asymmetry for \( P_L \). In the present model, through the short distance contribution due to the neutral Higgs exchange diagrams, there appears the large longitudinal polarization asymmetry \( P_L \). If we ignore the contribution from the standard model, the asymmetry is approximately given as,

\[ P_L \approx -\log \frac{M_{H^+}^2}{M_W^2} \tan^2 \beta \sin 2\theta_{AH} \left( \frac{M_D^2}{M_2^2} - \frac{M_D^2}{M_3^2} \right). \] (9)

The asymmetry is proportional to the neutral Higgs mixing \( \theta_{AH} \). Therefore by measuring the asymmetry, one may obtain the CP even and CP odd mixing angle. In contrast to the case discussed, when there is no mixing between CP even (H) and CP odd Higgs (A), then the CP odd Higgs generates the pseudoscalar term \( a \) and CP even Higgs generates the scalar term \( b \). In this case, the asymmetry vanishes. If two neutral Higgs bosons are mixed in their mass eigenstates, \( a \) and \( b \) depend on the mixing angle of neutral Higgs and the muon polarization asymmetry \( P_L \) is sensitive to the CP violating mixing angle of Higgs. In Fig.2 we showed the asymmetry \( P_L \) as a function of the mixing angle of CP even and CP odd states.

### III. CONCLUSION AND DISCUSSION

We study the CP violation of the two Higgs doublet model. CP violation of the Higgs potential leads to the mixings of CP even and CP odd Higgs. The Yukawa couplings of
FIG. 2: The muon longitudinal asymmetry for $D^0 \to \mu^+\mu^-$ of the two Higgs doublet model. The asymmetry is shown as a function of CP odd and CP even Higgs mixing angle $\theta_{AH}$. We assume the charged Higgs mass is 500 (GeV). We show the case for $M_{H_2} > M_{H_3}$ and we take, $(M_{H_2}, M_{H_3}) = (200, 400)$ (solid line) and $(300, 600)$ (dashed line).

down quarks and charged leptons with the neutral Higgs of the second doublet are large and are CP violating. The longitudinal muon polarizability $P_L$ of $D^0 \to \mu^+\mu^-$ is sensitive to CP even and CP odd Higgs mixing of the two Higgs doublet model with large $\tan \beta$. We have estimated the short-distance part of the new physics effect. The additional contribution together with the standard model Z penguin contribution leads to the non-zero asymmetry $P_L$. For more serious estimate, we must include the long-distance contribution from the amplitude $D^0 \to \gamma^*\gamma^* \to \mu^+\mu^-$. The estimate of the branching fraction from this amplitude is studied in [3] and it can dominate over the short distance contribution.

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