

## HIGGS PHYSICS AND CP VIOLATION

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The CP violation in  $K$  and  $B$  decays are discussed with the emphasize on the precise prediction for  $\epsilon'/\epsilon$  and the new physics effects from a class of models with additional Higgs doublets and fermions. The contributions from standard model with two-Higgs-doublet (S2HDM) to  $K$ ,  $B$  mixing and decays are briefly reviewed. The possible large effects on CP violation in  $B \rightarrow \phi K$  is discussed in an extended standard model with both an additional Higgs doublet and fourth generation quarks (S2HDM4). We show that although the S2HDM and the Standard model with fourth generation quarks *alone* are not likely to largely change the effective  $\sin 2\beta$  from the decay of  $B \rightarrow \phi K_S$ , the S2HDM4 model can easily account for the possible large deviation of  $\sin 2\beta$  without conflicting with other experimental constraints.

The origin of CP violation with the SM and beyond is currently under intense investigation. In this talk we will focus on the CP violations in hadronic  $K$  and  $B$  meson decays.

The decays  $K \rightarrow \pi\pi$  are described by a low energy effective Hamiltonian with short and long distance contributions absorbed into Wilson coefficients and matrix elements of local operators respectively. Matrix elements for two of these operators,  $Q_6$  and  $Q_8$ , are most important for the evaluation of direct CP violation parameter  $\epsilon'/\epsilon$ . The Wilson coefficients depend on scal  $\mu$  and to next-to-leading order (NLO) corrections in a more complicated way which depends also on the renormalization scheme. The main issue is the evaluation of long distance contributions. It was the first time pointed out in Ref.<sup>1</sup> that with long distance chiral-loop corrections to operator  $\langle Q_6 \rangle$ ,  $\epsilon'/\epsilon$  could reach  $\mathcal{O}(10^{-3})$ . For a consistent description to  $K \rightarrow \pi\pi$ , one needs a matching between short and long distance terms.

In the naive matching approaches<sup>2</sup> with the cut-off scale of  $M$  for matrix element being identified with short distance scale  $\mu$  at about 1 GeV, a large correction originates

from rescattering of the pions, i.e.,  $K \rightarrow \pi\pi \rightarrow \pi\pi$ , where the first step involves the weak operators  $Q_6$  or  $Q_8$  to  $\mathcal{O}(p^2/N_c)$  and the second process is the strong pion-pion scattering. The large dependence of the cut-off resides on the contact  $\pi - \pi$  scattering which is known to have a bad high-energy behaviour violating unitarity and needs to be moderated by some other amplitudes which restore unitarity. A standard prescription to restore unitarity is to introduce vector-meson exchange diagrams. For the  $\pi\pi \rightarrow \pi\pi$  scattering one shall use the contact and the  $\rho$  exchange diagrams. It can be accomplished by using a chiral Lagrangian for pseudo scalars with the introduction of vector mesons in the lowest order<sup>3</sup>. The calculation of the one-loop diagrams with a strong vertex was extended with the addition of a  $\rho$ -exchange diagram. The  $\rho$  is included to symbolically represent the effects of all other vector mesons (like  $K^*$ )<sup>4</sup>.

In order to restore unitarity it is demanded that quadratic divergences cancel between the contact and the  $\rho$ -exchange diagrams. It is indeed heartening to note that they come with opposite signs, and cancel ex-

actly if the following relation is satisfied<sup>4</sup>

$$\frac{h^2}{m_\rho^2} = \frac{1}{3F_\pi^2}. \quad (1)$$

Here  $h$  is the  $\rho\pi\pi$  coupling strength and  $F_\pi$  is the pion decay constant ( $F_\pi \approx 92\text{MeV}$ ). This relation is to be compared with the celebrated KSFR relation in which the factor is 2. The logarithmic divergences still remain and should be matched to the QCD logarithms in the region  $m_\rho$  to  $\mu \simeq 1$  GeV.

Though an exact matching to QCD needs to be checked, an improved stability of the values for  $\epsilon'/\epsilon$  was arrived in the region from  $m_\rho$  to  $\mu \simeq 1$  GeV. The main conclusion is that the presence of vector mesons improves the calculation of the matrix elements by making them more stable functions of the cut-off in the naive matching approach.

Alternatively, it has been realized that a functional matching scheme introduced in Ref.<sup>5</sup> can handle the problem and lead to an exact matching. Two important matching conditions were obtained for exactly matching chiral loop evaluation to QCD loop evaluation. A set of chiral algebraic relations were demonstrated to hold at chiral loop level. These chiral relations enable us to relate the direct CP violation  $\epsilon'/\epsilon$  with  $\Delta I = 1/2$  rule. As a consequence, the resulting predictions can lead to a consistent explanation for both  $\epsilon'/\epsilon$  and  $\Delta I = 1/2$  rule. Of particular, the results are no longer sensitive to the strange quark mass. Therefore all the large uncertainties were significantly reduced and it provided a more precise prediction for the direct CP violation  $\epsilon'/\epsilon$ .

We proceed to discuss CP violation in  $B$  decays. With the successful running of two  $B$  factories in KEK and SLAC, precise measurements of the time-dependent CP asymmetries as well as the directly CP asymmetries in rare  $B$  decays become available. However, the recent Belle results on  $\sin 2\beta$  from  $B \rightarrow \phi K_S$ , although with significant errors, have indicated that the value of  $\sin 2\beta$  from different

decay modes could be significantly different. The most recent measurements on  $\sin 2\beta$  give  $0.47 \pm 0.34^{+0.08}_{-0.06}$  (Babar) and  $0.00 \pm 0.23 \pm 0.05$  (Belle). It is of course too early to draw any robust conclusion. Nevertheless, it opens a possibility that large new physics effects may show up in the  $b \rightarrow s\bar{s}s$  processes.

There exist lots of possibilities for new physics. Here we would like to consider a simple S2HDM<sup>6</sup>. In this model, there are new Yukawa interactions between Higgs bosons and heavy fourth-generation quarks. Since in general the Yukawa interaction is expected to be proportional to the coupled quark mass, the new Yukawa couplings could be much stronger than that in the S2HDM<sup>7</sup> and SM4. Unlike in the case of S2HDM, where the  $b$  quark contribution to the QCD penguin diagram through neutral Higgs boson loop is strongly suppressed by the small  $b$  quark mass, the same diagram with intermediate  $b'$  quark may significantly contribute to the related processes<sup>6</sup>. This new feature only exists in this combined model, and is of particular interest in studying the CP violation of  $b \rightarrow s\bar{s}s$  and other penguin dominant processes.

The Lagrangian for the S2HDM4 is<sup>8</sup>

$$\begin{aligned} \mathcal{L}_Y = & \bar{\psi}_L Y_1^U \widetilde{\phi}_1^U u_R + \bar{\psi}_L Y_1^D \phi_1 d_R \\ & + \bar{\psi}_L Y_2^U \widetilde{\phi}_2^U u_R + \bar{\psi}_L Y_2^D \phi_2 d_R + H.c \end{aligned}$$

with the extended quark content of  $u_{L,R} = (u, c, t, t')$  and  $d_{L,R} = (d, s, b, b')$ . The Yukawa coupling matrices  $Y_i^{U(D)}$  are 4-dimensional matrices accordingly. The two Higgs fields  $\phi_1, \phi_2$  have vacuum expectation values (VEV) of  $v_1 e^{i\delta_1}$  and  $v_2 e^{i\delta_2}$  respectively, with  $\sqrt{|v_1|^2 + |v_2|^2} = v = 246$  GeV. The relative phase  $\delta = \delta_1 - \delta_2$  between two VEVs is physical and provides a new source of CP violation. In the mass eigenstates, the three physical Higgs bosons are denoted by  $H^0, A^0$ , and  $H^\pm$  respectively. Due to the non-zero phase  $\delta$ , all the Yukawa couplings become complex numbers in the physical mass basis. For simplicity, we assume that the

CKM matrix elements associating with  $t'$ , i.e.  $V_{t'q}$  are negligible and only focus on the neutral Higgs boson contributions.

Note that the new contributions to QCD and electro(chromo)-magnetic operators depends on different parameter sets. In the QCD penguin sector, the contribution depends on  $\xi_{bb'}^* \xi_{sb'}$  where in electro(chromo)-magnetic sector it depends on both  $\xi_{b'b} \xi_{sb'}$  and  $\xi_{bb'}^* \xi_{sb'}$ . It is convenient to define two weak phases  $\theta_1$  and  $\theta_2$  through

$$\xi_{bb'}^* \xi_{sb'} = |\xi_{bb'} \xi_{sb'}| e^{i\theta_1}, \quad \xi_{b'b} \xi_{sb'} = |\xi_{b'b} \xi_{sb'}| e^{i\theta_2}.$$

Since in general  $\xi_{b'b}$  and  $\xi_{bb'}^*$  are complex numbers and  $\xi_{b'b} \neq \xi_{bb'}^*$ , the two phases are not necessary to be equivalent. The presence of two rather than one independent phases is particular for this model, which gives different contributions to the QCD penguin and electro(chromo)-magnetic Wilson coefficients. The interference between them greatly enlarges the allowed parameter space.

Before making any predictions, one first needs to know how the new parameters are constrained by other experiments. For the process of concern, the most strict constraints comes from  $b \rightarrow s\bar{s}s$  processes such as  $B \rightarrow X_s \gamma$  and  $B_s^0 - \bar{B}_s^0$  mixing, etc.

The expression for  $B \rightarrow X_s \gamma$  normalized to  $B \rightarrow X_c e \bar{\nu}_e$  reads

$$\frac{\text{Br}(B \rightarrow X_s \gamma)}{\text{Br}(B \rightarrow X_c e \bar{\nu}_e)} = \frac{6|V_{tb} V_{ts}^*|^2 \alpha_{\text{em}}}{\pi |V_{cb}|^2 f(m_c/m_b)} |C_{7\gamma}(\mu)|^2 \quad (2)$$

with  $f(z) = 1 - 8z^2 - 24z^4 \ln z + 8z^6 - z^8$  and  $\text{Br}(B \rightarrow X_c e \bar{\nu}_e) = 10.45\%$ . The low energy scale  $\mu$  is set to be  $m_b$ . Using the Wilson coefficients at the scale  $m_W$  and running down to the  $m_b$  scale through re-normalization group equations, we obtain the predictions for  $\text{Br}(B \rightarrow X_s \gamma)$ . For simplicity, we focus on the case in which the  $b'$  contribution dominates through  $H^0$  loop, namely, we push the masses of the charged Higgs  $H^\pm$  and the other pseudo-scalar boson  $A^0$  to be very high ( $m_{H^\pm}, m_{A^0} > 500$  GeV) and ignore their con-

tributions. We take the following typical values of the couplings

$$|\xi_{bb'}| = 50, |\xi_{b'b}| = 0.8, |\xi_{sb'}| = 0.8, \\ m_{H^0} = m_b' = 200 \text{ GeV}, \quad (3)$$

and found two separated ranges for parameters  $\theta_1$  and  $\theta_2$  are allowed by the experiments.

$$-1.4 \lesssim \theta_2 \lesssim -1.2, \quad 0.4 \lesssim \theta_1 \lesssim 0.7 \quad (4)$$

for  $0.5 \lesssim \theta_1 \lesssim 1.5$  Note that we do not make a scan for the full parameter space, the above obtained range are already enough for our purpose.

The other  $b \rightarrow s\bar{s}s$  process which could impose strong constraint is the mass difference of neutral  $B_s^0$  meson. The measurements from LEP give a lower bound of  $\Delta m_{B_s} > 14.9 \text{ ps}^{-1}$ . In this model, the  $b'$  contributes to  $\Delta m_{B_s}$  only through box-diagrams with the parameter  $\xi_{bb'}^* \xi_{sb'}$ . The numerical calculations show that the constraint is weak.

The neutron electric dipole moment (EDM) is expected to give strong constraints on the new physics. However, all the above three type of mechanisms are not related to  $b \rightarrow s$  flavor-changing transitions and therefore will involve different parameters. Thus the neutron EDM will impose strong constraints on other parameters in this model and has less significance in current studying of decay  $B \rightarrow \phi K_S$ . This is significantly different from the S2HDM case in which the  $t$ -quark always dominates the loop contribution and the couplings  $\xi_{tt}$  and  $\xi_{bb}$  are subjected to a strong constraint from neutron EDM. Other constraints may come from  $K^0 - \bar{K}^0$  and  $B_d^0 - \bar{B}_d^0$  mixings. But again those processes contain additional free parameters such as the Yukawa coupling of  $\xi_{b'd}$  and  $\xi_{sb'}$ , the constraints from those processes are much weaker.

Now we are ready to discuss CP asymmetry in  $B \rightarrow \phi K_S$ . The decay amplitude for  $\bar{B} \rightarrow \phi \bar{K}^0$  reads

$$\mathcal{A}(\bar{B}_d^0 \rightarrow \phi \bar{K}^0) = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (a_3 + a_4 + a_5 - \frac{1}{2}(a_7 + a_9 + a_{10})) X, \quad (5)$$

with  $X$  being a factor related to the hadronic matrix elements. In the naive factorization approach  $X = 2f_\phi m_\phi (\epsilon \cdot p_B) F_1(m_\phi)$ , where  $\epsilon$ ,  $p_B$ ,  $F_1$  are the polarization vector of  $\phi$ , the momentum of  $B$  meson and form factor respectively. The coefficients  $a_i$  are known combinations of the Wilson coefficients. Since the heavy particles such as  $H^{\pm,0}$ ,  $A^0$  and  $b'$  has been integrated out below the scale of  $m_W$ , the procedures to obtain the effective Wilson coefficients  $C_i^{eff}$  are exactly the same as in SM.

Using the above obtained parameters allowed by the current data, the prediction for the time dependent CP asymmetry for  $B \rightarrow \phi K_S$  are shown in Fig.1 In the figure,

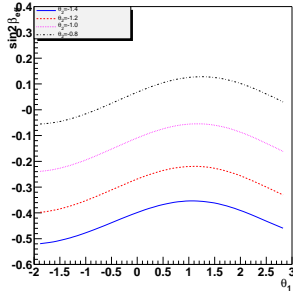


Figure 1. The prediction for  $\sin 2\beta_{eff}$  as a functions of  $\theta_1$  with different value of  $\theta_2$ . The solid, dashed, dotted and dot-dashed curves corresponds to  $\theta_2 = -1.4, -1.2, -1.0, -0.8$  respectively.

we give the value of  $\sin 2\beta_{eff}$  as a function of  $\theta_1$  with different values of  $\theta_2=1.4, 1.2, 1.0$  and  $0.8$ . Comparing with the constraints obtained from  $B \rightarrow X_s \gamma$  and  $B_s^0 - \bar{B}_s^0$  mixings, one sees that in the allowed range of  $-1.4 < \theta_2 < -1.2$  and  $0.5 < \theta_1 < 1.5$ , the predicted  $\sin 2\beta_{eff}$  can reach  $-0.4$ . It is evident that the large negative value of  $\sin 2\beta_{eff}$  is a consequence of the interference effects between  $\theta_1$  and  $\theta_2$  and therefore is particular for

this model.

In conclusion, we have briefly discussed the precise consistent prediction for the direct CP violation  $\epsilon'/\epsilon$  in kaon decays and the possible large effects on CP violation in  $B \rightarrow \phi K$  is discussed in a model of S2HDM4 which contains both an additional Higgs doublet and fourth generation quarks, since the fourth generation  $b'$  quark is much heavier than  $b$  quark, the Yukawa interactions between neutral Higgs boson and  $b'$  is greatly enhanced. This results in significant modification to the QCD penguin diagrams. The effective  $\sin 2\beta_{eff}$  in the decay  $B \rightarrow \phi K_S$  is predicted. We have shown that this model can easily account for the possible large deviation of  $\sin 2\beta$  from it's SM value without conflicting with other experimental constraints.

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