CP Violation Beyond the Standard Model in Hadronic B Decays

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Abstract

In this talk I discuss three different methods, using $B_d \rightarrow J/\psi K_S$, $J/\psi K_S \pi^0$, $B_d \rightarrow K^- \pi^+, \pi^+ \pi^-$ and $B_u \rightarrow K^- \pi^0, \bar{K}^0 \pi^-, \pi^- \pi^0$, to extract hadronic model independent information about new physics.

1. Introduction

The Gold-plated mode for the study of CP violation in the Standard Model (SM) is $B \rightarrow J/\psi K_S$. This decay mode can be used to measure $\sin 2\beta$ in the SM without hadronic uncertainties. CDF and ALEPH data obtain $\sin 2\beta = 0.91 \pm 0.35$ which is consistent with $\sin 2\beta = 0.75^{+0.055}_{-0.065}$ from fitting other experimental data. The best fit value for $\gamma$ from the same fitting gives $\gamma_{\text{best}} = 59.9^\circ$. Rare hadronic B decays also provide important information. Using factorization calculations for rare hadronic B decays measured by CLEO, $\gamma$ is determined to be $114^{+25}_{-21}$ degrees. It seems that there is a conflict between $\gamma$ obtained from rare B decay data and from other fits. At present it is not possible to conclude whether this possible inconsistence is due to experimental and theoretical uncertainties or due to new physics. It is important to find ways to test the SM and to study new physics without large hadronic uncertainties. In this talk I discuss three methods, using $B_d \rightarrow J/\psi K_S$, $J/\psi K_S \pi^0$, $B_d \rightarrow K^- \pi^+, \pi^+ \pi^-$ and $B_u \rightarrow K^- \pi^0, \bar{K}^0 \pi^-, \pi^- \pi^0$ to extract hadronic model independent information about the SM and models beyond.

In the SM the Hamiltonian for hadronic B decays is given by,

$$H_{\text{eff}} = \frac{(4G_F/\sqrt{2})[V_{tb} V_{ts}^* (c_1 O_1^{(q)} (L) + c_2 O_2^{(q)} (L)) - \sum_{i=(3-12),j=(u,c,t)} V_{tb} V_{ts} c_i O_i]].$$

$O_{11,12}$ are the gluonic and electromagnetic dipole operators and $O_{1-10}$ are defined in Ref. [1]. I use the values of $c_i$ obtained for the SM in Ref. [2] with $(c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_{10'}, c_{11}, c_{12}) = (-0.313, 1.150, -0.017, -0.037, -0.046, -0.001\alpha_{em}, 0.049\alpha_{em}, -1.321\alpha_{em}, 0.267 \alpha_{em}, -0.3, -0.6)$. $c_i$ are due to c and u quarks in the loop and can be found in Ref. [3]. When going beyond the SM, there are new contributions. I take three models for illustrations.

Model i): R-parity violation model

In R-parity violating supersymmetric (SUSY) models, there are new CP violating phases. Here I consider the effects due to $L = (\lambda_{ijkl}'/2)U_R^{ij} D_R^{kl} D_R^{kl}$, R-
parity violating interaction. Exchange of $\tilde{d}_i$ squark can generate the following effective Hamiltonian at tree level, $H_{\text{eff}} = (4G_F/\sqrt{2}) V_{tb}^* V_{tq} c_{f}^{(q)} |O_1^{(q)}(R) - O_2^{(q)}(R)]$. Here $O_1^{(q)}(R) = \bar{f} \gamma_{\mu} R f \bar{q} \gamma_{\mu} R b$ and $O_2^{(q)}(R) = \bar{f} \gamma_{\mu} R f \bar{q} \gamma_{\mu} R b$. The operators $O_{1,2}(R)$ have the opposite chirality as those of the tree operators $O_{1,2}(L)$ in the SM. The coefficients $c_{f}^{(q)}$ with QCD corrections are given by $(c_1 - c_2)(\sqrt{2}/4G_FV_{tb}V_{tq}^*)(-\lambda_{f_1}^{\nu}/2m_{\tilde{t}}^2)$. Here $m_{\tilde{t}}$ is the squark mass. $B_u \rightarrow \pi^- K^0$ and $B_d \rightarrow K^- K^0$ data constrain $|c_{f}^{(q)}|$ to be less than $O(1)$.

The new contributions can be larger than the SM ones. I will take the values to be 10% of the corresponding values for the SM with arbitrary phases $\delta_f^{(q)}$ for later discussions.

Model ii): SUSY with large gluonic dipole interaction

In SUSY models with R-parity conservation, potential large contributions to B decays may come from gluonic dipole interaction by exchanging gluino at loop level with left- and right-handed squark mixing. In the mass insertion approximation, $c_{11}^{\text{new}} = -(\sqrt{2} \pi / G_F m_\lambda)(m_\lambda/m_b)\delta_{R q}^{LR}(m_b^2/m_q^2)$, where $m_\lambda$ is the gluino mass, and $\delta_{R q}^{LR}$ is the squark mixing parameter. $G(x)$ is from loop integral. $c_{11}^{\text{new}}$ is constrained by experimental data from $b \rightarrow s \gamma$ which, however, still allows $c_{11}^{\text{new}}$ to be as large as three times of the SM contribution in magnitude with an arbitrary CP violating phase $\delta_{\text{dipole}}$. I will take $c_{11}^{\text{new}}$ to be 3 times of the SM value with an arbitrary $\delta_{\text{dipole}}$.

Model iii): Anomalous gauge boson couplings

Anomalous gauge boson couplings can modify $c_\xi$ (mainly on $c_{7-10}^i$) with the same CP violating source as that for the SM. The largest contribution may come from the $WWZ$ anomalous coupling $\Delta g_7^{\xi}$. To the leading order in QCD corrections, the new contributions to $c_{7-10}^{ii}$ due to $\Delta g_7^{\xi}$ are given by $(c_{7-10}^{i}, c_{7-10}^{ii}, c_{9-10}^{i AC}, c_{9-10}^{ii AC}) = \alpha_{em} \Delta g_7^{\xi} (1.397, 0.391, -5.651, 1.143)$. LEP data constrain $\Delta g_7^{\xi}$ to be within $-0.113 < \Delta g_7^{\xi} < 0.126$ at the 95% c.l.. $c_{i AC}$ can be very different from those in the SM.

2. Test new physics using $\sin 2\beta$ from $B \rightarrow J/\psi K_S, J/\psi K_S \pi^0$

The usual CP violation measure for B decays to CP eigenstates is $\text{Im} \xi = \text{Im} \{q/p(A^* A/|A|^2)\}$, where $q/p = e^{-2i\phi_B}$ is from $B^0 - \bar{B}^0$ mixing, while $A, A$ are $B, \bar{B}$ decay amplitudes. For $B \rightarrow J/\psi K_S$, the final state is $P$-wave hence CP odd. Setting the weak phase in the decay amplitude to be $2\phi_0 = \text{Arg}(A/\bar{A})$, one has \( \text{Im}(\xi(B \rightarrow J/\psi K_S)) = -\sin(2\phi_B + 2\phi_0) \equiv -\sin 2\beta_{J/\psi K_S} \).

For $B \rightarrow J/\psi K^* \rightarrow J/\psi K_S \pi^0$, the final state has both $P$-wave (CP odd) and $S$- and $D$-wave (CP even) components. If $S$- and $D$-wave have a common
weak phase $\tilde{\phi}_1$ and P-wave has a weak phase $\phi_1$.

$$\text{Im} \xi(B \to J/\psi K_S \pi^0) = \text{Im} \left\{ e^{-2i\phi_0} \left[ e^{-2i\tilde{\phi}_1} |P|^2 - e^{-2i\tilde{\phi}_1} (1 - |P|^2) \right] \right\}$$

$$\equiv (1 - 2|P|^2) \sin 2\beta_{J/\psi K_S \pi^0},$$

(1)

where $|P|^2$ is the fraction of P-wave component. In the SM one has $\phi_B = \beta$ and $2\phi_0 = 2\phi_1(2\tilde{\phi}_1) = \text{Arg} \left\{ V_{cb}V_{cs}^* \{ c_1 + a(a')c_2 \} \right\} = 0$, in the Wolfenstein phase convention. Here $a$ and $a'$ are parameters which indicate the relative contribution from $O_2^{(s)}(L)$ compared with $O_1^{(s)}(L)$ for the P-wave and (S-, D-) wave. In the factorization approximation $1/a = 1/a' = N_c$ (the number of colors). Therefore $\sin 2\beta_{J/\psi K_S} = \sin 2\beta_{J/\psi K_S \pi^0} = \sin 2\beta$. $|P|^2$ has been measured with a small value $3 \pm 0.08 \pm 0.04$ by CLEO which implies that the measurement of $\sin 2\beta$ using $B \to J/\psi K_S \pi^0$ is practical although there is a dilution factor of 30%.

When one goes beyond the SM, $\sin 2\beta_{J/\psi K_S} = \sin 2\beta_{J/\psi K_S \pi^0}$ is not necessarily true. The difference $\Delta \sin 2\beta$ is not sensitive to new physics in Models ii) and iii). However, for Model i), the contributions can be large. The weak phases are given by $2\phi_0 = 2\phi_1(2\tilde{\phi}_1) = \text{Arg} \left\{ V_{cb}V_{cs}^* \{ c_1 + ac_2 + (-)c^{(s)}(1 - a(a')) \} \right\} = 0$. Taking the new contributions to be 10% of the SM ones, one obtains $\phi_0 = \phi_1 \approx -\tilde{\phi}_1 \approx 0.1 \sin \delta^{(s)}$. From this, $\Delta \sin 2\beta \approx 4((1 - |P|^2)/(1 - 2|P|^2)) \cos 2\phi_B (0.1 \sin \delta^{(s)}) \approx 0.5 \cos 2\phi_B \sin \delta^{(s)}$. $\phi_B$ may be different from the SM one due to new contributions. Using the central value $\sin 2\beta_{J/\psi K_S} = 0.91$ measured from CDF and ALEPH, $\Delta \sin 2\beta \approx 0.2 \sin \delta^{(s)}$ which can be as large as 0.2. Such a large difference can be measured at B factories. Information about new CP violating phase $\delta^{(s)}$ can be obtained.

3. Test new physics using rate differences between $B_d \to \pi^+ K^-, \pi^+ \pi^-$

Theoretical calculations for rare hadronic B decays have large uncertainties. Information extracted using model calculations is unreliable. I now show that hadronic model independent information about CP violation can be obtained using SU(3) analysis for rare hadronic B decays.

The operators $O_{1,2}$, $O_{1-6,11,12}$, and $O_{7-10}$ transform under SU(3) symmetry as $\bar{3}_a + \bar{3}_b + 6 + \bar{15}$, $3$, and $\bar{3}_a + \bar{3}_b + 6 + \bar{15}$, respectively. These properties enable one to write the decay amplitudes for $B \to PP$ in only a few SU(3) invariant amplitudes. There are relations between different decays. When small annihilation contributions are neglected, one has
\[ A(B_d \to \pi^+\pi^-) = V_{ub}V_{td}^* P + V_{ub}V_{td}^* P, \]

\[ A(B_d \to \pi^+K^-) = V_{ub}V_{tb}^* P + V_{ub}V_{tb}^* P. \]

Due to different KM matrix elements involved in these decays, although the amplitudes have similarities, the branching ratios are not simply related. However, when considering the rate difference, \( \Delta(PP) = \Gamma(B_d \to PP) - \Gamma(\bar{B}_d \to \bar{P}\bar{P}) \), the situation is dramatically different because the simple relation

\[ \text{Im}(V_{ub}V_{td}^* V_{tb}V_{td}) = -\text{Im}(V_{ub}V_{us}^* V_{tb}V_{ts}). \]

In the SU(3) limit,

\[ \Delta(\pi^+\pi^-) = -\Delta(\pi^+K^-). \quad (2) \]

This non-trivial equality does not depend on detailed models for the hadronic physics and provides test for the SM. Including SU(3) breaking effect from factorization calculation, one has, \( \Delta(\pi^+\pi^-) \approx -f_\pi^2 \Delta(\pi^+K^-) \). Although there is correction, the relative sign is not changed.

When going beyond the SM, there are new CP violating phases leading to violation of the equality above. Among the three models described in the first section, Models i) and ii) can alter the equality significantly, while Model iii) cannot because the CP violating source is the same as that in the SM. To illustrate how the situation is changed in Models i) and ii), I calculate the normalized asymmetry \( A_{\text{norm}}(PP) = \Delta(PP)/\Gamma(\pi^+K^-) \) using factorization approximation following Ref.\(^{16}\). The new effects may come in such a way that only \( B_d \to \pi^+K^- \) is changed but not \( B_d \to \pi^+\pi^- \). This scenario leads to maximal violation of the equality discussed here. I will take this scenario for illustration.

The results are shown in Figure 1. The solid curve is the SM prediction for \( A_{\text{norm}}(\pi^+K^-) \) as a function of \( \gamma \). For \( \gamma_{\text{best}} \approx 10\% \). It is clear from Figure 1 that within the allowed range of the parameters, new physics effects can dramatically violate the equality discussed above. Experimental study of the rate differences \( \Delta(\pi^+\pi^-, \pi^+K^-) \) can provide model independent information about CP violation beyond the SM in the near future.

4. Test new physics using SU(3) relation for \( B_u \to \pi^-\bar{K}^0, \pi^0K^-, \pi^0\pi^- \)

I now discuss another method which provides important information about new physics using \( B_u \to \pi^-\bar{K}^0, \pi^0K^-, \pi^0\pi^- \). Using SU(3) relation and factorization estimate for the breaking effects, one obtains\(^{13}\)

\[ A(B_u \to \pi^-\bar{K}^0) + \sqrt{2} A(B_u \to \pi^0K^-) = \epsilon A(B_u \to \pi^-\bar{K}^0)e^{i\Delta\phi}(e^{-i\gamma} - \delta_{EW}), \]

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Figure 1: $A_{\text{norm}}(\pi^+K^-)$ vs phases $\gamma$, $\delta_{\text{dipole}}$ and $\delta_{\text{dipole}}$ for the SM (solid), Models i) (dashed) and ii) (dotted). For Models i) and ii), $\gamma = 59.9^\circ$ is used. $A_{\text{norm}}(\pi^+K^-) = -(f_K/f_K)^2 A_{\text{norm}}(\pi^+\pi^-)$ is satisfied in the SM. For Models i) and ii) $-(f_K/f_K)^2 A_{\text{norm}}(\pi^+\pi^-)$ is approximately the same as that in the SM (dot-dashed curve).

$$\delta_{EW} = -\frac{3}{2} \frac{|V_{cb}| |V_{cs}|}{|V_{ub}| |V_{us}|} \epsilon (1 + \epsilon \delta_{EW}),$$

$$\epsilon = \sqrt{2} \frac{|V_{us}|}{|V_{ud}|} \left( \frac{f_K}{f_\pi} \right) A(\pi^+\pi^0).$$

where $\Delta\phi$ is the difference of the final state rescattering phases for $I = 3/2, 1/2$ amplitudes. For $f_K/f_\pi = 1.22$ and $Br(B^{\pm} \rightarrow \pi^+\pi^0) = (0.54^{+0.21}_{-0.20} \pm 0.15) \times 10^{-3}$, one obtains $\epsilon = 0.21 \pm 0.06$.

Neglecting small tree contribution to $B_u \rightarrow \pi^-\bar{K}^0$, one obtains

$$\cos \gamma = \delta_{EW} - \frac{(r_+^2 + r_-^2)/2 - 1 - \epsilon^2(1 - \delta_{EW}^2)}{2\epsilon(\cos \Delta\phi + \epsilon\delta_{EW})}, \quad r_+^2 - r_-^2 = 4\epsilon \sin \Delta\phi \sin \gamma,$$

where $r_+^2 = 4Br(\pi^0 K^\pm)/[Br(\pi^+ K^-) + Br(\pi^- K^0)] = 1.33 \pm 0.45$.

The relation between $\gamma$ and $\delta_{EW}$ is complicated. However it is interesting to note that even in the most general case, bound on $\cos \gamma$ can be obtained. For $\Delta = (r_+^2 + r_-^2)/2 - 1 - \epsilon^2(1 - \delta_{EW}^2)$, $\geq (\leq) > 0$, we have

$$\cos \gamma \leq (\geq) \delta_{EW} - \frac{\Delta}{2\epsilon(1 + \epsilon\delta_{EW})}, \quad \text{or} \quad \cos \gamma \geq (\leq) \delta_{EW} - \frac{\Delta}{2\epsilon(-1 + \epsilon\delta_{EW})}. \quad (3)$$

The bounds on $\cos \gamma$ as a function of $\delta_{EW}$ are shown in Fig. 2 by the solid curves for three representative cases: a) Central values for $\epsilon$ and $r_+^2$; b) Central values for $\epsilon$ and $1\sigma$ upper bound $r_+^2 = 1.78$; and c) Central value for $\epsilon$ and $1\sigma$ lower bound $r_+^2 = 0.88$. The bounds with $|\cos \gamma| \leq 1$ for a), b) and c) are indicated by the curves (a1, a2), (b) and (c1, c2), respectively. For cases a) and c) there are two allowed regions, the regions below (a1, c1) and the regions above (a2, c2). For case b) the allowed range is below (b).
Figure 2: $\cos \gamma$ vs. $\delta_{EW}$. The solutions for the cases a), b) and c) are indicated by the dashed, dot-dashed and dotted curves respectively.

When the decay amplitudes for $B^\pm \rightarrow K\pi$, $B^\pm \rightarrow \pi^\pm\pi^0$ and the rate asymmetries for these decays are determined to a good accuracy, $\gamma$ can be determined, one obtains,

$$(1 - \cos^2 \gamma)[1 - (\frac{\Delta}{2\epsilon(\delta_{EW} - \cos \gamma)} - \epsilon\delta_{EW})^2] - \frac{(r_+^2 - r_-^2)^2}{16\epsilon^2} = 0. \quad (4)$$

To have some idea about the details, I analyze the solutions of $\cos \gamma$ as a function of $\delta_{EW}$ for the three cases discussed earlier with a given value for the asymmetry $A_{asy} = (r_+^2 - r_-^2)/(r_+^2 + r_-^2) = 15\%$.

In the SM for $r_v = |V_{ub}|/|V_{cb}| = 0.08$ and $|V_{us}| = 0.2196$, $\delta_{EW} = 0.81$. The central values for $r_\pm$ and $\epsilon$ prefers $\cos \gamma < 0$ which is different from the result obtained in Ref.[3] by fitting other data. The parameter $\delta_{EW}$ is sensitive to new physics in the tree and electroweak sectors. Model i) has large corrections to the tree level contributions. However, the contribution is proportional to the sum of the coefficients of operators $O_{1,2}^{(s)}(R)$ which is zero in Model i). The above method does not provide information about new physics due to Model i). This method would not provide information about new physics due to Model ii) neither because the gluonic dipole interaction transforms as $\bar{3}$ which does not affect $\delta_{EW}$. Model iii) can have large effect on $\delta_{EW}$. In this model $\delta_{EW} = 0.81(1 + 4.33\Delta g_Z^2)$ which can vary in the range $0.40 \sim 1.25$. Constraint on $\cos \gamma$ can be very different from the SM prediction.

For case a), in the SM $\cos \gamma < 0.18$ which is inconsistent with $\cos \gamma_{\text{best}} \approx 0.5$. In Model iii) $\cos \gamma$ can be consistent with $\cos \gamma_{\text{best}}$. For case b), $\cos \gamma$ is less than zero in both the SM and Model iii). If this is indeed the case, other types of new physics is needed. For case c) $\cos \gamma$ can be close to $\cos \gamma_{\text{best}}$ for both the SM and Model iii). Improved measurements of $\epsilon$ and $r_\pm$ can provide...
important information about $\gamma$ and new physics.

5. Conclusion

From discussions in previous sections, it is clear that using $B_d \rightarrow J/\psi K_S$, $J/\psi K_S \pi^0$, $B_u \rightarrow \pi^- K^+$, $\pi^+ \pi^-$ and $B^- \rightarrow \pi^0 K^-$, $\pi^- K^0$, $\pi^0 \pi^-$ important information free from uncertainties in hadronic physics about the Standard Model and models beyond can be obtained. These analyses should be carried out at B factories.

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