New Physics Effects in $B \to J/\Psi K$

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1 Introduction

At present, we are at the beginning of the B-factory era in particle physics, which will provide valuable insights into CP violation and various tests of the CKM picture of this phenomenon. Among the most interesting B-decay channels is the "gold-plated" mode $B_d \to J/\psi K_S$ [1], which allows the determination of the angle β of the unitarity triangle of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. The present status of these measurements is summarized in other contributions to this conference [2, 3].

In this talk, which is based on a collaboration with Robert Fleischer [4], I consider the neutral mode $B_d \to J/\psi K_S$ together with its charged counterpart $B^\pm \to J/\psi K^\pm$. Making use of the isospin symmetry of strong interactions, we derive a model-independent parametrization of the corresponding decay amplitudes. After a careful analysis of the standard-model contributions, we consider possible new-physics amplitudes and introduce a set of observables, which allows us a general analysis of new-physics effects in the $B \to J/\psi K$ system.

There is a large variety of possible new physics scenarios. One of the most popular one is a supersymmetric extension of the standard model, which has in its most general form a very complicated flavour sector. Other models, like large extra dimension or left-right symmetric models, have similar disadvantages, and a general feature of all these models is an unacceptably large CP violation. It is fair to say that currently there is no generally accepted way to model new physics effects in the flavour sector.

The standard model is the most general renormalizable theory with the desired particle spectrum and interactions, and a generic parametrization of new-physics effects can in principle be obtained by adding "non-renormalizable" dimension-6 operators $\mathcal{O}_i$ [5]

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i \mathcal{O}_i \tag{1}$$

where the C_i are their coefficients and Λ^2 is the scale of new physics. The problem with this parametrization is that the number of possible operators $\mathcal{O}_i$ is $\mathcal{O}(100)$, such that this parametrization in its full generality is useless for practical applications. Still it is useful to get an estimate of the size of a possible new physics contribution.

Once we have added the new contributions given by the dimension-6 operators, we proceed in the same way as before and consider a low-energy effective theory by integrating out the top quark and the heavy gauge bosons. The result of this step are four-fermion operators with couplings proportional to

$$G_F = \frac{g^2}{M_W^2} = \frac{1}{< v >^2} \tag{2}$$

while contributions from new physics effects enter with coefficients of order $1/\Lambda^2$. Furthermore, in the standard model we have in addition also CKM factors, such that certain transitions in this model are small and a possible new physics contribution could be observable even for large scales Λ.

However, focussing on $\Delta B = \pm 2$ transition operators the number of possible dimension-6 operators is not very large. Generically these are given by

$$\mathcal{L}_{new}^{\Delta B=2} = \frac{1}{\Lambda^2} \sum C_i \left[(\bar{b} \Gamma_i S_i d_1)(\bar{b} \Gamma_i S_i d_2) \right] \tag{3}$$

where Γ_i is an arbitrary Dirac matrix and S_i indicates the color structure ($S_i \times S_i = 1 \times 1$ or $T^a \times T^a$). Such a contribution will not only change the frequency of the $B - \overline{B}$ oscillations, but can also contribute to the mixing phase, which in the standard model is simply $\sin(2\beta)$.

The interesting point about the $\Delta B = \pm 2$ contribution is that the standard model contribution is very small. The only non-vanishing coefficient in the standard model is the one for $\Gamma_i \times \Gamma_i = \gamma_\mu (1 - \gamma_5) \times \gamma^\mu (1 - \gamma_5)$ and $S_i \times S_i = 1 \times 1$. This coefficient is of the order

$$C_{SM} = \frac{G_{\rm F}}{\sqrt{2}} \left(\frac{G_{\rm F} M_W^2}{\sqrt{128} \pi^2} \right) (V_{td} V_{tb}^*)^2 \tag{4}$$

which is small due to the CKM suppression by two powers of $|V_{td}|$. Furthermore, the standard model diagramms are at least one-loop, in which case one finds another suppression by a loop factor $1/(16\pi^2)$. It has already been pointed out some time ago [6] that this leads to a significant sensitivity to new physics in the $\Delta B = \pm 2$ sector. Furthermore, an ansatz of this type is the B-physics analogue of the superweak model invented in the context of kaon-CP violation.

To get a rough idea of possible new physics effects in $B - \overline{B}$ mixing, we assume the same coupling strenght (including the loop factor) as in the standard model and find

$$C_{NP} = \frac{G_{\rm F}}{\sqrt{2}} \left(\frac{G_{\rm F} M_W^2}{\sqrt{128} \pi^2} \right) \frac{M_W^2}{\Lambda^2} \tag{5}$$

where ψ is an additional weak phase induced by new physics. Adding this new piece to the standard-model contribution we get an estimate for the phase $\phi_{\rm M}$ of $B-\overline{B}$ mixing

$$\tan\phi_{\rm M} = \frac{\sin(2\beta)+\varrho^2\sin(2\psi)}{\cos(2\beta)+\varrho^2\cos(2\psi)}, \tag{6}$$

with

$$\varrho = \left(\frac{1}{\lambda^3 A R_t}\right)\left(\frac{M_W}{\Lambda}\right) \tag{7}$$

where λ is the Wolfenstein parameter and R_t is the length of side opposite to γ of the unitarity triangle. Note that ϱ could be $\mathcal{O}(1)$ due to the presence of the CKM factors, yielding a significant deviation. In turn, this yields a sensitivity up to very high scale, roughly $\Lambda \sim 8$ TeV.

2 Analysis of $B \to J/\Psi K$

The analysis of the $\Delta B = \pm 1$ transitions is much more involved than the $\Delta B = \pm 2$ case, since the number of possible operators is much larger. For that reason it is more convenient to study a particular decay.

For the class of decays $B \to J/\Psi K$ it is convenient to first perform an isospin analysis. The initial as well as the final state carry $I = 1/2$, consequently the effective interaction has either $I = 0$ or $I = 1$. Taking into account the neutral and the charged decay modes we have the following isospin doublets

$$\begin{pmatrix} |+1/2\rangle \\ |-1/2\rangle \end{pmatrix} : \quad \underbrace{\begin{pmatrix} |B^+\rangle \\ |B_d^0\rangle \end{pmatrix}, \begin{pmatrix} |\overline{B_d^0}\rangle \\ -|B^-\rangle \end{pmatrix}}_{CP}, \underbrace{\begin{pmatrix} |J/\psi K^+\rangle \\ |J/\psi K^0\rangle \end{pmatrix}, \begin{pmatrix} |J/\psi \overline{K^0}\rangle \\ -|J/\psi K^-\rangle \end{pmatrix}}_{CP} \tag{8}$$

where we indicated their relation through the CP tranformation.

Purely from isospin we find the relations

$$\langle J/\psi K^+|\mathcal{H}_{\rm eff}^{I=0}|B^+\rangle = +\langle J/\psi K^0|\mathcal{H}_{\rm eff}^{I=0}|B_d^0\rangle \tag{9}$$

$$\langle J/\psi K^+|\mathcal{H}_{\rm eff}^{I=1}|B^+\rangle = -\langle J/\psi K^0|\mathcal{H}_{\rm eff}^{I=1}|B_d^0\rangle \tag{10}$$

where $\mathcal{H}_{\rm eff}^{I}$ indicates the different isospin components of the effective interaction. Note that these relations are completely general and thus hold even in the presence of new physics.

In the standard model we can write the amplitudes for the decays as

$$A(B^+ \to J/\psi K^+) = \frac{G_{\rm F}}{\sqrt{2}}\left[V_{cs}V_{cb}^*\left\{A_c^{(0)} - A_c^{(1)}\right\} + V_{us}V_{ub}^*\left\{A_u^{(0)} - A_u^{(1)}\right\}\right] \tag{11}$$

$$A(B_d^0 \to J/\psi K^0) = \frac{G_{\rm F}}{\sqrt{2}}\left[V_{cs}V_{cb}^*\left\{A_c^{(0)} + A_c^{(1)}\right\} + V_{us}V_{ub}^*\left\{A_u^{(0)} + A_u^{(1)}\right\}\right], \tag{12}$$

where

$$A_c^{(0)} = A_{\rm CC}^c - A_{\rm QCD}^{\rm pen} - A_{\rm EW}^{(0)}, \quad A_c^{(1)} = -A_{\rm EW}^{(1)} \tag{13}$$

$$A_u^{(0)} = A_{\rm CC}^{u(0)} - A_{\rm QCD}^{\rm pen} - A_{\rm EW}^{(0)}, \quad A_u^{(1)} = A_{\rm CC}^{u(1)} - A_{\rm EW}^{(1)} \tag{14}$$

where CC indicates the contribution from the current-current operators, $QCD-pen$ the one from the QCD penguin operators and EW the one from the electroweak penguins, while the superscript index denotes the isospin of the contribution.

Relations (11) yield an idea about the sizes of the various terms. The explicit CKM factors show a suppression of the terms carrying a weak phase by a factor λ^2. Furthermore, all these contributions correspond to penguin topologies and hence one expects a further, dynamical suppression. It is commonly believed that this is of the order of the Wolfenstein parameter λ, and we shall asusme for the sake of "power counting" that this suppression factor is just λ. Due to the fact that the electroweak penguin contributions are also strongly suppressed by the dynamics and CKM factors, we get the well-known standard-model result

$$A(B^+ \to J/\psi K^+) = A(B_d^0 \to J/\psi K^0) = \frac{G_{\rm F}}{\sqrt{2}} \left(1 - \frac{\lambda^2}{2}\right) \lambda^2 A\, A_c^{(0)} + \mathcal{O}(\lambda^3) \tag{15}$$

A possible new physics contribution can enter this decay mode in various ways. Firstly, there could be an additional weak phase from new physics in the $\Delta B = \pm 2$ which has been discussed above. Secondly, there could be new contributions in both the $I=0$ and $I=1$ pieces of the effective Hamiltonian. These contributions are parametrized as

$$A(B^+ \to J/\psi K^+) \;=\; A_{\rm SM}^{(0)} \left[1 + \sum_k r_0^{(k)} e^{i\delta_0^{(k)}} e^{i\varphi_0^{(k)}} - \sum_j r_1^{(j)} e^{i\delta_1^{(j)}} e^{i\varphi_1^{(j)}}\right] \tag{16}$$

$$A(B_d^0 \to J/\psi K^0) \;=\; A_{\rm SM}^{(0)} \left[1 + \sum_k r_0^{(k)} e^{i\delta_0^{(k)}} e^{i\varphi_0^{(k)}} + \sum_j r_1^{(j)} e^{i\delta_1^{(j)}} e^{i\varphi_1^{(j)}}\right] \tag{17}$$

where $A_{\rm SM}^{(0)}$ is the standard model amplitude, $r_I^{(l)}$ is the Modulus, $\delta_I^{(l)}$ is the strong and $\varphi_I^{(l)}$ the weak phase of the l^{th} contribution with isospin I. Note that according to the above discussion we have $r_I^{(l)} \sim \mathcal{O}(M_W^2/\Lambda^2)$

In order to test for these additional contributions, we look at the observables in the $B \to j/\Psi K$ system. Aside from the information gathered from the measurement of the time-dependent asymmetry in the neutral modes

$$a_{\rm CP}(t) = \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta M_d t) + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta M_d t) \tag{18}$$

we suggest to also measure the direct CP asymmetry in the charged modes

$$\mathcal{A}_{\rm CP}^{(+)} = \frac{|A(B^+ \to J/\psi K^+)|^2 - |A(B^- \to J/\psi K^-)|^2}{|A(B^+ \to J/\psi K^+)|^2 + |A(B^- \to J/\psi K^-)|^2} \tag{19}$$

as well as the difference of the CP averaged rates of the charged and the neutral modes ($\langle ... \rangle$ denotes the CP average)

$$B = \frac{\langle |A(B_d \to J/\psi K)|^2 \rangle - \langle |A(B^\pm \to J/\psi K^\pm)|^2 \rangle}{\langle |A(B_d \to J/\psi K)|^2 \rangle + \langle |A(B^\pm \to J/\psi K^\pm)|^2 \rangle} \tag{20}$$

Given the parametrization (16) of new-physics effects, we suggest a slightly different set of observables which is

$$S = \frac{1}{2}\left[\mathcal{A}_{\rm CP}^{\rm dir} + \mathcal{A}_{\rm CP}^{(+)}\right], \quad D = \frac{1}{2}\left[\mathcal{A}_{\rm CP}^{\rm dir} - \mathcal{A}_{\rm CP}^{(+)}\right] \tag{21}$$

and B as given before.

In terms of the parameters introdued in (16) we see that S measures the $I = 0$ new physics contribution

$$S = -2\left[\sum_k r_0^{(k)} \sin\delta_0^{(k)} \sin\varphi_0^{(k)}\right]\left[1 - 2\sum_l r_0^{(l)} \cos\delta_0^{(l)} \cos\varphi_0^{(l)}\right], \tag{22}$$

B is sensitive to a CP conserving $I = 1$ new-physics contribution, while D is sensitive to a CP violating new physics contribution

$$B = +2\sum_j r_1^{(j)} \cos\delta_1^{(j)} \cos\varphi_1^{(j)} \quad D = -2\sum_j r_1^{(j)} \sin\delta_1^{(j)} \sin\varphi_1^{(j)} \tag{23}$$

However, one has to keep in mind the limitations of this approach. The size of the standard-model contributions which are under poor theoretical control is $\mathcal{O}(\lambda^3)$ which means that a possible new physics contributions has to be larger than this.

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