New Physics in $B \to J/\psi K^*$[1]

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CP violation in the B system [1] has been established by the recent measurements of $\sin 2\beta$, with a world average of $\sin 2\beta = 0.78 \pm 0.08$ [2]. The main B decay used to probe the weak phase β is the so-called "gold-plated" mode $B_d^0(t) \to J/\psi K_s$. In order to extract weak-phase information cleanly, i.e. with no hadronic uncertainties, a given B decay must be dominated by a single weak decay amplitude. However, even within the SM, $B_d^0 \to J/\psi K_s$ receives contributions from two weak amplitudes: the tree amplitude and the $b \to s$ penguin amplitude. Nevertheless, this decay mode is very clean for the following two reasons. First, the $c\overline{c}$ quark pair must be produced in a color-singlet state, requiring three gluons in the penguin amplitude. Consequently, the penguin contribution is expected to be considerably smaller than the tree contribution. Second, in the Wolfenstein parameterization [3] the CKM matrix elements involved in the $b \to s$ penguin amplitude ($V_{tb}^* V_{ts}$) and in the tree amplitude ($V_{cb}^* V_{cs}$) are both real. Thus, the weak phases of these two amplitudes are the same, so that effectively only a single weak amplitude contributes to $B_d^0 \to J/\psi K_s$. The extraction of the CP phase β from this decay mode is therefore extremely clean.

The decay $B_d^0(t) \to J/\psi K^*$ is also a clean mode, for exactly the same reasons as above. The complication, in comparison to $B_d^0(t) \to \psi K_s$, is that the final state now consists of two vector particles, so that the CP-even and CP-odd components must be distinguished by performing an angular analysis [1]. Each component can then be treated separately, and β can be obtained cleanly.

In the presence of new physics, the extraction of the weak phase β may not be clean. If the new physics contributes only to B_d^0–$\overline{B}_d^0$ mixing, the measurement of β remains clean, though the measured value is not the true SM value, but rather one which is shifted by a new-physics phase. On the other hand, if new physics affects the decay amplitude, then the extraction of β is no longer clean – it may be contaminated by hadronic uncertainties. It is this situation which interests us.

[1] Talk given by Rahul Sinha

How can new physics affect the decay amplitude? This can occur if there are new contributions to the $b \to s$ penguin amplitude[4], so that this amplitude no longer has the same weak phase as the tree amplitude. There are a variety of new-physics models in which this can occur. These include, for example, supersymmetric models with R-parity breaking, Z- and Z'-mediated flavor-changing neutral currents [5], and the Top-Higgs doublet model [6].

An obvious question is then: how does one see new-physics contributions to the decay amplitudes if they are present? The standard method is to search for direct CP violation. In the presence of two decay amplitudes, the full amplitude for the decay $B \to f$ can be written as

$$A(B \to f) = ae^{i\phi_a}e^{i\delta^a} + be^{i\phi_b}e^{i\delta^b} \ . \tag{1}$$

Here, $\phi_{a,b}$ and $\delta^{a,b}$ are, respectively, the weak and strong phases of the two contributing amplitudes. The amplitude for the CP-conjugate decay $\overline{B} \to \overline{f}$ can be obtained from the above by changing the signs of the weak phases. The direct CP asymmetry a_{dir}^{CP} is then given by

$$a_{dir}^{CP} = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})} = -\frac{2ab\sin(\phi_a - \phi_b)\sin(\delta^a - \delta^b)}{a^2 + b^2 + 2ab\cos(\phi_a - \phi_b)\cos(\delta^a - \delta^b)} \ . \tag{2}$$

This expression holds for both neutral and charged B decays. Thus, if new physics is present, we can expect to see direct CP violation in both $\overset{(-)}{B}_d \to J/\psi K_s$ and $B^\pm \to J/\psi K^\pm$ decays.

It is obvious from Eq. (2) that an observable direct asymmetry requires not only a nonzero weak-phase difference between the two decay amplitudes, but also a strong-phase difference. However, it has been argued that since the b-quark is rather heavy, all strong phases in B decays should be quite small. If the strong phases of the two amplitudes happen to be almost equal, there will be no observable signal of direct CP violation, even though new physics is present. Hence new physics may be hard to find using direct asymmetries.

One is therefore led to the question: *if the strong-phase differences vanish, is there any way of detecting the presence of new physics?* As we show below, the answer to this question is *yes*, if one uses the final state $J/\psi K^*$ rather than $J/\psi K$. As above, we assume that there are two contributions to the decay amplitude, coming from the SM and from new physics. The weak phase of the SM contribution is zero, while the new physics contribution has a nonzero weak phase. Since the final state consists of two vector mesons, there are three helicity amplitudes. These take the form

$$\begin{aligned} A_\lambda \equiv Amp(B \to J/\psi K^*)_\lambda &= a_\lambda e^{i\delta_\lambda^a} + b_\lambda e^{i\phi}e^{i\delta_\lambda^b} \ , \\ \overline{A}_\lambda \equiv Amp(\overline{B} \to J/\psi \overline{K}^*)_\lambda &= a_\lambda e^{i\delta_\lambda^a} + b_\lambda e^{-i\phi}e^{i\delta_\lambda^b} \ , \end{aligned} \tag{3}$$

where the a_λ and b_λ represent the SM and new physics amplitudes, ϕ is the new-physics weak phase, the $\delta_\lambda^{a,b}$ are the strong phases, and the helicity index λ takes the values $\{0, \|, \perp\}$. Using CPT invariance, the full decay amplitudes can be written as

$$\mathcal{A} = Amp(B \to J/\psi K^*) = A_0 g_0 + A_\| g_\| + i\, A_\perp g_\perp \quad , \tag{4}$$

$$\overline{\mathcal{A}} = Amp(\overline{B} \to J/\psi \overline{K}^*) = \overline{A}_0 g_0 + \overline{A}_\| g_\| - i\, \overline{A}_\perp g_\perp \quad , \tag{5}$$

where the g_λ are the coefficients of the helicity amplitudes written in the linear polarization basis. The g_λ depend only on the angles describing the kinematics [7, 8].

We first consider neutral B decays and assume that the $\overset{(-)}{K}{}^*$ is detected through its decay to $K_S\pi^0$, so that both B_d^0 and $\overline{B}_d^0$ decay to the same final state. With the above equations, the time-dependent decay rates for $\overset{(-)}{B}_d(t) \to J/\psi \overset{(-)}{K}{}^*$ can be written as

$$\Gamma(\overset{(-)}{B}_d(t) \to J/\psi K^*) = e^{-\Gamma t} \sum_{\lambda \le \sigma} \Big(\Lambda_{\lambda\sigma} \pm \Sigma_{\lambda\sigma} \cos(\Delta M t) \mp \rho_{\lambda\sigma} \sin(\Delta M t) \Big) g_\lambda g_\sigma \ . \tag{6}$$

By performing a time-dependent study and angular analysis of the decays $\overset{(-)}{B}_d(t) \to J/\psi \overset{(-)}{K}{}^*$, one can measure the observables $\Lambda_{\lambda\sigma}$, $\Sigma_{\lambda\sigma}$ and $\rho_{\lambda\sigma}$. In terms of the helicity amplitudes $A_0, A_\|, A_\perp$, these can be expressed as follows:

$$\Lambda_{\lambda\lambda} = \frac{|A_\lambda|^2 + |\overline{A}_\lambda|^2}{2} \ , \qquad \Sigma_{\lambda\lambda} = \frac{|A_\lambda|^2 - |\overline{A}_\lambda|^2}{2} \ ,$$

$$\Lambda_{\perp i} = -\mathrm{Im}(A_\perp A_i^* - \overline{A}_\perp \overline{A}_i{}^*) \ , \quad \Lambda_{\|0} = \mathrm{Re}(A_\| A_0^* + \overline{A}_\| \overline{A}_0{}^*) \ ,$$

$$\Sigma_{\perp i} = -\mathrm{Im}(A_\perp A_i^* + \overline{A}_\perp \overline{A}_i{}^*) \ , \quad \Sigma_{\|0} = \mathrm{Re}(A_\| A_0^* - \overline{A}_\| \overline{A}_0{}^*) \ ,$$

$$\rho_{\perp i} = -\mathrm{Re}\Big(\tfrac{q}{p}[A_\perp^* \overline{A}_i + A_i^* \overline{A}_\perp]\Big) \ , \quad \rho_{\perp\perp} = -\mathrm{Im}\Big(\frac{q}{p} A_\perp^* \overline{A}_\perp\Big) \ ,$$

$$\rho_{\|0} = \mathrm{Im}\Big(\tfrac{q}{p}[A_\|^* \overline{A}_0 + A_0^* \overline{A}_\|]\Big) \ , \quad \rho_{ii} = \mathrm{Im}\Big(\frac{q}{p} A_i^* \overline{A}_i\Big) \ , \tag{7}$$

where $i = \{0, \|\}$. In the above, $q/p = \exp(-2\, i\phi_M)$, where ϕ_M is the weak phase in B_d^0–$\overline{B}_d^0$ mixing (in the SM, $\phi_M = \beta$). Note that the direct CP asymmetry a_{dir}^{CP} is proportional to the $\Sigma_{\lambda\lambda}$ observables.

The key observable in the $B \to J/\Psi K^*$ mode is $\Lambda_{\perp i}$. Using the expressions for the amplitudes found in Eq. (3), this can be written as

$$\Lambda_{\perp i} = 2\left[a_\perp b_i \cos(\delta_\perp^a - \delta_i^b) - a_i b_\perp \cos(\delta_\perp^b - \delta_i^a)\right] \sin\phi \ . \tag{8}$$

Even if the strong-phase differences vanish, this observable is still nonzero in the presence of new physics ($\phi \neq 0$), in contrast to the direct CP asymmetry a_{dir}^{CP} given

in Eq. (2). Thus, a complete search for new physics should include the measurement of $\Lambda_{\perp i}$ in addition to a_{dir}^{CP}.

The reason that $\Lambda_{\perp i}$ is proportional to $\cos(\delta_\perp^{a,b} - \delta_i^{b,a})$, rather than $\sin(\delta_\perp^{a,b} - \delta_i^{b,a})$, is that the $\perp$ helicity is CP-odd, while the 0 and $\|$ helicities are CP-even. Thus, $\perp$–0 and $\perp$–$\|$ interferences are CP-odd and switch sign [7, 9, 10, 11] between process and conjugate process. This results in the $\cos(\delta_\perp^{a,b} - \delta_i^{b,a})$ term. Obviously, such interferences will not occur for final states such as $J/\psi K_S$, which have only one helicity state.

As can be seen from Eq. (6), the $\Lambda_{\perp i}$ term is common to both $B_d^0(t)$ and $\overline{B}_d^0(t)$ decay rates. Thus, if one does not distinguish between $B_d^0(t)$ and $\overline{B}_d^0(t)$ decays, and instead simply adds the two rates together, the $\Lambda_{\lambda\sigma}$ terms remain. Note also that these terms are time-independent (i.e. they are not proportional to $\cos\Delta Mt$ or $\sin\Delta Mt$). Therefore, *no tagging or time-dependent measurements are needed to extract* $\Lambda_{\perp i}$! It is only necessary to perform an angular analysis of the final state $J/\psi \overset{(-)}{K}{}^*$, with $\overset{(-)}{K}{}^* \to K_S\pi^0$. Thus, this measurement can even be made at a symmetric B-factory such as CLEO.

The decays $B^\pm \to J/\psi K^{*\pm}$ are even simpler to analyze since no mixing is involved. It is straightforward to see that it is not even necessary to distinguish between B^+ and B^- decays for this measurement. In light of this, one can in principle combine charged and neutral B decays to increase the sensitivity to new physics. One simply performs an angular analysis on all decays in which a J/ψ is produced accompanied by a charged or neutral K^*. A nonzero value of $\Lambda_{\perp i}$ is a smoking-gun signal for new physics.

Now, suppose that $\Lambda_{\perp i}$ is measured to be nonzero. This means that new physics is present, which in turn implies that the measured value of β as extracted from $B_d^0(t) \to J/\psi K_S$ or $B_d^0(t) \to \psi K^*$ is not the true SM value of β. This then raises the following questions. Is it nevertheless possible to obtain the true value of β from measurements of $B_d^0(t) \to \psi K^*$? If not, can one at least constrain the difference $|\beta - \beta^{meas}|$? We explore these questions below.

It is straightforward to show that one cannot extract the true value of β. There are a total of six amplitudes describing $B_d^0(t) \to \psi K^*$ [Eq. (3)]. Experimentally, at best one can measure the magnitudes and relative phases of these six amplitudes, giving 11 measurements. However, there are a total of 13 theoretical parameters describing these amplitudes: 3 a_λ's, 3 b_λ's, 5 strong phase differences, ϕ and β. Since there are more unknown parameters than there are measurements, one cannot obtain any of the unknowns. In particular, it is impossible to extract β.

However, it is still possible to constrain the theoretical parameters. For example, with a bit of algebra one can express b_λ as follows:

$$b_\lambda^2 = \frac{1}{2\sin^2\phi}\left[\Lambda_{\lambda\lambda} - \sqrt{\Lambda_{\lambda\lambda}^2 - \Sigma_{\lambda\lambda}^2}\cos(2\beta_\lambda^{meas} - 2\beta)\right]. \tag{9}$$

The minimum value of b_λ^2 is easy to find:

$$b_\lambda^2 \geq \frac{1}{2}\left[\Lambda_{\lambda\lambda} - \sqrt{\Lambda_{\lambda\lambda}^2 - \Sigma_{\lambda\lambda}^2}\right]. \tag{10}$$

Thus, if direct CP violation is observed ($\Sigma_{\lambda\lambda} \neq 0$), one can place a lower bound on the new-physics amplitude b_λ, and consequently the scale of new physics. The above bound becomes trivial, i.e. $b_\lambda \geq 0$, if all strong phases are quite small, leading to a vanishing value of $\Sigma_{\lambda\lambda}$. However, even if the strong phases vanish, it is still possible to obtain lower bounds on b_λ and $|\beta - \beta^{meas}|$ using measurements of $\Lambda_{\perp i}$ [12].

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