The Golden Modes $B^0 \to J/\psi K_{S,L}$ in the Era of Precision Flavour Physics

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Abstract

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The Golden Modes $B^0 \rightarrow J/\psi K_{S,L}$ in the Era of Precision Flavour Physics

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The $B^0 \rightarrow J/\psi K_{S,L}$ channels are outstanding probes of CP violation. We have a detailed look at the associated Standard-Model uncertainties, which are related to doubly Cabibbo-suppressed penguin contributions, and point out that these usually neglected effects can actually be taken into account unambiguously through the CP asymmetries and the branching ratio of the $B^0 \rightarrow J/\psi K^0$ decay. Using the most recent $B$-factory measurements, we find a negative shift of the extracted value of $\beta$, which softens the tension in the fits of the unitarity triangle. In addition, this strategy can be used to constrain a possible new-physics phase in $B^0-\bar{B}^0$ mixing. The proposed strategy is crucial to fully exploit the tremendous accuracies for the search for this kind of new physics that can be achieved at the LHC and future super-flavour factories.

Keywords: CP violation, non-leptonic $B$ decays

CP-violating effects in $B^0$ decays into CP eigenstates $f$ are studied through time-dependent rate asymmetries:

$$A_{CP}(t; f) = \frac{\Gamma(B^0(t) \rightarrow f) - \bar{\Gamma}(\bar{B}^0(t) \rightarrow f)}{\Gamma(B^0(t) \rightarrow f) + \bar{\Gamma}(\bar{B}^0(t) \rightarrow f)} = C(f) \cos(\Delta M_d t) - S(f) \sin(\Delta M_d t),$$

(1)

where $C(f)$ and $S(f)$ describe direct and mixing-induced CP violation, respectively. The key application is given by $B^0 \rightarrow J/\psi K_{S,L}$ decays, which arise from $b \rightarrow c\bar{s}s$ processes. If we assume the Standard Model (SM) and neglect doubly Cabibbo-suppressed contributions to the $B^0 \rightarrow J/\psi K^0$ amplitude, we obtain

$$C(J/\psi K_{S,L}) \approx 0, \quad S(J/\psi K_{S,L}) \approx -\eta_{S,L} \sin 2\beta,$$

(2)

where $\eta_S = -1$ and $\eta_L = +1$ are the CP eigenvalues of the final states, and $\beta$ is an angle of the unitarity triangle (UT) of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. The usual experimental analyses assume that $\eta_L = +1$ is valid exactly; the most recent data then result in

$$\sin(2\beta)_{J/\psi K^0} = 0.657 \pm 0.024,$$

(3)

which is obtained from the average of the measured $S(J/\psi K_{S,L})$ values [2,3]. It is the purpose of the present letter to critically review this assumption.

Using also data for CP violation in $B^0 \rightarrow J/\psi K^*$ decays [4], $\beta$ can be fixed unambiguously, where the value in [3] corresponds to $\beta = (20.5 \pm 0.9)^\circ$. In Fig. 1 created with the CKMfitter software [5], we show the resulting constraint for the apex of the UT in the $\rho-\eta$ plane of the generalized Wolfenstein parameters [6,7]. Moreover, we include the circle coming from the UT side $R_6 \equiv (1 - \lambda^2/2)|V_{ub}/(\lambda V_{cb})|$, where $\lambda \equiv |V_{us}| = 0.22521 \pm 0.00083[10]$; taking the most recent developments in the determination of $|V_{ub}|$ and $|V_{cb}|$ from semileptonic $B$ decays into account [8], we find $R_6 = 0.423^{+0.015}_{-0.025} \pm 0.029$, where here and in the following the first error comes from experiment and the second from theory. We show also the range corresponding to $\gamma = (65 \pm 10)^\circ$, which is well in accordance with the analyses of the UT in Refs. [9,10] and the information from $B_{d,s} \rightarrow \pi\pi, \pi K, KK$ decays [11]. This angle will be determined with only a few degrees uncertainty thanks to CP violation measurements in pure tree decays at LHCb (CERN). In analogy to $R_6$, the value of $\gamma$ extracted in this way is expected to be very robust with respect to new-physics (NP) effects. In Fig. 1 we can see the tension that is also present in more refined fits of the UT for a couple of years [9,10].

Since $B^0-\bar{B}^0$ mixing is a sensitive probe for NP (see, e.g., [12,13,14]), this effect could be a footprint of such contributions. Provided they are CP-violating, we have

$$\phi_d = 2\beta + \phi_d^{NP},$$

(4)

where $\phi_d$ denotes the $B^0-\bar{B}^0$ mixing phase and $\phi_d^{NP}$ is its NP component. If we assume that NP has a minor impact on the $B^0 \rightarrow J/\psi K^0$ amplitude, the relations in [2] remain valid, with the replacement $2\beta \rightarrow \phi_d$.

Using Fig. 1 the “true” value of $\beta$ can be determined through $R_6$ and tree-level extractions of $\gamma$. We find $\beta^{\text{true}} = (24.9^{+1.0}_{-1.5} \pm 1.9)^\circ$, which is essentially independent of the error on $\gamma$ for a central value around $65^\circ$ and yields $(\sin 2\beta)^{\text{true}} = 0.76^{+0.02+0.04}_{-0.04-0.03}$. Consequently,

$$\phi_d^{J/\psi K^0} - 2\beta^{\text{true}} = -(8.7^{+2.6}_{-3.6} \pm 3.8)^\circ.$$

(5)

Let us now have a critical look at the hadronic SM
uncertainties affecting the extraction of $\phi_d$ from $B^0 \to J/\psi K_{S,L}$. In the SM, we may write \[ A(B^0 \to J/\psi K^0) = (1 - \lambda^2/2) A \left[ 1 + e^{i\phi_2} e^\gamma \right], \] where
\[
A \equiv \lambda^2 A \left[ A_T^{(c)} + A_P^{(c)} - A_P^{(t)} \right] \tag{7}
\]
and
\[
a e^{i\theta} \equiv R_0 \left[ A_P^{(u)} - A_P^{(t)} \right] \tag{8}
\]
are CP-conserving parameters, with $A_T^{(c)}$ and $A_P^{(d)}$ denoting strong amplitudes that are related to tree-diagram-like and penguin topologies (with internal $j \in \{u, c, t\}$ quarks), respectively, while $A \equiv |V_{cb}|^2/\lambda^2 = 0.809 \pm 0.026$ and $\epsilon \equiv \lambda^2/(1 - \lambda^2) = 0.053$ are CKM factors.

Looking at (6), we observe that $ae^{i\theta}$ enters with the tiny parameter $\epsilon$. Therefore, this term is usually neglected, which yields (2). However, $ae^{i\theta}$ suffers from large hadronic uncertainties, and may be enhanced through long-distance effects. As discussed in detail in Ref. [16], the generalization of these expressions to take also the penguin effects into account reads as follows:
\[
\frac{-\Re a S(J/\psi K_{S,L})}{\sqrt{1 - C(J/\psi K_{S,L})^2}} = \sin(\phi_d + \Delta \phi_d), \tag{9}
\]
where
\[
\sin \Delta \phi_d = \frac{2e a \cos \theta \sin \gamma + e^2 a^2 \sin 2\gamma}{N \sqrt{1 - C(J/\psi K_{S,L})^2}} \tag{10}
\]
\[
\cos \Delta \phi_d = \frac{1 + 2e a \cos \theta \cos \gamma + e^2 a^2 \cos 2\gamma}{N \sqrt{1 - C(J/\psi K_{S,L})^2}} \tag{11}
\]
with $N \equiv 1 + 2e a \cos \theta \cos \gamma + e^2 a^2$, so that
\[
\tan \Delta \phi_d = \frac{2e a \cos \theta \sin \gamma + e^2 a^2 \sin 2\gamma}{1 + 2e a \cos \theta \cos \gamma + e^2 a^2 \cos 2\gamma}. \tag{12}
\]
Concerning direct CP violation, we have
\[
C(J/\psi K^0) = -0.003 \pm 0.019, \tag{13}
\]
which is again an average over the $J/\psi K_S$ and $J/\psi K_L$ final states [2, 3]. Consequently, the deviation of the terms $\sqrt{1 - C(J/\psi K_{S,L})^2}$ from one is at most at the level of 0.0002, and is hence completely negligible.

In order to probe the importance of the penguin effects described by $ae^{i\theta}$, we may use a $b \to d\bar{c}c$ transition, as this parameter is here not doubly Cabibbo suppressed [15, 17]. In the following, we will use the decay $B^0 \to J/\psi \pi^0$. In Ref. [18], a similar ansatz was used to constrain the penguin effects in the golden mode. However, the quality of the data has improved such that we go beyond this paper by allowing for $\phi_d^{NP} \neq 0$. Moreover, as we will see below, the current $B$-factory data point already towards a negative value of $\Delta \phi_d$, where mixing-induced CP violation in $B^0 \to J/\psi \pi^0$ is the driving force, thereby reducing the tension in the fit of the UT.

In the SM, we have
\[
\sqrt{2} A(B^0 \to J/\psi \pi^0) = \lambda A' \left[ 1 - a' e^{i\theta'} e^{i\gamma} \right], \tag{14}
\]
where the $\sqrt{2}$ factor is associated with the $\pi^0$ wavefunction, while $A'$ and $a' e^{i\theta'}$ are the counterparts of (7) and (13), respectively. We see now explicitly that – in contrast to (9) – the latter quantity does not enter (14) with the $\epsilon$. The CP asymmetry $A_{CP}(t; J/\psi \pi^0)$ (see [1]) was recently measured by the BaBar (SLAC) [19] and Belle (KEK) [20] collaborations, yielding the following averages [4]:
\[
C(J/\psi \pi^0) = -0.10 \pm 0.13, \tag{15}
\]
\[
S(J/\psi \pi^0) = -0.93 \pm 0.15. \tag{16}
\]
Note that the error of $S(J/\psi \pi^0)$ is that of the HFAG, which is not inflated due to the inconsistency of the data.

The values of these CP asymmetries allow us to calculate $a'$ as functions of $\theta'$. We obtain two relations from $C(J/\psi \pi^0)$ and $S(J/\psi \pi^0)$ ($O = C$ and $S$, respectively),
\[
\left. a' \right|_{O=C} = U_C \sqrt{U_C^2 - V_C^2}, \tag{17}
\]
where
\[
U_C \equiv \cos \theta' \cos \gamma + \sin \theta' \sin \gamma \left( C(J/\psi \pi^0) \right), \quad V_C \equiv 1, \tag{18}
\]
and
\[
\left. a' \right|_{O=S} = \frac{\sin(\phi_d + \gamma) + S(J/\psi \pi^0) \cos \gamma}{\sin(\phi_d + 2\gamma) + S(J/\psi \pi^0)} \cos \theta', \tag{19}
\]
\[
V_S \equiv \frac{\sin \phi_d + S(J/\psi \pi^0)}{\sin(\phi_d + 2\gamma) + S(J/\psi \pi^0)}. \tag{20}
\]
The intersection of the $C(J/\psi \pi^0)$ and $S(J/\psi \pi^0)$ contours fixes then the hadronic parameters $a'$ and $\theta'$ in the SM; when allowing for an additional NP phase, one has to take into account $S(J/\psi K^0)$ together with $S(J/\psi \pi^0)$ in order to have a constraint in the $a' - \theta'$ plane. From $C(J/\psi K^0)$ comes another constraint, which is of the form (17) with the replacements $a' \to e a$ and $\theta' \to 180^\circ + \theta$. It should be stressed that (17) and (20) are valid exactly as these expressions follow from the SM structure of $B^0 \to J/\psi \pi^0$.

Neglecting penguin annihilation and exchange topologies, which contribute to $B^0 \to J/\psi \pi^0$ but have no counterpart in $B^0 \to J/\psi K^0$ and are expected to play a minor rôle (which can be probed through $B_s^0 \to J/\psi \pi^0$), we obtain in the $SU(3)$ limit
\[
a' = a, \quad \theta' = \theta. \tag{21}
\]
Thanks to these relations, we can determine the shift \( \Delta \phi_d \) by means of \([9,13]\) from the data. We expect them to hold to a reasonable accuracy; however, one has to keep in mind that sizable non-factorizable effects may induce \( SU(3) \)-breaking corrections. Their impact on the determination of \( \Delta \phi_d \) can be easily inferred from \([12]\). Neglecting terms of order \( \epsilon^2 \), we have a linear dependence on \( a \cos \theta \). Consequently, corrections to the left-hand side of \([21]\) propagate linearly, while \( SU(3) \)-breaking effects in the strong phases will generally lead to an asymmetric uncertainty for \( \Delta \phi_d \).

Before having a closer look at the picture emerging from the current \( B \)-factory data, let us discuss another constraint which follows from the CP-averaged branching ratios. To this end, we introduce

\[
H = \frac{2}{\epsilon} \left[ \frac{\text{BR}(B_d \to J/\psi \pi^0)}{\text{BR}(B_d \to J/\psi K^0)} \right] \frac{A}{A'}^2 \frac{\Phi_{J/\psi K^0}}{\Phi_{J/\psi \pi^0}} \equiv \frac{1 - 2a' \cos \theta' \cos \gamma + a'^2}{1 + 2a \cos \theta \cos \gamma + \epsilon^2},
\]

where the \( \Phi_{J/\psi P} = \Phi(M_{J/\psi}/M_{B^0}, M_P/M_{B^0}) \) are phase-space factors \([13]\). In order to extract \( H \) from the data, we have to analyze the \( SU(3) \)-breaking corrections to \( |A/A'| \). We assume them to be factorizable, and thus given by the ratio of two form factors, evaluated at \( q^2 = M^2_{J/\psi} \). This ratio has been studied in detail using QCD light-cone sum rules (LCSR) \([21]\). We shall use the latest result for the form factor ratio at \( q^2 = 0 \) \([22,23]\),

\[
\frac{f_{B \to K}^+(0)}{f_{B \to \pi}^+(0)} = 1.38_{-0.10}^{+0.11},
\]

and perform the extrapolation to \( q^2 = M^2_{J/\psi} \) by using a simple BK parametrization \([24]\)

\[
f^+(q^2) = f^+(0) \left[ \frac{M^2_B}{M^2_{J/\psi}} - \frac{M^2_B}{M^2_{J/\psi} - \alpha q^2} \right].
\]

Here \( M_s \) is the mass of the ground state vector meson in the relevant channel and the pole at \( M^2/\alpha \) models the contribution of the hadronic continuum for \( q^2 > M^2_s \). The BK parameter \( \alpha \) has been fitted to the \( B \to \pi \) lattice data to be \( \alpha = 0.53 \pm 0.06 \). Nothing is known about the value of \( \alpha \) for the \( B \to K \) form factor and we shall use the simple assumption that the main \( SU(3) \)-breaking effect is due to the shift of the continuous part of the spectral function from the \( B\pi \) to the BK threshold. This leads to \( \alpha_K = 0.49 \pm 0.05 \), and - extrapolating in this way to \( q^2 = M^2_{J/\psi} \) - we get

\[
\frac{f_{B \to K}^+(M^2_{J/\psi})}{f_{B \to \pi}^+(M^2_{J/\psi})} = 1.34 \pm 0.12.
\]

Using \( \text{BR}(B^0 \to J/\psi K^0) = (8.63 \pm 0.35) \times 10^{-4} \) and \( \text{BR}(B^0 \to J/\psi \pi^0) = (0.20 \pm 0.02) \times 10^{-4} \) \([4]\), we obtain \( H = 1.53 \pm 0.10_{\text{BR}} \pm 0.27_{\text{FF}}, \) where we give the errors induced by the branching ratios and the form-factor ratio. Using \([21]\), we obtain the following relation \([15]\):

\[
C(J/\psi K^0) = -\epsilon HC(J/\psi \pi^0),
\]

which would offer an interesting probe for \( SU(3) \) breaking. However, the value of \( H \) given above yields \( C(J/\psi K^0) = 0.01 \pm 0.01 \), which is consistent with \([13]\), but obviously too small for a powerful test.

If we apply once more \([17]\) with

\[
U_H = \left( \frac{1 + \epsilon H}{1 - \epsilon^2 H} \right) \cos \theta' \cos \gamma \quad \text{and} \quad V_H = \frac{(1 - H)(1 - \epsilon^2 H)},
\]

i.e. \( O = H \), we may again calculate \( a' \) as function of \( \theta' \). In contrast to the CP asymmetries of \( B^0 \to J/\psi \pi^0 \), we have to deal here with \( SU(3) \)-breaking effects, which enter implicitly through the determination of \( H \).

In Fig. 2 we show the fits in the \( \theta' - a' \) plane for the current data with 1 \( \sigma \) ranges. The major implication of \( S(J/\psi \pi^0) = \theta' \in [90^0,270^0] \). Looking at \([8]\), this is actually what we expect. \( S(J/\psi K^0) \) fixes the NP phase essentially to \( (\phi_0)_{J/\psi K^0} - 2\phi_{\text{true}} \) as the NP phase is an \( O(1) \) effect in \( S(J/\psi K^0) \), while the additional SM contribution is suppressed by \( \epsilon \). The negative central value of \( C(J/\psi \pi^0) \) prefers \( \theta' > 180^0 \). The intersection of the \( C(J/\psi \pi^0) \) and \( H \) bands, which falls well into the region \( S(J/\psi \pi^0, J/\psi K^0) \) as well as the \( C(J/\psi K^0) \) region, gives then \( a' \in [0.15,0.67] \) and \( \theta' \in [174,213]^0 \) at the 1 \( \sigma \) level. Note that all three constraints give finally an unambiguous solution for these parameters.
Since the experimental uncertainty of $(\phi_d)_{J/\psi K^0}$ could be reduced to $\sim 0.3^\circ$ at an upgrade of LHCb and an $e^+e^-$ super-$B$ factory, these corrections will be essential. It is interesting to note that the quality of the data will soon reach a level in the era of precision flavour physics where subleading effects, i.e. doubly Cabibbo-suppressed penguin contributions, have to be taken into account. In particular, in the analyses of CP violation in the golden $B^0 \to J/\psi K^0$ modes this is mandatory in order to fully exploit the physics potential for NP searches.

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