Effect of Penguin Operators in the $B^0 \to J/\psi K^0$ CP Asymmetry

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(Received 27 July 2005; published 23 November 2005)

Performing a fit to the available experimental data, we quantify the effect of long-distance contributions from penguin contractions in $B^0 \to J/\psi K^0$ decays. We estimate the deviation of the measured S_{CP} term of the time-dependent CP asymmetry from $\sin 2\beta$ induced by these contributions and by the penguin operators. We find $\Delta S \equiv S_{CP}(J/\psi K) - \sin 2\beta = 0.000 \pm 0.012$ ($[-0.025, 0.024]$@95% probability), an uncertainty much larger than previous estimates and comparable to the present systematic error quoted by the experiments at the B factories.

DOI: 10.1103/PhysRevLett.95.221804 PACS numbers: 13.25.Hw, 12.15.Hh

The measurement of the phase of the B^0-$\bar{B}^0$ mixing amplitude, given by twice the angle β of the unitarity triangle (UT) in the standard model (SM), is one of the main successes of B factories, and a crucial ingredient to test the SM and to look for new physics. The golden mode for this measurement is given by $B^0 \to J/\psi K^0$ decays [1]. These modes give a value of $\sin 2\beta$ which is considered practically free of theoretical uncertainties and thus serves as a benchmark for indirect searches for new physics. Indeed, new physics can reveal itself by comparing different observables—which all determine $\sin 2\beta$ in the SM—to the reference value from the $J/\psi K^0$ modes. For instance, $\sin 2\beta$ can be extracted from the UT fit or from $b \to s$ penguin-dominated modes such as $B^0 \to \phi K_S$ or $B^0 \to \eta' K_S$. Actually, possible hints of a discrepancy are being seen in both cases [2,3].

Impressive progress has been recently achieved at the B factories in the measurement of the coefficient S_{CP} of the time-dependent CP asymmetry in $B^0 \to J/\psi K^0$ decays. The experimental error on S_{CP} has been pushed down to ± 0.028 (statistical) ± 0.020 (systematic) [4]. On the theoretical side, previous estimates of the uncertainty in the extraction of $\sin 2\beta$ from S_{CP} gave results below 10^{-3} [for a recent study, see Ref. [5]] and therefore completely negligible. In this Letter, we reanalyze this issue with a new approach, described in detail below, obtaining a substantially larger uncertainty comparable to the present experimental systematic error.

The decays of neutral B mesons into $J/\psi K^0$ final states are dominated by a tree-level amplitude proportional to $V_{cb} V_{cs}^*$. Assuming the absence of additional contributions with different weak phases, it is possible to extract the value of $\sin 2\beta$ from the coefficient S_{CP} of the time-dependent CP asymmetry in these decays. As already mentioned, the identification of $S_{CP}(J/\psi K_{S/L})$ with $\sin 2\beta$ is affected by a theoretical uncertainty, coming from the presence of additional contributions having a different weak phase and possibly a relative strong phase with respect to the dominant contribution [6]. Using the OPE, we write the expression of the decay amplitudes arranging all the contractions of effective operators into renormalization group invariant parameters [7]. In this way, we have

$$A(B^0 \to J/\psi K^0) = V_{cb}^* V_{cs}(E_2 - P_2) + V_{ub}^* V_{us}(P_2^{\rm GIM} - P_2), \quad (1)$$

where E_2 represents the dominant tree contribution and the other terms are penguin corrections. Although three parameters (E_2, P_2, and $P_2^{\rm GIM}$) enter the amplitude, for the purpose of this Letter they can be treated as two effective parameters $E_2 - P_2$ and $P_2^{\rm GIM} - P_2$. Neglecting the doubly Cabibbo-suppressed combination $P_2^{\rm GIM} - P_2$, a penguin pollution could come from P_2. Even though this contribution might have an impact on the branching ratio, it certainly does not affect the CP asymmetry, since the two amplitudes carry the same weak phase. Conversely, because of the weak phase of V_{ub}, $P_2^{\rm GIM} - P_2$ might produce an effect on S_{CP} and C_{CP}, although the impact on the branching ratio is expected to be very small.

Being doubly Cabibbo suppressed, the value of $P_2^{\rm GIM} - P_2$ is hardly determined from $B \to J/\psi K$ decays alone. Therefore, one needs to extract the range of this parameter from a different decay in order to study the impact of such a subdominant effect on $\sin 2\beta$. Indeed, the induced uncertainty on S_{CP} increases with the upper bound of this range. It is then of the utmost importance to quantify this upper bound in a reliable way. Previous detailed discussions of

TABLE I. Input values used in the analysis. All dimensionful quantities are given in GeV.

$F^{B\to\pi}$	0.27 ± 0.08	$F^{B\to K}/F^{B\to\pi}$	1.2 ± 0.1
$f_{J/\psi}$	0.131	m_B	5.2794
$\bar{\rho}$	0.207 ± 0.038	$\bar{\eta}$	0.341 ± 0.023
A	0.86 ± 0.04	λ	0.2258 ± 0.0014
G_F	1.166×10^{-5}	$\alpha_{\rm em}$	$1/129$

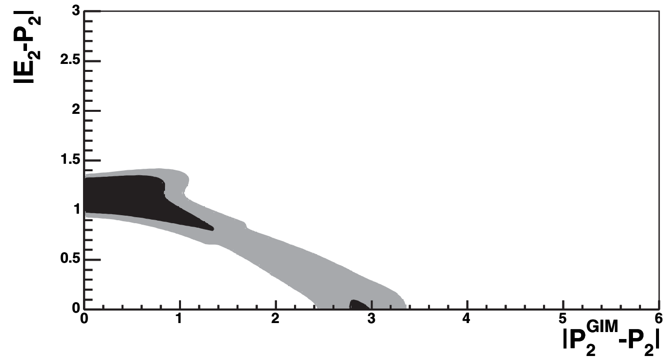

FIG. 1. Correlation between the hadronic parameters $|E_2 - P_2|$ and $|P_2^{\rm GIM} - P_2|$, as obtained from the fit to $B^0 \to J/\psi\pi^0$.

the uncertainty $\Delta S \equiv S_{CP}(J/\psi K) - \sin2\beta$ have estimated the effect of $P_2^{\rm GIM} - P_2$ using the Bander-Silverman-Soni mechanism [8], recently supported by QCD factorization, to express penguin contractions in terms of local four-fermion operators [5]. However, QCD factorization holds only formally for this channel [9]. Clearly, the importance of this measurement for testing the SM and looking for new physics calls for a more general assessment of the theoretical uncertainty. In the present work, we aim at providing a model-independent estimate of ΔS.

To fulfill our task, we proceed in three steps: (i) neglecting $P_2^{\rm GIM} - P_2$, we extract the absolute value of $E_2 - P_2$, using the experimental value of the branching ratio. (ii) We extract $|E_2 - P_2|$, $|P_2^{\rm GIM} - P_2|$, and the relative strong phase δ_P from a fit to the $SU(3)$-related (up to the assumption discussed below) channel $B^0 \to J/\psi\pi^0$. In this decay mode, $P_2^{\rm GIM} - P_2$ is not doubly Cabibbo suppressed and can be determined with good accuracy. At the same time, we can compare the value of $E_2 - P_2$ obtained in the two channels to test the $SU(3)$ invariance and the additional assumption. We can then take the range of $P_2^{\rm GIM} - P_2$ from this fit (at 99.9% probability) as a reliable

TABLE II. Results of the fit of $B^0 \to J/\psi\pi^0$ (see the text for details).

$C_{CP}^{\rm th}$	-0.08 ± 0.16	$C_{CP}^{\rm exp}$	-0.11 ± 0.20
$S_{CP}^{\rm th}$	-0.71 ± 0.18	$S_{CP}^{\rm exp}$	-0.69 ± 0.25
$\lvert E_2 - P_2\rvert$	1.13 ± 0.19	$\lvert P_2^{\rm GIM} - P_2\rvert$	0.44 ± 0.44
δ_P	$(31 \pm 25)°$ $(151 \pm 57)°$		

estimate of the range to be used in $B^0 \to J/\psi K^0$. (iii) We repeat the first step, varying $P_2^{\rm GIM} - P_2$ in the range obtained in the second step. In this way, we get the distribution of S_{CP}, to be compared with the input $\sin2\beta$ to obtain ΔS.

Let us provide some details about the second step. Using the same formalism of Eq. (1) we can write the decay amplitude of $B^0 \to J/\psi\pi^0$ as:

$$A(B^0 \to J/\psi\pi^0) = V_{\rm cb}^* V_{\rm cd}(E_2 - P_2) + V_{\rm ub}^* V_{\rm ud}(P_2^{\rm GIM} - P_2), \quad (2)$$

where all the combinations of Cabibbo-Kobayashi-Maskawa elements now are of the same order of magnitude and the additional (Okubo-Zweig-Iizuka-suppressed) contribution of the emission-annihilation EA_2 parameter has been ignored [11]. Even though the $SU(3)$ symmetry is not exact (so that assuming the parameters to be the same in the two fits would require a difficult estimate of the associated error), we think that $SU(3)$ is good enough to give us a reasonable estimate of the allowed range of $|P_2^{\rm GIM} - P_2|$.

In the three fits, we use as input the determination of the Cabibbo-Kobayashi-Maskawa matrix obtained by the **UT***fit* Collaboration discarding the bound on $\bar\rho$ and $\bar\eta$ from $B^0 \to J/\psi K^0$ [3]. To give a reference normalization factor for all the results, we use the value of E_2, computed using naïve factorization. All the inputs used in the fit are summarized in Table I. We assume flat distributions for $F^{B\to\pi}$ and for $F^{B\to K}/F^{B\to\pi}$ in the ranges specified [12].

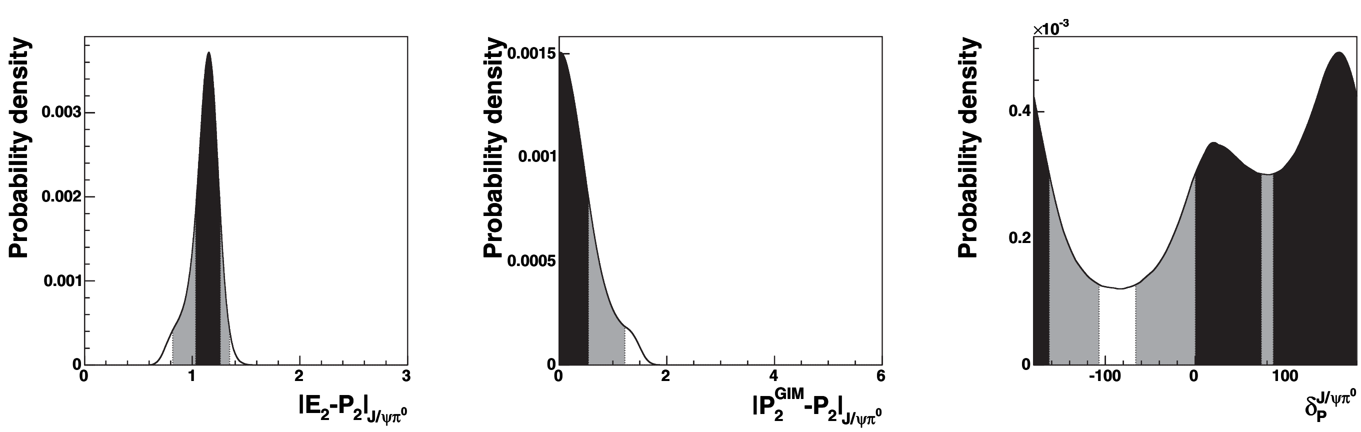

FIG. 2. Output distributions of hadronic parameters $|E_2 - P_2|$ (left), $|P_2^{\rm GIM} - P_2|$ (middle), and δ_P (right), as obtained from the fit to $B^0 \to J/\psi\pi^0$ with the cut $|P_2^{\rm GIM} - P_2| < 2|E_2 - P_2|$ (see the text for details).

TABLE III. Results of the fit of $B^0 \to J/\psi\pi^0$ with the cut $|P_2^{\rm GIM} - P_2| < 2|E_2 - P_2|$ (see the text for details).

$C_{CP}^{\rm th}$	-0.08 ± 0.15	$C_{CP}^{\rm exp}$	-0.11 ± 0.20
$S_{CP}^{\rm th}$	-0.75 ± 0.15	$S_{CP}^{\rm exp}$	-0.69 ± 0.25
$\lvert E_2 - P_2\rvert$	1.15 ± 0.11	$\lvert P_2^{\rm GIM} - P_2\rvert$	0.27 ± 0.27
δ_P	$(37 \pm 37)^\circ \cup (145 \pm 52)^\circ$		

Using the experimental value of BR $(B^0 \to J/\psi K^0)$, we bound the absolute value of $E_2 - P_2$ [13]. Using the statistical method of **UT***fit* [14], we assign a flat *a priori* distribution to the absolute value $|E_2 - P_2|$ in a range large enough to fully include the region where the *a posteriori* distribution is nonvanishing. In this way, we reproduce the experimental value of the branching ratio with an indication of a significant effect of nonfactorizable corrections in $|E_2 - P_2|$, as already noted in [15]. We obtain $|E_2 - P_2| = 1.44 \pm 0.05$. Notice that, in the single-amplitude approximation used in this first step, the predicted C_{CP} is exactly vanishing while S_{CP} is, as expected, equal to the input value for $\sin 2\beta$ ($S_{CP} = 0.729 \pm 0.042$).

We now extract $P_2^{\rm GIM} - P_2$ from $B^0 \to J/\psi\pi^0$. For this fit, we use the same approach but we retain in the amplitude $|E_2 - P_2|$, $|P_2^{\rm GIM} - P_2|$ and the relative strong phase δ_P. Together with the experimental information from the branching ratio and C_{CP}, we impose the constraint coming from S_{CP} [16]. We allow $|E_2 - P_2|$ and $|P_2^{\rm GIM} - P_2|$ to vary in a range larger than the support of the output distributions, and $\delta_P \in [-\pi, \pi]$. The results are given in Table II.

As can be seen from the correlation plot in Fig. 1, two solutions are possible, with $|E_2 - P_2|$ and $|P_2^{\rm GIM} - P_2|$ exchanging roles. Comparing the results of this fit with the value for $|E_2 - P_2|$ obtained from $B \to J/\psi K^0$, it is evident that only the favored solution (corresponding to $|E_2 - P_2| = 1.13 \pm 0.19$ quoted in Table II) is compatible with $SU(3)$ and with our expectations on the relative sizes of E_2, P_2, and $P_2^{\rm GIM}$. Assuming, therefore, that this ambiguity is resolved in favor of this solution, we repeated the fit with the cut $|P_2^{\rm GIM} - P_2| < 2|E_2 - P_2|$. The results are presented in Fig. 2 and in Table III. We underline the good agreement between this result and the determination of $|E_2 - P_2|$ from $B \to J/\psi K^0$, and we conclude that there is no evidence of $SU(3)$-breaking effects beyond the expected level of ~20%–30%. We thus decide to use as input for the determination of ΔS in $B^0 \to J/\psi K^0$ a uniform distribution in the range $[0, 1.22]$ for $|P_2^{\rm GIM} - P_2|$. This corresponds to the 99.9% probability range for $|P_2^{\rm GIM} - P_2|$ obtained in the fit.

Repeating the fit of $B^0 \to J/\psi K^0$ with the additional contribution of $P_2^{\rm GIM} - P_2$ in the range obtained above, we get the results in Table IV. We also show in Fig. 3 the output probability density function for $|P_2^{\rm GIM} - P_2|$ and δ_P, together with the difference ΔS. The result is

$$\Delta S = 0.000 \pm 0.012([-0.025, 0.024]@95\%\text{prob.}). \quad (3)$$

Notice that, as anticipated, $|P_2^{\rm GIM} - P_2|$ and δ_P are poorly determined in this fit. In particular, Fig. 3 shows how the bound on the range of $|P_2^{\rm GIM} - P_2|$ from $B^0 \to J/\psi\pi^0$ is extremely effective in cutting out a long tail at large values of $|P_2^{\rm GIM} - P_2|$, thus reducing the uncertainty on ΔS. Without this additional information, $|P_2^{\rm GIM} - P_2|$ could have reached much larger values and correspondingly we would have obtained values of ΔS of order one.

Had we boldly borrowed from the previous step not only the range but also the shape of $|P_2^{\rm GIM} - P_2|$, we would have constrained the deviation of S_{CP} from $\sin 2\beta$ even more, obtaining a value $\Delta S = 0.018 \pm 0.009$. However, given the theoretical uncertainties related to the $SU(3)$ breaking and the neglected emission-annihilation contribution, this result is quoted for illustration only, and should not be used for phenomenology. A more reliable result can be obtained by adding a 100% error to the $SU(3)$ relation between the hadronic parameters in the two channels. In this way we obtain

$$\Delta S = 0.000 \pm 0.014([-0.023, 0.022]@95\%\text{prob.}),$$

fully compatible with our main result in Eq. (3). We conclude that our approach of extracting from $B \to J/\psi\pi^0$ the *range* of $|P_2^{\rm GIM} - P_2|$ to be used in $B \to J/\psi K^0$ is fully consistent and does not sizably overestimate the error in ΔS. We also stress the importance of improving experimental results on $B \to J/\psi\pi^0$ in order to reduce the uncertainty in the extraction of $\sin 2\beta$ from $B \to J/\psi K^0$ decays.

TABLE IV. Results of the fit of $B^0 \to J/\psi K^0$ (see the text for details). $S_{CP}^{\rm out}$ ($S_{CP}^{\rm in}$) represent the input (output) values of S_{CP}, respectively.

$C_{CP}^{\rm th}$	0.00 ± 0.02	$C_{CP}^{\rm exp}$	-0.01 ± 0.04
$S_{CP}^{\rm out}$	0.73 ± 0.05	$S_{CP}^{\rm in}$	0.73 ± 0.04
$\lvert E_2 - P_2\rvert$	1.44 ± 0.05	$\lvert P_2^{\rm GIM} - P_2\rvert$, δ_P: see text	

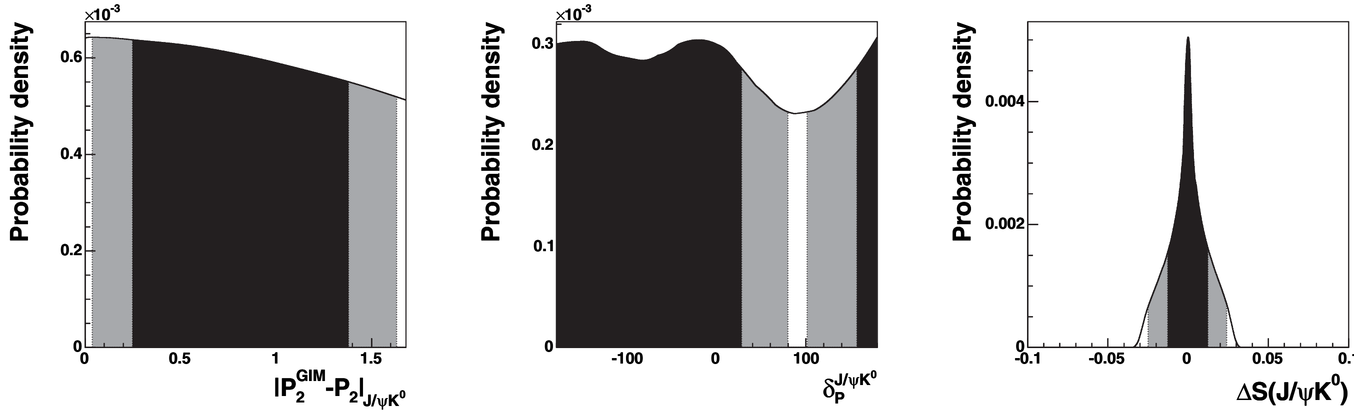

FIG. 3. Output distributions of hadronic parameters $|P_2^{\rm GIM} - P_2|$ (left), δ_P (middle), and ΔS (right).

Our estimate of the error in ΔS is more than an order of magnitude larger than previous estimates and comparable to the present experimental systematic error. This uncertainty should therefore be included in the value and error of $\sin 2\beta$ extracted from $S_{CP}^{\rm exp}$. We believe that additional experimental information on the decay modes considered in our analysis will allow to reduce the uncertainty in ΔS using the new method sketched in this Letter and without any need of additional theoretical input.

This work has been supported in part by Bundesministerium für Bildung und Forschung under the Contract No. 05HT4WOA/3 and by the EU network "The Quest for Unification" under the Contract No. MRTN-CT-2004-503369.

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