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Measurement of direct CP violation in the $B_s^0 \to K^-\pi^+$ decay

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Summary. — In this paper the measurement of direct CP violation in $B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays performed by the LHCb experiment is reviewed. Using pp collision data, corresponding to an integrated luminosity of $1.0\,\text{fb}^{-1}$, collected by LHCb at a center-of-mass energy of 7 TeV, LHCb measured: $A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$. Furthermore, LHCb provided an improved determination of direct CP violation in $B^0 \to K^+\pi^-$ decays $A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$.

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PACS 13.25.Hw – Decays of bottom mesons.

1. – Introduction

The study of CP violation in charmless charged two-body decays of neutral B mesons provides stringent tests of the Cabibbo-Kobayashi-Maskawa (CKM) picture in the Standard Model (SM) [1, 2], and is a sensitive probe to search for the presence of non-SM physics [3-9]. However, quantitative SM predictions for CP violation in these decays are challenging because of the presence of hadronic factors in the decay amplitudes, which cannot be accurately calculated from quantum chromodynamics (QCD) at present. It is crucial to combine several measurements from such two-body decays, exploiting approximate flavor symmetries in order to cancel the unknown parameters. An experimental program for measuring the properties of these decays has been carried out during the last decade at the B factories [10,11] and at the Tevatron [12], and is now continued by LHCb with increased sensitivity. The discovery of direct CP violation in the $B^0 \to K^+\pi^-$ decay dates back to 2004 [13,14]. This observation raised the question of whether the effect could be accommodated by the SM or was due to non-SM physics. A simple but powerful model-independent test was proposed in refs. [4, 7], which required the measurement of direct CP violation in the $B_s^0 \to K^-\pi^+$ decay.

In this paper the measurements of direct CP-violating asymmetries in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays using pp collision data, corresponding to an integrated luminosity of $1.0\,\text{fb}^{-1}$, collected with the LHCb detector at a center-of-mass energy of 7 TeV are reviewed [15].

2. – Detector, trigger and event selection

The LHCb detector [16] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The trigger [17] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage that applies a full event reconstruction. The hadronic hardware trigger selects large transverse energy clusters in the hadronic calorimeter. The software trigger requires a two-, three-, or four-track secondary vertex with a large sum of the transverse momenta (p_{T}) of the tracks and a significant displacement from the primary pp interaction vertices (PVs). At least one track should have p_{T} and impact parameter (d_{IP}) χ^2 with respect to all PVs exceeding given thresholds. The d_{IP} is defined as the distance between the reconstructed trajectory of a particle and a given pp collision vertex, and the d_{IP} χ^2 is the difference between the χ^2 of the PV reconstructed with and without the considered track. A multivariate algorithm is used for the identification of secondary vertices consistent with the decay of a b hadron. In order to improve the trigger efficiency on hadronic two-body decays, a dedicated two-body software trigger is also used. This trigger imposes requirements on the following quantities: the quality of the online reconstructed tracks, their p_{T} and d_{IP}; the distance of closest approach (d_{CA}) of the decay products of the B meson candidate, its p_{T} (p_{T}^B), d_{IP} (d_{IP}^B) and the decay time in its rest frame, computed under the $\pi\pi$ hypothesis ($t_{\pi\pi}$).

More selective requirements are applied offline. Two sets of criteria have been optimized with the aim of minimizing the expected statistical uncertainty either on $A_{CP}(B^0 \to K^+\pi^-)$ or on $A_{CP}(B_s^0 \to K^-\pi^+)$. In addition to the requirements on the kinematic variables already used in the trigger, requirements on the largest p_{T} and d_{IP} of the B daughter particles are applied.

In the case of $B_s^0 \to K^-\pi^+$ decays, a tighter selection is needed to achieve stronger rejection of combinatorial background. This is because the probability for a b quark to form a B_s^0 meson, which subsequently decays to the $K^-\pi^+$ final state, is one order of magnitude smaller than that to form a B^0 meson decaying to $K^+\pi^-$ [18].

3. – Particle identification

The two samples are then subdivided according to the various final states using the particle identification (PID) provided by the two ring-imaging Cherenkov (RICH)

TABLE I. – *Summary of selection criteria adopted for the measurement of* $A_{CP}(B^0 \to K^+\pi^-)$ *and* $A_{CP}(B_s^0 \to K^-\pi^+)$. *More details on the event selection can be found in ref.* [19].

Variable	$A_{CP}(B^0 \to K^+\pi^-)$	$A_{CP}(B_s^0 \to K^-\pi^+)$
Track quality χ^2/ndf	< 3	< 3
Track p_{T} [GeV/c^2]	> 1.1	> 1.2
Track d_{IP} [mm]	> 0.15	> 0.20
$\max(p_{\mathrm{T}}^K, p_{\mathrm{T}}^\pi)$ [GeV/c^2]	> 2.8	> 3.0
$\max(d_{\mathrm{IP}}^K, d_{\mathrm{IP}}^\pi)$ [mm]	> 0.3	> 0.4
d_{CA} [mm]	< 0.08	< 0.08
p_{T}^B [GeV/c^2]	> 2.2	> 2.4
d_{IP}^B [mm]	< 0.06	> 0.06
$t_{\pi\pi}$ [ps]	> 0.9	> 1.5

detectors. Two sets of PID selection criteria are applied: a loose set optimized for the measurement of $A_{CP}(B^0 \to K^+\pi^-)$ and a tight set for that of $A_{CP}(B_s^0 \to K^-\pi^+)$. More details on the event selection can be found in table I.

To determine the amount of background events from other two-body b-hadron decays with a misidentified pion or kaon (cross-feed background), the relative efficiencies of the RICH PID selection criteria must be determined. This is achieved by means of a data-driven method that uses $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\Lambda \to p\pi^-$ decays as control samples. The production and decay kinematic properties of the $D^0 \to K^-\pi^+$ and $\Lambda \to p\pi^-$ channels differ from those of the b-hadron decays under study. Since the RICH PID information is momentum dependent, a calibration procedure is performed by reweighting the distributions of the PID variables obtained from the calibration samples, in order to match the momentum distributions of signal final-state particles observed in data.

4. – Fits to the $B_{(s)}^0 \to K\pi$ invariant-mass spectra

Signal yields of every decay channels and raw asymmetries in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays are extracted from fits to the invariant-mass spectra of offline selected candidates. For each selection the fits are performed simultaneously to all the final state hypotheses in order to deal with cross-feed backgrounds, *i.e.* signal decay channels where one or both final-state particles have been misidentified. In this way, taking into account the appropriate PID efficiency factors, it is possible to constrain the yield of each cross-feed background channel to the yield of the corresponding signal component.

The $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ signal components are described by double Gaussian functions convolved with a function that describes the effect of final-state radiation [20]. The background due to partially reconstructed three-body B decays is parameterized by means of two ARGUS functions [21] convolved with a Gaussian resolution function. The combinatorial background is modeled by an exponential function and the shapes of the cross-feed backgrounds, mainly due to $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

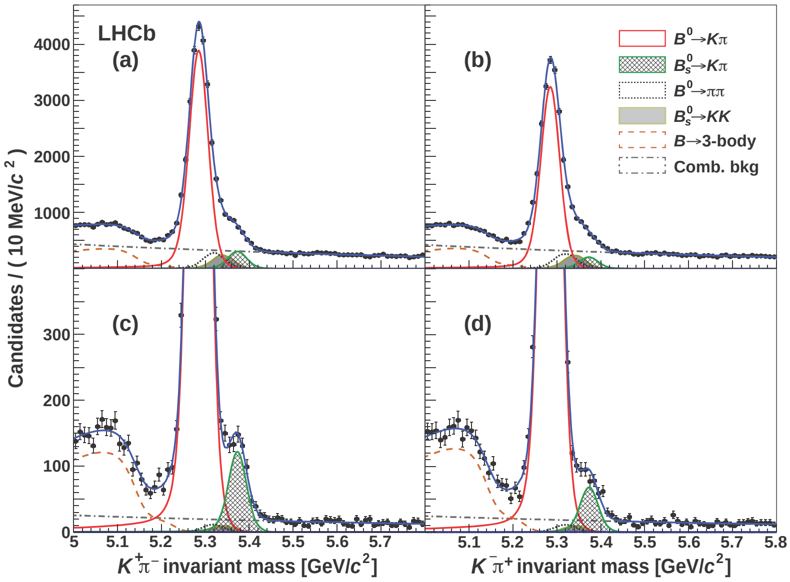

Fig. 1. – Invariant-mass spectra obtained using the event selection adopted for the best sensitivity on (a, b) $A_{CP}(B^0 \to K^+\pi^-)$ and (c, d) $A_{CP}(B_s^0 \to K^-\pi^+)$. Panels (a) and (c) represent the $K^+\pi^-$ invariant mass, whereas panels (b) and (d) represent the $K^-\pi^+$ invariant mass. The results of the unbinned maximum-likelihood fits are overlaid. The main components contributing to the fit model are also shown.

decays with one misidentified particle in the final state, are obtained from simulation. The cross-feed background yields are determined from the $\pi^+\pi^-$, K^+K^-, $p\pi^-$ and pK^- mass spectra, using events passing the same selection as the signal and taking into account the appropriate PID efficiency factors. The $K^+\pi^-$ and $K^-\pi^+$ mass spectra for the events passing the two selections are shown in fig. 1. The average invariant-mass resolution is about $22\,\text{MeV}/c^2$.

4·1. *Determination of signal yields.* – From the two mass fits the signal yields $N(B^0 \to K^+\pi^-) = 41\,420 \pm 300$ and $N(B_s^0 \to K^-\pi^+) = 1065 \pm 55$ are determined. The observed raw asymmetries are

$$A_{\text{raw}}(B^0 \to K^+\pi^-) = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.091 \pm 0.006,$$

$$A_{\text{raw}}(B_s^0 \to K^-\pi^+) = \frac{N(\overline{B}_s^0 \to K^+\pi^-) - N(B_s^0 \to K^-\pi^+)}{N(\overline{B}_s^0 \to K^+\pi^-) + N(B_s^0 \to K^-\pi^+)} = 0.28 \pm 0.04,$$

where the uncertainties are statistical only. In order to derive the CP asymmetries from the observed raw asymmetries, effects induced by the detector acceptance and event reconstruction, as well as due to interactions of final-state particles with the detector material, must be accounted for. Furthermore, the possible presence of a $B_{(s)}^0 - \overline{B}_{(s)}^0$ production asymmetry must also be considered.

5. – Corrections to the raw CP asymmetries

The physical CP asymmetries are related to the raw asymmetries by

$$A_{CP}(B^0 \to K\pi) = A_{\text{raw}}(B^0 \to K\pi) - A_{\text{D}}(K\pi) + \kappa_d A_{\text{P}}(B^0) \tag{1}$$

and

$$A_{CP}(B_s^0 \to K\pi) = A_{\text{raw}}(B_s^0 \to K\pi) - A_{\text{D}}(K\pi) + \kappa_s A_{\text{P}}(B_s^0), \tag{2}$$

where $A_{\text{D}}(K\pi)$ is the asymmetry between the reconstruction efficiencies of $K^+\pi^-$ and $K^-\pi^+$ final states, $A_{\text{P}}(B^0_{(s)})$ is the asymmetry between the production rates of B and $\overline{B}$ mesons,, and the factors κ_d and κ_s are dilution factors depending on the decay time evolution of B mesons and on the decay time acceptance introduced by the event selection. Their values also depend on event reconstruction and selection, and are $\kappa_d = 0.303 \pm 0.005$ and $\kappa_s = -0.033 \pm 0.003$ [19]. The factor κ_s is ten times smaller than κ_d, owing to the large B_s^0 oscillation frequency.

5˙1. *Detection asymmetry.* – The detection asymmetry $A_{\text{D}}(K\pi)$ is measured from data using $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $D^{*+} \to D^0(K^-K^+)\pi^+$ decays. The combination of the time-integrated raw asymmetries of these two decay modes is used to disentangle the various contributions to each raw asymmetry. The presence of open charm production asymmetries arising from the primary pp interaction constitutes an additional complication. The following equations relating the observed raw asymmetries to the physical CP asymmetries can be written:

$$A^*_{\text{raw}}(K\pi) = A_{CP}(K\pi) + A^*_{\text{D}}(\pi_s) + A^*_{\text{D}}(K\pi) + A_{\text{P}}(D^*), \tag{3}$$

$$A^*_{\text{raw}}(KK) = A_{CP}(KK) + A^*_{\text{D}}(\pi_s) + A_{\text{P}}(D^*), \tag{4}$$

where $A^*_{\text{raw}}(K\pi)$ and $A^*_{\text{raw}}(KK)$ are the time-integrated raw asymmetries in D^*-tagged $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ decays, respectively; $A_{CP}(K\pi)$ and $A_{CP}(KK)$ are the physical $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ CP asymmetries; $A^*_{\text{D}}(K\pi)$ is the detection asymmetry in reconstructing $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$ decays; $A^*_{\text{D}}(\pi_s)$ is the detection asymmetry in reconstructing positively and negatively charged pions originated from D^* decays; and $A_{\text{P}}(D^*)$ is the production asymmetry for prompt charged D^* mesons. In eq. (3) $A_{CP}(K\pi)$, the CP asymmetry in the Cabibbo-favored $D^0 \to K^-\pi^+$ decay is neglected [22]. By subtracting eqs. (3) and (4), one obtains

$$A^*_{\text{raw}}(K\pi) - A^*_{\text{raw}}(KK) = A^*_{\text{D}}(K\pi) - A_{CP}(KK). \tag{5}$$

Once the raw asymmetries are measured, this equation determines unambiguously the detection asymmetry $A^*_{\text{D}}(K\pi)$, using the world average for the CP asymmetry of the $D^0 \to K^-K^+$ decay. Since the measured value of the time-integrated asymmetry depends on the decay-time acceptance, the existing measurements of $A_{CP}(KK)$ [23-25] are corrected for the difference in acceptance with respect to LHCb [26]. This leads to the value $A_{CP}(KK) = (-0.24 \pm 0.18)\%$. Furthermore, B meson production and decay kinematic properties differ from those of the D decays being considered, and different trigger and selection algorithms are applied. In order to correct the raw asymmetries of B decays, using the detection asymmetry $A^*_{\text{D}}(K\pi)$ derived from D decays, a reweighting

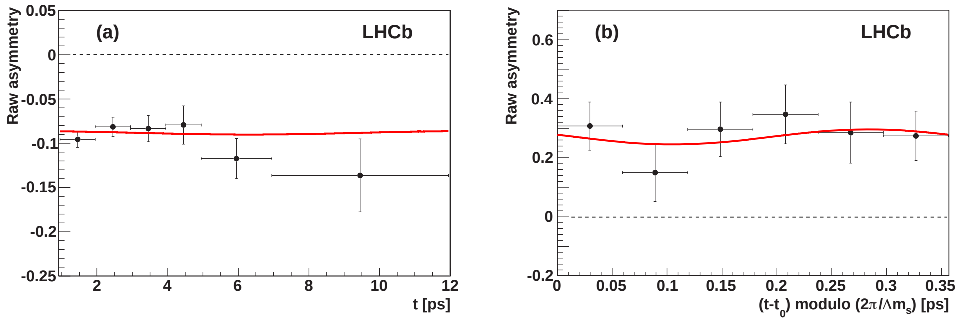

Fig. 2. – Raw asymmetries as a function of the decay time for (a) $B^0 \to K^+\pi^-$ and (b) $B_s^0 \to K^-\pi^+$ decays. In (b), the offset $t_0 = 1.5\,\mathrm{ps}$ corresponds to the minimum value of the decay time required by the $B_s^0 \to K^-\pi^+$ event selection. The curves represent the asymmetry projections of fits to the decay time spectra.

procedure is needed. The D^0 momentum, transverse momentum and azimuthal angle in $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ decays are reweighted, to match the respective $B^0_{(s)}$ distributions in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays. The raw asymmetries are determined by means of χ^2 fits to the reweighted $\delta m = M_{D^*} - M_{D^0}$ distributions, where M_{D^*} and M_{D^0} are the reconstructed D^* and D^0 candidate invariant masses, respectively.

The instrumental asymmetries $A_{\mathrm{D}}(K\pi) = (-1.15\pm0.23)\%$ for the $B^0 \to K^+\pi^-$ decay and $A_{\mathrm{D}}(K\pi) = (-1.22 \pm 0.21)\%$ for the $B_s^0 \to K^-\pi^+$ decay are obtained.

5˙2. *Production asymmetry*. – Production asymmetries are determined by studying the decay time spectra of $B^0_{(s)} \to K\pi$. In the presence of a production asymmetry, the untagged decay time spectrum exhibits an oscillatory behaviour whose amplitude is related to the size of the production asymmetry.

$$\mathcal{A}(t) \approx A_{CP} + A_{\mathrm{D}} + A_{\mathrm{P}} \cos\left(\Delta m_{d(s)} t\right). \tag{6}$$

By studying the full time-dependent decay rate it is then possible to determine A_{P} unambiguously.

In order to measure the production asymmetry A_{P} for B^0 and B_s^0 mesons, fits to the decay time spectra of the B candidates, separately for the events passing the two selections are performed. The B^0 production asymmetry is determined from the sample obtained applying the selection optimized for the measurement of $A_{CP}(B^0 \to K^+\pi^-)$, whereas the B_s^0 production asymmetry is determined from the sample obtained applying the selection optimized for the measurement of $A_{CP}(B_s^0 \to K^-\pi^+)$. The values $A_{\mathrm{P}}(B^0) = (0.1 \pm 1.0)\%$ and $A_{\mathrm{P}}(B_s^0) = (4 \pm 8)\%$ are obtained. Figure 2 shows the raw asymmetries as a function of the decay time, obtained by performing fits to the invariant-mass distributions of events restricted to independent intervals of the B candidate decay times.

6. – Systematic uncertainties

Systematic uncertainties on the asymmetries are related to PID calibration, modeling of the signal and background components in the maximum-likelihood fits and

TABLE II. – *Systematic uncertainties on $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to K^-\pi^+)$. The total systematic uncertainties are obtained by summing the individual contributions in quadrature.*

Systematic uncertainty	$A_{CP}(B^0 \to K^+\pi^-)$	$A_{CP}(B_s^0 \to K^-\pi^+)$
PID calibration	0.0006	0.0012
Final state radiation	0.0008	0.0020
Signal model	0.0001	0.0064
Combinatorial background	0.0004	0.0042
Three-body background	0.0005	0.0027
Cross-feed background	0.0010	0.0033
Detection asymmetry	0.0025	0.0023
Total	0.0029	0.0094

instrumental charge asymmetries. An imperfect determination of the PID efficiencies may alter the estimated amount of cross-feed backgrounds under the signal peaks. The maximum likelihood fits have been performed altering the relative PID efficiencies according to their uncertainties. An estimate of the systematic error due to an incorrect description of the final-state radiation is determined by varying in a wide range the value of the parameter governing the amount of emitted radiation. The possibility of an incorrect description of the signal mass model is investigated by replacing the double Gaussian function with the sum of three Gaussian functions, where the third component has fixed fraction (5%) and width ($50\,\mathrm{MeV}/c^2$), and is aimed at describing long tails, as observed in simulation. For the modeling of the combinatorial background component, the fit is repeated using a straight line. Finally, for the case of the cross-feed backgrounds, two distinct systematic uncertainties are estimated: one due to a relative bias in the mass scale of the simulated distributions with respect to the signal distributions in data, and another accounting for the difference in mass resolution between simulation and data. All shifts from the relevant baseline values are accounted for as systematic uncertainties. Systematic uncertainties related to the determination of detection asymmetries are calculated by summing in quadrature the respective uncertainties on $A_\Delta(B^0 \to K^+\pi^-)$ and $A_\Delta(B_s^0 \to K^-\pi^+)$ with an additional uncertainty of 0.10%, accounting for residual differences in the trigger composition between signal and calibration samples. The systematic uncertainties for $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to K^-\pi^+)$ are summarized in table II.

7. – Conclusions

Applying the corresponding corrections to the raw asymmetries obtained from the invariant-mass fits, the direct CP-violating asymmetries in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays have been measured to be [15]

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\mathrm{stat}) \pm 0.003\,(\mathrm{syst}),$$
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst}).$$

where the first error is statistical and the second is systematic.

TABLE III. – *Measurements of the direct CP asymmetries for the $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays.*

	BaBar [10]	Belle [11]	CDF [27]	LHCb [19]
$A_{CP}(B^0)$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.083 \pm 0.013 \pm 0.003$	$-0.088 \pm 0.011 \pm 0.008$
$A_{CP}(B_s^0)$	–	–	$0.22 \pm 0.07 \pm 0.02$	$0.27 \pm 0.08 \pm 0.02$

Dividing the central values by the sum in quadrature of statistical and systematic uncertainties, the significances of the measured deviations from zero are 10.5σ and 6.5σ, respectively. The former is the most precise measurement of $A_{CP}(B^0 \to K^+\pi^-)$ to date, whereas the latter represents the first observation of CP violation in decays of B_s^0 mesons with significance exceeding 5σ. Both measurements are in good agreement with previous measurements, as shown in table III.

These results allow a stringent test of the validity of the relation between $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to K^-\pi^+)$ in the SM given in ref. [7] as

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0, \tag{7}$$

where $\mathcal{B}(B^0 \to K^+\pi^-)$ and $\mathcal{B}(B_s^0 \to K^-\pi^+)$ are CP-averaged branching fractions, and τ_d and τ_s are the B^0 and B_s^0 mean lifetimes, respectively. Using additional results for $\mathcal{B}(B^0 \to K^+\pi^-)$ and $\mathcal{B}(B_s^0 \to K^-\pi^+)$ [18] and the world averages for τ_d and τ_s [28], one obtains $\Delta = -0.02 \pm 0.05 \pm 0.04$, where the first uncertainty is from the measurements of the CP asymmetries and the second is from the input values of the branching fractions and the lifetimes. No evidence for a deviation from zero of Δ is observed with the present experimental precision.

* * *

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