

Observation of CP Violation in $B^0 \rightarrow J/\psi\rho(770)^0$ DecaysR. Aaij *et al.*^{*}
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The time-dependent CP asymmetry in $B^0 \rightarrow J/\psi\rho(770)^0$ decays is measured using proton-proton collision data corresponding to an integrated luminosity of 6 fb^{-1} , collected with the LHCb detector at a center-of-mass energy of 13 TeV during the years 2015–2018. The CP -violation parameters for this process are determined to be $2\beta_{\text{eff}}^{\text{eff}} = 0.710 \pm 0.084 \pm 0.051 \text{ rad}$ and $|\lambda| = 1.019 \pm 0.034 \pm 0.024$, where the first uncertainty is statistical and the second systematic. This constitutes the first observation of time-dependent CP violation in $B^0 \rightarrow J/\psi\rho(770)^0$ decays. Assuming approximate SU(3) flavor symmetry, these results are combined with the previous consistent LHCb measurement to set the most stringent constraint on the penguin contribution, $\Delta\phi_s$, to the CP -violating phase ϕ_s in $B_s^0 \rightarrow J/\psi\phi(1020)$ decays, yielding $\Delta\phi_s = 5.0 \pm 4.6 \text{ mrad}$.

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Studies of CP violation in B mesons are essential for understanding the matter–antimatter asymmetry in the Universe [1,2]. This phenomenon was first observed in B^0 meson by the BABAR [3] and Belle [4] experiments. Such measurements play a vital role in testing the standard model (SM) and exploring new physics phenomena. The CP -violating phase associated with the B_s^0 – $\bar{B}_s^0$ mixing process, ϕ_s , is a key observable sensitive to contributions of new particles in the mixing [5]. In the SM, its value at tree level is precisely determined by a global fit to experimental data to be $-37.6^{+0.6}_{-0.5} \text{ mrad}$ [6]. It is measured through the interference between B_s^0 – $\bar{B}_s^0$ mixing and subsequent decays via $b \rightarrow c\bar{c}s$ transitions, neglecting subleading electroweak-loop (penguin) contributions. Current measurements in the golden decay channel $B_s^0 \rightarrow J/\psi\phi(1020)$ yield an average value of $\phi_s = -50 \pm 17 \text{ mrad}$ [7–9], with an experimental uncertainty now comparable to the possible shift, $\Delta\phi_s$, due to the neglected penguin contamination with a different weak phase from the leading tree amplitude [10–14]. Thus, a thorough understanding of the penguin effects becomes mandatory for precision tests of the SM.

Long-distance nonperturbative effects in $B_s^0 \rightarrow J/\psi\phi(1020)$ decays prevent a precise theoretical calculation of $\Delta\phi_s$. An estimate of $\Delta\phi_s$ can be obtained using CP -violation parameters in $b \rightarrow c\bar{c}s$ and $b \rightarrow c\bar{c}d$ decays employing SU(3) flavor symmetry, assuming that the

corresponding ratios of the hadronic amplitudes of the penguin and tree decay topologies are identical [10–14]. The decay $B^0 \rightarrow J/\psi\rho(770)^0$, which proceeds via the Cabibbo-suppressed $b \rightarrow c\bar{c}d$ transition, serves as a control channel due to its enhanced sensitivity to the hadronic parameters of penguin contributions relative to $B_s^0 \rightarrow J/\psi\phi(1020)$ [13].

The measured CP -violation parameters in $B^0 \rightarrow J/\psi\rho(770)^0$ and $B^0 \rightarrow J/\psi K_S^0$ decays allow for a determination of the penguin contributions in the former, which is used to estimate the penguin shift $\Delta\phi_s$. This estimate was performed by the LHCb collaboration using proton-proton (pp) collision data collected in 2011–2012 (Run 1) at center-of-mass energies of $\sqrt{s} = 7$ and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1} [15]. The obtained result of $\Delta\phi_s = 0.9 \pm 9.8 \text{ mrad}$ remains insufficiently precise to constrain the penguin effects on the ϕ_s measurement. This Letter reports an updated study of CP violation in $B^0 \rightarrow J/\psi\rho(770)^0$ decays, with $J/\psi \rightarrow \mu^+\mu^-$ and $\rho(770)^0 \rightarrow \pi^+\pi^-$, using pp collision data collected by the LHCb experiment during 2015–2018 (Run 2), corresponding to an integrated luminosity of 6 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$, which leads to the first observation of CP violation in this process. These results are combined with those of the Run 1 measurement [15] to determine $\Delta\phi_s$. As the analysis procedures for the $B^0 \rightarrow J/\psi\pi^+\pi^-$ and $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ decays are similar, this Letter largely follows the procedures described in Refs. [15,16].

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [17,18]. Simulated events are generated with the software described in Refs. [19–22]. They are tuned to match data-taking conditions and are used to study selection requirements, as well as to model detector acceptance

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and resolution effect. The trigger system performs the online selection [23] via a hardware stage with requirements of high transverse momentum of hadrons, followed by a software stage using two trigger algorithms based on the muon kinematics and two-muon vertex information. Since only the first algorithm requires a large impact parameter significance relative to pp interaction point (primary vertex), the two selections exhibit different efficiency dependencies on the B^0 decay time, decay angles, and the $\pi^+\pi^-$ invariant mass. Consequently, these dependencies are studied separately.

The reconstruction and selection of $B^0 \rightarrow J/\psi(\mu^+\mu^-)\pi^+\pi^-$ candidates, which include contributions from the $\rho(770)^0$ and other resonances in the full $\pi^+\pi^-$ invariant-mass spectrum, follow the strategy of Ref. [16]. A boosted decision tree classifier is employed to suppress combinatorial background, using variables with good discriminating power, in particular the fit quality of B^0 decay vertex, as well as the particle-identification information and impact parameter of the pions [17]. This selection improves the signal purity under the B^0 peak, defined as within ± 20 MeV/ c^2 of the known B^0 mass [2], by approximately a factor of eight. Peaking backgrounds due to kaon and proton misidentification from $B_{(s)}^0 \rightarrow J/\psi K^{*0}$, $\Lambda_b^0 \rightarrow J/\psi p h^-$ ($h = K, \pi$), and $B^+ \rightarrow J/\psi K^+$ decays are removed by stringent particle identification and mass requirements, while $B^0 \rightarrow J/\psi K_S^0$ decays are vetoed using the $\pi^+\pi^-$ invariant mass. The same-sign decays $B^0 \rightarrow J/\psi \pi^+\pi^\pm$, containing two pions with same charge and selected using the same criteria, are used to study the mass shape of the combinatorial background.

Selected $B^0 \rightarrow J/\psi \pi^+\pi^-$ candidates in the mass range [5250, 5500] MeV/ c^2 are retained for further analysis. The invariant mass of a B^0 candidate, $m(J/\psi \pi^+\pi^-)$, is calculated by requiring the B^0 momentum vector to point back to the closest primary vertex and constraining the $\mu^+\mu^-$ invariant mass to the known J/ψ mass [2]. An unbinned maximum-likelihood fit to the $m(J/\psi \pi^+\pi^-)$ distribution is performed to discriminate the signal from background contributions. The mass shape of the combinatorial background is described by a fifth-order polynomial function, which can account for a dip caused by the veto of the $B^0 \rightarrow J/\psi K^{*0}$ decays. Its parameters are shared between the $B^0 \rightarrow J/\psi \pi^+\pi^-$ and $B^0 \rightarrow J/\psi \pi^+\pi^\pm$ data samples and obtained via a simultaneous fit to both samples.

The B^0 and B_s^0 peaks are each modeled by the sum of a Hypatia function [24] and a Gaussian function, where the mass difference between B^0 and B_s^0 peaks is constrained to its known value [2]. Partially reconstructed backgrounds from $B_s^0 \rightarrow J/\psi \eta'(\rho^0 \gamma)$ and $B_s^0 \rightarrow J/\psi \eta(\pi^+\pi^-\gamma)$ decays are included in the fit. Their shapes are modeled using simulations, and their yield ratios relative to the B^0 signal are constrained to the values determined from simulations.

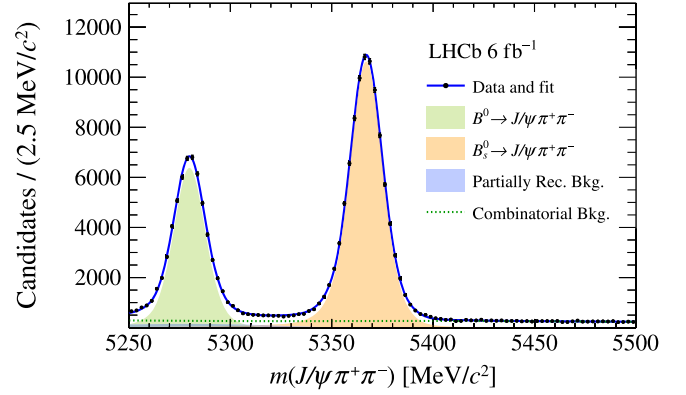


FIG. 1. Distribution of the $J/\psi \pi^+\pi^-$ invariant mass in the full Run 2 data sample. Projections of the total fit and different contributions are also shown.

The resulting fit is shown in Fig. 1 and is used to estimate the yield of each component under the B^0 peak.

A signal sample of approximately 51 000 $B^0 \rightarrow J/\psi \pi^+\pi^-$ decays is obtained. In the subsequent analysis, the residual backgrounds under the B^0 peak are statistically subtracted by injecting events with negative weights, with the total weight matching the corresponding background yield [16,25]. The combinatorial background is subtracted by using candidates in the mass interval [5312, 5332] MeV/ c^2 , while simulated samples are used for the partially reconstructed backgrounds. The small contamination from the tail of the $B_s^0 \rightarrow J/\psi \pi^+\pi^-$ decays is subtracted using an amplitude-corrected simulation sample [16].

The measurement of CP violation in $B^0 \rightarrow J/\psi \pi^+\pi^-$ decays requires an amplitude analysis to separate different polarization components. A weighted multidimensional maximum-likelihood fit is performed to the background-subtracted distributions of the decay time, the invariant mass $m(\pi^+\pi^-)$, and the angular variables ($\cos \theta_\pi, \cos \theta_\mu, \chi$). The helicity angle θ_π (θ_μ) is defined as the angle between the π^+ (μ^+) momentum and the direction opposite to the B^0 momentum in the $\pi^+\pi^-(\mu^+\mu^-)$ rest frame, and χ is the azimuthal angle between the $\pi^+\pi^-$ and $\mu^+\mu^-$ decay planes [15,26].

The fit is performed simultaneously across six subsamples, categorized by data-taking period and trigger category, with a common set of physics parameters. The signal probability density function (PDF) in each subsample closely follows the formalism detailed in Refs. [16,27]. It incorporates the effects of flavor tagging, decay-time resolution, decay-time and angular detection efficiencies, and also considers the contributions of the intermediate resonances to the $m(\pi^+\pi^-)$ spectrum. The PDF is convolved with a Gaussian function whose width is taken as the per-candidate decay-time uncertainty, derived from the uncertainties of the measured momentum and decay distance of B^0 mesons and calibrated using control samples.

The average decay-time resolution for signal candidates is determined to be 41 fs, which is significantly smaller than the B^0 oscillation period and has a negligible impact on the measurement.

The acceptance, the reconstruction, and the selection generate a nonuniform efficiency as a function of the B^0 decay time, decay angles, and the invariant $\pi^+\pi^-$ mass. In the following, the efficiency related to the decay angles and the invariant $\pi^+\pi^-$ mass is generically denoted as angular efficiency, and it is assumed to be independent of that of the decay time. A four-dimensional angular efficiency is parametrized by a combination of Legendre and spherical harmonic moments [16], using simulated signal candidates kinematically corrected to match data.

The decay-time efficiency is determined with a well-established data-driven method [16,28], using the control channel $B^0 \rightarrow J/\psi K^{*0}$, which is topologically similar to the signal decay. The decay-time efficiency is modeled by a cubic spline function, determined from the decay-time distribution of selected candidates divided by that of generated candidates, where the latter decay-time distribution is modeled by an exponential distribution with the B^0 lifetime fixed to its known value [2], convolved with a Gaussian resolution function whose parameters are determined from the resolution study described above. The kinematic differences between signal and control modes are corrected using the corresponding simulated samples.

The flavor of the B^0 meson at production is identified with two independent flavor-tagging algorithms, the opposite-side (OS) tagger [29] and same-side (SS) tagger [30]. Both methods provide a tagging decision Q and an imperfectly estimated mistag probability κ for each B^0 meson. The decision Q takes values of +1, -1, or 0, corresponding to classifications as B^0 , $\bar{B}^0$, or untagged, respectively. The calibration of the mistag probability $\omega(\kappa)$ follows the strategy in Ref. [16], using a linear function for each algorithm. The OS calibration is performed using $B^+ \rightarrow J/\psi K^+$ decays, with ω determined from the number of correct and wrong tagging decisions. The SS calibration employs $B^0 \rightarrow J/\psi K^{*0}$ decays, whose flavors at decay are determined by the charge of final states, and ω is estimated by fitting the decay-time distribution. The SS tagging algorithm is trained on samples whose selection biases the decay time and decay angles [30], resulting in different detection efficiencies for tagged and untagged candidates. The effective tagging power, defined as $\epsilon_{\text{tag}}(1 - 2\omega)^2$ with ϵ_{tag} being the tagging efficiency, is measured to be 4.5% for the combined OS and SS taggers in the full Run 2 dataset. To simplify the analysis, untagged candidates representing 12% of the signal are excluded in the fit as they are insensitive to the CP violation.

The $m(\pi^+\pi^-)$ spectrum is modeled with six resonances, using the same configuration of amplitude magnitudes and relative phases for each polarization component as in Ref. [15]. The $f_0(500)$ resonance is modeled using a

Bugg function, with its parameters fixed to the values of the solution (iii) proposed in Ref. [31]. The $f_0(1270)$ and $\omega(782)$ resonances are described by relativistic Breit-Wigner (RBW) functions [2], while the $\rho(770)^0$, $\rho(1450)^0$, and $\rho(1700)^0$ resonances are described by Gounaris-Sakurai functions [32]. Their pole masses and decay widths are constrained to the world-average values [2]. The $\rho(770)^0$ resonance has an independent set of CP -violation parameters $2\beta_{\text{c}\bar{c}d}^{\text{eff}}$ and $|\lambda|$, while all the other resonances share another common set. The mass difference, decay width, and decay width difference of B^0 mass eigenstates, as well as the B^0 production asymmetry are shared across all the resonances. Among these, the first two parameters are constrained to their known values [2], while the latter two are fixed to zero. This Letter reports two fits, where the parameters $2\beta_{\text{c}\bar{c}d}^{\text{eff}}$ and $|\lambda|$ are either identical or not across all polarization amplitudes (A_i , $i = 0, \perp, \parallel$), which are defined in the transversity basis [15,27]. The polarization-independent fit is used later to constrain $\Delta\phi_s$, while the polarization-dependent one accounts for potential differences in the hadronization dynamics among the polarization states. The decay-time resolution parameters, as well as the coefficients of the angular and decay-time efficiencies, are fixed in the fit, while the flavor-tagging parameters are constrained to the calibration results.

Potential difference in the angular efficiency between simulated samples and data, arising from mismatches in the momenta of final-state particles, is corrected using an iterative fit as detailed in Ref. [28]. The measured CP -violation parameters are summarized in Table I, where statistical uncertainties are estimated using the bootstrapping method [33,34]. This approach allows the uncertainties from the $J/\psi\pi^+\pi^-$ mass fit, including the uncertainties on the contribution of the partially reconstructed background, to be propagated into the statistical uncertainties of the CP -violation parameters. All results are mutually

TABLE I. Physics parameters of interest determined from the polarization-independent and -dependent fits [15,27], where the first uncertainty is statistical and the second systematic. The statistical correlation coefficient between $2\beta_{\text{c}\bar{c}d}^{\text{eff}}$ and $|\lambda|$ is 0.203, while those for the polarization-dependent results are given in the End Matter.

Parameter	Value		
$2\beta_{\text{c}\bar{c}d}^{\text{eff}}$ (rad)	0.710	± 0.084	± 0.051
$ \lambda $	1.019	± 0.034	± 0.024
$2\beta_0^{\text{eff}}$ (rad)	0.706	± 0.086	± 0.070
$2\beta_{\parallel}^{\text{eff}}$ (rad)	0.674	± 0.097	± 0.053
$2\beta_{\perp}^{\text{eff}}$ (rad)	0.696	± 0.096	± 0.066
$ \lambda_0 $	1.004	± 0.045	± 0.056
$ \lambda_{\parallel} $	0.996	± 0.072	± 0.068
$ \lambda_{\perp} $	1.203	± 0.154	± 0.080

consistent, showing no evidence for a polarization-dependent effect. The statistical significance of a nonzero value of $2\beta_{ccd}^{\text{eff}}$ is found to be around ten Gaussian standard deviations using Wilks's theorem [35], establishing the first observation of CP violation in the $B^0 \rightarrow J/\psi \rho(770)^0$ decays. The corresponding time-dependent CP asymmetry varies at different points in the phase space, leading to a dilution on this asymmetry. To reduce this dilution, a variable t' , determined as the decay time adjusted by a factor dependent on phase-space position, is used. As described in the End Matter, it aligns the oscillation phases at different phase-space positions to reduce the dilution on the CP asymmetry. The resulting CP asymmetry is shown in Fig. 2. The background-subtracted distributions of $m(\pi^+\pi^-)$ and the decay angles, along with their fit projections, are shown in Fig. 3. As a cross-check, the fit is repeated on subsets of the data, divided by the year of data-taking, magnet polarity, trigger, and tagging category. In all cases, the obtained results are consistent with the baseline results.

The total systematic uncertainties reported in Table I are obtained by summing the individual contributions in quadrature. These contributions are described below and summarized in the End Matter. The uncertainties of input parameters constrained in the fit are already incorporated into the statistical uncertainties of the fit results. The impact of the decay-time resolution is found to be negligible on the fit results. The systematic uncertainties from the decay width difference and production asymmetry of the B^0 meson are evaluated by varying their values by one

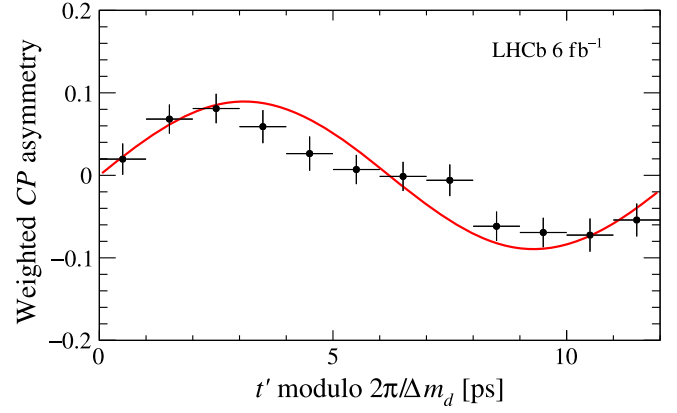


FIG. 2. Weighted CP asymmetry as a function of the transformed decay-time and phase-space variable t' over one oscillation period in the background-subtracted $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays, together with the fit projection.

standard deviation, taken as the quadrature sum of the central values and uncertainties reported by Refs. [2] and [36], respectively.

Systematic uncertainties related to the $J/\psi \pi^+ \pi^-$ mass fit model are evaluated by two alternative fits using a double-sided Crystal Ball function [37] for the signal and a fourth-order polynomial function for the combinatorial background, respectively. Potential differences between the sideband candidates used for background subtraction and the true background under the B^0 peak are conservatively accounted for by retaining 20% of the combinatorial

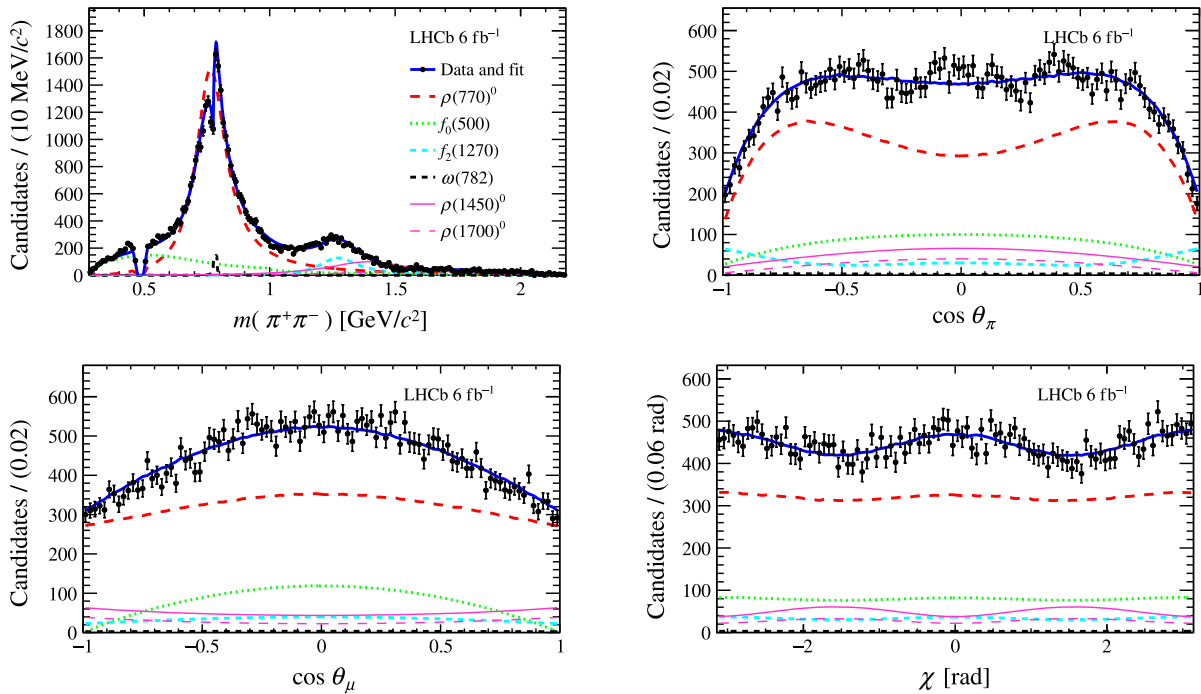


FIG. 3. Background-subtracted distributions of $m(\pi^+\pi^-)$ and three angular variables of the $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays, together with the fit projections.

background candidates in the fit. Systematic uncertainties related to the resonance model are evaluated using RBW functions for the ρ resonances and the Bugg function, with solution (ii) from Ref. [31], for the $f_0(500)$ resonance. The impact of the configuration of CP -violation parameters is assessed by allowing independent parameters for each resonance in the fit. Alternative fits are performed including either an $f_0(980)$, $f_0(1500)$, $f_0(1700)$, or a nonresonant component, and the maximum observed variations are assigned as systematic uncertainties.

Systematic uncertainties from the correction of the simulated samples in the determination of the angular efficiency are evaluated by changing the variables used to derive the corrections. Conservative systematic uncertainties from the iterative fit procedure are evaluated by comparing the results with and without the iterative correction. Untagged candidates, which exhibit different detection efficiencies compared to tagged candidates, are excluded in the baseline fit. However, as tagging information is unavailable in the control samples, untagged candidates are retained in the acceptance studies. An alternative fit that includes the untagged candidates is performed to assess the impact of this effect.

Systematic uncertainties due to the limited sizes of the control samples for the angular and decay-time efficiencies are estimated by varying the corresponding coefficients according to their statistical covariance matrices, where the decay-time contribution is found to be negligible. Varying the parametrization models of these efficiencies yields negligible changes. The impact of neglecting correlations between the angular and decay-time efficiencies is assessed using pseudoexperiments.

The results in Table I and Ref. [15] are consistent. Their combination, performed accounting for the correlations of systematic uncertainties, yields $2\beta_{\text{eff}}^{\text{eff}} = 0.718 \pm 0.088$ rad and $|\lambda| = 1.033 \pm 0.035$, with a correlation coefficient of 0.11. A summary of the LHCb measurements of these parameters is shown in Fig. 4 in the End Matter. Parametrizing the magnitude and phase of the strong parts of the effective penguin amplitude relative to the tree amplitude as $ae^{i\theta}$ in the $B^0 \rightarrow J/\psi\rho(770)^0$ and $a'e^{i\theta'}$ in the $B_s^0 \rightarrow J/\psi\phi(1020)$ decays, and assuming these two ratios are identically quantified, the penguin shift $\Delta\phi_s$ can be estimated through [15]

$$\Delta\phi_s = -\arg\left(\frac{(\xi e^{2i\gamma} - 1) + \epsilon(\xi - 1)}{(\xi e^{2i\gamma} - 1) + \epsilon(\xi - 1)e^{2i\gamma}}\right),$$

with

$$\xi \equiv |\lambda| e^{-i(2\beta_{\text{eff}}^{\text{eff}} - 2\beta_{\text{eff}}^{\text{eff}})} = \frac{1 - ae^{i\theta}e^{-i\gamma}}{1 - ae^{i\theta}e^{i\gamma}},$$

where $\epsilon = \nu^2/(1 - \nu^2)$ is the Cabibbo-suppression factor [13]. The Wolfenstein parameter $\nu = 0.22501 \pm 0.00068$

and the Cabibbo–Kobayashi–Maskawa (CKM) angle $\gamma = (65.7 \pm 3.0)^\circ$ are taken from Ref. [2], and the CP -violating phase $2\beta_{\text{eff}}^{\text{eff}}$ from measurements of $B^0 \rightarrow J/\psi K_S^0$ decays [36]. The penguin contribution $\Delta\phi_s$ is determined to be 5.0 ± 4.6 mrad, with an uncertainty significantly smaller than the current precision on ϕ_s . A study of SU(3) flavor symmetry breaking is performed by simultaneously scanning the amplitude magnitude ratio a/a' in the range [0.5, 1.5] and the phase difference $\theta - \theta'$ over $[-180, 180]^\circ$. As shown in the Supplemental Material [38], the resulting $\Delta\phi_s$ values vary within the range $[-7.8, 7.8]$ mrad and its corresponding uncertainty increases to at most 6.9 mrad, indicating that the uncertainty induced by the breaking of SU(3) flavor symmetry may exceed the precision of the estimate itself.

In summary, time-dependent CP violation in $B^0 \rightarrow J/\psi\rho(770)^0$ decays is observed for the first time. From a time-dependent amplitude analysis of $B^0 \rightarrow J/\psi\pi^+\pi^-$ decays using the full Run 2 dataset collected by the LHCb experiment, the CP -violation parameters in the $B^0 \rightarrow J/\psi\rho(770)^0$ process are measured to be $2\beta_{\text{eff}}^{\text{eff}} = 0.710 \pm 0.084 \pm 0.051$ rad and $|\lambda| = 1.019 \pm 0.034 \pm 0.024$. These results are consistent with, and two times more precise than the previous measurement [15]. Using SU(3) flavor symmetry to relate the sizes of the penguin contributions in $B^0 \rightarrow J/\psi\rho(770)^0$ and $B_s^0 \rightarrow J/\psi\phi(1020)$ decays, and combining the previous results in Ref. [15], the most stringent constraint on the penguin contribution is determined to be $\Delta\phi_s = 5.0 \pm 4.6$ mrad. The measured CP -violation parameters will ultimately provide essential inputs to a global study of $B \rightarrow J/\psi X$ decays that aims to simultaneously determine the phases 2β and ϕ_s in the presence of penguin pollution [13,14].

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Data availability—The data that support the findings of this article are openly available [40].

- [1] A. D. Sakharov, Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe, *Pis'ma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967).
- [2] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [3] B. Aubert *et al.* (BABAR Collaboration), Observation of CP violation in the B^0 meson system, *Phys. Rev. Lett.* **87**, 091801 (2001).
- [4] K. Abe *et al.* (Belle Collaboration), Observation of large CP violation in the neutral B meson system, *Phys. Rev. Lett.* **87**, 091802 (2001).
- [5] A. J. Buras, Flavour theory: 2009, *Proc. Sci. EPS-HEP2009* (2010) 024 [arXiv:0910.1032].
- [6] J. Charles *et al.* (CKMfitter Group), Current status of the standard model CKM fit and constraints on $\Delta F = 2$ new physics, *Phys. Rev. D* **91**, 073007 (2015).
- [7] R. Aaij *et al.* (LHCb Collaboration), Improved measurement of CP violation parameters in $B_s^0 \rightarrow J/\psi K^+ K^-$ decays in the vicinity of the $\phi(1020)$ resonance, *Phys. Rev. Lett.* **132**, 051802 (2024).
- [8] G. Aad *et al.* (ATLAS Collaboration), Measurement of the CP -violating phase ϕ_s in $B_s^0 \rightarrow J/\psi \phi$ decays in ATLAS at 13 TeV, *Eur. Phys. J. C* **81**, 342 (2021).
- [9] A. Hayrapetyan *et al.* (CMS Collaboration), Evidence for CP violation and measurement of CP -violating parameters in $B_s^0 \rightarrow J/\psi \phi(1020)$ decays in pp collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **136**, 181801 (2026).
- [10] X. Liu, W. Wang, and Y. Xie, Penguin pollution in $B \rightarrow J/\psi V$ decays and impact on the extraction of the $B_s - \bar{B}_s$ mixing phase, *Phys. Rev. D* **89**, 094010 (2014).
- [11] K. De Bruyn and R. Fleischer, A roadmap to control penguin effects in $B_d^0 \rightarrow J/\psi K_S^0$ and $B_s^0 \rightarrow J/\psi \phi$, *J. High Energy Phys.* **03** (2015) 145.
- [12] P. Frings, U. Nierste, and M. Wiebusch, Penguin contributions to CP phases in $B_{d,s}$ decays to charmonium, *Phys. Rev. Lett.* **115**, 061802 (2015).
- [13] M. Z. Barel, K. De Bruyn, R. Fleischer, and E. Malami, In pursuit of new physics with $B_d^0 \rightarrow J/\psi K^0$ and $B_s^0 \rightarrow J/\psi \phi$ decays at the high-precision frontier, *J. Phys. G* **48**, 065002 (2021).
- [14] K. De Bruyn, R. Fleischer, and E. Malami, How to tame penguins: Advancing to high-precision measurements of ϕ_d and ϕ_s , *Eur. Phys. J. C* **86**, 215 (2026).
- [15] R. Aaij *et al.* (LHCb Collaboration), Measurement of the CP -violating phase β in $\bar{B}^0 \rightarrow J/\psi \pi^+ \pi^-$ decays and limits on penguin effects, *Phys. Lett. B* **742**, 38 (2015).
- [16] R. Aaij *et al.* (LHCb Collaboration), Measurement of the CP -violating phase ϕ_s from $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays in 13 TeV pp collisions, *Phys. Lett. B* **797**, 134789 (2019).
- [17] A. A. Alves, Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
- [18] LHCb Collaboration, LHCb detector performance, *Int. J. Mod. Phys. A* **30**, 1530022 (2015).
- [19] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008); PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026.
- [20] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, *J. Phys. Conf. Ser.* **331**, 032047 (2011).
- [21] D. J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [22] N. Davidson, T. Przedzinski, and Z. Was, PHOTOS interface in c++: Technical and physics documentation, *Comput. Phys. Commun.* **199**, 86 (2016).
- [23] R. Aaij *et al.*, The LHCb trigger and its performance in 2011, *J. Instrum.* **8**, P04022 (2013).
- [24] D. Martínez Santos and F. Dupertuis, Mass distributions marginalized over per-event errors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **764**, 150 (2014).
- [25] R. Aaij *et al.* (LHCb Collaboration), Search for time-dependent CP violation in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays, *Phys. Rev. D* **104**, 072010 (2021).
- [26] R. Aaij *et al.* (LHCb Collaboration), First measurement of the CP -violating phase in $B_s^0 \rightarrow J/\psi(e^+ e^-) \phi$ decays, *Eur. Phys. J. C* **81**, 1026 (2021).
- [27] L. Zhang and S. Stone, Time-dependent Dalitz-plot formalism for $B_q \rightarrow J/\psi h^+ h^-$, *Phys. Lett. B* **719**, 383 (2013).
- [28] R. Aaij *et al.* (LHCb Collaboration), Updated measurement of time-dependent CP -violating observables in $B_s^0 \rightarrow J/\psi K^+ K^-$ decays, *Eur. Phys. J. C* **79**, 706 (2019); **80**, 601(E) (2020).
- [29] R. Aaij *et al.* (LHCb Collaboration), Opposite-side flavour tagging of B mesons at the LHCb experiment, *Eur. Phys. J. C* **72**, 2022 (2012).
- [30] R. Aaij *et al.* (LHCb Collaboration), New algorithms for identifying the flavour of B^0 mesons using pions and protons, *Eur. Phys. J. C* **77**, 238 (2017).
- [31] D. V. Bugg, The mass of the sigma pole, *J. Phys. G* **34**, 151 (2007).
- [32] G. J. Gounaris and J. J. Sakurai, Finite width corrections to the vector meson dominance prediction for $\rho \rightarrow e^+ e^-$, *Phys. Rev. Lett.* **21**, 244 (1968).
- [33] B. Efron, Bootstrap methods: Another look at the jackknife, *Ann. Stat.* **7**, 1 (1979).
- [34] C. Langenbruch, Parameter uncertainties in weighted unbinned maximum likelihood fits, *Eur. Phys. J. C* **82**, 393 (2022).
- [35] S. S. Wilks, The large-sample distribution of the likelihood ratio for testing composite hypotheses, *Ann. Math. Stat.* **9**, 60 (1938).

- [36] R. Aaij *et al.* (LHCb Collaboration), Measurement of CP violation in $B^0 \rightarrow \psi(\rightarrow \ell^+ \ell^-) K_S^0(\rightarrow \pi^+ \pi^-)$ decays, *Phys. Rev. Lett.* **132**, 021801 (2024).
- [37] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, PhD thesis, Institute of Nuclear Physics, Krakow, 1986; Report No. DESY-F31-86-02.
- [38] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/6f6r-51br> for additional fit results, CP -violat-

- ing coefficients and a study of SU(3) flavor symmetry breaking, which includes Refs. [15,39].
- [39] I. Adachi *et al.* (Belle-II Collaboration), Observation of time-dependent CP violation and measurement of the branching fraction of $B^0 \rightarrow J/\psi \pi^0$ decays, *Phys. Rev. D* **111**, 012011 (2025).
- [40] <https://cds.cern.ch/record/2953189>.

End Matter

The CP asymmetry shown in Fig. 2 is obtained by the following procedure. The time-dependent CP asymmetry in the $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays is described by

$$\frac{\bar{\Gamma}(t) - \Gamma(t)}{\bar{\Gamma}(t) + \Gamma(t)} = S \sin(\Delta m_d t) - C \cos(\Delta m_d t),$$

where Δm_d is the mass difference of B^0 mass eigenstates [2], and S and C are CP -violation coefficients depending on $(m_{\pi\pi}, \cos \theta_\mu, \cos \theta_\pi, \chi)$ [27]. Since the asymmetry depends on the location in the $(m_{\pi\pi}, \cos \theta_\mu, \cos \theta_\pi, \chi)$ phase space, the overall asymmetry integrated over the phase space is diluted as S or C changes sign. Moreover, it is also diluted by the flavor tagging effects. To view the CP asymmetry, the decay time t is transformed to $t' = t + dt(m_{\pi\pi}, \cos \theta_\mu, \cos \theta_\pi, \chi)$ using

$$\begin{aligned} \cos(\Delta m_d dt) &= S / \sqrt{S^2 + C^2}, \\ \sin(\Delta m_d dt) &= -C / \sqrt{S^2 + C^2}, \end{aligned}$$

where S and C are determined by the fit to data. The asymmetry is transformed to a single sine function with positive coefficient

$$\frac{\bar{\Gamma}(t') - \Gamma(t')}{\bar{\Gamma}(t') + \Gamma(t')} = \sqrt{\langle S \rangle^2 + \langle C \rangle^2} \sin(\Delta m_d t'),$$

where $\langle S \rangle$ ($\langle C \rangle$) is the average values of S (C) integrating over the phase space. The new asymmetry is not diluted because only positive coefficients are

TABLE II. Systematic uncertainties of polarization-independent results from different sources.

Source	$2\beta_{\text{eff}}^{\text{eff}}$ (mrad)	$ \lambda $ (10^{-3})
Decay width difference	8.9	0.3
Production asymmetry	1.7	1.4
$m(J/\psi \pi^+ \pi^-)$ fit model	0.1	0.0
Background subtraction	11.3	1.5
Configuration of CPV parameters	6.5	1.3
Resonance model	13.8	12.5
Resonance contribution	38.9	18.5
Variables for kinematic correction	6.8	1.2
Iterative fit	17.0	2.0
Acceptance of untagged events	11.0	8.3
Angular efficiency	1.2	0.4
Efficiency correlation	11.6	1.9
<i>Total</i>	50.5	24.1

TABLE III. Systematic uncertainties of polarization-dependent results from different sources.

Source	$2\beta_0^{\text{eff}}$ (mrad)	$2\beta_{\parallel}^{\text{eff}}$ (mrad)	$2\beta_{\perp}^{\text{eff}}$ (mrad)	$ \lambda_0 $ (10^{-3})	$ \lambda_{\parallel} $ (10^{-3})	$ \lambda_{\perp} $ (10^{-3})
Decay width difference	8.2	7.9	17.7	0.7	2.8	6.7
Production asymmetry	2.2	1.8	2.8	2.4	0.7	3.5
$m(J/\psi \pi^+ \pi^-)$ fit model	0.2	0.2	0.5	0.1	0.6	0.2
Background subtraction	9.5	12.5	14.0	1.3	11.6	1.5
Configuration of CPV parameters	37.6	27.3	35.4	42.1	65.3	32.2
Resonance model	18.4	14.8	14.1	24.8	14.5	7.5
Resonance contribution	43.9	32.8	43.7	24.2	0.5	58.1
Variables for kinematic correction	7.6	7.3	6.5	1.9	1.3	5.5
Iterative fit	18.4	17.9	17.4	1.6	1.9	15.2
Acceptance of untagged events	20.6	7.0	3.1	11.1	3.0	40.1
Angular efficiency	1.5	1.1	1.4	0.8	0.4	1.5
Efficiency correlation	14.3	11.1	13.5	3.5	1.8	6.6
<i>Total</i>	69.8	53.0	66.4	55.9	68.0	80.3

TABLE IV. Statistical correlations between the polarization-dependent CP -violation parameters.

Parameter	$2\beta_0^{\text{eff}}$	$2\beta_{\parallel}^{\text{eff}}$	$2\beta_{\perp}^{\text{eff}}$	$ \lambda_0 $	$ \lambda_{\parallel} $	$ \lambda_{\perp} $
$2\beta_0^{\text{eff}}$	1.000	0.784	0.767	0.311	-0.021	0.027
$2\beta_{\parallel}^{\text{eff}}$	0.784	1.000	0.830	0.094	0.036	-0.070
$2\beta_{\perp}^{\text{eff}}$	0.767	0.830	1.000	0.095	0.108	-0.097
$ \lambda_0 $	0.311	0.094	0.095	1.000	-0.074	0.105
$ \lambda_{\parallel} $	-0.021	0.036	0.108	-0.074	1.000	-0.388
$ \lambda_{\perp} $	0.027	-0.070	-0.097	0.105	-0.388	1.000

summed, and the dilution due to flavor tagging effects still remain. The quantity Δm_{d^*} can be in any 2π period, so Δm_{d^*} is taken to be modulo of 2π .

The systematic uncertainties from different sources for the measured CP -violation parameters are summarized in Tables II and III. The correlations for the polarization-dependent results are shown in Table IV. Figure 4

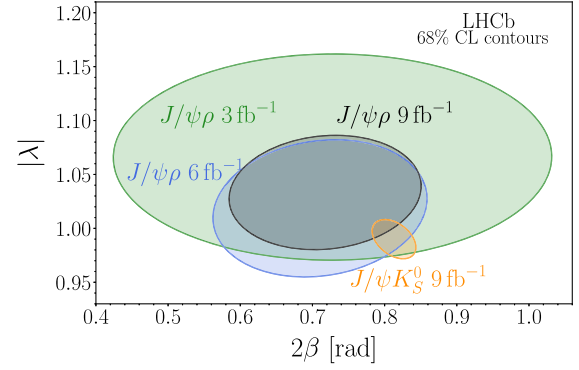


FIG. 4. Comparison of LHCb measurements of the CP -violation parameters in the $B^0 \rightarrow J/\psi\rho(770)^0$ and $B^0 \rightarrow J/\psi K_S^0$ decays, where 2β represents $2\beta_{\text{eff}}^{\text{eff}}$ or $2\beta_{\text{eff}}^{\text{eff}}$.

summarizes the LHCb measurements of the CP -violation parameters in the $B^0 \rightarrow J/\psi\rho(770)^0$ and $B^0 \rightarrow J/\psi K_S^0$ decays.

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