Measurement of the CP-violating phase $\phi_s$ from $B^0_S \to J/\psi \pi^+\pi^-$ decays in 13 TeV pp collisions

LHCb Collaboration

**Abstract**

Decays of $B^0_S$ and $B^0$ mesons into $J/\psi \pi^+\pi^-$ final states are studied in a data sample corresponding to 1.9 fb$^{-1}$ of integrated luminosity collected with the LHCb detector in 13 TeV pp collisions. A time-dependent amplitude analysis is used to determine the final-state resonance contributions, the CP-violating phase $\phi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad}$, the decay-width difference between the heavier mass $B^0_S$ eigenstate and the $B^0$ meson of $-0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1}$, and the CP-violating parameter $|\lambda| = 1.01 \pm 0.004 \pm 0.03$, where the first uncertainty is statistical and the second systematic. These results are combined with previous LHCb measurements in the same decay channel using 7 TeV and 8 TeV pp collisions obtaining $\phi_s = 0.002 \pm 0.044 \pm 0.012 \text{ rad}$, and $|\lambda| = 0.949 \pm 0.036 \pm 0.019$.

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1. Introduction

Measurements of CP violation in final states that can be populated both by direct decay and via mixing provide an excellent way of looking for physics beyond the Standard Model (SM) [1]. As yet unobserved heavy bosons, light bosons with extremely small couplings, or fermions can be present virtually in quantum loops, and thus affect the relative CP phase. Direct decays into non-flavour-specific final states can interfere with those that undergo $B^0_S \to B^0$ mixing prior to decay. This interference can result in CP violation. In certain $B^0_S$ decays one CP-violating phase that can be measured, called $\phi_s$, can be expressed in terms of Cabibbo–Kobayashi–Maskawa matrix elements as $-\arg \left(-V_{ts} V_{tb}^*/V_{cb} V_{cs}^* \right)$. It is not predicted in the SM, but can be inferred with high precision from other experimental data giving a value of $-36.5^{+7.1}_{-5.3} \text{ mrad}$ [2]. This number is consistent with previous measurements, which did not have enough sensitivity to determine a non-zero value [3–7]. In this paper we present the results of a new analysis of the $B^0_S \to J/\psi \pi^+\pi^-$ decay using data from 13 TeV pp collisions collected using the LHCb detector in 2015 and 2016. The existence of this decay and its use in CP-violation studies was suggested in Ref. [8].

2. Detector and simulation

The LHCb detector [9,10] 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 [11], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 m, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of the momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15+29/p_T) \text{ mm}$, where $p_T$ is the component of the momentum transverse to the beam, in GeV. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [12]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [13]. The online event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

At the hardware trigger stage, events are required to have a muon with high $p_T$ or a hadron, photon or electron with high transverse energy in the calorimeters. The software trigger is composed of two stages, the first of which performs a partial reconstruction and requires either a pair of well-reconstructed, oppo-

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1 In this paper mention of a particular final state implies use of the charge-conjugate state, except when dealing with CP-violating processes.

2 We use natural units where $h = c = 1$. 

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sitely charged muons having an invariant mass above 2.7 GeV, or a single well-reconstructed muon with \( p_T > 1 \) GeV and have a large IP significance \( X^2 > 7.4 \). The latter is defined as the difference in the \( x^2 \) of the vertex fit for a given PV reconstructed with and without the considered particles. The second stage applies a full event reconstruction and for this analysis requires two opposite-sign muons to form a good-quality vertex that is well-separated from all of the PVs, and to have an invariant mass within \( \pm 120 \) MeV of the known \( J/\psi \) mass [14].

Simulation is required to model the effects of the detector acceptance and the imposed selection requirements. In the simulation, \( pp \) collisions are generated using Pythia [15] with a specific LHCb configuration [16]. Decays of unstable particles are described by EvtGen [17], in which final-state radiation is generated using Photino [18]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [19] as described in Ref. [20].

3. Decay amplitude

The resonance structure in \( B^0 \bar{B}^0 \) and \( B^0 \bar{B}^0 \to J/\psi \pi^+ \pi^- \) decays has been previously studied with a time-integrated amplitude analysis using 7 and 8 TeV \( pp \) collisions [21]. The final state was found to be compatible with being entirely \( CP \)-odd, with the \( CP \)-even state fraction below 2.3\% at 95\% confidence level, which allows the determination of the decay width of the heavy \( B^0 \) mass eigenstate, \( \Gamma_H \). The possible presence of a \( CP \)-even component is taken into account when determining \( \phi_f \) [22].

The total decay amplitude for a \( B^0 \) meson at decay time equal to zero is assumed to be the sum over individual \( \pi^+ \pi^- \) resonant transversity amplitudes [23], and one nonresonant amplitude, with each transversity component labelled as \( A_1 (A_i) \). Because of the spin-1 \( J/\psi \) meson in the final state, the three possible polarizations of the \( J/\psi \) generate longitudinal (0), parallel (\( || \)) and perpendicular (\( \perp \)) transversity amplitudes. When the \( \pi^+ \pi^- \) pair forms a spin-0 state the final system only has a longitudinal component, and thus is a pure \( CP \) eigenstate. The parameter \( \lambda_i = \frac{q}{p} \pi^i \) relates \( CP \) violation in the interference between mixing and decay associated with the polarization state \( i \) for each resonance in the final state. Here the quantities \( q \) and \( p \) relate the mass and flavour eigenstates, \( p = (B^0 \bar{B}^0)B_L \), and \( q = (B^0 \bar{B}^0)B_L \), where \( B_L \) is the lighter mass eigenstate [1]. The total amplitudes \( \mathcal{A} \) and \( \bar{\mathcal{A}} \) can be expressed as the sums of the individual \( B^0 \) amplitudes, \( A = \sum A_i \) and \( \bar{\mathcal{A}} = \sum \bar{A}_i = \sum \lambda_i A_i = \sum \eta_i |\lambda_i| \text{e}^{-i\phi_i} A_i \), with \( \eta_i \) being the \( CP \) eigenvalue of the state. For each transversity state \( i \) there is a \( CP \)-violating phase \( \phi_i \equiv -\arg(\eta_i \lambda_i) \) [24]. Assuming that \( CP \) violation in the decay is the same for all amplitudes, then \( \lambda \equiv \eta \lambda_1 \) and \( \phi_f \equiv -\arg(\lambda) \). Using \( |p/q| = 1 \), the decay rates for \( B^0 \) and \( B^0 \) into the \( J/\psi \pi^+ \pi^- \) final state are

\[
\Gamma (t) \propto e^{-\Gamma_H t} \left\{ \frac{|A|^2 + |\bar{A}|^2}{2} \cos \frac{\Gamma_H t}{2} \pm \frac{|A|^2 - |\bar{A}|^2}{2} \cos (\Delta m t) \right\}
- \text{Re}(\bar{A}^* A) \sin \frac{\Gamma_H t}{2} \pm i \text{Im}(\bar{A}^* A) \sin (\Delta m t),
\]

where the sign before the \( \cos (\Delta m t) \) term and sign before the \( \sin (\Delta m t) \) term apply to \( \bar{T}(t) \), \( \Delta m \equiv m_1 - m_0 \) is the decay-width difference between the light and the heavy mass eigenstates, \( \Delta m \equiv m_{B_0} - m_0 \) the corresponding mass difference, and \( \Gamma_1 \equiv (\Gamma_1 + \Gamma_{H1})/2 \) is the average \( B^0 \) meson decay width [26].

For \( J/\psi \) decays to \( \mu^+ \mu^- \) final states the \( A_i \) amplitudes are themselves functions of four variables: the \( \pi^+ \pi^- \) invariant mass \( m_{\pi \pi} \), and three angular variables \( \Omega \equiv (\cos \theta_{\pi \pi}, \cos \theta_{\psi \mu \mu}, \chi) \), defined in the helicity basis. These angles are defined as \( \theta_{\pi \pi} \) between the \( \pi^+ \pi^- \) direction in the \( \pi^+ \pi^- \) rest frame with respect to the \( \pi^+ \pi^- \) direction in the \( B^0 \) rest frame, \( \theta_{\psi \mu \mu} \) between the \( \mu^+ \mu^- \) direction in the \( J/\psi \) rest frame with respect to the \( \pi^+ \pi^- \) direction in the \( B^0 \) rest frame [22,24]. (These definitions are the same for \( B^0 \) and \( B^0 \), namely, using \( \pi^+ \) and \( \pi^- \) to define the angles for both \( B^0 \) and \( B^0 \) decays.) The explicit forms of the \( |A(m_{\pi \pi}, \Omega)|^2, |\bar{A}(m_{\pi \pi}, \Omega)|^2, \) and \( A^*(m_{\pi \pi}, \Omega)A(m_{\pi \pi}, \Omega) \) terms in Eq. (1) are given in Ref. [22].

The analysis proceeds by performing an unbinned maximum-likelihood fit to the \( \pi^+ \pi^- \) mass distribution, the decay time, and helicity angles of \( B^0 \) candidates identified as \( B^0 \) or \( B^0 \) by a flavour-tagging algorithm [27]. The fit provides the \( CP \)-even and \( CP \)-odd components, and since we include the initial flavour tag, the fit also determines the \( CP \)-violating parameters \( \phi_f \) and \( |\lambda| \), and the decay width. In order to proceed, we need to select a clean sample of \( B^0 \) decays, determine acceptance corrections, perform a calibration of the decay-time resolution in each event as a function of its uncertainty, and calibrate the flavour-tagging algorithm.

4. Selection requirements

The selection of \( J/\psi \pi^+ \pi^- \) right-sign (RS), and wrong-sign (WS) \( J/\psi \pi^+ \pi^- \) final states, proceeds in two phases. Initially we impose loose requirements and subsequently use a multivariate analysis to further suppress the combinatorial background. In the first phase we require that the \( J/\psi \) decay tracks be identified as muons, have \( p_T > 500 \) MeV, and form a good vertex with vertex fit \( x^2 \) less than 16. The identified pions are required to have \( p_T > 250 \) MeV, not originate from any PV, and form a good vertex with the muons. The resulting \( B^0 \) candidate is assigned to the PV for which it has the smallest \( \chi^2 \). Furthermore, we require that the smallest \( \chi^2 \) is not greater than 25. The \( B^0 \) candidate is required to have its momentum vector aligned with the vector connecting the PV to the \( B^0 \) decay vertex, and to have a decay time greater than 0.3 ps. Reconstructed tracks sharing the same hits are vetoed.

In addition, background from \( B^+ \to J/\psi K^+ \) decays, where the \( K^+ \) is misidentified as a \( \pi^+ \) and combined with a random \( \pi^- \), is vetoed by assuming that each detected pion is a kaon, computing the \( J/\psi K^+ \) mass, and removing those candidates that are within \( \pm 36 \) MeV of the known \( B^0 \) mass [14]. Backgrounds from \( B^0 \to J/\psi K^+ \pi^- \) or \( B^0 \to J/\psi K^+ K^- \) decays with misidentified kaons result in masses lower than the \( B^0 \) peak and thus do not need to be vetoed.

For the multivariate part of the selection, we use a Boosted Decision Tree, BDT [28,29], with the uBoost algorithm [30]. The algorithm is optimized to not further bias acceptance on the variable \( \cos \theta_{\pi \pi} \). The variables used to train the BDT are the difference between the muon and pion identifications for the muon identified with lower quality, the \( p_T \) of the \( B^0 \) candidate, the sum of the \( p_T \) of the two pions, and the natural logarithms of: the \( \chi^2 \) of each of the pions, the \( x^2 \) of the \( B^0 \) vertex and decay tree fits [31], and the \( \chi^2_{BDT} \) of the \( B^0 \) candidate. In the fit, the \( B^0 \) momentum vector is constrained to point to the PV, the two muons are constrained to

\[ p/q^2 = 1.0039 \pm 0.0033 \] [25].

\[ \chi^2 \] We utilize the same likelihood construction that we used to determine \( \phi_f \) and \( |\lambda| \) in \( B^0 \to J/\psi K^+ K^- \) decays with \( K^+ K^- \) above the \( \phi(1020) \) mass region [6].

\[ \phi(1020) \] When discussing flavour-specific decays, mention of a particular mode implies the additional use of the charge-conjugate mode.
Finally, in the component function, the misidentified values of the sample are compared with the RS points (grey and black lines) where the effect of mass is shown to be very small. This is due to the hypothesis that the background distributions are large, and the differences are almost zero. The model gives an excellent representation of the simulated data. The efficiency is uniform within about $\pm 4\%$ for cos $\theta_{\psi\bar{\psi}}$ and about $10\%$ for $\chi$ variables; however, the $m_{\pi\pi}$ and cos $\theta_{\pi\pi}$ variables show large efficiency variations and correlations (see Fig. 3), due to the $\chi_{D}^{2} > 4$ requirements on the hadrons. The loss of efficiency in the lower $m_{\pi\pi}$ region can be interpreted as the projection of the effects of cuts on $\chi_{D}^{2}$, which is due to the $m_{D}$ and $m_{K}$ of the datasets. The efficiencies are shown in Table 2, where the efficiency is shown to be very small. 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decays combined with two pions of opposite charge. Taking into account the decay-time uncertainty distribution of the $B_s^0$ signal, the average effective resolution is found to be 41.5 fs. The method is validated using simulation; we estimate the accuracy of the resolution determination to be ±3%.

6. Flavour tagging

Knowledge of the $B_s^0$ flavour at production is necessary. We use information from decays of the other $b$ hadron in the event (opposite-side, OS) and fragments of the jet that produced the $B_s^0$ meson that contain a charged kaon, called same-side kaon (SSK) [27]. The OS tagger infers the flavour of the other $b$ hadron in the event from the charges of muons, electrons, kaons, and the net charge of the particles that form reconstructed secondary vertices.

The flavour tag, $q$, takes values of +1, −1 or 0 if the signal meson is tagged as $B_s^0$, $B_s^0$ or untagged, respectively. The wrong-tag probability, $\eta$, is estimated event-by-event based on the output of a neural network. It is subsequently calibrated with data in order to relate it to the true wrong-tag probability of the event by a linear relation as

$$\omega(\eta) = p_0 + \frac{\Delta p_0}{2} + \left(p_1 + \frac{\Delta p_1}{2}\right) \cdot (\eta - \langle \eta \rangle);$$

$$\bar{\omega}(\eta) = p_0 - \frac{\Delta p_0}{2} + \left(p_1 - \frac{\Delta p_1}{2}\right) \cdot (\eta - \langle \eta \rangle).$$

where $p_0$, $p_1$, $\Delta p_0$ and $\Delta p_1$ are calibration parameters, and $\omega(\eta)$ and $\bar{\omega}(\eta)$ are the calibrated probabilities for a wrong-tag assignment for $B_s^0$ and $B_s^0$ mesons, respectively. The calibration is performed separately for the OS and the SSK taggers using $B^+ \to J/\psi K^+$ and $B_s^0 \to D_s^- \pi^+$ decays, respectively. When events are tagged by both the OS and the SSK algorithms, a combined tag decision is formed. The resulting efficiency and tagging powers are listed in Table 1.
The decay-time distribution including flavour tagging is

\[
R(\hat{t}, m_{\pi\pi\pi}, \Omega, q|\eta) = \frac{1}{1 + |q| \left[ 1 + q \left( 1 - 2\cos(\eta) \right) \right]^2 \Gamma(\hat{t}, m_{\pi\pi\pi}, \Omega)
+ \left[ 1 - q \left( 1 - 2\cos(\eta) \right) \right]^{1 + A_P} \Gamma(\hat{t}, m_{\pi\pi\pi}, \Omega),}
\]

where \( \hat{t} \) is the true decay time, \( \Gamma \) is defined in Eq. (1), and \( A_P \) is the production asymmetry of \( B^0_s \) mesons.

The fit function for the signal is modified to take into account the decay-time resolution and acceptance effects resulting in

\[
F(\hat{t}, m_{\pi\pi\pi}, \Omega, q|\eta, \delta_t)
= \left[ R(\hat{t}, m_{\pi\pi\pi}, \Omega, q|\eta) \otimes T(\hat{t} - \hat{t}|\delta_t) \right] e^{m_P(\Omega)} \Delta \Omega d\Omega.
\]

8. Likelihood definition

7. Description of the \( \pi^+\pi^-\pi^- \) mass spectrum

We fit the entire \( \pi^+\pi^-\) mass spectrum including the resonance contributions listed in Table 2, and a nonresonant (NR) component. We use an isobar model [21]. All resonances are described by Breit–Wigner amplitudes, except for the \( f_0(980) \) state, which is modelled by a Flatté function [34]. The nonresonant amplitude is treated as being constant in \( m_{\pi\pi} \). Other theoretically motivated amplitude models are also proposed to describe this decay [35, 36]. The previous publication [21] used an unconfirmed \( f_0(1790) \) resonance, reported by the BES collaboration [37], instead of the \( f_0(1710) \) state. We test which one gives a better fit.

The amplitude \( A_R(m_{\pi\pi}) \), generally represented by a Breit–Wigner function or a Flatté function, is used to describe the mass line shape of resonance \( R \). To describe the resonance from the \( B^0_s \) decays, the amplitude is combined with the \( B^0_s \) and resonance decay properties to form the following expression

\[
A_R(m_{\pi\pi}) = \sqrt{2 J_R + 1} P_R \left( \frac{L_B}{L_R} \right) \left( \frac{P_B}{m_B} \right)^{L_B} \left( \frac{P_R}{m_R} \right)^{L_R} \times A_R(m_{\pi\pi}).
\]

(4)

Here \( P_B \) is the \( j/\psi \) momentum in the \( B^0_s \) rest frame, \( P_R \) is the momentum of either of the two hadrons in the dihadron rest frame, \( m_B \) is the \( B^0_s \) mass, \( m_R \) is the mass of resonance \( R \), \( J_B \) is the spin of the resonance \( B \), \( L_B \) is the orbital angular momentum between the \( j/\psi \) meson and \( \pi^+\pi^- \) system, and \( L_R \) is the orbital angular momentum in the \( \pi^+\pi^- \) system, and thus is the same as the spin of the \( \pi^+\pi^- \) resonance. The terms \( F^{(L_B)}(R) \) and \( F^{(L_R)}(R) \) are the Blatt–Weisskopf barrier factors for the \( B^0_s \) meson and \( R \) resonance, respectively [39]. The shape parameters for the \( f_0(980) \) and \( f_0(1500) \) resonances are allowed to vary.

---

Table 1

<table>
<thead>
<tr>
<th>Category</th>
<th>( \epsilon_{tag} ) (%)</th>
<th>( \epsilon_{tag} D^2 ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS only</td>
<td>11.0 ± 0.6</td>
<td>0.86 ± 0.05</td>
</tr>
<tr>
<td>SSK only</td>
<td>42.6 ± 0.6</td>
<td>1.54 ± 0.33</td>
</tr>
<tr>
<td>OS and SSK</td>
<td>24.9 ± 0.6</td>
<td>2.66 ± 0.19</td>
</tr>
<tr>
<td>Total</td>
<td>78.5 ± 0.7</td>
<td>5.06 ± 0.38</td>
</tr>
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Table 2

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>( f_0(500) )</td>
<td>471 ± 21</td>
<td>534 ± 53</td>
<td>LHCb [38]</td>
</tr>
<tr>
<td>( f_0(980) )</td>
<td>Varied in fits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( f_2(1270) )</td>
<td>1275.5 ± 0.8</td>
<td>186.7 ± 3.5</td>
<td>PDG [14]</td>
</tr>
<tr>
<td>( f_0(1590) )</td>
<td>Varied in fits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( f_0(1525) )</td>
<td>1522 ± 1.7</td>
<td>78.0 ± 4.8</td>
<td>LHCb [6]</td>
</tr>
<tr>
<td>( f_0(1710) )</td>
<td>1723 ± 5</td>
<td>139 ± 8</td>
<td>PDG [14]</td>
</tr>
<tr>
<td>( f_0(1790) )</td>
<td>1790 ± 30</td>
<td>270 ± 60</td>
<td>BES [37]</td>
</tr>
</tbody>
</table>

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6. Equation (4) is modified from that used in previous publications [4,21] and follows the convention suggested by the PDG [14].

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Table 3
Likelihoods of various resonance model fits. Positive or negative interferences (Int) among the contributing resonances are indicated. The Solutions are indicated by I.

<table>
<thead>
<tr>
<th>#</th>
<th>Resonance content</th>
<th>Int</th>
<th>$-2 \ln \mathcal{L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$f_0(980) + f_0(1500) + f_0(1790) + f_2(1270) + f_2(1525) + \text{NR}$</td>
<td></td>
<td>-4850</td>
</tr>
<tr>
<td>II</td>
<td>$f_0(980) + f_0(1500) + f_0(1790) + f_2(1270) + f_2(1525) + \text{NR}$</td>
<td></td>
<td>-4834</td>
</tr>
<tr>
<td>III</td>
<td>$f_0(980) + f_0(1500) + f_0(1790) + f_2(1270) + f_2(1525) + \text{NR}$</td>
<td></td>
<td>-4830</td>
</tr>
<tr>
<td>IV</td>
<td>$f_0(980) + f_0(1500) + f_0(1790) + f_2(1270) + f_2(1525)$</td>
<td></td>
<td>-4828</td>
</tr>
<tr>
<td>V</td>
<td>$f_0(980) + f_0(1500) + f_0(1790) + f_2(1270) + f_2(1525)$</td>
<td></td>
<td>-4706</td>
</tr>
</tbody>
</table>

Table 4
Fit results for the CP-violating parameters for Solution I. The first uncertainties are statistical, and the second systematic. The last three columns show the statistical correlation coefficients for the three parameters.

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<thead>
<tr>
<th>Fit result</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_H - \Gamma_{G^0}$ (ps$^{-1}$)</td>
<td>$-0.050 \pm 0.004 \pm 0.004$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
<tr>
<td>$\phi_{\psi}$ (rad)</td>
<td>$-0.057 \pm 0.060 \pm 0.011$</td>
</tr>
</tbody>
</table>

9. Fit results
We first choose the resonances that best fit the $m_{\pi\pi}$ distribution. Table 3 lists the different fit components and the value of $-2 \ln \mathcal{L}$. In these comparisons, the mass and width of most resonances are fixed to the central values listed in Table 2, except for the $f_0(980)$ and $f_0(1500)$ resonances, whose parameters are allowed to vary. We find two types of fit results, one with a positive integrated sum of all interfering components and one with a negative one. The first listed Solution I is better than Solution II by four standard deviations, calculated by taking the square root of the $-2 \ln \mathcal{L}$ difference. We take Solution I for our measurement and II for systematic uncertainty evaluation. The models corresponding to Solutions I and II are very similar to those found in our previous analysis of the same final state [21].

Fig. 5. Data distribution of $m_{\pi\pi}$ with the projection of the Solution I fit result overlaid. The data are described by the points (black) with error bars. The solid (blue) curve shows the overall fit.

For the fit we assume that the CP-violation quantities ($\phi_{\psi}, |\lambda|$) are the same for all the resonances. We also fix $\Delta m_{\psi}$ to the central value of the world average $17.757 \pm 0.021$ ps$^{-1}$ [14], and fix $\Gamma_1$ to the central value of $0.6995 \pm 0.0047$ ps$^{-1}$ from the LHCb $B^0 \rightarrow J/\psi K^+ K^-$ results [6].

The fit values and correlations of the CP-violating parameters are shown in Table 4 for Solution I. The shape parameters of $f_0(980)$ and $f_0(1500)$ resonances are found to be consistent with our previous results [21]. The angular and decay-time fit projections are shown in Fig. 4. The $m_{\pi\pi}$ fit projection is shown in Fig. 5, where the contributions of the individual resonances are also displayed. All solutions listed in Table 3 give very similar fit values for $\phi_{\psi}$ and $\Gamma_1$. We also find that the CP-odd fraction is greater than 97% at 95% confidence level. The resonant content for Solutions I and II are listed in Table 5.
Table 5  
Fit results of the resonant structure for both Solutions I and II. These results do not supersede those in Ref. [21] for the resonant fractions because no systematic uncertainties are quoted. The sum of fit fraction is not necessary 100% due to possible interferences between resonances with the same spin. 

<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fractions (%)</th>
<th>Transversity fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Solution I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_0$ (980)</td>
<td>60.09 ± 1.48</td>
<td>100</td>
</tr>
<tr>
<td>$f_0$ (1500)</td>
<td>8.88 ± 0.87</td>
<td>100</td>
</tr>
<tr>
<td>$f_0$ (1790)</td>
<td>1.72 ± 0.29</td>
<td>100</td>
</tr>
<tr>
<td>$f_2$ (1270)</td>
<td>3.24 ± 0.48</td>
<td>13 ± 3</td>
</tr>
<tr>
<td>$f_2$ (1525)</td>
<td>1.23 ± 0.86</td>
<td>40 ± 13</td>
</tr>
<tr>
<td>NR</td>
<td>2.64 ± 0.73</td>
<td>100</td>
</tr>
<tr>
<td>Solution II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_0$ (980)</td>
<td>93.05 ± 1.12</td>
<td>100</td>
</tr>
<tr>
<td>$f_0$ (1500)</td>
<td>6.47 ± 0.41</td>
<td>100</td>
</tr>
<tr>
<td>$f_0$ (1710)</td>
<td>0.74 ± 0.11</td>
<td>100</td>
</tr>
<tr>
<td>$f_2$ (1270)</td>
<td>3.22 ± 0.44</td>
<td>17 ± 4</td>
</tr>
<tr>
<td>$f_2$ (1525)</td>
<td>1.44 ± 0.36</td>
<td>35 ± 8</td>
</tr>
<tr>
<td>NR</td>
<td>8.13 ± 0.79</td>
<td>100</td>
</tr>
</tbody>
</table>

10. Systematic uncertainties

The systematic uncertainties for the CP-violating parameters, $\lambda$ and $\phi_3$, are smaller than the statistical ones. They are summarized in Table 6 along with the uncertainty on $\Gamma_H - \Gamma_{g0}$. The uncertainty on the decay-time acceptance is found by varying the parameters of the acceptance function within their uncertainties and repeating the fit. The same procedure is followed for the uncertainty on the $B^0$ lifetime, $\Delta m_B$, $\Gamma_L$, and angular efficiencies, resonance masses and widths, flavour-tagging calibration, and allowing for a 2% production asymmetry [41]; this uncertainty also includes any possible difference in flavour tagging between $B^0_L$ and $B^0_S$. Simulation is used to validate the method for the time-resolution simulation. The uncertainties of the parameters of the time-resolution model are estimated using the difference between the signal simulation and prompt $J/\psi$ simulation. These uncertainties are varied to obtain the effects on the physics parameters. Resonance modelling uncertainty includes varying the Breit–Wigner factors, changing the default values of $L_B = 1$ for the D-wave resonances to one or two, the differences between the two best solutions, and replacing the NR component by the $f_0(500)$ resonance. Furthermore, including an isospin-violating $\rho(770)^0$ component in the fit, results in a negligible contribution of $(1.1 \pm 0.3)\%$. The largest shift among the modelling variations is taken as systematic uncertainty. The inclusion of $\rho$ components results in the largest shifts of the three physics parameters quoted. The process $B^+ \rightarrow \pi^+ \pi^0$ can affect the measurement of $\Gamma_H - \Gamma_{g0}$. An estimate of the fraction of these decays in our sample is 0.8% [5]. Neglecting the $B^0_L$ contribution leads to a bias of 0.00005 ps$^{-1}$, which is added as a systematic uncertainty. Other parameters are unchanged.

Corrections from penguin amplitudes are ignored because their effects are known to be small [42–44] compared to the current experimental precision.

11. Conclusions

Using $B^0_L$ and $B^0_S \rightarrow J/\psi \pi^+\pi^-$ decays, we measure the CP-violating phase, $\phi_3 = -0.057 \pm 0.060 \pm 0.011$ rad, the decay-width difference $\Gamma_H - \Gamma_{g0} = -0.050 \pm 0.004 \pm 0.004$ ps$^{-1}$, and the parameter $|\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03$, where the quoted uncertainties are statistical and systematic. These results are more precise than those obtained from the previous study of this mode using 7 TeV and 8 TeV $pp$ collisions (Run 1) [4]. To combine the Run-1 results with these, we reanalyze them by fixing $\Delta m_B = 17.757 \pm 0.021$ ps$^{-1}$ from Ref. [14], and $\Gamma_L = 0.6995 \pm 0.0047$ ps$^{-1}$ from the LHCb $B^0 \rightarrow J/\psi K^+ K^-$ results [6]. We remove the Gaussian constraint on $\Delta m_B$ and let $\Gamma_H$ vary. Instead of taking the uncertainties of flavour tagging and decay-time resolution into the statistical uncertainty, we place these sources in the systematic uncertainty and assume 100% correlation with our new results. The updated results are: $\phi_3 = 0.075 \pm 0.065 \pm 0.014$ rad and $|\lambda| = 0.898 \pm 0.051 \pm 0.013$ with a correlation of 0.025. We then use the updated $\phi_3$ and $|\lambda|$ Run-1 results as a constraint into our new $\phi_3$ fit. The combined results are $\Gamma_H - \Gamma_{g0} = -0.050 \pm 0.004 \pm 0.004$ ps$^{-1}$, $|\lambda| = 0.949 \pm 0.036 \pm 0.019$, and $\phi_3 = 0.002 \pm 0.044 \pm 0.012$ rad. The correlation coefficients among the fit parameters are 0.025 ($\rho_{12}$), $-0.001$ ($\rho_{13}$), and 0.026 ($\rho_{23}$).

Our results still have uncertainties greater than the SM prediction and are slightly more precise than the measurement using $B^0_L \rightarrow J/\psi K^+ K^-$ decays, based only on Run-1 data, which has a precision of 0.049 rad [5]. Hence this is the most precise determination of $\phi_3$ to date.

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5. We do not include an average value of $\Gamma_H$ since no systematic uncertainty was assigned for the Run-1 result.

1 Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
2 Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3 Center for High Energy Physics, Tsinghua University, Beijing, China
4 University of Chinese Academy of Sciences, Beijing, China
5 Institute of High Energy Physics (ihep), Beijing, China
6 Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France
7 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
8 Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
9 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
10 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
11 I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
12 Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
13 Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
14 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
15 School of Physics, University College Dublin, Dublin, Ireland
16 INFN Sezione di Bari, Bari, Italy
17 INFN Sezione di Bologna, Bologna, Italy
18 INFN Sezione di Ferrara, Ferrara, Italy
19 INFN Sezione di Firenze, Firenze, Italy
20 INFN Laboratori Nazionali di Frascati, Frascati, Italy
21 INFN Sezione di Genova, Genova, Italy
22 INFN Sezione di Milano-Bicocca, Milano, Italy
23 INFN Sezione di Milano, Milano, Italy
24 INFN Sezione di Cagliari, Cagliari, Italy
25 INFN Sezione di Padova, Padova, Italy
26 INFN Sezione di Pisa, Pisa, Italy
27 INFN Sezione di Roma Tor Vergata, Roma, Italy
28 INFN Sezione di Roma La Sapienza, Roma, Italy
29 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
30 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
31 AGH – University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
32 National Center for Nuclear Research (NCBJ), Warsaw, Poland
33 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
34 Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia
35 Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
36 Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
37 Yandex School of Data Analysis, Moscow, Russia
38 Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
39 Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia
40 Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia, St. Petersburg, Russia
41 ICCUB, Universitat de Barcelona, Barcelona, Spain
42 Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
43 European Organization for Nuclear Research (CERN), Geneva, Switzerland
44 Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
45 Physik-Institut, Universität Zürich, Zürich, Switzerland
46 NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
47 Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
48 University of Birmingham, Birmingham, United Kingdom
49 University of Bristol, Bristol, United Kingdom
50 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
51 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom