



CERN-EP-2017-317
 LHCb-PAPER-2017-033
 22 December 2017

Amplitude analysis of the decay $\bar{B}^0 \rightarrow K_S^0 \pi^+ \pi^-$ and first observation of the CP asymmetry in $\bar{B}^0 \rightarrow K^*(892)^- \pi^+$

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Abstract

The time-integrated Dalitz plot of the three-body hadronic charmless decay $\bar{B}^0 \rightarrow K_S^0 \pi^+ \pi^-$ is studied using a pp collision data sample recorded with the LHCb detector, corresponding to an integrated luminosity of 3.0 fb^{-1} . The decay amplitude is described with an isobar model. Relative contributions of the isobar amplitudes to the $\bar{B}^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay branching fraction and CP asymmetries of the flavour-specific amplitudes are measured. The CP asymmetry between the conjugate $\bar{B}^0 \rightarrow K^*(892)^- \pi^+$ and $B^0 \rightarrow K^*(892)^+ \pi^-$ decay rates is determined to be -0.308 ± 0.062 .

Submitted to Phys. Rev. Lett.

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The breaking of the invariance of the weak interaction under the combined action of the charge conjugation (C) and parity (P) transformations is firmly established in the K - and B -meson systems [1–3]. In particular, significant CP asymmetries at the level of 10% or more have been measured in the decays of B mesons into two light pseudoscalars. The CP asymmetries in the decays of $\bar{B}^0 \rightarrow K^-\pi^+$ and $B^- \rightarrow K^-\pi^0$ are observed to be different [4], while, in predictions based on the QCD factorisation approach, the two asymmetries are expected to be similar [5]. This apparent discrepancy is often referred to in the literature as the $K\pi$ puzzle [6–9]. The study of the flavour-specific quasi-two-body amplitudes which contribute to the decay $\bar{B}^0 \rightarrow K_s^0\pi^+\pi^-$ offers the possibility to measure CP asymmetries. In particular, the decays with a vector and a pseudoscalar in the final state, such as $\bar{B}^0 \rightarrow K^*(892)^-\pi^+$, may help to shed light on the $K\pi$ puzzle.

In the Standard Model (SM) [10, 11], the mixing-induced CP asymmetries in the quark-level transitions $b \rightarrow q\bar{q}s$ ($q = u, d, s$) which govern the decay $\bar{B}^0 \rightarrow K_s^0\pi^+\pi^-$ are predicted to be approximately equal to those in $b \rightarrow c\bar{c}s$ transitions, such as $B^0 \rightarrow J/\psi K_s^0$. The existence of new particles in extensions of the SM could introduce additional weak phases that contribute along with the SM mixing phase [12–15]. In general, for each of the studied CP eigenstates, the current experimental measurements of $b \rightarrow q\bar{q}s$ decays [4] show good agreement with the results from $b \rightarrow c\bar{c}s$ decays [4]. There is nonetheless room for contributions from physics beyond the SM and, hence, the need for precision measurements of these weak mixing phases.

The mixing-induced CP -violating phase can be measured by means of a decay-time-dependent analysis of the Dalitz plot (DP) [16] of the decay $\bar{B}^0 \rightarrow K_s^0\pi^+\pi^-$ [17–20]. Such an analysis requires the initial flavour of the \bar{B}^0 meson to be determined or “tagged”. A recent study of the yields of the charmless three-body decays $\bar{B}^0 \rightarrow K_s^0\pi^+\pi^-$ has been reported in Ref. [21]. The $\bar{B}^0 \rightarrow K_s^0\pi^+\pi^-$ yields are comparable to those obtained at the BaBar and Belle experiments but the lower tagging efficiency at LHCb does not yet allow a precise flavour-tagged analysis to be performed. The decay-time-integrated untagged DP of this mode is studied in this Letter. The DP of the decay $\bar{B}^0 \rightarrow K_s^0\pi^+\pi^-$ is modelled by a sum of quasi-two-body amplitudes (the isobar parameterisation) and the model is fit to the LHCb data to measure the relative branching fractions and the CP asymmetries of flavour-specific final states.

The analysis reported in this Letter is performed using pp collision data recorded with the LHCb detector, corresponding to integrated luminosities of 1.0 fb^{-1} at a centre-of-mass energy of 7 TeV in 2011 and to 2.0 fb^{-1} at a centre-of-mass energy of 8 TeV in 2012. The LHCb detector [22, 23] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Signal candidates are accepted if one of the final-state particles from the signal decay deposits sufficient energy transverse to the beamline in the hadronic calorimeter to pass the hardware trigger. Events that are triggered at the hardware level by another particle in the event are also retained. In a second step, a software trigger requires a two-, three- or four-track secondary vertex with a significant displacement from any primary pp interaction vertex (PV). At least one charged particle must have a large transverse momentum and be inconsistent with originating from a PV. A multivariate algorithm [24] is used for the identification of secondary vertices consistent with the decay of a b hadron.

The selection procedure is described in detail in Ref. [21]. Decays of $K_s^0 \rightarrow \pi^+\pi^-$ are reconstructed in two different categories: the first involving K_s^0 mesons that decay early enough for the resulting pions to be reconstructed in the vertex detector; and the

second containing those K_s^0 mesons that decay later, such that track segments of the pions cannot be formed in the vertex detector. These categories are referred to as Long and Downstream, respectively. Downstream K_s^0 were not reconstructed in the software trigger in 2011, but they were reconstructed and used for triggering in 2012. Furthermore, an improved software trigger with larger b -hadron efficiency, in particular in the Downstream category, was used for the second part of the 2012 data taking. To take into account the different levels of trigger efficiency, the data sample is divided into 2011, 2012a, and 2012b data-taking periods, and each period is further divided according to the K_s^0 reconstruction category, giving a total of six subsamples. The 2012b sample is the largest, corresponding to an integrated luminosity 1.4fb^{-1} , and has the highest trigger efficiency.

The events passing the trigger requirements are then filtered in two stages. Initial requirements are applied to further reduce the size of the data sample and increase the signal purity, before a multivariate classifier, based mostly on topological variables derived from the vertexing of the candidates, is implemented [21]. The selection requirement placed on the output of the multivariate classifier is defined for each data subsample to yield a signal purity close to 90%. Particle identification (PID) requirements are applied in order to reduce backgrounds from decays where either a proton, kaon or muon is misidentified as a pion. These criteria are optimised to reduce the cross-feed background coming from the decays $B_s^0 \rightarrow K_s^0 K^\pm \pi^\mp$, where the kaon is misidentified as a pion. The same invariant-mass vetoes on charmed and charmonium resonances as in Ref. [21] are used in this analysis. The invariant-mass distribution of signal candidates from the six aforementioned subsamples is displayed in Fig. 1 with the result of a simultaneous fit. The candidates selected for the subsequent DP analysis are those in the $K_s^0 \pi^+ \pi^-$ mass range [5227,5343] MeV/ c^2 .

The DP analysis technique [16] is employed to study the dynamics of the three-body decay $\bar{B}^0 \rightarrow K_s^0 \pi^+ \pi^-$. A decay-time-integrated untagged probability density function (p.d.f.) is built to describe the phase space of the decay as a function of the DP kinematical variables. In this case, the p.d.f. becomes an incoherent sum of the $\mathcal{A}(s_+, s_-)$ and $\bar{\mathcal{A}}(s_+, s_-)$ Lorentz-invariant transition amplitudes of the decays $B^0 \rightarrow K_s^0 \pi^+ \pi^-$ and $\bar{B}^0 \rightarrow K_s^0 \pi^+ \pi^-$, respectively,

$$\mathcal{P}(s_+, s_-) = \frac{|\mathcal{A}(s_+, s_-)|^2 + |\bar{\mathcal{A}}(s_+, s_-)|^2}{\iint_{\text{DP}} (|\mathcal{A}(s_+, s_-)|^2 + |\bar{\mathcal{A}}(s_+, s_-)|^2) ds_+ ds_-}, \quad (1)$$

where the kinematical variables s_\pm denote the mass squared, $m_{K_s^0 \pi^\pm}^2$.

The total amplitude $\bar{\mathcal{A}}(s_+, s_-)$ of the decay $\bar{B}^0 \rightarrow K_s^0 \pi^+ \pi^-$ is described as a coherent sum of the amplitudes of possible intermediate resonances and nonresonant contributions. The decay amplitudes for B^0 and \bar{B}^0 are given by

$$\mathcal{A} = \sum_{j=1}^N c_j F_j(s_+, s_-), \quad \bar{\mathcal{A}} = \sum_{j=1}^N \bar{c}_j \bar{F}_j(s_+, s_-), \quad (2)$$

where F_j and \bar{F}_j are the DP spin-dependent dynamical functions for the resonance j and c_j are complex coefficients that account for the relative magnitudes and phases of the N intermediate (resonant and nonresonant) components. The spin-dependent functions $F_j(s_+, s_-)$, embedding the resonance lineshape and the angular distributions, are constructed in the Zemach tensor formalism [25]. The weak-phase dependence is

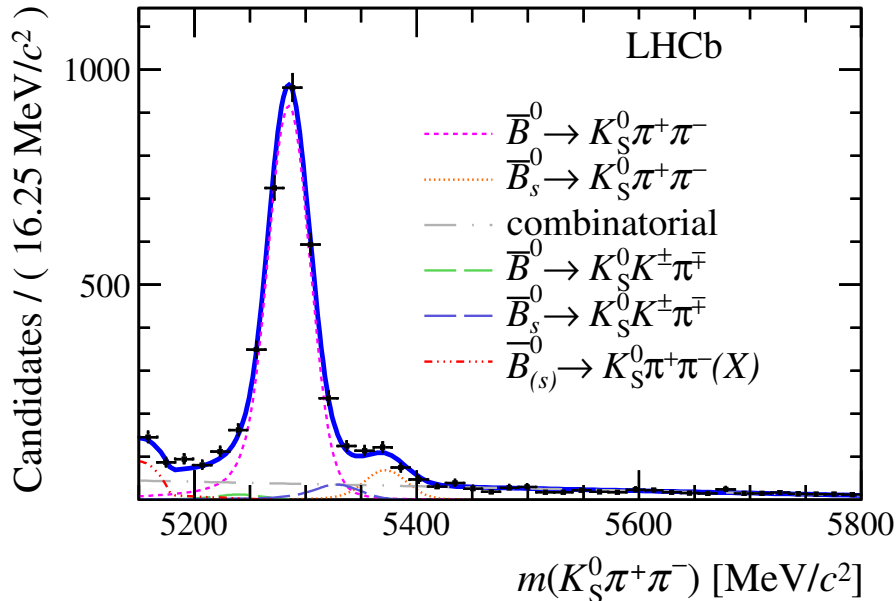


Figure 1: Invariant mass distributions of $K_S^0\pi^+\pi^-$ candidates, summing the two years of data taking and the two K_S^0 reconstruction categories. The sum of the partially reconstructed contributions from B to open charm decays, charmless hadronic decays, $\bar{B}^0 \rightarrow \eta' K_S^0$ and charmless radiative decays are denoted $\bar{B}_{(s)}^0 \rightarrow K_S^0\pi^+\pi^-(X)$.

included in the c_j coefficients. The results obtained for each isobar amplitude are expressed in this paper as a magnitude and a phase.

The analysis method consists of a simultaneous DP fit to the six data subsamples defined above, with the shared isobar parameters determined using an unbinned maximum likelihood fit. The DP model is built starting from the most significant amplitudes as determined in previous studies [17–20]. An algorithm to select the relevant additional amplitudes is defined before examining the data. A resonant amplitude is retained in the DP model if at least one of the following requirements is met: (1) a goodness-of-fit estimator based on the point-to-point dissimilarity test [26] decreases when the component is removed from the fit, (2) the likelihood ratio of the two hypotheses (component in and out) decreases, or (3) the significance of the magnitude of the component is at least three statistical standard deviations, neglecting systematic uncertainties. In particular, the components of the isobar DP model, $f_0(1500)K_S^0$ and $K^*(1680)^-\pi^+$, which were not considered in previous studies, meet all three criteria. By contrast, the amplitude $f_2(1270)K_S^0$ is not retained.

The signal DP model p.d.f. $\mathcal{S}(s_+, s_-)$ is built from the coherent sum of the amplitudes listed in Table 1, normalising each isobar coefficient to the $K^*(892)^+\pi^-$ reference amplitude. The choice of the $K^*(892)^\pm\pi^\mp$ amplitudes as a reference provides the most stable DP fit. The phases of the reference amplitude and its conjugate are fixed to zero and the magnitude of the reference amplitude is arbitrarily fixed at 2.

Two dominant backgrounds contaminate the $\bar{B}^0 \rightarrow K_S^0\pi^+\pi^-$ candidate samples: a combinatorial background and a cross-feed background from the decay $\bar{B}_s^0 \rightarrow K_S^0 K^\pm\pi^\mp$. The fractions of these backgrounds are measured from the invariant-mass fits performed in Ref. [21] and their DP distributions are determined from the data. The combinatorial

Table 1: Components of the DP model used in the fit. The individual amplitudes are referred to by the resonance they contain. The parameter values are given in MeV/c^2 for the masses and MeV for the widths, except for $f_0(980)$ resonance. The parameter m_0 is the pole mass of the resonance and Γ_0 its natural width. The mass-dependent lineshapes employed to model the resonances are indicated in the third column. Relativistic Breit-Wigner and Gounaris-Sakurai lineshapes are denoted RBW and GS, respectively. EFKLLM is a parameterisation of the $K_S^0\pi^-$ S-wave lineshape, $(K\pi)_0^-$.

Resonance	Parameters	Lineshape	Value references
$K^*(892)^-$	$m_0 = 891.66 \pm 0.26$ $\Gamma_0 = 50.8 \pm 0.9$	RBW	[27]
$(K\pi)_0^-$	$\mathcal{R}e(\lambda_0) = 0.204 \pm 0.103$ $\mathcal{I}m(\lambda_0) = 0$ $\mathcal{R}e(\lambda_1) = 1$ $\mathcal{I}m(\lambda_1) = 0$	EFKLLM [28]	[28]
$K_2^*(1430)^-$	$m_0 = 1425.6 \pm 1.5$ $\Gamma_0 = 98.5 \pm 2.7$	RBW	[27]
$K^*(1680)^-$	$m_0 = 1717 \pm 27$ $\Gamma_0 = 332 \pm 110$	Flatté [29]	[27]
$f_0(500)$	$m_0 = 513 \pm 32$ $\Gamma_0 = 335 \pm 67$	RBW	[30]
$\rho(770)^0$	$m_0 = 775.26 \pm 0.25$ $\Gamma_0 = 149.8 \pm 0.8$	GS [31]	[27]
$f_0(980)$	$m_0 = 965 \pm 10$ $g_\pi = 0.165 \pm 0.025 \text{ GeV}$ $g_K = 0.695 \pm 0.119 \text{ GeV}$	Flatté	[32]
$f_0(1500)$	$m_0 = 1505 \pm 6$ $\Gamma_0 = 109 \pm 7$	RBW	[27]
χ_{c0}	$m_0 = 3414.75 \pm 0.31$ $\Gamma_0 = 10.5 \pm 0.6$	RBW	[27]
Nonresonant (NR)		Phase space	

background DP model is built from the DP histogram of the $\bar{B}^0 \rightarrow K_S^0\pi^+\pi^-$ candidates with an invariant mass larger than $5450 \text{ MeV}/c^2$. The DP model of the cross-feed background is measured from $\bar{B}_s^0 \rightarrow K_S^0 K^\pm\pi^\mp$ candidates, where the K^\pm is reconstructed under the π^\pm hypothesis [33]. The signal fraction depends on the reconstruction category; it is determined from the fit to the invariant-mass distribution and ranges from 85% (Downstream) to 95% (Long). The p.d.f. in Eq. 1 is modified to account for the background components and the signal reconstruction efficiency across the DP, as determined from simulated events.

Two additional observables are formed from the isobar complex coefficients and are measured in the simultaneous DP fit. The asymmetry observables \mathcal{A}_{raw} are derived from

the measured isobar parameters of an amplitude j , c_j and \bar{c}_j

$$\mathcal{A}_{\text{raw}} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2}. \quad (3)$$

These observables are directly measured for flavour-specific final states. By contrast, the asymmetry of the mode $\bar{B}^0 \rightarrow f_0(980)K_s^0$ is determined using the patterns of its interference with flavour-specific amplitudes. The CP asymmetry is related to the raw asymmetry by $\mathcal{A}_{CP} = \mathcal{A}_{\text{raw}} - \mathcal{A}_{\Delta}$. The correction asymmetry is defined at first order as $\mathcal{A}_{\Delta} = A_P(B^0) + A_D(\pi)$, where $A_P(B^0)$ is the production asymmetry between the B^0 and \bar{B}^0 mesons and $A_D(\pi)$ is the detection asymmetry between π^+ and π^- mesons. The production asymmetry $A_P(B^0)$ has been determined to be $A_P(B^0) = (-0.35 \pm 0.81)\%$ [34]. Using D_s^+ decay modes [35], the pion detection asymmetry is measured to be consistent with zero with a 0.25% uncertainty. The difference in the nuclear cross-sections for K^0 and \bar{K}^0 interactions in material results in a negligible bias [36]. The uncertainty due to the correction asymmetries and the experimental systematic uncertainty are added in quadrature.

The rate of a single process is proportional to the square of the relevant matrix element (see Eq. 1). This involves the ensemble of its interferences with other components. It is convenient to define the fit fraction of the process i , \mathcal{F}_i , as

$$\mathcal{F}_i = \frac{\iint_{\text{DP}} |c_i F_i(s_+, s_-)|^2 ds_+ ds_-}{\iint_{\text{DP}} \left| \sum_j c_j F_j(s_+, s_-) \right|^2 ds_+ ds_-}. \quad (4)$$

Simulation is used to determine the selection efficiency of the signal. The simulation does not perfectly reproduce the detector response and these imperfections are corrected for in several respects. Firstly, the particle identification and misidentification efficiencies are determined from a calibration sample using reconstructed $D^{*+} \rightarrow D^0 \pi^+$ decays, where the D^0 meson decays to the Cabibbo-favoured $K^- \pi^+$ final state. The variation of the PID performance with the track kinematics is included in the procedure. The calibration is performed using samples from the same data-taking period, accounting for the variation in the performance of the hadron identification detectors over time. Secondly, inaccuracies of the tracking simulation are mitigated by a weighting of the simulated tracking efficiency to match that measured in a calibration sample [37]. Analogous corrections are applied to the K_s^0 decay-products tracking and vertexing efficiencies. Finally, a control sample of $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+$ decays is used to quantify the differences of the hardware trigger response in data and simulation for pions and kaons, separated by positive and negative hadron charges, as a function of their transverse momentum [38]. The uncertainties assigned to these corrections are taken as a source of systematic uncertainties.

Two categories of systematic uncertainties are considered: experimental and related to the DP model. The former category comprises the uncertainties on the fraction of signal, the fit biases, the variation of the signal efficiency across the DP (including the choice of the efficiency binning) and the background DP models. The DP model uncertainties arise from the limited knowledge of the fixed parameters of the resonance-lineshape models, the marginal components neglected in the amplitude fit model and the modelling of the $K_s^0 \pi^-$ and $\pi^+ \pi^-$ S-wave components.

All experimental uncertainties are estimated by means of pseudoexperiments, in which samples for each reconstruction category are simulated and fitted exactly as for the data

sample. For each pseudoexperiment, a single parameter governing a systematic effect (*e.g.* the signal fraction) is varied according to its uncertainty. The standard deviation of the distribution of the fit results in an ensemble of 500 pseudoexperiments is taken as the corresponding systematic error estimate. The largest biases observed are at the few percent level. The final result is corrected for any observed bias where it is significant. The dominant contribution to the experimental uncertainty is the efficiency determination.

The mass and the width of each resonance given in Table 1 are varied individually and symmetrically by one standard deviation to evaluate the impact of the fixed parameters of the isobar resonance lineshapes. The Blatt-Weisskopf radius parameter, fixed at 4 GeV^{-1} , is varied by $\pm 1 \text{ GeV}^{-1}$.

To evaluate the systematic uncertainties related to the marginal components of the DP model, the effect of adding the resonance $f_2(1270)$ (which is not retained by the previous criteria) and removing of the $f_0(500)$ component (the least significant contribution in the nominal model) is considered by repeating the fit with and without these components. Based upon this new model, a pseudoexperiment with a signal yield much larger than that of the data is then generated and fit back with the nominal model. The related systematic uncertainty estimate is taken as the difference between the generated and fitted values.

A critical part of the isobar model design is the description of $K_S^0 \pi^\pm$ S-wave components. Two parameterisations of these contributions have been studied: LASS [39] and EFKLLM [28]. The latter provides the best fit to the data. The log-likelihood difference between the two model hypotheses is $-2\Delta \ln \mathcal{L} = 85$. Given this large difference, no systematic uncertainty is then assigned to the choice of the EFKLLM parameterisation. All model uncertainties are combined in quadrature to form the total model systematic uncertainty

The Dalitz plot projections are shown in Fig. 2 with the result of the fit superimposed. The CP -averaged fit fractions related to the quasi two-body and nonresonant amplitudes are derived from the isobar coefficients with Eq. 4

$$\begin{aligned}
\mathcal{F}(K^*(892)^-\pi^+) &= 9.43 \pm 0.40 \pm 0.33 \pm 0.34 \%, \\
\mathcal{F}((K\pi)_0^-\pi^+) &= 32.7 \pm 1.4 \pm 1.5 \pm 1.1 \%, \\
\mathcal{F}(K_2^*(1430)^-\pi^+) &= 2.45 \pm_{-0.08}^{+0.10} \pm 0.14 \pm 0.12 \%, \\
\mathcal{F}(K^*(1680)^-\pi^+) &= 7.34 \pm 0.30 \pm 0.31 \pm 0.06 \%, \\
\mathcal{F}(f_0(980)K_S^0) &= 18.6 \pm 0.8 \pm 0.7 \pm 1.2 \%, \\
\mathcal{F}(\rho(770)^0 K_S^0) &= 3.8 \pm_{-1.6}^{+1.1} \pm 0.7 \pm 0.4 \%, \\
\mathcal{F}(f_0(500)K_S^0) &= 0.32 \pm_{-0.08}^{+0.40} \pm 0.19 \pm 0.23 \%, \\
\mathcal{F}(f_0(1500)K_S^0) &= 2.60 \pm 0.54 \pm 1.28 \pm 0.60 \%, \\
\mathcal{F}(\chi_{c0}K_S^0) &= 2.23 \pm_{-0.32}^{+0.40} \pm 0.22 \pm 0.13 \%, \\
\mathcal{F}(K_S^0 \pi^+ \pi^-)^{\text{NR}} &= 24.3 \pm 1.3 \pm 3.7 \pm 4.5 \%,
\end{aligned}$$

where the statistical, experimental systematic and model uncertainties are split accordingly in that order. The results are in agreement with the measurements obtained by the BaBar and Belle collaborations with decay-time-dependent flavour-tagged analyses [17,18], insofar as the DP model components can be compared.

The measurements of the CP asymmetries are

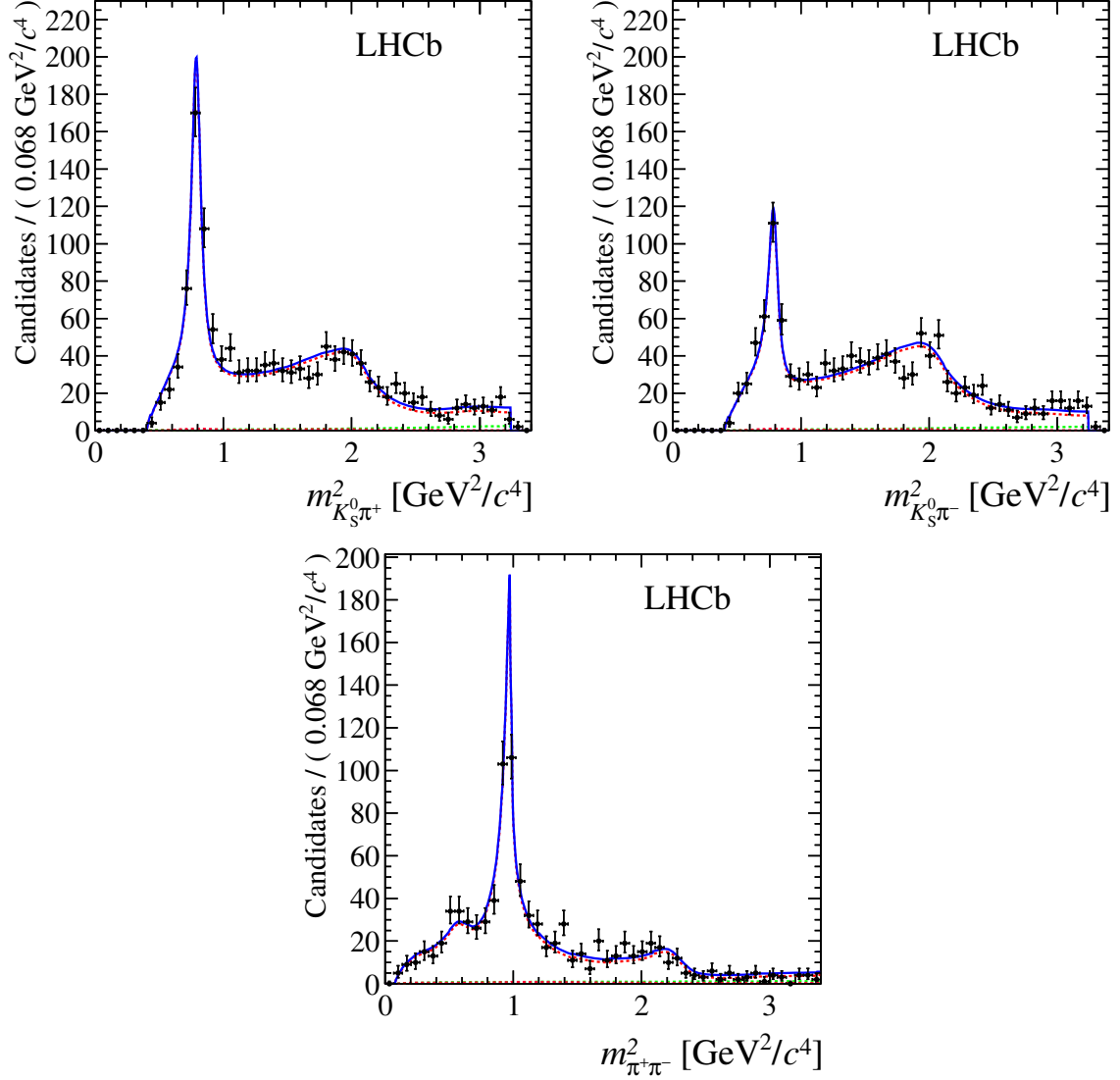


Figure 2: Projections of the sum of all data categories (black points) and the nominal fit function onto the DP variables (left) $m_{K_S^0 \pi^+}^2$, (right) $m_{K_S^0 \pi^-}^2$ and (bottom) $m_{\pi^+ \pi^-}^2$, restricted to the two-body low invariant-mass regions. The full fit is shown by the solid blue line and the signal model by the dashed red line. The observed difference is due to the (green) combinatorial and (light red) cross-feed background contributions, barely visible in these projections.

$$\begin{aligned}
\mathcal{A}_{CP}(K^*(892)^- \pi^+) &= -0.308 \pm 0.060 \pm 0.011 \pm 0.012, \\
\mathcal{A}_{CP}((K\pi)_0^- \pi^+) &= -0.032 \pm 0.047 \pm 0.016 \pm 0.027, \\
\mathcal{A}_{CP}(K_2^*(1430)^- \pi^+) &= -0.29 \pm 0.22 \pm 0.09 \pm 0.03, \\
\mathcal{A}_{CP}(K^*(1680)^- \pi^+) &= -0.07 \pm 0.13 \pm 0.02 \pm 0.03, \\
\mathcal{A}_{CP}(f_0(980)K_S^0) &= 0.28 \pm 0.27 \pm 0.05 \pm 0.14,
\end{aligned}$$

where the uncertainties are statistical, experimental systematic and from the model. The

statistical significance of having observed a nonvanishing CP asymmetry in the decay $\overline{B}^0 \rightarrow K^*(892)^-\pi^+$, built from the likelihood ratio for the null hypothesis, is 6.7 standard deviations and reduces to about 6 standard deviations taking into account the systematic uncertainties. This measurement constitutes the first observation of a CP -violating asymmetry in the decay $\overline{B}^0 \rightarrow K^*(892)^-\pi^+$. The measured value is in good agreement with the world average $\mathcal{A}_{CP}(K^*(892)^-\pi^+) = -0.23 \pm 0.06$ with a similar precision.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (The Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FASO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany), EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), ANR, Labex P2IO, ENIGMASS and OCEVU, and Région Auvergne-Rhône-Alpes (France), RFBR and Yandex LLC (Russia), GVA, XuntaGal and GENCAT (Spain), Herchel Smith Fund, the Royal Society, the English-Speaking Union and the Leverhulme Trust (United Kingdom).

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