Search for \( CP \) violation and observation of \( P \) violation in \( \Lambda^0_b \to p\pi^-\pi^+\pi^- \) decays

LHCb collaboration†

Abstract
A search for \( CP \) violation in the \( \Lambda^0_b \to p\pi^-\pi^+\pi^- \) decay is performed using LHCb data corresponding to an integrated luminosity of 6.6 fb\(^{-1}\) collected in \( pp \) collisions at centre-of-mass energies of 7, 8 and 13 TeV. The analysis uses both triple product asymmetries and the unbinned energy test method. The highest significances of \( CP \) asymmetry are 2.9 standard deviations from triple product asymmetries and 3.0 standard deviations for the energy test method. Once the global \( p \)-value is considered, all results are consistent with no \( CP \) violation. Parity violation is observed at a significance of 5.5 standard deviations for the triple product asymmetry method and 5.3 standard deviations for the energy test method.


© 2019 CERN for the benefit of the LHCb collaboration. CC-BY-4.0 licence

†Authors are listed at the end of this Letter.
The violation of \( CP \) symmetry, where \( C \) and \( P \) are the charge-conjugation and
parity operators, is a well-established phenomenon in the decays of \( K \) and \( B \) mesons [1,3].
Recently, it has also been observed in the decays of \( D \) mesons by the LHCb collaboration [4].
However, \( CP \) violation has yet to be established in baryonic decays, although first evidence
was recently found [5]. Such decays offer a novel environment to probe the mechanism for
quark-flavour mixing and for \( CP \) violation, which is regulated by the Cabibbo-Kobayashi-
Maskawa (CKM) matrix in the Standard Model (SM) [6,7].

In this Letter searches for \( CP \) and \( P \) violation with \( \Lambda^0_b \to p\pi^-\pi^+\pi^- \) decays are
reported. Throughout, the inclusion of charge-conjugate processes is implied, unless
otherwise indicated. This decay is mediated mainly by tree and loop processes of similar
magnitudes, proportional to the product of the CKM matrix elements \( V_{ub}V_{ud}^* \) and \( V_{tb}V_{td}^* \),
respectively. This allows for significant interference effects with a relative weak phase
\( \alpha \) of the Unitary Triangle between the amplitudes. If matter and antimatter exhibit
different effects, \( CP \) violation manifests as either global asymmetries in decay rates, or
as local asymmetries within the phase space. The \( \Lambda^0_b \to p\pi^-\pi^+\pi^- \) decay is particularly
well suited for \( CP \)-violation searches [8] due to a rich resonant structure in the decay.

The dominant contributions proceed through the \( N^{*+} \to \Delta^{++}(1234)\pi^- \) (referred as \( \Delta^{++} \)
hereinafter), \( \Delta^{++} \to p\pi^+ \), \( a_1^-(1260) \to \rho^0(770)\pi^- \) and \( \rho^0(770) \to \pi^+\pi^- \) decays, where the
proton excited states are indicated as \( N^{*+} \). The searches for \( CP \) violation are performed
by separating the \( P \)-odd and \( P \)-even contributions [9], as discussed below. In these studies,
a large control sample of Cabibbo-favored \( \Lambda^0_b \to \Lambda^+_b \to p\pi^-\pi^+\pi^- \) decays is used, where
no \( CP \) violation is expected, to assess potential experimental biases and systematic effects.

The LHCb collaboration has previously studied the \( \Lambda^0_b \to p\pi^-\pi^+\pi^- \) decay and found
evidence for \( CP \) violation with a significance of 3.3 standard deviations including systematic
uncertainties [5]. This Letter supersedes the previous results using \( pp \) collision data
corresponding to an integrated luminosity of 6.6 fb\(^{-1}\) collected from 2011 to 2017 at
centre-of-mass energies of 7, 8 and 13 TeV that represents a four times larger sample in
signal yield.

The LHCb detector [10,11] is a single-arm forward spectrometer covering the pseudo-
rapidity range \( 2 < \eta < 5 \), designed for the study of particles containing \( b \) or \( c \) quarks. The
detector elements that are particularly relevant to this analysis are: a silicon-strip vertex
detector surrounding the \( pp \) interaction region that allows \( b \) hadrons to be identified from
their characteristically long flight distance; a tracking system that provides a measurement
of the momentum, \( p \), of charged particles; and two ring-imaging Cherenkov detectors
that are able to discriminate between different species of charged hadrons. Simulation is
required to model the effects of the detector acceptance and the selection requirements.
The \( pp \) collisions are generated using PYTHIA [12] with a specific LHCb configuration [13],
and neither \( CP \)- nor \( P \)-violating effects are present in the signal channel. Decays of unstable
particles are described by EVTGEN [14], in which final-state radiation is generated
using PHOTOS [15]. The interaction of the generated particles with the detector, and its
response, are implemented using the GEANT4 toolkit [16] as described in Ref. [17].

The analysis searches for \( CP \) and \( P \) violation by measuring triple product asymmetries
(TPA) and by exploiting the unbinned energy test method [18–24]. In the TPA analysis,
both local and integrated asymmetries are considered. The analysis also benefits from
additional studies of amplitude models [9,25] to maximise the sensitivity. The energy
test method is designed to look for localized differences in the phase space between two
samples.
The scalar triple products are defined as $C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi_{\text{fast}}^+} \times \vec{p}_{\pi^-})$ and $\overline{C}_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi_{\text{fast}}^-} \times \vec{p}_{\pi^-})$, for $\Lambda_b^0$ and $\overline{\Lambda}_b^0$ respectively. Hereinafter $\pi_{\text{fast}}^- \ (\pi_{\text{slow}}^-)$ refers to the faster (slower) of two negative pions in the $\Lambda_b^0$ rest frame. Following these definitions, four statistically independent subsamples are considered, labeled with $I$ for $C_{\hat{T}} > 0$, $II$ for $C_{\hat{T}} < 0$, $III$ for $-\overline{C}_{\hat{T}} > 0$ and $IV$ for $-\overline{C}_{\hat{T}} < 0$. Samples $I$ and $III$ are related by a $CP$ transformation, as are samples $II$ and $IV$. Samples $I$ and $II$ are related by a $P$ transformation, as are samples $III$ and $IV$. Both $CP$- and $P$-violating effects appear as differences between the triple product observables related by $CP$ and $P$ transformations.

The $\hat{T}$ operator reverses momentum and spin three-vectors $[26, 27]$. The quantities $C_{\hat{T}}$ and $\overline{C}_{\hat{T}}$ are odd under this operator. This enables studies of the $P$-odd $CP$ violation, which occurs via interference of the $\hat{T}$-even and $\hat{T}$-odd amplitudes with different $CP$-odd (‘weak’) phases $[9, 25, 27]$.

The TPA are defined as

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \quad \overline{A}_{\hat{T}} = \frac{N(-\overline{C}_{\hat{T}} > 0) - N(-\overline{C}_{\hat{T}} < 0)}{N(-\overline{C}_{\hat{T}} > 0) + N(-\overline{C}_{\hat{T}} < 0)},$$

where $N$ and $\overline{N}$ are the yields of $\Lambda_b^0$ and $\overline{\Lambda}_b^0$ decays, respectively. The $CP$- and $P$-violating asymmetries are then defined as

$$a_{CP}^{\text{odd}} = \frac{1}{2} \left( A_{\hat{T}} - \overline{A}_{\hat{T}} \right), \quad a_{P}^{\text{odd}} = \frac{1}{2} \left( A_{\hat{T}} + \overline{A}_{\hat{T}} \right).$$

Two types of asymmetries are determined from data. The first are localized in the phase space in order to enhance sensitivity to local effects and the second are integrated over the whole phase space. By construction, such asymmetries are largely insensitive to particle-antiparticle production and detector-induced asymmetries $[28]$.

The previous LHCb result $[5]$ showed evidence for a dependence of the $CP$ asymmetry as a function of $|\Phi|$, the absolute value of the angle between the planes defined by the $p\pi_{\text{fast}}^-$ and $\pi^+\pi_{\text{slow}}^-$ systems in the $\Lambda_b^0$ rest frame. In the present analysis a binning scheme, labeled $A$, is considered, based on the results of an approximate amplitude analysis performed on $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays. The binning scheme consists in dividing the data sample into 16 subsamples to explore the distribution of the polar and azimuthal angles of the proton ($\Delta^{++}$) in the $\Delta^{++}$ ($N^{*+}$) rest frame. A second binning scheme, labeled $B$, is used to probe the asymmetries as a function of $|\Phi|$, dividing the data sample into ten subsamples uniformly distributed in the range $[0, \pi]$. The invariant-mass regions $m(p\pi^+\pi_{\text{slow}}^-) > 2.8 \text{ GeV}/c^2$ (samples $A_1, B_1$), dominated by the $a_1$ resonance, and $m(p\pi^+\pi_{\text{slow}}^-) < 2.8 \text{ GeV}/c^2$ (samples $A_2, B_2$), dominated by the $N^{*+}$ decay, are studied separately. The compatibility of the measured asymmetries with $CP$ and $P$ conservation is checked by means of a $\chi^2$ test taking into account statistical and systematic effects.

The energy test is a model-independent unbinned test sensitive to local differences between two samples, as might arise from $CP$ violation. It can provide superior discriminating power between different samples than traditional $\chi^2$ tests $[21, 22]$. The test is performed through the calculation of a test statistic

$$T \equiv \frac{1}{2n(n-1)} \sum_{i \neq j}^n \psi_{ij} + \frac{1}{2n(n-1)} \sum_{i \neq j}^n \psi_{ij} - \frac{1}{n} \sum_{i=1}^n \sum_{j=1}^n \psi_{ij},$$
where there are $n$ ($\bar{n}$) candidates in the first (second) sample. The first (second) term
sums over pairs of candidates drawn from the first (second) sample and the final term
sums over pairs with one candidate drawn from each sample. Each pair of candidates
$i,j$ is assigned a weight $\psi_{ij} = e^{-d_{ij}/c^2}$, where $d_{ij}$ is their Euclidean distance in phase
space, while the tunable parameter $\delta$ determines the distance scale probed using the
energy test. The phase space is defined using the squared masses $m^2(p\pi^+)$, $m^2(\pi^+\pi_{\text{slow}})$,
$m^2(p\pi^+\pi_{\text{slow}})$, $m^2(\pi^+\pi_{\text{slow}})$ and $m^2(p\pi_{\text{slow}}^-)$. The value of $T$ is large when there are
significant localized differences between samples and has an expectation of zero when there
are no differences. The distribution of $T$ under the hypothesis of no sample differences,
and the assignment of $p$-values, are determined using a permutation method [21][23].

Similarly to the TPA method, the comparison of subsamples I and IV to subsamples
II and III allows for a $P$-odd and $CP$-odd test; the comparison of subsamples I and
II to subsamples III and IV for a $P$-even and $CP$-odd test. The $P$ violation is also
tested by comparing the combination of subsamples I and III with the combination of
subsamples II and IV. This provides three test configurations. The length scale at which
$CP$ violation might appear is not known. Therefore three different scales are probed in
each configuration, chosen following Refs. [21][22] as $\delta = 1.6$ GeV$^2$/c$^4$, 2.7 GeV$^2$/c$^4$ and
13 GeV$^2$/c$^4$. For each of the three test configurations all three scales are probed, such
that nine tests are made overall: six tests for effects arising from $CP$ violation (three
probing $P$-even $CP$ violation and three $P$-odd $CP$ violation) and three tests for effects
arising from $P$ violation.

The candidate $A_0^0 \rightarrow p\pi^+\pi^-\pi^-$ decays are formed by combining tracks with transverse
(total) momentum greater than 250 MeV/c (1.5 GeV/c) identified as protons and pions
that originate from a common vertex displaced from the primary vertex. A cut on the
invariant-mass $m(pK^-\pi^+) \in [2.26, 2.30]$ GeV/c$^2$ is applied to select $A_0^0 \rightarrow A_+^0 (\rightarrow pK^-\pi^+\pi^-)$
decay candidates used as control sample. A boosted decision tree classifier [29] (BDT)
is constructed from a set of kinematic variables that discriminate between signal and
background. The result of an unbinned extended maximum-likelihood fit to the invariant-
mass distribution, $m(p\pi^+\pi^-)$, is shown in Fig. 1 for the dataset integrated over the
phase space. The invariant-mass distribution of the signal is modelled by a Gaussian
function core with power-law tails [30], with the mean and width of the Gaussian function
determined from the fit to data. All other parameters of the signal fit model are taken
from simulation except for the yields. The combinatorial background is parameterised
with an exponential function where the parameters are left free to vary in the fits.
Partially reconstructed $A_0^0$ decays, as for example $A_0^0 \rightarrow p\pi^-\pi^+\pi^-\pi^0$, are described by
an ARGUS function [31] convolved with a Gaussian function to account for resolution
effects. The shapes of backgrounds from other $b$-hadron decays due to incorrectly identified
particles, e.g. kaons identified as pions or protons identified as kaons, are modelled using
simulated events. These consist mainly of $A_0^0 \rightarrow pK^-\pi^+\pi^-$ and $B^0 \rightarrow K^+\pi^-\pi^-\pi^-$
decays. Their yields are obtained from fits to data where the invariant-mass distributions are
reconstructed under the appropriate mass hypotheses and then fixed in the baseline fits.
The signal yields for the $A_0^0 \rightarrow p\pi^-\pi^+\pi^-\pi^-$ decay and the $A_0^0 \rightarrow A_+^0 (\rightarrow pK^-\pi^+\pi^-)$ control
test the assignments of $A_+^0$ and $\bar{A}_+^0$ in each region, assigning signal
candidates to four categories according to $A_0^0$ or $\bar{A}_0^0$ flavour and sign of $C_T$ or $\bar{C}_T$. The
asymmetries $A_T$ and $\bar{A}_T$ are found to be uncorrelated. Corresponding asymmetries for
each of the background components are also determined in the fit; they are found to be
consistent with zero, and do not lead to significant systematic uncertainties in the signal asymmetries.

For the energy test, $\Lambda^0_b$ candidates are selected in a window corresponding to 2.5 standard deviations of the Gaussian function around the known $\Lambda^0_b$ mass [32], which optimises the sensitivity to $CP$ violation. The background component with this selection is small and does not affect the analysis.

The reconstruction efficiency for signal candidates with $C_T^\hat{=} > 0$ is consistent with that for candidates with $C_T^\hat{=} < 0$. This indicates that the detector and the reconstruction algorithms do not bias the measurements. This is confirmed using the control sample and a large sample of simulated events. The same check is performed for the $C_T^\hat{=}$ observable. As a general cross-check, the $CP$ asymmetry is measured in the control sample and found to be compatible with zero, $a_T^{\hat{=}+\pi^-} = (+0.04 \pm 0.16)\%$.

The main sources of systematic uncertainties in the TPA analysis are selection criteria, reconstruction and detector acceptance. They are evaluated using the control sample. In the TPA analysis, a systematic uncertainty of 0.16% is assigned for the integrated measurements, while uncertainties in the range (0.6–2.5)% are assigned for local measurements. The systematic uncertainty arising from the experimental resolution of the triple products $C_T$ and $C_T^\hat{=}^\text{d}$, which could introduce a migration of candidates between bins, is estimated from simulation. The difference between the reconstructed and generated asymmetries, 0.01%, is taken as a systematic uncertainty in the TPA analysis. To assess the systematic uncertainty associated with the fit model, an alternative is used to compare the results measured on pseudoexperiments with respect to the baseline model. A value of 0.06% (0.08%) for $a_T^{\hat{=}+\pi^-}/a_T^{\hat{=}+\pi^-}$ is assigned as systematic uncertainty. No significant differences are observed comparing results from different running conditions, trigger requirements and selection criteria.

Several studies are made to confirm the reliability of the energy test method. The method is insensitive to global asymmetries, and so is not affected by differences between
Λ^0 and $\bar{\Lambda}^0$ production rates. However, local asymmetries due to detector effects may yield significant results that would lead to an incorrect conclusion. The potential presence of such effects is studied using the control sample. No evidence is found for any local asymmetry.

Contributions from background decays are considered, in case they contain localized asymmetries not related to CP violation. A high-mass selection is applied (5.75 < m($p\pi^-\pi^+\pi^-$) < 6.10 GeV/c^2) to identify candidates predominantly produced by random combinations of particles. No significant effect is found in the six configurations of the energy test probing the CP-conserving hypothesis. Moreover, a small independent sample of the dominant peaking background ($A^0_b \rightarrow pK^-\pi^+\pi^-$) is selected using the same requirements as in Ref. [5], with the number of candidates corresponding to the size of the relevant background in the $A^0_b \rightarrow p\pi^-\pi^+\pi^-$ sample. Again, no p-values corresponding to a significance above 3 standard deviations are observed when the six configurations of the energy test probing CP violation are applied to this sample. The background contribution from the $B^0 \rightarrow K^+\pi^-\pi^+\pi^-$ decay is negligible within the mass window selected for the energy test.

Finally, the proton detection asymmetry in simulation is replicated in the $A^0_b \rightarrow p\pi^-\pi^+\pi^-$ data sample by setting the $A^0_b$ flavour in the data sample at random to create the same asymmetry. The P-even and P-odd configurations of the energy test are then run for all three distance scales to test for effects that might lead to an incorrect rejection of the CP-conserving hypothesis. This is repeated multiple times for each test with different flavour assignments for the $A^0_b$ candidates. In all six tests the distribution of p-values is consistent with being uniform, so no evidence for any bias from the proton detection asymmetry is found.

The measured TPA from the fit to the full data set are $a_{TP}^{P=0} = (0.7 \pm 0.7 \pm 0.2)\%$ and $a_{TP}^{P=1} = (-1.0 \pm 0.7 \pm 0.2)\%$. Consistency with the CP-conserving hypothesis is observed, while a significant non-zero value for the $a_{TP}^{P=0}$ asymmetry is found. The effect, estimated with the profile likelihood-ratio test, has a significance of 5.5 standard deviations and indicates parity violation in the $A^0_b \rightarrow p\pi^-\pi^+\pi^-$ decay.

The values of the TPA for the binning schemes A1, A2, B1 and B2 are shown in Fig. [2] In the binning schemes A2 and B2 the contribution from N^*+ resonances dominates and therefore larger CP asymmetries are possible relative to the A1 and B1 binning schemes. However, in the A2 and B2 phase-space regions, p-values with respect to the CP-conserving hypothesis corresponding to statistical significances of 0.5 and 2.9 standard deviations are measured, respectively. The evidence of CP violation previously observed [5] is therefore not established.

The same binning scheme B with the present data provides a deviation at 2.8 standard deviations from the CP conservation hypothesis. The compatibility with the previous published measurement [3] is determined to be at 2.6 standard deviations, a value which decreases to 2.1 when the same BDT selection is applied. Pseudoexperiments are generated by randomly assigning the flavour and CP sign to each candidate. The asymmetries are extracted and the difference between the Run 1 and full datasets is determined as a $\chi^2$ value. The fraction of pseudoexperiments with a $\chi^2$ value greater than the observed $\chi^2$ in data represents the p-value.

The observed p-value for the P-symmetry hypothesis corresponds to a statistical significance of 5.1 standard deviations for the binning scheme B. The p-values measured in the case of binning schemes B1 and B2 indicate that the P violation has a large
contribution from the $Λ^0_b → p a_1 (1260)^-$ decay, for which the statistical significance is 5.5 standard deviations.

The $p$-values obtained for different configurations of the energy test are summarised in Table [1]. All CP-violation searches using the energy test result in $p$-values with a significance of 3 standard deviations or smaller. Given the reported $p$-value for the $P$-even configuration of the energy test at a distance scale of 2.7 GeV$/c^4$ is marginally consistent with the CP-conserving hypothesis, the different distance scales considered are combined to obtain a global $p$-value for the $P$-even configuration. A new test statistic is defined as $Q = p_1 p_2 p_3$, where $p_i$ corresponds to a $p$-value for a distance scale $i$. The value of $Q$ observed in data is then compared to the corresponding values from permutations, considering correlations between the different distance scales. The combined $p$-value for the $P$-even energy test configuration is $4.6 \times 10^{-3}$. In addition, the test for parity violation is also performed using the same three distance scales with the energy test. The results are reported in Table [1]. The $p$-values found with this study correspond to the observation of local parity violation for the two smaller distance scales probed.

In conclusion, this Letter reports the searches for CP violation in $Λ^0_b → p π^- π^+ π^-$ decays both globally and in regions of phase space, using two different methods. The results are marginally compatible with the no CP-violation hypothesis. Violation of $P$ symmetry is observed using both methods, locally with a significance of over 5 standard deviations, and, when the triple product asymmetries are evaluated having integrated

![Figure 2: Measured asymmetries for the binning scheme (left) $A_1$ and $A_2$ and (right) $B_1$ and $B_2$. The error bars represent the sum in quadrature of the statistical and systematic uncertainties. The χ² per ndof is calculated with respect to the null hypothesis and includes statistical and systematic uncertainties.](image)

Table 1: The $p$-values from the energy test for different distances scales and test configurations.

<table>
<thead>
<tr>
<th>Distance scale $δ$</th>
<th>1.6 GeV$/c^4$</th>
<th>2.7 GeV$/c^4$</th>
<th>13 GeV$/c^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value (CP conservation, $P$ even)</td>
<td>$3.1 \times 10^{-2}$</td>
<td>$2.7 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>$p$-value (CP conservation, $P$ odd)</td>
<td>$1.5 \times 10^{-1}$</td>
<td>$6.9 \times 10^{-2}$</td>
<td>$6.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$p$-value ($P$ conservation)</td>
<td>$1.3 \times 10^{-7}$</td>
<td>$4.0 \times 10^{-7}$</td>
<td>$1.6 \times 10^{-1}$</td>
</tr>
</tbody>
</table>
over the entire sample, with a significance of 5.5 standard deviations.

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 (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA).

We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (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 and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom).

References


LHCb collaboration

R. Aaij31, C. Abellán Beteta49, T. Ackernley59, B. Adeva45, M. Adinolfi53, H. Afsharnia9,
C.A. Aidala79, S. Aiola25, Z. Ajaltouni9, S. Akai64, P. Albicocco22, J. Albrecht14, F. Alessio47,
M. Alexander58, A. Alfonso Aliero44, G. Alkhazov37, P. Alvarez Cartelle60, A.A. Alves Jr55,
S. Amato2, Y. Amhis11, L. An21, L. Anderlini21, G. Andreassi48, M. Andreotti20, F. Archilli16,
J. Arnau Romeu10, A. Artamonov45, M. Artuso57, K. Arzymatov41, E. Aslanides10, M. Atzeni99,
B. Audurier26, S. Bachmann16, J.J. Back55, S. Baker60, V. Balagura11, W. Baldini20,47,
A. Baranov41, R.J. Barlow61, S. Barsuk11, W. Bartel60, M. Bartolini23,47, F. Baryshnikov76,
G. Bassi28, V. Batozskaya35, B. Batsukh67, A. Battig14, V. Battistoni48, A. Bay18, M. Becker14,
F. Bedeschi28, I. Bediaga1, A. Beite67, L.J. Beil31, V. Belavin41, S. Belin62, N. Belli59,
V. Bellee48, K. Belous43, I. Belyaev38, G. Bencivenni22, E. Ben-Haim12, S. Benson31,
S. Beranek13, A. Berezhnoy39, R. Bernet49, D. Berninghoff16, H.C. Bernstein67, E. Bertholet12,
A. Bertolin27, C. Betancourt49, F. Betti19,e, M.O. Bettler54, Ia. Bezhysikyo49, S. Bhasin53,
J. Bhom33, M.S. Bieker14, S. Bifani52, P. Bilbor12, A. Birnkraut14, A. Bizzet21,u, M. Bjorn62,
M.P. Blago17, T. Blake55, F. Blanc48, S. Blusk67, D. Bobulska58, V. Bocci30,
O. Boente Garcia45, T. Boettcher63, A. Boldyrev7, A. Bondar42,x, N. Bondar37, S. Boghli61,47,
M. Borisyat41, M. Borsato16, J.T. Borsuk33, T.J.V. Bowcock49, C. Bozzi40,47, S. Braun49,
A. Breu Rodriguez45, M. Brodski47, J. Brodzicka33, A. Brossa Goncalo65, D. Brundu26,
E. Buchanan53, A. Buonaura49, C. Burr26, A. Bursche26, J.S. Butter31, J. Byutaert47,
W. Byczynski47, S. Cadeddu26, H. Cal17, R. Calabrese20,u, S. Cali22, R. Calladine52,
M. Calvi24,4, M. Calvo Gomez44,m, A. Camboni44,m, P. Campagna22, D.H. Campora Perez47,
L. Capriotti19,e, A. Carbone19,e, G. Carboni39, R. Cardinale23,h, A. Cardini26, P. Carniti24,4,
K. Carvalho Akiba31, A. Casais Vidal45, G. Casse59, M. Cattaneo47, G. Cavallero47,
R. Cenci28,p, J. Cerasoli10, M.G. Chapman53, M. Charles12,47, Ph. Charpentier47,
G. Chatzikoustantinidis52, M. Chefdievillev8, V. Chekalina41, C. Chen3, S. Chen26, A. Chernov33,
S.-G. Chitic47, V. Chobanova45, M. Chrzaszcz47, A. Chubykin37, P. Ciambrone22, M.F. Cicala55,
X. Cid Vidal45, G. Ciezarek47, F. Cindolo39, P.E.L. Clarke57, M. Clemencic47, H.V. Cliff55,
J. Closier47, J.L. Cobbledick61, V. Coco47, J.A.B. Coelho11, J. Cogan10, E. Cogneras9,
L. Cojocarini36, P. Collins47, T. Colombo47, A. Comerma-Montells16, A. Contu26, N. Cooke52,
G. Coombs58, S. Coquereau14, G. Corti37, C.M. Costa Sobral55, B. Couturier47, D.C. Craik63,
A. Crocombe55, M. Cruz Torres4, R. Currie57, C.L. Da Silva66, E. Dall’Occo31, J. Dalseno45,53,
C. D’Ambrosio47, A. Danilina38, P. d’Argento16, A. Davis61, O. De Aguilar Francisco47,
K. De Bruyn47, S. De Capua61, M. De Cian48, J.M. De Miranda41, L. De Paula2, M. De Serio18,d,
P. De Simone22, J.A. de Vries31, C.T. Dean66, W. Dean79, D. Decamp8, L. Del Buono12,
B. Delaney54, H.-P. Dembinski15, M. Demm14, A. Dendek34, V. Denysenko49, D. Derkach77,
O. Deschamps9, F. Desse11, F. Dettoni26, B. Dey7, A. Di Canto47, P. Di Nezza22, S. Didenko76,
H. Dijkstra47, F. Dorder26, M. Dorigo28,y, A.C. dos Reis1, L. Douglas58, A. Dovbnya50,
D. Dutta61, R. Dzhelyadin43,t, M. Dzie wiecki16, A. Dziewa33, A. Dzyuba37, S. Ease56,
U. Egede60, V. Egorychev38, S. Eidelman42,x, S. Eisenhardt57, R. Ekelhof14, S. Ek-In18,
L. Ekhdn58, S. Ely67, A. Eno36, S. Escher13, S. Esen31, T. Evans47, A. Falabella19, J. Fan3,
N. Farley52, S. Farra59, D. Fazzini11, M. Fco47, P. Fernandez-Declar47, A. Fernandez Prieto45,
F. Ferrari19,e, L. Ferreira Lopes48, F. Ferreira Rodrigues4, S. Ferreiras Sole31, M. Ferro-Luzzi47,
S. Filip0, R.A. Fini18, M. Fiorini20,y, M. Firle33, K.M. Fischer62, C. Fitzpatrick47,
T. Fluowski34, F. Fleuret11,b, M. Fontana47, F. Fontanelli23,h, R. Forty47, V. Franco Lima59,
M. Franco Sevilla65, M. Frank47, C. Frei47, D.A. Friday58, J. Fu25,g, M. Fuehring14, W. Funk47,
E. Gabriel57, A. Gallas Torreira45, D. Galli19,e, S. Gallerini27, S. Gambetta67, Y. Gan3,
M. Gandelsman2, P. Gandini25, Y. Gao4, L.M. Garcia Martin26, J. Garcia Pardinas49,
B. Garcia Plana45, F.A. Garcia Rosales11, J. Garra Tico44, L. Garrido44, D. Gascon44,

Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
Center for High Energy Physics, Tsinghua University, Beijing, China
School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
University of Chinese Academy of Sciences, Beijing, China
Institute Of High Energy Physics (IHEP), Beijing, China
Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China
Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France
Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
Université Paris-Saclay, CNRS/IN2P3, UPMC, Paris 06, France
Institut de Physique Théorique, CEA, CNRS/IN2P3, F-91191 Gif-sur-Yvette Cedex, France
Université de Lille, CNRS/INSU, LPC, F-59000 Lille, France
Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
IPhT, CNRS/CEA, CEA/Saclay, F-91191 Gif-sur-Yvette, France
School of Physics, University College Dublin, Dublin, Ireland
INFN Sezione di Bari, Bari, Italy
INFN Sezione di Bologna, Bologna, Italy
INFN Sezione di Ferrara, Ferrara, Italy
INFN Sezione di Firenze, Firenze, Italy
INFN Laboratori Nazionali di Frascati, Frascati, Italy
INFN Sezione di Genova, Genova, Italy
INFN Sezione di Milano-Bicocca, Milano, Italy
INFN Sezione di Milano, Milano, Italy
INFN Sezione di Padova, Padova, Italy
INFN Sezione di Pisa, Pisa, Italy
INFN Sezione di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma La Sapienza, Roma, Italy
Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands
Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
National Center for Nuclear Research (NCBJ), Warsaw, Poland
Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia
Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia
Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
Yandex School of Data Analysis, Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia
Protvino, Russia
ICCCUB, Universitat de Barcelona, Barcelona, Spain
Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

13
Physik-Institut, Universität Zürich, Zürich, Switzerland

NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine

Institute for Nuclear Research of the National Academy of Sciences (KIIR), Kyiv, Ukraine

University of Birmingham, Birmingham, United Kingdom

H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, University of Warwick, Coventry, United Kingdom

STFC Rutherford Appleton Laboratory, Didcot, United Kingdom

School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Imperial College London, London, United Kingdom

Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

Department of Physics, University of Oxford, Oxford, United Kingdom

Massachusetts Institute of Technology, Cambridge, MA, United States

University of Cincinnati, Cincinnati, OH, United States

University of Maryland, College Park, MD, United States

Los Alamos National Laboratory (LANL), Los Alamos, United States

Syracuse University, Syracuse, NY, United States

Laboratory of Mathematical and Subatomic Physics, Constantine, Algeria, associated to 2

Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to 2

South China Normal University, Guangzhou, China, associated to 3

School of Physics and Technology, Wuhan University, Wuhan, China, associated to 3

Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia, associated to 12

Institut für Physik, Universität Rostock, Rostock, Germany, associated to 16

Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to 31

National Research Centre Kurchatov Institute, Moscow, Russia, associated to 38

National University of Science and Technology "MISIS", Moscow, Russia, associated to 38

National Research University Higher School of Economics, Moscow, Russia, associated to 41

National Research Tomsk Polytechnic University, Tomsk, Russia, associated to 38

University of Michigan, Ann Arbor, United States, associated to 67

Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil

Laboratoire Leprince-Ringuet, Palaiseau, France

P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia

Università di Bari, Bari, Italy

Università di Bologna, Bologna, Italy

Università di Cagliari, Cagliari, Italy

Università di Ferrara, Ferrara, Italy

Università di Genova, Genova, Italy

Università di Milano Bicocca, Milano, Italy

Università di Roma Tor Vergata, Roma, Italy

Università di Roma La Sapienza, Roma, Italy

AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland

LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain

Hanoi University of Science, Hanoi, Vietnam

Università di Padova, Padova, Italy

Università di Pisa, Pisa, Italy

Università degli Studi di Milano, Milano, Italy

Università di Urbino, Urbino, Italy

Università della Basilicata, Potenza, Italy

Scuola Normale Superiore, Pisa, Italy

Università di Modena e Reggio Emilia, Modena, Italy

Università di Siena, Siena, Italy

MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines

Novosibirsk State University, Novosibirsk, Russia
INFN Sezione di Trieste, Trieste, Italy
School of Physics and Information Technology, Shaanxi Normal University (SNU), Xi’an, China
Physics and Micro Electronic College, Hunan University, Changsha City, China
Lanzhou University, Lanzhou, China
†Deceased