EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-256
07 November 2019

Search for *CP* violation and observation of *P* violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

LHCb collaboration[†]

Abstract

A search for *CP* violation in the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decay is performed using LHCb data corresponding to an integrated luminosity of $6.6\,\text{fb}^{-1}$ 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.

Submitted to Phys. Rev. Lett.

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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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 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 α 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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 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 Δ^{++} 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 $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ decays is used, where no CP violation is expected, to assess potential experimental biases and systematic effects.

The LHCb collaboration has previously studied the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 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 $6.6\,\text{fb}^{-1}$ 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 pseudorapidity 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 $C_{\widehat{T}} \equiv \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{\rm fast}} \times \vec{p}_{\pi^+}\right)$ and $\overline{C}_{\widehat{T}} \equiv \vec{p}_{\overline{p}} \cdot \left(\vec{p}_{\pi^+_{\rm fast}} \times \vec{p}_{\pi^-}\right)$, for Λ_b^0 and $\overline{\Lambda}_b^0$ respectively. Hereinafter $\pi^-_{\rm fast}$ ($\pi^-_{\rm slow}$) refers to the faster (slower) of two negative pions in the Λ_b^0 rest frame. Following these definitions, four statistically independent subsamples are considered, labeled with I for $C_{\widehat{T}} > 0$, II for $C_{\widehat{T}} < 0$, III for $-\overline{C}_{\widehat{T}} > 0$ and IV for $-\overline{C}_{\widehat{T}} < 0$. 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 $\widehat{T}$ operator reverses momentum and spin three-vectors [26, 27]. The quantities $C_{\widehat{T}}$ and $\overline{C}_{\widehat{T}}$ are odd under this operator. This enables studies of the P-odd *CP* violation, which occurs via interference of the $\widehat{T}$-even and $\widehat{T}$-odd amplitudes with different *CP*-odd ('weak') phases [9, 25–27].

The TPA are defined as

$$A_{\widehat{T}} = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}, \overline{A}_{\widehat{T}} = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}, \quad (1)$$

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

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

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 $p\pi^-_{\rm fast}$ and $\pi^+\pi^-_{\rm slow}$ systems in the Λ_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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 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 (Δ^{++}) in the Δ^{++} (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 $m(p\pi^+\pi^-_{\rm slow}) > 2.8\,\text{GeV}/c^2$ (samples A_1, B_1), dominated by the a_1 resonance, and $m(p\pi^+\pi^-_{\rm slow}) < 2.8\,\text{GeV}/c^2$ (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 χ^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 χ^2 tests [21, 22]. The test is performed through the calculation of a test statistic

$$T \equiv \frac{1}{2n(n-1)}\sum_{i\neq j}^{n}\psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)}\sum_{i\neq j}^{\overline{n}}\psi_{ij} - \frac{1}{n\overline{n}}\sum_{i=1}^{n}\sum_{j=1}^{\overline{n}}\psi_{ij}, \quad (3)$$

where there are n ($\overline{n}$) 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 ij is assigned a weight $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, where d_{ij} is their Euclidean distance in phase space, while the tunable parameter δ determines the distance scale probed using the energy test. The phase space is defined using the squared masses $m^2(p\pi^+)$, $m^2(\pi^+\pi^-_{\rm slow})$, $m^2(p\pi^+\pi^-_{\rm slow})$, $m^2(\pi^+\pi^-_{\rm slow}\pi^-_{\rm fast})$ and $m^2(p\pi^-_{\rm slow})$. 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 $\delta = 1.6\ {\rm GeV}^2/c^4$, $2.7\ {\rm GeV}^2/c^4$ and $13\ {\rm GeV}^2/c^4$. 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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays are formed by combining tracks with transverse (total) momentum greater than $250\,{\rm MeV}/c$ ($1.5\,{\rm GeV}/c$) identified as protons and pions that originate from a common vertex displaced from the primary vertex. A cut on the invariant-mass $m(pK^-\pi^+) \in [2.26, 2.30]\,{\rm GeV}/c^2$ is applied to select $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ 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, $m(p\pi^-\pi^+\pi^-)$, 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 Λ_b^0 decays, as for example $\Lambda_b^0 \to p\pi^-\pi^+\pi^-\pi^0$, 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 $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and $B^0 \to K^+\pi^-\pi^+\pi^-$ 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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decay and the $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ control sample are $27\,600 \pm 200$ and $434\,500 \pm 800$, respectively. Fits in bins of phase space are also performed to determine asymmetries $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$ in each region, assigning signal candidates to four categories according to Λ_b^0 or $\overline{\Lambda}_b^0$ flavour and sign of $C_{\widehat{T}}$ or $\overline{C}_{\widehat{T}}$. The asymmetries $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$ are found to be uncorrelated. Corresponding asymmetries for each of the background components are also determined in the fit; they are found to be

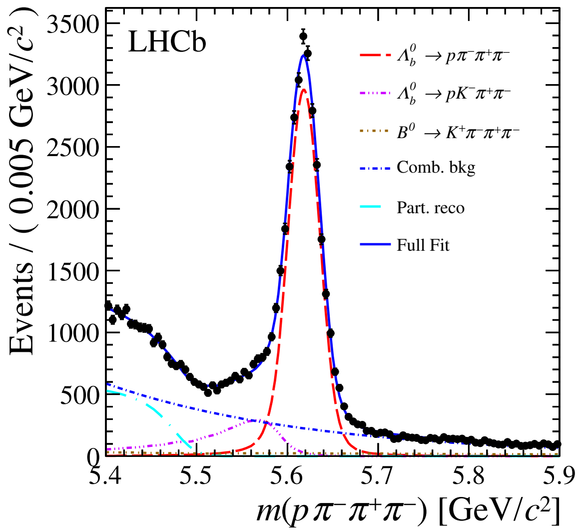

Figure 1: Invariant-mass distribution for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ candidates with the result of the fit overlaid. The solid and dotted lines describe the projections of the fit results for various components as listed in the legend.

consistent with zero, and do not lead to significant systematic uncertainties in the signal asymmetries.

For the energy test, Λ_b^0 candidates are selected in a window corresponding to 2.5 standard deviations of the Gaussian function around the known Λ_b^0 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 $C_{\widehat{T}} > 0$ is consistent with that for candidates with $C_{\widehat{T}} < 0$. 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 $\overline{C}_{\widehat{T}}$ observable. As a general cross-check, the *CP* asymmetry is measured in the control sample and found to be compatible with zero, $a_{CP}^{\widehat{T}\text{-odd}}(\Lambda_c^+\pi^-) = (+0.04 \pm 0.16)\%$.

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 $C_{\widehat{T}}$ and $\overline{C}_{\widehat{T}}$, 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 $a_{CP}^{\widehat{T}\text{-odd}}/a_{P}^{\widehat{T}\text{-odd}}$ $(A_{\widehat{T}}/\overline{A}_{\widehat{T}})$ 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_b^0 and $\overline{\Lambda}_b^0$ 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 ($5.75 < m(p\pi^-\pi^+\pi^-) < 6.10\,\mathrm{GeV}/c^2$) 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 ($\Lambda_b^0 \to pK^-\pi^+\pi^-$) 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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 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 $B^0 \to K^+\pi^-\pi^+\pi^-$ decay is negligible within the mass window selected for the energy test.

Finally, the proton detection asymmetry in simulation is replicated in the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ data sample by setting the Λ_b^0 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 Λ_b^0 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 $a_{CP}^{\widehat{T}\text{-odd}} = (-0.7 \pm 0.7 \pm 0.2)\%$ and $a_{P}^{\widehat{T}\text{-odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$. Consistency with the CP-conserving hypothesis is observed, while a significant non-zero value for the $a_{P}^{\widehat{T}\text{-odd}}$ 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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decay.

The values of the TPA for the binning schemes A_1, A_2, B_1 and B_2 are shown in Fig. 2. In the binning schemes A_2 and B_2 the contribution from N^{*+} resonances dominates and therefore larger CP asymmetries are possible relative to the A_1 and B_1 binning schemes. However, in the A_2 and B_2 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 [5] 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 $C_{\widehat{T}}$ sign to each candidate. The asymmetries are extracted and the difference between the Run 1 and full datasets is determined as a χ^2 value. The fraction of pseudoexperiments with a χ^2 value greater than the observed χ^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 B_1 and B_2 indicate that the P violation has a large

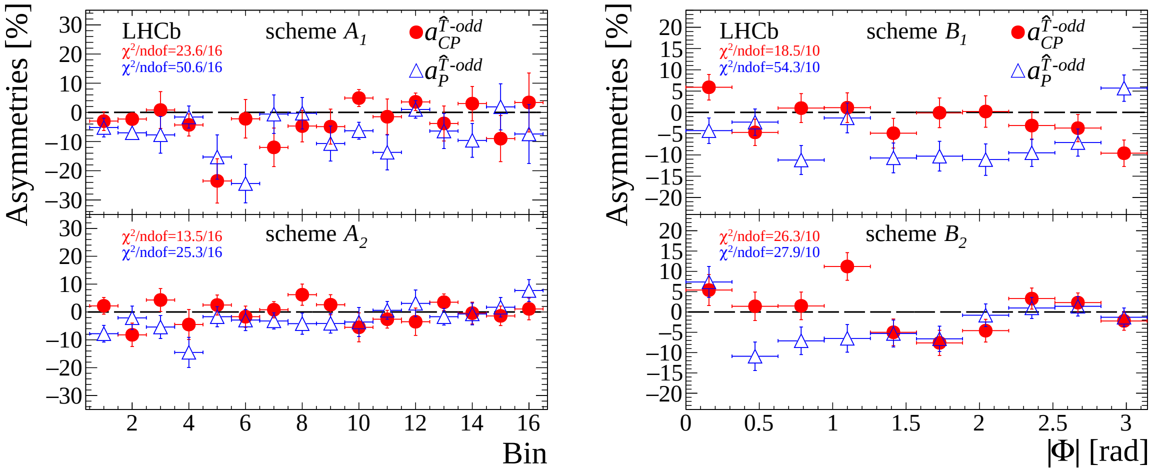

Figure 2: Measured asymmetries for the binning scheme (left) A_1 and A_2 and (right) B_1 and B_2. The error bars represent the sum in quadrature of the statistical and systematic uncertainties. The χ^2 per ndof is calculated with respect to the null hypothesis and includes statistical and systematic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

contribution from the $\Lambda_b^0 \to p a_1(1260)^-$ 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^2/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 4.6×10^{-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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 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

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

Distance scale δ	1.6 GeV^2/c^4	2.7 GeV^2/c^4	13 GeV^2/c^4
p-value (CP conservation, P even)	3.1×10^{-2}	2.7×10^{-3}	1.3×10^{-2}
p-value (CP conservation, P odd)	1.5×10^{-1}	6.9×10^{-2}	6.5×10^{-2}
p-value (P conservation)	1.3×10^{-7}	4.0×10^{-7}	1.6×10^{-1}

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).

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