Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \to J/\psi p\pi^-$ Decays

R. Aaij et al. (LHCb Collaboration)

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A full amplitude analysis of $\Lambda_b^0 \to J/\psi p\pi^-$ decays is performed with a data sample acquired with the LHCb detector from 7 and 8 TeV $pp$ collisions, corresponding to an integrated luminosity of 3 fb$^{-1}$. A significantly better description of the data is achieved when, in addition to the previously observed nucleon excitations $N \to p\pi^-$, either the $P_c(4380)^+$ and $P_c(4450)^+$ states, previously observed in $\Lambda_b^0 \to J/\psi pK^-$ decays, or the $Z_c(4200)^- \to J/\psi\pi^-$ state, previously reported in $B^0 \to J/\psi K^+\pi^-$ decays, or all three, are included in the amplitude models. The data support a model containing all three exotic states, with a significance of more than three standard deviations. Within uncertainties, the data are consistent with the $P_c(4380)^+$ and $P_c(4450)^+$ production rates expected from their previous observation taking account of Cabibbo suppression.

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From the birth of the quark model, it has been anticipated that baryons could be constructed not only from three quarks, but also four quarks and an antiquark [1,2], hereafter referred to as pentaquarks [3,4]. The distribution of the $J/\psi p$ mass $(m_{J/\psi p})$ in $\Lambda_b^0 \to J/\psi pK^-$, $J/\psi \to \mu^+\mu^-$ decays (charge conjugation is implied throughout the text) observed with the LHCb detector at the LHC shows a narrow peak suggestive of $uud\bar{c}\bar{c}$ pentaquark formation, amidst the dominant formation of various excitations of the $\Lambda$ [uds] baryon ($\Lambda^*$) decaying to $K^-p$ [5,6]. It was demonstrated that these data cannot be described with $K^-p$ contributions alone without a specific model of them [7]. Amplitude model fits were also performed on all relevant masses and decay angles of the six-dimensional data [5], using the helicity formalism and Breit-Wigner amplitudes to describe all resonances. In addition to the previously well-established $\Lambda^*$ resonances, two pentaquark resonances, named the $P_c(4380)^+$ (9$\sigma$ significance) and $P_c(4450)^+$ (12$\sigma$), are required in the model for a good description of the data [5]. The mass, width, and fractional yields (fit fractions) were determined to be $4380 \pm 8 \pm 29$ MeV, $205 \pm 18 \pm 86$ MeV, $(8.4 \pm 0.7 \pm 4.3)\%$, and $4450 \pm 2 \pm 3$ MeV, $39 \pm 5 \pm 19$ MeV, $(4.1 \pm 0.5 \pm 1.1)\%$, respectively. Observations of the same two $P_c^+$ states in another decay would strengthen their interpretation as genuine exotic baryonic states, rather than kinematical effects related to the so-called triangle singularity [8], as pointed out in Ref. [9].

In this Letter, $\Lambda_b^0 \to J/\psi p\pi^-$ decays are analyzed, which are related to $\Lambda_b^0 \to J/\psi pK^-$ decays via Cabibbo suppression. LHCb has measured the relative branching fraction $B(\Lambda_b^0 \to J/\psi p\pi^-)/B(\Lambda_b^0 \to J/\psi pK^-) = 0.0824 \pm 0.0024 \pm 0.0042$ [10] with the same data sample as used here, corresponding to 3 fb$^{-1}$ of integrated luminosity acquired by the LHCb experiment in $pp$ collisions at 7 and 8 TeV center-of-mass energy. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [11,12]. The data selection is similar to that described in Ref. [5], with the $K^-$ replaced by a $\pi^-$ candidate. In the preselection a larger significance for the $\Lambda_b^0$ flight distance and a tighter alignment between the $\Lambda_b^0$ momentum and the vector from the primary to the secondary vertex are required. To remove specific $B^0$ and $\bar{B}^0$ backgrounds, candidates are vetoed within a $3\sigma$ invariant mass window around the corresponding nominal $B$ mass [13] when interpreted as $B^0 \to J/\psi\pi^-K^-$ or as $\bar{B}^0 \to J/\psi K^+K^-$. In addition, residual long-lived $\Lambda \to p\pi^-p$ background is excluded if the $p\pi^-$ invariant mass $(m_{p\pi})$ lies within $\pm 5$ MeV of the known $\Lambda$ mass [13]. The resulting invariant mass spectrum of $\Lambda_b^0$ candidates is shown in Fig. 1. The signal yield is $1885 \pm 50$, determined by an unbinned extended maximum likelihood fit to the mass spectrum. The signal is described by a double-sided crystal ball function [14]. The combinatorial background is modeled by an exponential function. The background of $\Lambda_b^0 \to J/\psi pK^-$ events is described by a histogram obtained from simulation, with yield free to vary. This fit is used to assign weights to the candidates using the sPlot technique [15], which allows the signal component to be projected out by weighting each event depending on the $J/\psi p\pi^-$ mass. Amplitude fits are performed by minimizing a six-dimensional unbinned negative log likelihood, $-2\ln L$, with the background subtracted using these...
weights and the efficiency folded into the signal probability density function, as discussed in detail in Ref. [5].

Amplitude models for the $Λ^0_b \to J/ψ π^- p$ decays are constructed to examine the possibility of exotic hadron contributions from the $P_c(4380)^+ + P_c(4450)^+ \to J/ψ p$ states and from the $Z_c(4200)^- \to J/ψ π^-$ state, previously reported by the Belle Collaboration in $B^0 \to J/ψ K^+ π^-$ decays [16] (spin parity $J^P = 1^+$, mass and width of $4196^{+31}_{-29}^{+17}_{-13}$ MeV and $370 \pm 70^{+132}_{-132}$ MeV, respectively). By analogy with kaon decays [17], $pπ^-$ contributions from conventional nucleon excitations (denoted as $N^*$) produced with $\Delta I = 1/2$ in $Λ^0_b$ decays are expected to dominate over $\Delta I = 3/2$, where $I$ is isospin. The decay matrix elements for the two interfering decay chains, $Λ^0_b \to J/ψ N^*$, $N^* \to p π^-$ and $Λ^0_b \to P^+_c π^-$, $P^+_c \to J/ψ p$ with $J/ψ \to μ^+ μ^-$ in both cases, are identical to those used in the $Λ^0_b \to J/ψ p K^-$ analysis [5], with $K^-$ and $Λ^*$ replaced by $π^-$ and $N^*$. The additional decay chain, $Λ^0_b \to Z_c^- p$, $Z_c^- \to J/ψ π^-$, is also included. Helicity couplings, describing the dynamics of the decays, are expressed in terms of $LS$ couplings [5], where $L$ is the decay orbital angular momentum, and $S$ is the sum of spins of the decay products. This is a convenient way to incorporate parity conservation in strong decays and to allow for reduction of the number of free parameters by excluding high $L$ values for phase-space suppressed decays.

Table I lists the $N^*$ resonances considered in the amplitude model of $pπ^-$ contributions. There are 15 well-established $N^*$ resonances [13]. The high-mass and high-spin states ($9/2$ and $11/2$) are not included, since they require $L \geq 3$ in the $Λ^0_b$ decay and therefore are unlikely to be produced near the upper kinematic limit of $m_{pπ}$. Theoretical models of baryon resonances predict many more high-mass states [18], which have not yet been observed. Their absence could arise from decreased couplings of the higher $N^*$ excitations to the simple production and decay channels [19] and possibly also from experimental difficulties in identifying broad resonances and insufficient statistics at high masses in scattering experiments. The possibility of high-mass, low-spin $N^*$ states is explored by including two very significant, but unconfirmed, resonances claimed by the BESIII Collaboration in $ψ(2S) \to p\bar{p} N^0$ decays [20]: $1/2^+ N(2300)$ and $5/2^- N(2570)$. A nonresonant $J^P = 1/2^- pπ^-$ $S$-wave component is also included. Two models, labeled “reduced” (RM) and “extended” (EM), are considered and differ in the number of resonances and of $LS$ couplings included in the fit as listed in Table I. The reduced model, used for the central values of fit fractions, includes only the resonances and $L$ couplings that give individually significant contributions. The systematic uncertainties and the significances for the exotic states are evaluated with the extended model by including all well-motivated resonances and the maximal number of $LS$ couplings for which the fit is able to converge.

All $N^*$ resonances are described by Breit-Wigner functions [5] to model their line shape and phase variation as a function of $m_{pπ}$, except for the $N(1535)$, which is described by a Flatté function [21] to account for the threshold of the $m_γ$ channel. The mass and width are fixed to the values determined from previous experiments [13]. The couplings to the $m_γ$ and $pπ^-$ channels for the $N(1535)$ state are determined by the branching fractions of the two channels [22]. The nonresonant $S$-wave component is described with a function that depends inversely on $m_{pπ}^2$, as this is found to be preferred by the data. An alternative description of the $1/2^- pπ^-$ contributions, including the $N(1535)$ and nonresonant components, is provided by a $K$-matrix model obtained from multichannel partial wave

| State          | $J^P$ | Mass (MeV) | Width (MeV) | RM | EM |
|----------------|-------|------------|-------------|----|----|
| $NR pπ$       |       | 1/2$^-$   | ...         | 4  | 4  |
| $N(1440)$     | 1/2$^+$| 1430      | 350         | 3  | 4  |
| $N(1520)$     | 3/2$^-$| 1515      | 115         | 3  | 3  |
| $N(1535)$     | 1/2$^-$| 1535      | 150         | 4  | 4  |
| $N(1650)$     | 1/2$^-$| 1655      | 140         | 1  | 4  |
| $N(1675)$     | 5/2$^-$| 1675      | 150         | 3  | 5  |
| $N(1680)$     | 5/2$^+$| 1685      | 130         | ... | 3 |
| $N(1700)$     | 3/2$^+$| 1700      | 150         | ... | 3 |
| $N(1710)$     | 1/2$^+$| 1710      | 100         | ... | 4 |
| $N(1720)$     | 3/2$^+$| 1720      | 250         | 3  | 5  |
| $N(1875)$     | 3/2$^-$| 1875      | 250         | ... | 3 |
| $N(1900)$     | 3/2$^+$| 1900      | 200         | ... | 3 |
| $N(2190)$     | 7/2$^-$| 2190      | 500         | ... | 3 |
| $N(2300)$     | 1/2$^+$| 2300      | 340         | ... | 3 |
| $N(2570)$     | 5/2$^-$| 2570      | 250         | ... | 3 |

Free parameters 40 106

**TABLE I.** The $N^*$ resonances used in the different fits. Parameters are taken from the PDG [13]. The number of $LS$ couplings is listed in the columns to the right for the two versions (RM and EM) of the $N^*$ model discussed in the text. To fix overall phase and magnitude conventions, the $N(1535)$ complex coupling of lowest $LS$ is set to (1, 0).
analysis by the Bonn-Gatchina group [22,23] and is used to estimate systematic uncertainties.

The limited number of signal events and the large number of free parameters in the amplitude fits prevent an open-ended analysis of $J/\psi p$ and $J/\psi \pi^-$ contributions. Therefore, the data are examined only for the presence of the previously observed $P_c(4380)^+, P_c(4450)^+$ states [5] and the claimed $Z_c(4200)^-$ resonance [16]. In the fits, the mass and width of each exotic state are fixed to the reported central values. The $LS$ couplings describing $P_c^+ \rightarrow J/\psi p$ decays are also fixed to the values obtained from the Cabibbo-favored channel. This leaves four free parameters per $P_c^+$ state for the $\Lambda_b^0 \rightarrow P_c^+ \pi^-$ couplings. The nominal fits are performed for the most likely $(3/2^-, 5/2^+)$ $J^P$ assignment to the $P_c(4380)^+, P_c(4450)^+$ states [5]. All couplings for the $1^+ Z_c(4200)^-$ contribution are allowed to vary (ten free parameters).

The fits show a significant improvement when exotic contributions are included. When all three exotic contributions are added to the EM $N^*$-only model, the $\Delta(-2\ln L)$ value is 49.0, which corresponds to their combined statistical significance of $3.9\sigma$. Including the systematic uncertainties discussed later lowers their significance to $3.1\sigma$. The systematic uncertainties are included in subsequent significance figures. Because of the ambiguity between the $P_c(4380)^+$, $P_c(4450)^+$ and $Z_c(4200)^-$ contributions, no single one of them makes a significant difference to the model. Adding either state to a model already containing the other two, or the two $P_c^+$ states to a model already containing the $Z_c(4200)^-$ contribution, yields significances below $1.7\sigma$ [0.4\sigma for adding the $Z_c(4200)^-$ after the two $P_c^+$ states]. If the $Z_c(4200)^-$ contribution is assumed to be negligible, adding the two $P_c^+$ states to a model without exotics yields a significance of $3.3\sigma$. On the other hand, under the assumption that no $P_c^+$ states are produced, adding the $Z_c(4200)^-$ to a model without exotics yields a significance of $3.2\sigma$. The significances are determined using Wilks’ theorem [24], the applicability of which has been verified by simulation.

A satisfactory description of the data is already reached with the RM $N^*$ model if either the two $P_c^+$, or the $Z_c^-$, or all three states, are included in the fit. The projections of the full amplitude fit onto the invariant masses and the decay angles reasonably well reproduce the data, as shown in Figs. 2–5. The EM $N^*$-only model does not give good descriptions of the peaking structure in $m_{J/\psi p}$ observed for $m_{p\pi} > 1.8$ GeV [Fig. 3(b)]. In fact, all contributions to $\Delta(-2\ln L)$ favoring the exotic components belong to this $m_{p\pi}$ region. The models with the $P_c^+$ states describe the $m_{J/\psi p}$ peaking structure better than with the $Z_c(4200)^-$ alone (see Supplemental Material [25]).

The model with all three exotic resonances is used when determining the fit fractions. The sources of systematic uncertainty are listed in Table II. They include varying the masses and widths of $N^*$ resonances, varying the masses and widths of the exotic states, considering $N^*$ model
dependence and other possible spin parities $J^P$ for the two $P_c^+$ states, varying the Blatt-Weisskopf radius [5] between 1.5 and 4.5 GeV$^{-1}$, changing the angular momenta $L$ in $\Lambda_b^0$ decays that are used in the resonant mass description by one or two units, using the K-matrix model for the $S$-wave $p\pi$ resonances, varying the fixed couplings of the $P_c^+$ decay by their uncertainties, and splitting $\Lambda_b^0$ and $J/\psi$ decay angles into bins when determining the weights for the background subtraction to account for correlations between the invariant mass of $J/\psi p\pi^-$ and these angles. A putative $Z_c(4430)^-$ contribution [16,26,27] hardly improves the value of $-2\ln L$ relative to the EM $N^*$-only model, and thus is considered among systematic uncertainties. Exclusion of the $Z_c(4200)^-$ state from the fit model is also considered to determine the systematic uncertainties for the two $P_c^+$ states.

The EM model is used to assess the uncertainty due to the $N^*$ modeling when computing significances. The RM model gives larger significances. All sources of systematic uncertainties, including the ambiguities in the quantum number assignments to the two $P_c^+$ states, are accounted for in the calculation of the significance of various contributions, by using the smallest $\Delta(-2\ln L)$ among the fits representing different systematic variations.

The fit fractions for the $P_c(4380)^+$, $P_c(4450)^+$ and $Z_c(4200)^-$ states are measured to be $(5.1 \pm 1.5^{+2.6}_{-1.6})\%$,

![FIG. 4. Background-subtracted data and fit projections onto $m_{J/\psi}$ for (a) all events and (b) the $m_{P_c} > 1.8$ GeV region. See the legend and caption of Fig. 2 for a description of the components.](image)

![FIG. 5. Background-subtracted data and fit projections of decay angles describing the $N^*$ decay chain, which are included in the amplitude fit. The helicity angle of particle $P$, $\theta_P$, is the polar angle in the rest frame of $P$ between a decay product of $P$ and the boost direction from the particle decaying to $P$. The azimuthal angle between decay planes of $\Lambda_b^0$ and $N^*$ (of $J/\psi$) is denoted as $\phi_\pi (\phi_P)$. See Ref. [5] for more details.](image)

**TABLE II. Summary of absolute systematic uncertainties of the fit fractions in units of percent.**

| Source                                  | $P_c(4450)^+$ | $P_c(4380)^+$ | $Z_c(4200)^-$ |
|-----------------------------------------|--------------|--------------|--------------|
| $N^*$ masses and widths                  | $\pm 0.05$   | $\pm 0.23$   | $\pm 0.31$   |
| $P_c^+, Z_c^-$ masses and widths        | $\pm 0.32$   | $\pm 1.27$   | $\pm 1.56$   |
| Additional $N^*$                        | $+0.08$      | $+0.59$      | $+0.71$      |
| Inclusion of $Z_c(4430)^-$              | $-0.23$      | $-0.55$      | $-0.92$      |
| Exclusion of $Z_c(4200)^-$              | $+0.01$      | $+0.97$      | $+2.78$      |
| Other $J^P$                             | $-0.15$      | $+1.61$      | $\cdots$    |
| Inclusion of $Z_c(4430)^-$              | $\pm 0.38$   | $\pm 0.92$   | $\pm 0.00$   |
| Exclusion of $Z_c(4200)^-$              | $\pm 0.00$   | $\pm 0.28$   | $\pm 2.16$   |
| Inclusion of $Z_c(4430)^-$              | $\pm 0.00$   | $\pm 0.17$   | $\pm 0.21$   |
| Exclusion of $Z_c(4200)^-$              | $\pm 0.00$   | $\pm 0.46$   | $\pm 0.04$   |
| Other $J^P$                             | $\pm 0.05$   | $\pm 0.17$   | $\pm 0.09$   |
| Inclusion of $Z_c(4430)^-$              | $\pm 0.07$   | $\pm 0.22$   | $\pm 0.53$   |
| Exclusion of $Z_c(4200)^-$              | $\pm 0.07$   | $\pm 0.31$   | $\pm 0.36$   |
| $K$-matrix model                        | $\pm 0.14$   | $\pm 0.31$   | $\pm 0.36$   |
| $P_c^+$ couplings                       | $-0.07$      | $-0.13$      | $-0.39$      |
| Background subtraction                  | $+0.55$      | $+2.61$      | $+3.43$      |
| Total                                   | $-0.48$      | $-1.58$      | $-4.04$      |
(1.6^{+0.8}_{-0.6} + 0.6%)\% and (7.7 \pm 2.8^{+3.4}_{-4.0})\% respectively, and to be less than 8.9%, 2.9%, and 13.3% at 90% confidence level, respectively. When the two $P_c^+$ states are not considered, the fraction for the $Z_c(4200)^-$ state is surprisingly large, (17.2 \pm 3.5)\%, where the uncertainty is statistical only, given that its fit fraction was measured to be only (1.0^{+0.7}_{-0.5} - 0.4)\% in $B^0 \to J/\psi K^+\pi^-$ decays [16]. Conversely, the fit fractions of the two $P_c^+$ states remain stable regardless of the inclusion of the $Z_c(4200)^-$ state. We measure the relative branching fraction $R_{Z_c/K} \equiv B(\Lambda_b^0 \to \pi^- P_c^+)/B(\Lambda_b^0 \to K^- P_c^0)$ to be $0.050 \pm 0.016 - 0.026 \pm 0.025$ for $P_c(4380)^+$ and $0.033 - 0.014 - 0.010 \pm 0.009$ for $P_c(4450)^+$ respectively, where the first error is statistical, the second is systematic, and the third is due to the systematic uncertainty on the fit fractions of the $P_c^+$ states in $J/\psi pK^-$ decays. The results are consistent with a prediction of (0.07 – 0.08) [28], where the assumption is made that an additional diagram with internal $W$ emission, which can only contribute to the Cabibbo-suppressed mode, is negligible. Our measurement rules out the proposal that the $P_c^+$ state in the $\Lambda_b^0 \to J/\psi pK^-$ decay is produced mainly by the charmless $\Lambda_b^0$ decay via the $b \to u\bar{u}s$ transition, since this predicts a very large value for $R_{Z_c/K} = 0.58 \pm 0.05$ [29].

In conclusion, we have performed a full amplitude fit to $\Lambda_b^0 \to J/\psi p\pi^-$ decays allowing for previously observed conventional ($p\pi^-$) and exotic ($J/\psi p$ and $J/\psi\pi\pi^-$) resonances. A significantly better description of the data is achieved by either including the two $P_c^+$ states observed in $\Lambda_b^0 \to J/\psi pK^-$ decays [5], or the $Z_c(4200)^-$ state reported by the Belle Collaboration in $B^0 \to J/\psi\pi^-K^+$ decays [16]. If both types of exotic resonances are included, the total significance for them is $3.1\sigma$. Individual exotic hadron components, or the two $P_c^+$ states taken together, are not significant as long as the other(s) is (are) present. Within the statistical and systematic errors, the data are consistent with the $P_c(4380)^+$ and $P_c(4450)^+$ production rates expected from their previous observation and Cabibbo suppression. Assuming that the $Z_c(4200)^-$ contribution is negligible, there is a $3.3\sigma$ significance for the two $P_c^+$ states taken together.

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O. Schneider,40 A. Schopper,39 M. Schubiger,40 M.-H. Schune,7 R. Schwemmer,39 B. Sciascia,19 A. Sciubba,26,r A. Semennikov,32 A. Sergi,46 N. Serra,41 J. Serrano,6 L. Sestini,23 P. Seyfert,21 M. Shapkin,36 I. Shapoval,17,44,a Y. Shcheglov,31 T. Shears,53 L. Shekhtman,35 V. Shevchenko,46 A. Shires,10 B. G. Siddi,17 R. Silva Coutinho,41 L. Silva de Oliveira,2 G. Simi,23 L. Sikdar,12 S. Sridharan,39 F. Stagni,39 M. Stahl,12 S. Stahl,39 P. Stefko,40 S. Stefkova,54 O. Steinkamp,41 O. Stenyakin,36 S. Stevenson,56 S. Stoica,30 S. Stone,60 B. Storaci,41 S. Stracka,24,i M. Straticiuc,30 U. Straumann,41 L. Sun,58 W. Sutcliffe,54 K. Swientek,28 V. Syropoulos,43 M. Szczekowski,29 T. Szumlak,28 S. T'Jampens,4 A. Tayduganov,6 T. Tekampe,10 G. Tellarini,17,a F. Teubert,39 C. Thomas,39 E. Thomas,39 J. van Tilburg,42 V. Tisserand,4 M. Tobin,40 S. Tolk,48 L. Tomassetti,17,a D. Tonelli,39 S. Topp-Joergensen,36 F. Torelli,60 E. Tourneur,4 K. Trabelsi,40 M. Traill,52 M. T. Tran,40 M. Tresch,41 A. Trisovic,39 A. Tsaregorodtsev,6 P. Tsopelas,42 A. Tully,48 N. Tuning,42 A. Ukleja,20 A. Ustyuzhanin,67,66 U. Uwer,12 C. Vacca,16,31 V. Vagnoni,15,39 S. Valat,41 G. Valentí,15 A. Vallier,7 R. Vazquez Gomez,19 P. Vázquez Regueiro,38 S. Vecchi,17 M. van Veghel,42 J. J. Velthuis,47 M. Veltri,18,a G. Veneziano,40 A. Venkateswaran,60 M. Vesterinen,12 B. Viaud,7 D. Vieira,1 M. Vieites Diaz,38 X. Vilasis-Cardona,37,e V. Vollertsen,39,a T. Volpe,10 G. Voss,12,49 J. A. de Vries,42 C. Vázquez Sierra,38 R. Waldi,65 C. Wallace,49 R. Wallace,13 J. Walsh,24 J. Wang,60 D. R. Ward,48 H. M. Ward,53 N. K. Watson,46 D. Websdale,54 A. Weiden,41 M. Whitehead,39 J. Wicht,49 G. Wilkinson,60 M. Wilkinson,60 M. Williams,39 M. P. Williams,38 M. Williams,57 T. Williams,40 F. F. Wilson,50 J. Wimberley,39 J. Wishahi,10 W. Wislicki,29 M. Witek,27 G. Wormser,7 S. A. Wotton,48 K. Wraith,48 K. Wyllie,39 Y. Xie,63 Z. Xu,40 Z. Yang,3 H. Yin,63 J. Yu,63 X. Yuan,35 O. Yushchenko,36 M. Zangoi,15 K. A. Zarebski,46 M. Zavertyaev,11,a L. Zhang,3 Y. Zhang,7 Y. Zhang,62 A. Zhelzov,12 Y. Zheng,62 A. Zhokhov,32 V. Zhukov,9 and S. Zucchelli15

(LHCb Collaboration)

1Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
2Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3Center for High Energy Physics, Tsinghua University, Beijing, China
4LAPP, Université Savoie Mont-Blanc, CNRS/IN2P3, Annecy-Le-Vieux, France
5Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
6CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
7LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
8LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
9I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
10Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
11Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
12Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
13School of Physics, University College Dublin, Dublin, Ireland
14Sezione INFN di Bari, Bari, Italy
15Sezione INFN di Bologna, Bologna, Italy
16Sezione INFN di Cagliari, Cagliari, Italy
17Sezione INFN di Ferrara, Ferrara, Italy
18Sezione INFN di Firenze, Firenze, Italy
19Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy
20Sezione INFN di Genova, Genova, Italy
21Sezione INFN di Milano Bicocca, Milano, Italy
22Sezione INFN di Milano, Milano, Italy
23Sezione INFN di Padova, Padova, Italy
24Sezione INFN di Pisa, Pisa, Italy
25Sezione INFN di Roma Tor Vergata, Roma, Italy
26Sezione INFN di Roma La Sapienza, Roma, Italy
27Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
28AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
29National Center for Nuclear Research (NCBJ), Warsaw, Poland
30Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
31Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia

082003-8
32 Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
33 Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
34 Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
35 Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
36 Institute for High Energy Physics (IHEP), Protvino, Russia
37 Universitat de Barcelona, Barcelona, Spain
38 Universidad de Santiago de Compostela, Santiago de Compostela, Spain
39 European Organization for Nuclear Research (CERN), Geneva, Switzerland
40 Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
41 Physik-Institut, Universität Zürich, Zürich, Switzerland
42 Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
43 NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
44 Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
45 University of Birmingham, Birmingham, United Kingdom
46 H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
47 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
48 School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
49 School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
50 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
51 Imperial College London, London, United Kingdom
52 Oxford University, Oxford, United Kingdom
53 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
54 University of Cincinnati, Cincinnati, Ohio, USA
55 University of Maryland, College Park, Maryland, USA
56 Syracuse University, Syracuse, New York, USA
57 Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Institution Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
58 Department of Physics, University of Oxford, Oxford, United Kingdom
59 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
60 University of Cincinnati, Cincinnati, Ohio, USA
61 Van Swinderen Institute, University of Groningen, Groningen, The Netherlands (associated with Institution Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands)
62 Yandex School of Data Analysis, Moscow, Russia (associated with Institution Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)
63 Universidad de Alcalá, Madrid, Spain (associated with Institution Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia)
64 Instituto de Física Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain (associated with Institution Instituto de Fisica Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain)
65 Van Swinderen Institute, University of Groningen, Groningen, The Netherlands (associated with Institution Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands)
66 Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Institution Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
Also at Università di Padova, Padova, Italy.
Also at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.
Also at Università di Cagliari, Cagliari, Italy.
Also at Università di Genova, Genova, Italy.
Also at Laboratoire Leprince-Ringuet, Palaiseau, France.
Also at Università di Bologna, Bologna, Italy.
Also at Università di Modena e Reggio Emilia, Modena, Italy.
Also at Università di Pisa, Pisa, Italy.
Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.