

Branching Fraction Measurements of the Rare $B_s^0 \rightarrow \phi\mu^+\mu^-$ and $B_s^0 \rightarrow f_2'(1525)\mu^+\mu^-$ Decays

R. Aaij *et al.*^{*}
(LHCb Collaboration)

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The branching fraction of the rare $B_s^0 \rightarrow \phi\mu^+\mu^-$ decay is measured using data collected by the LHCb experiment at center-of-mass energies of 7, 8, and 13 TeV, corresponding to integrated luminosities of 1, 2, and 6 fb⁻¹, respectively. The branching fraction is reported in intervals of q^2 , the square of the dimuon invariant mass. In the q^2 region between 1.1 and 6.0 GeV²/c⁴, the measurement is found to lie 3.6 standard deviations below a standard model prediction based on a combination of light cone sum rule and lattice QCD calculations. In addition, the first observation of the rare $B_s^0 \rightarrow f_2'(1525)\mu^+\mu^-$ decay is reported with a statistical significance of 9 standard deviations and its branching fraction is determined.

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Recent studies of rare semileptonic $b \rightarrow s\ell^+\ell^-$ decays exhibit tensions between experimental results and standard model (SM) predictions of branching fractions [1–5], angular distributions [6–11], and lepton universality [11–19]. Since these decays are only allowed via higher-order electroweak (loop) diagrams in the SM, they constitute powerful probes for non-SM contributions. One of the most significant discrepancies appears in the branching fraction of the $B_s^0 \rightarrow \phi\mu^+\mu^-$ decay [1,2]. Using 3 fb⁻¹ of data collected with the LHCb experiment at center-of-mass energies of 7 and 8 TeV, the branching fraction was measured below the SM prediction at the level of 3 standard deviations (σ) [1]. This Letter presents an updated measurement using data taken at center-of-mass energies of 7, 8, and 13 TeV during the 2011, 2012, and 2015–2018 data-taking periods, with integrated luminosities corresponding to 1, 2, and 6 fb⁻¹, respectively. Compared to the 3 fb⁻¹ sample alone, this represents an increase of about a factor of 4 in the number of produced B_s^0 mesons. The branching fraction is determined in intervals of q^2 , the squared invariant mass of the dimuon system. In addition, the observation of the $B_s^0 \rightarrow f_2'(1525)\mu^+\mu^-$ decay and a determination of its branching fraction are reported. This constitutes the first observation of a rare semileptonic decay involving a spin-2 meson in the final state and provides complementary information to transitions involving pseudoscalar or vector mesons. In the following, the shorthand

notation f_2' is used to refer to the $f_2'(1525)$ meson. The inclusion of charge-conjugate processes is implied throughout.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, detailed in Refs. [20,21]. The online event selection is performed by a trigger [22] that consists of hardware and software stages. The former selects signal candidates containing a muon with significant transverse momentum with respect to the beam axis. At the software stage, a full event reconstruction is applied. Simulated events are used in this analysis to determine the reconstruction and selection efficiency of signal candidates and to estimate contamination from residual background. The simulated samples are produced using the software described in Refs. [23–25]. Residual mismodeling in simulation is corrected for using control samples from data.

The $B_s^0 \rightarrow \phi\mu^+\mu^-$ and $B_s^0 \rightarrow f_2'\mu^+\mu^-$ decays are reconstructed in the $K^+K^-\mu^+\mu^-$ final state. Particle identification criteria are applied to the kaon and muon candidates. The muons (kaons) are further required to have $\chi_{\text{IP}}^2 > 9(6)$ with respect to any primary pp interaction vertex (PV) in the event, where χ_{IP}^2 denotes the difference in the vertex-fit χ^2 of the PV when reconstructed with or without the considered track. The four final-state tracks are fit to a common vertex that is required to have good quality and to be significantly displaced from any PV in the event. Signal candidates are retained if the $K^+K^-\mu^+\mu^-$ invariant mass $m(K^+K^-\mu^+\mu^-)$ lies between 5270 and 5700 MeV/c². The invariant mass of the dikaon system $m(K^+K^-)$ is required to be within 12 MeV/c² of the known ϕ mass for the $B_s^0 \rightarrow \phi\mu^+\mu^-$ decay or within 225 MeV/c² of the known mass of the wider f_2' resonance for the $B_s^0 \rightarrow f_2'\mu^+\mu^-$ decay [26].

The q^2 regions between 8.0 and 11.0 GeV²/c⁴ and between 12.5 and 15.0 GeV²/c⁴ are dominated by

^{*}Full author list given at the end of the article.

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tree-level B_s^0 decays into final states with a J/ψ or $\psi(2S)$ meson. While these regions are vetoed in the selection of the signal modes, the decays to charmonium are used as high-yield control modes. The $B_s^0 \rightarrow J/\psi\phi$ decay is used for normalization. The q^2 region from 0.98 to 1.1 GeV^2/c^4 is also vetoed to remove contributions from $B_s^0 \rightarrow \phi(\rightarrow \mu^+\mu^-)\phi$ decays.

To reduce combinatorial background, formed from random track combinations, a boosted decision tree (BDT) algorithm [27,28] is applied. The BDT classifier is trained on data using cross-validation techniques [29], with $B_s^0 \rightarrow J/\psi\phi$ events as signal proxy and candidates from the upper mass sideband $m(K^+K^-\mu^+\mu^-) > 5567 \text{ MeV}/c^2$ as background proxy. The classifier combines the B_s^0 transverse momentum and χ_{IP}^2 , the angle between the B_s^0 momentum and the vector connecting the PV and the decay vertex of the B_s^0 candidate, the fit quality of the B_s^0 vertex and its displacement from the associated PV, particle identification information, and χ_{IP}^2 of the final-state particles.

The criterion on the BDT output is optimized by maximizing the expected significance of the $B_s^0 \rightarrow \phi\mu^+\mu^-$ and $B_s^0 \rightarrow f_2'\mu^+\mu^-$ signals separately, due to different levels of background contamination. The requirement on the BDT classifier yields a signal efficiency of 96% (85%) and a background rejection of 96% (95%) for the $B_s^0 \rightarrow \phi\mu^+\mu^-$ ($B_s^0 \rightarrow f_2'\mu^+\mu^-$) decay mode. Finally, information from particle identification is combined with invariant mass variables, constructed under the relevant particle hypotheses, to reject background from $\Lambda_b^0 \rightarrow pK^-\mu^+\mu^-$ decays, where the proton is misidentified as a kaon, and from $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow \psi(2S)\phi$ and $B^0 \rightarrow J/\psi K^{*0}$ decays, where a final-state hadron is misreconstructed as a muon and vice versa.

The differential branching fraction of the $B_s^0 \rightarrow \phi\mu^+\mu^-$ decay is determined in intervals of q^2 , relative to the $B_s^0 \rightarrow J/\psi\phi$ normalization mode, according to

$$\frac{d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)}{dq^2} = \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi\phi) \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{q_{\text{max}}^2 - q_{\text{min}}^2} \times \frac{N_{\phi\mu^+\mu^-}}{N_{J/\psi\phi}} \times \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu^+\mu^-}}, \quad (1)$$

where $N_{J/\psi\phi}$ and $\epsilon_{J/\psi\phi}$ are the yields and efficiencies of the normalization mode, and $N_{\phi\mu^+\mu^-}$ and $\epsilon_{\phi\mu^+\mu^-}$ are the corresponding parameters for the signal mode in the $[q_{\text{min}}^2, q_{\text{max}}^2]$ interval. The branching fractions related to the normalization mode are given by $\mathcal{B}(B_s^0 \rightarrow J/\psi\phi) = (1.018 \pm 0.032 \pm 0.037) \times 10^{-3}$ [30] and $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) = (5.961 \pm 0.033)\%$ [26].

As the relative efficiencies vary according to the data-taking conditions, the data are split into the 2011–2012, 2015–2016, and 2017–2018 periods. The yields of the normalization mode for the different data-taking periods are determined using extended unbinned maximum-likelihood fits to the $m(K^+K^-\mu^+\mu^-)$ distribution. The $B_s^0 \rightarrow J/\psi\phi$ decay is modeled using the sum of two Gaussian functions with a common mean and a power-law tail toward upper and lower mass. The combinatorial background is modeled using an exponential function. The $m(K^+K^-\mu^+\mu^-)$ distribution of the normalization mode for the full data sample, overlaid with the fit projections, is shown in Fig. 1 (left). The yields of the normalization mode $N_{J/\psi\phi}$ are determined to be 62980 ± 270 , 70970 ± 290 , and 148490 ± 410 for the three different data-taking periods, where the uncertainties are statistical only.

For the rare $B_s^0 \rightarrow \phi\mu^+\mu^-$ decay, a simultaneous extended maximum-likelihood fit of the data samples for the different periods is performed in intervals of q^2 , where the signal yields are parametrized using Eq. (1) and the differential branching fraction is shared between the samples. The model used to describe the $m(K^+K^-\mu^+\mu^-)$ distribution is the same as for the $B_s^0 \rightarrow J/\psi\phi$ normalization mode. The model parameters for the signal component are fixed to those from the fit of the normalization mode, where the q^2 dependence of the mass resolution is

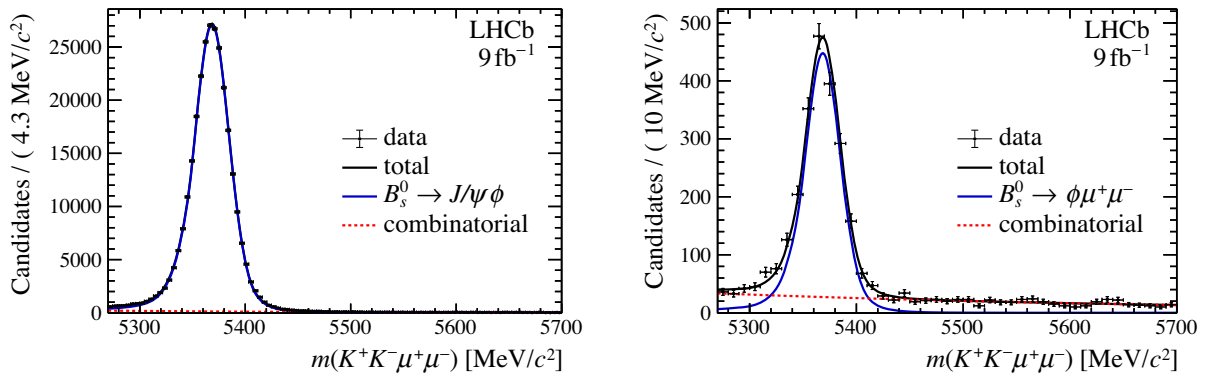


FIG. 1. Reconstructed invariant mass of the $K^+K^-\mu^+\mu^-$ system for (left) the $B_s^0 \rightarrow J/\psi\phi$ normalization mode and (right) the $B_s^0 \rightarrow \phi\mu^+\mu^-$ signal candidates, integrated over q^2 and overlaid with the fit projections.

TABLE I. Differential $d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)/dq^2$ branching fraction, both relative to the normalization mode and absolute, in intervals of q^2 . The uncertainties are, in order, statistical, systematic, and due to the uncertainty on the branching fraction of the normalization mode.

q^2 interval (GeV^2/c^4)	$d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)dq^2$ ($10^{-5} \text{ GeV}^{-2} c^4$)	$d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)/dq^2$ ($10^{-8} \text{ GeV}^{-2} c^4$)
0.1 – 0.98	$7.61 \pm 0.52 \pm 0.12$	$7.74 \pm 0.53 \pm 0.12 \pm 0.37$
1.1 – 2.5	$3.09 \pm 0.29 \pm 0.07$	$3.15 \pm 0.29 \pm 0.07 \pm 0.15$
2.5 – 4.0	$2.30 \pm 0.25 \pm 0.05$	$2.34 \pm 0.26 \pm 0.05 \pm 0.11$
4.0 – 6.0	$3.05 \pm 0.24 \pm 0.06$	$3.11 \pm 0.24 \pm 0.06 \pm 0.15$
6.0 – 8.0	$3.10 \pm 0.23 \pm 0.06$	$3.15 \pm 0.24 \pm 0.06 \pm 0.15$
11.0 – 12.5	$4.69 \pm 0.30 \pm 0.07$	$4.78 \pm 0.30 \pm 0.08 \pm 0.23$
15.0 – 17.0	$5.15 \pm 0.28 \pm 0.10$	$5.25 \pm 0.29 \pm 0.10 \pm 0.25$
17.0 – 19.0	$4.12 \pm 0.29 \pm 0.12$	$4.19 \pm 0.29 \pm 0.12 \pm 0.20$
1.1 – 6.0	$2.83 \pm 0.15 \pm 0.05$	$2.88 \pm 0.15 \pm 0.05 \pm 0.14$
15.0 – 19.0	$4.55 \pm 0.20 \pm 0.11$	$4.63 \pm 0.20 \pm 0.11 \pm 0.22$

accounted for with scaling factors determined from simulation.

Negligible contributions from physical background, including $B_s^0 \rightarrow K^+K^-\mu^+\mu^-$ decays with the K^+K^- system in an S -wave configuration, are not considered in the fit and a systematic uncertainty is assigned. Integrated over the full q^2 range, signal yields, $N_{\phi\mu^+\mu^-}$, of 458 ± 12 , 484 ± 13 , and 1064 ± 28 are found from the simultaneous fit to the different datasets. Figure 1 (right) shows the $m(K^+K^-\mu^+\mu^-)$ distribution of the full data sample, integrated over q^2 and overlaid with the fit projections. Figures for the different data-taking periods are available as Supplemental Material [31].

The relative branching fraction measurement is affected by systematic uncertainties on the fit model and the efficiency ratio, where the latter is determined using SM simulation. A summary of the systematic uncertainties is provided in the Supplemental Material [31]. The dominant systematic uncertainty on the absolute branching fraction [Eq. (1)] originates from the model used to simulate $B_s^0 \rightarrow \phi\mu^+\mu^-$ events ($0.04 - 0.10 \times 10^{-8} \text{ GeV}^{-2} c^4$). The model depends on $\Delta\Gamma_s$, the decay width difference in the B_s^0 system [32], and the specific form factors used. The effect of the model choice on the relative efficiency is assessed by varying $\Delta\Gamma_s$ by 20%, corresponding to the difference in $\Delta\Gamma_s$ between the default value [33] and that of Ref. [26], and by comparing the form factors in Ref. [34] with the older calculations in Ref. [35]. The observed differences are taken as a systematic uncertainty. Other leading sources of systematic uncertainty arise from the limited size of the simulation sample ($0.02 - 0.07 \times 10^{-8} \text{ GeV}^{-2} c^4$) and the omission of small background contributions from the fit model ($0.01 - 0.04 \times 10^{-8} \text{ GeV}^{-2} c^4$).

The resulting relative and total branching fractions are given in Table I. In addition, the differential branching fraction is shown in Fig. 2, overlaid with SM predictions. These predictions are based on form factor calculations

using light cone sum rules (LCSRs) [34,36] at low q^2 and lattice QCD (LQCD) [37,38] at high q^2 , which are implemented in the FLAVIO software package [39]. In the q^2 region between 1.1 and 6.0 GeV^2/c^4 , the measured branching fraction of $(2.88 \pm 0.22) \times 10^{-8} \text{ GeV}^{-2} c^4$, lies 3.6σ below a precise SM prediction of $(5.37 \pm 0.66) \times 10^{-8} \text{ GeV}^{-2} c^4$, which uses both LCSR and LQCD calculations. A less precise SM prediction of $(4.77 \pm 1.01) \times 10^{-8} \text{ GeV}^{-2} c^4$ based on LCSRs alone lies 1.8σ above the measurement. To determine the total branching fraction, the branching fractions of the individual q^2 intervals are summed and corrected for the vetoed q^2 regions using $\epsilon_{q^2\text{veto}} = (65.47 \pm 0.27)\%$. This efficiency is determined using SM simulation, and its uncertainty originates from the comparison of form factors from Refs. [34,35]. The resulting branching fractions are

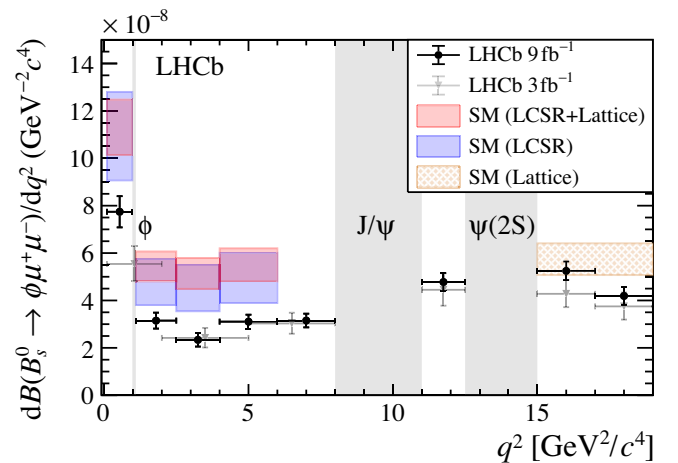


FIG. 2. Differential branching fraction $d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)/dq^2$, overlaid with SM predictions using light cone sum rules [34,36,39] at low q^2 and lattice calculations [37,38] at high q^2 . The results from the LHCb 3 fb^{-1} analysis [1,30] are shown with gray markers.

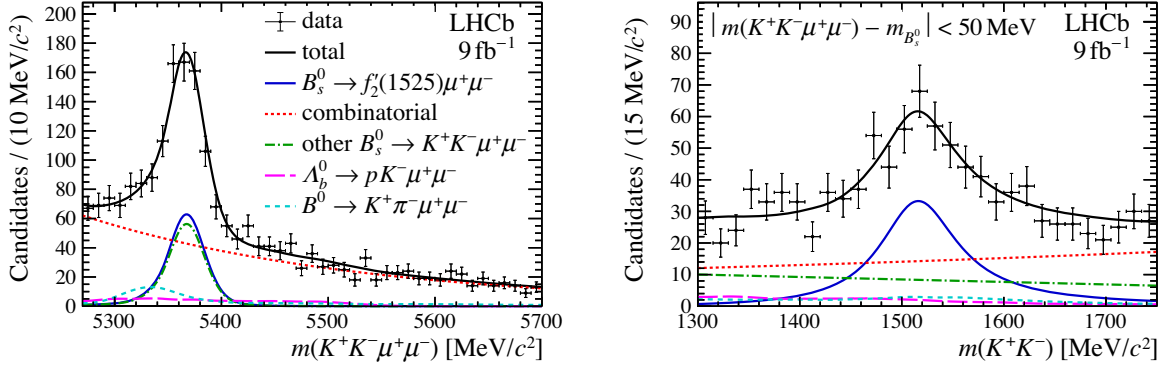


FIG. 3. Reconstructed invariant mass of (left) the $K^+K^-\mu^+\mu^-$ system and (right) the K^+K^- system for $B_s^0 \rightarrow f_2'\mu^+\mu^-$ candidates, overlaid with the fit projections. The $m(K^+K^-)$ distribution is shown in the B_s^0 signal region ± 50 MeV/ c^2 around the known B_s^0 mass.

$$\frac{\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)} = (8.00 \pm 0.21 \pm 0.16 \pm 0.03) \times 10^{-4},$$

$$\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-) = (8.14 \pm 0.21 \pm 0.16 \pm 0.03 \pm 0.39) \times 10^{-7},$$

where the uncertainties are, in order, statistical, systematic, from the extrapolation to the full q^2 region, and for the absolute branching fraction, from the branching fraction of the normalization mode.

The $B_s^0 \rightarrow f_2'\mu^+\mu^-$ decay is searched for using the combined q^2 region $[0.1, 0.98] \cup [1.1, 8.0] \cup [11.0, 12.5]$ GeV $^2/c^4$. The branching fraction of the signal decay is determined relative to the $B_s^0 \rightarrow J/\psi\phi$ normalization mode, according to

$$\begin{aligned} \frac{\mathcal{B}(B_s^0 \rightarrow f_2'\mu^+\mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)} &= \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) \times \frac{\mathcal{B}(\phi \rightarrow K^+K^-)}{\mathcal{B}(f_2' \rightarrow K^+K^-)} \\ &\times \frac{N_{f_2'\mu^+\mu^-}}{N_{J/\psi\phi}} \times \frac{\epsilon_{J/\psi\phi}}{\epsilon_{f_2'\mu^+\mu^-}}, \end{aligned} \quad (2)$$

where the ratio of branching fractions $\mathcal{B}(\phi \rightarrow K^+K^-)/\mathcal{B}(f_2' \rightarrow K^+K^-) = 1.123 \pm 0.030$ [26] is used. To separate the f_2' signal from S - and P -wave contributions to the wide $m(K^+K^-)$ mass window, a two-dimensional fit to the $m(K^+K^-\mu^+\mu^-)$ and $m(K^+K^-)$ distributions is performed. The $B_s^0 \rightarrow f_2'\mu^+\mu^-$ signal decay is modeled in $m(K^+K^-\mu^+\mu^-)$ using the sum of two Gaussian functions, with a power-law tail toward upper and lower mass, and in $m(K^+K^-)$ using a relativistic spin-2 Breit-Wigner function. The model parameters are determined from data using fits to the $B_s^0 \rightarrow J/\psi f_2'$ control mode and are fixed for the signal mode. Contributions from the S -wave and P -wave resonances, e.g., the ϕ and the $\phi(1680)$ mesons, are combined and described with a linear function in $m(K^+K^-)$ and use the same model as the signal in $m(K^+K^-\mu^+\mu^-)$. Interference effects are neglected as these were found to be small in the study of $B_s^0 \rightarrow J/\psi K^+K^-$ decays in Ref. [40]. The combinatorial background is modeled using an exponential function in both the reconstructed B_s^0 mass and the mass of the dikaon system.

Background from $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ and $\Lambda_b^0 \rightarrow pK^-\mu^+\mu^-$ decays is found to be non-negligible in the wide $m(K^+K^-)$ window. These background components are included in the fit model, with their yields constrained to the expected values and line shapes determined on simulated events.

The branching fraction of the $B_s^0 \rightarrow f_2'\mu^+\mu^-$ decay is determined using a simultaneous fit to the three data samples. The branching fraction of the signal and the S - and P -wave contributions are shared between the data samples. From this fit, the signal yields $N_{f_2'\mu^+\mu^-}$ are found to be 62 ± 8 , 67 ± 8 , and 161 ± 20 for the different data-taking periods. Figure 3 shows the $m(K^+K^-\mu^+\mu^-)$ and $m(K^+K^-)$ mass distributions, where the latter is shown within 50 MeV/ c^2 of the known B_s^0 mass [26], overlaid with the fit projections. The significance of the signal is determined using Wilks's theorem [41], comparing the log-likelihood with and without the signal component. The $B_s^0 \rightarrow f_2'\mu^+\mu^-$ decay is observed with a statistical significance of 9σ . Systematic effects on the significance due to the choice of fit model are negligible.

The dominant systematic uncertainties on the relative branching fraction of the $B_s^0 \rightarrow f_2'\mu^+\mu^-$ decay originate from the uncertainty of the branching fraction ratio $\mathcal{B}(\phi \rightarrow K^+K^-)/\mathcal{B}(f_2' \rightarrow K^+K^-)$ (0.04×10^{-7}), the modeling of the parameters of the Breit-Wigner function describing the f_2' resonance, and the simplified fit model for the $m(K^+K^-)$ distribution (0.03×10^{-7}). The effect of the simplified fit model is evaluated using pseudoexperiments, in which events are generated using the amplitude model in Ref. [40] and fit with the default model. The observed difference in the determined yield is taken as a systematic uncertainty. Further details on the systematic uncertainties associated with $\mathcal{B}(B_s^0 \rightarrow f_2'\mu^+\mu^-)$ are given in the Supplemental Material [31].

The fraction of signal events within the considered q^2 region is calculated using the q^2 -differential distribution in Ref. [42] and found to be $\epsilon_{q^2\text{veto}} = (73.8 \pm 2.8)\%$. Accounting for this factor, the relative and total branching fractions are determined to be

$$\frac{\mathcal{B}(B_s^0 \rightarrow f_2' \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)} = (1.55 \pm 0.19 \pm 0.06 \pm 0.06) \times 10^{-4},$$

$$\mathcal{B}(B_s^0 \rightarrow f_2' \mu^+ \mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7},$$

where the given uncertainties are, in order, statistical, systematic, from the extrapolation to the full q^2 range and, for the absolute branching fraction, from the uncertainty on the branching fraction of the normalization mode. The total $B_s^0 \rightarrow f_2' \mu^+ \mu^-$ branching fraction is found to be in agreement with SM predictions [42–44].

In summary, the most precise measurement of the branching fraction of the rare $B_s^0 \rightarrow \phi \mu^+ \mu^-$ decay is presented, using LHCb data corresponding to an integrated luminosity of 9 fb^{-1} . Consistent with earlier measurements [1,2], the data are found to lie below SM expectations. In the q^2 region between 1.1 and $6.0 \text{ GeV}^2/c^4$ the measurement deviates by 3.6σ with respect to a precise SM prediction [34,36–39]. These results supersede, and are consistent with, those of Refs. [1,2]. In addition, the first observation of the rare $B_s^0 \rightarrow f_2' \mu^+ \mu^-$ decay is reported with a statistical significance of 9 standard deviations and the resulting branching fraction is found to be in agreement with SM predictions [42–44].

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F. Blanc,⁴⁹ S. Blusk,⁶⁸ D. Bobulska,⁵⁹ J. A. Boelhaue,¹⁵ O. Boente Garcia,⁴⁶ T. Boettcher,⁶⁵ A. Boldyrev,⁸² A. Bondar,⁴³
 N. Bondar,^{38,48} S. Borghi,⁶² M. Borisyak,⁴² M. Borsato,¹⁷ J. T. Borsuk,³⁵ S. A. Bouchiba,⁴⁹ T. J. V. Bowcock,⁶⁰ A. Boyer,⁴⁸
 C. Bozzi,²¹ M. J. Bradley,⁶¹ S. Braun,⁶⁶ A. Brea Rodriguez,⁴⁶ M. Brodski,⁴⁸ J. Brodzicka,³⁵ A. Brossa Gonzalo,⁵⁶
 D. Brundu,²⁷ A. Buonauro,⁵⁰ C. Burr,⁴⁸ A. Bursche,⁷² A. Butkevich,³⁹ J. S. Butter,³² J. Buytaert,⁴⁸ W. Byczynski,⁴⁸
 S. Cadeddu,²⁷ H. Cai,⁷³ R. Calabrese,^{21,b} L. Calefice,^{15,13} L. Calero Diaz,²³ S. Cali,²³ R. Calladine,⁵³ M. Calvi,^{26,c}
 M. Calvo Gomez,⁸⁵ P. Camargo Magalhaes,⁵⁴ P. Campana,²³ A. F. Campoverde Quezada,⁶ S. Capelli,^{26,c} L. Capriotti,^{20,d}
 A. Carbone,^{20,d} G. Carboni,³¹ R. Cardinale,²⁴ A. Cardini,²⁷ I. Carli,⁴ P. Carniti,^{26,c} L. Carus,¹⁴ K. Carvalho Akiba,³²
 A. Casais Vidal,⁴⁶ G. Casse,⁶⁰ M. Cattaneo,⁴⁸ G. Cavallero,⁴⁸ S. Celani,⁴⁹ J. Cerasoli,¹⁰ A. J. Chadwick,⁶⁰ M. G. Chapman,⁵⁴
 M. Charles,¹³ Ph. Charpentier,⁴⁸ G. Chatzikonstantinidis,⁵³ C. A. Chavez Barajas,⁶⁰ M. Chefdeville,⁸ C. Chen,³ S. Chen,⁴
 A. Chernov,³⁵ V. Chobanova,⁴⁶ S. Cholak,⁴⁹ M. Chrzasczcz,³⁵ A. Chubykin,³⁸ V. Chulikov,³⁸ P. Ciambone,²³ M. F. Cicala,⁵⁶
 X. Cid Vidal,⁴⁶ G. Ciezarek,⁴⁸ P. E. L. Clarke,⁵⁸ M. Clemencic,⁴⁸ H. V. Cliff,⁵⁵ J. Closier,⁴⁸ J. L. Cobbledick,⁶² V. Coco,⁴⁸
 J. A. B. Coelho,¹¹ J. Cogan,¹⁰ E. Cogneras,⁹ L. Cojocariu,³⁷ P. Collins,⁴⁸ T. Colombo,⁴⁸ L. Congedo,^{19,e} A. Contu,²⁷
 N. Cooke,⁵³ G. Coombs,⁵⁹ I. Corredoira Fernandez,⁴⁶ G. Corti,⁴⁸ C. M. Costa Sobral,⁵⁶ B. Couturier,⁴⁸ D. C. Craik,⁶⁴
 J. Crkovská,⁶⁷ M. Cruz Torres,¹ R. Currie,⁵⁸ C. L. Da Silva,⁶⁷ S. Dadabaev,⁸³ E. Dall'Occo,¹⁵ J. Dalseno,⁴⁶
 C. D'Ambrosio,⁴⁸ A. Danilina,⁴¹ P. d'Argent,⁴⁸ A. Davis,⁶² O. De Aguiar Francisco,⁶² K. De Bruyn,⁷⁹ S. De Capua,⁶²
 M. De Cian,⁴⁹ J. M. De Miranda,¹ L. De Paula,² M. De Serio,^{19,e} D. De Simone,⁵⁰ P. De Simone,²³ J. A. de Vries,⁸⁰
 C. T. Dean,⁶⁷ D. Decamp,⁸ L. Del Buono,¹³ B. Delaney,⁵⁵ H.-P. Dembinski,¹⁵ A. Dendek,³⁴ V. Denysenko,⁵⁰ D. Derkach,⁸²
 O. Deschamps,⁹ F. Desse,¹¹ F. Dettori,^{27,f} B. Dey,⁷⁷ A. Di Cicco,²³ P. Di Nezza,²³ S. Didenko,⁸³ L. Dieste Maronas,⁴⁶
 H. Dijkstra,⁴⁸ V. Dobishuk,⁵² A. M. Donohoe,¹⁸ F. Dordei,²⁷ A. C. dos Reis,¹ L. Douglas,⁵⁹ A. Dovbnya,⁵¹ A. G. Downes,⁸
 K. Dreimanis,⁶⁰ M. W. Dudek,³⁵ L. Dufour,⁴⁸ V. Duk,⁷⁸ P. Durante,⁴⁸ J. M. Durham,⁶⁷ D. Dutta,⁶² A. Dziurda,³⁵
 A. Dzyuba,³⁸ S. Easo,⁵⁷ U. Egede,⁶⁹ V. Egorychev,⁴¹ S. Eidelman,^{43,g} S. Eisenhardt,⁵⁸ S. Ek-In,⁴⁹ L. Eklund,^{59,h} S. Ely,⁶⁸
 A. Ene,³⁷ E. Eppe,⁶⁷ S. Escher,¹⁴ J. Eschle,⁵⁰ S. Esen,¹³ T. Evans,⁴⁸ A. Falabella,²⁰ J. Fan,³ Y. Fan,⁶ B. Fang,⁷³ S. Farry,⁶⁰
 D. Fazzini,^{26,c} M. Féo,⁴⁸ A. Fernandez Prieto,⁴⁶ J. M. Fernandez-tenllado Arribas,⁴⁵ A. D. Fernez,⁶⁶ F. Ferrari,^{20,d}
 L. Ferreira Lopes,⁴⁹ F. Ferreira Rodrigues,² S. Ferreres Sole,³² M. Ferrillo,⁵⁰ M. Ferro-Luzzi,⁴⁸ S. Filippov,³⁹ R. A. Fini,¹⁹
 M. Fiorini,^{21,b} M. Firlej,³⁴ K. M. Fischer,⁶³ D. S. Fitzgerald,⁸⁶ C. Fitzpatrick,⁶² T. Fiutowski,³⁴ A. Fkiaras,⁴⁸ F. Fleuret,¹²
 M. Fontana,¹³ F. Fontanelli,^{24,i} R. Forty,⁴⁸ V. Franco Lima,⁶⁰ M. Franco Sevilla,⁶⁶ M. Frank,⁴⁸ E. Franzoso,²¹ G. Frau,¹⁷
 C. Frei,⁴⁸ D. A. Friday,⁵⁹ J. Fu,²⁵ Q. Fuehring,¹⁵ W. Funk,⁴⁸ E. Gabriel,³² T. Gaintseva,⁴² A. Gallas Torreira,⁴⁶ D. Galli,^{20,d}
 S. Gambetta,^{58,48} Y. Gan,³ M. Gandelman,² P. Gandini,²⁵ Y. Gao,⁵ M. Garau,²⁷ L. M. Garcia Martin,⁵⁶ P. Garcia Moreno,⁴⁵
 J. García Pardiñas,^{26,c} B. Garcia Plana,⁴⁶ F. A. Garcia Rosales,¹² L. Garrido,⁴⁵ C. Gaspar,⁴⁸ R. E. Geertsema,³² D. Gerick,¹⁷
 L. L. Gerken,¹⁵ E. Gersabeck,⁶² M. Gersabeck,⁶² T. Gershon,⁵⁶ D. Gerstel,¹⁰ Ph. Ghez,⁸ V. Gibson,⁵⁵ H. K. Giemza,³⁶
 M. Giovannetti,^{23,j} A. Gioventù,⁴⁶ P. Gironella Gironell,⁴⁵ L. Giubega,³⁷ C. Giugliano,^{21,48,b} K. Gizdov,⁵⁸
 E. L. Gkougkousis,⁴⁸ V. V. Gligorov,¹³ C. Göbel,⁷⁰ E. Golobardes,⁸⁵ D. Golubkov,⁴¹ A. Golutvin,^{61,83} A. Gomes,^{1,k}
 S. Gomez Fernandez,⁴⁵ F. Goncalves Abrantes,⁶³ M. Goncerz,³⁵ G. Gong,³ P. Gorbounov,⁴¹ I. V. Gorelov,⁴⁰ C. Gotti,²⁶
 E. Govorkova,⁴⁸ J. P. Grabowski,¹⁷ T. Grammatico,¹³ L. A. Granado Cardoso,⁴⁸ E. Graugés,⁴⁵ E. Graverini,⁴⁹ G. Graziani,²²
 A. Grecu,³⁷ L. M. Greeven,³² P. Griffith,^{21,b} L. Grillo,⁶² S. Gromov,⁸³ B. R. Gruberg Cazon,⁶³ C. Gu,³ M. Guarise,²¹
 P. A. Günther,¹⁷ E. Gushchin,³⁹ A. Guth,¹⁴ Y. Guz,⁴⁴ T. Gys,⁴⁸ T. Hadavizadeh,⁶⁹ G. Haefeli,⁴⁹ C. Haen,⁴⁸ J. Haimberger,⁴⁸
 T. Halewood-leagas,⁶⁰ P. M. Hamilton,⁶⁶ J. P. Hammerich,⁶⁰ Q. Han,⁷ X. Han,¹⁷ T. H. Hancock,⁶³
 S. Hansmann-Menzemer,¹⁷ N. Harnew,⁶³ T. Harrison,⁶⁰ C. Hasse,⁴⁸ M. Hatch,⁴⁸ J. He,⁶¹ M. Hecker,⁶¹ K. Heijhoff,³²
 K. Heinicke,¹⁵ A. M. Hennequin,⁴⁸ K. Hennessy,⁶⁰ L. Henry,⁴⁸ J. Heuel,¹⁴ A. Hicheur,² D. Hill,⁴⁹ M. Hilton,⁶² S. E. Hollitt,¹⁵
 J. Hu,¹⁷ J. Hu,⁷² W. Hu,⁷ X. Hu,³ W. Huang,⁶ X. Huang,⁷³ W. Hulsbergen,³² R. J. Hunter,⁵⁶ M. Hushchyn,⁸² D. Hutchcroft,⁶⁰
 D. Hynds,³² P. Ibis,¹⁵ M. Idzik,³⁴ D. Ilin,³⁸ P. Ilten,⁶⁵ A. Inglessi,³⁸ A. Ishteev,⁸³ K. Ivshin,³⁸ R. Jacobsson,⁴⁸ S. Jakobsen,⁴⁸
 E. Jans,³² B. K. Jashal,⁴⁷ A. Jawahery,⁶⁶ V. Jevtic,¹⁵ M. Jezabek,³⁵ F. Jiang,³ M. John,⁶³ D. Johnson,⁴⁸ C. R. Jones,⁵⁵
 T. P. Jones,⁵⁶ B. Jost,⁴⁸ N. Jurik,⁴⁸ S. Kandybei,⁵¹ Y. Kang,³ M. Karacson,⁴⁸ M. Karpov,⁸² F. Keizer,⁴⁸ M. Kenzie,⁵⁶
 T. Ketel,³³ B. Khanji,¹⁵ A. Kharisova,⁸⁴ S. Kholodenko,⁴⁴ T. Kim,¹⁴ V. S. Kirsebom,⁴⁹ O. Kitouni,⁶⁴ S. Klaver,³²
 K. Klimaszewski,³⁶ S. Koliiev,⁵² A. Kondybayeva,⁸³ A. Konoplyannikov,⁴¹ P. Kopciwicz,³⁴ R. Kopečna,¹⁷
 P. Koppenburg,³² M. Korolev,⁴⁰ I. Kostiuk,^{32,52} O. Kot,⁵² S. Kotriakhova,^{21,38} P. Kravchenko,³⁸ L. Kravchuk,³⁹
 R. D. Krawczyk,⁴⁸ M. Kreps,⁵⁶ F. Kress,⁶¹ S. Kretschmar,¹⁴ P. Krokovny,^{43,g} W. Krupa,³⁴ W. Krzemien,³⁶ W. Kucewicz,^{35,m}
 M. Kucharczyk,³⁵ V. Kudryavtsev,^{43,g} H. S. Kuindersma,^{32,33} G. J. Kunde,⁶⁷ T. Kvaratskheliya,⁴¹ D. Lacarrere,⁴⁸
 G. Lafferty,⁶² A. Lai,²⁷ A. Lampis,²⁷ D. Lancierini,⁵⁰ J. J. Lane,⁶² R. Lane,⁵⁴ G. Lanfranchi,²³ C. Langenbruch,¹⁴ J. Langer,¹⁵

- O. Lantwin,⁵⁰ T. Latham,⁵⁶ F. Lazzari,^{29,n} R. Le Gac,¹⁰ S. H. Lee,⁸⁶ R. Lefèvre,⁹ A. Leflat,⁴⁰ S. Legotin,⁸³ O. Leroy,¹⁰
 T. Lesiak,³⁵ B. Leverington,¹⁷ H. Li,⁷² L. Li,⁶³ P. Li,¹⁷ S. Li,⁷ Y. Li,⁴ Y. Li,⁴ Z. Li,⁶⁸ X. Liang,⁶⁸ T. Lin,⁶¹ R. Lindner,⁴⁸
 V. Lisovskyi,¹⁵ R. Litvinov,²⁷ G. Liu,⁷² H. Liu,⁶ S. Liu,⁴ A. Loi,²⁷ J. Lomba Castro,⁴⁶ I. Longstaff,⁵⁹ J. H. Lopes,²
 G. H. Lovell,⁵⁵ Y. Lu,⁴ D. Lucchesi,^{28,o} S. Luchuk,³⁹ M. Lucio Martinez,³² V. Lukashenko,³² Y. Luo,³ A. Lupato,⁶²
 E. Luppi,^{21,b} O. Lupton,⁵⁶ A. Lusiani,^{29,p} X. Lyu,⁶ L. Ma,⁴ R. Ma,⁶ S. Maccolini,^{20,d} F. Machefert,¹¹ F. Maciuc,³⁷
 V. Macko,⁴⁹ P. Mackowiak,¹⁵ S. Maddrell-Mander,⁵⁴ O. Madejczyk,³⁴ L. R. Madhan Mohan,⁵⁴ O. Maev,³⁸ A. Maevskiy,⁸²
 D. Maisuzenko,³⁸ M. W. Majewski,³⁴ J. J. Malczewski,³⁵ S. Malde,⁶³ B. Malecki,⁴⁸ A. Malinin,⁸¹ T. Maltsev,^{43,g}
 H. Malygina,¹⁷ G. Manca,^{27,f} G. Mancinelli,¹⁰ D. Manuzzi,^{20,d} D. Marangotto,^{25,q} J. Maratas,^{9,r} J. F. Marchand,⁸
 U. Marconi,²⁰ S. Mariani,^{22,s} C. Marin Benito,⁴⁸ M. Marinangeli,⁴⁹ J. Marks,¹⁷ A. M. Marshall,⁵⁴ P. J. Marshall,⁶⁰
 G. Martellotti,³⁰ L. Martinazzoli,^{48,c} M. Martinelli,^{26,c} D. Martinez Santos,⁴⁶ F. Martinez Vidal,⁴⁷ A. Massafferri,¹
 M. Materok,¹⁴ R. Matev,⁴⁸ A. Mathad,⁵⁰ Z. Mathe,⁴⁸ V. Matiunin,⁴¹ C. Matteuzzi,²⁶ K. R. Mattioli,⁸⁶ A. Mauri,³²
 E. Maurice,¹² J. Mauricio,⁴⁵ M. Mazurek,⁴⁸ M. McCann,⁶¹ L. McConnell,¹⁸ T. H. Mcgrath,⁶² A. McNab,⁶² R. McNulty,¹⁸
 J. V. Mead,⁶⁰ B. Meadows,⁶⁵ G. Meier,¹⁵ N. Meinert,⁷⁶ D. Melnychuk,³⁶ S. Meloni,^{26,c} M. Merk,^{32,80} A. Merli,²⁵
 L. Meyer Garcia,² M. Mikhasenko,⁴⁸ D. A. Milanese,⁷⁴ E. Millard,⁵⁶ M. Milovanovic,⁴⁸ M.-N. Minard,⁸ A. Minotti,²¹
 L. Minzoni,^{21,b} S. E. Mitchell,⁵⁸ B. Mitreska,⁶² D. S. Mitzel,⁴⁸ A. Mödden,¹⁵ R. A. Mohammed,⁶³ R. D. Moise,⁶¹
 T. Mombächer,⁴⁶ I. A. Monroy,⁷⁴ S. Monteil,⁹ M. Morandin,²⁸ G. Morello,²³ M. J. Morello,^{29,p} J. Moron,³⁴ A. B. Morris,⁷⁵
 A. G. Morris,⁵⁶ R. Mountain,⁶⁸ H. Mu,³ F. Muheim,^{58,48} M. Mulder,⁴⁸ D. Müller,⁴⁸ K. Müller,⁵⁰ C. H. Murphy,⁶³
 D. Murray,⁶² P. Muzzetto,^{27,48} P. Naik,⁵⁴ T. Nakada,⁴⁹ R. Nandakumar,⁵⁷ T. Nanut,⁴⁹ I. Nasteva,² M. Needham,⁵⁸ I. Neri,²¹
 N. Neri,^{25,q} S. Neubert,⁷⁵ N. Neufeld,⁴⁸ R. Newcombe,⁶¹ T. D. Nguyen,⁴⁹ C. Nguyen-Mau,^{49,i} E. M. Niel,¹¹ S. Nieswand,¹⁴
 N. Nikitin,⁴⁰ N. S. Nolte,⁶⁴ C. Normand,⁸ C. Nunez,⁸⁶ A. Oblakowska-Mucha,³⁴ V. Obratsov,⁴⁴ D. P. O'Hanlon,⁵⁴
 R. Oldeman,^{27,f} M. E. Olivares,⁶⁸ C. J. G. Onderwater,⁷⁹ R. H. O'neil,⁵⁸ A. Ossowska,³⁵ J. M. Otalora Goicochea,²
 T. Ovsianikova,⁴¹ P. Owen,⁵⁰ A. Oyanguren,⁴⁷ B. Pagare,⁵⁶ P. R. Pais,⁴⁸ T. Pajero,⁶³ A. Palano,¹⁹ M. Palutan,²³ Y. Pan,⁶²
 G. Panshin,⁸⁴ A. Papanestis,⁵⁷ M. Pappagallo,^{19,e} L. L. Pappalardo,^{21,b} C. Pappenheimer,⁶⁵ W. Parker,⁶⁶ C. Parkes,⁶²
 C. J. Parkinson,⁴⁶ B. Passalacqua,²¹ G. Passaleva,²² A. Pastore,¹⁹ M. Patel,⁶¹ C. Patrignani,^{20,d} C. J. Pawley,⁸⁰ A. Pearce,⁴⁸
 A. Pellegrino,³² M. Pepe Altarelli,⁴⁸ S. Perazzini,²⁰ D. Pereima,⁴¹ P. Perret,⁹ M. Petric,^{59,48} K. Petridis,⁵⁴ A. Petrolini,^{24,i}
 A. Petrov,⁸¹ S. Petrucci,⁵⁸ M. Petruzzo,²⁵ T. T. H. Pham,⁶⁸ A. Philippov,⁴² L. Pica,^{29,p} M. Piccini,⁷⁸ B. Pietrzyk,⁸
 G. Pietrzyk,⁴⁹ M. Pili,⁶³ D. Pinci,³⁰ F. Pisani,⁴⁸ Resmi P. K.,¹⁰ V. Placinta,³⁷ J. Plews,⁵³ M. Plo Casasus,⁴⁶ F. Polci,¹³
 M. Poli Lener,²³ M. Poliakova,⁶⁸ A. Poluektov,¹⁰ N. Polukhina,^{83,u} I. Polyakov,⁶⁸ E. Polcarpo,² G. J. Pomery,⁵⁴ S. Ponce,⁴⁸
 D. Popov,^{64,8} S. Popov,⁴² S. Poslavskii,⁴⁴ K. Prasanth,³⁵ L. Promberger,⁴⁸ C. Prouve,⁴⁶ V. Pugatch,⁵² H. Pullen,⁶³
 G. Punzi,^{29,v} H. Qi,³ W. Qian,⁶ J. Qin,⁶ N. Qin,³ R. Quagliani,¹³ B. Quintana,⁸ N. V. Raab,¹⁸ R. I. Rabadan Trejo,¹⁰
 B. Rachwal,³⁴ J. H. Rademacker,⁵⁴ M. Rama,²⁹ M. Ramos Pernas,⁵⁶ M. S. Rangel,² F. Ratnikov,^{42,82} G. Raven,³³
 M. Reboud,⁸ F. Redi,⁴⁹ F. Reiss,⁶² C. Remon Alepuz,⁴⁷ Z. Ren,³ V. Renaudin,⁶³ R. Ribatti,²⁹ S. Ricciardi,⁵⁷ K. Rinnert,⁶⁰
 P. Robbe,¹¹ G. Robertson,⁵⁸ A. B. Rodrigues,⁴⁹ E. Rodrigues,⁶⁰ J. A. Rodriguez Lopez,⁷⁴ E. Rodriguez Rodriguez,⁴⁶
 A. Rollings,⁶³ P. Roloff,⁴⁸ V. Romanovskiy,⁴⁴ M. Romero Lamas,⁴⁶ A. Romero Vidal,⁴⁶ J. D. Roth,⁸⁶ M. Rotondo,²³
 M. S. Rudolph,⁶⁸ T. Ruf,⁴⁸ J. Ruiz Vidal,⁴⁷ A. Ryzhikov,⁸² J. Ryzka,³⁴ J. J. Saborido Silva,⁴⁶ N. Sagidova,³⁸ N. Sahoo,⁵⁶
 B. Saitta,^{27,f} M. Salomoni,⁴⁸ D. Sanchez Gonzalo,⁴⁵ C. Sanchez Gras,³² R. Santacesaria,³⁰ C. Santamarina Rios,⁴⁶
 M. Santimaria,²³ E. Santovetti,^{31,j} D. Saranin,⁸³ G. Sarpis,⁵⁹ M. Sarpis,⁷⁵ A. Sarti,³⁰ C. Satriano,^{30,w} A. Satta,³¹ M. Saur,¹⁵
 D. Savrina,^{41,40} H. Sazak,⁹ L. G. Scantlebury Smead,⁶³ A. Scarabotto,¹³ S. Schael,¹⁴ M. Schiller,⁵⁹ H. Schindler,⁴⁸
 M. Schmelling,¹⁶ B. Schmidt,⁴⁸ O. Schneider,⁴⁹ A. Schopper,⁴⁸ M. Schubiger,³² S. Schulte,⁴⁹ M. H. Schune,¹¹
 R. Schwemmer,⁴⁸ B. Sciascia,²³ S. Sellam,⁴⁶ A. Semennikov,⁴¹ M. Senghi Soares,³³ A. Sergi,²⁴ N. Serra,⁵⁰ L. Sestini,²⁸
 A. Seuthe,¹⁵ P. Seyfert,⁴⁸ Y. Shang,⁵ D. M. Shangase,⁸⁶ M. Shapkin,⁴⁴ I. Shchemerov,⁸³ L. Shchutka,⁴⁹ T. Shears,⁶⁰
 L. Shekhtman,^{43,g} Z. Shen,⁵ V. Shevchenko,⁸¹ E. B. Shields,^{26,c} E. Shmanin,⁸³ J. D. Shupperd,⁶⁸ B. G. Siddi,²¹
 R. Silva Coutinho,⁵⁰ G. Simi,²⁸ S. Simone,^{19,e} N. Skidmore,⁶² T. Skwarnicki,⁶⁸ M. W. Slater,⁵³ I. Slazyk,^{21,b}
 J. C. Smallwood,⁶³ J. G. Smeaton,⁵⁵ A. Smetkina,⁴¹ E. Smith,⁵⁰ M. Smith,⁶¹ A. Snoch,³² M. Soares,²⁰ L. Soares Lavra,⁹
 M. D. Sokoloff,⁶⁵ F. J. P. Soler,⁵⁹ A. Solovet,³⁸ I. Solov'yev,³⁸ F. L. Souza De Almeida,² B. Souza De Paula,² B. Spaan,¹⁵
 E. Spadaro Norella,^{25,q} P. Spradlin,⁵⁹ F. Stagni,⁴⁸ M. Stahl,⁶⁵ S. Stahl,⁴⁸ P. Stefko,⁴⁹ O. Steinkamp,^{50,83} O. Stenyakin,⁴⁴
 H. Stevens,¹⁵ S. Stone,⁶⁸ M. E. Stramaglia,⁴⁹ M. Straticiu,³⁷ D. Strekalina,⁸³ F. Suljik,⁶³ J. Sun,²⁷ L. Sun,⁷³ Y. Sun,⁶⁶
 P. Svihra,⁶² P. N. Swallow,⁵³ K. Swientek,³⁴ A. Szabelski,³⁶ T. Szumlak,³⁴ M. Szymanski,⁴⁸ S. Taneja,⁶² A. R. Tanner,⁵⁴
 A. Terentev,⁸³ F. Teubert,⁴⁸ E. Thomas,⁴⁸ D. J. D. Thompson,⁵³ K. A. Thomson,⁶⁰ V. Tisserand,⁹ S. T'Jampens,⁸ M. Tobin,⁴

L. Tomassetti,^{21,b} D. Torres Machado,¹ D. Y. Tou,¹³ M. T. Tran,⁴⁹ E. Trifonova,⁸³ C. Trippel,⁴⁹ G. Tuci,^{29,v} A. Tully,⁴⁹
 N. Tuning,^{32,48} A. Ukleja,³⁶ D. J. Unverzagt,¹⁷ E. Ursov,⁸³ A. Usachov,³² A. Ustyuzhanin,^{42,82} U. Uwer,¹⁷ A. Vagner,⁸⁴
 V. Vagnoni,²⁰ A. Valassi,⁴⁸ G. Valenti,²⁰ N. Valls Canudas,⁸⁵ M. van Beuzekom,³² M. Van Dijk,⁴⁹ E. van Herwijnen,⁸³
 C. B. Van Hulse,¹⁸ M. van Veghel,⁷⁹ R. Vazquez Gomez,⁴⁶ P. Vazquez Regueiro,⁴⁶ C. Vázquez Sierra,⁴⁸ S. Vecchi,²¹
 J. J. Velthuis,⁵⁴ M. Veltri,^{22,x} A. Venkateswaran,⁶⁸ M. Veronesi,³² M. Vesterinen,⁵⁶ D. Vieira,⁶⁵ M. Vieites Diaz,⁴⁹
 H. Viemann,⁷⁶ X. Vilasis-Cardona,⁸⁵ E. Vilella Figueras,⁶⁰ A. Villa,²⁰ P. Vincent,¹³ D. Vom Bruch,¹⁰ A. Vorobyev,³⁸
 V. Vorobyev,^{43,g} N. Voropaev,³⁸ K. Vos,⁸⁰ R. Waldi,¹⁷ J. Walsh,²⁹ C. Wang,¹⁷ J. Wang,⁵ J. Wang,⁴ J. Wang,³ J. Wang,⁷³
 M. Wang,³ R. Wang,⁵⁴ Y. Wang,⁷ Z. Wang,⁵⁰ Z. Wang,³ H. M. Wark,⁶⁰ N. K. Watson,⁵³ S. G. Weber,¹³ D. Websdale,⁶¹
 C. Weissner,⁶⁴ B. D. C. Westhenry,⁵⁴ D. J. White,⁶² M. Whitehead,⁵⁴ D. Wiedner,¹⁵ G. Wilkinson,⁶³ M. Wilkinson,⁶⁸
 I. Williams,⁵⁵ M. Williams,⁶⁴ M. R. J. Williams,⁵⁸ F. F. Wilson,⁵⁷ W. Wislicki,³⁶ M. Witek,³⁵ L. Witola,¹⁷ G. Wormser,¹¹
 S. A. Wotton,⁵⁵ H. Wu,⁶⁸ K. Wyllie,⁴⁸ Z. Xiang,⁶ D. Xiao,⁷ Y. Xie,⁷ A. Xu,⁵ J. Xu,⁶ L. Xu,³ M. Xu,⁷ Q. Xu,⁶ Z. Xu,⁵ Z. Xu,⁶
 D. Yang,³ S. Yang,⁶ Y. Yang,⁶ Z. Yang,³ Z. Yang,⁶⁶ Y. Yao,⁶⁸ L. E. Yeomans,⁶⁰ H. Yin,⁷ J. Yu,⁷¹ X. Yuan,⁶⁸ O. Yushchenko,⁴⁴
 E. Zaffaroni,⁴⁹ M. Zavertyaev,^{16,u} M. Zdybal,³⁵ O. Zenaiev,⁴⁸ M. Zeng,³ D. Zhang,⁷ L. Zhang,³ S. Zhang,⁵ Y. Zhang,⁵
 Y. Zhang,⁶³ A. Zharkova,⁸³ A. Zhelezov,¹⁷ Y. Zheng,⁶ X. Zhou,⁶ Y. Zhou,⁶ X. Zhu,³ Z. Zhu,⁶ V. Zhukov,^{14,40}
 J. B. Zonneveld,⁵⁸ Q. Zou,⁴ S. Zucchelli,^{20,d} D. Zuliani,²⁸ and G. Zunica⁶²

(LHCb Collaboration)

¹*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*

²*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*

³*Center for High Energy Physics, Tsinghua University, Beijing, China*

⁴*Institute Of High Energy Physics (IHEP), Beijing, China*

⁵*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

⁶*University of Chinese Academy of Sciences, Beijing, China*

⁷*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*

⁸*Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*

⁹*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*

¹⁰*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*

¹¹*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*

¹²*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*

¹³*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*

¹⁴*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*

¹⁵*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*

¹⁶*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*

¹⁷*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*

¹⁸*School of Physics, University College Dublin, Dublin, Ireland*

¹⁹*INFN Sezione di Bari, Bari, Italy*

²⁰*INFN Sezione di Bologna, Bologna, Italy*

²¹*INFN Sezione di Ferrara, Ferrara, Italy*

²²*INFN Sezione di Firenze, Firenze, Italy*

²³*INFN Laboratori Nazionali di Frascati, Frascati, Italy*

²⁴*INFN Sezione di Genova, Genova, Italy*

²⁵*INFN Sezione di Milano, Milano, Italy*

²⁶*INFN Sezione di Milano-Bicocca, Milano, Italy*

²⁷*INFN Sezione di Cagliari, Monserrato, Italy*

²⁸*Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy*

²⁹*INFN Sezione di Pisa, Pisa, Italy*

³⁰*INFN Sezione di Roma La Sapienza, Roma, Italy*

³¹*INFN Sezione di Roma Tor Vergata, Roma, Italy*

³²*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*

³³*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*

³⁴*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*

³⁵*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*

³⁶*National Center for Nuclear Research (NCBJ), Warsaw, Poland*

³⁷*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*

- ³⁸*Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia*
- ³⁹*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*
- ⁴⁰*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
- ⁴¹*Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia*
- ⁴²*Yandex School of Data Analysis, Moscow, Russia*
- ⁴³*Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*
- ⁴⁴*Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia, Protvino, Russia*
- ⁴⁵*ICCUB, Universitat de Barcelona, Barcelona, Spain*
- ⁴⁶*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
- ⁴⁷*Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
- ⁴⁸*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ⁴⁹*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁵⁰*Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁵¹*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁵²*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁵³*University of Birmingham, Birmingham, United Kingdom*
- ⁵⁴*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁵⁵*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁵⁶*Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁵⁷*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵⁸*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵⁹*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁶⁰*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁶¹*Imperial College London, London, United Kingdom*
- ⁶²*Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁶³*Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁶⁴*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ⁶⁵*University of Cincinnati, Cincinnati, Ohio, USA*
- ⁶⁶*University of Maryland, College Park, Maryland, USA*
- ⁶⁷*Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*
- ⁶⁸*Syracuse University, Syracuse, New York, USA*
- ⁶⁹*School of Physics and Astronomy, Monash University, Melbourne, Australia*
(associated with Department of Physics, University of Warwick, Coventry, United Kingdom)
- ⁷⁰*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil*
(associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
- ⁷¹*Physics and Micro Electronic College, Hunan University, Changsha City, China*
(associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)
- ⁷²*Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou, China*
(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
- ⁷³*School of Physics and Technology, Wuhan University, Wuhan, China*
(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
- ⁷⁴*Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia*
(associated with LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)
- ⁷⁵*Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*
(associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
- ⁷⁶*Institut für Physik, Universität Rostock, Rostock, Germany*
(associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
- ⁷⁷*Eotvos Lorand University, Budapest, Hungary*
(associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland)
- ⁷⁸*INFN Sezione di Perugia, Perugia, Italy*
(associated with INFN Sezione di Ferrara, Ferrara, Italy)
- ⁷⁹*Van Swinderen Institute, University of Groningen, Groningen, Netherlands*
(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
- ⁸⁰*Universiteit Maastricht, Maastricht, Netherlands*
(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
- ⁸¹*National Research Centre Kurchatov Institute, Moscow, Russia*
(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia)
- ⁸²*National Research University Higher School of Economics, Moscow, Russia*
(associated with Yandex School of Data Analysis, Moscow, Russia)

⁸³National University of Science and Technology “MISIS”, Moscow, Russia

(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia)

⁸⁴National Research Tomsk Polytechnic University, Tomsk, Russia

(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia)

⁸⁵DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain

(associated with ICCUB, Universitat de Barcelona, Barcelona, Spain)

⁸⁶University of Michigan, Ann Arbor, USA

(associated with Syracuse University, Syracuse, New York, USA)

^aAlso at Università di Modena e Reggio Emilia, Modena, Italy.

^bAlso at Università di Ferrara, Ferrara, Italy.

^cAlso at Università di Milano Bicocca, Milano, Italy.

^dAlso at Università di Bologna, Bologna, Italy.

^eAlso at Università di Bari, Bari, Italy.

^fAlso at Università di Cagliari, Cagliari, Italy.

^gAlso at Novosibirsk State University, Novosibirsk, Russia.

^hAlso at Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden.

ⁱAlso at Università di Genova, Genova, Italy.

^jAlso at Università di Roma Tor Vergata, Roma, Italy.

^kAlso at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.

^lAlso at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China.

^mAlso at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.

ⁿAlso at Università di Siena, Siena, Italy.

^oAlso at Università di Padova, Padova, Italy.

^pAlso at Scuola Normale Superiore, Pisa, Italy.

^qAlso at Università degli Studi di Milano, Milano, Italy.

^rAlso at MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.

^sAlso at Università di Firenze, Firenze, Italy.

^tAlso at Hanoi University of Science, Hanoi, Vietnam.

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

^vAlso at Università di Pisa, Pisa, Italy.

^wAlso at Università della Basilicata, Potenza, Italy.

^xAlso at Università di Urbino, Urbino, Italy.