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

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The branching fraction of the rare $B_s^0 \to \phi\mu^+\mu^-$ 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 GeV^2/c^4, 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 $B_s^0 \to f_2'(1525)\mu^+\mu^-$ 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 $b \to s\ell^+\ell^-$ 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 $B_s^0 \to \phi\mu^+\mu^-$ 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 $B_s^0 \to f_2'(1525)\mu^+\mu^-$ 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 $B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2'\mu^+\mu^-$ 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 $\chi^2_{\mathrm{IP}} > 9(6)$ with respect to any primary pp interaction vertex (PV) in the event, where χ^2_{IP} 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/c^2. The invariant mass of the dikaon system $m(K^+K^-)$ is required to be within 12 MeV/c^2 of the known ϕ mass for the $B_s^0 \to \phi\mu^+\mu^-$ decay or within 225 MeV/c^2 of the known mass of the wider f_2' resonance for the $B_s^0 \to f_2'\mu^+\mu^-$ decay [26].

The q^2 regions between 8.0 and 11.0 GeV^2/c^4 and between 12.5 and 15.0 GeV^2/c^4 are dominated by

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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 $B_s^0 \to J/\psi\phi$ 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 $B_s^0 \to \phi(\to \mu^+\mu^-)\phi$ 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 $B_s^0 \to J/\psi\phi$ events as signal proxy and candidates from the upper mass sideband $m(K^+K^-\mu^+\mu^-) > 5567\ \mathrm{MeV}/c^2$ as background proxy. The classifier combines the B_s^0 transverse momentum and χ^2_{IP}, 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^2_{IP} of the final-state particles.

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

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

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

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 $[q^2_{\mathrm{min}}, q^2_{\mathrm{max}}]$ interval. The branching fractions related to the normalization mode are given by $\mathcal{B}(B_s^0 \to J/\psi\phi) = (1.018 \pm 0.032 \pm 0.037) \times 10^{-3}$ [30] and $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$ [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 $B_s^0 \to J/\psi\phi$ 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 $B_s^0 \to \phi\mu^+\mu^-$ 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 $B_s^0 \to J/\psi\phi$ 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

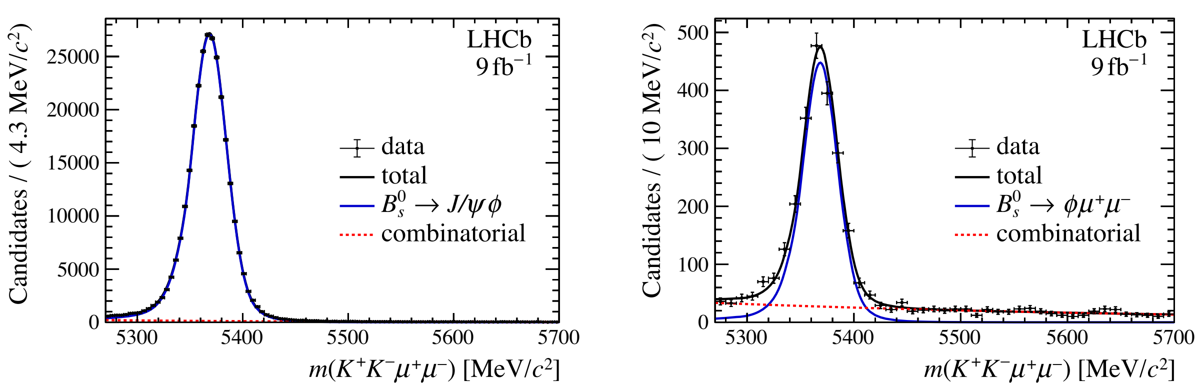

FIG. 1. Reconstructed invariant mass of the $K^+K^-\mu^+\mu^-$ system for (left) the $B_s^0 \to J/\psi\phi$ normalization mode and (right) the $B_s^0 \to \phi\mu^+\mu^-$ signal candidates, integrated over q^2 and overlaid with the fit projections.

TABLE I. Differential $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/dq^2$ 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$^2/c^4$)	$d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/\mathcal{B}(B_s^0 \to J/\psi\phi)dq^2$ (10^{-5} GeV^{-2} c^4)	$d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/dq^2$ (10^{-8} 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 $B_s^0 \to K^+K^-\mu^+\mu^-$ 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 $B_s^0 \to \phi\mu^+\mu^-$ events ($0.04 - 0.10 \times 10^{-8}$ 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 ($0.02 - 0.07 \times 10^{-8}$ GeV^{-2} c^4) and the omission of small background contributions from the fit model ($0.01 - 0.04 \times 10^{-8}$ 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 $(2.88 \pm 0.22) \times 10^{-8}$ GeV^{-2} c^4, lies 3.6σ below a precise SM prediction of $(5.37 \pm 0.66) \times 10^{-8}$ GeV^{-2} c^4, which uses both LCSR and LQCD calculations. A less precise SM prediction of $(4.77 \pm 1.01) \times 10^{-8}$ 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

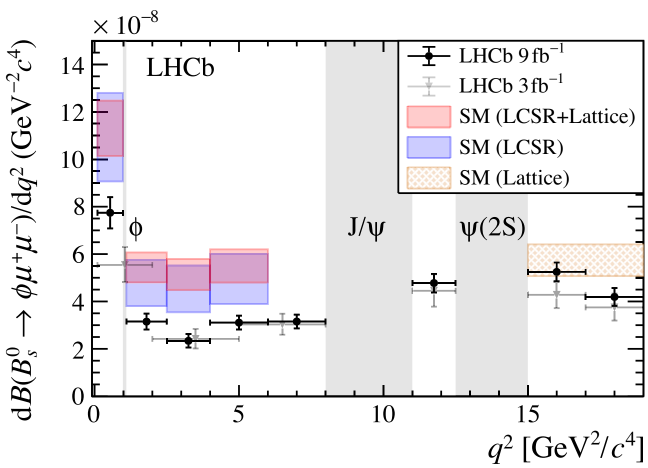

FIG. 2. Differential branching fraction $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/dq^2$, overlaid with SM predictions using light cone sum rules [34,36,39] at low q^2 and lattice calculations [37,38] at high q^2. The results from the LHCb 3 fb^{-1} analysis [1,30] are shown with gray markers.

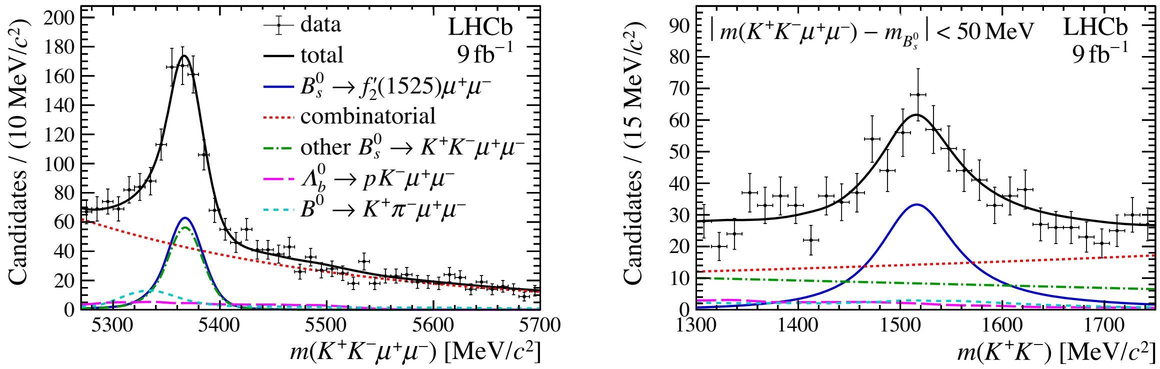

FIG. 3. Reconstructed invariant mass of (left) the $K^+K^-\mu^+\mu^-$ system and (right) the K^+K^- system for $B_s^0 \to f_2'\mu^+\mu^-$ candidates, overlaid with the fit projections. The $m(K^+K^-)$ distribution is shown in the B_s^0 signal region ± 50 MeV$/c^2$ around the known B_s^0 mass.

$$\frac{\mathcal{B}(B_s^0\to\phi\mu^+\mu^-)}{\mathcal{B}(B_s^0\to J/\psi\phi)} = (8.00\pm0.21\pm0.16\pm0.03)\times10^{-4},$$

$$\mathcal{B}(B_s^0\to\phi\mu^+\mu^-) = (8.14\pm0.21\pm0.16\pm0.03\pm0.39)\times10^{-7},$$

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

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

where the ratio of branching fractions $\mathcal{B}(\phi \to K^+K^-)/\mathcal{B}(f_2' \to K^+K^-) = 1.123 \pm 0.030$ [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 $B_s^0 \to f_2'\mu^+\mu^-$ 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 $B_s^0 \to J/\psi f_2'$ 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 $B_s^0 \to J/\psi K^+K^-$ 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 $B^0 \to K^+\pi^-\mu^+\mu^-$ and $\Lambda_b^0 \to pK^-\mu^+\mu^-$ 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 $B_s^0 \to f_2'\mu^+\mu^-$ 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 $B_s^0 \to f_2'\mu^+\mu^-$ 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 $B_s^0 \to f_2'\mu^+\mu^-$ decay originate from the uncertainty of the branching fraction ratio $\mathcal{B}(\phi \to K^+K^-)/\mathcal{B}(f_2' \to K^+K^-)$ (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 $\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-)$ 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

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

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

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 $B_s^0 \to f_2'\mu^+\mu^-$ 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 $B_s^0 \to \phi\mu^+\mu^-$ 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 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 $B_s^0 \to f_2'\mu^+\mu^-$ 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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