Analysis of neutral $B$-meson decays into two muons

LHCb collaboration†

Abstract

Branching fraction and effective lifetime measurements of the rare decay $B^0_s \to \mu^+\mu^-$ and searches for the decays $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$ are reported using proton-proton collision data collected with the LHCb detector at centre-of-mass energies of 7, 8 and 13 TeV, corresponding to a luminosity of $9 \text{fb}^{-1}$. The branching fraction $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ and the effective lifetime $\tau(B^0_s \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03 \text{ps}$ are measured, where the first uncertainty is statistical and the second systematic. No significant signal for $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$ decays is found and upper limits $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ and $\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$ at the 95% CL are determined, where the latter is limited to the range $m_{\mu\mu} > 4.9 \text{GeV}/c^2$. The results are in agreement with the Standard Model expectations.

Published in Phys. Rev. Lett. 128, (2022) 041801

© 2022 CERN for the benefit of the LHCb collaboration. CC BY 4.0 licence

†Full author list given at the end of the article.
The leptonic decays $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ are very rare in the Standard Model (SM) of particle physics because they only proceed via quantum-loop transitions and are helicity and Cabibbo-Kobayashi-Maskawa (CKM) suppressed. The SM predictions of their time-integrated branching fractions, $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$ and $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$, have small uncertainties owing to the leptonic final state and to the progress in lattice QCD calculations [3][7]. Precise measurements of these observables may reveal discrepancies with the expected values due to the existence of new particles contributing to the decay amplitudes, such as heavy $Z'$ gauge bosons, leptoquarks or non-SM Higgs bosons (see e.g. [8]). For these reasons, over the last decades the measurement of the $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ rates has attracted considerable interest in both theoretical and experimental communities, culminating with the observation of the $B^0 \to \mu^+\mu^-$ decay using the joint LHCb and CMS Run 1 data sets [9] followed by the first single-experiment observation by LHCb [10]. Recently, the LHCb measurement has been combined with the ATLAS and CMS measurements [11, 12], resulting in $\mathcal{B}(B^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$ and $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ at 95% confidence level (CL) [13], consistent with SM predictions within two standard deviations.

The $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ decays can be accompanied by the emission of final-state radiation (FSR) from the muons or initial-state radiation (ISR) from the valence quarks, with negligible interference between the two processes [14][16]. Photons from FSR are predominantly soft and their contribution is included experimentally in the reconstructed $B^0_s$ mass shape as a radiative tail. On the contrary, the ISR process, indicated as $B^0_s \to \mu^+\mu^+\gamma$ in this Letter, is characterised by a larger momentum of the photon. This contribution, searched for in the present analysis for the first time, has a SM branching fraction of the order of $10^{-10}$ for a dimuon mass above the lower bound of the search window, 4.9 GeV/\textit{c}², and can be affected by new physics contributions in a different way than the $B^0_s \to \mu^+\mu^-$ decay [14][15][17][22]. Throughout this Letter, $B^0_s \to \mu^+\mu^-$ candidates include $B^0_s \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$ or $B^0_s \to \mu^+\mu^+\gamma$ decays with the dimuon pair selected in the mass range $[4900, 6000]$ MeV/\textit{c}² and the photon not reconstructed [16]. The contribution from $B^0 \to \mu^+\mu^+\gamma$ decays is considered negligible compared to that from $B^0_s \to \mu^+\mu^+\gamma$ because of the additional CKM suppression and the mass shift to lower values.

The $B^0_s$ mass eigenstates are characterised by a sizeable difference in their decay widths ($\Delta \Gamma_s$) compared to their average value $(1/\tau_{B_s})$, such that $y_s \equiv \tau_{B_s} \Delta \Gamma_s/2 = 0.065 \pm 0.003$ [23]. The effective lifetime, defined as the average decay time, is given by [24]

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B^0_s}(1 + 2A^\mu\mu_{\Delta \Gamma_s}s + y^2_s)}{(1 - y^2_s)(1 + A^\mu\mu_{\Delta \Gamma_s}s)}$$

where $A^\mu\mu_{\Delta \Gamma_s} = 1$ ($-1$) if only the heavy (light) $B^0_s$ eigenstate can decay to the $\mu^+\mu^-$ final state. In the SM $A^\mu\mu_{\Delta \Gamma_s} = 1$, but any value in the range $[-1, 1]$ may be possible in new physics scenarios. As a consequence, the effective lifetime of $B^0_s \to \mu^+\mu^-$ decays can probe new physics in a way complementary to the branching fraction [25].

This Letter reports improved measurements of the $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ time-integrated branching fractions and of the $B^0 \to \mu^+\mu^-$ effective lifetime, which supersede the previous LHCb results [10], and a first search for $B^0_s \to \mu^+\mu^+\gamma$ decays.
A more comprehensive description of these measurements is reported in a companion article [26]. Inclusion of charge-conjugated processes is implied throughout the Letter. Results are based on data collected with the LHCb detector in the years 2011-2012 and 2015-2018, corresponding to an integrated luminosity of 1 fb$^{-1}$ of proton-proton ($pp$) collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV, 2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV and 6 fb$^{-1}$ recorded at $\sqrt{s} = 13$ TeV. The first two data sets are referred to as Run 1 and the latter as Run 2.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [27-28]. The simulated events used in this analysis are produced with the software described in Refs. [29-33] taking into account the variations of the accelerator and detector conditions over time. In particular, FSR is simulated using PHOTOS [34]. ISR $B_s^0 \rightarrow \mu^+\mu^-\gamma$ decays are simulated according to the study in Ref. [14]. The analysis strategy is similar to that employed in Ref. [10], optimised to enhance the sensitivity to both $B_s^0$ and $B^0$ decays to $\mu^+\mu^-$. After loose trigger and selection requirements, $B_{(s)}^0 \rightarrow \mu^+\mu^-$ candidates are classified based on the dimuon mass and the output variable, BDT, of a boosted decision tree classifier [35,36] designed to distinguish signal from combinatorial background. To avoid the experimenter’s bias, the candidates in the region [5200, 5445] MeV/$c^2$, where the $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ signal processes peak, were not examined until the full procedure had been finalised. The signal yields are determined from a maximum-likelihood fit to the dimuon mass distribution of the candidates in regions of BDT, and are converted into branching fractions using the effective lifetime measured from the background-subtracted decay-time distribution of signal candidates.

Events are selected by a hardware trigger followed by a software trigger [37]. The $B_{(s)}^0 \rightarrow \mu^+\mu^-$ candidates are predominantly selected by single-muon and dimuon triggers. The $B^+ \rightarrow J/\psi K^+$ candidates are selected in the same way except for a different dimuon mass requirement in the software trigger. Candidate $B_{(s)}^0 \rightarrow h^+h'^-$ decays, with $h'^{(s)} = \pi$ or $K$, are used as control and normalisation channels and are triggered independently of the $B_{(s)}^0$ decay products to avoid selection biases.

The $B_{(s)}^0 \rightarrow \mu^+\mu^-$ candidates are reconstructed by combining two oppositely charged tracks with transverse momentum with respect to the proton beam direction, $p_T$, in the range $0.25 < p_T < 40$ GeV/$c$, momentum $p < 500$ GeV/$c$, and high-quality muon identification [38]. The muon candidates are required to be inconsistent with originating from any primary $pp$ interaction vertex (PV) and to form a good quality secondary vertex well displaced from any PV. In the selection, $B_{(s)}^0$ candidates must have a decay time less than 13.25 ps, $p_T > 0.5$ GeV/$c$ and they must be consistent with originating from at least one PV. A $B_{(s)}^0$ candidate is rejected if either of the two candidate muons combined with any other oppositely charged muon candidate in the event has a mass consistent with the $J/\psi$ mass [39]. The $B_{(s)}^0 \rightarrow h^+h'^-$ selection is the same as that of $B_{(s)}^0 \rightarrow \mu^+\mu^-$, except that the muon identification criteria are replaced with hadron identification requirements and the $J/\psi$ veto is not applied. The $B^+ \rightarrow J/\psi K^+$ decay is reconstructed by combining a muon pair, consistent with a $J/\psi$ from a detached vertex, and a kaon candidate inconsistent with originating from any PV in the event. The selection criteria for signal and normalisation candidates include a loose requirement on the response of a different multivariate classifier,
The selected events are dominated by combinatorial background, mainly composed of muons originating from two semileptonic $b$-hadron decays. The separation between signal and combinatorial background is achieved by means of the BDT classifier, which is optimised using simulated samples of $B^0_s \rightarrow \mu^+\mu^-$ events for signal and of $b\bar{b} \rightarrow \mu^+\mu^-X$ events for background. The classifier combines information from the following input variables: $\sqrt{\Delta \phi^2 + \Delta \eta^2}$, where $\Delta \phi$ and $\Delta \eta$ are the azimuthal angle and pseudorapidity differences between the two muon candidates; the minimum $\chi^2_{IP}$ of the two muons candidates with respect to the PV$_B$, where PV$_B$ is the PV most compatible with the $B^0_s$ candidate trajectory and $\chi^2_{IP}$ is defined as the difference between the vertex-fit $\chi^2$ of the PV formed with and without the particle in question; the angle between the direction of the $B^0_s$ candidate momentum and the vector joining the $B^0_s$ decay vertex and PV$_B$; the $B^0_s$ candidate vertex-fit $\chi^2$ and impact parameter significance with respect to the PV$_B$; and two isolation variables that quantify how much the other tracks of the event are likely to originate from the same hadron decay as the signal tracks. The BDT variable is constructed to be approximately uniform in the range [0,1] for signal, and to peak strongly at zero for background. Its linear correlation with the dimuon mass is below 5%. The Run 1 and Run 2 data sets are each divided into six subsets based on BDT regions with boundaries 0.0, 0.25, 0.4, 0.5, 0.6, 0.7 and 1.0; candidates having BDT < 0.25 are not included in the fit to the dimuon mass distribution. The mass distribution of the $B^0_s \rightarrow \mu^+\mu^-$ candidates with BDT > 0.5 is shown in Fig. 1.

The BDT distributions of $B^0_s \rightarrow \mu^+\mu^-$ decays are calibrated using simulated samples which have been reweighted to improve the agreement with the data. The $p_T$, $\eta$ and $\chi^2_{IP}$ quantities of simulated $B^0$ and $B^0_s$ samples are corrected using data samples of $B^+ \rightarrow J/\psi K^+$ and $B^0_s \rightarrow J/\psi\phi$ decays, respectively. The event occupancy is also corrected, separately for each BDT region, by comparing the fraction of $B^+ \rightarrow J/\psi K^+$ candidates in four intervals of the number of tracks in simulated events and in data. To align the reconstruction with that of the $B^0 \rightarrow \mu^+\mu^-$ signal, the BDT response for the $B^+ \rightarrow J/\psi K^+$ candidates is evaluated using the information from the final state muons and the $B^+$ candidate, with two exceptions: the $B$ vertex-fit $\chi^2$ is replaced with that of the $J/\psi$, and the muon isolation variables are computed without considering the final-state kaon. The effect of the trigger selection on the BDT distribution is estimated using control channels in data. The resulting $B^0 \rightarrow \mu^+\mu^-$ and $B^0_s \rightarrow \mu^+\mu^-$ BDT variable distributions are found to be compatible with that of $B^0 \rightarrow K^+\pi^-$ decays selected in data when corrected for the different trigger and particle identification selection and, in the case of $B^0_s \rightarrow \mu^+\mu^-$, the different lifetime.

The mass distributions of the $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ signals are described by two-sided Crystal Ball functions with core Gaussian parameters calibrated from the mass distributions of $B^0_s \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ data samples, respectively. A mass resolution of about 22 MeV$/c^2$ is determined by interpolating the measured resolutions of charmonium and bottomonium resonances decaying into two muons. The radiative tails are obtained from simulation. Small differences in the resolution and tail parameters of the mass shape for the different BDT regions are taken into account. The mass distribution of the $B^0_s \rightarrow \mu^+\mu^-\gamma$ decays is described with a threshold function modelled on simulated events that were generated using the theoretical predictions of Refs. [14][15], convoluted with the experimental resolution.
The signal branching fractions are determined using the relation

\[ B(B_{(s)}^0 \rightarrow \mu^+\mu^-) = \frac{B_{\text{norm}} \epsilon_{\text{norm}} f_{\text{norm}}}{N_{\text{norm}} \epsilon_{\text{sig}} f_{d(s)}} \times N_{B_{(s)}^0 \rightarrow \mu^+\mu^-} \equiv \alpha_{B_{(s)}^0 \rightarrow \mu^+\mu^-} \times N_{B_{(s)}^0 \rightarrow \mu^+\mu^-}, \]

where \( N_{B_{(s)}^0 \rightarrow \mu^+\mu^-} \) is the signal yield determined in the mass fit, \( N_{\text{norm}} \) is the number of selected normalisation decays \( (B^+ \rightarrow J/\psi K^+ \text{ or } B^0 \rightarrow K^+\pi^-) \), \( B_{\text{norm}} \) the corresponding branching fraction [44], and \( \epsilon_{\text{sig}} (\epsilon_{\text{norm}}) \) is the total efficiency for the signal (normalisation) channel. For each signal mode, the two single event sensitivities, \( \alpha_{B_{(s)}^0 \rightarrow \mu^+\mu^-} \), are then averaged in a combined \( \alpha_{B_{(s)}^0 \rightarrow \mu^+\mu^-} \) taking the correlations into account. The fraction \( f_{d(s)} \) indicates the probability for a b quark to fragment into a \( B_{(s)}^0 \) meson. The value of \( f_s/f_d \) has been measured by LHCb to be 0.254 ± 0.008 in pp collision data at \( \sqrt{s} = 13 \text{ TeV} \), while the average value in Run 1 is lower by a factor of 1.064 ± 0.007 [43]. The fragmentation probabilities for the \( B^0 \) and \( B^+ \) are assumed to be equal, hence \( f_{\text{norm}} = f_d \) for both normalisation modes.

The acceptance, reconstruction and selection efficiencies are computed with samples of simulated events generated with the decay-time distribution predicted by the SM. The tracking and particle identification efficiencies are determined using control channels in data [46,47]. The trigger efficiencies are evaluated with control channels in data [48].

The yields of selected \( B^+ \rightarrow J/\psi K^+ \) and \( B^0 \rightarrow K^+\pi^- \) decays are \( (4733 \pm 3) \times 10^3 \) and \( (94 \pm 1) \times 10^3 \), respectively. The normalisation factors measured with the two channels are consistent and their weighted averages, taking correlations into account, are \( \alpha_{B^0 \rightarrow \mu^+\mu^-} = (3.51 \pm 0.13) \times 10^{-11} \), \( \alpha_{B^0 \rightarrow \mu^+\mu^-} = (9.20 \pm 0.17) \times 10^{-12} \) and \( \alpha_{B_s^0 \rightarrow \mu^+\mu^-} = (4.57 \pm 0.17) \times 10^{-11} \). Assuming SM predictions for the branching fractions, the analysed data sample is expected to contain an average of 104 ± 6 \( B_s^0 \rightarrow \mu^+\mu^- \), 11 ± 1 \( B^0 \rightarrow \mu^+\mu^- \) and about 2 \( B_s^0 \rightarrow \mu^+\mu^- \) decays in the BDT > 0.25 range and in the mass range [4900, 6000] MeV/c².

The combinatorial background is distributed exponentially over the whole mass range. In addition, the \( B^0 \) and \( B_s^0 \) signal regions and the low-mass sideband are populated by background from specific b-hadron decays divided into two categories: those with the misidentification of at least one hadron as a muon and those where two real muons are present and the decay is partially reconstructed. The first category includes \( B_{(s)}^0 \rightarrow h^+h^- \), \( B^0 \rightarrow \pi^+\mu^+\nu_\mu \), \( B_s^0 \rightarrow K^-\mu^+\nu_\mu \), and \( A_0^0 \rightarrow p\mu^-\overline{\nu}_\mu \) decays, of which branching fractions are taken from Refs. [44,49,50]. The mass and BDT distributions of these decays are determined from simulated samples after calibrating the \( K \rightarrow \mu, \pi \rightarrow \mu \) and \( p \rightarrow \mu \) momentum-dependent misidentification probabilities using control channels in data. An independent estimate of the \( B_{(s)}^0 \rightarrow h^+h^- \) background yield is obtained by extracting the yields of misidentified \( B_{(s)}^0 \rightarrow h^+h^- \) decays from the mass spectrum of \( \pi^+\mu^- \) or \( K^+\mu^- \) combinations in data, and rescaling the observed yields according to the misidentification probabilities. The difference with respect to the result from the first method is assigned as a systematic uncertainty. The second category of background in the low-mass sideband includes the decays \( B_c^+ \rightarrow J/\psi\mu^+\nu_\mu \), with \( J/\psi \rightarrow \mu^+\mu^- \), and \( B_{(s)}^{0(+)} \rightarrow \pi^{0(+)}\mu^+\mu^- \), which have at least two muons in the final state. The rate of \( B_c^+ \rightarrow J/\psi\mu^+\nu_\mu \) decays is evaluated from Refs. [51,52] and those of \( B_{(s)}^{0(+)} \rightarrow \pi^{0(+)}\mu^+\mu^- \) decays from Refs. [53,54]. The expected yields of the background contributions originating from specific processes are estimated by normalising to the \( B^+ \rightarrow J/\psi K^+ \) decay, except for the \( B_{(s)}^0 \rightarrow h^+h^- \) decays, which are normalised to the \( B^0 \rightarrow K^+\pi^- \) channel. Their expected yields with BDT > 0.25 in the
full mass range are $37 \pm 2 B_{(s)}^0 \rightarrow h^+ h^-$, $161 \pm 6 B^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $31 \pm 3 B_{(s)}^0 \rightarrow K^- \mu^+ \nu_\mu$, $53 \pm 4 B_{(s)}^{0(+)} \rightarrow \pi^{0(+)} \mu^+ \mu^-$, $7 \pm 3 \Lambda_b^0 \rightarrow pp \mu^- \nu_\mu$ and $28 \pm 1 B^+ \rightarrow J/\psi \mu^+ \nu_\mu$ decays.

The $B_s^0 \rightarrow \mu^+ \mu^-$, $B^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ branching fractions are determined with a simultaneous unbinned maximum-likelihood fit \cite{55} to the dimuon mass distribution in the BDT regions of the Run 1 and Run 2 data sets, with BDT $> 0.25$. The fractions of $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ yield in each BDT region and the parameters of the Crystal Ball functions \cite{42} describing the shapes of the mass distribution are Gaussian constrained according to their expected values and uncertainties. The combinatorial background in each BDT region is described by an exponential function with the yield and slope allowed to vary freely, but the slope parameter is common to all regions within a given data set. Each other background is included as a separate component in the fit. Their yields as well as the fractions in each BDT region are Gaussian-constrained according to their expected values, while their mass shapes are determined from simulation and fixed in the fit, separately in each BDT region. Figure 1 shows the fit results projected on the dimuon mass distribution for BDT $> 0.5$.

The branching fractions of the $B_s^0 \rightarrow \mu^+ \mu^-$, $B^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ decays obtained from the fit are

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10},$$
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} \text{ with } m_{\mu\mu} > 4.9 \text{ GeV}/c^2.$$  

The statistical uncertainty is obtained by re-running the fit with all nuisance parameters fixed to the values found in the default fit. The systematic uncertainties of $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ are dominated by the uncertainty on $f_s/f_d$ (3%) and the knowledge of the background from specific processes (9%), respectively. The correlation between the $B_s^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^-$ branching fractions is $-11\%$ while that between the $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ and $B^0 \rightarrow \mu^+ \mu^- (B_s^0 \rightarrow \mu^+ \mu^-)$ branching fractions is $-25\%$ (9%).

Two-dimensional profile likelihoods are evaluated by taking the ratio of the likelihood value of a fit where the parameters of interest are fixed and the likelihood value of the standard fit. They are shown in Figure 2 for the possible combinations of two branching fractions.

An excess of $B_s^0 \rightarrow \mu^+ \mu^-$ decays with respect to the expectation from background is observed with a significance of about 10 standard deviations ($\sigma$), while the significance of the $B^0 \rightarrow \mu^+ \mu^-$ signal is $1.7\sigma$, as determined using Wilks’ theorem \cite{56} from the difference in likelihood between fits with and without the specific signal component. The negative fluctuation of the $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ signal has a $1.6\sigma$ significance.

Since the $B^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ signals are not significant, an upper limit on each branching fraction is set using the CL$_S$ method \cite{57} with a profile likelihood ratio as a one-sided test statistic \cite{58}. The likelihoods are computed with the nuisance parameters Gaussian-constrained to their fit values. The test statistic is then evaluated on an ensemble of pseudoexperiments where the nuisance parameters are floated according to their uncertainties. The resulting upper limit on $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ is $2.6 \times 10^{-10}$ at 95% CL, obtained without constraining the $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ yield. Similarly, the upper limit on $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ with $m_{\mu\mu} > 4.9 \text{ GeV}/c^2$ is evaluated to be $2.0 \times 10^{-9}$ at 95% CL. Fixing the $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ signal to zero, the $B_s^0 \rightarrow \mu^+ \mu^-$ branching fraction increases by about 2% and the upper limit on $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ decreases by about 10%.

5
Figure 1: Mass distribution of the selected $B^0_{(s)} \to \mu^+ \mu^-$ candidates (black dots) with $\text{BDT} > 0.5$. The result of the fit is overlaid and the different components are detailed: $B^0_{s} \to \mu^+ \mu^-$ (red solid line), $B^0 \to \mu^+ \mu^-$ (green solid line), $B^0_{s} \to \mu^+ \mu^- \gamma$ (violet solid line), combinatorial background (blue dashed line), $B^0_{(s)} \to h^+ h^-$ (magenta dashed line), $B^0 \to \pi^- \mu^+ \nu_\mu$, $B^0_s \to K^- \mu^+ \nu_\mu$, $B^+_c \to J/\psi \mu^+ \nu_\mu$ and $A^0_{b^0} \to p \mu^- \nu_\mu$ (orange dashed line), and $B^{0(+)} \to \pi^{0(+)} \mu^+ \mu^-$ (cyan dashed line). The solid bands around the signal shapes represent the variation of the branching fractions by their total uncertainty.

The selection efficiency of $B^0_{s} \to \mu^+ \mu^-$ decays depends on the lifetime, introducing a model dependence in the measured time-integrated branching fraction. In the fit the SM value for $\tau_{\mu^+ \mu^-}$, $1.620 \pm 0.007 \text{ps}$ [44], is assumed, corresponding to $A_{\Delta s}^{\mu \mu} = 1$. The model dependence is evaluated by repeating the fit under the assumptions $A_{\Delta s}^{\mu \mu} = 0$ and $-1$, finding an increase of the branching fraction with respect to the SM hypothesis of 4.7% and 10.9%, respectively. The dependence is approximately linear in the physically allowed $A_{\Delta s}^{\mu \mu}$ range. A similar dependence is present for the $B^0_{s} \to \mu^+ \mu^- \gamma$ decay with a negligible impact on the branching fraction limit.

The criteria used to select data for the $B^0_{s} \to \mu^+ \mu^-$ lifetime measurement differ slightly from those used in the branching fraction measurement. As shown in Fig. 1, the contribution from the misidentified background is negligible under the peak, and therefore a narrower dimuon mass range of $[5320, 6000] \text{MeV/c}^2$ is selected, while particle-identification requirements are relaxed slightly due to the lower expected contamination from the misidentified background in the $B^0_{s} \to \mu^+ \mu^-$ signal region, with a corresponding increase in signal efficiency. Finally, candidate $B^0_{s} \to \mu^+ \mu^-$ decays are required to fall into two trigger categories: the trigger requirements must be satisfied entirely either by the $B^0_{s} \to \mu^+ \mu^-$ candidates themselves, or by objects from the $pp$ collision that do not
Figure 2: Two-dimensional profile likelihood of the branching fractions for the decays (top) $B^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$, (bottom left) $B^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-\gamma$ and (bottom right) $B^0_s \rightarrow \mu^+\mu^-$ and $B^0_s \rightarrow \mu^+\mu^-\gamma$. The $B^0_s \rightarrow \mu^+\mu^-\gamma$ branching fraction is limited to the range $m_{\mu\mu} > 4.9\text{ GeV}/c^2$. The measured central values of the branching fractions are indicated with a blue dot. The profile likelihood contours for 68%, 95% and 99% CL regions of the result are shown as blue contours, while in the top plot the brown contours indicate the previous measurement [10] and the red cross shows the SM prediction.

form part of the $B^0_s \rightarrow \mu^+\mu^-$ candidate. These more restrictive trigger requirements are imposed in order to improve the modelling of the decay-time dependence of the trigger efficiency in simulation.

In order to determine the $B^0_s \rightarrow \mu^+\mu^-$ effective lifetime the data are divided into two
which are dominated by the uncertainty on the measured luminosity of 9 fb
by the LHCb experiment during Run 1 and Run 2, corresponding to a total integrated

The mass fits used in the background subtraction include \( B^0_s \rightarrow \mu^+\mu^- \) and combinatorial background components, where the signal is modelled with the same function as in the branching fraction analysis and the background with exponential functions, with freely-floating slope parameters in each BDT region. The correlation between the reconstructed mass and the reconstructed decay time of the selected candidates is consistent with zero in both data and simulation, as required by the sPlot technique.

A simultaneous fit is then performed to the two background-subtracted decay-time distributions, where each distribution is modelled by a single exponential multiplied by an acceptance function that models the decay time dependence of the reconstruction and selection efficiency. The acceptance functions are determined in each BDT region by fitting parametric functions to the efficiency distributions of simulated \( B^0_s \rightarrow \mu^+\mu^- \) decays that have been weighted in order to improve the agreement with the data. The correction for the acceptance is validated by measuring the lifetimes of \( B^0 \rightarrow K^+\pi^- \) and \( B^0_s \rightarrow K^+K^- \) decays in data. The resulting values are 1.510 ± 0.015 ps and 1.435 ± 0.026 ps, respectively, where uncertainties are statistical only. These are consistent with the world averages [44]. The statistical uncertainty on the measured \( B^0_s \rightarrow K^+K^- \) lifetime is taken as the systematic uncertainty associated with the use of simulated events to determine the \( B^0_s \rightarrow \mu^+\mu^- \) acceptance function.

A number of sources of systematic bias are evaluated using a large number of simulated pseudoexperiments. The fit procedure is found to produce an unbiased estimate of the lifetime with uncertainties that provide the correct coverage. The effect of the contamination from \( B^0 \rightarrow \mu^+\mu^- \), \( B \rightarrow h^+h^- \) and semileptonic \( b \)-hadron decays in the mass fit is found to introduce a small effect of up to 0.012 ps. The effect of the acceptance on the relative admixture of light and heavy mass eigenstates in the decay-time distribution is found to be negligible. Likewise, the uncertainty in the decay-time distribution of the combinatorial background, the production asymmetry between \( B^0_s \) and \( B^0 \) mesons and the mismodelling of the acceptance function in simulation is found to have a small effect on the final result. Together, these sources result in a systematic uncertainty of 0.031 ps, which is dominated by the uncertainty on the measured \( B^0_s \rightarrow K^+K^- \) lifetime.

The mass distributions of the selected \( B^0_s \rightarrow \mu^+\mu^- \) candidates are shown in Fig. 3 (top) for the two BDT regions. Figure 3 (bottom) shows the corresponding background-subtracted \( B^0_s \rightarrow \mu^+\mu^- \) decay-time distribution with the fit function superimposed [55]. The effective lifetime is found to be 2.07 ± 0.29 ± 0.03 ps, where the first uncertainty is statistical and the second systematic. This value lies outside the range between the lifetimes of the light (\( A_{\Delta\Gamma} = -1 \)) and heavy (\( A_{\Delta\Gamma} = +1 \)) mass eigenstates, which are \( \tau_L = 1.423 \pm 0.005 \) ps and \( \tau_H = 1.620 \pm 0.007 \) ps [44], but is consistent with these values at 2.2 and 1.5 standard deviations, respectively.

In summary, a new measurement of the rare decay \( B^0_s \rightarrow \mu^+\mu^- \) and a search for \( B^0 \rightarrow \mu^+\mu^- \) and \( B^0_s \rightarrow \mu^+\mu^- \gamma \) decays has been performed using the full dataset collected by the LHCb experiment during Run 1 and Run 2, corresponding to a total integrated luminosity of 9 fb\(^{-1}\). The time-integrated branching fraction of \( B^0_s \rightarrow \mu^+\mu^- \) is measured to be \( (3.09^{+0.46}_{-0.43}^{+0.15}) \times 10^{-9} \). The \( B^0_s \rightarrow \mu^+\mu^- \) effective lifetime is 2.07 ± 0.29 ± 0.03 ps. No evidence for \( B^0 \rightarrow \mu^+\mu^- \) or \( B^0_s \rightarrow \mu^+\mu^- \gamma \) signals is found, and the upper limits \( \mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 2.6 \times 10^{-10} \) and \( \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-\gamma) < 2.0 \times 10^{-9} \) at 95% CL are set, where
Figure 3: Top: dimuon mass distributions with the fit models used to perform the background subtraction superimposed. Bottom: the background-subtracted decay-time distributions with the fit model used to determine the $B^0_s \rightarrow \mu^+ \mu^-$ effective lifetime superimposed. The distributions in the low and high BDT regions are shown in the left and right columns, respectively.

the latter is limited to the range $m_{\mu\mu} > 4.9$ GeV/c$^2$. The results are in agreement with the SM predictions and can be used to further constrain possible new physics contributions to these observables.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions
and ERC (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).
References

[1] C. Bobeth et al., B_{s,d} \rightarrow l^+l^- in the Standard Model with reduced theoretical uncertainty, Phys. Rev. Lett. 112 (2014) 101801, arXiv:1311.0903

[2] M. Beneke, C. Bobeth, and R. Szafron, Power-enhanced leading-logarithmic QED corrections to B_q \rightarrow \mu^+\mu^-, JHEP 10 (2019) 232, arXiv:1908.07011

[3] Flavour Lattice Averaging Group, S. Aoki et al., FLAG Review 2019, arXiv:1902.08191.

[4] Fermilab Lattice and MILC collaborations, A. Bazavov et al., B- and D-meson leptonic decay constants from four-flavor lattice QCD, Phys. Rev. D98 (2018) 074512, arXiv:1712.09262.

[5] ETM collaboration, A. Bussone et al., Mass of the b quark and B meson decay constants from N_f=2+1+1 twisted-mass lattice QCD, Phys. Rev. D93 (2016) 114505, arXiv:1603.04306.

[6] HPQCD collaboration, R. J. Dowdall et al., B-meson decay constants from improved lattice nonrelativistic QCD with physical u, d, s, and c quarks, Phys. Rev. Lett. 110 (2013) 222003, arXiv:1302.2644.

[7] C. Hughes, C. T. H. Davies, and C. J. Monahan, New methods for B meson decay constants and form factors from lattice NRQCD, Phys. Rev. D97 (2018) 054509, arXiv:1711.09981.

[8] W. Altmannshofer, C. Niehoff, and D. M. Straub, B_s \rightarrow \mu^+\mu^- as current and future probe of new physics, JHEP 05 (2017) 076, arXiv:1702.05498.

[9] CMS and LHCb collaborations, V. Khachatryan et al., Observation of the rare B_s^0 \rightarrow \mu^+\mu^- decay from the combined analysis of CMS and LHCb data, Nature 522 (2015) 68, arXiv:1411.4413.

[10] LHCb collaboration, R. Aaij et al., Measurement of the B_s^0 \rightarrow \mu^+\mu^- branching fraction and effective lifetime and search for B^0 \rightarrow \mu^+\mu^- decays, Phys. Rev. Lett. 118 (2017) 191801, arXiv:1703.05747.

[11] ATLAS collaboration, M. Aaboud et al., Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector, JHEP 04 (2019) 098, arXiv:1812.03017.

[12] CMS collaboration, A. M. Sirunyan et al., Measurement of properties of B_s^0 \rightarrow \mu^+\mu^- decays and search for B^0 \rightarrow \mu^+\mu^- with the CMS experiment, JHEP 04 (2020) 188, arXiv:1910.12127.

[13] ATLAS, CMS, LHCb collaborations, Combination of the ATLAS, CMS and LHCb results on the B_{s(0)}^0 \rightarrow \mu^+\mu^- decays, LHCb-CONF-2020-002, 2020, ATLAS-CONF-2020-049, CMS PAS BPH-20-003.

[14] D. Melikhov and N. Nikitin, Rare radiative leptonic decays B_{d,s} \rightarrow l^+l^-\gamma, Phys. Rev. D70 (2004) 114028, arXiv:hep-ph/0410146.

11
[15] A. Kozachuk, D. Melikhov, and N. Nikitin, Rare FCNC radiative leptonic $B_{s,d} \to \gamma l^+l^-$ decays in the standard model, Phys. Rev. D97 (2018) 053007, arXiv:1712.07926.

[16] F. Dettori, D. Guadagnoli, and M. Reboud, $B^0 \to \mu^+\mu^-\gamma$ from $B^0_s \to \mu^+\mu^-$, Phys. Lett. B768 (2017) 163, arXiv:1610.00629.

[17] G. Eilam, C.-D. Lu, and D.-X. Zhang, Radiative dileptonic decays of $B$ mesons, Phys. Lett. B391 (1997) 461, arXiv:hep-ph/9606444.

[18] T. M. Aliev, A. Ozpineci, and M. Savci, $B_q \to l^+l^-\gamma$ decays in light cone QCD, Phys. Rev. D55 (1997) 7059, arXiv:hep-ph/9611393.

[19] C. Q. Geng, C. C. Lih, and W.-M. Zhang, Study of $B_{s,d} \to l^+l^-\gamma$ decays, Phys. Rev. D62 (2000) 074017, arXiv:hep-ph/0007252.

[20] S. Dubnička et al., Study of $B_s \to \ell^+\ell^-\gamma$ decays in covariant quark model, Phys. Rev. D99 (2019) 014042, arXiv:1808.06261.

[21] M. Beneke, C. Bobeth, and Y.-M. Wang, $B_{d,s} \to \gamma\ell\bar{\ell}$ decay with an energetic photon, JHEP 12 (2020) 148, arXiv:2008.12494.

[22] D. Guadagnoli, M. Reboud, and R. Zwicky, $B_s^0 \to \ell^+\ell^-\gamma$ as a test of lepton flavor universality, JHEP 11 (2017) 184, arXiv:1708.02649.

[23] Heavy Flavor Averaging Group, Y. Amhis et al., Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of 2018, Eur. Phys. J. C81 (2021) 226, arXiv:1909.12524, updated results and plots available at https://hflav.web.cern.ch.

[24] K. De Bruyn et al., Branching ratio measurements of $B_s$ decays, Phys. Rev. D86 (2012) 014027, arXiv:1204.1735.

[25] K. De Bruyn et al., Probing New Physics via the $B_s^0 \to \mu^+\mu^-$ effective lifetime, Phys. Rev. Lett. 109 (2012) 041801, arXiv:1204.1737.

[26] LHCb collaboration, R. Aaij et al., Measurement of the $B_s^0 \to \mu^+\mu^-\gamma$ decays and search for the $B_s^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$ decays, arXiv:2108.09283, submitted to PRD.

[27] LHCb collaboration, A. A. Alves Jr. et al., The LHCb detector at the LHC, JINST 3 (2008) S08005.

[28] LHCb collaboration, R. Aaij et al., LHCb detector performance, Int. J. Mod. Phys. A30 (2015) 1530022, arXiv:1412.6352.

[29] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852, arXiv:0710.3820; T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, JHEP 05 (2006) 026, arXiv:hep-ph/0603175.

[30] I. Belyaev et al., Handling of the generation of primary events in Gauss, the LHCb simulation framework, J. Phys. Conf. Ser. 331 (2011) 032047.
[31] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Meth. A462 (2001) 152.

[32] Geant4 collaboration, J. Allison et al., Geant4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270; Geant4 collaboration, S. Agostinelli et al., Geant4: A simulation toolkit, Nucl. Instrum. Meth. A506 (2003) 250.

[33] M. Clemencic et al., The LHCb simulation application, Gauss: Design, evolution and experience, J. Phys. Conf. Ser. 331 (2011) 032023.

[34] N. Davidson, T. Przedzinski, and Z. Was, PHOTOS interface in C++: Technical and physics documentation, Comp. Phys. Comm. 199 (2016) 86, arXiv:1011.0937.

[35] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, Classification and regression trees, Wadsworth international group, Belmont, California, USA, 1984.

[36] Y. Freund and R. E. Schapire, A decision-theoretic generalization of on-line learning and an application to boosting, J. Comput. Syst. Sci. 55 (1997) 119.

[37] R. Aaij et al., The LHCb trigger and its performance in 2011, JINST 8 (2013) P04022, arXiv:1211.3055.

[38] F. Archilli et al., Performance of the muon identification at LHCb, JINST 8 (2013) P10020, arXiv:1306.0249.

[39] V. V. Anashin et al., Final analysis of KEDR data on J/ψ and ψ(2S) masses, Phys. Lett. B749 (2015) 50.

[40] LHCb collaboration, R. Aaij et al., Strong constraints on the rare decays B_s^0 → μ^+μ^- and B^0 → μ^+μ^-, Phys. Rev. Lett. 108 (2012) 231801, arXiv:1203.4493.

[41] A. Rogozhnikov, Reweighting with Boosted Decision Trees, J. Phys. Conf. Ser. 762 (2016) 012036, arXiv:1608.05806, https://github.com/arogozhnikov/hep_ml.

[42] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.

[43] P. Golonka and Z. Was, PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays, Eur. Phys. J. C45 (2006) 97, arXiv:hep-ph/0506026.

[44] Particle Data Group, P. A. Zyla et al., Review of particle physics, Prog. Theor. Exp. Phys. 2020 (2020) 083C01.

[45] LHCb collaboration, R. Aaij et al., Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B_s^0 decay branching fractions, Phys. Rev. D104 (2021) 032005, arXiv:2103.06810.

[46] LHCb collaboration, R. Aaij et al., Measurement of the track reconstruction efficiency at LHCb, JINST 10 (2015) P02007, arXiv:1408.1251.

[47] L. Anderlini et al., The PIDCalib package, LHCb-PUB-2016-021 (2016).
S. Tolk, J. Albrecht, F. Dettori, and A. Pellegrino, Data driven trigger efficiency determination at LHCb, LHCb-PUB-2014-039 (2014).

LHCb collaboration, R. Aaij et al., First observation of the decay $B^0_s \rightarrow K^- \mu^+ \nu_\mu$ and measurement of $|V_{ub}|/|V_{cb}|$, Phys. Rev. Lett. 126 (2021) 081804, arXiv:2012.05143

LHCb collaboration, R. Aaij et al., Determination of the quark coupling strength $|V_{ub}|$ using baryonic decays, Nature Physics 11 (2015) 743, arXiv:1504.01568

LHCb collaboration, R. Aaij et al., Measurement of $B^+_c$ production in proton-proton collisions at $\sqrt{s}=8$ TeV, Phys. Rev. Lett. 114 (2015) 132001, arXiv:1411.2943

LHCb collaboration, R. Aaij et al., Measurement of the ratio of $B^+_c$ branching fractions to $J/\psi \pi^+$ and $J/\psi \mu^+\nu_\mu$, Phys. Rev. D90 (2014) 032009, arXiv:1407.2126

LHCb collaboration, R. Aaij et al., First measurement of the differential branching fraction and CP asymmetry of the $B^+ \rightarrow \pi^+ \mu^+\mu^-$ decay, JHEP 10 (2015) 034, arXiv:1509.00414

W.-F. Wang and Z.-J. Xiao, The semileptonic decays $B/B_s \rightarrow (\pi, K)(\ell^+\ell^-, \ell\nu, \nu\bar{\nu})$ in the perturbative QCD approach beyond the leading-order, Phys. Rev. D86 (2012) 114025, arXiv:1207.0265

W. Verkerke and D. Kirkby, The RooFit toolkit for data modeling, arXiv:physics/0306116

S. S. Wilks, The large-sample distribution of the likelihood ratio for testing composite hypotheses, Ann. Math. Stat. 9 (1938) 60

A. L. Read, Presentation of search results: The CLS technique, J. Phys. G28 (2002) 2693

LHCb collaboration, R. Aaij et al., Measurement of the CKM angle $\gamma$ from a combination of LHCb results, JHEP 12 (2016) 087, arXiv:1611.03076

M. Pivk and F. R. Le Diberder, sPlot: A statistical tool to unfold data distributions, Nucl. Instrum. Meth. A555 (2005) 356, arXiv:physics/0402083.
LHCb collaboration

R. Aaij, C. Abellán Beteta, T. Ackernley, B. Adeva, M. Adinolfi, A. Afsharnia, C.A. Aidala, S. Aiola, Z. Ajaltouni, S. Akai, J. Albrecht, F. Alessio, M. Alexander, A. Alfonso Albero, Z. Aliouche, G. Alkhazov, P. Alvarez Cartelle, S. Amato, Y. Amhis, L. An, A. Anderlini, A. Andreianov, M. Andreotti, F. Archilli, A. Artamonov, M. Artuso, K. Arzyamov, E. Aslanides, M. Atzeni, B. Audurier, S. Bannich, M. Bachmayer, J.J. Back, P. Baladrón Rodríguez, V. Balagura, W. Baldini, J. Baptista Leite, R.J. Barlow, S. Barsuk, W. Barter, M. Bartolini, F. Baryshnikov, J.M. Basels, G. Bassi, B. Batsukh, A. Battig, A. Bay, M. Becker, F. Bedeschi, I. Bediaga, A. Beiter, V. Belavin, S. Belin, V. Bellec, K. Belous, I. Belov, I. Belyaev, G. Benvenuti, E. Ben-Haim, A. Berezin, R. Bernert, D. Berninghoff, H.C. Bernstein, C. Bertella, A. Bertolín, C. Betancourt, F. Bettì, Ia. Bezshyiko, S. Bhasin, J. Bhom, L. Bian, M.S. Bieker, S. Bifani, P. Billoir, M. Birch, F.C.R. Bishop, A. Bitadze, A. Bizzeti, M. Björn, M.P. Blago, T. Blake, F. Blanc, S. Blusk, D. Bobulska, J.A. Boelhaeve, O. Boente Garcia, T. Boettcher, A. Boldyrev, A. Bondar, N. Bondar, S. Borgli, M. Borisyyak, M. Borsato, J.T. Borsuk, S.A. Boucheiba, J.V. Bowcock, A. Boyer, C. Bozzi, M.J. Bradley, S. Braun, A. Brea, G. Brodski, J. Brodzicka, A. Brossa Gonzalo, D. Brundu, A. Buonaura, C. Burr, A. Bursche, A. Butkevich, J.S. Butter, J. Buytaert, W. Byczynski, S. Cadeddu, H. Cai, R. Calabrese, L. Calefice, L. Calero Díaz, S. Cali, R. Calladine, M. Calvi, M. Calvo, E. Camriri, M. Campagnoli, A. Camboni, P. Campana, A.F. Campoverde Quezada, S. Capelli, L. Capriotti, A. Carboni, G. Carboni, R. Cardinale, A. Cardini, I. Carli, P. Carniti, L. Carus, K. Carvalho Akiba, A. Casais Vidal, G. Casse, M. Cattaneo, G. Cavallerio, S. Celani, J. Cerasoli, A.J. Chadwick, M.G. Chapman, M. Charles, P. Charpentier, G. Chatzikonstantinidis, C.A. Chavez Barajas, M. Chedeville, C. Chen, S. Chen, A. Chernov, V. Chobanova, S. Cholak, M. Chrzaszcz, A. Chubynski, V. Chulikov, P. Ciambrone, M.F. Cicala, X. Cid Vidal, G. Ciezarek, P.E.L. Clarke, M. Clemencie, H.V. Cliff, J. Cloizer, J.L. Cobbledick, V. Coco, J.A.B. Coelho, J. Cogan, E. Cognneras, L. Cojocariu, P. Collins, T. Colombo, L. Congedo, A. Contu, N. Cooke, G. Coombs, G. Corti, C.M. Costa Sobral, B. Couturier, D.C. Craik, J. Crkovský, M. Cruz Torres, R. Currie, C.L. Da Silva, S. Dadareva, E. Dall’Occo, J. Dalseno, C. D’Ambrosio, A. Danilina, P. d’Argent, A. Davis, O. De Aguiar Francisco, K. De Bruyn, S. De Capua, M. De Cian, J.M. De Miranda, L. De Paula, M. De Serio, D. De Simone, P. De Simone, F. De Vellis, J.A. De Vries, C.T. Dean, D. Decamp, L. Del Buono, B. Delaney, H.-P. Dembinski, A. Dender, V. Denysenko, D. Derlakhach, O. Deschamps, F. Desse, F. Dettori, B. Dev, A. Di Cicco, P. Di Nezza, S. Didenko, L. Dieste Maronas, H. Dijkstra, V. Dobushuk, A.M. Donohoe, F. Dordei, A.C. dos Reis, L. Douglas, A. Dovbnya, A.G. Downes, K. Drei曼en, M.W. Dudek, L. Dufour, V. Duk, P. Durante, J.M. Durham, D. Dutta, A. Dziruč, A. Dzyuba, S. Easo, U. Egede, V. Egorychev, S. Eidelman, S. Eisenhardt, E. Eknund, S. Ely, A. Enho, E. Eppe, S. Escher, J. Eschle, S. Esen, T. Evans, A. Falabella, J. Fan, Y. Fan, B. Fang, S. Farry, D. Fazzini, M. Fèo, A. Fernandez Prieto, A.D. Ferré, F. Ferrari, L. Ferreir, A. Ferrer, M. Ferreres, S. Ferreres, M. Ferrill, M. Ferro-Luzzi, S. Filippow, R.A. Fini, M. Fiorini, M. Firlej, K.M. Fischer, D.S. Fitzgerald, C. Fitzpatrick, T. Fiutowski, F. Fleuret, M. Fontana, F. Fontanelli, R. Forty, V. Franco Lima, M. Franco Sevilla, M. Frank, E. Franzoso, C. Frei, D.A. Friday, J. Fu, P. Furlong, W. Funk.
E. Gabriel, T. Gaintseva, A. Gallas Torreira, D. Galli, S. Gambetta, Y. Gan, M. Gandelman, P. Gandini, Y. Gao, M. Garani, L.M. Garcia Martin, P. Garcia Moreno, J. Garcia Pardiñas, B. Garcia Plana, F.A. Garcia Rosales, L. Garrido, C. Gaspar, R.E. Geertsena, D. Gerick, L.L. Gerken, E. Gersabeck, M. Gersabeck, T. Gershon, D. Gerstel, Ph. Ghez, V. Gibson, H.K. Giemza, M. Giovannetti, A. Gioventù, P. Gironella Gironell, L. Giubega, C. Giugliano, K. Gizdov, E.L. Gkougkousis, V.V. Gilgorov, C. Göbel, E. Golobardes, D. Golubov, A. Golutvin, A. Gomes, S. Gomez Fernandez, F. Goncalves Abrantes, M. Goncerz, G. Gong, P. Gorbounov, I.V. Gorelov, C. Gotti, E. Govorkova, J.P. Grabowski, T. Grammatico, L.A. Granado Cardoso, E. Grangès, E. Graverini, G. Graziani, A. Greco, L.M. Greeven, L. Griffith, L. Grillo, S. Gromov, B.R. Gruberg Cazon, C. Gu, M. Guarise, P. A. Günther, E. Guschchin, A. Guth, Y. Guz, T. Gyś, T. Hadavidze, G. Haefeli, C. Haen, J. Haimberger, T. Halewood-leagas, P.M. Hamilton, J.P. Hammerich, Q. Han, X. Han, T.H. Hancock, S. Hansmann-Menzen, N. Harnew, T. Harrison, C. Hasse, M. Hatch, J. He, M. Hecker, K. Heijhoff, K. Heinicke, A.M. Hennequin, K. Hennessy, L. Henri, J. Heuë1, A. Hicheur, M. Heuberger, M. Hilton, S.E. Hollitt, J. Hu, J. Hu, W. Hu, X. Hu, W. Huang, X. Huang, W. Hulsbergen, R.J. Hunter, M. Hushchyn, D. Hutchcroft, D. Hynds, P. Ibì, M. Idzik, D. Illi, P. Ilten, A. Inglessi, A. Ishteev, K. Ivshin, R. Jacobsson, S. Jakobsen, E. Janse, B.K. Jashai, A. Jawahery, V. Jevtic, F. Jiang, M. John, D. Johnson, C.R. Jones, T.P. Jones, B. Jost, N. Jurik, S. Kandybei, Y. Kang, M. Karaasch, M. Karpov, F. Keizer, M. Kenzie, T. Ketel, B. Khani, A. Kharisova, S. Klotokendek, T. Kirn, V.S. Kirsebom, K. Klimaszewski, S. Koliiev, A. Konoplyannikov, R. Kopeciewicz, R. Kopecina, P. Koppenburg, M. Korolev, I. Kostiuk, O. Kot, S. Kotriakhova, P. Kravchenko, L. Kravchuk, R.D. Krawczyk, M. Kreps, F. Kress, S. Kretzschmar, P. Krokovny, W. Krupa, W. Kremien, W. Kucewicz, M. Kucharczyk, V. Kudryavtsev, H.S. Kuindersma, G.J. Kunde, T. Kvaratskheliya, D. Lacarrere, G. Laffert, A. Lai, A. Lampis, D. Lancieri, J.J. Lane, R. Lane, G. Lanfranchi, C. Langenbruch, J. Langer, O. Lantwin, T. Latham, F. Lazzari, R. Le Gac, S.E. Hollitt, S. Lehe, R. Lefèvre, A. Leflat, S. Legotin, O. Leroy, T. Lesiak, B. Leverington, H. Li, L. Li, P. Li, S. Li, Y. Li, Z. Li, X. Liang, T. Liu, R. Lindner, V. Lisovskyi, R. Litvinov, G. Liu, H. Liu, A. Loi, J. Lomba Castro, I. Longstaff, J.H. Lopes, G.H. Lovel, Y. Lu, D. Lucchesi, S. Luchuk, M. Lucio Martinez, V. Lukashenko, Y. Luo, A. Lupato, E. Luppi, O. Lupton, A. Lusiani, L. Lyu, L. Ma, R. Ma, S. Maccolini, F. Machefit, F. Maciuc, V. Macko, P. Mackowiak, S. Maddrell-Mander, O. Madejczyk, L.R. Madhan, M. Mahajan, O. Maevski, M. Maisuzenko, M.W. Majewski, J.J. Mackiewski, S. Malde, B. Malecki, A. Malini, T. Maltevs, H. Malygina, G. Manca, G. Mancinelli, D. Manuzi, D. Marangotto, J. Maratass, J.F. Marchand, U. Marconi, S. Mariani, C. Marin Benito, M. Marinangeli, J. Marks, A.M. Marshall, P.J. Marshall, G. Martellotti, L. Martinazzoli, M. Martinelli, D. Martinez Santos, F. Martinez Vidal, A. Massaffer, M. Materok, R. Matev, A. Mathad, Z. Mathe, V. Matiuni, C. Matteucci, K.R. Mattiol, A. Mauri, E. Maurice, J. Mauricio, M. Mazurek, M. McCann, T.H. McGregor, A. McNab, R. McNulty, J.V. Mead, B. Meadows, G. Meier, N. Meinert, D. Melnychuk, S. Meloni, M. Merk, A. Merli, L. Meyer Garcia, M. Mikhailsen, D.A. Milanés, E. Millar, M. Milovanovic, M.-N. Minard, A. Minotti, L. Minzoni, S.E. Mitchell, B. Mitreska, D.S. Mitzel, A. Mödden, R.A. Mohammed, R.D. Moise, T. Mombacher, I.A. Monroy, S. Montei, M. Morandin, G. Morello, M.J. Morello.
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia
Yandex School of Data Analysis, Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia, Protvino, Russia
ICCCUB, Universitat de Barcelona, Barcelona, Spain
Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Physik-Institut, Universität Zürich, Zürich, Switzerland
NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
University of Birmingham, Birmingham, United Kingdom
H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Warwick, Coventry, United Kingdom
STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Imperial College London, London, United Kingdom
Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, MA, United States
University of Cincinnati, Cincinnati, OH, United States
University of Maryland, College Park, MD, United States
Los Alamos National Laboratory (LANL), Los Alamos, United States
Syracuse University, Syracuse, NY, United States
School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to
Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to
Physics and MicroElectronic College, Hunan University, Changsha City, China, associated to
Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to
School of Physics and Technology, Wuhan University, Wuhan, China, associated to
Departamento de Fisica , Universidad Nacional de Colombia, Bogotá, Colombia, associated to
Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to
Institut für Physik, Universität Rostock, Rostock, Germany, associated to
Eötvös Loránd University, Budapest, Hungary, associated to
INFN Sezione di Perugia, Perugia, Italy, associated to
Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to
Universiteit Maastricht, Maastricht, Netherlands, associated to
National Research Centre Kurchatov Institute, Moscow, Russia, associated to
National Research University Higher School of Economics, Moscow, Russia, associated to
National University of Science and Technology “MISIS”, Moscow, Russia, associated to
National Research Tomsk Polytechnic University, Tomsk, Russia, associated to
DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain, associated to
University of Michigan, Ann Arbor, United States, associated to
Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China
Università di Bari, Bari, Italy
Università di Bologna, Bologna, Italy

Università di Cagliari, Cagliari, Italy

Università di Ferrara, Ferrara, Italy

Università di Firenze, Firenze, Italy

Università di Genova, Genova, Italy

Università degli Studi di Milano, Milano, Italy

Università di Milano Bicocca, Milano, Italy

Università di Modena e Reggio Emilia, Modena, Italy

Università di Padova, Padova, Italy

Scuola Normale Superiore, Pisa, Italy

Università di Pisa, Pisa, Italy

Università della Basilicata, Potenza, Italy

Università di Roma Tor Vergata, Roma, Italy

Università di Siena, Siena, Italy

Università di Urbino, Urbino, Italy

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

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

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

Novosibirsk State University, Novosibirsk, Russia

Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden

Hanoi University of Science, Hanoi, Vietnam