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CMS measurements of rare B meson decays to two muons

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We report a measurement of the $\mathrm{B_s^0} \to \mu^+\mu^-$ branching fraction and its effective lifetime, as well as results of a search for the $\mathrm{B^0} \to \mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC. The analysis is based on data collected with the CMS detector in 2016-2018 corresponding to an integrated luminosity of 140 $\mathrm{fb^{-1}}$. The measured branching fraction of the $\mathrm{B_s^0} \to \mu^+\mu^-$ decay and the effective $\mathrm{B_s^0}$ lifetime are the most precise measurements to date. No evidence for the $\mathrm{B^0} \to \mu^+\mu^-$ decay has been found. All results are found to be consistent with the standard model predictions.

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1. Introduction

Rare B meson decays provide a sensitive probe for beyond-the-standard-model (BSM) effects and allow exploring energy scales much higher than the ones directly accessible at the LHC to be explored. A key factor in the success of these studies is the availability of precise theoretical predictions for experimentally accessible processes. The $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays represent such a case, where theoretically clean predictions are matched with a clear experimental signature. These rare decays are examples of flavor changing neutral current processes, which are strongly suppressed in the standard model (SM), making them sensitive to BSM physics contributions. In the SM, the average time-integrated branching fractions for these decays are very small [1]:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}.$$

The most precise measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction is achieved in a combined analysis of data of the three LHC experiments (ATLAS, CMS and LHCb) [2]. It shows a deviation from the SM prediction at the level of 2.1σ. A few other recent measurements of $b \to s\ell^+\ell^-$ processes have reported disagreements at the level of 2–3 standard deviations from the SM predictions. The global fits of rare B decay data show a strong preference of the BSM physics scenario over the SM by more than 4 standard deviations [3].

The effective lifetime of the B_s^0 meson measured in the $B_s^0 \to \mu^+\mu^-$ decay is an independent theoretically clean probe for BSM physics [4]. In the SM, only the heavy $B_{s,H}^0$ mass eigenstate can decay to the $\mu^+\mu^-$ final state. Any significant deviation of the measured lifetime from the SM prediction would indicate a BSM physics contribution. Currently, the most precise measurement of the B_s^0 meson lifetime in $B_s^0 \to \mu^+\mu^-$ decays of $\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29$ ps comes from the LHCb experiment [5].

We report a summary of a new measurement [6] of the $B_s^0 \to \mu^+\mu^-$ decay and a search for the $B^0 \to \mu^+\mu^-$ decay based on the proton-proton (pp) collision data at a center-of-mass energy of 13 TeV collected by the CMS experiment in 2016–2018, and corresponding to an integrated luminosity of 140 fb^{-1}.

2. Data analysis

The B meson decays are reconstructed by combining two oppositely charged muons with $p_T > 4$ GeV and $|\eta| < 1.4$. Probability of a common vertex fit is required to be greater than 0.025 and the vertex is required to be displaced from the primary vertex with the statistical significance greater than 6. The dominant background sources are the combinatorial background where the two muons originate from two different heavy quarks, the partially reconstructed semileptonic decays where both muons originate from the same B meson, and the peaking background coming from the charmless two-body hadronic decays of B mesons.

The combinatorial and partially reconstructed backgrounds are the main limiting factors in the analysis sensitivity. Despite being reducible backgrounds with several distinct features, they are copious, which makes it difficult to reject them completely without losing a significant fraction of signal events. To maximize the analysis sensitivity, we perform a multivariate analysis (MVA) combining multiple discriminating observables in a single powerful discriminator using a boosted decision tree algorithm.

The charmless two-body decays, such as $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$, could mimic signal when both charged hadrons are misidentified as muons. We measure the misidentification probabilities in data using the $K_S^0 \to \pi^+\pi^-$, $\phi(1020) \to K^+K^-$, and $\Lambda \to p\pi^-$ decays after restricting the decay distance to match that of the B mesons. We find a reasonable agreement between the data and Monte Carlo (MC) simulation for pions and kaons, where the misidentification probability is dominated by pion and kaon decays to a muon and a muon antineutrino. The probability to misidentify protons as muons is an order of magnitude smaller making contributions from the associated processes unimportant. With a stringent muon identification based on a multivariate analysis [7], we reduce the charmless two-body backgrounds to a negligible level.

The results are extracted using simultaneous unbinned maximum likelihood fits in multiple categories. For the branching fraction measurements, we perform a two-dimensional fit using the dimuon invariant mass and its uncertainty as observables. For the lifetime extraction, we perform a three-dimensional fit using the dimuon mass, the decay time, and the decay time uncertainty as observables.

The branching fractions are calculated by normalizing them to the $B^+ \to J/\psi K^+$ decay with $J/\psi \to \mu^+\mu^-$. The advantage of this approach is that it allows for a cancellation of many systematic uncertainties in the selection and reconstruction efficiencies of the signal and normalization channels. The ratio of the production rate of B^+ and B^0 mesons (f_u/f_d) is expected to be 1 in the SM due to isospin symmetry. For B_s^0 and B^+ mesons the f_s/f_u ratio is derived from the p_T-dependent measurement of the f_s/f_u ratio by LHCb [8]. We are using the p_T distribution observed in this measurement, to compute an effective f_s/f_u ratio for the corresponding phase space and find $f_s/f_u = 0.231 \pm 0.008$.

To reduce unintentional bias, the analysis employs a “data blinding" technique. All optimization studies are performed using signal from MC simulation and background from data that does not include events with a dimuon mass of 5.15–5.50 GeV range. Once the selection criteria and measurement procedure have been finalized, the data were unblinded.

3. Systematic uncertainties

The branching fraction measurements have multiple sources of systematic uncertainties. They are dominated by the uncertainty in the $B \to \mu^+\mu^-$ signal efficiency corrections due to mismodeling of MVA output in MC simulation (2-3%), the kaon reconstruction and selection efficiency for the $B^+ \to J/\psi K^+$ normalization measurements (2%), and the trigger efficiency difference between the signal and normalization channels (2-4%). The uncertainties in the branching fraction of the $B^+ \to J/\psi K^+$ decays, as well as in f_s/f_u, are considered to be external uncertainties, which are factorized out in the final results (3.5%).

The lifetime of B_s^0 meson has a significant impact on the signal efficiency for the $B_s^0 \to \mu^+\mu^-$ decays. The branching fraction measurements are reported assuming the SM value for the lifetime (1.61 ps). Since the lifetime affects the branching fraction measurements, we provide a correction

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for alternative lifetime hypotheses. The scale factor for the branching fraction is $1.577 - 0.358\tau$, where τ is the B_s^0 meson lifetime in ps.

The dominant source of systematic uncertainties in the lifetime measurement is associated with mismodeling of the correlation between the MVA output and the decay time (2-10%). This correlation stems from the most discriminating MVA variables, the pointing angle and its uncertainty, both of which are strongly correlated with the decay time. The correlation enters via the decay distance: the larger the decay distance is, the better one knows the direction from the primary interaction vertex to the $\mu^+\mu^-$ vertex. As the decay distance gets shorter, the uncertainty in the pointing angle increases, making such events harder to distinguish from the background. Mismodeling of these correlations in simulation can have a significant impact on the decay time distribution.

4. Results

Using the result of the $B^+ \to J/\psi K^+$ normalization fit, we find the branching fractions to be:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\,(\text{stat})\,^{+0.08}_{-0.09}\,(\text{syst})\right] \times 10^{-10}.$$

The effective lifetime for the $B_s^0 \to \mu^+\mu^-$ decay is found to be:

$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\,\text{ps}.$$

The mass and decay-time projections of the fits are shown in Fig. 1.

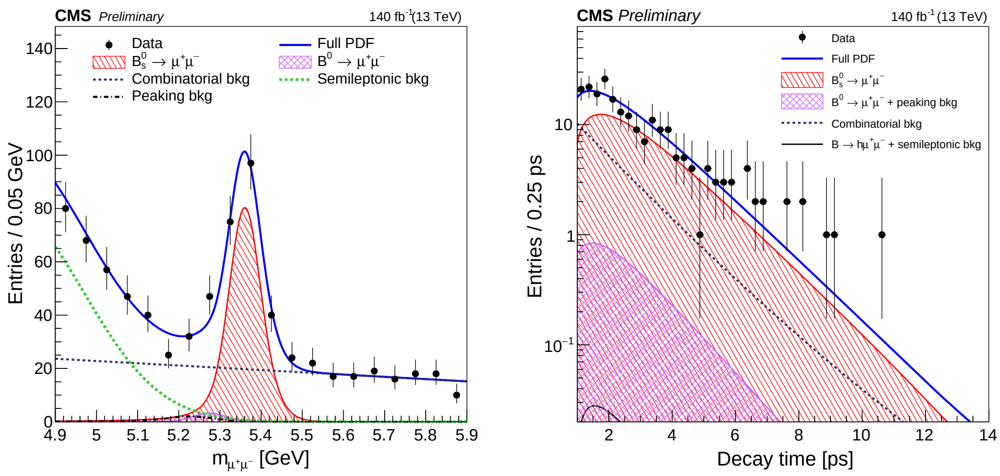

Figure 1: The dimuon mass projection of the branching fraction fit (left) and the decay time projection of the lifetime fit (right). The dimuon projection is made using a tight MVA selection and the decay time one with $5.28 < m_{\mu^+\mu^-} < 5.48$ GeV. The solid blue curves represent the corresponding projections of the final fit model, while the individual components of the fit are represented by the dashed curves (backgrounds) and hatched histograms (signals). Figures are from Ref [6].

The 95% confidence level (CL) upper limit on $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)$ is evaluated using the CL$_\mathrm{s}$ criterion [9, 10] and found to be:

$$\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL},$$

as shown in Fig. 2, which also shows the 2D contour plots of the two branching fraction measurements.

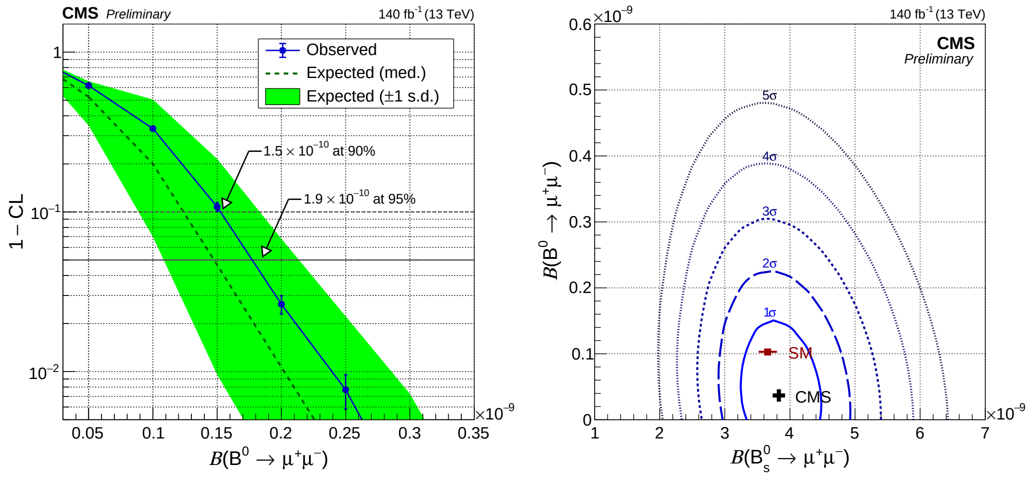

Figure 2: The upper limit on the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ branching fraction (left) and the 2D contour plot (right) of the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ branching fractions. The contours enclose the regions with 1–5 σ coverage, where 1, 2, and 3 σ regions correspond to 68.3%, 95.4%, and 99.7% confidence levels, respectively. Figures are from Ref [6].

5. Summary

New measurements of the branching fraction of the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ decay and the effective B^0_s meson lifetime in this decay are the most precise to date. The relative uncertainty is reduced from 23 to 11% compared with the previous CMS measurement [7]. The effective B^0_s meson lifetime measurement in the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ decay has achieved a level of uncertainty comparable with the lifetime difference between the heavy and light B^0_s meson mass eigenstates, thus offering sensitivity to potential beyond-the-SM physics effects in the effective lifetime.

Compared with the latest LHCb measurement of $\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}) \times 10^{-9}$ [5], our result $\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = (3.83^{+0.38}_{-0.36}{}^{+0.24}_{-0.21}) \times 10^{-9}$ is about 1.2 standard deviations higher, which will shift the world average from its current value of $\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$ [2] to a larger value, more consistent with the SM prediction, thus reducing the overall tension. The new measurement of the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ branching fraction is an important input to the global fits to the flavor data (e.g., Ref. [3]) in light of the reported $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$ anomalies.

The search for the $\mathrm{B}^0 \to \mu^+\mu^-$ decay has not revealed a significant event excess with respect to the dominant combinatorial background prediction. All results are consistent with the standard model predictions.

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