SEARCH FOR RARE MUONIC B DECAYS AT CMS*

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Received 28 March 2025, accepted 24 April 2025,
published online 26 June 2025

In this paper, we present the search for three highly-suppressed Standard Model processes at the CMS experiment: $B^0 \to \mu^+\mu^-$, $B_s^0 \to \mu^+\mu^-$, and $B_s^0 \to \mu^+\mu^-\gamma$. The latest and most precise results to date are presented for the first two decays, while the feasibility and experimental strategy for the third, yet unobserved at CMS, are discussed. The search for New Physics is the primary motivation for studying these flavour-changing neutral current decays.

DOI:10.5506/APhysPolBSupp.18.5-A15

1. Introduction

The B-physics sector provides an excellent testing ground for the Standard Model (SM) and searches for New Physics. B-meson oscillations offer an opportunity to study CP violation and the elements of the Cabbibo–Kobayashi–Maskawa (CKM) matrix. Moreover, in recent years, tensions between SM predictions and experimental results at the 2–3σ level have been reported in flavour-changing neutral currents (FCNCs) of the $b \to s\ l\ l$ type. Deviations have been observed in the branching fractions of such processes, one of the biggest ones reported in $B_s^0 \to \phi\mu\mu$ [1] and $B^0 \to K^*\mu\mu$ [2] studies, as well as in angular observables (for instance in $B^0 \to K^*\mu\mu$ channel [3]).

The Compact Muon Solenoid (CMS) detector [4] is well-suited for studying rare decays involving muons in the final state, due to its high muon detection efficiency. Combining last year's record-breaking integrated luminosity with data collected since the beginning of Run 3 in 2022, the total integrated luminosity for Run 3 now amounts to approximately 200 fb^{-1}. This substantial dataset raises the prospect of observing processes that have so far remained beyond the experimental reach.

* Presented at the 31st Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

The $B^0_{d,s} \to \mu^+\mu^-$ decays are promising candidates for searching for effects beyond the SM. These channels are highly suppressed, making potential New Physics contributions suggested by the mentioned tension with the SM within this sector easier to detect.

2. Characteristics of $B^0_{d,s}$ muonic decays

The leading-order diagrams for the $B^0_{d,s} \to \mu^+\mu^-$ decay are presented in Fig. 1, with the penguin diagram being the dominant contribution. Both processes are strongly suppressed due to three main factors. First, they proceed via FCNCs which are forbidden at leading order in the SM. Second, the decay channel is CKM suppressed due to the involvement of the t–d (B^0) or t–s (B^0_s) quark couplings, with the B^0 decay being significantly more suppressed. Finally, the process is helicity suppressed by a factor of $(\frac{m_\mu}{m_B})^2$, where m_μ and m_B denote the masses of the muon and the B meson, respectively. The SM predicion for the branching ratios are [5]

$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) = (3.66 \pm 0.14) \times 10^{-9}\,, \tag{1}$$

$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) = (1.03 \pm 0.05) \times 10^{-10}\,. \tag{2}$$

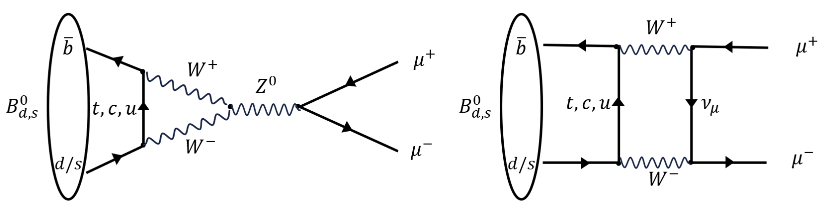

Fig. 1. Two leading Feynman diagrams of the $B^0_{d,s} \to \mu^+\mu^-$ decay — penguin (left) and box diagrams (right).

Despite its extreme rarity, these decay channels feature a clean di-muon signature, making them experimentally accessible.

An important feature of the $B^0_s \to \mu^+\mu^-$ decay is that, in the absence of CP violation, the lifetime measured in this channel should match that of the heavy-mass eigenstate of the parent B^0_s meson. This is because the heavy state ($B^0_{s,\mathrm{H}}$) is CP-odd, like the muon pair, while the light state ($B^0_{s,\mathrm{L}}$) is CP-even. As a result, the observed lifetime in this process should match the lifetime of the heavy state [6]

$$\tau_{B^0_{s,\mathrm{H}}} = (1.622 \pm 0.008)\ \mathrm{ps}\,, \qquad \tau_{B^0_{s,\mathrm{L}}} = (1.429 \pm 0.006)\ \mathrm{ps}\,. \tag{3}$$

Another decay channel of the B^0_s meson, $B^0_s \to \mu^+\mu^-\gamma$, also offers an opportunity to search for New Physics. It is the final- or initial-state radiation from the $B_s^0 \to \mu^+\mu^-$ process. Thanks to the photon emission, the decay is not helicity suppressed, unlike the non-radiative one. The branching ratios of the radiative and non-radiative processes are proportional to each other and of the same order of magnitude. The relationship is determined by the involvement of the photon and the absence of helicity suppression

$$\mathcal{B}\left(B_s^0 \to \mu\mu\gamma\right) \propto \mathcal{B}\left(B_s^0 \to \mu\mu\right)\left(\frac{m_\mu}{m_B}\right)^{-2} \alpha_{\mathrm{em}} \,. \tag{4}$$

The theoretically predicted (SM) branching fraction is [7]

$$\mathcal{B}\left(B_s^0 \to \mu\mu\gamma\right) \approx (6.01 \pm 0.08 \pm 0.70) \times 10^{-9} \,. \tag{5}$$

This channel remains unexplored, with only upper limits on the branching ratio reported so far by LHCb [8].

3. Latest results on $B^0 \to \mu\mu$ and $B_s^0 \to \mu\mu$ decays

The most recent and precise results for these channels come from [9]. The analysis was based on proton–proton collision data collected by the CMS detector at 13 TeV during 2016–2018, corresponding to an integrated luminosity of 140 fb^{-1}.

3.1. Background components

The background for these processes can be classified into three main categories. The first is a combinatorial background, which arises from the accidental pairing of two muons originating from the decays of different heavy quarks. The second category is a partially reconstructed background, stemming from semileptonic $B \to \mu^+\mu^- h$ decays, where a hadron h remains undetected, or $B \to h\mu\nu$, where a hadron is misidentified as a muon. The third, least significant category is a peaking background, which originates from charmless two-body decays $B \to hh$, where both hadrons are misidentified as muons. The first two were significantly reduced using multivariate analysis (MVA).

3.2. Results: branching fraction and effective lifetime

The plots in Fig. 2 show the resulting di-muon invariant mass and decay time distributions. A statistically significant signal was observed only for the $B_s^0 \to \mu^+\mu^-$ decay, since the analogous process for B^0 is more strongly CKM suppressed.

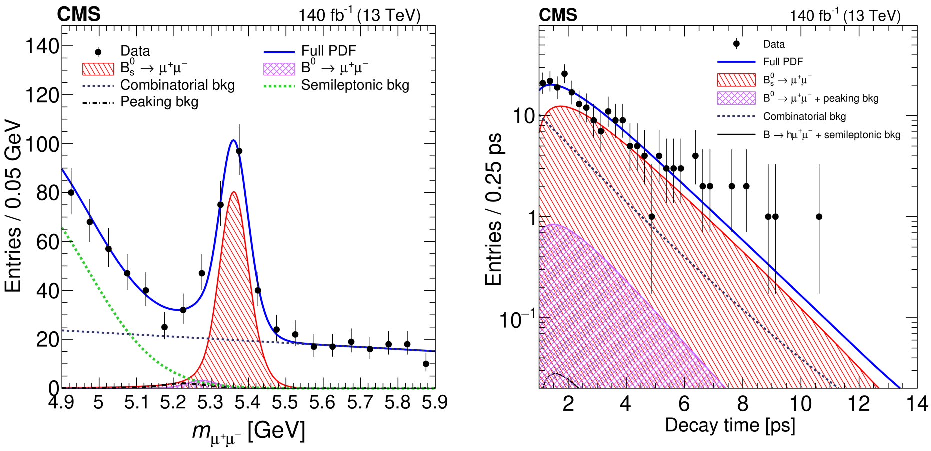

Fig. 2. Di-muon mass distribution (left) and decay time distribution (right) obtained by [9]. Figures include unbinned maximum likelihood (UML) fits (blue line), signal events denoted by histograms (red for B_s^0, purple for B^0), and three components of the background (dashed lines).

The $B^+ \to J/\psi K^+$ decay was used as the normalisation channel for both processes of interest. The formula for the branching fraction,

$$\mathcal{B}\left(B^0_{d,s} \to \mu^+\mu^-\right) = \mathcal{B}\left(B^+ \to J/\psi K^+\right) \frac{N_{B^0_{d,s}\to\mu^+\mu^-}}{\epsilon_{B^0_{d,s}\to\mu^+\mu^-}} \frac{\epsilon_{B^+\to J/\psi K^+}}{N_{B^+\to J/\psi K^+}} \frac{f_u}{f_{d,s}}, \tag{6}$$

includes the well-known branching fraction of the normalization channel and the ratio of fragmentation factors f_u/f_s, accounting for the different initial states of the signal and normalization channels. Both of these values were taken from external measurements [10, 11], while the efficiencies $\epsilon_{B^0_{d,s}\to\mu^+\mu^-}$, $\epsilon_{B^+\to J/\psi K^+}$ for both channels were derived from Monte Carlo simulations. Signal event counts were extracted from unbinned maximum likelihood fits (Fig. 2).

For the $B_s^0 \to \mu^+\mu^-$ channel, both the effective lifetime and branching ratio were successfully determined

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat.})^{+0.19}_{-0.16}\,(\text{syst.})^{+0.14}_{-0.13}\right] \times 10^{-9}, \tag{7}$$

$$\tau_{B_s^0\to\mu^+\mu^-} = 1.83^{+0.23}_{-0.20}\,(\text{stat.})^{+0.04}_{-0.04}\,(\text{syst.})\text{ ps}. \tag{8}$$

For the $B^0 \to \mu^+\mu^-$ channel, only an upper limit on the branching fraction could be set due to the low number of observed events

$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) < 1.9 \times 10^{-10} \quad (95\%\text{ C.L.}). \tag{9}$$

The effective lifetime of the B_s^0 meson aligns with the prediction for the heavy state (Eq. (3)), as expected. Moreover, both branching fractions are consistent with the SM (Eq. (2)) and are not in line with the tensions observed in this sector [1–3]. The comparison between the SM prediction and the discussed results is presented in Fig. 3.

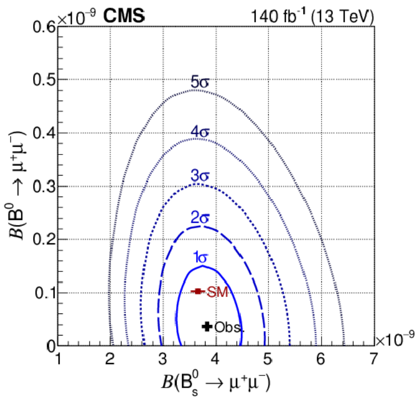

Fig. 3. The profile likelihood contours as a function of the branching fractions for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays [9]. The regions corresponding to 1σ–5σ coverage, with the 1σ, 2σ, and 3σ areas representing 68.3%, 95.4%, and 99.7% confidence levels, respectively.

4. Challenges and ideas for investigation of $B_s^0 \to \mu\mu\gamma$ channel

As an experimentally unexplored channel in a region marked by several tensions with the SM, this decay mode attracts interest in the search for physics beyond the SM. Within the framework of effective field theory, this process is sensitive to three Wilson coefficients [7, 12] (C_7, C_9, C_{10}), which are relevant to potential New Physics contributions.

4.1. Photon reconstruction

The experimental approach to studying the $B_s^0 \to \mu\mu\gamma$ channel would rely on a common vertex fit of the decay products, analogous to the non-radiative process. However, the main challenge lies in photon reconstruction, which is crucial for performing the fit. The photons in this decay are typically low-energy, while the CMS detector is optimized for measuring high-energy photons with transverse momentum above 10 GeV. As a result, in addition to the intrinsic suppression of the process, the available statistics are further reduced since only a small fraction of signal events fall within the reconstruction energy range.

This limitation could potentially be mitigated by reconstructing photon conversions using electromagnetic calorimeter data. Additionally, there is a potential for optimizing low-momentum photon reconstruction, possibly by developing a dedicated reconstruction approach.

The primary source of background is the $B_s^0 \to J/\psi(\mu\mu)\pi^0$ decay, where the neutral pion is misidentified as a photon. Suitable candidates for normalization and control channels are $B_s^0 \to J/\psi(\mu\mu)\eta(\gamma\gamma)$ and $B_s^0 \to \phi\gamma$, respectively. The latter could closely mimic the photon characteristics, making it a particularly suitable control channel for this analysis.

5. Conclusions

This paper presents the latest results on the search for rare muonic decays of B^0 and B_s^0 mesons at CMS, offering valuable insights into potential deviations from the Standard Model. The results obtained using Run 2 data are consistent with SM predictions, including both the measured branching fraction and effective lifetime for the $B_s^0 \to \mu^+\mu^-$ decay and stringent upper limits for the $B^0 \to \mu^+\mu^-$ channel. The $B_s^0 \to \mu^+\mu^-\gamma$ decay, while experimentally challenging, offers a potential avenue for discovering New Physics. The primary difficulty in studying this decay lies in photon reconstruction, as the photons involved are typically low-energy. However, proposed solutions to this issue and the large dataset accumulated at CMS raise the prospects for observing and further investigating this channel.

This contribution is partly supported by the Ministry of Science and Higher Education, Poland, grant No. 2022/WK/14.

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