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# Rare and forbidden decays

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Recent measurements of rare decays involving the b-flavor changing neutral current at the CMS and ATLAS experiments are presented. The full set of optimized CP-averaged observables is measured in the angular analysis of the decay $B^0 \to K^{*0}(892)\mu^+\mu^-$ using CMS Run 2 data. The results are among the most precise experimental measurements, and clear tensions are observed between the observed values and theoretical predictions in P2 and P5' observables. The ${B_s}^0 \to \mu^+\mu^-$ lifetime is also measured using partial ATLAS Run 2 data and is found to be consistent with the Standard Model prediction.

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## 1. Introduction

The measurement of the rare decays of hadrons is one of the most promising methods for probing new physics. The small contribution from the standard model (SM) makes it sensitive to the potential contribution from the new physics effects. Rare decays, which undergo a flavor-changing neutral current (FCNC), are forbidden at leading order and have a branching fraction typically under $10^{-6}$. At this level, new physics could enter at tree level. Anomalies in B rare decays involving $\mathrm{b} \to \mathrm{sll}$ have been observed in the previous measurements, making such searches extremely interesting. Two measurements of the B rare decays have recently been conducted, including the angular measurement of the decay $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ [1] by the CMS experiment [2] and the lifetime measurement of $\mathrm{B_s}^0 \to \mu^+\mu^-$ [3] by the ATLAS experiment [4].

## 2. Angular analysis of $\mathrm{B}^0 \to \mathrm{K}^{*0}(892)\mu^+\mu^-$

The CMS collaboration reported on the angular analysis of the decay $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ using Run-2 data collected by the CMS experiment. The measurements of the angular observables of this decay were carried out by several experiments. The recent result from the LHCb Collaboration [5] has found some tension with the predictions based on the SM. However, these predictions could be affected by sizable and poorly understood uncertainties from long-range charm loop contributions [6].

The analysis is performed in bins of the invariant mass squared of the dimuon system, $q^2$, ranging from 1.1 to 16 $\mathrm{GeV}^2$. The decay $\mathrm{B}^0 \to \mathrm{K}^{*0}(\mathrm{K}^+\pi^-)\mu^+\mu^-$ is characterized by three decay angles, $\theta_l$, $\theta_\mathrm{K}$, and $\phi$. The angle $\theta_l$ is defined as the angle between the direction of the $\mu^+$ and the direction opposite that of the $\mathrm{B}^0$ in the dimuon rest frame; the angle $\theta_K$ is defined as the angle between the direction of the kaon and the direction opposite that of the $\mathrm{B}^0$ in the $\mathrm{K}^{*0}$ rest frame; the angle $\phi$ is the angle between the plane containing the $\mu^+$ and $\mu^-$ and the plane containing the kaon and the pion from the $\mathrm{K}^{*0}$ decay in the $\mathrm{B}^0$ rest frame.

The angular distribution is described using CP-averaged observables, $F_L$, and the set $S_i$, and optimized observables [7] to reduce hadronic form-factor uncertainties. Using the optimized observables $P_{1,2,3}$ and $P'_{4,5,6,8}$, the $CP$-averaged angular distribution of the $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ decay can be described as

$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{dcos}\theta_l\mathrm{dcos}\theta_\mathrm{K}\mathrm{d}\phi} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_L)\sin^2\theta_\mathrm{K} + F_L\cos^2\theta_\mathrm{K} \\
&+ (\frac{1}{4}(1-F_L)\sin^2\theta_\mathrm{K} - F_L\cos^2\theta_\mathrm{K})\cos 2\theta_l \\
&+ \frac{1}{2}P_1(1-F_L)\sin^2\theta_\mathrm{K}\sin^2\theta_l\cos 2\phi \\
&+ \sqrt{(1-F_L)F_L}(\frac{1}{2}P'_4\sin 2\theta_\mathrm{K}\sin 2\theta_l\cos\phi + P'_5\sin 2\theta_\mathrm{K}\sin\theta_l\cos\phi) \\
&- \sqrt{(1-F_L)F_L}(P'_6\sin 2\theta_\mathrm{K}\sin\theta_l\sin\phi - \frac{1}{2}P'_8\sin 2\theta_\mathrm{K}\sin 2\theta_l\sin\phi) \\
&+2P_2(1-F_L)\sin^2\theta_\mathrm{K}\cos\theta_l - P_3(1-F_L)\sin^2\theta_\mathrm{K}\sin^2\theta_l\sin 2\phi)\Big],
\end{aligned}
\tag{1}
$$

where $F_L$ is the fraction of longitudinal polarization of the $\mathrm{K}^{*0}$ meson. The $\mathrm{K}^+\pi^-$ system can also be in an S-wave configuration and is included in the signal component.

Candidates for $B^0 \to K^{*0}\mu^+\mu^-$ decays are reconstructed with two oppositely charged muons and two oppositely charged tracks from the $K^{*0} \to K\pi$ process. The four components of the $B^0$ candidate are constrained to the same vertex. A multivariate analysis is used to optimize background rejection, utilizing information on decay-vertex quality and displacement, isolation of the candidate, and the invariant mass of the $K\pi$ system. Additional vetoes on the mass are applied to reduce contamination from other B meson decays, such as processes $B^+ \to K^+\mu^+\mu^-$ and ${B_s}^0 \to \mu^+\mu^-\phi$.

The analysis uses a four-dimensional (4D) probability density function (PDF) to model the decay using distributions of the invariant mass of the $B^0$ candidate, $m$, and the three angular variables, $\cos\theta_K$, $\cos\theta_l$, and $\phi$. The signal modeling is determined from the MC simulation and further corrected using $J/\psi$ and $\psi'$ control samples. The background modeling is extracted using the data sidebands. Systematic uncertainties are evaluated to account for potential biases introduced by the analysis procedure, mismodeling between simulation and data, and unaccounted background sources. In each $q^2$ bin, a 4D unbinned maximum likelihood fit is performed. The fit procedure and results are validated through fits to pseudoexperiments, MC simulation samples, and $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi' K^{*0}$ control channels.

The projections of the fitted pdf on the mass and angular distributions are shown in Fig. 1 for the $4.3 < q^2 < 6$ GeV $^2$ bin. The pdf projections are in agreement with the data.

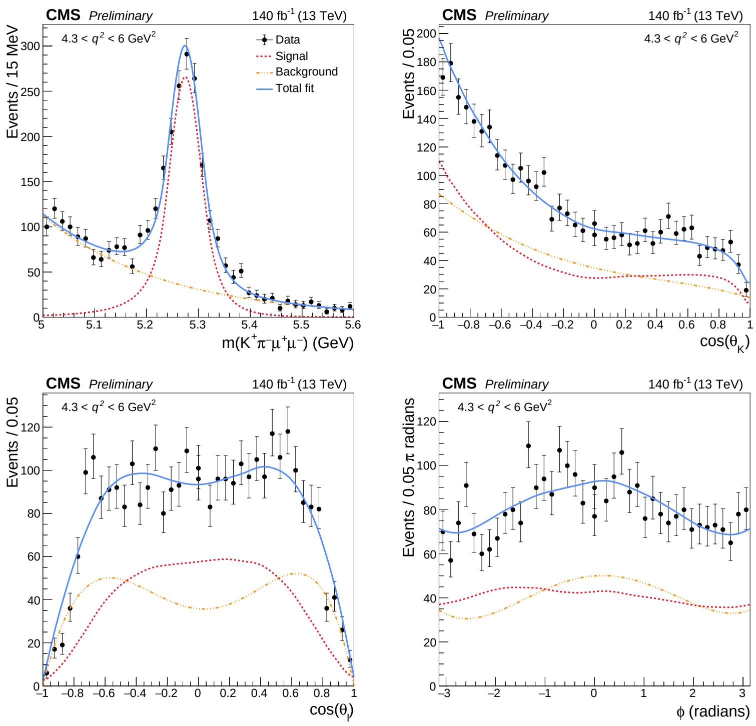


**Figure 1:** Mass and angular distributions for $4.3 < q^2 < 6$ GeV $^2$. The projections of the total fitted distribution (in blue) and its different components are overlaid. igures are from Ref [2].

Fig. 2 provides the measured values of the $CP$-averaged observables $P_2$ and $P_5'$ in bins of $q^2$ along with the corresponding uncertainties in comparison to different predictions based on the SM.

The results are among the most precise experimental measurements of the angular observables of this decay. The results for most parameters are compatible with the predictions based on the SM. However, in the region of $q^2$ below the $J/\psi$ resonance, they show clear tensions with the measured values of $P_5'$ and $P_2$. There is no firm conclusion about the source of those tensions, as they can be the indication of the new physics effect, or of large hadronic uncertainties not accounted for in some SM predictions.

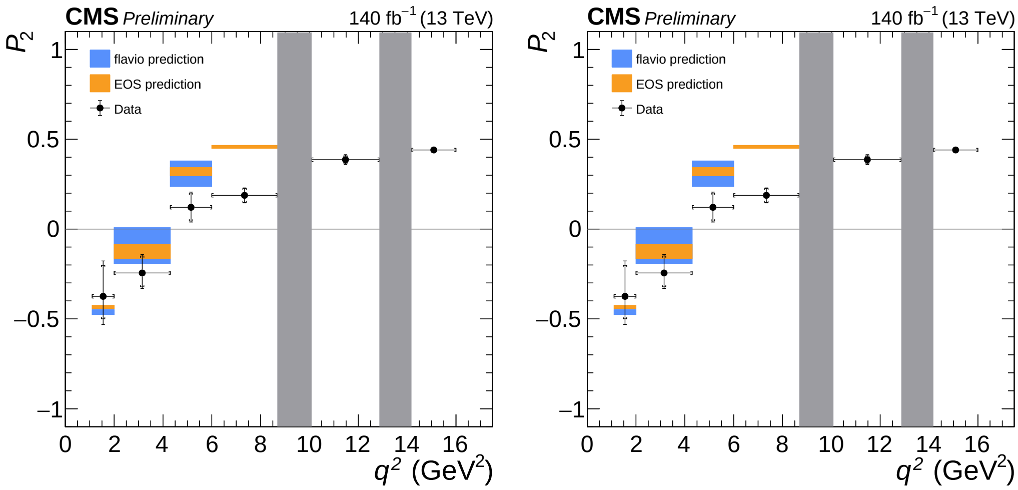


**Figure 2:** Measurements of the angular parameters versus $q^2$. The inner vertical bars represent the statistical uncertainties, while the outer vertical bars give the total uncertainties. The horizontal bars show the bin widths. The vertical shaded regions correspond to the $J/\psi$ and $\psi(2S)$ resonances. The data are compared to two sets of predictions averaged in each bin. Figures are from Ref [2].

## 3. Lifetime measurement of $B_s^0 \to \mu^+\mu^-$

The lifetime of the $B_s{}^0 \to \mu^+\mu^-$ process provides a different aspect to probe the new physics since only the CP-odd heavy mass eigenstate of $B_s{}^0$ meson decays into a dimuon final state and there is a 0.2 ps lifetime difference between light and heavy state. Different compositions of states may be allowed by new physics, which could lead to a deviation in the lifetime of the $B_s{}^0 \to \mu^+\mu^-$ process. Previously, measurements of $B_s{}^0 \to \mu^+\mu^-$ lifetime are performed at CMS [8, 9] and LHCb [10, 11]. ATLAS also reported on the effective lifetime measurement of the $B_s{}^0 \to \mu^+\mu^-$ decay [3], using proton-proton collection data at $\sqrt{s} = 13$ TeV collected during 2015–2016.

The dimuon final states are used to extract the signal candidates, while the $B^+ \to J/\psi K^+$ decay with $J/\psi \to \mu^+\mu^-$ is employed as the reference channel. B meson candidates are reconstructed based on a decay vertex fitted to two or three tracks for the signal and the reference channels, respectively. The mass distribution of the B meson candidates in the signal channel is shown in Fig. 3.

The proper decay time of the $B_s{}^0 \to \mu^+\mu^-$ is calculated based on the decay length and the reconstructed $B_s{}^0$ transverse momentum. The proper decay time distribution in data with background subtracted is derived using *sPlot* technique[12]. Subsequently, the measured lifetime

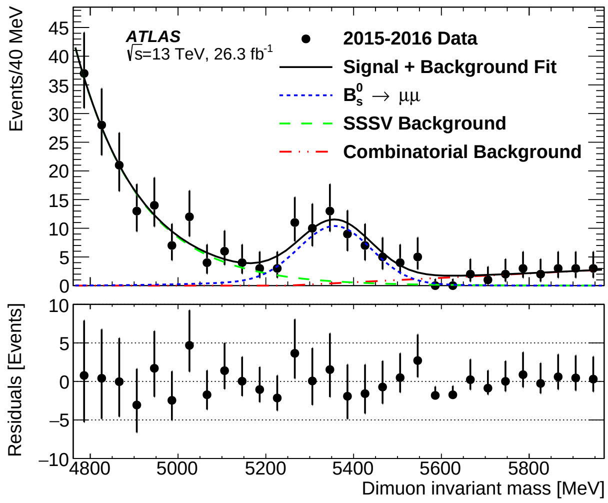


**Figure 3:** Invariant mass distribution of dimuon candidates in the 2015-2016 dataset. Figures are from Ref [3].

is obtained by minimizing the $\chi^2$ between the data and signal MC temples with different lifetimes, and the uncertainty is further derived from the Neyman CL band, as shown in Fig. 4.

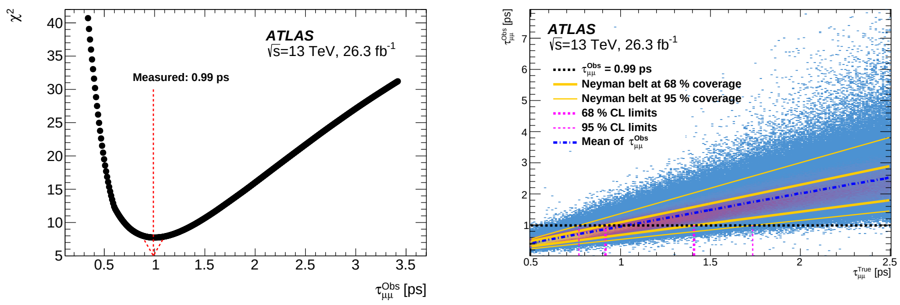


**Figure 4:** $\chi^2$ scan vs MC lifetime (left). 68% and 95% CL bands obtained with a Neyman construction (right). Figures are from Ref [3].

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

$$\tau = 0.99\,^{+0.42}_{-0.07}(\mathrm{stat}) \pm 0.17(\mathrm{syst})\mathrm{ps}.$$

The observed lifetime is consistent with the SM prediction $\tau^{SM} = (1.624 \pm 0.009)$ps and the world average value from the previous experimental measurements.

## 4. Conclusion

B rare decays are sensitive probes to new physics. Recent measurements of the B rare decays at CMS and ATLAS are reported. The angular analysis of the $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ decay was conducted at

CMS, providing some of the most precise experimental measurements of the angular observables. The effective lifetime of the $\mathrm{B_s}^0 \to \mu^+\mu^-$ decay was also measured at ATLAS, and the result is consistent with the standard model prediction.

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