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Review

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Review

Rare Decays in CMS †

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Abstract: The CMS experiment at the LHC has advanced precision measurements of rare B-meson and charm decays, offering insights into phenomena beyond the Standard Model (SM). This paper highlights key results from Run 2 and Run 3 data, including the branching fraction and lifetime of $B_s \to \mu^+\mu^-$, angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$, the first observation of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$, and stringent limits on $D^0 \to \mu^+\mu^-$. These findings provide tests of SM predictions while probing subtle hints of new physics.

Keywords: particle physics; B physics; rare processes

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1. Introduction

Rare decays of heavy-flavor hadrons provide a powerful framework for probing potential physics beyond the Standard Model (BSM). These decays, mediated by flavor-changing neutral currents (FCNCs), are forbidden at tree level in the SM and proceed only through higher-order loop diagrams. Such suppression renders these processes highly sensitive to new particles or interactions, even if these exist at mass scales inaccessible to direct searches. Consequently, rare decay studies have become an essential component of indirect BSM searches as direct collider experiments have so far yielded no conclusive evidence of new physics (NP).

In recent years, rare B-meson decays, especially those involving $b \to s\ell^+\ell^-$ transitions, have garnered particular attention due to their unique sensitivity to subtle deviations from SM predictions. CMS, despite being a general-purpose detector, has made significant efforts in studying these phenomena. Key measurements, such as differential branching fractions and angular observables, have enabled precise comparisons with SM expectations. Some anomalies at the level of 3σ to 4σ have been reported by the LHCb Collaboration in the differential branching fractions of decays like $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$, and $B^0_s \to \phi\mu^+\mu^-$ in specific kinematic regions, alongside discrepancies in angular observables such as P'_5 [1–3].

Beyond differential rates, tests of Lepton Flavor Universality (LFU), have revealed intriguing hints of deviations. Ratios of branching fractions involving muons and electrons, such as $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$, have shown tensions with the SM prediction of unity in certain measurements. Although recent updates by the LHCb Collaboration have reconciled some discrepancies, the potential implications of these anomalies continue to drive theoretical and experimental interest [4].

Rare decays of charm hadrons ($c \to u$) further expand the scope of indirect BSM searches. While theoretical uncertainties are larger due to contributions from lighter quarks, these decays remain a valuable probe for NP. Processes like $D^0 \to \mu^+\mu^-$, predicted to have branching fractions as low as 10^{-13} in the SM, offer opportunities to test alternative models, with CMS setting world-leading limits on such rare transitions.

This paper focuses on the latest CMS results from Run 2 data (2016–2018) and Run 3 data (2022–2023), showcasing advancements in branching fraction measurements and angular analysis tests in rare B- and D-meson decays. These findings provide stringent constraints on SM predictions and open avenues for exploring subtle hints of BSM physics.

2. The CMS Detector

The CMS detector [5,6] is a general-purpose particle physics experiment designed to explore fundamental questions in high-energy physics. Located at one of the Large Hadron Collider (LHC) interaction points, CMS combines state-of-the-art components to achieve exceptional performance in tracking, calorimetry, and muon detection.

The CMS tracker, situated at the heart of the detector, plays a crucial role in reconstructing charged particle trajectories. The system is composed of silicon pixel and strip detectors, optimized for precision and high granularity. The tracker covers a pseudorapidity range of $|\eta| < 2.5$, with a spatial resolution of 10–20 micrometers for the silicon pixel layers and 50–80 micrometers for the silicon strips. Its design ensures minimal material budget to reduce multiple scattering and photon conversion, critical for precision momentum measurements.

A key feature of the tracker is its ability to operate in the intense magnetic field generated by the superconducting solenoid (3.8 T). This field causes charged particles to follow curved paths, allowing their momenta to be measured with high accuracy. The relative transverse momentum resolution is approximately 1% for tracks with $p_T \approx 100\,\text{GeV}$, enabling detailed studies of high-momentum particles.

The muon system, a defining component of CMS, provides robust identification and precise momentum measurement for muons. It is composed of three types of gaseous detectors: drift tubes (DTs) in the barrel, cathode strip chambers (CSCs) in the endcaps, and resistive plate chambers (RPCs) spanning both regions. This layered design ensures redundancy, robustness, and high efficiency across the detector's large pseudorapidity range ($|\eta| < 2.4$).

The muon system's chambers are embedded within the steel return yoke of the magnet, using the magnetic field to measure muon momentum with resolutions of 1–3% for muons with $p_T \approx 100\,\text{GeV}$. Combined with the tracker, the system achieves an overall momentum resolution of better than 10% for p_T values up to 1 TeV. The CMS muon system's performance in terms of trigger and reconstruction efficiency is instrumental in achieving the physics goals presented in this paper.

3. $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ Decays

The rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are hallmark processes in the search for BSM physics. These decays occur via FCNCs, forbidden at tree level and highly suppressed in the SM due to helicity and Cabibbo–Kobayashi–Maskawa (CKM) factors. They are sensitive to higher-order effects and new particles potentially present in quantum loops.

Theoretical predictions for the branching fractions of these decays are exceptionally precise, taking into account next-to-leading-order electroweak and next-to-next-to-leading-order QCD corrections. Specifically, the SM predicts branching fractions of $(3.66 \pm 0.14) \times 10^{-9}$ for $B_s \to \mu^+\mu^-$ and $(1.03 \pm 0.05) \times 10^{-10}$ for $B^0 \to \mu^+\mu^-$ [7].

The CMS experiment utilized 140 fb^{-1} of data collected during LHC Run 2 (2016–2018) to analyze these decays [8]. This analysis employed advanced data acquisition methods and multivariate techniques to maximize sensitivity. Oppositely charged dimuon candidates were reconstructed and their invariant mass distributions were analyzed using simultaneous unbinned maximum likelihood fits. The dominant backgrounds, including combinatorial and partially reconstructed events, were effectively mitigated using boosted decision trees and rigorous muon identification criteria. The analysis yielded a branching fraction for $B_s \to \mu^+\mu^-$ of $(3.83^{+0.38}_{-0.36}(\text{stat})^{+0.19}_{-0.16}(\text{syst})^{+0.14}_{-0.13}(\text{external})) \times 10^{-9}$, consistent with SM predictions but slightly higher than previous measurements. No significant signal was observed for the $B^0 \to \mu^+\mu^-$ decay, and stringent upper limits were set at 1.9×10^{-10} at the 95% confidence level.

CMS also measured the effective lifetime of B_s mesons in this decay channel, yielding $\tau = 1.83^{+0.23}_{-0.20}(\text{stat})^{+0.04}_{-0.04}(\text{syst})$ ps. This measurement aligns closely with SM expectations of 1.62 ps and offers an additional avenue to probe BSM contributions. The effective lifetime provides a unique handle on CP-violating effects, as any deviations could hint at new interactions altering the dynamics of B_s-$\overline{B}_s$ mixing and decay.

The precise alignment of these results with SM predictions emphasizes the sensitivity of $B_s \to \mu^+\mu^-$ as a probe for NP. However, slight tensions between measurements from CMS and LHCb, as well as small anomalies in related semileptonic decays, underscore the need for additional data from LHC Run 3 and beyond.

4. Angular Analysis of $B^0 \to K^{*0}\mu^+\mu^-$

The decay $B^0 \to K^{*0}\mu^+\mu^-$ is a key process for probing physics beyond the SM. It proceeds via an FCNC, a rare and loop-mediated transition suppressed within the SM. These features make it highly sensitive to potential contributions from new particles or interactions, even if they exist at high energy scales inaccessible to direct collider searches.

The CMS experiment performed a comprehensive angular analysis of this decay using 140 fb^{-1} of data collected during Run 2 at $\sqrt{s} = 13\,\text{TeV}$ [9]. The analysis measured CP-averaged angular observables across the q^2 spectrum (the invariant mass squared of the dimuon system), excluding regions dominated by charmonium resonances J/ψ and $\psi(2S)$. These measurements include the full set of optimized observables, such as P_5', which showed mild but persistent deviations from SM predictions, consistent with earlier tensions reported by the LHCb experiment.

The angular distribution of the decay is described by the angles θ_ℓ, θ_K, and ϕ, and parameters such as F_L (the longitudinal polarization fraction of the K^*) and P_i' (optimized observables constructed to reduce theoretical uncertainties). A multi-dimensional unbinned maximum likelihood fit was used to extract these parameters, accounting for detector effects, resolution, and misidentified events. Simulations based on PYTHIA and EVTGEN were employed to model signal distributions, while background contributions were estimated from sidebands in the invariant mass spectrum.

The P_5' parameter, associated with the transverse polarization, showed significant deviations in certain q^2 bins from SM predictions derived using light-cone sum rules and lattice QCD. In the $4.3 < q^2 < 6\,\text{GeV}^2$ region, the measured value of $P_5' = -0.435 \pm 0.096$ (stat.) $\pm\, 0.027$ (syst.) contrasted with the SM expectation of a slightly higher value; moreover, the P_2 angular observable showed a discrepancy in the same q^2 bin (see Figure 1). These deviations are consistent with earlier results from CMS and LHCb and may suggest contributions from NP in the form of modified Wilson coefficients for the effective operators governing the $b \to s\ell^+\ell^-$ transition, or that the theoretical predictions need to be improved.

Systematic uncertainties were carefully evaluated, including detector resolution, efficiency modeling, and mismodeling of backgrounds. The uncertainties varied across q^2 bins but remained smaller than statistical uncertainties for most observables, ensuring the robustness of the results. The analysis confirmed the compatibility of other parameters, such as F_L and P_4', with SM predictions while narrowing the parameter space for potential NP contributions.

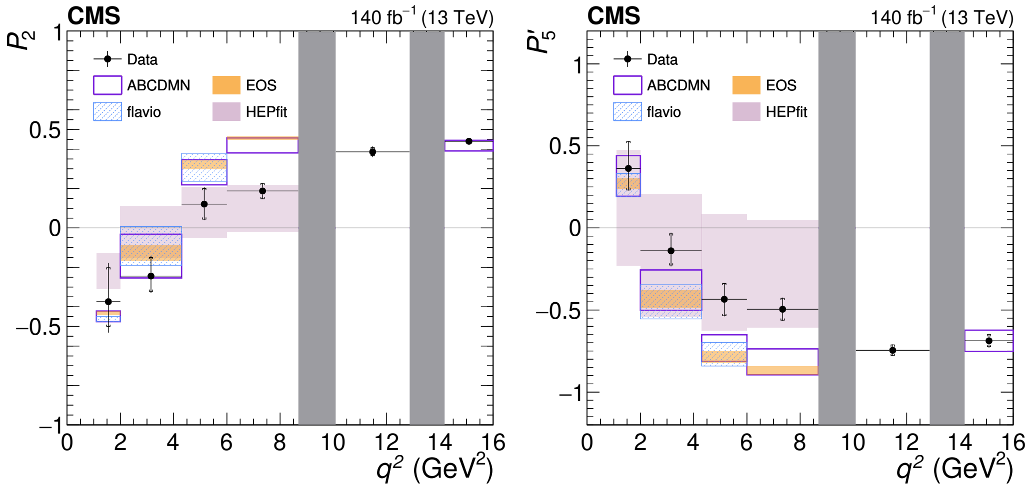

Figure 1. Measurements of the P_2 and P_5' angular observables versus q^2 [9]. The inner vertical bars represent the statistical uncertainties, while the outer vertical bars give the total uncertainties. The horizontal bars show the bin widths. The vertical shaded regions correspond to the J/ψ and $\psi(2S)$ resonances. Predictions are shown, averaged in each bin, from Ref. [10] (labeled ABCDMN), and the EOS [11], flavio [12], and HEPfit [13] libraries.

This angular analysis complements branching fraction studies and LFU tests, collectively enhancing our understanding of rare decays and their potential as probes of BSM physics.

5. First Observation of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

The decay $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ represents a rare and theoretically significant process in multilepton final-state physics. CMS achieved the first observation of this decay with a statistical significance exceeding five standard deviations [14]. The analysis utilized 33.6 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV in 2018, employing the B parking dataset, which is enriched in b-hadron decays through specialized triggering and storage techniques [15].

The branching fraction of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ was measured relative to the well-known $J/\psi \to \mu^+\mu^-$ decay. This approach significantly reduces systematic uncertainties, as both decay channels share similar topologies and are subject to the same triggering conditions. The measured relative branching fraction is

$$\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} = \left(16.9^{+5.5}_{-4.6}\,(\text{stat.}) \pm 0.6\,(\text{syst.})\right) \times 10^{-6},$$

resulting in an absolute branching fraction of

$$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = \left(10.1^{+3.3}_{-2.7}\,(\text{stat.}) \pm 0.4\,(\text{syst.})\right) \times 10^{-7}.$$

This value is consistent with the SM predictions, which incorporate quantum electrodynamics (QED) and higher-order corrections.

The signal was extracted using an unbinned maximum likelihood fit to the invariant mass distribution of the four muons. The signal was modeled by a Crystal Ball function to capture the resolution effects, while backgrounds were represented by a linear function. The excellent agreement between the fit and the data highlighted the robustness of the analysis (see Figure 2). Additionally, stringent selection criteria, including muon transverse momentum ($p_T > 3.5$ GeV) and isolation from misidentified tracks, minimized backgrounds from non-resonant multimuon production.

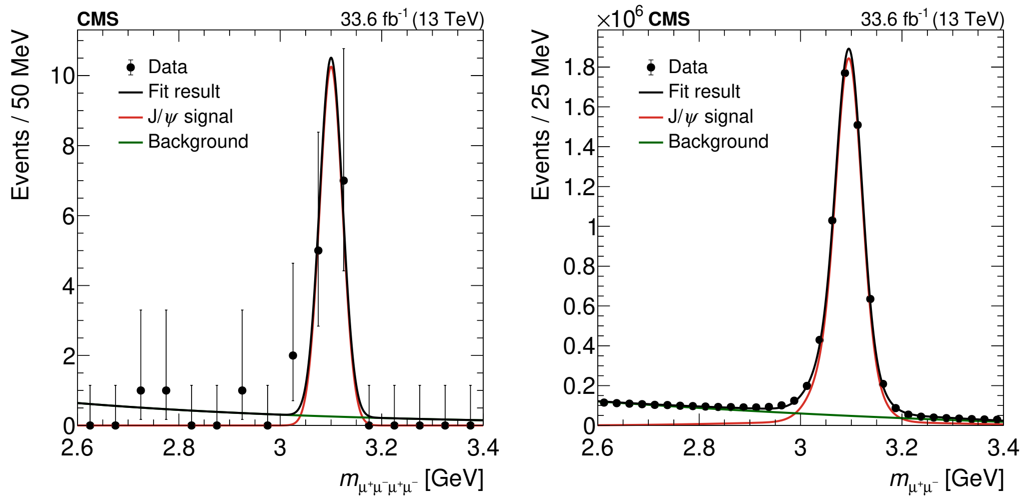

Figure 2. The measured four-muon (**left**) and dimuon (**right**) mass distributions. The vertical bars represent the statistical uncertainties. The solid black line represents the result of the unbinned fit described in the text, while the red and green lines represent the signal and background terms, respectively [14].

This observation not only establishes the branching fraction but also offers a sensitive test of QED in a novel regime. The process $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ probes multilepton production dynamics and potential contributions from virtual photons or Z-bosons, which could reveal deviations arising from NP scenarios. As the first measurement of its kind, it sets a benchmark for future studies in this domain.

6. $D^0 \to \mu^+\mu^-$ Decays

The decay $D^0 \to \mu^+\mu^-$ is one of the rarest charm meson decays and a crucial probe for BSM physics. Within the SM, the branching fraction for this decay is suppressed to approximately 3×10^{-13} due to the interplay of helicity suppression and the Glashow–Iliopoulos–Maiani (GIM) mechanism [16]. This suppression makes $D^0 \to \mu^+\mu^-$ an ideal candidate for exploring potential BSM contributions from new particles or interactions that could enhance the decay rate.

The CMS experiment conducted a search for $D^0 \to \mu^+\mu^-$ using $\sqrt{s} = 13.6\,\text{TeV}$ proton–proton collision data collected during the years 2022–2023, corresponding to an integrated luminosity of 64.5 fb^{-1} [17]. Utilizing a novel high-rate low-momentum dimuon trigger, CMS achieved an unprecedented sensitivity to this decay. The analysis incorporated advanced selection techniques, including multivariate classifiers, and applied a two-dimensional unbinned maximum likelihood fit to simultaneously evaluate the D^0 invariant mass and the $D^* - D^0$ mass difference (Δm), significantly reducing the combinatorial background.

Despite the improved sensitivity, no significant excess over the background was observed. The resulting upper limit on the branching fraction was set at

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9} \text{ at } 95\% \text{ CL},$$

improving the previous best limit of 3.5×10^{-9} set by the LHCb Collaboration by approximately 35% [18]. This result marks the most stringent constraint to date on FCNCs in the charm sector and places additional limits on various BSM scenarios, such as leptoquark models, R-parity-violating supersymmetry, and extended Higgs sectors.

The analysis strategy capitalized on the decay chain $D^* \to D^0\pi^+$, where the presence of a soft pion helps suppress combinatorial backgrounds. Signal events were discriminated using vertexing techniques to exploit the displaced nature of D^0 decays. Systematic uncertainties, including those from tracking efficiency, misidentification rates, and fit biases, were minimized through rigorous calibration and the use of control samples. This robust methodology underscores the potential for future analyses with larger datasets and refined techniques.

These findings not only constrain BSM physics but also highlight the unique challenges of rare charm decays, such as their susceptibility to long-distance SM contributions, which introduce significant theoretical uncertainties. As CMS continues to improve its data acquisition and analysis capabilities, the decay $D^0 \to \mu^+\mu^-$ will remain a focal point in the search for NP.

7. Conclusions

The CMS experiment has delivered excellent results in the study of rare heavy-flavor decays, significantly enhancing the precision of key measurements and providing stringent tests of the SM. By leveraging the high-energy collisions of the LHC and innovative data acquisition strategies, CMS has achieved notable milestones:

- The measurement of the branching fraction and effective lifetime for $B_s \to \mu^+\mu^-$ has reached unparalleled precision, confirming SM predictions but revealing slight tensions that hint at potential NP contributions.
- Angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$ have continued to observe intriguing deviations in specific observables such as P'_5, complementing global efforts to resolve anomalies in rare $b \to s\ell^+\ell^-$ transitions.
- The first observation of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ represents a major step in the study of multilepton decay dynamics, opening new avenues to test QED and constrain exotic contributions.
- In the charm sector, the search for $D^0 \to \mu^+\mu^-$ has achieved the most sensitive upper limit to date, setting new constraints on flavor-changing neutral currents in charm decays and restricting a range of BSMRaton laveur scenarios.

These results not only reinforce the validity of the SM but also reveal subtle hints of possible deviations, underscoring the importance of precision measurements in rare decays as a window to NP. As the LHC transitions to the High-Luminosity era, CMS is poised to further refine these analyses with larger datasets and improved detector capabilities. These advancements promise to address outstanding questions in particle physics, such as the nature of lepton universality violations, the origins of flavor anomalies, and the role of rare charm decays in probing uncharted territories of the SM.

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