PROCEEDINGS OF SCIENCE

Rare decays

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A number of recent results by the LHC collaborations on rare decays of heavy hadrons are discussed, including the $b \to s\, l^{+}l^{-}$ transitions, lepton-flavor-violating decays, and fully-leptonic neutral meson decays.

The Tenth Annual Conference on Large Hadron Collider Physics - LHCP2022
16-20 May 2022
online

[*] Speaker

PoS(LHCP2022)018

The ATLAS [1], CMS [2], and LHCb [3] experiments at the LHC are searching for the signs of physics beyond the Standard model (SM), using both direct and indirect approaches. The latter ones include studies of rare decays and searches for forbidden decays of heavy mesons and baryons, where small contributions of New Physics (NP) effects can have an amplitude comparable to the (very small) SM amplitude for the process under study. This makes such rare decays a sensitive laboratory for NP.

In this report, recent results from the LHC collaborations on rare and lepton-flavor-violating decays are discussed.

1. $\mathbf{b \to s l^+ l^-}$ transitions

1.1 $\mathbf{b \to s l^+ l^-}$ processes as probes for New Physics

Flavor-changing neutral current (FCNC) transitions are suppressed in the SM, as they proceed only through amplitudes that involve electroweak loop diagrams. Such processes are sensitive to virtual contributions from the NP particles, which could have masses that exceed the reach of the direct searches. NP contributions can shift some characteristics of the decay, such as a branching fraction or a parameter of the angular distributions, from the SM prediction. Several recent results on B meson decays involving FCNC $\mathrm{b} \to \mathrm{s} l^+ l^-$ transition are discussed below.

1.2 Angular analysis of the $\mathbf{B^0 \to K^*(892)^0 \mu^+ \mu^-}$ decay

A large number of experiments have performed an angular analysis of the $\mathrm{B}^0 \to \mathrm{K}^*(892)^0 \mu^+ \mu^-$ decay: BaBar, CDF, LHCb, Belle, ATLAS, CMS. The latest and most precise measurement, performed by the LHCb Collaboration, uses the data collected between 2011 and 2016 in pp collisions at $\sqrt{s}$ of 7, 8, and 13 TeV [4]. The analysis is performed in the bins of dimuon mass squared, q^2, and the ϕ, J/ψ, and $\psi(2\mathrm{S})$ resonances are vetoed. The measurement is based on about 4 500 signal candidates and measures the full set of angular observables: CP-averaged ones, F_L, A_{FB}, $S_3 - S_9$, and the optimized ones, $P^{(\prime)}_{1-9}$.

The results for S_5 and $P_5^{'}$ are shown in Figure 1. There are visible discrepancies in the low-q^2 region, particularly notable for the $P_5^{'}$ observable. The overall tension w.r.t the SM prediction was evaluated to be 3.3 standard deviations (σ) [4], which underlines that full Run-2 results from all 3 collaborations are highly-awaited.

1.3 Differential branching fraction of the $\mathbf{B_s^0 \to \phi \mu^+ \mu^-}$ decay

The LHCb Collaboration has performed the differential branching fraction measurement and an angular analysis of the $\mathrm{B_s^0} \to \phi \mu^+ \mu^-$ decay [5, 6] using about 2 000 signal candidates found in Run-1 and Run-2 data. The measured branching fraction in the q^2 region between 1.1 and 6 GeV is found to be 3.6σ below the SM prediction, while the parameters of angular distributions agree with the SM. In addition, the decay $\mathrm{B_s^0} \to \mathrm{f}_2^{'} \mu^+ \mu^-$ is observed for the first time using the same $\mathrm{K^+ K^-} \mu^+ \mu^-$ final state.

1.4 Angular analysis of the $\mathbf{B^+ \to K^*(892)^+ \mu^+ \mu^-}$ decay

The LHCb Collaboration has also performed an angular analysis of the $\mathrm{B}^+ \to \mathrm{K}^*(892)^+ \mu^+ \mu^-$ decay [7] using full Run-1 and Run-2 data. The angular analysis is based on about 740 signal

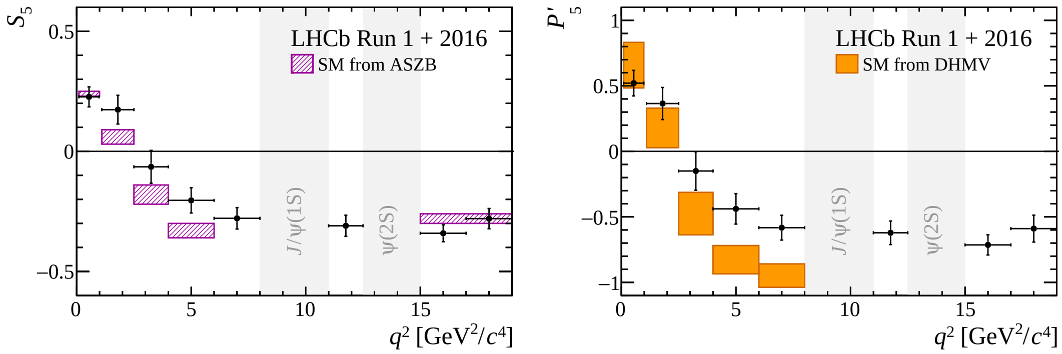

Figure 1: The measured angular observables S_5 and P'_5 in the $\mathrm{B}^0 \to \mathrm{K}^*(892)^0\mu^+\mu^-$ decay, compared to the SM predictions [4].

candidates and measures, for the first time, all the angular observables: F_L, A_{FB}, $S_3 - S_9$, as well as the $P^{(\prime)}_{1-9}$. Most of the parameters are found to agree with SM predictions, with few exceptions, such as P_2 in $6 < q^2 < 8\,\mathrm{GeV}$ range, which shows about 3σ discrepancy. Overall, the pattern of deviations from the SM is close to that reported for the isospin-partner decay $\mathrm{B}^0 \to \mathrm{K}^*(892)^0\mu^+\mu^-$ [4], discussed in Sect. 1.2.

2. Fully-leptonic decays

2.1 $\mathrm{B}^0_s \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ decays

The branching fractions of the $\mathrm{B}^0_s \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ decays are predicted very precisely in the SM due to the absence of hadronic uncertainties, since the final state only contains leptons. These decays are very suppressed, with the expected branching fractions being of the order of 10^{-9} (10^{-10}) for B^0_s (B^0).

The first observation of the $\mathrm{B}^0_s \to \mu^+\mu^-$ decay was reported from the combined analysis of CMS and LHCb data in 2014 [8]. In summer 2020 the ATLAS, CMS, and LHCb presented a combined result of Run-1 and partial Run-2 analyses, which was in about 2σ tension w.r.t. the SM prediction, however, these results were not published.

More recently, the LHCb Collaboration presented a full Run-1 + Run-2 analysis [9]. The observed yields are normalized using the $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$ [$\mathrm{J}/\psi \to \mu^+\mu^-$] and $\mathrm{B}^0 \to \mathrm{K}^+\pi^-$ decays, which are also used for calibration, together with the $\mathrm{B}^0_s \to \mathrm{K}^+\mathrm{K}^-$, $\mathrm{J}/\psi \to \mu^+\mu^-$, $\psi(2\mathrm{S}) \to \mu^+\mu^-$, and $\Upsilon(n\mathrm{S}) \to \mu^+\mu^-$ decays. The backgrounds are suppressed with a BDT selection, and the events are split into different sensitivity categories based on the BDT value. The observed mass distribution of the dimuon candidates in the most sensitive BDT bin is shown in Figure 2 (left) with the fit results overlaid.

The reported values for $\mathcal{B}(\mathrm{B}^0_s \to \mu^+\mu^-)$ (most precise single-experiment measurement at the time of publication) and $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)$ are [9]:

$$\begin{aligned}\mathcal{B}(\mathrm{B}^0_s \to \mu^+\mu^-) &= (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},\\ \mathcal{B}(\mathrm{B}^0_s \to \mu^+\mu^-) &< 2.6 \times 10^{-10} \text{at } 95\% \text{ CL}.\end{aligned}$$

The measured branching fractions are compared to the SM prediction in Figure 2 (right), which illustrates a good consistency between the experiment and the theory. In the same analysis, also the effective lifetime of the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ decay is measured and the first search for the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-\gamma$ decay is reported [9].

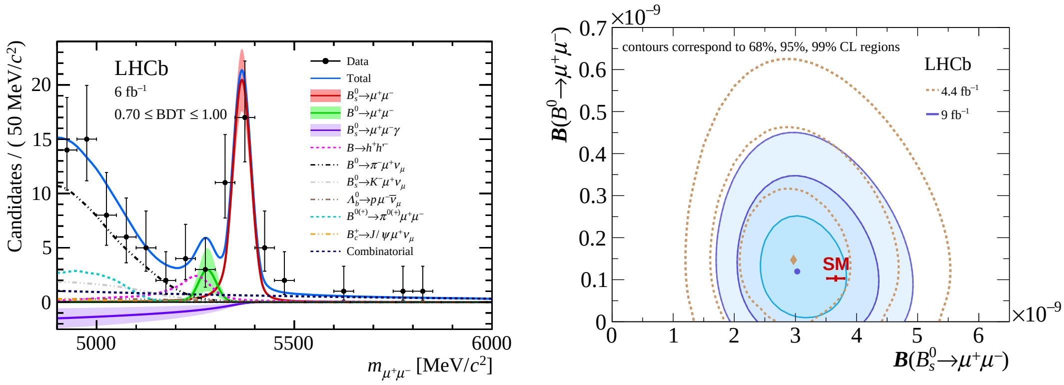

Figure 2: The observed dimuon mass distribution in the most sensitive BDT bin (left); the measured likelihood contours for $\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-)$ vs $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)$ [9].

Very recently, the CMS Collaboration presented the full Run-2 analysis of $\mathrm{B} \to \mu^+\mu^-$ decays [10], where the world-best precision in the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ branching fraction and effective lifetime were achieved. Once the ATLAS Collaboration presents their results using full Run-2 data, it is planned to perform a combination of the measurements of the three experiments.

2.2 $\mathrm{B} \to e^+e^-$ and $\mathrm{B} \to \tau^+\tau^-$ decays

Similarly to the $\mathrm{B} \to \mu^+\mu^-$ decays, the dilepton decays of B mesons to e^+e^- and $\tau^+\tau^-$ are precisely predicted in the SM and are rare: B^0_s branching fractions are of the order of 10^{-13} and 10^{-6}, respectively, and for B^0 the predicted values are two orders of magnitude lower. However, these decays are more challenging for the experiments compared to $\mathrm{B} \to \mu^+\mu^-$, as taus are not fully-reconstructed, while electrons emit bremsstrahlung radiation in the magnetic field, worsening the mass resolution. These decays were recently searched for by the LHCb Collaboration, and no significant signals were observed. The obtained 95% CL upper limits [11, 12] of

$$\begin{aligned} \mathcal{B}(\mathrm{B}^0_\mathrm{s} \to e^+e^-) &< 11.2 \times 10^{-9}, \quad \mathcal{B}(\mathrm{B}^0 \to e^+e^-) &< 3.0 \times 10^{-9}, \\ \mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \tau^+\tau^-) &< 6.8 \times 10^{-3}, \quad \mathcal{B}(\mathrm{B}^0 \to \tau^+\tau^-) &< 2.1 \times 10^{-3}, \end{aligned}$$

are the most stringent to date, while still being many orders of magnitude larger than the predicted branching fractions.

2.3 $\mathrm{B} \to 4\mu$ decays

The 4-muon decays of B^0_s (B^0) mesons proceed through the same diagrams as $\mathrm{B} \to \mu^+\mu^-$ decays, with an additional ISR virtual photon; and the predicted values of $\mathcal{B}$ are of the order of 10^{-10} (10^{-12}). Some NP models predict larger values for these branching fractions, in particular, if the decays proceeds through an intermediate scalar resonance a with a mass around 1 GeV. LHCb has performed a search for $B \to 4\mu$ decays [13] and, with no significant signal observed, upper limits of the order of $10^{-10} - 10^{-9}$ were set on the branching fractions, using full Run-1 and Run-2 dataset.

2.4 $K_S^0 \to \mu^+\mu^-$ decay

The $K_S^0 \to \mu^+\mu^-$ decay is suppressed in the SM and has not yet been observed, with the predicted branching fraction being about 5×10^{-12}. LHCb has searched for this decay using the 13 TeV pp collision data collected between 2016 and 2018 [14]. The signal was normalized to the $K_S^0 \to \pi^+\pi^-$ decay, which is also the dominant background source. No significant signal was observed and an upper limit $\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 2.4 \times 10^{-10}$ at 95% CL was set.

3. Lepton flavor violation

Searches for lepton-flavor violating (LFV) decays provide another important method of searching for beyond-the-standard-model physics. Processes violating the lepton flavor are either forbidden of very strongly suppressed in the SM.

3.1 Search for $\tau \to \mu\mu\mu$ decay

The LHC collaborations have searched for the LFV decay of the tau lepton into 3 muons. At LHCb, taus produced in the decays of charm and beauty hadrons were used in the analysis based on Run-1 data [15]. The ATLAS experiment used high-p_T τ leptons from W boson decays produced during Run-1 [16], while the more recent CMS analysis, based on part of Run-2 data, uses both sources of taus [17]. The reported by ATLAS, CMS, and LHCb upper limits are several times weaker than the current world-best limit set by the Belle Collaboration of $\mathcal{B}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ [18], however, improved limits can be obtained using the large data sets collected during the LHC Run-2.

3.2 Search for $B^+ \to K^+\mu^-\tau^+$ and $B^+ \to K^+\mu^\mp e^\pm$ decays

At the hadron collider, the decays with missing neutrinos, such as $B^+ \to K^+\mu^-\tau^+$, are rather challenging to study, because there is no narrow invariant mass peak to be reconstructed. The LHCb experiment has performed a full Run-1 + Run-2 search for this decay via the excited B_s^0 meson states that decay into B^+K^- [19]. Using several kinematic and topological constraints, a variable m^2_{miss} is calculated, such that the signal process will show itself as a peak in the distribution of m^2_{miss}. No significant signal is observed, and, with the $B^+ \to J/\psi K^+$ channel used for the normalization, an upper limit is set $\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < [4.5 - 5] \times 10^{-5}$ at 95% CL, depending on the assumed decay model [19].

Based on Run-1 data, the LHCb experiment has also searched for LFV $B^+ \to K^+\mu^\mp e^\pm$ decays. With no significant signals observed, world-best upper limits were set at 95% CL: $\mathcal{B}(B^+ \to K^+\mu^+e^-) < 8.8 \times 10^{-9}$ and $\mathcal{B}(B^+ \to K^+\mu^-e^+) < 9.5 \times 10^{-9}$ [20].

3.3 Search for $B^0 \to K^*(892)^0\mu^\mp e^\pm$ and $B_s^0 \to \phi\mu^\mp e^\pm$ decays

Another recent LHCb search for LFV decays of B^0 and B_s^0 mesons targets the decays with vector resonances $K^*(892)^0$ and ϕ. Figure 3 shows the observed mass distributions obtained using the full Run-1 and Run-2 dataset.

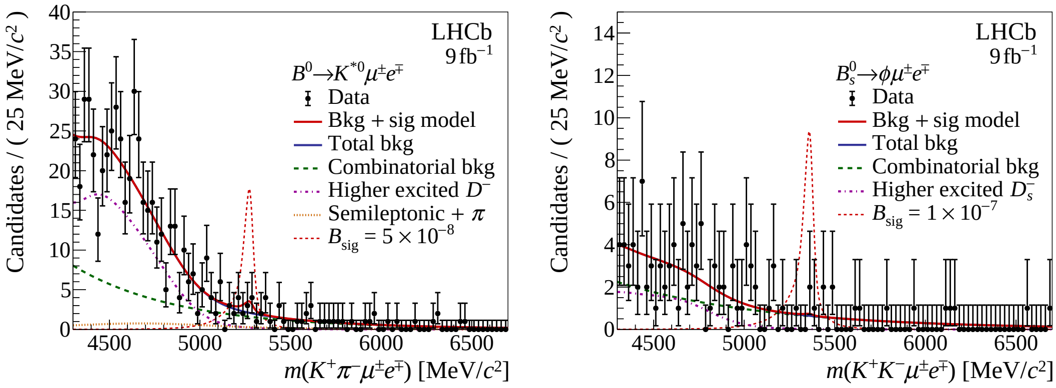

Figure 3: The observed mass distribution for the $B^0 \to K^*(892)^0\mu^\mp e^\pm$ and $B_s^0 \to \phi\mu^\mp e^\pm$ (right) candidates [21]. The displayed signal shapes are scaled to the $\mathcal{B}$ of 5×10^{-8} and 1×10^{-7}, respectively.

No significant excesses are observed in the mass distributions, and the obtained upper limits on the branching fractions are of the order of 10^{-9}, heavily depending on the assumed decay models [21]. The limits for $B^0 \to K^*(892)^0\mu^+e^-$ and $B^0 \to K^*(892)^0\mu^-e^+$ decays are the most stringent to date, while the constraints on the $\mathcal{B}(B_s^0 \to \phi\mu^\mp e^\pm)$ are obtained for the first time.

4. Summary

Rare and forbidden decays of hadrons containing heavy quarks are known to be a sensitive laboratory for New Physics searches. The LHC experiments search for any deviations from the Standard model prediction in a large number of processes. Several tensions have been found at the level of 3-4 standard deviations in $b \to sl^+l^-$ transitions. More data from the LHC Run-3, that has just started, will be needed, as well as combined efforts from all the experiments, to understand if those discrepancies are fluctuations in the data or, if they are indeed the significant pointers to New Physics effects.

Acknowledgments

The author's work was supported by the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental properties of elementary particles and cosmology" No 0723-2020-0041. The author would like to thank the LHCP 2022 conference organizers for the excellent program and opportunity to present these important results.

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