PROCEEDINGS OF SCIENCE

Rare heavy-flavour decays

Alessio Boletti[a,*] **on behalf of the ATLAS, CMS, and LHCb Collaborations**

[a] *Laboratório de Instrumentação e Física Experimental de Partículas (LIP)*
Av. Gama Pinto 2, Lisbon, Portugal

The search and study of rare decays of B hadrons and of the τ lepton are among the most promising approaches of putting the Standard Model of particle physics to the test. In recent years, the study of these decays, and in particular of flavour-changing neutral current decays $b \to s\ell\ell$, helped shed light on a set of tensions in the data with respect to theoretical predictions for branching ratios, angular distributions and lepton flavour universality. In this work, the most recent results in the study of rare heavy-flavour decays at the Large Hadron Collider experiments are presented.

The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021
7-12 June 2021
Online

*Speaker

https://pos.sissa.it/

PoS(LHCP2021)139

1. Introduction

The study of rare decays of heavy-flavour particles has been proven to be a very powerful tool to test the Standard Model of particle physics (SM), and to search for new-physics phenomena.

The decays described in this work are flavour-changing neutral current (FCNC) decays of the B hadrons, which are forbidden at tree-level within the SM, and a lepton-flavour violating decay of the τ lepton. The rarity of these kinds of decays makes them more prone to virtual contributions of beyond-the-SM (BSM) phenomena, allowing for their sensitivity to go far beyond the energy scale reached in the particle colliders. This indirect search for new physics is model independent.

The ATLAS [1], CMS [2], and LHCb [3] experiments at the Large Hadron Collider (LHC) are ideal instruments to study such decays, thanks to the huge number of collisions and to the large cross-section for heavy-flavour particle production. These factors facilitate the precise probing of decays that are predicted to have extremely small branching fractions.

2. Search for the $\tau \to \mu\mu\mu$ decay

The decay of the τ lepton in three muons is extremely rare, according to the SM, allowed only through the mechanism of neutrino oscillation. This aspect makes the search for the $\tau \to \mu\mu\mu$ decay a powerful tool to probe BSM phenomena that would increase its branching fraction to an experimentally-accessible value.

The CMS Collaboration has recently published the result of the search for the τ decay into three muons, using the data collected in proton-proton collisions during 2016 [4]. This search combines the result of two analyses, performed using τ leptons produced in W boson decays to $\tau\nu_\tau$, and using the ones produced in the semileptonic decays of heavy-flavour hadrons.

The events used in the W-decay channel are selected using a dedicated Boosted Decision Tree (BDT). The candidates are divided in two categories, according to their pseudo-rapidity, and the three-muon invariant mass is fitted in each category.

The analysis of the heavy-flavour-decay channel is performed by combination of τ leptons produced in decays of $\mathrm{D_s}$ mesons that are directly produced in the proton-proton collisions, in decays of $\mathrm{D_s}$ mesons that are produced in decays of B hadrons, and in decays of B hadrons. A key aspect of the analysis is the use of the $\mathrm{D_s} \to \phi\pi \to \mu\mu\pi$ decay to normalize the signal yield, and to evaluate the fraction of $\mathrm{D_s}$ produced from a B decay, with respect to the promptly produced ones. The candidates are selected using a dedicated BDT, and they are divided into six categories, according to the BDT score and the resolution of the three-muon invariant mass. In each category, the distribution of the three-muon invariant mass is fitted.

The results of the fits for each of the eight categories in the two analyses is shown in Fig. 1. No signal is observed, and an upper limit on the BR of the $\tau \to \mu\mu\mu$ decay is set to $8 \cdot 10^{-8}$ at 90% of CL.

3. Analysis of $b \to s\ell\ell$ decays

The study of the FCNC class of decays $b \to s\ell\ell$ is one of the most active areas in high-energy physics in recent years. Several analyses have been recently published, achieving unprecedented

PoS(LHCP2021)139

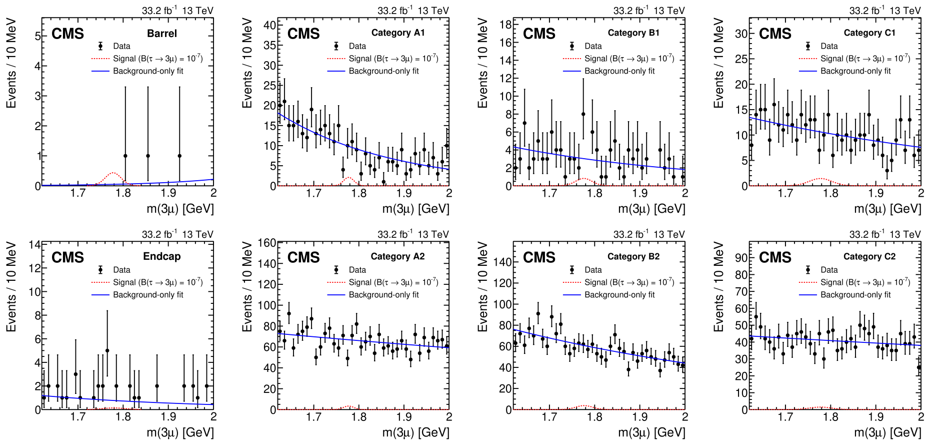

Figure 1: Three-muon invariant mass distributions of the eight event categories defined in the CMS search for the $\tau \to \mu\mu\mu$ decay, in the W-decay (first column) and heavy-flavour decay (second, third, and forth columns) channels. Figures from [4].

precision in the measurement of angular distributions, BRs and lepton-flavour universality (LFU) tests.

One of the most recent results in this category of studies is the angular analysis of the $B^+ \to K^*(892)^+\mu\mu$ decay. This analysis has been recently performed by the CMS Collaboration with the data collected in 2012 [5], and by the LHCb collaboration with the combined datasets collected in the Run-1 and Run-2 data-taking periods [6].

In both these analyses, the decay is reconstructed through the decay chain $K^*(892)^+ \to \pi^+ K_s^0(\to \pi^+\pi^-)$. Although the final state is composed only of charged particles, the relatively long lifetime of the K_s^0 causes its decay vertex to be displaced by the B^+ decay vertex, and it makes the reconstruction of the candidates more challenging.

In the CMS analysis, a fit is performed to the B invariant mass distribution and two helicity angles. The forward-backward asymmetry of the muons, A_{FB}, and the fraction of longitudinally polarized K^*, F_L, are measured in three ranges of the dimuon invariant mass, q^2. The resulting values, in agreement with the SM prediction, are shown in Fig. 2.

In the LHCb analysis, the fit is performed on the B invariant mass distribution and the three helicity angles, to extract the full set of eight angular parameters in eight bins of the q^2 spectrum. The results of two of these angular parameters, P_2 and P_5', are shown in Fig. 3. Performing a global fit that includes all the results of the eight parameters, a tension is observed with respect to the SM predictions, corresponding to 3.1 standard deviations. The results for the P_5' parameter, which alone are not significantly different from the SM predictions, show a similar trend as the one observed in the angular analysis of the equivalent decay of the neutral meson $B^0 \to K^*(892)^0\mu\mu$, suggesting a coherent picture.

Another $b \to s\ell\ell$ angular analysis that has been recently published is the one of the B_s meson decay to $\phi\mu\mu$, performed by the LHCb Collaboration combining the data collected in the Run-1 and Run-2 data-taking periods [7]. The ϕ meson is reconstructed in the decay to K^+K^-. A fit is performed on the B_s invariant mass distribution and the three helicity angles, to measure eight

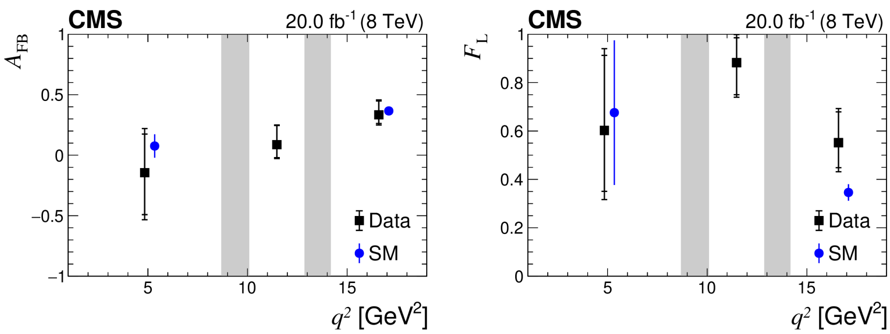

Figure 2: Results of the A_{FB} (left) and F_L (right) parameters from analysis of the $B^+ \to K^*(892)^+\mu\mu$ decay. Figures from [5].

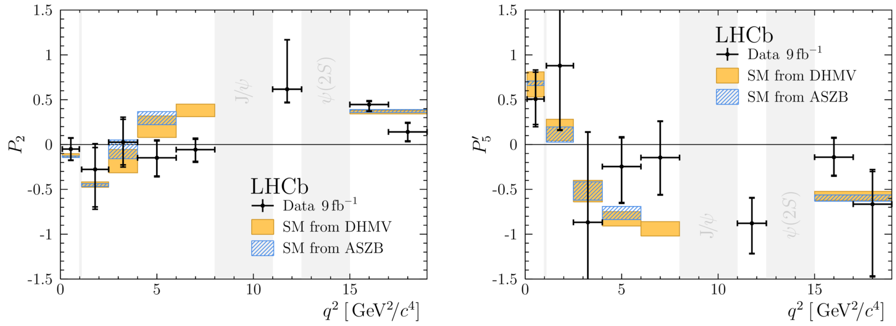

Figure 3: Results of the P_2 (left) and P'_5 (right) parameters from analysis of the $B^+ \to K^*(892)^+\mu\mu$ decay. Figures from [6].

angular parameters in 6 bins of the q^2 distribution. The projections of the fit results in the q^2 range between 1.1 and 6 GeV^2 are shown in Fig. 4. The resulting parameters are compatible with the SM prediction, and the result of the global fit shows a 1.9σ tension with respect to the SM, which shows a trend consistent with the other $b \to s\ell\ell$ angular analyses.

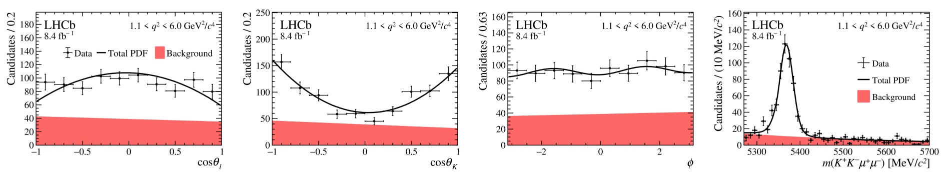

Figure 4: Distributions of the three helicity angles and B_s invariant mass, and projections of the fit result, used in the angular analysis of the B_s meson decay to $\phi\mu\mu$. Figures from [7].

In addition to angular analyses, the measurement of the BR of the $b \to s\ell\ell$ decays is an important way to probe new-physics contributions. The LHCb Collaboration performed the measurement of two decays of the B_s meson: the one in $\phi\mu\mu$, and the one in $f_2(1525)\mu\mu$, combining the data collected in the Run-1 and Run-2 data-taking periods [8]. Both the ϕ and $f_2(1525)$ mesons are reconstructed in their decays into K^+K^-.

The differential branching fraction of the $B_s \to \phi\mu\mu$ decay is measured in eight bins of q^2 by fitting the B_s invariant mass distribution. The $B_s \to \phi J/\psi$ channel is used as normalization channel. The results are shown in Fig. 5 (left), and they present a tension of 1.8σ with respect to the SM prediction computed with the light-cone sum rule, and 3.6σ with respect to the one obtained including lattice calculations.

The branching fraction of the $B_s \to f_2(1525)\mu\mu$ decay is measured by performing a fit to the B_s and $f_2(1525)$ invariant mass distributions. The $B_s \to \phi J/\psi$ and $B_s \to f_2(1525)J/\psi$ decays are used as normalization and control channels, respectively. The projections of the fit results are shown in Fig. 5 (centre and right). This analysis constitutes the first observation of this decay, with a significance of about 9σ, and the resulting BR value is in agreement with the SM predictions.

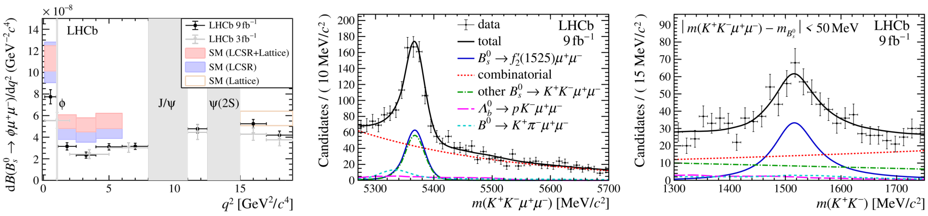

Figure 5: Left: results of the differential branching fraction measurement of the $B_s \to \phi\mu\mu$ decay. Centre and right: B_s and $f_2(1525)$ invariant mass distributions, and projections of the fit results, used in the $B_s \to f_2(1525)\mu\mu$ branching fraction measurement. Figures from [8].

Another way to probe $b \to s\ell\ell$ decays is to study the LFU, by measuring the set of ratios $R(H_s)$, defined as $\mathcal{B}(B \to H_s\mu\mu)/\mathcal{B}(B \to H_s ee)$. Since most of the theoretical uncertainties cancel out in this ratio, the predictions are robust and precise at the percent level.

The LHCb Collaboration tested the LFU hypothesis in the $B^+ \to K^+\ell\ell$ decay, by measuring $R(K)$ on the combined Run-1 and Run-2 datasets [9]. In order to control the effect of different reconstruction efficiencies in the muonic and electronic channel, the ratio between the BR of the resonant decays mediated by a $J/\psi \to \ell\ell$ is measured to be compatible with one. In addition, $R(K)$ is measured as a double ratio between the resonant and non-resonant decays:

$$R(K) = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu\mu))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ee)}{\mathcal{B}(B^+ \to K^+J/\psi(\to ee))}$$

The result is shown in Fig. 6, and presents a 3.1σ discrepancy with respect to the SM predictions.

4. Study of the $B_s \to \mu\mu$ decay and search for the $B_d \to \mu\mu$ and $B_s \to \mu\mu\gamma$ decays

The leptonic decay of the B_d and B_s mesons into a pair of muons are optimal laboratories to test for contribution from new-physics phenomena: several mechanisms contribute to suppress these decays, according to the SM, whose predictions for the BR are at the order of $10^{-9} - 10^{-10}$, with very small uncertainties.

The LHCb Collaboration has recently published the result of the measurement of the $B_s \to \mu\mu$ BR and effective lifetime, and the search for the $B_d \to \mu\mu$ and $B_s \to \mu\mu\gamma$ decays, using the combined dataset collected during the Run-1 and Run-2 data-taking periods [10, 11]. The events

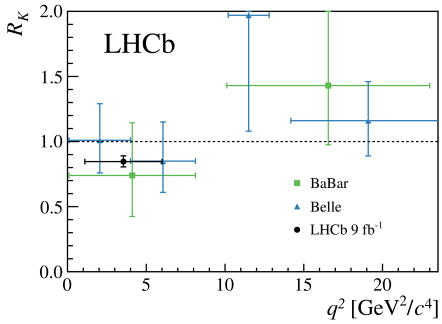

Figure 6: Results of the $R(K)$ measurement. Figure from [9].

are selected using a BDT, based on vertexing and isolation variables, and by applying dedicated particle-identification criteria to the muons. The $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$ decays are used to normalize both the signal and the backgrounds originated from other B decays. The invariant mass of the dimuon system is fitted, and the result is shown in Fig. 7 (left). The resulting BR of the $B_s \to \mu\mu$ decay is $(3.09^{+0.46+0.15}_{-0.43-0.11}) \cdot 10^{-9}$, while 95% CL upper limits are set at $2.6 \cdot 10^{-10}$ for the BR of the $B_d \to \mu\mu$ decay, and at $2.0 \cdot 10^{-9}$ for the BR of the $B_s \to \mu\mu\gamma$ decay. The results, shown in Fig. 7 (centre), are in good agreement with the SM predictions.

The background-subtracted event distribution of the decay time of the $B_s \to \mu\mu$ candidates is fitted to extract the effective lifetime of this decay. The decay time distribution, for one of the BDT-defined event categories, is shown in Fig. 7 (right). The acceptance correction is validated by measuring the lifetime of the $B^0 \to K^+\pi^-$ and $B_s \to K^+K^-$ decays. The result is measured to be $2.07 \pm 0.29 \pm 0.03$ ps, which is in agreement with the SM prediction.

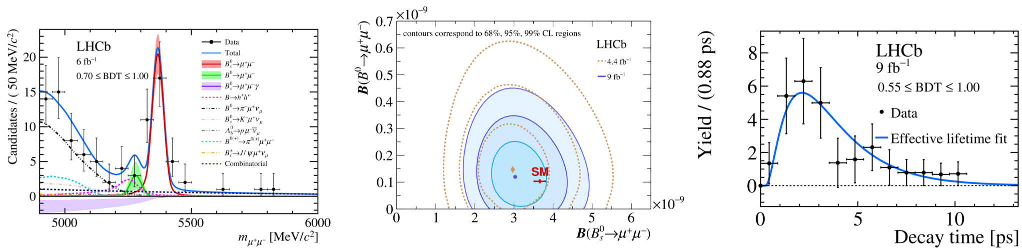

Figure 7: Left: distribution of the dimuon invariant mass. Centre: branching ratio results for the $B_s \to \mu\mu$ and $B_d \to \mu\mu$ decays. Right: background-subtracted distribution of the $B_s \to \mu\mu$ decay time. Figures from [10].

5. Conclusions

The most recent results from the study of rare heavy-flavour decays by the LHC experiments have been presented, including a first set of analyses performed using the full set of data collected in the Run-1 and Run-2 data-taking periods.

While many results are found to be consistent with the SM, a set of tensions with respect to the predictions is observed in the studies performed on the $b \to s\ell\ell$ decays, consistent with the discrepancies observed in the past.

References

[1] ATLAS Collaboration, JINST **3** (2008) S08003

[2] CMS Collaboration, JINST **3** (2008) S08004

[3] LHCb Collaboration, JINST **3** (2008) S08005

[4] CMS Collaboration, JHEP **01** (2021), 163

[5] CMS Collaboration, JHEP **04** (2021), 124

[6] LHCb Collaboration, Phys. Rev. Lett. **126** (2021) no.16, 161802

[7] LHCb Collaboration, arXiv:2107.13428 [hep-ex]

[8] LHCb Collaboration, arXiv:2105.14007 [hep-ex]

[9] LHCb Collaboration, arXiv:2103.11769 [hep-ex]

[10] LHCb Collaboration, arXiv:2108.09283 [hep-ex]

[11] LHCb Collaboration, arXiv:2108.09284 [hep-ex]