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Rare decays in $b \to s/d$ sector

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The coupling of the electroweak gauge bosons of the Standard Model (SM) of particle physics to leptons is flavour universal. Experimental tests of this principle are highly sensitive to New Physics particles which couple differently among the leptonic families. The flavour anomalies that have been observed could imply the existence of lepton-flavour violating b-hadron decays. Recent results in the study of rare decays in the $b \to s/d$ sector from the ATLAS, CMS and LHCb collaborations are presented. Measurements of the branching fraction in B_s^0 and Ξ_b^- decays, study of the angular properties of B^0, B^+ and B_s^0 decays, and test of the lepton flavour universality via $B^+ \to K^+ l^+ l^-$ processes are discussed in these proceedings.

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1. Introduction

Rare b-hadron decays proceeding through $b \to s/dll$ transitions are flavour-changing neutral-currents (FCNC) which, in the SM, are loop-suppressed and therefore allow for indirect search for new physics (NP). Rare b decays can be described by effective field theory (EFT), in which different di-lepton invariant mass squared regions are sensitive to different operator contributions and corresponding Wilson coefficients. Significant deviations from SM predictions could arise in NP models with global fit results in the Wilson coefficient plane [1]. Observing properties of rare b decays would be a major breakthrough in understanding the matter content of the universe [2, 3]. Latest experimental results from the ATLAS, CMS and LHCb collaborations are presented in these proceedings.

2. Branching fraction measurements and search for new rare b-hadron decays

The branching fraction measurement of the rare $B^0_s \to \phi\mu^+\mu^-$ decay is performed by the LHCb experiment using 9 fb^{-1} of integrated luminosity of pp collisions at a centre-of-mass energy of 7, 8 and 13 TeV. The first observation of the rare $B^0_s \to f_2'\mu^+\mu^-$ decay is also reported, and the mesurement of its branching fraction is determined [4]. The signal candidates in $B^0_s \to \phi\mu^+\mu^-$ and $B^0_s \to f_2'\mu^+\mu^-$ decays are reconstructed in the $K^+K^-\mu^+\mu^-$ final state. The largest deviation of 3.6σ is found in $B^0_s \to \phi\mu^+\mu^-$ decay between the measured branching fraction and the SM prediction using both Light Cone Sum Rules (LCSRs) and Lattice QCD (LQCD) calculations [5–7] in the $1.1 < q^2 < 6.0\text{GeV}^2/c^4$ region, as shown in the left of the Fig. 1. A less precise SM prediction lies 1.8σ above the measurement is presented based on LCSRs [5, 6]. The signal of $B^0_s \to f_2'\mu^+\mu^-$ is observed with 9σ significance after separating the S- and P-wave contributions.

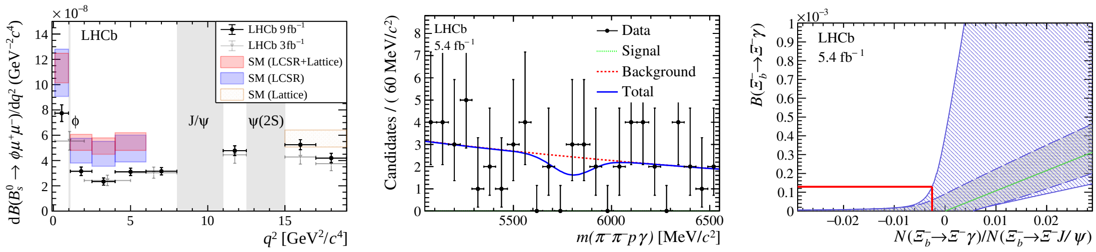

Figure 1: Distribution of the differential branching fraction $\mathrm{d}\mathcal{B}(B^0_s \to \phi\mu^+\mu^-)/\mathrm{d}q^2$ overlaid with SM predictions (left), invariant mass $m(\pi^-\pi^-p\gamma)$ in the final states for $\Xi_b^- \to \Xi^-\gamma$ decays (middle), and the confidence interval at 95% CL showing the upper limit for $\mathcal{B}(\Xi_b^- \to \Xi^-\gamma)$ as a function of the $\frac{N(\Xi_b^-\to\Xi^-\gamma)}{N(\Xi_b^-\to\Xi^- J/\psi)}$ ratio (right).

The search for the radiative b-baryon decay $\Xi_b^- \to \Xi^-\gamma$, which proceeds through a $b \to d\gamma$ transition, is presented, using 5.4 fb^{-1} of integrated luminosity of pp collisions at a centre-of-mass energy of 13 TeV [8]. Due to the spin 1/2 ground state, absence of flavor mixing and the presence of two spectator quarks, this radiative decay of b-baryons could provide access to the photon polarization by means of an angular analysis of the decay products. The normalization mode used in this analysis is $\Xi_b^- \to \Xi^- J/\psi$ decay, where $J/\psi \to \mu^+\mu^-$. This is the first attempt to measure this radiative decay channel. No signal being observed as shown in the middle of Fig. 1, an upper limit of $\mathcal{B}(\Xi_b^- \to \Xi^-\gamma) < 1.3 \times 10^{-4}$ is set at 95% confidence level on the branching fraction in the right of Fig. 1. The obtained result excludes the predictions from LCSRs [9] and is consistent with flavour-symmetry driven predictions [10].

3. Angular analysis of B^0, B^+ and B_s^0 decays

Angular analysis is another way to measure the properties of rare b decays and possibly reveal flavour anomalies. The dynamics of these decays can be fully described by four variables, namely the di-lepton invariant mass squared (q^2) and three angles $\overrightarrow{\Omega} = (\theta_l, \theta_K, \phi)$, where $\theta_l(\theta_K)$ is the angle of the lepton(kaon) with respect to the direction of flight of the mother B meson in the $\mu^+\mu^-(KH$, where H stands for hardons) centre-of-mass frame, and ϕ as the angle between the $\mu^+\mu^-$ and KH planes in the B meson centre-of-mass frame. The measured CP-observables are expressed as a function of four variables.

The angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ has been performed by the ATLAS and CMS collaborations with data collected during 2012 at a centre-of-mass energy of 8 TeV [11, 12], and an updated result was presented by the LHCb with data collected in 2011-2012 and 2016 at a centre-of-mass energy of 7, 8 and 13 TeV [13]. The results of the optimized CP-observable $P_5^{'}$ is presented in Fig. 2, and compared with the SM predictions. A possible discrepancy can be seen at low q^2 in Fig. 2.

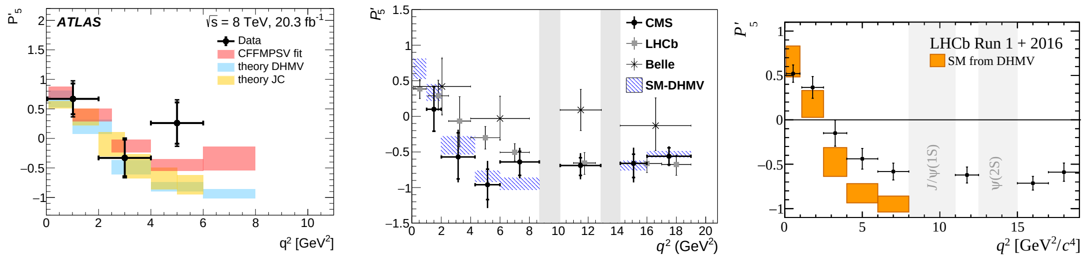

Figure 2: Distribution of the measured $P_5^{'}$ value compared with SM predictions from the theoretical calculations for ATLAS (left), CMS (middle) and LHCb (right) results in $B^0 \to K^{*0}\mu^+\mu^-$ decay.

Recent studies of $B^+ \to K^{*+}\mu^+\mu^-$ decays were presented by both the CMS and LHCb collaborations [14, 15]. The latest CMS result studied two sets of CP-averaged observables with data collected in 2012, showing consistency with the SM predictions. The same process was studied at LHCb using the data collected in 2011-2012 and 2015-2018, in which the full sets of CP-averaged observables are measured for the first time. The comparison between the results and the SM prediction is studied, and a global tension with the SM is observed which comfirms the tension seen in the other B^0 decay [13].

The latest angular result presented by the LHCb collaboration is the $B_s^0 \to \phi\mu^+\mu^-$ decay using 8.4fb^{-1} of data collected at a centre-of-mass energy of 7, 8 and 13 TeV [16]. The CP-asymmetries and CP-averages have been extracted from the angular distributions of the decay products. The S-wave contribution has been considered negligible. The distribution of the CP-average observable F_L (the ϕ longitudinal polarization fraction) is shown in the left of Fig. 3, where a tension is found in the low q^2 region. In order to compare with the SM prediction, CP-averages are considered, showing tension with the SM hypothesis at the 1.9σ level (right of Fig. 3).

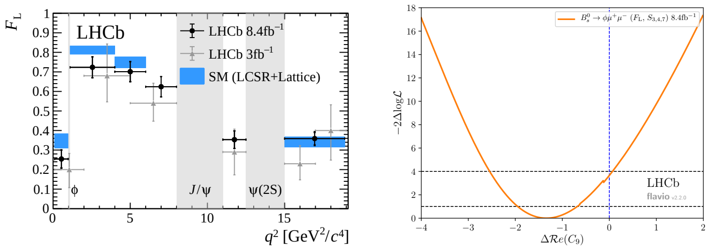

Figure 3: Distribution of the measured CP-observable F_L compared with SM predictions (left), and the logarithmic likelihood for the scan over $\Delta\mathcal{R}e(\mathcal{C}_9)$(right) in $B_s^0 \to \phi\mu^+\mu^-$ decays.

4. Test of lepton universality in beauty-quark decays

The uncertainties coming from form-factors cannot be neglected in branching fraction measurements and angular analysis. A distinctive feature of the SM is that the different leptons have the same interaction strengths, which is known as 'lepton flavor universality (LFU)'. The way to test the LFU with the branching fraction's ratio can cancel the theoretical uncertainties. This analysis, performed by the LHCb collaboration, presents evidence for the breaking of lepton universality in $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ decays, with 9 fb^{-1} of data collected at centre-of-mass energy of 7, 8 and 13 TeV [17]. The measurement of R_K ratio (namely the branching ratio between $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ decays), which using the double ratio adding the information from the control mode $B^+ \to K^+J/\psi(l^+l^-)$, follows essentially identical procedure in the previous measurement [18]. The distributions of the signal candidates in data are shown in Fig. 4, together with the measured R_K ratio compared with other experiments' results. The precision superseded the previous LHCb analysis [18] with a tension of 3.1σ with the SM.

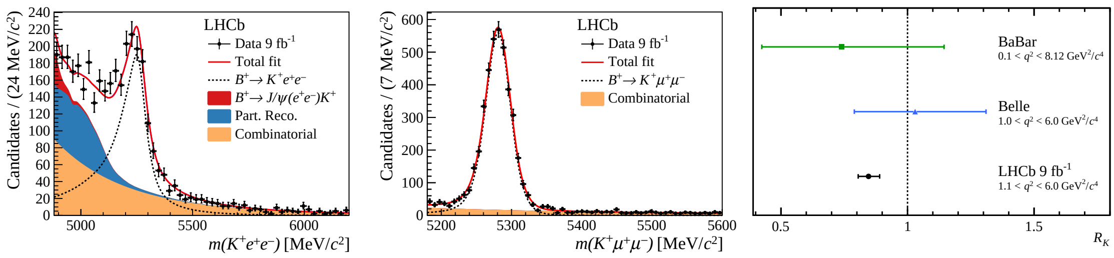

Figure 4: Distribution of the invariant mass $m(K^+l^+l^-)$ with electron(left) and muon pairs(middle) in the final states for $B^+ \to K^+l^+l^-$ decays. The comparison between R_K measurements(right) is presented.

5. Conclusions

Results of the studies performed by ATLAS, CMS and LHCb of the rare b-hadron decays through $b \to s/d$ transition have been presented. The results are compatible with SM predictions with a tension below or around 3σ. Considering global fit results [1, 19] with different experiments, a larger significance deviation appears. Many more measurements of rare b-hadron decays are in progress, with larger data samples to be collected in the future at CERN LHC. The future of rare decays to discover the hints of NP is bright.

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