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Latest rare decay results from LHCb

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Summary. — Rare decays of B mesons and τ leptons are studied using up to $2\,\mathrm{fb}^{-1}$ of pp collisions collected by the LHCb experiment in 2011 and 2012. We present results of branching ratios; angular distributions and CP and isospin asymmetries.

PACS 14.40.Nd – Bottom mesons.
PACS 14.60.Fg – Taus.

1. – Introduction

Rare decays are by definition suppressed in the Standard Model (SM). In some of the processes studied here, the suppression is due to the fact that flavour-changing neutral currents (FCNC) are forbidden at tree level within the SM. In others, the source of the suppresion is that the processes are lepton-flavour violating (LFV).

The study of rare decays provides powerful tests of both the SM and new physics (NP) models, as new particles from NP can give rise to diagrams with amplitudes competing to that of the SM, hence affecting properties of the decays in sizeable manners. Several rare B meson and τ decays have been studied in LHCb, by measuring not only branching ratios (BR), but also angular distributions and CP and isospin asymmetries. The measurements reported here make use of $1\,\mathrm{fb}^{-1}$ of pp collisions collected at a center-of-mass energy of 7 TeV in 2011 unless stated otherwise.

2. – Measurement of branching fractions

2·1. *Branching ratio of* $B^+ \to \pi^+\mu^+\mu^-$. – The reaction $b \to dl^+l^-$ has never been observed before LHC. A search of the mode $B^+ \to \pi^+\mu^+\mu^-$ has been perforened at LHCb. The SM prediction for this mode is $BR(B^+ \to \pi^+\mu^+\mu^-) = 2.0 \pm 0.2 \times 10^{-8}$ [1], while the previous experimental 90% confidence level (CL) limit was more than a factor three larger [2]. The result obtained is $BR(B^+ \to \pi^+\mu^+\mu^-) = (2.3 \pm 0.6(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-8}$ [3]. The probability of a background-only fluctuation is at the level of 5.2σ.

TABLE I. – 95% *CL BR limits in the Majorana neutrino modes studied.*

Mode	BR upper limit
$B^- \to D^+\mu^-\mu^-$	6.9×10^{-7}
$B^- \to D^{*+}\mu^-\mu^-$	2.4×10^{-6}
$B^- \to \pi^+\mu^-\mu^-$	1.3×10^{-8}
$B^- \to D_s^+\mu^-\mu^-$	5.8×10^{-7}
$B^- \to D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}

2˙2. *Branching ratio of* $B_s^0 \to \mu^+\mu^-$ *and* $B^0 \to \mu^+\mu^-$. – The dominant contribution to these modes in the SM stems from the Z-penguin diagram, while the box diagram is suppressed by a factor $|m_W/m_t|^2$. The Higgs annihilation diagram has a negligible contribution (about 1/1000). These are FCNC modes which, in addition, are also helicity suppressed. Hence the SM expectations are as small as $BR(B_s^0 \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$ and $BR(B^0 \to \mu^+\mu^-) = (0.107 \pm 0.01) \times 10^{-9}$ [4].

These BRs are very sensitive to NP with new scalar or pseudoscalar interactions, as well as to models with an extended Higgs sector and high $tan\beta$. Experimental limits previous to LHC were one order of magnitude away from the SM prediction.

In LHCb, the search for these decay modes is performed on the full data sample collected in 2011 and half of that collected in 2012 (a total of $2\,\text{fb}^{-1}$). The sensitivity of the analysis is enhanced by assigning to each B candidate a likelihood to be signal or background-like in a two-dimensional space [5]. The two variables used are the invariant mass and a multivariate classifier based on nine variables describing event topology and kinematics.

Evidence is found for the first time ever for the mode $B_s^0 \to \mu^+\mu^-$, yielding $BR(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.4}_{-1.2}(\text{stat.})^{+0.5}_{-0.3}(\text{syst.})) \times 10^{-9}$. The probability of a background-only fluctuation corresponds to 3.5σ.

For the case of $B^0 \to \mu^+\mu^-$, a 95% CL limit is set at $BR(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$. This is the current World-best limit.

2˙3. *Search for Majorana neutrinos in B meson decays.* – LHCb has performed a search in $1\,\text{fb}^{-1}$ from 2011 for heavy Majorana neutrinos in decays with two same-charge leptons in the final state. These decays are forbidden in the SM but allowed if Majorana neutrino-like particles can enter the loops.

In some processes, like $B^- \to D^{(*)+}\mu^-\mu^-$, the neutrino would enter the diagrams virtually, hence the analysis is sensitive to any neutrino mass. In other decays like $B^- \to h^+\mu^-\mu^-$, with $h^+ = \pi^+, D_s^+$, or $B^- \to D^0\pi^+\mu^-\mu^-$, the neutrino contributes on-shell, so the search is restricted to neutrino masses allowed by the kinematics of the decay. No signal is observed in either channel and the limits obtained [6] are shown in table I.

2˙4. *Search for lepton-flavour violating* τ *decays.* – LFV happens in the SM because of neutrino oscillations. It is an extremely suppressed phenomenon and way beyond current experimental sensitivities. In some NP models, however, it can be enhanced by huge factors. For example, Little Higgs models predict $BR(\tau^- \to \mu^-\mu^+\mu^-) \sim 10^{-7}$ [7]. The best previous experimental limit from Belle is $BR(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$ at 90% CL [8].

LHCb profits from the large τ production cross section at the LHC. After a loose selection, events are classified in a three-dimensional space formed by the invariant mass and two multivariate operators, one for PID information and the other for geometrical and kinematical variables. The resulting measurement is $BR(\tau^- \to \mu^+\mu^-\mu^-) < 7.8 \times 10^{-8}$ at 95% CL [9], which is comparable with the previous best limits.

In addition, LHCb sets the following first-ever limits at 95% CL [10]: $BR(\tau^- \to \bar{p}\mu^+\mu^-) < 4.5 \times 10^{-7}$ and $BR(\tau^- \to p\mu^-\mu^-) < 6.0 \times 10^{-7}$.

3. – Radiative decays

In the SM, B radiative decays are largely dominated by electromagnetic penguins transitions. Extensions of the SM predict additional one-loop contributions which can modify the BRs, but also give raise to interference and hence new sources of CP violation.

LHCb observes 5279 ± 93 $B^0 \to K^*\gamma$ and 691 ± 36 $B_s^0 \to \phi\gamma$ candidates, respectively [11]. These are the largest samples of rare radiative B^0 and B_s^0 decays collected so far by a single experiment.

LHCb has measured $BR(B^0 \to K^*\gamma)/BR(B_s^0 \to \phi\gamma) = 1.23 \pm 0.006(\text{stat.}) \pm 0.04(\text{syst.}) \pm 0.10(f_s/f_d)$, where the latest uncertainty is due to uncertainty on B hadronization fractions. This is the most precise measurement of this ratio, and it is compatible with the SM expectation of 1 ± 0.2 [12].

Another World-best measurement performed is $A_{CP}(B^0 \to K^*\gamma) = (0.8 \pm 1.7(\text{stat.}) \pm 0.9(\text{syst.}))\%$, which is compatible with the SM expectation of a small asymmetry.

4. – Study of $b \to s\mu^+\mu^-$ transitions

4·1. *Angular observables in* $B^0 \to K^*\mu^+\mu^-$. – This reaction is a highly sensitive probe for new right handed currents and new scalar and pseudoscalar couplings.

The most prominent observable is the forward-backward asymmetry (A_{FB}), which refers to the fraction of events in which the μ^+ flies forward and backward with respect to the K^* direction in the $\mu^+\mu^-$ rest frame. A_{FB} varies with the invariant mass-squared of the dimuon pair (q^2) and in the SM it changes sign at a point at which the leading hadronic uncertainties cancel.

The LHCb analysis uses several control samples to limit the dependence on MC in terms of trigger corrections, selection, reconstruction efficiencies, and acceptance. The selection is based on BDTs. The yield is of 900 events,which is more than BaBar, Belle, and CDF combined.

The angular analysis is based on the fact that the decay can be described as a function of three angles and the dimuon invariant mass and parametrized in terms of several angular observables, like the A_{FB}, or the fraction of longitudinally-polarized K^*, F_L. All the observables are measured as a function of q^2, and the results [13] for these two particular examples are shown in fig. 1.

The LHCb results are all compatible with the SM predictions, and are the most precise to date. In particular, LHCb has measured for the first time the zero crossing point of A_{FB} to be $q_0^2 = 4.9^{+1.1}_{-1.3}\,\text{GeV}^2/c^4$.

4·2. *CP asymmetry in* $B^0 \to K^*\mu^+\mu^-$. – The direct CP asymmetry relating the $B^0 \to K^*\mu^+\mu^-$ and $\bar{B}^0 \to \bar{K}^*\mu^+\mu^-$ decay widths is predicted to be $A_{CP}(B^0 \to K^*\mu^+\mu^-) \sim 10^{-3}$ in the SM [14,15]. NP models predict enhancements up to $A_{CP}(B^0 \to K^*\mu^+\mu^-) \sim 0.15$ [16].

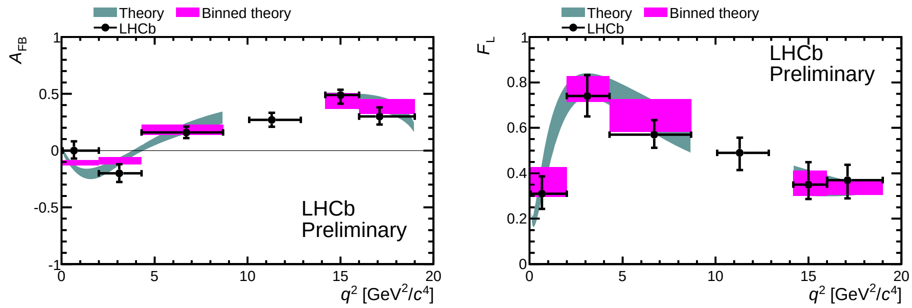

Fig. 1. – The A_{FB} and F_L observables as a function of q^2 for $B^0 \to K^*\mu^+\mu^-$.

The measurement in LHCb yields $A_{CP}(B^0 \to K^*\mu^+\mu^-) = 0.072 \pm 0.040(\text{stat.}) \pm 0.005(\text{syst.})$, which is compatible with the SM prediction, with an uncertainty which is half of that achieved at the B factories.

4·3. *Isospin asymmetry in* $B^{0/+} \to K^{(*)(+)}\mu^+\mu^-$. – Two isospin asymmetries are studied at LHCb:

$$A_I(K^*) \equiv \frac{\Gamma(B^0 \to K^{*0}\mu^+\mu^-) - \Gamma(B^+ \to K^{*+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{*0}\mu^+\mu^-) - \Gamma(B^+ \to K^{*+}\mu^+\mu^-)}$$

and

$$A_I(K) \equiv \frac{\Gamma(B^0 \to K^0_s\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^0 \to K^0_s\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}\,.$$

At leading order, these asymmetries are expected to vanish in the SM. Isospin breaking effects are sub-leading $1/m_b$ effects, which are difficult to estimate due to unknown power corrections. The prediction is $A_I(K^*) \sim 1\%$ for $q^2 < m^2(J/\psi)$ and $A_I(K^*) \sim 10\%$ for $q^2 \to 0$. For $A_I(K)$ there is no quantitative prediction beyond the expectation that it should be vanishingly small.

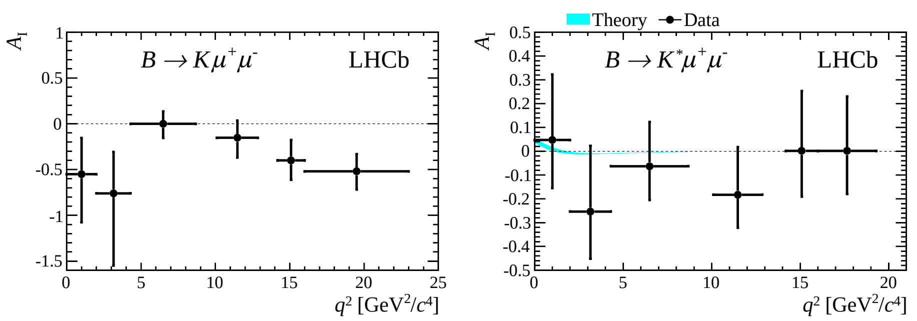

Fig. 2. – The $A_I(K)$ (left) and $A_I(K^*)$ (right) isospin asymmetries as a function of q^2.

The LHCb measurements as a function of q^2 [17] are shown in fig. 2. $A_I(K^*)$ is compatible with the SM expectation, but $A_I(K)$ is found to be significatively negative at low and high q^2. These regions are far from the charmonium resonances and therefore are theoretically well predicted. This is consistent with what seen at previous experiments, but inconsistent with the naive expectation of $A_I(K) \sim 0$ at the 4.4σ level.

5. – Conclusions

LHCb has dramatically reduced the room for NP in many observables related with rare decays. This is the case for $BR(B^0_S \to \mu^+\mu^-)$, for which LHCb obtained the first evidence, and for angular distributions and asymmetries in $b \to s\mu^+\mu^-$ transitions. A 4.4σ discrepancy with the null expectation is observed for the isospin asymmetry in some $b \to s\mu^+\mu^-$ modes.

LHCb has published World-best measurements of branching ratios and CP asymmetries for radiative B decays, with no deviations from the SM expectations.

Concerning LFV τ decays, with $1\,\text{fb}^{-1}$ LHCb approaches the B factory sensitivities in $BR(\tau^- \to \mu^+\mu^-\mu^-)$, and provides first-ever measurements of $BR(\tau^- \to \bar{p}\mu^+\mu^-)$ and $BR(\tau^- \to p\mu^-\mu^-)$.

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