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# Testing the Standard Model with rare decays at the LHCb.

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**Abstract.** The study of rare decays of B, D and K mesons (as well as $\tau$ leptons) can provide either very stringent tests for the Standard Model or excellent opportunities to search for hints of new physics beyond the SM. A review of the recent results of studies of such rare decays from analysis of *pp* collision data recorded at the LHCb experiment at CERN, is presented. All decays channels studied so far are in agreement with SM predictions.

## 1. Introduction

The LHCb experiment [1] at CERN's Large Hadron Collider (LHC) is focused on the study of b-quark hadrons to perform precision measurements of CP violating observables and rare decays that could unravel possible contributions from new physics (NP) beyond the Standard Model (SM). At the LHC proton-proton (*pp*) collision energies, charmed mesons and tau leptons are also copiously produced (at the level of b-hadrons or higher), and therefore, the corresponding equivalent observables can also be studied. These proceedings concentrate on key measurements of rare decays, while the measurements on CP violation observables are described on separate proceedings contribution [2]. The LHCb detector, described elsewhere [1], has been performing extremely well in the first LHC runs. With around 99% of operational readout channels and approximately a 95% of data taking efficiency, the LHCb experiment has been able to fully exploit the provided luminosity delivered by the LHC accelerator. The measurements presented here, unless mentioned otherwise, have been performed using the data set, corresponding to an integrated luminosity of 1.0 $\mathrm{fb}^{-1}$ of *pp* collisions collected at a centre-of-mass energy of 7 TeV during 2011. Roughly an additional 2 $\mathrm{fb}^{-1}$ of data at a centre-of-mass energy of 8 TeV have been collected during 2012 and, therefore, some of the analyses here presented might reach an increased sensitivity, once the entire data set is analysed.

The study of very suppressed, within the SM, beauty and charmed meson decays searching for any possible unpredicted enhancement of their respective branching fractions (BF) , is an excellent place to look for hints for NP processes, beyond the SM, that could provide extra contributions to the otherwise very suppressed decay amplitudes. Those extra contributions could also affect the Lorentz structure of the decay amplitudes and therefore the angular distributions of the decay products become also a very sensitive observable. Processes like $B_d \to K^{*0}\gamma$, $B_s \to \phi\gamma$, $B \to K^{*}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $B^+ \to \pi^+\mu^+\mu^-$, $B^0/B_s \to \mu^+\mu^-$, $K_s \to \mu^+\mu^-$ and $D \to \mu^+\mu^-$ are examples of flavour-changing neutral current processes (FCNC) which are expected to be very rare, since they cannot occur at tree level in the SM.

Additionally, searching for processes that are directly forbidden by the SM, such as those violating baryon (BNV) or lepton number conservation (or both) like $\tau \to p\mu^+\mu^-$ or $B^+ \to h\mu^+\mu^+$, would, if found, be unequivocally a signature of physics beyond the SM. Another example would be the $\tau$ lepton decay $\tau^- \to \mu^-\mu^+\mu^-$, which would correspond to lepton-flavor violating (LFV) decays, which are essentially forbidden in the SM because they can occur only through lepton mixing.

## 2. Rare B, D and K meson decays.

The SM decays of $B_d \to K^{*0}\gamma$ and $B_s \to \phi\gamma$ occur through a FCNC transition involving loop diagrams. In LHCb, the relative ratio of BFs of the former decay channels, that only differ in the B meson spectator quark, is measured to be [3]

$$\frac{BF(B_d \to K^{*0}\gamma)}{BF(B_s \to \phi\gamma)} = 1.23 \pm 0.06\ (\text{stat.}) \pm 0.04\ (\text{syst.}) \pm 0.10\ (f_s/f_d),$$

where the first uncertainty is statistical, the second systematic, and the third is associated with the ratio of fragmentation fractions $f_s/f_d$. This result is in good agreement with the theoretical prediction of 1.0 ± 0.2 [4].

Since the initial B meson flavour in the $B_d \to K^{*0}\gamma$ decay channel is self tagged through the ulterior decay process $K^* \to K^+\pi^-$, the direct CP asymmetry of this decay can be easierly measured. Even though, in the SM, this CP asymmetry is predicted to be below 1% level [5], some NP models [6] predict it to be enhanced up to values around 15%. In LHCb, the most precise measurement to date of this CP asymmetry results in [7]

$$A_{CP}(B^0 \to K^{*0}\gamma) = (\ 0.8 \pm 1.7\ (\text{stat.}) \pm 0.9\ (\text{syst.})\ )\ \%,$$

in agreement with the SM expectation [5]. Similarly the CP asymmetry of the $B^0 \to K^{*0}\mu^+\mu^-$ decay channel is measured to be [8]

$$A_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = \text{-}\ 0.072 \pm 0.040\ (\text{stat.}) \pm 0.005\ (\text{syst.}),$$

which is also consistent with the SM prediction [9].

Studying the same former B meson decay channel, it is possible to access other observables sensitive to possible NP effects. For instance the forward-backward asymmetry defined in bins of invariant mass squared of the dimuon system $A_{FB}(q^2 = m^2_{\mu^+\mu^-})$ flips sign, according to the SM, at a precisely predicted value of $q^2$ between 4 - 4.3 GeV$^2$/c$^4$ [10]. The zero-crossing point of the forward-backward asymmetry is measured in LHCb and it is determined to be $q_0^2 = 4.9^{+1.1}_{-1.3}$ GeV$^2$/c$^4$. Also, the measured differential branching fractions (in $q^2$ bins) and other angular observables sensitive to NP are measured to be consistent with the SM predictions [11]. The same observables have been studied and measured in the similar, but charged B meson decay, $B^+ \to K^+\mu^+\mu^-$ channel [12], and no significant inconsistency with the SM predictions [13] has been found. Comparing the (neutral and charged) B meson decays $B^0 \to K^{(*)0}\mu^+\mu^-$ and $B^+ \to K^{(*)+}\mu^+\mu^-$, it is possible to measure the so-called isospin asymmetry, defined as

$$\mathrm{A}_I = \frac{\mathbf{BF}(B^0 \to K^{(*)0}\mu^+\mu^-)\ -\ (\tau_0/\tau_+)\mathbf{BF}(B^+ \to K^{(0)+}\mu^+\mu^-)}{\mathbf{BF}(B^0 \to K^{(*)0}\mu^+\mu^-)\ +\ (\tau_0/\tau_+)\mathbf{BF}(B^+ \to K^{(0)+}\mu^+\mu^-)},$$

in bins of $q^2$. The LHCb measurements for the $B \to K^*\mu^+\mu^-$ channels are in agreement with the SM expectations, while the isospin asymmetry measurement for the $B \to K\mu^+\mu^-$ channels, if integrated over the whole $q^2$ range, show a disgreement at the level of 4.4 standard deviations from the SM prediction of a 0 value [14]. These results are nevertheless consistent with previous measurement by other experiments [15].

Another rare B meson decay studied is the $B_s \to \phi\mu^+\mu^-$, whose BF is measured [16], normalized to the decay of $B_s \to \phi\ J/\psi$ (where $J/\psi \to \mu^+\mu^-$) , to be

$$\mathrm{BF}(B_s \to \phi\mu^+\mu^-) = (\ 0.78 \pm 0.10\ (\mathrm{stat.}) \pm 0.06(\mathrm{syst.}) \pm 0.28\ (\mathrm{BF})\ ) \times 10^{-6},$$

where the first error is statistical, the second error is systematic and the third error is due to the uncertainty on branching fractions, in this case $\mathrm{BF}(J/\psi \to \mu^+\mu^-)$.

The rarest B meson decay ever observed, that is, the $B^+ \to \pi^+\mu^+\mu^-$ decay, was first observed in LHCb. This decay corresponds to a FCNC transition from a $b$ to a $d$ quark type. Its BF was measured in LHCb to be $\mathrm{BF}(B^+ \to \pi^+\mu^+\mu^-) = (\ 2.4 \pm 0.6\ (\mathrm{stat.}) \pm 0.2(\mathrm{syst.})\ ) \times 10^{-8}$, in agreement with the SM prediction [17].

One of the key LHCb measurements and an excellent B meson decay channel to search for hints of NP beyond the SM is the $B^0/B_s \to \mu^+\mu^-$. These decays are doubly suppressed since they correspond to a FCNC trasition and the amplitudes of these processes are helicity supressed. The SM prediction [18] for these decay channels are of the order of $10^{-9}$ - $10^{-10}$. Therefore, if any significant signal is found, implying an enhancement of the predicted BFs, it could be a very strong hint for NP. The search for these decay channels has been carried out using a data set of $pp$ collisions of approximately 2fb$^{-1}$, collected by the LHCb experiment during 2011 and 2012 with a centre of mass energy of 7 TeV and 8 TeV respectively. Evidence for signal, with a significance of 3.5 standard deviations, is found [19] in the $B_s \to \mu^+\mu^-$ decay and the corresponding BF is measured to be

$$\mathrm{BF}(B_s \to \mu^+\mu^-) = (\ 3.2\ \ {}^{+1.5}_{-1.2}\ ) \times 10^{-9},$$

in impressive agreement with the precise SM predictions. No significant signal yield is found in the $B^0 \to \mu^+\mu^-$ decay channel search [19], and the corresponding upper limit (UL) at 95 % confidence level (CL) is set at

$$\mathrm{BF}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}.$$

Similar analysis techniques have been used to look for other meson decays into a muon pair, that are as supressed as the B meson decays. Particularly the search for the decays of the $\mathrm{K}^0_s$ and $\mathrm{D}^0$ mesons has been carried out in LHCb. The $\mathrm{K}^0_s \to \mu^+\mu^-$ decay has a BF predicted by the SM [20] of the order of $10^{-12}$ while the $\mathrm{D}^0 \to \mu^+\mu^-$ BF is expected to be of the order of $10^{-11}$ [21]. No significant signal above the background level has been found in both decays [22] [23] and the corresponding UL on the BF's at 95% CL have been set at

$$\mathrm{BF}\ (\mathrm{K}^0_s \to \mu^+\mu^-) < 11 \times 10^{-9}$$
$$\mathrm{BF}\ (\mathrm{D}^0 \to \mu^+\mu^-) < 1.3 \times 10^{-8}$$

The result for the $\mathrm{K}^0_s$ decay is a improvement of a factor 30 with respect to previous measurements, whilst in the result on the $\mathrm{D}^0$ decay, an order of magnitude improvement is achieved with respect from the previous best limit [24].

## 3. Search for lepton number and flavor violation decays.

Lepton flavor violation is allowed in the SM when accomodating the neutrino oscillations. Nevertheless the BF for the LFV decay $\tau^- \to \mu^-\mu^+\mu^-$ predicted by the SM is beyond the actual experimental scope (some estimates consider it of the order of $10^{-54}$). That might not be the case if NP models are considered, since some of them predict enhancements in its BF up to the $10^{-10}$ - $10^{-8}$ range. With a production cross section of $\tau$ leptons of approximately 22$\mu$b within the LHCb acceptance, nearly $10^{11}$ $\tau$ leptons are produced per fb$^{-1}$ of collected $pp$ collision data at a centre of mass energy of 7 TeV (mostly from $\mathrm{D}^+_s$ decays). No signal has been observed as a result of analysing this data set, and the corresponding UL on the BF at 95% CL has been set at [25]

$$\mathrm{BF}(\tau^- \to \mu^-\mu^+\mu^-) < 7.8 \times 10^{-8}.$$

Additionally a search is performed for the lepton and baryon number violating decays $\tau \to p\mu^+\mu^-$ and $\tau \to \bar{p}\mu^+\mu^-$. If found, this kind of process could provide clues for extra (beyond SM) sources of BNV, that could shed light into the explanation for the matter/antimatter univers asymmetry. Unfortunately, no signal is found in the data [26] and the corresponding UL at 95% CL are set to

$$\mathrm{BF}(\tau \to p\mu^+\mu^-) < 4.5 \times 10^{-7}$$
$$\mathrm{BF}(\tau \to \bar{p}\mu^+\mu^-) < 6.0 \times 10^{-7}.$$

Finally, a search for Majorana type neutrinos in $\mathrm{B}^-$ decays in final states containing hadrons plus a $\mu^-\mu^-$ pair have been performed using 0.41 $\mathrm{fb}^{-1}$ of data collected with LHCb detector in *pp* collisions at a centre of mass energy of 7 TeV. No signals are found and the UL are set on Majorana neutrino production as a function of mass, and also on $\mathrm{B}^-$ decay branching fractions [27].

## 4. Summary and Outlook.

The LHCb experiment is revealing itself as a fantastic experiment to look ar rare B, D and K meson decays that are very sensistive NP. So far, the analysis of the data have resulted in measurements, all of them consistent with the SM predictions and, therefore, in establishing very strong constraints for NP models beyond the SM. No evidence for LFV neither for LNV(BNV) has been found in analyzing specific $\tau$ lepton and B meson decays. Nevertheless, the precision of the current measurements is bound to be improved with the addition in the physics analysis of data set of *pp* collisions at a centre of mass energy of 8 TeV gathered in LHCb during 2012. The energy of the LHC is expected to increase up to 13 TeV, after a shutdown period of about two years (2013-2014), and an extra $5\mathrm{fb}^{-1}$ are expected to be collected, allowing for a further improvement of the measurements precision and physics reach. An upgrade of the LHCb detector is foreseen during the period 2018-2019, just after a second long shut down of the LHC accelerator. The main goal of that upgrade is to operate the experiment at higher instantaneous luminosity (increasing the data collected) and to improve further the trigger efficiency for heavy quark decays to purely hadronic final states.

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