# Search for New Physics with rare decays at LHCb

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**Abstract**

We discuss the potential of the LHCb experiment to study rare $B$ decays and their impact on various scenarios for New Physics. Some possible experimental strategies are presented.

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## 1. Introduction

A major aim of the LHC is to discover new physical interactions and to probe their nature. There are two main approaches to New Physics (NP) searches: direct and indirect. Within the direct approach, one could expect new particles to be produced and observed as real paticles at energy frontier machines (e.g. LHC). But, the indirect search is also powerful tool, since new particles can give additional contributions in to loop or box diagrams through which the decays can take place: their existence could then be probed by measuring the decay rate and kinematic distributions. Rare decays in the beauty sector encompass a wide range of processes offering a valuable tool in the search for NP as well as in precision measurements of the Standard Model (SM) parameters, e.g. the Cabbibo-Kobayashi-Maskawa (CKM) matrix elements. The focus of this paper is made on the processes with the final states containing photons or leptons in addition to daughter hadron(s). The examples considered include the electromagnetic or electroweak penguin decays $B \to K^*\gamma$, $B_s \to \phi\gamma$, $B \to K^*\ell^+\ell^-$ ($\ell = \mu$ or $e$) and the dilepton decay $B_s \to \mu^+\mu^-$. Most of these rare decays correspond to diagrams with internal loops or boxes leading to effective flavor-changing neutral current (FCNC) transitions. Presence of new virtual particles (e.g. supersymmetric

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ones) may manifest itself in altering the decay rate, $CP$ asymmetry and other observable quantities. Exciting new perspectives for the $B$ physics emerge owing to the large statistics to be collected by the LHCb experiment, which will enable us to enter a new realm of high precision studies of rare $B$ decays.

## 2. LHCb experiment

The LHCb experiment features a forward magnetic spectrometer with a polar angle coverage of 15–300 mrad and a pseudo-rapidity range of $1.8 < \eta < 4.9$ [1]. In order to maximize the probability of a single interaction per bunch crossing, it was decided to limit the luminosity in the LHCb interaction region to $\sim 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$. This has the additional advantage of limiting the radiation damage due to the high particle flux at small angles. The $b\bar{b}$ cross-section at the nominal LHCb luminosity is large enough to produce $\sim 10^{12}$ $b\bar{b}$ pairs per year ($10^7$ s).

The detector consists of a silicon vertex locator, followed by a first Ring Imaging Cherenkov Counter (RICH), a silicon trigger tracker, a 4 Tm spectrometer dipole magnet, tracking chambers, a RICH2 detector, a calorimeter system and a muon identifier. One of the main features is a versatile trigger with a 2 kHz output rate dominated by $pp \to b\bar{b}X$ events. The reconstruction of rare $B$ decays at LHCb is a challenge due to their small rates and large backgrounds from various sources. The $B$-mesons are separated from the large background produced directly at the interaction point in a detached vertex analysis by exploiting the relatively long lifetime of $B$-meson and a large average transverse momentum ($p_T$) of the $B$-meson decay products. Therefore, the signature for a $B$ event is based upon selection of particles with high $p_T$ coming from a displaced vertex. The most critical background is the combinatorial background from $pp \to b\bar{b}X$ events, containing secondary vertices and characterized by high charged and neutral multiplicities.

## 3. The search for $B_s \to \mu^+\mu^-$

The decay $B_s \to \mu^+\mu^-$ can potentially be a window on the existence of new particles and provide a constraint on the parameter space of NP. It is highly suppressed in the SM, since it can only be produced through a box diagram or a $Z$ penguin. Due to its sensitivity to NP contributions the branching ratio of the very rare decay $B_s \to \mu^+\mu^-$ is one of the most interesting measurements using the first data from the LHC accelerator. The

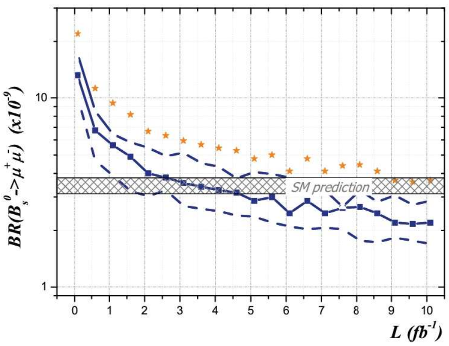


Figure 1: 3 $\sigma$ (blue squares) or 5 $\sigma$ (orange stars) observation reach for BR $B_s \rightarrow \mu^+\mu^-$ as a function of the integrated luminosity (for 14 TeV collisions).

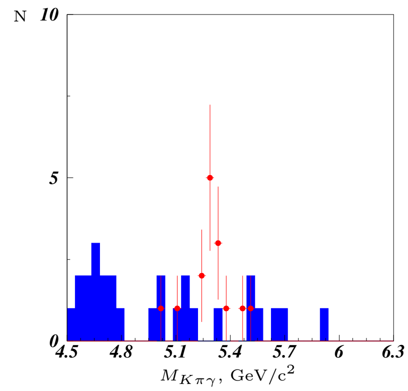


Figure 2: The invariant mass distribution for selected $B_d^0 \rightarrow K^*\gamma$ candidates (the blue filled histogram represents combinatorial background; $\sqrt{s} = 14$ TeV).

current SM prediction is $Br(B_s \rightarrow \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$ [2] while the present experimental limit given by Tevatron is $Br(B_s \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-8}$ at 90% C.L. [3]. In some new physics scenarios, the branching fraction can be enhanced by a high power of $\tan\beta$ (e.g. $Br \propto \tan^6\beta$), where $\tan\beta$ is the ratio of the Higgs vacuum expectation values. For large values of $\tan\beta$, the branching fraction could be enhanced by two orders of magnitude, which is currently within the reach of the CDF and D0 experiments.

The large background (opposite sign muons originating from $B$ decays or $B$ decays into hadrons which are misidentified as muons) expected in the search for this decay is kept under control thanks to an excellent tracking performance of LHCb (namely the invariant mass resolution for dimuons $\sim 18$ MeV/$c^2$), a good particle identification and good vertex resolution. The LHCb sensitivity as a function of integrated luminosity is shown in Fig 1. LHCb has the potential to claim a three standard deviation observation at the level of the SM prediction with $\sim 2$ fb$^{-1}$ whereas a five standard deviation observation would require about 10 fb$^{-1}$ [4].

## 4. The search for NP in $b \rightarrow s\gamma$ and $b \rightarrow s\ell^+\ell^-$

Phenomenologically the $b \rightarrow s\gamma$ and $b \rightarrow s\ell^+\ell^-$ decays are closely linked. SM calculations for these rare decays are performed using an effective Hamiltonian that is written in terms of several short-distance operators [5]. The process $b \to s\gamma$ is dominated by the photon penguin operator, with Wilson coefficient $C_7$, while $b \to s\ell^+\ell^-$ has contributions also from semileptonic vector and axial-vector operators with Wilson coefficients $C_9$ and $C_{10}$ respectively. To further pin down the values of these coefficients, it is necessary to exploit interference effects between the contributions from different operators. This is possible in the exclusive decay $B \to K^*\ell^+\ell^-$ decays by measuring the forward-backward asymmetry $A_{FB}(q^2)$ (a function of the invariant mass squared of the $\ell^+\ell^-$ system). The invariant mass of the lepton pair and three angles between the decay products are required to describe a $B \to K^*(\to K^+\pi^-)\ell^+\ell^-$ event. The distributions of these angles can be computed from asymmetries and transversity amplitudes [9], which are in turn functions of the Wilson coefficients.

### *4.1. Electroweak penguin decay* $B_d^0 \to K^*\mu^+\mu^-$

The decay $B_d^0 \to K^*\mu^+\mu^-$ is loop-suppressed in the SM, $Br(B_d^0 \to K^*\mu^+\mu^-) = (1.22^{+0.38}_{-0.32} \times 10^{-6})$ [6]. NP contributions could drastically change the shape of the $A_{FB}(q^2)$ curve. For example, the sign of $A_{FB}(q^2)$ can be flipped, the zero-crossing point may be shifted, or $A_{FB}(q^2)$ may not even cross zero [7]. The procedure is to measure the $A_{FB}$ asymmetry of the angular distribution of daughter $\mu^+$ relative to the $B$ direction in the $\mu^+\mu^-$ rest frame as a function of the $\mu^+\mu^-$ invariant mass. The expected number of events in one year of data taking ($2\ fb^{-1}$) by LHCb is 7200 ± 2100 (the error is due to the branching ratio), with a background-to-signal ratio $B/S < 0.5$ [8]. LHCb expects to extract the $C_9/C_7$ Wilson coefficients ratio from the value of the $\mu^+\mu^-$ invariant mass for which the $A_{FB}$ is equal to zero to a precision of 13% after 5 years of running (10 fb$^{-1}$) [10].

### *4.2. Radiative decays* $b \to s\gamma$

The polarization of the photons emitted in the $b \to s\gamma$ transition provides an important test of the SM which predicts left-handed photons with a tiny contamination of right handed photons at the level of $m_s/m_b$. In the LHCb experiment these radiative decays can be reconstructed in the modes $B_d \to K^*\gamma$, $B_s \to \phi\gamma$ or $\Lambda_b \to \Lambda\gamma$. The reconstruction procedures for $B_{d,s} \to K^*(\phi)\gamma$ decays are similar. To suppress the background from $B_{d,s} \to K^*(\phi)\pi^0$ in which the $\pi^0$ is misidentified as a single photon, a cut on the angle between the $B$ and the $K^+$ in the $K^*(\phi)$ rest frame is applied. The yield for 2 fb$^{-1}$ for $B_d^0 \to K^*\gamma$ is expected to be 68 $k$ reconstructed events with B/S = 0.71 ± 0.11. For $B_s^0 \to \phi\gamma$ decays the annual yield is estimated to be 11.5 $k$

Table 1: Annual yields and background-to-signal ratios for radiative $\Lambda_b$ decays (upper limits calculated at 90 % C.L.).

| channel | yield/2 $fb^{-1}$ | B/S |
|---|---|---|
| $\Lambda_b \to \Lambda\gamma$ | 750 | $< 42$ |
| $\Lambda_b \to \Lambda(1520)\gamma$ | $4.2 \times 10^3$ | $< 10$ |
| $\Lambda_b \to \Lambda(1670)\gamma$ | $2.5 \times 10^3$ | $< 18$ |
| $\Lambda_b \to \Lambda(1690)\gamma$ | $4.2 \times 10^3$ | $< 18$ |

with $B/S \ < 0.95$ at 95 % C.L [11]. The invariant mass distribution for selected $B_d^0 \to K^*\gamma$ candidates after 13 minutes of data taking is presented in Fig. 2. The expected signal yield for 2 fb$^{-1}$ integrated luminosity together with the estimate of $B/S$ ratios for radiative $\Lambda_b$ decays [12] are given in Table 1.

The radiative decay $B_s \to \phi\gamma$ is one of the benchmark channels in the physics programme of the LHCb experiment. It allows us to thest the SM through the indirect measurement of the photon polarization in $b \to s\gamma$ transitions. The photon polarization is observable through the interference between the mixing and the decay, which can only occur if the ratio between the right and left polarization amplitudes is not equal 0. The CP asymmetry is defined as:

$$A_{CP}(t) = \frac{\Gamma[\bar{B}_s \to \phi\gamma] - \Gamma[\bar{B}_s \to \phi\gamma]}{\Gamma[\bar{B}_s \to \phi\gamma] + \Gamma[\bar{B}_s \to \phi\gamma]} = -\frac{Ccos(\Delta m_s t) + Ssin(\Delta m_s t)}{A^{\Delta} sinh(\Delta\Gamma_s t/2) + cosh(\Delta\Gamma_s t/2)}, \quad (1)$$

where

$$S = \sin 2\psi \sin\varphi,$$
$$A^{\Delta} = \sin 2\psi \cos\varphi,$$
$$\tan\psi = \mid \frac{A(\bar{B}_s \to \phi^{CP}\gamma_R)}{A(\bar{B}_s \to \phi^{CP}\gamma_L)} \mid$$

and $\varphi$ is the sum of $B_s$ mixing and $CP-$odd weak phases for right and left amplitudes. For $B_s$-system, the parameter $A^{\Delta} \approx \sin 2\psi$, and the measurement of $A^{\Delta}$ determines the wrong-polarized photon fraction. With 2 fb$^{-1}$, the expected relative uncertainties are 0.22 for $A^{\Delta}$ and 0.1 for $\psi, S$ and $C$, hence stringent tests of the SM will already be possibile with this integrated luminosity [13].

## 5. Conclusions

The LHCb experiment has an excellent potential for the study of rare $B$ decays sensitive to New Physics in many Standard Model extensions. In the present work the capabilities to study exclusive $b \to s\gamma$ decays, the asymmetry $A_{FB}$ in the transition $B_d \to K^{\star 0}\mu^+\mu^-$ and the very rare decay $B_s \to \mu^+\mu^-$ have been shown.

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