Rare B decays at LHCb

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Abstract. Rare loop-induced decays are sensitive to New Physics in many Standard Model extensions. In this paper we discuss the potential of the LHCb experiment to very rare $B_s \to \mu^+\mu^-$ decays, radiative penguin $b \to s\gamma$ decays and electroweak penguin $b \to s\ell\ell$ decays. The experimental strategies and the expected sensitivities are presented.

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1 Introduction

Although the Standard Model (SM) is successful in explaining almost all experimental results of elementary particle physics, it is possible that physics beyond the SM exists just above the presently reachable energy scale. New Physics is expected to be accessible from rare decays where standard model contributions are suppressed enough to allow potential small effects to emerge. In this paper we will focus on the flavor-changing neutral currents (FCNCs) processes, which, in the Standard Model, are forbidden at the tree level and can proceed only via loop diagrams. If additional box and/or penguin diagrams with non-SM particles contribute to these processes, the complex couplings of new particles may result in an enhancement of decay rates or in the appearance of non-trivial CP-violating phases.

The LHC will be a copious source of B mesons, with a total $b\bar{b}$ cross-section of $\sim 500\ \mu b$. LHCb is a forward spectrometer for b physics. Its main features are a precise vertex detector, two RICH detectors and a versatile trigger with a 2 kHz output rate dominated by $b\bar{b}$ events. LHCb will operate at a luminosity of $L = 2 \times 10^{32} cm^{-2}s^{-1}$, corresponding to 2 fb^{-1} per year.

The reconstruction of rare b decays at LHC is a challenge due to the small rates and large backgrounds from various sources. The most critical is the combinatorial background from $pp \to b\bar{b}X$ events, containing secondary vertices and characterized by high charged and neutral multiplicities. The studies reported in this paper have been performed using fully simulated events.

2 Very rare decay $B_s^0 \to \mu^+\mu^-$

Given its simple experimental signature and the clear theoretical picture for its prediction, the measurement of the BR of the very rare decay $B_s^0 \to \mu^+\mu^-$ is an excellent probe of New Physics effects. This FCNC process is also helicity suppressed, resulting in a prediction for the SM branching ratio of $(3.55 \pm 0.33) \times 10^{-9}$. This branching ratio is known to increase as the sixth power of the ratio of the Higgs vacuum in MSSM expectation value, $\tan\beta$ [1]. Any improvement on the limit on this BR is therefore particularly important to probe large-$\tan\beta$ models. The anomalus muon magnetic moment measured at BNL disagrees with the SM expectation by 2.7σ. In the context of CMSSM at large $\tan\beta$ (~ 50), this indicates that the gaugino mass is in the range 400-650 GeV/c^2, that corresponds to a $B_s^0 \to \mu^+\mu^-$ branching ratio of $10^{-7} - 10^{-9}$. The present limit on the BR provided by Tevatron is $< 7.5 \times 10^{-8}$ at 90% CL, that is expected to improve up to $< 2.0 \times 10^{-8}$ by the end of the Tevatron run. This is still about 6 times higher than the SM expected value. Given the extremely low branching ratio of the signal, a detailed understanding of the background is crucial in this analysis. Several sources of background were considered: combinatorial background (two real muons that combine to form a signal candidate); misidentified hadrons and exclusive decays with very small branching ratios, that could simulate the signal.

A good invariant mass resolution is crucial to reduce the combinatorial background, but also to reduce the contamination of misidentified two-body decays. Good mass resolution also allows a clear separation between B_d and B_s decays. Good muon identification and good vertex resolution are also critical. The LHCb two-track vertex resolution is $\sim 110\ \mu m$ in the z direction, while the average precision of the track impact parameter is $\sim 40\ \mu m$. A Gaussian fit to the reconstructed invariant mass distribution for signal events gives a resolution of 18 MeV/c^2. The efficiency to identify real muons from B decays is $\sim 95\%$, while the probability to misidentify a hadron either due to the occupancy in muon chambers or because it decays in flight is below 1% for hadrons with momenta larger

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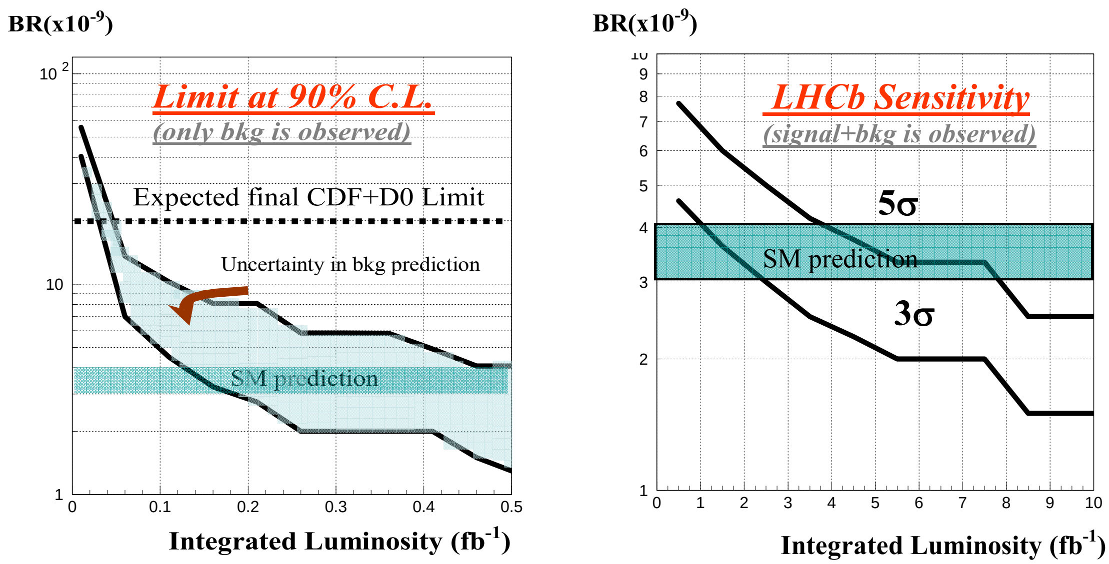

Fig. 1. Left: BR (10 ^{9}) exclusion at 90% con dence level as a function of the integrated luminosity (fb ^{1}), under the assumption that only background is present. Right: BR (10 ^{9}) observation (3) or discovery (5) as a function of the integrated luminosity (fb ^{1}).

than 10 GeV/c. The combined trigger e ciency, for signal events passing the selection used in the analysis, is greater than 90% .

The analysis is based on a very e cient soft preselection that removes a good fraction of the background while keeping most of the signal falling within the LHCb acceptance [2]. Each event is then weighted by its likelihood ratio on the relevant distributions. Three likelihoods were de ned: a geometrical likelihood that takes into account variables related to the vertex, pointing and isolation; the muon identi cation likelihood; and the invariant mass likelihood.

In Fig. 1 (left), the 90% CL exclusion region for the branching ratio is shown as a function of the integrated luminosity, under the assumption that only the expected background is observed. The two lines correspond to two background hypothesis (i.e., nominal and shifted values), and the region between them represents the uncertainty coming from the limited MC statistics. LHCb has the potential to exclude the interesting region between 10 ^{8} and the SM prediction with very little luminosity (0.5 fb ^{1}).

In Fig. 1 (right), the LHCb potential to discover a signal is shown as a function of the integrated luminosity. LHCb has the potential for a 3 (5) observation (discovery) of the SM prediction with 2 fb ^{1} (6 fb ^{1}) of data.

3 Radiative decays b ! s

The radiative penguin b ! s decay is another example of remarkable interest. Its total branching fraction is very sensitive to physics beyond the SM as it may be a ected by the presence of charged Higgs or SUSY particles in the loop. Presently, the world average is in good agreement with the theoretical SM prediction. Nevertheless, in the SM the emitted photon in radiative decays is expected to be predominantly left-handed; this SM prediction is still untested, and right-handed components arise in a variety of new physics models. No clarifying results have been obtained up to now due to limited statistics.

In principle, a test of the Standard Model can be made by measuring the direct CP violation that results in a di erence of the decay rates B ! X and B ! X . In SM the direct CP asimmetry is reliably predicted to be less than 1% ; however in some SM extensions the contribution from new particles in the loop could increase it up to 10% 40% [3]. Unfortunatly, inclusive decays are well described theoretically but are di cult to access experimentally; while exclusive cases are theoretically much more di cult to calculate.

A more sensitive test of the SM can be made by measuring the CP asymmetries from the interference of mixing and decay amplitudes in radiative B neutral decays when B^0_s and B^0_s are required to have transitions to the same nal state X ^{0} . If the photon is polarized, as predicted in the SM, the CP asymmetry from the mixing should vanish [4]. The current world average for this CP asymmetry is consistent with 0, but the errors are still large.

In the LHCb experiment, radiative b ! s decays can be reconstructed in the modes B ^{0} ! K ^{0} and B^0_s ! [5]. The main source of background is assumed to be bb inclusive events where at least one b-hadron is emitted in the LHCb acceptance region. The reconstruction algorithms and the o ine selection criteria for the decays B ^{0} ! K ^{0} , K ^{0} ! K $^{+}$ and B^0_s ! , ! K^{+}K are similar. Charged tracks have to be consistent with the requested particle identi cation and inconsistent with originating from the reconstructed primary vertex. Selected K ^{0} or candidates are combined with photon candidates of transverse energy larger than 2.8 GeV, in order to remove

Table 1. Annual yields and background-to-signal ratios for selective decays at LHCb. B=S ratios are limited by MC statistics.

Mode	Yield	B=S
B meson decays		
$B^0 \to K^0$	68000	< 0.6
$B^0_s \to$	11500	< 0.55
B baryon decays		
$_b \to$	750	< 42
$_b \to$ (1520)	4200	< 10
$_b \to$ (1670)	2500	< 18
$_b \to$ (1690)	2200	< 18
Electroweak decays		
$B^0 \to K^0_s$	18774	3
$B^0 \to eeK^0_s$	9240	5

low energy and ^{0}. The reconstructed B candidate is required to be compatible with coming from a primary vertex, which is a very powerful cut against combinatorial background. Finally, to suppress the correlated background from the decays $B^0 \to K^0\ ^0$ and $B^0_s \to\ ^0$, a cut on the K^0 and decay (helicity) angle with respect to the B direction is applied. The mass distributions of B candidates after the trigger and off-line selection are expected to be $(69.9 \quad 2.2)$ MeV$=c^2$ and $(70.9 \quad 2.1)$ MeV$=c^2$ respectively. The expected annual (2 fb^{1}) yields and background over signal ratios (B=S) are given in Tab. 1.

4 $_b \to$ polarization measurements

Radiative decays of polarized $_b$ baryons to $_b \to$ represent an attractive possibility to measure the helicity of the photon emitted in the $b \to s$ quark transition [6]. The photon polarization can be tested by measuring the angular distribution of the photon in the $_b$ decay or even through the angular distribution of the proton coming from the $\to p$ decay.

The study of this channel is challenging because the long lifetime of baryon means that it will typically traverse a large fraction of the tracking system before decaying. A possible solution is to consider decays to heavier resonances; the subsequent decay to K allows to trace back the decay of the $_b$. The event selection is similar to the one presented above for B mesons [7]. The expected event yields and B=S ratios for 2 fb^{1} are given in Tab. 1. It can be noted that the heavier modes are have a higher statistical power, but since the distribution of the proton polarization is expected to be at (i.e. the proton asymmetry is uniform $_p = 0$ due to parity conservation), the intrinsic sensitivity is lower. The main conclusion is that, assuming a $_b$ polarization of at least 20%, LHCb can measure the right-handed component of the photon polarization from $_b \to$ (1115) decays down to 15% at 3 significance after five years of running. The additional contribution from the (X) resonances to the measurable range has been estimated to be 2% at most. The dependence of the photon polarization sensitivity on the initial $_b$ polarization (in the range $P_b = 20 \quad 100\%$) has been found to be of the order of a few percent.

5 A_{FB} measurement

Electroweak $b \to s``$ decay is a FCNC process which proceeds via a $b \to s$ transition through a penguin diagram. New Physics processes can therefore enter at the same level as SM processes.

In particular the branching ratio as a function of the squared invariant mass of the dilepton system can be affected in most New Physics scenarios.

However, the experimentally accessible exclusive decays are affected theoretically by hadronic uncertainties. A possible solution is to study ratios where hadronic uncertainties are significantly reduced.

The forward{backward asymmetry A_{FB} is defined for the transition $b \to s``$ s by the angle between the $`^+$ and the b hadron flight directions in the di-lepton rest frame. The shape of the asymmetry $A_{FB}$ as a function of the lepton-lepton effective mass $m^2_{``}$, and especially the position of the zero crossing (i.e. the $m^2_{``}$ value corresponding to $A_{FB} = 0$) are almost unaffected by hadronic form factor uncertainties, thus providing a good basis for searching for deviations from the SM predictions [8].

Thanks to its very clean experimental signature, the exclusive decay $B_d \to K$ has been chosen to extract A_{FB}. The selection is based on the identification of two muons with opposite charge and of the relevant hadronic final state [9]. Very strict requirements on the vertex quality are applied to reduce the backgrounds from cascade semileptonic $b \to c, c \to s$ and from two semileptonic $b \to c$ decays. These processes have to be well under control, as they can induce a bias on A_{FB}. The background from cc resonances is removed by vetoing the J= and (2S) mass windows in the di-muon effective mass distribution.

LHCb expects a 15 MeV$/c^2$ resolution on the B mass and 10 MeV$/c^2$ on the di-muon mass. The resolution for $_{FB}$ is 4 mrad. The expected yield for one nominal year of running at LHCb (2 fb^{1}) is about 7200 events with a background to signal ratio $B=S \simeq 0.5$. The overall trigger and reconstruction efficiency is estimated to be around 1%.

Using the results obtained from the full simulation of the $B^0 \to K^0$ channel, LHCb has estimated the sensitivity to the forward-backward asymmetry in a "toy" MC study. The typical behaviour of A_{FB} versus m^2, after one year of running at the nominal luminosity (2fb^{1}) is shown in Fig. 2. With 2 fb^{1} of data the precision on the point of zero-crossing ($A_{FB} = 0$) is expected to be 0.46 GeV$^2=c^4$; while at 10 fb^{1} the precision improves to 0.27 GeV$^2=c^4$. No bias in the mean of the measured zero-crossing point is observed.

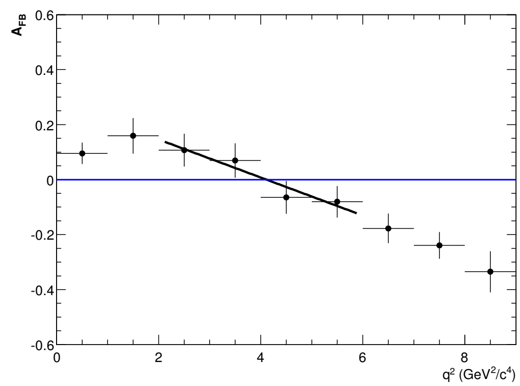

Fig. 2. The A_{FB} distribution from an example 2 fb ^{1} toy experiment. The solid line shows the t result.

Recent theoretical work [10] has highlighted other interesting asimmetries to be studied, as the longitudinal polarization fraction of the K ^{0} (F_L) and the second of the two polarization amplitude asymmetries ($A_T^{(2)}$). The parameters are all predicted with high precision from theory in the SM and many extensions beyond the SM. The available statistics are limited by the requirement to restrict the region of the di-muon masses from 1 to 6 GeV^2, which is favoured by small theoretical errors. In this region, the LHCb expected resolution with an integrated luminosity of 2 fb ^{1} is 0.016 in F_L and 0.42 in $A_T^{(2)}$ [11].

6 R_K measurements at LHCb

Finally, the ratio of b ! s and b ! ees decays in any exclusive mode is also a clean probe of the SM. Lepton universality predicts this ratio to be unity with a theoretical error below 1% [12]. In the SM, the ratio of b ! s and b ! ees decays is expected to be very close to unity, namely $R_K = 1{:}000 \quad 0{:}001$. Deviations of the order of 10% can occur with neutral Higgs boson exchange in models that distinguish between lepton avours (for istance, the minimal SUSY model at large tan).

In LHCb the reconstruction of the two decay modes B^+ ! K^+ and B^+ ! K^+ee allows an extraction of the ratio R_K of the two branching fractions, integrated over a given di-lepton mass range [13]. The two decays are reconstructed with the same procedure and requirements described above, except that a proper brems-strahlung correction is essential in the B^+ ! K^+ee channel. The di-lepton mass range is chosen to be $1 < m_{ll}^2 < 6$ GeV^2=c^4 in order to avoid cc resonances. The event yields are extracted from a two-dimensional t to the K `` and `` masses in order to take into account the backgrounds from b ! J= s and B^0 ! K^0 ``. The expected yields are given in Tab. 1. With 10 fb ^{1} we expect a relative error on R_K between 4% and 6% depending on the level of background and the efciency of the trigger. The study of the most likely sources of systematic errors shows that this error will be statistics-dominated.

7 Conclusions

The LHCb experiment has a promising potential for the study of rare loop-induced decays, which are sensitive to new physics in many Standard Model extensions. In particular, for the very rare decay B_s^0 ! , present experiments will detect a signal only when the BR is strongly enhanced by New Physics. With a sensitivity exceeding the BR expected in the SM, LHCb will be able to discover both enhancements and suppression. In addition, LHCb has good potential for measuring the helicity of the photon emitted in the b ! s decay, the forward-backward asymmetry A_{FB} for the transition b ! lls and the ratio of b ! s and b ! ees decays in a number of exclusive modes.

The experimental strategies, the expected annual signal event yields and the estimates on background to signal ratios have been presented.

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