Rare B decays at LHCb

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Abstract. The 10^{12} B hadrons produced yearly at the LHCb interaction region will provide a unique opportunity for studying very rare B decays. Such processes occur via loops in the SM, and hence offer a high sensitivity to new physics through the effect of new particles in additional loops. At LHCb, many rare decay observables will allow either discovering new physics or constraining extensions of the SM. This article describes the LHCb potential on three of them. The first observable is the photon polarization in B_s \rightarrow \phi ( \rightarrow K^+K^-) \gamma, which has not been measured yet. The second case considered are the angular distributions in B^0 \rightarrow K^*( \rightarrow K^+\pi^-) \mu^+\mu^-, for which some studies have already been performed at the B factories. The third observable is the branching ratio of B_s \rightarrow \mu^+\mu^-. This extremely rare process is subject to large enhancements in many SUSY models, and it is potentially one of the first observables to be sensitive to new physics at the LHC.

1. Introduction

Transitions between b and s quarks are flavor-changing neutral currents. In the Standard Model (SM), such transitions happen only via loops. Such processes are therefore rare, but they offer a great potential for discovery of new physics, as virtual contributions from new particles can be sizeable compared to the SM expectations.

The study of b\rightarrow s transitions will remain statistically limited at the end of the programmes of the B factories and the Tevatron. At the Large Hadron Collider (LHC), B hadrons will be produced at an unprecedented rate. The LHCb detector [2] has been specifically designed to trigger on and to reconstruct B decays.

This article discusses the potential of LHCb in three b\rightarrow s observables for which there are clean theoretical predictions from the SM and for which popular extensions of the SM predict significant...
effects: the photon polarization in $B_s \rightarrow \phi \gamma$; the angular distributions of the decay products of $B^0 \rightarrow K^* \mu^+ \mu^-$; and the branching ratio (BR) of $B_s \rightarrow \mu^+ \mu^-$. All the results are obtained using full Monte Carlo (MC) simulation, including the effects of pile-up (multiple proton-proton collisions in a single bunch crossing) and spill-over (signal tails in the detector from particles originated in previous bunch-crossings). For the computation of background yields, events in which a $b\bar{b}$ pair is present are assumed to be the only relevant contributions. All results are given for an integrated luminosity of 2 $fb^{-1}$, equivalent to one year (10$^7$ seconds) of LHC running at nominal conditions.

The study of rare processes requires excellent background rejection. Excellent vertexing capabilities, momentum resolution and particle identification are key ingredients for the case of rare B decays. The LHCb vertex detector (VELO) provides an impact parameter resolution of 14 $\mu m + 35$ $\mu m/(p_T/GeV)$ that results in a measurement of the B lifetime with a resolution of $\sigma(\tau) \sim 40 - 100$ fs depending on the decay mode. The VELO together with the main tracking stations provide a track momentum measurement with $\sigma(p)/p \sim (0.4 + 1.5 p/TeV)$, or an invariant mass resolution of 20 (15) MeV for $B_s \rightarrow \mu^+ \mu^-(B^0 \rightarrow K^*(\rightarrow K^+\pi^-)\mu^+ \mu^-)$. The muon chambers and ring imaging Cherenkov detectors (RICH) provide, at an example working point, an 88% kaon identification efficiency with a 3% pion contamination, and a 95% muon identification efficiency with a 5% hadron contamination.

2. Photon polarization in $B_s \rightarrow \phi(\rightarrow K^*K^-)\gamma$

The BR of this decay has been measured by Belle to be $3 \times 10^{-6}$ [3]. While the SM prediction of the exclusive BR has large uncertainties, the polarization of the photon is predicted with enough accuracy to provide a stringent test of the SM. At leading order, the allowed transitions are $B^0 \rightarrow X_s \gamma_R$ and $B^0 \rightarrow X_s \gamma_L$, with the crossed amplitudes being suppressed by $m_\gamma/m_B$. The parameter $\psi$ is defined as the ratio between the right and left polarization amplitudes for the case of the $B^0$. This parameter is predicted to be $\sim 0.1$ at leading order in the SM. However, higher order effects like gluon interchange [4] allow for the polarization to be flipped, resulting in a SM prediction of $\psi \sim 0.1$. Some SM extensions like left-right-symmetric models [5] and unconstrained MSSM [6] predict large values of $\psi$, while still predicting values of the inclusive BR ($b \rightarrow s \gamma$) which agree with current measurements.

The photon polarization is observable through the interference between the mixing and the decay, which can only occur for $\psi \neq 0$. The differential decay rates for $B^0 (\rightarrow B^0)$ are given by:

$$\Gamma(B_q (\bar{B}_q) \rightarrow f^{CP} \gamma) \propto \cosh(\Delta\Gamma t/2) - A^\Delta \sinh(\Delta\Gamma t/2) \mp C \cos(\Delta m_q t) \mp S \sin(\Delta m_q t)$$

The sub-index $q$ refers either to the $B_q$ or the $B^0 (\rightarrow B^0)$ system; $C$ is the direct CP asymmetry; $\Delta\Gamma = \Gamma_L - \Gamma_H$ and $\Delta m = m_H - m_L$ are the width and mass differences between the two mass eigenstates, and

$$S = \sin 2\psi \, \sin \varphi,$$
$$A^\Delta = \sin 2\psi \, \cos \varphi.$$
and it takes the form:

\[ A_{CP}(t) = -\frac{C \cos(\Delta m_t t) + S \sin(\Delta m_t t)}{A^\pm \sinh(\Delta \Gamma_q t/2) + \cosh(\Delta \Gamma_q t/2)}. \]

The SM predicts \( C = 0 \) and \( \cos \phi \approx 0 \). The term containing \( A^\pm \Delta \) in \( \Gamma(t) \) has the same sign for \( B_0/B_s \) and \( B^0/B_s \), hence \( \Gamma(t) \) offers the possibility to measuring \( \psi \) without tagging the B meson flavor at its production. Note also that the sensitivity to \( \psi \) disappears for both \( \Gamma(t) \) and \( A_{CP}(t) \) in the case of the \( B_0 \) system, due to the vanishing value of \( \Delta \Gamma_d \).

The combined trigger, reconstruction and selection efficiency for \( B_s \rightarrow \phi(\rightarrow K^-K^+)\gamma \) in LHCb is 0.3% [7]. That includes acceptance effects, as well as 85% (80%) efficiencies for the hardware (software) levels of the trigger. The dominating source of background is combinations of true \( \phi \) decays with collimated \( \pi^0 \) decays which are identified as single photons. The contributions from the specific decays \( B_s \rightarrow \phi(\rightarrow K^-K^+)\pi^0 \) and \( B^0 \rightarrow K^{*0}(\rightarrow K^-\pi^+)\gamma \) have been studied in detail and proved to be negligible.

For the extraction of the mixing parameters, a fit of the tagged differential decay rates and asymmetry is performed [8], using event-by-event uncertainties in the B lifetime. That uncertainty has a dependence on the event kinematics that will be calibrated with real data using the decay channel \( B^0 \rightarrow K^{-}\pi^{+}\phi(\rightarrow K^-K^+)\gamma \), with \( BR = (40.1 \pm 2.0) \times 10^{-6} \) [9]. The effect of the background is corrected by fitting the apparent lifetime distribution of the upper and lower mass sidebands.

The signal yields for 2 fb\(^{-1}\) are 11,000 and 68,000 for \( B_s \rightarrow \phi(\rightarrow K^-K^+)\gamma \) and \( B^0 \rightarrow K^{*0}(\rightarrow K^-\pi^+)\gamma \), with B/S estimated to be <0.55 and ~0.60 respectively. The B mass resolution for both channels is 90 MeV.

With 2 fb\(^{-1}\), the expected relative uncertainties, including background subtraction but statistical uncertainties only, are 0.22 for \( A^\pm \), and 0.1 for \( \psi, S \) and \( C \), hence stringent tests of the SM will already be possible with this integrated luminosity.

3. Angular distributions in \( B^0 \rightarrow K^{*}(\rightarrow K^-\pi^+)\mu^+\mu^- \)

The BR of this decay has been measured in the B factories to be \( (1.10^{+0.32}_{-0.24}) \times 10^{-6} \) [9]. Many observables related to the angular distributions can be predicted with low relative uncertainties as functions of the Wilson coefficients.

A popular theoretically clean observable is the forward-backward asymmetry \( A_{FB} \). It refers to the direction of the \( \mu^+ \) with respect to that of the \( B^0 \) in the rest reference frame of the \( \mu^+\mu^- \) system. \( A_{FB} \) is predicted to be a function of the invariant mass squared of the \( \mu^+\mu^- \) system \( (q^2) \), with low theoretical uncertainties in the range between 1 and 6 GeV\(^2\). The SM predicts a sign flip of \( A_{FB}(q^2) \) at \( q^2 = 4.36^{+0.33}_{-0.35} \) GeV\(^2\) [10]. This crossing point is usually referred to as \( s_0 \). The position of \( s_0 \) depends on the values and signs of \( C_7, C_9 \) and \( C_{10} \).

The studies in BaBar and Belle show some slight hints of deviations from the SM [11, 12] but they suffer from the limited event statistics, with 60 and 230 events collected respectively. At the Tevatron, the CDF analysis is based on 20 events with 0.9 fb\(^{-1}\) [13]. In LHCb, however, the selection being developed [14] will yield 8,000 events per 2 fb\(^{-1}\), while ensuring a B/S of 0.3. The overall efficiency is expected to be 1%, including trigger efficiencies of 90% and 75% for the hardware and software levels respectively.

The main sources of background have been found to be pairs of muons from different B decays (about 60%) and pairs of muons from the same b\( \rightarrow \mu c(\rightarrow \mu) \) decay chain (40%). The latter can fake asymmetry effects due to the charge correlation between the muon with the highest momentum and the eventual kaon from the c decay. This can however be corrected from the mass sidebands. The contribution from the specific background sources \( B_s \rightarrow \phi\mu^+\mu^- \) and \( B_{d,u} \rightarrow \mu^+\mu^- \) and from muon misidentification has been found to be negligible.
The analysis of the angular distribution will be performed in LHCb using different methods, with increasing sensitivity and model independence, but also with increasingly stringent requirements in statistics and knowledge of acceptance functions.

3.1. Counting $A_{FB}$ in bins of $q^2$

Following the method of the Babar and Belle analyses, LHCb is expected to reach the same level of sensitivity to $s_0$ with 0.07 fb$^{-1}$ only [15]. The sensitivity will be 0.5 GeV$^2$ with 2 fb$^{-1}$, and will match that of the SM prediction (see above) with 10 fb$^{-1}$. For the binned method, a linear behavior of $A_{FB}(q^2)$ is assumed around the crossing point.

3.2. Unbinned $A_{FB}(q^2)$

In the methods described in [16, 17], $A_{FB}(q^2)$ and $s_0$ are extracted from unbinned fits. This yields a similar precision in $s_0$, but removes the assumption of a linear behavior around the crossing point.

3.3. Fitting angular distributions

The invariant mass of the muon pair and three angles between the decay products are required to completely describe a $B^0 \rightarrow K^*(-\rightarrow K^+\pi^-)\mu^+\mu^-$ event. The distributions of these angles can be computed from asymmetries and transversity amplitudes [17], which are in turn functions of the Wilson coefficients. In this third method, the values of the asymmetries and the transversity amplitudes are extracted from a simultaneous fit of the three angular distributions. Figure 1 shows the evolution of the transversity amplitude $A_T^{(2)}$ as a function of $q^2$ as predicted by the SM and some SUSY models consistent with the rest of high and low energy measurements [18, 19], as well as the expected LHCb precision after 2 fb$^{-1}$. The use of this method improves the sensitivity to $s_0$ by a factor of 2.

![Figure 1](image)

**Figure 1.** Evolution of the $A_T^{(2)}$ transversity amplitude with $q^2$ for the SM (clear and dark green bands indicate 1 and 2 $\sigma$ theoretical uncertainties), and for the SUSY models described in [18] (dotted and solid lines). Crosses represent the expected LHCb measurements with 2 fb$^{-1}$ assuming the SM dependence.

In a further refinement of this method, the three angles are simultaneously fitted to extract the transversity amplitudes and asymmetries [20, 21], so the available information is optimally used. However, this requires large statistics (at least 2 fb$^{-1}$) and a good knowledge of detector acceptance effects. Figure 2 shows an example of the potential of this method to distinguish between the SM and some SUSY models [20] after 2 fb$^{-1}$.
Figure 2. SM prediction for the $A_{T}(4)$ transversity amplitude (dashed line) with 1σ and 2σ theoretical uncertainty bands and prediction from SUSY models with large gluino mass and positive mass insertion [20] (dotted line) with 1σ and 2σ statistical uncertainty bands for 2 fb$^{-1}$ at LHCb.

4. Branching ratio of $B_{s} \rightarrow \mu^{+}\mu^{-}$

The SM prediction for this BR is $(3.35\pm0.32) \cdot 10^{-9}$ [22]. The current experimental limit at the Tevatron is $45 \cdot 10^{-9} (75 \cdot 10^{-9})$ @ 90% confidence level (CL) at CDF (D0) [23, 24], and it is expected to be reduced to $20 \cdot 10^{-9}$, still far from the SM prediction, when the Tevatron provides 8 fb$^{-1}$.

This BR is sensitive to $C_{S}^{P}$ and $C_{S}^{P}$. In the SM, $C_{S}$ is null, and $C_{S}$ represents the negligible contribution from Higgs loops. The latter can be considerably enhanced in some extensions of the SM. In the case of the MSSM, for instance, it is proportional to $\tan^{2}\beta$. As an example, in the non-universal Higgs masses framework (generalization of CMSSM) [25], a fit to the inclusive $b \rightarrow s$ BR, $(g_{\mu}-2)$, direct Higgs search limits and WMAP dark matter density predicts $BR(B_{s} \rightarrow \mu^{+}\mu^{-}) \sim 20 \cdot 10^{-9}$.

The overall trigger, reconstruction and selection efficiency for this channel in LHCb is about 6%, including 95% (90%) for the hardware (software) trigger. The analysis is based on a categorization of the candidates according to their likelihood of being signal, by binning in three variables: a geometrical likelihood (combining variables like impact parameter of the muons, secondary vertex separation, etc); the invariant mass of the muon pair, and a combination of the muon identification likelihood of the two tracks. The exclusion limits (or observation significance) is obtained by combining the information in all the bins using the CL method described in [26]. This method yields 20% better exclusion limits than simple cuts in the three variables to define one signal region.

In 2 fb$^{-1}$, LHCb will collect 42 signal events if the BR corresponds to the SM prediction. 180 background events are expected within the range of values of the geometrical likelihood where some contribution to the final significance is expected. The main contribution (172 events) corresponds to pairs of real muons each coming from a different B hadron decay. The remaining 8 events are $B_{s} \rightarrow h^{+}h^{-}$, with $h, h'=\pi, K$, and with the pions and/or kaons decaying in flight to muons. The combinatorial background from pairs of hadrons misidentified as muons and the specific $B_{c}^{+} \rightarrow J/\psi(\rightarrow \mu^{+}\mu^{-})\mu^{+}\nu_{\mu}$ have been shown to be negligible.

The number of signal and background events stated above are evenly distributed in the bins of the three variables used to categorize the signal likelihood. Figure 3 shows the 90% CL exclusion limit expected as a function of integrated luminosity, in the absence of signal events. With 2 fb$^{-1}$, the BR predicted by the SM would be excluded. Figure 4 shows the reach in BR for evidence (3σ) and observation (5σ) as a function of integrated luminosity. A 5σ observation of the BR predicted by the SM will be possible after 10 fb$^{-1}$ (5 years of nominal operation).
Figure 3. 90% CL exclusion limit of BR \( (B_s \to \mu^+ \mu^-) \) as a function of the integrated luminosity, in absence of signal events. The solid line is the value obtained with the Monte Carlo sample used, and dotted lines correspond to ±1σ of the uncertainty due to Monte Carlo statistics.

Figure 4. 3σ (blue squares) and 5σ (orange stars) observation reach for BR \( (B_s \to \mu^+ \mu^-) \) as a function of the integrated luminosity. The solid line is the 3σ value obtained with the Monte Carlo sample studied, while dotted lines correspond to ±1σ of the uncertainty due to Monte Carlo statistics.

For the absolute normalization of the BR measurement, trigger, reconstruction and selection efficiencies need to be determined. At LHCb, control channels rather than Monte Carlo simulation will be used for that purpose. The use of other \( B_s \) decays has the drawback that the BR measurements from Belle have relative uncertainty (\( \sigma_{BR}/BR \)) larger than 20%. Hence decays from other \( B \) mesons need to be used, and the main source of uncertainty then becomes the ratio between \( b \) quark fragmentations to \( B_s \) and \( B_d \), and between \( B_s \) and \( B^+ \), which is currently 13% [27]. Some useful channels will be \( B_s \to K^+\pi^- \) and \( B^+ \to J/\psi (\mu^+ \mu^-) K^+ \). The former has an expected annual yield of 350,000 events, \( \sigma_{BR}/BR = 4\% \), and the reconstruction and selection efficiencies are expected to be identical to that of the signal. For the later, the annual yield is 1.6 millions of events, \( \sigma_{BR}/BR = 3\% \), and the trigger response is expected to be similar to that of the signal. Assuming that the 13% uncertainty from fragmentation fractions will
be dominant, the performance shown in Figures 3 and 4 will not be significantly modified when systematic uncertainties are included.

5. Conclusions
The study of rare B decays provides stringent tests of the SM and its extensions. The LHCb experiment will be ready to collect such processes when LHC delivers proton-proton collisions in 2009. The photon polarization in $B_s \rightarrow \phi (\rightarrow K'K)\gamma$ will be measured at a 10% level after 2 fb$^{-1}$. For the angular distributions in $B^0 \rightarrow K (\rightarrow K'\pi)\mu^+\mu^-$ and BR ($B_s \rightarrow \mu^+\mu^-$), LHCb is expected to already achieve a significantly better precision than that of the B factories and/or the Tevatron experiments with 2 fb$^{-1}$.

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