Search for New Physics with Rare Heavy Flavour Decays at LHCb

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Abstract. Rare, flavour changing neutral current processes provide an excellent probe of many new physics models. LHCb’s sensitivity at $\sqrt{s} = 7$ TeV to three promising modes ($B_d \rightarrow K^{*0} \gamma$, $B_s \rightarrow \mu^+ \mu^-$ and $B_d \rightarrow K^{*0} \mu^+ \mu^-$) is explored based on knowledge of the first 37 pb$^{-1}$ of integrated luminosity from the LHC.

1. Introduction

The term rare decay is used to describe a class of decays that are mediated by electroweak flavour changing neutral current (FCNC) processes in the Standard Model (SM). Examples include $b \rightarrow s \ell^+ \ell^-$, $b \rightarrow s \gamma$ and $B_{d,s} \rightarrow \mu^+ \mu^-$. The presence of new physics (NP) particles entering in competing diagrams, in the absence of a dominant SM tree level process, can lead to comparatively large deviations from SM predictions. These deviations may be deviations in measured branching ratios (in the case of $B_s \rightarrow \mu^+ \mu^-$), angular distributions (in $B_d \rightarrow K^{*0} \mu^+ \mu^-$) or CP or Isospin asymmetries. Rare decay searches provide a complementary approach to direct searches at ATLAS, CMS and the TeVatron and already provide strong constraints on a wide range of NP models. A concrete example of this is shown in Figure 1.

In terms of Effective Field Theory and the operator product expansion, the process $b \rightarrow s \gamma$ is highly sensitive to operator $O_7$ and its helicity flipped counterpart $O'_7$. The process $b \rightarrow s \ell^+ \ell^-$ is sensitive to $O_{10}^{(0)}$ and to contributions from the vector and axial-vector operators, $O_9^{(0)}$ and $O_{10}^{(0)}$. $B_s \rightarrow \mu^+ \mu^-$ can see large enhancements from scalar ($O_S$) and pseudo-scalar operators ($O_P$). In the SM the Wilson coefficients associated with the the scalar and pseudo-scalar operators are highly suppressed ($C_{S,P} \approx m_\ell m_b / m_W^2 \sim 0$) as are contributions from helicity flipped operators, corresponding to right-handed currents ($\propto m_s / m_b$). Beyond the SM there can be significant contributions to both helicity flipped operators and from new operators (including $O_{S,P}$).

LHCb’s sensitivity to $B_d \rightarrow K^{*0} \gamma$, $B_d \rightarrow K^{*0} \mu^+ \mu^-$ and $B_s \rightarrow \mu^+ \mu^-$ is discussed below.

2. The LHCb detector

The LHCb detector is a forward-arm spectrometer at the LHC covering a rapidity range (with respect to the LHC beam axis) of $2 < \eta < 5$. The detector geometry profits from the fact that $b\bar{b}$ pairs are predominantly produced, by gluon-gluon fusion in proton-proton collisions, in

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1 On behalf of the LHCb collaboration
2 See for example reference [2]
**Figure 1.** Experimental exclusion limits in the $m_A - \tan \beta$ plane of a MSSM NP model. The shaded region in the lower left-hand corner is the limit coming from the branching ratio of inclusive $b \to s\gamma$. The shaded exclusion region at the top of the figure comes from measurements of the muon $g - 2$. Finally, the solid and dashed lines excluding from the top-left to the bottom-right of the figure come from limits on the $B_s \to \mu^+\mu^-$ branching ratio. The current experimental limit is $\sim 3.6 \times 10^{-8}$ [1]. Figure from reference [3].

the same forward (or backward) cone. This allows the interaction region to be offset in the cavern providing a long lever-arm for tracking and momentum resolutions of $\Delta p/p \sim 0.5\%$. The detector is described in detail elsewhere [4] but, briefly, it comprises: a silicon $r - \phi$ geometry vertex detector (the VELO); tracking stations with silicon strip detectors upstream of a warm dipole magnet and a combination of silicon strip detectors and straw-drift tubes downstream; a pair of ring imaging Cherenkov (RICH) detectors, to provide pion, kaon and proton separation in the momentum range $2 < p < 100\text{ GeV}/c$; electromagnetic and hadronic calorimeters and furthest from the interaction region muon chambers.

2.1. Detector performance
Much of the emphasis in 2010 has been placed on understanding the detector performance. For the rare decay measurements discussed here, the key elements are the ability to separate cleanly primary and secondary vertices and an excellent particle identification performance. The first of these elements is provided by the VELO detector which during data taking approaches within 8 mm of the LHC beam axis and provides an impact parameter resolution of 14 $\mu$m at large transverse momenta (and typically $< 50 \mu$m for charged tracks from $B$ decays).

The muon identification performance has been measured to be $97 \pm 1\%$ using a tag-and-probe approach with $J/\psi \to \mu^+\mu^-$ decays (at a mis-id rate from decays in flight better than 1%). The kaon identification performance has been measured using a sample of tagged $D^* \to D(\to K\pi)\pi$ decays where the kaon and pion can be unambiguously identified. At a typical working point an average efficiency (over $2 < p < 100\text{ GeV}/c$) of 95% can be achieved for a mis-id rate of 7%.
2.2. Running conditions

During 2010, the performance of the LHC has been excellent delivering 37 pb$^{-1}$ of integrated luminosity to LHCb at a peak instantaneous luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$. Whilst this instantaneous luminosity is some way from the nominal $10^{34}$ cm$^{-2}$s$^{-1}$ conditions for the general purpose detectors it is already the design luminosity of LHCb, albeit with only 400 colliding bunches. The high instantaneous luminosity, with a mean number of visible interactions that is approximately $5 \times$ the design value, has consequences for the efficiency and purity of the trigger and offline selections and is reflected in the numbers shown here.

3. Radiative decays

As described in section 1, the presence of new physics particles in loop diagrams can lead to increased contributions from right-handed currents. One of LHCb’s long term goals is a measurement of the decays $B_s \to \phi \gamma$ [5] and $B_d \to K^{*0}e^+e^-$ [6] that can be sensitive to the right-handed component of the photon polarisation (which is suppressed in the SM). These decay modes are not discussed here, but a logical pre-cursor to understanding LHCb’s sensitivity to radiative decays is a measurement of $B_d \to K^{*0}\gamma$, a mode that has been well established at BABAR and Belle. Here the interest is not in a measurement of the branching ratio but of a measurement of the CP asymmetry. The most precise single measurement comes from BABAR [7]:

$$A_{CP} = -0.016 \pm 0.022 \pm 0.007$$

based on $\sim 2400$ signal candidates. In 26 pb$^{-1}$ LHCb observes $49 \pm 17 B_d \to K^{*0}(\to K^+\pi^-)\gamma$ candidates with a mass resolution of $\sigma_{K\pi\gamma} = (133 \pm 55)$ MeV/c$^2$ (see figure 2). $B_d \to K^{*0}\gamma$ candidates have been selected offline from $K^{\pm}\pi^{\mp}\gamma$ combinations where the kaon is identified as a good kaon in LHCb’s RICH detectors, the vertex of the $K\pi$ is highly displaced from the primary vertex and the photon has a large transverse energy. The full selection is described in the LHCb roadmap document [5].
The yield seen in Figure 2 is below the Monté Carlo expectation but is expected to improve with improved calorimeter calibration. Based on the observed yield, LHCb would require $\mathcal{O}(1 \text{ fb}^{-1})$ of integrated luminosity to make a measurement that is competitive with the B-Factories. Such a data sample is expected in 2011.

4. $B_d \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb
The rare decay $B_d \rightarrow K^{*0} \mu^+ \mu^-$ has particular sensitivity to new physics models that provide additional right-handed currents or introduce large contributions from scalar or pseudo-scalar operators. In many models the presence of NP particles can lead to size-able differences in angular observables from the SM predictions. To achieve ultimate sensitivity the long term goal is a full angular analysis of the decay [8], but with $< 2 \text{ fb}^{-1}$ LHCb’s focus is a measurement of the forward-backward asymmetry ($A_{FB}$) of the muon pair. This angular observable varies with the invariant mass squared of the dimuon pair ($q^2$) and in the standard model changes sign at well defined point, where the leading uncertainties coming from form-factors cancel. The variation of $A_{FB}$ in the SM and several new physics models can be seen in Figure 3.

Measurements of $A_{FB}$ from the B-Factories and CDF offer a possible hint of the effects of new physics, where the $A_{FB}$ measured by the three experiments has the opposite sign to SM prediction at low $q^2$. These measurements, however, are highly limited by the available statistics. The most precise single measurement comes from Belle, based on $\sim 250$ signal candidates [10].

$B_d \rightarrow K^{*0} \mu^+ \mu^-$ candidates in LHCb are selected by combining a track that has been identified as a good kaon by the LHCb RICH detectors, with two muon candidates and another track. The $B_d$ vertex is then required to be highly displaced and the candidate to point back to a primary vertex. Transverse momentum cuts are avoided offline to limit possible acceptance biases on a measurement of $A_{FB}$.

For the early studies with the 2010 data sample the $B_d \rightarrow K^{*0} \mu^+ \mu^-$ signal region has been blinded and the sample split into two $17 \text{ pb}^{-1}$ sub-samples. The first $17 \text{ pb}^{-1}$ was used to optimise the offline event selection using $B_d \rightarrow K^{*0} J/\psi$ candidates as a proxy for the $B_d \rightarrow K^{*0} \mu^+ \mu^-$ signal and background candidates that sit outside a $\pm 50 \text{ MeV}$ window around the $B_d$ mass and a $\pm 60 \text{ MeV}$ window around the $J/\psi$ and $\psi(2S)$ masses. The second $17 \text{ pb}^{-1}$
Figure 4. $B_d \rightarrow K^{*0} J/\psi$ candidates selected by a $B_d \rightarrow K^{*0} \mu^+ \mu^-$ offline selection (left). The expected $B_d \rightarrow K^{*0} \mu^+ \mu^-$ signal, scaled appropriately from $B_d \rightarrow K^{*0} J/\psi$, imposed on background events that lie outside a $\pm 50$ MeV $B_d$ mass and $\pm 60$ MeV $J/\psi$ and $\psi(2S)$ mass windows in data (right). The figure is described in the text and created from 17 pb$^{-1}$ of integrated luminosity.

was used to validate the selection. The invariant mass distribution of the offline selected $B_d$ candidates is shown in the left-hand figure of Figure 4. It is dominated by $B_d \rightarrow K^{*0} J/\psi$ events that provide a useful control channel for $B_d \rightarrow K^{*0} \mu^+ \mu^-$. The right-hand figure shows the distribution of background events outside $J/\psi$ and $\psi(2S)$ mass windows. To give an indication of the expected $B_d \rightarrow K^{*0} \mu^+ \mu^-$ performance, the expected $B_d \rightarrow K^{*0} \mu^+ \mu^-$ signal has been extrapolated and scaled appropriately from the observed $B_d \rightarrow K^{*0} J/\psi$ yield (the mass peak itself remains blinded). This results in an expected signal yield of between 0.5 and 1 signal candidate per pb$^{-1}$ at a signal-to-background ratio of better than one-to-one.

5. $B_s \rightarrow \mu^+ \mu^-$ at LHCb

The final rare decay measurement, that completes the set of channels identified in the LHCb roadmap document, is $B_s \rightarrow \mu^+ \mu^-$. As discussed in section 1 this decay is highly sensitive to new scalar and pseudo-scalar couplings and can see large enhancements in the expected branching ratio in models with an extended Higgs sector. The ‘classic’ example of this is the MSSM, where the presence of a second Higgs doublet can lead to enhancements in the amplitude of $C_S \propto \tan^3 \beta/m_A^2$. In the SM this decay is highly supressed with an expected $B(B_s \rightarrow \mu^+ \mu^-) = (3.4 \pm 0.3) \times 10^{-9}$.

At LHCb, a potential $B_s \rightarrow \mu^+ \mu^-$ signal is extracted by taking dimuon combinations and calculating a two-component likelihood. The likelihood is based on the mass of the dimuon system and a geometrical likelihood that discriminates signal and background using the $B_s$ kinematics; its lifetime, impact parameter and isolation. It is driven by LHCb’s excellent secondary vertex resolution and is constructed to be uniformly distributed between 0 – 1 for signal events. For details please see reference [5].

The geometrical likelihood and mass resolution of signal events in the data can be characterized using $B \rightarrow hh$ decays (such as $B_{d,s} \rightarrow K\pi$, $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow K^+K^-$). The mass distribution of reconstructed $K^+\pi^+$ and $K^+K^-$ events can be seen in Figure 5. The candidates have a fitted two-body mass resolution of $\sigma_{m_B} \sim 23$ MeV.

The geometrical likelihood distribution of background events has been explored using the first 215 nb$^{-1}$ of integrated luminosity and is shown in Figure 6. Background candidates sit at
Reconstructed $B \rightarrow K\pi$ (left) and $B_s \rightarrow K^+K^-$ (right) decays in 26 pb$^{-1}$ of integrated luminosity from the LHC. The lines represent the result of a fit to the data with: an exponential to describe the combinatorial background component; gaussian pdf’s to describe the $B_d \rightarrow K\pi$, $B_s \rightarrow K\pi$ and $B_s \rightarrow K^+K^-$ signal and a component to describe the low-mass background in $B \rightarrow K\pi$. The observed mass resolution is 23 MeV.

The invariant mass distribution of $B_s \rightarrow \mu^+\mu^-$ candidates in 215 nb$^{-1}$ of integrated luminosity (left) and the geometrical likelihood of these candidates (right). The points in the left-hand figure are the observed distribution in the data and the solid line the MC expectation. Geometrical likelihoods close to zero and there is every indication from the 2010 data that the geometrical likelihood is a good discriminating variable. Furthermore the level of background is in good agreement with MC predictions. The mass distribution of background events is shown in the left-hand plot of Figure 6. In a $\pm 600$ MeV window about the nominal $B_s$ mass the ratio of data to the MC expectation is consistent with one (1.5 $\pm$ 0.4). A first measurement is now being performed on the full 2010 dataset.

Figure 7 shows the expected exclusion limit (in the background only hypothesis) on the $B_s \rightarrow \mu^+\mu^-$ branching fraction at LHCb as a function of integrated luminosity. The plot has been updated from the LHCb roadmap document to reflect the knowledge of the background and the $B_s$ mass resolution from the 2010 data. With 100 pb$^{-1}$ LHCb should be able to make a world leading measurement.
Figure 7. The expected LHCb exclusion limit on the $B_s \rightarrow \mu^+\mu^-$ BR as a function of integrated luminosity (solid curve). Superimposed on the figure are the DØ and CDF exclusion limits with 6.1 and 3.7 fb$^{-1}$ integrated luminosity (solid horizontal lines) and the expected DØ and CDF exclusion limits with 11 fb$^{-1}$ (dashed lines). The SM prediction for the BR is represented by the shaded region. Finally the “•” highlights the expected LHCb sensitivity with 35 pb$^{-1}$.

6. Summary
In 2010, the performance of LHC and LHCb has been excellent, accumulating 37 pb$^{-1}$ at a high detector efficiency. This data has been used to understand LHCb’s expected performance in three rare decay channels. For $B_d \rightarrow K^{*0}\mu^+\mu^-$ early indications are that 0.5-1 signal candidates are expected per pb$^{-1}$ allowing LHCb to make a world leading measurement with 200-400 pb$^{-1}$. For $B_s \rightarrow \mu^+\mu^-$ the observed background (in the first 215 nb$^{-1}$) indicates that limits below $3 \times 10^{-9}$ could be achieved with only 100 pb$^{-1}$ of integrated luminosity. LHCb expects to record 1 fb$^{-1}$ in 2011.

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