Search for New Physics in rare heavy flavour decays at LHCb

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Abstract. LHCb first searches for rare heavy flavour decays are reported in this contribution. 2010 dataset has been used to put bounds on $B^0_d,s \to \mu^+\mu^-$ decays which are comparable with present best limits. Searches for lepton number violating $B^+ \to h^-\mu^+\mu^+$ decays have lead to tight limits on their branching ratios. Radiative and $B^0_d \to K^*\mu^+\mu^-$ decays have already been observed and will produce sensitive results in the very near future. Present results and future prospects are described in view of their potential for new physics searches.

1. Introduction

The study of rare decays is an effective method to search for physics beyond the Standard Model (SM) and is complementary to direct production searches; while the latter aim to the production of new real particles, the former explore the production of new virtual particles, which, by mediating these reactions, can modify their branching ratios or other sensitive parameters. For this reason higher energy ranges than directly accessible can be probed with rare decays. Furthermore, being suppressed or forbidden in the SM, the New Physics (NP) contributions can be at the same level or larger than the SM ones.

In this contribution we report the first searches for heavy flavour rare decays, in particular for $b$-hadron decays, obtained by the LHCb detector exploiting data taken in proton-proton collisions at $\sqrt{s} = 7$ TeV provided in 2010 and 2011 by the LHC. Most of the results presented here are based on the 2010 total integrated luminosity of 37 pb$^{-1}$, while some are updated with data from 2011 run. The LHCb detector is appositely designed to collect the forward $b\bar{b}$ pairs production in high energy $pp$ collisions ($\sigma(pp \to b\bar{b}X) \sim 75.3\mu b$ at 7 TeV in the pseudorapidity range $2 < \eta < 6$); it is built as a forward single arm spectrometer covering a rapidity range of $1.8 < y < 4.9$. LHCb is equipped as a standard multipurpose detector with a tracking system with excellent momentum, and therefore mass, resolution, RICH detectors and muon stations for particle identification and electromagnetic and hadronic calorimeters. A fully detailed description is available elsewhere [2].

In the following we describe different studies which are already or about to be published and prospects for important channels which will be subject of future publications.

1 On behalf of the LHCb Collaboration
2. Search for $B_{d,s}^0 \to \mu^+ \mu^-$ decays

The $B_{d,s}^0 \to \mu^+ \mu^-$ decays are very rare decays in the Standard Model being flavour changing neutral currents (FCNC) and further suppressed for helicity reasons. Within SM their branching ratios are precisely predicted to be [3]:

$$B^{SM}(B^0_s \to \mu^+ \mu^-) = (3.35 \pm 0.32) \cdot 10^{-9}$$
$$B^{SM}(B^0 \to \mu^+ \mu^-) = (0.10 \pm 0.01) \cdot 10^{-9}$$

while in different NP models these rates can be highly enhanced and are therefore golden channels for the search of New Physics also for their clear experimental signature.

The search for $B_{d,s}^0 \to \mu^+ \mu^-$ decays presented here is based on about 37pb$^{-1}$ of integrated luminosity collected in 2010. We provide here only an overview of this analysis, while for further details the reader should view Ref. [4]. This analysis starts with a soft preselection aiming at reducing the dataset to a manageable level and preserving high and similar signal and control channel efficiencies while reducing background. Good quality tracks displaced from the primary vertex are selected and fitted to form a vertex if the distance of closest approach between them is less than 3 mm; the secondary vertex is required to have good quality fit and to be displaced from the primary vertex. Tracks are identified as muons if they have a minimum of two hits in the last four muon stations. The dominant background after this selection is the combinatorial $bb \to \mu^+ \mu^- X$, while the double misidentification background from hadronic two-body decays is negligible.

After this selection a further discrimination is obtained exploiting two variables: the invariant mass of the muon pair and a multivariate likelihood discriminant (GL). The GL is built upon information from the distance of closest approach of the two muons, the $B$ candidate lifetime, the impact parameter of the $B$ and of the muons with respect to the primary vertex, the transverse momentum of the $B$ and the isolation variable, which takes into account the number of tracks surrounding the candidate muons. The GL is by construction distributed uniformly between 0 and 1 for the signal, while background events accumulate at 0, as shown in Fig. 1(a) for LHCb Monte Carlo (MC) simulations as described in Ref. [5]. The GL probability distribution has been trained using MC simulations but calibrated using real data with hadronic two-body decays ($B^0 \to h^+ h^-$) in order to mimic the signal and di-muon invariant mass sidebands for the background. The result of this calibration is shown in Fig. 1(b) where the measured GL distributions are in agreement with what expected from MC simulations.

The signal invariant mass distribution has been parametrised using a Crystal Ball function. Its resolution, the $\sigma$ of the gaussian portion, has been estimated with two methods. The first method interpolates the resolution obtained for charmonium and bottomonium resonances ($J/\psi$, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$), while the second exploits $B \to h^+ h^-$ decays without particle identification, which would modify the momentum spectra of the selected particles. The two methods agree and the estimated average resolution is $\sigma = 26.7 \pm 0.9$ MeV$/c^2$. The mean values of the $B$ masses, obtained instead from fits to exclusive $B \to h^+ h^-$ decays isolated using particle identification, are $M_{B^0} = 5275.0 \pm 1.0$ MeV$/c^2$ and $M_{B^0_s} = 5363.1 \pm 1.5$ MeV$/c^2$.

Three different channels, $B^+ \to J/\psi(\mu^+ \mu^-)K^+$, $B^0_s \to J/\psi(\mu^+ \mu^-)\phi(K^+ K^-)$ and $B^0 \to K^+ \pi^-$, are used to normalise the signal branching ratio in following way:

$$B(B^0 \to \mu^+ \mu^-) = B_{\text{norm}} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \times \frac{f_{\text{norm}}}{f_{B^0}} \times \frac{N_{B^0 \to \mu^+ \mu^-}}{N_{\text{norm}}} = \alpha_{B^0 \to \mu^+ \mu^-} \times N_{B^0 \to \mu^+ \mu^-}$$

where $\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$ is the efficiency ratio, $N$ and $B$ are respectively the number of observed events and branching ratio of each channel, and $f_{\text{norm}}/f_{B^0}$ the ratio of the probabilities for a $b$ quark to hadronise in the given $B$ meson. This last factor gives the largest contribution to the
normalisation error in channels with different $B$ meson with respect to the signal one; the currently used value [6] is $f_{B^0_s}/f_{B^0} = 3.71 \pm 0.47$, however the LHCb experiment is improving this observable [7] and consequently will reduce this error in the future. The single event sensitivity, $\alpha$ of Eq.(3), is calculated with each of the normalisation channels and the results are in agreement with each other, giving an average value of:

$$\alpha_{B^0 \rightarrow \mu^+\mu^-} = (8.6 \pm 1.1) \cdot 10^{-9}$$

for the $B^0_s$ meson and

$$\alpha_{B^0 \rightarrow \mu^+\mu^-} = (2.24 \pm 0.16) \cdot 10^{-9}$$

for the $B^0$ meson.

The search has been performed in $4 \times 6$ two dimensional bins of GL and invariant mass (in the signal region of $\pm 60$ MeV/$c^2$ around the B masses). The two dimensional scatter plot of data events is shown in Fig. 2. For each of the 24 bins the compatibility of the number of observed events with the background only and the background plus signal hypotheses is calculated with the CL method [8] as a function of the signal branching ratio. Since no deviation is observed from the background-only hypothesis, the following upper limits on the signal branching ratios are put:

$$B^0 \rightarrow \mu^+\mu^- < 4.3(5.6) \cdot 10^{-8} \text{ at } 90\%(95\%)\text{C.L.}$$

$$B^0_s \rightarrow \mu^+\mu^- < 1.2(1.5) \cdot 10^{-8} \text{ at } 90\%(95\%)\text{C.L.}$$

This analysis is going to be updated soon to include 2011 data. Currently, exploiting 58pb$^{-1}$ of integrated luminosity collected in 2011, prospect for the sensitivity of this analysis has been produced. Yields are compatible with what have been observed in 2010 and resolutions and signal to background ratio are unchanged. Furthermore the analysis will take advantage of the use of full particle identification system and improved multivariate discriminants. Therefore it can be foreseen that the analysis of 2011 dataset will give results equal or better to the extrapolation with statistics of 2010 results presented here. In particular, in Fig. 3(a) the exclusion possibility for $B^0_s \rightarrow \mu^+\mu^-$ branching ratio as a function of the integrated luminosity is shown, reaching the level of $5 \cdot 10^{-9}$ with 1fb$^{-1}$, i.e. 2011 year-end expected statistics. Conversely in Fig. 3(b) the discovery potential for a given branching ratio is shown, displaying that a $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) \sim 7 \cdot 10^{-9}$ could be measured at 3$\sigma$ by the end of the year.
Figure 2. Scatter plot, GL versus di-muon invariant mass, of real data events observed by the LHCb experiment. The dashed green lines and the dotted orange lines indicate respectively the $B^0$ and $B^0_s$ signal regions.

Figure 3. Prospects for the search of $B^0_s \rightarrow \mu^+ \mu^-$ decay in LHCb, as a function of integrated luminosity, obtained by extrapolating the 37pb$^{-1}$ results. The exclusion possibility on branching ratio value at 90% (95%) C.L. is shown in blue (red) in (a) while the 3 (5) $\sigma$ discovery potential is shown in blue (orange) in (b).
3. Angular observables in $B^0_d \to K^* \mu^+ \mu^-$ decay

The $B^0_d \to K^* \mu^+ \mu^-$ is a FCNC $b \to s \ell \ell$ reaction and is therefore at loop level in the SM. While its measured branching ratio ($1.05 \times 10^{-6}$ [9]) is in agreement with SM prediction within errors, NP can modify the differential decay rate as a function of the di-muon invariant mass ($q^2$). This translates into different observables which are sensitive to NP; for example the forward-backward asymmetry ($A_{FB}$) of the muons with respect to $K^*$ in the di-muon rest frame and in particular its zero-crossing point [10] which is free of hadronic uncertainties.

Previous measurements [11, 12, 13] of $A_{FB}$ are in fair agreement with SM predictions within the errors, which are still large. However the data points have opposite sign of $A_{FB}$ with respect to SM in the region with $q^2$ lower than the $J/\psi$ mass, favouring an opposite sign for the Wilson coefficient of the electromagnetic dipole coupling, which would be a symptom of NP models [14].

![Invariant mass distribution of $K^* \mu^+ \mu^-$](image)

**Figure 4.** Invariant mass distribution of $K^* \mu^+ \mu^-$ in 36pb$^{-1}$ of integrated luminosity from 2010 dataset.

LHCb is well suited for the measurement of angular observables in $B^0_d \to K^* \mu^+ \mu^-$. Exploiting an analysis based on a Boosted Decision Tree (BDT) discriminant 36 signal events were observed in the 2010 dataset, as is shown in the invariant mass distribution in Fig. 4. With about 200pb$^{-1}$ a dataset comparable to the previous measurements is expected at LHCb while about 1000 (600) events are expected in 1fb$^{-1}$ with background to signal ratio $\sim 1(0.2)$, allowing precision measurements of $A_{FB}(q^2)$.

4. Photon polarisation in $b \to s \gamma$ transitions

Radiative $b \to s \gamma$ transitions are crucial to understand the possibility of NP couplings. While the branching ratios of these decays are in agreement with SM expectations, they offer the opportunity to measure the photon polarisation which in the SM should be dominantly leftly (rightly) polarised for $b$ ($\bar{b}$) decays. On the other hand NP scenarios can host different couplings leading to a different photon polarisation.

As far as the $B^0_s \to \phi \gamma$ process is concerned, since the dominant decays are $B^0_s \to \phi \gamma_R$ and $\bar{B}^0_s \to \phi \gamma_L$, the final state photon polarisation is related to the time dependent decay rate by means of the $B$ mixing [15]. Firstly seen by Belle [16] the $B^0_s \to \phi \gamma$ decay has been already observed at LHCb as demonstrated by Fig. 5(b) which shows the $\phi \gamma$ invariant mass for 88pb$^{-1}$ of integrated luminosity which combine 2010 with part of 2011 dataset.

The photon polarisation measurement in the $B^0 \to K^* \gamma$ decay instead exploits the angular distribution of the $e^+e^-$ from the photon conversion. Furthermore $B^0 \to K^* \gamma$ is also a
benchmark for all other radiative decays. The observation of this decay in LHCb is shown in Fig. 5(a).

First measurements of CP observables with radiative decays will be produced with a subset of 2011 data and are expected to be competitive with current results.

5. Search for $B^+ \rightarrow h^- \mu^+ \mu^+$ decays

The $B$ meson decays $B^+ \rightarrow h^- \mu^+ \mu^+ (h = \pi, K)$, with lepton number violation $\Delta L = 2$, are forbidden in the Standard Model but could be present in new physics scenarios. In particular, allowing the existence of heavy Majorana neutrinos [17] leads naturally to diagrams as the one in Figure 6 for the $B^+ \rightarrow K^- \mu^+ \mu^+$ decay and similarly for $B^+ \rightarrow \pi^- \mu^+ \mu^+$. The rate of these processes is highly suppressed by the mixing level between SM and heavy neutrinos but could be enhanced in case the latter is on its mass shell [18].

The search for $B^+ \rightarrow h^- \mu^+ \mu^+$ decays has been done in LHCb using 36 pb$^{-1}$ of integrated luminosity collected in 2010. The analysis strategy was developed exploiting opposite sign muons and in particular, in order to optimise the selection, $B^+ \rightarrow h^+ J/\psi (\rightarrow \mu^+ \mu^-)$ was used as signal and the right invariant mass sideband of $B^+ \rightarrow K^+ \mu^+ \mu^-$ for the background. Same selection criteria were used for channels with a kaon or a pion in the final state, with the exception of the particle identification of the hadron.

Simple kinematic cuts exploiting transverse momentum, impact parameter with respect to primary vertex, secondary vertex fit $\chi^2$ and flight distance were used in order to reject
Figure 6. Feynman diagram of the $B^+ \rightarrow K^- \mu^+ \mu^+$ transition mediated by a Majorana neutrino.

Figure 7. Invariant mass distributions of $B^+ \rightarrow K^- \mu^+ \mu^+$ decays with the two muons (a) in the $J/\psi$ mass region and (b) not in it.

combinatorial background from primary vertex tracks. The invariant mass for $B^+ \rightarrow h^+ \mu^+ \mu^-$ with $|m_{\mu^+ \mu^-} - m_{J/\psi}| < 50\text{MeV}/c^2$ is shown in Fig. 7(a) where it can be seen the peak of the $B^+ \rightarrow K^+ J/\psi$ decay; conversely requiring $|m_{\mu^+ \mu^-} - m_{J/\psi}| > 70\text{MeV}/c^2$ the plot in Fig. 7(b) is produced, showing the peak of the rare $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay. From the latter distribution, the combinatorial background has been estimated to be $0.55 \pm 0.31 \pm 0.36 \pm 0.25$ events in the signal region of the $B^+ \rightarrow K^-(\pi^-) \mu^+ \mu^+$ channel.

Different types of exclusive peaking backgrounds were studied using Monte Carlo simulations and the resulting invariant mass spectra are shown in Fig. 8 where it can be seen that all the contributions are well below 0.1 events in the signal regions of both the $B^+ \rightarrow h^- \mu^+ \mu^+$ channels. No events were observed in the signal mass region of both $B^+ \rightarrow K^- \mu^+ \mu^+$ and $B^+ \rightarrow \pi^- \mu^+ \mu^+$ channels leading to upper limits on the branching ratios of:

$$B(B^+ \rightarrow K^- \mu^+ \mu^+) < 4.3 \cdot 10^{-8}$$  \hspace{1cm} (6)

$$B(B^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.5 \cdot 10^{-8}$$ \hspace{1cm} (7)

at 90% C.L. improving significantly previous upper limits [19].
Figure 8. Invariant mass distributions of simulated peaking background that can fake the \(B^+ \rightarrow h^-\mu^+\mu^+\) decays.

6. Conclusions

LHCb experiment is starting to show its potential in the rare \(B\) decays sector after only one year of data taking and 36 pb\(^{-1}\) of integrated luminosity. Bounds on the \(B^0_{d,s} \rightarrow \mu^+\mu^-\) decays branching ratios have been put which are comparable to current world best limits. Searches for \(B^+ \rightarrow h^-\mu^+\mu^+\) decays have put limits on their rate improving significantly previous measurements. Radiative decays and \(B^0_{d,s} \rightarrow K^*\mu^+\mu^-\) decays have been observed and will produce very sensitive results in the near future.

Exploiting the increasing statistics, LHCb in 2011-2012 will be able to discover or to put tight limits on various New Physics models, confirming the importance of rare decays in NP searches.

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