Search for New Physics in rare decays at LHCb

Johannes Albrecht

Johannes.Albrecht@cern.ch
CERN, Geneva, Switzerland

Abstract

Rare heavy flavor decays provide stringent tests of the Standard Model of particle physics and allow to test for possible new Physics scenarios. The LHCb experiment at CERN is the ideal place for these searches as it has recorded the world’s largest sample of beauty mesons. The status of the rare decay analyses with 1 fb\(^{-1}\) of \(\sqrt{s} = 7\text{ TeV}\) of \(pp\)–collisions collected by the LHCb experiment in 2011 is reviewed. The world’s most precise measurements of the angular structure of \(B^0 \rightarrow K^*\mu^+\mu^-\) decays is discussed, as well as the isospin asymmetry measurement in \(B \rightarrow K^{(*)}\mu^+\mu^-\) decays. The most stringent upper exclusion limit on the branching fraction of \(B^0_s \rightarrow \mu^+\mu^-\) decays is shown, as well as searches for lepton number and lepton flavor violating processes.

Keywords: Flavor physics, LHC, rare decays, FCNC, leptonic decays, lepton flavor violation

1. Introduction

Rare processes which proceed via flavor changing neutral currents (FCNC) are forbidden at tree level in the Standard Model (SM). They can proceed via loop level electroweak (\(Z^0, \gamma\)) penguin or box diagrams. In extensions to the SM, new virtual particles can enter at loop level, modifying the amplitude of the process or the Lorentz structure of the decay vertex. Possible deviations from the SM predictions on branching fractions or angular distributions could lead to the discovery of physics beyond the SM.

This article reviews some of the most sensitive probes for possible extensions of the Standard Model that were measured by the LHCb collaboration with a dataset of 1 fb\(^{-1}\) of \(\sqrt{s} = 7\text{ TeV}\) of \(pp\)–collisions collected in 2011. An angular analysis of \(B^0 \rightarrow K^*\mu^+\mu^-\) decays allows a stringent test of the Lorentz structure of the electroweak penguin process and is particularly sensitive to right-handed currents. The measurement of the decay rate of \(B^0_s \rightarrow \mu^+\mu^-\) decays are highly sensitive to scalar and pseudoscalar currents, which are non-existent in the SM. The article closes with a discussion of searches for lepton number and lepton flavor violation and \(B\)-hadron and \(\tau\)-lepton decays.

The rare decay processes presented here provide a complementary approach to direct searches at the general purpose detectors and can give sensitivity to new particles at higher mass scales than those accessible directly.

2. Electroweak penguin decays

2.1. Angular analysis of \(B^0 \rightarrow K^*\mu^+\mu^-\) decays

The decay \(B^0 \rightarrow K^*\mu^+\mu^-\) allows the construction of several observables with small hadronic uncertainties, that are sensitive to physics beyond the Standard Model (see \(\cite{1, 2}\) and references therein). These observables include \(\cite{2, 3, 4, 5}\):

- \(A_{FB}\), the forward-backward asymmetry of the dimuon system,
- \(F_L\), the fraction of \(K^*\) longitudinal polarization,
• $S_3$, the transverse asymmetry, which is also often referred to as $\frac{1}{2}(1 - F_L)A_T^2$ and

• $S_8$, a CP averaged quantity corresponding to the imaginary component of the product of the longitudinal and transverse amplitudes of the $K^{*0}$.

The LHCb collaboration performs an angular analysis in bins of the squared dimuon invariant mass ($q^2$) and the three angles $\theta_1$, $\theta_2$ and $\phi$. $\theta_1$ is defined as the angle between the $\mu^+$ and the $B^0$ in the dimuon rest frame, $\theta_2$ as angle between the kaon and the $B^0$ in $K^{*0}$ rest frame and $\phi$ as angle between the plane spanned by the dimuon system and the $K^{*0}$ decay plane.

The differential branching ratio as a function of $q^2$ is shown in Fig. 1 together with recent measurements from other collaborations. The measurements from the BABAR, Belle, CDF and LHCb collaborations are consistent with each other. Measurements of the observables $A_{FB}$, $F_L$, $S_3$ and $S_8$ are shown in Fig. 2. These are the most precise measurements of these observables and no deviations from the SM predictions have been seen.

The zero-crossing point of $A_{FB}$, $q_0$, is a particularly sensitive probe for NP and, as the form factor uncertainties cancel at first order, it is theoretically very clean. The LHCb collaboration has reported the worlds first measurement as $q_0 = 4.9^{+1.1}_{-1.0}$ GeV$^2$/c$^4$, in good agreement with the SM prediction. This measurement strongly disfavours scenarios with a flipped sign of the Wilson coefficient $C_7$.

2.2. Isospin asymmetry in $B \rightarrow K^{(*)}\mu^+\mu^-$

The isospin asymmetry of the decays $B \rightarrow K^{(*)}\mu^+\mu^-$, $A_I$, is defined as

$$A_I = \frac{\frac{1}{\tau}B(B^0 \rightarrow K^{(*)}\mu^+\mu^-) - \frac{\tau}{\tau}B(B^+ \rightarrow K^{(*)}\mu^+\mu^-)}{\frac{1}{\tau}B(B^0 \rightarrow K^{(*)}\mu^+\mu^-) + \frac{\tau}{\tau}B(B^+ \rightarrow K^{(*)}\mu^+\mu^-)} ,$$

where $\tau_{0,+}$ is the lifetime of the $B^0$ and $B^+$ meson respectively. For the $B \rightarrow K^*\mu^+\mu^-$ system, in the SM, $A_I$ is predicted to be $-0.01$ with a slight increase at low values of $q^2$. For the $B \rightarrow K\mu^+\mu^-$ system, no SM calculation of $A_I$ exists, but it is similarly expected to be close to zero. The most precise measurement of $A_I$ is performed by the LHCb collaboration [11], it is shown in Fig. 3 together with previous measurements of this quantity. All measurements are consistent with each other and the $B \rightarrow K^*\mu^+\mu^-$ measurement is also consistent with the SM prediction. The $B \rightarrow K\mu^+\mu^-$ measurements are consistent amongst the experiments but are less consistent with the naive expectation that $A_I = 0$. The deviation from zero has a significance of greater than four standard deviations [11].

![Figure 1: Differential decay rate of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ measured by the BABAR [6], Belle [7], CDF [8] and LHCb [9] experiments. The SM prediction, from Ref. [10], is also shown. Figure reproduced from Ref. [6].](image1.png)

![Figure 2: Correlation for the $A_{FB}$ measurement.](image2.png)

![Figure 3: Isospin asymmetries for the decays $B \rightarrow K^{(*)}\mu^+\mu^-$ measured in the muonic channels by CDF [8] and LHCb [11] as well as in both the electron and the muon channel by BABAR [6] and Belle [7]. Figure reproduced from Ref. [11].](image3.png)
there is a significant tension with respect to expectations for the decays with a kaon. These measurements agree with each other and with SM predictions for the decays with a kaon. Constraints for several NP models. The isospin asymmetry in the decays is strongly suppressed by loop and helicity factors, a summary is given in Ref. [14]. For example, in the minimal supersymmetric Standard Model (MSSM), the enhancement is proportional to \( \tan^6 \beta \), where \( \tan \beta \) is the ratio of the vacuum expectation values of the two Higgs fields. For large values of \( \tan \beta \), this search belongs to the most sensitive probes for physics beyond the SM which can be performed at collider experiments.

A review of the experimental status of the searches for \( B_{s,d}^0 \to \mu^+\mu^- \) can be found in [15].

The measurements presented here use 1 fb\(^{-1}\) of data recorded by the LHCb experiment in 2011. Assuming the SM branching ratio, about 12 (1.3) \( B_s^0 \) (\( B_d^0 \)) decays are expected to be triggered, reconstructed and selected in the analyzed dataset.

The first step of the analysis is a simple selection, which removes the dominant part of the background and keeps about 60% of the reconstructed signal events. As second step, a preselection, based on a Boosted Decision Tree (BDT) reduces 80% of the remaining background while retaining 92% of the signal.

Each event is then given a probability to be signal or background in a two-dimensional probability space defined by the dimuon invariant mass and a multivariate discriminant likelihood. This likelihood combines...
The method provides CLs+b section hypothesis is computed using the CLs+b events with that expected for a given branching fraction hypothesis. The invariant mass resolution is calibrated with an interpolation of $J/\psi, \phi(2S)$ and $\Upsilon(1S), \Upsilon(2S)$ and $\Upsilon(3S)$ decays to two muons. The background shapes are calibrated simultaneously in the mass and the BDT using the invariant mass sidebands. This procedure ensures that even though the BDT is defined using simulated events, the result will not be biased by discrepancies between data and simulation.

The number of expected signal events is evaluated by normalizing with channels of known branching fraction. Three independent channels are used: $B^+ \to J/\psi K^+$, $B_s^0 \to J/\psi \phi$ and $B^0 \to K^+\pi^-$. The first two decays have similar trigger and muon identification efficiency to the signal but a different number of particles in the final state, while the third channel has the same two-body topology but is selected with a hadronic trigger. The event selection for these channels is specifically designed to be as close as possible to the signal selection. The ratios of reconstruction and selection efficiencies are estimated from the simulation, while the ratios of trigger efficiencies on selected events are determined from data. The observed pattern of events in the high BDT range is shown in Fig. 4 for $B_s^0 \to \mu^+\mu^-$ (top) and $B^0 \to \mu^+\mu^-$ (bottom). A moderate excess over the background expectations is seen in the $B_s^0$ channel. This excess is consistent with the SM prediction. No excess is seen in the $B^0$ channel.

The compatibility of the observed distribution of events with a given branching fraction hypothesis is computed using the CLs+b method. The measured upper limit for the branching ratio is at 95% confidence level (CL)

$$B(B_s^0 \to \mu^+\mu^-)_{LHCb} < 4.5 \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-)_{LHCb} < 1.0 \times 10^{-9}$$

which are the world's best upper exclusion limit on the branching fraction of this decay. A combination of this measurement with the ATLAS and CMS upper exclusion limits yields a 95% CL

$$B(B_s^0 \to \mu^+\mu^-)_{LHC} < 4.2 \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-)_{LHC} < 0.8 \times 10^{-9}$$

which is only a factor 20% above the SM prediction given in Eq. 3. This puts tight constraints on various extensions of the Standard Model, especially on supersymmetric models at high values of $\tan\beta$.

The CMS and LHCb collaborations have excellent prospects to observe the decay $B_s^0 \to \mu^+\mu^-$ with the dataset collected in 2012. This observation, and the precision measurement of $B(B_s^0 \to \mu^+\mu^-)$ in the coming years will allow to put strong constraints on the scalar sector of any extension of the Standard Model. The next step will be to limit and then measure the ratio of the decay rates of $B_s^0 \to \mu^+\mu^-/B^0 \to \mu^+\mu^-$, which allows a stringent test of the hypothesis of minimal flavor violation and a good discrimination between various extensions of the Standard Model.

In the absence of an observation, limits on $B(B_s^0 \to \mu^+\mu^-)$ are complementary to those provided by high $p_T$ experiments. The interplay between both

Figure 4: Distribution of selected signal candidates. Events observed in LHCb in the $B_s^0$ channel (top) and the $B^0$ channel (bottom) for BDT $> 0.5$ and expectation for, from top, SM signal (grey), combinatorial background (light grey), $B(\to J/\psi K^+)$ background (light grey), $B(\to J/\psi K^+)$ background (light grey), and cross-feed between both modes (dark grey). The hatched area depicts the uncertainty on the total background expectation. Figure reproduced from Ref. 19.
channels allows the SUSY parameter space to be optimally constrained.

3.2. Searches for an Majorana neutrinos in B decays

A search for Majorana neutrinos with a mass of $O(1 \text{ GeV})$ can be made in lepton number violating (LNV) $B$ and $D$ meson decays. These indirect searches are performed by analysing the decay rate of processes as $B^+ \rightarrow \pi^+ \mu^+\mu^−$ \cite{20,21}. These same sign di-leptonic decays can only occur via exchange of heavy Majorana neutrinos. Resonant production may be possible if the heavy neutrino is kinematically accessible, which could put the rates of these decays within reach of the present or future LHCb luminosity. Alternatively, limits on these LNV processes, together with low energy neutrino data, results in better constraints for neutrino masses and mixing parameters in models with extended neutrino sectors.

Using 0.4 fb$^{-1}$ of integrated luminosity from LHCb, limits have been set on the branching fraction of $B^+ \rightarrow D^{(*)}_s \mu^+\mu^−$ decays at the level of a few times $10^{-7}$ and on $B^+ \rightarrow \pi^+\mu^+\mu^−$ at the level of $1 \times 10^{-8}$ \cite{22,23}. These branching fraction limits imply a limit on the coupling $|V_{\mu d}|$ between $\nu_d$ and a Majorana neutrino with a mass in the range $1 < m_N < 4 \text{ GeV/c}^2$ of $|V_{\mu d}|^2 < 5 \times 10^{-5}$.

3.3. Search for lepton flavor violation in $\tau^- \rightarrow \mu^+\mu^−\mu^−$

Lepton flavor violating (LFV) $\tau^- \rightarrow \mu^+\mu^−\mu^−$ decays are forbidden in the classical SM and are vanishing small after the extension of the SM with neutrino mixing. Many New Physics models predict enhancements, up to observably large values which are close to the current experimental bounds.

The neutrinoless decay $\tau^- \rightarrow \mu^+\mu^−\mu^−$ is a particularly sensitive mode in which to search for LFV at LHCb as the experimental signature with the three muon final state is very clean. The inclusive $\tau^−$ production cross-section at LHCb is very large, about 80 fb. The composition of the $\tau^−$ production can be calculated from the $bb$ and $c\bar{c}$ \cite{24} cross-sections measured at the LHCb experiment and the inclusive branching ratios $b \rightarrow \tau$ and $c \rightarrow \tau$ \cite{25}. About 80% of the produced $\tau^−$-leptons originate from $D^+_s$ decays.

LHCb has performed a search for the decay $\tau^- \rightarrow \mu^+\mu^−\mu^−$ using 1.0 fb$^{-1}$ of data \cite{26}. The upper limit on the branching fraction was found to be $\mathcal{B}(\tau^- \rightarrow \mu^+\mu^−\mu^−) < 7.8 (6.3) \times 10^{-8}$ at 95% (90%) C.L., to be compared with the current best experimental upper limit from the Belle collaboration: $\mathcal{B}(\tau^- \rightarrow \mu^+\mu^−\mu^−) < 2.1 \times 10^{-8}$ at 90% C.L. As the data sample increases this limit is expected to scale with the square root of the luminosity, with possible further reduction depending on improvements in the analysis. The large integrated luminosity that will be collected by the upgraded LHCb experiment will provide a sensitivity corresponding to an upper limit of a few times $10^{-9}$ \cite{27}.

4. Conclusion

Most scenarios of physics beyond the Standard Model of particle physics predict measurable effects in the flavor sector, in particular in rare $B$ meson decays. No sign of physics beyond the Standard Model has yet been observed and stringent limits on its scale have been set.

Sensitive probes for NP are the lepton decays $B^0 \rightarrow \mu^+\mu^−$ and the rare electroweak penguin decay $B^0 \rightarrow K^{(*)}\mu^+\mu^−$. The most recent measurements performed by the LHCb collaboration in these two modes are in good agreement with SM predictions and set strong constraints on possible extensions of the SM. The isospin asymmetry in the decays $B \rightarrow K^{(*)}\mu^+\mu^−$ has been measured by several experiments. These measurements agree with each other and with SM predictions for the decays with a $K^{(*)}$, but there is a significant tension with respect to expectations for the decays with a kaon. Precise calculations are needed to interpret this tension.

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