## Latest results from LHCb on $\mathbf{B^0_{(s)}} \to \mu\mu$ and other very rare decays

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In this review I present the latest updates on the searches for very rare decays to muonic final states performed within the LHCb collaboration using pp collisions at 7 and 8 TeV centre of mass energy. Flavour changing neutral current processes, such as $K^0_s \to \mu^+\mu^-$, $B^0_{(s)} \to \mu^+\mu^-$and $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$are highly suppressed in the Standard Model (SM) and are therefore excellent probes of New Physics (NP) processes or heavy particles that can significantly modify the expected SM rates. Out of the many interesting results obtained by the LHCb collaboration in the study of rare decays, this review covers in detail the searches for $K^0_s \to \mu^+\mu^-$, $B^0_d \to \mu^+\mu^-$and $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$decays and the first evidence for the $B^0_s \to \mu^+\mu^-$decay.

## 1 Introduction

The aim of the LHCb experiment [1] at the Large Hadron Collider at CERN is to perform precise tests of the Standard Model (SM) in the flavour sector, in order to disentangle possible New Physics (NP) effects.

While the direct evidence of NP processes, like the measurement of the masses and properties of new particles, will provide an indisputable proof of existence, the accurate analysis of the transitions occurring in the flavour sector can be a powerful discovery tool, in scenarios where the NP energy scale is not completely decoupled from the flavour one. Rare decays are excellent probes of possible NP contributions to the decay rates that are heavily suppressed in the SM description, like the decays occurring through a Flavour Changing Neutral Current (FCNC) process. In particular, deviations of the values of the branching fractions (BF) from the SM predictions of rare FCNC leptonic decays of the $B$, $D$ and $K$ mesons can give hints of the presence of NP particles at the tree and loop levels.

The LHCb detector is well suited to study decays with muons in the final states: very efficient trigger allows to collect events containing one or two muons with very low transverse momenta; very good momentum resolution $\delta$p/p $= (0.4\text{-}0.6)\%$ reflects into excellent invariant mass resolution ($\sigma(M) \sim 25$ MeV for B two-body decays); the offline muon identification permits to have a good muon efficiency, $\epsilon \sim 90\%$, for a muon misidentification rate less than 1% for $1 < p < 100$ GeV/c.

The latest results obtained for the search of the $K^0_s \to \mu^+\mu^-$and $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$decays, performed with $\sim 1\,\text{fb}^{-1}$ of $pp$ collisions collected by LHCb in 2011 at $\sqrt{s} = 7$ TeV and of the $B^0_{(s)} \to \mu^+\mu^-$decays, that in addition uses 1.1 fb$^{-1}$of $pp$ collisions collected by LHCb in 2012 at $\sqrt{s} = 8$ TeV are presented in this review.

## 2 Search for the $\mathbf{K}_s \to \mu\mu$ decay.

The measurement of the BF of the rare decay $K_s^0 \to \mu^+\mu^-(\mathcal{B}(K_S \to \mu^+\mu^-))$ can provide very useful information on the short-distance structure of $\Delta S = 1$ Flavour Changing Neutral Current (FCNC) transitions. This decay is suppressed in the SM and the prediction on its BF[2,3] is $\mathcal{B}(K_S \to \mu^+\mu^-)_{SM} = (5.0 \pm 1.5) \times 10^{-12}$. The previous best limit on this decay[4], obtained in 1973, is equal to $\mathcal{B}(K_S \to \mu^+\mu^-) < 3.2 \times 10^{-7}$ at 90% of C.L. The contributions of NP to the BF, e.g. from light scalars, are allowed up to one order of magnitude above the SM expectation.

A blind analysis is performed on 1 fb$^{-1}$ of data collected during 2011 that contains $\sim 10^{13}$ $K_S$ within the LHCb acceptance. The main sources of background are due to combinatorial muons from semileptonic decays and to $K_S \to \pi^+\pi^-$ decays where both pions are misidentified as muons, while the contribution from $K_L \to \mu^+\mu^-$ decays is not significant and is thus neglected.

The LHCb mass resolution is exploited to discriminate the $K_S \to \pi^+\pi^-$ with both pions misidentified as muons. Moreover, to increase the signal and background separation a multivariate classifier, a boosted decision tree (BDT), based on geometrical and kinematic informations is used. The number of expected signal events, for a given branching fraction hypothesis, is evaluated by normalizing to the $K_S \to \pi^+\pi^-$ events. This normalization reduces the common systematic uncertainties between the two channels. The modified frequentist method, $CL_s$, is used for the upper limit determination[5]. The $CL_s$ curves for $\mathcal{B}(K_S \to \mu^+\mu^-)$ are shown in Fig.1. The observed upper limit is: $\mathcal{B}(K_S \to \mu^+\mu^-) < 11.0(9.0) \times 10^{-9}$ at 95 (90)% C.L., with

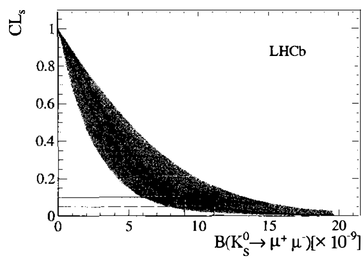


Figure 1: Expected $CL_s$ (dashed blue line) under the hypothesis to observe background-only. The green (dark) band covers 68% ($1\sigma$) of the $CL_s$ curves obtained in the background-only pseudo-experiments, while the yellow (light) band covers 95% ($2\sigma$). The solid line corresponds to the observed $CL_s$.

an improvement of a factor $\sim 30$ with respect to the previous best limit.

## 3 Search for the $\mathbf{B}_s \to 4\mu$ and $\mathbf{B}_d \to 4\mu$ decays.

The $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ is a FCNC process and takes its largest contribution from the resonant decay $B_s \to J/\psi\phi$, in which both mesons decay into two muons and whose BF[6] is $(2.3 \pm 0.9) \times 10^{-8}$. In the SM a non-resonant process can also occur through the exchange of a virtual photon[7] with a $\mathcal{B} \sim 10^{-10}$. However, NP processes can contribute and enhance the $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-)$ by the exchange of new particles at the tree level[8].

The 1 fb$^{-1}$ data sample collected during the year 2011 by LHCb at the 7 TeV centre of mass energy has been analyzed using a cut-based selection algorithm tuned using the resonant decay mode and optimized without using the events falling in the signal region. The combinatorial background is estimated from the mass sidebands, defined using the mass ranges of 4776-5220 and 5426-5966 MeV/$c^2$, where no signal is expected.

The selection criteria for signal and control channels are based on particle identification, separation between the B vertex and the primary vertex, the quality of the B decay vertex. A veto on $J/\psi$ and $\phi$ masses is applied to select signal non resonant four muons candidates. All the non-resonant peaking background yields in the signal region are found to be negligible.

The signal BF is measured by normalizing to $B_d^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ decays selected with the same criteria. Systematic uncertainties are evaluated by comparing Monte Carlo simulation with data.

After unblinding, one event is observed in the $B_d$ signal window and no events are observed in the $B_s$ window (defined as IM windows of $\pm 40$ MeV/$c^2$ around around the nominal $B^0_{(s)}$ masses), as shown in Fig. 2.

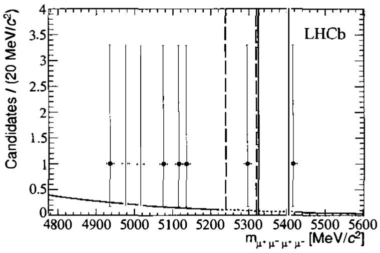


Figure 2: Invariant mass distribution of non-resonant $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$candidates. The solid (dashed) black lines indicate the boundaries of the $B_s^0$ ($B^0$) signal window. The blue curve shows the model used to fit the mass sidebands and extract the expected number of combinatorial background events in the $B_s^0$ and $B^0$ signal regions. Only events in the region in which the line is solid have been considered in the fit.

The number of observed events is consistent with the expected background yields. The $CL_s$ method has been used to evaluate the upper limits on BF [9]: $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) < 1.6(1.2) \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.6(5.4) \times 10^{-9}$ both at 95 (90)% C.L.

## 4 Search for $\mathbf{B}_s^0 \to \mu\mu$ and $\mathbf{B}_d^0 \to \mu\mu$ decays.

Within the SM, $B^0_{(s)} \to \mu^+\mu^-$decays are rare processes as they occur only via loop diagrams and are helicity suppressed. The amplitudes contributing to the branching fraction ($\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$ can be expressed in terms of the scalar ($c_S$), pseudoscalar ($c_P$) and axial vector ($c_A$) Wilson coefficients in a general approach [10]. Within the SM, $c_S$ and $c_P$ contributions are negligible while $c_A$ is calculated with a few percent accuracy [11] and leads [12] to a prediction of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.27 \pm 0.27) \times 10^9$ and $\mathcal{B}(B_d^0 \to \mu^+\mu^-)_{SM} = (1.07 \pm 0.10) \times 10^{10}$ .

Models beyond the SM could contribute to these Wilson coefficients and change significantly the BF. For instance, within the Minimal Supersymmetric SM (MSSM) in the large tan$\beta$ approximation [13], $c_{S,P}^{MSSM} \propto tan^3\beta/M_A^2$, where $M_A$ denotes the pseudoscalar Higgs mass and tan$\beta$ the ratio of Higgs vacuum expectation values.

The LHCb experiment, already in summer 2012, was able to set the most restrictive upper limits [14] on the branching fractions, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^9$ and $\mathcal{B}(B_d^0 \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ at 95% C.L., by using only the data sample collected at 7 TeV centre of mass energy collected during 2011. In this review, I present the updated results that uses an additional 1.1 fb$^{-1}$collected at 8 TeV centre of mass energy in 2012.

The strategy of the analysis is to derive the expected numbers of events of background and signal for a given $\mathcal{B}$ hypothesis and to compare these numbers to the observed ones with the $CL_s$ method [5]. The method provides $CL_{s+b}(CL_b)$, a measure of the compatibility of the observed distribution with the signal plus background (background only) hypothesis, and $CL_s = CL_{s+b}/CL_b$ which is used to set upper limits on the $\mathcal{B}$. In order to avoid any bias, the mass region $m_{\mu\mu} = [m(B^0) - 60\,MeV/c^2, m(B_s^0) + 60\,MeV/c^2]$ is blinded until the analysis is finalized. For a given $\mathcal{B}$, the number of events is obtained by normalizing the yields observed in three controls channels, $B_s^0 \to J/\psi\phi$, $B^0 \to K^+\pi$ and $B^+ \to J/\psi K^+$, by the ratio of the $\mathcal{B}$ hypothesis to the control channel $\mathcal{B}$. The scaling factor corrects also for the different efficiencies between signal and control channels and for different intial states using $f_s/f_d$ measured at LHCb [15]. For the analysis of 2012 data sample the $B_s^0 \to J/\psi\phi$ decay channel was dropped as control channel, given its large BF uncertainties, and was used only to verify the stability of the $f_s/f_d$ against the change in centre of mass energy: no significant change was observed in 2012 data, and the same value has been thus used for both (2011 and 2012) datasets.

The $B^0_{(s)} \to \mu^+\mu^-$candidates are selected by requiring two high quality muon candidates displaced with respect to any *pp* interaction vertex (primary vertex, PV), and forming a secondary vertex separated from the PV in the downstream direction by a flight distance selection. After the selection, the surviving background comprises mainly random combinations of muons from semileptonic decays of two different $b$ hadrons ($b\bar{b} \to \mu^+\mu^- X$, where $X$ is any other set of particles), and from peaking background from $B^0_{(s)} \to h^+h^-$($h$ standing for K or $\pi$) where hadrons are identified as muons. The first type of background is reduced by cutting on topological and kinematical variables and on a combination of them obtained with a Boosted Decision Tree (BDT). This selection has an efficiency similar on the signal, normalisation and control channels. The peaking background is reduced using information from the particle identification detectors. After this selection, events are classified in bins of the di-muon invariant mass and bins of a topological variable built with a second BDT. In each bin the expected numbers of signal and background events are derived. The signal mass shape is assumed to be a Crystal Ball shape, where the mean and the resolution are obtained on data while the transition point is derived from simulations.

The BDT shape is obtained on data by extracting with a fit to the mass distribution, in each BDT bin, the yields of $B^0_{(s)} \to h^+h^-$. For the combinatorial background, the mass and the BDT shape are obtained simultaneously by interpolating, in each BDT bin, the mass side-bands into the signal regions with an exponential function. Finally, the peaking background BDT shape is assumed to be the same as the signal one (correcting for trigger bias) and the mass shape is taken from simulations. The total number of peaking backgrounds is derived by a data driven method. The comparison of the distributions of observed events and expected background events, using the full (2011 + 2012) data sample, results in a p-value (1-$CL_b$) of 11% for the $B_d^0 \to \mu^+\mu^-$decay. From our data we constrain the $B_d^0 \to \mu^+\mu^-$branching fraction to be less than $9.4 \times 10^{-10}$, at 95% C.L. [16], which is the world-best limit from a single experiment. The expected and observed $CL_s$ values are shown in Fig.3 for the $B_d^0 \to \mu^+\mu^-$and $B_s^0 \to \mu^+\mu^-$channels, each as a function of the assumed BF.

The probability that background processes can produce the observed number of $B_s^0 \to \mu^+\mu^-$candidates or more is $5 \times 10^{-4}$ and corresponds to a statistical significance of $3.5\,\sigma$. The value of the $B_s^0 \to \mu^+\mu^-$branching fraction is obtained from an unbinned likelihood fit to the mass spectrum, performed simultaneously in different BDT bins. Figure 4 shows the invariant mass distribution of selected $B^0_{(s)} \to \mu^+\mu^-$candidates (black points) for combined 2011 and 2012 dataset and for BDT>0.7 with the fit results overlaid.

From the fit we obtain[16] $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$, which is in agreement with the SM expectation. This is the first evidence for the decay $B_s^0 \to \mu^+\mu^-$. In order to compare the upper limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ with the theoretical prediction, this value has to be multiplied by $0.911 \pm 0.014$, which takes into account the effective lifetime of the $B_s$ meson [17].

After decades of experimental efforts, the present result represents a major achievement

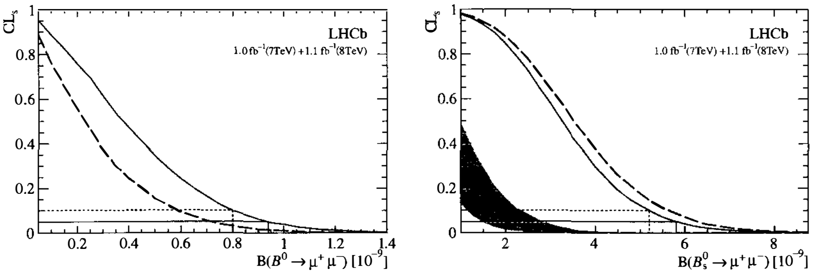


Figure 3: Expected $CL_s$ (dashed black line) under the hypothesis to observe background-only (left) for the $B^0 \to \mu^+\mu^-$ and $CL_s$ under background-plus-signal events according to the SM rate (right) for $B_s^0 \to \mu^+\mu^-$, with yellow area covering the region of $\pm 1\sigma$ of compatible observations; the observed $CL_s$ is given by the blue dotted line; the expected (observed) upper limits at 90% and 95% C.L. are also shown as dashed and solid grey (red) lines.

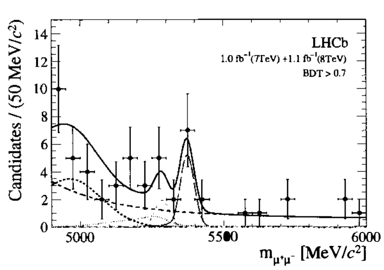


Figure 4: Invariant mass distribution of selected $B^0_{(s)} \to \mu^+\mu^-$candidates (black points) for combined 2011 and 2012 dataset and for BDT>0.7. The result of the fit is overlaid (blue solid line) and thc different components detailed: $B_s^0 \to \mu^+\mu^-$(red long dashed), $B_d^0 \to \mu^+\mu^-$(green long dashed), $B^0_{(s)} \to h^+h^-$(pink dotted), $B^0 \to \pi^-\mu^+\nu_\mu$(black dashed), $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$ (light blue dot dashed), and combinatorial (blue long dashed).

of the LHC. However the current precision on the decay rate is not sufficient to exclude contributions from new physics processes that could also decrease significantly the BF value. In particular, even if strong enhancements from scalar Higgs have been already ruled out, we start to experimentally probe only now possible new physics contributions from the semileptonic operators.

## 5 Conclusions

In this contribution, the status of some of the rare decays searches and measurements ongoing at LHCb have been reviewed, focusing on the most significant and updated results. The latest results of the $K_s^0 \to \mu^+\mu^-$and $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$searches, based on $1\,\mathrm{fb}^{-1}$ collected by LHCb during the 2011 run, have been presented. The LHCb results on the upper limit on $\mathcal{B}(K_S \to \mu^+\mu^-)$ improves the previous best limit by a factor $\sim 30$. At the same time, the LHCb collaboration was able to set the first experimental limit to date, recently submitted for publication on *Phys. Rev. Lett.*, in the searches of $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ and $B^0 \to \mu^+\mu^-\mu^+\mu^-$ decays.

In November 2012 LHCb presented an update in the searches of $B^0_{(s)} \to \mu^+\mu^-$decays, using a 2.1 $\mathrm{fb}^{-1}$data sample collected at 7 and 8 TeV centre of mass energy. While the $\mathcal{B}(B^0 \to \mu^+\mu^-)$

still escaped the experimental observation, and a corresponding limit $\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ (at 95% C.L.) has been placed, a first observation of the $B_s^0 \to \mu^+\mu^-$decay has been reported: $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ is measured to be equal to $(3.2^{+1.4}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$ with a 3.5 $\sigma$ significance. This is the first observation ever made of this extremely rare $B_s$ meson decay.

Those important results achieved by the LHCb collaboration, are placing severe constraints on the phase space parameters of many NP models. And still, many improvements are foreseen in the near future: the full data sample collected in 2012 still has to be fully analyzed, and the analysis strategies are being re-optimized also using a significantly improved MC statistics. With those improvements LHCb expects to put even more stringent constraints on the phase space of many NP models.

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