Rare B meson decays searches with LHCb

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A search for the very rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ has been performed using 1.0 fb^{-1} integrated luminosity of pp collisions at $\sqrt{s} = 7$ TeV collected by the LHCb experiment at LHC during the year 2011. Stringent limits has been imposed on the upper branching fractions: $\mathcal{B}(B_s^0 \to \mu^- + \mu^-) < 4.5\,(3.8) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu-) < 1.0\,(0.81) \times 10^{-9}$ at 95% (90%) confidence level.

1 Introduction

The LHCb experiment exploits the large amount of B mesons produced in the forward region of the pp collisions at LHC to search for rare B decays. Observables of these decays can be modified with respect the Standard Model (SM) predictions by the presence of New Physics (NP). The $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ proceed via a Flavor Changing Neutral Currents which are highly suppressed in the SM. The branching fractions of these decays are predicted in the SM to be $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < (3.2 \pm 0.2) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu-) < (0.1 \pm 0.01) \times 10^{-9}$ [1,2] . But they could be modified by the presence on the loops of an hypothetical neutral scalar particle. At the time of the conference there were several experimental limits on the branching fractions published [4] [5] [6], the lowest upper limit was set by the LHCb collaboration using 0.37 fb^{-1} of integrated luminosity: $\mathcal{B}(B_s^0 \to \mu^+\mu-) < 1.4 \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.2 \times 10^{-9}$ at 95 % Confidence Level (CL) [3]. We presented at this conference an update of this search using 1 fb^{-1} of integrated luminosity collected during 2011. There are other LHCb B rare decays analysis of great interest, such as the study of radiative decays $B^0 \to K^{*0}\gamma$, $B_s^0 \to \phi\gamma$, and the angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$, but they are not covered in this proceedings.

The LHCb detector [7] is a single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$. The tracking system includes a silicon-strip vertex detector, located around the interaction point, upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of slicion-strip detectors and straw drift tubes placed downstream. The combined tracking system has a momentum resolution of $\Delta p/p$ that varies from 0.4 % at 5 GeV/c to 0.6 % at 100 GeV/c. Muons are identified by alternating layers of iron and multi wire proportional chambers, located after the electromagnetic and hadronic calorimeters.

The trigger consists of a hardware stage and a software stage (HLT) that applies a full event reconstruction. Events with muon final states are triggered using two hardware trigger decisions: a single muon decision (events with a muon candidate with transverse momentum $p_{\mathrm{T}} > 1.5$ GeV/c), and a di-muon decision (two candidates with $p_{\mathrm{T},1}, p_{\mathrm{T},2}$ such that $\sqrt{p_{\mathrm{T},1}p_{\mathrm{T},2}} > 1.3$ GeV/c). At HLT stage, a single muon trigger decision selects tracks with an IP> 0.1 mm and $p_{\mathrm{T}} > 1$ GeV/c; and a di-muon trigger decision requires $\mu^+\mu^-$ pairs with an invariant mass $m_{\mu\mu} > 4700$ MeV/c^2. In addition, a J/Ψ trigger decision requires $2970 < m_{\mu\mu} < 3210$ MeV/c^2

to select the event. The trigger efficiency on signal events that pass the selection described bellow is (91.4 ± 3.9) %. It was computed using simulated events and data driven techniques.

The $B^0_{(s)} \to \mu^+\mu^-$ selection requires two high quality muon candidates, displaced with respect to any primary vertex. The di-muon secondary vertex is required to be well measured. The $B^0_{(s)}$ candidates are required to point to the primary vertex with an impact parameter significance $IP/\sigma(IP) < 5$ and have a transverse momentum $p_{\mathrm{T}} > 0.5$ GeV/c. The last cut removes, accordingly with our simulation, 90% of the elastic di-photon production background. The surviving background mainly composes random combinations of muons from semileptonic b-hadron decays ($b\bar{b} \to \mu^+\mu^- X$, where X is any other set of particles).

The channels $B^+ \to J/\psi K^+$, $B^0_s \to J/\psi\phi$ and $B^0 \to K^+\pi^-$ (and their charged conjugates, along the text we will not make distintion between both) serve for the normalization. The selection of these decays is very similar to the $B^0_{(s)} \to \mu^+\mu^-$ candidates to cancel systematic uncertainties. The $B^0_{(s)} \to h^+h'^-$ decays (where h, h' are π or K) are used as control channel as they have the same kinematics of the signal decays. We used an unbias trigger $B^0_{(s)} \to h^+h'^-$ sample to avoid the differences on the trigger between the signal and control channels.

A boosted decision tree entering six variables is used to reduce 80 % of the remaining background while keeping 90% of the signal. The six variables are: the angle between the direction of the momentum of the B candidate and the direction defined by the vector joining the secondary and the primary vertices, the B candidate IP and its vertex χ^2, the minimum IP of the muons with respect to any PV, the minimum distance between the two daughter tracks and the χ^2 of the SV. The same selection is applied to the normalization and control samples (when necessary to slightly modified variables). After this selection, we expect 11.6 $B^0_s \to \mu^+\mu^-$ and 1.3 $B^0 \to \mu^+\mu^-$ events accordingly to the SM prediction.

$B^0_{(s)} \to \mu^+\mu^-$ events are classified in a two dimensional plane. In one axis is the invariant mass of the di-muon pair ($m_{\mu\mu}$), and in the second axis, a Boosted Decision Tree output (BDT). The variables than enter in the BDT are: the B candidate IP, the minimum IP significance, the sum of the degrees of isolation of the muons (the number of good two-track vertices a muon can make with other tracks in the event), the B candidate decay time, p_{T}, and degree of isolation [6], the distance of closest approach between the two muons, the minimum p_{T} of the muons, and the cosine of the angle between the muon momentum in the di-muon rest frame and the vector perpendicular to the B candidate momentum and to the beam axis. The BDT was trained using simulated data and its output on simulated signal events is uniform between 0 and 1. The BDT range is divided in the following bins: [0,0.25,0.4,0,5,0.6,0.7,0.8,0.9,.1]. In each bin the mass distribution of the control sample is fitted to obtain the number of $B^0_{(s)} \to h^+h'^-$ events. Several fit models were used and the spread on the number of events considered as a systematic uncertainty. The invariant mass axis in divided into nine bins: $m_{B^0_s} \pm 18, 30, 36, 48, 60$ MeV/c^2, where $m_{B^0_{(s)}}$ is the expected mass of B^0_s and B^0, obtained from $B^0_s \to K^+K^-$ and $B^0 \to K^+\pi^-$ samples. The signal mass line shape is a Crystal Ball function which resolution parameter is extracted from data with a power-law interpolation between the measured resolutions of charmonium and bottomonium resonances decaying into two muons; the values are: $\sigma(m_{B^0_s}) = 24.8 \pm 0.8$ MeV/c^2 and $\sigma(m_{B^0}) = 24.3 \pm 0.7$ MeV/c^2. The number of expected combinatorial background events in each BDT bin and in the mass range (defined as $m_{B^0_s} \pm 60$ MeV/c^2) are determined from data by fitting to an exponential function events in the mass sidebands defined by [4900, 5000] MeV/c^2 and [$m_{B^0_s}$+60 MeV/c^2, 6000 MeV/c^2]. Peaking background from $B^0_{(s)} \to h^+h'^-$ events have been evaluated by folding the $K \to \mu$ and $\pi \to \mu$ misidentification rates obtained from a $D^0 \to K^-\pi^+$ sample from data in bins of p and p_{T}. In total $0.5^{+0.2}_{-0.1}(2.6^{+1.1}_{-0.4})$ doubly-misidentifies events are expected in the $B^0_s(B^0)$ mass regions.

The $B_s^0 \to \mu^+\mu-$ and $B^0 \to \mu^+\mu^-$ yields are translated into branching fractions using

$$\begin{aligned}\mathcal{B} &= \mathcal{B}_{\mathrm{norm}} \times \frac{\epsilon_{\mathrm{norm}}}{\epsilon_{\mathrm{sig}}} \times \frac{f_{\mathrm{norm}}}{f_{d(s)}} \times \frac{N_{B^0_{(s)}\to\mu^+\mu^-}}{N_{\mathrm{norm}}} \\ &= \alpha^{\mathrm{norm}}_{B^0_{(s)}\to\mu^+\mu^-} \times N_{B^0_{(s)}\to\mu^+\mu^-}, \qquad (1)\end{aligned}$$

where $f_{d(s)}$ and f_{norm} are the probabilities that a b quark fragments into a $B^0_{(s)}$ and into the hadron involved in the given normalization mode respectively. We use $f_s/f_d = 0.267^{+0.021}_{-0.020}$ [8] and we assume $f_d = f_u$. With $\mathcal{B}_{\mathrm{norm}}$ we indicate the branching fraction and with N_{norm} the number of signal events in the normalization channel obtained from a fit to the invariant mass distribution. The efficiency $\epsilon_{\mathrm{sig(norm)}}$ for the signal (normalization channel) is the product of the reconstruction efficiency of all the final state particles of the decay including the geometric acceptance of the detector, the selection efficiency for reconstructed events, and the trigger efficiency for reconstructed and selected events. The ratio of acceptance and reconstruction efficiencies are computed using the Monte Carlo simulation. The differences between the simulation and data are included as systematic uncertainties. The selection efficiencies are determined using Monte Carlo simulation and cross-checked with data. Reweighting techniques have been used for all the Monte Carlo distributions that do not match those from data. The trigger efficiency is evaluated with data driven techniques. Finally, $N_{B^0_{(s)}\to\mu^+\mu^-}$ is the number of observed signal events. The observed numbers of $B^+ \to J/\psi K^+$, $B_s^0 \to J/\psi\phi$ and $B^0 \to K^+\pi^-$ candidates are 340 100 ± 4500, 19 040 ± 160 and 10 120 ± 920, respectively. The three normalization factors are in agreement within the uncertainties and their weighted average, taking correlations into account, gives $\alpha^{\mathrm{norm}}_{B_s^0\to\mu^+\mu^-} = (3.19 \pm 0.28) \times 10^{-10}$ and $\alpha^{\mathrm{norm}}_{B^0\to\mu^+\mu^-} = (8.38 \pm 0.39) \times 10^{-11}$.

For each bin in the two-dimensional space formed by the invariant mass and the BDT we count the number of candidates observed in the data, and compute the expected number of signal and background events. The systematic uncertainties in the background and signal predictions in each bin are computed by fluctuating the mass and BDT shapes and the normalization factors along the Gaussian distributions defined by their associated uncertainties. The distribution of the invariant mass for BDT>0.5 is shown in Fig. 1 for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ candidates.

The compatibility of the observed distribution of events with that expected for a given branching fraction hypothesis is computed using the $\mathrm{CL_s}$ method [9]. The expected and measured limits for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ at 90 % and 95 % CL are shown in Table 1. The expected limits are computed allowing the presence of $B^0_{(s)} \to \mu^+\mu^-$ events according to the SM branching fractions, including cross-feed between the two modes. The comparison of the distributions of observed events and expected background events results in a p-value of 18 % (60 %) for the $B_s^0 \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$) decay.

Table 1: Expected and observed limits on the $B^0_{(s)} \to \mu^+\mu-$ branching fractions.

Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

In summary, a search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ has been performed on a data sample corresponding to an integrated luminosity of 1.0 fb^{-1}. The data are consistent with both the background-only hypothesis and the combined background plus SM signal expectation

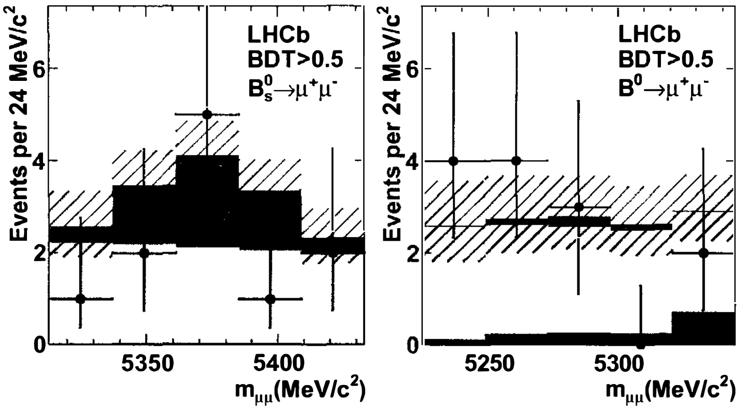

Figure 1: Distribution of selected candidates (black points) in the (left) $B_s^0 \to \mu^+\mu^-$ and (right) $B^0 \to \mu^+\mu^-$ mass window for BDT>0.5, and expectations for, from the top, $B^0_{(s)} \to \mu^+\mu^-$ SM signal (gray), combinatorial background (light gray), $B^0_{(s)} \to h + h'^-$ background (black), and cross-feed of the two modes (dark gray). The hatched area depicts the uncertainty on the sum of the expected contributions.

at the 1σ level. For these modes we set the most stringent upper limits to date: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.03 \times 10^{-9}$ at 95 % CL.

Note: during the process of elaborating this proceeding, CMS published an updated search[10], and LHCb published[11] the results presented here, that are the strongest limits.

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