Search for the rare decays $B^0_{(s)} \to \mu^+\mu^-$ at LHCb

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A search for the $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ decays is presented using $\sim 300\,\mathrm{pb}^{-1}$ of pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ collected by the LHCb experiment at the Large Hadron Collider at CERN. The measured upper limit for the branching ratio of the $B_s \to \mu^+\mu^-$ decay is $\mathscr{B}(B_s \to \mu^+\mu^-) < 1.3\,(1.6) \times 10^{-8}$ at 90 % (95 %) confidence level (CL), while in the case of the $B_d \to \mu^+\mu^-$ decay the measured upper limit is $\mathscr{B}(B_d \to \mu^+\mu^-) < 4.2\,(5.1) \times 10^{-9}$ at 90 % (95 %) CL. A combination with the 2010 dataset results in $\mathscr{B}(B_s \to \mu^+\mu^-) < 1.2\,(1.5) \times 10^{-8}$ at 90 % (95 %) CL.

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1. Introduction

Measurements at low energies may provide interesting indirect constraints on the masses of particles that are too heavy to be produced directly. This is particularly true for Flavour Changing Neutral Currents (FCNC) processes which are highly suppressed in the Standard Model (SM) and can only occur through higher order diagrams. The SM prediction for the branching ratios ($\mathscr{B}$) of the FCNC decays $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ have been computed to be $(3.2 \pm 0.2) \times 10^{-9}$ and $(0.10 \pm 0.01) \times 10^{-9}$ respectively [1]. However New Physics (NP) contributions can significantly enhance these values.

The best published limits from the Tevatron at 95% CL are obtained using 6.1 fb^{-1} by the D0 collaboration [2], and using 2 fb^{-1} by the CDF collaboration [3]. The CDF collaboration has also presented a preliminary result [4] with 6.9 fb^{-1} in which an excess of $B_s \to \mu^+\mu^-$ candidates is reported, compatible with a $\mathscr{B}(B_s \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$.

The LHCb collaboration has previously obtained the limits $\mathscr{B}(B_s \to \mu^+\mu^-) < 5.4 \times 10^{-8}$ and $\mathscr{B}(B_d \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95% CL based on 37 pb^{-1} of luminosity collected in the 2010 run [5]. We present here a measurement based on 300 pb^{-1} of integrated luminosity collected between March and June 2011.

2. Analysis strategy

The general structure of the analysis is similar to the one described in Ref. [5] and is detailed in Ref. [6].

The selection procedure treats signal and control/normalization channels in the same way in order to minimize the systematic uncertainties. Assuming the SM branching ratio and the $b\bar{b}$ cross-section, measured within the LHCb acceptance, of $\sigma_{b\bar{b}} = 75 \pm 14\,\mu$b [7], approximately 3.4 (0.32) $B^0_s \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$) events are expected to be reconstructed and selected in the analysed sample.

After the selection, each event is given a probability to be signal or background in a two-dimensional space defined by two independent likelihoods: the invariant mass and the output of a Boosted Decision Tree (BDT) from the TMVA package [8]. The combination of variables entering the BDT is optimized using Monte Carlo (MC) simulation. The following variables have been used: the B lifetime, impact parameter and transverse momentum of the B, the minimum impact parameter significance of the muons, the distance of closest approach between the two muons, the degree of isolation of the two muons with respect to any other track in the event, the cosine of the polarization angle, the B isolation and the minimum p_T of the muons. The BDT distribution is then transformed in order to be flat for the signal and peaked at 0 for the background.

The calibration of the invariant mass and the BDT likelihoods are obtained from data using control samples. The signal BDT shape is obtained from $B^0_{(s)} \to h^+h^-$ events free from trigger biases while the background shape is obtained using sideband $B^0_{(s)} \to \mu^+\mu^-$ candidates. The resulting distributions are shown in Fig. 1.

The parameters describing the invariant mass line shape of the signal are extracted from data using control samples. The average mass values are obtained from $B^0 \to K^+\pi^-$ and $B^0_s \to K^+K^-$ exclusive samples. The B^0_s and B^0 mass resolutions are estimated by interpolating the ones obtained
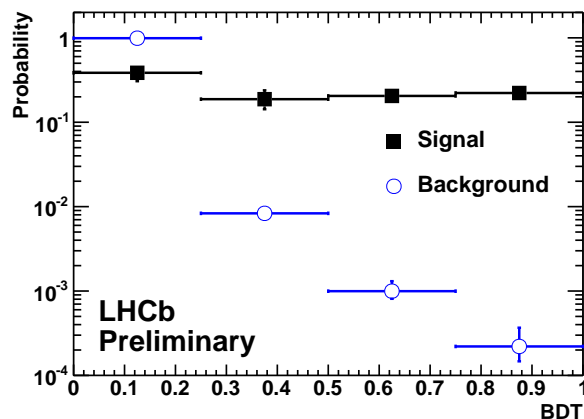
Figure 1: BDT calibration for signal and background.

with the dimuon resonances (J/ψ, $\psi(2S)$ and $\Upsilon(1S, 2S, 3S)$) and cross-checked via a fit to the invariant mass distribution of the $B^0_{(s)} \to h^+ h^-$ inclusive decays and of the $B^0 \to K^+\pi^-$ exclusive decay. The interpolation yields $\sigma(B) = 24.6 \pm 0.2_{stat} \pm 1.0_{syst}$.

The number of expected signal events is obtained by normalizing to channels of known branching ratios, $B^+ \to J/\psi K^+$, $B^0_s \to J/\psi\phi$, and $B^0 \to K^+\pi^-$, that are selected in a way as similar as possible to the signal.

The probability for a background event to have a given BDT and invariant mass value is obtained by a fit of the mass distribution of events in the mass sidebands, in bins of BDT. Different fit functions and mass ranges are used to compute the systematics uncertainties. The two-dimensional space formed by the invariant mass and BDT is binned, and for each bin we compute how many events are observed in data, how many signal events are expected for a given $\mathscr{B}$ hypothesis and luminosity, and how many background events are expected for a given luminosity. The compatibility of the observed distribution of events in all bins with the expected one for a given $\mathscr{B}$ hypothesis is computed using the CLs method [9], which allows to exclude a given hypothesis at a given confidence level.

In order to avoid unconscious biases, the data in the mass region defined by $M_{B^0} - 60\,\mathrm{MeV}/c^2$ and $M_{B^0_s} + 60\,\mathrm{MeV}/c^2$ have been blinded until the completion of the analysis.

3. Results

The distribution of events in the invariant mass versus BDT plane is reported Fig. 2. The expected limit at 90 (95) % CL for the $B_s \to \mu^+\mu^-$ is 0.8 $(1.0) \times 10^{-8}$ in the case of background only hypothesis. When adding signal events according to the SM branching fraction, these limits become 1.2 $(1.5) \times 10^{-8}$. The observed values for the $B_s \to \mu^+\mu^-$ channel is 1.3 $(1.6) \times 10^{-8}$ with a CLb value of 0.80. The observed events are in good agreement with the background expectations and the presence of $B_s \to \mu^+\mu^-$ events according to SM predictions.

For the $B_d \to \mu^+\mu^-$, the expected limit at 90 (95) % CL is 2.4 $(3.1) \times 10^{-9}$ in the case of background only hypothesis. The observed values is 4.2 $(5.2) \times 10^{-9}$ with a CLb value of 0.79. The comparison of the observed distribution of events with the expected background distribution
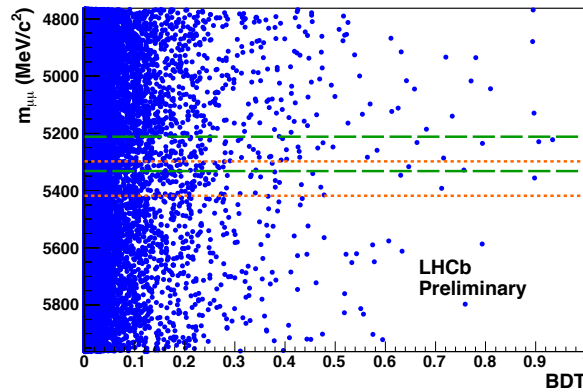
Figure 2: Distribution of selected dimuon events in the invariant mass *vs* BDT plane. The orange short-dashed (green long-dashed) lines indicate the $\pm 60\,\mathrm{MeV}/c^2$ search window around the B^0_s (B^0).

results in a p-value (1-CL$_b$) of 20 % (21 %) for the $B_s \to \mu^+\mu^-$ ($B_d \to \mu^+\mu^-$) decays. In the case of $B_d \to \mu^+\mu^-$, the slightly low p-value is due to an excess of the observed events in the most sensitive BDT bin with respect to the background expectations. A larger data sample will allow to clarify the situation. In the case of $B_s \to \mu^+\mu^-$, when a signal is included at the level expected in the Standard Model, the p-value increases to 50 %.

Finally, the $B_s \to \mu^+\mu^-$ limit is combined with the one published from the 2010 data to obtain $\mathscr{B}(B_s \to \mu^+\mu^-) < 1.2\,(1.5) \times 10^{-8}$ at 90 % (95 %) CL. This 90 % CL upper limit is still 3.8 times above the standard model prediction.

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