Search for the rare decays $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

LHCb Collaboration

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**A B S T R A C T**

A search for the decays $B^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ is performed with 0.37 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV collected by the LHCb experiment in 2011. The upper limits on the branching fractions are $B(B^0_s \rightarrow \mu^+\mu^-) < 1.6 \times 10^{-8}$ and $B(B^0 \rightarrow \mu^+\mu^-) < 3.6 \times 10^{-9}$ at 95% confidence level. A combination of these results with the LHCb limits obtained with the 2010 dataset leads to $B(B^0_s \rightarrow \mu^+\mu^-) < 1.4 \times 10^{-8}$ and $B(B^0 \rightarrow \mu^+\mu^-) < 3.2 \times 10^{-9}$ at 95% confidence level.

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1. **Introduction**

Measurements of low-energy processes can provide indirect constraints on particles that are too heavy to be produced directly. This is particularly true for Flavour Changing Neutral Current (FCNC) processes which are highly suppressed in the Standard Model (SM) and can only occur through higher-order diagrams. The SM predictions for the branching fractions of the FCNC decays

- $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ are $B(B^0_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $B(B^0 \rightarrow \mu^+\mu^-) = (0.10 \pm 0.01) \times 10^{-9}$ [1]. However, contributions from new processes or new heavy particles can significantly enhance these values. For example, within Minimal Supersymmetric extensions of the SM (MSSM), in the large tan$\beta$ regime, $B(B^0_s \rightarrow \mu^+\mu^-)$ is found to be approximately proportional to tan$^6\beta$ [2], where tan$\beta$ is the ratio of the vacuum expectation values of the two neutral CP-even Higgs fields. The branching fractions could therefore be enhanced by orders of magnitude for large values of tan$\beta$.

The best published limits from the Tevatron are $B(B^0_s \rightarrow \mu^+\mu^-) < 5.1 \times 10^{-8}$ at 95% confidence level (CL) by the D0 Collaboration using 6.1 fb$^{-1}$ of data [3], and $B(B^0 \rightarrow \mu^+\mu^-) < 6.0 \times 10^{-9}$ at 95% CL by the CDF Collaboration using 6.9 fb$^{-1}$ of data [4]. In the same dataset the CDF Collaboration observes an excess of $B^0_s \rightarrow \mu^+\mu^-$ candidates compatible with $B(B^0_s \rightarrow \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ and with an upper limit of $B(B^0_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% CL. The CMS Collaboration has recently published $B(B^0_s \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-8}$ at 95% CL and $B(B^0 \rightarrow \mu^+\mu^-) < 4.6 \times 10^{-9}$ at 95% CL using 1.14 fb$^{-1}$ of data [5]. The LHCb Collaboration has published the limits [6] $B(B^0_s \rightarrow \mu^+\mu^-) < 5.4 \times 10^{-8}$ and $B(B^0 \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95% CL based on about 37 pb$^{-1}$ of integrated luminosity collected in the 2010 run.

This Letter presents an analysis of the data recorded by LHCb in the first half of 2011 which correspond to an integrated luminosity of $\sim 0.37$ fb$^{-1}$. The results of this analysis are then combined with those published from the 2010 dataset.

2. **The LHCb detector**

The LHCb detector [7] is a single-arm forward spectrometer designed to study production and decays of hadrons containing $b$ or $c$ quarks. The detector consists of a vertex locator (VELO) providing precise locations of primary $pp$ interaction vertices and detached interaction vertices of long lived hadrons.

The momenta of charged particles are determined using information from the VELO together with the rest of the tracking system, composed of a large area silicon tracker located before a warm dipole magnet with a bending power of $\sim 4$ Tm, and a combination of silicon strip detectors and straw drift chambers located after the magnet. Two Ring Imaging Cherenkov (RICH) detectors are used for charged hadron identification in the momentum range 2–100 GeV/c. Photon, electron and hadron candidates are identified by electromagnetic and hadronic calorimeters. A muon system of alternating layers of iron and drift chambers provides muon identification. The two calorimeters and the muon system provide the energy and momentum information to implement a first level (L0) hardware trigger. An additional trigger level (HLT) is software...
based, and its algorithms are tuned to the experimental operating condition.

Events with a muon final states are triggered using two L0 trigger decisions: the single-muon decision, which requires one muon candidate with a transverse momentum $p_T$ larger than 1.5 GeV/c, and the di-muon decision, which requires two muon candidates with transverse momenta $p_{T1}$ and $p_{T2}$ satisfying the relation $\sqrt{p_{T1}^2 - p_{T2}^2} > 1.3$ GeV/c. The single muon trigger decision in the second trigger level (HLT) includes a cut on the impact parameter (IP) with respect to the primary vertex, which allows for a lower $p_T$ requirement ($p_T > 1$ GeV/c, IP > 0.1 mm). The di-muon trigger decision requires muon pairs of opposite charge with $p_T > 500$ MeV/c, forming a common vertex and with an invariant mass $m_{\mu\mu} > 4.7$ GeV/c$^2$. A second trigger decision, primarily to select $J/\psi$ events, requires $2.97 < m_{\mu\mu} < 3.21$ GeV/c$^2$. The remaining region of the di-muon invariant mass range is also covered by trigger decisions that in addition require the di-muon secondary vertex to be well separated from the primary vertex.

Events with purely hadronic final states are triggered by the L0 trigger if there is a calorimeter cluster with transverse energy $E_T > 3.6$ GeV. Other HLT trigger decisions select generic displaced vertices, providing high efficiency for purely hadronic decays.

3. Analysis strategy

Assuming the branching fractions predicted by the SM, and using the $b\bar{b}$ cross-section measured by LHCb in the pseudorapidity interval $2 < \eta < 6$ and integrated over all transverse momenta of $\sigma_{b\bar{b}} = 75 \pm 14$ mb [8], approximately 3.9 $B^0 \rightarrow \mu^+\mu^-$ and 0.4 $B^0 \rightarrow \mu^+\mu^-$ events are expected to be triggered, reconstructed and selected in the analyzed sample embedded in a large background.

The general structure of the analysis is based upon the one described in Ref. [6]. First a very efficient selection removes the biggest amount of background while keeping most of the signal within the LHCb acceptance. The number of observed events is compared to the number of expected signal and background events in bins of two independent variables, the invariant mass of the di-muon events and the confidence level related to the different phase space accessible to each final state. The BDT output and invariant mass distributions for combinatorial background events in the signal regions are obtained using fits of the mass distribution of events in the mass sidebands in bins of the BDT output.

The two-dimensional space formed by the invariant mass and the BDT output is binned. For each bin we count the number of candidates observed in the data, and compute the expected number of signal events and the expected number of background events. The binning is unchanged with respect to the 2010 analysis [6]. The compatibility of the observed distribution of events in all bins with the distribution expected for a given branching fraction hypothesis is computed using the CLs method [11], which allows a given hypothesis to be excluded at a given confidence level.

4. Selection

The $B^0_{s(J)} \rightarrow \mu^+\mu^-$ selections require two muon candidates of opposite charge. Tracks are required to be of good quality and to be displaced with respect to any primary vertex. The secondary vertex is required to be well fitted ($x^2/\text{ndf} < 9$) and must be separated from the primary vertex in the forward direction by a distance of flight significance $(L/\sigma(L))$ greater than 15. When more than one primary vertex is reconstructed, the one that gives the minimum impact parameter significance for the candidate is chosen. The reconstructed candidate has to point to this primary vertex ($\text{IP}/\sigma(\text{IP}) < 5$).

Improvements have been made to the selection developed for 2010 data [6]. The RICH is used to identify kaons in the $B^0_{s(J)} \rightarrow J/\psi\phi$ normalization channel and the Kullback-Leibler (KL) distance [12] is used to suppress duplicated tracks created by the reconstruction. This procedure compares the parameters and correlation matrices of the reconstructed tracks and where two are found to be similar, in this case with a symmetrized KL divergence less than 5000, only the one with the higher track fit quality is considered.

The inclusive $B^0_{s(J)} \rightarrow h^+h^-$ sample is the main control sample for the determination from data of the probability distribution function (PDF) of the BDT output. This sample is selected in exactly the same way as the $B^0_{s(J)} \rightarrow \mu^+\mu^-$ signals apart from the muon identification requirement. The same selection is also applied to the $B^0 \rightarrow K^+\pi^-$ normalization channel.

The muon identification efficiency is uniform within $\sim 1\%$ in the considered phase space therefore no correction is added to the BDT PDF extracted from the $B^0_{s(J)} \rightarrow h^+h^-$ sample. The remaining phase space dependence of the muon identification efficiency is instead taken into account in the computation of the normalization factor when the $B^0 \rightarrow K^+\pi^-$ channel is considered.

The $J/\psi \rightarrow \mu\mu$ decay in the $B^0 \rightarrow J/\psi K^+$ and $B^0_{s(J)} \rightarrow J/\psi\phi$ normalization channels is selected in a very similar way to the $B^0_{s(J)} \rightarrow \mu^+\mu^-$ channels, apart from the pointing requirement. $K^\pm$ candidates are required to be identified by the RICH detector and to pass track quality and impact parameter cuts.

To avoid pathological events, all tracks from selected candidates are required to have a momentum less than 1 TeV/c. Only $B$ candidates with decay times less than $5 \tau_{B^0_{s(J)}}$, where $\tau_{B^0_{s(J)}}$ is the $B$ lifetime [13], are accepted for further analysis. Di-muon candidates coming from elastic di-photon production are removed by requiring a minimum transverse momentum of the $B$ candidate of 500 MeV/c.
Three new variables are:

- The two muons with respect to any other track in the event.
- The minimum impact parameter significance (IP/σ(IP)) of the muons, the distance of closest approach between the two muons and the isolation of the two muons with respect to any other track in the event.
- The minimum transverse momentum with respect to the beam line and the sum is over all the tracks, excluding the muon candidates, that satisfy \( \delta \eta < 2 \) and \( \delta \phi < 2 \).

The variables entering the BDT discriminant are the six variables used as input to the GL in the 2010 analysis plus three new variables. The six variables used in the 2010 analysis are the time, impact parameter, transverse momentum, the minimum impact parameter significance (IP/σ(IP)) of the muons, the distance of closest approach between the two muons and the isolation of the two muons with respect to any other track in the event. The three new variables are:

1. The minimum \( p_t \) of the two muons;
2. The cosine of the angle between the muon momentum in the \( B \) rest frame and the vector perpendicular to the \( B \) momentum and the beam axis:

\[
\cos \theta = \frac{p_y,\mu_1 p_x,\mu_2 - p_x,\mu_1 p_y,\mu_2}{p_T,B(m_{\mu\mu}/2)}
\]

where \( \mu_1 \) labels one of the muons and \( m_{\mu\mu} \) is the reconstructed \( B \) candidate mass;

3. The \( B \) isolation [14]

\[
I_B = \frac{p_T(B)}{p_T(B) + \sum_i p_T,i}
\]

where \( p_T(B) \) is the \( B \) transverse momentum with respect to the beam line and the sum is over all the tracks, excluding the muon candidates, that satisfy \( \sqrt{\delta \eta^2 + \delta \phi^2} < 1.0 \), where \( \delta \eta \) and \( \delta \phi \) denote respectively the difference in pseudorapidity and azimuthal angle between the track and the \( B \) candidate.

The BDT output is found to be independent of the invariant mass for both signal and background and is defined such that the signal is uniformly distributed between zero and one and the background peaks at zero. The BDT range is then divided in four bins of equal width. The BDT is trained using simulated samples (\( B^0 \rightarrow \mu^+\mu^- \) for signal and \( b\bar{b} \rightarrow \mu^+\mu^-X \) for background where \( X \) is any other set of particles) and the PDF obtained from data as explained below.

### 5.1. Combinatorial background PDFs

The BDT and invariant mass shapes for the combinatorial background inside the signal regions are determined from data by interpolating the number of expected events using the invariant mass sidebands for each BDT bin. The boundaries of the signal regions are defined as \( m_{b\bar{b}} \pm 60 \text{ MeV}/c^2 \) and \( m_{b\bar{b}} \pm 60 \text{ MeV}/c^2 \) and the mass sidebands as \( [m_{b\bar{b}} - 60 \text{ MeV}/c^2, m_{b\bar{b}} - 60 \text{ MeV}/c^2] \) and \( [m_{b\bar{b}} + 60 \text{ MeV}/c^2, m_{b\bar{b}} + 60 \text{ MeV}/c^2] \).

Fig. 1 shows the invariant mass distribution for events that lie in each BDT output bin. In each case the fit model used to estimate the expected number of combinatorial background events in the signal regions is superimposed. The BDT output distribution is found to be independent of the invariant mass for both signal and background and is defined such that the signal is uniformly distributed between zero and one and the background peaks at zero. The BDT output is then divided in four bins of equal width. The BDT is trained using simulated samples (\( B^0 \rightarrow \mu^+\mu^- \) for signal and \( b\bar{b} \rightarrow \mu^+\mu^-X \) for background where \( X \) is any other set of particles) and the PDF obtained from data as explained below.
high-mass sideband. As a cross-check, two other models, a single exponential function and the sum of two exponential functions, have been used to fit the events in different ranges of sidebands providing consistent background estimates inside the signal regions.

5.2. Peaking background PDFs

The peaking backgrounds due to \( B_0^{±} \rightarrow h^+h^- \) events in which both hadrons are misidentified as muons have been evaluated from data and simulated events to be \( N_{BG} = 1.0 \pm 0.4 \) events and \( N_{BG}= 5.0 \pm 0.9 \) events within the two mass windows and in the whole BDT output range. The mass line shape of the peaking background is obtained from a simulated sample of doubly-misidentified \( B_0^{±} \rightarrow h^+h^- \) events and normalized to the number of events expected in the two search windows from data, \( N_{BG} \) and \( N_{BG}^0 \). The BDT PDF of the peaking background is assumed to be the same as for the signal.

5.3. Signal PDFs

The BDT PDF for signal events is determined using an inclusive \( B_0^{±} \rightarrow h^+h^- \) sample. Only events which are triggered independently on the signal candidates have been considered (TIS events).

The number of \( B_0^{±} \rightarrow h^+h^- \) signal events in each BDT output bin is determined by fitting the \( hh\) invariant mass distribution under the \( \mu\mu \) mass hypothesis [15]. Fig. 2 shows the fit to the mass distribution of the full sample and for the three highest BDT output bins for \( B_0^{±} \rightarrow h^+h^- \) TIS events. The \( B_0^{±} \rightarrow h^+h^- \) exclusive decays, the combinatorial background and the physical background components are drawn under the fit to the data; the physical background is due to the partial reconstruction of three-body B meson decays.

In order to cross-check this result, two other fits have been performed on the same dataset. The signal line shape is parametrized either by a single or a double Crystal Ball function [10], the combinatorial background by an exponential function and the physical background by an ARGUS function [16]. In addition, exclusive \( B_0^{±} \rightarrow \pi^-K^+, \pi^-\pi^+, K^-K^+ \) channels, selected using the \( K-\pi \) separation capability of the RICH system, are used to cross-check the calibration of the BDT output both using the \( \pi^-K^+, \pi^-\pi^+, K^-K^+ \) inclusive yields without separating \( B \) and \( B_0^0 \) and using the \( B_0^0 \rightarrow K^\mp\pi^- \) exclusive channel alone. The maximum spread in the fractional yield obtained among the different models has been used as a systematic uncertainty in the signal yield. The BDT PDFs for signals and combinatorial background are shown in Fig. 3.

The invariant mass shape for the signal is parametrized as a Crystal Ball function. The mean value is determined using the \( B_0^0 \rightarrow K^\mp\pi^- \) and \( B_0^0 \rightarrow K^\mp\pi^- \) exclusive channels and the transition point of the radiative tail is obtained from simulated events [6]. The central values are

\[ m_{B_0^0} = 5358.0 \pm 1.0 \text{ MeV/c}^2, \]
\[ m_{B_0^0} = 5272.0 \pm 1.0 \text{ MeV/c}^2. \]

The measured values of \( m_{B_0^0} \) and \( m_{B_0^0} \) are 7–8 MeV/c\(^2\) below the PDG values [13] due to the fact that the momentum scale is uncalibrated in the dataset used in this analysis. The mass resolutions are extracted from data with a linear interpolation between the measured resolution of charmonium and bottomonium resonances decaying into two muons: \( J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S) \) and \( \Upsilon(3S) \). The mass line shapes for quarkonium resonances are
shown in Fig. 4. Each resonance is fitted with two Crystal Ball functions with common mean value and common resolution but different parameterization of the tails. The background is fitted with an exponential function.

The results of the interpolation at the \(m_{B^0}\) and \(m_{B^0}\) masses are

\[
\begin{align*}
\sigma(m_{B^0}) &= 24.6 \pm 0.2\text{ (stat)} \pm 1.0\text{ (syst)} \text{ MeV/c}^2, \\
\sigma(m_{B^0}) &= 24.3 \pm 0.2\text{ (stat)} \pm 1.0\text{ (syst)} \text{ MeV/c}^2.
\end{align*}
\]

This result has been checked using both the fits to the \(B^0_{(s)} \to h^+h^-\) inclusive decay line shape and the \(B^0 \to K^+\pi^-\) exclusive decay. The results are in agreement within the uncertainties.

6. Normalization

To estimate the signal branching fraction, the number of observed signal events is normalized to the number of events of a channel with a well-known branching fraction. Three complementary normalization channels are used: \(B^+ \to J/\psi(K^+)\) and \(B^0 \to J/\psi\) candidates are shown in Fig. 5, while the \(B^0 \to K^+\pi^-\) yield is obtained from the full \(B^0_{(s)} \to h^+h^-\) fit as shown in the top left of Fig. 2. The numbers used to calculate the normalization factors are summarized in Table 1. A weighted average of the three normalization channels, assuming the tracking and trigger efficiencies to be correlated between the two \(J/\psi\) normalization channels and the uncertainty on \(f_s/f_t\) to be correlated between the \(B^+ \to J/\psi K^+\) and \(B^0 \to K^+\pi^-\) yields, gives

\[
\alpha^\text{norm}_B = 8.38 \pm 0.74 \times 10^{-10},
\]

\[
\alpha^\text{norm}_B = 2.20 \pm 0.11 \times 10^{-10}.
\]

These normalization factors are used to determine the limits.

7. Results

The results for \(B^0 \to \mu^+\mu^-\) and \(B^0 \to \mu^+\mu^-\) are summarized in Tables 2 and 3 respectively and in each of the bins the expected number of combinatorial background, peaking background, signal events, with the SM prediction assumed, is shown together with the observations on the data. The uncertainties in the signal and
### Table 1
Summary of the quantities and their uncertainties required to calculate the normalization factors ($\alpha_{B_c \to \mu^+\mu^-}$) for the three normalization channels considered. The branching fractions are taken from Refs. [13,18]. The trigger efficiency and the number of $B^0 \to K^+\pi^-$ candidates correspond to TIS events.

<table>
<thead>
<tr>
<th>$B$ ($\times 10^{-3}$)</th>
<th>$N_{\text{Events}}$</th>
<th>$N_{\text{Expected}}$</th>
<th>$N_{\text{Norm}}$</th>
<th>$\alpha_{B_c \to \mu^+\mu^-}$ ($\times 10^{-5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to J/\psi K^+$</td>
<td>$6.01 \pm 0.21$</td>
<td>$0.48 \pm 0.014$</td>
<td>$0.95 \pm 0.01$</td>
<td>$124518 \pm 2025$</td>
</tr>
<tr>
<td>$B^0 \to J/\psi\phi$</td>
<td>$3.4 \pm 0.9$</td>
<td>$0.24 \pm 0.014$</td>
<td>$0.95 \pm 0.01$</td>
<td>$6940 \pm 93$</td>
</tr>
<tr>
<td>$B^0 \to K^+\pi^-$</td>
<td>$1.94 \pm 0.06$</td>
<td>$0.86 \pm 0.02$</td>
<td>$0.049 \pm 0.004$</td>
<td>$4146 \pm 608$</td>
</tr>
</tbody>
</table>

### Table 2
Expected combinatorial background events, expected peaking ($B^0_{(s)} \to h^+h^-$) background events, expected signal events assuming the SM branching fraction prediction, and observed events in the $B^0_{(s)} \to \mu^+\mu^-$ search window.

<table>
<thead>
<tr>
<th>Invariant mass [MeV/c$^2$]</th>
<th>BDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>Expected comb. bkg 575.5±0.5</td>
</tr>
<tr>
<td>Observed</td>
<td>533</td>
</tr>
<tr>
<td>0.250</td>
<td>Expected comb. bkg 566.8±0.8</td>
</tr>
<tr>
<td>Observed</td>
<td>525</td>
</tr>
<tr>
<td>0.50</td>
<td>Expected comb. bkg 558.2±0.6</td>
</tr>
<tr>
<td>Observed</td>
<td>561</td>
</tr>
<tr>
<td>0.75</td>
<td>Expected comb. bkg 549.8±0.6</td>
</tr>
<tr>
<td>Observed</td>
<td>515</td>
</tr>
<tr>
<td>1.00</td>
<td>Expected comb. bkg 541.5±0.5</td>
</tr>
<tr>
<td>Observed</td>
<td>501</td>
</tr>
</tbody>
</table>
The distribution of selected di-muon events in the invariant mass–BDT plane.

The orange short-dashed (green long-dashed) lines indicate the expected cross-feed events from B_{s}^{0} \rightarrow \mu^{+}\mu^{-} assuming the SM branching fraction and observed events in the B_{s}^{0} \rightarrow \mu^{+}\mu^{-} search window.

<table>
<thead>
<tr>
<th>Invariant mass [MeV/c^{2}]</th>
<th>BDT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0−0.25</td>
</tr>
<tr>
<td>5212−5232</td>
<td>Expected comb. bkg</td>
</tr>
<tr>
<td></td>
<td>Expected peak. bkg</td>
</tr>
<tr>
<td></td>
<td>Cross-feed</td>
</tr>
<tr>
<td></td>
<td>Expected signal</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>5232−5252</td>
<td>Expected comb. bkg</td>
</tr>
<tr>
<td></td>
<td>Expected peak. bkg</td>
</tr>
<tr>
<td></td>
<td>Cross-feed</td>
</tr>
<tr>
<td></td>
<td>Expected signal</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>5252−5272</td>
<td>Expected comb. bkg</td>
</tr>
<tr>
<td></td>
<td>Expected peak. bkg</td>
</tr>
<tr>
<td></td>
<td>Cross-feed</td>
</tr>
<tr>
<td></td>
<td>Expected signal</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>5272−5292</td>
<td>Expected comb. bkg</td>
</tr>
<tr>
<td></td>
<td>Expected peak. bkg</td>
</tr>
<tr>
<td></td>
<td>Cross-feed</td>
</tr>
<tr>
<td></td>
<td>Expected signal</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>5292−5312</td>
<td>Expected comb. bkg</td>
</tr>
<tr>
<td></td>
<td>Expected peak. bkg</td>
</tr>
<tr>
<td></td>
<td>Cross-feed</td>
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<tr>
<td></td>
<td>Expected signal</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>5312−5332</td>
<td>Expected comb. bkg</td>
</tr>
<tr>
<td></td>
<td>Expected peak. bkg</td>
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<td></td>
<td>Cross-feed</td>
</tr>
<tr>
<td></td>
<td>Expected signal</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
</tr>
</tbody>
</table>
Fig. 7. Distribution of selected di-muon events in the $B^0_s \rightarrow \mu^+\mu^-$ mass window for the four BDT output bins. The black dots are data, the light grey histogram shows the contribution of the combinatorial background, the black filled histogram shows the contribution of the $B^0_s \rightarrow h^+h^-$ background and the dark grey filled histogram the contribution of $B^0_s \rightarrow \mu^+\mu^-$ signal events according to the SM rate. The hatched area depicts the uncertainty on the sum of the expected contributions.

Fig. 8. Distribution of selected di-muon events in the $B^0 \rightarrow \mu^+\mu^-$ mass window for the four BDT output bins. The black dots are data, the light grey histogram shows the contribution of the combinatorial background, the black filled histogram shows the contribution of the $B^0_s \rightarrow h^+h^-$ background and the dark grey filled histogram shows the cross-feed of $B^0_s \rightarrow \mu^+\mu^-$ events in the $B^0$ mass window assuming the SM rate. The hatched area depicts the uncertainty on the sum of the expected contributions.
The observed events in the $B^0_s$ and in the $B^0$ mass windows are compatible with the background expectations at 5% and 32% confidence level, respectively. For the $B^0_s \to \mu^+\mu^-$ decay, the probability that the observed events are compatible with the sum of expected background events and signal events according to the SM rate is 33%. The upper limits for the branching fractions are evaluated to be

$$B(B^0_s \to \mu^+\mu^-) < 1.3 \ (1.6) \times 10^{-8} \text{ at 90\% (95\%) CL},$$

$$B(B^0 \to \mu^+\mu^-) < 3.0 \ (3.6) \times 10^{-9} \text{ at 90\% (95\%) CL}.$$  

The $B(B^0_s \to \mu^+\mu^-)$ and $B(B^0 \to \mu^+\mu^-)$ upper limits have been combined with those published previously by LHCb [6] and the results are

$$B(B^0_s \to \mu^+\mu^-)(2010 + 2011)$$

$$< 1.2 \ (1.4) \times 10^{-8} \text{ at 90\% (95\%) CL},$$

$$B(B^0 \to \mu^+\mu^-)(2010 + 2011)$$

$$< 2.6 \ (3.2) \times 10^{-9} \text{ at 90\% (95\%) CL}.$$  

The above 90\% (95\%) CL upper limits are still about 3.8 (4.4) times the SM branching fractions for the $B^0_s$ and 26 (32) times for the $B^0$. These results represent the best upper limits to date.

### Acknowledgements

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