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Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ with the CMS Detector

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The rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ provide an excellent test of the flavor sector of the Standard Model with sensitivity to many new physics models. We report on a search for these decays with the CMS experiment using $1.14\,\text{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 7\,\text{TeV}$ collected in the first half of 2011. The number of events observed after all selection requirements is consistent with the expectation from Standard Model sources. The resulting upper limits on the branching fractions are $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$, at 95 % confidence level.

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1. Introduction

Flavor-changing neutral currents (FCNC) are forbidden at tree level in the Standard Model (SM) of particle physics and proceed only through higher-order loop diagrams. The decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ have very small expected branching fractions in the SM since they involve not only FCNC transitions, but are furthermore helicity suppressed and require an internal quark annihilation within the B meson. The SM-predicted branching fractions are $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$. The dominant theoretical uncertainties arise from the non-perturbative bag parameters [1]. The branching fractions can be enhanced significantly in extensions of the SM, though lowered branching fractions are also possible. In supersymmetric models, the enhancement is strongest at large $\tan\beta$. Various models allow for a different enhancement of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$, and therefore both channels should be studied experimentally. Recently, the CDF collaboration reported an excess of $B_s^0 \to \mu^+\mu^-$ events, corresponding to $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ [2].

We report [3] on the search for the decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ with $1.14\,\text{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 7\,\text{TeV}$, collected in 2011 with the CMS experiment [4]. The subdetectors used are the silicon tracker, consisting of pixel and strip detectors, immersed in a $3.8\,\text{T}$ solenoidal magnetic field. The muon stations are embedded in the steel return yoke and provide muon triggering and reconstruction for pseudorapidities up to $|\eta| < 2.4$. The analysis is not affected by multiple proton-proton collisions because the spatial resolution of the tracker is sufficient to correctly identify the pp collision point from which the signal candidates originate.

The dimuon invariant mass signal region was kept blind until after all selection criteria were established. Events of the type $B^\pm \to J/\psi K^\pm$ ($J/\psi \to \mu^+\mu^-$) are used as a normalization sample. The signal Monte Carlo (MC) simulation sample is validated with data by using events of the type $B_s^0 \to J/\psi\,\phi$ ($J/\psi \to \mu^+\mu^-, \phi \to K^+K^-$).

2. Analysis

The events are triggered by a two-level trigger system. The first level demands two muons

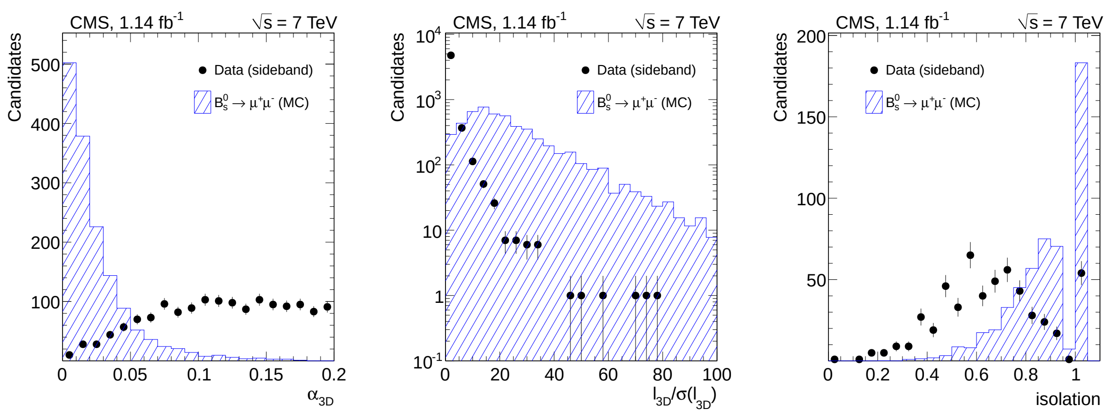

Figure 1: Comparison of signal MC and data background (sideband) distributions of discriminating variables: 3D pointing angle (left), flight length significance (middle), and isolation (right).

without explicit transverse momentum ($p_\perp$) requirements. The second level uses additional information from the silicon tracker. The trigger efficiency for selected events amounts to 80%, both for the signal and normalization samples.

The reconstruction of B candidates starts with two muons, constrained to come from a common vertex. The isolation of the B candidate is computed as $I = p_\perp(B)/(p_\perp(B) + \sum_{\rm trk} p_\perp)$, where the sum includes all tracks with $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $p_\perp > 0.9\,\mathrm{GeV}$. The tracks must either be consistent with originating from the same primary vertex as the B candidate or have a distance of closest approach less than 0.5 mm to the B candidate vertex. A second isolation variable, $d_{\rm ca}^{\rm min}$, is determined from the minimum distance of closest approach of all tracks in the event with respect to the B candidate vertex. The flight length significance $\ell_{\rm 3D}/\sigma(\ell_{\rm 3D})$ is computed from $\ell_{\rm 3D}$, the distance between the primary and dimuon vertices, and its uncertainty $\sigma(\ell_{\rm 3D})$. The pointing angle $\alpha_{\rm 3D}$ is the angle between the flight direction and the B candidate momentum.

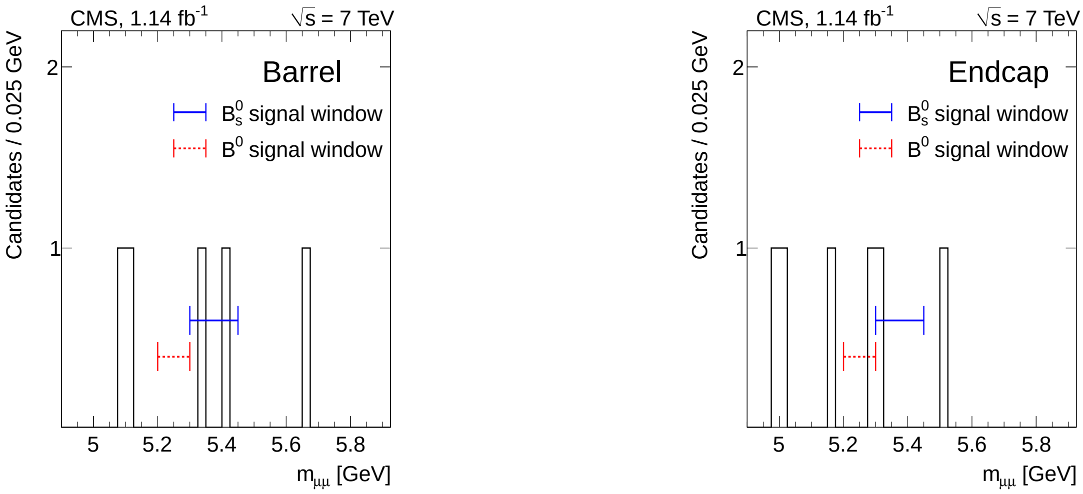

Figure 2: Dimuon invariant mass distributions in the barrel (left) and the endcap (right).

Since the background level varies strongly with B candidate pseudorapidity, the events are separated into two categories: the 'barrel channel' contains events where both muons have $|\eta| < 1.4$ and the 'endcap channel' contains those where at least one muon has $|\eta| > 1.4$. The selection criteria were optimized for the best expected upper limits separately in the barrel and endcap channels with signal MC events and data sideband events. The optimized requirements are $p_\perp > 4.5\,\mathrm{GeV}$ for one muon and $p_\perp > 4.0\,\mathrm{GeV}$ for the other, B candidate $p_\perp > 6.5\,\mathrm{GeV}$ and $I > 0.75$. Two requirements differ in the barrel and endcap channels: $\alpha_{\rm 3D} < 0.050$ (0.025) and $\ell_{\rm 3D}/\sigma(\ell_{\rm 3d}) > 15.0$ (20.0) for the barrel (endcap). Endcap candidate are furthermore required to fulfill $d_{\rm ca}^{\rm min} > 0.15$ mm. Figure 1 illustrates three of the discriminating variables.

3. Results

The $B_s^0 \to \mu^+\mu^-$ branching fraction is measured using

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_{\rm S}}{N_{\rm obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{\rm tot}^{B^+}}{\varepsilon_{\rm tot}} \mathscr{B}(B^+), \tag{3.1}$$

Table 1: The signal event selection efficiencies $\varepsilon_{\rm tot}$, the SM prediction $N^{\rm exp}_{\rm signal}$, the expected combinatorial background $N^{\rm exp}_{\rm comb}$ and peaking background $N^{\rm exp}_{\rm peak}$, and the number of observed events $N_{\rm obs}$.

	Barrel		Endcap	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
$\varepsilon_{\rm tot}$	$(3.6\pm0.4)\times10^{-3}$	$(3.6\pm0.4)\times10^{-3}$	$(2.1\pm0.2)\times10^{-3}$	$(2.1\pm0.2)\times10^{-3}$
$N^{\rm exp}_{\rm signal}$	0.065 ± 0.011	0.80 ± 0.16	0.025 ± 0.004	0.36 ± 0.07
$N^{\rm exp}_{\rm comb}$	0.40 ± 0.23	0.60 ± 0.35	0.53 ± 0.27	0.80 ± 0.40
$N^{\rm exp}_{\rm peak}$	0.25 ± 0.06	0.07 ± 0.02	0.16 ± 0.04	0.04 ± 0.01
$N_{\rm obs}$	0	2	1	1

and analogously for the $B^0 \to \mu^+\mu^-$ case, where $N_{\rm S}$ is the background-subtracted number of observed $B^0_{s(d)} \to \mu^+\mu^-$ candidates in the signal window ($5.3 < m_{\mu\mu} < 5.45\,{\rm GeV}$ for B_s^0 and $5.2 < m_{\mu\mu} < 5.3\,{\rm GeV}$ for B^0) and $\varepsilon_{\rm tot}$ is the total signal efficiency of all selection requirements. The observed number of $B^\pm \to J/\psi K^\pm$ candidates in the barrel (endcap) channel is $N^{B^+}_{\rm obs} = 13\,045\pm652$ (4450 ± 222). The ratio of the B_s^0 and B^+ meson production fractions is $f_s/f_u = 0.282\pm0.037$ and $\mathscr{B}(B^+) \equiv \mathscr{B}(B^+ \to J/\psi K^+ \to \mu^+\mu^-K^+) = (6.0\pm0.2)\times10^{-5}$ [5].

Figure 2 shows the dimuon invariant mass distributions, consistent with the SM expectation for signal plus background. We determine upper limits with the $\mathrm{CL_s}$ approach [6]. Table 1 provides the values needed for the extraction of the results. The median expected upper limits at 95% CL are 1.8×10^{-8} (4.8×10^{-9}) for $B_s^0 \to \mu^+\mu^-$($B^0 \to \mu^+\mu^-$). The measured upper limits on the branching fractions are $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 1.9\times10^{-8}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 4.6\times10^{-9}$ at 95% CL. The background-only p-value is 0.11 (0.40) for $B_s^0 \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$), corresponding to 1.2 (0.27) standard deviations. The p-value is 0.053 when assuming a $B_s^0 \to \mu^+\mu^-$ signal at 5.6 times the SM value [2].

In conclusion, we have searched for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$. The observed event numbers after all selection criteria are in good agreement with the SM predictions for background and signal.

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