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Search for New Physics with a Monojet and Missing Transverse Energy in pp Collisions at √s= 7 TeV

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Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ Decays in pp Collisions at $\sqrt{s} = 7$ TeV

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A search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ is performed in pp collisions at $\sqrt{s} = 7$ TeV, with a data sample corresponding to an integrated luminosity of 1.14 fb^{-1}, collected by the CMS experiment at the LHC. In both cases, the number of events observed after all selection requirements is consistent with expectations from background and standard-model signal predictions. The resulting upper limits on the branching fractions are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$, at 95% confidence level.

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In the standard model (SM) of particle physics, flavor-changing neutral current (FCNC) decays are forbidden at tree level and can only proceed through higher-order loop diagrams. The decays $B_{d(s)} \to \ell^+\ell^-$ (where $\ell = e, \mu$), besides involving $b \to s(d)$ FCNC transitions through penguin and box diagrams, are helicity suppressed by factors of $(m_\ell/m_B)^2$, where m_ℓ and m_B are the masses of the lepton and B meson, respectively. They also require an internal quark annihilation within the B meson that further reduces the decay rate by $(f_B/m_B)^2$, where f_B is the decay constant of the B meson.

The SM-predicted branching fractions, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$ [1], are significantly enhanced in several extensions of the SM, although in some cases the decay rates are lowered [2]. For example, in the minimal supersymmetric extension of the SM, the rates are strongly enhanced at large values of $\tan\beta$ [3,4]. In specific models involving leptoquarks [5] and in supersymmetric models with nonuniversal Higgs boson masses [6], the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions can be enhanced by different factors and, therefore, both channels must be studied in parallel. Several experiments have published upper limits at 95% confidence level (C.L.) on these decays: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 5.1 \times 10^{-8}$ by D0 [7]; $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.8 \times 10^{-8}$ by CDF [8]; $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 5.6 \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ by LHCb [9]. CDF recently reported a new limit of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.0 \times 10^{-9}$ and an excess of $B_s^0 \to \mu^+\mu^-$ events, corresponding to $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ [10].

In this Letter, a simultaneous search for the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays is presented, using a data sample of pp collisions at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of (1.14 ± 0.07) fb^{-1}, collected in the first half of 2011 by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). An event-counting experiment is performed in dimuon mass regions around the B_s^0 and B^0 masses. To avoid any possible bias, the signal region was kept blind until after all selection criteria were established. The backgrounds are evaluated from the yields measured in data mass sidebands and from Monte Carlo (MC) simulations for rare hadronic two-body B decays. The MC event samples are generated with PYTHIA 6.409 [11], the unstable particles are decayed via EVTGEN [12], and the detector response is simulated with GEANT4 [13]. Events of the type $B^+ \to J/\psi K^+, J/\psi \to \mu^+\mu^-$ are used as a normalization sample to minimize uncertainties related to the $b\bar{b}$ production cross section and to the integrated luminosity. The signal and normalization efficiencies are determined with MC simulation studies. A control sample of reconstructed $B_s^0 \to J/\psi\phi, J/\psi \to \mu^+\mu^-$ events is used to validate the MC simulation (such as the B_s^0 transverse momentum p_T spectrum) and to evaluate potential effects resulting from differences in fragmentation between B^+ and B_s^0. The analysis is not affected by multiple pp collisions in the same bunch crossing (pileup) because the spatial vertex resolution is good enough to correctly identify the pp vertex from which signal candidates originate. In the present data set, an average of 5.5 primary vertices are reconstructed per event.

A detailed description of the CMS experiment can be found in Ref. [14]. The main subdetectors used in this analysis are the silicon tracker, composed of pixel and strip layers immersed in a 3.8 T axial magnetic field, and the muon stations, made of gas-ionization detectors embedded in the steel return yoke, and divided into a barrel section and two end caps. The muons are tracked within the pseudorapidity region $|\eta| < 2.4$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the counterclockwise beam direction. A muon p_T resolution of about 1.5% is obtained for muons in this analysis.

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The events are selected with a two-level trigger system. The first level only requires two muon candidates, without an explicit p_T requirement, while the high-level trigger (HLT) uses additional information from the silicon tracker. The HLT selection for the signal data sample requires two muons each with $p_T > 2$ GeV, dimuon $p_T > 4$ GeV, invariant mass within $4.8 < m_{\mu\mu} < 6.0$ GeV, and a 3D distance of closest approach to each other $d'_{\rm ca} < 5$ mm.

The normalization ($B^+ \rightarrow J/\psi K^+$) and control ($B_s^0 \rightarrow J/\psi \phi$) samples were collected with HLT requirements gradually tightened as the LHC luminosity increased. This time evolution does not affect the analysis presented here, which uses selection criteria significantly tighter than any trigger requirements. More than 95% of the normalization and control sample events were collected by requiring two muons each with $p_T > 3$ GeV, dimuon $p_T > 6.9$ GeV, invariant mass within $2.9 < m_{\mu\mu} < 3.3$ GeV, $d'_{\rm ca} < 5$ mm, and a larger than 0.5% probability of the χ^2 per degree of freedom (d.o.f.) of the dimuon vertex fit. Two additional trigger requirements, measured in the transverse plane, significantly reduce the rate of prompt J/ψ candidates: the significance of the flight distance $\ell_{xy}/\sigma(\ell_{xy})$ must be larger than 3, where ℓ_{xy} is the distance between the primary and dimuon vertices and $\sigma(\ell_{xy})$ is its uncertainty, and the pointing angle α_{xy} between the B candidate momentum and the vector from the primary vertex to the dimuon vertex must fulfill $\cos\alpha_{xy} > 0.9$. The average trigger efficiency, calculated after all other selection criteria have been applied, for events in the signal and normalization samples is about 80%, as determined from MC simulation. The uncertainty on the ratio of trigger efficiencies between the signal and normalization samples is estimated to be 2% by comparing these ratios in simulation studies and in data.

Muon candidates are required to be reconstructed by two different algorithms, one matching silicon-tracker tracks to segments in the muon stations and the other performing global fits using tracks in both detector systems [15]. The uncertainty on the ratio of muon identification efficiencies between the signal and normalization samples is estimated to be 5%.

The $B \rightarrow \mu^+\mu^-$ candidates require two oppositely charged muons with an invariant mass in the region $4.9 < m_{\mu\mu} < 5.9$ GeV, after constraining their tracks to come from a common vertex. The B candidate momentum and vertex position are used to choose a primary vertex based on the distance of closest approach. Since the background level depends significantly on the pseudorapidity of the B candidate, the events are separated into two categories: the "barrel channel" contains the candidates where both muons have $|\eta| < 1.4$ and the "end cap channel" contains those where at least one muon has $|\eta| > 1.4$. An isolation variable $I = p_T(B)/(p_T(B) + \sum_{\rm trk} p_T)$ is calculated from the transverse momentum of the B candidate $p_T(B)$ and the transverse momenta of all other charged tracks satisfying $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle between a charged track and the B candidate momentum. The sum includes all tracks with $p_T > 0.9$ GeV that are consistent with originating from the same primary vertex as the B candidate or have a distance of closest approach $d_{\rm ca} < 0.5$ mm with respect to the B vertex. The minimum distance of closest approach with respect to the B vertex among all tracks in the event, $d_{\rm ca}^{\rm min}$, is also determined as a complementary isolation variable. Figure 1 illustrates the transverse momentum, the 3D pointing angle $\alpha_{\rm 3D}$, the 3D flight length significance $\ell_{\rm 3D}/\sigma(\ell_{\rm 3D})$, and the isolation distributions for signal MC events and for sideband background data events. The sideband covers the range $4.9 < m_{\mu\mu} < 5.9$ GeV, excluding the signal window $5.2 < m_{\mu\mu} < 5.45$ GeV.

The following selection requirements were optimized for the best expected upper limit using MC signal events and data sideband events. The requirements were established before observing the number of data events in the signal region. The optimized requirements include $p_T > 4.5$ GeV on one muon and $p_T > 4.0$ GeV on the other, B candidate $p_T > 6.5$ GeV, $I > 0.75$, and B-vertex fit $\chi^2/\text{d.o.f.} < 1.6$. Two requirements are different for the barrel and end cap channels: $\alpha_{\rm 3D} < 0.050$ (0.025) and

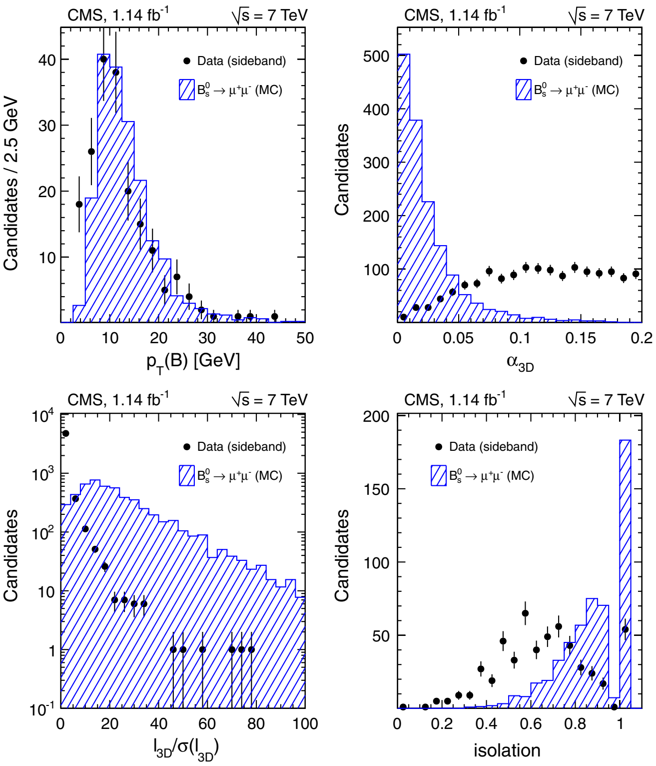

FIG. 1 (color online). Comparison of MC signal and sideband data distributions, for the transverse momentum (top left), the 3D pointing angle (top right), the flight length significance (bottom left), and the isolation (bottom right). The MC histograms are normalized to the number of events in the data.

TABLE I. The event selection efficiencies for signal events $\varepsilon_{\rm tot}$, the SM-predicted number of signal events $N^{\rm exp}_{\rm signal}$, the expected number of combinatorial background events $N^{\rm exp}_{\rm comb}$ and peaking background events $N^{\rm exp}_{\rm peak}$, and the number of observed events $N_{\rm obs}$ in the barrel and end cap channels for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$.

	Barrel		End cap	
	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$
$\varepsilon_{\rm tot}$	$(3.6 \pm 0.4) \times 10^{-3}$	$(3.6 \pm 0.4) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$
$N^{\rm exp}_{\rm signal}$	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

$\ell_{3D}/\sigma(\ell_{3d}) > 15.0$ (20.0) for the barrel (end cap). Furthermore, for events in the end cap there is an additional requirement, $d^{\rm min}_{\rm ca} > 0.15$ mm. The signal efficiencies $\varepsilon_{\rm tot}$ of these selections are provided in Table I. The dimuon mass resolution for signal events depends on the pseudorapidity of the B candidate and ranges from 36 MeV for $\eta \approx 0$ to 85 MeV for $|\eta| > 1.8$, as determined from simulated signal.

The reconstruction of $B^+ \to J/\psi K^+ \to \mu^+\mu^-K^\pm$ ($B^0_s \to J/\psi\phi \to \mu^+\mu^-K^+K^-$) candidates requires two oppositely charged muons with an invariant mass in the range 3.0–3.2 GeV, which are combined with one (two) track(s), assumed to be (a) kaon(s), fulfilling $p_T >$ 0.5 GeV and $|\eta| < 2.4$. To ensure a well-measured trigger efficiency, the selected candidates must have dimuon $p_T >$ 7 GeV and the two muons must bend away from each other in the magnetic field (to avoid spurious detector-induced pair correlations). The $d'_{\rm ca}$ between all pairs among the three (four) tracks is required to be less than 1 mm. For $B^0_s \to J/\psi\phi$ candidates the two assumed kaon tracks must have an invariant mass in the range 0.995–1.045 GeV and $\Delta R(K^+, K^-) < 0.25$. The tracks from all decay products are used in the B-vertex fit and only B candidates with an invariant mass in the range 4.8–6.0 GeV are considered. The efficiencies of individual selection criteria agree to better than 4% (6%) between data and MC simulation for the normalization (control) sample, where the efficiencies have been calculated for each selection requirement with event yield fits after applying all other selection criteria. Figure 2 compares several distributions for $B^0_s \to J/\psi\phi$ candidates between MC simulation and sideband-subtracted data.

The total efficiency for $B^+ \to J/\psi K^+ \to \mu^+\mu^-K^+$, including the detector acceptance, is $\varepsilon^{B^+}_{\rm tot} = (7.7 \pm 0.8) \times 10^{-4}$ and $(2.7 \pm 0.3) \times 10^{-4}$, respectively, for the barrel and end cap channels, where statistical and systematic uncertainties are combined. The acceptance has a systematic uncertainty of 4%, estimated by comparing the values obtained with different $b\bar{b}$ production mechanisms (gluon splitting, flavor excitation, and flavor creation). The uncertainty on the event selection efficiency for the $B^+ \to J/\psi K^+$ normalization sample is 4%, evaluated from differences between measured and simulated $B^+ \to J/\psi K^+$ events. The uncertainty on the signal efficiency (7.9%) is evaluated using the $B^0_s \to J/\psi\phi$ control sample. The invariant mass distributions are fitted with a Gaussian function for the signal and an exponential (barrel) or a first-degree polynomial (end cap) plus an error function for the background, as shown in Fig. 3. Applying the same selection requirements as for the signal sample, the observed number of $B^+ \to J/\psi K^+$ candidates in the barrel (end cap) channel is $N^{B^+}_{\rm obs} = 13\,045 \pm 652$ (4450 ± 222). The uncertainty includes a systematic term estimated to

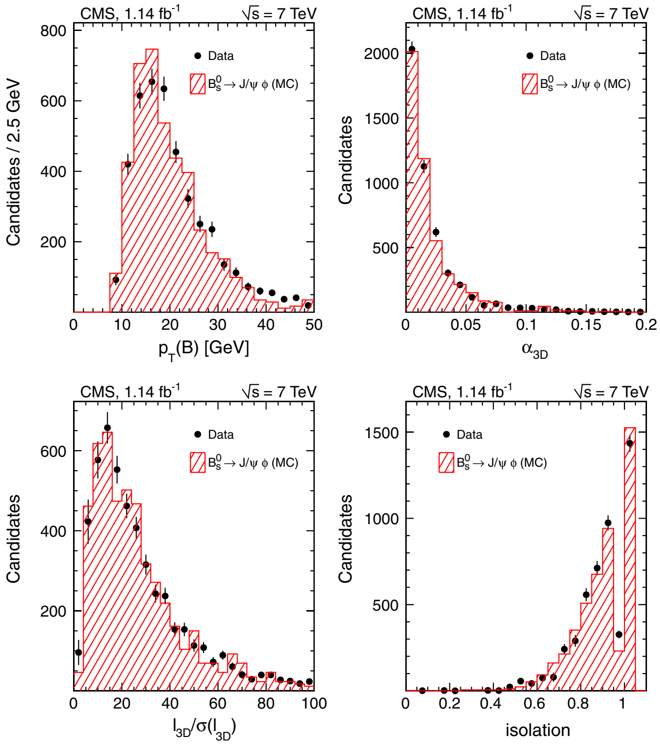

FIG. 2 (color online). Comparison of measured and simulated $B^0_s \to J/\psi\phi$ distributions, for the transverse momentum (top left), the 3D pointing angle (top right), the flight length significance (bottom left), and the isolation (bottom right). The MC histograms are normalized to the number of events in the data.

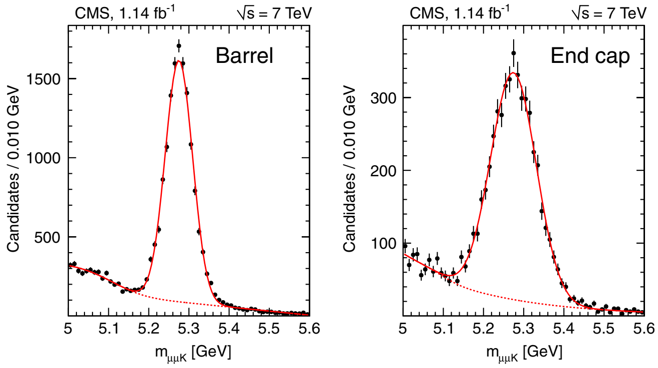

FIG. 3 (color online). $B^+ \to J/\psi K^+$ invariant mass distributions in the barrel (left) and end cap (right) channels. The solid (dashed) lines show the fits to the data (background).

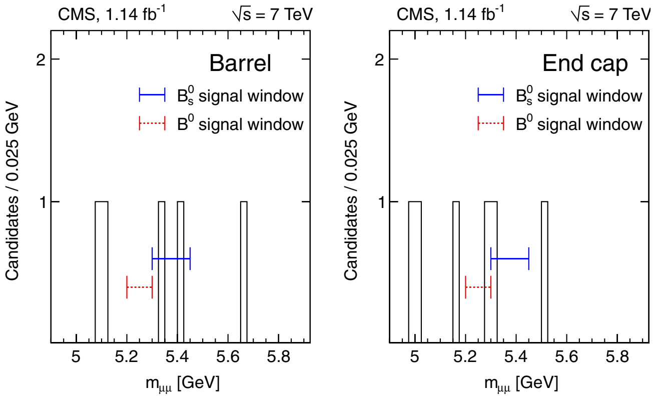

FIG. 4 (color online). Dimuon invariant mass distributions in the barrel (left) and end cap (right) channels. The signal windows for B_s^0 and B^0 are indicated by horizontal lines.

be 5% from MC studies by considering alternative fitting functions.

To quantify a possible dependence on the pileup, the efficiencies of the isolation and the flight length significance requirements are calculated as functions of the number of reconstructed primary vertices. No dependence is observed for events with up to 12 primary vertices for the normalization and control samples.

The $B_s^0 \to \mu^+\mu^-$ branching fraction is measured separately in the barrel and end cap channels using

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_S}{N_{\text{obs}}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{\text{tot}}^{B^+}}{\varepsilon_{\text{tot}}} \mathcal{B}(B^+), \qquad (1)$$

and analogously for the $B^0 \to \mu^+\mu^-$ case, where N_S is the background-subtracted number of observed $B_{d(s)} \to \mu^+\mu^-$ candidates in the signal window ($5.3 < m_{\mu\mu} < 5.45$ GeV for B_s^0 and $5.2 < m_{\mu\mu} < 5.3$ GeV for B^0) and ε_{tot} is the total signal efficiency of all selection requirements. The ratio of the B_s^0 and B^+ meson production fractions is $f_s/f_u = 0.282 \pm 0.037$ and $\mathcal{B}(B^+) \equiv \mathcal{B}(B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+) = (6.0 \pm 0.2) \times 10^{-5}$ [16]. (We use $f_s = 0.113 \pm 0.013$ and $f_u = 0.401 \pm 0.013$ from the main section of Ref. [16] and account for the correlations in the ratio.)

Events in the signal window can result from real signal decays, combinatorial background, and "peaking" background from decays of the type $B_{d(s)} \to hh'$, where h, h' are charged hadrons misidentified as muons. The expected number of signal events, $N_{\text{signal}}^{\text{exp}}$, is calculated assuming the SM branching fraction and is normalized to the B^+ yield. The expected number of combinatorial background events, $N_{\text{comb}}^{\text{exp}}$, is evaluated by interpolating to the signal window the number of events observed in the sideband regions which is equal to three (four) for the barrel (end cap) channel. The interpolation procedure assumes a flat background shape and has a systematic uncertainty of 4%, evaluated by varying the flight length significance selections and by using a floating slope. The expected number of peaking background events, $N_{\text{peak}}^{\text{exp}}$, is evaluated from MC simulation and muon misidentification rates measured in $K_S^0 \to \pi^+\pi^-$, $\phi \to K^+K^-$, and $\Lambda \to p\pi^-$ samples [15].

Figure 4 shows the measured dimuon invariant mass distributions. Three events are observed in the $B_s^0 \to \mu^+\mu^-$ signal windows (two in the barrel and one in the end cap), while only one event is observed in the $B^0 \to \mu^+\mu^-$ end cap channel. This observation is consistent with the SM expectation for signal plus background. Upper limits are determined with the CL$_s$ approach [17]. Table I shows the values needed for the extraction of the results, separately for the barrel and end cap channels. The obtained upper limits on the branching fractions are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ (1.6×10^{-8}) and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$ (3.7×10^{-9}), at 95% (90%) C.L. The median expected upper limits at 95% C.L. are 1.8×10^{-8} (4.8×10^{-9}) for $B_s^0 \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$). 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, as reported in Ref. [10].

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 of pp collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 1.14 fb^{-1}. The observed event yields are consistent with those expected adding background and SM signals. Upper limits on the branching fractions have been determined at 90% and 95% C.L.

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