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

Marco De Mattia[*†]
Purdue University
E-mail: marco.de.mattia@cern.ch

A search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ in pp collisions at $\sqrt{s}$ = 7 TeV is presented, with a data sample corresponding to an integrated luminosity of 5 fb^{-1} collected by the CMS experiment at the LHC. The number of events observed after all selection requirements is found to be consistent with the expectation from background plus standard model signal predictions in both decays. The resulting upper limits on the branching fractions are B($B_s^0 \to \mu^+\mu^-$) $< 7.7 \times 10^{-9}$ and B($B^0 \to \mu^+\mu^-$) $< 1.8 \times 10^{-9}$ at 95% confidence level.

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[*]Speaker.
[†]On behalf of the CMS Collaboration.

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1. Introduction

The decays $B_s^0(\mathrm{B}^0) \to \mu^+\mu^-$ are highly suppressed in the standard model (SM) of particle physics, which predicts the branching fractions to be B($B_s^0 \to \mu^+\mu^-$) = $(3.2 \pm 0.2) \times 10^{-9}$ and B($B^0 \to \mu^+\mu^-$) = $(1.0 \pm 0.1) \times 10^{-10}$ [1]. Several extensions of the SM predict enhancements (or in some cases suppressions) to the branching fractions for these rare decays [2, 3, 4, 5, 6]. We report on a simultaneous search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays using data collected in 2011 by the CMS experiment in pp collisions at $\sqrt{s} = 7$ TeV at the LHC. The dataset corresponds to an integrated luminosity of 5 fb$^-$1. An event-counting experiment is performed in the mass regions around the B_s^0 and B^0 masses. A "blind" analysis approach is applied where the signal region is observed only after all selection criteria are established to avoid potential bias. Backgrounds due to B decays are estimated using Monte Carlo (MC) simulations, while combinatorial backgrounds are evaluated from the data in dimuon invariant mass (m) sidebands. The mass resolution, influencing the separation between $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays, depends on the pseudorapidity of the reconstructed particles. The pseudorapidity is defined as = -ln[tan(θ/2)], where θ is the polar angle with respect to the counterclockwise proton beam direction. The η of the B candidate also influences the background level. For this reason, the analysis is performed separately in two channels, "barrel" and "endcap", and then combined for the final result. The "barrel" channel includes candidates where both muons have $|\eta| < 1.4$ and the "endcap" channel has all the other candidates. The sample of events with $B^+ \to J/\psi K^+$ decays (where $J/\psi \to \mu^+\mu^-$) is used as "normalization" sample to remove uncertainties related to the $b\bar{b}$ production cross section and the integrated luminosity. Signal and normalization efficiencies are determined from MC. To validate the simulation distributions and potential effects resulting from differences in the fragmentation of B^+ and B_s^0 , a sample with $B_s^0 \to J/\psi\phi$ decays (where $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$) is used as a "control" sample.

2. Analysis

A $B^0 \to \mu^+\mu^-$ candidate is reconstructed with two oppositely-charged muons originating from a common vertex and with invariant mass in the range $4.9 < m_{\mu\mu} < 5.9$ GeV. A fit of the B-candidate vertex is performed and its χ^2/dof is evaluated. The two muon tracks are combined to form the B-candidate track. The primary vertex associated with a B candidate is chosen from all reconstructed primary vertices as the one which has minimal separation along the z axis from the z intercept of the extrapolated B candidate track. This procedure largely eliminates reconstruction effects due to pileup. The position of this primary vertex is then refit without the tracks of the B candidate with an adaptive vertex fit [7]. Background events in data are defined as B candidates with a dimuon mass in the sidebands covering the range $4.9 < m < 5.9$ GeV, and excluding the (blinded) signal windows from $5.20 < m < 5.45$ GeV. Figure 1 shows the distribution of variables used in the analysis for events passing a tight selection that is close to the final one. For each distribution, the selection requirements for all variables, apart from the one plotted, are applied. This figure illustrates the differences in the distributions of signal and background events, and shows which variables are effective in reducing the background events. Likewise, figure 2 shows the

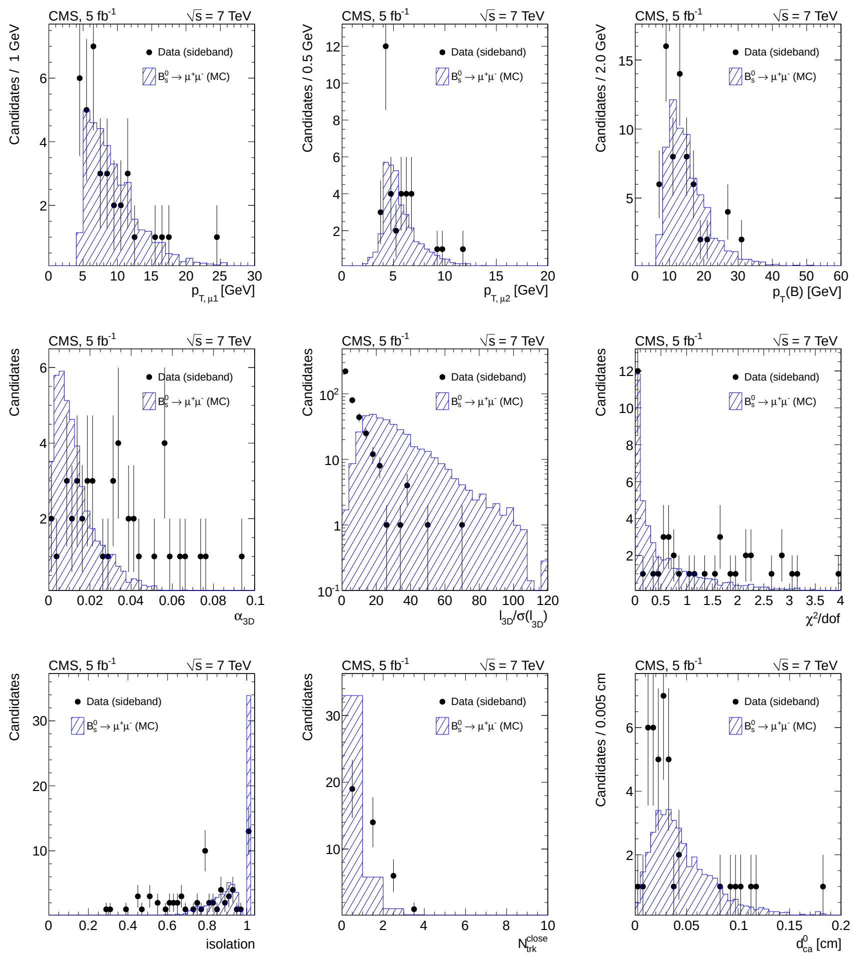

Figure 1: Comparison of simulated $B_s^0 \to \mu^+\mu^-$ decays and background dimuon distributions as measured in the mass sidebands. Top row: transverse momentum for the leading muon, sub-leading muon, and B-candidate; middle row: 3D pointing angle, flight length significance, and B-candidate's vertex χ^2/dof; bottom row: isolation variables I, N_{trk}^{close}, and d_{ca}^0. The MC histograms are normalized to the number of events in the data.

same distributions for the control sample $B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+$, derived with an analogous procedure [12].

3. Results

The variables discussed in section 2 are optimized to obtain the best expected upper limit using MC signal events and data sideband events for the background. The exact procedure and the resulting selection are detailed in [12]. The requirements were established before observing the number of data events in the signal region. Hence, the analysis was blind to the signal events in the $5.20 < m < 5.45$ GeV mass range. The signal efficiencies (ε_{tot}) for these selections are shown in table 1. The quoted errors include all the systematic uncertainties. Branching fractions are measured separately in the barrel and endcap channels using the following equation $\mathrm{B}(B_s^0 \to \mu^+\mu^-)$

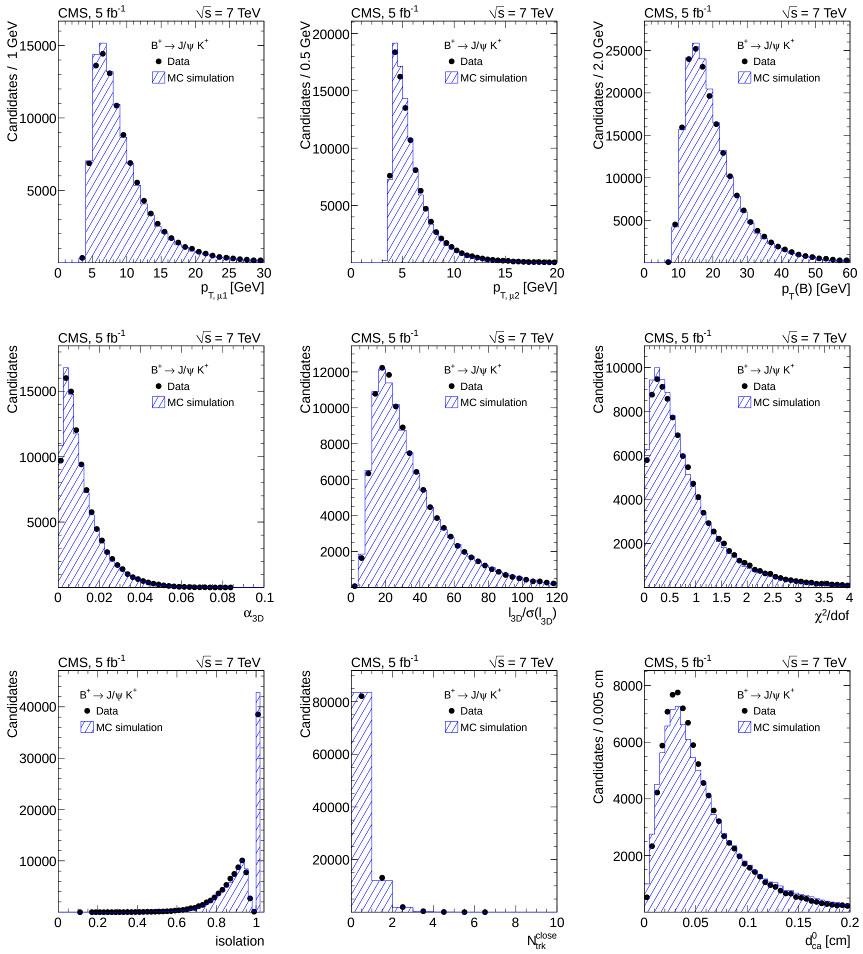

Figure 2: Comparison of measured and simulated $B^+ \to J/\psi K^+$ distributions. Top row: transverse momentum for the leading muon, sub-leading muon, and B-candidate; middle row: 3D pointing angle, flight length significance, and B-candidate's vertex χ^2/dof; bottom row: isolation variables I, N_{trk}^{close}, and d_{ca}^0. The MC histograms are normalized to the number of events in the data.

$= \frac{N_s}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} \mathrm{B}(B^+)$, where ε_{tot} is the total signal efficiency, $N_{obs}^{B^+}$ is the number of reconstructed $B^+ \to J/\psi K^+$ decays, $\varepsilon_{tot}^{B^+}$ is the total efficiency of B^+ reconstruction, $\mathrm{B}(B^+)$ is the branching fraction for $B^+ \to J/\psi K^+ \to \mu^+\mu^- K+$, f_u/f_s is the ratio of the B^+ and B_s^0 production cross sections, and N_S is the background-subtracted number of observed $B_s^0 \to \mu^+\mu^-$ candidates in the signal window $5.30 < m < 5.45$ GeV. The width of the signal windows is chosen to maximize the efficiency for the $B_s^0 \to \mu^+\mu^-$ decay, and it is approximately equal to twice the expected mass resolution in the endcap region. We use the value $f_s/f_u = 0.267 \pm 0.021$, measured by LHCb for $2 < \eta < 5$ [8] and $\mathrm{B}(B^+) = \mathrm{B}(B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+) = (6.0 \pm 0.2)10^{-5}$ [9]. An analogous equation is used to measure the $B^0 \to \mu^+\mu^-$ branching fraction, with the signal window $5.2 < m < 5.3$ GeV and the ratio $f_d = f_u$ taken to be 1. The number of reconstructed B^+ mesons $N_{obs}^{B^+}$ is $(82.7 \pm 4.2)10^3$ in the barrel and $(23.8 \pm 1.2)10^3$ in the endcap. The invariant mass distributions are fit with a double-Gaussian function for the signal and an exponential plus an error function for the background.

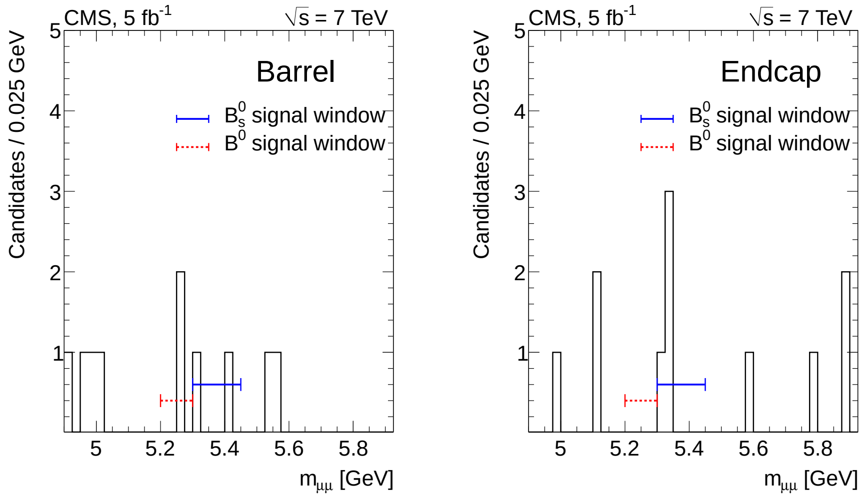

Figure 3: Dimuon invariant-mass distributions in the barrel (left) and endcap (right) channels. The signal windows for B_s^0 and B^0 are indicated by horizontal lines.

Table 1 shows the expected numbers of signal events N_{signal}^{exp} for the barrel and endcap channels. They are calculated assuming the SM branching fractions [1] and are normalized to the measured B^+ yield. The systematic uncertainty on the background includes the uncertainties on the production ratio (for B_s^0 and b decays), the branching fraction, and the misidentification probability. Also shown in table 1 are the expected numbers of combinatorial background events N_{comb}^{exp}. They are evaluated by interpolating into the signal window the number of events observed in the sideband regions, after subtracting the expected rare semileptonic background. Figure 3 shows the measured dimuon invariant-mass distributions. The number of observed events in the sidebands is six (seven) for the barrel (endcap) channel. Six events are observed in the $B_s^0 \to \mu^+\mu^-$ signal windows (two in the barrel and four in the endcap), while two events are observed in the $B^0 \to \mu^+\mu^-$ barrel channel and none in the endcap channel. This observation is consistent with the SM expectation for signal plus background, as indicated by the numbers shown in table 1. The CLs method [10, 11] is used to determine upper limits on the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions. The combined upper limits for the barrel and endcap channels are B($B_s^0 \to \mu^+\mu^-$) $< 7.7\times10^{-9}(6.4\times10^{-9})$ and B($B^0 \to \mu^+\mu^-$) $< 1.8\times10^{-9}(1.4\times10^{-9})$ at 95% (90%) CL. The median expected upper limits at 95% CL are $8.4\times10^{-9}(1.6\times10^{-9})$ for $B_s^0 \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$), where the number of expected signal events is based on the SM value. Including cross-feed between the B^0 and B_s^0 decays, the background-only p value is 0.11 (0.24) for $B_s^0 \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$), corresponding to 1.2 (0.7) standard deviations. The p value for the background plus SM signal hypotheses is 0.71 (0.86) for $B_s^0 \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$).

4. Summary

An analysis searching for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ has been performed in pp collisions at $\sqrt{s} = 7$ TeV. A data sample corresponding to an integrated luminosity of 5 fb^{-1} has been used. The observed number of events is found to be consistent with background plus SM

variable	$B^0 \to \mu^+\mu^-$ Barrel	$B^0_s \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B^0_s \to \mu^+\mu^-$ Endcap
ε_{tot}	0.0029 ± 0.0002	0.0029 ± 0.0002	0.0016 ± 0.0002	0.0016 ± 0.0002
N^{exp}_{signal}	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
N^{exp}_{peak}	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
N^{exp}_{comb}	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
N^{exp}_{total}	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
N_{obs}	2	2	0	4

Table 1: Event selection efficiency for signal events ε_{tot}, the SM-predicted number of signal events N^{exp}_{signal}, the expected number of peaking background events N^{exp}_{peak} and combinatorial background events N^{exp}_{comb}, and the number of observed events N_{obs} in the barrel and endcap channels for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$. The quoted errors include both the statistical and the systematic uncertainties.

signals. The resulting upper limits on the branching fractions are B($B^0_s \to \mu^+\mu^-$) $< 7.7 \times 10^{-9}$ and B($B^0 \to \mu^+\mu^-$) $< 1.8 \times 10^{-9}$ at 95% CL. These upper limits can be used to improve bounds on the parameter space for a number of potential extensions to the standard model.

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