Search for $B_s \to \mu^+\mu^-$ and $B_0 \to \mu^+\mu^-$ decays in CMS

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Introduction

In the standard model (SM) of particle physics, flavor-changing neutral current decays are highly suppressed:

1. are forbidden at tree level and can only proceed through higher-order loop diagrams
2. are helicity suppressed by factors of $(m_l/m_B)^2$, where m_l and m_B are the masses of the lepton and B meson
3. require an internal quark annihilation within the B meson

The SM predictions are significantly enhanced in several extensions of the SM, although in some cases the decay rates are lowered.

A search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ is presented here, using 1.14 fb^{-1} of integrated luminosity collected by the CMS experiment in 2011.

Decay channel	BF SM predictions
$B_s^0 \to \mu^+\mu^-$	$(3.2 \pm 0.2) \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$(1.1 \pm 0.1) \times 10^{-10}$

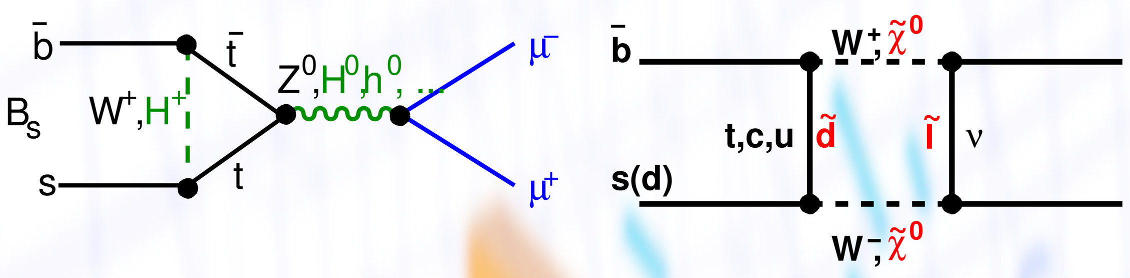


Illustration of the rare decays $B_{s(d)}^0 \to \mu^+\mu^-$
In the SM these decays proceed through penguin (left) and box (right) interactions

A blind analysis

We perform a counting experiment in the dimuon mass distribution centered on the B_s^0 (B^0) meson mass.

The background is estimated from the sidebands and from Monte Carlo (MC) simulation.

The analysis uses a relative normalization to the well-measured decay $B^\pm \to J/\psi K^\pm$ to avoid a dependence on the uncertainties of the $b\bar{b}$ production cross section and luminosity measurements:

$$B_f\left(B_s^0 \to \mu^+\mu^-\right) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} B_f\left(B^+\right)$$

Since the mass resolution in the CMS detector depends strongly on the pseudorapidity (η) of the reconstructed particles, the analysis is performed in two 'channels', barrel (if both muons have |η| < 1.4) and endcap (elsewhere), that are then combined for the final result.

The determination of the signal efficiency in this analysis depends on MC simulation.

The MC simulation is validated through two samples of fully reconstructed *B* decays:

1. The decay $B^\pm \to J/\psi K^\pm$ provides a high-statistics sample to allow fine-grained comparisons.
2. The decay $B_s^0 \to J/\psi\, \varphi$ is essential to compare B_s^0 mesons in data and MC simulations and to estimate systematic uncertainties for the analysis efficiency.

Region definitions	Invariant mass (GeV)	Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu 1 \mu 2} < 5.90$	$B^0 \to \mu^+\mu^-$ window	$5.20 < m_{\mu 1 \mu 2} < 5.30$
blinding window	$5.20 < m_{\mu 1 \mu 2} < 5.45$	$B_s^0 \to \mu^+\mu^-$ window	$5.30 < m_{\mu 1 \mu 2} < 5.45$

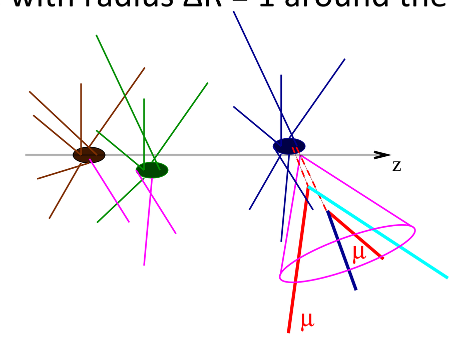
The signal channel: $B_{(s)}^0 \to \mu^+\mu^-$

The events are selected with a two-level trigger system. The first hardware level only requires two muon candidates, while the high-level software trigger uses additional information from the silicon tracker.

For the offline event selection, variables related to the muons, the primary vertex, and the B_s^0 candidate with its associated secondary vertex are calculated.

- The primary vertex is determined with the standard algorithm used in CMS.
- The candidate's secondary vertex and its momentum are used to select a matching primary vertex based on the distance of closest approach.
- The flight length significance is computed as the ratio of the flight length to its error: $S_{3D} = l_{3d}/\sigma(l_{3d})$.
- The pointing angle α is defined as the angle in three dimensions between the *B* candidate momentum and the vector from the primary vertex to the *B* decay vertex.
- The isolation (I) is determined from the *B* candidate transverse momentum and other charged tracks in a cone with radius ΔR = 1 around the *B* momentum as follows:

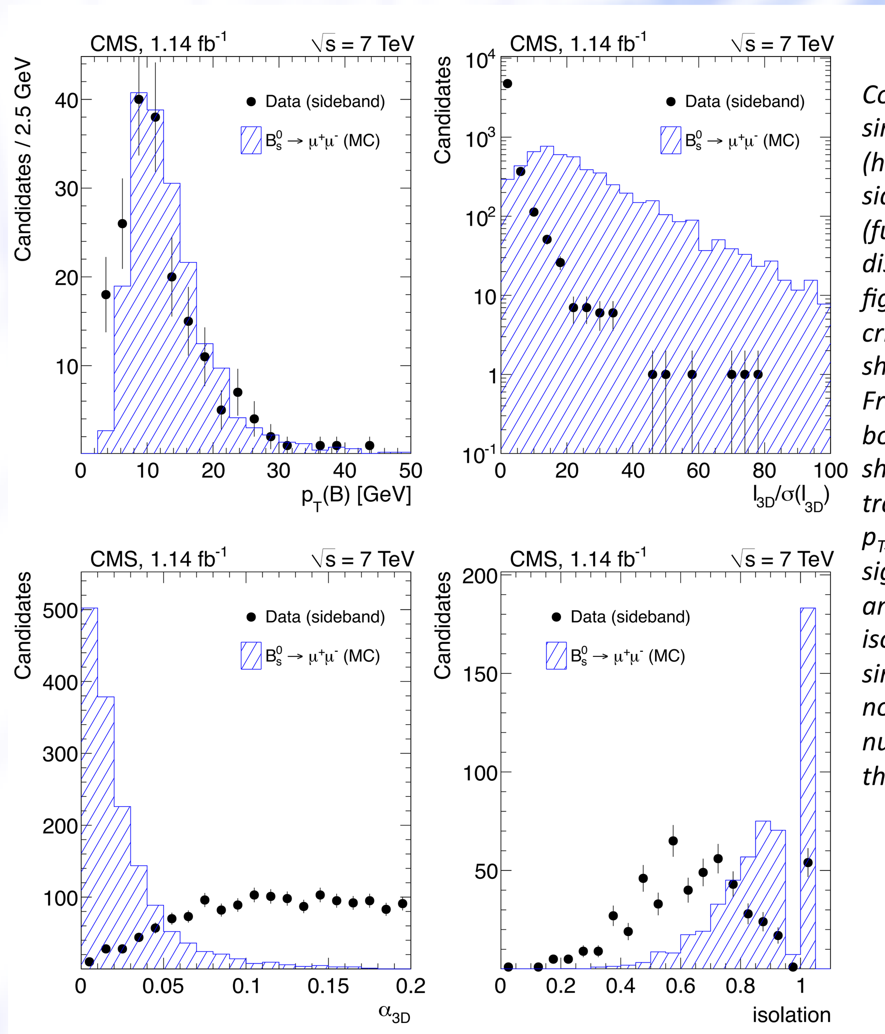
$$I = \frac{p_\perp(B)}{p_\perp(B) + \sum_{trk} |p_\perp|}$$



Background

The background sources that mimic the signal topology can be grouped into three categories.

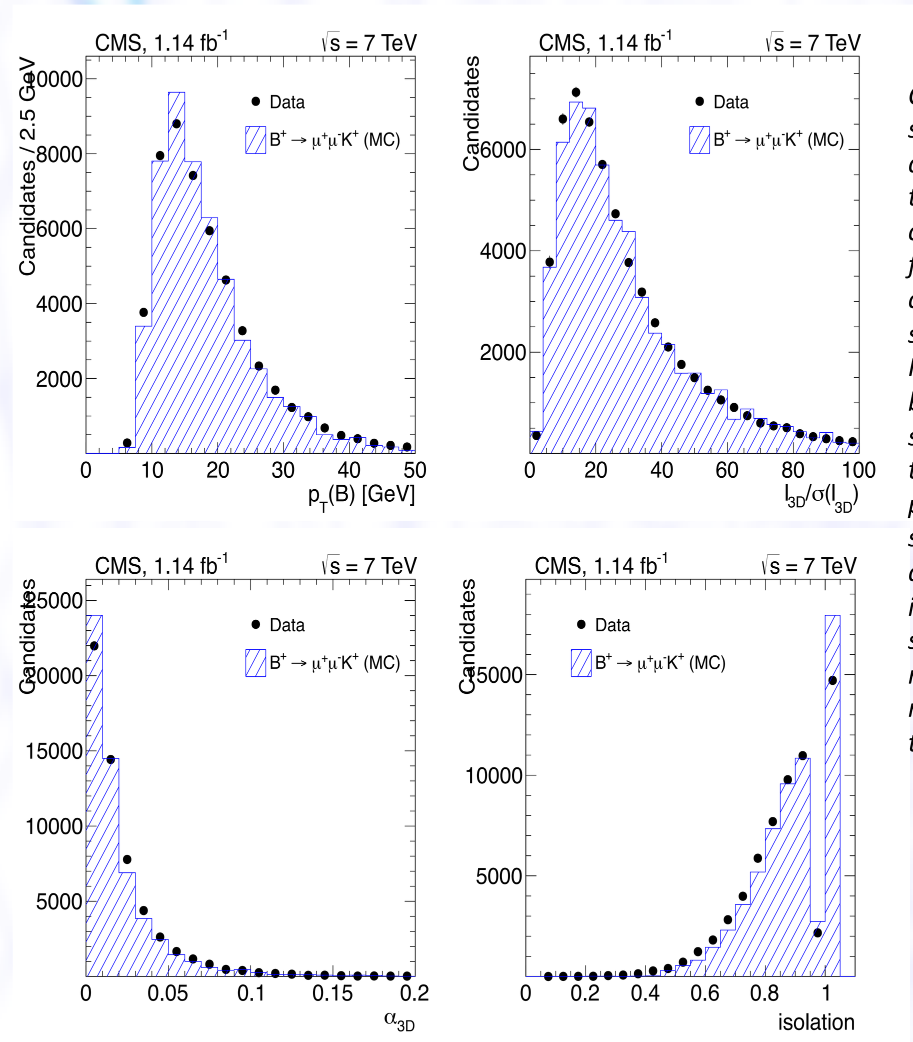
1. $q\bar{q}$ events (where *q = b, c*) with $q \to X\mu\bar{\nu}$ (prompt or cascade) decays of both *q* hadrons.
2. events where a true muon is combined with a hadron misidentified as a muon (punch-through or in-flight decay of a hadron).
3. rare B^0, B^+, B_s^0 and Λ_b decays, mostly from semileptonic decays:
   i. Peaking backgrounds from rare decays, where a heavy particle decays into a pair of hadrons. Examples for these decays include $B_s^0 \to K^+K^-$, $\Lambda_b \to pK^-$.
   ii. Non-peaking backgrounds from rare B^0, B^+, and B_s^0 decays, comprising hadronic, semileptonic, and radiative decays.



Comparison of the MC simulation signal (histogram) and the sideband background (full circle) from data distributions. For each figure, all selection criteria except the one shown are applied. From left to right, top to bottom, the figures show: dimuon transverse momentum p_T, flight length significance, pointing angle α, and the isolation I. The MC simulation histogram is normalized to the same number of events like the data histogram.

The normalization channel: $B^\pm \to J/\psi K^\pm$

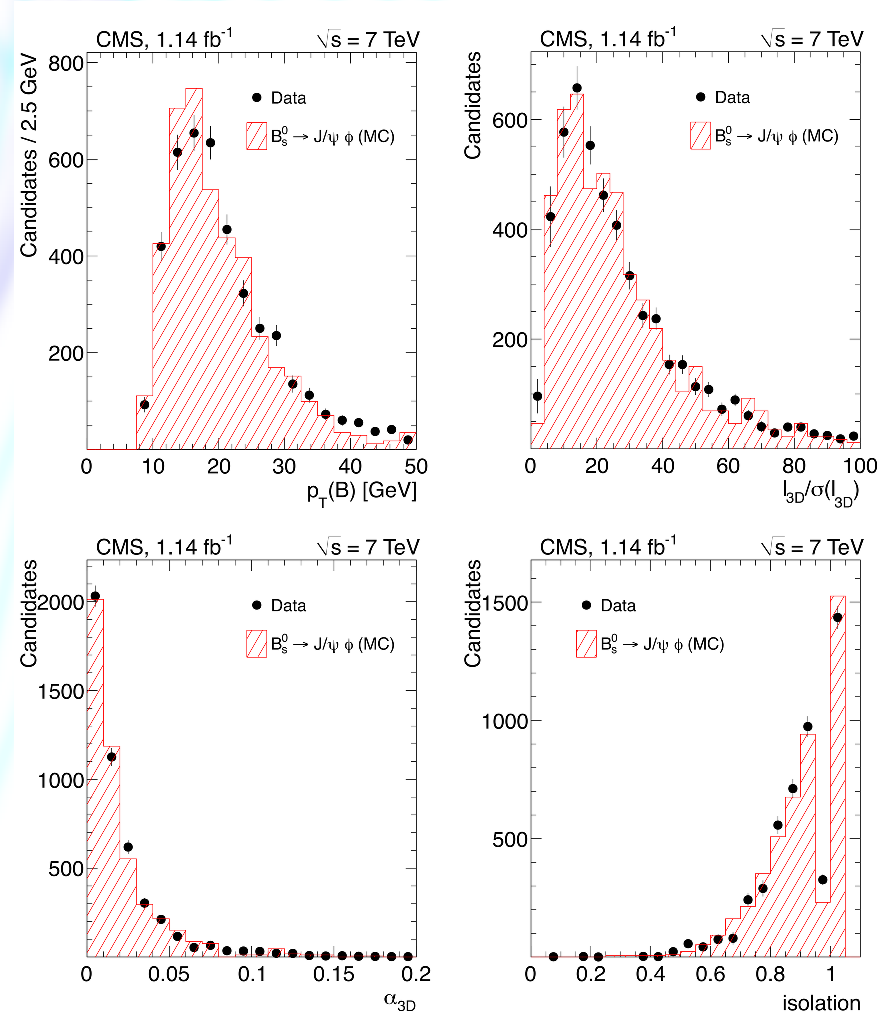
The reconstruction of $B^\pm \to J/\psi K^\pm$ candidates starts from two unlike-charged muons with an invariant mass $3.0 < m_{\mu 1 \mu 2} < 3.2$ GeV, which are combined with a track, assumed to be a kaon, fulfilling $p_T > 0.5$ GeV. The distance of closest approach between all pairs among the three tracks is required to be less than 1 mm. All three tracks are used in the vertex reconstruction. For the analysis only candidates with an invariant mass $4.8 < m_{\mu 1 \mu 2} < 6.0$ GeV are kept. The data distributions are sideband subtracted.



Comparison of the MC simulation (histogram) and data (full circle) for the normalization channel. For each figure, all selection criteria except the one shown are applied. From left to right, top to bottom, the figures show: dimuon transverse momentum p_T, flight length significance, pointing angle α, and the isolation I. The MC simulation histogram is normalized to the same number of events like the data histogram.

The control channel: $B_s^0 \to J/\psi\, \varphi$

The $B_s^0 \to J/\psi\, \varphi$ decay channel is used to check that exclusive B_s^0 meson decays are correctly simulated in MC. The reconstruction of $B_s^0 \to J/\psi\, \varphi$ candidates starts from two unlike-charged muons, which are combined with two tracks assumed to be kaons, fulfilling $p_T > 0.5$ GeV and |η| < 2.4. The distance of closest approach between all pairs among the four tracks is required to be less than 1 mm. All four tracks are used in secondary vertex reconstruction. The two muons of the candidate must have an invariant mass $3.0 < m_{\mu 1 \mu 2} < 3.2$ GeV. The two kaons must have an invariant mass of $0.995 < m_{KK} < 1.045$ GeV and ΔR < 0.25 in the ηϕ plane. For the analysis only B_s^0 candidates with an invariant mass $4.0 < m_{\mu 1 \mu 2} < 6.0$ GeV are kept.



Comparison of the MC simulation (histogram) and data (full circle) for the control channel. For each figure, all selection criteria except the one shown are applied. From left to right, top to bottom, the figures show: dimuon transverse momentum p_T, flight length significance, pointing angle α, and the isolation I. The MC simulation histogram is normalized to the same number of events like the data histogram.

Main systematic uncertainties

Branching fractions and production mechanisms: The main source is the error of *b*-quark hadronization fractions f_u and f_s: 12.5%. The acceptance dependence on different production mechanisms has been evaluated for signal and normalization samples: 4%.

Selection efficiency: The uncertainty on the analysis efficiency is determined as the quadratic sum of the efficiency differences between data and MC simulation in the control sample: 7.9%.

Background estimate: Candidate counts from the sidebands are interpolated in the signal boxes to estimate the background candidate yield: 4%.

For the peaking rare *B* decays, a set of rare hadronic backgrounds was generated, simulated, and passed through the full detector simulation and evaluated taking into account the muon misidentification.

Results

To optimize the analysis selection, a grid of selection requirements was defined and searched for the best expected upper limit. For the determination of the upper limit the selection criteria summarized in the table below are applied:

Selections	Barrel	Endcap	units	Selections	Barrel	Endcap	units
$p_{T\mu,1} >$	4.5	4.5	GeV	$\chi/dof <$	1.6	1.6	
$p_{T\mu,2} >$	4.0	4.0	GeV	$A <$	0.050	0.025	rad
$P_{TB} >$	6.5	6.5	GeV	$l_{3d}/\sigma(l_{3d}) >$	15.0	20.0	
I >	0.75	0.75		$d_{ca}^0 >$	n/a	0.015	cm

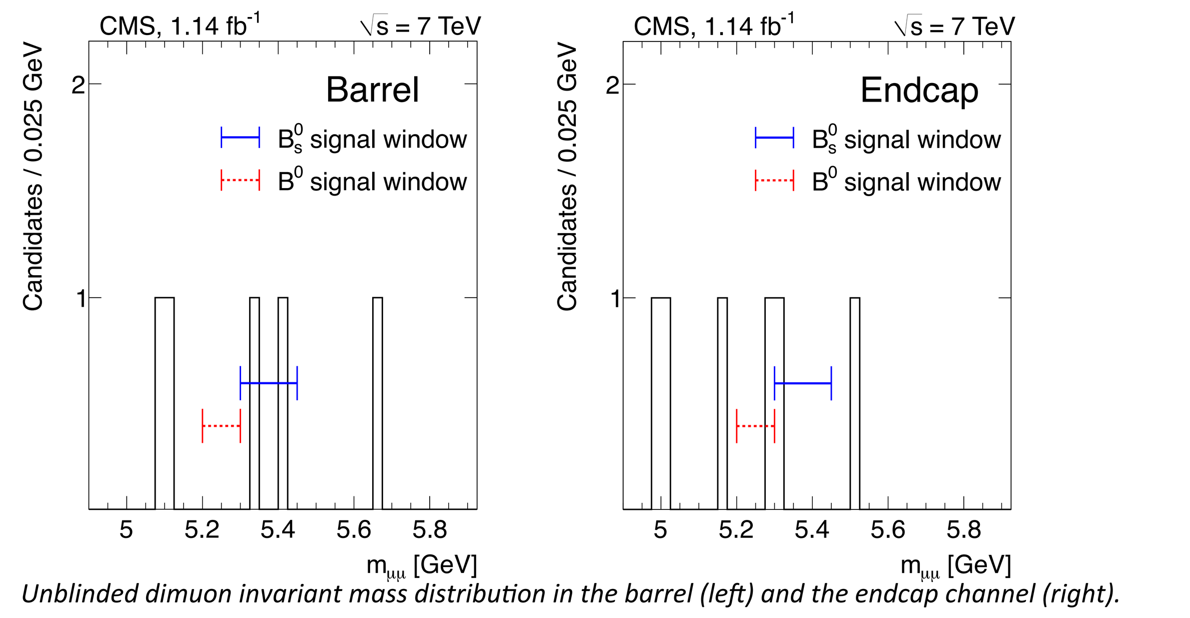
The table below summarizes all numbers relevant for the extraction of the upper limit in the barrel and endcaps regions separately.

Final results	$B_s^0 \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Barrel	$B_s^0 \to \mu^+\mu^-$ Endcap	$B^0 \to \mu^+\mu^-$ Endcap
ε_{tot}	0.0036 ± 0.0001	0.0035 ± 0.0001	0.0021 ± 0.0001	0.0019 ± 0.0001
N_{bg}^{obs}(in SB)	3		4	
N_{bg}^{exp}	0.60 ± 0.35	0.40 ± 0.23	0.80 ± 0.40	0.53 ± 27
N_{peak}^{exp}	0.071 ± 0.020	0.245 ± 0.056	0.044 ± 0.011	0.158 ± 0.039
N_{obs}	2	0	1	1

Including all statistical and systematic uncertainties the following upper limits with CLs method are extracted:

Decay channel	Upper limit at 95% CL	Decay channel	Upper limit at 90% CL
$B_s^0 \to \mu^+\mu^-$	$< 1.9 \times 10^{-8}$	$B_s^0 \to \mu^+\mu^-$	$< 1.6 \times 10^{-8}$
$B^0 \to \mu^+\mu^-$	$< 4.6 \times 10^{-9}$	$B^0 \to \mu^+\mu^-$	$< 3.7 \times 10^{-9}$

A combination of this result with the LHCb public result using 0.34 fb^{-1} has been performed. The combination results in an upper limit on the branching ratio of $B(B_s^0 \to \mu^+\mu^-) < 1.1 \times 10^{-8}$ at 95% CL.



Unblinded dimuon invariant mass distribution in the barrel (left) and the endcap channel (right).

Conclusions

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 √s = 7 TeV corresponding to an integrated luminosity of 1.14 fb^{-1} collected by CMS. The observed event yields are consistent with those expected adding background and SM signals.

Bibliography
Phys. Rev. Lett. 107, 191802 (2011)
CMS-PAS-BPH-11-019