# LHC program for very rare B decays

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This paper gives an overview of ATLAS, CMS and LHCb potential in measurement of di-muonic rare B-decays $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$. The branching ratios (BR) are small due to helicity suppression and flavour changing neutral currents forbidden at tree level. Accounting for a clear theoretical picture of the BR prediction and a simple experimental signature, the BR measurement provides an excellent probe of New Physics effects. Present experimental upper limits from Tevatron are roughly 50 times above the Standard Model (SM) prediction. The LHC experiments will overcome the Tevatron results already by the first year of measurements during initial low-luminosity stage of LHC (10 fb$^{-1}$). In the paper, offline analysis and the expected number of signal and background events are presented. Because of small BR, a background coming from misidentification effects as well as rare exclusive and exotic decays can be important. Therefore part of this paper is devoted to study of these background sources.

## 1. Introduction

In the Standard Model (SM), Flavour Changing Neutral Currents (FCNC) can occur through higher order diagrams only. Di-muonic FCNC B-decays $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ are also helicity suppressed, resulting in branching ratios $(3.42 \pm 0.52) \cdot 10^{-9}$ and $(1.00 \pm 0.14) \cdot 10^{-10}$ respectively [1]. The $B_d^0 \to \mu^+\mu^-$ rate is in SM further suppressed by the ratio of $|V_{\rm td}/V_{\rm ts}|^2$. These small rates provide room for New Physics (NP) effects, that can enhance/suppress the BR significantly. Observation of both $B_d^0$ and $B_s^0$ decays is important in determining the flavour structure of NP, because in some models like e.g. R-parity violating SUSY [2] the relative suppression of $B_d^0$ with respect to $B_s^0$ may not retain.

Present best limits on the BRs, provided by Tevatron: CDF measurements at 780 pb$^{-1}$ and DØ expectation at 700 pb$^{-1}$ [3,4] - are shown in table 1. Expected improvement by the end of Tevatron run is by factor of 5-8 [4], thus remaining one order above SM values. Because NP can also suppress the branching, it is important to have sensitivity below SM rates. This is what LHC experiments are able to provide, especially after LHC enters the high luminosity stage.

Table 1
Present experimental BR limits at 95% CL

| Branching ratio: | $B_s^0 \to \mu^+\mu^-$ | $B_d^0 \to \mu^+\mu^-$ |
|---|---|---|
| CDF (780 pb$^{-1}$) | $1.0 \cdot 10^{-7}$ | $3.0 \cdot 10^{-8}$ |
| DØ (700 pb$^{-1}$) | $2.3 \cdot 10^{-7}$ | – |
| SM prediction | $3.4 \cdot 10^{-9}$ | $1.0 \cdot 10^{-10}$ |

## 2. Trigger Strategies

Trigger strategies for di-muonic very rare decays at ATLAS, CMS and LHCb depend on each experiment. Details can be found in [5].

LHCb trigger is divided into three steps. The first level (L0) requires two high transverse momenta ($p_{\rm T} \sim 1-5$ GeV) tracks found in muon stations. At the next stage (L1) topological cuts are performed on reconstructed B-vertex. Finally, high-level trigger (HLT) consists of full event reconstruction and application of specific cuts.

At ATLAS and CMS, the situation is different from LHCb due to detector acceptance (central geometry compared to forward) and higher instantaneous luminosity ($10^{33}/10^{34}$ cm$^{-2}$s$^{-1}$ vs. $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$). The $p_{\rm T}$ cuts on muons are

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higher at the first stage: 6 GeV at ATLAS and (3-6) GeV at CMS. Vertexing and specific cuts are applied at the higher trigger levels (HLT).

## 3. Offline Analysis

The offline analysis is based on similar cuts as in CDF and DØ measurements. The simplicity of the experimental signature limits variety of cuts, that can be used, to following:

- B-hadron invariant mass window
- Secondary vertex displacement and quality
- Pointing of B-hadron momentum to primary vertex (PV)
- Isolation in tracker and/or in calorimeters

The invariant mass window is driven by detector resolution. But it should be accounted that the resolution may not be sufficient to distinguish $B_d^0$ from $B_s^0$. In that case joint analysis is needed. Secondary vertex displacement and quality cuts reduce combinatorial background from primary-vertex tracks. Isolation requirement rejects secondary vertices with more than two tracks and pointing to primary vertex constraint prevents from existence of detector invisible particles originating in the same vertex.

### 3.1. ATLAS

The ATLAS offline analysis combines high-$p_{\rm T}$ muon tracks to di-muon pairs with invariant mass $M_{\mu^-\mu^+} = M_{B_s^0}{}^{+140MeV}_{-70MeV}$. The asymmetry is to separate $B_s^0$ from $B_d^0$. $B_s^0 \to \mu^+\mu^-$ mass resolution at ATLAS is 80 MeV. In the present study, isolation in ATLAS tracker is used, requiring no charged tracks with $p_{\rm T} > 0.8$ GeV in cone $\theta < 15^o$ around B-meson momentum. Vertex fit with pointing constraint is performed and vertices with transverse decay length significance $L_{\rm xy}/\sigma(L_{\rm xy}) < 11$ or $\chi^2 > 15$ are cut out. The expected number of SM signal and background events, corresponding upper limits on BR and single event sensitivity (SES) are shown in table 2. The upper limits are calculated according to [7]. SES is defined as $1/(total\ no.\ of\ BG\,events) \times \sigma_{\rm BG}/(\sigma_{B_s^0} \cdot \alpha) \cdot \epsilon_\mu^2$. Where $\sigma_{B_s^0}$ is cross-section and $\alpha$ acceptance of $B_s^0 \to \mu^+\mu^-$ decay with $p_{\rm T}(\mu) > 6$ GeV and $|\eta(\mu)| < 2.5$ ($\sigma_{B_s^0} \cdot \alpha = 0.42$ $\mu$b), $\sigma_{\rm BG} = 600$ pb is $b\bar{b} \to \mu^+\mu^- X$ cross-section within the same $p_{\rm T}(\mu)$ and $\eta(\mu)$ cuts, and $\epsilon_\mu$ stands for muon identification efficiency.

Table 2
ATLAS offline analysis - $B_s^0 \to \mu^+\mu^-$

| $L_{\rm int}$ | SES | S/BG | 90% CL limit |
|---|---|---|---|
| 100 pb$^{-1}$ | $2.7 \cdot 10^{-8}$ | $\sim$ 0/0.2 | $1.3 \cdot 10^{-7}$ |
| 10 fb$^{-1}$ | $2.7 \cdot 10^{-10}$ | $\sim$ 7/20 | $1.4 \cdot 10^{-8}$ |
| 30 fb$^{-1}$ | $0.9 \cdot 10^{-10}$ | $\sim$ 21/60 | $1.3 \cdot 10^{-8}$ |

### 3.2. CMS

CMS mass resolution allows for $\sim 2\sigma$ separation of $B_s^0$ to $B_d^0$. The $B_s^0 \to \mu^+\mu^-$ analysis uses $|M_{\mu^+\mu^-} - M_{B_s^0}| < 100$ MeV invariant mass cut. Muons are required to fulfill $p_{\rm T} > 4$ GeV and separation in $\eta\phi$ by $0.3 < \Delta R_{\mu^+\mu^-} < 1.2$. Secondary vertex fit quality cut $\chi^2 < 1.0$ is applied. $B_s^0$ candidates are supposed to have $p_{\rm T} > 5$ GeV and decay flight length significance $L_{\rm xy}/\sigma(L_{\rm xy}) > 18$. Pointing constraint is represented by cosine of angle between momentum and vertex direction to be above 0.995. Finaly isolation of the muon pairs is asured by $p_{\rm T}(B_s^0)/(p_{\rm T}(B_s^0) + \sum_{tracks}|p_{\rm T}|) > 0.85$ cut, where the sum runs over all tracks with $p_{\rm T} > 0.9$ GeV in cone $r = \sqrt{\eta^2 + \phi^2} < 1$. The expected number of signal and background events at $L_{\rm int} = 10$ fb$^{-1}$ is $6.1 \pm 0.1$ (includes both statistical and systematical errors) and $13.8^{+22.0}_{-13.8}$ respectively. Extracting upper limit with Bayesian procedure would result in $BR(B_s^0 \to \mu^+\mu^-) < 1.4 \cdot 10^{-8}$ at 90% confidence level (CL) after 10 fb$^{-1}$ measurement.

### 3.3. LHCb

LHCb constructs di-muons from $p_{\rm T} > 1.3$ GeV muon candidates. With 18 GeV mass resolution, the analysis selects $\pm 60$ MeV mass window around $M_{B_s^0}$ [8]. Cut on muon tracks impact parameter is applied: $IP_\mu/\sigma_\mu > 3$. In the vertex, $B_s^0$ impact parameter is required to be $IP_{B_s^0}/\sigma_{B_s^0} < 3$, vertex $\chi^2 < 3^2$ and pointing constraints angle momentum-vertex below 5 mrad. This study results in expectation of $\geq 30$ events/year. Background rejection was tested on

$30 \cdot 10^6$ $b\bar{b} \rightarrow$ *inclusive* events, where none with $M_{\mu^+\mu^-} > 4$ GeV passed the cuts.

## 4. Backgrounds

The main source of background comes from random combinatorics. The two muon candidates can originate either from semileptonic decays of $b$ and $\bar{b}$ quarks or from cascade decays of one of the $b\bar{b}$ quarks. Due to extremely low BR of the signal, relatively rare effects can become important. For Monte Carlo (MC) studies it has to be accounted that common generators do not include rare decay channels ($BR \leq\sim 10^{-5}$). Misidentification can also not-negligibly contribute to the background. Some of the effects can be suppressed or excluded by convenient mass cut.

MC background production is limited by slowness of a full detector simulation chain (100× events/day/CPU). Therefore correlation between cuts have to be studied and rejection of events already at generator level applied (e.g. based on invariant mass of high-$p_{\mathrm{T}}$ muons, selection of special channels etc.). Fast approximate simulations (like e.g. Atlfast in ATLAS) are not advisable, since the background events come from rather tail resolutions effects.

### 4.1. Two-body hadronic decays

An example of rare-cases are two-body hadronic decays of B-mesons, when one or both mesons have short lifetime, so that they decay inside tracker (ID):

- $B_d^0 \rightarrow D^+_{\rightarrow\mu^+X_s} D^-_{\rightarrow\mu^-X_s}$ in ID: $BR \sim 10^{-6}$
- $B_d^0 \rightarrow D^+_{\rightarrow\mu^+X_d} D^-_{\rightarrow\mu^-X_d}$ in ID: $BR \sim 10^{-8}$

and similar decays $B_d^0 \rightarrow K^+D^-$, $B_s^0 \rightarrow K^+D_s^-$ or $B_s^0 \rightarrow D_s^{*+}D_s^{*-}$. None of these channels is included in common MC generators and therefore separated study have to be performed.

### 4.2. Very rare decays $B^{0\pm} \rightarrow (\pi^{0\pm}, \gamma)\mu^+\mu^-$

Branching ratio of these decays is $\sim 2 \cdot 10^{-8}$ [6]. The background comes from soft $\pi/\gamma$ escaping a detection. In case of $B^{0\pm} \rightarrow \pi^{0\pm}\mu^+\mu^-$ decay, the resulting invariant mass is $M_{\mu^+\mu^-} \sim M_{B^{0\pm}} - M_{\pi^{0\pm}}$, which remains in the detector resolution of ATLAS only. Background from $B^{\pm}$ is expected to be less significant than from $B^0$, due to the lower $p_{\mathrm{T}}$ limit excluding the pion detection: ATLAS example:

- for $\pi^{\pm}$ not to be detected by inner tracker, $p_{\mathrm{T}} \leq 0.5$ GeV
- for $\pi$ not to be detected by electromagnetic calorimeter, $p_{\mathrm{T}} \leq\sim 2$ GeV

Initial study based on particle-level simulation was performed. Di-muon invariant mass distribution from these two background channels compared to signal peaks indicates, that the $B^0 \rightarrow \gamma\mu^+\mu^-$ do not significantly contribute, while $B^{0\pm} \rightarrow \pi^{0\pm}\mu^+\mu^-$ needs more checking.

At this point, it should be also mentioned, that these two very rare decay channels may be worth to study as signal too, since some of their properties (like e.g. di-muon invariant mass spectrum) are also sensitive to NP contributions [6].

### 4.3. Four-leptonic B-decays

Another decay channels that were found to be able to produce $B_{s,d}^0 \rightarrow \mu^+\mu^-$ background are purely leptonic decays $B_{(c)}^+ \rightarrow \mu^+\mu^-l^+\nu_l$. If the $p_{\mathrm{T}}$ of one of the leptons is out of reconstruction capabilities (e.g. $p_{\mathrm{T}} \leq 0.5$ GeV at ATLAS), then there are only two tracks observed from the B-meson vertex and the invariant mass of the di-lepton pair can be close to $B_{s,d}^0$ mass. Branching ratio of these decays are $5 \cdot 10^{-6}$ and $8 \cdot 10^{-5}$ for $B^+$ and $B_c^+$ respectively. In spite of higher BR, the contribution from $B_c^+$ will be less significant due to 400× lower production cross-section and 4× shorter lifetime, therefore more efficiently rejected by secondary vertex cut. The di-muonic spectrum from these four-leptonic decays is shown in figure 1, showing particle-level simulation biased by not-requiring B-meson momentum pointing to primary vertex.

### 4.4. Misidentification effects

Considering a typical hadron misidentification probability of being a muon $\sim 0.5\%$, such effects are obviously not negligible with respect to the $\sim 10^{-9}$ branching. The most simpler background comes from two body hadronic decays: $B_{d,s}^0 \rightarrow K^{\pm}\pi^{\mp}$, $B_{d,s}^0 \rightarrow K^{\pm}K^{\mp}$, $B_{d,s}^0 \rightarrow \pi^{\pm}\pi^{\mp}$

etc. The fake probability can be estimated by: $BR(B_d^0 \to K^{\pm}\pi^{\mp}) \times (0.5\%)^2 = 2 \cdot 10^{-5} \times (0.005)^2 = 0.5 \cdot 10^{-9}$, which is of the same order as the BR of signal channels. The background contribution can be calculated by convoluting the fake probability with $K$ and $\pi$ spectrum. Such a study at LHCb resulted in having $\sim$ 2 events per 2 fb$^{-1}$ (in $\pm 2 \cdot \sigma$ mass window). Decays of $\pi$ and $K$ to muons were found not producing significant background (at ATLAS).

Fake signal events can also originate from two-body hadronic decays with a soft muon in a final state, e.g.: $B^+ \to J/\psi_{\to\mu^+\mu^-} K^+$ ($BR \sim 6 \cdot 10^{-5}$). Considering $K - \mu$ misidentification and a soft $\mu^+$ not reconstructed by tracker (e.g. $p_{\rm T} \leq 0.5$ GeV at ATLAS with probability $\sim$ 0.1), the fake rate can be calculated as: $6 \cdot 10^{-5} \times 0.5\% \times 0.1 \sim 10^{-8}$. Other contributing channels are $B^+_{(c)} \to (J/\psi \to \mu^+\mu^-)\pi^+$ and $B^+ \to (\psi(2S) \to \mu^+\mu^-)K^+$.

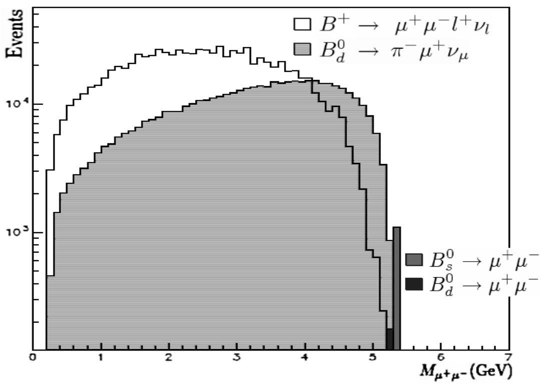


Figure 1. Di-muonic invariant mass spectrum from four-leptonic B-decays and misidentification in $B_d^0 \to \pi^-\mu^+\nu_\mu$. Particle level simulation only without pointing to PV constraint.

Finally the fake events can also be generated by semileptonic B-decays like $B_d^0 \to \pi^-\mu^+\nu_\mu$ with $BR \sim 10^{-4}$. As in previous case, accounting $\pi - \mu$ misidentification and soft-neutrino phase space (probability $\sim$ 0.1), the fake rare would be $0.5 \cdot 10^{-7}$. Similar channels to be accounted are $B_s^0 \to K^-\mu^+\nu_\mu$ and $B^+ \to K^+\mu^+\mu^-$. The di-muonic spectrum coming from semileptonic B-decay $B_d^0 \to \pi^-\mu^+\nu_\mu$ is shown in figure 1.

## 5. Summary

$B^0_{s,d} \to \mu^+\mu^-$ branching ratios measurement provides powerful tool for indirect New Physics search. Due to $BR \sim 10^{-9}$, present experiments will detect signal only when the BR is strongly enhanced by New Physics, while LHC sensitivity below SM expectation allow for discovering both enhancement and suppression of BR.

When estimating the background at LHC, rare and exotic decays have to be taken into account (some of them would be interesting to measure as signal too). Present experiments are not so sensitive to be challenged by this kind of background, however LHC and any future projects will have to consider such effects carefully. The other non-negligible contribution can come from hadron-muon misidentification.

The offline analyses foreseen, that Tevatron limits will be overcome by 1$^{\rm st}$ year measurement at low luminosity. ATLAS, CMS and LHCb are also putting large effort to ensure continuation of very rare decay program at high luminosity stage.

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