Backgrounds for rare muonic $B$–meson decays at ATLAS.

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Abstract

This note gives an overview of expected exclusive backgrounds for rare muonic $B$–meson decays at ATLAS from the theoretical point of view. The goal of this work is to show which of backgrounds are most important for further full detector simulation. It is shown that the most important noncombinatorial background comes from $B_0^+ \rightarrow \pi^- \mu^- \nu_{\mu}$ fake rate. Another important BG sources are $B^+ \rightarrow \mu^+ \mu^- \ell^+ \nu_{\ell}$, $B^+_c \rightarrow J/\psi (\mu^+ \mu^-) \ell \nu_{\ell}$ and two-body hadronic $B$–meson decays.

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1 FOREWORD

This note gives estimations of new potential background sources for rare muonic decays $B_{d,s}^0 \to \mu^+\mu^-$. These dedicated backgrounds have never been considered in $B_{d,s}^0 \to \mu^+\mu^-$ searches at Tevatron or B-factories, however LHC will approach sensitivity limits at which they may play a role. The current work represents the first step in the study: estimations based on the particle-level Monte–Carlo simulation to prove these ideas. This simulation was done using PythiaB Athena module. PythiaB is specially tuned default Pythia version for $b$-physics at LHC energies [1]. PythiaB provided also an interface to the code written for some of the B-decay models considered in this note. It is possible, that more detailed calculations and full Monte–Carlo simulations will demonstrate that some of these backgrounds are unimportant. The aim of this note is to help to initiate such studies.

2 INTRODUCTION

Rare $B$–decays, produced by $b \to d, s$ quark transitions, are forbidden at tree level in the framework of the Standard Model (SM). These decays only occur at the lowest order through one-loop ”penguin” and ”box” diagrams. The branching ratios of these decays are very small: from $4 \times 10^{-5}$ for rare radiative decay $B_d^0 \to K^\pm\gamma$ (discovered by CLEO at 1993 [2]) to $10^{-15}$ for the rare Cabibbo-suppressed leptonic decay $B_d^0 \to e^+e^-$ (which cannot be discovered even with the LHC).

The study of rare decays gives us an opportunity:
1) to check the Standard Model predictions in high perturbative orders; 2) to search for ”new physics” (SUSY, LR, Extra Dimensions, Technicolor, Two Higgs-doublet models, etc) when SM contributions are suppressed; 3) to measure the values of the $|V_{ts}|$ and $|V_{td}|$ CKM matrix elements; 4) to provide new information on the long-distance QCD eects in the matrix elements. It is important to note, that some rare decays could provide essential background for other rare decays with extremely small branching ratios.

Two of the most important decays with extremely small branching ratios are the decays $B_{d,s}^0 \to \mu^+\mu^-$. The Standard Model predictions for these branching ratios are [3]:

\[
Br(B_s^0 \to \mu^+\mu^-) = 3.5 \times \frac{|V_{ts}^*V_{tb}|^2}{2.2 \times 10^{-3}} \times 10^{-9},
\]

\[
Br(B_d^0 \to \mu^+\mu^-) = 0.9 \times \frac{|V_{td}^*V_{tb}|^2}{6.9 \times 10^{-5}} \times 10^{-10}.
\]

Rare muonic $B$–mesons decays are interesting from both the theoretical and experimental points of view. In theory we have high precision SM predictions with minimal non-perturbative uncertainties and uncertainties linked to the factorization scale (see Section 3). Also, these branching ratios are sensitive to SM extensions. For example in the MSSM these branching ratios are proportional to $\tan^6(\beta)$.

The LHC will deliver enough statistics to allow the detection of rare muonic B-decays. The ATLAS (and CMS) detectors will have some advantages over the LHCb detector as they can study rare muonic channels at full LHC luminosity. For details see [4, 5]. Also, rare muonic decays have a simple signature which facilitates the experimental search.

$^6$\textit{tan}(\beta) - is the ratio of vacuum averages for charged and neutral Higgs bosons.
3 THEORETICAL DESCRIPTION

For theoretical calculations, the $b \to q$ transitions $q = \{d, s\}$ are described using the effective Hamiltonian:

$$H_{\text{eff}}(b \to q) = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu)O_i(\mu) + \text{h.c.} \quad (2)$$

in the form of the Wilson expansion. The set of Wilson coefficients $C_i(\mu)$ depend on the current model and contain the lowest order model contributions and perturbative QCD corrections [6]. The scale parameter $\mu$ is approximately equal to the mass of the $b$–quark and is about 5 GeV. This parameter separates the perturbative and non-perturbative contributions of the strong interactions. The non-perturbative contribution is contained in the matrix elements of the basis operators $O_i(\mu)$ between the initial and final hadronic states. For the calculation of these matrix elements it is necessary to use different non-perturbative methods: QCD Sum Rules, Quark Models and Lattice calculations. The accuracy of the non-perturbative calculations depends on the chosen method, but is not less than 15%. The accuracy of the Wilson coefficients for SM with NLO and NNLO QCD-corrections [6] is not greater than 15% if the parameter $\mu \in [m_b/2, 2m_b]$.

In the SM the decay width of the rare muonic decays is:

$$\Gamma(B_q^0 \to \mu^+ \mu^-) = \frac{G_F^2 \alpha_{\text{em}}^2}{16 \pi^3} |V_{tb}^* V_{ts}|^2 \left( f_{B_q} m_\mu C_{10A} \right)^2 \sqrt{M_{B_q}^2 - 4m_\mu^2}.$$  

This expression contains only one non-perturbative constant $f_{B_q}$. The value of this constant is known with high accuracy (about 5-10%), better than the typical error of non-perturbative calculations. Furthermore the Wilson coefficient $C_{10A}$ in the NLO approach is not dependent on the scale parameter $\mu$, and does not add any new uncertainties in the theoretical predictions. The main uncertainties (of the order of 30%) are contained in the numerical values of the CKM-matrix elements.

The Standard Model decay matrix element contains only the pseudoscalar leptonic current $\bar{\mu}(x) \gamma^\mu \mu(x)$. Note that non-standard models can add only one new contribution to this matrix element from the scalar leptonic current $\bar{\mu}(x) \mu(x)$.

4 BACKGROUNDS FOR $B_{d,s}^0 \to \mu^+ \mu^-$ DECAYS

In order to find physics beyond the SM in rare muonic decays, we need to know all possible SM backgrounds.

As was demonstrated in earlier studies [4] for ATLAS the main contribution to the combinatorial background comes from the processes $b\bar{b} \to b\bar{b}b\bar{b}, b\bar{c}c\bar{c} \to \mu^+ \mu^- X$ with the muons originating mainly from semileptonic $b$– and $c$–quark decays. This background has always been taken into account when studying the discovery potential for rare B-decays at ATLAS. Predictions of this BG value depend on our ability to extrapolate the Tevatron’s heavy quark production data to the LHC energy. Unfortunately there is an uncertainty of the order of a factor of three in these BG predictions. This uncertainty is the crucial item for discovery of new physics in rare muonic decays at ATLAS. We will not discuss this BG further in this note, because this problem can be successfully resolved only after the direct study of heavy quark production cross sections during LHC running.
We will concentrate, instead, on the BG from exclusive decays with small branching ratios, and exotic decays with topologies similar to the signal. They are not included into standard MC-generators like PYTHIA or EvtGen. However these packages have mechanisms to include some additional channels, for example in the phase space approach. Some of the exclusive channels become backgrounds due to misidentification effects. Without cuts, background rates from exclusive decays and fake rates are both smaller than rates from the combinatorial BG. But after applying the necessary signal selection cuts, the situation can change. Exclusive BG processes and the fake rates can be potentially dangerous as they have signatures very similar to \(B \rightarrow \mu^+ \mu^-\). Below, we will analyze all such backgrounds.

### 4.1 Decays \(B^{0,\pm} \rightarrow \pi^{0,\pm} \mu^+ \mu^-\) as BG for \(B_{d,s}^0 \rightarrow \mu^+ \mu^-\)

First, let us consider the BG coming from \(B \rightarrow \pi^+ \mu^-\) transitions. This BG appears because the \(B\)-mass resolution of the ATLAS detector in \(B \rightarrow \mu^+ \mu^-\) decays \(\sigma_{B \rightarrow \mu \mu} \approx 80\) MeV (see the Table 8 in [7]) is about the same as \(\pi\)-meson mass.

Let us estimate the contributions of these backgrounds. The SM branching ratios of \(B \rightarrow \pi^+ \mu^-\) decays have been predicted at a level of [6, 9, 10]:

\[
Br(B_d^0 \rightarrow \pi^0 \mu^+ \mu^-) = Br(B^\pm \rightarrow \pi^{\pm} \mu^+ \mu^-) = 2.0 \times \frac{|V_{td} V_{tb}|^2}{6.9 \times 10^{-5}} \times 10^{-8}.
\]

![Figure 1](image_url)
This is 10 times larger than the SM prediction for $B^0_d \rightarrow \mu^+\mu^-$ and 100 times larger than the SM prediction for $B^0_s \rightarrow \mu^+\mu^-$ (see Section 2). These backgrounds appear when there is a soft pion in the final state of the $B \rightarrow \pi \mu^+\mu^-$ decay. In this case the invariant mass of the muon pair is close to its maximal possible value $M_{\mu\mu} = M_B - M_{\pi}$. This maximal value falls into the mass interval $[M_B - 2\sigma_{B-\mu\mu}, M_B - \sigma_{B-\mu\mu}]$. In the ATLAS detector the background from $B^\pm \rightarrow \pi^+\mu^+\mu^-$ is less important than one from $B^0_d \rightarrow \mu^+\mu^-$. In the case of the $B^\pm \rightarrow \pi^+\mu^+\mu^-$ decay there are three reconstructed charged tracks from $B$–meson vertex, except for the cases of $p_T(\pi^\pm) < 0.5$ GeV. Whilst for the $B^0 \rightarrow \pi^0\mu^+\mu^-$ decay we always have two charged tracks from $B$–vertex. The minimum $E_T$ to reconstruct the $\pi^0$ in the electromagnetic calorimeter is limited by calorimeter performance and can achieve values as low as 2-4 GeV.

The invariant dimuon mass distribution for the $B^0_d \rightarrow \pi^0\mu^+\mu^-$ and $B^0_{d,s} \rightarrow \mu^+\mu^-$ decays is shown in fig. 1. The distributions were obtained by MC-simulation at the the particle level. Let us emphasize again, that these events didn’t pass through neither full detector simulation, nor through the ATLAS fast simulation program Atlfast [8]. Both figures 1a and 1b contain selected events where the $\pi^0$ escapes identification in ATLAS. The plot shown in the figure 1a is for the events with pion with $E_T < 4$ GeV while the events with $E_T < 2$ GeV are in the figure 1b. One histogram bin in the fig. 1 is equal 100 MeV, corresponding to $B$–mass resolution for $B \rightarrow \mu^+\mu^-$ decays at the ATLAS detector $\sigma_{B-\mu\mu}$. For muons, the LVL1 and LVL2 trigger cuts (|$\eta(\mu)$| < 2.5 and $p_T(\mu) > 6$ GeV) were applied. For the $B^0_d \rightarrow \pi^0\mu^+\mu^-$ decay we used theoretically calculated matrix element [6, 9, 10].

The kinematical end-point (fig. 1) of the dimuon mass spectrum from the $B^0_d \rightarrow \pi^0\mu^+\mu^-$ decay does not reach the areas of the reconstructed $B^0_d \rightarrow \mu^+\mu^-$ and $B^0_s \rightarrow \mu^+\mu^-$ signals, nevertheless it is very close to them. Thus the kinematical study proved a necessity of a full detector simulation for this type of background.

After a full detector simulation, the vertex fit, the isolation and the angle cuts [4, 11] could be used to reduce the background from $B \rightarrow \mu^+\mu^-$. These cuts only have meaning when the detector resolution is simulated and so are not included in the present document.

### 4.2 Decays $B^0_{d,s} \rightarrow \mu^+\mu^-\gamma$ as background for $B^0_{d,s} \rightarrow \mu^+\mu^-$

The ATLAS Electromagnetic Calorimeter detects photons with $p_T(\gamma) > 4$ GeV (or possibly 2 GeV). If $p_T(\gamma)$ is less than this, then $B^0_{d,s} \rightarrow \mu^+\mu^-\gamma$ decays can produce potential BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$. In order to check such a possibility the $B^0_{d,s} \rightarrow \mu^+\mu^-\gamma$ decays were simulated at the particle level using the theoretical matrix element and resonant branching ratios from [12]:

$$Br(B^0_s \rightarrow \gamma\mu^+\mu^-) = 1.9 \times \frac{|V_{ts}^*V_{tb}|^2}{2.2 \times 10^{-3}} \times 10^{-8}.$$  

The results of this simulation are shown in fig. 2. The fig. 2a shows the invariant dimuon mass distribution for the $B^0_{d,s} \rightarrow \mu^+\mu^-\gamma$ and $B^0_d \rightarrow \mu^+\mu^-$ decays with $p_T(\gamma) < 2$ GeV and the standard LVL1 and LVL2 muon trigger cuts. The high peak on the left side of the distribution corresponds to the $\phi$-resonant contribution in the $B^0 \rightarrow \mu^+\mu^-\gamma$ channel. Note the $\phi$-resonant peak is few orders of magnitude higher than $B^0_d \rightarrow \mu^+\mu^-$ signal peak, and so only bottom part of $\phi$-resonant peak is shown in fig. 2a. The same distribution with $p_T(\gamma) < 4$ GeV is shown in the fig. 2b. It is obvious that the decays $B^0_{d,s} \rightarrow \mu^+\mu^-\gamma$
Figure 2: The invariant dimuon mass distribution for $B_{d,s}^0 \rightarrow \mu^+\mu^-$ and $B_d^0 \rightarrow \mu^+\mu^-$ decays with a) $p_T(\gamma) < 2$ GeV and b) $p_T(\gamma) < 4$ GeV. The standard LVL1 and LVL2 trigger cuts applied. Note that only the bottom part of $\phi$-resonant peak is shown.

do not give any significant background for $B_d^0 \rightarrow \mu^+\mu^-$. The peak from $B_s^0 \rightarrow \mu^+\mu^-$ is four times higher than that from $B_d^0 \rightarrow \mu^+\mu^-$. As the $B_{d,s}^0 \rightarrow \mu^+\mu^-\gamma$ process does not produce any significant background for the decays $B_{d,s}^0 \rightarrow \mu^+\mu^-$, it is not necessary to perform a full detector simulation and reconstruction.

4.3 Four-leptonic decays of $B^+$ and $B^+_c$-mesons as backgrounds for $B_{d,s}^0 \rightarrow \mu^+\mu^-$

In this subsection we consider the four-leptonic $B$–meson decays $B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ and $B_c^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$, where $\ell$ is an electron or muon. Feynman diagrams for such nonresonant decays are presented in the fig. 3a and fig. 3b. The decays with neutrino can be partially eliminated using kinematical constraints (e.g. pointing to primary vertex). However these methods are limited. If the $p_T$ of one of the charged leptons is below the threshold for reconstruction, $p_T(\ell) < 0.5$ GeV, then there are only two charged lepton tracks observed from the $B$–meson decay vertex and the invariant mass of the dilepton pair is about the mass of the $B$–mesons\textsuperscript{7}. In such a case four-leptonic $B$–decays can produce backgrounds for rare semimuonic decays.

The branching ratio of the decays $B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ probably lies in the range interval

\textsuperscript{7}Let us consider the situation when two charged tracks correspond to oppositely charged leptons.
Figure 3: Feynman diagrams for a)–b) nonresonant four–leptonic decays $B^+(B_c^+) \rightarrow \mu^+\mu^-\ell^+\nu_\ell$, c) resonant decay $B_c^+ \rightarrow J/\psi (\mu^+\mu^-) \mu^+\nu_\mu$ and d) four–leptonic decays $B_{d,s}^0 \rightarrow \mu^+\nu_\mu\mu^-\nu_\mu$.

from $8 \times 10^{-5}$ to $10^{-7}$. For the $B_c^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ decays the branching ratios are between $9 \times 10^{-4}$ to $10^{-6}$.

At the LHC the $B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ decay is more important than the $B_c^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ decay, because $B_c^+$-meson’s production cross-section is 400 times smaller than the production cross-section of $B^+$ at LHC energies, but the $Br (B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell)$ is only 10 to 15 times smaller than the $Br (B_c \rightarrow \mu^+\mu^-\ell^+\nu_\ell)$. So, the background from $B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ is 25 to 40 times bigger than one from $B_c^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$.

In addition, the lifetime of the $B_c^+$-meson is approximately 4 times smaller than lifetime of $B^+$ and $B^0$-mesons. So, the decay vertices of $B_c^+$ are closer to the collision point than the decay vertexes of $B^0$ and $B^+$ providing a good discriminant against these four-leptonic backgrounds.

Fig. 4 shows the invariant dimuon mass distribution for the decays $B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ and $B_{d,s}^0 \rightarrow \mu^+\mu^-$. These distributions were produced using a particle-level MC-generation with a simple phase space approach. In generation we applied LVL1 and LVL2 trigger requirements for muons ($|\eta(\mu)| < 2.5$ and first muon $p_T(\mu) > 5$ and second muon $p_T(\mu) > 6$ GeV). In the decay $B^+ \rightarrow \mu^+\mu^-\mu^+\nu_\mu$ we have chosen the dilepton combination with mass closest to $B_{d,s}^0$-mesons mass.

The grey color corresponds to the invariant mass distributions of dimuon pairs for the decays $B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell$ where $\ell = \{e, \mu\}$. For electron, $p_T(e) < 0.5$ GeV. In this case the track from the electron in not detected in the Inner Detector. For the decay

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8There are no theoretical predictions for the branching ratios of four-leptonic decays. Also there are no experimental data for these channels. So, we use few rough estimations in order to get those branching ratios. All the predictions in this article are for $Br (B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell) = 5 \times 10^{-6}$. This branching ratio is probably overestimated. Full theoretical calculations are in progress.

9We assume this branching to be $8 \times 10^{-5}$. 

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Figure 4: The invariant dimuon mass distribution for the decays \(B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell\) and \(B^0_{d,s} \rightarrow \mu^+\mu^-\). One histogram bin is equal 100 MeV, approximately corresponding to \(B\)-mass resolution for \(B \rightarrow \mu^+\mu^-\) decays at ATLAS detector \(\sigma_{B-\mu\mu}\). The histogram a) is the magnified area of the end kinematical point of \(B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell\) decays in the histogram b).

\(B^+ \rightarrow \mu^+\mu^-\mu^+\nu_\mu\) the \(p_T\) of the second positively charged muon \(p_T(\mu^+) < 0.5\) GeV \(^{10}\). In this case the track from \(\mu^+\) in not detected in the Inner Detector. These backgrounds are important for \(B^0_{d,s} \rightarrow \mu^+\mu^-\) decays taking into account the \(B\)-meson mass resolution. This may remain true even if the branching of \(B^+ \rightarrow \mu^+\mu^-\ell^+\nu_\ell\) decay will appear to be 10 times smaller than our current expectations.

Despite the fact that background from four-lepton decays of the \(B^+_c\)-meson is significantly smaller than the background from four-lepton decays of the \(B^+\)-meson, the \(B^+_c\) source of the background can be important because its end kinematical point lies right from the \(B^0_{d,s}\)-meson masses. For more detailed studies we need full detector simulation and reconstruction.

Analyzing the noncombinatorial BG from \(B^+_c\)-decays we will also include the resonant contribution from the decay \(B^+_c \rightarrow J/\psi (\mu^+\mu^-) \mu^+\nu_\mu\) (see fig. 3c), when \(\mu^+\) from \(J/\psi\) and \(\nu_\mu\) are both soft in the laboratory system of ATLAS detector. For more detailed study the full detector simulation of such decays is needed.

4.4 Four-leptonic decays of \(B^0_{d,s}\)-mesons as BG for \(B^0_{d,s} \rightarrow \mu^+\mu^-\)

Another BG candidate for \(B^0_{d,s} \rightarrow \mu^+\mu^-\) (see fig. 3d) is a process \(B^0_{d,s} \rightarrow (W^+W^-) \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu\), when both neutrinos are soft. Comparing to \(B^0_{d,s} \rightarrow \mu^+\mu^-\) these four-leptonic decays offer an additional advantage in their 

\(^{10}\)It’s obvious that first two oppositely charged muons should accept the LVL1 and LVL2 trigger requirements.
decays do not have loop-suppression, leading to the branching of approximately $1/16\pi^2 \approx 6 \times 10^{-3}$. Even if part of the contribution when neutrino is soft is expected to be rejected by signal selection cuts, the high branching ratio classifies the processes into a category of those requiring a full detector simulation.

4.5 Two-body hadronic $B$-meson decays as background for $B_{d,s}^0 \rightarrow \mu^+\mu^-$

4.5.1 Case of decays in flight

Here we consider two-body $B$-decays to hadrons, that would become a background, if both hadrons decay to muons. The two-body hadronic decays $B_d^0 \rightarrow K^+K^-$, $B_d^0 \rightarrow K^+\pi^-$, $B_d^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ with branching ratios from $10^{-5}$ to $10^{-6}$ were not included in the combinatorial background during TDR and all consequent studies [4, 5]. Such decays can be important, because they are not removed by the invariant dimuon mass cut.

Let’s make a simple estimation for the case of $B_d^0 \rightarrow K^+\pi^-$. The semi-muonic branching ratios for $K^-$ and $\pi^-$-mesons are:

$$Br(\pi^\pm \rightarrow \mu^\mp\nu) \sim 1, \quad Br(K^\pm \rightarrow \mu^\pm\nu) \sim 0.6,$$

with decay length $c\tau(\pi) \approx 7.8$ m and $c\tau(K) \approx 3.7$ m. The pion or kaon will not be identified as a hadron if it decays to $\mu\nu$ before the calorimeter. If $R$ is the a transverse distance from $pp$-collision point to calorimeter, then the background contribution from the decay $B_d^0 \rightarrow K^+\pi^-$ to the decays $B_{d,s}^0 \rightarrow \mu^+\mu^-$ can be estimated by the following formula:

$$Br(BG) \sim Br(B \rightarrow K\pi) \times f_K \times f_\pi$$

$$f_K = Br(K \rightarrow \mu\nu) \times \frac{R}{\gamma(K) \times c\tau(K)},$$

$$f_\pi = Br(\pi \rightarrow \mu\nu) \times \frac{R}{\gamma(\pi) \times c\tau(\pi)},$$

where $\gamma(K)$ and $\gamma(\pi)$ are the kaon and pion $\gamma$-factors. It is easy to see that maximum gamma-factors of mesons will correspond to $p_T = 5$ GeV. In this case $\gamma^{-1}(\pi) = 3 \times 10^{-2}$, $\gamma^{-1}(K) = 10^{-1}$. For ATLAS the distance $R \approx 1.2$ m, where 1 m is a radius of the Inner Detector, and 20 cm represents possible decays later in the detector. For these values we get $Br(BG) \approx 2 \times 10^{-9}$. We should also notice that this BG can be reduced by applying an algorithms for identifying and rejection of tracks with a kink as well well as by vertex selection cuts. The simulation is necessary for this case.

4.5.2 Case of misidentifcation and fake rates

Two-body hadronic decays of $B$-mesons can produce even more backgrounds to $B \rightarrow \mu\mu$. These backgrounds are determined by the probability of hadron-muon misidentification in the ATLAS detector. A value for the misidentification probability was estimated

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11 We estimate the $\gamma$-factor using the formula: $\gamma^{-1} \approx \sqrt{1 - \frac{p_T^2}{M^2 + M^2}}$, where $M$ is the meson mass.

12 Furthermore, the backgrounds from subsection 4.5.1 can be included in these backgrounds.
as 0.3-0.5% (see [13], Figure 8-23). We will show the importance of this BG with one example in current paragraph and with another two examples in the next subsection.

The first example\textsuperscript{13} is the two-body hadronic decay $B_d^0 \rightarrow K^+\pi^-$. The branching ratio for this decay is $\text{Br}(B_d^0 \rightarrow K^+\pi^-) \approx 2 \times 10^{-5}$. So the fake rate for $B \rightarrow \mu^+\mu^-$ is equal to $\text{Br}(B_d^0 \rightarrow K^+\pi^-) \times (0.005)^2 \approx 0.5 \times 10^{-9}$, nearly equal to $\text{Br}(B_s^0 \rightarrow \mu^+\mu^-)$ and exceeding the rate from the $\mu^+\mu^-$ backgrounds described in the previous subsection.

4.6 Other backgrounds from decays in flight or muon misidentification

The second example of misidentification is also linked with two-body hadronic decays, but differs from the first example in the origin of the misidentification of the muon pair. Let us consider the decay $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$. The branching ratio of this decay is $\text{Br}(B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+) \sim 10^{-3} \times 6 \times 10^{-2}$. If we will take into account the $K - \mu$ misidentification, we get about 1/200 of kaons misidentified as muons. Let us consider the case where the $\mu^+$ from $J/\psi$ decay has a $p_T < 0.5$ GeV, i.e. is "soft" and is not detected by the Inner Detector (this assumption will add a suppression factor of 1/10 into the corresponding background branching ratio). Then the invariant mass of the $\mu^-$ from the $J/\psi$ and the misidentified $K^+$ should be close to invariant mass of $B_{d,s}^0$-mesons. The fake rate for this case is approximately $3 \times 10^{-8}$ and so the $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ decay can produce a significant background for $B_{d,s}^0 \rightarrow \mu^+\mu^-$. The third example of misidentification importance is associated with semi-leptonic $B$-meson decays. Let us consider the decay $B_d^0 \rightarrow \pi^-\mu^+\nu_\mu$. It has a branching ratio of about $10^{-4}$. This channel was included in our combinatorial BG sample, but its contribution to the background is only through the decay $\pi^- \rightarrow \mu^-\bar{\nu}_\mu$. The rate for the unphysical decay $B^0 \rightarrow \mu^-\mu^+\nu_\mu$ through $\pi - \mu$ misidentification is roughly equal to $\text{Br}(B_d^0 \rightarrow \pi^-\mu^+\nu_\mu) \times 1/200 \approx 0.5 \times 10^{-6}$. To estimate the BG contribution from $B^0 \rightarrow \mu^-\mu^+\nu_\mu$ decay we choose only the phase space area where neutrino is so soft, then misidentified "muon pair" effectively enters into the signal area (we estimate the soft neutrino phase space as 10\% of total phase space of $B^0 \rightarrow \mu^-\mu^+\nu_\mu$ decay). Fig. 5 shows the invariant dimuon mass distribution for the decay $B_d^0 \rightarrow \pi^-\mu^+\nu_\mu$ with fake muon and $B_{d,s}^0 \rightarrow \mu^+\mu^-$. These distributions were produced using a particle-level MC-generation with a simple phase space approach. During generation we applied LVL1 and LVL2 trigger requirements for muons ($|\eta(\mu)| < 2.5$ and $p_T(\mu) > 5$ or 6 GeV).

So, the fake rate from semileptonic decays of $B$-mesons is more significant than the fake rate from two-body hadronic $B$-meson decays. However all of these fake rates need detailed investigation using a full-detector simulation.

In conclusion let us list all potentially dangerous decays contributing to the fake rate:

1. All two-body hadronic decays of $B_{d,s}^0$-mesons with charged hadrons in the final state, with branching ratios $\geq 10^{-6}$.

2. Two-body hadronic decays of the $B^+$-meson with branching ratios $\geq 10^{-5}$.

3. Two-body hadronic decays of the $B_s^+$-meson with branching ratios $\geq 10^{-3}$.

4. Semileptonic decays $B_d^0 \rightarrow \pi^-\mu^+\nu_\mu$, $B_s^0 \rightarrow K^-\mu^+\nu_\mu$ and $B^+ \rightarrow K^+\mu^+\mu^-$.\textsuperscript{13}The authors express gratitude to A. Golutvin for bringing this example to our attention.
Figure 5: The invariant dimuon mass distribution for the decay $B^0_d \to \pi^- \mu^+ \nu_\mu$ with fake muon and $B^0_{d,s} \to \mu^+ \mu^-$ decays. One histogram bin is equal 100 MeV, corresponding to $B$-mass resolution for $B \to \mu^+ \mu^-$ decays at ATLAS detector $\sigma_{B-\mu\mu}$. The histogram a) is the magnified area of the end kinematical point of $B^0_d \to \pi^- \mu^+ \nu_\mu$ decay in the histogram b).

### 4.7 Rare leptonic decays in external fields

Charged particle interactions with an electromagnetic field are defined by the invariant parameter $\chi = e \sqrt{(F_{\mu\nu} p_T^\mu)^2 / m^2}$, where $F_{\mu\nu}$ is the electromagnetic external field tensor and $e$ is the charge of the particle. In the ATLAS Inner Detector there is an external magnetic field strength of $B = 2$ T and electric and magnetic fields in the detector matter. The density of the electric field is $E \approx 10^{10}$ V/m, and so the strength of the magnetic field in the detector matter is nearly equal to the external field strength. Under these conditions the parameter $\chi_\mu \approx 10^{-9} - 10^{-12}$ for a range of different muon $p_T$. So electromagnetic fields in ATLAS are weak.

Using the Volkov solution [14], Farry technique for external field calculations [15], and weak-field approximation for finding the correction to a branching ratio due to an external field, we can obtain:

$$Br(B^0_q \to \mu^+ \mu^-, \chi_\mu) = Br(B^0_q \to \mu^+ \mu^-) \times \frac{1}{4\sqrt{\pi}} \frac{M_{B_q}}{E_{B_q}} \chi_\mu^{1/2} e^{-8/3\chi_\mu},$$

where $E_{B_q}$ is the $B_q$-meson energy in the Laboratory System, $M_{B_q}$ - the mass of $B^0_q$-meson and $Br(B^0_q \to \mu^+ \mu^-)$ - the branching ratios without external fields from equation (1). So, for ATLAS the external field contributions are completely negligible.
5 REQUIREMENTS FOR CSC PRODUCTION

Based on the studies in previous sections we can estimate the requirements for simulation of noncombinatorial BG channels in the framework of the upcoming large-scale CSC production. The following channels need the full detector simulation to be performed in order to determine the contribution to BG: \(B^0 \rightarrow \pi^- \mu^+ \nu_{\mu}, B^+ \rightarrow \mu^+ \mu^- \ell^+ \nu_{\ell}, B^0_{d,s} \rightarrow KK, K\pi, \pi\pi\) and the decay \(B_c^+ \rightarrow J/\psi (\mu^+ \mu^-) \ell \nu_{\ell}\). Processes with decays in flight will be simulated using new GEANT4 mechanism for forcing K, \(\pi\)-decays. A possibility to use Atlfast for some of processes is under investigation.

6 CONCLUSION

1. It has been shown that certain classes of exclusive \(B\)-decays are capable to provide background contributions comparable to the combinatorial BG from \(bb (bbbb, bbbc) \rightarrow \mu^+ \mu^- X\) processes with muons originating mainly from semileptonic \(b\)- and \(c\)-quark decays.

2. The most important background contribution is expected to come from \(B^0 \rightarrow \pi^- \mu^+ \nu_{\mu}\) process, followed by a subsequent decay in flight of the final state \(\pi^+\) producing another muon.

3. The rare exclusive decays \(B^+ \rightarrow \mu^+ \mu^- \ell^+ \nu_{\ell}, B_c^+ \rightarrow J/\psi (\mu^+ \mu^-) \ell \nu_{\ell}\) and \(B^+ \rightarrow J/\psi (\mu^+ \mu^-) K^+\) can provide significant background to the decays \(B^0_{d,s} \rightarrow \mu^+ \mu^-\). For more detailed study it will be necessary to perform a full detector simulation for events generated using the theoretical matrix elements.

4. The hadronic two-body exclusive decays \(B^0_{d,s} \rightarrow KK, K\pi, \pi\pi\), followed by secondary decays in flight of charged final-state hadrons into muons are expected to be less significant background comparing to processes in previous item. The rare decays \(B_c^+ \rightarrow \mu^+ \mu^- \ell^+ \nu_{\ell}, B^0_d \rightarrow \pi^0 \mu^+ \mu^-\) and \(B^\pm \rightarrow \pi^\pm \mu^+ \mu^-\) can also be classified as less important background sources.

5. The exclusive decays \(B^0_s \rightarrow \mu^+ \mu^- \gamma, B^0_{d,s} \rightarrow \mu^+ \nu_{\mu} \mu^- \bar{\nu}_{\mu}\) and external fields corrections for the decays \(B^0_{d,s} \rightarrow \mu^+ \mu^-\) give negligible background contributions.

Summary of the predictions for noncombinatorial backgrounds is given in the Table 1.

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Table 1: The predictions for noncombinatorial backgrounds. The "Effective BR in $B \rightarrow \mu \mu$ signature space" means the part of the exclusive channels branchings for muon pair from BG exclusive channel to be in the $B \rightarrow \mu \mu$ signal space.

<table>
<thead>
<tr>
<th>BG Channel</th>
<th>BR of BG Channel</th>
<th>Effective BR in $B \rightarrow \mu \mu$ signal space</th>
<th>Section or Subsection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d^0 \rightarrow \pi^- \mu^+ \nu_\mu$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 5 \times 10^{-8}$</td>
<td>4.6</td>
</tr>
<tr>
<td>$B^+ \rightarrow \mu^+ \mu^- \ell \nu_\ell$</td>
<td>$&lt; 5 \times 10^{-6}$</td>
<td>$&lt; 5 \times 10^{-8}$</td>
<td>4.3</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi (\mu^+ \mu^-) K^+$</td>
<td>$\sim 6 \times 10^{-5}$</td>
<td>$\sim 10^{-8}$</td>
<td>4.6</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow \mu^+ \mu^- \ell \nu_\ell$</td>
<td>$&lt; 10^{-4}$</td>
<td>$&lt; 10^{-8}$</td>
<td>4.3</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow J/\psi (\mu^+ \mu^-) \ell \nu_\ell$</td>
<td>$\sim 5 \times 10^{-4}$</td>
<td>depends on kinematics</td>
<td>4.3</td>
</tr>
<tr>
<td>$B_{d,s}^0 \rightarrow K \pi, \pi \pi, K K$</td>
<td>$\sim 10^{-5}$</td>
<td>$\sim 10^{-9}$</td>
<td>4.5.1 and 4.5.2</td>
</tr>
<tr>
<td>$B_d^0 \rightarrow \pi^0 \mu^+ \mu^-$</td>
<td>$\sim 2 \times 10^{-8}$</td>
<td>$\sim 10^{-10}$</td>
<td>4.1</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow \gamma \mu^+ \mu^-$</td>
<td>$\sim 2 \times 10^{-8}$</td>
<td>$\sim 10^{-10}$</td>
<td>4.2</td>
</tr>
<tr>
<td>$B_{d,s}^0 \rightarrow \mu^+ \nu_\mu \mu^- \bar{\nu}_\mu$</td>
<td>$\sim 10^{-7}$</td>
<td>$&lt; 10^{-10}$</td>
<td>4.4</td>
</tr>
</tbody>
</table>

References