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Rare B Decays: Results and Prospects in ATLAS

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Searches of processes beyond the Standard Model (SM) are among the main topics of interest at the ATLAS experiment. Indirect evidence of such processes may be obtained by observing rare leptonic and semi-leptonic decays of hadrons consisting of b quarks. The branching ratio of the decay $B_s \to \mu^+\mu^-$ is sensitive to theoretical models extending the SM. Its measurement may exclude specific models.
The trigger strategy to be used for the study of rare B decays relies on di-muon triggers. Preliminary results regarding the performance of the trigger system are shown. The ATLAS strategy for measuring the branching ratio of $B_s \to \mu^+\mu^-$ is presented, based on simulated data.

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1. Introduction

The study of leptonic and semi-leptonic decays of B hadrons plays an important part in the B physics programme at the ATLAS experiment. These decays are highly suppressed in the Standard Model (SM). They are forbidden at tree level and are only possible through loop diagrams. New Physics (NP) processes, which are not yet described by the SM, may manifest themselves in the loops. Therefore rare decays are excellent benchmark channels for probing NP effects. Measuring their properties may give indirect evidence for physics beyond the SM, or constrain the parameter space of the new theoretical models. In this article, the focus is set on the study of the $B_s \to \mu^+\mu^-$ decay.

2. Rare B decays considered in ATLAS

$\mathbf{B_s} \to \boldsymbol{\mu^+\mu^-}$ The $B_s \to \mu^+\mu^-$ decay is highly suppressed in the SM, with a prediction of the branching ratio of $(3.6\pm0.3)\times10^{-9}$ [1]. However, theoretical extensions of the SM predict higher values. For example, in the Minimal Supersymmetric Standard Model (MSSM), the branching ratio is proportional to $\tan^6\beta$, which may produce a value of the branching ratio exceeding the SM prediction by a factor of 10^3 [2]. Values smaller than the SM prediction are also possible. The current best exclusion limits on the branching ratio are measured by the Tevatron experiments: $BR(B_s^0 \to \mu^+\mu^-) < 5.1\times10^{-8}$ @ 95% CL [3]. This result is a factor 12 larger than the value predicted in the SM and is limited by the statistics available. It is expected that ATLAS will benefit from higher statistics and will be able to eventually perform a measurement.

$\mathbf{b} \to \mathbf{s}\boldsymbol{\mu^+\mu^-}$ transitions These are rare decays with branching ratios of the order of $10^{-6}-10^{-7}$. There are several channels considered in ATLAS: $B_d^0 \to K^{0*}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda^0\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^{+*}\mu^+\mu^-$. The forward-backward asymmetry (A_{FB}) might provide an indirect evidence of NP. The dependence of A_{FB} on the di-muon invariant mass shows a different behaviour depending on the assumptions of the theoretical model.

3. ATLAS detector

The ATLAS detector [4] is a general purpose detector located at the Large Hadron Collider (LHC) [5]. As of March 2010, the accelerator provides proton-proton collisions at a center of mass energy of $\sqrt{s} = 7$ TeV. ATLAS is composed of several subdetectors with different functions. The Inner Detector (ID) records hits of charged particles, which are used to determine particle momenta and decay vertices. The relative resolution of the transverse momentum $\sigma(p_T)/p_T$ was measured to 0.004 ± 0.002 in the barrel ID region ($|\eta| < 1.2$) and to 0.015 ± 0.008 in the endcap region ($|\eta| > 1.2$) [6]. The Muon Spectrometer (MS) provides a muon trigger system and a precise measurement of the muon momentum. The Monitored Drift Tubes (MDT) and the Cathode Strip Chambers (CSC) are capable of accurate measurements of charged tracks, with a relative transverse momentum resolution $\sigma(p_T)/p_T$ less than 10% [7]. Additionally, dedicated fast trigger chambers offer a time resolution lower than 10 ns. The ID covers the pseudorapidity (η) range up to $|\eta| < 2.5$ and the MS up to $|\eta| < 2.7$.

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4. ATLAS trigger employed for rare B decays

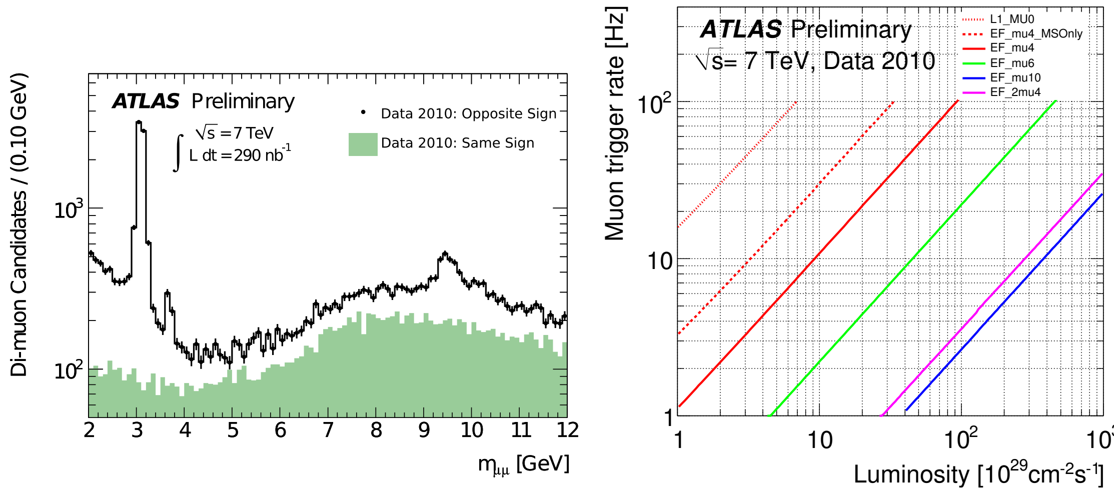

Figure 1: Di-muon invariant mass spectrum recorded from collision data at $\sqrt{s} = 7$ TeV, representing 290 nb^{-1} integrated luminosity (left). Extrapolated trigger rates for different single and di-muon trigger signatures as a function of instantaneous luminosity (right).

Trigger strategy There are two basic muon trigger algorithms considered in ATLAS: the single-muon and the di-muon trigger. The former is seeded by one LVL1 muon. At LVL2 the second muon is searched inside an enlarged RoI around the direction of the LVL1 muon. The di-muon trigger is seeded by two LVL1 muons, which are confirmed at LVL2 inside small RoIs around each muon. The choice between the two algorithms is made according to their output rates. Fig. 1 (right) shows the output rates of various trigger scenarios as a function of instantaneous luminosity. The single muon trigger is only feasible at low luminosities. Once the luminosity increases, it is necessary to either use the di-muon trigger, or increase the threshold of the muon p_T. Prescaling of the triggers with a low threshold is also possible. The lowest threshold is 4 GeV.

Trigger performance The single muon trigger performance can be determined from collision data recorded with a minimum bias trigger, i.e., independently of the muon trigger. Fig. 2 shows the efficiency of the single muon LVL1 trigger in the barrel region for a p_T threshold of 6 GeV (left) and the efficiency of the EF for a muon p_T threshold of 4 GeV (right). The value of the efficiency at the plateau is determined after a fit to the Fermi function $f = A/(1+e^{\frac{-(x-B)}{C}})$, where the parameter A gives the value at the plateau. These values have been determined for various trigger configurations. For LVL1 (barrel), the value determined is $A = 76\%$. This has to be related to the limited geometrical acceptance of the trigger chambers in the barrel region, which is about 82%. For LVL1 (end-cap), this value is $A = 94\%$, where the acceptance covered by the trigger chambers in the end-cap region is close to 100%. For LVL2, the value found is $A = 97\%$ (determined with respect to LVL1). For the EF, it is computed to $A = 99\%$ (determined with respect to LVL2). The di-muon trigger performance can also be determined from collision data, using the tag and probe method as explained in [7]. This method creates efficiency maps as a function of the muon transverse momentum, pseudorapidity and azimuthal angle $\varepsilon^{\mu}(p_T^{\mu}, \eta^{\mu}, \phi^{\mu})$. They can be used to determine the di-muon trigger efficiency also in cases where the muon p_T is below the plateau region.

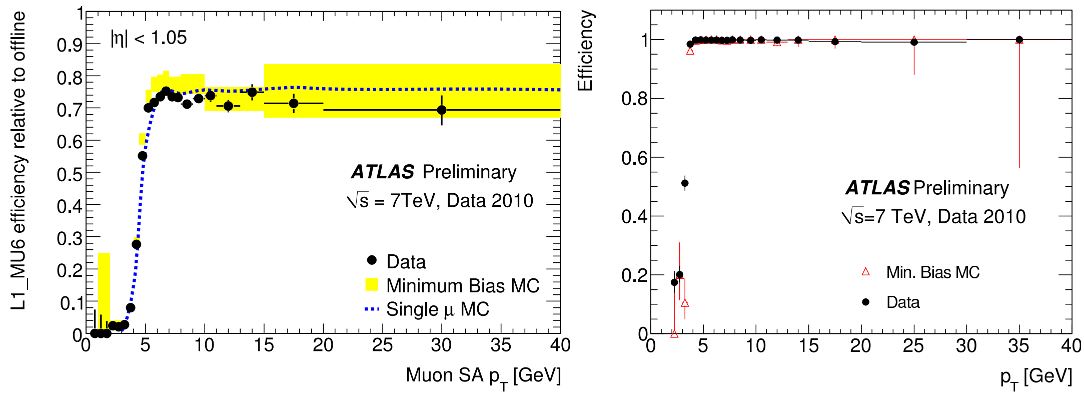

Figure 2: Trigger efficiency as a function of the muon p_T for the LVL1 muon trigger with a threshold of 6 GeV in the barrel region ($|\eta| < 1.05$) (left) and for the EF muon trigger with a muon p_T threshold of 4 GeV (right).

5. $B_s \to \mu^+\mu^-$ analysis

Strategy The aim of this analysis is to select candidates of this decay and measure the $B_s^0 \to \mu^+\mu^-$ branching ratio. A common practice is to normalise the number of observed events to another well measured channel (the reference channel). At ATLAS, the reference channel is $B^+ \to J/\psi(\mu^+\mu^-)K^+$. This channel has the advantage that it has a topology similar to the signal channel, i.e., two muons in the final state. The branching ratio for $B_s^0 \to \mu^+\mu^-$ is computed from:

$$BR(B_s^0 \to \mu^+\mu^-) = \frac{N_{B_s^0}}{N_{B^+}} \frac{\alpha_{B^+}}{\alpha_{B_s^0}} \frac{\varepsilon_{B^+}}{\varepsilon_{B_s^0}} \frac{f_u}{f_s} BR(B^+ \to J/\psi K^+)\, BR(J/\psi \to \mu^+\mu^-). \tag{5.1}$$

$N_{B_s^0}$ and N_{B^+} are the numbers of observed events after event selection for the signal and the reference channels. $\alpha_{B_s^0}$ and α_{B^+} are the kinematic and geometric acceptances. $\varepsilon_{B_s^0}$ and ε_{B^+} are the total event selection efficiencies. f_s/f_u is the ratio of the b-quark fragmentation probabilities corresponding to the $b \to s$ and the $b \to u$ scenarios.

Reference channel The subdecay $J/\psi \to \mu^+\mu^-$ has been observed early in ATLAS in collisions at $\sqrt{s} = 7$ TeV [8]. Fig. 3 (left) shows the invariant mass distribution for di-muon pairs representing an integrated luminosity of 41 pb^{-1}. Events have been recorded with a combination of triggers requiring one LVL1 muon confirmed at the high level trigger (HLT) with thresholds of 4, 6 or 10 GeV, single-muon triggers with thresholds of 4 or 6 GeV, or di-muon triggers with thresholds of (4, 4) or (4, 6) GeV imposed on the two muons. For the single-muon triggers, the di-muon invariant mass is required to be in the range $0.5 < M_{\mu\mu} < 12$ GeV or in the range $2.4 < M_{\mu\mu} < 4.2$ GeV. For the di-muon triggers an invariant mass range of $0.5 < M_{\mu\mu} < 12$ GeV was required. Offline cuts of 2.5 and 4 GeV have been applied on the p_T of the two muons. An unbinned maximum-likelihood fit, consisting of a Gaussian distribution for the signal peak and a third order polynomial for the background side-bands, results in 846000 ± 1000 observed J/ψ candidates. The mass resolution observed is 65 ± 1 MeV.

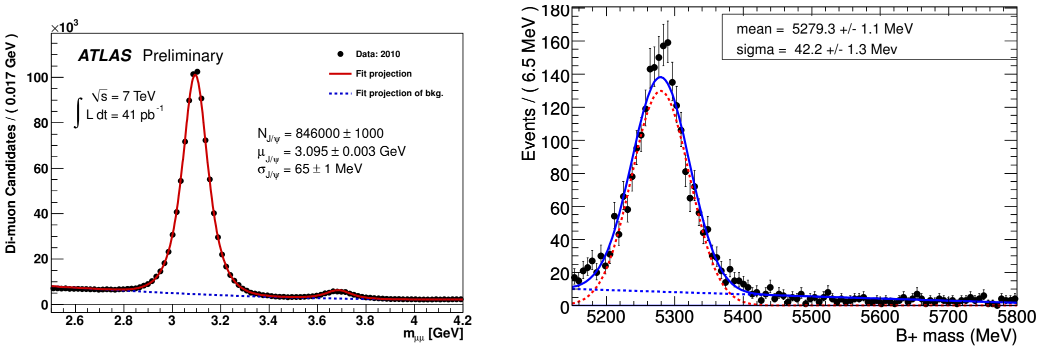

Figure 3: The $\mu^+\mu^-$ invariant mass spectrum recorded with 41 pb^{-1} of collision data at $\sqrt{s} = 7$ TeV (left). The $\mu^+\mu^-K^+$ invariant mass spectrum observed in simulated data with $\sqrt{s} = 14$ TeV (right).

The early data taking period offers too little statistics to observe the reference channel $B^+ \to J/\psi K^+$. This has been studied using simulated data, with $\sqrt{s} = 14$ TeV [7]. Fig. 3 (right) shows the $\mu^+\mu^-K^+$ invariant mass spectrum recorded from a sample of inclusive $b\bar{b} \to J/\psi(\mu^+\mu^-)X$ decays. The mass fit was performed using a Gaussian function for the signal region and a flat function for the side-bands. The mass resolution for the signal is 42.2 ± 1.3 MeV.

Sources of background There are several sources of background events which might be misidentified as $B_s^0 \to \mu^+\mu^-$ signal. Hadronic or semi-leptonic decays of B mesons are considered, where one or two of the decay products (typically kaons or pions) are misidentified as muons. The exclusive decays $B_s^0 \to K^-\mu^+\nu_\mu$ and $B_s^0 \to K^-\pi^+$ are considered in this Monte Carlo study. Other exclusive decays have been shown to give a similar or lower background contribution in the signal region. The most important contribution is the combinatorial background $b\bar{b} \to \mu^+\mu^-X$. Events containing $c\bar{c}$ pairs or Drell-Yan processes may also have a similar topology with two muon in the final state.

Event selection The selection of B_s^0 candidates starts by chosing events containing pairs of oppositely charged muons. A vertex fitting tool is used to create a $B_s \to \mu^+\mu^-$ decay candidate. A quality cut on the goodness of the fit is applied as $\chi^2/n.d.f. < 10$. Only those candidates with an invariant mass $M(\mu^+\mu^-) \in [4.3$ GeV, 7 GeV$]$ are accepted, excluding the regions corresponding to the J/ψ and Υ resonances.

Cuts on several discriminating variables are applied in order to suppress background events. The *track isolation* ($I_{\mu\mu}$) is defined as $I_{\mu\mu} = p_T^{\mu\mu}/(p_T^{\mu\mu} + \sum_i p_T^i)$, where the sum runs over all tracks inside a cone described by $\Delta R < 1$ around the direction of the B_s^0 candidate, excluding the two muon tracks. ΔR is given by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle between the considered track and the B_s^0 candidate. The cut chosen is $I_{\mu\mu} > 0.9$. The *pointing angle* (α) is the angle between the direction connecting the primary and the secondary vertices and the direction of the total di-muon momentum. The cut imposed is $\alpha < 0.017$ rad. Another variable is the *transverse decay length* (L_{xy}) of the B_s^0 candidate projected on the total transverse momentum of the di-muon pair. The cut chosen for this variable is $L_{xy} > 0.5$ mm. Finally, the *invariant mass* window $M \in [M_{B_s^0}^{PDG} - 90 \text{ MeV }, M_{B_s^0}^{PDG} + 180 \text{ MeV }]$ is used. The asymmetry of the cuts is aimed at minimising the overlap with the B_d^0 mass region.

The distributions of the first three variables are shown in Fig. 4 for the signal (full circles) and the combinatorial background (open circles). The mass resolution observed is 70 ± 1 MeV (barrel) and 124 ± 1 MeV (end-cap).

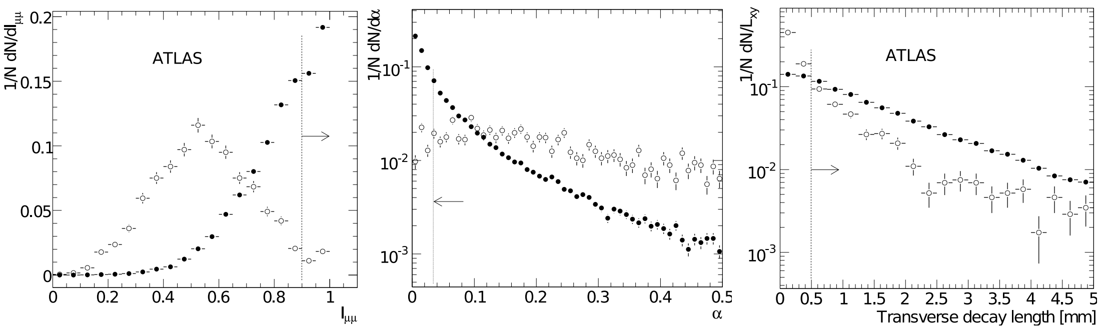

Figure 4: Discriminating variables used for background suppression: $I_{\mu\mu}$ (left), α (centre) L_{xy} (right). Full circles represent the signal sample and open circles the combinatorial background sample.

The rejection power of the cut variables on the background samples is displayed in Fig. 5, which shows $b\bar{b} \to \mu^+\mu^- X$ (full circles), $B_s^0 \to K^-\mu^+\nu_\mu$ (open circles) and $B_s^0 \to K^-\pi^+$ (triangles) in comparison to the $B_s^0 \to \mu^+\mu^-$ signal (full line). The left (right) plot shows the di-muon invariant mass spectrum observed for each of these channels before (after) the cut based selection has been applied. The number of events has been extrapolated to 10 fb^{-1}. It is observed that the two exclusive channels are well suppressed in the B_s^0 mass region, with the only notable contribution remaining from the combinatorial background.

Event yield In the case of the background sample, the statistics available is not large enough to compute the total efficiency and a factorisation of the cuts has been performed. Due to the strong correlation between α and L_{xy}, the combined efficiency for the α and L_{xy} cuts has been computed, while the efficiency for the $I_{\mu\mu}$ and $M_{\mu\mu}$ cuts has been computed independently. This resuts in a total event selection efficiency for the background channel of $\varepsilon_{total} = \varepsilon_{L_{xy},\alpha} \cdot \varepsilon_{I_{\mu\mu}} \cdot \varepsilon_{M_{\mu\mu}}$. In addition, the total trigger efficiency considered here has been determined to 46% in an independent study based on simulated data [7]. The di-muon trigger with p_T thresholds of 6 and 4 GeV on the two muons has been used. Finally, the numbers of expected signal and background events were determined as summarised in Table 1. With 10 fb^{-1} of recorded data, 5.7 signal and 14 background events are expected.

6. Conclusions

The study of rare B decays has the potential to give indirect evidence for processes beyond the SM. The ATLAS data from the early running period at a center of mass energy of 7 TeV are used to measure the detector performance and to reconstruct known particles like the J/ψ. The reference channel $B^+ \to J/\psi K^+$ used in the search for the $B_s^0 \to \mu^+\mu^-$ decay is expected to be seen soon.

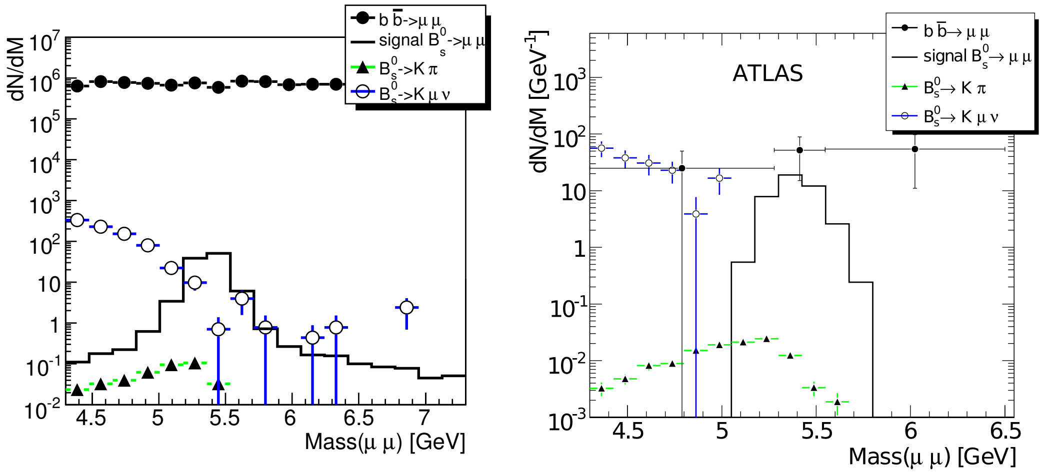

Figure 5: The $\mu^+\mu^-$ invariant mass spectrum obtained from the signal sample, from the combinatorial background and from two exclusive channels, before (left) and after (right) the cut based selection has been applied.

Selection cut	$B_s^0 \to \mu^+\mu^-$	$b\bar{b} \to \mu^+\mu^- X$
$I_{\mu\mu} > 0.9$	0.24	$(2.6 \pm 0.3) \times 10^{-2}$
$L_{xy} > 0.5$ mm	0.26	$(1.0 \pm 0.7) \times 10^{-3}$
$\alpha < 0.017$ rad	0.23	
$M \in [M_{B_s^0}^{PDG} - 90, M_{B_s^0}^{PDG} + 180]$	0.76	0.079
TOTAL	0.04	$(2.0 \pm 1.4) \times 10^{-6}$
Events (10fb^{-1})	5.7	14^{+13}_{-10}

Table 1: Selection efficiencies and event yield for signal and combinatorial background samples.

The ATLAS strategy to search for $B_s^0 \to \mu^+\mu^-$ and to eventually measure the branching ratio has been developed based on simulated data. It is expected that 5.7 signal events and 14 background events will be observed with 10 fb^{-1} of recorded data at $\sqrt{s} = 14$ TeV.

References

[1] A. J. Buras, *Prog. Theor. Phys.* **122** (2009), 145 [`arXiv:hep-ph/0904.4917`]

[2] G. Buchalla et. al., *Eur. Phys. J. C* **57**, 309-492 (2008) [`arXiv:hep-ph/0801.1833v1`]

[3] D0 Collaboration, *proceedings of ICHEP 2010 (to be published)*

[4] G. Aad et. al. (ATLAS Collaboration), *JINST* **3** S08003 (2008)

[5] L. Evans and P. Bryant, *JINST* **3** S08001 (2008)

[6] ATLAS Collaboration, *ATLAS-CONF-2010-009* (2010)

[7] ATLAS Collaboration, *CERN-OPEN-2008-020* (2008) [`arXiv:hep-ex/0901.0512`]

[8] ATLAS Collaboration, *ATLAS-CONF-2010-045* (2010)