Search for Pure Leptonic B Decays at ATLAS and CMS

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1 Introduction

In the Standard Model (SM) the decays $B_{s,d}^0 \rightarrow \mu^+ \mu^-$ are mediated by flavour changing neutral currents (FCNC). They are CKM suppressed, and happen via higher-order electroweak Feynman diagrams. Their decay rates, additionally, suffer helicity suppression. For the $B_s^0 \rightarrow \mu^+ \mu^-$ channel a rate of $(3.54 \pm 0.30) \times 10^{-9}$ has been predicted [1, 2], and for $B_d^0 \rightarrow \mu^+ \mu^-$ the prediction is $(1.07 \pm 0.10) \times 10^{-10}$ [1]. In Standard Model extensions these rates may be enhanced. Any deviation from the SM predictions will indicate new physics. These channels are important probes for physics beyond the SM.

This paper describes the latest measurements of $B_{s,d}^0 \rightarrow \mu^+ \mu^-$ from the ATLAS and CMS experiments [3, 4] at the LHC.

2 Analysis Strategy

The branching fractions BR($B_{s,d}^0 \rightarrow \mu^+ \mu^-$) can be measured relative to a well measured reference channel to minimize uncertainties, e.g. detector acceptance uncertainties, while keeping the analysis independent of luminosity variations and $b\bar{b}$ production cross-section uncertainties. For this purpose both ATLAS and CMS use $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$ as the reference channel, because of large available statistics, and similar (di-muon) final states. To keep systematic uncertainties low, similar selection cuts are applied to both the signal and the reference channel events.

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The branching fractions are computed as

\[ \text{BR}(B_{s,d}^0 \to \mu^+\mu^-) = \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^\pm}} \times \text{BR}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \times R_{A\epsilon} \times \frac{f_u}{f_{s,d}}, \quad (1) \]

where \( N_{\mu^+\mu^-} \) and \( N_{J/\psi K^\pm} \) are the number of observed signal and reference channel events, respectively. The factor \( R_{A\epsilon} = \frac{A_{J/\psi K^\pm} \epsilon_{J/\psi K^\pm}}{A_{\mu^+\mu^-} \epsilon_{\mu^+\mu^-}} \) is to correct for the detector acceptances \((A)\) and event selection efficiencies \((\epsilon)\) estimated for the two channels using Monte Carlo events (MC). The ratios \( f_u/f_{s,d} \) are the ratios of the \( b \)-quark hadronization probabilities to correct for the different production rates of \( B^\pm \) and \( B_{s,d}^0 \). The reference channel branching fraction \( \text{BR}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) = (6.01 \pm 0.21) \times 10^{-5} \), and the ratio \( f_s/f_u = 0.267 \pm 0.021 \) are taken from other measurements \([5, 6]\). The ratio \( f_d/f_u \) is taken to be 1 \([7]\).

3 ATLAS Analysis

The ATLAS analysis expresses the branching fraction as a product of the observed number of signal events and a Single Event Sensitivity (SES):

\[ \text{BR}(B_s^0 \to \mu^+\mu^-) = N_{\mu^+\mu^-} \times \text{SES}. \quad (2) \]

For a single observed signal event, the branching fraction \( \text{BR}(B_s^0 \to \mu^+\mu^-) \) would be equal to the SES.

The analysis uses \( pp \) collision data at \( \sqrt{s} = 7 \) TeV recorded by the ATLAS detector in the period April-August 2011. This corresponds to an integrated luminosity of 2.4 fb\(^{-1}\). The analysis is robust against pileup effects. The details of the analysis can be found in reference \([8]\).

A topological trigger selects di-muon candidates above a transverse momentum \((p_T)\) threshold of 4 GeV. The signal channel events in the invariant mass range \( m_{\mu^+\mu^-} \in [5066,5666] \) MeV are hidden in the analysis (‘blind’ analysis) until event selection cuts are finalized. The events in the side bands \( m_{\mu^+\mu^-} \in [4766,5066] \) MeV, \( m_{\mu^+\mu^-} \in [5666,5966] \) MeV) are split into two sets. To avoid statistical biases, one set is used for cut optimization (odd numbered events in data), and the other for estimation of the background under the signal (even numbered events in data).

The event selection cuts are optimized using a multivariate technique. The method uses Boosted Decision Trees (BDT) with 14 input variables to compute an event classifier, \( Q \). The signal search window, \( \Delta m_{\mu^+\mu^-} \), in the \( B_s^0 \to \mu^+\mu^- \) invariant mass spectrum is optimized together with the BDT classifier \( Q \). The method determines the optimal \( \Delta m_{\mu^+\mu^-} \) and \( Q \) to get the maximum value for the estimator:

\[ P(Q, \Delta m_{\mu^+\mu^-}) = \frac{\epsilon_{\text{sig}}}{1 + \sqrt{N_{\text{bkg}}}}, \quad (3) \]

\[ 2 \]
where $\epsilon_{\text{sig}}$ is the signal selection efficiency and $N_{\text{bkg}}$ is the continuum background interpolated from the side bands (two times the number of odd events).

The events are split into three mass resolution categories distinguished by the maximum pseudorapidity ($|\eta|^\text{max}$) of the muon tracks. The $\Delta m_{\mu^+\mu^-}$ and $Q$ are separately optimized for each category. The same classifier cut is used to compute the acceptance and efficiency ratio $R_A$ from the MC, and the reference channel yield, $N_{J/\psi K^\pm}$, in the three categories. The $B^\pm$ yield is determined by fitting the $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+\mu^- K^\pm$ invariant mass spectrum, and computing the $N_{J/\psi K^\pm}$ in a band $m_{J/\psi K^\pm} \in [5180, 5380]$ MeV. The SES is thus computed for the three categories using Equations (1) and (2). In the di-muon invariant mass spectrum there is an expected background due hadronic decays, where hadrons are misidentified as muons. The $B \rightarrow hh$ background is the dominating resonant background. It is estimated from the MC.

![Figure 1: The di-muon invariant mass spectrum (points) (in the ATLAS analysis [3]) after unblinding in the three mass resolution categories. The search window is shown by dashed blue lines. The shaded grey regions reflect the sidebands used in the analysis. The solid curve shows the $B^0_s \rightarrow \mu^+\mu^-$ distribution in MC scaled by a factor of 10.](image_url)
3.1 Results

The upper limit on the $B^0_s \rightarrow \mu^+\mu^-$ branching fraction is computed using the CL$_s$ method [9]. A likelihood expression combines the SES computed in the three mass resolution categories, its uncertainties, and the expected resonant ($B \rightarrow hh$) and non-resonant background contributions to the $B^0_s \rightarrow \mu^+\mu^-$ invariant mass spectrum [8]. An expected limit of $(2.3^{+1.0}_{-0.5}) \times 10^{-8}$ on BR($B^0_s \rightarrow \mu^+\mu^-$) is obtained. The data in the blinded region is analysed, and the signal yield is measured in the optimized search window for the three mass resolution categories (see Figure 1). The observed upper limit is $2.2 (1.9) \times 10^{-8}$ at 95% (90%) confidence level (CL). The observed limit is comparable with the expected limit (Figure 2).

![Figure 2: The observed CL$_s$ (points) as a function of $B^0_s \rightarrow \mu^+\mu^-$ branching fraction in the ATLAS analysis [8]. The upper limit is read at the intersection of the red line with the observed CL$_s$ line, which corresponds to 95% CL. The green and yellow bands indicate $\pm 1\sigma$ and $\pm 2\sigma$ deviation from the expected limit (dashed line).](image)

4 CMS Analysis

In this section the key features in the CMS analysis different from the ATLAS one are presented.

The CMS analysis uses 5 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV recorded by the CMS detector in the year 2011. In this analysis a cut-and-count approach is taken. The optimization of the selection cuts is performed using the signal MC and all the side-band ($m_{\mu^+\mu^-} \in [4900, 5200]$ MeV, $m_{\mu^+\mu^-} \in [5450, 5900]$ MeV) events in the data. The events inside the signal region (in data) are kept blinded until the cuts are
established. A random-grid search method is used to tune the cuts on 11 analysis variables to get the best upper limit [11]. A different set of selection cuts is used for events in the endcap region of the detector than in the barrel region.

The analysis shows good agreement between the reconstructed distributions in data and MC, and it is not sensitive to pileup events.

4.1 Results

The branching fractions for both $B_0^d \rightarrow \mu^+\mu^-$ and $B_0^s \rightarrow \mu^+\mu^-$ decays are measured simultaneously using two asymmetric search windows around the $B_0^d$ and $B_0^s$ masses. Figure 3 shows the di-muon invariant mass spectrum after the unblinding.

Figure 3: The di-muon invariant mass spectrum (in the CMS analysis [11]) after unblinding in the two detector regions. The solid and the dashed horizontal lines indicates the search windows for $B_0^s$ and $B_0^d$ events, respectively.

The limit extraction takes into account the expected combinatorial and the resonant background contributions (estimated using MC), and also the number of expected signal events assuming the SM branching fractions. The resonant background includes $B_{s,d}^0 \rightarrow h^+h^0$ decays, where hadrons are misidentified as muons, and $B_{s,d}^0 \rightarrow h^-\mu^+\nu$ rare semileptonic decays. The limits are computed using the CL$_s$ method [9, 10]. The expected upper limits for $B_0^s \rightarrow \mu^+\mu^-$ ($B_0^d \rightarrow \mu^+\mu^-$) are $8.4 \times 10^{-9}$ ($1.6 \times 10^{-9}$) at 95% CL [11]. The upper limit for $B_d^0 \rightarrow \mu^+\mu^-$ is $1.8 (1.4) \times 10^{-9}$ at 95% (90%) CL. Figure 4 shows the dependence of CL$_{s+b}$ on the $B_0^s \rightarrow \mu^+\mu^-$ branching fraction.
Figure 4: The observed CL_{s+b} (solid line) as a function of B_s^0 \rightarrow \mu^+\mu^- branching fraction (in the CMS analysis [11]) assuming the SM expectations. The green and yellow bands indicate ±1σ and ±2σ deviation from the expected limit (dashed line).

5 Summary

The B_s^0 \rightarrow \mu^+\mu^- and B_d^0 \rightarrow \mu^+\mu^- are important decay channels to search for new physics. The latest limits on their branching fractions were set by the LHC experiments. These are summarized in Table 1. The best B_s^0 \rightarrow \mu^+\mu^- upper limit, 4.2 \times 10^{-9}, is the combined result [13] of the measurements performed by ATLAS, CMS and LHCb experiments. It is close to the SM expectation, (3.54 ± 0.30) \times 10^{-9}. The ATLAS and CMS collaborations are working on extending their analyses to the full available statistics collected from the LHC.

|                | B_s^0 \rightarrow \mu^+\mu^- | B_d^0 \rightarrow \mu^+\mu^- |
|----------------|-----------------------------|-----------------------------|
| ATLAS          | 2.2 \times 10^{-8}          | -                           |
| CMS            | 7.7 \times 10^{-9}          | 1.8 \times 10^{-9}          |
| LHCb           | 4.5 \times 10^{-9}          | 1.0 \times 10^{-9}          |
| LHC Combined   | 4.2 \times 10^{-9}          | 8.1 \times 10^{-10}         |

Table 1: Limits at 95% CL measured by different LHC experiments [8, 11, 12, 13].
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