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Rare and Suppressed Decays of $\mathbf{B^0_{(s)}}$ Mesons with the ATLAS Detector

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The large amount of Heavy Flavor data collected by the ATLAS experiment at the LHC is potentially sensitive to New Physics, which could be evident in processes that are naturally suppressed in the Standard Model. The most recent results for 4.9 fb^{-1} of ATLAS data on the search for the rare decay $B_s^0 \to \mu^+\mu^-$ are presented, as well as results of the angular analysis of the semileptonic rare decay $B^0 \to K^{\star 0}\mu^+\mu^-$ with $K^{\star 0} \to K^+\pi^-$, extracting the angular distribution parameters A_{FB} and F_L. The accuracy obtained from data collected in 2011 is comparable to the best measurements in the region $q^2(\mu^+\mu^-) > 16\ \mathrm{GeV}^2$.

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1. Introduction

The ATLAS experiment [1] at the Large Hadron Collider (LHC) [2] at CERN is able to perform indirect searches for New Physics such as in the decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to K^{\star 0}\mu^+\mu^-$. These measurements, being complementary to direct searches, can be compared to Standard Model (SM) predictions and used to provide constraints on New Physics models. In this contribution, the results of analyses of the decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to K^{\star 0}\mu^+\mu^-$ using 4.9 fb^{-1} of data collected by the ATLAS detector in 2011 are discussed. Both analyses are based on events predominantly selected by a di-muon trigger, requiring pairs of oppositely-charged muons with transverse momenta $p_T > 4$ GeV. The events are reconstructed in the Inner Detector and the Muon Spectrometer.

2. Search for $B^0_s \to \mu^+\mu^-$

The decay $B^0_s \to \mu^+\mu^-$ is highly suppressed in the Standard Model with a predicted branching fraction of $(3.27 \pm 0.27) \cdot 10^{-9}$ [3]. The experimental results need to be compared to the time-integrated branching fraction of $(3.54 \pm 0.30) \cdot 10^{-9}$ [4]. Recently the CMS and LHCb collaborations reported evidence for the $B^0_s \to \mu^+\mu^-$ decay with a measured branching fraction of $(2.9 \pm 0.7) \cdot 10^{-9}$ [5, 6],

The strategy of the $B^0_s \to \mu^+\mu^-$ analysis [7] is based on the relative measurement of the $B^0_s \to \mu^+\mu^-$ branching fraction with respect to the branching fraction of the prominent reference decay $B^\pm \to J/\psi K^\pm$ [8] in order to minimise systematic uncertainties in the evaluation of the integrated luminosity as well as of the efficiencies and acceptances. The $B^0_s \to \mu^+\mu^-$ branching fraction can be expressed as

$$\mathscr{B}(B^0_s \to \mu^+\mu^-) = N_{\mu^+\mu^-} \cdot \underbrace{\frac{1}{N_{J/\psi K^\pm}} \cdot \frac{\varepsilon_{J/\psi K^\pm} \cdot A_{J/\psi K^\pm}}{\varepsilon_{\mu^+\mu^-} \cdot A_{\mu^+\mu^-}} \cdot \frac{f_u}{f_s} \cdot \mathscr{B}(B^\pm \to J/\psi K^\pm) \cdot \mathscr{B}(J/\psi \to \mu^+\mu^-)}_{\text{SES}}.$$

For each mode, the number of observed events in the signal window N_i is counted and corrected for the corresponding efficiencies ε_i and acceptances A_i which are determined from Monte Carlo reweighted to resemble the p_T and η distributions observed in $B^\pm \to J/\psi K^\pm$ data. The f_u/f_s term, taken from [9], accounts for the relative b-quark hadronisation probability of $B^\pm$ and B^0_s in pp collisions.

The selection of $B^0_s \to \mu^+\mu^-$ events consists of a set of baseline criteria followed by a final event selection using a Boosted Decision Tree (BDT) method. The BDT effectively reduces non-resonant continuum background events using 13 discriminating variables. It is trained on Monte Carlo events, and the cut on the BDT output variable as well as the width of the signal window are optimised on half of the sideband data and $B^0_s \to \mu^+\mu^-$ signal Monte Carlo. The contribution of resonant background from $B \to hh'$ events ($h = K^\pm$ or $\pi^\pm$) in the signal region is estimated using Monte Carlo events.

In order to avoid biases in the final results, the optimisation of the event selection and the setup of the limit extraction is performed with the invariant mass region $m_{B^0_s} \pm 300$ MeV blinded.

The reference channel yield $N_{J/\psi K^\pm} = 15\,214 \pm 1.1\%$ (stat) $\pm 2.4\%$ (syst) is obtained by an unbinned maximum likelihood fit in two dimensions after applying a selection similar to that applied to the signal channel in order to minimise systematic uncertainties in the ratio. The main

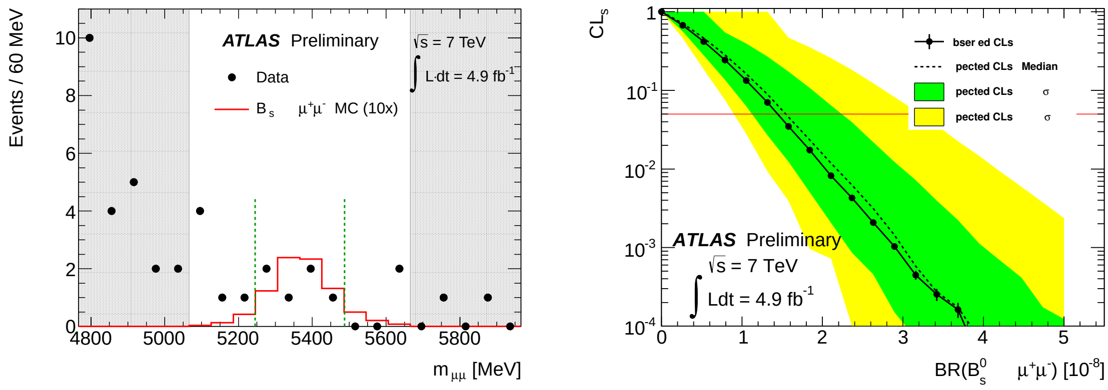

Figure 1: Left: Invariant-mass distributions of selected candidates in data (dots) [7]. The plot also indicates the signal (continuous line) as predicted by Monte Carlo assuming $\mathscr{B}(B^0_s \to \mu^+\mu^-) = 3.5 \times 10^{-8}$ (i.e. scaled by a factor 10), the signal region (two dashed vertical lines) corresponding to the optimised Δm cut and the sidebands used in the analysis (grey areas). The expected number of $B^0_s \to \mu^+\mu^-$ signal in the signal region is 1.7 ± 0.2 events. The expected background yield per bin in the signal region is 1.7 events.
Right: Observed CL$_s$ (circles) as a function of $\mathscr{B}(B^0_s \to \mu^+\mu^-)$ [7]. The 95% CL limit is indicated by the horizontal (red) line. The dark (green) and light (yellow) bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ ranges of the background-only pseudo-experiments with the median of the expected CL$_s$ given by the dashed line.

contribution to the systematic uncertainty is given by the variation of the continuum background models.

The Single-Event-Sensitivity (SES), the $B^0_s \to \mu^+\mu^-$ branching fraction corresponding to one observed event in the data sample, is determined to SES $= (2.07 \pm 2.1\%\ (\text{stat})) \cdot 10^{-9}$ with a systematic uncertainty of $\pm 12.5\%$ which is dominated by the uncertainties on $\mathscr{B}(B^\pm \to J/\psi K^\pm)$, f_u/f_s and the $\varepsilon \cdot A$ ratio. The systematic uncertainty on the $\varepsilon \cdot A$ ratio is estimated using the residual data-Monte Carlo discrepancies observed in the $B^\pm \to J/\psi K^\pm$ control sample.

The number of signal events $N_{\mu^+\mu^-}$ is estimated from the number of events observed in the signal window less the number of expected non-resonant and resonant background events in the same region (6.75 events), where the contiuum background contribution is interpolated from the second half of the sideband sample. After unblinding, 6 events are observed in the signal region (Fig. 1, left).

The upper limit for $\mathscr{B}(B^0_s \to \mu^+\mu^-)$ is obtained following the ATLAS prescription for the extraction of frequentist limits by means of a standard implementation [10, 11] of the CL$_s$ method [12]. The resulting upper limit (Fig. 1, right) is $\mathscr{B}(B^0_s \to \mu^+\mu^-) < 1.5\ (1.2) \times 10^{-8}$ at 95% (90%) confidence level (CL) with an the expected upper limit of $\mathscr{B}(B^0_s \to \mu^+\mu^-) < 1.6\ (1.3) \times 10^{-8}$ at 95% (90%) CL.

3. Angular analysis of $B^0 \to K^{\star 0}\mu^+\mu^-$

In the SM, the decay $B^0_d \to K^{*0}\mu^+\mu^-$ with subsequent $K^{*0} \to K^+\pi^-$ decay occurs via loop diagrams that mediate the transition $b \to s\ \ell^+\ell^-$ and therefore has a small branching fraction of $(1.06 \pm 0.1) \cdot 10^{-6}$ [8]. The angular distributions of the 4-particle final state, as well as the decay amplitudes, are sensitive to New Physics due to interference of new diagrams with the SM diagrams.

In the angular analysis of the $B_d^0 \to K^{*0}\mu^+\mu^-$ decay [13] four kinematic variables describe the decay: the invariant mass q^2 of the di-muon system and the three angles describing the geometrical configuration of the final state. θ_L is the angle between the μ^+ and the direction opposite to the B_d^0 in the di-muon rest frame, θ_K is the angle between the K^+ and the direction opposite to the B_d^0 in the K^{*0} rest frame, and ϕ is the angle between the plane defined by the two muons and the plane defined by the kaon-pion system in the B_d^0 rest frame.

Due to the limited statistics of the 2011 data, the differential decay rate is projected into 2-dimensional distributions obtained by integrating over the other two variables:

$$\begin{aligned}
\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_L} &= \frac{3}{4}F_L(q^2)\left(1-\cos^2\theta_L\right)+\frac{3}{8}\left(1-F_L(q^2)\right)\left(1+\cos^2\theta_L\right)+A_{FB}(q^2)\cos\theta_L, \\
\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_K} &= \frac{3}{2}F_L(q^2)\cos^2\theta_K+\frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_K\right).
\end{aligned}$$

The values of the K^{*0} longitudinal polarisation fraction F_L and of the lepton forward-backward asymmetry A_{FB} are extracted in intervals of q^2 coinciding with those used in [16].

Events containing resonant background from J/ψ and $\psi(2S)$ candidates are vetoed. In order to suppress background from $b\bar{b} \to \mu^+\mu^- X$ combinatorial events and small contributions from $c\bar{c} \to \mu^+\mu^- X$ and Drell-Yan, selections on the lifetime significance $\tau/\sigma_\tau > 12.75$ and on the pointing angle $\cos\theta > 0.999$ are applied. The selection criteria are optimised by maximising the estimator $N_{sig}/\sqrt{N_{sig}+N_{bkg}}$, where N_{sig} is the number of selected signal events and N_{bkg} the number of background events. In addition, radiative charmonium decays $B_d^0 \to K^{*0}J/\psi$ (with $J/\psi \to \gamma\mu^+\mu^-$) and $B_d^0 \to K^{*0}\psi(2S)$(with $\psi(2S) \to \gamma\mu^+\mu^-$) as well as tails from the J/ψ and $\psi(2S)$ contributions are removed by a dedicated selection.

A two-dimensional unbinned maximum likelihood fit of the invariant mass distribution $m_{K\pi\mu^+\mu^-}$ using a Gaussian model for the signal and an exponential model for the background over the whole di-muon invariant mass range ($0.04\ \mathrm{GeV}^2 < q^2 < 19.00\ \mathrm{GeV}^2$) results in 466 ± 34 signal and $1\,132 \pm 43$ background events.

Due to the low available statistics, the F_L and A_{FB} parameters for the individual q^2 bins are extracted by a sequential unbinned maximum likelihood fit to provide a more stable fitting procedure. In a first step the $m_{K\pi\mu^+\mu^-}$ distribution is fitted, and in second step the angular distributions are fitted keeping the parameters from the first fit, especially the signal and background yields, fixed.

The final results for A_{FB} and F_L are reported in Fig. 2 with comparisons to SM expectations and measurements performed by other experiments. The measurement is mostly consistent with SM predictions but still statistically limited.

4. Summary

With a dataset of 4.9 fb^{-1} of integrated luminosity collected by the ATLAS detector in 2011 at 7 TeV, an upper limit on $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ of $1.5 \cdot 10^{-8}$ at 95% confidence level is set, and the lepton forward backward-asymmetry A_{FB} as well as the fraction of longitudinally polarised K^{*0} mesons F_L are measured using the $B_d^0 \to K^{*0}\mu^+\mu^-$ decay. Neither measurement exhibits signs of New

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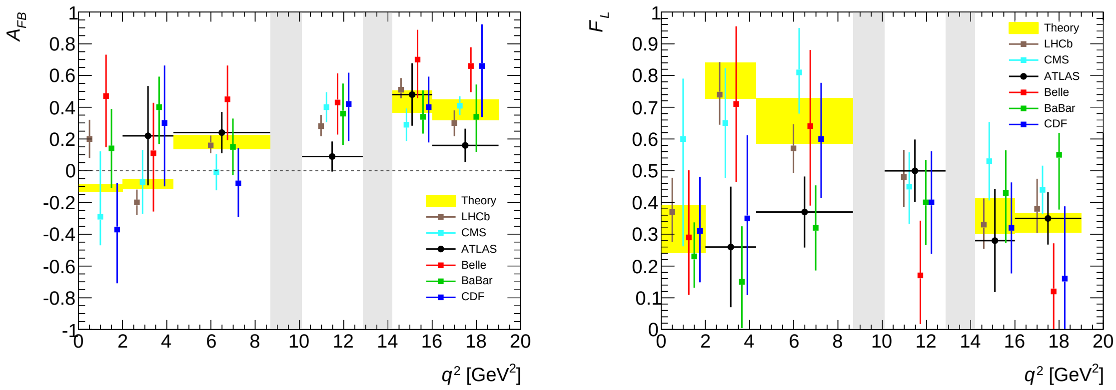

Figure 2: Forward-backward asymmetry A_{FB} (left) and fraction of longitudinally polarised K^{*0} mesons F_L (right) as a function of the di-muon invariant mass squared q^2 measured by ATLAS (black dots) [13]. In each q^2 bin, ordered from left to right, results of other experiments are shown as coloured squares: LHCb [14], CMS [15], Belle [16], BaBar [17], and CDF [18]. All errors include statistical and systematic uncertainties. The experimental results are compared to theoretical predictions [19, 20] including theoretical uncertainties.

Physics or significant deviations from the SM. Currently, the measurements are statistically limited and analyses on the full ATLAS dataset collected at 8 TeV in 2012 (about 20 fb^{-1} of integrated luminosity) are being prepared.

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