Rare and Semi-rare Decays of Beauty Mesons in ATLAS

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The ATLAS experiment at the Large Hadron Collider has performed measurements of the rare flavor-changing neutral-current processes $b \rightarrow s \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ which are sensitive to New Physics effects. This contribution presents recent ATLAS results from the angular analysis of the $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$ decay with LHC Run 1 data, the $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ measurement with 2015 and 2016 data as well as projections for the $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ measurements for the High-Luminosity LHC phase.

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1. Introduction

New physics beyond the Standard Model (SM) may manifest itself in angular distributions of $b \to s \mu^+ \mu^-$ processes or the branching fractions of very rare $B$ meson decays. The ATLAS experiment [1] at the Large Hadron Collider (LHC) [2] at CERN performs indirect searches for New Physics by an angular analysis of the $B^0_d \to K^{*0} \mu^+ \mu^-$ decay and measuring the branching fractions of the rare decays $B^0_d \to \mu^+ \mu^-$ and $B^0 \to \mu^+ \mu^-$. In addition, expected sensitivities for the angular analysis in the decay channel $B^0_d \to K^{*0} \mu^+ \mu^-$ and for the branching fractions of the rare decay $B^{(*)}_s \to \mu^+ \mu^-$ at the High-Luminosity LHC (HL-LHC) [3] are presented.

2. Angular Analysis of $B^0_d \to K^{*0} \mu^+ \mu^-$

Mediated by flavour-changing neutral curents (FCNC), in the Standard Model (SM) the decay $B^0_d \to K^{*0} \mu^+ \mu^-$ with $K^{*0} \to K^+ \pi^-$ proceeds via loop diagrams. The complex angular structure of this decay is fully described by three angles and the dimuon invariant mass squared $q^2$. Multiple angular observables provided by this decay are sensitive to different types of New Physics (NP). A $3.4 \sigma$ deviation from SM calculations is reported by the LHCb collaboration [4]. The measurement [5] with the ATLAS detector [1], using 20.3 fb$^{-1}$ of $pp$ collision data at a centre-of-mass energy of $\sqrt{s} = 8$ TeV collected in 2012, adopts the LHCb analysis method including the definitions of angular observables and of optimised parameters $P^i_g$ [6]. The latter are designed to minimise uncertainties from hadronic form factors and therefore increase the sensitivity to NP. Due to the limited statistics a set of trigonometric transformations of the angular variables [6] is employed in the analysis presented.

In order to maximise the signal yield, data are combined from trigger chains with one, two or at least three identified muons. Furthermore this ensures a sensitivity of the analysis down to the kinematic threshold of $q^2 = 0.04$ GeV$^2$. Signal candidates are reconstructed from two charged tracks satisfying $m_{K \pi \mu \mu} \in [846, 946]$ MeV and two muons, requiring $m_{K \pi \mu \mu} \in [5110, 5700]$ MeV. Cut-based selections on the vertex fit quality $\chi^2$/n.d.f. < 2, the $B^0$ lifetime significance $t/\sigma_t > 12.75$, the pointing angle $\cos \theta > 0.999$ and the $K^{*0}$ momentum $p_T(K^{*0}) > 3$ GeV are used to suppress the combinatorial background. This selection results in a data sample of 787 events in the signal range of $q^2 \in [0.04, 6.0]$ GeV$^2$. Data with a $q^2$ above 6 GeV$^2$ are excluded in order to suppress a radiative tail from $B^0 \to K^{*0} J/\psi$ events.

To extract the angular parameters an extended unbinned maximum-likelihood fit to the invariant mass $m_{K \pi \mu \mu}$ and the angular distributions $\cos \theta_K$, $\cos \theta_L$ and $\phi$ is performed in six bins of $q^2$, with three of the bins overlapping. The fit yields a total of 342 $\pm$ 39 signal events. A distinct background contribution from $B^0 \to D^0 / D^*_0 (s) X$ decays at $\cos \theta_L \sim 0.7$ is excluded by vetoing the $D^0 / D^*_0 (s)$ mass ranges. The background from fake $K^{*0}$ candidates and $B^+ \to K^+ / \pi^+ \mu^+ \mu^-$ decays, observed at $\cos \theta_K \sim 1$, is treated as a systematic uncertainty with the fake $K^{*0}$ candidates providing the largest contribution. Overall, the measurement is largely dominated by statistical uncertainty.

Figure 1 compares the results for the $P_4'$ and $P_5'$ parameters to the theoretical computations of Jäger and Camalich (JC) [9, 10], Descotes-Genon et al. (DHMV) [8] and Ciuchini et al. (CFFMPSV) [7]. Experimental results from LHCb [4], CMS [11] and Belle [12] are overlaid as well. The $P_4'$ and $P_5'$ measurements in the $q^2 \in [4.0, 6.0]$ GeV$^2$ bin differ by $\sim 2.7 \sigma$ from the
DHMV model, a deviation observed similarly by the LHCb collaboration [4]. Overall, all ATLAS measurements are compatible with the different predictions at the three-standard-deviation level as well as with the results provided by the other experiments.

3. Branching fractions of $B^{0}_{s} \to \mu^{+}\mu^{-}$ and $B^{0} \to \mu^{+}\mu^{-}$

The rare decays $B^{0}_{s} \to \mu^{+}\mu^{-}$ and $B^{0} \to \mu^{+}\mu^{-}$, which are sensitive to New Physics in the decays via loop diagrams, are highly suppressed in the Standard Model (SM) with predicted branching fractions [13, 14] of $(3.65 \pm 0.23) \times 10^{-9}$ and $(1.06 \pm 0.09) \times 10^{-10}$, respectively. The ATLAS Run 1 result [15] is compatible with the SM at the $2 \sigma$ level, and the $B(\overline{B}^{0}_{s} \to \mu^{+}\mu^{-})$ values are lower than the CMS-LHCb combined result [16]. Recent measurements by the LHCb [17] and CMS [18] collaborations, including part of the Run 2 data, set upper limits of $B(\overline{B}^{0} \to \mu^{+}\mu^{-}) < 3.4 \times 10^{-10}$ and $B(\overline{B}^{0} \to \mu^{+}\mu^{-}) < 3.6 \times 10^{-10}$ at 95% confidence level (CL), respectively, which reduces the tension in this parameter.

The updated ATLAS measurement [19] of the $B^{0}_{s} \to \mu^{+}\mu^{-}$ branching fractions includes 36.2 fb$^{-1}$ of data taken at a centre-of-mass energy of 13 TeV during 2015 and 2016 (LHC Run 2) and a combination with the result based on 25 fb$^{-1}$ data taken at 7 and 8 TeV during LHC Run 1. For Run 2, events triggered by two muons ($p_{T}(\mu_{1}) > 6$ GeV, $p_{T}(\mu_{2}) > 4$ GeV, $|\eta| < 2.5$) with the invariant di-muon mass $m_{\mu^{+}\mu^{-}}$ in the range of 4 to 8.5 GeV are selected. The dominant combinatorial background ($b \to \mu X \times \overline{b} \to \mu X$ pairs) is rejected by a 15-variable Boosted Decision Tree (BDT) which is trained and tested on data sidebands and simulated signal events. Tails from partially reconstructed $b \to \mu^{+}\mu^{-}X$ decays like $B \to \mu^{+}\mu^{-}X$, $B \to c\mu X \to s(d)\mu^{+}\mu^{-}X$ or $B_{s} \to J/\psi\mu\nu$, which involve real di-muons at low $m_{\mu^{+}\mu^{-}}$, and semi-leptonic decays ($B_{s}/A_{s}^{0} \to h\mu\nu$ with $h = \pi, K, \rho$) contribute to the signal region and are taken into account in the signal fit. A small contribution of $B \to h\ell^{+}$ ($h^{0} = \pi^{\pm}, K^{\pm}$) decays, with hadrons misidentified as muons, peaks in the $B^{0}_{s} \to \mu^{+}\mu^{-}$ signal region contributing $2.9 \pm 2.0$ events after a “tight” muon selection is applied. The yield in the normalisation channel $B^{\pm} \to J/\psi K^{\pm}$ with $J/\psi \to \mu^{+}\mu^{-}$ is determined by an unbinned maximum likelihood fit to $m_{J/\psi K^{\pm}}$ while the efficiency relative to $B^{0}_{s} \to \mu^{+}\mu^{-}$ is extracted.
Figure 2: (a): Dimuon invariant mass distribution in the unblinded data, for the highest interval of BDT output. The result of the maximum-likelihood fit is superimposed. The total fit is shown as a continuous line, with the dashed lines corresponding to the observed signal component, the $b \rightarrow \mu^+ \mu^- X$ background, and the continuum background. The signal components are grouped in one single curve, including both the $B_s^0 \rightarrow \mu^+ \mu^-$ and the (negative) $B^0 \rightarrow \mu^+ \mu^-$ component. The curve representing the peaking $B^0_{s(\Lambda)} \rightarrow hh'$ background lies very close to the horizontal axis [19].

(b): Likelihood contours for the combination of the Run 1 and 2015–2016 Run 2 results (shaded areas). The contours are obtained with the combination of the likelihood for the two analyses, for values of $-2\Delta \ln L$ equal to 2.3, 6.2 and 11.8. The contours for the individual 2015–2016 Run 2 and Run 1 results as well as the ones from the latest LHCb result [17] are overlaid. The SM predictions and their uncertainties [13] are included. Figures taken from [19].

from Monte Carlo (MC) within a fiducial volume defined by $p_T(B) > 8$ GeV and $|\eta_B| < 2.5$. The overall efficiency ratio $R_e = \epsilon_{J/\psi K^+} / \epsilon_{\mu^+ \mu^-}$ is $0.1176 \pm 0.0009$ (stat.) $\pm 0.0047$ (syst.) with the largest contribution to the systematic uncertainties originating from data-MC discrepancies in the BDT input quantities. A correction of 2.7% has been applied to $R_e$ to account for the effective $B_s^0$ lifetime.

Due to the limited mass resolution the overlapping $B_s^0$ and $B_d^0$ peaks are statistically separated by an unblinned maximum likelihood fit to the $m_{\mu^+ \mu^-}$ distributions in four BDT bins. The signal and $B \rightarrow hh'$ distributions are modelled by three double-Gaussian PDFs, each with a common mean, while the background is described by a first-order polynomial (combinatorial background) in combination with an exponential distribution ($b \rightarrow \mu^+ \mu^- X$ and semi-leptonic background) whose shape parameters and normalisations are obtained from data (Figure 2 (a)).

For the Run 2 data, yields of $N_s = 80 \pm 22 B_s^0 \rightarrow \mu^+ \mu^-$ and $N_d = -12 \pm 20 B^0 \rightarrow \mu^+ \mu^-$ events are extracted, consistent with SM expectations of $N_s^{SM} = 91$ and $N_d^{SM} = 10$, respectively. Employing a Neyman construction a branching fraction of $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \left(3.21^{+0.96}_{-0.91} (\text{stat.})^{+0.49}_{-0.30} (\text{syst.})\right) \times 10^{-9}$ and an upper limit of $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-10}$ at 95% CL are obtained. A combination of the likelihood contours of the Run 2 (2015 and 2016) and Run 1 results (Figure 2 (b)) is compatible with the SM at the 2.4 $\sigma$ level and results in $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10}$ at 95% CL.
4. High-Luminosity LHC Prospects

At the High-Luminosity LHC (HL-LHC), due to a new all-silicon Inner Tracker (ITk) the mass resolution of the 4-prong FCNC decay \(B^0_d \to K^{*0} \mu^+ \mu^-\) is expected to improve by 30% with respect to the Run 1 measurement which is used as a baseline for the HL-LHC projections of the measurement. For the HL-LHC case three potential trigger scenarios are considered: two muons with \(p_T > 10\) GeV (“conservative”), one muon with \(p_T > 10\) GeV and another with \(p_T > 6\) GeV (“intermediate”) as well as two muons with \(p_T > 6\) GeV (“high yield”) providing 50, 160 and 250 times the Run 1 statistics, respectively. This includes a factor 1.7 due to the increase of the \(b\) production cross-section as the center-of-mass energy of the \(pp\) collisions rises from 8 TeV to 14 TeV. Estimates for the achievable experimental precision are obtained from pseudo-MC experiments based on the Run 1 signal and background angular distributions and by applying the same fitting procedure as in the Run 1 analysis.

Assuming that the increased statistics will allow for an improved fit model and a better understanding of the exclusive backgrounds, the corresponding systematic uncertainties are scaled by \(1/\sqrt{\text{stat}}\). The expected improvement in the measurement accuracy of the \(P'_4\) and \(P'_5\) parameters is demonstrated in Figure 3, compared to the current theoretical predications. Depending on the trigger scenario, the measurement precision for the \(P'_3\) parameter is expected to improve by a factor 5, 8 or 9 relative to the Run 1 measurement.

The branching fraction measurement of the very rare decays \(B^0_s \to \mu^+ \mu^-\) and \(B^0 \to \mu^+ \mu^-\) will also benefit from the increased statistics and the improved invariant mass resolution at the HL-LHC. The separation of the \(B^0_s\) and \(B^0_d\) mass peaks increases by a factor of 1.65 (1.5) to 2.3 \(\sigma\) (1.3 \(\sigma\)) in the barrel (end-cap) region compared to Run 1 [21].

The projection of the ATLAS detector performance for measuring \(\mathcal{B}(B^0_{(s)} \to \mu^+ \mu^-)\) with the expected datasets during the full LHC Run 2 (130 fb\(^{-1}\)) and at the HL-LHC (3 000 fb\(^{-1}\)) [22] us-

Figure 3: Projected ATLAS HL-LHC measurement precision in the \(P'_4\) (a) and \(P'_5\) (b) parameters for the intermediate \(\mu10\mu6\) trigger scenario compared to the ATLAS Run 1 measurement. Alongside, theory predictions (CFFMPSV [7], DHMV [8] and JC [9, 10]) are also shown. Both the projected statistical and the total (statistical and systematic) uncertainties are shown. While the HL-LHC toy-MC were generated with the DHMV central values of the \(P'_4\) and \(P'_5\) parameters, in these plots the central values are moved to the ATLAS Run 1 measurement for better visualization of the improvement in the precision [20].

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include the external systematic uncertainties on the pseudo-experiments based again on the likelihood of the Run 1 analysis. The signal statistics for the (10 GeV, 10 GeV), the (6 GeV, 10 GeV) and the (6 GeV, 6 GeV) dimuon trigger scenarios, respectively [22].

The contours of the 2-dimensional Neyman belt construction for the full LHC Run 2 case (a): Comparison of 68.3% (solid), 95.5% (dashed) and 99.7% (dotted) confidence level contours obtained exploiting the 2D Neyman belt construction for the full LHC Run 2 case [22]. Red contours are statistical only; blue contours include systematics uncertainties from the ATLAS Run 1 analysis [10].

Figure 4: (a): Comparison of 68.3% (solid), 95.5% (dashed) and 99.7% (dotted) confidence level contours obtained exploiting the 2D Neyman belt construction for the full LHC Run 2 case [22]. Red contours are statistical only; blue contours include systematics uncertainties from the ATLAS Run 1 analysis [15] extrapolated to Run 2 statistics. The black points show the SM theoretical prediction and its uncertainty [13].

(b) – (d): Comparison of confidence level profiled likelihood ratio contours for (b) the “conservative”, (c) the “intermediate” and (d) the “high-yield” HL-LHC extrapolation with ×15, ×60 and ×75 the Run 1 statistics for the (10 GeV, 10 GeV), the (6 GeV, 10 GeV) and the (6 GeV, 6 GeV) dimuon trigger scenarios, respectively [22].

The signal statistics estimate for the Run 2 scenario applies scaling factors for the integrated luminosity, the cross-section increase due to the higher center-of-mass energy of 13 TeV and the muon pair selection with topological triggers with \((p_T(\mu_1,2) > 6 \text{ GeV})\) or \((p_T(\mu_1) > 6 \text{ GeV}, p_T(\mu_2) > 4 \text{ GeV})\) thresholds resulting in 7 times the number of signal events in Run 1. The contours of the 2-dimensional Neyman construction (Figure 4 (a)) include the external systematic uncertainties on the b-quark fragmentation fractions \(f_s/f_d\) and \(\mathcal{B}(B^\pm \to J/\psi K^\mp)\) which were kept the same as in the Run 1 analysis as well as internal ones like the fit shapes and efficiencies which were scaled according to the increase in statistics. For the HL-LHC case the same three potential trigger scenarios as for the \(B^0_d \to K^0 \mu^+ \mu^-\) analysis are considered resulting in 15 (“conservative”), 60 (“intermediate”) and 75 (“high yield”) times the Run 1 statistics, respectively. The profile likelihood contours of pseudo-experiments based again on the likelihood of the Run 1 analysis demonstrate the increased sensitivity of the ATLAS detector for \(\mathcal{B}(B^0_s \to \mu^+ \mu^-)\) and \(\mathcal{B}(B^0 \to \mu^+ \mu^-)\) at the HL-LHC.
ure 4 (b) – (d)). The uncertainty on the $f_s/f_d$ value, conservatively taken as 8.3% from the ATLAS measurement [23], dominates the systematic uncertainty contributions on $\mathcal{B}(B^0_s \to \mu^+\mu^-)$.

5. Summary

Measurements of semi-rare flavor-changing neutral-current decays and of very rare decays, both sensitive to New Physics, by the ATLAS collaboration at the LHC have been presented.

The results of the angular analysis of the $B^0_d \to K^{*0}\mu^+\mu^-$ decay with 20.3 fb$^{-1}$ of Run 1 data agree well with the theoretical predictions in the SM and other measurements, with the largest deviation from theory ($\sim 2.7\sigma$) observed for the $P'_4$ and $P'_5$ parameters in the $q^2 \in [4.0, 6.0]$ GeV$^2$ bin.

The results for $\mathcal{B}(B^0 \to \mu^+\mu^-)$ and the search for the decay $\mathcal{B}(B^0 \to \mu^+\mu^-)$ with 36.2 fb$^{-1}$ of Run 2 data agree with the Standard Model and other measurements. There is no sign for the decay $B^0 \to \mu^+\mu^-$ in ATLAS data, but ATLAS will add the data taken in 2017 and 2018 to the analysis ($\sim 107$ fb$^{-1}$).

Both analyses will profit considerably from the increased statistics expected from the 3000 fb$^{-1}$ of HL-LHC data as well as detector improvements providing better mass and proper decay time resolutions. This will allow more stringent tests of the Standard Model.

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