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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 $b \to s\mu^+\mu^-$ and $B^0_{(s)} \to \mu^+\mu^-$ which are sensitive to New Physics effects. This contribution presents recent ATLAS results from the angular analysis of the $B^0_d \to K^{*0}\mu^+\mu^-$ decay with LHC Run 1 data, the $\mathscr{B}(B^0_{(s)} \to \mu^+\mu^-)$ measurement with 2015 and 2016 data as well as projections for the $B^0_d \to K^{*0}\mu^+\mu^-$ and $\mathscr{B}(B^0_{(s)} \to \mu^+\mu^-)$ 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 $B_d^0 \to K^{*0}\mu^+\mu^-$ decay and measuring the branching fractions of the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$. In addition, expected sensitivities for the angular analysis in the decay channel $B_d^0 \to K^{*0}\mu^+\mu^-$ and for the branching fractions of the rare decays $B_{(s)}^0 \to \mu^+\mu^-$ at the High-Luminosity LHC (HL-LHC) [3] are presented.

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

Mediated by flavour-changing neutral curents (FCNC), in the Standard Model (SM) the decay $B_d^0 \to K^{*0}\mu^+\mu^-$ 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 3.4σ 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 $P_i^{(\prime)}$ [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 $m_{K\pi} \in [846, 946]$ MeV and two muons, requiring $m_{K\pi\mu\mu} \in [5110, 5700]$ MeV. Cut-based selections on the vertex fit quality $\chi^2/\text{n.d.f.} < 2$, the B^0 lifetime significance $t/\sigma_t > 12.75$, the pointing angle $\cos\theta > 0.999$ and the $K^{\star 0}$ momentum $p_\text{T}(K^{\star 0}) > 3$ 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 $B^0 \to K^{\star 0}J/\psi$ 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 ϕ is performed in six bins of q^2, with three of the bins overlapping. The fit yields a total of 342 ± 39 signal events. A distinct background contribution from $B^0 \to D^0/D_{(s)}^+X$ decays at $\cos\theta_L \sim 0.7$ is excluded by vetoing the $D^0/D_{(s)}^+$ mass ranges. The background from fake $K^{\star 0}$ 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 $K^{\star 0}$ 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

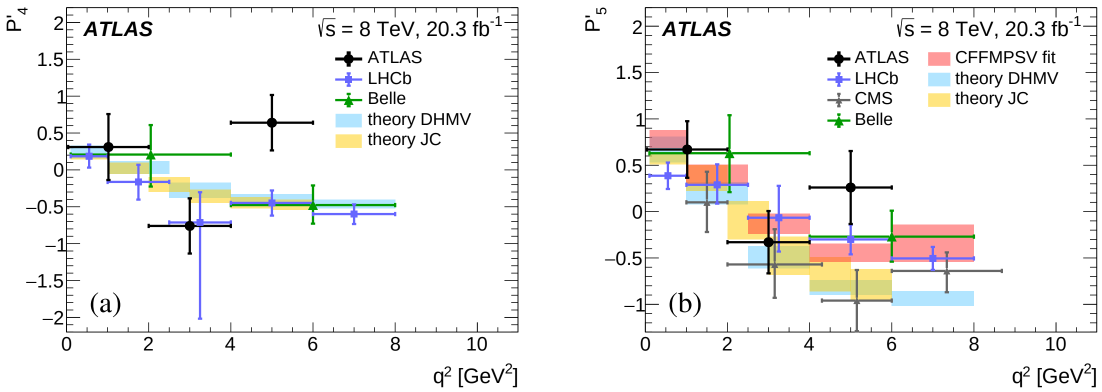

Figure 1: The measured values of P_4' (a) and P_5' (b) compared with predictions from the theoretical groups CFFMPSV [7] (only for P_5'), DHMV [8] and JC [9, 10]. Experimental results from LHCb [4], CMS [11] (only for P_5') and Belle [12] are shown as well. Figures taken from [5].

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 $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

The rare decays $B_s^0 \to \mu^+\mu^-$ 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 2σ level, and the $\mathscr{B}(B_{(s)}^0 \to \mu^+\mu^-)$ 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 $\mathscr{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ at 95% confidence level (CL), respectively, which reduces the tension in this parameter.

The updated ATLAS measurement [19] of the $B_{(s)}^0 \to \mu^+\mu^-$ 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 ($b \to \mu X \times \bar{b} \to \mu X$ 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 $B_c \to J/\psi\mu\nu$, which involve real di-muons at low $m_{\mu^+\mu^-}$, and semi-leptonic decays ($B_{(s)}/\Lambda_b^0 \to h\mu\nu$ with $h = \pi, K, p$) contribute to the signal region and are taken into account in the signal fit. A small contribution of $B \to hh'$ ($h^{(\prime)} = \pi^\pm, K^\pm$) decays, with hadrons misidentified as muons, peaks in the $B_{(s)}^0 \to \mu^+\mu^-$ signal region contributing 2.9 ± 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 $B_{(s)}^0 \to \mu^+\mu^-$ is extracted

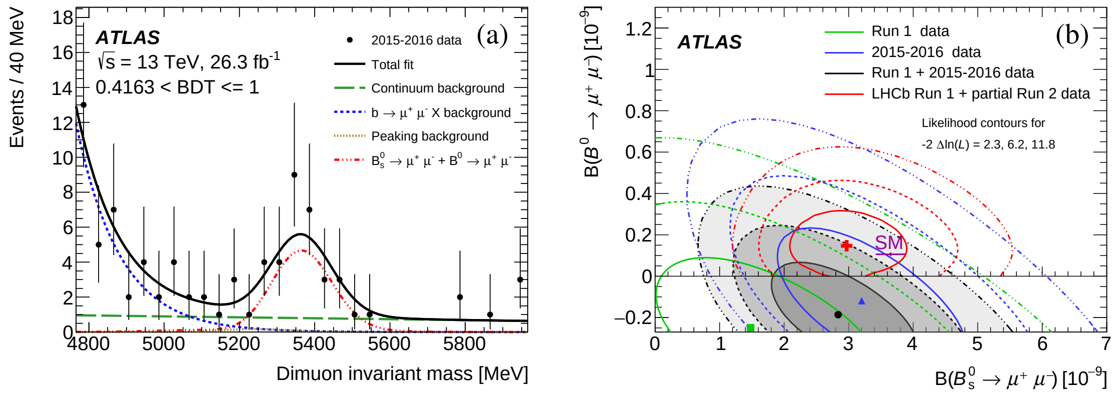

Figure 2: (a): Dimuon invariant mass distribution in the unblinded data, for the highest interval of BDT output. The result of the maximum-likelihood fit is superimposed. The total fit is shown as a continuous line, with the dashed lines corresponding to the observed signal component, the $b \to \mu^+\mu^- X$ background, and the continuum background. The signal components are grouped in one single curve, including both the $B_s^0 \to \mu^+\mu^-$ and the (negative) $B^0 \to \mu^+\mu^-$ component. The curve representing the peaking $B^0_{(s)} \to hh'$ 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 $-2\Delta\ln\mathscr{L}$ 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 $R_\varepsilon = \varepsilon_{J/\psi K^\pm}/\varepsilon_{\mu^+\mu^-}$ is 0.1176 ± 0.0009 (stat.) ± 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_ε 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 unbinned maximum likelihood fit to the $m_{\mu^+\mu^-}$ distributions in four BDT bins. The signal and $B \to hh'$ 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 ($b \to \mu^+\mu^- X$ and semi-leptonic background) whose shape parameters and normalisations are obtained from data (Figure 2 (a)).

For the Run 2 data, yields of $N_s = 80 \pm 22$ $B_s^0 \to \mu^+\mu^-$ and $N_d = -12 \pm 20$ $B^0 \to \mu^+\mu^-$ events are extracted, consistent with SM expectations of $N_s^{\rm SM} = 91$ and $N_d^{\rm SM} = 10$, respectively. Employing a Neyman construction a branching fraction of $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96}_{-0.91}\,(\text{stat.})^{+0.49}_{-0.30}\,(\text{syst.})\right) \times 10^{-9}$ and an upper limit of $\mathscr{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$ 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 σ level and results in $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 95% CL.

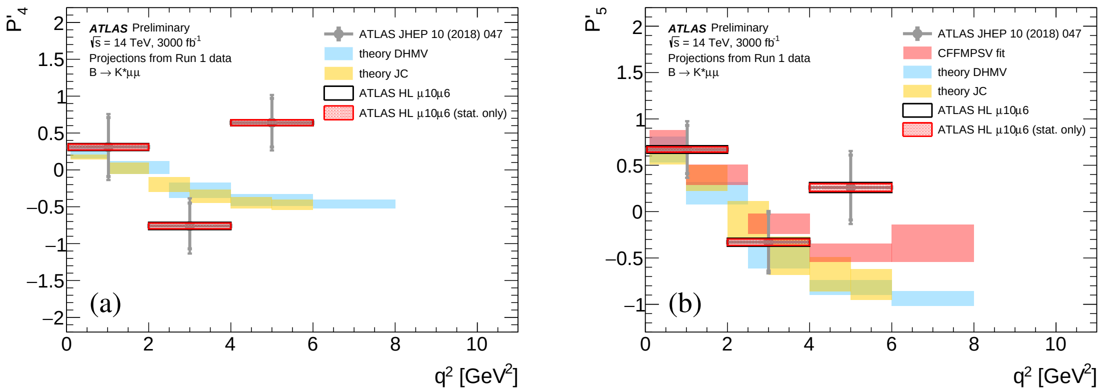

Figure 3: Projected ATLAS HL-LHC measurement precision in the P_4' (a) and P_5' (b) parameters for the intermediate $\mu10\mu6$ trigger scenario compared to the ATLAS Run 1 measurement. Alongside, theory predictions (CFFMPSV [7], DHMV [8] and JC [9, 10]) are also shown. Both the projected statistical 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].

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 $B_d^0 \to K^{*0}\mu^+\mu^-$ 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 $p_\mathrm{T} > 10$ GeV ("conservative"), one muon with $p_\mathrm{T} > 10$ GeV and another with $p_\mathrm{T} > 6$ GeV ("intermediate") as well as two muons with $p_\mathrm{T} > 6$ 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 $1/\sqrt{L_\mathrm{int}}$. 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_5' 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 $B_s^0 \to \mu^+\mu^-$ 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_s^0 and B_d^0 mass peaks increases by a factor of 1.65 (1.5) to 2.3 σ (1.3 σ) in the barrel (end-cap) region compared to Run 1 [21].

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

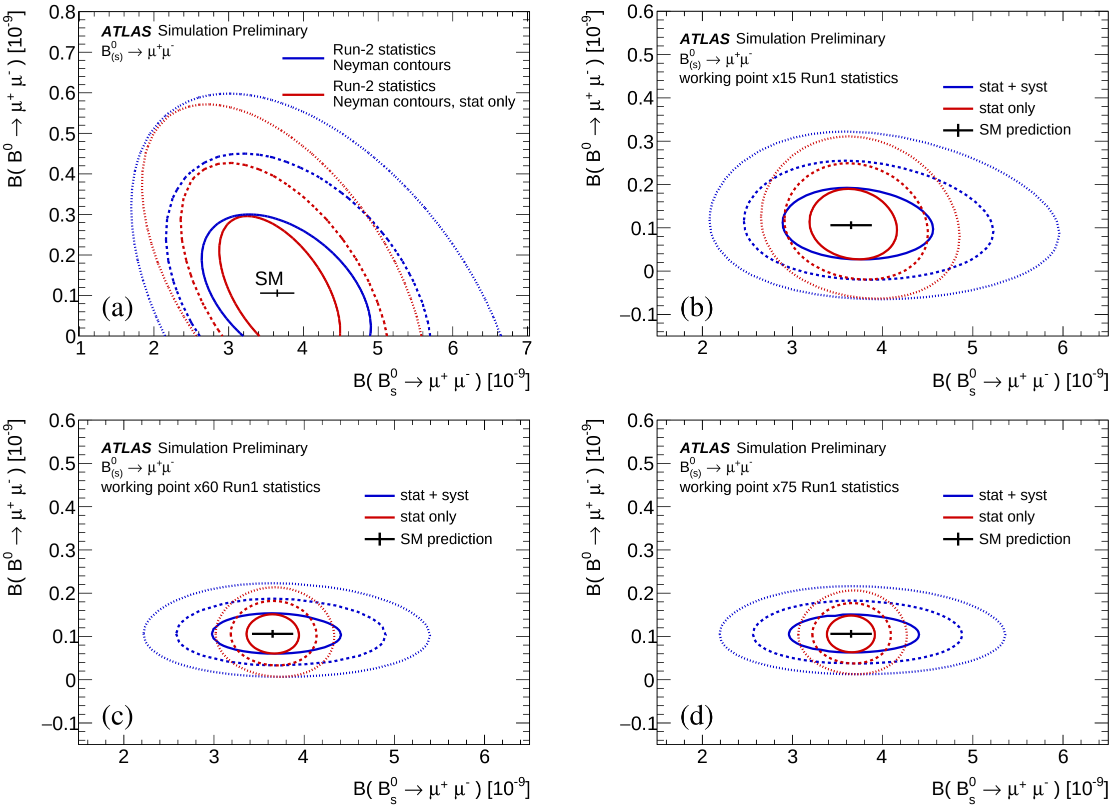

Figure 4: (a): Comparison of 68.3% (solid), 95.5% (dashed) and 99.7% (dotted) confidence level contours obtained exploiting the 2D Neyman belt construction for the full LHC Run 2 case [22]. Red contours are statistical only; blue contours include systematics uncertainties from the ATLAS Run 1 analysis [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].

ing pseudo-MC experiments is based on the likelihood of the Run 1 analysis. 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 ($p_T(\mu_{1,2}) > 6$ GeV) or ($p_T(\mu_1) > 6$ GeV, $p_T(\mu_2) > 4$ 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 $\mathscr{B}(B^\pm \to J/\psi K^\pm)$ 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 $\mathscr{B}(B^0_s \to \mu^+\mu^-)$ and $\mathscr{B}(B^0 \to \mu^+\mu^-)$ at the HL-LHC (Figure 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 $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$.

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 $B_d^0 \to K^{*0}\mu^+\mu^-$ 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 $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ and the search for the decay $\mathscr{B}(B^0 \to \mu^+\mu^-)$ 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 3 000 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.

Acknowledgments

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