Prospects for New Physics searches with $A_0^\prime \to \Lambda (1520) \ell^+ \ell^-$ decays

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Abstract

We present the prospects of an angular analysis of the $A_0^\prime \to \Lambda (1520) \ell^+ \ell^-$ decay. Using the expected yield in the current dataset collected at the LHCb experiment, as well as the foreseen ones after the LHCb upgrades, sensitivity studies are presented to determine the experimental precision on angular observables related to the lepton distribution and their potential to identify New Physics. The forward-backward lepton asymmetry at low dilepton invariant mass is particularly promising. NP scenarios favoured by the current anomalies in $b \to s \ell^+ \ell^-$ decays can be distinguished from the SM case with the data collected between the Run 3 and the Upgrade 2 of the LHCb experiment.

1 Introduction

Over the last few years, the rare $b \to s \ell^+ \ell^-$ decays have shown a growing set of deviations with respect to Standard Model (SM) expectations. On one hand, there have been deviations observed in the branching ratios for $B \to K \mu^+ \mu^-$ [1], $B \to K^* \mu^+ \mu^-$ [3], $B_s \to \phi \mu^+ \mu^-$ [4] as well as for the optimised angular observables $\tilde{G}_5, \tilde{G}_6$ in $B \to K^* \mu^+ \mu^-$ [7,11], with deviations up to 2.6 $\sigma$. These deviations have been recently confirmed by the analysis of part of the Run 2 data set by the LHCb collaboration [12]. On the other hand, no such deviations have been observed in $b \to se^+e^-$ branching.

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ratios and angular observables, as was summarised in measurements of the $R_K$ and $R_{K^*}$ ratios of branching ratios and $B \to K^* \ell^+ \ell^-$ angular observables for several values of the dilepton invariant mass, hinting at a violation of lepton flavour universality (LFU).

Flavour-changing neutral currents have been used as a powerful tool to probe quantum intermediate states much more massive than the initial and final particles. In the case of $b \to s \ell^+ \ell^-$, steady theoretical progress has been achieved to understand various SM effects and define observables with smaller sensitivity to hadronic uncertainties. Moreover, a framework for model-independent analyses in terms of the weak effective Hamiltonian (described below) has been exploited to disentangle long- and short-distance contributions to these decays. It turns out that the various deviations observed can be explained consistently and economically in terms of a few shifts in the Wilson coefficients describing short-distance physics, as could be expected from New Physics (NP) violating lepton flavour universality and coupling to muons but not (or little) to electrons (see the updated results in Ref. [17] and other works in Refs. [18–27]). The corresponding violation of LFU between muons and electrons is indeed significant, around 25% of the SM value for the semileptonic operator $O_{9 \mu}$, with several scenarios showing an equivalent ability to explain the observed deviations [28].

In order to confirm these hints of NP in $b \to s \ell^+ \ell^-$, it is interesting to exploit the growing set of data from the LHCb experiment not only to measure known observables more accurately, but also to investigate other decays probing the same physics. This is true in particular for $A_b^0$ decays which offer completely different theoretical and experimental environments. A first step in this direction has been attempted through the study of the decay $A_b^0 \to \Lambda (\to p \pi) \mu^+ \mu^-$, showing deviations from the SM in the branching ratio and some of the angular observables, but with rather large uncertainties so that these results agree both with the SM and with NP interpretations already hinted at in rare meson decays.

Another promising possibility consists in looking at decays of the $A_b^0$ baryon into excited $\Lambda$ states through the decay chain $A_b^0 \to \Lambda^*(\to pK) \ell^+ \ell^-$. Recently, the LHCb experiment has measured the ratio $R_{pK}$ comparing $\mathcal{B}(A_b^0 \to pK \mu^+ \mu^-)$ and $\mathcal{B}(A_b^0 \to pKe^+e^-)$ for a squared dilepton invariant mass, $q^2$, between 0.1 and 6 $\text{GeV}^2/\text{c}^4$ and a $pK$ invariant mass below 2.6 $\text{GeV}/\text{c}^2$. The result is compatible with SM expectations, but it suggests a suppression of $\mathcal{B}(A_b^0 \to pK \mu^+ \mu^-)$ compared to $\mathcal{B}(A_b^0 \to pKe^+e^-)$.

However, the interpretation of this result would require a precise theoretical knowledge of the various excited $\Lambda$ states contributing in this large $pK$ region. A deeper understanding could be achieved by focusing on a single of these resonances as an intermediate state. The most interesting one seems to be the $\Lambda(1520)$ baryon, which is narrow and features prominently in previous related studies, for instance in pentaquark searches using $A_b^0 \to pKJ/\psi$. It appears thus interesting
to study both the branching ratio and the angular geometry of the decay \( \Lambda^0_b \to \Lambda(1520)\ell^+\ell^- \). A first theoretical study was proposed in Ref. [43] (confirmed in Ref. [44]), and we want to investigate here the prospects of studying this decay with the LHCb experiment in the near future. The definition of the LHCb run periods and upgrades, as well as the size of the collected and expected datasets can be found in Ref. [45].

2 Theoretical framework

It is possible to analyse \( b \to s\ell^+\ell^- \) decays using a model-independent approach, namely the effective Hamiltonian, so that heavy/energetic degrees of freedom have been integrated out in short-distance Wilson coefficients \( C_i \), leaving only operators \( O_i \) describing long-distance physics

\[
\mathcal{H}_{\text{eff}}(b \to s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i + h.c.,
\]

(up to small corrections proportional to \( V_{ub} V_{us}^* \) in the SM). The factorisation scale for the Wilson coefficients is taken as \( \mu_b = 4.8 \text{ GeV} \). The main operators are

\[
\begin{align*}
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \\
\mathcal{O}_9^{\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \\
\mathcal{O}_{10}^{\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),
\end{align*}
\]

where \( P_{L,R} = (1 + \gamma_5)/2 \) and \( m_b \equiv m_b(\mu_b) \) denotes the running \( b \) quark mass in the \( \overline{\text{MS}} \) scheme. In the SM, three operators play a leading role in the discussion: the electromagnetic operator \( \mathcal{O}_7 \) and the semileptonic operators \( \mathcal{O}_9^{\ell} \) and \( \mathcal{O}_{10}^{\ell} \) that differ through the chirality of the emitted charged leptons. NP contributions could either modify the value of the short-distance Wilson coefficients \( C_{7,9,10} \), or make other operators contribute in a significant manner, such as the chirality-flipped operators \( \mathcal{O}_{7',9',10'} \) defined above, or other operators (scalar, pseudoscalar, tensor).

Using this separation, one can express the decay amplitude for \( \Lambda^0_b \to \Lambda(1520)\ell^+\ell^- \) in terms of Wilson coefficients and hadronic matrix elements of operators. Most of them can be expressed in terms of form factors to be computed using quark models, light-cone sum rules or lattice QCD computations. Some remaining contributions correspond to long-distance charmonium contributions which have still to be investigated for this particular decay (see below).
In Ref. [43], the resulting angular distribution was computed:

\[
\frac{8\pi}{3} \frac{d^4\Gamma}{dq^2 d\cos \theta_t d\cos \theta_p d\phi} = \cos^2 \theta_p \left( L_{1c} \cos \theta_t + L_{1cc} \cos^2 \theta_t + L_{1ss} \sin^2 \theta_t \right) \\
+ \sin^2 \theta_p \left( L_{2c} \cos \theta_t + L_{2cc} \cos^2 \theta_t + L_{2ss} \sin^2 \theta_t \right) \\
+ \sin^2 \theta_p \left( L_{3ss} \sin^2 \theta_t \cos^2 \phi + L_{4ss} \sin^2 \theta_t \sin \phi \cos \phi \right) \\
+ \sin \theta_p \cos \theta_p \cos \phi \left( L_{5s} \sin \theta_t + L_{5sc} \sin \theta_t \cos \theta_t \right) \\
+ \sin \theta_p \cos \theta_p \sin \phi \left( L_{6s} \sin \theta_t + L_{6sc} \sin \theta_t \cos \theta_t \right), \tag{3}
\]

where \( \theta_p, \theta_t, \phi \) describe the kinematics of the decay in agreement with the kinematics of Refs. [35, 37, 38] (up to the identifications \( \theta_p = \theta_A^* = \theta_b \) and \( \phi = \chi \)). Each angular coefficient corresponds to a sum of interferences between pairs of helicity amplitudes (they are not linearly independent: \( L_{2ss} = L_{1ss}/4 + L_{2cc}/2 - L_{1cc}/8 - L_{3ss}/2 \)). Each helicity amplitude (12 in total) is defined in terms of the helicities of the hadrons involved and expressed in terms of Wilson coefficients and form factors (14 in total). The expressions including the lepton mass can be found in Ref. [44].

One can define derived observables using a particular weight \( \omega \) to integrate the differential decay rate over the whole phase space

\[
X[\omega](q^2) \equiv \int \frac{d^4\Gamma}{dq^2 d\cos \theta_t d\cos \theta_p d\phi} \omega(q^2, \theta_t, \theta_p, \phi) d\cos \theta_t d\cos \theta_p d\phi. \tag{4}
\]

The differential decay width is

\[
\frac{d\Gamma}{dq^2} = X[1] = \frac{1}{3}[L_{1cc} + 2L_{1ss} + 2L_{2cc} + 4L_{2ss} + 2L_{3ss}], \tag{5}
\]

which we can use to normalise the CP-averaged angular observables and the corresponding CP-asymmetries

\[
S_i = \frac{L_i + \bar{L}_i}{d(\Gamma + \bar{\Gamma})/dq^2}, \quad A_i = \frac{L_i - \bar{L}_i}{d(\Gamma + \bar{\Gamma})/dq^2}. \tag{6}
\]

One can also define various derived quantities from these angular observables, in particular the forward-backward asymmetry with respect to the leptonic scattering angle normalised to the differential rate

\[
A_{FB}^\ell = X \left[ \frac{\text{sgn}[\cos \theta_t]}{d\Gamma/dq^2} \right] = \frac{3(L_{1c} + 2L_{2c})}{2(L_{1cc} + 2(L_{1ss} + L_{2cc} + 2L_{2ss} + L_{3ss})}. \tag{7}
\]

The CP-averaged version of this asymmetry is defined by taking the ratio of the CP averages of the numerator and the denominator in Eq. (7).

In Ref. [43], the sensitivity of these angular observables on hadronic uncertainties and on NP contributions was investigated. Several of them
were shown to exhibit sensitivity with respect to NP contributions currently favoured by global fits to the $b \to s\ell^+\ell^-$ data, even though the hadronic uncertainties were certainly overestimated due to a limited knowledge of the form factors. The estimates provided in Ref. [43] were based on a quark model [46], waiting for more accurate estimates to be provided by lattice QCD computations (interestingly, the recent results in Refs. [47, 48] show a good agreement with this quark model), and assuming that long-distance charmonium contributions were small in the regions of interest.

Since we want to discuss the potential of experimental measurements, we consider a more complete approach to determine theoretical uncertainties. On one hand, we keep the same form factors as in Ref. [43] with various assumptions on the uncertainties based on the foreseen improvement of theoretical computations. On the other hand, we include an estimate for the charmonium contribution inspired by estimates for $B^0 \to K^{*0}\ell^+\ell^-$ and $B^0 \to K\ell^+\ell^-$ [49–51] at large recoil. Their results suggest a contribution of order 10% of $C_9$ with a moderate dependence on $q^2$ in the large-recoil region of interest (further discussion on this topic can be found in Refs. [17,19–21,24,52–69]).

Inspired by these results, we include an estimate of the charmonium contribution to our decay as an additional contribution to the SM value of $C_{9\ell}$

$$C_{9\ell}^{\text{SM}} = C_{9\ell}^{\text{Hqet}} (1 + \rho e^{i\phi}), \quad \rho \in [0, 0.1], \quad \phi \in [0, 2\pi], \quad (8)$$

where $C_{9\ell}^{\text{Hqet}}$ corresponds to the Wilson coefficient appearing in Eq. (1). Admittedly, this procedure is a very rough attempt at obtaining an estimate for this effect, as it includes no dependence on $q^2$ nor on the spins of the baryons and its size is only guesstimated. This estimate for this baryon decay lacks thus the theoretical grounds of the dedicated calculations and sophisticated phenomenological studies for the equivalent meson decays. An extension to the $\Lambda_b^0 \to \Lambda^* (\to pK)\ell^+\ell^-$ decay would be highly commendable and it will be needed in the future once measurements are available and to be interpreted within an effective theory approach, but it is clearly out of the scope of the present study limited to the potential of observing this decay at the LHCb experiment and of triggering further theoretical studies.

The large number of (poorly known) form factors could be tackled by taking the heavy-quark limit $m_b \to \infty$ either at low or large recoil of the $\Lambda$ baryon (high $q^2$ or low $q^2$), leading to two distinct effective field theories called Heavy Quark Effective Theory and Soft-Collinear Effective Theory respectively.

In both limits, some form factors (denoted collectively as $f_{qX}^N$ in Ref. [43]) vanish, which means that they are expected to be small in general. Neglecting these form factors means that the amplitudes denoted as $B$ in Ref. [43] and corresponding to transitions to a $\Lambda^*$ with helicity 3/2 vanish. Indeed the heavy-quark limit allows one to consider the angular momentum of the
heavy-quark $b$ and that of the light quarks as good quantum numbers to describe the $\Lambda_0^b$ state and its transitions. Since the light quarks are in a spin-0 diquark state and the heavy quark carries a spin 1/2, the $b \rightarrow s\ell^+\ell^-$ transition can never yield a $\Lambda$ with a helicity 3/2 in this limit \cite{[70],[71]}. This assumption simplifies quite a lot the angular distribution

$$\frac{8\pi}{3} \frac{d^4\Gamma}{dq^2 d\cos \theta_\ell d\cos \theta_\mu d\phi} \simeq \frac{1}{4} (1 + 3 \cos^2 \theta_\mu) \left( L_{1c} \cos \theta_\ell + L_{1cc} \cos^2 \theta_\ell + L_{1ss} \sin^2 \theta_\ell \right),$$

where all three angular observables are independent. The forward-backward asymmetry becomes:

$$A_{FB}^\ell \simeq \frac{3L_{1c}}{2(L_{1cc} + 2L_{1ss})}. \tag{10}$$

In this limit, we notice that the angular distribution Eq. (9) factorises into the product of two terms, i.e. a trivial dependence on the angle describing the hadronic final state and a nontrivial dependence on the angle describing the leptonic final state.

Interestingly, the branching ratio for $\Lambda_b^0 \rightarrow \Lambda(1520)\ell^+\ell^-$ for $\ell = \mu$ was shown to decrease for the NP scenarios favoured to explain the deviations observed in the meson sector. This agrees perfectly with the trend shown by the recent LHCb measurement of $R_{pK}$ for $m_{pK} < 2.6$ GeV/$c$ and $0.1 < q^2 < 6$ GeV/$c^2$ \cite{41}. Indeed this measurement involves several intermediate $\Lambda$ resonances, but with a prominent contribution of the $\Lambda(1520)$ baryon. If one assumes that this measurement is indeed dominated by the contribution of $\Lambda(1520)$ and one neglects long-distance $c\bar{c}$ contributions at large $\Lambda$ recoil, we can get the measured central value of 0.85 as the central value of the predictions from Ref. \cite{43} for the following three NP points: $C_{9\mu}^{NP} = -0.76$, or $C_{10\mu}^{NP} = -0.29$, or $C_{9\mu}^{NP} = -C_{9\ell}^{NP} = -0.99$ (in each scenario, all the other Wilson Coefficients are purely SM). These points are in remarkable agreement with the results of global fits to $b \rightarrow s\ell^+\ell^-$ and $b \rightarrow s\gamma$ transitions in $B$ meson decays \cite{17}. This exercise is obviously purely illustrative and its significance should not be overstated, but it shows the interest of identifying the fraction due to the $\Lambda(1520)$ excited state in $R_{pK}$, and to measure the angular distribution of the decay $\Lambda_b^0 \rightarrow pK\ell^+\ell^-$ through this specific baryon intermediate state.

## 3 Sensitivity studies

The $\Lambda_b^0 \rightarrow \Lambda(1520)\ell^+\ell^-$ decay width and angular coefficients can be conveniently accessed experimentally in bins or regions of squared dilepton invariant mass, $q^2$, as discussed in the introduction of this paper. Due to the available phase space in this decay, and avoiding the region dominated by the
observables are considered. We choose the CP-averaged forward-backward asymmetry of the angular distribution presented in Eq. (9) and only CP-averaged for this mode, sensitivity studies are performed using the simplified expression of the angular observables to the effect of NP, the predictions of a scenario with a NP contribution $C_9$ supported by the current global fits to $b\bar{b}$ decays by LHCb and assuming form factor uncertainties of 5%. In both cases an uncertainty of 10% is included on $C_9$ using the conservative uncertainties of Ref. [43], the theoretical precision obtained assuming a 5% uncertainty on the form factors due to foreseeable improvements in lattice QCD studies [48] is also given. To illustrate the sensitivity of these observables to the effect of NP, the predictions of a scenario with a NP contribution $C_{9NP}$ = −1.11 are also computed. Such a scenario is supported by the current global fits to $b \to s \ell^+\ell^−$ data [17].

In the recent test of LFU in $Λ_b^0 \to pK\mu^+\mu^−$ decays by LHCb [41], around 400 $Λ_b^0 \to pK\mu^+\mu^−$ and 100 $Λ_b^0 \to pKe^+e^−$ signal events were observed in the $q^2$ region [0.1, 6] GeV$^2$/c$^4$ and $m(pK) < 2600$ MeV/c$^2$, in a dataset corresponding to 3 fb$^{-1}$ recorded at 7 and 8 TeV and 1.7 fb$^{-1}$ recorded at

| Observable | [0.1, 3] | [3, 6] | [6, 8.68] | [1, 6] |
|------------|---------|--------|---------|-------|
| $d^2\Gamma/dq^2/\Gamma_{Λ_b^0}$ [10$^{-9}$] | | | |
| SM | 0.397 ± 0.054 | 1.29 ± 0.18 | 3.22 ± 0.42 | 0.95 ± 0.13 |
| SM - 5% | 0.397 ± 0.032 | 1.29 ± 0.11 | 3.22 ± 0.28 | 0.95 ± 0.08 |
| NP | 0.337 ± 0.042 | 1.04 ± 0.13 | 2.58 ± 0.32 | 0.77 ± 0.10 |
| NP - 5% | 0.337 ± 0.023 | 1.04 ± 0.08 | 2.58 ± 0.20 | 0.77 ± 0.06 |
| $A_{FB}$ | | | |
| SM | 0.048 ± 0.018 | -0.127 ± 0.033 | -0.235 ± 0.040 | -0.098 ± 0.031 |
| SM - 5% | 0.048 ± 0.013 | -0.127 ± 0.020 | 0.235 ± 0.022 | 0.098 ± 0.019 |
| NP | 0.098 ± 0.022 | -0.059 ± 0.034 | -0.166 ± 0.041 | 0.031 ± 0.032 |
| NP - 5% | 0.098 ± 0.016 | -0.059 ± 0.026 | -0.166 ± 0.030 | -0.031 ± 0.025 |
| $S_{1ic}$ | | | |
| SM | 0.218 ± 0.031 | 0.242 ± 0.042 | 0.361 ± 0.051 | 0.221 ± 0.038 |
| SM - 5% | 0.218 ± 0.019 | 0.242 ± 0.021 | 0.361 ± 0.026 | 0.221 ± 0.020 |
| NP | 0.24 ± 0.038 | 0.263 ± 0.042 | 0.371 ± 0.050 | 0.246 ± 0.039 |
| NP - 5% | 0.24 ± 0.024 | 0.263 ± 0.022 | 0.371 ± 0.026 | 0.246 ± 0.021 |

Table 1: Theory predictions for $A_{FB}^\ell$ and $S_{1ic}$ in the SM and in a NP model with $C_{9NP}$ = −1.11. The precision of the theory predictions is given both using the conservative uncertainties of Ref. [43] and assuming form factor uncertainties of 5%. In both cases an uncertainty of 10% is included on $C_9$ to account for $c\bar{c}$ contributions.

The precision of the theory predictions is given both using the conservative uncertainties of Ref. [43] and assuming form factor uncertainties of 5%.
Table 2: Completed and planned LHC runs, corresponding start and end dates, center-of-mass $pp$ collision energy and accumulated integrated luminosity expected to be recorded at LHCb.

| Run period | Run 1 – 2 | Run 3 | Run 4 | Run 5 |
|------------|-----------|-------|-------|-------|
| Start date | 2010      | 2022  | 2027  | 2032  |
| End date   | 2018      | 2024  | 2030  | 2035  |
| Energy     | 7, 8, 13 TeV | 13–14 TeV | 14 TeV | 14 TeV |
| Luminosity | $9 \text{ fb}^{-1}$ | $23 \text{ fb}^{-1}$ | $50 \text{ fb}^{-1}$ | $300 \text{ fb}^{-1}$ |

Table 3: Extrapolated $\Lambda^0_b \to \Lambda(1520)\mu^+\mu^-$ signal yields in each $q^2$ bin for the accumulated luminosity expected at LHCb at the end of Run 2, Run 3, Run 4 and High-Lumi LHC.

| $q^2$ bin [GeV$^2$/c$^4$] | Dataset [fb$^{-1}$] | 9 | 23 | 50 | 300 |
|---------------------------|--------------------|---|----|----|-----|
| [0.1, 3]                  | 50                 | 140 | 300 | 1750 |
| [3.6]                     | 150                | 400 | 900 | 5250 |
| [6, 8,68]                 | 400                | 1100 | 2400 | 14000 |
| [1,6]                     | 190                | 510 | 1140 | 6650 |

13 TeV. The main difference between the muon and electron modes arises from the trigger and selection efficiencies in the experimental study. In the following, we focus on the muon mode due to the larger experimental yields but the results can be directly extrapolated to the electron case by scaling the yields accordingly. LHCb also published the background subtracted invariant mass of the hadronic system for $\Lambda^0_b \to pK\mu^+\mu^-$ candidates (available in the supplementary material of Ref. [41]), from where we estimate that roughly around 90 events correspond to the $\Lambda^0_b \to \Lambda(1520)\mu^+\mu^-$ decay. The LHCb experiment has already recorded a total of 6 fb$^{-1}$ at 13 TeV and will accumulate a total of 23 and 50 fb$^{-1}$ after Run 3 and Run 4 of the LHC, respectively. Moreover, it has been proposed to install an upgraded detector to take data during the High-Luminosity phase of the LHC to collect 300 fb$^{-1}$ [45]. A summary of the completed and planned LHCb running periods is provided in Table 2. Table 3 collects the estimated yields of $\Lambda^0_b \to \Lambda(1520)\mu^+\mu^-$ decays in the different $q^2$ bins and running periods, extrapolated from the published LHCb data and the SM prediction for the $q^2$ distribution. These numbers are used to estimate the sensitivity to NP of an angular analysis of this decay mode. For the electron case, fewer events are expected [41], although the trigger-less readout foreseen for LHCb from Run 3 onwards should allow a higher experimental efficiency for this mode.

The angular distributions of the $\Lambda^0_b \to \Lambda(1520)\mu^+\mu^-$ decay are distorted by the geometrical acceptance of the detector, the trigger and the selection
The shapes of the acceptance have been estimated using a stand-alone fast simulation software called RapidSim by applying the LHCb geometrical acceptance and transverse momentum ($p_T$) requirements, as needed for the track reconstruction and background rejection, on the final-state particles. These are known to be the dominant effects in shaping the acceptance distributions. In particular, the $p_T$ of the muons is required to be larger than 400 MeV. Using the simplified angular distribution of Eq. (3) there is no need to model the angular acceptances of the $\phi$ and $\cos \theta_p$ variables since they only appear as a common scale factor in the probability density function (PDF).

The $\cos \theta_\ell$ acceptance curve is expected to be symmetric due to the symmetry between the two leptons in the decay with a loss of events for large $|\cos \theta_\ell|$ values due to the muon $p_T$ requirement. This last characteristic is mainly visible in the low-$q^2$ region as shown in Appendix A.

The sensitivity of the differential measurement of the $\Lambda^0_b \to \Lambda(1520)\mu^+\mu^-$ decay width and angular observables to NP effects is studied comparing the theoretical predictions for these observables in the SM and the NP scenario to the expected experimental precision. The experimental sensitivity to the decay width is directly extracted from the expected signal yield in each bin given in Table 3, assuming poissonian uncertainties on the yields and neglecting the effect of potential backgrounds, which are observed to be very small in this decay mode [41]. One of the main experimental challenges in the selection of $\Lambda^0_b \to \Lambda(1520)\ell^+\ell^-$ decays is the contamination from other $\Lambda^*$ resonances that overlap in the $pK$ spectrum with the $\Lambda(1520)$ state. In the amplitude analysis of the related $\Lambda^0_b \to pK J/\psi$ mode [42] three other resonances were observed to contribute to the $pK$ mass region around the $\Lambda(1520)$ state, namely $\Lambda(1405)$, $\Lambda(1600)$ and $\Lambda(1800)$. However, all these resonances have spin $1/2$, in contrast to the $3/2$ spin of $\Lambda(1520)$, which gives place to a different angular distribution that should allow to disentangle them, following a similar strategy to the one used in the angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ to account for the $S$-wave contribution [12].

The experimental sensitivity to the angular observables is studied with pseudoexperiments. Events are generated according to a PDF that is the product of Eq. (9) and the experimental acceptance described above. Distributions of the $\cos \theta_\ell$ variable are generated using both the SM and NP predictions for the angular parameters and are fitted back with the same PDF, letting the $A_{FB}$ and $S_{1cc}$ parameters float. A large number of experiments is generated for all the $q^2$ bins and expected signal yields in the different data-taking periods of LHC. The resulting distributions for the parameters, their uncertainties and pull distributions are examined. Small biases on the central values of the parameters in the low and central $q^2$ bins are observed in the low-statistics scenarios corresponding to the datasets expected in Run 2 and 3 of LHCb. The effect is larger on $S_{1cc}$ and in the SM case but it is always below 20% of the statistical uncertainty and can be
added as a systematic to the measurement. The fit uncertainty is checked to provide good coverage in all the cases so it is taken as the experimental sensitivity to the angular observables.

The sensitivity for different accumulated statistics is compared to the theoretical predictions in Figs. 1, 2 and 3 for the \( d\Gamma/dq^2/\Gamma_{\Lambda_b} \), \( A_{FB} \) and \( S_{1cc} \) observables, respectively, for the three narrow \( q^2 \) bins. The values for all the bins are also reported in Table 4, where one can observe the experimental improvement in the broader \([0, 1, 6] \text{ GeV}^2/c^4\) bin. With the conservative theoretical uncertainties used in Ref. [43] the decay width provides little sensitivity to separate the SM from the NP scenario studied. However, with improved uncertainties on the form factors at the level of 5%, one can disentangle with precision the two scenarios in the \( q^2 \) bins \([1, 6] \) and \([6, 8.68] \text{ GeV}^2/c^4\). For a better visualisation, the relative values with respect to the SM prediction in each bin are shown in the bottom plots of Fig. 1 for all the \( q^2 \) bins considered. In this case, the bin number, which follows the order presented in Tables 1, 3 and 4 is used in the x-axis. For the angular observables, while \( S_{1cc} \) exhibits a poor sensitivity to NP, \( A_{FB} \) is more promising. In the conservative scenario for theory uncertainties, one could statistically separate the SM and the studied NP model with the data sample collected by LHCb after Upgrade 2. If the theory uncertainties on the form factors can be reduced down to 5%, a good separation is already achieved after Run 3 in the \( q^2 \) bins \([1, 6] \) and \([6, 8.68] \text{ GeV}^2/c^4\).

| Observable | 9 fb\(^{-1}\) | 23 fb\(^{-1}\) | 50 fb\(^{-1}\) | 300 fb\(^{-1}\) |
|------------|-------------|-------------|-------------|-------------|
| \( d\Gamma/dq^2/\Gamma_{\Lambda_b}[10^{-9}] \) | | | | |
| \([0, 1, 3]\) | 0.060 | 0.036 | 0.024 | 0.010 |
| \([3, 6]\) | 0.106 | 0.064 | 0.043 | 0.018 |
| \([6, 8.68]\) | 0.176 | 0.107 | 0.072 | 0.030 |
| \([1, 6]\) | 0.070 | 0.042 | 0.029 | 0.012 |
| \( A_{FB} \) | | | | |
| \([0, 1, 3]\) | 0.140 | 0.079 | 0.053 | 0.022 |
| \([3, 6]\) | 0.061 | 0.037 | 0.025 | 0.010 |
| \([6, 8.68]\) | 0.036 | 0.022 | 0.015 | 0.006 |
| \([1, 6]\) | 0.058 | 0.035 | 0.023 | 0.010 |
| \( S_{1cc} \) | | | | |
| \([0, 1, 3]\) | 0.241 | 0.148 | 0.099 | 0.041 |
| \([3, 6]\) | 0.104 | 0.062 | 0.041 | 0.017 |
| \([6, 8.68]\) | 0.061 | 0.036 | 0.024 | 0.010 |
| \([1, 6]\) | 0.100 | 0.060 | 0.040 | 0.017 |

Table 4: Estimated experimental uncertainties for the differential decay width, \( d\Gamma/dq^2/\Gamma_{\Lambda_b} \) (top), \( A_{FB} \) (middle) and \( S_{1cc} \) (bottom) for different data-taking scenarios in the considered \( q^2 \) bins in GeV\(^2/c^4\).
Figure 1: Theory predictions for $d\Gamma/dq^2$ in the considered $q^2$ bins in the SM (blue area) and the NP scenario with $C_{9\mu}^{NP} = -1.11$ (red area) from Ref. [43], using the nominal theory uncertainties (left) and improved ones with 5% uncertainties on the form factors (right). In both cases an uncertainty of 10% is included on $C_9$ to account for $c\bar{c}$ contributions. The expected LHCb sensitivity with the full Run 2, Run 3, Run 4 and Upgrade 2 samples is shown by grey-scale markers in increasing sensitivity. The bottom plots show the relative values with respect to the SM prediction in each bin ($\mu$) for all the $q^2$ bins considered (see text for details).
Figure 2: Theory predictions for $A_{FB}^\ell$ in the considered $q^2$ bins in the SM (blue area) and the NP scenario with $C_{9}\mu = -1.11$ (red area) from Ref. [43], using the nominal theory uncertainties (left) and improved ones with 5% uncertainties on the form factors (right). In both cases an uncertainty of 10% is included on $C_9$ to account for $c\bar{c}$ contributions. The expected LHCb sensitivity with the full Run 2, Run 3, Run 4 and Upgrade 2 samples is shown by the grey-scale markers in increasing sensitivity.

Potential biases arising from the usage of the simplified angular PDF in Eq. (9) are checked by generating a large number of pseudoexperiments with the full PDF, Eq. (3), and fitting the observables of interest, $A_{FB}^\ell$ and $S_{1cc}$, with the simplified PDF. At small signal yields no effect can be observed, while a small bias is found, which is less than 10% of the statistical uncertainty, with the events expected during Upgrade 2 of LHCb. This study confirms that Eq. (9) is a safe approximation to apply at least until 300 fb$^{-1}$ have been recorded by LHCb.

4 Conclusion

The persistent deviations in $b \to s \mu^+ \mu^-$ decays and the hints of violation of lepton-flavour universality between electrons and muons in these modes provide a strong incentive to look for confirmations using other modes with different theoretical and experimental uncertainties. In this article, we presented the prospects of angular analyses of $\Lambda^0_b \to \Lambda(1520)\ell^+\ell^-$ decays, motivated in particular by recent results on lepton-flavour universality in $\Lambda^0_b \to p K^+\ell^+\ell^-$ at LHCb.

We first recalled the theoretical framework needed to analyse the $\Lambda^0_b \to \Lambda(1520)\ell^+\ell^-$ transition, separating short and long-distance contributions. The involvement of spin-1/2 and spin-3/2 states yields a fairly complicated differential decay rate in terms of 12 angular observables with many hadronic inputs involved, but the heavy-quark limit provides significant simplifications that are supported by the theoretical estimates currently available for
The angular distribution then factorises into the product of two terms, i.e. a trivial dependence on the angle describing the hadronic final state and a nontrivial dependence on the angle describing the leptonic final state. The three observables can be reexpressed as the branching ratio, the lepton forward-backward asymmetry and a third angular observable $S_{1cc}$. The first two observables present some sensitivity to NP contributions to the short-distance Wilson coefficient $C_9$ for $b \to s \mu^+ \mu^-$ transitions.

Using the expected yield from the data to be collected at the LHCb experiment in a near future, sensitivity studies were presented to determine the experimental precision on angular observables related to the lepton distribution and their potential to identify New Physics. We studied the impact of acceptance effects on the extraction of these angular observables using published LHCb data together with the fast simulation software RapidSim.

The lepton forward-backward asymmetry $A_{FB}^\ell$ seems particularly promising: depending on the progress made in reducing the uncertainties on the theory predictions, at some point between Run 3 and Upgrade 2, one could use this observable at low dilepton invariant mass to distinguish between the SM and a scenario with NP contributions to $C_9$ supported by the current $b \to s \ell^+ \ell^-$ data. We checked that our conclusions were not biased by the significant simplifications of the angular distribution that we proposed based on the heavy-quark limit and supported by phenomenological estimates.

We hope that our study will motivate further theoretical and experimental studies of the $A_b^0 \to A(1520)\ell^+\ell^-$ transitions, which could then constitute a new stepping stone to definite conclusions on the presence of New Physics.

Figure 3: Theory predictions for $S_{1cc}$ in the considered $q^2$ bins in the SM (blue area) and the NP scenario with $C_9^{NP} = -1.11$ (red area) from Ref. [43], using the nominal theory uncertainties (left) and improved ones with 5% uncertainties on the form factors (right). In both cases an uncertainty of 10% is included on $C_9$ to account for $c\bar{c}$ contributions. The expected LHCb sensitivity with the full Run 2, Run 3, Run 4 and Upgrade 2 samples is shown by the grey-scale markers in increasing sensitivity.
in $b \rightarrow s\ell^+\ell^-$ transitions.

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A Angular acceptance

The $\mu^+$ and $\mu^-$ efficiencies, introduced by the selection requirements discussed in Section 3 being the same, give the acceptance shown in Figure 4 that can be modelled by an even function of Legendre polynomials:

$$
\epsilon(\cos \theta_\ell) = 1 + c_2/2(3 \cos^2 \theta_\ell - 1) + c_4/8(35 \cos^4 \theta_\ell - 30 \cos^2 \theta_\ell + 3) + c_6/16(231 \cos^6 \theta_\ell - 315 \cos^4 \theta_\ell + 105 \cos^2 \theta_\ell - 5).
$$

The parameters $c_i$ are fitted in simulation and used throughout the sensitivity studies.

Figure 4: Acceptance shapes for $\cos \theta_\ell$ for $q^2$ in $[0,1,3], [3,6], [6,8.68]$, and $[1,6]$ GeV$^2$/c$^4$ respectively.
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