Bayesian analysis of $b \to s\mu^+\mu^-$ Wilson coefficients using the full angular distribution of $\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-$ decays

Thomas Blake

Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

Stefan Meinel

Department of Physics, University of Arizona, Tucson, Arizona 85721, USA

Danny van Dyk

Physik Department, Technische Universität München, James-Franck-Straße 1, 85748 Garching b. München, Germany

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Following updated and extended measurements of the full angular distribution of the decay $\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-$ by the LHCb collaborations, as well as a new measurement of the $\Lambda \to p\pi^- \mu^+\mu^-$ decay asymmetry parameter by the BESIII collaboration, we study the impact of these results on searches for nonstandard effects in exclusive $b \to s\mu^+\mu^-$ decays. To this end, we constrain the Wilson coefficients $C_9$ and $C_{10}$ of the numerically leading dimension-six operators in the weak effective Hamiltonian, in addition to the relevant nuisance parameters. In stark contrast to previous analyses of this decay mode, the changes in the updated experimental results lead us to find very good compatibility with both the Standard Model and with the $b \to s\mu^+\mu^-$ anomalies observed in rare $B$-meson decays. We provide a detailed analysis of the impact of the partial angular distribution, the full angular distribution, and the $\Lambda_b \to \Lambda\mu^+\mu^-$ branching fraction on the Wilson coefficients. In this process, we are also able to constrain the size of the production polarization of the $\Lambda_b$ baryon at LHCb.

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I. INTRODUCTION

The persistent anomalies in the rare flavor-changing decays of $B$ mesons, which arise in analyses of branching fractions, angular distributions and lepton flavor universality tests, have sparked considerable interest in constructing candidate theories to replace the Standard Model (SM) of particle physics; see for example Ref. [1] for a comprehensive guide. If these anomalies are indeed a hint of physics beyond the SM (BSM), then we should see similar deviations in the baryonic partners of these rare $B$ meson decays, e.g., in $\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-.$

The decay mode $\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-$ is quite appealing from a theoretical point of view. Like the $B \to K^*(\to K\pi)\mu^+\mu^-$ decay, it provides a large number of angular observables and is sensitive to all Dirac structures in the effective weak Hamiltonian [2–5]. At the same time, because the $\Lambda$ baryon is stable under the strong interactions, lattice QCD calculations of the $\Lambda_b \to \Lambda$ form factors [6] do not require a complicated finite-volume treatment of multihadron states, as would be necessary for a rigorous calculation of $B \to K^*(\to K\pi)$ form factors [7].

A previous analysis of the constraints of $\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-$ on the $b \to s\mu^+\mu^-$ Wilson coefficients [13] using—by now—outdated experimental inputs found a central value of $C_9$ shifted in the opposite direction from the SM point compared to the $B$-meson findings. In this paper we confront this previous analysis with new, updated, and reinterpreted experimental results, and constrain BSM effects in $b \to s\mu^+\mu^-$ operators.

II. FRAMEWORK

We use the standard weak effective field theory that describes flavor-changing neutral $b \to s\{\mu^+\mu^-, \gamma, q\bar{q}\}$

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1The lattice determination of the $B \to K^*$ form factors in Ref. [8] and light-cone sum rule (LCSR) estimates in Refs. [9–11] treat the $K^*$ as if it is stable, leading to systematic uncertainties that are difficult to quantify; see Ref. [12] for a first study of the finite width effects in LCSRs.
TABLE I. Prior distributions of selected nuisance parameters: the Cabibbo-Kobayashi-Maskawa (CKM) parameters, the decay constant of the $B_s$, $f_{B_s}$, and the $\Lambda \rightarrow p\pi^-$ parity-violating decay parameter, $\alpha$. For the CKM parameters, we use the Summer’18 update of a Bayesian analysis of only tree-level decays performed by the UTfit Collaboration [18]. All distributions are Gaussian. The prior distribution for the $\Lambda_b \rightarrow \Lambda$ form factors is a multivariate Gaussian with inputs directly taken from the lattice QCD calculation in Ref. [6].

| Quantity                                      | Prior            | Unit          | Reference |
|------------------------------------------------|------------------|---------------|-----------|
| L $\rightarrow p\pi^-$ decay parameter       | $0.750 \pm 0.010$| $-$           | [20]      |
| $\Lambda \rightarrow p\pi^-$ decay parameter| $230.7 \pm 1.3$  | MeV           | [19]      |
| $\alpha$                                      | $0.826 \pm 0.012$| $-$           | [18]      |
| $\lambda$                                     | $0.225 \pm 0.001$| $-$           | [18]      |
| $\rho$                                        | $0.148 \pm 0.043$| $-$           | [18]      |
| $\bar{\eta}$                                  | $0.348 \pm 0.010$| $-$           | [18]      |
| $B_s$ decay constant                           | $-$              | $-$           | [6]       |
| $f_{B_s}$                                      | $-$              | $-$           | [6]       |
| CKM Wolfenstein parameters                    | $-$              | $-$           | [6]       |

transitions up to mass-dimension six [14]. Following the conventions in Ref. [15], the effective Hamiltonian can be expressed as

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \alpha_\mu \sum_i C_i(\mu) O_i + \mathcal{O}(V_{ub} V^*_{us}) + \text{H.c.}$$

(1)

where $G_F$ denotes the Fermi constant as extracted from muon decays, $V_{ij}$ are Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, and $\alpha_\mu$ is the electromagnetic coupling at the scale of the $b$-quark mass, $m_b$. We write the short-distance (Wilson) coefficients as $C_i(\mu)$, taken at a renormalization scale $\mu \simeq m_b$, and long-distance physics is expressed through matrix elements of the effective field operators, $O_i$. For the decay in hand, the numerically leading operators are

$$\mathcal{O}_{9(10)} = \frac{m_b}{\alpha_\mu} [\bar{s}_u \mu P_L(b) \gamma_\mu \gamma_5 \bar{l} ],$$

$$\mathcal{O}_{9(10)} = \frac{m_b}{\alpha_\mu} [\bar{s}_u \mu P_L(b) \gamma_\mu \gamma_5 \bar{l} ],$$

(2)

A prime indicates a flip of the quarks’ chiralities with respect to the unprimed, Standard Model (SM)-like operator. The ten form factors describing the hadronic matrix elements $\langle \Lambda | \bar{s} \Gamma | B \rangle | \Lambda_b \rangle$ for $\Gamma \in \{ \gamma_\mu, \gamma_\mu \gamma_5, \gamma_\mu \} \gamma_5 \} \gamma_5 \}$ are taken from the lattice QCD calculation of Ref. [6]. The inclusion of nonlocal charm effects follows the usual operator product expansion (OPE) at large momentum transfer $q^2$ in combination with the assumption of global quark-hadron duality; see refs. [16,17] for the theoretical basis and Ref. [2] for the phenomenological application to $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ decays. At leading power in the OPE, the matrix elements can be expressed in terms of the aforementioned form factors. The uncertainty of the form factors and the breaking of the quark-hadron duality assumption are treated through a large set of nuisance parameters in the same way as discussed in Ref. [13].

We define four fit scenarios labeled “SM($\nu$-only)”, (9), “($9, 10$)” and “((9, 10, 9', 10'))”:

$$\mathcal{O}_{9, 10} \nu \text{ within priors}$$

$$\mathcal{O}_{9, 9', 10'} \nu \text{ within priors}$$

$$\mathcal{O}_{9, 10} \text{ within priors}$$

$$\mathcal{O}_{9, 9', 10'} \text{ within priors}$$

(3)

In the above, $\vec{\theta} = (\theta_9)$, $\vec{\theta} = (\theta_9, \theta_{10})$ or $\vec{\theta} = (\theta_9, \theta_{10}, \theta_9', \theta_{10}')$ denotes the parameters of interest. Nuisance parameters $\nu$ emerge in the parametrization of the (local) hadronic matrix elements in terms of $\Lambda_b \rightarrow \Lambda$ form factors; in the amount of parity violation in $\Lambda \rightarrow p\pi^-$ decays ($\alpha_{\Lambda \rightarrow p\pi^-}$); and when accounting for duality violating effects that go beyond the low-recoil OPE. The values of the nuisance parameters are given in Table I. Our statistical setup is identical to the one in [13].

III. DATA

The following new experimental results supersede those used in the previous analysis in Ref. [13]:

1. The BESIII collaboration has recently measured [20] the parity-violating parameter $\alpha$ in $\Lambda \rightarrow p\pi^-$ decays in $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\Lambda$ production. This measurement is incompatible with the previous world average from secondary scattering data [21]. Given the inability to validate assumptions and intermediate results used in the measurements entering the
previous world average of $\alpha$, the Particle Data Group (PDG) has replaced their previous average with the BESIII measurement for the upcoming “Review of Particle Physics.” We use the new BESIII result in this paper.

(2) The LHCb collaboration has recently published [22] their measurement of the complete set of angular observables in decays of polarized $\Lambda_b$ baryons to $\Lambda \mu^+\mu^-$ final states. This supersedes the three angular observables measured in Ref. [23]. Of particular interest is an erratum to the 2015 LHCb measurement [23], which explains that the reported result for the leptonic forward-backward asymmetry $A_{FB}'$ was misattributed. In effect LHCb had accidentally reported the value of the $CP$-asymmetry of this observable, rather than its $CP$-average.

(3) The ATLAS, CMS, and LHCb collaborations have each measured [24–26] the time-integrated branching ratio of the decay $B_s \to \mu^+\mu^-$, denoted here as $B(B_s \to \mu^+\mu^-)$ [27]. Within our fit scenarios, the combination $|C_{10} - C_{10'}|$ is constrained by these measurements.

(4) The LHCb measurement of the $\Lambda_b \to \Lambda \mu^+\mu^-$ branching fraction is normalized to the $\Lambda_b \to \Lambda J/\psi$ fraction. In converting this relative ratio to an absolute branching fraction, LHCb used the PDG world average for the product [23]

$$f(b \to \Lambda_b) \times B(\Lambda_b \to \Lambda J/\psi),$$

where $f(b \to \Lambda_b)$ is the $\Lambda_b$ fragmentation fraction. The LHCb measurement used an old average of $f(b \to \Lambda_b)$ that included measurements from the LEP and Tevatron experiments. The fragmentation fraction as a function of the $b$-quark transverse momentum has since been measured by the LHCb collaboration [28]. Given the strong dependence on the $b$-quark production processes and the $b$-quark transverse momentum, combining the LEP and Tevatron results appears unwise. Hence, we remove the LEP results from the average, and calculate the branching fraction of the $\Lambda_b \to \Lambda \mu^+\mu^-$ decay anew, using only the average of the TeVatron results. This calculation follows the approach by the Heavy Flavour Averaging group in Ref. [29]. The $\Lambda_b$ production fraction is derived from $f(b \to \text{baryon}) = 0.218 \pm 0.047$, assuming isospin symmetry in $\Xi_b^0$ and $\Xi_b^-$ production, i.e.,

$$f(b \to \text{baryon}) = f(b \to \Lambda_b) + 2f(b \to \Xi_b^0) + f(b \to \Omega_b^-).$$

An updated value for $f(b \to \Lambda_b)$ is determined using the ratios $f(b \to \Xi_b^0)/f(b \to \Lambda_b)$ and $f(b \to \Omega_b^-)/f(b \to \Lambda_b)$ from ref. [30], assuming equal partial widths for the $\Lambda_b \to J/\psi \Lambda$, $\Xi_b^- \to J/\psi \Xi^-$ and $\Omega_b^- \to J/\psi \Omega^-$ decays. The updated value of $f(b \to \Lambda_b)$ results in an updated branching fraction for the $\Lambda_b \to J/\psi \Lambda$ decay of $B(\Lambda_b \to J/\psi \Lambda) = (3.7 \pm 1.0) \times 10^{-4}$. Using this branching fraction value we obtain, for the bin $15 \text{ GeV}^2 \leq q^2 \leq 20 \text{ GeV}^2$,

$$B(\Lambda_b \to \Lambda \mu^+\mu^-)_{[15,20]} = (3.49 \pm 0.26 \pm 0.92) \times 10^{-7}. \quad (5)$$

This is significantly smaller than the branching fraction reported by LHCb in Ref. [23]. This result, alongside the original, unmodified, LHCb result for the branching ratio and the SM predictions for the differential branching ratio is juxtaposed in Fig. 1.

(5) The fits of Ref. [13] include data on the inclusive $B \to X_s \ell^+\ell^-$ branching fraction. Given the improved precision of the $\Lambda_b \to \Lambda \mu^+\mu^-$ results and the $B_s \to \mu^+\mu^-$ branching fraction, this is no longer necessary.

For the following fits we define three datasets entering the likelihood:

- **dataset 1** includes the three measurements of $B(\bar{B}_s \to \mu^+\mu^-)$ and the LHCb measurement of the nine independent angular observables in the $\Lambda_b \to \Lambda (\to p\pi^\mp) \mu^+\mu^-$ angular distribution for an unpolarized $\Lambda_b$ baryon;
- **dataset 2** includes the three measurements of $B(\bar{B}_s \to \mu^+\mu^-)$ and the LHCb measurement of the
33 independent angular observables in the $\Lambda_b \to \Lambda(\rightarrow p\pi^-)\mu^+\mu^-$ angular distribution for a polarized $\Lambda_b$ baryon;

dataset 3 contains dataset 2, but also includes the reinterpreted branching ratio of $\Lambda_b \to \Lambda\mu^+\mu^-$ decays. Our nominal dataset, which we use for our main results and conclusions, is dataset 2.

IV. RESULTS

We use eos [31] to carry out 12 fits for the three datasets and four fit scenarios. Summaries of the goodness of fit in their respective best-fit points are collected in Table II. Our findings are summarized as follows:

(1) The $\Lambda_b \to \Lambda(\rightarrow p\pi^-)\mu^+\mu^-$ angular distribution is compatible with the SM prediction, with acceptable $p$ values larger than 11% for all three datasets.

(2) The $\Lambda_b$ polarization is compatible with zero in all four fit scenarios. We find $P_{\Lambda_b} = (0 \pm 5)\%$ at 68% probability, and an upper limit for the magnitude of the polarization of $|P_{\Lambda_b}| \leq 11\%$ at 95% probability (see Fig. 2); these results are independent of the choice of fit scenario. We show the two-dimensional marginalized posterior for the polarization and the decay parameter $\alpha$ in Fig. 3.

(3) In the (9) scenario, the $p$ values decrease slightly for all three datasets, with the minimal value of 10% still acceptable. The best-fit point in our nominal fit using dataset 2 is

$$C_9 = 4.8 \pm 0.8.$$

TABLE II. Summary of the goodness of fit for all combinations of fit models and datasets. We present the $\chi^2$ values for each contribution to the total likelihood, the $\chi^2$ of the total likelihood, and the corresponding $p$ value at the respective best-fit points. For the purpose of a Bayesian model comparison we also present the model evidence for each fit.

| Contribution | #obs | SM(\nu-only) | (9) | (9,10) | (9,9') | (9,9',10') | (9,9',10',10') |
|--------------|------|--------------|-----|--------|--------|-------------|----------------|
| $B(\bar{B} \to \mu^+\mu^-)$ | 3    | 1.87         | 1.87| 1.84   | 1.87   | 1.83        | 0.04           |
| ang. obs. (unpol.) | 9    | 7.85         | 7.60| 7.60   | 7.68   | 7.39        | 0.11           |
| ang. obs. (all) | 33   | 43.11        | 42.72| 42.82 | 42.83 | 42.84       | 42.28          |
| $B(\Lambda_b \to \Lambda\mu^+\mu^-)$ | 1    | 0.06         | 0.19| 0.00   | 0.07   | 0.15        | 0.16           |
| $\Lambda_b \to \Lambda$ form factors | 12   | 9.84         | 9.57| 9.57   | 7.83   | 7.49        |
| total | 36   | 45.25        | 44.83| 43.14 | 42.47 |
| total | 37   | 45.30        | 45.13| 43.14 | 42.58 |
| $p$ value | 0.63 | 0.11         | 0.13| 0.13   | 0.07   | 0.08        | 0.10           |
| log$_{10}$ evidence | 22.41| 38.41        | 38.41| 38.41 | 38.41 | 35.93       |

FIG. 2. Contours for the joint 2D posterior for the asymmetry parameter, $\alpha$, and the $\Lambda_b$ production polarization at LHCb, $P_{\Lambda_b}$. We show 68% probability contours for datasets 2 and 3, and the 95% contour for dataset 2.

FIG. 3. Contours of the joint 2D posterior for the parameters $C_9$ and $C_{10}$ in scenario (9,10). All three datasets are used for both plots. We show 68% probability contours for all datasets, and in addition 95% and 99% contours for our nominal dataset 2.
We find compatibility with the best-fit point obtained in rare semileptonic $B$ meson decays at $\simeq 1.5\sigma$, and compatibility with the SM point at less than $1\sigma$. We show the two-dimensional marginalized posteriors in Fig. 4.

(6) We compute the model evidence for all combinations of datasets and fit scenarios. Our results are listed in Table II. From these results we compute the Bayes factors:

\[
\log_{10} \frac{P(\text{dataset } 2|\{9\})}{P(\text{dataset } 2|\text{SM}(\nu\text{-only}))} = -0.48, \\
\log_{10} \frac{P(\text{dataset } 2|\{9,10\})}{P(\text{dataset } 2|\text{SM}(\nu\text{-only}))} = -1.15, \\
\log_{10} \frac{P(\text{dataset } 2|\{9,10,9',10'\})}{P(\text{dataset } 2|\text{SM}(\nu\text{-only}))} = -2.97.
\]

According to Jeffrey’s interpretation of the Bayes factor [33], we find the degree to which the scenario SM($\nu$-only) is favored over scenarios (9), (9,10), and (9,10,9',10') to be barely worth mentioning, strong, and decisive, respectively.

V. CONCLUSION

We carry out the first beyond the Standard Model (BSM) analysis of the measurements of the full angular distribution in $\Lambda_b \to \Lambda(p\pi)\mu^+\mu^-$ decays. In this analysis we challenge the available data in four fit scenarios, corresponding to the absence of BSM effects [scenario SM($\nu$-only)]; BSM effects only in operators present in the SM [scenarios (9) and (9,10)]; and BSM effects in all (axial)vector operators [scenario (9,10,9',10')]. Our results supersede those of a previous analysis of this decay mode in Ref. [13], due to updates to various experimental results and a correction in the numerical code.

The best-fit points in our three BSM scenarios are compatible with both the SM and the best-fit points obtained from phenomenological analyses of exclusive $b \to s\mu^+\mu^-$ decays of $B$ mesons. The overall compatibility between such fits to the rare $\Lambda_b$ decay observables and the rare $B$ decay observables has significantly improved since the previous analysis [13]. The primary reason for this improvement is the use of an entirely new dataset that corrects an error in the measurement of the leptonic forward-backward asymmetry. Another change is the removal of the inclusive $B \to X_s e^+e^-$ branching fractions from the fit. For dataset 3, we also use an updated value for the $\Lambda_b \to \Lambda\mu^+\mu^-$ branching ratio that is substantially smaller than what was used in the previous analysis. Finally, we corrected an error in the handling of the tensor

\[
C_9 = +4.3 \pm 0.9, \quad C_{10} = -3.3 \pm 0.7, \\
C_{9'} = +0.8 \pm 0.8, \quad C_{10'} = +0.5 \pm 0.7.
\]
form factors within eos (fixed as of v0.3 [31]), which reduces the predicted branching fraction by a small amount and affects the BSM interpretation.

We find that the scenarios SM(υ-only) and (9) are almost equal in their efficiency of describing the $Λ_b → Λ μ^+ μ^−$ data. Moreover, the remaining scenarios (9,10) and (9,10,9′,10′) are strongly and decisively disfavored in a Bayesian model comparison.

As a side result of our BSM analysis, we infer $p_{Λ_b}^{LHCb}$, the $Λ_b$ polarization in the LHCb phase space, from a rare decay for the first time. We find $p_{Λ_b}^{LHCb} = (0 \pm 5\%)$ at 68% probability. This bound is independent of the fit scenarios, and is competitive with value obtained in the LHCb analysis of $Λ_b → Λ J/ψ$ decays of $6 \pm 7\%$ [34].

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