New Predictions for $\Lambda_b \to \Lambda_c$ Semileptonic Decays and Tests of Heavy Quark Symmetry

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The heavy quark effective theory makes model independent predictions for semileptonic $\Lambda_b \to \Lambda_c$ decays in terms of a small set of parameters. No subleading Isgur-Wise function occurs at order $\Lambda_{\mathrm{QCD}}/m_{c,b}$, and only two subsubleading functions enter at order $\Lambda_{\mathrm{QCD}}^2/m_c^2$. These features allow us to fit the form factors and decay rates calculated up to order $\Lambda_{\mathrm{QCD}}^2/m_c^2$ to LHCb data and lattice QCD calculations. We derive a significantly more precise standard model prediction for the ratio $\mathcal{B}(\Lambda_b \to \Lambda_c \tau\bar{\nu})/\mathcal{B}(\Lambda_b \to \Lambda_c \mu\bar{\nu})$ than prior results, and find the expansion in $\Lambda_{\mathrm{QCD}}/m_c$ well behaved, addressing a long-standing question. Our results allow more precise and reliable calculations of $\Lambda_b \to \Lambda_c \ell\bar{\nu}$ rates, and are systematically improvable with better data on the μ (or e) modes.

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Introduction.—Semileptonic decays mediated by $b \to c\ell\bar{\nu}$ transitions give tantalizing hints of deviations from the standard model (SM) in the ratios

$$R(D^{(*)}) = \Gamma[B \to D^{(*)}\tau\bar{\nu}]/\Gamma[B \to D^{(*)}l\bar{\nu}], \qquad (1)$$

where $l = \mu,\ e$. Combining the D and D^* results, the tension with the SM is 4σ [1]. Precision control of hadronic matrix elements are crucial to predict the ratios of decay rates: a better understanding of the heavy quark expansion to $\mathcal{O}(\Lambda_{\mathrm{QCD}}^2/m_c^2)$ is required, as it is largely responsible for the different uncertainty estimates of $R(D^*)$ in the SM [2–4]. The same hadronic matrix elements are also crucial to resolve tensions between inclusive and exclusive determinations of $|V_{cb}|$ [2–9]. These anomalies triggered exploring a vast array of models, e.g., with TeV-scale leptoquarks or exotic gauge bosons, as well as new high-p_T searches at the LHC for the possible mediators.

The $\Lambda_b \to \Lambda_c \ell\bar{\nu}$ baryon decays provide a theoretically cleaner laboratory than $B \to D^{(*)}\ell\bar{\nu}$ to examine $\mathcal{O}(\Lambda_{\mathrm{QCD}}^2/m_c^2)$ terms, as heavy quark symmetry [10–12] provides stronger constraints. The $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_{c,b})$ contributions yield no new nonperturbative functions beyond the leading order Isgur-Wise function, significantly reducing the number of hadronic parameters order by order in the heavy quark effective theory (HQET) [13,14] description of these decays. This allows us to determine the $\mathcal{O}(\Lambda_{\mathrm{QCD}}^2/m_c^2)$ contributions to an exclusive decay for the first time, without any model dependent assumption.

In this Letter, we examine the HQET predictions at $\mathcal{O}(\Lambda_{\mathrm{QCD}}^2/m_c^2)$ and fit them to a recent LHCb measurement of $\Lambda_b \to \Lambda_c \mu\bar{\nu}$ [15] and/or lattice QCD (LQCD) results [16]. Doing so, we obtain the most precise SM prediction so far for

$$R(\Lambda_c) = \Gamma(\Lambda_b \to \Lambda_c \tau\bar{\nu})/\Gamma(\Lambda_b \to \Lambda_c \mu\bar{\nu}), \qquad (2)$$

improvable with future data. We find that the $\mathcal{O}(\Lambda_{\mathrm{QCD}}^2/m_c^2)$ corrections have the expected characteristic size, suggesting that the heavy quark expansion in $\Lambda_{\mathrm{QCD}}/m_c$ is well behaved in such decays.

Testing HQET predictions not only provides a path to reducing theoretical uncertainties in precision determinations of $R(D^{(*)})$ and the extraction of $|V_{cb}|$, but also improves the sensitivity to possible new physics contributions. Measuring semileptonic decays mediated by the same parton-level transition between different hadrons is important, as it improves the statistics, entails different systematic uncertainties, and gives complementary information on possible new physics. LHCb projections show that the precision of $R(\Lambda_c)$ will be near those of $R(D^{(*)})$ in the future [17], making this channel very important.

HQET expansion of the form factors.—The semileptonic $\Lambda_b \to \Lambda_c \ell\bar{\nu}$ form factors in HQET are conventionally defined for the SM currents as [18–20]

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$$\langle\Lambda_c(p',s')|\bar{c}\gamma_\nu b|\Lambda_b(p,s)\rangle = \bar{u}_c(v',s')[f_1\gamma_\mu + f_2 v_\mu + f_3 v'_\mu]u_b(v,s),$$
$$\langle\Lambda_c(p',s')|\bar{c}\gamma_\nu\gamma_5 b|\Lambda_b(p,s)\rangle = \bar{u}_c(v',s')[g_1\gamma_\mu + g_2 v_\mu + g_3 v'_\mu]\gamma_5 u_b(v,s), \quad (3)$$

where $p = m_{\Lambda_b} v$, $p' = m_{\Lambda_c} v'$, and the f_i and g_i form factors are functions of $w = v \cdot v'$. The spinors are normalized to $\bar{u}u = 2m$.

The $\Lambda_{b,c}$ baryons are singlets of heavy quark spin symmetry, with the "brown muck" of the light degrees of freedom (d.o.f.) in the spin-0 ground state. Therefore,

$$m_{\Lambda_Q} = m_Q + \bar{\Lambda}_\Lambda - \lambda_1^\Lambda/2m_Q +, \ldots, \quad (4)$$

where $Q = b$, c, the ellipsis denotes terms higher order in $\Lambda_{\rm QCD}/m_Q$ and $m_{\Lambda_b} = 5.620$ GeV, $m_{\Lambda_c} = 2.286$ GeV [21]. The parameter $\bar{\Lambda}_\Lambda$ is the energy of the light d.o.f. in the $m_Q \gg \Lambda_{\rm QCD}$ limit, and λ_1^Λ is related to the heavy quark kinetic energy in the $\Lambda_{b,c}$ baryons. Using a short-distance quark mass scheme, ambiguities in the pole mass and $\bar{\Lambda}_\Lambda$ can be canceled, and the behavior of the perturbation series improved. We use the $1S$ scheme [22–24] and treat $m_b^{1S} = (4.71 \pm 0.05)$ GeV and $\delta m_{bc} = m_b - m_c = (3.40 \pm 0.02)$ GeV as independent parameters [25,26]. (The latter is well constrained by $B \to X_c \ell\bar{\nu}$ spectra [27,28].) We match HQET onto QCD at $\mu = \sqrt{m_c m_b}$, so that $\alpha_s \simeq 0.26$. For example, using Eq. (4) for both Λ_b and Λ_c to eliminate λ_1^Λ, at $\mathcal{O}(\alpha_s)$ we obtain $\bar{\Lambda}_\Lambda = (0.81 \pm 0.05)$ GeV.

Making the transition to HQET [13,14], at leading order in the heavy quark expansion

$$\langle\Lambda_c(p',s')|\bar{c}\Gamma b|\Lambda_b(p,s)\rangle = \zeta(w)\bar{u}_c(v',s')\Gamma u_b(v,s), \quad (5)$$

where $u(v,s)$ satisfies $\not{v}u = u$ and $\zeta(w)$ is the leading order Isgur-Wise function [18], satisfying $\zeta(1) = 1$. In the heavy quark limit, $f_1 = g_1 = \zeta$, while $f_{2,3} = g_{2,3} = 0$.

At order $\Lambda_{\rm QCD}/m_{c,b}$, a remarkable simplification occurs compared to meson decays: the $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ corrections from the matching of the $\bar{c}\Gamma b$ heavy quark current onto HQET [29–31] can be expressed in terms of $\bar{\Lambda}_\Lambda$ and the leading order Isgur-Wise function $\zeta(w)$ [32]. In addition, for $\Lambda_b \to \Lambda_c$ transitions, there are no $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ contributions from the chromomagnetic operator. The kinetic energy operator in the $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ HQET Lagrangian gives rise to a heavy quark spin symmetry conserving subleading term, parametrized by $\zeta_{\rm ke}(w)$, which can be absorbed into the leading order Isgur-Wise function by redefining ζ via

$$\zeta(w) + (\varepsilon_c + \varepsilon_b)\zeta_{\rm ke}(w) \to \zeta(w), \quad (6)$$

where $\varepsilon_{c,b} = \bar{\Lambda}_\Lambda/(2m_{c,b})$. Thus, no additional unknown functions beyond $\zeta(w)$ are needed to parametrize the $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ corrections. Luke's theorem [33] implies $\zeta_{\rm ke}(1) = 0$, so the normalization $\zeta(1) = 1$ is preserved. Perturbative corrections to the heavy quark currents can be computed by matching QCD onto HQET [29–31], and introduce no new hadronic parameters.

The $\mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2)$ corrections are parametrized by six unknown functions of w [19], but only two linear combinations of subsubleading Isgur-Wise functions, $b_{1,2}$, occur at $\mathcal{O}(\Lambda_{\rm QCD}^2/m_c^2)$. Spurious terms introduced by the redefinition in Eq. (6) at order $\Lambda_{\rm QCD}^2/m_c^2$ can also be absorbed into $b_{1,2}$. We define the rescaled form factors,

$$\hat{x}_i(w) = x_i(w)/\zeta(w), \qquad x = \{f_i, g_i, b_i\}. \quad (7)$$

Including α_s, $\Lambda_{\rm QCD}/m_{c,b}$, $\alpha_s\Lambda_{\rm QCD}/m_{c,b}$ [34], and $\Lambda_{\rm QCD}^2/m_c^2$ corrections, the SM form factors are

$$\hat{f}_1 = 1 + \hat{\alpha}_s C_{V_1} + \varepsilon_c + \varepsilon_b + \hat{\alpha}_s(C_{V_1} + 2(w-1)C'_{V_1})(\varepsilon_c + \varepsilon_b) + \frac{\hat{b}_1 - \hat{b}_2}{4m_c^2} +, \ldots,$$
$$\hat{f}_2 = \hat{\alpha}_s C_{V_2} - \frac{2\varepsilon_c}{w+1} + \hat{\alpha}_s\left(C_{V_2}\frac{3w-1}{w+1}\varepsilon_b - [2C_{V_1} - (w-1)C_{V_2} + 2C_{V_3}]\frac{\varepsilon_c}{w+1} + 2(w-1)C'_{V_2}(\varepsilon_c + \varepsilon_b)\right) + \frac{\hat{b}_2}{4m_c^2} +, \ldots,$$
$$\hat{f}_3 = \hat{\alpha}_s C_{V_3} - \frac{2\varepsilon_b}{w+1} + \hat{\alpha}_s\left(C_{V_3}\frac{3w-1}{w+1}\varepsilon_c - [2C_{V_1} + 2C_{V_2} - (w-1)C_{V_3}]\frac{\varepsilon_b}{w+1} + 2(w-1)C'_{V_3}(\varepsilon_c + \varepsilon_b)\right) +, \ldots,$$
$$\hat{g}_1 = 1 + \hat{\alpha}_s C_{A_1} + (\varepsilon_c + \varepsilon_b)\frac{w-1}{w+1} + \hat{\alpha}_s\left(C_{A_1}\frac{w-1}{w+1} + 2(w-1)C'_{A_1}\right)(\varepsilon_c + \varepsilon_b) + \frac{\hat{b}_1}{4m_c^2} +, \ldots,$$
$$\hat{g}_2 = \hat{\alpha}_s C_{A_2} - \frac{2\varepsilon_c}{w+1} + \hat{\alpha}_s\left(C_{A_2}\frac{3w+1}{w+1}\varepsilon_b - [2C_{A_1} - (w+1)C_{A_2} + 2C_{A_3}]\frac{\varepsilon_c}{w+1} + 2(w-1)C'_{A_2}(\varepsilon_c + \varepsilon_b)\right) + \frac{\hat{b}_2}{4m_c^2} +, \ldots,$$
$$\hat{g}_3 = \hat{\alpha}_s C_{A_3} + \frac{2\varepsilon_b}{w+1} + \hat{\alpha}_s\left(C_{A_3}\frac{3w+1}{w+1}\varepsilon_c + [2C_{A_1} - 2C_{A_2} + (w+1)C_{A_3}]\frac{\varepsilon_b}{w+1} + 2(w-1)C'_{A_3}(\varepsilon_c + \varepsilon_b)\right) +, \ldots, \quad (8)$$

where the C_{Γ_i} are functions of w [2,31], $z = m_c/m_b$, and $\hat{\alpha}_s = \alpha_s/\pi$. (We use the notation of Ref. [20]; explicit expressions for C_{Γ_i} are in Ref. [2].) In Eq. (8), a prime denotes $\partial/\partial w$ and the ellipses denote $\mathcal{O}(\varepsilon_c\varepsilon_b, \varepsilon_b^2, \varepsilon_c^3)$ and higher order terms. Equation (8) agrees with Eq. (4.75) in Ref. [34] [where a different form of Eq. (6) is used].

The $\hat{b}_{1,2}(w)$ functions are not constrained by heavy quark symmetry. The model dependent estimate $\hat{b}_1(1) \approx -3\bar{\Lambda}_\Lambda^2$, obtained in Eq. (5.5) of Ref. [19], would imply that $\hat{b}_1/(4m_c^2)$ terms can give $\mathcal{O}(20\%)$ corrections. Even corrections of such size would not necessarily imply a breakdown of the heavy quark expansion: a matrix element $\sim 3\bar{\Lambda}_\Lambda^2$ is consistent with HQET power counting, as dependence of the form factors on the energy of the brown muck in the hadron, $\bar{\Lambda}_\Lambda$, arises from using the equations of motion. Since $\bar{\Lambda}_\Lambda$ is greater than $\bar{\Lambda}$ in the $B \to D^{(*)}$ case [2], it would not be surprising if the HQET expansions for $\Lambda_b \to \Lambda_c$ form factors converge slower than for $B \to D^{(*)}$. At the same time, the structure of the expansion is simpler for $\Lambda_b \to \Lambda_c$ form factors (cf. similar HQET-based discussions of $B \to D^{(*)}\ell\bar{\nu}$ [2], $B \to D^{**}\ell\bar{\nu}$ [26,35–37], and $\Lambda_b \to \Lambda_c^*\ell\bar{\nu}$ [38,39]).

Fits to LHCb and lattice QCD data.—To determine the nonperturbative quantities that occur in the HQET expansion of the form factors in Eq. (8), assess the behavior of the expansion in $\Lambda_{\rm QCD}/m_c$, and derive precise SM predictions for $R(\Lambda_c)$ in Eq. (2), we fit the LHCb measurement of $d\Gamma(\Lambda_b \to \Lambda_c\mu\bar{\nu})/dq^2$ [15] or/and a LQCD determination of the six form factors [16].

The LHCb experiment measured the q^2 spectrum in seven bins, normalized to unity [15]. This reduces its effective d.o.f. from seven to six (as any one bin is determined by the sum of the others). The measurement is shown as the data points in Fig. 1.

The lattice QCD results [16] for the six form factors are published as fits to the BCL parametrization [40], using either 11 or 17 parameters. We derive predictions for $f_{1,2,3}$ and $g_{1,2,3}$ using the 17 parameter result at three q^2 values, near the two ends and the middle of the spectrum, $q^2 = \{1\ \mathrm{GeV}^2, q^2_{\rm max}/2, q^2_{\rm max} - 1\ \mathrm{GeV}^2\}$, preserving their full correlation, in order to construct an appropriate covariance matrix. The difference in the form factor values obtained using the 17 or the 11 parameter results is added as an uncorrelated uncertainty. This differs slightly from the prescription in Ref. [16], based on the maximal differences, which cannot preserve the correlation structure between the form factor values. The 18 form factor values used in our fits are shown as data points in Fig. 2. The LQCD predictions, following the prescription of Ref. [16], are shown as heather gray bands, and the uncertainties are in good agreement. The heather gray band in Fig. 1 shows the LQCD prediction for the normalized spectrum, using the BCL parametrization.

The SM prediction for the decay rate for arbitrary charged lepton mass is

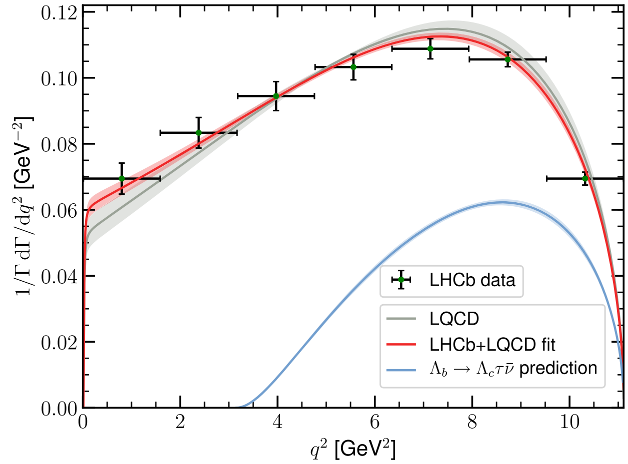

FIG. 1. The red band shows our fit of the HQET predictions to $d\Gamma(\Lambda_b \to \Lambda_c\mu\bar{\nu})/dq^2$ measured by LHCb [15] and the LQCD form factors [16]. The heather gray band shows the LQCD prediction. The blue curve shows our prediction for $d\Gamma(\Lambda_b \to \Lambda_c\tau\bar{\nu})/dq^2$.

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_{\Lambda_b}^5 |V_{cb}|^2}{24\pi^3} \frac{(\hat{q}^2 - \rho_\ell)^2}{\hat{q}^4} r^3 \sqrt{w^2-1} \Bigg\{ \left(1 + \frac{\rho_\ell}{2\hat{q}^2}\right) \times [(w-1)(2\hat{q}^2 f_1^2 + \mathcal{F}_+^2) + (w+1)(2\hat{q}^2 g_1^2 + \mathcal{G}_+^2)] + \frac{3\rho_\ell}{2\hat{q}^2}[(w+1)\mathcal{F}_0^2 + (w-1)\mathcal{G}_0^2] \Bigg\}, \tag{9}$$

where $\rho_\ell = m_\ell^2/m_{\Lambda_b}^2$, $r = m_{\Lambda_c}/m_{\Lambda_b}$, $\hat{q}^2 \equiv q^2/m_{\Lambda_b}^2 = 1 - 2rw + r^2$, and

$$\begin{aligned}
\mathcal{F}_+ &= (1+r)f_1 + (w+1)(rf_2+f_3) = (1+r)f_+,\\
\mathcal{G}_+ &= (1-r)g_1 - (w-1)(rg_2+g_3) = (1-r)g_+,\\
\mathcal{F}_0 &= (1-r)f_1 - (rw-1)f_2 + (w-r)f_3 = (1-r)f_0,\\
\mathcal{G}_0 &= (1+r)g_1 + (rw-1)g_2 - (w-r)g_3 = (1+r)g_0.
\end{aligned} \tag{10}$$

Combined with $f_1 = f_\perp$ and $g_1 = g_\perp$, Eqs. (10) relate f_i and g_i to the other common form factor basis, $f_{\perp,+,0}$ and $g_{\perp,+,0}$, used in Ref. [16]. Our result in Eq. (9) agrees with those in Refs. [16,41].

In our fits to the LHCb data, we integrate the rate predictions that follow from Eqs. (8) and (9) over each bin, and minimize a χ^2 function. The LQCD predictions are fitted by minimizing a χ^2 function that includes the 18 values and their correlations, as described above.

We explore three scenarios: (i) fitting only the LHCb spectrum, (ii) fitting only the LQCD data, and (iii) a combined fit the LHCb data and the LQCD information. The resulting HQET parameters are summarized in Table I. For the fit to only the LHCb spectrum, the unknown absolute normalization of the measurement removes the sensitivity to $\hat{b}_{1,2}$. Therefore, we constrain them to zero by a Gaussian with a 2 GeV^2($\approx 3\bar{\Lambda}_\Lambda^2$) uncertainty, motivated by a model dependent estimate for $\hat{b}_1(1)$ [19]. This allows our

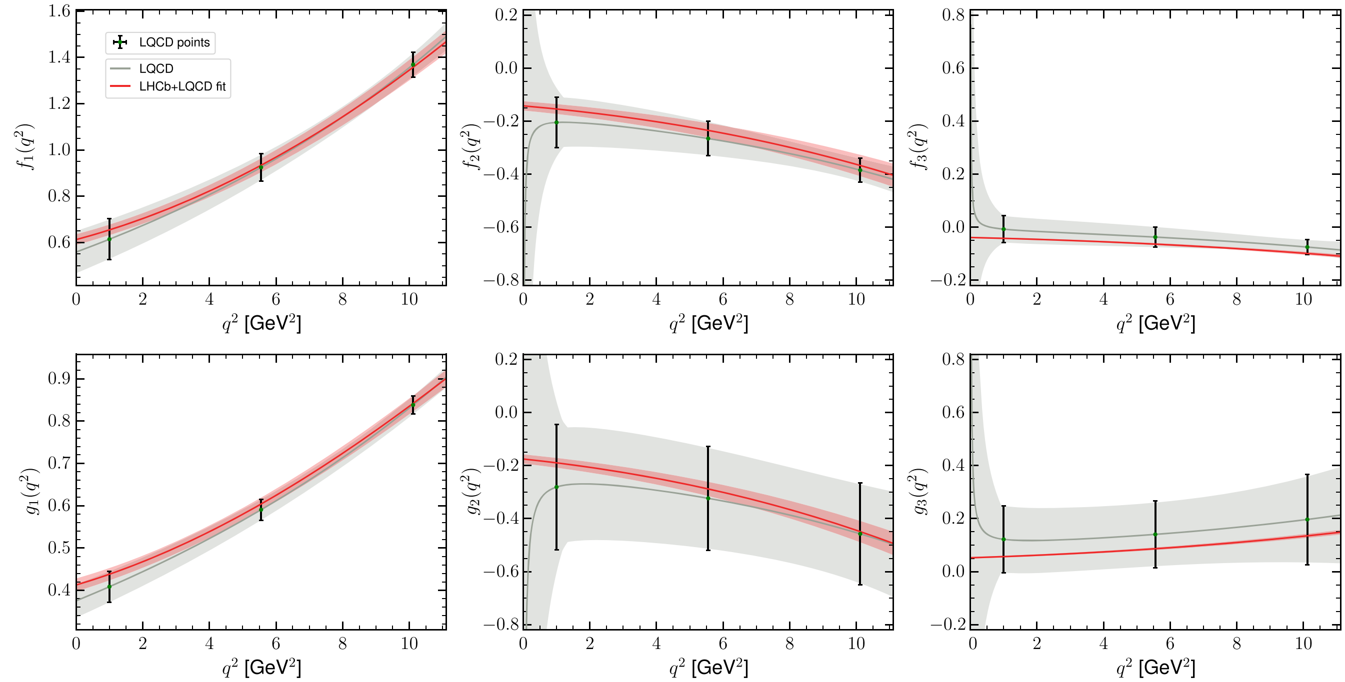

FIG. 2. Fit of the HQET predictions in Eq. (8) to the LQCD results [16] and the LHCb spectrum [15] for the six form factors (red bands). The heather gray bands and data points show the LQCD prediction; see text for details.

three fits to have the same parameters, and be compared to one another. In all fits, m_b^{1S} and δm_{bc} are constrained using Gaussian uncertainties. The leading order Isgur-Wise function is fitted as $\zeta = 1 + (w-1)\zeta' + \frac{1}{2}(w-1)^2\zeta''$. Alternative expansions using the conformal parameters z or z^* instead of w yield nearly identical fits. Fits with ζ linear in either w, z, or z^* are poor. Adding more q^2 values from the BCL fit of the LQCD result to our sampling indicates no preference for the inclusion of higher order terms in $w-1$, nor does it noticeably affect the fit results. We fit $\hat{b}_{1,2}$ as constants, which is appropriate at the current level of sensitivity. We do not include explicitly an uncertainty for neglected higher order terms in Eq. (8); two form factors, f_3 and g_3, receive no $\Lambda^2_{\mathrm{QCD}}/m_c^2$ corrections, so their agreement with LQCD in the rightmost plots in Fig. 2 indicates that these terms are probably small.

All fits have acceptable χ^2 values, and they all yield compatible values for the slope and curvature of $\zeta(w)$ at zero recoil. The fit of the HQET predictions to the lattice QCD form factors determines fairly precisely the $\hat{b}_{1,2}$ parameters, that enter at order $\Lambda^2_{\mathrm{QCD}}/m_c^2$. The significance of $\hat{b}_1 \neq 0$ is over 3σ. However $\hat{b}_1(1)$ is much smaller than the model dependent estimate $\hat{b}_1(1) \simeq -3\bar{\Lambda}^2_\Lambda$ [19].

The red bands in Figs. 1 and 2 show the combined fit using both LHCb and LQCD information. The agreement therein shows that the HQET predictions in Eq. (8) describe the form factors and the experimental spectrum at the current level of uncertainties. This also holds for the fit using the LHCb spectrum (with constraints on $\hat{b}_{1,2}$). Table II shows the correlation matrix of the

TABLE I. HQET parameters extracted from the three fits discussed in the text. Predictions for $R(\Lambda_c)$ for each fit are shown in the last row. The $\hat{b}_{1,2}$ values marked with an asterisk were constrained in the fit; see text for details.

	LHCb	LQCD	LHCb + LQCD
ζ'	-2.17 ± 0.26	-2.05 ± 0.13	-2.04 ± 0.08
ζ''	4.10 ± 1.05	2.93 ± 0.43	3.16 ± 0.38
$\hat{b}_1/\,\mathrm{GeV}^2$	$0.24 \pm 1.92^*$	-0.44 ± 0.16	-0.46 ± 0.15
$\hat{b}_2/\,\mathrm{GeV}^2$	$0.45 \pm 1.88^*$	-0.41 ± 0.40	-0.39 ± 0.39
$m_b^{1S}/\,\mathrm{GeV}$	4.71 ± 0.05	4.72 ± 0.05	4.72 ± 0.05
$\delta m_{bc}/\,\mathrm{GeV}$	3.40 ± 0.02	3.40 ± 0.02	3.40 ± 0.02
χ^2/ndf	$0.77/4$	$2.42/14$	$7.20/20$
$R(\Lambda_c)$	0.3209 ± 0.0041	0.3313 ± 0.0101	0.3237 ± 0.0036

TABLE II. Correlation matrix of the HQET parameters determined from the fit to the LHCb measurement and the LQCD form factors.

	ζ'	ζ''	$\hat{b}_1$	$\hat{b}_2$	m_b^{1S}	δm_{bc}
ζ'	1.00	−0.94	−0.14	0.11	0.11	−0.01
ζ''	−0.94	1.00	0.13	−0.02	−0.10	0.00
$\hat{b}_1$	−0.14	0.13	1.00	0.10	−0.21	0.10
$\hat{b}_2$	0.11	−0.02	0.10	1.00	−0.63	0.05
m_b^{1S}	0.11	−0.10	−0.21	−0.63	1.00	−0.00
δm_{bc}	−0.01	0.00	0.10	0.05	−0.00	1.00

LHCb + LQCD fit. Table I also shows the resulting SM predictions for $R(\Lambda_c)$ from the three fits, and Fig. 1 shows the predicted $d\Gamma(\Lambda_b \to \Lambda_c \tau\bar{\nu})/dq^2$ spectrum as a blue band.

Conclusions.—Measurement of $\Lambda_b \to \Lambda_c \ell \bar{\nu}$ decays will play an important role in elucidating the tantalizing hints of new physics in the measurements of $R(D^{(*)})$, and refining our understanding of determinations of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$. We derived new model independent predictions for these decays, and found that fitting the LHCb data for $d\Gamma(\Lambda_b \to \Lambda_c \mu\bar{\nu})/dq^2$ substantially reduces the uncertainty of the SM prediction for $R(\Lambda_c)$. We obtained

$$R(\Lambda_c) = 0.324 \pm 0.004 \tag{11}$$

by combining the lattice information with the measured spectrum. This produces the most precise prediction of $R(\Lambda_c)$ to date, significantly improving the precision over the lattice QCD prediction, $R(\Lambda_c) = 0.3328 \pm 0.0070 \pm 0.0074$ [16]. This large improvement arises because the experimental data constrain combinations of form factors relevant for the prediction of $R(\Lambda_c)$.

Using the lattice QCD form factor calculations, we performed new tests of heavy quark symmetry, determining $\Lambda_{\mathrm{QCD}}^2/m_c^2$ corrections to an exclusive decay, without any model dependent assumptions, for the first time. The HQET expansion at order $\Lambda_{\mathrm{QCD}}^2/m_c^2$ appears well behaved, and we find good agreement between lattice QCD and HQET predictions. More details and extensions of these results including new physics contributions will be presented elsewhere [42].

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