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Limit on a right-handed admixture to the weak $b \to c$ current from semileptonic decays

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We determine an upper bound for a possible right-handed $b \to c$ quark current admixture in semileptonic $\bar{B} \to X_c \ell^- \bar{\nu}$ decays from a simultaneous fit to moments of the lepton-energy and hadronic-mass distribution measured as a function of the lower limit on the lepton energy, using data measured by the *BABAR* detector. The right-handed admixture is parametrized by a new parameter c_R as coefficient of computed moments with right-handed quark current. For the standard-model part we use the prediction of the heavy-quark expansion up to order $1/m_b^3$ and perturbative corrections and for the right-handed contribution only up to order $1/m_b^2$ and perturbative corrections. We find $c_R' = 0.05^{+0.33}_{-0.50}$ in agreement with the standard-model prediction of zero. Additionally, we give a constraint on a possible right-handed admixture from exclusive decays, which is with a value of $c_R' = 0.01 \pm 0.03$ more restrictive than our value from the inclusive fit. The difference in $|V_{cb}|$ between the inclusive and exclusive extraction is only slightly reduced when allowing for a right-handed admixture in the range of $c_R' = 0.01 \pm 0.03$.

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I. INTRODUCTION

Parity violation is implemented in the standard model (SM) by assigning different weak quantum numbers to left- and right-handed quarks and leptons and it is fair to say that there is yet no deeper understanding of the symmetry breaking mechanism in weak interactions with respect to parity transformations. On the experimental side, parity violation is well established in the leptonic sector, e.g. through the measurements of the Michel parameters in the decay of muons.

However, in hadronic transitions parity violation is much harder to test due to the uncertainties present in the calculation of the hadronic matrix elements of the quark currents. In turn, this leaves sizable room for a possible non-left-handed admixture. While this is mainly true in the case of light quark systems, the calculational methods have significantly developed for heavy quarks using the fact that the heavy-quark masses are large compared to the binding energy of heavy hadrons.

In particular for inclusive semileptonic $b \to c$ transitions the theoretical methods are in a mature state and are applied in the framework of the SM to extract, e.g. the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ with an unprecedented relative precision of less than 2% [1].

Clearly the precision of the data as well as of the theoretical methods may serve also to perform a test for nonstandard couplings. In two recent papers [2,3] the necessary calculations have been performed to check for a non-left-handed coupling in inclusive semileptonic $b \to c$ transitions. In the present paper we use these results together with the *BABAR* data to obtain information on a possible right-handed admixture to the weak $b \to c$ current.

Recently the tension between the inclusive and exclusive determinations of $|V_{ub}|$ and—to a lesser extend—also of $|V_{cb}|$ motivated speculations to explain this by right-handed admixtures in the weak hadronic currents. In [4] it is shown that a right-handed admixture can soften the tension and that a right-handed admixture can be obtained within the minimal supersymmetric standard model.

In the next section we recapitulate the theoretical input and fix our notation. In Sec. III we perform the analysis based on *BABAR* data. In Sec. IV we discuss our result and compare them in Sec. V to limits from exclusive decays. Finally, in Sec. VI we conclude.

II. THEORY BACKGROUND AND NOTATION

It is well known that any new physics effect beyond the SM can be parametrized in terms of higher-dimensional operators, which are singlets under the SM symmetry $SU(3)_{QCD} \times SU(2)_{weak} \times U(1)_Y$. Assuming that the Higgs sector is minimal (i.e. if one considers only a single Higgs doublet) there is only one operator at dimension five which is related to a Majorana mass of the neutrino and hence only affects the leptonic sector. At dimension six one finds a long list of possible operators [5] among which we find also operators modifying the helicity structure that appears in the semileptonic $b \to c$ decays.

After spontaneous symmetry breaking $SU(3)_{QCD} \times SU(2)_{weak} \times U(1)_Y \to SU(3)_{QCD} \times U(1)_{em}$ and after running down to the scale of the b-quark mass one finds for the effective interaction [2,3]

$$\mathcal{H}_{\mathrm{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} J_{q,\mu} J_l^{\mu}, \tag{1}$$

where $J_l^{\mu} = \bar{e}\gamma^{\mu} P_- \nu_e$ is the usual leptonic current and $J_{h,\mu}$ is the generalized hadronic $b \to c$ current which is given by

$$\begin{aligned} J_{h,\mu} = {} & c_L \bar{c}\gamma_{\mu} P_- b + c_R \bar{c}\gamma_{\mu} P_+ b + g_L \bar{c} i\overleftrightarrow{D}_{\mu} P_- b \\ & + g_R \bar{c} i\overleftrightarrow{D}_{\mu} P_+ b + d_L i\partial^{\mu}(\bar{c} i\sigma_{\mu\nu} P_- b) \\ & + d_R i\partial^{\mu}(\bar{c} i\sigma_{\mu\nu} P_+ b), \end{aligned} \tag{2}$$

where $P_{\pm}$ denotes the projector on positive/negative chirality and D_{μ} is the QCD covariant derivative. Note that the leading term contributing to the rate will be the interference term with the SM ($\propto c_L c_R$), which means that the leptonic current remains as in the SM since we consider only final states with electrons and muons and thus can neglect the lepton mass.

Furthermore, c_L contains the SM contribution and hence $c_L = 1 + \mathcal{O}(v^2/\Lambda^2)$, where v is the vacuum expectation value from spontaneous symmetry breaking and Λ is the new-physics' scale. All other contributions can only appear through a new-physics effect. In particular, the effective field theory approach reveals that $c_R = \mathcal{O}(v^2/\Lambda^2)$, while all helicity changing contributions are expected to be further suppressed by a small Yukawa coupling [2,6].

As it is argued in [2,3] we assume that the new physics contributions are small, and hence we may expand in the couplings c_R, g_L, g_R, d_L, d_R and $c_L - 1$. The leading pieces for the rates are hence the interference terms with the SM amplitude, which is purely left handed. Thus, any helicity flip of the charm quark will cost a factor m_c/m_b, which is, in particular, true for a right-handed admixture; thereby reducing the sensitivity to such a contribution slightly.

Furthermore, it will be even more difficult to reveal a new physics contribution to the left-handed current since the amplitude depends on $G_F|V_{cb}|c_L$ and hence a contribution with $c_L \neq 1$ can be absorbed either into G_F or $|V_{cb}|$. In order to disentangle this one needs to take into account completely different observables such as e.g. neutral current processes. This lies below the scope of the present work, which deals exclusively with $b \to c$ transitions. An example for a new physics contribution to the left-handed current which can be absorbed into G_F or $|V_{cb}|$ is a fourth generation of quarks and leptons as discussed in [7].

In the following analysis we restrict ourselves to an investigation of the parameter c_R. As has been shown in [3] the lepton-energy moments and hadronic-mass moments are not very sensitive to the parameters g_L, g_R, d_L and d_R. Because the moments depend on the squared matrix element the parameters appear in pairs, of which the leading contributions are c_L^2 and $c_L c_R$. For the combined fit the parameter c_L can also be dropped as an overall factor being absorbed in $|V_{cb}|$. Thus the parameter used in the fit is $c_R' = c_R/c_L$.

III. ANALYSIS

A. Fit setup

The combined fit for the extraction of the new parameter c_R' is performed along the lines as described in [8] using the HQEFITTER package [9]. It is based on the χ^2 minimization,

$$\chi^2 = (\vec{M}_{\mathrm{exp}} - \vec{M}_{\mathrm{theo}})^T \mathcal{C}_{\mathrm{tot}}^{-1} (\vec{M}_{\mathrm{exp}} - \vec{M}_{\mathrm{theo}}), \tag{3}$$

with the included measured moments $\vec{M}_{\mathrm{exp}}$, the corresponding theoretical prediction of these moments $\vec{M}_{\mathrm{theo}}$ and the total covariance matrix $\mathcal{C}_{\mathrm{tot}}$ defined as the sum of the experimental ($\mathcal{C}_{\mathrm{exp}}$) and the theoretical ($\mathcal{C}_{\mathrm{theo}}$) covariance matrix, respectively.

In the analysis of [8] the theoretical prediction for the moments $\vec{M}_{\mathrm{HQE}}$ are calculated perturbatively in a heavy-quark expansion (HQE) in the kinetic-mass scheme up to $\mathcal{O}(1/m_b^3)$ with perturbative contributions [10–12] resulting in a dependence on six parameters: the running masses of the b and c quarks, $m_b(\mu)$ and $m_c(\mu)$, the parameters μ_{π}^2 and μ_G^2 at $\mathcal{O}(1/m_b^2)$ in the HQE, and, at $\mathcal{O}(1/m_b^3)$, the parameters ρ_D^3 and ρ_{LS}^3.

New in this analysis is the inclusion of possible right-handed quark currents in the calculation of the theoretical prediction of the moments. The right-handed contributions are calculated and used here up to $\mathcal{O}(1/m_b^2)$ in the HQE and $\mathcal{O}(\alpha_s)$ in the perturbative correction. The aim of this fit is to give an upper bound for the relative contribution of a right-handed current compared with the standard-model left-handed current, which is parametrized by a prefactor c_R' for the new contributions to test. Thus the theoretical prediction of the moments depends on seven parameters to fit:

$$\vec{M}_{\mathrm{theo}} = \vec{M}_{\mathrm{theo}}(c_R', m_b, m_c, \mu_{\pi}^2, \mu_G^2, \rho_D^3, \rho_{LS}^3).$$

B. Determination of $|V_{cb}|$

In the presence of a right-handed mixture the definition of the parameter $|V_{cb}|$ becomes ambiguous. Out of the three parameters $|V_{cb}|$, c_L, c_R' only two are independent, since c_L can be absorbed into $|V_{cb}|$. To this end we choose to define

$$|V_{cb}|\bar{b}_L\gamma_{\mu}c_L \to |V_{cb}|(\bar{b}_L\gamma_{\mu}c_L + c_R'\bar{b}_R\gamma_{\mu}c_R).$$

For the determination of $|V_{cb}|$ the fit uses a linearized form of the semileptonic rate Γ_{SL} expanded around *a priori* estimates of the HQE parameters [10]:

$$\frac{|V_{cb}|}{0.0417} = \sqrt{\frac{\mathcal{B}_{clv}}{0.1032}\frac{1.55}{\tau_B}}[1 + 0.30(\alpha_s(m_b) - 0.22)] \times [1 - 0.66(m_b - 4.60) + 0.39(m_c - 1.15) + 0.013(\mu_\pi^2 - 0.40) + 0.09(\rho_D^3 - 0.20) + 0.05(\mu_G^2 - 0.35) - 0.01(\rho_{LS}^3 + 0.15) + 0.341c'_R]. \quad (4)$$

Note the last term ($0.341c'_R$), taking into account the possible contributions from a right-handed quark current. The *a priori* estimate of c'_R is zero, i.e. the standard-model value. Because of the sizable factor and positive sign, a positive value of c'_R increases $|V_{cb}|$ compared to the standard-model fit without c'_R.

The total branching fraction $\mathcal{B}(\bar{B} \to X_c \ell^- \bar{\nu})$ in the fit is extrapolated from measured partial branching fractions $\mathcal{B}_{p^*_{\ell,\min}}(\bar{B} \to X_c \ell^- \bar{\nu})$, with $p^*_\ell \geq p^*_{\ell,\min}$. This is done by comparison with the HQE prediction of the relative decay fraction (right-hand side):

$$\frac{\mathcal{B}_{p^*_{\ell,\min}}(\bar{B} \to X_c \ell^- \bar{\nu})}{\mathcal{B}(\bar{B} \to X_c \ell^- \bar{\nu})} = \frac{\int_{p^*_{\ell,\min}} \frac{d\Gamma_{SL}}{dE^*_\ell} dE^*_\ell}{\int_0 \frac{d\Gamma_{SL}}{dE^*_\ell} dE^*_\ell}. \quad (5)$$

Thus the total branching fraction can be introduced as a free parameter in the fit. By adding the average B-meson lifetime τ_B (average between neutral and charged B mesons, see also next paragraph) to the measured and predicted values, $|V_{cb}|$ can as well be introduced as a free parameter using (4).

C. Experimental input

The combined fit is performed with a selection of the following 25 moment measurements by *BABAR* which are characterized by correlations below 95% to ensure the invertibility of the covariance matrix:

(i) Lepton energy moments measured by *BABAR* [13]. We use the partial branching fraction $\mathcal{B}_{p^*_{\ell,\min}}$ at the minimal lepton momentum $p^*_\ell \geq 0.6$, 1.0, 1.5 GeV$/c$, the moments $\langle E_\ell \rangle$ for $p^*_\ell \geq 0.6$, 0.8, 1.0, 1.2, 1.5 GeV$/c$, the central moments $\langle (E_\ell - \langle E_\ell \rangle)^2 \rangle$ for $p^*_\ell \geq 0.6$, 1.0, 1.5 GeV$/c$ and $\langle (E_\ell - \langle E_\ell \rangle)^3 \rangle$ for $p^*_\ell \geq 0.8$, 1.2 GeV$/c$.

(ii) Hadronic-mass moments measured by *BABAR* [8]. We use the moment $\langle m_X^2 \rangle$ for $p^*_\ell \geq 0.9$, 1.1, 1.3, 1.5 GeV$/c$ and the central moments $\langle (m_X^2 - \langle m_X^2 \rangle)^2 \rangle$ and $\langle (m_X^2 - \langle m_X^2 \rangle)^3 \rangle$ both for $p^*_\ell \geq 0.8$, 1.0, 1.2, 1.4 GeV$/c$.

Furthermore, we use the average B meson lifetime $\tau_B = f_0\tau_0 + (1 - f_0)\tau_\pm = (1.585 \pm 0.007)$ ps with the lifetimes of neutral and charged B mesons τ_0 and $\tau_\pm$ and the relative production rate, $f_0 = 0.491 \pm 0.007$, as quoted in [14].

D. Theoretical uncertainties

Theoretical uncertainties for the prediction of the moments $\vec{M}_{\rm theo}$ are estimated by variation of the parameters. The standard-model parameters, that are all except c'_R, are treated as in [8]. The uncertainty in the nonperturbative part are estimated by varying the corresponding parameters μ_π^2 and μ_G^2 by 20% and ρ_D^3 and ρ_{LS}^3 by 30% around their expected value. For the uncertainties of the perturbative corrections $\alpha_S = 0.22$ is varied up and down by 0.1 for the hadronic-mass moments and 0.04 for the lepton energy moments and the uncertainties of the perturbative correction of the quark masses m_b and m_c are estimated by varying them 20 MeV$/c^2$ up and down. An additional error of 1.4% is added to $|V_{cb}|$ from the fit for the uncertainty in the expansion of the semileptonic rate Γ_{SL}, which is not included in the fit, but quoted separately as theoretical uncertainty on $|V_{cb}|$.

Additionally the influence of the right-handed contributions on the theoretical uncertainties in the predictions of the moments has to be included. Varying c'_R in a similar fashion as the other parameters, around the a priory estimate of zero showed only very little influence on the fit results. Because of the fact that the right-handed contributions are included up to $1/m_b^2$ in the nonperturbative and $\mathcal{O}(\alpha_s)$ in the perturbative corrections for all moments, the uncertainties in the prediction of the moments are not sizable and thus the variation of c'_R has to be rather small. For the final results the variation of c'_R has not been included, because of no influence on the significant digits.

IV. RESULTS

Table I shows the fit results and Table II the corresponding standard-model fit results, which were obtained by performing the fit with c'_R fixed to zero. Figures 1 and 2 show a comparison of the fit results with the measured moments for the lepton moments and the hadronic-mass moments, respectively. The uncertainties $\Delta_{\rm exp}$ and $\Delta_{\rm theor}$ are the expected experimental and theory errors determined by toy Monte-Carlo studies (see [8]) while $\Delta_{\rm tot}$ is the total uncertainty provided by the fit. Figure 3 shows the $\Delta\chi^2 = 1$ contours in the ($c'_{\rm R}$, $|V_{cb}|$), ($c'_{\rm R}$, m_b), and ($c'_{\rm R}$, m_c) planes for the results obtained in the fit.

The estimate for $c'_R = 0.05^{+0.33}_{-0.50}$ is consistent with the standard-model prediction of zero, but the uncertainty reveals an unexpected low sensitivity of the semileptonic fit to possible right-handed contributions. We state the upper relative admixture limit of $|c'_R| = 0.9$ at 95% confidence level.

The extracted value of $|V_{cb}| = (43^{+5}_{-6}) \times 10^{-3}$ is consistent with the value from the standard-model fit, but its uncertainty is quite different. In our fit, this is due to the influence of a sizable c'_R uncertainty on the determination of $|V_{cb}|$ in (4), which becomes evident in the contour plot of the (c'_R, $|V_{cb}|$) plane, showing a shallow and steep covariance ellipse.

TABLE I. Results of the full fit for c'_R and the canonical set of parameters $|V_{cb}|$, m_b, m_c, $\mathcal{B}$, μ_π^2, μ_G^2, ρ_D^3 and ρ_{LS}^3, separated by experimental and theoretical uncertainties. For $|V_{cb}|$ we take into account an additional error of 1.4% for the uncertainty in the expansion of the semileptonic rate $\Gamma_{\rm SL}$. Correlation coefficients for the parameters are listed below. The uncertainties $\Delta_{\rm exp}$ and $\Delta_{\rm theor}$ are the expected experimental and theory errors determined by toy Monte-Carlo studies (see [8]) while $\Delta_{\rm tot}$ is the total uncertainty provided by the fit.

	c'_R	$\lvert V_{cb}\rvert \times 10^{-3}$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]
Results	0.0517	42.61	4.588	1.133	10.674	0.472	0.303	0.192	−0.122
$\Delta_{\rm exp}$	0.1335	2.00	0.000	0.000	0.241	0.032	0.052	0.015	0.096
$\Delta_{\rm theo}$	0.4209	5.55	0.110	0.149	0.068	0.094	0.035	0.056	0.012
$\Delta_{\Gamma_{\rm SL}}$		0.60							
$\Delta_{\rm tot}$	$^{+0.3356}_{-0.4962}$	$^{+4.76}_{-6.34}$	$^{+0.081}_{-0.158}$	$^{+0.112}_{-0.226}$	$^{+0.240}_{-0.274}$	$^{+0.121}_{-0.086}$	$^{+0.061}_{-0.064}$	$^{+0.095}_{-0.043}$	$^{+0.095}_{-0.099}$
c'_R	1.00	0.99	0.78	0.74	0.67	−0.79	0.33	−0.84	0.21
$\lvert V_{cb}\rvert$		1.00	0.75	0.72	0.72	−0.77	0.29	−0.82	0.22
m_b			1.00	0.99	0.64	−0.72	0.28	−0.68	0.17
m_c				1.00	0.65	−0.70	0.16	−0.64	0.20
$\mathcal{B}$					1.00	−0.47	0.16	−0.52	0.14
μ_π^2						1.00	−0.21	0.84	−0.14
μ_G^2							1.00	−0.31	0.03
ρ_D^3								1.00	−0.29
ρ_{LS}^3									1.00

TABLE II. Results of the standard-model fit with c'_R fixed to zero.

	$\lvert V_{cb}\rvert \times 10^{-3}$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]
Results	41.93	4.578	1.120	10.654	0.482	0.300	0.198	−0.125
$\Delta_{\rm exp}$	0.44	0.058	0.085	0.175	0.023	0.040	0.015	0.081
$\Delta_{\rm theo}$	0.38	0.045	0.067	0.061	0.055	0.043	0.027	0.049
$\Delta_{\Gamma_{\rm SL}}$	0.59							
$\Delta_{\rm tot}$	$^{+0.83}_{-0.83}$	$^{+0.074}_{-0.070}$	$^{+0.106}_{-0.107}$	$^{+0.185}_{-0.185}$	$^{+0.058}_{-0.060}$	$^{+0.059}_{-0.059}$	$^{+0.031}_{-0.031}$	$^{+0.094}_{-0.094}$
$\lvert V_{cb}\rvert$	1.00	−0.35	−0.21	0.67	0.29	−0.39	0.35	0.06
m_b		1.00	0.98	0.25	−0.26	0.06	−0.08	0.01
m_c			1.00	0.29	−0.29	−0.11	−0.07	0.07
$\mathcal{B}$				1.00	0.14	−0.08	0.10	0.00
μ_π^2					1.00	0.08	0.52	0.04
μ_G^2						1.00	−0.07	−0.04
ρ_D^3							1.00	−0.20
ρ_{LS}^3								1.00

To compare the quality of the fits the P value (prob(χ^2, $n_{\rm dof}$)) suits best, because the fits differ by their number of degrees of freedom and thus the χ^2 value alone is not sufficient. For the fit with c'_R we find $\chi^2 = 7.299$ with 17 degrees of freedom and thus prob$(7.299, 17) = 0.979$ and for the standard-model fit prob$(7.312, 18) = 0.987$, which shows neither improvement nor worsening.

The uncertainty of the result for c'_R is dominated by the theory error $\Delta_{\rm theo} = 0.42$ in Table I compared to $\Delta_{\rm exp} = 0.13$. As a consequence including additional experimental data, e.g. from Belle, will not improve the limit for a possible right-handed contribution at this point. We investigated the theory error by changing the variation of the parameters as described in Sec. III D. It turned out that the theory error cannot be pinned down to the uncertainty of a specific parameter. Furthermore, decreasing all theory errors had only little effect on the theory error of c'_R. We come to the conclusion that the shape of the considered spectra and hence their moments are too similar for a left and right-handed $b \to c$ current, ending up in a low sensitivity of c'_R and a weak constraint therein. Thus, improving the theoretical description, either for the standard-model part or the right-handed contributions, e.g. including the $1/m_b^3$ and Brodsky-Lepage-Mackenzie corrections of the right-handed current, will not reduce the uncertainty of c'_R significantly in the performed moment analysis.

V. RIGHT-HANDED ADMIXTURE FROM EXCLUSIVE DECAYS

It is interesting to note that the value of $|V_{cb}|$ extracted in this way $|V_{cb}| = (43^{+5}_{-6}) \times 10^{-3}$ is in agreement with $|V_{cb}|$

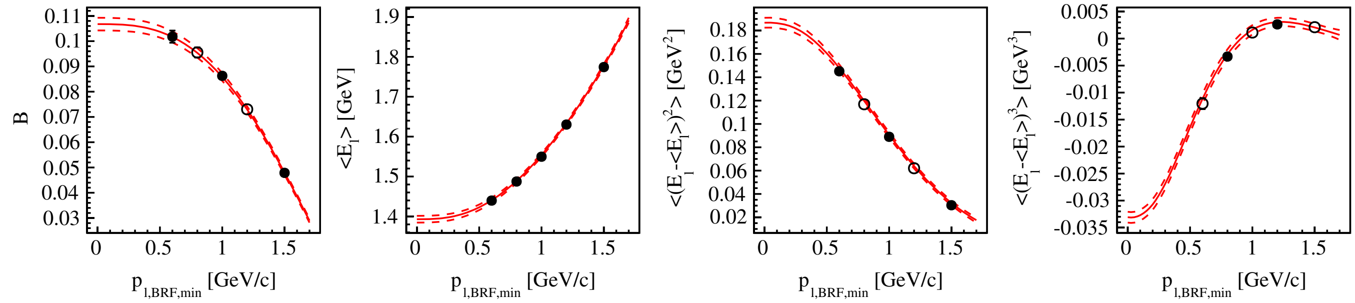

FIG. 1 (color online). The measured lepton moments (●/○) compared with the result of the simultaneous fit (solid red line) as function of the minimal lepton momentum $p^*_{\ell,\min}$. The measurements included in the fit are marked by solid data points (●). The dashed lines indicate the theoretical fit uncertainty obtained by the variation of the fit parameters in order to convert their theoretical uncertainty into an error of the moments.

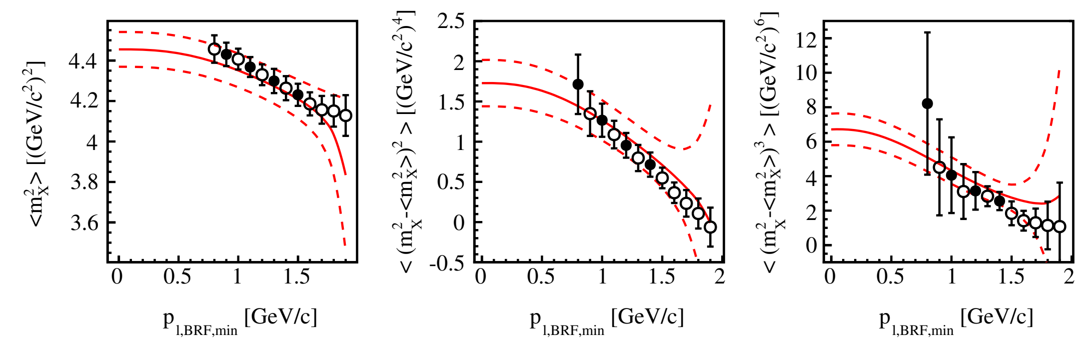

FIG. 2 (color online). The measured hadronic-mass moments (●/○) compared with the result of the simultaneous fit (solid red line) as function of the minimal lepton momentum $p^*_{\ell,\min}$. The measurements included in the fit are marked by solid data points (●). The dashed lines indicate the theoretical fit uncertainty obtained by the variation of the fit parameters in order to convert their theoretical uncertainty into an error of the moments.

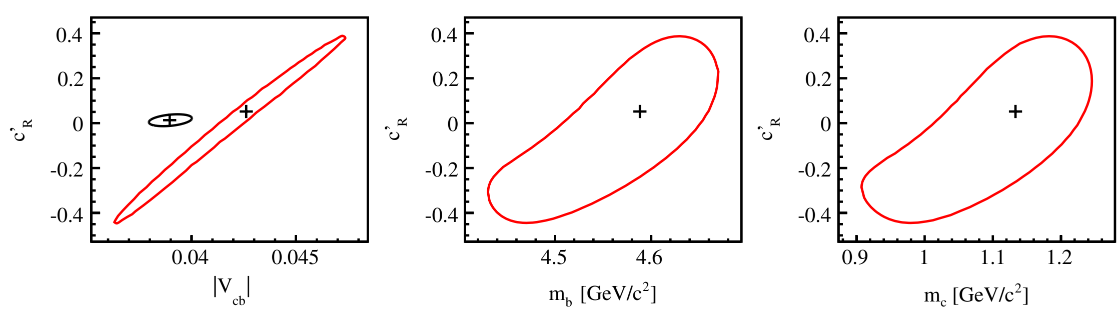

FIG. 3 (color online). The $\Delta\chi^2 = 1$ contours in the $(c'_R, |V_{cb}|)$, (c'_R, m_b), and (c'_R, m_c) planes for the results obtained in the fit. The small black contour in the $(c'_R, |V_{cb}|)$ plot shows the result from exclusive decays ($c'_R = 0.01 \pm 0.03$) as computed in Sec. V.

from exclusive decays, from which $|V_{cb}| = (38.6 \pm 1.3) \times 10^{-3}$ (from $\bar{B} \to D^* \ell^- \nu$) [15] is obtained, while the value from the standard-model fit $|V_{cb}| = (41.9 \pm 0.8) \times 10^{-3}$ is not. This is due to the low sensitivity of c'_R and thus the large uncertainty of the extracted value. In addition, also the exclusive decays allow us to constrain a possible right-handed admixture [16,17].

The most straightforward way of obtaining this information is to study the exclusive differential rates at the point of maximal momentum transfer to the leptons, corresponding to equal four-velocities of the initial and final hadron. We consider the decays $\bar{B} \to D \ell^- \nu$ and $\bar{B} \to D^* \ell^- \nu$. The corresponding rates in the standard model are usually parametrized in terms of two form factors; the relevant expressions close to the point of maximal momentum transfer read

$$\begin{aligned} \frac{d\Gamma^{B\to D}}{dw} &= \Gamma_0 16 r^3 (r+1)^2 (w^2-1)^{3/2} (|V_{cb}| \mathcal{G}(w))^2, \\ \frac{d\Gamma^{B\to D^*}}{dw} &= \Gamma_0 192 r_*^3 (r_* - 1)^2 (w^2-1)^{1/2} (|V_{cb}| \mathcal{F}(w))^2 \end{aligned} \tag{6}$$

where $w = v \cdot v'$ is the scalar product of the hadronic velocities, $r = m_D/m_B$, $r_* = m_{D^*}/m_B$, and $\Gamma_0 = G_F^2 m_B^5/(192\pi^3)$.

The information which is extracted by the experiments in the context of the $|V_{cb}|^2$ determination is

$$\lim_{w\to 1} \frac{d\Gamma^{B\to D}}{dw} \frac{1}{\Gamma_0 16 r^3 (r+1)^2 (w^2-1)^{3/2}}, \qquad \lim_{w\to 1} \frac{d\Gamma^{B\to D^*}}{dw} \frac{1}{\Gamma_0 192 r_*^3 (r_*-1)^2 (w^2-1)^{1/2}} \tag{7}$$

which in the standard model is the product of the form factors at $w = 1$ and $|V_{cb}|$. Combining this with a theoretical prediction of the form factors at $w = 1$ one extracts $|V_{cb}|$.

At the nonrecoil point $w = 1$ the $B \to D$ transition is completely dominated by the vector current, while the $B \to D^*$ decay is proportional to the axial vector current. Thus, including a right-handed admixture, the information extracted from (7) is $|c_L + c_R||V_{cb}|\mathcal{G}(1)$ for the case of the $B \to D$ transition and $|c_R - c_L||V_{cb}|\mathcal{F}(1)$ for $B \to D^*$. The current experimental data yield [18]:

$$|c_L + c_R||V_{cb}|\mathcal{G}(1) = (42.4 \pm 1.56) \times 10^{-3} \tag{8}$$

$$|c_R - c_L||V_{cb}|\mathcal{F}(1) = (35.41 \pm 0.52) \times 10^{-3} \tag{9}$$

Using the lattice data (which are also used to extract $|V_{cb}|$) [19–21]

$$\mathcal{G}(1) = 1.074 \pm 0.024, \tag{10}$$

$$\mathcal{F}(1) = 0.921 \pm 0.025, \tag{11}$$

we can extract the ratio $c_R' = c_R/c_L$ to be

$$c_R' = 0.01 \pm 0.03, \tag{12}$$

with the assumption of no sizable correlations between the experimental measurements of the right-hand sides of Eqs. (8) and (9) as well as between the form factor values given in (10) and (11). The value for $|V_{cb}|$ extracted from Eqs. (8) and (9) is found to be $|V_{cb}|_{\text{excl}} = (39.0^{+1.1}_{-1.0}) \times 10^{-3}$ which has to be compared to $|V_{cb}|_{\text{excl}} = (38.8 \pm 1.0) \times 10^{-3}$ when setting $c_R' = 0$ in Eqs. (8) and (9).

Recently also nonlattice QCD estimates have been performed for the relevant form-factor values [22,23]. Both values of the form factors turn out to be smaller by 1 standard deviation than the ones from lattice QCD, however, the uncertainties of these sum rule estimates are larger than the quoted lattice QCD uncertainty. Although both values are smaller, their ratio remains almost the same, and hence the conclusion on c_R' remains unaltered, since the extraction of c_R' depends only on the ratio of the form-factor values.

The result of c_R' is compatible with zero and, in fact, more restrictive than the determination from inclusive decays. Obviously the exclusive decay gives access to data separated by the handedness of the $b \to c$ current in contrast to the inclusive decay, leading to a better limit on possible right-handed contributions.

In turn, we can use the result for c_R' to determine $|V_{cb}|_{\text{incl}}$ and compare with $|V_{cb}|_{\text{excl}}$. This can be done by imposing a Gaussian constraint of $c_R' = 0.01 \pm 0.03$ in the fit with a possible right-handed current. The result $|V_{cb}|_{\text{incl}} = (42.0 \pm 0.9) \times 10^{-3}$ compared to $|V_{cb}|_{\text{excl}} = (39.0^{+1.1}_{-1.0}) \times 10^{-3}$ exhibits a tension by 3.0×10^{-3} of the central values. Determining $|V_{cb}|$ by (8) and (9) with c_R' set to zero gives $|V_{cb}|_{\text{excl}}(c_R' = 0) = (38.8 \pm 1.0) \times 10^{-3}$ and allows us to examine the differences in the tensions between inclusive and exclusive decays with and without a right-handed current, by comparing this value to the standard-model fit value $|V_{cb}|_{\text{incl}}(c_R' = 0) = (41.9 \pm 0.8) \times 10^{-3}$ (see Table II) yielding a tension of about 3.1×10^{-3} of the central values. As a consequence, the difference in the central values between $|V_{cb}|$ exclusive and inclusive is slightly reduced, and more importantly, the uncertainty on $|V_{cb}|$ exclusive is considerably larger when allowing for a right-handed admixture resulting in a smaller significance of the observed effect. In our analysis, which is using only the inclusive *BABAR* data, the difference between exclusive and inclusive is reduced from a 2.4σ to a 2.1σ effect.

VI. SUMMARY

We have performed a full-fledged fit to moments of the lepton-energy and hadronic-mass distribution of semileptonic $\bar{B} \to X_c \ell^- \bar{\nu}$ decays, including a possible right-handed admixture to the $b \to c$ current. We have considered the nonstandard contributions up to $1/m_b^2$ in the nonperturbative and $\mathcal{O}(\alpha_s)$ in the perturbative corrections. The corresponding fit in the framework of the standard model yields the most precise determination of $|V_{cb}|$, due to the elaborated theoretical description and the precise measurements of the B factories [15]. Our fit, including a right-handed admixture, is in agreement with the standard model assumption of zero for a right-handed contribution. Unfortunately, the result $c_R' = 0.05^{+0.33}_{-0.50}$ reveals a low sensitivity of the fit to a right-handed contribution, compelling us to state the upper relative admixture limit of $|c_R'| = 0.9$ at 95% confidence level. The moments of the spectra used in the fit are too similar for right- and left-handed contributions, resulting in the quoted low sensitivity and weak bound of c_R'.

Exclusive decays are competitive in the determination of $|V_{cb}|$, given the precise values for the form factors at the nonrecoil point obtained from lattice QCD calculations. The same precise values from lattice QCD calculations can be used to obtain a constraint on c_R', which is considerably stronger than the one obtained from inclusive decays: $c_R' = 0.01 \pm 0.03$. Using this result to determine $|V_{cb}|_{\rm incl}$ we can compare the tension between $|V_{cb}|_{\rm incl}$ and $|V_{cb}|_{\rm excl}$ without a right-handed current and with a right-handed current contribution as from exclusive decays. A right-handed current reduces the tension by about 3% and its significance from a 2.4σ to a 2.1σ effect.

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