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 $\bar{B} \to X_c l^- \bar{\nu}$ 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 (HQE) up to order $1/m_b^2$ and perturbative corrections. We find $c_R = 0.05_{-0.50}^{+0.33}$ in agreement with the standard-model prediction of zero. Additionally, we give a contraint on a possible right-handed admixture from exclusive decays, which is with a value of $c^c_R = 0.01\pm0.03$ 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 $c_R = 0.01\pm0.03$.

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 CKM 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 non-standard 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 righthanded 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 with the MSSM.

In the next section we recapitulate the theoretical input and fix our notation. In section [II] we perform the analysis based on BABAR data. In section [III] we discuss our result and compare them in section [IV] to limits from exclusive decays. Finally, in section [V] 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 $\text{SU}(3)_{\text{QCD}} \times \text{SU}(2)_{\text{weak}} \times U(1)_Y$. 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 $\text{SU}(3)_{\text{QCD}} \times \text{SU}(2)_{\text{weak}} \times U(1)_Y \to \text{SU}(3)_{\text{QCD}} \times U(1)_{\text{em}}$ and after running down to the scale of the $b$-quark mass one finds for the effective interaction [2,3]

$$ \mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} J_{\mu,\nu} J^{\mu}_{\nu}, $$

where $J^{\mu}_{\nu} = \bar{c} \gamma^\mu P_- \nu$ is the usual leptonic current and $J_{h,\nu}$ is the generalized hadronic $b \to c$ current which is
given by
\[ J_{h,\mu} = c_L \bar{c} \gamma_\mu P_- b + c_R \bar{c} \gamma_\mu P_+ b \]
\[ + g_L \bar{c} i D^\mu_P P_- b + g_R \bar{c} i D^\mu_P P_+ b \]
\[ + d_L i \partial^\mu (\bar{c} i \sigma_{\mu\nu} P_- b) + d_R i \partial^\mu (\bar{c} i \sigma_{\mu\nu} P_+ b), \]
where \( P_\pm \) denotes the projector on positive/negative chirality and \( D_P \) 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 \( \Lambda \) 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].

In the following analysis we restrict ourselves to an investigation of the parameter \( c_L \). 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 \( c_R = c_L/c_R \).

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 [7] using the HQEFitter package [8]. It is based on the \( \chi^2 \) minimization,
\[ \chi^2 = \left( \bar{M}_{\text{exp}} - \bar{M}_{\text{theo}} \right)^T C^{-1}_{\text{tot}} \left( \bar{M}_{\text{exp}} - \bar{M}_{\text{theo}} \right), \]
with the included measured moments \( \bar{M}_{\text{exp}} \), the corresponding theoretical prediction of these moments \( \bar{M}_{\text{theo}} \), and the total covariance matrix \( C_{\text{tot}} \) defined as the sum of the experimental (\( C_{\text{exp}} \)) and the theoretical (\( C_{\text{theo}} \)) covariance matrix, respectively.

In the analysis of [2] the theoretical prediction for the moments \( \bar{M}_{\text{HQE}} \) are calculated perturbatively in a Heavy-Quark Expansion (HQE) in the kinetic-mass scheme up to \( \mathcal{O}(1/m_c^2) \) with perturbative contributions [9,10] 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 \( \mu^2 \) and \( \mu_G^2 \) at \( \mathcal{O}(1/m_c^2) \) in the HQE, and, at \( \mathcal{O}(1/m_b^2) \), the parameters \( \rho_D^2 \) and \( \rho_{LS}^2 \).

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 \( c_R^p \) for the new contributions to test. Thus the theoretical prediction of the moments depends on seven parameters to fit:
\[ \bar{M}_{\text{theo}} = \bar{M}_{\text{theo}}(c_R^p, m_b, m_c, \mu^2, \mu_G^2, \rho_D^2, \rho_{LS}^2). \]

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 \( |V_{cb}|, c_L, c_R^p \) only two are independent, since \( c_L \) can be absorbed into \( |V_{cb}| \). To this end we choose to define
\[ |V_{cb}| \bar{b} L \gamma_\mu c_L \rightarrow |V_{cb}| (\bar{b} L \gamma_\mu c_L + c_R^p \bar{b} R \gamma_\mu c_R). \]

For the determination of \( |V_{cb}| \) the fit uses a linearized form of the semileptonic rate \( \Gamma_{SL} \) expanded around a-priori estimates of the HQE parameters [9]:
\[ |V_{cb}| = \frac{0.0417}{\sqrt{\frac{B(\bar{b} \rightarrow X_L \ell^- \nu)}{0.1032 \tau_B [1 + 0.30(\alpha_s(m_b) - 0.22)]}} \left[ 1 - 0.66(m_b - 4.60) + 0.39(m_c - 1.15) \right] + 0.013 \left( \rho_D^2 - 0.40 \right) + 0.99 (\rho_D^2 - 0.20) + 0.05 (\rho_{LS}^2 - 0.35) - 0.01 (\rho_{LS}^2 + 0.15) + 0.341 c_R^p}. \]

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

The total branching fraction \( B(\bar{B} \rightarrow X_L \ell^- \nu) \) in the fit is extrapolated from measured partial branching fractions \( B_{\ell, \min} (\bar{B} \rightarrow X_L \ell^- \tau) \), with \( \rho_{\ell, \min} \). This is done by comparison with the HQE prediction with the relative decay fraction (r.h.s.):
\[ \frac{B_{\ell, \min} (\bar{B} \rightarrow X_L \ell^- \nu)}{B(\bar{B} \rightarrow X_L \ell^- \nu)} = \int_{\rho_{\ell, \min}}^{\rho_{\ell, \max}} \frac{dE}{\rho_{\ell, \max}} \int_0^{\bar{M}_{\text{exp}}} \frac{d\bar{M}}{dE}. \]

Thus the total branching fraction can be introduced as a free parameter in the fit. By adding the average B-meson lifetime \( \tau_B \) (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:

- Lepton energy moments measured by BABAR \cite{12}. We use the partial branching fraction $B_{\nu_{\mu},\mu}$ at the minimal lepton momentum $p_{\ell,min}^t \geq 0.6, 1.0, 1.5$ GeV/c, the moments $\langle E_{\ell} \rangle$ for $p_{\ell}^t \geq 0.6, 0.8, 1.0, 1.2, 1.5$ GeV/c, the central moments $\langle (E_{\ell} - \langle E_{\ell} \rangle)^2 \rangle$ for $p_{\ell}^t \geq 0.6, 1.0, 1.5$ GeV/c and $\langle (E_{\ell} - \langle E_{\ell} \rangle)^3 \rangle$ for $p_{\ell}^t \geq 0.8, 1.2$ GeV/c.

- Hadronic mass moments measured by BABAR \cite{7}. We use the moment $\langle m_{X}^2 \rangle$ for $p_{\ell}^t \geq 0.9, 1.1, 1.3, 1.5$ 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 $p_{\ell}^t \geq 0.8, 1.0, 1.2, 1.4$ 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 $\tau_{0}$ and $\tau_{\pm}$ and the relative production rate, $f_0 = 0.491 \pm 0.007$, as quoted in \cite{15}.

D. Theoretical Uncertainties

Theoretical uncertainties for the prediction of the moments $\hat{M}_{\text{theo}}$ are estimated by variation of the parameters. The standard model parameters, that are all except $c_{R}$, are treated as in \cite{7}. The uncertainty in the non-perturbative part are estimated by varying the corresponding parameters $\mu^2$ and $\mu^2_G$ by 20\% and $\rho^2$ and $\rho^2_{G}$ 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 $m_q$ 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 $\Gamma_{SL}$, 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 priori estimate of zero showed only very little influence on the fit results. Due to the fact that the right-handed contributions are included up to $1/m_b^2$ in the non-perturbative
and $O(\alpha_s)$ in the perturbative corrections for all moments, the uncertainties in the prediction of the moments are not sizable and thus the variation of $c_R^f$ has to be rather small. For the final results the variation of $c_R^f$ 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 $c_R^f$ fixed to zero. Figs. 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 $\Delta_{\text{exp}}^c$ and $\Delta_{\text{theor}}$ are the expected experimental and theory errors determined by Toy-MC studies (see [14]) while $\Delta_{\text{tot}}^c$ is the total uncertainty provided by the fit.

The estimate for $c_R^f = 0.05 \pm 0.50$ 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 confidence level.

The value of $|V_{cb}| = (38.6 \pm 1.3) \cdot 10^{-3}$ is in agreement with $|V_{cb}|$ from exclusive decays, from which $|V_{cb}| = (41.9 \pm 0.8) \cdot 10^{-3}$ is not. This is due to the low sensitivity of $c_R^f$ and thus the large uncertainty of the extracted value. In addition, also the exclusive decays allow us to constrain a possible right-handed admixture.

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 $B \rightarrow D^{\ast}f^\nu$ and $B \rightarrow D^{\ast}f^\nu$. 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

$$\frac{d\Gamma(B \rightarrow D)}{dw} = \Gamma_0 \frac{1}{2}(r + 1)^2(u^2 - 1)^{3/2}|V_{cb}G(w)|^2,$$

$$\frac{d\Gamma(B \rightarrow D^\ast)}{d\omega} = \Gamma_0 \frac{1}{2}(r - 1)^2(u^2 - 1)^{3/2}|V_{cb}F(w)|^2,$$

where $w=\nu^\nu$ is the scalar product of the hadronic velocities, $r=m_D/m_B$, $u=m_{D^\ast}/m_B$, and $\Gamma_0=G_\pi^2m_B^3/(192\pi^3)$. The information which is extracted by the experiments in the context of the $|V_{cb}|^2$ determination is

$$\lim_{w\rightarrow 1} \frac{d\Gamma(B \rightarrow D)}{dw} = \frac{1}{2\Gamma_0 (r + 1)^2(u^2 - 1)^{3/2}},$$

$$\lim_{w\rightarrow 1} \frac{d\Gamma(B \rightarrow D^\ast)}{d\omega} = \frac{1}{2\Gamma_0 (r - 1)^2(u^2 - 1)^{3/2}}$$

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 non-recoil point $w=1$ the $B \rightarrow D$ transition is completely dominated by the vector current, while the $B \rightarrow D^\ast$ decay is proportional to the axial vector current. Thus, including a right-handed admixture, the information extracted from (7) is $|c_L^f + c_R^f||V_{cb}|G(1)$ for the case of the $B \rightarrow D$ transition and $|c_R^f - c_L^f||V_{cb}|F(1)$ for the $B \rightarrow D^\ast$. The current experimental data yield [15]:

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

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

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

$$G(1) = 1.074 \pm 0.024 \quad (10)$$

$$F(1) = 0.921 \pm 0.025 \quad (11)$$

V. RIGHT-HANDED ADMIXTURE FROM EXCLUSIVE DECAYS

It is interesting to note that the value of $|V_{cb}|$ extracted in this way $|V_{cb}| = (43.8 \pm 0.6) \cdot 10^{-3}$ is in agreement with $|V_{cb}|$ from exclusive decays, from which $|V_{cb}| = (38.6 \pm 1.3) \cdot 10^{-3}$ (from $B \rightarrow D^{\ast}\ell^\nu$) is obtained, while the value from the standard-model fit $|V_{cb}| = (41.9 \pm 0.8) \cdot 10^{-3}$ is not. This is due to the low sensitivity of $c_R^f$ and thus the large uncertainty of the extracted value. In addition, also the exclusive decays allow us to constrain a possible right-handed admixture.
Table I: Results of the full fit for $c_R^t$ and the canonical set of parameters $|V_{cb}|$, $m_c$, $m_b$, $\beta$, $\mu^2$, $\mu^2_{\rho}$, $\rho_D$ and $\rho_{LS}^2$, 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 $\Gamma_{SL}$. Correlation coefficients for the parameters are listed below. The uncertainties $\Delta_{\text{exp}}$ and $\Delta_{\text{theor}}$ are the expected experimental and theory errors determined by Toy-MC studies (see [13]) while $\Delta_{\text{tot}}$ is the total uncertainty provided by the fit.

| $c_R^t$ | $|V_{cb}|$ | $m_b$ [GeV/$c^2$] | $m_c$ [GeV/$c^2$] | $\beta$ [%] | $\mu^2$ [GeV$^2$] | $\mu^2_{\rho}$ [GeV$^2$] | $\rho_D$ [GeV$^3$] | $\rho_{LS}^2$ [GeV$^3$] |
|---------|-----------|-----------------|-----------------|------------|----------------|-----------------|-----------------|-----------------|
| Results | 0.0517    | 42.61           | 4.588           | 1.133      | 0.107         | 0.033           | 0.203           | 0.015           |
| $\Delta_{\text{exp}}$ | 0.1335    | 2.00            | 0.000           | 0.241      | 0.032         | 0.052           | 0.192           | -0.122          |
| $\Delta_{\text{theor}}$ | 0.4209    | 5.55            | 0.110           | 0.068      | 0.094         | 0.035           | 0.056           | 0.012           |
| $\Delta_{\text{tot}}$ | +0.3356   | +4.76           | +0.081          | +0.112     | +0.240        | +0.121          | +0.061          | +0.095          |

Table II: Results of the standard model fit with $c_R^t$ fixed to zero.

| $|V_{cb}|$ | $m_b$ [GeV/$c^2$] | $m_c$ [GeV/$c^2$] | $\beta$ [%] | $\mu^2$ [GeV$^2$] | $\mu^2_{\rho}$ [GeV$^2$] | $\rho_D$ [GeV$^3$] | $\rho_{LS}^2$ [GeV$^3$] |
|----------|-----------------|-----------------|------------|----------------|-----------------|-----------------|-----------------|
| Results  | 41.93           | 4.578           | 1.120      | 0.107         | 0.033           | 0.203           | 0.015           |
| $\Delta_{\text{exp}}$ | 0.44         | 0.058           | 0.085      | 0.175         | 0.023           | 0.040           | 0.008           |
| $\Delta_{\text{theor}}$ | 0.38         | 0.045           | 0.067      | 0.061         | 0.055           | 0.043           | 0.007           |
| $\Delta_{\text{tot}}$ | +0.239       | +0.074          | +0.106     | +0.185        | +0.058          | +0.059          | +0.003          |

Figure 3: The $\Delta\chi^2 = 1$ contours in the $(c_R^t, |V_{cb}|)$, $(c_R^t, m_b)$ and $(c_R^t, m_c)$ plane for the results obtained in the fit. The small black contour in the $(c_R^t, |V_{cb}|)$ plot shows the result from exclusive decays ($c_R^t = 0.01 \pm 0.03$) as computed in section V.
we can extract the ratio \( c_R = c_R / c_L \) to be

\[
c'_R = 0.01 \pm 0.03
\]

with the assumption of no sizable correlations between the experimental measurements of the right-hand sides of Eqsns. (3) and (9) as well as between the form factor values given in Eqsns. (10) and (11). The value for \( |V_{cb}| \) extracted from Eqsns. (3) and (9) is found to be

\[ |V_{cb}| = (39.0_{-1.0}^{+1.1}) \times 10^{-3} \]

which has to be compared to \( |V_{cb}|_{\text{excl}} = (38.8 \pm 1.0) \times 10^{-3} \) when setting \( c'_R = 0 \) in Eqsns. (3) and (9).

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 \( b \rightarrow c \) 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 by (8) and (9) with \( c'_R \) set to zero gives

\[ |V_{cb}|_{\text{incl}}(c'_R = 0) = (38.8 \pm 1.0) \times 10^{-3} \]

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 \( \times 10^{-3} \) 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 \( \bar{B} \rightarrow K^* \ell^+\nu \) data, the difference between exclusive and inclusive data is reduced from a 2.4 \( \sigma \) to a 2.1 \( \sigma \) effect.

VI. SUMMARY

We have performed a full-fledged fit to moments of the lepton-energy and hadronic-mass distribution of semileptonic \( \bar{B} \rightarrow X_c \ell^+\nu \) decays, including a possible right-handed admixture to the \( b \rightarrow c \) current. We have considered the non-standard contributions up to \( 1/m_B^2 \) in the non-perturbative and \( O(\alpha_s) \) 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 \( c'_R = 0.05^{+0.30}_{-0.26} \) 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 non-recoil 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 \( |V_{cb}|_{\text{incl}} \) we can compare the tension between \( |V_{cb}|_{\text{incl}} \) and \( |V_{cb}|_{\text{excl}} \) 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 2.4 \( \sigma \) to a 2.1 \( \sigma \) effect.

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