PROCEEDINGS OF SCIENCE

Magnitudes of V_{xb} CKM matrix elements

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We review the current status of the absolute values of the CKM matrix elements V_{xb}, with particular attention to latest determinations.

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1. Introduction

The Cabibbo-Kobayashi-Maskawa (CKM) matrix parameterizes the couplings between flavors of quarks under weak interactions. The values of the CKM matrix elements are not predicted by the Standard Model (SM), and, in the last decade, a large effort has gone towards their determination, driven by increasingly higher statistics at new and improved facilities and by theoretical advances. We summarize the current status of the absolute values of the CKM matrix elements V_{xb}, with particular attention to latest developments. For recent theoretical reviews and for notations, see e.g. [1, 2].

2. The $|V_{cb}|$ determination

Currently, $|V_{cb}|$ is inferred from semi-leptonic decays where the final lepton is an electron or a muon, $b \to \tau$ semileptonic decays being mostly studied for their sensitivity to New Physics (NP). In the massless limit, the exclusive $\bar{B} \to D^{(*)} l \bar{\nu}$ decays depend only on one form factor $\mathscr{G}(\omega)$ ($\mathscr{F}(\omega)$), where ω is the product of the velocities of the hadrons in the HQET framework. The determination of non-perturbative contributions to the form factors is the major theoretical challenge. The $\bar{B} \to D^* l \bar{\nu}$ decay is more advantageous for the exclusive estimate of $|V_{cb}|$, since it occurs at an higher rate than $\bar{B} \to D l \bar{\nu}$, and non-perturbative, linear corrections to the form factor $\mathscr{F}$ are absent at zero recoil. Lattice corrections to $\mathscr{F}(\omega)$ at finite momentum transfer ($\omega = 1.075$) are available in the quenched approximation [3]; combined with 2008 BaBar data [4] they give

$$|V_{cb}| = (37.4 \pm 0.5_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-3} \tag{2.1}$$

with a rather small nominal error. Lattice corrections to $\mathscr{G}(\omega)$ at the same finite momentum transfer are also available, in the quenched approximation [5, 6]. By using 2009 BaBar data [7], a slightly higher value is found

$$|V_{cb}| = (41.6 \pm 1.8 \pm 1.4 \pm 0.7_{\rm FF}) \times 10^{-3} \tag{2.2}$$

The errors are statistical, systematic and due to the theoretical uncertainty in the form factor $\mathscr{G}$, respectively. Unquenched calculations are only available at $\omega = 1$, and have been performed by the FNAL/MILC Collaboration. The Heavy Flavor Averaging Group (HFAG) experimental averages [8], combined with the latest update for $\mathscr{F}(1)$ [9], give

$$|V_{cb}| = (39.54 \pm 0.50_{\rm exp} \pm 0.74_{\rm th}) \times 10^{-3} \tag{2.3}$$

and

$$|V_{cb}| = (39.70 \pm 1.42_{\rm exp} \pm 0.89_{\rm th}) \times 10^{-3} \tag{2.4}$$

combined with the less recent unquenched lattice results for $\mathscr{G}(1)$ [10, 11], The two values are in good agreement, although the theoretical error in the determination based on $\bar{B} \to D l \bar{\nu}$ decays is slightly larger and the experimental one more than twice larger. Let us observe that a further update of $\mathscr{F}(1)$ by FNAL/MILC Collaboration has been announced [12], claiming a reduction of discretization effects and of the error on $|V_{cb}|$ down to 1.6%, but no new value for $|V_{cb}|$ has been published until now. Also studies of the form factor $\mathscr{G}(\omega)$ at non-zero recoil are in progress, some

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preliminary results being already available [13]. On the non-lattice side, recent estimates for $\mathscr{F}(1)$ have been reported in the zero-recoil sum rules framework [14], yielding to

$$|V_{cb}| = (41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}) \times 10^{-3} \tag{2.5}$$

combined with the HFAG experimental data fit [8]. The theoretical error is more than twice the error of the lattice determination given in Eq. (2.3), but the budget error from lattice has been questioned [14]. The claim is that existing differences between the power-suppressed deviations from the heavy flavour symmetry in the lattice theory with heavy quarks and in continuum QCD may be compensated by a matching between the two theories that has been performed, at the best, only at lower levels. The most recent non lattice calculation of non-perturbative contributions to $\mathscr{G}(1)$ dates 2004 and combines the heavy quark expansion with expanding around the point where the kinetic energy is equal to the chromomagnetic moment $\mu_\pi^2 = \mu_G^2$ ("BPS" limit) [15]. With this estimate, the PDG finds [16]

$$|V_{cb}| = (40.7 \pm 1.5_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-3} \tag{2.6}$$

in agreement, within the errors, with both lattice determinations (2.2) and (2.4). Semileptonic B decays to orbitally-excited P-wave charm mesons (D^{**}) contribute as a source of systematic error in the $|V_{cb}|$ measurements at the B factories (as previously at LEP), as a background to the direct decay $B^0 \to D^* l \nu$. The knowledge of these semileptonic decays is not complete yet: one example for all, the so called "1/2 versus 3/2" puzzle. Very recently, dynamical lattice computations of the $B \to D^{**} l \nu$ form factors have been attempted, although still preliminary and needing extrapolation to the continuum [17].

In most of the phase space for inclusive $B \to X_q l \nu$ decays, long and short distance dynamics are factorized by means of the heavy quark expansion. However, the phase space region includes a region of singularity, also called endpoint or threshold region, plagued by the presence of large double (Sudakov-like) perturbative logarithms at all orders in the strong coupling[1] and by enhanced non-perturbative effects. The $b \to c$ semileptonic decays are not affected by the small region of singularity in a significant way; in addition, corrections are not expected as singular as in the $b \to u$ case, being cut-off by the charm mass. Recently, a global fit [8] has been performed to the width and all available measurements of moments in $B \to X_c l \nu$ decays, yielding, in the kinetic scheme

$$|V_{cb}| = (41.88 \pm 0.73) \times 10^{-3} \tag{2.7}$$

and in the 1S scheme

$$|V_{cb}| = (41.96 \pm 0.45) \times 10^{-3} \tag{2.8}$$

Each scheme has its own non-perturbative parameters that have been estimated together with the charm and bottom masses. The inclusive averages are in substantial agreement with the values extracted from exclusive decays, within the errors.

[1] for theoretical aspects of threshold resummation in B decays see e.g. [18, 19, 20, 21, 22, 23].

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3. The $|V_{ub}|$ determination

The analysis of exclusive charmless semileptonic decays is currently employed to determine the CKM parameter $|V_{ub}|$, which plays a crucial role in the study of the unitarity constraints. Also here, information about hadronic matrix elements is required via form factors. Among all possible channels, the $B \to \pi l \nu$ mode benefits of more precise branching fraction measurements and is currently the channel of election to determine $|V_{ub}|$ exclusively. In the limit of zero leptonic masses, it is affected by a single form factor $f_+(q^2)$, The first lattice determinations of $f_+(q^2)$ based on unquenched simulations have been obtained by the FNAL/MILC [24] and the HPQCD [25] collaborations and are in substantial agreement. Recent results are also available on a fine lattice (lattice spacing $a \sim 0.04$ fm) in the quenched approximations by the QCDSF collaboration [26]. The measured partial $B \to \pi l \nu$ branching fractions can be directly fit at low and high q^2 according to light-cone sum rules (LCSR) and lattice approaches, respectively, the latter providing generally better fits. Alternatively, theoretical extrapolations to the full q^2 range can be employed, in a simultaneous fit to theoretical results and experimental data. The most recent simultaneous fit to the data over the full q^2 range and the FNAL/MILC lattice results [24] has been performed by BaBar [27] and has given the following average value

$$|V_{ub}| = (3.25 \pm 0.31) \times 10^{-3} \tag{3.1}$$

in agreement with the analogous fit by Belle [28]. The $|V_{ub}|$ determination inferred by using lattice QCD direct calculations, in the kinematic region $q^2 > 16$ GeV^2, with no extrapolations, is also in agreement with the previous value. In the complementary kinematic region, at large recoil, with an upper limit for q^2 varying between 6 and 16 GeV^2, direct LCSR calculations of the semileptonic form factors are available, which have benefited by recent progress in pion distribution amplitudes, NLO and LO higher order twists (see e.g. [29, 30, 31] and Refs. within). The $|V_{ub}|$ estimate are generally higher than the corresponding lattice ones, but still in agreement, within the relatively larger theoretical errors. The latest determination, from BaBar Collaboration [27], using LCSR results below $q^2 = 16$ GeV [29], gives

$$|V_{ub}| = (3.46 \pm 0.06 \pm 0.08^{+0.37}_{-0.32}) \times 10^{-3} \tag{3.2}$$

where the three uncertainties are statistical, systematic and theoretical, respectively. A consistent value has been found by the Belle collaboration [28], using a different LCSR form factor determination [32].

Recently, BaBar and Belle Collaborations have significantly improved the branching ratios of other heavy-to-light semileptonic decays, yielding to an increased precision for $|V_{ub}|$ values inferred by these decays [27]. The $|V_{ub}|$ values extracted from $B^+ \to \omega l^+ \nu$ [27] and $B \to \rho l \nu$ [33] agree with $|V_{ub}|$ determinations inferred from the $B \to \pi l \nu$ decay mode within the errors, which for the $B \to \rho l \nu$ channel are starting to become comparable. Other interesting channels are $B \to \eta^{(\prime)} l \nu$ [34, 35], but a value of $|V_{ub}|$ has not been extracted because the theoretical partial decay rate is not sufficiently precise yet. There has been also recent progress on the form factor evaluation of the $|V_{ub}|$ sensitive $\Lambda_b \to p l \nu$ decay in the LCSR framework [36] and from lattice with static b quarks [37].

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Theory	$\lvert V_{ub}\rvert \times 10^3$
BLNP	$4.40 \pm 0.15^{+0.19}_{-0.21}$
DGE	$4.45 \pm 0.15^{+0.15}_{-0.16}$
ADFR	$4.03 \pm 0.13^{+0.18}_{-0.12}$
GGOU	$4.39 \pm 0.15^{+0.12}_{-0.20}$

Table 1: Comparison of inclusive determinations of $|V_{ub}|$ [8].

The leptonic decay $B \to \tau\nu$ can also provide information on $|V_{ub}|$. Previous data have shown a disagreement of the measured branching ratio with the SM prediction, which has softened significantly with the new data from Belle Collaboration [38].

In principle, the method of extraction of $|V_{ub}|$ from inclusive $\bar{B} \to X_u l \bar{\nu}_l$ decays follows in the footsteps of the $|V_{cb}|$ determination from $\bar{B} \to X_c l \bar{\nu}_l$, but the copious background from the $\bar{B} \to X_c l \bar{\nu}_l$ process, which has a rate about 50 times higher, limits the experimental sensitivity to restricted regions of phase space, where the background is kinematically suppressed. The relative weight of the threshold region increases and new theoretical issues need to be addressed. Latest results by Belle [39] and BaBar [40] access about the 90% of the $\bar{B} \to X_u l \bar{\nu}_l$ phase space. On the theoretical side, several approaches have been devised to analyze data in the threshold region, with differences in treatment of perturbative corrections and the parameterization of nonperturbative effects. The latest experimental analysis [40], and the HFAG averages [8] rely on at least four different QCD calculations of the partial decay rate: the BLNP approach by Bosch, Lange, Neubert, and Paz [41], the GGOU one by Gambino, Giordano, Ossola and Uraltsev [42], the DGE one, dressed gluon exponentiation, by Andersen and Gardi [43, 44] and the ADFR approach, by Aglietti, Di Lodovico, Ferrara, and Ricciardi [45, 46, 47]. These calculations take into account the whole set of experimental results, or most of it, starting from 2002 CLEO data [48]. Other theoretical approaches have been proposed in Refs. [49, 50, 51]. The results listed in Table 1 give values in the range $\sim (3.9-4.6) \times 10^{-3}$, that are consistent within the errors, but the theoretical uncertainty among determinations can reach 10%. In spite of all the experimental and theoretical efforts, the values of $|V_{ub}|$ extracted from inclusive decays maintain about two σ above the values given by exclusive determinations. We can also compare with indirect fits, $|V_{ub}| = (3.65 \pm 0.13) \times 10^{-3}$ by UTfit [52] and $|V_{ub}| = (3.49^{+0.21}_{-0.10}) \times 10^{-3}$ at 1σ by CKMfitter [53]. At variance with the $|V_{cb}|$ case, the results of the global fit prefer a value for $|V_{ub}|$ that is closer to the exclusive determination.

4. The $|V_{tb}|$ determination

Ever since the existence of the b-quark was inferred from the discovery of the Υ family of resonances at Fermilab in 1977 [54], its weak isospin partner, the top quark, has been actively sought. For almost two decades, the top-quark eluded all direct searches at increasing higher energy, while indirect evidence of its existence and properties was provided by loop mediated processes. Only in 1995, eight years after the start of data taking at Tevatron, both CDF and DØ Collaborations announced the observation of the top quark in $p\bar{p} \to t\bar{t}$ processes [55, 56]. At leading order in perturbation theory, there are two processes that contribute to $\bar{t}t$ production, quark-antiquark annihilation $\bar{q}q \to \bar{t}t$ and gluon-gluon fusion $\bar{g}g \to \bar{t}t$. At the Tevatron the $\bar{t}t$ cross section is dominated by quark-antiquark annihilation, while at LHC at $\sqrt{14}$ TeV, the situation is reversed. The reason is that, because of the higher center of mass energy, at the LHC it is possible to produce $\bar{t}t$ already at lower x of the incoming partons, where the gluon parton density dominates over the quark densities. In addition, the Tevatron features antiquarks as constituent quarks of the antiproton, leading to a considerable large antiquark density at large x.

As for the other CKM matrix elements, the values of the top couplings are not predicted within the SM, but $|V_{tb}|$ is expected to be close to unity as a consequence of unitarity and of the measured values for the other CKM elements. A recent global fit result gives [52]

$$|V_{tb}| = 0.999106 \pm 0.000024 \tag{4.1}$$

The large value of $|V_{tb}|$ in the SM implies that the ratio of branching fractions

$$R = \frac{B(t \to Wb)}{B(t \to Wb)} = \frac{|V_{tb}|^2}{\sum_q |V_{tq}|^2} = |V_{tb}|^2 \qquad (q = d, s, b) \tag{4.2}$$

is close to unity, and that the top quark is expected to decay to a W boson and a b quark nearly 100% of the time. In several models beyond the SM, different assumptions, such as four quark generations and no CKM unitarity, hold, making a case for a measurement of $|V_{tb}|$ in the most direct possible way.

At hadron machines, the top quark is mainly produced in $t\bar{t}$ pairs via strong interactions. Around 56×10^5 $t\bar{t}$ pairs have been collected at ATLAS and CMS detectors, about 8 times the number of $t\bar{t}$ pairs collected at Tevatron. The measurement of the ratio R is based on the number of jet tagged as b-jets for each $t\bar{t}$ event. The latest DØ results give [57] $R = 0.90 \pm 0.04$ (stat.+syst.), which agrees within approximately 2.5 standard deviations with the SM prediction of R close to one. A simultaneous measurement of $R = 0.94 \pm 0.09$ and $\sigma_{\bar{t}t}$ has been recently performed by the CDF collaboration; they estimate [58]

$$|V_{tb}| = 0.97 \pm 0.05 \tag{4.3}$$

assuming the SM relation (4.2). At LHC at 7 TeV, the CMS collaboration has measured, in the dilepton channel, the value $R = 0.98 \pm 0.04$ [59], which is consistent with the SM prediction.

In strong interactions, top quark is produced in pair; in electroweak interactions, a single top can be produced. At hadron colliders, there are three channels of single top production at quark level, with different cross sections strongly dependent on the center of mass energy and the parton distribution function of the incoming partons. Apart from the Wt channel, which is the production of a (close to) on-shell W boson and a top quark, via the gluonic fusion, there are the t- and s-channels. The s-channel ($q_1\bar{q}_2 \to t\bar{b}$) involves production of an off-shell, time-like W boson, which decays into a top and a bottom quark. The t-channel ($q_1(\bar{q}_1)b \to q_2(\bar{q}_2)t$) mode is the exchange of a space-like W boson between a light quark, and a bottom quark inside the incident hadrons, resulting in a jet and a single top quark. Each mode has rather distinct event kinematics, and thus they are observable separately from each other. Single top production was observed at the Tevatron based on a combination of t- and s–channel processes in 2009 [60, 61], 14 yars after the top quark discovery, while ATLAS and CMS Collaborations, thanks to the much larger cross

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sections and better signal-over-background available at the LHC, observed single top already in 2011 and measured its cross section, in the t-channel, the year after [62, 63]. ATLAS and CMS Collaborations have also reported first evidence of the Wt channel at the 4σ level [64, 65]. Because of the massive particles in the final state, this mode has a negligible rate at the Tevatron, but not at the LHC, where more partonic energy is available. At the opposite, the s-channel has a larger rate at the Tevatron than at the LHC, because it is driven by initial state anti-quark parton densities. There is not yet evidence of this channel at LHC, but an upper limit has been set on the production cross-section [66]. At CDF, the cross section in the s-channel has been measured with two-third of the data set [67], and analyses are in progress to include the whole data set.

The single top quark production cross section is directly proportional to the square of $|V_{tb}|$, allowing a direct measurement of $|V_{tb}|$ without assuming unitarity of the CKM matrix or three fermion generations. The extraction of $|V_{tb}|$ employs the following relation

$$|f_L V_{tb}| = \sqrt{\frac{\sigma^{\text{meas}}}{\sigma^{\text{SM}}}} \tag{4.4}$$

where σ^{meas} and σ^{SM} are the measured and the SM cross section in a specific channel, respectively, while f_L takes into account a a possible left-handed anomalous coupling, being $f_L = 1$ in the SM. This equation assumes that $|V_{tb}|$ is much larger than $|V_{ts}|$ and $|V_{td}|$, since the other CKM matrix elements could contribute to the top decay if they were not very small. The current single top cross section measurements [68, 65, 67, 69, 64, 70], have uncertainties at the level of 10%, the more precise being the CMS 7 TeV measurement in the t-channel [63], with uncertainty of $\sim 5\%$, which yields

$$|V_{tb}| = 1.02 \pm 0.05 \pm 0.02 \tag{4.5}$$

assuming the SM value $f_L = 1$. Due to the large LHC statistics, single top measurements are (mostly) systematics limited. Dedicated strategies need to be developed to increase precision and usefully employ this process in the NP search.

Since unitarity of the 3×3 CKM matrix strongly constraints $|V_{tb}|$, deviations from the SM prediction in Eq. (4.1) are expected from NP that violate unitarity. Deviations of the CKM unitarity affect several observables, e.g. they may lead to flavour-changing neutral currents couplings which are known from experiment to be severely suppressed; therefore unitarity violations need to be accordingly small. A simple way to violate unitarity is enlarging the fermion sector, by including a fourth quark generation or vector-like quarks, see e.g. [71, 72, 73, 74, 75]. Vector-like fermions are fermions that transform as triplets under the colour gauge group and whose left- and right-handed chiralities belong to the same representation of the SM symmetry group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. In the SM with four generations, there are no tree level flavour-changing neutral currents due to an exact GIM mechanism, while contributions from vector-like quarks may be suppressed by inverse ratios of their heavy masses. Apart from dedicated models, vector-like quarks generically appears in a large number of extensions of the SM, from composite and Little Higgs models to Randall-Sundrum scenarios or E6 GUTs. They have been actively sought, and mass limits have been provided by Tevatron and LHC [76]. Other possible NP models involve flavour changing neutral currents in the top quark sector mediated by the t-channel exchange of a new massive Z' boson, see e.g. [77]. Experimental limits have also been set by both LHC and Tevatron on masses of new W' bosons or charged Higgs bosons, whose existence would especially affect the single top s-channel mode. Searches are also ongoing for single excited b^* quark production and decay to Wt [78]. Excited quarks appear in several models, for example in some Randall-Sundrum models or in composite Higgs models, see e.g. [79].

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