DETERMINATION OF V_{ub} FROM SEMILEPTONIC B DECAYS*

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We report on recent progress on V_{ub} determination from exclusive and inclusive semileptonic B decays.

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1. Introduction

The Standard Model does not predict the values of the CKM matrix elements that therefore have to be determined experimentally. Their precise knowledge is also important because new physics may be revealed through inconsistencies between independent determinations of the CKM matrix elements and CP-violating phase. In this respect, the CKM matrix element $|V_{ub}|$ plays a particularly significative role. Its determination proceeds through semileptonic decays, that are mediated by tree-level W-boson exchange in the leading Standard Model; such decays are generally considered not affected by new physics at the current level of achievable precision. Nevertheless, $|V_{ub}|$ is a crucial input also for other parameters sensitive to new physics, such as ϵ_K. The value of V_{ub} can be determined through exclusive decays ($B \to \pi\, l\, \nu$, but also $B \to \rho\, l\, \nu$, $B \to \eta\, l\, \nu$ or $B \to \eta'\, l\, \nu$) and through the inclusive process $B \to X_u\, l\, \nu$. The first approach provides a better background rejection, while the second gives higher signal efficiency. They are complementary, since they rely on independent calculations and employ different theoretical inputs to model the hadronization.

Presently, there is not a complete agreement among the resulting values for $|V_{ub}|$, with inclusive determination systematically higher than exclusive. Indirect measurement through the unitarity triangle fit, that includes direct measurements as well as indirect, prefers lower central values. Recently, the

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value for $|V_{ub}|$ has been extracted by the process $B \to \tau\nu$, which is sensitive to new physics, and the results give central values once again closer to the exclusive determinations, within larger errors.

2. Exclusive decays

In the exclusive approach, we extract from the measured branching fraction for a specific charmless decay channel the value for $|V_{ub}|$ by employing theoretical calculations of the form factors. Form factors are inherently non-perturbative and parametrize QCD effects. The $B \to \pi l \bar{\nu}$ decay is the simplest process to study, being affected by a single form factor $f_+(q^2)$. In the Standard Model, the differential decay rate for this process is:

$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{{G_{\mathrm{F}}}^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 \left| f_+ \left(q^2 \right) \right|^2 . \tag{1}$$

The theoretical predictions for the form factor split into two parts: normalization, $f_+(0)$, and functional form of its q^2 dependence.

With more and more statistics provided by the B-factories, it has become possible to compare the predicted form factor shapes with experimental data in different q^2 intervals. Recent data distribution from BaBar [1] have put on evidence inconsistencies with form factors calculations based on quark models [2]. Other theoretical approaches are light cone sum rules and lattice simulations, that are in a way complementary, since the former generally access low q^2 regions and the latter large q^2 ones.

From different calculations of form factors, different values of $|V_{ub}|$ follow. Recent results are listed in Table I: the theoretical error (up to $\sim 17\%$) dominates over the experimental error (about 4–6%). The two lattice calculations in Table I are unquenched and use different lattice formulations for the bottom quarks. The HPQCD Collaboration uses nonrelativistic (NRQCD) heavy quarks, whereas Fermilab uses relativistic clover quarks with the Fermilab interpretation via heavy quark effective theory. Both methods work quite well for heavy bottom quarks. They lead to consistent values for V_{ub},

TABLE I

Recent results for $|V_{ub}|$ from exclusive $B \to \pi l \bar{\nu}$ decay.

V_{ub} $[10^{-3}]$	Form factor calculation
$3.34 \pm 0.12 + 0.55 - 0.37$	LCSR Ball–Zwicky $q^2 < 16$ GeV$^2/c^4$ [3]
$3.5 \pm 0.4 \pm 0.2 \pm 0.1$	LCSR Duplancic *et al.* [4]
$3.40 \pm 0.20 + 0.59 - 0.39$	HPQCD $q^2 > 16$ GeV$^2/c^4$ [5]
$3.62 \pm 0.22 + 0.63 - 0.41$	Fermilab $q^2 > 16$ GeV$^2/c^4$ [6]
3.38 ± 0.36	Fermilab [7]

with similar total errors of about $\sim 15\%$. The last value in Table I follows from the latest Fermilab unquenched lattice QCD calculation, which improves previous results, also removing from the analysis model-dependent assumptions about the shape in q^2 of the form factor.

Results presented in Table I are in agreement with recent estimates by Belle, obtained using a data sample of 657×10^6 B pairs and events tagged by fully reconstructing one of the B mesons in a hadronic decay mode [8].

Recently, the availability of very large data sets at Belle and BaBar have made possible tagged analyses. Such analyses can achieve a higher background suppression, but have the disadvantage of a bigger statistical error because of the penalty introduced by the tag requirement. At present, untagged measurements of the $B \to \pi\, l\, \nu$ branching ratio still provide the more precise results and dominate the world average.

Let us observe that at the B factories also decays into higher states, like $B \to \rho\,(\eta, \eta', \omega)\, l\, \nu$, have been studied [9], but due to large errors, both theoretical and experimental, they are not yet competitive for $|V_{ub}|$ extraction.

2.1. Inclusive decays

Inclusive semileptonic decays $B \to X_c(X_u)\, l\, \nu$ can be calculated using the operator product expansion, that separates perturbative and non-perturbative contributions. Applied to heavy quark decays, the operator product expansion corresponds to an expansion in a series of inverse powers of the heavy quark mass. The non-perturbative inputs needed to predict the rate are matrix elements of local operators in the heavy quark effective theory.

One specificity of charmless B meson semileptonic decays $B \to X_u\, l\, \nu$ is related to the background rejection, since such decays constitute only about 1% of the total semileptonic width. Therefore, the available phase space consists of the regions where the experimentalists can suppress the large $b \to c$ background. Reproducing the experimental results requires theoretical predictions for the full (triple) differential $B \to X_u\, l\, \nu$ spectrum. Experimental cuts include regions where the operator product expansion fails and new effects come into play; due to the phase space reduction such effects become relevant and cannot be neglected. As in other heavy-to-light decays, for instance $B \to X_s\gamma$, there are phase space regions where the hadronic jet mass is much smaller than its energy, $m_X \ll E_X$. In such regions, final gluon radiation is strongly inhibited: soft and collinear singularities arise and the perturbative expansion of spectra is affected by large logarithms $\alpha_s^n \log^{2n}(2E_X/m_X)$ to be resummed at all orders in perturbation theory. Nonperturbative effects related to a small vibration of the b quark in the B meson (Fermi motion) are also enhanced at $m_X^2 \simeq \Lambda_{\mathrm{QCD}}\, E_X$.

Two complementary routes can be followed. One is to enlarge the phase space region, by selecting regions where opportune distributions are better behaved, and by improving background rejection, for instance developing experimental techniques that would feature a low lepton energy E_l cut in the end point of the lepton spectrum. Recently, the Belle Collaboration has presented results that access 90% of the phase space, claiming an overall uncertainty of 7% on $|V_{ub}|$ [10]. Another route is to model the region of large hadronic energy and small invariant mass, not well described by the operator product expansion. Present theoretical approaches can be divided roughly into predictions based on parameterizations of the shape function, and OPE constraints [11–13], and predictions based on resummed perturbative QCD [14, 15]. We list some results in Table II.

TABLE II

HFAG [16] results for $|V_{ub}|$ from inclusive $B \to X_u l \bar{\nu}$ decay.

V_{ub} $[10^{-3}]$	Collaboration
$4.06 \pm 0.15 + 0.25 - 0.27$	BLNP [11]
$4.03 \pm 0.15 + 0.20 - 0.25$	GGOU [12]
$4.87 \pm 0.24 + 0.38 - 0.38$	BLL [13]
$4.25 \pm 0.15 + 0.21 - 0.17$	DGE [14]
$3.84 \pm 0.13 + 0.23 - 0.20$	ADFR [15]

The shape function approach is based on the introduction of a non-perturbative distribution function (shape function) that at leading order is universal. The shape function takes care of singular terms in the theoretical spectrum; it has the role of a momentum distribution function of the b quark in the B meson. However, the operator product expansion does not predict the shape function and an ansatz is needed for its functional form. The subleading shape functions are difficult to constrain and are not process independent.

Predictions based on resummed perturbative QCD use resummed perturbation theory in moment space to provide a perturbative calculation of the on-shell decay spectrum in the entire phase space. They extend the standard Sudakov resummation framework by adding non-perturbative corrections in the form of power corrections, whose structure is determined by renormalon resumming [14] or by an effective QCD coupling [15]. The shape of the spectrum in the kinematic region, where the final state is jet-like, is largely determined by a calculation, and less by parametrization. In principle, there is no preclusion to why an effective coupling inserted in the perturbative resumming formula cannot adequately describe the non-perturbative Fermi motion as well as a fitting function [15]. The physical picture implied is that B fragmentation into the b quark and the spectator quark can be described as a radiation process off the b quark with a proper coupling. This effective coupling is universal in the sense that describes radiative decay processes as well as B fragmentation processes; once it is fixed, for instance on the basis of minimal analyticity arguments, there are no free parameters to be fitted in the model.

Although conceptually quite different, all the above approaches generally lead to roughly consistent results when the same inputs are used and the theoretical errors are taken into account.

Different phase space regions include problematic regions to different extent, and it can be interesting to compare results region by region, as done in Table III. The background given by $B \to X_c l\nu$ is suppressed by means of different experimental cuts: on the energy of the charged lepton $E_l > (m_B^2 - m_D^2)/2m_B$, on the hadronic invariant mass of the final state $m_X < m_D$, on the invariant mass squared of the lepton–neutrino pair $q^2 > (m_B - m_D)^2$, on the plus component of the total momentum of the final state hadrons $p_+ < m_D^2/m_B$. Let us observe that all the present estimates can be polluted by weak annihilation between the b quark and the spectator in the B meson. The uncertainty introduced depends strongly on the cuts employed; indeed, the effects of weak annihilation are expected to manifest themselves only at high q^2.

TABLE III

HFAG [16] results for $|V_{ub}|$ for different experimental cuts.

Experiment	ADFR	DGE	BLNP	GGOU
BaBar (E_l) [17]	$3.46 \pm 0.14^{+0.24}_{-0.23}$	$4.06 \pm 0.27^{+0.27}_{-0.26}$	$4.18 \pm 0.24^{+0.29}_{-0.31}$	$4.05 \pm 0.23^{+0.22}_{-0.32}$
Belle (E_l) [18]	$3.26 \pm 0.17^{+0.22}_{-0.22}$	$4.56 \pm 0.42^{+0.28}_{-0.24}$	$4.64 \pm 0.43^{+0.29}_{-0.31}$	$4.53 \pm 0.42^{+0.22}_{-0.30}$
CLEO (E_l) [19]	$3.49 \pm 0.20^{+0.24}_{-0.24}$	$3.58 \pm 0.42^{+0.28}_{-0.25}$	$3.83 \pm 0.45^{+0.32}_{-0.33}$	$3.68 \pm 0.43^{+0.24}_{-0.38}$
BaBar (m_X) [20]	$4.04 \pm 0.19^{+0.25}_{-0.26}$	$4.23 \pm 0.20^{+0.21}_{-0.16}$	$4.02 \pm 0.19^{+0.27}_{-0.29}$	$3.98 \pm 0.19^{+0.26}_{-0.28}$
Belle (m_X) [21]	$3.93 \pm 0.26^{+0.24}_{-0.24}$	$4.03 \pm 0.27^{+0.26}_{-0.20}$	$3.90 \pm 0.26^{+0.24}_{-0.26}$	$3.86 \pm 0.26^{+0.18}_{-0.21}$
BaBar ((m_X, q^2)) [20]	$4.15 \pm 0.27^{+0.24}_{-0.24}$	$4.26 \pm 0.28^{+0.23}_{-0.19}$	$4.32 \pm 0.28^{+0.29}_{-0.31}$	$4.22 \pm 0.28^{+0.38}_{-0.35}$
Belle ((m_X, q^2)) [22]	$3.97 \pm 0.42^{+0.23}_{-0.23}$	$4.20 \pm 0.44^{+0.23}_{-0.18}$	$4.23 \pm 0.45^{+0.29}_{-0.310}$	$4.14 \pm 0.44^{+0.33}_{-0.34}$
BaBar (p_+) [20]	$3.56 \pm 0.23^{+0.23}_{-0.23}$	$3.70 \pm 0.24^{+0.31}_{-0.24}$	$3.65 \pm 0.24^{+0.25}_{-0.27}$	$3.43 \pm 0.22^{+0.28}_{-0.27}$

All the tables show that most determinations from inclusive decays give a value of $|V_{ub}|$ higher than that from exclusive decays. The results can be compared with the indirect determinations of $|V_{ub}|$, which prefer a lower average, accordingly with the exclusive determinations: $|V_{ub}| = (3.67 \pm 0.21)$ x 10^{-3} [23], $|V_{ub}| = (3.79 \pm 0.09 \pm 0.41)$ x 10^{-3} [24]. The need to resolve this discrepancy motivates systematic improvements on all fronts, included different prospectives in the theoretical approach. On the experimental side, B factories are unique in studying $|V_{ub}|$; with a possible Super B factory with $75\, ab^{-1}$ the exclusive and inclusive uncertainty could be reduced as low as 3% and 2%, respectively.

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