# SEMILEPTONIC $B$ AND $D$ DECAYS — A REVIEW OF RECENT PROGRESS

M. MAZUR
*Department of Physics, University of California, Santa Barbara*
*Santa Barbara, CA 93106*

We present a review of semileptonic decays of $B$ and $D$ mesons, highlighting recent results from the $B$ factories. We discuss measurements of both inclusive and exclusive decays, measurements of the CKM quark-mixing matrix elements $|V_{cb}|$ and $|V_{ub}|$, studies of nonperturbative QCD effects, and a search for new physics effects using decays to $\tau$ leptons.

## 1 Introduction

Semileptonic decays provide an excellent laboratory in which to study electroweak physics, QCD, and to search for physics beyond the Standard Model. We present recent results on semileptonic $B$ and $D$ meson decays from the three $B$ factories, BABAR, Belle, and CLEO.

## 2 $|V_{cb}|$ and Heavy-quark Parameters from Inclusive $B$ Decays

The inclusive decay mode $B \to X_c \ell^- \overline{\nu}_\ell$ [1], where $X_c$ indicates any charmed hadronic system, can be used both to measure the CKM matrix element [2] $|V_{ub}|$ and to study nonperturbative QCD effects of quarks bound inside hadrons. The differential decay rate for this process is described in Heavy Quark Effective Theory (HQET) as an expansion in terms of $\alpha_s$, whose effects are perturbatively calculable, and in the $b$ quark mass, $m_b$, whose effects are nonperturbative and must be measured in data. At second order in $1/m_b$, two nonperturbative parameters arise, corresponding to the kinetic energy and chromomagnetic moment of the $b$ quark in the $B$ meson and denoted $\mu_\pi^2$ and $\mu_G^2$, respectively [3]; at third order in $1/m_b$, two further parameters arise, $\rho_{LS}^3$ and $\rho_D^3$. By measuring moments of the lepton energy spectrum and the $X_c$ mass spectrum in $B \to X_c \ell^- \overline{\nu}_\ell$ decays and the photon energy spectrum in $B \to X_s \gamma$ decays — and by studying the variation of these moments as a function of a low-energy cut on the lepton (or photon, in the case of $B \to X_s \gamma$) energy — we can measure these nonperturbative heavy-quark expansion parameters. By measuring the total rate of $B \to X_x \ell^- \overline{\nu}_\ell$ decays, we can simultaneously extract the value of $|V_{cb}|$.

The Belle and *BABAR* Collaborations recently presented measurements of the moments of the $E_\ell$ and $m_X$ spectra [4]. These measurements use a tagging technique where one of the two $B$ mesons in an $\Upsilon(4S) \to B\overline{B}$ event is fully reconstructed in a hadronic decay channel; by tagging one $B$ meson, the second $B$ can be reconstructed with reduced background and additional kinematic constraints, both of which are helpful when reconstructing decays with unobserved neutrinos. Corrections are applied to the observed kinematic variables $E_\ell$ and $m_X$ to account for finite detector resolution and the effects of unobserved particles. The Belle measurements use an unfolding technique, based on the Singular Valued Decomposition technique [5], while the *BABAR* analysis uses a set of calibration curves to make event-by-event corrections.

A global fit [6,7] for $|V_{cb}|$ and the heavy-quark expansion parameters is shown in Figure 1. The average includes the recent measurements from Belle and *BABAR*, as well as older measurements from CLEO, CDF, and DELPHI, and includes up to the third $E_\ell$ moment, the third $m_X$ moment, and the second $E_\gamma$ moment, all for a variety of lepton or photon energy cuts. The measured moments are highly correlated with one another takes into account the individual covariance matrices as well as a number of external constraints from theory and from other measurements. The measured value of $|V_{cb}|$ is $(42.04 \pm 0.34 \pm 0.59) \times 10^{-3}$, with a total error less than 2%, and the $b$ quark mass is measured as $(4.597 \pm 0.034)\,\mathrm{GeV}/c^2$, with an error less than 1%.

Inclusion of the $B \to X_s\gamma$ photon energy moments in this global fit is somewhat problematic, both from a theoretical and an experimental point of view [8]. Theoretically, including these moments is difficult, in part because all calculations are model dependent to some degree, and in part because the operator product expansion must take into account non-local operators which are difficult to estimate. Additionally, the experimental results display some tension, with the $B \to X_s\gamma$ results pulling down the value of $m_b$ by about 1%. If the $B \to X_s\gamma$ moments are excluded from the fit, we instead obtain $|V_{cb}| = (41.85 \pm 0.38 \pm 0.59) \times 10^{-3}$ and $m_b = (4.660 \pm 0.053)\,\mathrm{GeV}/c^2$. While the effect on $|V_{cb}|$ is rather small, the effect of this change on the value of $|V_{ub}|$ is much larger, $\approx 10\%$; for this reason, the extraction of $|V_{ub}|$ presented below uses only the $B \to X_c \ell^- \overline{\nu}_\ell$ moments.

## 3 $|V_{ub}|$ from Inclusive $B$ Decays

Precision measurement of $|V_{ub}|$ is one of the main goals of the $B$ factory physics program since, together with the angle $\beta$, $|V_{ub}|$ helps determine the apex of the Unitarity Triangle [2]. The most precise measurements of $|V_{ub}|$ come from the inclusive $B \to X_u \ell^- \overline{\nu}_\ell$ decay rate, which is proportional to $|V_{ub}|^2$.

The $B \to X_u \ell^- \overline{\nu}_\ell$ decay rate is difficult to measure because background from $B \to X_c \ell^- \overline{\nu}_\ell$ decays is 50 times larger than the signal. Measurements of $|V_{ub}|$ use cuts on kinematic variables — including the lepton energy, $m_X$, $q^2$, and $P_+ \equiv E_X - |p_X|$ — to suppress this $|V_{cb}|$ background, taking advantage of the fact that the $c$ quark is much heavier than the $u$. The partial decay rate in this restricted phase space is then extrapolated back to the full decay rate using theoretical models [9] based on heavy-quark parameters which are determined from $B \to X_c \ell^- \overline{\nu}_\ell$ decays as described above.

*BABAR* presented a measurement [10] of $|V_{ub}|$ using three kinematic variables: $m_X$, $q^2$, and $P_+$. One $B$ meson is fully reconstructed and a high-momentum lepton is identified in the recoil. Combinatorial backgrounds are subtracted by fitting distributions of the tag $B$ mass in bins of the three kinematic variables, and a fit to the resulting kinematic distributions is used to distinguish $B \to X_u \ell^- \overline{\nu}_\ell$ signal from the residudual $B \to X_c \ell^- \overline{\nu}_\ell$ events and other backgrounds. Several values of $|V_{ub}|$ are reported for different kinematic cuts and in different theoretical frameworks. A global average of inclusive $|V_{ub}|$ measurements [6], including this latest

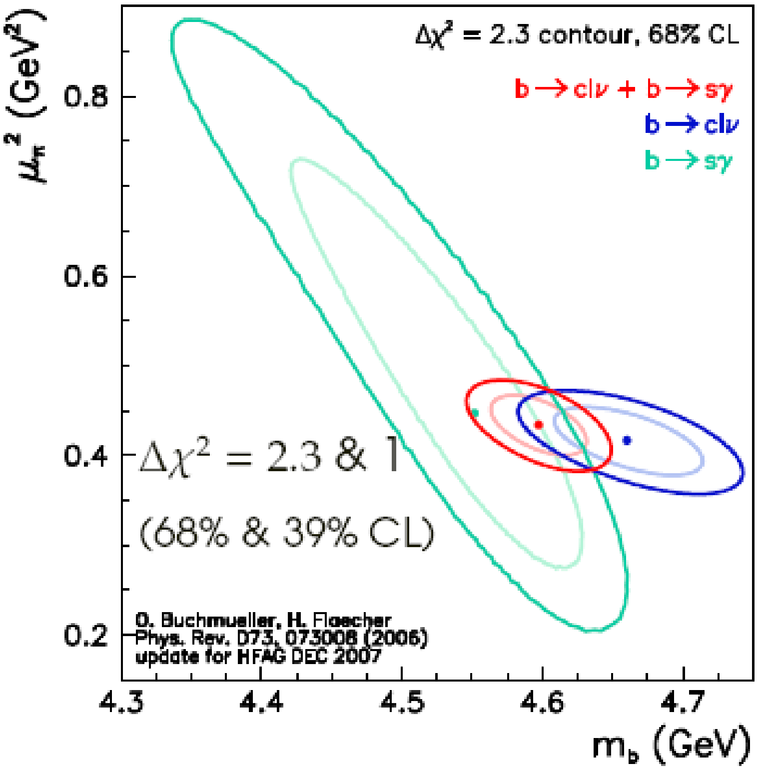


Figure 1: Projection of a global fit for $|V_{cb}|$ and heavy-quark expansion parameters using moments measurements, showing the error ellipse in the $m_b - -\mu_\pi^2$ plane. The ellipse is shown for three configurations of the fit: including all moments in the fit, including just the $B \to X_c\ell^-\overline{\nu}_\ell$ moments, and including just the $B \to X_s\gamma$ moments.

one and a similar analysis from Belle [11], is shown in Figure 2 for the BLNP framework; $|V_{ub}|$ is measured to be $(3.98 \pm 0.15 \pm 0.30) \times 10^{-3}$, with a total error of 8%, while similar results are obtained in the other theoretical frameworks [9].

## 4 Charm Semileptonic Decays and Form Factors

Studies of exclusive semileptonic decays, in which particular final state hadronic systems are selected, provide us with another approach to measuring CKM matrix elements and another way to help shed light on perturbative QCD processes. The dynamics of exclusive semileptonic decays are described by a set of form factors which are functions of the squared momentum transfer, $q^2$. A variety of theoretical techniques have been used to calculate these form factors [12]. Decays of charm mesons provide a clean environment in which to measure the dynamics of semileptonic decay and to study these form factors; testing form factor models in the charm sector also leads to improved understanding of the form factors in the bottom sector, improving the extraction of $|V_{cb}|$ and $|V_{ub}|$.

CLEO-c presented recent results on the semileptonic $D$ decays $D \to \pi\ell^-\overline{\nu}_\ell$ and $D \to K\ell^-\overline{\nu}_\ell$ for both charged and neutral $D$ mesons [13]. This analysis uses the missing four-momentum in the event to estimate the neutrino momentum, taking advantage of the good hermeticity of the detector. Signal events are required to have a squared missing mass, $m^2_{\text{miss}}$, consistent with zero, indicating that a single neutrino was undetected. Signals are further discriminated from background events using two kinematic variables, the mass and energy of the reconstructed $D$ candidate.

A fit is performed in bins of $q^2$ in order to measure the branching fractions and to extract

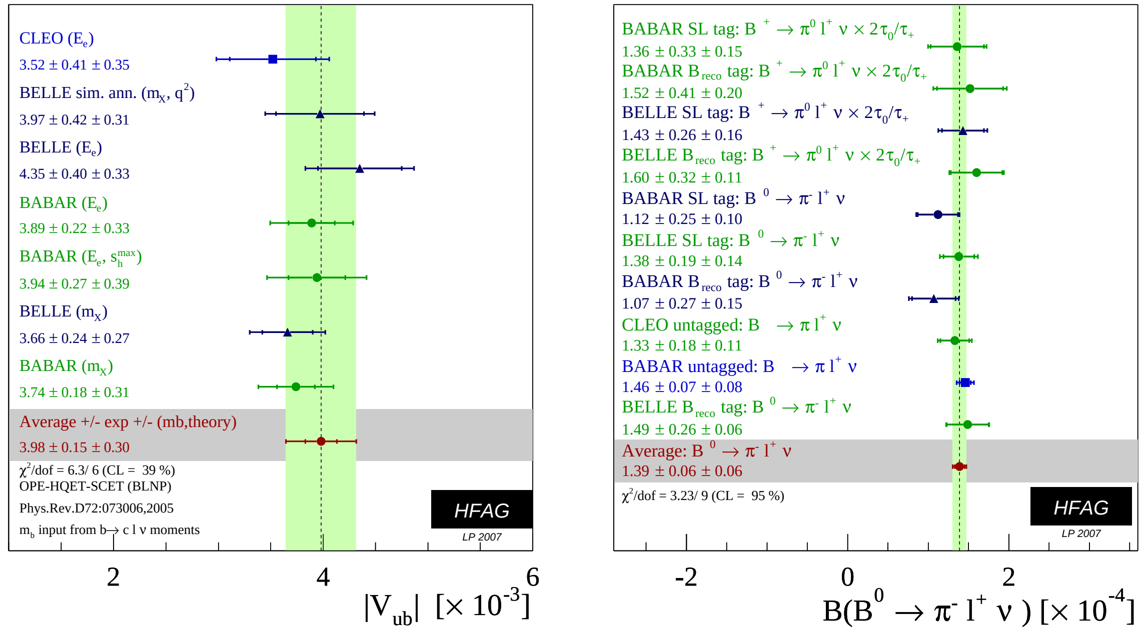


Figure 2: Global averages of inclusive $|V_{ub}|$ measurements (left) and the exclusive $B^0 \to \pi^-\ell^+\nu_\ell$ branching fraction (right), highlighting the consistency between many different measurement techniques as well as the precision obtained in recent years from the $B$ factories.

information about the form factors. The branching fractions measured are $\mathcal{B}(\overline{D}^0 \to \pi^+\ell^-\overline{\nu}_\ell) = (0.299 \pm 0.011 \pm 0.009)\%$, $\mathcal{B}(D^- \to \pi^0\ell^-\overline{\nu}_\ell) = (0.373 \pm 0.022 \pm 0.013)\%$, $\mathcal{B}(\overline{D}^0 \to K^+\ell^-\overline{\nu}_\ell) = (3.56 \pm 0.03 \pm 0.09)\%$, and $\mathcal{B}(D^- \to K^0\ell^-\overline{\nu}_\ell) = (8.53 \pm 0.13 \pm 0.23)\%$, consistent with similar recent results from Belle and *BABAR* [14]. The form factors for these decays are measured using both a model-independent series expansion and pole models. The expansion results are generally consistent with previous measurements. While the pole models also consistent with previous measurements, they only give a reasonable description of the data for unphysical parameter values. By using lattice QCD calculations of the form factor normalizations, they measure $|V_{cd}| = 0.217 \pm 0.009 \pm 0.004 \pm 0.023$ and $|V_{cs}| = 1.015 \pm 0.010 \pm 0.011 \pm 0.106$, in good agreement with previous measurements.

## 5 $|V_{ub}|$ from Exclusive $B$ Decays

Exclusive $b \to u$ decay modes, such as $B \to \pi\ell^-\overline{\nu}_\ell$, $B \to \rho\ell^-\overline{\nu}_\ell$, $B \to \omega\ell^-\overline{\nu}_\ell$, and $B \to \eta^{(\prime)}\ell^-\overline{\nu}_\ell$, allow us to measure $|V_{ub}|$ as well as to test form factor models in heavy-to-light meson decays. The experimental and theoretical errors on $|V_{ub}|$ from exclusive decays are orthogonal to those in inclusive decays, making these modes complementary to the inclusive studies discussed above.

The CLEO Collaboration recently published [15] a study of the exclusive modes $B \to h\ell^-\overline{\nu}_\ell$, where $h = \{\pi^+/\pi^0/\rho^+/\rho^0/\omega/\eta/\eta'\}$. As in the previous analysis, the missing momentum in the event must be consistent with a single neutrino, which is then used to reconstruct the $B \to h\ell^-\overline{\nu}_\ell$ candidate. Signal and background events are identified using two kinematic variables: $m_{h\ell^-\overline{\nu}_\ell}$, the mass of the $h\ell^-\overline{\nu}_\ell$ system after correcting for the neutrino energy resolution, and $\Delta E$, the difference between the observed energy of the $h\ell^-\overline{\nu}_\ell$ system and the beam energy. For the $\rho$ and $\omega$ modes, the invariant mass $m_h$ of the $\rho$ or $\omega$ is also used to discriminate signal from background. A binned fit is performed to the joint distribution of $m_{h\ell^-\overline{\nu}_\ell}$, $\Delta E$, $q^2$, $m_h$, and, for the $\rho$ mode, $\cos\theta_{W\ell}$, the cosine of the angle between the lepton and the $W$ in the $B$ rest frame; this last variable is sensitive to the helicity of the $\rho$.

Using isospin to combine the $\pi^+$ with $\pi^0$ results and the $\rho^+$, $\rho^0$, and $\omega$ results, they obtain $\mathcal{B}(\overline{B}^0 \to \pi^+\ell^-\overline{\nu}_\ell) = (1.31\pm0.15\pm0.11)\times10^{-4}$ and $\mathcal{B}(\overline{B}^0 \to \rho^+\ell^-\overline{\nu}_\ell) = (2.93\pm0.37\pm0.37)\times10^{-4}$, results which are among the most precise measurements to date. The branching fraction for $\overline{B}^0 \to \pi^+\ell^-\overline{\nu}_\ell$ can be compared to the world average [6], which is shown in Figure 2. From the $\pi$ channel, they also measure $|V_{ub}| = (3.6\pm0.4\pm0.2^{+0.6}_{-0.4})\times10^{-3}$, comparable in precision to recent results from the *BABAR* and Belle Collaborations [16] and consistent with the current world average. They find $3\sigma$ evidence for the $\eta'$ mode with $\mathcal{B}(B^- \to \eta'\ell^-\overline{\nu}_\ell) = (2.66\pm0.80\pm0.56)\times10^{-4}$ and set a 90% upper limit $\mathcal{B}(B^- \to \eta\ell^-\overline{\nu}_\ell) < 1.01\times10^{-4}$; these results are consistent with a previous *BABAR* upper limit at the 5% level, and may suggest a significant singlet contribution to the $\eta'$.

## 6 $B \to D\ell^-\overline{\nu}_\ell$, $D^*\ell^-\overline{\nu}_\ell$, and $D^{**}\ell^-\overline{\nu}_\ell$

Understanding the exclusive $b \to c$ semileptonic decays is another important part of the $B$ factory physics program, particularly since these modes have among the largest $B$ meson branching fractions. The dominant decay modes $B \to D\ell^-\overline{\nu}_\ell$ and $B \to D^*\ell^-\overline{\nu}_\ell$ make up about 70% of the total inclusive rate [6], with the remaining 30% not yet well measured. These decay modes provide us with complementary measurements of $|V_{cb}|$ and allow us to study decay form factors and HQET. Additionally, these processes are backgrounds in many other analyses, so improved understanding of these decays will lead to improvements in extraction of $|V_{ub}|$ and $|V_{cb}|$.

The *BABAR* Collaboration has presented a simultaneous measurement of the branching fractions $B \to D\ell^-\overline{\nu}_\ell$, $B \to D^*\ell^-\overline{\nu}_\ell$, $B \to D\pi^\pm\ell^-\overline{\nu}_\ell$, and $B \to D^*\pi^\pm\ell^-\overline{\nu}_\ell$, for both charged and neutral $B$ mesons [17]. Each of these modes is reconstructed in the recoil of a fully reconstructed $B$ meson, and signals are extracted using a fit to the $m^2_{\rm miss}$ distribution, where correctly reconstructed events with just one missing neutrino peak at zero $m^2_{\rm miss}$. Each of these eight branching fractions is the most precise measurement to date. The sum of these measurements, together with the inclusive branching fraction, suggests that $(11\pm4)\%$ of $B \to X_c\ell^-\overline{\nu}_\ell$ decays are still unaccounted for, and may likely be due to $B \to D^{(*)}n\pi\ell^-\overline{\nu}_\ell$ decays with $n > 1$ pions in the final state.

Studies of the decays $B \to D^{**}\ell^-\overline{\nu}_\ell$ (where $D^{**}$ means either a charm resonance heavier than the $D^*$ or a nonresonant $D^{(*)}n\pi$ system) are interesting because, as mentioned above, the known exclusive decay modes do not saturate the inclusive decay rate, and $D^{**}$ is expected to make up most of the remainder. These decays are also interesting because of what is known as the 1/2–3/2 puzzle: HQET strongly favors production of resonances where the light quark has angular momentum $j_q = 3/2$ (the $D_1$ and $D_2^*$ states) over those with angular momentum $j_q = 1/2$ (the $D_0^*$ and $D_1'$), but experimental results [18] suggest that the rates of the two angular momentum states are comparable.

Belle and *BABAR* recently presented studies of $B \to D^{**}\ell^-\overline{\nu}_\ell$ decays where the individual $D^{**}$ states are distinguished [19]. Both analyses identify a clean sample of $B \to D^{(*)}\pi^\pm\ell^-\overline{\nu}_\ell$ decays by reconstructing them in the recoil of a fully reconstructed $B$ meson and using $m^2_{\rm miss}$ to identify signal events. A fit to the $D\pi$ and $D^*\pi$ mass spectra is used to disentangle the individual $D^{**}$ contributions, and the branching fractions are summarized in Table 1. The results of the two analyses are largely consistent with one another and with previous results. The branching fractions for the $j_q = 1/2$ states are of the same magnitude as the $j_q = 3/2$ states, confirming earlier results yet perpetuating the 1/2–3/2 puzzle in HQET. Neither measuement sees evidence for a nonresonant $B \to D^{(*)}\pi\ell^-\overline{\nu}_\ell$ state. The most significant difference between the two sets of results is in the $B \to D_1'\ell^-\overline{\nu}_\ell$ state. Belle sees no evidence for these decays and sets an upper limit, while *BABAR*, with comparable sensitivity, sees a significant signal ($> 6\sigma$). It is difficult to accomodate a large rate for the $B \to D_0^*\ell^-\overline{\nu}_\ell$ state without a similarly large rate in $B \to D_1'\ell^-\overline{\nu}_\ell$, so further study of these modes will help to resolve this discrepancy.

Table 1: Measured product branching fractions $B(B \to D^{**}\ell^-\overline{\nu}_\ell) \times \mathcal{B}(D^{**} \to D^{(*)}\pi)$. Both analyses observe nonresonant $B \to D^{(*)}\pi\ell^-\overline{\nu}_\ell$ yields consistent with zero.

| Mode | $\mathcal{B}(B \to D^{**}\ell^-\overline{\nu}_\ell) \times \mathcal{B}(D^{**} \to D^{(*)}\pi)$ (%) | |
|---|---|---|
| | Belle | *BABAR* |
| $D\pi$ invariant mass fit | | |
| $B^- \to D_0^{*0}\ell^-\overline{\nu}_\ell$ | $0.24 \pm 0.04 \pm 0.06$ | $0.28 \pm 0.05 \pm 0.04$ |
| $B^- \to D_2^{*0}\ell^-\overline{\nu}_\ell$ | $0.22 \pm 0.03 \pm 0.04$ | $0.16 \pm 0.03 \pm 0.01$ |
| $\overline{B}^0 \to D_0^{*+}\ell^-\overline{\nu}_\ell$ | $0.20 \pm 0.07 \pm 0.05$ | $0.47 \pm 0.09 \pm 0.07$ |
| $\overline{B}^0 \to D_2^{*+}\ell^-\overline{\nu}_\ell$ | $0.22 \pm 0.04 \pm 0.04$ | $0.08 \pm 0.04 \pm 0.02$ |
| $D^*\pi$ invariant mass fit | | |
| $B^- \to D_1'^0\ell^-\overline{\nu}_\ell$ | $< 0.07$ (90% CL) | $0.27 \pm 0.05 \pm 0.05$ |
| $B^- \to D_1^0\ell^-\overline{\nu}_\ell$ | $0.42 \pm 0.07 \pm 0.07$ | $0.29 \pm 0.03 \pm 0.03$ |
| $B^- \to D_2^{*0}\ell^-\overline{\nu}_\ell$ | $0.18 \pm 0.06 \pm 0.03$ | $0.07 \pm 0.01 \pm 0.01$ |
| $\overline{B}^0 \to D_1'^+\ell^-\overline{\nu}_\ell$ | $< 0.5$ (90% CL) | $0.37 \pm 0.07 \pm 0.05$ |
| $\overline{B}^0 \to D_1^+\ell^-\overline{\nu}_\ell$ | $0.54 \pm 0.19 \pm 0.09$ | $0.25 \pm 0.05 \pm 0.03$ |
| $\overline{B}^0 \to D_2^{*+}\ell^-\overline{\nu}_\ell$ | $< 0.3$ (90% CL) | $0.04 \pm 0.02 \pm 0.01$ |

## 7 $B \to D^{(*)}\tau^-\overline{\nu}_\tau$

Semileptonic decays with $\tau$ leptons provide a new source of information on SM processes as well as a window into physics beyond the SM since the large $\tau$ mass gives sensitivity to decays mediated by a charged Higgs boson [20]. Because the corresponding decays to light leptons have been studied and the form factors have been measured, theoretical predictions for the $\tau$ modes are quite clean, making these modes attractive probes of new physics. These decays are extremely challenging experimentally, however, due to the presence of multiple neutrinos in the final state.

Belle and *BABAR* recently presented the first results on exclusive semitauonic $B$ decays [21]. Both experiments fully reconstruct one of the two $B$ mesons in the event and use the kinematic constraints to measure the missing four-momentum from the second $B$. Care must be taken to be sure that the decay products of both $B$ mesons are correctly reconstructed and account for all of the visible particles in the event, since mistakes tend to fake the missing momentum signature of signal events.

The Belle analysis reconstructs $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ with $\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau$ and $\tau^- \to \pi^-\nu_\tau$ and requires events to have a large value of $X_{\text{miss}}$, a kinematic variable closely related to the missing mass. This cut preferentially selects events in which multiple neutrinos have escaped detection. The signal yield is then extracted by fitting the tag $B$ mass distribution, yielding the result $\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$.

The *BABAR* analysis reconstructs four modes, $B^- \to D^0\tau^-\overline{\nu}_\tau$, $B^- \to D^{*0}\tau^-\overline{\nu}_\tau$, $\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$, and $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$, with $\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau$. The signal is extracted with a fit to the $m^2_{\text{miss}}$ and lepton momentum distributions (for signal events, this lepton is secondary), performed simultaneously in the $D^0$, $D^{*0}$, $D^+$, and $D^{*+}$ final states, as well as a set of control samples which simultaneously constrain background from $B \to D^{**}\ell^-\overline{\nu}_\ell$ decays. Combining results from charged and neutral $B$ modes, they obtain $\mathcal{B}(\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$ and $\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau) = (1.62 \pm 0.31 \pm 0.10 \pm 0.05)\%$, where the $D^*$ result is consistent with that of Belle.

Both the Belle and *BABAR* results are about one standard deviation higher than the SM prediction. These measurements are statistically limited, however, and with increased statistics, studies of these modes are expected to add significant constraints to new physics models. In addition to the branching fractions, several other observables are sensitive to possible non-SM contributions, including $q^2$ distributions and $D^*$ and $\tau$ polarization [20], which would add to the sensitivity of future studies of $B \to D^{(*)}\tau^-\overline{\nu}_\tau$.

## 8 Conclusion

We have presented an overview of recent results in semileptonic decays from the $B$ factories. $|V_{ub}|$ has been measured with several different techniques and is now known to better than 10%, while $|V_{cb}|$ is now known to better than 2%. Both of these measurements are fundamental to the $B$ factory goal of overconstraining the Unitarity Triangle. Work is ongoing to understand the composition of the exclusive states which make up $B \to X_c\ell^-\overline{\nu}_\ell$, particularly in disentangling the various $D^{**}$ contributions. New decay modes with $\tau$ leptons have been observed for the first time, opening up a new window into physics beyond the Standard Model.

## References


1. Charge conjugate processes are implied throughout.
2. N. Cabibbo, Phys. Rev. Lett. **10** 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** 652 (1973).
3. We use here the kinetic scheme: P. Gambino and N. Uraltsev, Eur. Phys. Jour. C **34** 181 (2004); D. Benson, I.I. Bigi, and N. Uraltsev, Nucl. Phys. B **710** 371 (2005). These decays can alternatively be described in the 1S scheme: C.W. Bauer *et al.*, Phys. Rev. D **67** 054012 (2003) and Phys. Rev. D **70** 094017 (2004).
4. P. Urquijo *et al.* (Belle Collab.), Phys. Rev. D **75** 032001 (2007); C. Schwanda *et al.* (Belle Collab.), Phys. Rev. D **75** 032005 (2007); B. Aubert *et al.* (*BABAR* Collab.), arXiv:0707.2670.
5. A. Höcker and V. Kartvelishvili, Nucl. Instrum. Methods Phys. Res., Sect. A **372** 469 (1996).
6. E. Barberio *et al.* (HFAG), arXiv:0704.3575 and online updates.
7. O. Buchmüller and H. Flächer, Phys. Rev. D **73** 073008 (2006).
8. M. Neubert at the Joint Workshop on $|V_{ub}|$ and $|V_{cb}|$ at the $B$ Factories, Heidelberg, (2007).
9. C.W. Bauer, Z. Ligeti, and M. Luke, Phys. Rev. D **64** 113004 (2001); B.O. Lange, M. Neubert, and G. Paz, Phys. Rev. D **72** 073006 (2005); J.R. Andersen and E. Gardi, JHEP **0601** 097 (2006).
10. B. Aubert *et al.* (*BABAR* Collab.), Phys. Rev. Lett. **100** 171802 (2008).
11. I. Bizjak *et al.* (Belle Collab.), Phys. Rev. Lett. **95** 241801 (2005).
12. A common model-independent parameterization is C.G. Boyd and M.J. Savage, Phys. Rev. D **56** 303 (1997). Some commonly used models include D. Scora and N. Isgur, Phys. Rev. D **52** 2783 (1995); I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. B **530** 153 (1998); D. Becirevic and A.B. Kaidalov, Phys. Lett. B **478** 417 (2000); and A. Khodjamirian *et al.*, Phys. Rev. D **62** 114002 (2000). Lattice QCD calculations include C. Aubin *et al.*, Phys. Rev. Lett. **94** 011601 (2005).
13. S. Dobbs *et al.* (CLEO Collab.), arXiv:0712:1020.
14. L. Widhalm *et al.* (Belle Collab.), Phys. Rev. Lett. **97** 061804 (2006); B. Aubert *et al.* (*BABAR* Collab.), Phys. Rev. D **76** 052005 (2007).
15. D. Asner *et al.* (CLEO Collab.), Phys. Rev. D **76** 012007 (2007).
16. T. Hokuue *et al.* (Belle Collab.), Phys. Lett. B **648** 139 (2007); B. Aubert *et al.* (*BABAR* Collab.), Phys. Rev. Lett. **98** 091801 (2007).
17. B. Aubert *et al.* (*BABAR* Collab.), Phys. Rev. Lett. **100** 151802 (2008).
18. J. Abdallah *et al.* (Delphi Collab.), Eur. Phys. Jour. C **45** 35 (2006).
19. D. Liventsev *et al.* (Belle Collab.), Phys. Rev. D **77** 091503 (2008); see also the contribution from D. Liventsev in these proceedings.

20. J.G. Körner and G.A. Schuler, Z. Phys. C **46** 93 (1990); A.F. Falk *et al.*, Phys. Lett. B **326** 145 (1994); M. Tanaka, Z. Phys. C **67** 321 (1995); K. Kiers and A. Soni, Phys. Rev. D **56** 5786 (1997); D.S. Hwang and D.-W. Kim, Eur. Phys. Jour. C **14** 271 (2000); H. Itoh, S. Komine, and Y. Okada, Prog. Theor. Phys. **114** 179 (2005); C.-H. Chen and C.-Q. Geng, JHEP **0610** 053 (2006); U. Nierste, S. Trine, and S. Westhoff, arXiv:0801.4938.
21. A. Matyja *et al.* (Belle Collab.), Phys. Rev. Lett. **99** 191807 (2007); B. Aubert *et al.* (*BABAR* Collab.), Phys. Rev. Lett. **100** 021801 (2008).