Semileptonic B decays and determination of $|V_{cb}|$ at Belle

E. Won[*] **(The Belle Collaboration)**

School of Physics, Seoul National University, Seoul, Korea
E-mail: `eiwon@hep1.snu.ac.kr`

Abstract: We present preliminary results on branching fraction measurements for semileptonic $\bar{B}^0 \to D^{(*)+} l^- \bar{\nu}$ decays, inclusive semileptonic decays with lepton tags, and the charmless semileptonic B decay $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$. The Kobayashi-Maskawa matrix element $|V_{cb}|$ is calculated from our results.

1. Introduction

In the Standard Model of electroweak interactions, the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix are constrained only by unitarity. Experimental measurements of elements of the CKM matrix have been extensively pursued in order to verify whether the Standard Model description of electroweak interactions among quarks is indeed the correct description or not. For example, an accurate measurement of $|V_{cb}|$ is important to constrain the Standard Model. This can be done by studying $\bar{B}^0 \to D^{(*)+} l^- \bar{\nu}$ decays and inclusive semileptonic B decays. It is also important to mesure $|V_{ub}|$ precisely, in conjunction with an accurate measurement of $\sin 2\phi_1$. The mode $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$ is one of the cleanest channels to extract $|V_{ub}|$. In this paper, we summarize measurements of the branching fractions of modes mentioned above and of $|V_{cb}|$.

We analysed data samples of 10.2, 5.1, and 21.2 fb^{-1}, collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- collider, for channels of $D^{(*)+} l^- \bar{\nu}$, inclusive semileptonic decay, and $\pi^+ l^- \bar{\nu}$, respectively.

2. $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$

We reconstruct $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ decays using the decay chain $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ and require l^- to be an election. In order to suppress $e^+e^- \to q\bar{q}$ continuum background, the ratio of the second to zeroth Fox-Wolfram moments (R_2) is required to be less than

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[*] Speaker.

0.4. Each event is required to contain at least one electron candidate with momentum in the range of 0.1 GeV/c to 2.45 GeV/c, in the center of mass (CM) frame. After a $K^-\pi^+$ combination is selected, its vertex is computed in space and the momentum vector of each particle is recalculated at this position. D^0 candidates are required to satisfy track quality cuts based on their impact parameters relative to the $K^-\pi^+$ vertex.

The $D^0 \to K^-\pi^+$ candidates must have an invariant mass within 3σ of the nominal D^0 mass value. We combine D^0 candiates to fully reconstruct D^{*+} mesons in the mode $D^{*+} \to D^0\pi^+$. These pion candidates are called slow pions (π_s^+) due to their low momentum in the laboratory frame. The ΔM ($M_{K\pi\pi_s} - M_{K\pi}$) signal region for D^{*+} is 6 MeV/c^2 wide and is centered at 145.4 MeV/c^2. Furthermore the momentum of D^{*+} candidates must satisfy $|\vec{p}_{D^*}|/\sqrt{E_B^2 - M_{D^*}^2}$ < 0.5, to be consistent with a B decay hypothesis. A D^0−lepton vertex is fit in space and the lepton momentum vector is recomputed by imposing the requirement that it is originated from this new vertex. For a signal event, we expect $P_{miss}^2 = P_\nu^2 = 0$, where

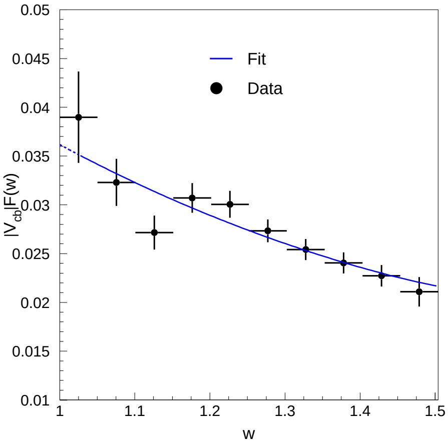

Figure 1: Distribution of $|V_{cb}|F(\omega)_{D^*}$ as a function of ω. Closed circles are data points and the curve is the result of the fit.

$$P_{miss}^2 = (P_B - P_{D^*l})^2 \equiv M_B^2 + M_{D^*l}^2 - 2E_B E_{D^*l} + 2|\vec{p}_B||\vec{p}_{D^*l}|\cos\theta_{D^*l}. \tag{2.1}$$

In order to suppress the background from $\bar{B} \to D^{**}l\bar{\nu}$, a cut of $|M_{miss}^2| < 1$ GeV$^2/c^4$ and a kinematic consistency condition through the requirement $|\cos\theta_{BD^*l}| <1$ is imposed. The partial width for $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ decays is given by

$$\frac{d\Gamma(\bar{B}^0 \to D^{*+}l^-\bar{\nu})}{d\omega} = \frac{G_F^2}{48\pi^3} M_{D^{*+}}^3 (M_{\bar{B}^0} - M_{D^{*+}})^2 g(\omega) |V_{cb}|^2 F(\omega)^2, \tag{2.2}$$

where $\omega = \vec{v}_B \cdot \vec{v}_{D(*)}$ and $g(\omega)$ is given in [1]. We fit the final yield after subtraction of background as a function of ω for $|V_{cb}|F(1)_{D^*}$ and ρ^2, fixing $R_1(1) = 1.27$ and $R_2(1)$ $= 0.8$ which are obtained using HQET and QCD sum rules. The fit result is shown in Fig. 1. We find $|V_{cb}|F(1)_{D^*} = (3.62 \pm 0.15) \times 10^{-2}$ and $\rho^2 = 1.36 \pm 0.13$. We obtain the branching fraction of $B(\bar{B}^0 \to D^{*+}l^-\bar{\nu}) = (4.77 \pm 0.38) \times 10^{-2}$ by integrating the function $d\Gamma/d\omega$ obtained above, where the errors above are statistical only. The largest systematic uncertainty comes from the reconstruction efficiency of slow pions and we assign 3.0 % in $|V_{cb}|F(1)_{D^*}$ as a systematic effect due to the low momentum track reconstruction.

3. $\bar{B}^0 \to D^+l^-\bar{\nu}$

This analysis is based on the neutrino reconstruction method, which exploits the hermeticity of the detector and the near zero value of the neutrino mass. We require first -2.0 $< M_{miss}^2 < 3.0$ GeV$^2/c^4$. We also require that the net charge $|\Delta Q| \leq 1$ to reject events with other missing charged particles. To reject events with undetected particles (mostly passing near the beam pipe) that make significant contributions to E_{miss} and $\vec{p}_{miss}$, we require $|\cos\theta_{\vec{p}_{miss}}| < 0.95$.

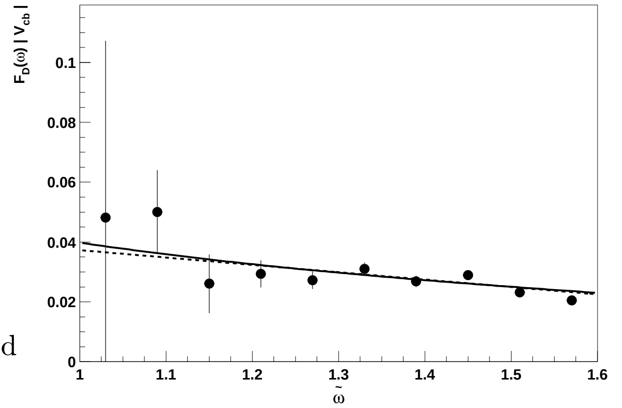

Figure 2: Distribution of $|V_{cb}|F(\omega)_D$ as a function of ω. Closed circles are data points and curves are results of the fit. Solid curve is based on Caprini *et al*[2] and the dashed one is based on the linear form factor model.

Leptons are required to satisfy $p_{lab} > 0.8$ GeV/c. Such a requirement helps to reduce the backgrounds from hadrons misidenfied as leptons and random combinations of leptons and D^+ mesons. D^+ candidates are reconstructed in the $D^+ \to K^-\pi^+\pi^+$ decay mode. Kaons are requred to be positively identified by the hadron identification devices. The three charged tracks are kinematically fit to a D^+ decay vertex, and we require that the impact parameter of each track with respect to the vertex point be consistent with zero. We further require $p_{D^+} < 2.5$ GeV/c in order to suppress continuum background. We select $K\pi\pi$ combinations where the invariant mass is within 20 MeV/c^2 of the nominal D^+ mass. To reduced the feed-down background from $B \to D^{*+}l\nu$ decays, we reject D^+ candidates that are consistent with being produced in the decay $D^{*+} \to D^+\pi^0$. A variable $\cos\theta_{B-Dl} = (2E_BE_{Dl} - M_B^2 - M_{Dl}^2)/2|\vec{p}_B||\vec{p}_{Dl}|$ is defined as the cosine of the angle between $\vec{p}_B$ and $\vec{p}_{Dl}$. The signal events are distributed mostly within the physically allowed region $|\cos\theta_{B-Dl}| < 1$, while the background events extend to a much wider range. We require that candidates satisfy $|\cos\theta_{B-Dl}| < 1$. We finally select events satisfying $-0.2 < \Delta E < 1$ GeV and $M_B > 5.24$ GeV/c^2. Using the form factor parameterization by Caprini *et al.* [2], we obtain $|V_{cb}|F(1)_D = (3.98 \pm 0.45) \times 10^{-2}$ and $\rho_D^2 = 1.07 \pm 0.24$. The distribution of $|V_{cb}|F(1)_D$ is shown in Fig 2. By integrating the differential decay rate, we obtain the branching fraction of $B(\bar{B}^0 \to D^+l^-\bar{\nu}) = (2.09 \pm 0.11)$ %, where the errors above are statistical only. The largest systematic uncertainty comes from the neutrino reconstruction simulation and we assign 8.8 % in $|V_{cb}|F(1)$ as a systematic effect due to the uncertainty in the neutrino reconstruction.

4. Inclusive semileptonic decay of B mesons with lepton tags

We also measure the semileptonic branching fraction $B(b \to Xe\nu)$ with lepton tags. High momentum leptons are first identified as either electrons or muons. Events containing leptons from J/ψ decays are rejected if a lepton candidate, when combined with an oppositely-charged track in the event, has an invariant mass consistent with that of the J/ψ. On the other hand, leptons from τ decays $(B \to X\tau\nu, \tau \to l\nu\nu)$ or D_s decays $(B \to X_cD_s, D_s \to Yl\nu)$ are included as tags, since they have the same sign charge as the lepton from $B \to Xl\nu$ decays. To extract the electron yield from the tagged events, a binned maximum likelihood fit is performed on the E/p distributions of the electron candidates in each momentum and theta bin. To distinguish between primary and secondary electrons, we use the charge and kinematical correlation between the tag lepton and the electron. The primary electron and the tag lepton have opposite charges unless the B mesons decay are of the same flavor due to $B^0\bar{B}^0$ mixing. In order to reject electrons from the same B, opposite-sign dileptons are required to satisfy, $P_e^* + \cos\theta_{le}^* > 1.2$ (p_e^* in GeV/c) or $\cos\theta_{le}^* > 0.3$, where θ_{le}^* is the opening angle between the tag lepton and the electron in the CM frame. We also require $-0.8 < \cos\theta_{le}^* < 0.998$ for both opposite-sign and same-sign dileptons to reduce the electron background from continuum events and fake tracks. The two electon spectra (opposite(N_{+-}) and same-sign($N_{\pm\pm}$) events) can be written as

$$\frac{dN_{+-}}{dp} = N_{tag}\eta(p)\epsilon_{k1}(p)[\frac{dB(b \to xl\nu)}{dp}(1-\chi) + \frac{dB(b \to c \to yl\nu)}{dp}\chi] \tag{4.1}$$

$$\frac{dN_{\pm\pm}}{dp} = N_{tag}\eta(p)\epsilon_{k2}(p)[\frac{dB(b \to xl\nu)}{dp}\chi + \frac{dB(b \to c \to yl\nu)}{dp}(1-\chi)] \tag{4.2}$$

where N_{tag} is the number of tag leptons, $\eta(p)$ is the electron identification efficiency as a function of the momentum, including the acceptance and reconstruction efficiencies, $\epsilon_k(p)$ is the efficiency of our kinematical cuts and χ is the mixing parameter. By solving the equations above, we obtain the momentum spectra for both the primary and secondary electrons.

To extract the semileptonic branching fraction, we fit the primary electron spectrum with the ISGW2 [3] model prediction and obtained $B(B \to Xe\nu) = (10.86 \pm 0.14 \pm 0.47)$ %. The first error is the statistical and the second is the systematic from the model dependence. This result is consistent with other measurements [4]. $|V_{cb}|$ is obtained from this measurement and results assuming four different models are summarized in Table 1.

Model	$\lvert V_{cb}\rvert \times 10^{-2}$
ACCMM	4.10 ± 0.10 ± 0.40
ISGW	4.00 ± 0.10 ± 0.40
M. Shifman	4.04 ± 0.10 ± 0.20
P. Ball	3.95 ± 0.09 ± 0.19

Table 1: Determinations of $|V_{cb}|$ assuming four different models.

5. $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$

This analysis presents a preliminary measurement of the branching fraction for $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$. We reconstruct the undetected neutrino from the missing energy and the missing momentum in an event, and reconstruct the B meson. The four momentum of the undetected neutrino is inferred from the missing energy and the missing momentum in an event and is required to satisfy $|M_{miss}^2| < 2$ GeV$^2/c^4$. We also require $|\cos\theta_{miss}| < 0.8$ and net charge $|\Delta Q| \leq 1$ to suppress events with undetected particles. We require $R_2 < 0.25$ to reduce the continuum background. With precisely known constraints $E_B = E_{beam}$ and $p_\nu^2 = (p_B - p_\pi - p_l)^2 = 0$, we compute the angle between the B momentum direction and that of the combined $Y = \pi + l$ system as

$$\cos\theta_{B-Y} = \frac{2E_B E_Y - M_B^2 - M_Y^2}{2|\vec{p}_B||\vec{p}_Y|}. \tag{5.1}$$

We suppress backgrounds by requiring $|\cos\theta_{B-Y}| < 1$. The $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$ signal yield is extracted by fitting the M_{bc} distribution ($M_{bc} > 5.1$ GeV/c^2) in the ΔE signal region ($|\Delta E| < 0.3$ GeV) with predicted signal and background shapes. The signal shape is simulated using the ISGW2 and the WSB [5] models. The average of the two is used with the normalization allowed to float in the fitting. The obtained branching fraction is $B(\bar{B}^0 \to \pi^+ l^- \bar{\nu}) = (1.28 \pm 0.20) \times 10^{-4}$ (the error is statistical only) and the electron spectrum in CM frame is shown in Fig. 3. The largest systematic uncertainty comes from the neutrino reconstruction and we assign 15.9 % as a systematic effect on the measurement of the branching fraction.

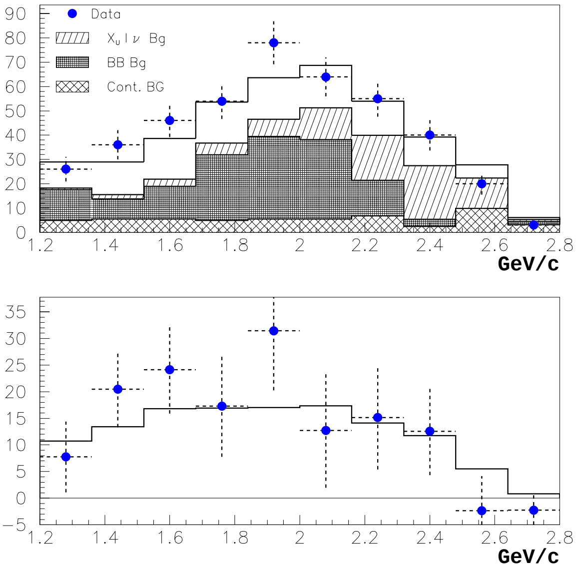

Figure 3: Momentum of the electron in CM frame is shown. Closed circles are data points and the histogram is the prediction. Top figure is shown with various background sources and the bottom one is after background substracted.

6. Conclusions

We measured branching fractions and $|V_{cb}|$ from semileptonic decay modes. From $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ and $\bar{B}^0 \to D^+ l^- \bar{\nu}$ modes, we obtained $|V_{cb}|F(1)_{D^*} = (3.62 \pm 0.15 \pm 0.18) \times 10^{-2}$ and $|V_{cb}|F(1)_D = (3.98 \pm 0.45 \pm 0.45) \times 10^{-2}$ respectively. From the inclusive semileptonic mode, we obtained $B(B \to X e \nu) = (10.86 \pm 0.14 \pm 0.47) \times 10^{-2}$ and from $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$, we obtained $B(\bar{B}^0 \to \pi^+ l^- \bar{\nu}) = (1.28 \pm 0.20 \pm 0.26) \times 10^{-4}$, where the first error is statistical and the second is the combined systematic errors in all cases.

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