New results on semileptonic $B$ decays and CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ at Belle

Eiasha Waheed$^{*\dagger}$
School of Physics, University of Melbourne
E-mail: waheede@student.unimelb.edu.au

Measurements of leptonic and semileptonic $B$ meson decays are vital for the determination of CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$. This article presents the measurements of semileptonic $B$ decays $B^0 \rightarrow D^* \ell \nu_\ell$, $B \rightarrow D^{(*)} \pi \ell \nu_\ell$, $B \rightarrow \eta^{(')} \ell \nu_\ell$ and the leptonic decay $B \rightarrow \mu^- \bar{\nu}_\mu$. These analyses use entire Belle data set collected at the $\Upsilon(4S)$ resonance containing 772 million $B\bar{B}$ meson pairs.

39th International Conference on High Energy Physics
4-11 July 2018
Seoul, Korea

$^*$Speaker.
$^\dagger$On behalf of the Belle Collaboration.
Introduction

Semileptonic B decays are a direct source to measure the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ which eventually leads to precision tests for electroweak decays of the Standard Model (SM). These decays also probe the $B$ meson structure and hence, the QCD form factors. In the note, $|V_{cb}|$ is calculated from the exclusive semileptonic $B^0 \to D^* \ell \nu$ decay. To measure the inclusive $B \to X \ell \nu$ rate, we must understand exclusive components where $X$ refers to the final states $B \to \eta \ell \nu$ and $B \to \eta' \ell \nu$. The decay rates depend upon calculations of hadronic contributions to the matrix element. In the case of pure leptonic $B$ decays such as $B \to \mu \nu$, the decay rate is proportional to $|V_{ub}|$ which governs the coupling between the $u$ and $b$ quarks. $B \to D^{(*)} \pi \ell \nu$ is an important background for high-multiplicity semileptonic $B$ decays such as $B \to D^* \ell \nu$ and $B \to D^* \tau \nu$, and hence a precise measurement of this decay is very important.

1. Measurement of $|V_{cb}|$ from $B^0 \to D^{*-} \ell^+ \nu_\ell$ decay

The decay is reconstructed in the following channel: $B^0 \to D^{*-} \ell^+ \nu_\ell$ where $D^{*-} \to \bar{B}^0 \pi^-$ and $D^0 \to K^- \pi^+$. This channel offers the best purity for the $|V_{cb}|$ measurement, which is critical as it is limited by systematic uncertainty. The experimentally most precise determination of $|V_{cb}|$ is presented in [3]. The differential decay rate of $B \to D^* \ell \nu$ decay is proportional to $|V_{cb}|$, and helicity amplitudes. The kinematics of the decay is characterised by four variables, three angular observables $\theta_\ell$, $\theta_\nu$, $\chi$ and $w = \frac{m^2_q + m^2_{D^*} - q^2}{2m_Bm_{D^*}}$. In the definition of $w$, $q^2$ is the momentum transfer between the $B$ and the $D^*$ meson, and $m_B$ and $m_{D^*}$ are their masses. Two different parameterisations of the hadronic transition form factors are used to extract $|V_{cb}|$: the model dependent Caprini-Lellouch-Neubert (CLN) form factor parameterisation [1] and the model independent Boyd-Grinstein-Lebed (BGL) parameterisation [2]. The theoretically favourable BGL parameterisation gives a higher value for $|V_{cb}|$, which is closer to the value measured by inclusive approach [4]. A simultaneous fit is performed to 1D projections of $w$, $\cos{\theta_\ell}$, $\cos{\theta_\nu}$, and $\chi$ to extract the form factor parameters and $|V_{cb}|$. The results from the fit are shown in Fig.[1]. The following values for $|V_{cb}|$ are extracted [3]:

$$|V_{cb}| = (38.7 \pm 0.2 \pm 0.6 \pm 0.5) \times 10^{-3} \quad \text{(CLN + LQCD)} \quad \text{and} \quad |V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3} \quad \text{(BGL + LQCD)}.$$  

(1.1)  

(1.2)

Lepton flavour universality between electron and muon channels has been calculated as [3],

$$\frac{\mathcal{B}(B^0 \to D^{*+} e^- \nu_e)}{\mathcal{B}(B^0 \to D^{*+} \mu^- \nu_\mu)} = 1.01 \pm 0.01 \pm 0.03.$$  

(1.3)

2. Measurement of the branching fraction of $B \to D^{(*)} \pi \ell \nu$ at Belle using hadronic tagging in fully reconstructed events

The process $B \to D^{(*)} \pi \ell \nu$ proceeds predominantly via $B \to D^{(*)+} \ell \nu$, where $D^{**}$ is an orbitally excited state of a charmed meson [7]. The decay is reconstructed by tagging one $B$ meson in a hadronic mode. Since neutrinos cannot be detected in the Belle detector, the signal mode is reconstructed using rest-of-event information excluding the final state neutrino and its invariant
mass, $M_\nu$, by employing kinematic constraints. The branching fraction is extracted by performing a fit to the spectrum of

$$M_\nu^2 = \left((p_{e^+} + p_{e^-}) - p_{B_{tag}} - p_D + p_\pi - p_\ell\right)^2 / c^2,$$

where $(p_{e^+} + p_{e^-})$ is the sum of the four-momenta of the colliding beam particles. $M_\nu^2$ is fitted with a probability density function (PDF) derived from simulation to extract the yields. Then $B$ is determined using the ratios of the fitted yields to MC and the branching fractions used in MC. Neutral and charged $B$ mesons are fitted separately where a simultaneous fit is performed to $B \to D\pi\ell\nu$ and $B \to D^*\pi\ell\nu$. The branching fractions calculated are as follows:

$$B(B^+ \to D^-\pi^+\ell^+\nu) = (4.55 \pm 0.27_{\text{stat.}} \pm 0.39_{\text{syst.}}) \times 10^{-3},$$
$$B(B^0 \to D^0\pi^+\ell^+\nu) = (4.05 \pm 0.36_{\text{stat.}} \pm 0.41_{\text{syst.}}) \times 10^{-3},$$
$$B(B^+ \to D^+\pi^+\ell^+\nu) = (6.03 \pm 0.43_{\text{stat.}} \pm 0.38_{\text{syst.}}) \times 10^{-3},$$
$$B(B^0 \to D^{*0}\pi^+\ell^+\nu) = (6.46 \pm 0.53_{\text{stat.}} \pm 0.52_{\text{syst.}}) \times 10^{-3}.$$

\(2.2\)

3. **Measurement of the decays in $B \to \eta\ell\nu_\ell$ and $B \to \eta^\prime\ell\nu_\ell$ fully reconstructed events at Belle**

Precise measurements of $B \to \eta\ell\nu_\ell$ and $B \to \eta^\prime\ell\nu_\ell$ decay rates will improve the inclusive determination of $|V_{ub}|$ because lack of knowledge on all exclusive $B \to u\ell\nu$ decays are the primary
contributions to the systematic uncertainty [8]. The branching fraction for $B^+ \rightarrow \eta \ell^+ \nu_\ell$ and $B^0 \rightarrow \eta' \ell^+ \nu_\ell$ is calculated. The decay is reconstructed by identifying $B_{\text{tag}}$ using the beam-constrained mass, $M_{\text{bc}} = \sqrt{E^2_{\text{beam}} - \sqrt{p^2_{B_{\text{tag}}}}^2}$, and the energy difference, $\Delta E = E^*_{B_{\text{tag}}} - E^*_{\text{beam}}$, where $E^*_{\text{beam}}$ is the energy of the colliding beam particles in the c.m. frame and $E^*_{B_{\text{tag}}}$ and $p^*_{B_{\text{tag}}}$ are the reconstructed energy and three-momentum of the $B_{\text{tag}}$ candidate respectively. $B_{\text{sig}}$, is reconstructed using all charged particles and neutral clusters not associated with the $B_{\text{tag}}$ candidate. The $B \rightarrow \eta^{(')}\ell \nu_\ell$ yield is extracted from the distribution of the missing mass squared, defined as $M^2_{\text{miss}} = (p_{B_{\text{tag}}} - p_{\eta^{(')}} - p_\ell)^2$, where $p_{B_{\text{tag}}}$, $p_{\eta^{(')}}$, and $p_\ell$ are the four-momenta of the $B_{\text{tag}}$, $\eta^{(')}$, and charged lepton candidates, respectively.

The results for the $B \rightarrow \eta \ell \nu_\ell$ branching fractions are [6],

$$
B^+ \rightarrow \eta \ell^+ \nu_\ell = (4.2 \pm 1.1_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-5},
$$

$$
B^0 \rightarrow \eta' \ell^+ \nu_\ell = (3.6 \pm 2.7_{\text{stat}} \pm 0.3_{0.4_{\text{syst}}}) \times 10^{-5}. \tag{3.1}
$$

4. Search for $B \rightarrow \mu^- \bar{\nu}_\mu$ decays at the Belle Experiment

In the Standard Model, the branching fraction for the purely leptonic decay of a $B$ meson is

$$
B \rightarrow \ell^- \bar{\nu}_\ell \quad B \rightarrow \mu^- \bar{\nu}_\mu \quad \text{at } 90\% \text{ C.L}
$$

The signal $B$ meson is reconstructed without the neutrino while the rest-of-event information is used in reconstructing the other $B$ meson. Neural networks (NN) are used to separate signal and background components. A fit is performed between $\mu$ momentum in the c.m. frame, $p_{\mu}^*$ and the NN output. The resulting branching fraction is [9],

$$
B^+ \rightarrow \mu^+ \nu_\mu = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7},
$$

$$
B^0 \rightarrow \mu^+ \nu_\mu \in [2.9, 10.7] \times 10^{-7} \text{ at } 90\% \text{ C.L}. \tag{4.2}
$$

References