PROCEEDINGS OF SCIENCE

Leptonic and Semileptonic B meson decays at Belle

Y. Yook*
Institute of Physics, Yonsei University
50 Yonsei-ro, Seodaemun-gu, Seoul, Korea
E-mail: yookym@yonsei.ac.kr

We report new results on searches for $B \to h\ell^+\nu_\ell$ and $B^+ \to \ell^+\nu_\ell$ decays by the Belle experiment, where h stands for a u quark meson and ℓ stands for a lepton. We apply hadronic-tag reconstruction, where a candidate B meson from $\Upsilon(4S)$ is fully reconstructed from hadronic modes. We use 711fb^{-1} data sample collected by the Belle detector at KEKB e^+e^- energy asymmetric collider at $\Upsilon(4S)$ resonance.

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*Speaker.

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1. Introduction

In the Standard Model (SM), there are parameters that must be measured by experiments. For instance, $|V_{ub}|$, one of the components in the Cabibbo-Kobayashi-Maskawa (CKM) [1, 2] matrix related to the weak transition between b and u quarks, is one of such parameters and precision measurement is required for testing the consistency of the Unitarity Triangle arising from the CKM formalism. This can be done by measuring the differential decay rate of exclusive semileptonic $B \to h\ell^+\nu_\ell$ decays, with theory input to determine the form factor $f_+(q^2)$. The differential decay rate for $B \to \pi\ell^+\nu$ decay is given as

$$\frac{d\Gamma(B \to \pi\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3}|p_\pi|^3|f_+(q^2)|^2 \tag{1.1}$$

where G_F is the Fermi coupling constant and q is the 4-momentum transferred form a B meson to outgoing leptons.
Purely leptonic decays $B \to \ell^+\nu_\ell$ may serve for the same purpose as they are clean processes for the measurement of B meson decay parameter f_B and $|V_{ub}|$. The branching fraction expected from the SM is given as

$$\mathscr{B}(B \to \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2|V_{ub}|^2\tau_B \tag{1.2}$$

where m_B is the mass of B meson, m_ℓ is the mass of lepton and τ_B is B^+ meson lifetime.
With low branching fraction expected from SM, $B^+ \to \ell^+\nu_\ell$ decays are considered as good probes for the physics beyond SM. With introduction of new physics scenarios, such as 2-Higgs Doublet Model (type-II) of Minimal Super Symmetric Models [3], the branching fraction of $B \to \ell^+\nu_\ell$ can be further enhanced.
In this report, we present recent measurements of branching fraction in the decays $B \to h\ell^+\nu_\ell$ and $B \to \ell^+\nu_\ell$ using hadronic-tag method, where a candidate B (B_{tag}) meson from $\Upsilon(4S)$ resonance is fully reconstructed in hadronic modes. We use 772M $\Upsilon(4S)$ data sample collected with the Belle detector [4] at KEKB asymmetric energy e^+e^- collider [5]. The data sample was reprocessed to improve the detection efficiency for neutral particles and charged tracks with low transverse momentum.
By completely tagging a B meson, we constrain the charge, flavor, energy-momentum of the recoiling B meson (B_{sig}). This results in high purity and allows the decay processes to be studied with virtually no background while it suffers in efficiency compared to untagged methods. Hadronic-tag method is the only method to analyze the missing momentum of rare decays with particles that cannot be detected at the Belle detector, such as neutrinos. The presented studies utilize an updated hadronic-tagging module based on neural network and Bayesian interpretation with more B/D decay reconstruction modes compared to the previous module [6].

2. Precise measurement of $\mathscr{B}(B \to h\ell^+\nu_\ell)$ $(\ell^+ = e^+, \mu^+)$

The Belle experiment measured the most precise branching fraction up to date for $B \to h\ell\nu_\ell$ decays: $B^+ \to \pi^0\ell^+\nu_\ell$, $B^0 \to \pi^-\ell^+\nu_\ell$, $B^+ \to \rho^0\ell^+\nu_\ell$, $B^0 \to \rho^-\ell^+\nu_\ell$, $B^+ \to \omega(\pi^+\pi^-\pi^0)\ell^+\nu_\ell$, and

$B^+ \to \eta \ell^+ \nu_\ell$ [7]. Also, a branching fraction upper limit is set for $B^+ \to \eta' \ell^+ \nu_\ell$ decay.
The events were selected with criteria concerning the quality of the B_{tag}, number of particles in the final state, suppression of backgrounds from wrongly reconstructed π^0. Signal yield is extracted from a one dimensional maximum likelihood fit to M^2_{miss} where the M^2_{miss} is defined as

$$M^2_{miss} = (E_{CM} - E_{Btag} - E_{Bsig})^2 - (\vec{p}_{Btag} + \vec{p}_{Bsig})^2 \tag{2.1}$$

where $(E,p)_{Btag}$ and $(E,p)_{Bsig}$ is the energy and momentum of the B_{tag} and final state particles in the B_{sig}, respectively, and E_{CM} is the energy of e^+e^- system in center of mass frame. With correct reconstruction of an event, the M_{miss} corresponds to the mass of neutrino. Thus, it is expected for the M^2_{miss} to peak around 0. Major systematic uncertainty, about 5%, arises from B_{tag} efficiency calibration to data.
In the Table 1, the number of signal and the obtained branching fraction for each mode is summarized. Calculation of $|V_{ub}|$ according to the $B \to \pi \ell \nu$ result with different theory input for different bins of q^2 are summarized in Table 2.

$B \to h \ell \nu_\ell$	Number of signal	Branching Fraction
$\mathscr{B}(B^0 \to \pi^- \ell^+ \nu_\ell)$	461 ± 28	$(1.49 \pm 0.09(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$
$\mathscr{B}(B^+ \to \pi^0 \ell^+ \nu_\ell)$	230 ± 22	$(0.80 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})) \times 10^{-4}$
$\mathscr{B}(B^0 \to \rho^- \ell^+ \nu_\ell)$	338 ± 28	$(3.17 \pm 0.27(\text{stat}) \pm 0.18(\text{syst})) \times 10^{-4}$
$\mathscr{B}(B^+ \to \rho^0 \ell^+ \nu_\ell)$	632 ± 35	$(1.86 \pm 0.10(\text{stat}) \pm 0.09(\text{syst})) \times 10^{-4}$
$\mathscr{B}(B^+ \to \omega \ell^+ \nu_\ell)$	99 ± 15	$(1.09 \pm 0.16(\text{stat}) \pm 0.08(\text{syst})) \times 10^{-4}$
$\mathscr{B}(B^+ \to \eta \ell^+ \nu_\ell)$	39 ± 11	$(0.42 \pm 0.12(\text{stat}) \pm 0.05(\text{syst})) \times 10^{-4}$
$\mathscr{B}(B^+ \to \eta' \ell^+ \nu_\ell)$	6.1 ± 4.7	$< 0.57 \times 10^{-4}$ at 90% C.L.

Table 1: The number of signal with statistical uncertainty and obtained branching fraction of each channel in $B \to h \ell \nu_\ell$.

$B \to h \ell \nu_\ell$	Theory	$q^2(\text{GeV}^2)$	$\lvert V_{ub} \rvert \times 10^3$
$\pi^0 \ell^+ \nu_\ell$	KMOW [8]	< 12	$3.30 \pm 0.22 \pm 0.09^{+0.35}_{-0.30}$
	Ball/Zwicky [9]	< 16	$3.62 \pm 0.20 \pm 0.10^{+0.60}_{-0.40}$
	FNAL [10]	> 16	$3.30 \pm 0.30 \pm 0.09^{+0.36}_{-0.30}$
	HPQCD [11]	> 16	$3.45 \pm 0.31 \pm 0.09^{+0.58}_{-0.38}$
$\pi^0 \ell^+ \nu_\ell$	KMOW [8]	< 12	$3.38 \pm 0.14 \pm 0.09^{+0.36}_{-0.32}$
	Ball/Zwicky [9]	< 16	$3.57 \pm 0.13 \pm 0.09^{+0.59}_{-0.39}$
	FNAL [10]	> 16	$3.69 \pm 0.22 \pm 0.09^{+0.41}_{-0.34}$
	HPQCD [11]	> 16	$3.86 \pm 0.23 \pm 0.09^{+0.66}_{-0.44}$

Table 2: Calculation of $|V_{ub}|$ from $B \to \pi \ell \nu$ branching fraction for different theory input for each q^2 range.

3. Search for $B^+ \to \ell^+ \nu_\ell$ ($\ell^+ = e^+, \mu^+$)

The Belle experiment updated the upper limit for $\mathscr{B}(B^+ \to \ell^+ \nu_\ell)$ using hadronic-tag reconstruction method. As $B^+ \to \ell^+ \nu_\ell$ is a two-body decay, the lepton from the recoiling B meson (B_{sig}) has nearly mono-energetic feature in the B_{sig} rest frame. To exploit this feature, the magnitude of the lepton momentum p_ℓ^B in the B_{sig} rest frame is used to extract the signal yield. The probability density function (PDF) of the background obtained from Monte Carlo (MC) was obtained by one dimensional unbinned maximum likelihood fit in p_ℓ^B. The background PDF was fitted to data and the expected number of the background in the signal region (about 2.6 GeV$/c < p_\ell^B <$ 2.7 GeV$/c$) was extrapolated from the sideband region (2.0 GeV$/c < p_\ell^B <$ 2.5 GeV$/c$) according to the obtained background PDF. No signal candidates are observed in the signal region.
90% confidence level branching fraction upper limit for each electron and muon mode were set using the POLE [12] program based on a frequentist approach [13]. We set the upper limits of branching fraction at $\mathscr{B}(B^+ \to e^+ \nu_e) < 3.5 \times 10^{-6}$ and $\mathscr{B}(B^+ \to \mu^+ \nu_\mu) < 2.5 \times 10^{-6}$. The expected number of backgrounds in the signal region and signal efficiency used for branching fraction calculation is summarized in the Table 3.

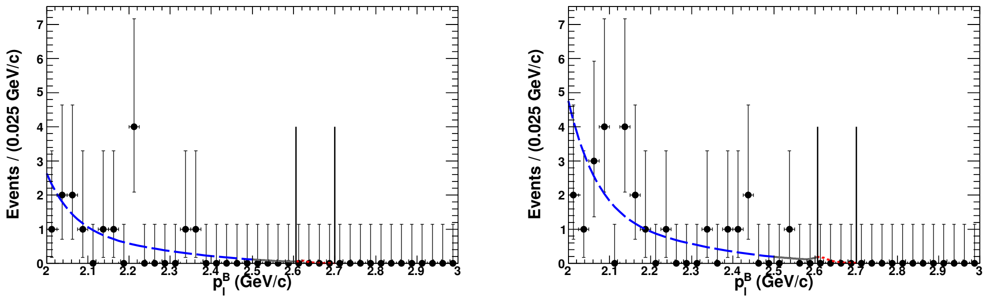

Figure 1: The p_ℓ^B distributions of background PDF and data sample for $B^+ \to e^+ \nu_e$ (left) and $B^+ \to \mu^+ \nu_\mu$ (right). Black dots with error bar are data sample. The blue line and the red dotted line denotes sideband region (2.0 GeV$/c < p_\ell^B <$ 2.5 GeV$/c$) and signal region (about 2.6 GeV$/c < p_\ell^B <$ 2.7 GeV$/c$), respectively. The background PDF was fitted to the sideband region of data sample.

	$B^+ \to e^+ \nu_e$	$B^+ \to \mu^+ \nu_\mu$
N_{exp}^{BKG}	$0.11^{+0.75}_{-0.06}$	$0.33^{+0.10}_{-0.08}$
ε_{sig}	$(9.1 \pm 1.5) \times 10^{-4}$	$(1.15 \pm 0.18) \times 10^{-3}$
$N_{\text{data observed}}$	0	0
$\mathscr{B}(B^+ \to \ell^+ \nu_\ell)$	$< 3.5 \times 10^{-6}$	$< 2.5 \times 10^{-6}$

Table 3: Results for $B^+ \to \ell^+ \nu_\ell$ study. N_{exp}^{BKG} is the expected number of background in the signal region. ε_{sig} is the signal efficiency. $N_{\text{data observed}}$ stands for the observed yield in the signal region.

4. An updated measurement of $B^+ \to \tau^+ \nu_\tau$

The Belle experiment has reported the first evidence for $B^+ \to \tau^+ \nu_\tau$ decay [14] in 2006 with a data sample of 449M $\Upsilon(4S)$ events and hadronic-tag reconstruction with a significance of 3.5 standard deviation (σ). The measured branching fraction was $\mathscr{B}(B^+ \to \tau^+ \nu_\tau) = 1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{0.51}(\text{syst})$ where signal was extracted from one dimensional maximum likelihood fit to E_{ECL}, where E_{ECL} is defined as the extra energy deposited to Electromagnetic Calorimeter aside from the energy contributed via B_{tag} and the constituents of the recoil B meson. The consistent measurements were made by Belle using the semileptonic tagging method [15], and BaBar collaboration with hadronic and semileptonic tagging methods [16, 17]. The world average of branching fraction with all experiments considered is $(1.67 \pm 0.30) \times 10^{-4}$. This value shows a tension with estimate based on a global fit by more than 2σ.

In this study, the update of branching fraction measurement was performed usign the full $\Upsilon(4S)$ data sample of Belle with afore-mentioned reprocessing, new hadronic tagging algorithm and signal extraction with two dimensional maximum likelihood fit to E_{ECL} and M^2_{miss} to improve handling of peaking backgrounds. To reconstruct a τ in B_{sig}, $\tau^- \to e^- \bar{\nu}_e \nu_\tau$, $\mu^- \bar{\nu}_\mu \nu_\tau$, $\pi^- \nu_\tau$, and $\rho^-(\pi^- \pi^0)\nu_\tau$ decay channels were used. K^0_L rejection was applied to further reduce the sensitivity to peaking backgrounds in E_{ECL}.

The analysis was validated with various control samples. Shapes of E_{ECL} and M^2_{miss} were tested with $B^+ \to D^{*0}\ell^+\nu_\ell$ sample, where the event shape is similar to $B^+ \to \tau^+\nu_\tau$. B_{tag} efficiency and K^0_L rejection efficiency was calibrated to data.

The two dimensional PDF was obtained by taking the product of one dimensional fits to E_{ECL} and M^2_{miss}. The obtained signal yield is $62^{+23}_{-22}(stat) \pm 6(syst)$. With equal neutral and charged $B\bar{B}$ pair production in $\Upsilon(4S)$ assumed, the obtained branching fraction is $\mathscr{B}(B^+ \to \tau^+\nu_\tau) = (0.72^{+0.27}_{-0.25}(stat) \pm 0.11(syst)) \times 10^{-4}$. This corresponds to 1.9σ difference from the previous hadronic tagging method result at the Belle experiment.

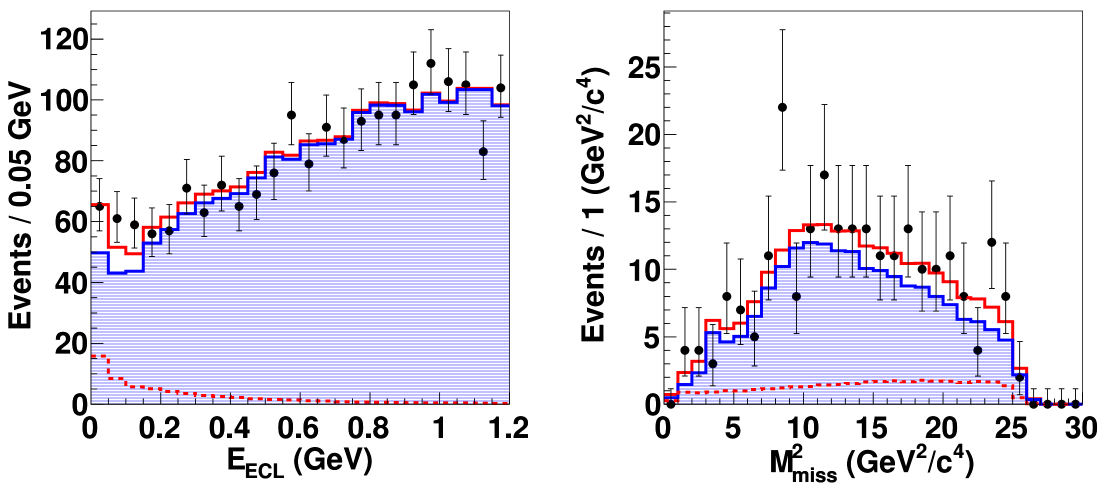

Figure 2: PDF projection of E_{ECL} (left) and M^2_{miss} (right) for all τ reconstruction channels combined. M^2_{miss} is plotted in the signal enhanced region of $E_{ECL} < 0.2$ GeV. The black dots with error bar are data. The solid red line is the total MC. The blue histogram and red dotted line are background and signal components, respectively.

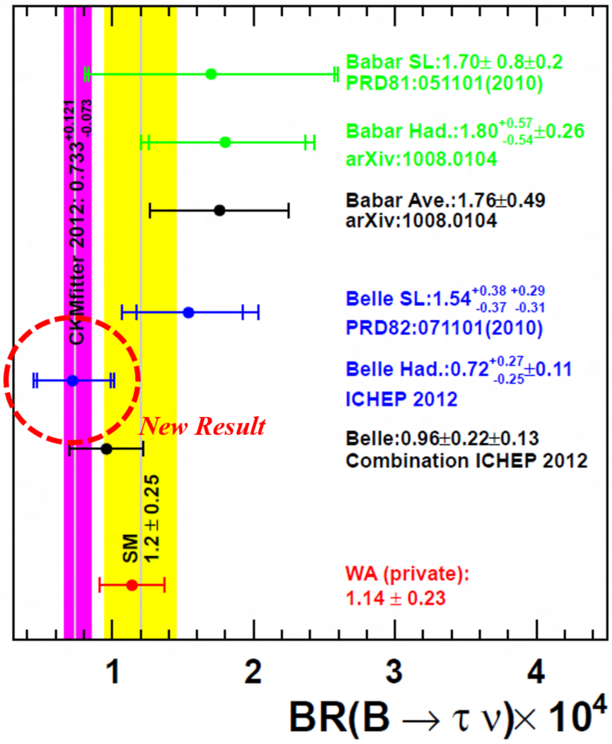

Figure 3: A summary of $B^+ \to \tau^+\nu_\tau$ studies. The new result is highlighted with red circle.

5. Summary

The Belle experiment measured exclusive charmless semileptonic $B \to h\ell^+\nu_\ell$ decays and purely leptonic B decays with much improved sensitivity by using the reprocessed full data sample with new hadronic tagging algorithm. There were updates on exclusive semileptonic decays and precise extraction of $|V_{ub}|$ was made with $d\Gamma(B \to \pi\ell\nu)/dq^2$. The search for $B^+ \to \mu^+\nu_\mu$ showed the best constraint to date among the $B^+ \to \ell^+\nu_\ell$ searches (e,μ) using hadronic-tag method. The newly measured branching fraction for $B^+ \to \tau^+\nu_\tau$ is consistent with the predicted value from the global CKM unitarity triangle fit.

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