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Experimental review and prospects on leptonic B^+ decays

Youngjoon Kwon[*†]
Yonsei University
E-mail: yjkwon63@yonsei.ac.kr

The leptonic B^+ decays are calculated in the Standard Model with great precision. Therefore it can be a very powerful probe of physics beyond the Standard Model. In this talk, we review experimental status of $B^+ \to \tau^+\nu$, $B^+ \to \ell^+\nu$ and other related decays. We discuss also future prospects with Belle II.

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*Speaker.
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1. Introduction

1.1 Motivations and general features

The decay rate of the purely leptonic $B^+ \to \ell^+ \nu$[1] decays are calculated within the Standard Model (SM) with very little uncertainty:

$$\Gamma_{\rm SM}(B^+ \to \ell^+ \nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \ .$$

The B-meson decay constant f_B, which contains the strong interaction information of the two quarks in the initial-state B^+ meson, is calculated to a high precision with lattice QCD. The magnitude of a CKM parameter $|V_{ub}|$ can be extracted from semileptonic B decays such as $B \to \pi \ell^+ \nu$. With these information in hand, the measured branching fraction of $B^+ \to \ell^+ \nu$ can become a very sensitive probe for new physics contributions beyond SM, e.g. from charged Higgs. For instance, in the two-Higgs doublet model (2HDM) of type II, the branching fraction is modified as:

$$\mathscr{B}(B^+ \to \tau^+ \nu) = \mathscr{B}_{\rm SM}(B^+ \to \tau^+ \nu) \times r_H \ ,$$

where $\mathscr{B}_{\rm SM} = \Gamma_{\rm SM} \tau_{B^+}$, with τ_{B^+} being the lifetime of B^+, and $r_H = \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$ [1].

With $\Gamma_{\rm SM} \propto m_\ell^2$, the expected branching fractions of $B^+ \to \mu^+ \nu$ and $B^+ \to e^+ \nu$ within the SM are much lower than that of $B^+ \to \tau^+ \nu$. While evidences of $B^+ \to \tau^+ \nu$ have been obtained by both Belle [2, 3] and BaBar[4, 5], there has not been any experimental evidence for $B^+ \to \mu^+ \nu$ and $B^+ \to e^+ \nu$. Taking the ratio between the decays, for instance $B^+ \to e^+ \nu$ and $\tau^+ \nu$, most of the SM uncertainties are cancelled and the lepton flavor universality can be tested with great precision.

1.2 Tagging

The $B^+ \to \ell^+ \nu$ modes have at least one invisible particle (ν) in the final state, thus it is not possible to fully reconstruct the decay. For $\ell = e$ or μ, the magnitude of the 3-momentum, p_ℓ^B, of the charged lepton in the rest frame of B can be determined analytically, making it a very clean experimental signature. On the other hand, $B^+ \to \tau^+ \nu$ mode has two or more neutrinos in the final state and we do not have such a clean signature as p_ℓ^B of $B^+ \to e^+ \nu$ and $B^+ \to \mu^+ \nu$. To improve experimental sensitivity, we exploit the feature of e^+e^- B-factory experiments that the $\Upsilon(4S)$ decay produces $B\overline{B}$ and nothing else. Reconstructing one of the B's ($B_{\rm tag}$) provides kinematic constraints on the signal B ($B_{\rm sig}$), and the signal purity and background suppression can be greatly improved. If the full decay chain of $B_{\rm tag}$ is reconstructed in hadronic decay modes ("hadronic tagging"), highest signal purity can be achieved, but the tagging efficiency becomes very low ($\sim \mathscr{O}(0.1\%)$). On the other hand, using semileptonic decays of $B_{\rm tag}$, the signal purity is a little sacrificed but much higher tagging efficiency is attained. In the studies of $B^+ \to \tau^+ \nu$ decays, both tagging methods have been used. For $B^+ \to \ell^+ \nu$ ($\ell = e,\ \mu$), untagged analyses as well as tagged analyses have been employed.

2. $B^+ \to \tau^+ \nu$

In this section, we review the existing measurements of $B^+ \to \tau^+ \nu$ by Belle and BaBar. Both hadronic and semileptonic B-tagging methods have been applied by both experiments. In all four

[1] In this write-up, charge-conjugate states are implied unless explicitly stated otherwise.

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analyses presented below, the following τ decay modes are used: $\tau^+ \to e^+\nu_e\overline{\nu}_\tau$, $\mu^+\nu_\mu\overline{\nu}_\tau$, $\pi^+\overline{\nu}_\tau$, and $\rho^+\overline{\nu}_\tau$.

2.1 Results with hadronic B-tagging analyses

In the Belle analysis [2] using hadronic B-tagging, the $B_{\rm tag}$ candidates are reconstructed in 615 exclusive B^+ decay modes using an algorithm based on artificial neural network combined with Bayesian interpretation [6]. Then the $B_{\rm sig}$ candidates are selected using the aforementioned τ decay modes. After reconstructing $B_{\rm tag}$ and $B_{\rm sig}$, it is demanded that no trace of π^0 and K_L^0 is left in the event ("π^0 and K_L^0 veto"). The K_L^0 veto provides $\sim 5\%$ improvement in the expected sensitivity, and the veto efficiency is calibrated by real data using $D^0 \to \phi K_S^0$, $\phi \to K_L^0 K_S^0$ decays.

The signal yield is extracted by two-dimensional (2D) fitting to $E_{\rm ECL}$ and $M^2_{\rm miss}$, where $E_{\rm ECL}$ is the extra energy in the electromagnetic calorimeter (ECL) which does not belong to either $B_{\rm tag}$ or $B_{\rm sig}$. This is in contrast to the previous Belle analysis in which 1D fit to $E_{\rm ECL}$ was used. The 2D fit method improve sensitivity by $\sim 20\%$, and is more robust against peaking background in the $E_{\rm ECL}$. The fit was performed simultaneously on all the τ modes analyzed. The fitted signal yeild is $62^{+23}_{-22} \pm 6$ events, from which Belle obtains $\mathscr{B}(B^+ \to \tau^+\nu) = \left(0.72^{+0.27}_{-0.25} \pm 0.11\right) \times 10^{-4}$. The signal significance is 3.0σ including systematic error.

BaBar has also measured $B^+ \to \tau^+\nu$ with hadronic B-tagging. Signal yeild is extracted in a 1D fit to $E_{\rm extra}$[2], obtaining $N_{\rm sig} = 62.1 \pm 17.3$ from simultaneous fit to the four τ modes. The branching fraction is $\mathscr{B}(B^+ \to \tau^+\nu) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$. Major systematic uncertainties include those from background PDF's (10%), B-tag efficiency (5%), etc. Including systematic uncertainty, the significance is 3.8σ.

2.2 Results with semileptonic B-tagging analyses

In the Belle analysis [3], the signal yield is extracted by 2D fitting to $(E_{\rm ECL}, p^*_{\rm sig})$, where $p^*_{\rm sig}$ is the magnitude of 3-momentum of the visible partilce of the τ decay measured in the rest frame of $\Upsilon(4S)$. Figure 1 shows the fit results on $E_{\rm ECL}$ and $p^*_{\rm sig}$ for all τ modes combined. The signal yield is 222 ± 50 events and the branching fraction is measured as $\mathscr{B}(B^+ \to \tau^+\nu) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$. By combining the two Belle analyses, using hadronic and semileptonic tagging, the significance is 4.6σ.

For BaBar analysis [5], signal yield is extracted by counting the number of events in the $E_{\rm extra}$ signal region, where the background contents are determined by the side-band of $E_{\rm extra}$. Combining the four τ modes, 583 events are observed in the signal region, with 509 ± 30 events of expected background. The branching fraction is determined as $\mathscr{B}(B^+ \to \tau^+\nu) = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$.

2.3 Discussions

The average branching fraction of the two Belle results, hadronic B tagging and semileptonic B tagging, is $\mathscr{B}_{\rm Belle}(B^+ \to \tau^+\nu) = (0.91 \pm 0.22) \times 10^{-4}$. Similarly, averaging the BaBar measurements gives $\mathscr{B}_{\rm BaBar}(B^+ \to \tau^+\nu) = (1.79 \pm 0.48) \times 10^{-4}$. The Belle and BaBar results are consitent with each other within $\sim 1.7\sigma$. The world average value $\mathscr{B}_{\rm WA}(B^+ \to \tau^+\nu) =$

[2]The variable $E_{\rm extra}$ is essentially the same as $E_{\rm ECL}$ of Belle analyses.

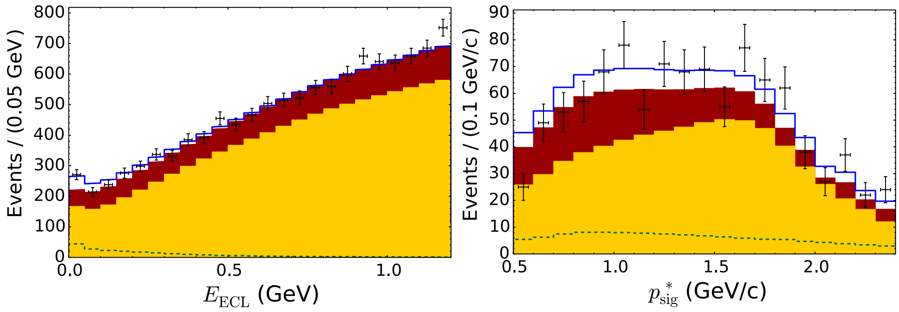

Figure 1: Distributions of $E_{\rm ECL}$ (left) and $p^*_{\rm sig}$ (right) for all τ modes combined in the semileptonic B-tagging $B^+ \to \tau^+\nu$ analysis of Belle. For $p^*_{\rm sig}$, a signal-enhanced condition $E_{\rm ECL} < 0.2$ GeV has been applied. The solid histograms show the projections of the fit results. The dashed histograms display the signal components. The orange (red) filled histograms show the $B\overline{B}$ (continuum) background.

$(1.09 \pm 0.24) \times 10^{-4}$ [7] is consistent with the SM-based prediction from the CKM unitarity triangle fit.

From the measured branching fraction, constraints can be made on the parameters related with charged Higgs. For example, BaBar shows the constraints on the parameter space $(m_{H^+}, \tan\beta)$ of the 2HDM (type II) [4], separately for inclusive and exclusive $|V_{ub}|$ measurements.

3. $B^+ \to \ell^+\nu$ and other related results

3.1 $B^+ \to \ell^+\nu$ ($\ell = e,\ \mu$)

The $B^+ \to \ell^+\nu$ decays, where $\ell = e$ or μ, are expected, in the SM, to have very small branching fractions compared to $\mathscr{B}(B^+ \to \tau^+\nu)$, due to helicity suppression. But being two-body B^+ decays, they have a very clean experimental signature: in the signal side, there is just a mono-energetic charged lepton and nothing else. Because of this, tagging is not necessary to study these decays. Indeed, the most stringent limits on the branching fractions for these decays have been obtained by untagged analyses: $\mathscr{B}(B^+ \to e^+\nu) < 0.98 \times 10^{-6}$ [8] and $\mathscr{B}(B^+ \to \mu^+\nu) < 1.0 \times 10^{-6}$ [9].

Even so, there has been interests in trying tagged analyses for these modes. For one, the resolution of the signal lepton momentum, p^B_ℓ, in the B^+ rest frame is nearly an order-of-magnitude better in the hadronic B-tagging analysis than in the untagged analysis. Moreover, as the SM-predicted branching fraction of $B^+ \to e^+\nu$ is much lower than the current experimental sensitivities ($\mathscr{B}_{\rm SM}(B^+ \to e^+\nu) \sim 10^{-11}$), observation of a non-zero signal shall not be interpreted within the SM and we will have to know more details of the decay in order to elucidate the true identity of such a signal.

Recently Belle searched for $B^+ \to \ell^+\nu$ with hadronic B-tagging analysis. Using the B-tagging algorithm shown in [6], Belle has obtained the following limits, $\mathscr{B}(B^+ \to e^+\nu) < 3.5 \times 10^{-6}$ and $\mathscr{B}(B^+ \to \mu^+\nu) < 2.7 \times 10^{-6}$ [10], which are the most stringent among the tagged analysis results of $B^+ \to \ell^+\nu$.

3.2 $B^+ \to \ell^+X^0$ ($\ell = e,\ \mu$)

While the neutrino oscillation requires small but non-zero mass of neutrinos, there exists no mechanism within the minimal SM for neutrinos to acquire mass. Many new physics (NP) models beyond the SM introduce heavy neutrinos which then may explain the masses of ordinary neutrinos via seesaw mechanism. Therefore, it is of siginifcant interest to search for massive neutrino-like particles which we denote as X^0. Possible candidates for X^0 in the NP models include sterile neutrinos in large extra dimension models, the lightest supersymmetric particle in R-parity-violating MSSM models.

Belle has searched for $B^+ \to \ell^+ X^0$ ($\ell = e,\ \mu$) using hadronic B-tagging [11]. Since X^0 is an unknown particle, Belle has scanned for the range $0.1 < m_{X^0} < 1.8$ GeV in the search. The mass of X^0 is inferred by p_ℓ^B which has been defined in Sec. 3.1. Other than m_{X^0}, the analysis follows a very similar procedure as in [10]. Figure 2(a) shows the Monte-Carlo (MC) distributions of p_ℓ^B of signal and background components, for the $B^+ \to e^+ X^0$ mode. The three signal peaks corrspond to, from left to right, $m_{X^0} = 1.8$, 1.0 and 0.1 GeV, respectively. Figure 2(b) shows the data distribution of p_ℓ^B for the $B^+ \to \mu^+ X^0$ mode. There is no significant excess of events beyond what is expected with background, in both e^+X^0 and μ^+X^0 modes in any m_{X^0} ranges. The upper limits are determined to be a few times 10^{-6} for each mode and all the m_{X^0} values tested. For the mumerical values of the limits, see [11].

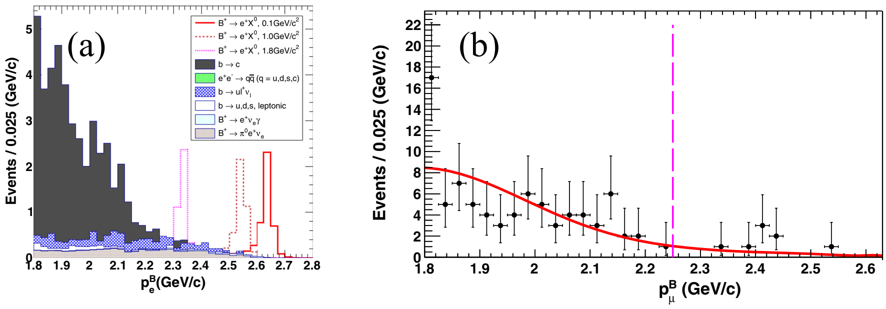

Figure 2: The p_ℓ^B distribution of $B^+ \to \ell^+ X^0$ search by Belle. (a) Signal and background MC distributions of p_ℓ^B for $B^+ \to e^+ X^0$ analysis. The three signal peaks corrspond to, from left to right, $m_{X^0} = 1.8$, 1.0 and 0.1 GeV, respectively. (b) Data distributions of p_ℓ^B for $B^+ \to \mu^+ X^0$. The region left to the vertical dashed line is the sideband to determine background.

3.3 Other modes

The helicity suppression of $B^+ \to \ell^+ \nu$ is avoided in $B^+ \to \ell^+ \nu \gamma$. The decay width of $B^+ \to \ell^+ \nu \gamma$ is sensitive to QCD factorization parameter, hence it is of interest. This mode has been studied by both BaBar and Belle [12]. The most stringent limit $\mathscr{B}(B^+ \to \ell^+ \nu \gamma) < 3.5 \times 10^{-6}$ has been obtained by Belle using hadronic B-tagging method.

The lepton-flavor-violating (LFV) $B^+ \to \ell^\pm \tau^\mp$ decays are forbidden in the minimal SM where neutrinos are massless. Even including the observed ν oscillations, the expected rate is very tiny. However in several NP models beyond SM, the branching fraction can be as large as $\mathscr{O}(10^{-10})$. In a hadronic B-tagging analysis very similar to $B^+ \to \ell^+ \nu$, BaBar has searched for $B^+ \to \ell^\pm \tau^\mp$. The results are: $\mathscr{B}(B^0 \to e^\pm \tau^\mp) < 2.8 \times 10^{-5}$, and $\mathscr{B}(B^0 \to \mu^\pm \tau^\mp) < 2.2 \times 10^{-5}$ [13].

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4. Prospects with Belle II

The Belle II experiment is an upgrade of Belle using SuperKEKB collider and is scheduled to start taking data in 2018. The target of peak instantaneous luminosity of SuperKEKB is 8×10^{35} cm^{-2}s^{-1}, which is 40 times that of KEKB. Because of this, the beam background of Belle II is expected to be much higher that Belle. The variable $E_{\rm ECL}$ is pivotal for studies of $B^+ \to \tau^+\nu$ and $B \to D^{(*)}\tau^+\nu$ and is sensitive to beam background. But these background can be under control by utilizing the shape and timing of the shower energy distributions in the electromagnetic calorimeter. Taking these into account, the expected precision of $\mathscr{B}(B^+ \to \tau^+\nu)$ in the Belle II with 1 ab^{-1} is approximately 27% including systematic error. The major sources of systematic error in the current Belle are due to background shape of $E_{\rm ECL}$, K_L^0-veto efficiency, B-tagging efficiency. These sources can be improved with more data by data-based calibration. Then the expected precision of $\mathscr{B}(B^+ \to \tau^+\nu)$ with $\int \mathscr{L} dt = 50$ ab^{-1}, which corresponds to the target of the total integrated luminosity of Belle II, is about 5%. The expected precision for $\mathscr{B}(B^+ \to \mu^+\nu)$ with a similar condition is about 7%.

Ciuchini and Stocchi [14] report the impacts of $B^+ \to \tau^+\nu$ and $B^+ \to \mu^+\nu$ on constraining the parameter space of charged Higgs in 2HDM (Type II). With $\int \mathscr{L} dt = 10$ ab^{-1}, $B^+ \to \mu^+\nu$ begins to make a significant contribution to this. Beyond 75 ab^{-1}, $B^+ \to \mu^+\nu$ takes over to become more important than $B^+ \to \tau^+\nu$ as the latter becomes limited by systematics. According to [14], charged Higgs of mass scale byeond TeV could be detected at Belle II with a large $\tan\beta$ scenario.

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