Recent Belle Results on Flavor Physics

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Belle is a B-factory experiment at KEK using KEKB asymmetric $e^+e^-$ collider. During 1999-2010, Belle has accumulated more than 711 fb$^{-1}$ of $\Upsilon(4S)$ resonance samples. At the conference, two recent Belle analyses, $B^0 \rightarrow \nu\bar{\nu}$ (invisible) and $B^+ \rightarrow \ell^+\nu$, using the hadronic-tagging method were reviewed. The hadronic-tagging method is used for collecting clean BB samples whereby the modes with one or more final state neutrinos can be unambiguously studied.

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1 Introduction

The $B$ factories, Belle [1] at KEK, Japan and BaBar [2] at SLAC, USA, primarily built for the verification of the CP violation mechanism [3], have been playing a major role in the search for the rare $b$-decays which are heavily suppressed or forbidden according to the Standard Model recently. The studies presented here focus on the purely leptonic decays which are highly suppressed by the helicity suppression. In the course of the study for such rare $b$-decays, the role of the hadronic tagging method, which some of the analyses presented here used, becomes important for that it is the only way to fully reconstruct the event with kinematical informations gained about the invisible neutrino(s). Most of the purely leptonic decays are highly suppressed beyond the reach of the sensitivity that the evidences of such modes is highly probable to conote the signs of the New Physics scenario. In the proceeding, the latest results on helicity suppressed decays of the $B$ meson recorded by the Belle detector at the KEKB energy asymmetric $e^+e^-$ collider are summarized.

2 Hadronic Tagging at BELLE

The Hadronic Tagging is a method which completely reconstructs one side of $B$ meson produced at the $B$-factory at $\Upsilon(4S)$ from the well-known $b \rightarrow c$ modes.

The clean event signature enjoyed at Belle is one of the advantage of lepton colliders over the hadron colliders like Tevatron or LHC. Being ran at the energy of $\Upsilon(4S)$, 10.58 GeV, the $e^-e^+$ pair would decay into a $B\bar{B}$ pair without any other particles being produced at the rate of over 96%. Therefore the complete reconstruction of one side of $B$-meson will reveal the energy-momentum of the other $B$-meson, and this turns out to be the only way to reconstruct rare modes with invisible final state particle(s) such as neutrino. Also from the fact that the one side of $B$-meson, with low momentum resulting in the spherical decay of the final state particles, has to be reconstructed, the hadronic tagging method works as a good way of suppressing continuum. Since the tagged $B$ mesons are reconstructed from the limited varieties of well-known $b \rightarrow c$ decays, the efficiency turns out to be lower than other methods, but the purity of well reconstructed $B$ mesons is high.

Recently, a new hadronic tagging tool was developed at Belle based on a multivariate analysis
software utilizing Neural Network [5]. The new tool ensures twice the efficiency over the old tool and the output of the network can be interpreted as Bayesian probability, giving user the power to adjust the efficiency and the purity depending on the need of the user’s analysis as in the Figure 3.

Figure 2: Event characteristic difference between $\Upsilon(4S)$ and continuum events

Figure 3: Comparison between the old and new Hadronic Tagging tools
3 Search for the Decay $B^0 \rightarrow \nu \bar{\nu}$(invisible)

The products of invisible $B^0$ decays are particles that cannot be detected by the Belle detector and the proper candidate for such particles can be a neutrino or some hypothetical particles like neutralino, $\tilde{\chi}^0_1$. The branching fraction for $B^0 \rightarrow \nu \bar{\nu}$ decay is given as in the equation below where $G_F$ is the Fermi coupling constant and $\tau_{B^0}$ is the life time of the $B$ meson. [6]

$$B(B^0 \rightarrow \nu \bar{\nu}) = \tau_{B^0} \frac{G_F^2}{\pi} \left( \frac{\alpha}{4\pi \sin^2 \Theta_W} \right)^2 \frac{F_{B^0}^2 m_{\nu}^2 m_{B^0}^2}{m_{B^0}^2} \sqrt{1 - \frac{4m_{\nu}^2}{m_{B^0}^2}} |V_{tb}V_{td}|^2 Y^2(x_t)$$ (1)

As the branching fraction of $B^0 \rightarrow \nu \bar{\nu}$ is highly suppressed by the helicity suppression and since the neutrino is almost massless, Standard Model implies an almost invisible experimental signature of this process.

However, there could be some New Physics scenario which can bring boost in the branching fraction of the process such as the $R-parity$ violation, allowing the $B^0$ meson to decay to a $\bar{\nu}u\tilde{\chi}^0_1$ pair. For the case, the branching fraction is expected to be at the order of $10^{-7}$ [7]. The previous result at BaBar showed the upper limit of $B(B^0 \rightarrow \nu \bar{\nu}) < 2.2 \times 10^{-5}$ [8]

Figure 4: Possible New Physics scenario from $R-parity$ violation.
Belle has searched for the decay using a data sample of 657M \( B \bar{B} \) pairs collected at the \( \Upsilon(4S) \) resonance. For the analysis, hadronic tagging method was used to reconstruct one side of \( B \) from \( D(\ast)^{\mp}\pi^{\mp}, D(\ast)^{\pm}\rho^{\mp}, D(\ast)-a_{1}^{\pm}, \) and \( D(\ast)-D_{s}(\ast)^{\pm} \). Conditions on the variables, \( \cos \theta_{B} \), the angle of the tagged \( B \) flight respect to the beam direction, which is needed for the agreement between the data sample and the MC simulated sample, and \( \cos \theta_{T} \), the angle of the tagged-\( B \) thrust axis respect to the beam axis in CM frame useful for the continuum suppression has been given. Appropriate \( M_{bc} \) and \( \Delta E \) cuts were given to choose well reconstructed \( B \). The events including track, \( \pi^{0}, K_{L} \) candidates on the signal side were vetoed. The \( E_{ECL} \) variable, which is the sum of all energies deposited to the ECL clusters not associated with the tagged-\( B \) meson, was optimized for the signal region selection.

Then 2-D Maximum Likelihood fitting was carried out on the \( E_{ECL} \) variable and the \( \cos \theta_{B} \) variable to extract the signal yield. The fit to 121 events in the optimized signal region resulted in \( 8.9^{+6.3}_{-5.5}(\text{stat})^{+2.6}_{-2.7}(\text{syst}) \) signal yield and with no significant signal being seen, the 90% C.L. upper limit is calculated for the branching fraction. The result of the study is \( \mathcal{B}(B^{0} \rightarrow \nu\nu) < 1.3 \times 10^{-4} \), a new best limit for the \( B^{0} \rightarrow (\text{invisible}) \) mode and is expected to give more stringent conditions on the New Physics models.

![Figure 5: The projection of the fit result of \( B \rightarrow \nu\nu \) study.](image)

4 Search for the Decay \( B^{+} \rightarrow \ell^{+}\nu_{\ell} \)

The purely leptonic decay, \( B^{+} \rightarrow \ell^{+}\nu_{\ell} \), decays through annihilation of the quarks in a charged \( B \) meson into a lepton and a neutrino corresponding to the lepton mediated by a virtual \( W \) boson in
the Standard Model picture. The branching ratio for the process is given as in the equation below.

\[ B(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left( 1 - \frac{m_\ell^2}{m_B^2} \right)^2 f_B^2 |V_{ub}|^2 \tau_B \]  

(2)

where \( G_F \) is the Fermi coupling constant, \( m_\ell \) and \( m_B \) are the masses of the lepton and the \( B \) meson, \( \tau_B \) is the \( B^+ \) life time, \( V_{ub} \) is one of the CKM matrix elements connecting the transition from \( b \) quark to \( u \) quark and \( f_B \) is the \( B \) decay constant.

This decay is suppressed by the helicity suppression factor of \( \left( \frac{m_\ell^2}{m_B^2} \right) \). The predicted branching fraction for \( B \rightarrow \tau \nu \) decay is at the order of \( 10^{-4} \), and thus, the cases for the process of \( e \) and \( \mu \) are suppressed by order of \( \sim 250 \), and \( \sim 10^7 \) respectively compared to \( B \rightarrow \tau \nu \) decay.

There are several New Physics models that may enhance the branching fraction of the \( B^+ \rightarrow \ell^+ \nu_\ell \) mode which can serve as a clean channel for the search of New Physics. The possible models can be the models with charged Higgs particle of the Minimal Super Symmetric Model or lepto-quarks from the Grand Unification Theory. For an example, the minimal model with a charged Higgs boson can mediate the decay and give alteration to the branching fraction. This model, 2 Higgs Doublet Model, predicts the change in the branching fraction as in the equation below. [9]

\[ B(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left( 1 - \frac{m_\ell^2}{m_B^2} \right)^2 f_B^2 |V_{ub}|^2 \tau_B \times \left( 1 - \tan^2 \beta \frac{m_B^2}{m_H^2} \right)^2 \]  

(3)

where \( \tan \beta \) is the ratio of the Higgs vacuum expectation values.

4.1 \( B^+ \rightarrow \tau^+ \nu_\tau \)

![Figure 6: \( E_{ECL} \) distribution after optimized cuts given from the recent Belle result.](image)

The search for \( B \rightarrow \tau \nu_\tau \) has been carried out by Belle and BaBar with hadronic tag method and semi-leptonic tag method. The semi-leptonic tagging has the procedure of first reconstructing a \( D^{(*)} \) meson and requiring a high momentum \( e \) or \( \mu \) on the tagged side to reconstruct a \( B \) meson from the \( D^{(*)} \ell \nu \) modes.

After optimization of several variables and conditions, \( E_{ECL} \), which is the total energy deposit in ECL with the energy deposit from the tagged-\( B \) side and the known particles from the signal side
subtracted, is fitted and the signal yield is obtained. The branching ratio as the result of the studies at Belle and BaBar are summarized as in the table below [10] [11] [12] [13].

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>×10⁻⁴</th>
</tr>
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<tbody>
<tr>
<td>Semi-leptonic tag</td>
<td>1.54±0.29</td>
<td></td>
</tr>
<tr>
<td>Hadronic tag</td>
<td>1.79±0.49</td>
<td></td>
</tr>
<tr>
<td>Babar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-leptonic tag</td>
<td>1.7±0.2</td>
<td></td>
</tr>
<tr>
<td>Hadronic tag</td>
<td>1.80±0.54</td>
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<tr>
<td>HFAG value</td>
<td>1.64±0.34</td>
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</table>

The results agree well with the Standard Model prediction \((1.20±0.25)×10⁻⁴\) calculated from the HPQCD value of \(f_B=190±13\text{MeV}\) and HFAG value of \(V_{ub}=(4.31±0.16^{+0.22}_{-0.23})×10^{-3}\), and this states that the effect of contributions from the the New Physics models is expected to be small. However, the measured results stay above the values provided by the UTfit \((0.84±0.11)×10⁻⁴\) [14] and the CKMfitter group \((0.757±0.098)×10⁻⁴\) [15] where the fit is done by varying CKM matrix elements and other parameters to satisfy the experimental results. World average value of the measured branching fraction of \(B^+→τ^+ν_τ\) process shows some tension with the fit group values by about 3σ.

![Figure 7: Excluded (at 90% C.L.) regions for the charged Higgs mass respect to tan β.](image)
4.2 $B^+ \rightarrow \ell^+ \nu_{\ell}(\ell = e, \mu)$

As noted on the section above, the branching fractions of $B^+ \rightarrow \ell^+ \nu_{\ell}(\ell = e, \mu)$ processes are very low due to the helicity suppression. There has been no evidence for the signal so far and the upper limits were set by each Belle and BaBar with hadronic tag method and inclusive search. The current best limits for both inclusive and exclusive methods were set as in the table below.

<table>
<thead>
<tr>
<th>Year</th>
<th>Collaboration</th>
<th>Integrated Luminosity</th>
<th>U.L. Result (90% C.L.)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Belle</td>
<td>253fb⁻¹</td>
<td>$B(B^+ \rightarrow e^+ \nu_e) &lt; 9.8 \times 10^{-7}$ [16]</td>
<td>inclusive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B(B^+ \rightarrow \mu^+ \nu_\mu) &lt; 1.7 \times 10^{-6}$ [16]</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>Babar</td>
<td>342fb⁻¹</td>
<td>$B(B^+ \rightarrow e^+ \nu_e) &lt; 5.2 \times 10^{-6}$ [17]</td>
<td>Hadronic Tag</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B(B^+ \rightarrow \mu^+ \nu_\mu) &lt; 5.6 \times 10^{-6}$ [17]</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Babar</td>
<td>426fb⁻¹</td>
<td>$B(B^+ \rightarrow e^+ \nu_e) &lt; 1.9 \times 10^{-6}$ [18]</td>
<td>Bayesian Approach</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>$B(B^+ \rightarrow \mu^+ \nu_\mu) &lt; 1.0 \times 10^{-6}$ [18]</td>
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</tr>
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</table>

Table 1: The best limits of the branching fraction for each exclusive and inclusive study respectively from Belle and BaBar.

Currently at Belle, both exclusive and inclusive study for $B^+ \rightarrow \ell^+ \nu_{\ell}(\ell = e, \mu)$ with 711 fb⁻¹ is being done and exclusive study expects new limits at the $O(10^{-6})$.

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References


