HOT TOPICS FROM BELLE, B TO τ DECAYS

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We report the results of studies of B decays to τ mesons, such as $B \to \tau\nu$, and $B \to D^*\tau\nu$. The analysis uses a large data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy e^+e^- collider. Talk presented for the Belle Collaboration.

1 Introduction

B decays to τ mesons represent a broad class of processes that can provide interesting tests of the Standard Model (SM) and its extensions. Difficulties related to multiple neutrinos in the final states mean that there is little experimental information about decays of this type. At B-factories B decays to multi-neutrino final states can be observed via the recoil of accompanying B meson (B_{tag}). The B_{tag} can be reconstructed inclusively from all the particles that remain after selecting B_{sig} candidates or exclusively in several, mostly hadronic decay modes. Reconstruction of B_{tag} strongly suppresses the combinatorial and continuum backgrounds and provides kinematical constraints on the signal meson (B_{sig}).

In this report, we present the results of studies of two types of B to τ decays: $B^{0/+} \to D^{*-/0}\tau^+\nu_\tau$ [1] and $B^+ \to \tau^+\nu_\tau$ [3,4,a]. These analyses are based on a data samples of 492 fb^{-1}, 414 fb^{-1} for $B^+ \to \tau^+\nu_\tau$ hadronic tagging and 605 fb^{-1} for semileptonic tagging decays recorded at the $\Upsilon(4S)$ resonance with the Belle detector [6] at the KEKB collider [7]. It corresponds to 535×10^6, 449×10^6 and 657×10^6 $B\bar{B}$ pairs respectively.

[a] Charge conjugate modes are implied throughout this report unless otherwise stated.

2 $B \to D^{(*)}\tau^+\nu_\tau$

B meson decays with $b \to c\tau\nu_\tau$ transitions, due to the large mass of the τ lepton, are sensitive probes of models with extended Higgs sectors[8] and provide observables sensitive to new physics, such as polarizations, which cannot be accessed in other semileptonic decays.

2.1 Tag-side Reconstruction

The $B_{\rm tag}$ candidates are reconstructed in the following decay modes: $B^+ \to \overline{D}^{(*)0}\pi^+$, $\overline{D}^{(*)0}\rho^+$, $\overline{D}^{(*)0}a_1^+$, $\overline{D}^{(*)0}D_s^{(*)+}$, and $B^0 \to D^{(*)-}\pi^+$, $D^{(*)-}\rho^+$, $D^{(*)-}a_1^+$, $D^{(*)-}D_s^{(*)+}$. Candidate ρ^+ and ρ^0 mesons are reconstructed in the decay modes $\pi^+\pi^0$ and $\pi^+\pi^-$. Then a_1^+ candidates are selected by combining a ρ^0 candidate and a pion. The D meson candidates are reconstructed in the following decay modes: $\overline{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K_S^0\pi^0$, $K_S^0\pi^-\pi^+$, $K_S^0\pi^-\pi^+\pi^0$, K^-K^+, and $D^- \to K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-$, $K_S^0\pi^-\pi^0$, $K_S^0\pi^+\pi^-\pi^-$,$K^+K^-\pi^+$, $D_s^+ \to K_S^0K^+$, $K^+K^-\pi^+$. The D candidates are required to have an invariant mass m_D within $4-5\sigma$ (σ is the mass resolution) of the nominal D mass value depending on the mode. D^* mesons are reconstructed as $D^{*+} \to D^0\pi^+$, $D^+\pi^0$, $D^{*0} \to D^0\pi^0$, $D^0\gamma$, and $D_s^{*+} \to D_s^+\gamma$. D^* candidates from modes that include a pion are required to have a mass difference $\Delta m = m_{D\pi} - m_D$ within $\pm 5{\rm MeV}/c^2$ of its nominal value. For the decays with a photon, we require that the mass difference $\Delta m = m_{D\gamma} - m_D$ be within $\pm 20{\rm MeV}/c^2$ of the nominal value.

The selection of $B_{\rm tag}$ candidates is based on the beam-constrained mass $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B - E_{\rm beam}$. Here, E_B and p_B are the reconstructed energy and momentum of the $B_{\rm tag}$ candidate in the e^+e^- center-of-mass (CM) system, and $E_{\rm beam}$ is the beam energy in the CM frame. The background from jet-like continuum events ($e^+e^- \to q\overline{q}, q = u, d, s, c$) is suppressed on the basis of event topology: we require the normalized second Fox-Wolfram moment (R_2) to be smaller than 0.5, and $|\cos\theta_{\rm th}| < 0.8$, where $\theta_{\rm th}$ is the angle between the thrust axis of the B candidate and that of the remaining tracks in an event. The latter requirement is not applied to $B^+ \to \overline{D}^0\pi^+$, $\overline{D}^{*0}(\to \overline{D}^0\pi^0)\pi^+$ and $B^0 \to D^{*-}(\to \overline{D}^0\pi^-)\pi^+$ decays, where this background is smaller. The selection criteria for $B_{\rm tag}$ are defined as $5.27 < M_{\rm bc} < 5.29$ GeV/c^2 and -80 MeV $< \Delta E < 60$ MeV. If an event has multiple $B_{\rm tag}$ candidates, we choose the one having the smallest χ^2 based on deviations from the nominal values of ΔE, the D candidate mass, and the $D^* - D$ mass difference if applicable. We estimate the number of B events (and their purity) in the selected region to be $(10.11 \pm 0.03) \times 10^5$ (Purity $= 0.58$) for B^+ and $(6.05 \pm 0.03) \times 10^5$ (Purity $= 0.51$) for B^0.

2.2 Signal-side Reconstruction

In the events where a $B_{\rm tag}$ is reconstructed, we search for decays of $B_{\rm sig}$ into a $D^{(*)}$, τ and a neutrino. The τ lepton is identified in the leptonic decay modes, $\mu^-\overline{\nu}\nu$ and $e^-\overline{\nu}\nu$. We require that the charge/flavor of the τ daughter particles and the D meson are consistent with the $B_{\rm sig}$ flavor, opposite to the $B_{\rm tag}$ flavor. Loss of the signal due to $B^0 - \overline{B^0}$ mixing is estimated by the MC simulation.

The decay modes used for D reconstruction are slightly different from those used for the tagging side: $\overline{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^+\pi^-\pi^0$, $K_S^0\pi^0$, $K_S^0\pi^-\pi^+$, $K_S^0\pi^-\pi^+\pi^0$, and $D^- \to K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-$. The D candidates are required to have an invariant mass m_D within 5σ of the nominal D mass value. D^* mesons are reconstructed using the same decay modes as for the tagging side: $D^{*+} \to D^0\pi^+$, $D^+\pi^0$, and $D^{*0} \to D^0\pi^0$, $D^0\gamma$. D^* candidates are required to have a mass difference $\Delta m = m_{D\pi(\gamma)} - m_D$ within 5σ of the nominal value.

For signal selection, we use the following variables that characterize the signal decay: the missing mass square in the event ($M_{\rm mis}^2$), the momentum (in c.m.s.) of the τ daughter leptons

($P_{\tau\to X}$), and extra energy in the ECL ($E^{\rm ECL}_{\rm extra}$). ECL clusters with energy greater than 50MeV in the barrel, and 100 (150)MeV in the forward (backward) end-cap ECL are used to calculate $E^{\rm ECL}_{\rm extra}$. The missing mass square is calculated as $M^2_{\rm mis} = (E_{B_{\rm tag}} - E_D - E_{\tau\to X})^2 - (\vec{P}_{B_{tag}} - \vec{P}_D - \vec{P}_{\tau\to X})^2$, using the energy and momenta of the $B_{\rm tag}$, the D candidate and the lepton from the τ decay. The signal decay is characterized by large $M^2_{\rm mis}$ due to the presence of more than two neutrinos in the final state. The lepton momentum ($P_{\tau\to X}, X = e^\pm, \mu^\pm$) distribute lower than those from the primary B decays. The extra energy in the ECL ($E^{\rm ECL}_{\rm extra}$) is the sum of the energy of photons that are not associated with either the $B_{\rm tag}$ or the $B_{\rm sig}$ reconstruction. For signal events, $E^{\rm ECL}_{\rm extra}$ must be either zero or a small value arising from beam background hits, therefore, signal events peak at low $E^{\rm ECL}_{\rm extra}$. On the other hand background events are distributed toward higher $E^{\rm ECL}_{\rm extra}$ due to the contribution from additional neutral clusters. We also require that the event has no extra charged tracks and no π^0 candidate other than the daughter track candidates from the signal decay and those used in the $B_{\rm tag}$ reconstruction.

The $B \to D\tau\nu$ and $B \to D^*\tau\nu$ signals are extracted using unbinned extended maximum likelihood fits to the two-dimensional ($M^2_{\rm mis}, E^{\rm ECL}_{\rm extra}$) distributions obtained after the selection of the signal decays. The fit components are two signal modes; $B \to D\tau\nu$ and $B \to D^*\tau\nu$, and the backgrounds from $B \to D\ell\nu$, $B \to D^*\ell\nu$ and other processes. The likelihood is constructed as,

$$L = \frac{e^{-\sum_j N_j}}{N!} \prod_{i=1}^{N} F(x_i^1, x_i^2) \quad , \tag{1}$$

where

$$\begin{aligned} F(x^1, x^2) &= N_{D\tau\nu} f_{D\tau\nu}(x^1, x^2) + N_{D^*\tau\nu} f_{D^*\tau\nu}(x^1, x^2) \\ &+ N_{D\ell\nu} f_{D\ell\nu}(x^1, x^2) + N_{D^*\ell\nu} f_{D^*\ell\nu}(x^1, x^2) \\ &+ N_{\rm other} f_{\rm other}(x^1, x^2) \quad . \end{aligned} \tag{2}$$

Here N_j and $f_j(x^1, x^2)$ represent the number of events and the two-dimensional probability distribution function (PDF) as a function of $M^2_{\rm mis}$ (x^1) and $E^{ECL}_{\rm extra}$ (x^2), respectively, for the process j. As for the fitting to the $B^0 \to D^{*-}\tau^+\nu$ distribution, the $D\tau\nu$ cross feed ($f_{D\tau\nu}$) and $D\ell\nu$ background ($f_{D\tau\nu}$) are not included, because their contribution are found to be small. The fit region is defined by ($-2 < M^2_{\rm mis}({\rm GeV}^2/c^4) < 8, 0 < E^{\rm ECL}_{\rm extra}({\rm GeV}) < 1.2$) for all the four signal modes.

The two-dimensional PDF's for $D^{(*)}\tau\nu$ and $D^{(*)}\ell\nu$ processes are created by taking the product of one-dimensional PDF for each variable, as correlation between $M^2_{\rm mis}$ and $E^{\rm ECL}_{\rm extra}$ for these processes are found to be small in the MC simulation. The one-dimensional PDF's for $M^2_{\rm mis}$ ($f_j(x^1)$) are modeled by asymmetric Gaussian or double Gaussian distributions, whereas the PDF's for $E^{\rm ECL}_{\rm extra}$ ($f_j(x^2)$) are made using the histograms obtained by the MC simulation. The PDF for the other background processes ($f_{\rm other}$) is made by using the two-dimensional histograms obtained by the MC simulation, since correlation between the two variables is significant for these background processes, which mainly come from hadronic B decays.

We fit the distributions for the B^0 and B^+ tags separately. The cross talk between the two tags is found to be small. Then for each B^0 and B^+ tag, we fit simultaneously the two distributions for the $D\tau\nu$ and $D^*\tau\nu$.

We present a relative measurement; we extract the yields of both the signal mode $\overline{B} \to D^{(*)}\tau^+\nu$ and the normalization mode $\overline{B} \to D^{(}(*))\ell^+\nu$ to deduce the four ratios,

$$R(\overline{D}^0) \equiv \mathcal{B}(B^+ \to \overline{D}^0\tau^+\nu)/\mathcal{B}(B^+ \to \overline{D}^0\ell^+\nu) \tag{3}$$

$$R(\overline{D}^{*0}) \equiv \mathcal{B}(B^+ \to \overline{D}^{*0}\tau^+\nu)/\mathcal{B}(B^+ \to \overline{D}^{*0}\ell^+\nu) \tag{4}$$

$$R(D^-) \equiv \mathcal{B}(B^0 \to D^-\tau^+\nu)/\mathcal{B}(B^0 \to D^-\ell^+\nu) \tag{5}$$

$$R(D^{*-}) \equiv \mathcal{B}(B^0 \to D^{*-}\tau^+\nu)/\mathcal{B}(B^0 \to D^{*-}\ell^+\nu). \tag{6}$$

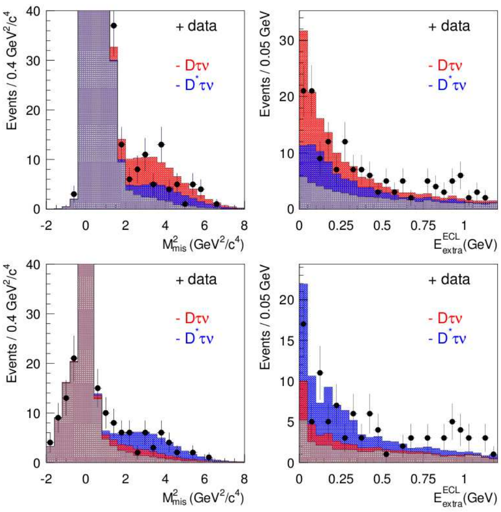

Figure 1: Fit results for $B^+ \to \overline{D}^0\tau^+\nu$ (top) and $B^+ \to \overline{D}^{*0}\tau^+\nu$ (bottom). The $M^2_{\rm mis}$ (left) and $E^{\rm ECL}_{\rm extra}$ (right) distributions are shown with the signal selection cut on the other variable.

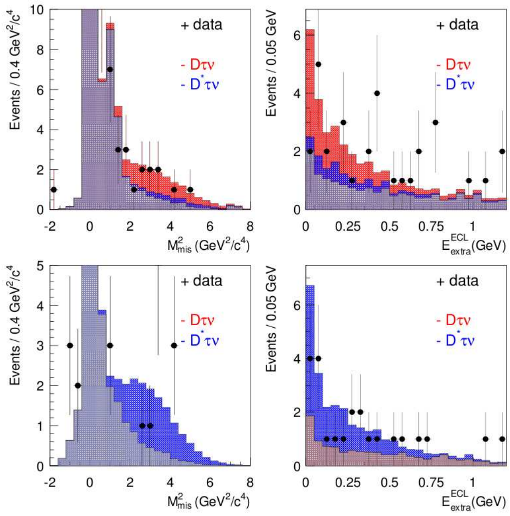

Figure 2: Fit results for $B^0 \to D^-\tau^+\nu$ (top) and $B^0 \to D^{*-}\tau^+\nu$ (bottom). The $M^2_{\rm mis}$ (left) and $E^{\rm ECL}_{\rm extra}$ (right) distributions are shown with the signal selection cut on the other variable.

Figure 1 and 2 show the fit results for $B^+ \to D^{(*)}\tau\nu$ and $B^0 \to D^{(*)}\tau\nu$, respectively. With the systematic errors the results for the four ratios are obtained as,

$$R(\overline{D}^0) = 0.70\ {}^{+0.19}_{-0.18}\ {}^{+0.11}_{-0.09} \quad (7)$$
$$R(\overline{D}^{*0}) = 0.47\ {}^{+0.11}_{-0.10}\ {}^{+0.06}_{-0.07} \quad (8)$$
$$R(D^-) = 0.48\ {}^{+0.22}_{-0.19}\ {}^{+0.06}_{-0.05} \quad (9)$$
$$R(D^{*-}) = 0.48\ {}^{+0.14}_{-0.12}\ {}^{+0.06}_{-0.04} \quad , \quad (10)$$

where the first error is the statistical and the second error is the systematic. With the systematic uncertainty for the yields convolved in the likelihood, the significance of the excess are found to be $3.8, 3.9, 2.6$ and 4.7 for $B \to \overline{D}^0\tau^+\nu$, $\overline{D}^{*0}\tau^+\nu$, $D^-\tau^+\nu$ and $D^{*-}\tau^+\nu$, respectively.

Using the branching fractions for the $B \to D^*\ell\nu$ normalization decays, reported in [5]: $\mathcal{B}(B^+ \to D\ell\nu) = (2.15\pm0.22)\%$, $\mathcal{B}(B^+ \to D^*\ell\nu) = (6.5\pm0.5)\%$, $\mathcal{B}(B^0 \to D\ell\nu) = (2.12\pm0.20)\%$, and $\mathcal{B}(B^0 \to D^*\ell\nu) = (5.33 \pm 0.20)\%$, the branching fractions for the $B \to D^*\tau\nu$ decays are obtained as,

$$\mathcal{B}(B^+ \to \overline{D}^0\tau^+\nu) = 1.51\ {}^{+0.41}_{-0.39}\ {}^{+0.24}_{-0.19} \pm 0.15\ [\%] \quad (11)$$
$$\mathcal{B}(B^+ \to \overline{D}^{*0}\tau^+\nu) = 3.04\ {}^{+0.69}_{-0.66}\ {}^{+0.40}_{-0.47} \pm 0.22\ [\%] \quad (12)$$
$$\mathcal{B}(B^0 \to D^-\tau^+\nu) = 1.01\ {}^{+0.46}_{-0.41}\ {}^{+0.13}_{-0.11} \pm 0.10\ [\%] \quad (13)$$
$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu) = 2.56\ {}^{+0.75}_{-0.66}\ {}^{+0.31}_{-0.22} \pm 0.10\ [\%] \quad , \quad (14)$$

where the first error is statistical, the second is systematic, and the third is due to the branching fraction error for the normalization mode.

2.3 $B^0 \to D^{*-}\tau^+\nu_\tau$ inclusive tag reconstruction

In 2007 the Belle collaboration reported the first observation of an exclusive decay with the $b \to c\tau\bar{\nu}_\tau$ transition[2]. The $B^0 \to D^{*-}\tau^+\nu_\tau$ decay is observed with $B_{\rm tag}$ reconstructed inclusively. The corresponding branching fraction is $2.02^{+0.40}_{-0.37}(stat) \pm 0.37(syst)\%$, consistent with SM expectations. The significance, after including systematic uncertainties, is 5.2σ.

3 $B^+ \to \tau^+\nu_\tau$

The purely leptonic decay $B^+ \to \tau^+\nu_\tau$ proceeds via W-mediated annihilation in the SM. It provides a direct determination of the product of B meson decay constant f_B and the magnitude of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{\rm ub}|$. The expected branching fraction is $(1.59 \pm 0.40) \times 10^{-4}$. Like the semi-taonic modes, the $B^+ \to \tau^+\nu_\tau$ decay is sensitive to non-SM contributions from charged Higgs boson mediated amplitudes [9].

3.1 $B^+ \to \tau^+\nu_\tau$ hadronic tag

This analysis uses a data sample of about 6.8×10^5 $B\bar{B}$ events with fully reconstructed $B_{\rm tag}$ decays, selected with a purity of 55%.

In this sample, we search for decays of $B_{\rm sig}$ into a τ and a neutrino; the τ lepton is reconstructed in five decay modes: $\mu^-\bar{\nu}_\mu\nu_\tau$, $e^-\bar{\nu}_e\nu_\tau$, $\pi^-\nu_\tau$, $\pi^-\pi^0\nu_\tau$ and $\pi^-\pi^+\pi^-\nu_\tau$, which taken together correspond to 81% of all τ decays. Further requirements on the magnitude and an angular distribution of missing momentum provide background suppression. The remaining energy in the electromagnetic calorimeter, $E_{\rm ECL}$, is the most powerfull variable for signal and backgroung separation. It takes values around zero for signal events, while background events are distributed toward higher $E_{\rm ECL}$ due to the contribution from additional neutral clusters.

The signal yield is extracted from a fit to the $E_{\rm ECL}$ distribution. The combined fit for all five τ decay modes gives $17.2^{+5.3}_{-4.7}$ signal events. It corresponds to the branching fraction $(1.79^{+0.56}_{-49}(stat)^{+0.46}_{-0.51}(syst)) \times 10^{-4}$. The significance is 3.5σ. This result represents the first evidence of the purely leptonic B decay. Based on this measurement and using the current value of $|V_{\rm ub}|$ [10], the first direct determination of B decay constant was obtained: $f_B = 0.229^{+0.036}_{-0.031}(stat)^{+0.034}_{-0.037}(syst)$ GeV.

3.2 $B^+ \to \tau^+\nu_\tau$ semileptonic tag

The measurement of the decay $B^- \to \tau^-\bar{\nu_\tau}$ with a semileptonic B tagging method is based a data sample containing 657×10^6 $B\bar{B}$ pairs. The strategy adopted for this analysis is same as in the previous measurements. We reconstruct one of the B mesons decaying semileptonically (referred as $B_{\rm tag}$) and compare the properties of the remaining particle(s) in the event ($B_{\rm sig}$) to those expected for signal and background.

We reconstruct the $B_{\rm tag}$ in $B^- \to D^{*0}l^-\bar{\nu}$ and $B^- \to D^0l^-\bar{\nu}$ decays. For D^{*0} reconstruction, we use $D^{*0} \to D^0\pi^0$ and $D^0\gamma$ decays. D^0 mesons are reconstructed in $K^-\pi^+$, $K^-\pi^+\pi^0$ and $K^-pi^+\pi^-\pi^+$. For $B_{\rm sig}$, we use τ - decays to only one charged particle and neutrinos: $\tau^- \to l^-\bar{\nu}_l\nu_\tau$ and $\tau^- \to \pi^-\nu_\tau$. We require that no charged particle or π^0 remain in the event after removing the particles from the $B_{\rm tag}$ and $B_{\rm sig}$ candidates.

We select B_{tag} candidates using the lepton momentum $P^*_{\rm l}$ and the cosine of the angle between the direction of the $B_{\rm tag}$ momentum and the direction of the momentum sum of the $D^{(*)0}$ and the lepton $\cos\theta_{B-D^{(*)}l}$. This angle is calculated using $\cos\theta_{B-D^{(*)}l} = (2E_{\rm beam}E_{D^{(*)}l} - m^2 - m^2_{D^{(*)}l})/(2P_{\rm B} \times P_{D^{(*)}l})$, where $E_{D^{(*)}l}$, $P_{D^{(*)}l}$ and $M_{D^{(*)}l}$ are the energy sum, momentum sum and invariant mass of the $D^{(*)0}$ and lepton.

For the signal side track, we require the momentum $P_{\tau \to X}$ to be in the region consistent with a $B \to \tau\nu$ decay. The selection criteria for $B_{\rm tag}$ and $B_{\rm sig}$ are optimized for each of the τ decay modes, because the background levels and the background components are mode-dependent.

The signal yield is extracted from a fit to the $E_{\rm ECL}$ distribution (Figure 3).We see a clear excess of signal events in the region near $E_{\rm ECL} \sim 0$. We obtain the signal yield to be $n_s = 154^{+36}_{-35}$.

We measure the branching fraction to be $(1.65^{+0.38}_{-0.37}(stat)^{+0.35}_{-0.37}(syst)) \times 10^{-4}$ with a significance of 3.8 standard deviations including systematics. We confirm the evidence based on measurement with $B\bar{B}$ pair events tagged by hadronic B decays. Using the measured branching

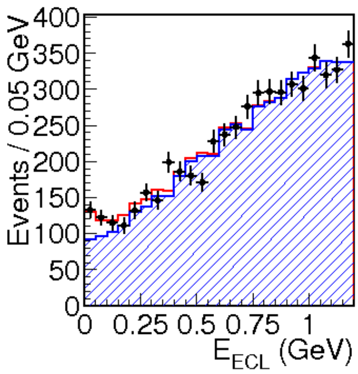

Figure 3: E_{ECL} distribution of semileptonic tagged events with the fit for $B^+ \to \tau^+\nu_\tau$ decay. The points with error bars are data. The hatched histogram and solid open histogram are the background and the signal, respectively.

fraction and known values of G_{F}, m_{B}, m_τ and τ_{B}[11], the product of the B meson decay constant f_B and the magnitude of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{\mathrm{ub}}|$ is determined to be $f_B|V_{\mathrm{ub}}| = (9.7 \pm 1.1^{+1.0}_{-1.1}) \times 10^{-4}$ GeV. The measured branching fraction is consistent with the SM expectation from other experimental constraints[12].

4 Summary

The studies of B decays to τ at Belle brought significant advances in this field, providing the first evidence of the purely leptonic $B^+ \to \tau^+\nu_\tau$ mode and the first observation of an exclusive semi-tauonic B decay in the $B^0 \to D^{*-}\tau^+\nu_\tau$ channel.We have measured the B semileptonic decays to the τ channel, by fully reconstructing hadronic decays of the accompanying B meson. We have extracted the signals for the four decays modes, $B^+ \to \overline{D}^0\tau^+\nu$, $B^+ \to \overline{D}^{*0}\tau^+\nu$, $B^0 \to D^-\tau^+\nu$, and $B^0 \to D^{*-}\tau^+\nu$, and deduced the branching fractions. The obtained branching fractions are consistent within errors to the earlier Belle result[2], and BaBar results for the four signal modes[13].

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