Abstract. We report the results of studies of $B$ decays with missing energy due to two or more neutrinos, such as $B \to \tau \nu$, $B \to D^* \tau \nu$ and $B \to h(\ast) \nu \bar{\nu}$. 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.

1. Introduction

$B$ decays with missing energy 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 ($B_{\text{tag}}$). The $B_{\text{tag}}$ can be reconstructed inclusively from all the particles that remain after selecting $B_{\text{sig}}$ candidates or exclusively in several, mostly hadronic decay modes. Reconstruction of $B_{\text{tag}}$ strongly suppresses the combinatorial and continuum backgrounds and provides kinematical constraints on the signal meson ($B_{\text{sig}}$).

In this report, we present the results of studies of three types of multi neutrino $B$ decays:

\begin{enumerate}
\item $B^0 \to D^{*-} \tau^+ \nu_{\tau}$ \[1\],
\item $B^+ \to \tau^+ \nu_{\tau}$ \[2\] and $B \to h(\ast) \nu \bar{\nu}$ \[3\].
\end{enumerate}

These analyses are based on a data sample of 492 fb$^{-1}$ (414 fb$^{-1}$ for $B^+ \to \tau^+ \nu_{\tau}$ decays) recorded at the $\Upsilon(4S)$ resonance with the Belle detector [4] at the KEKB collider [5]. It corresponds to $535 \times 10^6$ ($449 \times 10^6$) $B$ meson pairs.

2. $B^0 \to D^{*-} \tau^+ \nu_{\tau}$

$B$ meson decays with $b \to c \tau \nu_{\tau}$ transitions, due to the large mass of the $\tau$ lepton, are sensitive probes of models with extended Higgs sectors [6] and provide observables sensitive to new physics, such as polarizations, which cannot be accessed in other semileptonic decays.

The signal decay is reconstructed by selecting combinations of a $D^{*-}$ meson and a charged track expected from $\tau^+$ decay, and the remaining particles are used to reconstruct inclusively the $B_{\text{tag}}$ decay. $D^*$ mesons are reconstructed in the $D^{*-} \to D^0 \pi^-$ decay mode. $D^0$s are chosen to decay to $K^+\pi^-$ or $K^+\pi^-\pi^0$. The $\tau$ lepton candidates are reconstructed in $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ and $\tau^+ \to \pi^+\nu_{\tau}$ decays. For $\tau^+ \to \pi^+\nu_{\tau}$ decays only $\bar{D}^0 \to K^+\pi^-$ mode is used to avoid the higher combinatorial background. The following variables, $M_{\text{tag}} = \sqrt{E_{\text{beam}}^2 - p_{\text{tag}}^2}$ and $\Delta E_{\text{tag}} = E_{\text{tag}} - E_{\text{beam}}$, are used to check the consistency of a $B_{\text{tag}}$ with $B$ meson decay. $E_{\text{beam}}$ is the beam energy and $p_{\text{tag}}$, and $E_{\text{tag}}$ are momentum and energy of residual particles, respectively.

\[1\] Charge conjugate modes are implied throughout this report unless otherwise stated.
Additional requirements such as zero total event charge, no additional leptons in the event and zero barion number are imposed to improve the the $B_{\text{tag}}$ purity.

Background suppression employs observables that are sensitive to missing energy in $B_{\text{sig}}$ decay, like missing energy $E_{\text{mis}} = E_{\text{beam}} - E_{D^*} - E_{e,\pi}$ and visible energy of the event. The most effective variable $X_{\text{mis}}$, is defined by $(E_{\text{mis}} - |p_{D^*} + p_{e,\pi}|)/\sqrt{E_{\text{beam}} - m^2_{D^0}}$ and is closely related to the missing mass in the $B_{\text{sig}}$ decay.

The signal yield is extracted from an unbinned maximum likelihood fit to the $M_{\text{tag}}$ distribution. The result of a simultaneous fit to all analysed subchannels constrained to a common value of $B(B^0 \to D^{*-}\tau^+\nu_\tau)$ is shown in Figure 1. We obtain $60^{+12}_{-11}$ events for the $B^0 \to D^{*-}\tau^+\nu_\tau$ decay. This corresponds to the branching fraction $2.02^{+0.40}_{-0.37}(\text{stat})\pm0.37(\text{syst})\%$, consistent with SM expectations. The significance, after including systematic uncertainties, is $5.2\sigma$. This is the first observation of an exclusive decay with the $b \to c\tau\bar{\nu}_\tau$ transition.

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 $|V_{ub}|$. 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 [7].

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

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

The flavor-changing neutral-current process $B \to h^{(*)}\nu\bar{\nu}$ proceed through a box and an electroweak penguin diagrams. The SM predicts the branching fractions of the order $10^{-5} - 10^{-6}$ for $B \to K^{(*)}\nu\bar{\nu}$ and lower for other modes [9]. Decays of this type are sensitive to NP in loop amplitudes [9]. Possibilities of discovering light dark matter in $b \to s$ transitions with large missing momentum have been also considered [10].

Belle performed a search of the decays $B \to h^{(*)}\nu\bar{\nu}$ with $h^{(*)} = K^+, K^0_S, K^0, K^{*+}, \pi^+, \pi^0, \rho^0, \rho^+$ and $\phi$. Channels with $h^{(*)} = K^{*+}, K^0, \pi^0, \rho^0, \rho^+$ and $\phi$ have been studied for the first time. The method of analysis is the same as in the $B^+ \to \tau^+\nu_\tau$ mode. The fully reconstructed $B_{tag}$ selection yields samples of $7.88 \times 10^5 B^+B^-$ events and of $4.91 \times 10^5 B^0B^0$ pairs.

Requirements on the hadron momentum to be between 1.6 GeV/c and 2.5 GeV/c suppress the dominant background sources: $B\bar{B}$ decays with a $b \to c$ transition and radiative two-body decays such as $B \to K^*\gamma$. The $E_{ECL}$ distributions are used to search for the signal. None of the analysed modes has significant signal and upper limits (U.L.) are calculated using an extension of the Feldman-Cousins method [11]. The effects of both statistical and systematic uncertainties are included. The observed number of events and expected background contribution in the signal box ($E_{ECL} < 0.3$ GeV) and the obtained U.L.’s at 90% confidence level are listed in Table 1.

| Mode       | $N_{obs}$ | $N_b$ | U.L.          | Mode       | $N_{obs}$ | $N_b$ | U.L.          |
|------------|-----------|-------|---------------|------------|-----------|-------|---------------|
| $K^{*0}\nu\bar{\nu}$ | 7         | 4.2 ± 1.4 | $< 3.4 \times 10^{-4}$ | $\pi^0\nu\bar{\nu}$ | 33        | 25.9 ± 3.9 | $< 1.7 \times 10^{-4}$ |
| $K^{*+}\nu\bar{\nu}$ | 4         | 5.6 ± 1.8 | $< 1.4 \times 10^{-4}$ | $\pi^0\nu\bar{\nu}$ | 11        | 3.8 ± 1.3 | $< 2.2 \times 10^{-4}$ |
| $K^+\nu\bar{\nu}$    | 10        | 20 ± 4.0  | $< 1.4 \times 10^{-5}$ | $\rho^0\nu\bar{\nu}$ | 21        | 11.5 ± 2.3 | $< 4.4 \times 10^{-4}$ |
| $K^0\nu\bar{\nu}$    | 2         | 2.0 ± 0.9 | $< 1.6 \times 10^{-4}$ | $\rho^+\nu\bar{\nu}$ | 15        | 17.8 ± 3.2 | $< 1.5 \times 10^{-4}$ |
|            |           |        |               | $\phi\nu\bar{\nu}$ | 1         | 1.9 ± 0.9  | $< 5.8 \times 10^{-5}$ |

5. Summary

The recent studies of multineutrino $B$ decays 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. New (first) upper limits for six decays of the type $B \to h^{(*)}\nu\bar{\nu}$ have been set. These results are consistent with the SM and provide valuable constraints on NP scenarios.

References

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