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Charmless semileptonic B decays at Belle

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We report two analyses involving semileptonic B meson decays to charmless final states: $B^+ \to \eta^{(\prime)}\ell^+\nu_\ell$ and $B^0 \to \pi^-\tau^+\nu_\tau$. These results are based on a 711 fb^{-1} data sample, corresponding to 772×10^6 $B\bar{B}$ pairs, collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy e^+e^- collider. One of the two B mesons is fully reconstructed into hadronic decay modes, whereas the remainder of the event is used to study the signal channel. Branching ratios are extracted using a binned maximum likelihood fit method, resulting in $\mathscr{B}(B^+ \to \eta\ell^+\nu_\ell) = (0.42 \pm 0.11_{\text{stat}} \pm 0.03_{\text{syst}}) \times 10^{-4}$. However, given the low significance for the other channels, an upper limit at 90% confidence level is provided: $\mathscr{B}(B^+ \to \eta'\ell^+\nu_\ell) < 0.76 \times 10^{-4}$ and $\mathscr{B}(B^0 \to \pi^-\tau^+\nu_\tau) < 2.5 \times 10^{-4}$.

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1. Introduction

Charmless semileptonic B decays have been used to extract the magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{ub}|$ [1]. Currently, there are two approaches to determine this value: on one hand an inclusive measurement takes into account all possible hadronic final states for a given $b \to u$ quark transition within a region of phase space. On the other hand, an exclusive measurement focus on a specific hadronic final state, for instance $B^+ \to \pi^- \ell^+ \nu_\ell$. These two approaches rely on different theoretical and experimental techniques. The quantity $|V_{ub}|$ measured from these approaches presents a discrepancy in the 3σ level [2]. A precise measurement of this quantity is important to understand the nature of the weak interaction and CP violation in the Standard Model.

We present two analyses carried out at the Belle experiment at the asymmetric electron-positron collider KEKB [3]. First, we show the measurement of the branching ratio of the $B^+ \to \eta^{(\prime)} \ell^+ \nu_\ell$. Second, we determine an upper limit calculation for the $B^0 \to \pi^- \tau^+ \nu_\tau$ decay, which corresponds to the first experimental result on this channel.

2. Reconstruction of B mesons

The study of B mesons at the $B-$factories is possible due to tuning the beam energies to the energy of the $\Upsilon(4S)$ resonance. This particle decays exclusively into a $B\bar{B}$ meson pair ($\mathscr{B}(\Upsilon(4S) \to B^+B^-) = (51.4 \pm 0.6)\%$ and $\mathscr{B}(\Upsilon(4S) \to B^0\bar{B}^0) = (48.6 \pm 0.6)\%$) [4], which allows for precision measurements of B decays to be carried out. In analyses where the signal involves a semileptonic final state, one B meson is partially reconstructed by combining a lepton with a reconstructed hadron, which in turn results from a combination of final state particles visible to the detector such as $\pi^\pm$, π^0, γ, $e^\pm$, $\mu^\pm$, $K^\pm$ and K^0_S. Since the neutrino cannot be reconstructed, its information is inferred from the missing four-momentum,

$$P_{\text{miss}} = P_{\text{beam}} - \sum_i P_i, \tag{2.1}$$

which is defined to be the difference between the beam four-momentum and the sum of all four-momenta of the reconstructed particles. In the reconstruction of the signal B meson three methods are commonly used: untagged, hadronic tagging and semileptonic tagging [5]. These methods differ in whether or not the accompanying B meson (tag B) is reconstructed, and how it is reconstucted. In the untagged technique only the particles on the signal side are reconstructed and the estimation of the neutrino momentum is determined from the missing four-momentum of the whole event. Additional constraints may be applied on the neutrino four-momentum. For example, the energy of the candidate neutrino can be taken as the magnitude of the missing momentum, since this is less prone to bias from lost particles or additional tracks thant the missing energy. The untagged technique offers a large sample of signal candidates but also incurs in a large background; in other words, the signal reconstruction efficiency is high but the signal purity is poor. Typical values for signal reconstruction efficiency are of the order of 5%. In the semileptonic tagging method, the other B meson or tag B is reconstructed in semileptonic decays to charm mesons such as D or D^*, which are subsequently reconstructed in hadronic decay modes. Although the branching

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ratio of semileptonic decays of the tag B to charm mesons is large (of the order of 11% [4]), the presence of an additional neutrino limits the kinematic constraints that can be imposed, for example the signal B direction cannot be determined. The signal reconstruction efficiency for semileptonic tagging is around 0.6%. Finally, in the hadronic tag method the other B is reconstructed in hadronic decays to charm mesons, leading to the determination of the direction, momentum, flavor and charge of the signal B. This method offers a very high signal purity, however there is a price to pay: the signal reconstruction efficiency is very low, of the order of 0.1%. The two analyses presented in this paper make use of the hadronic tag method.

3. Measurement $B^+ \to \eta^{(\prime)}\ell^+\nu_\ell$ with hadronic tag at Belle

Given the current tension between inclusive and exclusive measurements, precise measurements of other charmless semileptonic decays such as $B^+ \to \eta\ell^+\nu_\ell$ and $B^+ \to \eta'\ell^+\nu_\ell$ are necessary to improve the inclusive signal modelling, where these decays are one of the largest systematic uncertainty. In charmless exclusive semileptonic decays, the calculation of the decay rate requires the magnitudes of the CKM matrix element $|V_{ub}|$ and the form factors as input parameters. These form factors are calculated using non-perturbative methods to describe the hadronization process, and depend on the square of the momentum transferred or dilepton invariant mass squared $q^2 = (P_\ell + P_\nu)^2$, where P_ℓ and P_ν are the lepton and neutrino four-momentum, respectively. These form factors represent a theoretical challenge and are limited to certain regions in q^2, for instance theoretical predictions from light cone sum rules (LCSR) are valid for low values of q^2, whereas Lattice QCD (LQCD) are constrained to high q^2 values. In cases where the final state hadron is a pseudoscalar, e.g. $\eta^{(\prime)}$, the decay rate can be written as [11]

$$\frac{d\Gamma(B \to P\ell\nu)}{dq^2} = \frac{G_F^2|p_P|^3}{24\pi^3}|V_{ub}|^2|f_+(q^2)|^2, \tag{3.1}$$

where $f_+(q^2)$ is a form factor, G_F is the Fermi constant and p_P is the momentum of the pseudoscalar meson. Presently, a calculation of $|V_{ub}|$ for the $B^+ \to \eta^{(\prime)}\ell^+\nu_\ell$ decay is not possible, since there are no mature calculations of $f_+(q^2)$ available.

In this analysis the signal $B^+ \to \eta^{(\prime)}\ell^+\nu_\ell$ is generated using the ISGW2 model [6]. The η meson is searched for in two decay channels, $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$, and the η' meson is reconstructed in $\eta' \to \eta\pi^+\pi^-$ with η decaying into $\gamma\gamma$. A cut-based technique is implemented in order to reduce background, which is dominated by semileptonic B decays to charm mesons. The existence of the neutrino is inferred from the missing four-momentum, and since the tag B is fully reconstructed, eq. 2.1 becomes $P_{\text{miss}} = P_{\text{beam}} - P_{B^{\text{tag}}} - P_\ell - P_{\eta^{(\prime)}}$, where P_{beam} is the designed momentum of the beam, $P_{B^{\text{tag}}}$ is the momentum of the reconstructed tag B meson, P_ℓ and $P_{\eta^{(\prime)}}$ are the momenta of the reconstructed lepton and $\eta^{(\prime)}$ meson, respectively. The $B^+ \to \eta^{(\prime)}\ell^+\nu_\ell$ yield is extracted from an extended binned maximum likelihood fit to the missing mass squared distribution $M^2_{\text{miss}} = |P_{\text{miss}}|^2$. For well reconstructed signal events, the M^2_{miss} is expected to peak close to zero, as the only remaining particle in the event is the neutrino. In the fit the background is categorized in three components: decays from $b \to u\ell\nu$, $b \to c\ell\nu$ and continuum. The fit components are taken form Monte Carlo (MC) simulation and the fitting algorithm accounts for both statistical fluctuations in the real and in the MC simulated data. Since the continuum contribution is small, it is fixed to the MC expected yield. The M^2_{miss} distributions after the fit are shown in Fig. 1. For the $B^+ \to \eta \ell^+ \nu_\ell$ we consider the fit with both η modes combined ($\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$) as our main result. For this channel a total of 38.8 ± 10.1 events were determined with a significance of 2.6σ, which corresponds to a branching ratio of $(4.2 \pm 1.1_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-5}$, where the first error is statistical and the second is systematic. For the $B^+ \to \eta' \ell^+ \nu_\ell$ we obtain 5.7 ± 4.4 signal events with a significance of 1.3σ, for which we calculate a branching ratio of $(3.6 \pm 2.7_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-5}$. However, given the low significance, we convert this result into an upper limit at 90% confidence level corresponding to 7.6×10^{-5}.

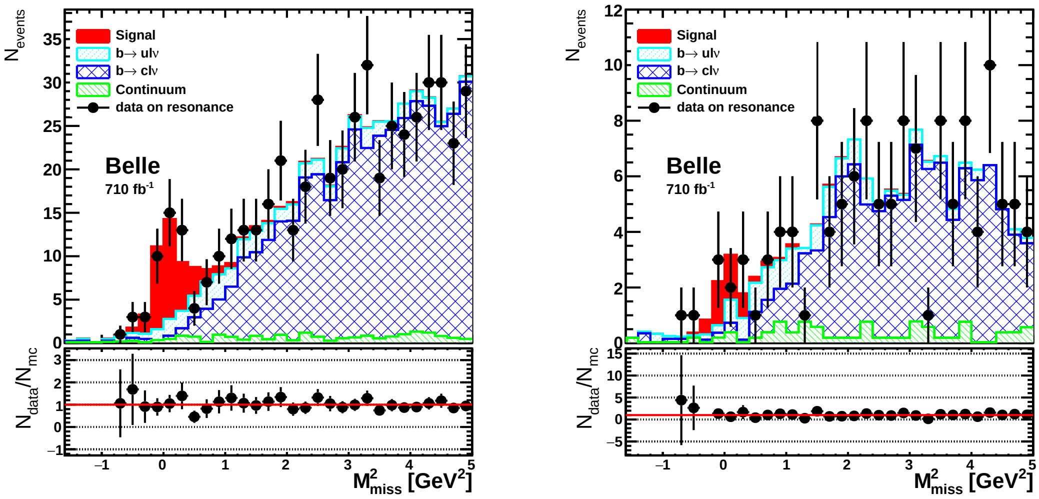

Figure 1: Result of the fit to M^2_{miss}: (left) η modes combined, $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$; (right) $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$.

4. Search for $B^0 \to \pi^-\tau^+\nu_\tau$ with hadronic tagging at Belle [7]

In the Standard Model (SM) the transition amplitude for the decay $B^0 \to \pi^-\tau^+\nu_\tau$ is given by [8]

$$\langle \pi^- | u \gamma_\mu \bar{b} | B^0 \rangle = f_+(q^2) \left[2p_\mu + \left(\frac{1 - m_B^2 - m_\pi^2}{q^2} \right) q_\mu \right] + f_0(q^2) \frac{m_B^2 - m_\pi^2}{q^2} q_\mu, \tag{4.1}$$

where f_+ and f_0 are the vector and scalar form factors for the $B \to \pi\tau\nu$ decays, respectively. The pion momentum is defined as p and q is the momentum transfer to the lepton pair. An useful quantity to test the SM is the ratio $R(\pi) = \mathscr{B}(B \to \pi\tau\nu)/\mathscr{B}(B \to \pi\ell\nu)$, which depends solely on the ratio of the scalar and vector form factors f_0/f_+. $R(\pi)$ have been estimated to be 0.641 ± 0.017 using lattice QCD calculations [9] and $B \to \pi\ell\nu$ data from Belle [10, 11] and BaBar [12, 13], resulting in a prediction of the branching ratio for $B \to \pi\tau\nu$ decay to be $(9.35 \pm 0.38) \times 10^{-5}$. An additional motivation for studying this decay comes from new physics models such as the two-Higgs-doublet model (2HDM) [14, 15], where in addition to a $W^\pm$ boson, the $B \to \pi\tau\nu$ decay can also be mediated by a charged Higgs boson, affecting the value of $R(\pi)$ and consequently the branching ratio for $B \to \pi\tau\nu$.

Signal candidates are selected by considering all tracks and clusters not associated to the fully reconstructed B meson on the tag side. The τ lepton is reconstructed in the following three decay channels: $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$, $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $\tau^+ \to \rho^+\bar{\nu}_\tau$. Therefore, a signal candidate must have exactly two oppositely charged tracks, of which at least one is identified as a $\pi^\pm$. A $\rho^\pm$ meson candidate is formed from a combination of a $\pi^\pm$ with a π^0, with the invariant mass restricted to $M_{\pi^+\pi^-} \in [625, 925]$ MeV. To further separate signal from background, a Boosted Decision Tree (BDT) is trained and optimized for each channel individually. An additional selection is imposed on the $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ mode, where the decay $B^0 \to \pi^-\ell^+\nu_\ell$ mimics the signal. The latter peaks strongly at zero in M^2_{miss}, however, due to the presence of three neutrinos in the signal, this distribution peaks at higher values, thus the condition $M^2_{\text{miss}} > 2.2$ GeV is demanded.

To extract the number of signal events a binned maximum likelihood fit on the E_{ECL} is performed. The E_{ECL} is defined as all the energy deposited in the Electromagnetic Calorimeter by particles that are neither associated to the B_{tag}, nor the two tracks from the signal decay. The floating parameters in the fit correspond to the signal strength and the dominant background $b \to c$ transitions, where the other background contributions are fixed to the MC prediction. The systematic uncertainties are taken into account as nuissance parameters in the likelihood description and a toy MC approach is used to calculate the significance level. A total of 52 ± 24 signal events are observed with a significance of 2.4σ in the three τ modes, as shown in Fig. 2. An upper limit of $\mathscr{B}(B^0 \to \pi^-\tau^+\nu_\tau) < 2.5 \times 10^{-4}$ at 90% confidence level is calculated, which is consistent with the SM expectation. This analysis is the first experimental result on this decay channel.

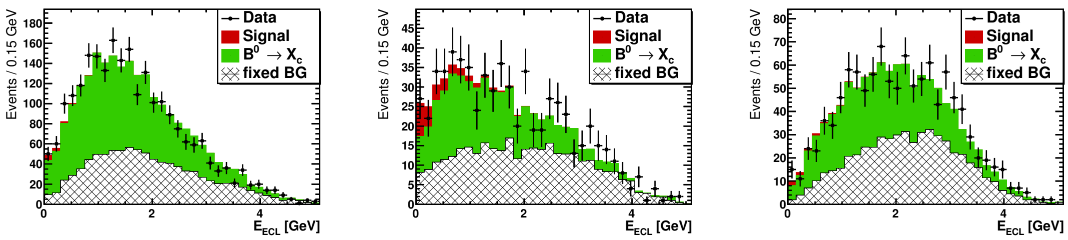

Figure 2: Simultaneous fit in E_{ECL}: (left) $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$, (center) $\tau^+ \to \pi^+\bar{\nu}_\tau$ and (right) $\tau^+ \to \rho^+\bar{\nu}_\tau$.

5. Conclusions

We presented two analyses exploring charmless semileptonic B decays at Belle, implementing a hadronic tag method. On one hand we measured a branching ratio for the $B \to \eta\ell\nu$ decay of $(0.42 \pm 0.11_{\text{stat}} \pm 0.03_{\text{syst}}) \times 10^{-4}$ and set an upper limit at 90% confidence level on the branching ratio for the $B \to \eta'\ell\nu$ of 7.6×10^{-5}. In addition, with more reliable form factor calculations for $B \to \eta\ell\nu$ decays, a measurement of $|V_{ub}|$ would be feasible and serve as a cross check for measurements from other exclusive modes such as $B \to \pi\ell\nu$ or $B \to \rho\ell\nu$. On the other hand, we report the first experimental result for $B \to \pi\tau\nu$ obtaining an upper limit of $\mathscr{B}(B^0 \to \pi^-\tau^+\nu_\tau) < 2.5 \times 10^{-4}$ at 90% confidence level, which is compatible with the SM prediction. These results are limited by the size of the Belle data sample. Significant improvements can thus be expected from the Belle II super flavor factory.

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