Leptonic Decays at BABAR

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Abstract. We present recent results on leptonic B decays using data collected by the BaBar detector at the PEP-II asymmetric-energy e+e- collider at the Stanford Linear Accelerator Center. We report searches for the $B^+ \to \tau^+ \nu$ decay based on two statistically independent data samples.

PACS. 13.20.-v − 13.25.Hw

1 Introduction

The purely leptonic decay $B^+ \to \tau^+ \nu$ [1] is sensitive to the product of the B meson decay constant f_B, and the absolute value of Cabibbo-Kobayashi-Maskawa matrix element V_{ub} [2,3]. In the Standard Model (SM), the decay proceeds via quark annihilation into a W^+ boson, with a branching fraction given by:

$$\mathcal{B}(B^+ \to \tau^+ \nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left[1 - \frac{m_\tau^2}{m_B^2} \right]^2 \tau_{B^+} f_B^2 |V_{ub}|^2,$$
(1)

where G_F is the Fermi constant, τ_{B^+} is the B^+ lifetime, and m_B and m_τ are the B^+ meson and τ lepton masses.

The process $B^+ \to \tau^+ \nu$ is also sensitive to extensions of the SM. For instance, in two-Higgs doublet models [4] and in the MSSM [5,6] it could be mediated by charged Higgs bosons. The branching fraction measurement can therefore also be used to constrain the parameter space of extensions to the SM. The Belle Collaboration has reported evidence from a search for this decay and the branching fraction was measured to be $(1.79^{+0.56}_{-0.49}(\text{stat.})^{+0.46}_{-0.51}(\text{syst.})) \times 10^{-4}$ [7]. We present here two results from the BABAR collaboration using a sample of $383 \times 10^6 \ \Upsilon(4S) \to B\bar{B}$ decays, based on the reconstruction of a semileptonic [8] and of an hadronic [9] B decay on the tag side.

2 Tag B Reconstruction

In the hadronic tags analysis, the tag B candidate is reconstructed in hadronic B decay modes $B^- \to D^{(*)0}X^-$, where X^- denotes a system of charged and neutral hadrons with total charge -1 composed of $n_1\pi^\pm$, $n_2K^\pm$, $n_3K_s^0$, $n_4\pi^0$, where $n_1 + n_2 \leq 5$, $n_3 \leq 2$, and $n_4 \leq 2$. We reconstruct $D^{*0} \to D^0\pi^0, D^0\gamma$; $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K_s^0\pi^+\pi^-$ and $K_s^0 \to$

$\pi^+\pi^-$. Tag B candidates are required to be kinematically consistent with decay from an $\Upsilon(4S)$ using the beam energy-substituted mass $m_{\text{ES}} = \sqrt{s/4 - \boldsymbol{p}_B^2}$ and the energy difference $\Delta E = E_B - \sqrt{s}/2$. Here $\sqrt{s}$ is the total energy in the $\Upsilon(4S)$ center-of-mass (CM) frame, and $\boldsymbol{p}_B$ and E_B denote, respectively, the momentum and energy of the tag B candidate in the CM frame. The purity $\mathcal{P}$ of each reconstructed B decay mode is estimated, using on-resonance data, as the ratio of the number of peaking events with $m_{\text{ES}} > 5.27 \ \text{GeV}/c^2$ to the total number of events in the same range. If multiple tag B candidates are reconstructed, the one with the highest purity $\mathcal{P}$ is selected. If more than one candidate with the same purity is reconstructed, the one with the lowest value of $|\Delta E|$ is selected. The set of decay modes used is defined by the requirement that the purity of the resulting sample is not less than 30%.

The background consists of $e^+e^- \to q\bar{q}$ events and other $\Upsilon(4S) \to B^0\overline{B}^0$ or B^+B^- decays in which the tag B candidate is mis-reconstructed using particles coming from both B mesons in the event. To reduce the $e^+e^- \to q\bar{q}$ background, we require $|\cos\theta_{TB}^*| < 0.9$, where θ_{TB}^* is the angle in the CM frame between the thrust axis [10] of the tag B candidate and the thrust axis of the remaining reconstructed charged and neutral candidates.

In order to determine the number of correctly reconstructed B^+ decays, the background events are classified in four categories: $e^+e^- \to c\bar{c}$; $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}$; $\Upsilon(4S) \to B^0\overline{B}^0$; and $\Upsilon(4S) \to B^+B^-$. The m_{ES} shapes of these background distributions are taken from MC simulation. The normalization of the $e^+e^- \to c\bar{c}$ and $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}$ backgrounds is taken from off-resonance data, scaled by the luminosity and corrected for the different selection efficiencies evaluated with the MC. The normalization of the $B^0\overline{B}^0$, B^+B^- components are obtained by means of a χ^2 fit to the m_{ES} distribution in the data sideband region ($5.22 \, \text{GeV}/c^2 < m_{\text{ES}} < 5.26 \, \text{GeV}/c^2$). The number of background events in the signal region ($m_{\text{ES}} > 5.27 \, \text{GeV}/c^2$) is extrapolated from the fit and subtracted from the data. We estimate the total number of tagged B's in the data

Contributed to 15th International Conference on Supersymmetry and the Unification of Fundamental Interactions (SUSY07),

7/26/2007-8/1/2007, Karlsruhe, Germany

to be $N_B = (5.92 \pm 0.11(\text{stat})) \times 10^5$. Figure 1 shows the tag B candidate m_{ES} distribution, with the combinatorial background, estimated as the sum of the four components described above, overlaid.
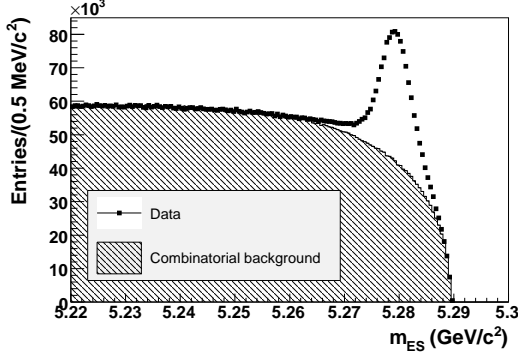
Fig. 1. Distribution of the energy substituted mass, m_{ES}, of the tag B candidates in data. The combinatorial background is overlaid.

In the semileptonic tag analysis, the tag B is reconstructed in semileptonic B decay modes $B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell X$, where ℓ is either an electron or a muon, and X can be either nothing, a π^0 or a photon. Events where the best tag candidate is consistent with neutral B decay are rejected. The identified electron or muon in the $D^0 \ell$ candidates are required to have momentum above $0.8\,\text{GeV}/c$ in the e^+e^- center-of-mass (CM) frame. The flight direction of the D^0 is required to intersect with the lepton track. We reconstruct the D^0 candidates in four decay modes: $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^0$, and $K^0_S\pi^+\pi^-$, only considering K^0_S candidates decaying to charged pions. The π^0 candidates are required to have invariant masses between 0.115 and $0.150\,\text{GeV}/c^2$ and the photon daughter candidates of the π^0 must have a minimum laboratory energy of 30 MeV and have shower shapes consistent with electromagnetic showers. The mass of the reconstructed D^0 candidates in the $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, and $K^0_S\pi^+\pi^-$ modes is required to be within $20\,\text{MeV}/c^2$ of the nominal mass [11], while in the $K^-\pi^+\pi^0$ decay mode the mass is required to be within $35\,\text{MeV}/c^2$ of the nominal mass. Furthermore, the sum of the charges of all the particles in the event must be equal to zero.

We calculate the cosine of the angle between the $D^0\ell$ candidate and the B meson as

$$\cos\theta_{B-D^0\ell} = \frac{2E_B E_{D^0\ell} - m_B^2 - m_{D^0\ell}^2}{2|\boldsymbol{p}_B||\boldsymbol{p}_{D^0\ell}|}, \qquad (2)$$

where $(E_{D^0\ell}, \boldsymbol{p}_{D^0\ell})$ is the four-momentum of the $D^0\ell$ candidate in the CM frame, and $m_{D^0\ell}$ and m_B are the invariant masses of the $D^0\ell$ candidate and the B^+ meson nominal mass [11], respectively. We expect $\cos\theta_{B-D^0\ell}$ for correctly reconstructed tag B candidates to be in the range $[-1, 1]$, whereas combinatorial backgrounds can have values outside this range. We select events with $-2.0 < \cos\theta_{B-D^0\ell} < 1.1$, If multiple tag are re-

constructed the $D^0\ell$ candidate with the largest probability of originating from a single vertex is selected.

From signal MC we estimate the tag reconstruction efficiency to be $(6.64 \pm 0.03) \times 10^{-3}$, where the error is due to the statistics of the signal MC sample. This corresponds to a tag B yield of $(2.54 \pm 0.03) \times 10^6$.

3 Selection of Signal Events

After the reconstruction of the tag B meson, the rest of the event (recoil) is examined for $B^+ \rightarrow \tau^+\nu$ decays. We require the presence of only one well-reconstructed charged track (signal track) with charge opposite to that of the tag B. The signal track is required to have at least 12 hits in the drift chamber, momentum transverse to the beam axis, p_T, greater than $0.1\,\text{GeV}/c$, and the point of closest approach to the interaction point less than 10 cm along the beam axis and less than 1.5 cm transverse to it.

The τ lepton is identified in four decay modes constituting approximately 71% of the total τ decay width: $\tau^+ \rightarrow e^+\nu\bar{\nu}$, $\tau^+ \rightarrow \mu^+\nu\bar{\nu}$, $\tau^+ \rightarrow \pi^+\bar{\nu}$, and $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}$. Particle identification criteria on the signal track are used to separate the four categories.

The $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}$ sample is obtained by associating the signal track, identified as pion, with a π^0 reconstructed from a pair of neutral clusters with invariant mass between 0.115 and 0.155 GeV/c^2. In the hadronic tag analysis and $\pi^+\pi^0$ energy is required to be greater than 250 MeV and in case of multiple candidates, the one with largest center-of-mass momentum $p^*_{\pi^+\pi^0}$ is chosen. In the semileptonic tag analysis the energy of the neutral clusters is required to be greater than 50 MeV.

The selection is further refined with additional requirements exploiting the kinematics of the signal, including cuts on the momentum of visible τ^+ decay products, the missing momentum, the missing mass, the invariant mass of the $\pi^+\pi^0$ candidate, charged tracks and π^0 candidates multiplicities. The semileptonic tag analysis also includes a veto on signal of K^0_L in the calorimeter and in the muon detector.

We optimize the selection by maximizing $s/\sqrt{s+b}$ using the MC simulation, where b is the expected background and s is the expected number of signal events in the hypothesis of a branching fraction of 1×10^{-4}. The optimization is performed separately for each τ decay mode and with all the cuts applied simultaneously in order to take into account any correlations among the discriminating variables. The semileptonic tag analysis uses the PRIM algorithm [12] to find the optimal set of cuts.

For both the analyses, the most powerful discriminating variable is E_{extra} defined as the sum of the energies of the neutral clusters not associated with the tag B or with the signal π^0 from the $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}$ mode, and passing a minimum energy requirement. In the hadronic tag analysis the required energy depends on the selected signal mode and on the calorimeter region involved and varies from 50 to 70 MeV. In the semileptonic tag analysis, the minimum energy requirement

is fixed to 20 MeV, and the energy of charged tracks not associated with the tag B or the signal candidate are included in the E_{extra} computation. Signal events peak at low E_{extra} values, whereas background events, which contain additional sources of neutral clusters, are distributed toward higher E_{extra} values.

The total selection efficiency is estimated from signal MC to be $\varepsilon = (9.8 \pm 0.3)\%$, and $\varepsilon = (12.7 \pm 0.2)\%$ for the hadronic tag analysis and the semileptonic tag analysis, respectively.

4 Background yield

In the hadronic tag analysis, we define a sideband region $0.4 \, \text{GeV} < E_{\text{extra}} < 2.4 \, \text{GeV}$ and a τ mode-dependent signal regions. We perform an extended unbinned maximum likelihood fit to the m_{ES} distribution in the E_{extra} data sideband region of the final sample. For the peaking component of the background we use a probability density function (PDF) which is a Gaussian function joined to an exponential tail (Crystal Ball function) [13]. As a PDF for the non-peaking component, we use a phase space motivated threshold function (ARGUS function) [14]. From this fit, we determine a peaking yield $N_{pk}^{\text{side,data}}$ and signal shape parameters, to be used in later fits. The same procedure is applied to B^+B^- MC events which pass the final selection to determine the peaking yield $N_{pk}^{\text{side,MC}}$. To determine the MC peaking yield in the E_{extra} signal region $N_{pk}^{\text{sig,MC}}$, we fit m_{ES} in the E_{extra} signal region of the B^+B^- MC sample with the Crystal Ball parameters fixed to the values determined in the E_{extra} sideband fits described above. Analogously, we fit the m_{ES} distribution of data in the E_{extra} signal region to extract the combinatorial background n_{comb}, evaluated as the integral of the ARGUS shaped component in the $m_{\text{ES}} > 5.27 \, \text{GeV}/c^2$ region. The total expected background in the signal region is determined as

$$ b = \frac{N_{pk}^{\text{sig,MC}}}{N_{pk}^{\text{side,MC}}} \times N_{pk}^{\text{side,data}} + n_{\text{comb}}. \qquad (3) $$

In the semileptonic tag analysis, the sideband region is defined by $E_{\text{extra}} > 0.5 \, \text{GeV}$, and the signal regions in E_{extra} are signal mode-dependent. Using the number of events in the sideband ($N_{\text{MC,sb}}$) and signal ($N_{\text{MC,sig}}$) regions from MC simulation and the number of data events in the sidebands $N_{\text{data,sb}}$, we estimate the number of expected background events in the signal region in data $N_{\text{exp,sig}}$

$$ N_{\text{exp,sig}} = N_{\text{data,sb}} \cdot \frac{N_{\text{MC,sig}}}{N_{\text{MC,sb}}}. \qquad (4) $$

The background estimate is validated using sidebands in the D^0 mass distribution.

Table 1. Observed number of on-resonance data events in the signal region compared with the number of expected background events, for the hadronic tag analysis.

| τ decay mode	Expected background	Observed
$\tau^+ \to e^+ \nu \overline{\nu}$	1.47 ± 1.37	4
$\tau^+ \to \mu^+ \nu \overline{\nu}$	1.78 ± 0.97	5
$\tau^+ \to \pi^+ \overline{\nu}$	6.79 ± 2.11	10
$\tau^+ \to \pi^+ \pi^0 \overline{\nu}$	4.23 ± 1.39	5
All modes	14.27 ± 3.03	24

5 Results

We measure the yield of events in each decay mode in on-resonance data. Table 1 reports, for the hadronic tag analysis, the number of observed events together with the expected number of background events, for each τ decay mode. Figure 2 shows the E_{extra} distribution for data and expected background at the end of the selection. The signal MC, normalized to a branching fraction of 3×10^{-3} for illustrative purposes, is overlaid for comparison. The E_{extra} distribution is also plotted separately for each τ decay mode.
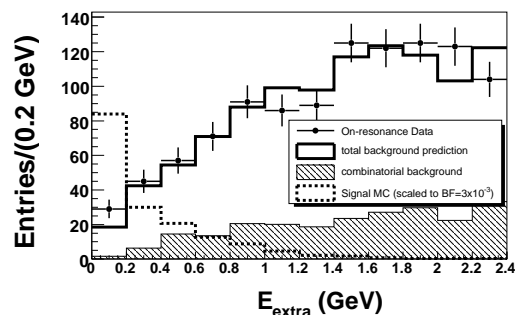
Fig. 2. E_{extra} distribution after all selection criteria have been applied. The on-resonance data (black dots) distribution is compared with the total background prediction (continuous histogram). The hatched histrogram represents the combinatorial background component. $B^+ \to \tau^+ \nu$ signal MC (dashed histogram), normalized to a branching fraction of 3×10^{-3} for illustrative purposes, is shown for comparison.

Table 2 lists, for the semileptonic tag analysis, the number of observed events in on-resonance data in the signal region, together with the expected number of background events in the signal region. Figure 3 shows the E_{extra} distribution for all data and MC in the signal region, with signal MC shown for comparison.

In both the analyses, we combine the results on the observed number of events n_i and on the expected background b_i from each of the four signal decay modes (n_{ch}) using the estimator $Q = \mathcal{L}(s+b)/\mathcal{L}(b)$, where $\mathcal{L}(s+b)$ and $\mathcal{L}(b)$ are the likelihood functions for signal plus background and background-only hypotheses,
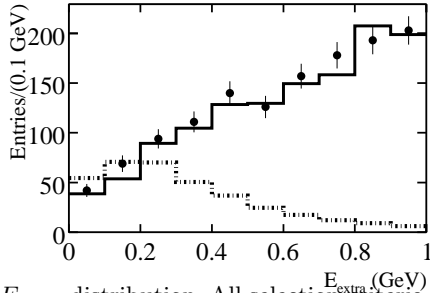
Fig. 3. E_{extra} distribution. All selection criteria have been applied and all signal modes combined. Background MC (solid histogram) has been normalized to the luminosity of the on-resonance data (black dots), and then additionally scaled according to the ratio of predicted background from data and MC. $B^+ \to \tau^+\nu$ signal MC (dotted histogram) is normalized to a branching fraction of 10^{-3} and shown for comparison.

Table 2. Observed number of on-resonance data events in the signal region are shown, together with number of expected background events, for the semileptonic tag analysis.

τ	Expected background	Observed
$\tau^+ \to e^+\nu\overline{\nu}$	44.3 ± 5.2	59
$\tau^+ \to \mu^+\nu\overline{\nu}$	39.8 ± 4.4	43
$\tau^+ \to \pi^+\overline{\nu}$	120.3 ± 10.2	125
$\tau^+ \to \pi^+\pi^0\overline{\nu}$	17.3 ± 3.3	18
All modes	221.7 ± 12.7	245

respectively:

$$\mathcal{L}(s+b) \equiv \prod_{i=1}^{n_{ch}} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{n_i}}{n_i!}, \ \ \mathcal{L}(b) \equiv \prod_{i=1}^{n_{ch}} \frac{e^{-b_i}b_i^{n_i}}{n_i!}.$$
(5)

The estimated number of signal candidates s_i in data, for each decay mode, is related to the $B^+ \to \tau^+\nu$ branching fraction by:

$$s_i = \frac{\varepsilon_{\text{sig}}^{\text{tag}}}{\varepsilon_B^{\text{tag}}} N_{B^+}^{\text{tag}} \varepsilon_i \mathcal{B}(B^+ \to \tau^+\nu),$$
(6)

where $N_{B^+}^{\text{tag}}$ is the number of tag B^+ mesons correctly reconstructed, $\varepsilon_B^{\text{tag}}$ and $\varepsilon_{\text{sig}}^{\text{tag}}$ are the tag B efficiencies in generic $B\bar{B}$ and signal events respectively, and ε_i are the signal selection efficiencies for each channel, including the τ^+ branching fractions. In the hadronic tag analysis, we find the ratio from MC simulation to be $\varepsilon_{\text{sig}}^{\text{tag}}/\varepsilon_B^{\text{tag}} = 0.939 \pm 0.007(\text{stat.})$.

We estimate the branching fraction (including statistical uncertainty and uncertainty from the background [15]) by scanning over signal branching fraction hypotheses and computing the value of $\mathcal{L}(s+b)/\mathcal{L}(b)$ for each hypothesis. The branching fraction is the hypothesis which minimizes the likelihood ratio $-2\ln Q = -2\ln(\mathcal{L}(s+b)/\mathcal{L}(b))$, and we determine the statistical uncertainty by finding the points on the likelihood scan that occur at one unit above the minimum.

In the hadronic tag analysis, we measure the branching fraction

$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-4}, \quad (7)$$

where the first error is statistical, the second is due to the background uncertainty, and the third is due to other systematic sources. Taking into account the uncertainty on the expected background, as described above, we obtain a significance of $2.2\ \sigma$.

In the semileptonic tag analysis, we measure the branching fraction

$$\mathcal{B}(B^+ \to \tau^+\nu) = (0.9 \pm 0.6 \pm 0.1) \times 10^{-4}, \quad (8)$$

where the first error is statistical, and the second is due to the systematics uncertainties.

The combination of the two results yields:

$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.2 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}, \quad (9)$$

where the first uncertainty is statistical, the second is the uncertainty on the expected background and the third is from the other source of systematic effects. The significance of the combined result is $2.6\ \sigma$ including the uncertainty on the expected background ($3.2\ \sigma$ if this uncertainty is not included).

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