A Search for $B^+ \rightarrow \tau^+ \nu$ Recoiling Against $B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell X$.

The BABAR Collaboration

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Abstract

We present a search for the decay $B^+ \rightarrow \tau^+ \nu_\tau$ using 288 fb$^{-1}$ of data collected at the $\Upsilon(4S)$ resonance with the BABAR detector at the SLAC PEP-II $B$-Factory. A sample of events with one reconstructed semileptonic $B$ decay ($B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell X$) is selected, and in the recoil a search for $B^+ \rightarrow \tau^+ \nu_\tau$ signal is performed. The $\tau$ is identified in the following channels: $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_{\tau}$, $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_{\tau}$, $\tau^+ \rightarrow \pi^+ \bar{\nu}_{\tau}$ and $\tau^+ \rightarrow \pi^+ \pi^0 \nu_{\tau}$. We measure a branching fraction of $B(B^+ \rightarrow \tau^+ \nu_\tau) = (0.88^{+0.68}_{-0.67} \text{(stat.)} \pm 0.11 \text{(syst.)}) \times 10^{-4}$ and extract an upper limit on the branching fraction, at the 90% confidence level, of $B(B^+ \rightarrow \tau^+ \nu_\tau) < 1.8 \times 10^{-4}$. We calculate the product of the $B$ meson decay constant and $|V_{ub}|$ to be $f_B \cdot |V_{ub}| = (7.0^{+2.3}_{-3.6} \text{(stat.)}^{+0.4}_{-0.5} \text{(syst.)}) \times 10^{-4}$ GeV.

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1 INTRODUCTION

In the Standard Model (SM), the purely leptonic decay $B^+ \rightarrow \tau^+ \nu_\tau$ proceeds via quark annihilation into a $W^+$ boson (Fig. 1). Its amplitude is thus proportional to the product of the $B$-decay constant $f_B$ and the quark-mixing-matrix element $V_{ub}$. The branching fraction is given by:

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

where we have set $\hbar = c = 1$, $G_F$ is the Fermi constant, $V_{ub}$ is a quark mixing matrix element [1, 2], $f_B$ is the $B^+$ meson decay constant which describes the overlap of the quark wave-functions inside the meson, $\tau_B^+$ is the $B^+$ lifetime, and $m_B$ and $m_\tau$ are the $B^+$ meson and $\tau$ masses. This expression is entirely analogous to that for pion decay. Physics beyond the SM, such as a two-Higgs doublet models, could enhance or suppress the $B(B^+ \rightarrow \tau^+ \nu_\tau)$ through the introduction of a charged Higgs boson [3].

Current theoretical values for $f_B$ (obtained from lattice QCD calculations) [4] have large uncertainties, and purely leptonic decays of the $B^+$ meson may be the only clean experimental method of measuring $f_B$ precisely. Given measurements of $|V_{ub}|$ from semileptonic $B \rightarrow u\ell\nu$ decays, $f_B$ could be extracted from the measurement of the $B^+ \rightarrow \tau^+ \nu_\tau$ branching fraction. In addition, by combining the branching fraction measurement with results from $B$ mixing, the ratio $|V_{ub}|/|V_{td}|$ can be extracted from $B(B^+ \rightarrow \tau^+ \nu_\tau)/\Delta m$, where $\Delta m$ is the mass difference between the heavy and light neutral $B$ meson states.

![Figure 1](image-url)  

**Figure 1:** The purely leptonic $B$ decay $B^+ \rightarrow \tau^+ \nu_\tau$ proceeding via quark annihilation into a $W^+$ boson.

The decay amplitude is proportional to the lepton mass and as such decay to the lighter leptons is suppressed. This mode is the most promising for discovery of leptonic $B$ decays. However, experimental challenges such as the large missing momentum from several neutrinos make the signature for $B^+ \rightarrow \tau^+ \nu_\tau$ less distinctive than for other leptonic modes.

The SM estimate of this branching fraction is $(1.59\pm0.40)\times10^{-4}$, using $|V_{ub}| = (4.39\pm0.33)\times10^{-3}$ [5] and $f_B = 0.216 \pm 0.022$ GeV [4] in Eq. 1.

In a previously published analysis of a smaller sample of $223 \times 10^6 \ Upsilon(4S)$ decays the $\textbf{BABAR}$ collaboration set an upper limit of:

$$B(B^+ \rightarrow \tau^+ \nu_\tau) < 2.6 \times 10^{-4} \text{ at the 90\% CL.} \quad (2)$$

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5Charge-conjugate modes are implied throughout this paper. The signal $B$ will always be denoted as a $B^+$ decay while the semi-leptonic $B$ will be denoted as a $B^-$ to avoid confusion.
The Belle collaboration reported evidence of a signal in this channel recently [7]; a central value of $(1.06^{+0.34}_{-0.28}(\text{stat.})^{+0.18}_{-0.10}(\text{syst.})) \times 10^{-4}$ was extracted. The analysis presented herein is a detailed update of the previous BaBar search.

2 THE BaBar DETECTOR AND DATASET

The data used in this analysis were collected with the BaBar detector at the PEP-II storage ring. The sample corresponds to an integrated luminosity of 288 fb$^{-1}$ at the $\Upsilon(4S)$ resonance (on-resonance) and 27.5 fb$^{-1}$ taken 40 MeV below $B\bar{B}$ threshold (off-resonance). The on-resonance sample consists of about $320 \times 10^6 \Upsilon(4S)$ decays ($B\bar{B}$ pairs). The collider is operated with asymmetric beam energies, producing a boost of $\beta\gamma \approx 0.56$ of the $\Upsilon(4S)$ along the collision axis.

The BaBar detector is optimized for asymmetric energy collisions at a center-of-mass (CM) energy corresponding to the $\Upsilon(4S)$ resonance. The detector is described in detail in Ref. [8]. The components used in this analysis are the tracking system composed of a five-layer silicon vertex detector and a 40-layer drift chamber (DCH), the Cherenkov detector (DIRC) for charged $\pi-K$ discrimination, the CsI calorimeter (EMC) for photon and electron identification, and the 18-layer flux return (IFR) located outside of the 1.5T solenoidal coil and instrumented with resistive plate chambers for muon and neutral hadron identification. For the most recent 51 fb$^{-1}$ of data, a portion of the muon system has been upgraded to limited streamer tubes (LST) [9]. We separate the treatment of the data to account for varying accelerator and detector conditions. “Runs 1–3” corresponds to the first 111.9 fb$^{-1}$, “Run 4” the following 99.7 fb$^{-1}$ and “Run 5” the subsequent 76.8 fb$^{-1}$.

A GEANT4-based [10] Monte Carlo (MC) simulation is used to model the signal efficiency and the physics backgrounds. Simulation samples equivalent to approximately three times the accumulated data were used to model $B\bar{B}$ events, and samples equivalent to approximately 1.5 times the accumulated data were used to model continuum events where $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ and $\tau^+\tau^-$. A large sample of signal events is simulated, where a $B^+$ meson decays to $\tau^+\nu_\tau$ and a $B^-$ meson decays to an acceptable $B$ mode. Beam related background and detector noise from data are overlayed on the simulated events.

3 ANALYSIS METHOD

Due to the presence of multiple neutrinos, the $B^+ \rightarrow \tau^+\nu_\tau$ decay mode lacks the kinematic constraints which are usually exploited in $B$ decay searches in order to reject both continuum and $B\bar{B}$ backgrounds. The strategy adopted for this analysis is to reconstruct exclusively the decay of one of the $B$ mesons in the event, referred to as “tag” $B$. The remaining particle(s) in the event, referred to as the “signal side”, are then compared with the signature expected for $B^+ \rightarrow \tau^+\nu_\tau$. In order to avoid experimenter bias, the signal region in data is not examined (“blinded”) until the final yield extraction is performed.

The tag $B$ is reconstructed in the set of semileptonic $B$ decay modes $B^- \rightarrow D^0\ell^-\bar{\nu}_\ell X$, where $\ell$ is $e$ or $\mu$ and $X$ can be either nothing or a transition particle from a higher mass charm state decay which we do not attempt to reconstruct (although those tags consistent with neutral $B$ decays are vetoed). The $D^0$ is reconstructed in four decay modes: $K^-\pi^+, K^-\pi^+\pi^-\pi^+, K^-\pi^+\pi^0$, and $K^0_s\pi^+\pi^-$. The $K^0_s$ is reconstructed only in the mode $K^0_s \rightarrow \pi^+\pi^-$. These cases where the low momentum transition daughter of $D^{*0}$ decays need not be reconstructed and the final state $B \rightarrow D^0\ell\nu_X$ as observed provides a higher efficiency but somewhat lower purity than the exclusive reconstruction method of $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_\ell$. The choice of reconstructing the tag $B$ as $B^- \rightarrow D^0\ell^-\bar{\nu}_\ell X$ was optimized by maximizing $s/\sqrt{s+b}$ where $s =$ signal and $b =$ background where a branching fraction for $B^+ \rightarrow \tau^+\nu_\tau$ of $1 \times 10^{-4}$ is assumed.
The $B^+ \rightarrow \tau^+ \nu_\tau$ signal is searched for in both leptonic and hadronic $\tau$ decay modes: $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$, $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$, $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$ and $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$. The branching fractions of the above $\tau$ decay modes are listed in Table 1.

Table 1: Branching fractions for the $\tau$ decay modes used in the $B^+ \rightarrow \tau^+ \nu_\tau$ search [11].

| Decay Mode        | Branching Fraction (%) |
|-------------------|------------------------|
| $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ | 17.84 ± 0.06           |
| $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ | 17.36 ± 0.06           |
| $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$       | 11.06 ± 0.11           |
| $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$ | 25.42 ± 0.14           |

3.1 Tag B Reconstruction

The tag $B$ reconstruction proceeds as follows. First we reconstruct the $D^0$ candidates in the aforementioned four decay modes using reconstructed tracks and photons where a $\pi^0$ is included. The tracks are required to meet particle identification criteria consistent with the particle hypothesis, and are required to converge at a common vertex. The $\pi^0$ candidate is required to have invariant mass between 0.115–0.150 GeV/$c^2$ and its daughter photon candidates must have a minimum energy of 30 MeV. The mass of the reconstructed $D^0$ candidates in $K^-\pi^+\pi^-\pi^+$, and $K^0\pi^+\pi^-\pi^0$ modes are required to be within 20 MeV/$c^2$ of the nominal mass [11]. In the $K^-\pi^+\pi^0$ decay mode the mass is required to be within 35 MeV/$c^2$ of the nominal mass [11].

Finally $D^{0}\ell$ candidates are reconstructed by combining the $D^0$ with an identified electron or muon with momentum above 0.8 GeV/$c$ in the CM frame. The $D^0$ and $\ell$ candidates are required to meet at a common vertex. An additional kinematic constraint is imposed on the reconstructed $D^{0}\ell$ candidates: assuming that the massless neutrino is the only missing particle, we calculate the cosine of the angle between the $D^{0}\ell$ candidate and the $B$ meson,

$$\cos \theta_{B-D^{0}\ell} = \frac{2E_B E_{D^{0}\ell} - m_B^2 - m_{D^{0}\ell}^2}{2|\vec{p}_B||\vec{p}_{D^{0}\ell}|}.$$  

Here $(E_{D^{0}\ell}, \vec{p}_{D^{0}\ell})$ and $(E_B, |\vec{p}_B|)$ are the four-momenta in the CM frame, and $m_{D^{0}\ell}$ and $m_B$ are the masses of the $D^{0}\ell$ candidate and $B$ meson, respectively. $E_B$ and the magnitude of $\vec{p}_B$ are calculated from the beam energy: $E_B = E_{CM}/2$ and $|\vec{p}_B| = \sqrt{E_B^2 - m_B^2}$, where $E_B$ is the $B$ meson energy in the CM frame. Correctly reconstructed candidates populate the range $[-1, 1]$, whereas combinatorial backgrounds can take unphysical values outside this range. We retain events in the interval $-2.0 < \cos \theta_{B-D^{0}\ell} < 1.1$, where the upper bound takes into account the detector resolution and the loosened lower bound accepts those events where a soft transition particle from a higher mass charm state is missing.

If more than one suitable $D^{0}\ell$ candidate is reconstructed in an event, the best candidate is taken to be the one with the largest vertex probability. The sum of the charges of all the particles in the event (net charge) must be equal to zero.

At this stage of the selection, the observed yield in data and the predicted yield in the MC simulation agree to within approximately 3%. This discrepancy is corrected by scaling the yield and efficiency obtained from MC simulation. By multiplying the relevant branching fractions and reconstruction efficiencies, from signal MC simulation, $B$ tagging efficiencies are extracted. Scale factors of 1.05, 1.00 and 0.97 are used.
to correct these efficiencies for Runs 1–3, Run 4 and Run 5 respectively. The systematic error associated with this correction is described in Sec. 5. The corrected tag reconstruction efficiency in the signal MC simulation is $(7.61 \pm 0.05) \times 10^{-3}$ for Runs 1–3, $(6.31 \pm 0.05) \times 10^{-3}$ for Run 4 and $(5.87 \pm 0.06) \times 10^{-3}$ for Run 5 where the errors are statistical only.

3.2 Selection of $B^+ \to \tau^+ \nu_\tau$ signal candidates

After the tag $B$ reconstruction, in the signal side the $\tau$ from the $B^+ \to \tau^+ \nu_\tau$ decay is identified in one of the following modes: $\tau^+ \to e^+ \nu_e \bar{\nu}_e$, $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\mu$, $\tau^+ \to \pi^+ \bar{\nu}_\tau$ or $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$. We select events with one signal-side track which must satisfy the following selection criteria: it must have at least 12 DCH hits, its momentum transverse to the beam axis, $p_T$, is greater than 0.1 GeV/c, and its point of closest approach to the interaction point is less than 5.0 cm along the beam axis and less than 1.5 cm transverse to the beam axis. The invariant mass of a signal-side $\pi^0$ candidate must be between 0.115–0.150 GeV/c$^2$, the shower shape of the daughter photon candidates must be consistent with an electromagnetic shower shape and the photons must have a minimum energy of 50 MeV in the CM frame.

The different signal tau decay modes are distinguished by their selection criteria. The $\tau^+ \to e^+ \nu_e \bar{\nu}_e$, $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\mu$, $\tau^+ \to \pi^+ \bar{\nu}_\tau$ and $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$ signal modes, all of which contain one charged track, are separated by particle identification. Both the $\tau^+ \to \pi^+ \bar{\nu}_\tau$ and the $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$ modes contain a pion signal track and are characterized by the number of signal-side $\pi^0$ mesons.

- **Particle identification:**
  - For the $\tau^+ \to e^+ \nu_e \bar{\nu}_e$ selection the track must be identified as an electron and not identified as a muon.
  - For the $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\mu$ selection the track must be identified as a muon and not identified as an electron.
  - For the $\tau^+ \to \pi^+ \bar{\nu}_\tau$ selection we require that the track is not identified as an electron or a muon.
  - For the $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$ selection we require that the track is not identified as an electron or a muon or a kaon.

- **Signal-side $\pi^0$ multiplicity:**
  - For the $\tau^+ \to \pi^+ \bar{\nu}_\tau$ selection we require the event to contain no signal-side $\pi^0$.
  - For the $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$ selection we require that the event contains at least one signal-side $\pi^0$.

Background consists primarily of $B^+ B^-$ events in which the tag $B$ meson has been correctly reconstructed and the recoil side contains one signal candidate track and additional particles which are not reconstructed by the tracking detectors or calorimeters. Typically these events contain $K^0_L$ candidates and/or neutrinos, and frequently also additional charged or neutral particles which pass outside of the tracking and calorimeter acceptance. Background events also contain $B^0 \bar{B}^0$ events. The continuum background contributes to hadronic $\tau$ decay modes. In addition some excess events in data, most likely from two-photon and QED processes which are not modeled in the MC simulation, are also seen. These backgrounds have a distinctive event shape and are suppressed by the following constraints on the kinematics of the $B^+ \to \tau^+ \nu_\tau$ candidates.
• Missing mass: The missing mass is calculated as follows.

\[ M_{\text{miss}} = \sqrt{(E_{\Upsilon(4S)} - E_{\text{vis}})^2 - (\vec{p}_{\Upsilon(4S)} - \vec{p}_{\text{vis}})^2}. \]  

(4)

Here \((E_{\Upsilon(4S)}, \vec{p}_{\Upsilon(4S)})\) is the four-momentum of the \(\Upsilon(4S)\), known from the beam energies. The quantities \(E_{\text{vis}}\) and \(\vec{p}_{\text{vis}}\) are the total visible energy and momentum of the event which are calculated by adding the energy and momenta, respectively, of all the reconstructed charged tracks and photons in the event.

- For the \(\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau\) selection events with missing mass between 4.6 and 6.7 GeV/c\(^2\) are selected.
- For the \(\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau\) selection events with missing mass between 3.2 and 6.1 GeV/c\(^2\) are selected.
- For the \(\tau^+ \rightarrow \pi^+\bar{\nu}_\tau\) selection the missing mass is required to be greater than 1.6 GeV/c\(^2\).
- For the \(\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}_\tau\) selection the missing mass is required to be less than 4.6 GeV/c\(^2\).

• Maximum CM momentum of the \(\tau\) daughter:

The following maximum CM momentum requirements are applied to the \(\tau\) daughter particles.

- The electron candidate from the \(\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau\) decay must have a CM momentum of less than 1.5 GeV/c. The CM momentum requirement is not applied to the \(\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau\) selection because the momentum spectrum of the muon from \(\tau\) decays peaks below 1 GeV/c and the particle identification efficiency for low momentum muons is lower than that for low momentum electrons. Therefore, applying the maximum momentum cut reduces the selection efficiency of the \(\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau\) mode significantly.
- For the two hadronic \(\tau\) decay modes, the CM momentum of the \(\pi\) from \(\tau^+ \rightarrow \pi^+\bar{\nu}_\tau\) must be greater than 1.6 GeV/c. The \(\pi\pi^0\) combination from \(\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}_\tau\) must have CM momentum greater than 1.7 GeV/c.

• Continuum Rejection using the \(R_{\tau\tau}\) variable:

An effective way to remove \(e^+e^- \rightarrow \tau^+\tau^-\) background is to place a cut in a plane defined by two variables: the cosine of the angle between the signal candidate and the tag \(B\)’s thrust vector (in the CM frame), and the minimum invariant mass constructable from any three tracks in an event (regardless of whether they are already used in a tag or signal candidates). For the background, the cosine of the thrust angle peaks at \(-1\) and 1, while the minimum invariant mass peaks below 1.5 GeV/c\(^2\). We transformed this 2-D variable into a 1-D variable using the following empirically derived equation

\[ R_{\tau\tau} \equiv \sqrt{(3.7 - |\cos(\theta_{\text{TD}\ell,\text{signal}})|)^2 + (M_3^{\text{min}} - 0.75)^2}, \]  

(5)

where \(M_3^{\text{min}}\) is the minimum invariant mass of any three charged tracks and \(\theta_{\text{TD}\ell,\text{signal}}\) is the angle between the thrust axes of the reconstructed \(D\ell\) and the signal candidates. Because other continuum backgrounds also peak in the cosine of the thrust angle, this variable is good at rejecting other similar categories of non-\(b\bar{b}\) background. The selection criteria imposed on this quantity are:

- For \(\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau\): \(2.78 < R_{\tau\tau} < 4.0\)
– For $\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau$: $R_{\tau\tau} > 2.74$
– For $\tau^+ \rightarrow \pi^+\bar{\nu}_\tau$: $R_{\tau\tau} > 2.84$
– For $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}_\tau$: $R_{\tau\tau} > 2.94$

The $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}_\tau$ decay proceeds via an intermediate resonance. For this mode further background rejection can be achieved by applying the following requirements on the intermediate meson.

– $\rho^+$ selection:
The signal-side track is combined with a signal-side $\pi^0$ to form the $\rho^+$ candidate. In events with more than one signal-side $\pi^0$, the candidate with invariant mass closest to the nominal $\pi^0$ mass [11] is chosen. The invariant mass of the reconstructed $\rho^+$ is required to be within $0.64–0.86$ GeV/$c^2$. A quantity similar to $\cos \theta_{B-D^0\ell}$, which is defined in section 3.1, can be reconstructed for $\tau \rightarrow \rho\nu$ as follows:

$$\cos \theta_{\tau-\rho} = \frac{2E_\tau E_\rho - m_\tau^2 - m_\rho^2}{2|\vec{p}_\tau||\vec{p}_\rho|},$$

(6)

where $(E_\tau, \vec{p}_\tau)$ and $(E_\rho, \vec{p}_\rho)$ are the four-momenta in the CM frame, $m_\tau$ and $m_\rho$ are the masses of the $\tau$ and $\rho$ candidate, respectively. The quantities $|\vec{p}_\tau|$ and $E_\tau$ are calculated assuming the $\tau$ is from the $B^+ \rightarrow \tau^+\nu_\tau$ decay, and the $B^+$ is almost at rest in the CM frame. We accept candidates with $\cos \theta_{\tau-\rho} > 0.87$.

• $E_{\text{extra}}$ requirement:
The most powerful variable for separating signal and background is the remaining energy ($E_{\text{extra}}$), calculated by adding the CM energy of the neutral clusters and charged tracks that are not associated with either the tag $B$ or the signal. The photon candidates contributing to the $E_{\text{extra}}$ variable have minimum cluster energies of 20 MeV in the CM frame. For signal events the neutral clusters contributing to $E_{\text{extra}}$ arise predominantly from processes such as beam-background, hadronic split-offs and Bremsstrahlung. Signal events tend to peak at low $E_{\text{extra}}$ values whereas background events, which contain additional sources of neutral clusters, are distributed towards higher $E_{\text{extra}}$ values. The most signal sensitive region is optimized for each mode and is blinded in on-resonance data until the selection is finalized. The $E_{\text{extra}} < 0.5$ GeV region is defined as the nominal blinding region which is slightly larger than the signal region for each mode.

For all the signal modes $E_{\text{extra}}$ is optimized for the best signal significance (assuming the branching fraction is $1 \times 10^{-4}$). The optimization yields to following requirements:

– For $\tau^+ \rightarrow e^+\nu_\tau\bar{\nu}_\tau$: $E_{\text{extra}} < 0.31$ GeV
– For $\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau$: $E_{\text{extra}} < 0.26$ GeV
– For $\tau^+ \rightarrow \pi^+\bar{\nu}_\tau$: $E_{\text{extra}} < 0.48$ GeV
– For $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}_\tau$: $E_{\text{extra}} < 0.25$ GeV

The signal selection criteria for all signal modes are summarized in Table 2.
Table 2: The selection criteria for different signal modes using a $B^-\rightarrow D^{0}\ell^-\bar{\nu}_\ell$ tag are listed in this table.

| Mode | 4.6 $\leq M_{miss}$ $\leq$ 6.7 | 3.2 $\leq M_{miss}$ $\leq$ 6.1 | 1.6 $\leq M_{miss}$ | $M_{miss}$ $\leq$ 4.6 |
|------|--------------------------------|--------------------------------|---------------------|----------------------|
| $p_{\text{signal}}$ $\leq$ 1.5 | - | 1.6 $\leq p_{\text{signal}}$ | 1.7 $\leq p_{\text{signal}}$ |

No IFR $K_l^0$

| SR1 | SR2 | SR3 | SR4 |
|-----|-----|-----|-----|
| $2.78 < R_{\tau\tau} < 4.0$ | $2.74 < R_{\tau\tau} < 2.84 < R_{\tau\tau} < 2.94 < R_{\tau\tau}$ |
| $m_{\text{ex}} > 0.1 \text{ GeV/c}^2$ | $N_{\text{extra}}^{\tau\tau} \leq 2$ | $N_{\text{extra}}^{\mu\mu} \leq 2$ | $N_{\text{EMC}}\rho^0 \leq 2$ |
| - | - | - | - |
| $E_{\text{extra}} > 0.31 \text{ GeV}$ | $E_{\text{extra}} > 0.26 \text{ GeV}$ | $E_{\text{extra}} > 0.48 \text{ GeV}$ | $E_{\text{extra}} > 0.25 \text{ GeV}$ |

Table 3: The signal efficiencies, mode-by-mode, relative to the number of tags. The branching fraction for the given $\tau$ decay mode selected is included in the efficiency.

| Mode | Efficiency (BF Included) |
|------|--------------------------|
| $\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau$ | $0.0414 \pm 0.0009$ |
| $\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau$ | $0.0242 \pm 0.0007$ |
| $\tau^+ \rightarrow \pi^+\bar{\nu}_\tau$ | $0.0492 \pm 0.0010$ |
| $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}_\tau$ | $0.0124 \pm 0.0005$ |

3.2.1 Signal Efficiency

The signal-side selection efficiencies for the $\tau$ decay modes are determined from signal MC simulation and summarized in Table 3. The signal efficiencies correspond to the number of events selected in a specific signal decay mode, given that a tag $B$ has been reconstructed.

The selection efficiency for $\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau$ is low compared to that of the $\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau$ mode because the momentum spectrum of the signal muons peaks below 1 GeV/c, where the muon detection efficiency is low. Since no minimum momentum requirement and no tight pion identification criteria are applied to the $\tau^+ \rightarrow \pi^+\bar{\nu}_\tau$ signal selection, electron and muon signal tracks that fail particle identification requirement get selected in this mode. Any true $\tau^+ \rightarrow \pi^+\pi^0\bar{\nu}_\tau$ signal events, with a missed $\pi^0$ also get included in $\tau^+ \rightarrow \pi^+\bar{\nu}_\tau$ selection mode. Therefore the $\tau^+ \rightarrow \pi^+\bar{\nu}_\tau$ selection mode has the highest signal efficiency.

3.3 Validation of Background Estimation from $E_{\text{extra}}$ Sidebands

We further study the agreement between simulation and data by using the extra energy sideband region, and the ratio of the yields in this region to that in the signal region. This is used mainly to test the reliability of the background estimation in the low $E_{\text{extra}}$ region by extrapolation from the higher $E_{\text{extra}}$ region.

The $E_{\text{extra}} > 0.5 \text{ GeV}$ region is defined as the “sideband” (sb). The “signal region” is defined separately for each selection mode. For each control sample after applying appropriate selection cuts, the number of MC events in the signal region ($N_{\text{MC,Sig}}$) and sideband ($N_{\text{MC,sb}}$) are counted and their ratio ($R_{\text{MC}}$) is obtained.

$$R_{\text{MC}} = \frac{N_{\text{MC,Sig}}}{N_{\text{MC,sb}}}$$ (7)
Using the number of data events in the sideband \( N_{\text{data, sb}} \) and the ratio \( R^{MC} \), the number of expected background events in the signal region in data \( N_{\text{exp, Sig}} \) is estimated.

\[
N_{\text{exp, Sig}} = N_{\text{data, sb}} \cdot R^{MC}
\]  

(8)

The number of expected data events \( N_{\text{exp, Sig}} \) in the signal region is compared with the observed number of data events \( N_{\text{obs, Sig}} \) in the signal region. The agreement between the above two quantities provide validation of background estimation in the low \( E_{\text{extra}} \) region.

Table 4 illustrates the level of agreement between the sideband projections in MC and data. In general, the agreement is at the 1\( \sigma \) level between the direct count in the MC signal region and the projected data. The projections in data are used to predict background for the final extraction, hence we only rely on the data for this.

| Mode | ratio (MC) | upper sb (Data) | signal region (Proj) | signal region (MC) |
|------|------------|-----------------|----------------------|-------------------|
| electron | 0.137 ± 0.015 | 305.00 ± 17.46 | 41.91 ± 5.19 | 39.72 ± 4.07 |
| muon | 0.037 ± 0.004 | 965.00 ± 31.06 | 35.39 ± 4.16 | 36.13 ± 4.02 |
| pion | 0.043 ± 0.004 | 2288.00 ± 47.83 | 99.09 ± 9.10 | 87.69 ± 7.72 |
| rho | 0.005 ± 0.001 | 2805.00 ± 52.96 | 15.30 ± 3.48 | 15.81 ± 3.58 |

4 VALIDATION OF TAG B YIELD AND \( E_{\text{extra}} \) SIMULATION

The tag \( B \) yield and \( E_{\text{extra}} \) distribution in signal and background MC simulation are validated using various control samples. The level of agreement between the data and simulation distributions provides validation of the \( E_{\text{extra}} \) modeling in the simulation and corrects for differences in the yield of reconstructed tag \( B \)'s.

“Double-tagged” events, for which both of the \( B \) mesons are reconstructed in tagging modes, \( B^- \rightarrow D^0 \ell - \bar{\nu}_\ell X \) vs. \( B^+ \rightarrow D^0 \ell + \nu_\ell X \) are used as the main control sample. Due to the large branching fraction and high tagging efficiency for these events, a sizable sample of such events is reconstructed in the on-resonance dataset. Due to all of the decay products of the \( \Upsilon(4S) \) being correctly accounted for the double-tagged events reconstructed have a high purity.

To select double-tag events we require that the two tag \( B \) candidates do not share any tracks or neutrals. If there are more than two such non-overlapping tag \( B \) candidates in the event then the best candidates are selected as those with the largest \( D^0\ell \) vertex probability, as with the signal search. The number of double-tagged events \( (N_2) \) is given by

\[
N_2 = \varepsilon^2 N.
\]  

(9)

where \( N \) is the number of \( B\bar{B} \) events in the sample and \( \varepsilon \) is the tag efficiency that is compared between data and MC. Using the expression in equation 9 we calculate the efficiencies \( \varepsilon_{\text{data}} \) and \( \varepsilon_{\text{MC}} \). The correction factor, ratio of the efficiencies between data and simulation, from this method is given in equations 10, 11 and 12 for Runs 1–3, Run 4 and Run 5 respectively.

\[
\frac{\varepsilon_{\text{Runs 1–3}}}{\varepsilon_{\text{MC}}} = 1.05 \pm 0.02
\]  

(10)
It was directly verified that data taken during Runs 1–3 agreed in both shape and normalized yield whereas during Run 4 and Run 5 data were taken with the machine operating in a mode of continuous injection which may affect detector backgrounds differently. These runs are therefore considered separately.

The $E_{\text{extra}}$ for the double-tagged sample is calculated by summing the CM energy of the photons which are not associated with either of the tag $B$ candidates. The sources of neutrals contributing to the $E_{\text{extra}}$ distribution in double-tagged events are similar to those contributing to the $E_{\text{extra}}$ distribution in the signal MC simulation. Therefore the agreement of the $E_{\text{extra}}$ distribution between data and MC simulation for the double-tagged sample, in figure 2, is used as a validation of the $E_{\text{extra}}$ simulation in the signal MC.

\[ \frac{\epsilon_{\text{Run 4}}}{\epsilon_{\text{MC}}} = 1.00 \pm 0.03 \]  \hspace{1cm} (11)

\[ \frac{\epsilon_{\text{Run 5}}}{\epsilon_{\text{MC}}} = 0.97 \pm 0.03 \]  \hspace{1cm} (12)

Figure 2: The distribution of the remaining neutral energy ($E_{\text{extra}}$) for double-tagged events, plotted for generic MC and data: a) Runs 1-3, b) Run 4 and c) Run 5. No off-resonance data events are seen in the $E_{\text{extra}}$ region plotted here. In these events both of the $D^0 \ell$ candidates from double-tag are required to pass the selection described in section 3.1 and best candidate selection. The differences in these distributions are used for obtaining the systematic error for tagging efficiency correction.

The simulation is further validated by comparing a sample of events where the signal candidate and tag $B$ candidate are of the “wrong-sign” with non-zero net charge. The agreement between data and simulation for all signal modes for the background estimation in the $E_{\text{extra}}$ signal region provides a useful cross-check.

5 STUDIES OF SYSTEMATICS

The main sources of uncertainty in the determination of the $B^+ \rightarrow \tau^+ \nu_\tau$ branching fraction are the following:

- Uncertainty in tagging efficiency determination
- Uncertainty in determination of the efficiency $\epsilon_i$ for each selection mode.
- Uncertainty in the determination of the number of expected background events in the signal region for each selection mode.

A small uncertainty of 1.1% also enters the branching ratio limit calculation from the estimation of the number of $B^+B^-$ events present in the data sample [12]. The systematic uncertainties are summarized in table 5.
5.1 Tagging Efficiency Systematics

The tagging efficiency and yield in signal simulation is corrected using the double-tagged events. The selection of double-tagged events is described in section 4.

We take the 1.9%, 3.0% and 3.1% errors (from equations 10, 11 and 12) obtained from the double tag method as the systematic uncertainties associated with the tagging efficiency and yield correction in MC. The combined, luminosity weighted, tag B yield systematic uncertainty is 1.5%. The luminosity weighted tag B yield correction is 1.01.

5.2 $E_{\text{extra}}$ Systematic Uncertainty

The systematic uncertainty due to the mis-modeling of the $E_{\text{extra}}$ variable is extracted using the double-tagged events. The selection of double-tagged events is described in Section 4. A cut is imposed on the $E_{\text{extra}}$ distributions shown in Figures 2(a), 2(b) and 2(c) to extract the yield of candidates satisfying $E_{\text{extra}} < 0.5\text{GeV}$. This yield is then compared to the number of candidates in the full sample. Comparing the ratio extracted from MC to that extracted from data yields a correction factor, the error on which is taken as the systematic uncertainty for $E_{\text{extra}}$. These values are broken up by run and we extract the following numbers: Runs 1–3 = 0.98±0.06, Run 4 = 0.99±0.06, Run 5 = 1.02±0.08 The combined, luminosity weighted systematic uncertainty for $E_{\text{extra}}$ is 3.8%. The luminosity weighted $E_{\text{extra}}$ correction is 0.99.

5.3 Uncertainties in the signal selection efficiencies in each selection mode

Besides the tagging efficiency uncertainty, the contribution to the systematic uncertainties in the determination of the efficiencies comes from systematic uncertainty on the tracking efficiency, particle identification, and simulation of the neutral clusters in the calorimeter which contribute to the $E_{\text{extra}}$ distribution, and $K^0_L$ identification. The different contributions to the systematic uncertainty on the selection efficiencies are listed in table 5.

Table 5: Contribution to the systematic uncertainty on the signal selection efficiencies in different selection modes. These uncertainties are added together in quadrature with the uncertainty on the tag B yield, extracted from the double-tagged control sample, of 1.5%. The uncertainty on MC statistic is added in quadrature to obtain the total systematic uncertainty.

| Selection modes | tracking (%) | Particle Identification (%) | $K^0_L$ (\%) | $E_{\text{extra}}$ modeling (\%) | $\pi^0$ modeling (\%) | Total Systematic Error (\%) | Correction Factor |
|-----------------|--------------|----------------------------|--------------|-------------------------------|-----------------------|--------------------------|------------------|
| $e^+\nu_e\bar{\nu}_\tau$ | 0.3 | 2.0 | 3.6 | 3.8 | - | 5.8 | 0.982 |
| $\mu^+\nu_\mu\bar{\nu}_\tau$ | 0.3 | 3.0 | 3.6 | 3.8 | - | 6.2 | 0.893 |
| $\pi^+\bar{\nu}_\tau$ | 0.3 | 1.0 | 6.2 | 3.8 | - | 7.5 | 0.966 |
| $\pi^+\pi^0\bar{\nu}_\tau$ | 0.3 | 1.0 | 3.6 | 3.8 | 1.8 | 5.8 | 0.961 |

5.4 Uncertainties on $K^0_L$ modeling

The systematic uncertainty on the modeling of $K^0_L$ candidates is extracted using the double-tagged events outlined in section 4. A comparison between data and simulation is used to extract both a correction and
a systematic uncertainty, similarly to the method used for $E_{\text{extra}}$. We quantify this comparison by comparing the yield with a cut demanding exactly zero reconstructed IFR measured $K^0_L$ candidates remaining, with a sample where any number of $K^0_L$ candidates remain and take the ratio of ratios from the MC and data. We extract the following values for corrections and systematic uncertainties: Runs 1–3 = 0.98 ± 0.05, Run 4 = 1.00 ± 0.06, Run 5 = 0.98 ± 0.08, hence percentage uncertainties of 5.1%, 6.0% and 8.2%. The correction factors are all close to unity as expected. The combined, luminosity weighted systematic uncertainty for IFR $K^0_L$ candidates is 3.6%. The luminosity weighted IFR $K^0_L$ correction is 0.99.

The same exercise is performed for $K^0_L$ candidates reconstructed in the EMC. We extract the following values for corrections and systematic uncertainties: Runs 1–3 = 0.88 ± 0.05, Run 4 = 1.00 ± 0.10, Run 5 = 1.08 ± 0.11. Percentage uncertainties are 5.7%, 10% and 10.2%. The combined, luminosity weighted systematic uncertainty for EMC $K^0_L$ candidates is 5.1%. The luminosity weighted EMC $K^0_L$ correction is 0.97.

6 RESULTS

After finalizing the signal selection criteria, the signal region in the on-resonance data is examined. Table 6 lists 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. Figures 3 and 4 show the $E_{\text{extra}}$ distribution in data and simulation for each of the $\tau$ decay modes considered. Data is overlayed on the summed MC contribution, scaled to the dataset luminosity, and signal MC is plotted for comparison. Figure 5 shows the $E_{\text{extra}}$ distribution for all modes combined.

Figure 3: Total extra energy is plotted after all cuts have been applied in the mode (a) $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ and (b) $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$. Off-resonance data and MC have been normalized to the on-resonance luminosity. Simulated $B^+ \rightarrow \tau^+ \nu_\tau$ signal MC is plotted (lower) for comparison.
and also set an upper limit at the 90% confidence level of
(\text{similarly for \( \tau^- \)) of \( \tau \) decay modes calculated with respect to the total number of
reconstructed tag \( B \) mesons. Table 7 shows the values of \( N_{B\bar{B}}, \varepsilon_{\text{tag}} \) and \( \varepsilon_i \) after applying appropriate systematic corrections (see section 5). The
results from each decay mode are combined using the ratio \( Q = \mathcal{L}(s+b)/\mathcal{L}(b) \), where \( \mathcal{L}(s+b) \) and \( \mathcal{L}(b) \) are the likelihood functions for signal plus background and background-only hypotheses, respectively [13]:

\[
\mathcal{L}(s+b) = \prod_{i=1}^{n_{ch}} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{n_i}}{n_i!}, \quad \mathcal{L}(b) = \prod_{i=1}^{n_{ch}} \frac{e^{-b_i}b_i^{n_i}}{n_i!},
\]

We include the statistical and systematic uncertainties on the expected background \( (b_i) \) in the likelihood
definition by convolving it with a Gaussian distribution \( (G) \). The mean of \( G \) is \( b_i \), and the standard deviation
\( \sigma_{b_i} \) of \( G \) is the statistical and systematic errors on \( b_i \) added in quadrature [14],

\[
\mathcal{L}(s_i + b_i) \to \mathcal{L}(s_i + b_i) \otimes G(b_i, \sigma_{b_i})
\]

(similarly for \( \mathcal{L}(b_i) \)). The results from this procedure are illustrated in Figure 6.

We determine the following branching fraction

\[
B(B^+ \to \tau^+ \nu_\tau) = (0.88^{+0.68}_{-0.67} \text{(stat.)} \pm 0.11 \text{(syst.)}) \times 10^{-4},
\]

and also set an upper limit at the 90% confidence level of

\[
B(B^+ \to \tau^+ \nu_\tau) < 1.8 \times 10^{-4}.
\]
Figure 5: Total extra energy is plotted after all cuts have been applied with all modes combined. Off-resonance data and MC have been normalized to the on-resonance luminosity. Events in this distribution are required to pass all selection criteria. In addition the background MC have been scaled according to the ratio of predicted backgrounds from data and MC as presented in section 3.3. Simulated $B^+ \rightarrow \tau^+ \nu_\tau$ signal MC is plotted (lower) for comparison.

Figure 6 shows the distributions of confidence level vs branching fraction and the negative log likelihood curve illustrating the extracted upper limit and central value respectively.

Using the measured central value for $B(B^+ \rightarrow \tau^+ \nu_\tau)$ and taking the known values of $G_F, m_B, m_\tau$ and $\tau_B$ from Ref. [11] we calculate, from equation 1, the product of the $B$ meson decay constant and $|V_{ub}|$ to be $f_B \cdot |V_{ub}| = (7.0^{+2.3}_{-3.6}(\text{stat.})^{+0.4}_{-0.5}(\text{syst.})) \times 10^{-4}$ GeV.

7 SUMMARY

We have performed a search for the decay process $B^+ \rightarrow \tau^+ \nu_\tau$. To accomplish this a sample of semileptonic $B$ decays ($D^0 \ell^- \bar{\nu}_\ell X$) has been used to reconstruct one of the $B$ mesons and the remaining information in the event is searched for evidence of $B^+ \rightarrow \tau^+ \nu_\tau$. A branching fraction of

$$B(B^+ \rightarrow \tau^+ \nu_\tau) = (0.88^{+0.68}_{-0.67}(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4},$$

is measured and we set an upper limit at the 90% confidence level of

$$B(B^+ \rightarrow \tau^+ \nu_\tau) < 1.8 \times 10^{-4}. \quad (18)$$

Using the measured central value for $B(B^+ \rightarrow \tau^+ \nu_\tau)$ and taking the known values of $G_F, m_B, m_\tau$ and $\tau_B$ from Ref. [11] we calculate, from equation 1, the product of the $B$ meson decay constant and $|V_{ub}|$ to be $f_B \cdot |V_{ub}| = (7.0^{+2.3}_{-3.6}(\text{stat.})^{+0.4}_{-0.5}(\text{syst.})) \times 10^{-4}$ GeV.
Table 6: The observed number of on-resonance data events in the signal region are shown, together with number of expected background events. The background estimations include systematic corrections referred to in section 3.3.

| Selection                  | Expected Background Events | Observed Events in On-resonance Data |
|---------------------------|----------------------------|--------------------------------------|
| $e^+\nu_e\bar{\nu}_\tau$ | 41.9 ± 5.2                 | 51                                   |
| $\mu^+\nu_\mu\bar{\nu}_\tau$ | 35.4 ± 4.2                 | 36                                   |
| $\pi^+\bar{\nu}_\tau$     | 99.1 ± 9.1                 | 109                                  |
| $\pi^+\pi^0\bar{\nu}_\tau$ | 15.3 ± 3.5                 | 17                                   |
| All modes                 | 191.7 ± 11.8               | 213                                  |

Table 7: The corrected tag and signal efficiencies. Two errors are quoted: the first is the MC statistical uncertainty, and the second is the systematic error computed from the sources in section 5.

| Efficiency                  | Corrected                                              | Relative Systematic Error (%) |
|-----------------------------|--------------------------------------------------------|------------------------------|
| Tag                         | $(6.77 ± 0.05(\text{stat.}) ± 0.10(\text{syst.})) × 10^{-3}$ | 1.5                          |
| $\varepsilon(\tau^+ \to e^+\nu_e\bar{\nu}_\tau)$ | $(4.06 ± 0.09(\text{stat.}) ± 0.23(\text{syst.})) × 10^{-2}$ | 5.6                          |
| $\varepsilon(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau)$ | $(2.16 ± 0.06(\text{stat.}) ± 0.13(\text{syst.})) × 10^{-2}$ | 6.0                          |
| $\varepsilon(\tau^+ \to \pi^+\bar{\nu}_\tau)$     | $(4.88 ± 0.10(\text{stat.}) ± 0.35(\text{syst.})) × 10^{-2}$ | 7.3                          |
| $\varepsilon(\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau)$ | $(1.16 ± 0.05(\text{stat.}) ± 0.07(\text{syst.})) × 10^{-2}$ | 5.6                          |

Figure 6: The confidence level vs branching fraction is shown (left) to illustrate the extracted upper limit. The negative log likelihood curve (right) illustrates the central value and it’s corresponding uncertainty.
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