Measurement of $B^- \to \tau^- \nu_{\tau}$ with a Hadronic Tagging Method
Using the Full Data Sample of Belle

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In the absence of new physics, a measurement of the product of the $B$ and $\tau$ could significantly suppress or enhance the Standard Model (SM) and search for new physics. This is of great importance to improve the accuracy of the measurement, by increasing the luminosity and the detection efficiency. The Belle collaboration reported the first evidence of the purely leptonic decay $B^- \to \tau^- \bar{\nu}_\tau$ is of particular interest since it provides a unique opportunity to test the Standard Model (SM) and search for new physics beyond the SM. A recent SM estimation of the branching fraction based on a CKM fit is $0.733^{+0.121}_{-0.073} \times 10^{-4}$ [2]. In the absence of new physics, a measurement of $B^- \to \tau^- \bar{\nu}_\tau$ can provide a direct experimental determination of the product of the $B$ meson decay constant and the magnitude of the Cabibbo-Kobayashi-Maskawa matrix element $f_B |V_{ub}|$ [3]. Physics beyond the SM, however, could significantly suppress or enhance $B(B^- \to \tau^- \bar{\nu}_\tau)$ via exchange of a new charged particle such as a charged Higgs boson from supersymmetry or two-Higgs doublet models [4, 5].

Experimentally, it is challenging to detect the $B^- \to \tau^- \bar{\nu}_\tau$ decay because it involves more than one neutrino in the final state, and therefore cannot be kinematically constrained. At $e^+e^-$ $B$ factories, one can reconstruct one of the $B$ mesons in the $e^+e^- \to \Upsilon(4S) \to BB$ reaction, referred to hereafter as the tag side $(B_{\text{tag}})$, and in hadronic decays or semileptonic decays, one then compares the properties of the remaining particle(s), referred to as the signal side $(B_{\text{sig}})$, to those expected for signal and background. The method allows us to suppress strongly the combinatorial background from both $BB$ and continuum processes.

The Belle collaboration reported the first evidence of $B^- \to \tau^- \bar{\nu}_\tau$ with a measured branching fraction of $[1.79^{+0.56}_{-0.49} \text{(stat)}^{+0.46}_{-0.51} \text{(syst)}] \times 10^{-4}$, and a significance of 3.5 standard deviations including systematic uncertainty ($\sigma$), using hadronic tags on a $449 \times 10^6 BB$ data sample [8]. This was followed by measurements by Belle using the semileptonic tagging method [7], and also by the BaBar collaboration using both hadronic and semileptonic tagging methods. The four results are consistent, and their average branching fraction is found to be $(1.67 \pm 0.30) \times 10^{-4}$ [11], which is higher than the above SM prediction based on the CKM fit, although the significance of the deviation is less than $3\sigma$. Therefore, it is of great importance to improve the accuracy of the measurement, by increasing the luminosity and the detection efficiency.

In this paper, we present a new measurement of $B^- \to \tau^- \bar{\nu}_\tau$ using a hadronic tagging method and the full data sample of the Belle experiment. The analysis described here has a number of significant improvements. The major improvements are from an increased data sample (a factor of 1.7), significantly improved hadronic tagging efficiency (a factor of 2.2), and improved signal efficiency due to less restrictive selection requirements (a factor of 1.8). The combined effect of these improvements and the accompanying change in the signal to background ratio due to the looser selection criteria results in a reduction of the expected error by a factor of two. The new analysis has also improved systematic uncertainties.

We use a $711$ fb$^{-1}$ data sample containing $772 \times 10^6 BB$ pairs collected with the Belle detector [11] at the KEKB $e^+e^-$ collider operating at the $\Upsilon(4S)$ resonance [12]. Most of the data sample has been reprocessed using improved track finding and photon reconstruction. We use a dedicated Monte Carlo (MC) simulation based on GEANT [13] to determine the signal selection efficiency and study the background. In order to reproduce the effect of beam background, data taken with random triggers for each run period are overlaid on simulated events. The $B^- \to \tau^- \bar{\nu}_\tau$ signal MC events are generated by the
EVTGEN package with the radiative effects based on the PHOTOS code. To model the backgrounds from $e^+e^- \to BB$ and $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) processes, we use large MC samples corresponding to about 10 times and 6 times the luminosity of the data sample, respectively. We also use MC samples of rare $B$ decay processes containing charmless hadronic and leptonic decays and $b \to u$ semileptonic decays, where the sizes are expected to be about 50 times and 20 times the data sample, respectively.

The $B_{\text{tag}}$ candidates are reconstructed in 615 exclusive charged $B$ meson decay channels using an improved full-reconstruction algorithm. The output full reconstruction quality variable $N_{\text{tag}}$ ranges from zero for combinatorial background and continuum events to unity if an unambiguous $B_{\text{tag}}$ is obtained from the hierarchical neural network. We also use the energy difference $\Delta E = E_{\text{tag}} - E_{\text{CM}}/2$ and the beam-energy-constrained mass $M_{\text{bc}} = \sqrt{(E_{\text{CM}}/2)^2 - |\vec{p}_{\text{tag}}|^2}$, where $E_{\text{CM}}$ is the $e^+e^-$ center-of-mass (CM) energy, $E_{\text{tag}}$ and $\vec{p}_{\text{tag}}$ are the energy and the momentum, respectively, of the $B_{\text{tag}}$ candidate defined in the CM frame. Charged $B_{\text{tag}}$ candidates with $N_{\text{tag}} > 0.03$, $-0.08 \text{ GeV} < \Delta E < 0.06 \text{ GeV}$, and $5.27 \text{ GeV}/c^2 < M_{\text{bc}} < 5.29 \text{ GeV}/c^2$ are selected. Figure 1 shows a comparison of the $M_{\text{bc}}$ distributions for different data sets and tagging methods. The tag efficiency (0.24%) and the purity (65%) are improved by factors of 1.7 and 1.2, respectively, compared to Ref. [6]. The number of $B_{\text{tag}}$'s obtained for the full data set is $1.8 \times 10^6$. Note that in case of the $B^- \to \tau^- \bar{\nu}_\tau$ signal, in which the $BB$ event has lower than average particle multiplicity, the tag efficiency is 2.2 times higher than in Ref. [6] and is 0.31%.

In events where $B_{\text{tag}}$ candidates are reconstructed, we search for $B^- \to \tau^- \bar{\nu}_\tau$ decays. The $\tau^-$ lepton is identified in the $e^+\bar{\nu}_e\nu_e, \mu^+\bar{\nu}_\mu\nu_\mu, \pi^-\bar{\nu}_\pi\nu_\pi$, and $\pi^-\pi^0\nu_\tau$ decay channels. Candidate events are required to have one track with charge opposite to the $B_{\text{tag}}$ candidate. The charged tracks are required to satisfy $dz < 3 \text{ cm}$ and $dr < 0.5 \text{ cm}$, where $dz$ and $dr$ are unsigned impact parameters relative to the interaction point along the beam axis and the perpendicular plane, respectively. Charged tracks are classified as electron, muon, and pion candidates after rejecting kaon and proton candidates. Candidate $\tau^- \to \pi^-\pi^0\nu_\tau$ events are required to have one $\pi^0$ candidate reconstructed from $\pi^0 \to \gamma\gamma$ for which no daughter photons are used in the $B_{\text{tag}}$ reconstruction. The invariant mass of the $\pi^-\pi^0$ state is required to be within 0.15 GeV of the nominal $\rho$ mass. Multiple neutrons in the final states are distinguished using the missing mass squared variable $M^2_{\text{miss}} = (E_{\text{CM}} - E_{\text{tag}} - E_{B_{\text{tag}}})^2 - |\vec{p}_{B_{\text{tag}}} + \vec{p}_{\pi\pi}|^2$, where $E_{\text{tag}}$ and $\vec{p}_{\text{tag}}$ are the energy and the momentum, respectively, of the $B_{\text{tag}}$ candidate in the CM frame. To avoid potential backgrounds from $e^-\bar{\nu}_e, \mu^-\bar{\nu}_\mu, \pi^-K_L^0$, and $\rho^-K_L^0$, we require $M^2_{\text{miss}} > 0.7$ (GeV/c$^2$)$^2$.

After removing the particles from the $B_{\text{tag}}$ candidate and the charged tracks and $\pi^0$'s from the $B_{\text{sig}}$ candidate, there should be no other detected particles. We require that there are neither extra charged tracks with $dz < 75 \text{ cm}$ and $dr < 15 \text{ cm}$ nor extra $\pi^0$ candidates ("$\pi^0$ veto") nor $K_L^0$ candidates ("$K_L^0$ veto") [11]. We define the extra energy $E_{\text{ECL}}$, which is the sum of the energies of neutral clusters detected in the electromagnetic calorimeter that are not associated with either the $B_{\text{tag}}$ or the $\pi^0$ candidate from the $\tau^- \to \pi^-\pi^0\nu_\tau$ decay. The signal should have either zero or a small value of $E_{\text{ECL}}$, while background events have larger values due to the contributions from additional neutral clusters. For neutral clusters contributing to $E_{\text{ECL}}$, we require a minimum energy threshold of 50 MeV for the barrel and 100 (150) MeV for the forward (backward) end-cap calorimeter. A higher threshold is used for the end-cap calorimeter because the effect of beam background is more severe. We require $E_{\text{ECL}} < 1.2 \text{ GeV}$ as the correlation between $E_{\text{ECL}}$ and $M^2_{\text{miss}}$ is small for each background component in this region. The $B_{\text{sig}}$ reconstruction efficiency is improved by a factor of 1.8, compared to Ref. [6]. This improvement mainly comes from looser requirements on the track momentum, and from an improved $\pi^0$ veto, in which photons used in the $B_{\text{tag}}$ reconstruction are not used in the veto.

The signal detection efficiency is estimated based on MC samples after applying a correction for the $B_{\text{tag}}$ reconstruction efficiency. The correction factor is obtained...
by fitting the $M_{bc}$ distribution for an $E_{\text{ECL}}$ sideband sample defined by 0.4 GeV $<$ $E_{\text{ECL}}$ $<$ 1.2 GeV, for which the kinematics is expected to be similar to the signal. The resulting efficiencies are summarized in Table I. The validity of the efficiency estimation is checked by using a semileptonic decay sample in which $B_{\text{sig}}$ is reconstructed in the decay chain $B^- \rightarrow D^{*+}e^-\bar{\nu}_e$ ($\ell = e$ or $\mu$) followed by $D^{*+} \rightarrow D^0\pi^+$ and $D^0 \rightarrow K^-\pi^+$. The signal yield is extracted from a two-dimensional extended maximum likelihood fit to $E_{\text{ECL}}$ and $M^2_{\text{miss}}$. The likelihood is

$$L = \frac{e^{-\sum n_j} N!}{\prod_{i=1}^{N} n_j!} f_j(E_i, M^2_j),$$  

(1)

where $j$ is an index for the signal and background contributions, $n_j$ and $f_j$ are the yield and the probability density function (PDF), respectively, of the $j$th component, $E_i$ and $M^2_j$ are the $E_{\text{ECL}}$ and $M^2_{\text{miss}}$ values in the $i$th event, respectively, and $N$ is the total number of events in the data. We construct PDFs by taking products of one-dimensional histograms in $E_{\text{ECL}}$ and $M^2_{\text{miss}}$ obtained from MC, except for the contribution of cross-feed from other $B^- \rightarrow \tau^-\bar{\nu}_\tau$ decays in $B^- \rightarrow \tau^-\bar{\nu}_\tau$, $\tau^- \rightarrow \pi^-\nu_\tau$. The signal component in $\tau^- \rightarrow \pi^-\nu_\tau$ candidate events includes large cross-feed contributions from $\tau^- \rightarrow \ell^-\bar{\nu}_\ell\nu_\tau$ and $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ decays. A two-dimensional histogram PDF is used for the latter contribution to take into account the correlation originating from the misreconstructed $\pi^0$. The dominant background components are from $B\overline{B}$ decays to a final state with charm and continuum processes. The small background from charmless $B$ decays is also included in the fit. In the final sample with $E_{\text{ECL}} < 1.2$ GeV, the fractions of the background from $B$ to charm decays, continuum, and charmless $B$ decays are estimated from MC to be 89.8%, 0.5% and 9.7% for leptonic $\tau$ decays and 75.1%, 18.4% and 6.5% for hadronic $\tau$ decays.

Other $B$ decays from which only one charged particle is detected can make a peak near zero $E_{\text{ECL}}$ and mimic the signal. The dominant peaking decay modes are $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_\ell$ and $B^0 \rightarrow D^{*+}\ell^+\bar{\nu}_\ell$ where the $D$ decays semileptonically or to a final state with one or more $K_L$'s. Charmless $B$ decays such as $B^- \rightarrow \pi^0\ell^-\bar{\nu}_\ell$, $K^-\nu_\tau$, $K^0_L\pi^-$, $K^-\gamma$, and $\mu^-\bar{\nu}_\mu\gamma$ also contribute. The total fraction of these $B$ decay modes in the range $E_{\text{ECL}} < 0.2$ GeV is about 32% according to the MC simulation.

The simulation of the $E_{\text{ECL}}$ and $M^2_{\text{miss}}$ distributions in MC is validated using various control samples. The $E_{\text{ECL}}$ distribution for the $B^- \rightarrow \tau^-\bar{\nu}_\tau$ signal component is related to beam background and split-off showers originating from either $B_{\text{tag}}$ or $B_{\text{sig}}$ decay products. The contributions of these components in the signal MC sample are 0.04 GeV (16%), 0.12 GeV (50%), and 0.08 GeV (34%), respectively. The simulation of the $E_{\text{ECL}}$ distribution is checked with the $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_\ell$ sample, which has a final state similar to the $B^- \rightarrow \tau^-\bar{\nu}_\tau$ signal if the $D^{*0}$ decay products are removed. We also check the difference between the detector resolution in data and MC for $M^2_{\text{miss}}$ with the $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_\ell$ sample. We confirm that the $E_{\text{ECL}}$ distributions and $M^2_{\text{miss}}$ resolutions of data and MC are consistent for the $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_\ell$ sample. The background $E_{\text{ECL}}$ and $M^2_{\text{miss}}$ descriptions by MC are checked using sidebands in $M_{bc}$ and $E_{\text{ECL}}$, events with the $B_{\text{tag}}$ reconstructed in a $B^0$ mode and events with the same $B_{\text{sig}}$ charge as the $B_{\text{tag}}$. The $K^0_L$ detection efficiency that affects the estimation of the remaining peaking background component after the $K^0_L$ veto is calibrated using the $D^0 \rightarrow \phi K^0_L$ decay sample in data by comparing the yields of $\phi \rightarrow K^0_L \bar{K}^0_L$ and $\phi \rightarrow K^+K^-$ decays. We confirm the MC expectations for the $E_{\text{ECL}}$ and $M^2_{\text{miss}}$ shapes and verify that the normalization agrees with data after the calibrations of the $B_{\text{tag}}$ and $K^0_L$ reconstruction efficiencies.

In the final fit, five parameters are allowed to vary: the total signal yield and the sum of $B\overline{B}$ and continuum backgrounds for each $\tau^-\bar{\nu}_\tau$ decay mode. The ratio of the $B\overline{B}$ to the continuum background is fixed to the value obtained from MC after the $B_{\text{tag}}$ efficiency correction has been applied. Other background contributions are fixed to the MC expectation. We combine $\tau^-\bar{\nu}_\tau$ decay modes by constraining the ratios of the signal yields to the ratio of the reconstruction efficiencies obtained from MC including the branching fractions of $\tau^-\bar{\nu}_\tau$ decays.

Figure 2 shows the result of the fit to the $E_{\text{ECL}}$ and $M^2_{\text{miss}}$ distributions for all the $\tau^-\bar{\nu}_\tau$ decay modes combined. The signal yield is 62.2 $^{+23}_{-22}$ (stat) $\pm$ 6 (syst), where the first and second errors correspond to statistical and systematic uncertainties, respectively. The significance of the signal is estimated by $\sqrt{-2\ln(L_0/L_{\text{max}})}$, where $L_{\text{max}}$ and $L_0$ are the maximum likelihood and the likelihood obtained assuming zero signal yield, respectively. The likelihoods are obtained after convolving with a Gaussian distribution that corresponds to the systematic error. We obtain a significance of 3.0$\sigma$ including systematic uncertainties.

The branching fraction is calculated by $B = N_{\text{sig}}/(2cN_{B^+B^-})$, where $N_{\text{sig}}$ is the signal yield, $c$ is the efficiency, and $N_{B^+B^-}$ is the number of $B^+B^-$ events. Equal production of neutral and charged $B$ meson pairs in $\Upsilon(4S)$ decay is assumed. We obtain

$$B(B^- \rightarrow \tau^-\bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}.$$  

(2)
include the branching fractions of the $\tau$ decays. The uncertainties for the branching fractions of $B$ decays that peak near zero $E_{\text{ECL}}$ are estimated by changing the branching fractions in MC by their experimental errors if available, or by $\pm 50\%$ otherwise. To estimate the uncertainty associated with the $B_{\text{tag}}$ efficiency for the signal, $B(B^- \rightarrow D^{*0}\ell^-\bar{\nu}_{\ell})$ obtained from the $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_{\ell}$ sample is compared to the world average value. The results are consistent and the uncertainty of the measurement is assigned as the systematic error. The uncertainty for the fraction of the correctly reconstructed $B_{\text{tag}}$ in the background is obtained by changing the fractions by errors obtained from the $E_{\text{ECL}}$ sideband sample. The systematic errors in the signal-side efficiencies arise from the uncertainty in tracking efficiency, particle identification efficiency, branching fractions of $\tau$ decays, the reconstruction efficiency of $\pi^0$, and MC statistics. The systematic uncertainty related to the $K_L^0$ veto efficiency is estimated from the statistical uncertainties of the $D^0 \rightarrow \phi K_S^0$ control sample and the fraction of events with $K_L^0$ candidates in the $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_{\ell}$ sample. The estimated systematic errors are summarized in Table II.

### Table II: Summary of the systematic errors for the branching fraction measurement.

| Source               | $B$ syst. error (%) |
|----------------------|----------------------|
| Signal PDF           | 4.2                  |
| Background PDF       | 8.8                  |
| Peaking background   | 3.8                  |
| $B_{\text{tag}}$ efficiency | 7.1                  |
| Particle identification | 1.0                  |
| $\pi^0$ efficiency   | 0.5                  |
| Tracking efficiency  | 0.3                  |
| $\tau$ branching fraction | 0.6                  |
| MC efficiency statistics | 0.4                  |
| $K_L^0$ efficiency   | 7.3                  |
| $N_{B^+\rightarrow B^-}$ | 1.3                  |
| Total                | 14.7                 |

The branching fraction measured here is lower than the previous Belle result with a hadronic tagging method. Using the first sample of $449 \times 10^6 BB$ pairs, which corresponds to the data set used in Ref. 6 after reprocessing, we obtain $B(B^- \rightarrow \tau^-\bar{\nu}_\tau) = [1.08^{+0.37}_{-0.35}(\text{stat})] \times 10^{-4}$. Note that the overlap of events between the two analyses is small because the reconstruction efficiency has increased by more than a factor of three. Assuming that all the events used in the previous analysis over-

![Graph](image1)

**FIG. 2:** Distributions of $E_{\text{ECL}}$ (top) and $M^2_{\text{miss}}$ (bottom) combined for all the $\tau^-\rightarrow e^-\bar{\nu}_e\nu_e$ decays. The $M^2_{\text{miss}}$ distribution is shown for a signal region of $E_{\text{ECL}} < 0.2$ GeV. The solid circles with error bars are data. The solid histograms show the projections of the fits. The dashed and dotted histograms show the signal and background components, respectively.

### Table I: Results of the fit for signal yields ($N_{\text{sig}}$), detection efficiencies ($\epsilon$), and branching fractions ($B$). The efficiencies include the branching fractions of the $\tau^-\rightarrow e^-\bar{\nu}_e\nu_e$ decay modes. The errors for $N_{\text{sig}}$ and $B$ are statistical only.

| Decay mode       | $N_{\text{sig}}$ (10$^{-4}$) | $\epsilon$ (10$^{-4}$) | $B$ (10$^{-4}$) |
|------------------|------------------------------|------------------------|-----------------|
| $\tau^- \rightarrow e^-\bar{\nu}_e\nu_e$ | 16$^{+3}_{-1}$ | 3.0 | 0.68$^{+0.41}_{-0.39}$ |
| $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\mu$ | 26$^{+15}_{-14}$ | 3.1 | 1.06$^{+0.63}_{-0.58}$ |
| $\tau^- \rightarrow \pi^-\nu_\tau$ | 8$^{+10}_{-8}$ | 1.8 | 0.57$^{+0.29}_{-0.52}$ |
| $\tau^- \rightarrow \pi^0\bar{\nu}_\tau$ | 14$^{+19}_{-16}$ | 3.4 | 0.52$^{+0.33}_{-0.27}$ |
| Combined         | 62$^{+23}_{-22}$ | 11.2 | 0.72$^{+0.29}_{-0.25}$ |

Systematic errors for the measured branching fraction are associated with the uncertainties in the signal yield, the efficiencies, and the number of $B^+ B^-$ pairs. The systematic error from MC statistics of the PDF histograms is evaluated by varying the content of each bin by its statistical uncertainty. The ratio of data to MC for the $E_{\text{ECL}}$ histograms of the $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_{\ell}$ sample is fitted with a first-order polynomial and the signal $E_{\text{ECL}}$ PDF is modified within the fitted errors. The uncertainties for the branching fractions of $B$ decays are estimated by changing the branching fractions in MC by their experimental errors if available, or by $\pm 50\%$ otherwise.
lap with present analysis, the remaining events provide a result statistically consistent within $1.9\sigma$. Using the last $323 \times 10^6 \overline{B}\overline{B}$ pairs, we obtain $B(B^- \to \tau^- \bar{\nu}_\tau) = [0.24^{+0.39}_{-0.34}(\text{stat})] \times 10^{-4}$, which is statistically consistent with the result for the first $449 \times 10^6 \overline{B}\overline{B}$ data set within $1.6\sigma$. Our results are also consistent with other publications within the errors.\[7\]

In summary, we measure the branching fraction of the decay $B^- \to \tau^- \bar{\nu}_\tau$ with hadronic tagging using the final data sample containing $772 \times 10^6 \overline{B}\overline{B}$ pairs collected by the Belle experiment. We find evidence of $B^- \to \tau^- \bar{\nu}_\tau$ with a branching fraction of $[0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$, and a signal significance of $3.0\sigma$ including systematic uncertainties. By employing a neural network-based method for hadronic tagging and a two-dimensional fit for signal extraction, along with a larger data sample, both statistical and systematic precisions are significantly improved compared to the previous analysis\[8\]. The result presented in this paper supersedes the previous result reported in Ref.\[8\]. Combined with the Belle measurement based on a semileptonic $B$ tagging method\[8\], the branching fraction is found to be $B(B^- \to \tau^- \bar{\nu}_\tau) = [0.96 \pm 0.22(\text{stat}) \pm 0.13(\text{syst})] \times 10^{-4}$, with a $4.0\sigma$ signal significance including systematic uncertainties. The measured branching fraction is now consistent with the SM expectation obtained from other experimental constraints. Using this result and parameters found in Ref.\[17\], we obtain $f_B |V_{ub}| = [7.4 \pm 0.8(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-4} \text{ GeV}$. Our result provides stringent constraints on various models including charged Higgs bosons.

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[1] Charge-conjugate decays are implied throughout this paper unless otherwise stated.
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