Search for $B^- \to \tau^- \bar{\nu}$ at Belle

K. Abe, K. Abe, N. Abe, I. Adachi, H. Aihara, M. Akatsu, Y. Asano, T. Aso, V. Aulchenko, T. Aushev, T. Aziz, S. Bahinipati, A. M. Bakich, Y. Ban, M. Barbero, A. Bay, I. Bedny, U. Bitenc, I. Bizjak, S. Blyth, A. Bondar, A. Bozek, M. Bračko, J. Brodzicka, T. E. Brower, M.-C. Chang, P. Chang, Y. Chao, A. Chen, K.-F. Chen, W. T. Chen, B. G. Cheon, R. Chistov, S.-K. Choi, Y. Choi, Y. K. Choi, A. Chuvikov, S. Cole, M. Danilov, M. Dash, L. Y. Dong, R. Dowd, J. Dragic, A. Drutskoy, S. Eidelman, Y. Enari, D. Epifanov, C. W. Everton, F. Fang, S. Fratina, H. Fujii, N. Gabyshev, A. Garmash, T. Gershon, A. Go, G. Gokhroo, B. Golob, M. Grosse Perdekamp, H. Guler, J. Haba, F. Handa, K. Hara, T. Hara, N. C. Hastings, K. Hasuok, K. Hayasaka, H. Hayashii, M. Hazumi, E. M. Heenan, I. Higuchi, T. Higuchi, L. Hinz, T. Hojo, T. Hokuse, Y. Hoshi, K. Hoshina, S. Hou, W.-S. Hou, Y. B. Hsiung, H.-C. Huang, T. Igaki, Y. Igarashi, I. Iijima, K. Ikado, A. Imoto, K. Inami, A. Ishikawa, H. Ishino, K. Itoh, R. Itoh, M. Iwamoto, M. Iwasaki, Y. Iwasaki, R. Kagan, H. Kakuno, J. H. Kang, P. Kapusta, S. U. Kataoka, N. Katayama, H. Kawai, H. Kawai, Y. Kawakami, N. Kawamura, T. Kawashima, N. Kent, H. R. Khan, A. Kibayashi, H. Kichimi, H. J. Kim, H. O. Kim, Hyyunwoo Kim, J. H. Kim, S. K. Kim, T. H. Kim, K. Kinoshita, P. Koppenburg, S. Korpar, P. Križan, P. Krokovny, R. Kulasiri, C. C. Kuo, H. Kurashiro, E. Kurihara, A. Kusaka, A. Kuzmin, Y.-J. Kwon, S. S. Lange, G. Leder, E. Lee, S. H. Lee, Y.-J. Lee, T. Lesiak, J. Li, A. Limosani, S.-W. Lin, D. Liventsev, J. MacNaughton, G. Majumder, F. Mandl, D. Marlow, T. Matsuishi, H. Matsumoto, S. Matsumoto, T. Matsumoto, A. Matyja, Y. Mikami, W. Mitaroff, K. Miyabayashi, Y. Miyabayashi, H. Miyake, H. Miyata, R. Mizuk, D. Mohapatra, G. R. Moloney, G. F. Moorhead, T. Mori, A. Murakami, T. Nagamine, Y. Nagasaka, T. Nakadaira, Y. Nakamura, E. Nakano, M. Nakao, H. Nakazawa, Z. Natkaniec, K. Neichi, S. Nishida, N. Nitoh, S. Noguchi, T. Nozaki, O. Ogawa, S. Ogawa, T. Ohshima, T. Okabe, S. Okuno, S. L. Olsen, Y. Onuki, W. Ostrowicz, H. Ozaki, P. Pakhlov, H. Palka, C. W. Park, H. Park, K. S. Park, N. Parslov, L. S. Peak, M. Pernicka, J.-P. Perroud, M. Peters, L. E. Piilonen, A. Poluektov, F. J. Ronga, N. Root, M. Rozanska, H. Sagawa, M. Saigo, S. Saitoh, Y. Sakai, H. Sakamoto, T. R. Sarangi, M. Satapathy, N. Sato, O. Schneider, J. Schümann, C. Schwanda, A. J. Schwartz, T. Seki, S. Seimenov, K. Senyo, Y. Settai, R. Seuster, M. E. Sevior, T. Shibata, H. Shibuya, B. Shwartz, V. Sidorov, V. Siegel, J. B. Singh, A. Somov, N. Soni, R. Stamen, S. Stanić, M. Starić, A. Sugi, A. Sugiyama, K. Sumisawa, T. Sumiyoshi, S. Suzuki, Y. Suzuki, O. Tajima, F. Takasaki, K. Tanai, N. Tamura, K. Tanabe, M. Tanaka, G. N. Taylor, Y. Teramoto, X. C. Tian, S. Tokuda, S. N. Tovey, K. Trabelsi, T. Tsuboyama.
T. Tsukamoto,10 K. Uchida,9 S. Uehara,10 T. Uglov,14 K. Ueno,29 Y. Unno,3 S. Uno,10
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L. M. Zhang,40 Z. P. Zhang,40 V. Zhilich,2 T. Ziegler,37 D. Žontar,21,15 and D. Zürcher20

(The Belle Collaboration)

1 Aomori University, Aomori
2 Budker Institute of Nuclear Physics, Novosibirsk
3 Chiba University, Chiba
4 Chonnam National University, Kwangju
5 Chuo University, Tokyo
6 University of Cincinnati, Cincinnati, Ohio 45221
7 University of Frankfurt, Frankfurt
8 Gyeongsang National University, Chinju
9 University of Hawaii, Honolulu, Hawaii 96822
10 High Energy Accelerator Research Organization (KEK), Tsukuba
11 Hiroshima Institute of Technology, Hiroshima
12 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
13 Institute of High Energy Physics, Vienna
14 Institute for Theoretical and Experimental Physics, Moscow
15 J. Stefan Institute, Ljubljana
16 Kanagawa University, Yokohama
17 Korea University, Seoul
18 Kyoto University, Kyoto
19 Kyungpook National University, Taegu
20 Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne
21 University of Ljubljana, Ljubljana
22 University of Maribor, Maribor
23 University of Melbourne, Victoria
24 Nagoya University, Nagoya
25 Nara Women’s University, Nara
26 National Central University, Chung-li
27 National Kaohsiung Normal University, Kaohsiung
28 National United University, Miao Li
29 Department of Physics, National Taiwan University, Taipei
30 H. Niewodniczanski Institute of Nuclear Physics, Krakow
31 Nihon Dental College, Niigata
32 Niigata University, Niigata
33 Osaka City University, Osaka
34 Osaka University, Osaka
35 Panjab University, Chandigarh
36 Peking University, Beijing
37 Princeton University, Princeton, New Jersey 08545
Abstract

We present a search for the decay $B^- \rightarrow \tau^- \bar{\nu}$ in a 140 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $B$ factory. Combinatorial and continuum backgrounds are suppressed by selecting a sample of events with one fully reconstructed $B$. The decay products of the other side $B$ in the event are analyzed to search for a $B^- \rightarrow \tau^- \bar{\nu}$ decay. We find no significant evidence for a signal and set a 90% confidence level upper limit of $Br(B^- \rightarrow \tau^- \bar{\nu}) < 2.9 \times 10^{-4}$. All results are preliminary.

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The purely leptonic decay $B^- \to \ell^- \tau$ is of particular interest since it provides direct measurement of the product of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{ub}$ and the $B$ meson form factor $f_B$. In the Standard Model (SM), the branching fraction of the decay $B^- \to \ell^- \tau$ is given as

$$
Br(B^- \to \ell^- \tau) = \frac{G_F^2 m_B m_\ell^2}{8 \pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B
$$

where $G_F$ is the Fermi coupling constant, $m_\ell$ and $m_B$ are the charged lepton and $B$ meson masses, $\tau_B$ is the $B^-$ lifetime. The dependence of the lepton mass arises from helicity conservation and helicity suppresses the muon and electron channels.

In the extension of the Standard Model, one expects significant modification to the $B^- \to \tau^- \bar{\nu}$ decay branching fraction. In the two-Higgs doublet model, the decay can occur via a charged Higgs particle. The $B^- \to \tau^- \bar{\nu}$ branching fraction is given as

$$
Br(B^- \to \tau^- \bar{\nu}) = \frac{G_F^2 m_B m_\ell^2}{8 \pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \times r_H,
$$

where $r_H$ is defined as

$$
r_H = \left(1 - \frac{\tan^2 \beta m_\ell^2}{1 + \tan^2 \beta m_H^2}\right)^2
$$

and $\tan \beta$ is the ratio of vacuum expectation values of two Higgs doublets $H^+$ and $H^-$. Once we get an upper limit on $Br(B^- \to \tau^- \bar{\nu})$, we can give a constraint on $\tan \beta$ and $m_H$. Similarly, in $R$-parity violating extensions of the MSSM, $B^- \to \tau^- \bar{\nu}$ may be mediated by scalar supersymmetric particles. Hence, upper limits on the $B^- \to \tau^- \bar{\nu}$ branching fraction constrain $R$-parity violating couplings.

No evidence for an enhancement relative to the Standard Model prediction was observed in previous experimental studies by CLEO [3, 4], ALEPH [5], L3 [6], DELPHI [7] and BABAR [8]. The most stringent upper limit has been achieved by the BABAR Collaboration: $Br(B^- \to \tau^- \bar{\nu}) < 4.2 \times 10^{-4}$ at 90% C.L. from a sample of fully reconstructed $B$ and semi-leptonic decays.

We use a 140 fb$^{-1}$ data sample containing $152.0 \times 10^6$ $B$ meson pairs collected with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider operating at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV). The Belle detector is a large-solid-angle magnetic spectrometer consisting of a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), a system of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to identify $K_L^0$ and muons. The detector is described in detail elsewhere [10].

Fully reconstructed $B$ mesons, $B_{rec}$, are observed in the following decay modes: $B^+ \to \bar{D}^{(*)0} \pi^+$, $\bar{D}^{(*)0} \rho^+$, $\bar{D}^{(*)0} a_1^+$ and $\bar{D}^{(*)0} D_s^{(*)+}$. $D^0$ candidates are reconstructed as $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K^0_{\pi}\pi^0$, $K^0_{\pi}\pi^-\pi^+$, $K^0_{\pi}\pi^-\pi^+$ and $K^-K^+$. $\bar{D}^0$ mesons are reconstructed by combining the $\bar{D}^0$ candidates with a pion or a photon. $D_s^+$ candidates are reconstructed in the decay modes $D_s^+ \to K^0_s K^+$ and $K^+ K^- \pi^+$, and $D_s^{(*)+}$ mesons are reconstructed by combining the $D_s^+$ candidates with a photon. All the tracks and photon candidates in the event not used to reconstruct the $B_{rec}$ are studied to search for $B^- \to \tau^- \bar{\nu}$. The advantage
of having a sample of fully reconstructed $B$ meson is to provide a strong suppression of the combinatorial and continuum background events. The disadvantage is the low efficiency of full $B$ meson reconstruction (about 0.3%). Charged $B$ pair events are generated from $\Upsilon(4s)$ resonance ($\sqrt{s} \sim 10.58 \text{ GeV}$), where the $B^+$ or $B^-$ is generated with specific momentum and energy. Selection of the fully reconstructed $B$ candidates is made according to the values of two variables: the beam constraint mass $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$ and the energy difference $\Delta E \equiv E_B - E_{\text{beam}}$. Here, $E_B$ and $p_B$ are the reconstructed energy and momentum of the fully reconstructed $B$ candidate in the center-of-mass (CM) system, and $E_{\text{beam}}$ is the beam energy in the CM frame.

The $M_{bc}$ distribution of reconstructed $B$ candidates is fit with the sum of an Argus function [11] and a Crystal Ball function [12]. The Argus function models the continuum and combinatorial background whereas the Crystal Ball function models the signal component, which peaks at the $B$ mass. The purity is defined as $S/(S + B)$, where $S$ ($B$) is the number of signal (background) events for $M_{bc} > 5.27 \text{ GeV}/c^2$, as determined from a fit. Figure 1 shows the $M_{bc}$ distribution for all $B_{\text{rec}}$ candidates in our data set. The yield $N_{B^+B^-}$ of the sample containing one $B_{\text{rec}}$ is determined as the area of the fitted Crystal Ball function. We obtain $N_{B^+B^-} = (2.40 \pm 0.15) \times 10^5$ and 0.57 of the purity, where the uncertainty on $N_{B^+B^-}$ is dominated by systematic errors. We define the $B_{\text{rec}}$ signal region to be $-0.08 < \Delta E < 0.06 \text{ GeV}$ and $M_{bc} > 5.27 \text{ GeV}/c^2$. In order to avoid experimenter bias, the signal region in data is blinded until the selection criteria are finalized.

Once a reconstructed $B$ candidate has been identified, $B^- \rightarrow \tau^- \nu$ signal candidates are selected by considering all tracks and clusters in the event which are not used in the fully reconstructed $B$. Candidate events are required to have one or three signal-side charged track(s) with the total charge which is opposite that of the reconstructed $B$. In the events where a $B_{\text{rec}}$ is reconstructed, we search for decays into a $\tau$ plus a neutrino. The $\tau$ lepton is identified in the following decay channels: $\tau^- \rightarrow \mu^- \nu \bar{\nu}$, $\tau^- \rightarrow e^- \nu \bar{\nu}$, $\tau^- \rightarrow \pi^- \nu$, $\tau^- \rightarrow \pi^- \pi^0 \nu$, and $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu$.

We require the charged particles to be identified as leptons or pions. For the lepton and

FIG. 1: Distribution of the beam energy constrained mass in data for fully reconstructed $B$ mesons (histogram). The solid curve shows the result of the fit and the background components as the dotted curve.
single-pion modes we reject events with $\pi^0$ mesons in the recoil against $B_{rec}$. The event is required to have zero charge and $E_{ECL}$ less than a certain value ($E_{ECL} < 1.0$ GeV for $\tau^- \to \mu^-\nu\bar{\nu}$ and $e^-\nu\bar{\nu}$, $E_{ECL} < 1.2$ GeV for $\tau^- \to \pi^-\nu$ and $\pi^-\pi^+\pi^-\nu$ and $E_{ECL} < 2.2$ GeV for $\tau^- \to \pi^-\pi^0\nu$) where $E_{ECL}$ is defined as $E_{ECL} = E_{tot} - E_{Br} - E_{track}$, the energy deposition in the ECL calorimeter. An additional requirement $E_{\tau^0}/E_{ECL} > 0.2$ is applied for $\tau^- \to \pi^-\pi^0\nu$. Further requirements are made on the total momentum of the track(s) in the CM frame ($p_\pi > 1.0$ GeV/c for $\tau^- \to \pi^-\nu$, $p_{\pi^-\pi^+\pi^-} > 1.2$ GeV/c for $\tau^- \to \pi^-\pi^+\pi^-\nu$), the total missing momentum of the event ($P > 1.0$ GeV/c for $\tau^- \to \pi^-\nu$ and $\pi^-\pi^0\nu$, $P > 1.2$ GeV/c for $\tau^- \to \pi^-\pi^+\pi^-\nu$) and the invariant mass of two or three pions $0.55 < m_{\pi\pi} < 0.95$ GeV/c$^2$ and $1.0 < m_{\pi\pi\pi} < 1.4$ GeV/c$^2$. The selection efficiencies for the $\tau$ decay channels we consider in this analysis are determined from Monte Carlo simulations of $B^- \to \tau^-\bar{\nu}$ events. We compute the efficiency as the ratio of the number of events surviving each of our selections over the number of fully reconstructed $B$.

The expected background is composed of events from continuum and combinatorial background, along with fully reconstructed $B$ meson events. Backgrounds consists primarily of $B^+B^-$ events in which the fully reconstructed $B$ has been correctly reconstructed. This “peaking” background is directly determined from Monte Carlo simulations of $B^+B^-$ events. The continuum and combinatorial background is determined from the number of events in $M_{bc}$ sideband data, scaled by the ratio of the areas of the fitted Argus function in the signal and sideband regions. We fit $M_{bc}$ distributions after preselection and assume the ratio of the fitted Argus is unchanged after all selection criteria have been applied. This assumption is consistent with the observed distributions in the Monte Carlo as well as the data in $\Delta E$ sideband.

The main sources of uncertainty we consider in the determination of the $Br(B^- \to \tau^-\pi)$ are uncertainty in the number of $B^+B^-$ events with one reconstructed $B$, uncertainty in the determination of the signal efficiency and uncertainty in the determination of the number of expected background events. The number of $B^+B^-$ events is determined as the area of the Crystal Ball function fitted to the $M_{bc}$ distribution. Using a Gaussian function as an alternative fitting function, we obtain a relative change in the number of events and this difference is assigned as the systematic uncertainty on the number of $B^+B^-$ events. A systematic error due to uncertainty in the amount of neutral $B$ background in the number of $B^+B^-$ is also considered. The main contribution to the systematic uncertainties in the determination of the efficiencies come from uncertainty on tracking efficiency, Monte Carlo statistics, $E_{ECL}$ energy and particle identification. The uncertainty in the expected background comes from Monte Carlo statistics, $E_{ECL}$ energy uncertainty and use of the Argus fit function.

Figure 2 shows the $E_{ECL}$ distributions in the data after all selection requirements except the one on $E_{ECL}$ have been applied compared with the expected background. Each distribution refers to a different selections and the plots show no evidence of signal in data. We find a total of 28 candidates in the signal region where $33.5 \pm 5.0$ background events are expected. This uncertainty in the background expectation is due to both statistical and systematic errors.

In order to extract the upper limit on the branching fraction for $B^- \to \tau^-\pi$, we combine the results of the different selections. We use the likelihood ratio estimator, $Q$. Here, $Q$ is defined as $\mathcal{L}(s+b)/\mathcal{L}(b)$, where $\mathcal{L}(s+b)$ and $\mathcal{L}(b)$ are the likelihood functions for signal plus background and background only hypotheses, respectively. The likelihood functions $\mathcal{L}(s+b)$
FIG. 2: $E_{ECL}$ distributions in the data after all selection requirements except the one on $E_{ECL}$ have been applied. The vertical arrow is the requirement on the $E_{ECL}$ in each selection.

and $\mathcal{L}(b)$ are defined as

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

where $n_{ch}$ is the number of selection channels, $s_i$ and $b_i$ are the expected number of signal and background events, respectively, and $n_i$ is the number of observed events in each channel. The number of signal events $s_i$ can be written as $s_i = \varepsilon_i \cdot N_{B^+B^-} \cdot Br(B^- \rightarrow \tau^-\nu)$, where $\varepsilon_i$ is the selection efficiency for the $i$-th channel and $N_{B^+B^-}$ is the number of $B^+B^-$ events with one reconstructed $B_{rec}$. We set a 90% C.L. upper limit using a simple Monte Carlo generating random experiments for different values of the branching fraction $Br(B^- \rightarrow \tau^-\nu)$. The confidence level for the signal hypothesis can be written as

$$
CL_s = \frac{C_{L_{s+b}}}{C_{L_b}} = \frac{N_{Q_{s+b\leq Q}}}{N_{Q_{b\leq Q}}}
$$

where $N_{Q_{s+b\leq Q}}$ and $N_{Q_{b\leq Q}}$ are the number of the generated experiments which have a likelihood ratio less than or equal to the measured one, in the signal plus background hypothesis and background only hypothesis, respectively. The 90% C.L. upper limit is obtained for $CL_s = 1 - 0.9$, where Gaussian systematic uncertainties are incorporated. This “Modified Frequentist approach” or “CLs method” method is described in detail in reference [13].
Figure 3 shows the confidence level for the signal hypothesis $CL_s$ as a function of $Br(B^- \to \tau^- \nu)$ obtained from the likelihood approach. The solid curves are the observed results, the dashed curves the expected. The shaded areas represent the symmetric $1\sigma$ and $2\sigma$ bands. The intersections of the curves with the horizontal line at $CL_s = 0.1$ give the limits on $Br(B^- \to \tau^- \nu)$ at the 90% confidence level.

Table I shows the branching fraction times efficiency for signal, expected background, observed events and upper limit on the branching fraction for each $\tau$ decay mode. We obtain a combined limit on the branching fraction of

$$Br(B^- \to \tau^- \nu) < 2.9 \times 10^{-4} \text{ at the 90% C.L.} \quad (6)$$

In the two-Higgs doublet model, the branching fraction $Br(B^- \to \tau^- \nu)$ is enhanced by a factor of $[1 - (m_B/m_{H^\pm})^2 \tan^2 \beta]^2$ for $\tilde{\epsilon}_0 = 0$ in equation (3). With $m_B = 5279$ MeV/c$^2$ and $Br(B^- \to \tau^- \nu) = 7.5 \times 10^{-4}$ from the Standard Model prediction, we set the constraint

$$\frac{\tan \beta}{M_{H^\pm}} < 0.33 \text{ (GeV/c}^2\text{)}^{-1} \quad (7)$$

from the obtained limits on the branching fraction of $B^- \to \tau^- \nu$. Figure 4 shows the 90% C.L. exclusion boundaries in the $[M_{H^\pm}, \tan \beta]$ plane obtained from (7) compared with other experimental searches at LEP\cite{14} and at the Tevatron\cite{15}. The direct search for charged Higgs bosons at LEP gives the constraint $M_{H^\pm} > 78.6$ GeV/c$^2$. Figure 5 shows the summary of searches for $B^- \to \tau^- \nu$ and upper limits obtained by other experiments compared with
TABLE I: Branching fraction times efficiency for signal, expected background, observed events and upper limit on the branching fraction for each $\tau$ decay mode. The uncertainties on the efficiencies and the expected background are due to the combination of limited statistics and systematic errors.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{\tau Decay Mode} & \text{Efficiency} \times BR(\%) & \text{Background Expected} & \text{Observed Events} & \text{Observed limit (90\% C.L.)} \\
\hline
\tau^- \to \mu^- \nu \bar{\nu} & 9.2 \pm 1.5 & 9.8 \pm 2.9 & 6 & 3.0 \times 10^{-4} \\
\tau^- \to e^- \nu \bar{\nu} & 8.8 \pm 1.5 & 9.4 \pm 2.9 & 10 & 4.6 \times 10^{-4} \\
\tau^- \to \pi^- \nu \bar{\nu} & 4.1 \pm 0.4 & 5.4 \pm 2.1 & 6 & 7.2 \times 10^{-4} \\
\tau^- \to \pi^- \pi^0 \nu & 1.8 \pm 0.2 & 4.1 \pm 1.6 & 3 & 10.5 \times 10^{-4} \\
\tau^- \to \pi^+ \pi^- \pi^+ \nu & 1.6 \pm 0.2 & 4.8 \pm 1.6 & 3 & 11.7 \times 10^{-4} \\
\hline
\text{Combined} & & & & 2.9 \times 10^{-4} \\
\hline
\end{array}
\]

In conclusion, we have performed a search for the $B^- \to \tau^- \nu$ decay in a fully reconstructed $B$ sample. The analysis uses the following $\tau$ decay channels: $\tau^- \to \mu^- \nu \bar{\nu}$, $\tau^- \to e^- \nu \bar{\nu}$, $\tau^- \to \pi^- \nu$, $\tau^- \to \pi^- \pi^0 \nu$, and $\tau^- \to \pi^- \pi^+ \pi^- \nu$. The results of the search in the different channels have been combined. No signal is observed and an upper limit has been set:

\[
Br(B^- \to \tau^- \nu) < 2.9 \times 10^{-4} \ (90\% \ C.L.),
\]

which represents the most stringent upper limit on this process to date.

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* on leave from Nova Gorica Polytechnic, Nova Gorica

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FIG. 4: The 90% C.L. exclusion boundaries in the $[M_{H^+}, \tan \beta]$ plane obtained from the observed upper limit on $Br(B^- \rightarrow \tau^- \nu)$.

FIG. 5: Summary of searches for $B^- \rightarrow \tau^- \nu$ and upper limits compared with the corresponding SM prediction and the branching fraction predicted with the charged Higgs boson in two parameter sets.

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