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$B \to \tau\nu$ and related results

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Leptonic decay $B \to \tau\nu$ and related leptonic $B \to \ell\nu$, $\ell = e, \mu$ and semileptonic $B \to D^{(*)}\tau\nu$ decays provide opportunities for testing the Standard Model and for searching for new physics, *e.g.* extended models including the charged Higgs bosons. In this report, recent results obtained at the *B*-factories are reviewed. The comparison between the experimental results and the Standard Model predictions is shown. The constraints on the Type II two Higgs doublet model are reported.

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1. Introduction

The purely leptonic decay $B \to \tau\nu$ is of high interest since it provides a unique opportunity to test the Standard Model (SM) and search for new physics beyond the SM. In the absence of new physics, this measurement provides a direct experimental determination of the product of the B meson decay constant and the CKM matrix element $f_B|V_{ub}|$. Physics beyond the SM, however, could significantly suppress or enhance $\mathscr{B}(B \to \tau\nu)$ via exchange of a new charged particle, *e.g.* a charged Higgs boson from two-Higgs doublet models (2HDM) [1, 2]. Leptonic $B \to \ell\nu$, $\ell = e, \mu$ and semileptonic $B \to D^{(*)}\tau\nu$ decays are also sensitive to such exchange [3]. In this report, recent results obtained at the B-factories are reviewed. The comparison between the experimental results and the SM predictions is shown. The constraints on the Type II 2HDM are reported.

2. $B \to \tau\nu$

It is challenging to identify the $B \to \tau\nu$ decay experimentally, since it includes multiple neutrinos in the final state. At the e^+e^- B-factories a B meson pair is generated from the process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ and we can reconstruct one of the B mesons ("$B_{\rm tag}$") to identify the decay of the other B meson ("$B_{\rm sig}$"). Two independent types of the B meson decays may be used for reconstruction of $B_{\rm tag}$: hadronic decays such as $B^- \to D^0\pi^-$ ("hadronic tag") and semileptonic decays such as $B^- \to D^0\ell^-\nu$, $\ell = e, \mu$ ("semileptonic tag"). The efficiency for reconstructing $B_{\rm tag}$ is higher for the semileptonic tag, while the purity is higher for the hadronic tag.

The first evidence for $B \to \tau\nu$ was reported by the Belle collaboration using hadronic tag and a data sample corresponding to 449×10^6 $B\bar{B}$ events [4]. This was followed by a measurement using semileptonic tag and a data sample corresponding to 657×10^6 $B\bar{B}$ events [5]. The branching ratio obtained by the semileptonic tag analysis is $\mathscr{B}(B \to \tau\nu) = [1.54^{+0.38}_{-0.37}(stat)^{+0.29}_{-0.31}(syst)] \times 10^{-4}$, with a significance of 3.6σ. The hadronic tag result has been updated using Belle final data sample corresponding to 772×10^6 $B\bar{B}$ events [6]. By employing a neural network-based method for the hadronic tag [7] and a two-dimensional fit for the signal extraction, along with a larger data sample, both statistical and systematic precision is significantly improved. The branching ratio is obtained to be $\mathscr{B}(B \to \tau\nu) = [0.72^{+0.27}_{-0.25}(stat) \pm 0.11(syst)] \times 10^{-4}$, with significance of 3.0σ. Results of the fit are shown in Fig. 1. Combining the semileptonic tag and hadronic tag results and taking into account all the correlated systematic uncertainties, the branching ratio is found to be $\mathscr{B}(B \to \tau\nu) = (0.96 \pm 0.26) \times 10^{-4}$ with a significance of 4.0σ [6].

The BaBar collaboration also reported the results of $B \to \tau\nu$ using hadronic and semileptonic tags. Using semileptonic tag and a data sample corresponding to 459×10^6 $B\bar{B}$ events, the branching ratio is obtained to be $\mathscr{B}(B \to \tau\nu) = [1.7 \pm 0.8(stat) \pm 0.2(syst)] \times 10^{-4}$ [8]. An evidence for $B \to \tau\nu$ is obtained with a significance of 3.8σ using hadronic tag and a data sample corresponding to 468×10^6 $B\bar{B}$ events [9]. The branching ratio is obtained to be $\mathscr{B}(B \to \tau\nu) = [1.83^{+0.53}_{-0.49}(stat) \pm 0.24(syst)] \times 10^{-4}$. Combining the two results, the branching ratio is found to be $\mathscr{B}(B \to \tau\nu) = (1.79 \pm 0.48) \times 10^{-4}$, where both statistical and systematic errors are combined in quadrature [9].

A world average for $B \to \tau\nu$ branching ratio is calculated to be $\mathscr{B}(B \to \tau\nu)_{WA} = (1.15 \pm 0.23) \times 10^{-4}$. For this calculation, the correlation in the systematic errors between the Belle and

BaBar results was neglected since the statistical errors are dominant and the correlated parts in the systematic errors are relatively small. In the SM an estimate of $\mathscr{B}(B \to \tau\nu)_{SM} = (0.73^{+0.12}_{-0.07}) \times 10^{-4}$ is obtained by using f_B and $|V_{ub}|$ provided by a global fit to the CKM matrix elements [10]. The deviation is found to be 1.6σ.

In the Type II 2HDM [1], the branching ratio of $B \to \tau\nu$ is described by $\mathscr{B}(B \to \tau\nu) = \mathscr{B}(B \to \tau\nu)_{SM} \times r_H$, where $\mathscr{B}(B \to \tau\nu)_{SM}$ is the SM value of the branching ratio, r_H is a modification factor $r_H = (1 - \tan^2\beta\, m^2_{B^\pm}/m_{H^\pm}{}^2)^2$, $m_{B^\pm}$ is the charged B meson mass, $m_{H^\pm}$ is the charged Higgs mass and $\tan\beta$ is the ratio of the two Higgs bosons vacuum expectation values. Conservatively using $f_B = (191 \pm 9)\,\mathrm{MeV}$ from the lattice calculation provided by the HPQCD collaboration [11] and $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ from the $b \to u$ transitions provided by the PDG group [12], we evaluate excluded regions in the $\tan\beta - m_{H^\pm}$ plane as shown in Fig. 4 (left). Stringent constraint is obtained for relatively higher $\tan\beta$ region.

3. $B \to \ell\nu$

In Type 2 II 2HDM branching ratios of all leptonic B decays are modified by the same factor r_H and it is interesting to measure $B \to \ell\nu$ decays in addition to $B \to \tau\nu$ decay. The highly suppressed $B \to \ell\nu$, $\ell = e, \mu$ final states are predicted to have SM branching fractions of $\mathscr{O}(10^{-11})$ and $\mathscr{O}(10^{-7})$ for $\ell = e$ and $\ell = \mu$, respectively. As these decays are two-body decays, the charged lepton momentum in the rest frame of the decaying $B_{\rm sig}$ is $p^B_\ell \simeq m_B/2$. This gives a unique signature which can be exploited in this analysis because the $B_{\rm sig}$ rest frame is known from the hadronic tagging. Most backgrounds are not expected to produce high momentum leptons that can reach the signal region, defined as $2.6\,\mathrm{GeV}/c < p^B_\ell < 2.7\,\mathrm{GeV}/c$. In the analysis using full Belle data sample of 772×10^6 $B\bar{B}$ events no events are observed in the signal region, as shown in Fig. 2, and 90% C.L. upper limits on the branching fractions are determined: $\mathscr{B}(B \to e\nu) < 3.5 \times 10^{-6}$ and $\mathscr{B}(B \to \mu\nu) < 2.5 \times 10^{-6}$ [13]. These are the most stringent limits on $B \to \ell\nu$ decays using a hadronic tag method. Previous results from Belle and BaBar using a loose tagging method (*i.e.*

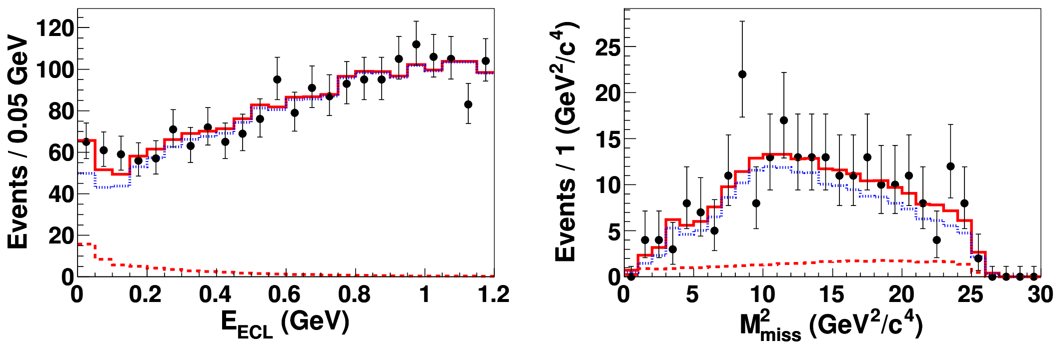

Figure 1: Signal extraction for $B \to \tau\nu$ in the latest Belle analysis [6]. Two-dimensional fit to residual energy E_{ECL} (left) and missing mass squared M_{miss} (right) is used. M_{miss} distribution is shown for a signal region of $E_{ECL} < 0.2\,\mathrm{GeV}$. Solid circles with error bars represent data. Solid histograms show projections of the fits, dashed and dotted histograms show signal and background components, respectively.

tracks and photons excluding the signal lepton have to be compatible with the recoiling B meson) are $\mathscr{B}(B \to e\nu) < 0.98 \times 10^{-6}$ [14] and $\mathscr{B}(B \to \mu\nu) < 1.0 \times 10^{-6}$ [15], respectively.

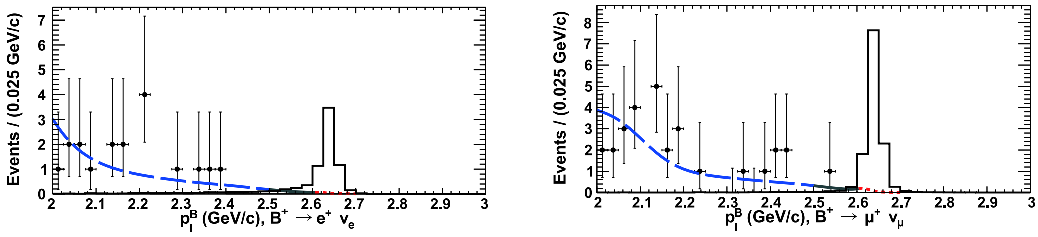

Figure 2: Results of the fit to the p_ℓ^B spectrum for $B \to e\nu$ (left) and $B \to \mu\nu$ (right) decays. Data is shown as points with error bars. The solid histogram shows the expected signal shape with arbitrary normalization. The sum of PDFs is shown as a dashed line in the sideband region ($2.0\,\mathrm{GeV} < p_\ell^B < 2.5\,\mathrm{GeV}$), where the normalization was obtained. In the signal region ($2.6\,\mathrm{GeV} < p_\ell^B < 2.7\,\mathrm{GeV}$) the sum of PDFs is shown as a dotted line.

4. $B \to D^{(*)}\tau\nu$

The semileptonic $B \to D^{(*)}\tau\nu$ decays also include multiple neutrinos in the final states considering the following τ decays. The results shown up to now are based on the tags using hadronic B decays. The ratios $R(D^{(*)}) = \mathscr{B}(B \to D^{(*)}\tau\nu)/\mathscr{B}(B \to D^{(*)}\ell\nu)$, which are independent of the CKM element $|V_{cb}|$ and of the parameterization of the strong interaction to a large extent, are measured. With larger statistics, the q^2 distributions and the angular distributions of the τ and $D^{(*)}$ decays could also provide useful information for testing the SM and constraining new physics models.

The $B^0 \to D^{*+}\tau^-\nu_\tau$ decay was first observed by the Belle collaboration using the 535×10^6 $B\bar{B}$ data sample [16]. The Belle collaboration also obtained the results for the charged B meson decays to $D^{(*)}\tau\nu$ using the 657×10^6 $B\bar{B}$ data sample [17]. These measurements are done by inclusively reconstructing the B_{tag} candidates using all the remaining particles after selecting the B_{sig} decay products. The Belle collaboration also obtained a preliminary result by exclusively reconstructing the B_{tag} candidates and the B_{sig} decay products using the 657×10^6 $B\bar{B}$ data sample [18]. Figure 3 shows the distributions of the kinematic variables used for the signal extraction. The naive averages of $R(D^{(*)})$ for the above results are obtained to be $R(D) = 0.430 \pm 0.091$ and $R(D^*) = 0.405 \pm 0.047$ [19]. For the calculation, the correlations in the statistical errors between the different tagging analyses are neglected since the event overlap is very limited. The correlations in the systematic errors between the different tagging analyses are assumed to be 60%.

The BaBar collaboration showed the latest results for the $B \to D^{(*)}\tau\nu$ decays using hadronic tag and the full 471×10^6 $B\bar{B}$ data sample [20]. This analysis includes a signal efficiency increase by more than a factor of three compared to the previous analysis [21]. This improvement is provided by adding more B_{tag} decay chains and using a looser charged lepton selection. The background events are subtracted by employing the boosted decision tree multivariate method. Combining the results for the neutral and charged B decays to $D^{(*)}\tau\nu$, the $R(D^{(*)})$ ratios are obtained to be $R(D) = 0.440 \pm 0.058(stat) \pm 0.042(syst)$ and $R(D^*) = 0.332 \pm 0.024(stat) \pm 0.018(syst)$. A negative correlation of -0.27 between $R(D)$ and $R(D^*)$ is obtained including systematic uncertainties.

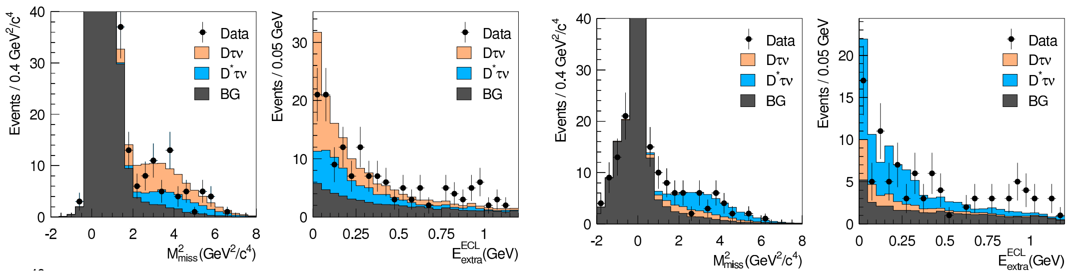

Figure 3: Signal extraction for $B \to D^{(*)}\tau\nu$ in Belle analysis [18] is shown for $B^+ \to \bar{D}^0\tau^+\nu$ (two left plots) and $B^+ \to \bar{D}^{*0}\tau^+\nu$ (two right plots). The missing mass squared M^2_{miss} and residual energy E^{ECL}_{extra} are used.

The results of $R(D^{(*)})$ are consistent between the Belle and BaBar experiments. The Belle results exceed the SM predictions $R(D)_{SM} = 0.297 \pm 0.017$ and $R(D^*)_{SM} = 0.252 \pm 0.003$ [22] by 1.4σ and 3.0σ, respectively [19]. The BaBar results exceed these SM predictions by 2.0σ and 2.7σ, respectively [20]. The combined disagreement of the discrepancy is at 4σ level [19].

In the Type II 2HDM, there is a substantial impact on the ratios $R(D^{(*)})$ due to the charged Higgs contribution [23]. The result for Belle, shown in Fig. 4 (right) has been obtained privately by ignoring the correlation between the experimental $R(D)$ and $R(D^{(*)})$ results and the dependency of the experimental $R(D^{(*)})$ results on $m_{H^\pm}$ and $\tan\beta$. The BaBar result includes both of them [20]. Both results disfavor the Type II 2HDM by a level of more than 3σ for all $\tan\beta/m_{H^\pm}$ region.

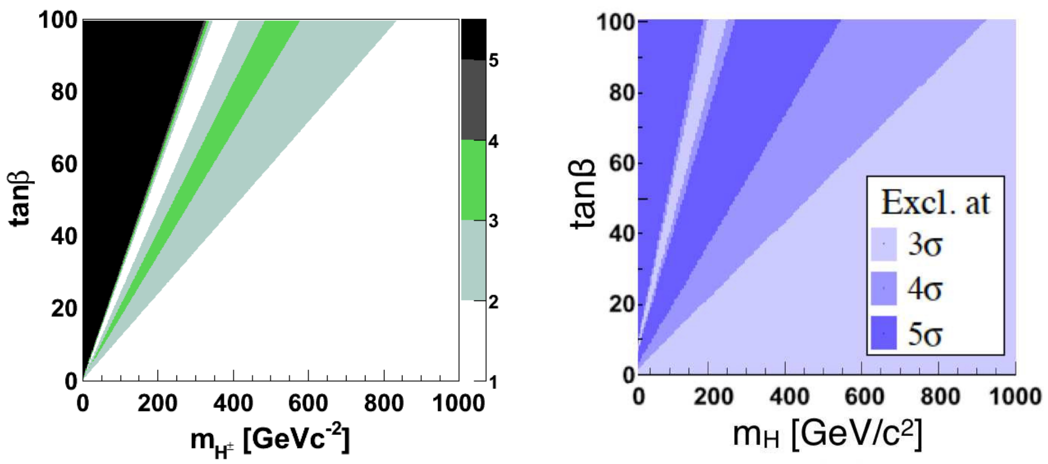

Figure 4: Constraint on $\tan\beta$ and $m_{H^\pm}$ in the Type II 2HDM obtained from Belle results, from measured $\mathscr{B}(B \to \tau\nu)$ (left) and $R(D^{(*)})$ values (right).

5. Summary

Exploiting the large number of events and the clean environment at the B-factories, the leptonic $B \to \tau\nu$ and the semileptonic $B \to D^{(*)}\tau\nu$ decays were measured with a good precision in spite of the existence of multiple neutrinos in the final states. Upper limits were set for the highly suppressed leptonic $B \to \ell\nu$, $\ell = e, \mu$ decays. Stringent constraints on the charged Higgs mass

$m_{H^\pm}$ and the vacuum-expectation-value ratio $\tan\beta$ were evaluated for the Type II 2HDM. Further investigation at the next-generation B-factories is important for testing the SM and for constraining new physics models.

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PoS(QFTHEP 2013)063