PROCEEDINGS OF SCIENCE

$R(D)$ and $R(D^*)$ at Belle

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A new measurement of the ratio of the branching fractions $R(D^{(*)}) = \mathscr{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathscr{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)$, $\ell = e, \mu$ is performed using a semileptonic tagging method with the data sample of 772×10^6 $B\overline{B}$ pairs collected at the Belle experiment. The obtained results are $R(D) = 0.307 \pm 0.037(\text{stat.}) \pm 0.016(\text{syst.})$ and $R(D^*) = 0.283 \pm 0.018(\text{stat.}) \pm 0.014(\text{syst.})$. These results are consistent with the SM prediction within 0.2σ and 1.1σ, respectively. Belle also performs the polarization measurements in $\overline{B} \to D^*\tau^-\overline{\nu}_\tau$ decays. The first preliminary result of the fraction of the longitudinal polarization of D^{*-}, $F_L^{D^*}$, is obtained to be $F_L^{D^*} = 0.60 \pm 0.08(\text{stat.}) \pm 0.04(\text{syst.})$ with an inclusive tagging method. The τ polarization measurement which has been performed earlier is also shown.

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1. Introduction

The semitauonic B decays, $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$[1], are important probes to search for the new physics beyond the Standard Model (SM). Compare to the other B semileptonic decays to e and μ, the heavier τ mass provides the unique sensitivity to new physics contributions such as an extended Higgs sector. After the first observation of the semitauonic B decay by Belle [1], many studies have been performed by Belle [2, 3, 4, 5, 6, 7], BaBar [8, 9], and LHCb [10, 11]. The main experimental results obtained are the ratios of branching fractions $R(D^{(*)}) = \mathscr{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathscr{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)$, where $\ell = e, \mu$ for Belle and BaBar and $\ell = \mu$ for LHCb. As of the end of 2018, the world average values of $R(D^{(*)})$ deviate from the SM prediction $R(D) = 0.299 \pm 0.003$ and $R(D^*) = 0.258 \pm 0.005$, which are the average of several calculations [12, 13, 14, 15] averaged by HFLAV [16], at the 3.8σ level combining $R(D)$ and $R(D^*)$ [16]. To conclude if it is due to the new physics or not, further verification with more precise and also complementary measurements are desired. For this purpose, the polarizations of τ and D^* are other important probes to distinguish the new physics model structure such as vector type, scalar type or tensor type interactions [17].

At the Belle experiment [18] at the KEKB collider [19], $B\overline{B}$ meson pairs are produced at the $\Upsilon(4S)$ resonance. Therefore, only one $B\overline{B}$ meson pair is produced with no additional particle. Utilizing this feature, the semitauonic B decays are identified by reconstructing one B as a tag of a $B\overline{B}$ pair event, reconstructing all final state particles except for neutrinos from the signal B meson decaying semitauonically, requiring nothing else detected in the event and the missing energy and momentum of the event to be consistent with the multiple neutrinos from the semitauonic B decays.

The most useful discriminant variable to require nothing remaining in the candidate events is the energy sum of the electromagnetic calorimeter clusters remaining in the event, $E_{\rm ECL}$. $E_{\rm ECL}$ peaks at zero for the signal events, while takes values more than zero for the background events with excess particles. Three $B\overline{B}$ event tagging methods are performed at Belle: hadronic, semileptonic and inclusive methods. In the hadronic tagging method, the tag B is fully reconstructed exclusively in one of more than one thousand hadronic B decay modes. The typical tagging efficiency of the hadronic tagging method is about 0.2 %. This method has less background than other tagging methods though the efficiency is lower. In the semileptonic tagging method, the tag B is partially reconstructed in $B \to D^{(*)}\ell\nu_\ell$ decays. The typical efficiency of the semileptonic tagging method is higher than the hadronic tagging method and about 0.5 % with larger background contribution. In the inclusive tagging method, the tag B candidates are reconstructed with the all particles remaining after removing the signal-side candidate particles without assuming any specific decay mode. This method has larger efficiency than the exclusive hadronic tagging method. It is effective for the clean signal modes because of the larger background.

In the hadronic tagging and inclusive tagging methods, the tag B candidates are reconstructed using the beam-energy-constrained mass $M_{\rm tag}$ and the energy difference ΔE. They are defined as $M_{\rm tag} \equiv \sqrt{(E^2_{\rm beam} - p^2_{\rm tag})}$ and $\Delta E \equiv E_{\rm tag} - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy in the $\Upsilon(4S)$ rest frame, $p_{\rm tag}$ and $E_{\rm tag}$ are the momentum and energy of the reconstructed tag B candidate, respectively. The $M_{\rm tag}$ and ΔE are required to be consistent with the B meson mass and zero, respectively. In the semileptonic tagging method, assuming only one massless particle is missing

[1] Throughout this proceedings, the inclusion of the charge-conjugate decay mode is implied.

in the B tag decay, the $\cos\theta_{B,D^{(*)}\ell}$ variable, which corresponds to the cosine of the angle between the momenta of B and $D^{(*)}\ell$ system in the $\Upsilon(4S)$ rest frame, is reconstructed as $\cos\theta_{B,D^{(*)}\ell} \equiv (2E_{\rm beam}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2)/(2|p_B||p_{D^{(*)}\ell}|)$. The calculated $\cos\theta_{B,D^{(*)}\ell}$ variable is required to be in the proper range as the cosine, between ± 1, with some margin for the detector resolution.

In this proceedings, we report the new measurement of $R(D^{(*)})$ with the semileptonic tagging method [20], the polarization measurement of τ performed at the Belle experiment using the hadronic tagging method [6, 7], and the preliminary result of the first polarization measurements of D^{*-} using the inclusive tagging method [21]. The analyses use the full $\Upsilon(4S)$ data sample containing 772×10^6 $B\overline{B}$ pairs recorded with the Belle detector produced at the asymmetric-beam-energy e^+e^- collider KEKB.

2. New $R(D)$ and $R(D^*)$ Measurement with Semileptonic Tagging Method

In the previous semileptonic tagging measurement at Belle, $R(D^*)$ with $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$, in which good purity is ensured by using clean $D^{*+}\to D^0\pi^+$ decays, was measured. In the new semileptonic analysis, the improved semileptonic tagging selection with the multivariate analysis technique based on the boosted decision tree developed in the Belle II analysis software framework is introduced [22]. Both $R(D)$ and $R(D^*)$ combining B^+ and B^0 decays are measured with the improved semileptonic tagging method.

For the signal τ^-, decays of $\tau^-\to\ell^-\overline{\nu}_\ell\nu_\tau$, $\ell = e,\mu$ are used. Therefore the actual final state is same as the normalization mode $\overline{B}\to D^{(*)}\ell^-\overline{\nu}_\ell$. To distinguish the $\overline{B}\to D^{(*)}\tau^-\overline{\nu}_\tau$ and the $\overline{B}\to D^{(*)}\ell^-\overline{\nu}_\ell$ decays in the signal side, the signal classifier variable $O_{\rm cls}$ is constructed with the boosted decision tree using $\cos\theta_{B,D(*)\ell}$, the approximated missing mass square $m_{\rm miss}^2 = (E_{\rm beam} - E_{D^{(*)}} - E_\ell)^2 - (p_{D^{(*)}} + p_\ell)^2$ and the visible energy $E_{\rm vis} = \Sigma_i E_i$, where (E_i, p_i) is the four-momentum of particle i in the event.

The number of reconstructed $\overline{B}\to D^{(*)}\tau^-\overline{\nu}_\tau$ and $\overline{B}\to D^{(*)}\ell^-\overline{\nu}_\ell$ decays are extracted by the two-dimensional binned extended maximum likelihood fit to $E_{\rm ECL}$ and the signal classifier variable $O_{\rm cls}$. The $R(D^{(*)})$ are obtained by

$$R(D^{(*)}) = \frac{1}{2\mathscr{B}(\tau^-\to\ell^-\overline{\nu}_\ell\nu_\tau)}\frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}\frac{N_{\rm sig}}{N_{\rm norm}}, \tag{2.1}$$

where $\varepsilon_{\rm sig(norm)}$ and $N_{\rm sig(norm)}$ are the reconstruction efficiency and yields of the signal (normalization) modes and $\mathscr{B}(\tau^-\to\ell^-\overline{\nu}_\ell\nu_\tau)$ is the average of the branching fractions for $\ell = e$ and μ. The isospin constraint is used in the fit so that $R(D^*)$ and $R(D)$ are same for B^+ and B^0 decay modes. The fit results projected to $E_{\rm ECL}$ are shown in Figure 1. The obtained $R(D^{(*)})$ are

$$\begin{aligned} R(D) &= 0.307 \pm 0.037({\rm stat.}) \pm 0.016({\rm syst.}), \\ R(D^*) &= 0.283 \pm 0.018({\rm stat.}) \pm 0.014({\rm syst.}). \end{aligned} \tag{2.2}$$

These results are in agreement with the SM predictions within 0.2σ and 1.1σ, respectively. Combining two results, the agreement with the SM predictions is within 0.8σ.

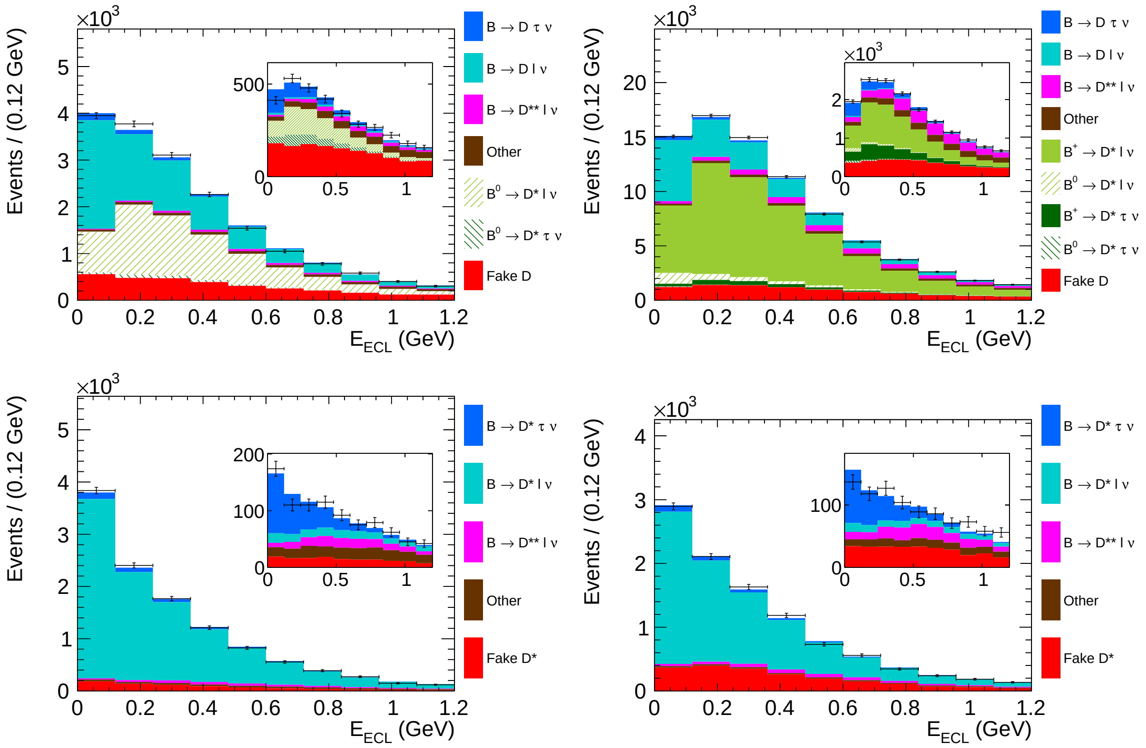

Figure 1: $E_{\rm ECL}$ fit projections and data points with statistical uncertainties in the $D^+\ell^-$ (top left), $D^0\ell^-$ (top right), $D^{*+}\ell^-$ (bottom left) and $D^{*0}\ell^-$ (bottom right) samples, for the full classifier region. The signal region, defined by the selection $O_{\rm cls} > 0.9$, is shown in the inset.

3. Measurement of τ Polarization with Hadronic Tagging Method

The τ polarization in $\overline{B} \to D^*\tau^-\overline{\nu}_\tau$ is defined to be $P_\tau(D^*) \equiv (\Gamma^+(D^*) - \Gamma^-(D^*))/(\Gamma^+(D^*) + \Gamma^-(D^*))$, where $\Gamma^\pm(D^*)$ represents the decay rate with a τ helicity of ± 1. The SM prediction is $P_\tau(D^*) = -0.497 \pm 0.013$ [17]. At Belle, the first measurement of τ polarization in $\overline{B} \to D^*\tau^-\overline{\nu}_\tau$ has been performed in [6, 7]. Using two-body hadronic τ decay modes $\tau \to h\nu_\tau, (h = \pi, \rho)$, the $P_\tau(D^*)$ is measured by the differential decay rate $d\Gamma(D^*)/d\cos\theta_{\rm hel} \propto (1 + \alpha P_\tau(D^*)\cos\theta_{\rm hel})/2$, where $\alpha = 1$ for $h = \pi$ and 0.45 for $h = \rho$ and $\theta_{\rm hel}$ is the angle between the momentum of h and the direction opposite to the momentum of the $\tau\overline{\nu}_\tau$ system. Although the $\overline{\nu}_\tau$ cannot be detected, the momentum of the $\tau\overline{\nu}_\tau$ system can be obtained to be $p_{e^+e^-} - p_{\rm tag} - p_{D^*}$, where p denotes four-momentum of the e^+e^- beam, tagging side B and D^*. Combining with the two body decay kinematics of $\tau \to h\nu_\tau$, we can calculate the $\cos\theta_{\rm hel}$. The fit result to $E_{\rm ECL}$ distribution is shown in Fig. 2. To extract $P_\tau(D^*)$, signal yields in $\cos\theta_{\rm hel} < 0$ and $\cos\theta_{\rm hel} > 0$ are also fitted. The obtained results are

$$\begin{aligned} R(D^*) &= 0.270 \pm 0.035(\text{stat.})^{+0.028}_{-0.025}(\text{syst.}), \\ P_\tau(D^*) &= -0.38 \pm 0.51(\text{stat.})^{+0.21}_{-0.16}(\text{syst.}). \end{aligned} \tag{3.1}$$

The comparison with the SM expectation is shown in Fig. 3. The results are consistent with the SM expectation, although the error of $P_\tau(D^*)$ is still large.

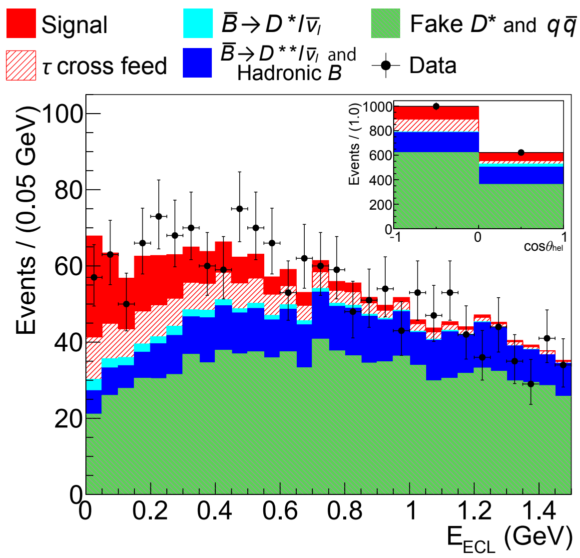

Figure 2: Fit result to the signal sample of $B \to D^* \tau \nu_\tau$ with hadronic τ decays. The main panel and the sub panel show the $E_{\rm ECL}$ and the $\cos\theta_{\rm hel}$ distributions, respectively.

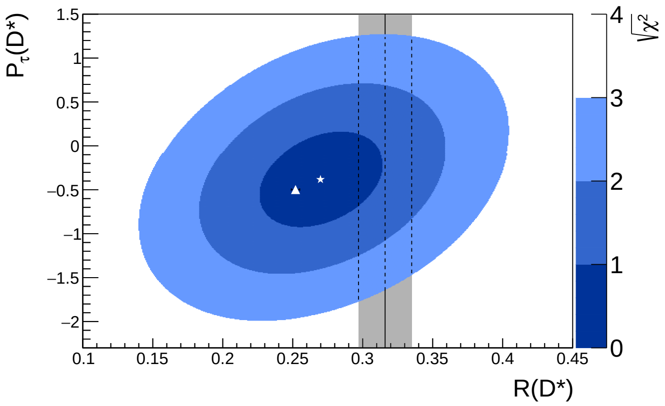

Figure 3: Comparison of fit results of $P_\tau(D^*)$ and $R(D^*)$ with the hadronic τ decays tagged by the hadronic tag (star for the best-fit value and 1σ, 2σ, 3σ contours) with the SM prediction (triangle). The white region corresponds to $> 3\sigma$. The shaded vertical band shows the world average as of early 2016 [25].

4. New Measurement of D^* Polarization with Inclusive Tagging Method

The first preliminary measurement of D^* polarization is newly performed at Belle in 2019. The signal decay $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ is reconstructed with the inclusive tagging method. The fraction of the longitudinal polarization $F_L^{D^*}$ is extracted from the angular distribution in $D^{*+} \to D^0\pi^+$ decay: $d\Gamma/d\cos\theta_{\rm hel}^{D^*} \propto \frac{3}{4}(2F_L^{D^*}\cos^2\theta_{\rm hel}^{D^*} + (1-F_L^{D^*})\sin^2\theta_{\rm hel}^{D^*})$, where $\theta_{\rm hel}^{D^*}$ is the angle between D^0 and the direction opposite to $\overline{B}^0$ in the D^{*+} rest frame. For the signal, $\tau \to e\overline{\nu}_e\nu_\tau$, $\tau \to \mu\overline{\nu}_\mu\nu_\tau$ and $\tau \to \pi\nu_\tau$ decays are used. The signal yields are obtained by fitting the beam-energy-constrained mass of the tagging B, $M_{\rm tag}$ for three equidistant bins dividing the range $-1 \le \cos\theta_{\rm hel}^{D^*} \le 0$. The signal yields of three $\cos\theta_{\rm hel}^{D^*}$ bins are shown in Fig. 4 with the $F_L^{D^*}$ fit result overlaid. From the fit,

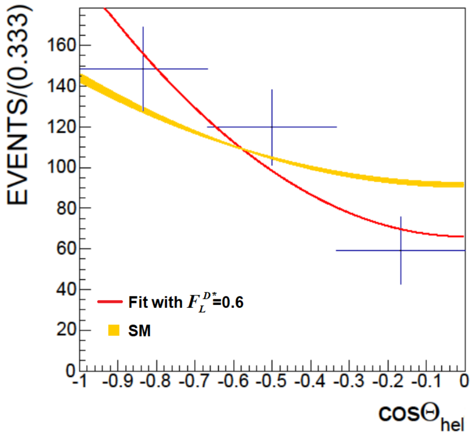

Figure 4: The measured $\cos\theta_{\rm hel}$ distribution in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays (data points with statistical errors); the fit result is overlaid (red line) with $F_L^{D^*} = 0.60$. The yellow band represents the SM prediction of Ref. [23].

the D^* polarization is obtained to be

$$F_L^{D^*} = 0.60 \pm 0.08(\text{stat.}) \pm 0.04(\text{syst.}). \tag{4.1}$$

It agrees within 1.6 (1.8) σ with the SM prediction $F_L^{D^*} = 0.457 \pm 0.010$ [24] (0.441 ± 0.006) [23].

5. Latest $R(D)$ and $R(D^*)$ Comparison

Averaging the most recent Belle results with the hadronic tagging and semileptonic tagging methods, the Belle combined $R(D^{(*)})$ are obtained to be $R(D) = 0.326 \pm 0.034$ and $R(D^{(*)}) = 0.283 \pm 0.018$ with a correlation of -0.47 [20]. The Belle combined results and the SM predictions are consistent within 1.6σ.

Together with other BaBar and LHCb results, the comparison to the SM expectation performed by HFLAV [16] is shown in Fig. 5. The deviation of the world average values of $R(D^{(*)})$ from the SM predictions are slightly reduced by the new Belle semileptonic tag measurement but still large at 3.1σ level.

6. Summary

B semitauonic decays are very important probes to search for the new physics beyond SM. Using the world largest $B\overline{B}$ pair data sample, Belle is still providing important results of $R(D^{(*)})$ and also the first polarization measurements of τ and D^*. The Belle results of $R(D^{(*)})$ and polarizations are so far consistent with the SM predictions although the results are still statistically limited. The deviation of the world average values of $R(D^{(*)})$ from the SM predictions is still large at 3.1σ level. More precise and interesting results to conclude if there is new physics effect and to distinguish the new physics model if exists will be obtained in the Belle II experiment that has started the physics run with the full detector in 2019.

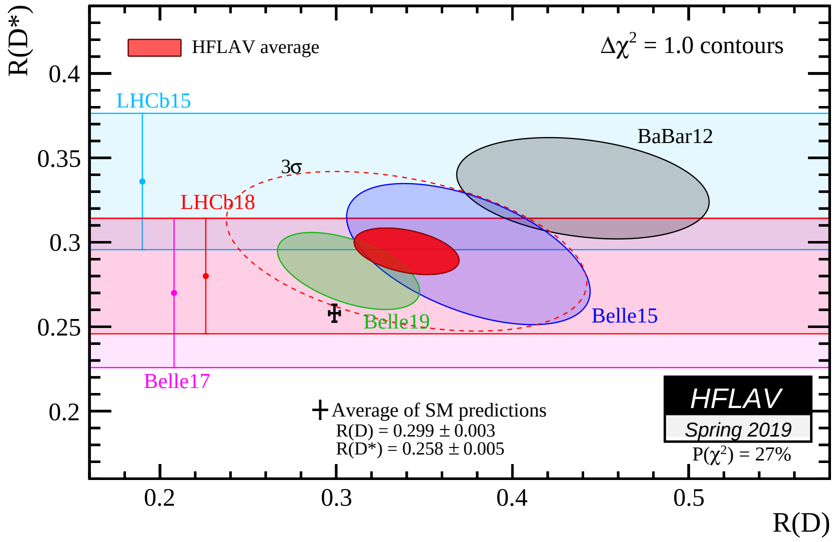

Figure 5: Latest comparison of $R(D)$ and $R(D^*)$ results of Belle, BaBar and LHCb with the SM expectation summarized by HFLAV [16]. The red dotted line is the 3σ contour of the average.

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