Recent $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ Studies at Belle

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The semi-tauonic decay $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ is sensitive to new physics beyond the Standard Model (SM) that has an enhanced coupling to the $\tau$ lepton. In the ratio of branching fractions $R(D^*) = B(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)/B(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)$, where $\ell^- = e^-$ or $\mu^-$, a $3.3\sigma$ anomaly was observed. In order to investigate the anomaly further, Belle performed a new $R(D^*)$ measurement using one-prong hadronic $\tau$ decays, which was statistically independent of the previous two measurements. This measurement included the first measurement of the $\tau$ polarization $P_\tau(D^*)$ using the kinematics of the two-body decays. The obtained results, $R(D^*) = 0.270 \pm 0.035^{\text{stat}}(0.028)^{\text{syst}}$ and $P_\tau(D^*) = -0.38 \pm 0.51^{\text{stat}}(0.21)^{\text{syst}}$, were consistent both with the SM and the world-average $R(D^*)$. Including this result, the $R(D^*)$ anomaly became $3.4\sigma$ away from the SM prediction.

1 Introduction

The decays $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ are the semileptonic $B$ meson decays containing a $\tau$ lepton in the final state. These processes are theoretically well studied within the Standard Model (SM), where a virtual $W$ boson mediates the decay at the tree level. If new physics (NP) beyond the SM exists with a non-universal coupling over the three generation, ratios of branching fractions $R(D^{(*)}) = B(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)/B(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)$, where $\ell^- = e^-$ or $\mu^-$, is modified. Three collaborations, Belle, BaBar and LHCb, have studied the ratios experimentally. As of early 2016, the averages of $R(D)$ and $R(D^*)^6$ were $1.9\sigma$ and $3.3\sigma$ away from the SM predictions, respectively.

Previously, all the measurements were performed by identifying the $\tau$ lepton from its leptonic decay in order to exploit the presence of one charged lepton in the signal decay for the signal selection. Additionally, hadronic $\tau$ decays can be used to reconstruct signal events. With the full dataset, Belle has performed a new measurement of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ using one-prong $\tau$ decays: $\tau^- \to \pi^-\nu_\tau$ and $\rho^-\nu_\tau$. This choice of the $\tau$ decays realizes to investigate the $R(D^*)$ anomaly under the different main background from the previous measurements, where semileptonic decays $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ with excited charmed mesons heavier than $D^*$ are the most important background modes. In addition, using the two-body kinematics of the $\tau$ decay, it is possible to measure the longitudinal polarization of the $\tau$ lepton, $P_\tau(D^*) = (\Gamma^+ - \Gamma^-)/\Gamma^+$, where $\Gamma^+/\Gamma^-$ is the decay rate of $\bar{B} \to D^\tau\bar{\nu}_\tau$ with a right-(left-)handed $\tau$ lepton. This variable is sensitive to NP independently of $R(D^*)$. The new measurement of $\bar{B} \to D^\tau\bar{\nu}_\tau$ by Belle includes the first experimental study of $P_\tau(D^*)$.

This study is performed based on the dataset accumulated at the center-of-mass $e^+e^-$ collision energy of 10.58 GeV using the KEKB accelerator. The energy corresponds to the mass of $\Upsilon(4S)$, and $B$ mesons are produced in the process $\Upsilon(4S) \to BB$. The data are recorded by the Belle detector, which consists of the inner detectors (silicon vertex detector, central drift chamber, time-of-flight counter, aerogel Cherenkov counter and electromagnetic calorimeter),
the superconducting solenoid providing a 1.5 T magnetic field, and the $K^0_L$ and muon detector.
Out dataset contains 772M $B\bar{B}$ pairs.

2 Measurement Method

2.1 Measurement of $R(D^*)$ and $P_\tau(D^*)$

The ratio $R(D^*)$ is determined by the yield ratio between the signal mode ($\bar{B} \to D^*\tau^-\bar{\nu}_\tau$) and the normalization mode ($\bar{B} \to D^*\ell^-\bar{\nu}_\ell$). It is represented by

$$R(D^*) = \frac{1}{B_\tau} \frac{\epsilon_{\text{norm}} N_{\text{sig}}}{\epsilon_{\text{sig}} N_{\text{norm}}},$$

where $B_\tau$ denotes the branching fraction of $\tau$, and $\epsilon_{\text{sig(norm)}}$ and $N_{\text{sig(norm)}}$ are the efficiency and the yield of the signal (normalization) mode, respectively. These quantities are determined separately for different $\tau$ decay modes.

The polarization $P_\tau(D^*)$ is measured by the differential decay rate \(^{13}\)

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{\text{hel}}} = \frac{1}{2} \left[ 1 + \alpha P_\tau(D^*) \cos\theta_{\text{hel}} \right],$$

where $\Gamma$ denotes the decay rate of $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$. The coefficient $\alpha$ denotes the $\tau$-mode-dependent sensitivity to $P_\tau(D^*)$; $\alpha = 1$ for $\tau^- \to \pi^-\nu_\tau$ and $\alpha = (m_\tau^2 - 2m_\rho^2)/(m_\tau^2 + 2m_\rho^2) \approx 0.45$ for $\tau^- \to \rho^-\bar{\nu}_\tau$, where $m_\tau(\rho)$ is the $\tau$ lepton ($\rho$ meson) mass. The angle $\theta_{\text{hel}}$ is determined as the direction of the $\tau$-daughter $\pi$ or $\rho$ momentum with respect to the direction opposite the momentum of the virtual $W$ boson. However, the complete $\tau$ momentum cannot be measured at Belle due to insufficient kinematic constraints. Here, we exploit the rotation symmetry in the rest frame of $W$. In this frame, we calculate $\cos\theta_{\tau d} = (2E_\tau E_d - m_\tau^2 - m_d^2)/(2|\vec{p}_\tau||\vec{p}_d|)$, where $E$ and $\vec{p}$ denote the energy and the momentum of $\tau$ and the $\tau$-daughter meson $d = \pi$ or $\rho$, respectively, and $m_d$ is the mass of $d$. The angle $\theta_{\tau d}$ is defined by the momenta of $\tau$ and $d$. Because $\tau$ is produced in the two-body decay, the energy and the magnitude of the $\tau$ momentum is determined only from the momentum transfer squared, $q^2 = (p_{\text{sig}^-} - p_{D^*})$, where $p$ is the four-momenta of the signal $B$ meson ($B_{\text{sig}}$) and $D^*$. Although $B_{\text{sig}}$ is not fully reconstructed due to two neutrinos, we obtain the $B_{\text{sig}}$ momentum from $p_{\text{sig}} = p_{e^+e^-} - p_{\text{tag}}$, where $p_{e^+e^-}$ and $p_{\text{tag}}$ denote the four-momenta of the $e^+e^-$ beam and the counterpart $B$ meson ($B_{\text{tag}}$), respectively. In this measurement, we fully reconstruct $B_{\text{tag}}$ from its hadronic decay.

Now, the $\tau$ momentum vector is fixed on the cone around the $\tau$-daughter meson momentum with an angle of $\theta_{\tau d}$. Owing to the rotation symmetry of the cone, any direction is kinematically equivalent. An arbitrary direction is therefore selected as a Lorentz boost vector, and we obtain the equation

$$|\vec{p}_d^*| \cos\theta_{\text{hel}} = -\gamma|\vec{\beta}|E_d + \gamma|\vec{p}_d| \cos\theta_{\tau d},$$

where $|\vec{p}_d^*| = (m_\tau^2 - m_d^2)/(2m_\tau)$ is the $\tau$-daughter momentum in the rest frame of $\tau$, and $\gamma = E_\tau/m_\tau$ and $|\vec{\beta}| = |\vec{p}_\tau|/E_\tau$. Solving this equation, the value of $\cos\theta_{\text{hel}}$ is obtained.

2.2 Event Reconstruction

The event selection starts with reconstructing $B_{\text{tag}}$ from one of the 1104 hadronic decay chains. The NeuroBayes-based multivariate analysis technique \(^{14}\) is employed. Good quality $B_{\text{tag}}$ candidates are selected based on the beam-constraint mass $M_{bc} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_B^*|^2}$, where $E_{\text{beam}}$ and $\vec{p}_B^*$ are the beam energy (5.29 GeV) and the three momentum of the $B_{\text{tag}}$ candidate, respectively, as well as the single NeuroBayes output classifier $C_{\text{NB}}$. Our requirements retain 90% of correctly reconstructed $B_{\text{tag}}$ candidates while rejecting 70% of misreconstructed candidates.
Using the remaining particles, we next reconstruct the $D^*$ meson as a daughter of $B_{\text{sig}}$. Reconstructed $D^*$ candidates are then combined with pions or $\rho$ meson candidates properly in terms of the charge. The $\rho$ meson candidates are reconstructed from the decay $\rho^- \to \pi^- \pi^0$. For the normalization mode, we require the existence of one $e^-$ or $\mu^-$ instead of $\pi^- \pi^0$. Finally, we select events with no extra charged track and $\pi^0$ candidate not used for the reconstruction of $B_{\text{tag}}$ and $B_{\text{sig}}$.

Details of the event reconstruction are discussed in Ref. 9.

### 3 Result

Signal extraction is performed by the two-step fit. First, a fit to the normalization events is performed based on the missing-mass squared $M_{\text{miss}}^2 = (p_{\ell^+e^-} - p_{\text{tag}} - p_{D^*} - p_{\ell})^2$, where $p_{\ell}$ denotes the four-momentum of $\ell$. Since there is only one neutrino in the normalization mode, the distribution of $M_{\text{miss}}^2$ peaks around 0 GeV$^2$. After determining the normalization yield, we perform a fit to the signal events using $E_{\text{ECL}}$, which is the sum of the cluster energies on the electromagnetic calorimeter that are not used for the event reconstruction. While the signal events tend to have $E_{\text{ECL}}$ close to 0 GeV, the background events have larger values due to additional physical photons. The $E_{\text{ECL}}$ has advantages for the signal yield extraction in terms of its small correlation to $P_\tau(D^*)$ and good signal separation from background processes. In the fit, the $P_\tau(D^*)$ is determined from two bins of $\cos\theta_{\text{hel}}$.

Figure 1 shows the fit results to the signal sample. From the fit, we obtain

$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst}).$$

The systematic uncertainty mainly arises from hadronic and semileptonic decays of $B$ mesons, and the statistics of the Monte Carlo simulated sample; details are described in Ref. 9. The signal significance is 7.1$\sigma$, and therefore our measurement has achieved the first observation of $B \to D^* \tau^- \nu_\tau$ only with $\tau$ decays. The region $P_\tau(D^*) > 0.5$ is excluded at the 90% confidence level, which is the first result of $P_\tau(D^*)$ in $B \to D^* \tau^- \nu_\tau$. 

### Figure 1 – Fit results to the signal sample. The main panel and the sub panel show the $E_{\text{ECL}}$ and the $\cos\theta_{\text{hel}}$. The red-hatched "\tau cross feed" contains $\bar{B} \to D^* \tau^- \nu_\tau$ signal events originating from $\tau$ decays different from the reconstruction channels.

### Figure 2 – Summary of the $R(D^*)$ measurements as of distributions, respectively. The red-hatched "\tau cross feed" contains $\bar{B} \to D^* \tau^- \nu_\tau$ signal events originating from $\tau$ decays different from the reconstruction channels. The systematic uncertainty mainly arises from hadronic and semileptonic decays of $B$ mesons, and the statistics of the Monte Carlo simulated sample; details are described in Ref. 9. The signal significance is 7.1$\sigma$, and therefore our measurement has achieved the first observation of $B \to D^* \tau^- \nu_\tau$ only with $\tau$ decays. The region $P_\tau(D^*) > 0.5$ is excluded at the 90% confidence level, which is the first result of $P_\tau(D^*)$ in $B \to D^* \tau^- \nu_\tau$. 

### Table 2

| Experiment | $R(D^*)$ (syst) | $P_\tau(D^*)$ (stat) |
|-----------|----------------|---------------------|
| S. Fajfer et al. (2012) | 0.336 | 0.270 |
| Belle (hadronic tag) | 0.332 | -0.38 |
| Belle sl.tag | 0.320 | -0.51 |
| HFLAV | 0.270 | -0.21 |
| Average | 0.304 | -0.16 |

The systematic uncertainty mainly arises from hadronic and semileptonic decays of $B$ mesons, and the statistics of the Monte Carlo simulated sample; details are described in Ref. 9. The signal significance is 7.1$\sigma$, and therefore our measurement has achieved the first observation of $B \to D^* \tau^- \nu_\tau$ only with $\tau$ decays. The region $P_\tau(D^*) > 0.5$ is excluded at the 90% confidence level, which is the first result of $P_\tau(D^*)$ in $B \to D^* \tau^- \nu_\tau$. 

### Figure 2 – Summary of the $R(D^*)$ measurements as of FPCP 2017.
4 Current Situation of \( R(D^*) \)

In addition to our new result, LHCb has performed a measurement of \( R(D^*) \) using three-prong hadronic \( \tau \) decays\(^{15}\). As shown in Fig. 2\(^{16}\), the current world-average \( R(D^*) = 0.304 \pm 0.013(\text{stat}) \pm 0.007(\text{syst}) \) is 3.4\( \sigma \) away from the SM prediction\(^{16}\). Including \( R(D) \), the overall discrepancy reaches 4.1\( \sigma \). In order to settle this puzzle, further \( \bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau \) studies using high statistics data at Belle II are essential.

5 Conclusion

The decays \( \bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau \) are interesting \( B \) decays in terms of their sensitivities to NP coupling to the \( \tau \) lepton. Belle has performed a new \( \bar{B} \to D^*\tau^-\bar{\nu}_\tau \) measurements, which results in the first observation of the \( \bar{B} \to D^*\tau^-\bar{\nu}_\tau \) signal using only hadronic \( \tau \) decays, and the first measurement of \( P_{\tau}(D^*) \). The obtained result is consistent with the SM predictions. The world averages of \( R(D^{(*)}) \) show the 4.1\( \sigma \) discrepancy from the SM predictions. This is an important topic to be further investigated with high precision of Belle II.

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