PROCEEDINGS OF SCIENCE

D^* and τ polarization measurements by Belle

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Semitauonic $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ decays provide a wide variety of observables sensitive to new physics contributions, such as differential distributions and polarizations. Of particular interest is τ polarization, that cannot be accessed in other semileptonic decays. Furthermore D^* polarization can be measured fairly accurately, so it can be good discriminant of some new physics scenarios. Correlations between various observables offer a rich laboratory to investigate the structure of interactions in semitauonic B decays. In this report, preliminary results on the first measurement of τ polarization and prospects for the D^* polarization measurements are presented.

9th International Workshop on the CKM Unitarity Triangle
28 November - 3 December 2016
Tata Institute for Fundamental Research (TIFR), Mumbai, India

PoS(CKM2016)052

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1. Experimental situation and motivation

Semitauonic B decays are sensitive to new physics (NP), beyond the Standard Model (SM), at the tree level[1, 2]. Due to the larger mass of τ compared to others leptons, decays $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ are sensitive to NP contributions, especially in the form of charged scalars[3, 4]. Semitauonic B decays have been studied experimentally by Belle[5, 6, 7, 8, 9], BaBar[10] and LHCb[11]. So far measurements concerned mainly branching fraction ratios of semitauonic and semileptonic B decays defined as

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\mathscr{B}(B \to \bar{D}^{(*)}\ell^+\nu_\ell)} \tag{1.1}$$

where ℓ refers to either an electron or a muon. The relative rates are independent of most theoretical (the $|V_{cb}|$ element of the CKM matrix, some form factors) and experimental uncertainties (reconstruction efficiencies). The world average of measured values of $R(D^{(*)})$ are approximately 4σ above the SM[12], with a surprisingly large effect observed in the $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ mode. Investigation of the nature of this tension is an important topic in flavor physics that requires comprehensive measurements covering a broad range of observables in semitauonic B decays. In particular, measurements of polarizations in semitauonic B decays can provide more information on a structure of new interactions.

$\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ decays are experimentally challenging since there are at least two neutrinos: one from B and one or two from τ decay, so they lack clear-cut kinematic constraints and cannot be fully reconstructed. In B-factories, that are clean sources of exclusive $B\overline{B}$ meson pairs, semitauonic B decays are tagged by reconstructing the recoiling B-meson (B_{tag}), which decays either hadronically or semileptonically. Most measurements employ hadronic decays of B_{tag} reconstructed in a large number of the exclusive modes [7, 9, 10]. B_{tag} reconstruction provides information on quantum numbers of the accompanying B meson (B_{sig}) and, in the case of hadronic B_{tag} decays, on the momentum vector of B_{sig}, allowing for a partial kinematic reconstruction of semitauonic B decays. Fig.1 shows kinematic variables describing $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ decay. Of special interest are the two helicity angles $\theta_{\text{hel}}(\tau)$ and $\theta_{\text{hel}}(D^*)$ (accessible at B-factories) that enable polarization measurements of τ and D^* respectively.

2. τ polarization measurement in $B \to D^*\tau\nu$ by Belle

The analysis is based on the full data sample of $772 \cdot 10^6$ $B\bar{B}$ pairs accumulated with the Belle detector at the $\Upsilon(4S)$ resonance in the e^+e^- asymmetric collider KEKB. Using hadronic tagging method and two-body τ decays $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to \rho^-\nu_\tau$ first measurement of P_τ simultaneously with $R(D^*)$ has been made[9] for combined $\overline{B}^0 \to D^{(*)-}\tau\overline{\nu_\tau}$ and $B^- \to D^{(*)0}\tau\overline{\nu_\tau}$ decays. The τ lepton polarization is defined as:

$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-},$$

where $\Gamma^\pm$ denotes the decay rate of $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ with a τ helicity of $\pm 1/2$. The SM value of τ polarization in $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ decay is $P_\tau = -0.497 \pm 0.013$[2], however it can be significantly modified by NP. The τ polarization is accessible in two-body τ decays ($\tau \to h\nu_\tau$), and can be

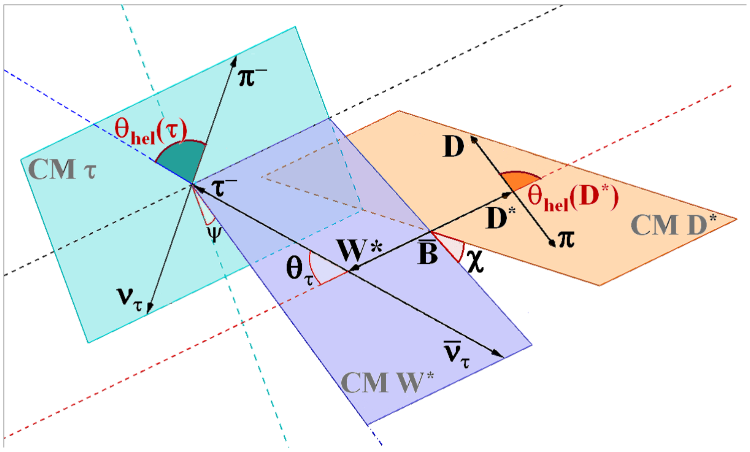

Figure 1: Kinematic variables used to describe semitauonic B decays: θ_τ - angle between τ and B in W^* rest frame; $\theta_{\rm hel}(D^*)$ - angle between D and direction opposite to B in D^* rest frame; $\theta_{\rm hel}(\tau)$ - angle between π and direction opposite to W^* in τ rest frame; χ - angle between the W^* $(\tau\overline{\nu_\tau})$ and D^* decay planes; $q^2 \equiv M_W^2 = (p_{\rm B_{tag}} - p_{D^*})^2$ - effective mass squared of the W^* $(\tau\overline{\nu_\tau})$ system; $M_{\rm M}^2 = (p_{\rm beam} - p_{\rm B_{tag}} - p_{D^*} - p_l)^2$ - missing mass squared (effective mass of neutrinos). M_W^2, M_M^2, $\theta_{\rm hel}(D^*)$ and $\theta_{\rm hel}(\tau)$ can be reconstructed at B-factories using hadronic decays of $B_{\rm tag}$.

extracted from the following formula:

$$\frac{d\Gamma}{d\cos\theta_{\rm hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{\rm hel}(\tau)),$$

where $\theta_{\rm hel}$ denotes the angle between meson momentum (the τ daughter) in the rest frame of the τ lepton with respect to the direction of τ lepton in the $(\tau\overline{\nu_\tau})$ rest frame. Optimal analyzing power have decays to pseudoscalar meson $h = \pi, K$, for which the coefficient $\alpha = 1$. In decays to vector meson $(h = \rho, a_1)$, $\alpha = \frac{m_\tau^2 - 2m_V^2}{m_\tau^2 + 2m_V^2}$, where m_τ is the mass of τ lepton, m_V is the mass of vector meson, and for $\tau \to \rho\nu$: $\alpha = 0.45$. Even though the τ vector is not fully reconstructed the $\cos\theta_{\rm hel}(\tau)$ can be uniquely determined from the following formula: $\cos\theta_{\rm hel}(\tau) = 1 - \frac{2m_\tau^2 M_M^2}{(M_W^2 - m_\tau^2)(m_\tau^2 - m_h^2)}$, where m_h is the mass of τ daughter. Measurement of $\cos\theta_{\rm hel}(\tau)$ distribution is demanding because it is modified by cross-feeds from signal events with other τ decays, and background contamination.

To measure P_τ, the region of $\cos\theta_{\rm hel}(\tau)$ is divided into two bins: $\cos\theta_{\rm hel}(\tau) > 0$ (forward) and $\cos\theta_{\rm hel}(\tau) < 0$ (backward). The value of P_τ is then extracted from the forward-backward asymmetry of the signal yields, and it is given by the formula

$$P_\tau = \frac{2}{\alpha} \frac{N_{\rm sig}^F - N_{\rm sig}^B}{N_{\rm sig}^F + N_{\rm sig}^B},$$

where the superscript $F(B)$ denotes the signal yield in the forward (backward) region. For the $\tau \to \pi\nu$ mode the region of $\cos\theta_{\rm hel} > 0.8$ is excluded from the analysis due to a large peaking background coming from $B \to D^*\ell\nu$ decays. Corrections to the raw P_τ value are applied to take into account detector effects (acceptance, asymmetric $\cos\theta_{\rm hel}(\tau)$ bins, crosstalks between different τ decays). In the presented analysis, the value of P_τ is measured simultaneously with $R(D^*)$. The number of events in normalization mode $(B \to \bar{D}^{(*)}\ell^+\nu_\ell)$ is extracted from missing mass distribution in the region $-0.2 < M_{\rm miss}^2 < 0.85$ GeV^2/c^4.

Backgrounds can be categorized into four components: $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$, $\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$ together with hadronic B decays, fake D^* and continuum. The semileptonic component contaminates the signal sample due to the misassignment of the lepton as a pion, and it is fixed from the fit to the normalization sample. In this analysis, the main background comes from the hadronic B decays with a few missing final-state particles, and its yield is determined as a free parameter in the final fit. The yield of the fake D^* component is fixed from a comparison of the data and MC in the $\Delta \mathrm{M} = \mathrm{M}_{\mathrm{D}^*} - \mathrm{M}_{\mathrm{D}}$ sidebands regions. The fraction of the continuum $e^+e^- \to q\bar{q}$ process is negligible and is fixed using MC expectation.

Signal extraction is done by a 2D extended binned maximum likelihood fit to E_{ECL}(summed energy of clusters not used in the reconstruction of $\mathrm{B}_{\mathrm{sig}}$ and $\mathrm{B}_{\mathrm{tag}}$ candidates) and M_{M}^2 distributions. The fit is performed in two steps; the first fit is to the normalization sample, and then a simultaneous fit for the eight signal samples: $(B^-, \overline{B}^0) \otimes (\pi^- \nu_\tau, \rho^- \nu_\tau) \otimes$ (forward, backward). The fit result is illustrated in fig.2. The obtained signal and normalization yields for $B^-(B^0)$ mode are, respectively, 210±27 (88±11) and 4711±81 (2502±52), where the errors are statistical.

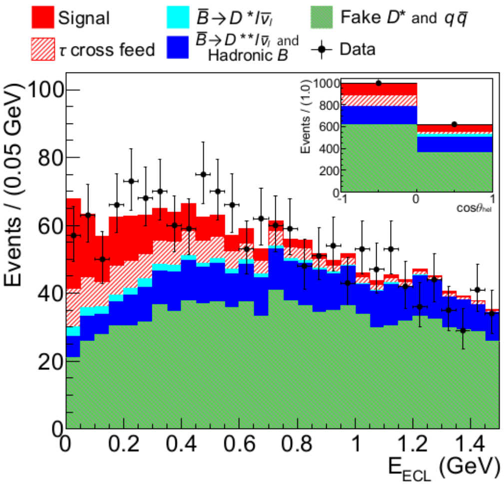

Figure 2: Result of the fit[13] to the combined signal sample. The main panel and the sub panel show the E_{ECL} and the $\cos\theta_{\mathrm{hel}}(\tau)$ distributions, respectively. The red-hatched histogram combines the $\rho \leftrightarrow \pi$ cross-feed and the other τ cross-feed components.

The following preliminary result[1] is obtained

$$P_\tau = -0.44 \pm 0.47(stat.)^{+0.20}_{-0.17}(syst.)$$
$$R(D^*) = 0.276 \pm 0.034(stat.)^{+0.029}_{-0.026}(syst.)$$

and is presented in fig.3. Dominant systematics come from hadronic B decays composition ($^{+7.6\%}_{-6.8\%}$, $^{+0.13}_{-0.10}$) and limited MC statistics for probability density functions (PDFs) of shapes ($^{+4.0\%}_{-2.8\%}$, $^{+0.15}_{-0.11}$). The first P_τ measurement in semitauonic B decays is achieved, and this is also the first $R(D^*)$ measurement using only the hadronic τ decays.

Combined $R(D^*)$ and P_τ result is consistent with the SM within 0.6σ. These are still crude constraints due to limited statistics but better precision can be expected at Belle II experiment.

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[1] Final result is published in[13]

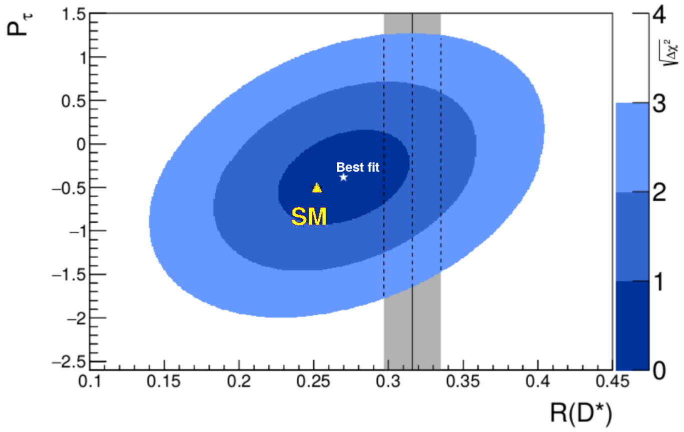

Figure 3: Comparison of Belle result (star for the best-fit value and 1σ, 2σ, 3σ contours) with the SM prediction[1, 2] (triangle). The shaded vertical band shows the world average[12] without Belle result.

3. Prospects for D^* polarization measurements

D^* polarization in $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ decays is capable to distinguish between NP operators, whose Lorentz structure is different from that of the SM[14, 15, 16, 17, 18, 19]. Especially it can be sensitive to scalar and tensor operators, which are present in leptoquark models[20].

The D^* polarization can be extracted from angular distribution in $D^* \to D\pi$ decays. The polar angle distribution in the helicity frame is given by

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{\rm hel}(D^*)) + (1-F_L^{D^*})\sin^2(\theta_{\rm hel}(D^*))],$$

where $F_L^{D^*}$ is fraction of longitudinal polarization of D^*. The SM theoretical predictions for $F_L^{D^*}$ are in the range of $[0.46-0.53]$[2, 21]

The D^* polarization is easier to measure than τ polarization because all τ decays are useful. Additionally, it is not affected by cross-feeds between different τ decays. Among the main experimental challenges to measure D^* polarization there are strong acceptance effects. In particular, the region of $\cos\theta_{\rm hel}(D^*) > 0$ is depleted due to the fact that at $\cos\theta_{\rm hel}(D^*)$ close to +1, the pion goes backwards in the D^* rest frame, and thus has lower momentum in the laboratory frame. The effect increases with increasing q^2, and effectively only the region of $\cos\theta_{\rm hel}(D^*) < 0$ is useful for measurement.

Using the full Belle data sample, and applying the most efficient technique of inclusive[2] $\mathrm{B_{tag}}$ reconstruction[5, 6] one can expect ~300 signal events in the cleanest decay mode $\overline{B^0} \to D^{*+}\tau^-\overline{\nu_\tau}$ (with the following decay chains: $D^{*+} \to D^0\pi; D^0 \to K^-\pi, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+; \tau^- \to \ell^-\nu_\tau\nu_{\overline{\tau}}, \pi^-\overline{\nu_\tau}$) allowing to measure $F_L^{D^*}$ with the statistical uncertainty of $\sim \pm 0.1$, so this observable can provide competitive tests of NP.

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[2] In this method $\mathrm{B_{tag}}$ is reconstructed from all particles that remain after reconstructing the signal side ($D^{(*)}$ and τ daughter).

4. Summary

Combined $R(D^{(*)})$ measurements by BaBar, Belle and LHCb show about 4σ tension with the SM, so more data of different observables are needed to explain the puzzle. Polarizations of τ and D^* in $\overline{B} \to D^{(*)}\tau\overline{\nu_\tau}$ are interesting observables sensitive to NP that can be measured at B factories. In this paper the first constraint on τ polarization and a new, statistically independent, measurement of $R(D^*)$ are reported. Preliminary results show $P_\tau = -0.44 \pm 0.47(stat.)^{+0.20}_{-0.17}(syst.)$, $R(D^*) = 0.276 \pm 0.034(stat.)^{+0.029}_{-0.026}(syst.)$. Prospects of D^* polarization measurement are also discribed. Precise determination of the polarizations in semitauonic B decays will be important topic at Belle II, where 50 times larger data sample will be accumulated.

5. Acknowledgments

I would like to thank the organizers of CKM2016 conference for the opportunity to give this talk and for partial financial support.

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