Exclusive semileptonic $b \rightarrow c$ decays at Belle

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on behalf of the Belle collaboration

We present analyses of exclusive semileptonic $b \rightarrow c$ decays based on data samples collected by the Belle detector at the KEK-B e^+e^- asymmetric collider.

The first topic are precision measurements of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ and the HQET form factor parameters ρ^2, R_1 and R_2 extracted from $B^+ \rightarrow \bar{D}^{*0}\ell^+\nu$ decays using untagged $\Upsilon(4S)$ events. Additionally, a test of the form factor parametrization is performed. Secondly, measurements of $B \rightarrow D^*\tau\nu$ and $B \rightarrow D\tau\nu$ decays are presented, where the accompanying second B meson is tagged and reconstructed. Branching fractions of the semi-tauonic decays are measured.

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1. KEKB and the Belle detector

The following analyses were performed using data samples collected at the $\Upsilon(4S)$ resonance with the Belle detector operating at the KEKB asymmetric-energy e^+e^- collider. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), a barrel-like arrangement of 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 the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail in Ref. [1].

2. Exclusive $B^+ \to D^{*0}\ell^+\nu$ decays

From semileptonic decays of the kind $B \to D^*\ell\nu$ one can extract the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ times the form factor normalization $\mathscr{F}(1)$ as well as the HQET form factors ρ^2, R_1 and R_2. One of the dominating systematic error components is related with the slow pion emitted by the D^* meson. Therefore it is worthwhile to investigate both B^0 and B^+ decays, where this systematic will not be identical.

The quadruple decay width of these processes is a four dimensional function depending on the kinematic variables [2, 3] $w = v_B \cdot v_{D^*}$ and the three angles $\cos\theta_V$, $\cos\theta_\ell$ and χ, defined in Fig. 1. We use the parametrization defined in Ref. [4], which introduces the three free parameters ρ^2, $R_1(1)$ and $R_2(1)$ to govern the shape of the form factors of the decay.
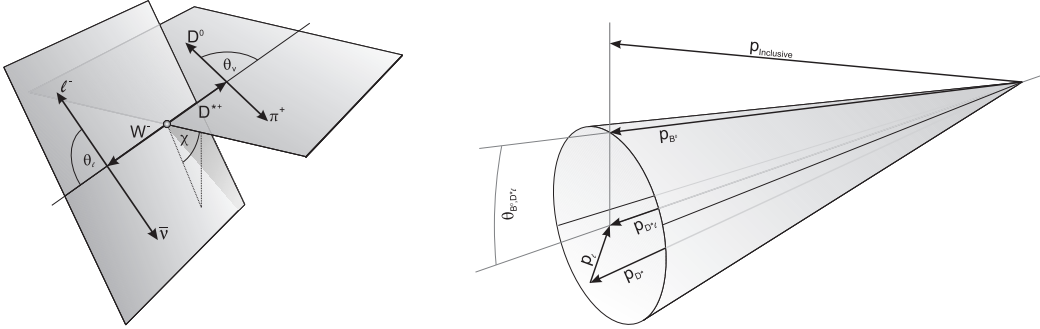

Figure 1: The definition of the four kinematic variables w, $\cos\theta_V$, $\cos\theta_\ell$ and χ and a sketch of the reconstruction of the signal B momentum using momentum conservation.

Preliminary results based on the analysis of B^0 events have been reported before [6]. In the results presented here, the decay cascade $B^- \to D^{*0}\ell^-\bar\nu$, $D^{*0} \to D^0\pi_s^0$ with the slow pion $\pi_s^0 \to \gamma\gamma$ and $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^+\pi^-$ is reconstructed. The light lepton ℓ is either an electron or a muon. Due to momentum conservation, the spatial momentum of the B meson has to lie on a specific cone around the spatial momentum of the $D^*\ell$ system. The inclusive sum of the entire remaining event is used to obtain the best B candidate by orthogonal projection, as sketched in the right hand plot of Fig. 1. Data recorded about 60 MeV below the $\Upsilon(4S)$ resonance is used to investigate background from $q\bar q$ decays, while Monte Carlo simulated events are used for a set of additional background components stemming from B decays.

The parameters $\mathscr{F}(1)|V_{cb}|$, ρ^2, $R_1(1)$ and $R_2(1)$ are obtained by a binned least squares fit to the four one-dimensional marginal distributions of the decay width. The bin-to-bin correlations between these one dimensional histograms have to be considered. Only the branching ratio of the mode $D^0 \to K^- \pi^+$ is used as an external parameter, the branching ratio of the mode $D^0 \to K^- \pi^+ \pi^+ \pi^-$ is determined by fitting the ratio between the two D^0 channels, $R_{K3\pi/K\pi}$. A χ^2 function is formed for each of the four channels separately and the sum of these four χ^2's is minimized numerically using the MINUIT package [5].

The preliminary results of the fit are $\rho^2 = 1.376 \pm 0.074 \pm 0.056$, $R_1(1) = 1.620 \pm 0.091 \pm 0.092$, $R_2(1) = 0.805 \pm 0.064 \pm 0.036$, $R_{K3\pi/K\pi} = 2.072 \pm 0.023$, $\mathscr{B}(B^+ \to \bar{D}^{*0}\ell^+ \nu_\ell) = (4.84 \pm 0.04 \pm 0.56)\%$ and $\mathscr{F}(1)|V_{cb}| = 35.0 \pm 0.4 \pm 2.2$, where the first error is the statistical error reported by MINUIT and the second (where shown) is the preliminary systematic error. The χ^2/n.d.f. of the fit gives 187.8/155.

Additionally, a cross check of the parametrization used to define the form factor parameters is performed by extracting the shapes of the longitudinal (Γ^L) and transversal (Γ^T) helicity amplitudes of the decay. There is good agreement between this cross check and the result by the parametrized fit, as shown in Fig. 2.
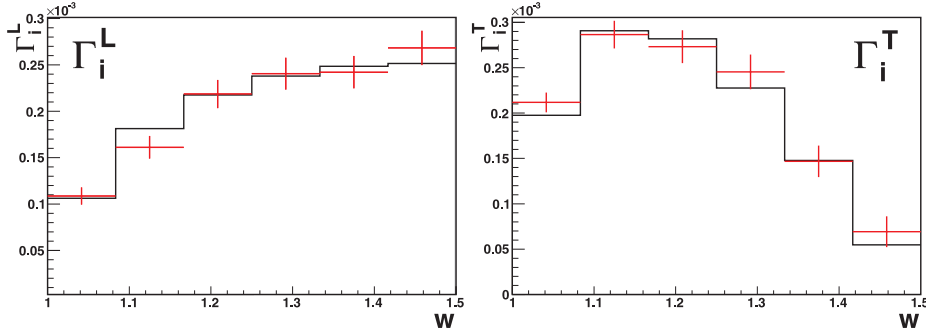

Figure 2: Results of the fit of the helicity amplitudes (red crosses) compared to the prediction obtained by using the parameters obtained by using the parametrization prescription by Caprini, Lellouch and Neubert (solid black line). The left plot shows the results for Γ_i^L, the right one for Γ_i^T. Only the statistical error is shown.

3. $B^0 \to D^{*-}\tau^+\nu$ decays with inclusive tag of the accompanying $\bar{B}^0$

Due to the large mass of the τ lepton, $b \to c\tau\nu$ decays can be used as probes for models containing charged Higgs bosons. The Belle collaboration was able to report the first observation of the decay $B^0 \to D^{*-}\tau^+\nu$ [7].

To reconstruct the signal, a D^* meson is combined with a charged track, expected to stem from a τ decay. The D^* candidates are reconstructed in the $D^* \to \bar{D}^0\pi^-$ mode, with the D^0 being reconstructed in the channels $K\pi$ or $K\pi\pi^0$. The charged track associated with the τ decay is either an electron, $\tau^- \to e^- \bar{\nu}_e \nu_\tau$, or a charged pion, $\tau^- \to \pi^- \nu_\tau$. In case of the $\tau^- \to \pi^- \nu_\tau$ channel, only the $D^0 \to K\pi$ mode is used due to background constraints. All remaining tracks and clusters in the event are used to inclusively reconstruct the second B meson, B_{tag}.

The variables $M_{\text{tag}} = \sqrt{E_{\text{beam}}^2 - p_{\text{tag}}^2}$ and $\Delta E = E_{\text{tag}} - E_{\text{beam}}$ discriminate signal from background, since they can be used to check the consistency between the B_{tag} candidate and the B hypothesis. Here E_{beam} is the beam energy and E_{tag} (p_{tag}) is the energy (spatial momentum) of the sum of the residual particles.
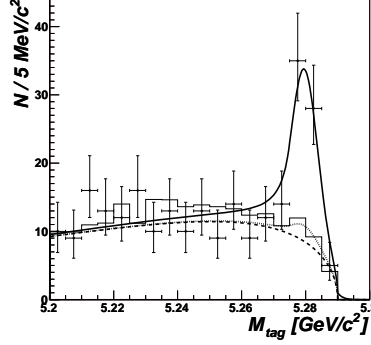
Figure 3: M_{tag} distribution for $B^0 \to D^{*-} \tau^+ \nu$ decays. The real data is shown as points with error bars, the expected background is represented by the histogram. The solid line shows the fit result. The dotted and dashed curves indicate the distributions of background components.

The final signal yield is extracted by an unbinned maximum likelihood fit to the M_{tag} distribution, the result is shown in Fig. 3. The fit result corresponds to 60^{+12}_{-11} events, which corresponds to $\mathscr{B}(B^0 \to D^{*-} \tau^+ \nu) = 2.02^{+0.40}_{-0.37}(stat) \pm 0.37(syst)\%$. This value is consistent with Standard model expectations. Including systematic uncertainties, the significance of this result is 5.2σ.

4. Measurement of $B \to D^{(*)} \tau \nu$ using hadronic tag

Measurements of the decays $B \to D\tau\nu$ suffer from large cross feeds from $B \to D^*\tau\nu$ decays. Therefore it is an efficient approach to measure both decays containing a D and a D^* meson within one analysis.

One B meson is reconstructed in purely hadronic decay modes. For B^+ reconstruction, the modes $B^+ \to \bar{D}^{(*)0}\pi^+$, $B^+ \to \bar{D}^{(*)0}\rho^+$, $B^+ \to \bar{D}^{(*)0}a_1^+$ and $B^+ \to \bar{D}^{(*)0}D_s^{(*)+}$ are used, while B^0 candidates are obtained in the channels $B^0 \to D^{(*)-}\pi^+$, $B^0 \to D^{(*)-}\rho^+$, $B^0 \to D^{(*)-}a_1^+$ and $B^0 \to D^{(*)-}D_s^{(*)+}$. The selection of the B_{tag} candidates is based on the beam-constraint mass $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - p_{\text{tag}}^2}$ and $\Delta E = E_{\text{tag}} - E_{\text{beam}}$, where E_{tag} (p_{tag}) is the energy (spatial momentum) of the B_{tag} candidate in the c.m. system and E_{beam} is the beam energy. Events satisfying $5.27 < M_{\text{bc}} < 5.29 \text{GeV}/c^2$ and $-80 < \Delta E < 60 \text{MeV}$ are considered to be well reconstructed B events.

In the remaining event, a $D^{(*)}$ meson is reconstructed and a light lepton (electron or muon) emitted by the τ decay $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ is looked for. D candidates are reconstructed in the channels $\bar{D}^0 \to \{K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^+\pi^-\pi^-, K^+\pi^+\pi^-\pi^-\pi^0, K_S^0\pi^0, K_S^0\pi^+\pi^-, K_S^0\pi^+\pi^-\pi^0\}$ and $D^- \to \{K^+\pi^-\pi^-, K^+\pi^-\pi^-\pi^0, K_S^0\pi^-\}$. The invariant mass of the D candidates has to be within 5σ of the nominal D mass. The reconstructed D^* modes are $D^{*+} \to D^0\pi^+$, $D^{*+} \to D^+\pi^0$, $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$. The mass difference $\Delta m = m_{D\pi(\gamma)} - m_D$ has to be within 5σ of the nominal value. The momentum of the lepton candidate, p_ℓ, is required to be below $1.2 \text{GeV}/c$.

Mode	$R = \mathscr{B}(B \to D^{(*)}\tau^+\nu)/\mathscr{B}(B \to D^{(*)}\ell^+\nu)$	Statistical significance
$B^+ \to \bar{D}^0\tau^+\nu$	$0.70^{+0.19}_{-0.18}(stat)^{+0.11}_{-0.09}(syst)$	3.8σ
$B^+ \to \bar{D}^{*0}\tau^+\nu$	$0.47^{+0.11}_{-0.10}(stat)^{+0.06}_{-0.07}(syst)$	3.9σ
$B^0 \to D^-\tau^+\nu$	$0.48^{+0.22}_{-0.19}(stat)^{+0.06}_{-0.05}(syst)$	2.6σ
$B^0 \to D^{*-}\tau^+\nu$	$0.48^{+0.14}_{-0.12}(stat)^{+0.06}_{-0.04}(syst)$	4.7σ

Table 1: The measured ratios $R(D^{(*)}\tau^+\nu) = \mathscr{B}(B \to D^{(*)}\tau^+\nu)/\mathscr{B}(B \to D^{(*)}\ell^+\nu)$ for each of the four signal modes and the statistical significance of the respective signal yields.

In signal events, one finds large values of missing mass, defined by $M^2_{\mathrm{miss}} = (E_{\mathrm{tag}} - E_D - E_\ell)^2 - (\vec{p}_{\mathrm{tag}} - \vec{p}_D - \vec{p}_\ell)^2$. The remaining, unmatched energy in the detector, $E^{\mathrm{ECL}}_{\mathrm{extra}}$, peaks at small values for signal. These two variables discriminate signal from background and a two-dimensional unbinned extended likelihood fit to these two distributions is used to extract the signal.

Due to large background contributions from $B \to D^{(*)}\ell^+\nu$ decays, the branching ratios are not determined directly. Rather, the ratio $R(D^{(*)}\tau^+\nu) = \mathscr{B}(B \to D^{(*)}\tau^+\nu)/\mathscr{B}(B \to D^{(*)}\ell^+\nu)$ is determined, which can then be multiplied with the world average of the ℓ modes to obtain the branching ratio of the τ modes. $R(D^{(*)}\tau^+\nu)$ is suited for investigating possible impacts due to a charged Higgs, since it depends neither on the decay constant f_B nor on the value of $\mathscr{B}(B \to D^{(*)}\ell^+\nu)$. The results are shown in Tab. 1.

5. Conclusions

We presented three analyses based on data samples collected by the Belle detector at the KEKB e^+e^- asymmetric energy collider: the determination of $\mathscr{F}(1)|V_{cb}|$ and the form factor parameters ρ^2, R_1 and R_2 in the exclusive decay $B^+ \to D^{*0}\ell^+\nu$, the observation of the decay $B^0 \to D^{*-}\tau^+\nu$ and the simultaneous measurement of the branching ratios of the four decays $B^+ \to \bar{D}^{(*)0}\tau^+\nu$ and $B^0 \to D^{(*)-}\tau^+\nu$.

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