PROCEEDINGS OF SCIENCE

Semileptonic B and B_s decays at Belle

PoS(EPS-HEP2015)554

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Based on the large data sample accumulated by the Belle experiment at the KEKB asymmetric energy e^+e^- collider at KEK, Japan, we present new results on semileptonic $B_{(s)}$ meson decays. Semileptonic decays $B \to X_c \ell \nu_\ell$ are the preferred modes for determining the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$, a fundamental parameter of the Standard Model. The decay $B \to D\ell\nu_\ell$ is measured for the first time with the full Belle data sample recorded at the $\Upsilon(4S)$ resonance. The preliminary results are $\eta_{\rm EW}|V_{cb}| = (40.93 \pm 1.33) \times 10^{-3}$ using the the parameterization of Caprini, Lelouch and Neubert and using the form-factor prediction $\mathcal{G}(w=1) = 1.0541 \pm 0.0083$ calculated by FNAL/MILC, and $\eta_{\rm EW}|V_{cb}| = (42.09 \pm 1.07) \times 10^{-3}$ using a combined fit of lattice data from FNAL/MILC and HPQCD with the Boyd, Grinstein and Lebed parameterization.
Measurements of semileptonic B_s decays provide a test of QCD calculations entering the $|V_{cb}|$ extraction. The heaviness of the s quark compared to the u and d quarks facilitates the theoretical description of B_s decays. We present results of branching fraction measurements of the semi-inclusive $B_s \to D_s^{(*)} X \ell \nu_\ell$ decays: $\mathcal{B}(B_s \to D_s X \ell \nu) = (8.2 \pm 0.2_{\rm stat} \pm 0.6_{\rm syst} \pm 1.4_{N_{B_s}})\%$ and $\mathcal{B}(B_s \to D_s^* X \ell \nu) = (5.4 \pm 0.4_{\rm stat} \pm 0.4_{\rm syst} \pm 0.9_{N_{B_s}})\%$. We also determine the number of B_s meson pairs produced at Belle as $N_{B_s\bar{B}_s} = [6.93 \pm 0.18(\mathrm{stat}) \pm 0.52(\mathrm{syst}) \pm 0.51(\mathrm{ext})] \times 10^6$.

The European Physical Society Conference on High Energy Physics
22-29 July 2015
Vienna, Austria

*Speaker.

1. Introduction

We present two measurements performed at the Belle experiment at the asymmetric electron positron collider KEKB [1]. First, we show the analysis of the decay $B \to D\ell\nu_\ell$ ($\ell = e,\mu$) which is used to measure $|V_{cb}|$. Second, we determine the branching fractions of $B_s \to D_s^{(*)} X\ell\nu_\ell$ ($\ell = e,\mu$), which have never been measured directly before and offer both a verification of theoretical models and a preparation for future measurements of $B_s \to D_s^{(*)}\ell\nu_\ell$.

2. Belle detector and data sets

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 threshold 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 super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [2].

Over 1000 fb^{-1} data were recorded at Belle, of those are 711 fb^{-1} at the $\Upsilon(4S)$ resonance which decays dominantly into a $B\bar{B}$ pair and 121 fb^{-1} at the $\Upsilon(5S)$ resonance which can also decay into a $B_s\bar{B}_s$ pair.

3. $B \to D\ell\nu_\ell$

We present the preliminary measurement of $B \to D\ell\nu_\ell$ with the full Belle data sample of 711 fb^{-1} at the $\Upsilon(4S)$ resonance. The differential decay width of the $B \to D\ell\nu_\ell$ decay is given by:

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2(w^2-1)^{3/2}\eta_{\text{EW}}^2|V_{cb}|^2|\mathcal{G}(w)|^2 \,, \tag{3.1}$$

where $w = v_B \cdot v_D$ is the product of the 4-velocities of the B and D meson and ranges from 1.0 to ~ 1.6. The electroweak correction factor η_{EW} takes into account residual interactions between the hadronic and leptonic currents [3]. $\mathcal{G}(w)$ is a form factor describing the hadronic current of the decay. Different parameterizations of $\mathcal{G}(w)$ are available in the literature. The most commonly used is the one of Caprini, Lelouch and Neubert (CLN) [4], which approximates the form factor based on multiple dispersive constraints and spin- and heavy-quark symmetries. A model-independent parameterization which relies only on QCD dispersion relations has been proposed by Boyd, Grinstein and Lebed (BGL) [5].

The neutrino from the semileptonic decay can not be directly detected. To regain the lost information a technique called hadronic tagging is applied which reconstructs the non-signal side B meson (B_{tag}) from the $\Upsilon(4S)$ resonance in a hadronic mode. This not only reduces background, it also gives access to the kinematics of the neutrino via 4-momentum conservation. Hadronic tagging at Belle applies a neural network based algorithm [6] and reconstructs 1104 different hadronic decay topologies.

We search $B \to D\ell\nu_\ell$ decays in events with a reconstructed B_{tag} from the charged tracks and neutral energy measurements not already assigned to B_{tag}. Lepton candidates are charged tracks

PoS(EPS-HEP2015)554

with a sufficiently high likelihood of being an electron or muon based on the particle identification possibilities of the Belle detector.

Excluding the $B_{\rm tag}$ particles and the charged lepton, we search the remaining particles in the event for D^+ meson decays into the following 10 hadronic final states: $K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^0$, $K^+K^-\pi^+$, $K^0_SK^+$, $K^0_S\pi^+\pi^+\pi^-$, $\pi^+\pi^0$, $\pi^+\pi^+\pi^-$, and $K^-\pi^+\pi^+\pi^+\pi^-$. Neutral D mesons are reconstructed in 13 different decay modes to: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^-$, $K^0_S\pi^+\pi^-\pi^0$, $K^0_S\pi^0$, K^+K^-, $\pi^+\pi^-$, $K^0_SK^0_S$, $\pi^0\pi^0$, $K^0_S\pi^0\pi^0$, $K^-\pi^+\pi^+\pi^-\pi^0$, and $\pi^+\pi^-\pi^0$.

One then compares the 4-momenta of the reconstructed particles to the known 4-momentum of the electron-positron beam and calculates the square of the invariant missing mass $M^2_{\rm miss} = (P_{\rm LER} + P_{\rm HER} - P_{B_{\rm tag}} - P_D - P_\ell)^2$. In genuinely reconstructed decays the only missing momentum belongs to the undetectable neutrino and $M^2_{\rm miss}$ shows a prominent peak at the neutrino mass of approximately 0, see for example Fig. 1. We use this distinct shape to separate signal from background. The main background source are $B \to D^*\ell\nu_\ell$ decays, other backgrounds are relatively small. A binned extended maximum likelihood fit [7] is used to extract the number of signal events. We model the different components with Monte Carlo (MC) templates and leave signal and background from $B \to D^*\ell\nu_\ell$ floating while other smaller backgrounds are fixed to their MC expectations. We perform these yield extraction fits separately for charged and neutral B mesons, electrons and muons, and in 10 different w bins covering the entire kinematic range. All in all we reconstruct 16992 signal events. Fits in different subranges of w in the sub-sample $B^0 \to D^-e^+\nu_e$ can be seen in Fig. 1. From the signal yields we then calculate the differential decay widths $\Delta\Gamma_i/\Delta w$ in the different w-bins and average over B-meson charge and lepton type.

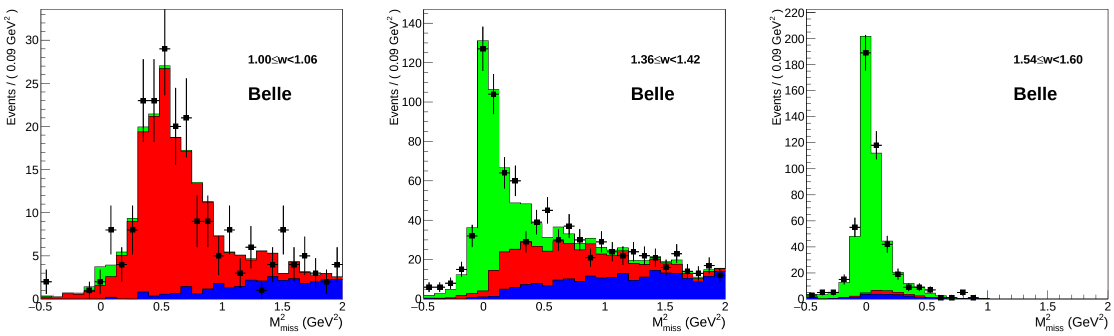

Figure 1: Preliminary fits to the missing mass squared distribution in three bins of w for the $B^0 \to D^-e^+\nu_e$ sub-sample. Points with error bars are Belle data. The components in the histograms are (from top to bottom) the $B \to D\ell\nu_\ell$ signal (green), the $B \to D^*\ell\nu_\ell$ cross-feed background (red), and other backgrounds (blue).

Fig. 2 shows the measured differential decay width spectrum and two different fits to its data. The differential decay width that is shown and used in the fits is a weighted average of the sub-samples using the inverse statistical variances as weights. Our first fit uses the CLN parameterization to determine $\eta_{\rm EW}\mathcal{G}(w=1)|V_{cb}|$. Using $\mathcal{G}(w=1)$ as measured by FNAL/MILC [8] this results in $\eta_{\rm EW}|V_{cb}| = (40.93 \pm 1.33) \times 10^{-3}$ (preliminary).

While this has been the preferred method for a long time, recent developments in lattice QCD have lead to form factor measurements at additional kinematic points other than $w = 1$. We perform a combined fit of the lattice data by FNAL/MILC [8] and HPQCD [9] and our measured $\Delta\Gamma/\Delta w$ spectrum following the methodology described in [8] and determine $\eta_{\rm EW}|V_{cb}| = (42.09 \pm 1.07) \times 10^{-3}$ (preliminary). The main difference between the two values does not come from the parameterization choice but rather the added constraint on the form factor slope from the additional lattice data points.

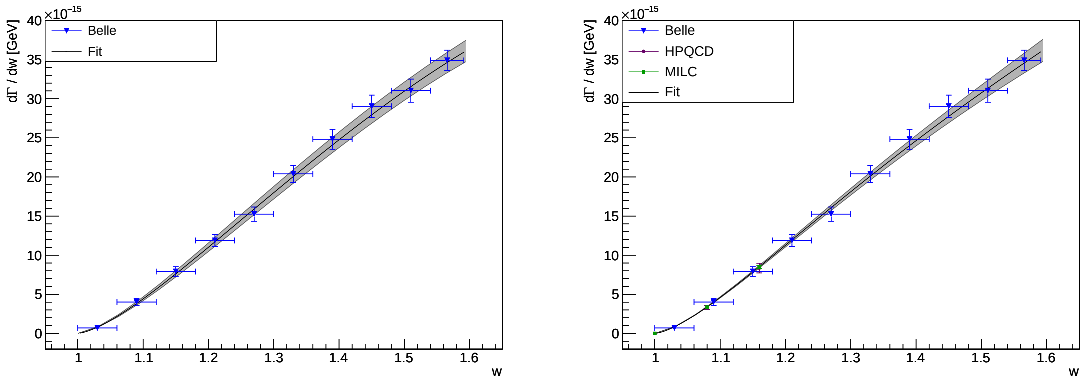

Figure 2: Differential width of $B \to D\ell\nu_\ell$ and result of the CLN fit to Belle data (left) and combined fit to experimental and lattice QCD (FNAL/MILC and HPQCD) data (right). The horizontal error bars on Belle data indicate the w-bin width. The solid curve corresponds to the result of the fit and the shaded area to its uncertainty.

4. $B_s \to D_s^{(*)} X \ell \nu_\ell$

Besides the 711 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance, Belle also gathered 121 fb^{-1} at the $\Upsilon(5S)$ resonance which by its higher energy allows production of $B_s\bar{B}_s$ pairs and the study of their decays. B_s mesons offer different advantages compared to B mesons, such as easier theoretical description due to the higher mass of the spectator quark. B_s measurements are very useful to verify the results from B measurements and to test predictions of QCD calculations. We present the first measurement of the semi-inclusive decays $B_s \to D_s^{(*)} X \ell \nu_\ell$ [10], where X denotes zero or more additional particles.

The analysis is based on reconstructed $D_s^- \ell^+$ and $D_s^{*-} \ell^+$ pairs. D_s mesons are reconstructed in the clean decay mode to $\phi(K^+K^-)\pi^-$ and D_s^* mesons are reconstructed in their dominant mode $D_s^* \to D_s\gamma$ by adding a reconstructed photon to a D_s, where the D_s is required to have a reconstructed mass between 1953.5 and 1983.5 MeV. Combinatorial background is reduced by applying a mass range for the ϕ meson: $1004\,\text{MeV} \leq m_\phi \leq 1034\,\text{MeV}$. The $D_s^{(*)}$ mesons are then combined with a lepton of opposite charge.

The number of genuinely reconstructed $D_s^{(*)}$ mesons can be measured by fits to the distribution of the reconstructed D_s mass; or for the D_s^* by fitting $\Delta m = m_{D_s^*} - m_{D_s}$; see Fig. 3. The shape of genuine D_s is modeled with a sum of two Gaussian functions with a common mean and the background is modeled with a first order Chebychev polynomial. The PDF of D_s^* is modeled with a sum of a Gaussian function and a Crystal Ball function with a common mean and for misreconstructed D_s^* a third order Chebychev polynomial is used.

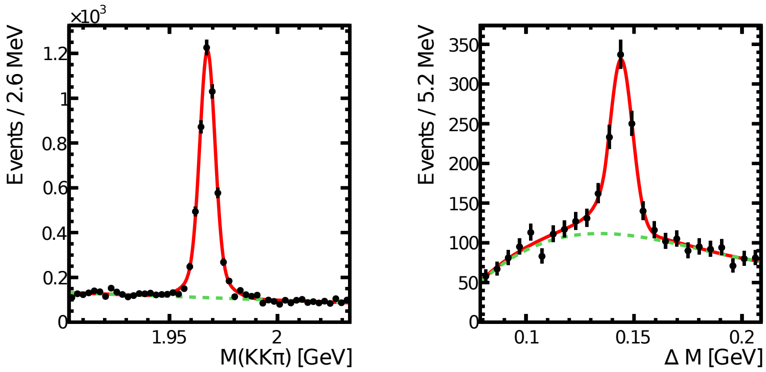

Figure 3: Fit to the D_s mass in the channel $B_s \to D_s X e \nu$ (left) and fit to $\Delta m = m_{D_s^*} - m_{D_s}$ in the channel $B_s \to D_s^* X e \nu$ (right). Events are from region **C** (for details on the regions refer to the main text).

Events containing a true $D_s^{(*)}$ meson can be organized into five categories: 1. background from $c\bar{c}$ continuum events, 2. $B_s \to D_s^{(*)} K \ell \nu$ events, 3. wrong-side combinations where the $D_s^{(*)}$ meson and the lepton candidate stem from different B_s decays, 4. other background where the lepton candidate stems either from a secondary decay or is a misreconstructed hadron, and 5. signal decays consisting of $D_s \ell \bar{\nu}$, $D_s^* \ell \bar{\nu}$ and $D_s^{**} \ell \bar{\nu}$ decays in the $D_s X \ell \nu$ channel; and $D_s^* \ell \bar{\nu}$ and $D_s^{**} \ell \bar{\nu}$ decays in the $D_s^* X \ell \nu$ channel.

Background (1) is determined from an off-resonance data sample and background (2) is estimated from MC simulation. The normalization of the remaining backgrounds and the signal component is determined by dividing the data sample into three regions according to the decay kinematics. The regions are defined using the lepton momentum p_ℓ^* and the variable

$$X_{\text{mis}} = \frac{E_{B_s}^* - (E_{D_s\ell}^* + p_{D_s\ell}^*)}{\sqrt{s/4 - m_{B_s}^2}} \tag{4.1}$$

where $E_{B_s}^*$ is the energy of the B_s meson in the center of mass (CM) system approximated by $\sqrt{s}/2$; $E_{D_s\ell}^* = |E_\ell^* + E_{D_s}^*|$ is the sum of the reconstructed energies in the CM system and $p_{D_s\ell}^* = |\vec{p}_\ell^* + \vec{p}_{D_s}^*|$ is the magnitude of the sum of the reconstructed lepton and D_s momenta in the CM system. The denominator of Eq. (4.1) corresponds to the B_s momentum in the CM system. Fig. 4 shows the X_{mis} distribution of correctly reconstructed D_s mesons in the $B_s \to D_s X e \nu$ sample. Signal events peak in the region $X_{\text{mis}} > -1$.

The reconstructed events are separated into 3 distinct regions, each of which enhances a certain component. Region **A** ($X_{\text{mis}} < -1$) enhances wrong side background, region **B** ($X_{\text{mis}} > -1$, $p^* < 1.4\,\text{GeV}$) enhances other background and region **C** ($X_{\text{mis}} > -1, p^* > 1.4\,\text{GeV}$) enhances signal. The separation can be seen in Fig. 4. The signal and the two remaining background components (3 and 4) form 3 degrees of freedom. Counting the events in each region constitutes 3 equations, which can be solved in order to determine the signal yields.

From the number of signal events the branching fraction can be calculated by:

$$\mathscr{B} = \frac{N_{\text{signal}}}{\varepsilon \cdot \mathscr{B}(D_s^- \to \phi(K^+K^-)\pi^-) \cdot N_{B_s}}, \tag{4.2}$$

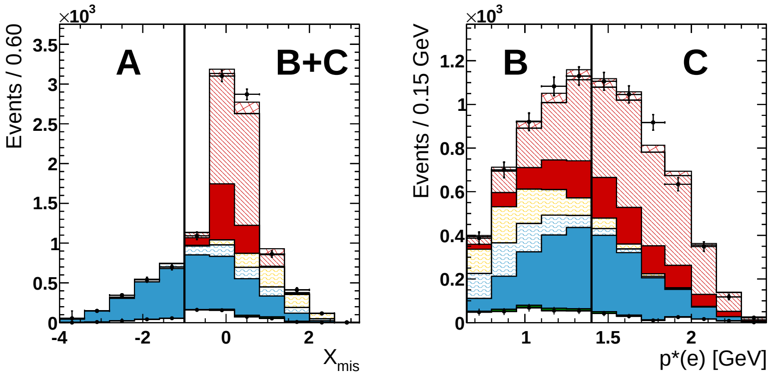

Figure 4: X_{mis} and lepton momentum in the center of mass frame for the sample $B_s \to D_s X e \nu$. White is continuum background, green $B_s \to D_s^{(*)} K \ell \nu$ decays, blue describes different kinds of wrong side background while yellow contains "other background" and red denotes the various signal components: solid red is $B_s \to D_s \ell \bar{\nu}$, hatched red is $B_s \to D_s^* \ell \bar{\nu}$ and crosshatched red is $B_s \to D_s^{**} \ell \bar{\nu}$. The letters "A","B" and "C" denote the 3 signal regions used in the counting experiment.

where ε is the efficiency of the reconstruction and N_{B_s} is the number of B_s meson pairs.

We measure the following values: $\mathscr{B}(B_s \to D_s X \ell \nu) = (8.2 \pm 0.2_{\text{stat}} \pm 0.6_{\text{syst}} \pm 1.4_{N_{B_s}})\%$ and $\mathscr{B}(B_s \to D_s^* X \ell \nu) = (5.4 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}} \pm 0.9_{N_{B_s}})\%$. Alternatively, by estimating the $B_s \to D_s^{(*)} X \ell \nu_\ell$ branching fraction with $\mathscr{B}_{\text{est}}(B_s \to D_s X \ell \nu) = (8.6 \pm 0.5)\%$ we determine the number of B_s meson pairs produced at Belle as $N_{B_s \bar{B}_s} = [6.93 \pm 0.18(\text{stat}) \pm 0.52(\text{syst}) \pm 0.51(\text{ext})] \times 10^6$.

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