PROCEEDINGS OF SCIENCE

$B \to X_c \ell \nu$ and $B \to X_s \gamma$ Moments from Belle

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The latest Belle measurements of the lepton energy and hadron mass moments in $B \to X_c \ell \nu$ decays and photon energy moments in $B \to X_s \gamma$ decays are presented. All measurements are based on the data collected near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy e^+e^- collider.

International Europhysics Conference on High Energy Physics
July 21st - 27th 2005
Lisboa, Portugal

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PoS(HEP2005)209

1. Introduction

The extraction of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ [1] from inclusive semileptonic decays is based on the operator product expansion, which makes use of the heavy quark expansion [2]. The leading term in this expansion of $\Gamma(B \to X_c \ell \nu)$ in powers of $1/m_b$ is the spectator model rate. Non-perturbative corrections arise at the order $1/m_b^2$.

The $1/m_b$ corrections are parametrized by quark masses and matrix elements of higher dimensional operators which are poorly known from theory alone. Given the current experimental uncertainty in the semileptonic B branching ratio, the limited knowledge of these non-perturbative parameters has become a limiting factor in the extraction of $|V_{cb}|$.

Recently, much progress has been made in the use of lepton energy and hadron mass moments in $B \to X_c \ell \nu$ and photon energy moments in $B \to X_s \gamma$ for determining these parameters from the data [3, 4]. In this article, we will review the Belle measurements of these moments, which are currently under preparation. All analyses are based on the data recorded with the Belle detector [5] at the asymmetric energy e^+e^- collider KEKB, operating at a center-of-mass (c.m.) energy near the $\Upsilon(4S)$ resonance.

2. Moments in $B \to X_c \ell \nu$ decays

The electron energy and the hadron mass moment analyses are based on an integrated luminosity of 140 fb^{-1} (152 million $B\bar{B}$ events). Another 15 fb^{-1} taken 60 MeV below the resonance are used to subtract the non-$B\bar{B}$ (continuum) background. Generic $B\bar{B}$ Monte Carlo (MC) data equivalent to 2.4 times the on-resonance luminosity are also used.

The hadronic decay of one B meson ($B_{\rm tag}$) is reconstructed using the decay modes $B^+ \to \bar{D}^{(*)0}\pi^+, \bar{D}^{(*)0}\rho^+, \bar{D}^{(*)0}a_1^+$ and $B^0 \to D^{(*)-}\pi^+, D^{(*)-}\rho^+, D^{(*)-}a_1^+$ [6]. $B_{\rm tag}$ candidates are selected based on their beam-constrained mass $M_{\rm bc} = \sqrt{(E_{\rm beam})^2 - (\vec{p}_B)^2}$ and the energy difference $\Delta E = E_B - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy in the c.m. system and $\vec{p}_B$ and E_B are the 3-momentum and the energy of the $B_{\rm tag}$ candidate in the same frame, respectively. After subtraction of the combinatorial background, $63,155 \pm 931$ $(40,032 \pm 475)$ B^+ (B^0) tags are found.

In the electron moment analysis, semileptonic decays of the other B meson ($B_{\rm signal}$) are selected by searching for an identified electron with $p > 4$ GeV/c (in the B rest frame) within the particles remaining in the event. At Belle, the responses of the electromagnetic calorimeter, the central drift chamber (dE/dx) and the aerogel threshold Čerenkov counters are combined to provide clean electron identification. For B^+ tags, the electron charge is required to be compatible with a prompt B decay. Energy losses due to bremsstrahlung radiation are partially recovered by combining the electron with photons candidates ($E_\gamma < 1$ GeV) found within a 0.05 radian cone around the electron direction.

The different backgrounds (secondary electrons, hadron fakes, misreconstructed tags and continuum) are estimated using MC and off-resonance real data (for continuum). The signal purity at $p > 0.4$ GeV/c is about 64.5%. The finite detector resolution in the background subtracted electron energy spectrum is removed using the SVD algorithm [7]. The unfolded spectrum is corrected for QED radiative effects using the PHOTOS algorithm [8].

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$E_{\rm cut}$ (GeV)	$\langle E_\ell \rangle$ (MeV)	$\langle (E_\ell - \langle E_\ell \rangle)^2 \rangle$ (10^{-3}GeV^2)	$\langle (E_\ell - \langle E_\ell \rangle)^3 \rangle$ (10^{-6}GeV^3)
0.4	$1397.7 \pm 5.1 \pm 5.4$	$172.8 \pm 2.4 \pm 2.2$	$-22.4 \pm 2.3 \pm 0.7$
0.6	$1431.8 \pm 4.8 \pm 4.3$	$148.2 \pm 1.9 \pm 1.2$	$-11.6 \pm 1.7 \pm 0.6$
0.8	$1481.0 \pm 4.4 \pm 3.4$	$119.9 \pm 1.6 \pm 0.9$	$-3.9 \pm 1.2 \pm 0.6$
1.0	$1550.8 \pm 4.0 \pm 2.9$	$89.0 \pm 1.2 \pm 0.4$	$0.5 \pm 0.8 \pm 0.3$
1.2	$1631.6 \pm 3.6 \pm 2.2$	$61.9 \pm 0.9 \pm 0.6$	$1.9 \pm 0.5 \pm 0.2$
1.5	$1775.8 \pm 3.0 \pm 2.3$	$29.4 \pm 0.6 \pm 0.3$	$1.6 \pm 0.2 \pm 0.1$

Table 1: Moments of the electron energy spectrum in $B \to X_c e \nu$ decays for the different electron energy thresholds. The first error is statistical, the second is systematic.

$p_{\rm cut}$ (GeV/c)	$\langle M_X^2 \rangle$ (GeV/c^2)	$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle$ (GeV$^2/c^4$)
0.7	$4.383 \pm 0.037 \pm 0.051$	$1.605 \pm 0.179 \pm 0.322$
0.9	$4.330 \pm 0.033 \pm 0.041$	$1.317 \pm 0.144 \pm 0.236$
1.1	$4.277 \pm 0.029 \pm 0.035$	$1.013 \pm 0.113 \pm 0.161$
1.3	$4.173 \pm 0.028 \pm 0.037$	$0.634 \pm 0.095 \pm 0.105$
1.5	$4.132 \pm 0.030 \pm 0.031$	$0.591 \pm 0.110 \pm 0.088$

Table 2: Moments of the M_X^2 distribution in $B \to X_c \ell \nu$ decays for the different lepton momentum thresholds. The first error is statistical, the second is systematic.

The truncated first three moments, $\langle E_e \rangle$, $\langle (E_e - \langle E_e \rangle)^2 \rangle$ and $\langle (E_e - \langle E_e \rangle)^3 \rangle$, of the electron energy spectrum in the B rest frame are measured for six electron energy thresholds, Table 1. The main contributions to the systematic uncertainty are from electron identification, background estimation and $B \to X_c \ell \nu$ model dependence.

The hadron mass moment analysis also uses the same sample of fully reconstructed events. Semileptonic decays of the signal-side B meson are selected by requiring exactly one identified lepton (electron or muon) within the remaining particles in the event. Muons are identified in the instrumented iron flux-return (KLM) located outside of the coil. To reconstruct the hadronic system recoiling against $\ell \nu$, the neutrino 4-momentum is infered from the missing momentum and energy in the event. Events in which the missing 4-momentum misrepresents the neutrino momentum are rejected, $M^2_{\rm miss} < 3$ GeV^2/c^4, and the neutrino 4-momentum is taken to be $(|\vec{p}_{\rm miss}|, \vec{p}_{\rm miss})$. The hadronic invariant mass squared is calculated as $M_X^2 = |(p_{\rm LER} + p_{\rm HER}) - p_{B_{\rm tag}} - p_\ell - p_\nu|$, where the labels LER and HER refer to the colliding beams. The M_X^2 resolution (defined as half width at the half maximum) obtained in this way is about 800 MeV$^2/c^4$.

As in the electron energy moment analysis, backgrounds in the M_X^2 distribution are subtracted and the detector resolution is unfolded. The first and the second moments of M_X^2, $\langle M_X^2 \rangle$ and $\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle$, are measured for five lepton momentum thresholds in the B rest frame, Table 2. Systematic uncertainties arise from detector and background modeling, unfolding and $B \to X_c \ell \nu$ model dependence.

The correlation coefficients between the different moment measurements in Tables 1 and 2 can be found in Refs. [9] and [10].

$E_{\rm cut}$ (GeV)	$\langle E_\gamma \rangle$ (GeV)	$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle$ (GeV^2)
1.8	$2.292 \pm 0.027 \pm 0.033$	$0.0305 \pm 0.0079 \pm 0.0099$
1.9	$2.309 \pm 0.023 \pm 0.023$	$0.0217 \pm 0.0060 \pm 0.0055$
2.0	$2.324 \pm 0.019 \pm 0.016$	$0.0179 \pm 0.0050 \pm 0.0036$
2.1	$2.346 \pm 0.017 \pm 0.010$	$0.0140 \pm 0.0046 \pm 0.0024$
2.2	$2.386 \pm 0.018 \pm 0.005$	$0.0091 \pm 0.0045 \pm 0.0025$
2.3	$2.439 \pm 0.020 \pm 0.004$	$0.0036 \pm 0.0045 \pm 0.0028$

Table 3: Moments of the E_γ distribution in $B \to X_s \gamma$ decays for the different photon energy thresholds. The first error is statistical, the second is systematic.

3. Moments in $B \to X_s \gamma$ decays

The measurement of the photon energy moments in $B \to X_s \gamma$ decays is based on Belle's published $B \to X_s \gamma$ spectrum [11], obtained with 140 fb^{-1} of $\Upsilon(4S)$ data. No attempt is made to correct for the part of the spectrum that is not measured with a satisfactory precision, *i.e.* below photon energies of 1.8 GeV.

The truncated first and second moments, $\langle E_\gamma \rangle$ and $\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle$, are calculated from the efficiency corrected spectrum and corrections for the small B meson boost in $\Upsilon(4S)$ frame, the 100 MeV wide binning and finite energy resolution are applied. The residual bias is estimated using $B \to X_s \gamma$ signal MC and corrected for.

The first and second photon energy moments for six different photon energy thresholds are given in Table 3. The main contributions to the systematic error are from systematic uncertainty in the original $B \to X_s \gamma$ spectrum, the bias correction (model uncertainty) and the energy resolution. The correlation coefficients between the different moment measurements are tabulated in Ref. [12].

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