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SEMILEPTONIC B-MESON DECAYS

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We give an overview about results of studies of semileptonic B-meson decays collected with the BABAR and Belle detectors at the PEP-II and the KEKB e^+e^--storage rings.

We present recent results on hadronic moments measured in inclusive $B \to X_c l\nu$ and $B \to X_u l\nu$ decays and extracted heavy quark masses m_b and m_c and dominant non-perturbative Heavy Quark Expansion (HQE) parameters.

We also report the measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ in inclusive and in exclusive semileptonic B-meson decays.

We describe the studies of the form-factor parameters for the decay $B^0 \to D^{*-}l^+\nu$ and present the measurement of the $B^0 \to \pi^- l^+ \nu$ form-factor shape.

1 Introduction

The study of the semileptonic B-meson decays is the most accessible and cleanest way to determine the CKM matrix elements $|V_{cb}|$ and V_{ub}. These decays also provide experimental access to study the QCD form-factors, heavy quark masses, and HQE parameters. The theoretical description of semileptonic B-meson decays at the parton level is very simple because there is no interaction between leptonic and hadronic currents. At the hadron level one needs to introduce corrections due to the strong interaction between quarks. Especially in the description of the inclusive B-meson decays the motion of the b-quark inside the B-meson plays a crucial role. All these effects are described in the frameworks of Heavy Quark Effective Theory (HQET) and Latice QCD (LQCD).

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2 Studies of $B \to X_c l\nu$ decays

2.1 Measurements of the hadronic moments

The inclusive $B \to X_c l\nu$ decays are described by the total semileptonic rate Γ_{SL} given as: $\Gamma_{SL} \propto |V_{cb}|\ ^2(1 + A_{ew})A_{pert}(r, \mu)A_{nonpert}$, where $r = m_c^2/m_b^2$.
In additional to electroweak (A_{ew}) and perturbative (A_{pert}) corrections, one needs to take into account also non-perturbative ($A_{nonpert}$) contributions. At leading order, the non-perturbative corrections are proportional to $1/m_b^2$ and are controlled by matrix elements μ_π^2 and μ_G^2. At order of $1/m_b^3$ there are two additional terms called Darwin and LS terms characterized by parameters ρ_D^3 and ρ_{LS}^3. In order to extract the CKM matrix elements $|V_{cb}|$ from the total branching fraction $\mathcal{B}\ (B \to X_c l\nu\ )$ the input of the HQE parameters and heavy quark masses is required:
$|V_{cb}|\ \propto \sqrt{\frac{\mathcal{B}\ (B\to X_c l\nu\ )}{\tau_B}} f_{HQE}(m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3)$.

The HQE parameters can be determined by measuring several hadronic moments. On the experimental side we are able to measure hadronic mass $\langle m_X^k \rangle$, lepton $\langle E_l^k \rangle$ and photon $\langle E_\gamma^k \rangle$ energy, and mixed $\langle n_X^k \rangle$ hadronic moments. All these moments also can be predicted by theory [1]. The values for $|V_{cb}|$, quark masses m_c and m_b, and the dominant non-perturbative HQE parameters μ_π^2, μ_G^2, ρ_D^3, and ρ_{LS}^3 can be extracted from a combined fit to the hadronic moments.

In the recent BABAR analysis [2] the hadronic mass moments are measured up to sixth order. The eight mass moments combined with 13 E_l and six E_γ moments are used to perform the combined HQE fit. The following fit results have been obtained in kinetic scheme [1, 3]:

$$
\begin{aligned}
m_b &= (4.552 \pm 0.038_{\rm exp} \pm 0.040_{\rm theo})\ \mathrm{GeV} \\
\mu_\pi^2 &= (0.471 \pm 0.034_{\rm exp} \pm 0.065_{\rm theo})\ \mathrm{GeV}^2 \\
|V_{cb}| &= (41.88 \pm 0.44_{\rm exp} \pm 0.35_{\rm theo} \pm 0.59_{\Gamma_{SL}}) \times 10^{-3}
\end{aligned}
$$

There is also a similar measurement of hadronic moments performed by the Belle collaboration [4]. The extracted results are based on seven mass, 14 E_l and four E_γ moments. The Fit was performed in both the kinetic and the 1S scheme [5].

2.2 Study of $B^0 \to D^{*-} l^+ \nu$ decay

The study of the decay $B^0 \to D^{*-} l^+ \nu$ is interesting in many respects. This decay allows a simultaneous measurement of the CKM matrix element $|V_{cb}|$, of the branching fraction

$\mathcal{B}$ ($B^0 \to D^{*-}l^+\nu$) and of the three form-factor parameters $\rho^2_{D^*}$, R_1, and R_2. The fully differential decay rate can be characterized by three decay angles and a lorentz-invariant variable ω which represents a boost of the D^*-meson in the B-meson rest frame. After integrating over all angles one obtains the rate as a function of ω:

$$\frac{d\Gamma}{d\omega} = \frac{G_F^2}{48\pi^3 m^3_{D^*}}[m_B - m_{D^*}]^2 G(w) F^2(w) |V_{cb}|^{\ 2},$$

where $G(\omega)$ is a known phase space factor and $F^2(\omega)$ is the form-factor parameter in terms of D^* helicity amplitudes.
The effect of the strong interaction in $B^0 \to D^{*-}l^+\nu$ decays can be parameterized by two axial and one vector form-factors [6]. Due to the heavy quark symmetry these three form-factors are related to each other, but there are still three free parameters R_1, R_2, and $\rho^2_{D^*}$ which must be determined from experiment.

The recent *BABAR* analysis [7] performs an extended least-squares fit to the one-dimensional projections of the $B^0 \to D^{*-}l^+\nu$ decay rate. The technique of this fit allows to measure the values for $\mathcal{F}(1)|V_{cb}|$, $\rho^2_{D^*}$, R_1, and R_2 simultaneously. The results combined with previous *BABAR* measurements [8] are:

$$\begin{aligned} R_1(1) &= 1.327 \pm 0.131_{\rm stat} \pm 0.043_{\rm syst} \\ R_2(1) &= 0.859 \pm 0.077_{\rm stat} \pm 0.021_{\rm syst} \\ \rho^2_{D^*} &= 1.157 \pm 0.094_{\rm stat} \pm 0.027_{\rm syst} \\ \mathcal{F}(1)|V_{cb}| &= (34.7 \pm 0.4_{\rm stat} \pm 1.0_{\rm syst}) \times 10^{-3} \end{aligned}$$

Using an unquenched lattice calculation for $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$ [9] one obtains for $|V_{cb}|$: $|V_{cb}| = (37.8 \pm 0.4 \pm 1.1^{+1.2}_{-1.4}{}_{\mathcal{F}(1)}) \times 10^{-3}$.

3 Studies of $B \to X_u l\nu$ decays

3.1 $|V_{ub}|$ extraction from inclusive $B \to X_u l\nu$ decays

The study of inclusive $B \to X_u l\nu$ transitions offers the most accurate way to determine the CKM matrix element $|V_{ub}|$. This process is described by a local Operator Product Expansion (OPE), including perturbative and non-perturbative corrections.

The extraction of $|V_{ub}|$ is complicated by the large background from $B \to X_c l\nu$ decays, which have a rate about 50 times higher than that of charmles semileptonic decays.

Therefore, stringent kinematical constraints must be applied in order to differentiate between signal and background. This introduces a theoretical factor ζ, which describes the extrapolation from partial to the full kinematic phase space: $\Delta\mathcal{B}\ (B \to X_u l\nu\ ) = \tau_B |V_{ub}|\ ^2\zeta$. This factor ζ is predicted by theory and depends on the selected phase space. The applied kinematic cuts also introduce sensitivity to the effects of b-quark motion inside the B-meson, which are described by Shape Functions and are the dominant sources of the theoretical errors. The experimental challenge is to select such kinematic phase space, where the dominant charm background is suppressed and theoretical uncertainties are minimized. The following variables could be used: lepton energy E_l, neutrino-lepton invariant mass q^2, and the invariant mass of X_u system M_X.

BABAR and Belle provide results [10, 11] on the extraction of $|V_{ub}|$ from M_X spectrum below 1.55 GeV and 1.7 GeV respectively. In order to extract the value of $|V_{ub}|$: $|V_{ub}|\ ^2 = \Delta\Gamma_{ul\nu}(\Delta\Phi)/R(\Delta\Phi)$, the measured partial decay rate $\Delta\Gamma_{ul\nu}$ in the selected phase space region $\Delta\Phi$ has to be interpolated to the full phase space using theoretical calculations of $R(\Delta\Phi)$ for the partial rate in the selected phase space region.
The following numerical results have been obtained in the framework of the BLNP [12] calculation:

$$\begin{aligned} |V_{ub}| &= (4.27 \pm 0.16_{\rm stat} \pm 0.13_{\rm syst} \pm 0.30_{\rm theo}) \times 10^{-3} \qquad BABAR \\ |V_{ub}| &= (4.09 \pm 0.19_{\rm stat} \pm 0.20_{\rm syst}{}^{+0.14}_{-0.15}{}_{\rm theo} \pm 0.18_{\rm SF}) \times 10^{-3} \qquad \text{Belle.} \end{aligned} \tag{1}$$

3.2 Measurements of the hadronic mass moments

The HQE parameters and the b-quark mass can be also extracted from $B \to X_u l\nu$ transitions, however with significantly lower precision due to the smaller branching fraction $\mathcal{B}\ (B \to X_u l\nu\ )$ compared to $\mathcal{B}\ (B \to X_c l\nu\ )$. The advantage of a study of the spectral moments in $B \to X_u l\nu$ decays is that the moments are directly sensitive to m_b instead of to $m_b - m_c$, as in the case of $B \to X_c l\nu$ decays.

The current *BABAR* analysis [13] provides the measurements of the HQE parameters μ_π^2 and ρ_D^3, and the quark mass m_b from a study of M_X spectra in $B \to X_u l\nu$ decays. The results obtained from a fit to the first three moments of the M_X^2 spectrum are:

$$\begin{aligned} m_b &= (4.604 \pm 0.125_{\rm stat} \pm 0.193_{\rm syst} \pm 0.097_{\rm theo})\ \text{GeV} \\ \mu_\pi^2 &= (0.398 \pm 0.135_{\rm stat} \pm 0.195_{\rm syst} \pm 0.036_{\rm theo})\ \text{GeV}^2 \\ \rho_D^3 &= (0.102 \pm 0.017_{\rm stat} \pm 0.021_{\rm syst} \pm 0.066_{\rm theo})\ \text{GeV}^3 \end{aligned}$$

It is the first measurement of the b-quark mass m_b in $B \to X_u l\nu$ decays.

3.3 Study of $B^0 \to \pi^- l^+ \nu$ decay

In exclusive $B \to X_u l\nu$ decays the X_u system is explicitely reconstructed. The QCD predictions are presently more precise for $B^0 \to \pi^- l^+ \nu$ than for other exclusive $B \to X_u l\nu$ decays. The differential decay rate $d\Gamma(B \to \pi l\nu)$ is proportional to $|V_{ub} f_+(q^2)|^2$ where the form factor $f_+(q^2)$ depends on the momentum transfer squared q^2. To extract $|V_{ub}|$, the measured partial branching fraction $\Delta\mathcal{B}$ is divided by the normalized rate ζ, which is predicted from form-factor calculation: $|V_{ub}| = \frac{\sqrt{\Delta\mathcal{B}\ (B\to\pi l\nu)}}{\zeta\tau_B}$.

The unquenched latice QCD (HPQCD [14] , FNAL [15]) calculations are presently reliable only at large q^2. The light cone sum rules calculation (LCSR [16]) is based on approximations and is only valid at small q^2. All these calculations - including the quark model calculation (ISGW2 [17]) - result in large theoretical uncertainties for the form-factor. Experimental data can be used to discriminate between the various calculations by precisely measuring the $f_+(q^2)$ shape, thereby leading to a smaller theoretical uncertainty on $|V_{ub}|$.

We have performed a measurement [18] of the decay $B^0 \to \pi^- l^+ \nu$, where partial branching fractions are obtained in 12 bins of q^2, the form-factor shape is extracted, and the total branching fraction and $|V_{ub}|$ are obtained as $\mathcal{B} = (1.46 \pm 0.07_{\rm stat} \pm 0.08_{\rm syst}) \times 10^{-4}$ and $|V_{ub}| = (4.1 \pm 0.2_{\rm stat} \pm 0.2_{\rm syst}{}^{+0.6}_{-0.4}{}_{\rm FF}) \times 10^{-3}$.
The $f_+(q^2)$ form-factor shape fitted to the partial branching fractions is clearly incompatible with ISGW2 model where the unquenched LQCD calculation seems to be provide best description of our data.

4 Conclusion

In the last years there were lots of efforts on B-factories for better understanding of semileptonic B-meson decays. The CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ can be precisely measured ($\sigma(|V_{cb}|\ ) \sim 2\%$, $\sigma(|V_{ub}|\ ) \sim 9\%$) and competitive measurements of HQE parameters and quark masses m_b and m_c can be provided. For the first time in inclusive $B \to X_u l\nu$ decays the value m_b is measured, which provides a very good crosscheck to the measurements in $B \to X_c l\nu$ decays.

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