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B semileptonic decays @ DELPHI

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Abstract. Updated results on B semileptonic decays at the DELPHI experiment are presented. Measurements of b-hadron lifetimes, exclusive $\overline{\mathrm{B}}^0_d \to \mathrm{D}^{*+}\ell^-\overline{\nu}_\ell$ decays and inclusive moments of the hadronic mass distribution are encompassed here. They focus on a precise determination of the CKM matrix element V_{cb}.

1 Introduction

The best means to determine the CKM matrix element V_{cb} lies in measuring semileptonic decay widths of b-hadrons. Those decays are theoretically well described by the Heavy Quark Effective Theory (HQET) and the Operator Product Expansion (OPE) and have the experimental advantage of a lepton signature in the final state. At DELPHI, the experimental environment of Z decays provides the additional benefit of allowing a good vertex determination. The b semileptonic decay widths have been obtained from exclusive $\overline{\mathrm{B}^0} \to \mathrm{D}^{*+}\ell^-\overline{\nu}_\ell$ and inclusive $b \to c\ell^-\overline{\nu}_\ell$ processes. In both cases precise measurements of the involved branching ratios and b-hadron lifetimes are requisite.

2 Lifetimes

Accurate B^+, B^0 and mean b-hadron lifetimes have been measured in DELPHI by inclusively reconstructing the proper decay time of b-hadron [1]:

$$t = \frac{L\, m_0}{p\, c} \tag{1}$$

L, m_0 and p being, respectively, the b-hadron decay length, rest mass, and momentum. Elaborated neural networks based on particle identification and secondary vertex reconstruction have been developed to accurately reconstruct the b-hadron energy. The measurement of the decay length has been improved using different algorithms which avoid bias from particles coming from tertiary vertices. The charge and the type of particles accompanying the b-hadron in the event allow to distinguish among the different b-species. Results for τ_{B^+}, τ_{B^0}, and for their ratio are given in Table 1. The result of the average b-hadron lifetime yields:
$\tau_b = 1.570 \pm 0.005_{stat.} \pm 0.008_{sys.}$ ps, this value being the most precise measurement worldwide.

Table 1. Measured lifetimes in b-hadron decays

$\tau_{B^+} = 1.624 \pm 0.014 \pm 0.018$ ps
$\tau_{B^0} = 1.531 \pm 0.021 \pm 0.031$ ps
$\tau_{B^+}/\tau_{B^0} = 1.060 \pm 0.021 \pm 0.024$

Table 2. Fitted parameters from exclusive $\overline{\mathrm{B}}^0_d \to \mathrm{D}^{*+}\ell^-\overline{\nu}_\ell$ decays

$\mathcal{F}_{D^*}(1)\lvert V_{cb}\rvert = (37.7 \pm 1.1 \pm 1.9) \times 10^{-3}$
$\rho^2_{D^*} = 1.39 \pm 0.10 \pm 0.33$
$\mathcal{B}(\overline{\mathrm{B}}^0_d \to \mathrm{D}^{*+}\ell^-\overline{\nu}_\ell) = (5.39 \pm 0.11 \pm 0.33)\%$

3 $\overline{\mathrm{B}}^0_\mathrm{d} \to \mathrm{D}^{*+}\ell^-\overline{\nu}_\ell$ decays

$|V_{cb}|$ has been extracted by DELPHI from the differential semileptonic decay width of $\overline{\mathrm{B}}^0_d \to \mathrm{D}^{*+}\ell^-\overline{\nu}_\ell$ [2,3]:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2\mathcal{F}^2_{D^*}(w)\mathcal{K}_{D^*}(w) \tag{2}$$

where w is the product of the four-velocities of the B and D* mesons, $\mathcal{K}_{D^*}(w)$ is a phase space function and $\mathcal{F}_{D^*}(w)$ is the form factor of the $\mathrm{B} \to \mathrm{D}^*$ transition. $\mathcal{F}_{\mathcal{D}^*}(w)$ is normalized to unity at zero recoil by HQET. The adopted value, considering finite quark masses and QCD corrections, results in $\mathcal{F}_{D^*}(1) = 0.91 \pm 0.04$ [4]. The shape of this form factor is parameterized in terms of the form factor slope $\rho^2_{D^*}$ and of the form factor ratios R_1 and R_2 [5], and it is constrained by dispersion relations [6]. A fit to the differential semileptonic decay width allows an extrapolation to the zero recoil point and the extraction of the $\mathcal{F}_{D^*}(1)|V_{cb}|$ and $\rho^2_{D^*}$ parameters. The average of the two DELPHI measurements, where the differential semileptonic decay width is studied by selecting the $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ decays in an inclusive way [2] and by exclusively reconstructing the D^0 into $\mathrm{K}^-\pi^+$, $\mathrm{K}^-\pi^+\pi^-\pi^+$ and $\mathrm{K}^-\pi^+\pi^0$ [3] is shown in Table 2. They yield the value: $|V_{cb}| = 41.4 \times (1 \pm 0.029_{exp.} \pm 0.051_{sys.} \pm 0.043_{theo.}) \times 10^{-3}$.

4 Inclusive moments

Presently, and with the large data samples collected by the B-factories, the only way to improve the accuracy on the $|V_{cb}|$ measurement extracted from exclusive decays, comes from theory. A precise determination of $\mathcal{F}_{D^*}(1)$ is expected in the next years by lattice computations. The other route, which is experimentally accessible, consists in using the inclusive semileptonic decay width. Since long [7] it has been professed that this approach is accurate, the main uncertainties coming from perturbative QCD corrections. To extract V_{cb}, what one does is to compare the measurement of the inclusive semileptonic b-decay width with a theoretical expression from OPE. In the present analysis low scale running heavy quark masses are used, and non-perturbative QCD corrections enter through four paremeters[1]. Two parameters, μ_G^2 and μ_π^2, contribute at order $1/m_b^2$ and the other two, ρ_D^3 and ρ_{LS}^3, at order $1/m_b^3$. The value of μ_G^2 can be extracted from the $\mathrm{B}^* - \mathrm{B}$ mass splitting with good accuracy [9]. In addition, it appears that final results are very insensitive to ρ_{LS}^3 and then, only μ_π^2 and ρ_D^3 need to be measured to control the non-perturbative QCD corrections. This has been achieved by considering other observables, such as moments of the lepton energy spectrum and of the hadronic mass distribution, in b-hadron semileptonic decays. Measurements of the moments are compared with corresponding theoretical expressions obtained using the same formalism, which also depend on μ_π^2 and ρ_D^3 parameters.

At DELPHI, moments of the hadron mass distribution in b semileptonic decays have been obtained from the mass distribution of $\overline{\mathrm{B}}_d^0 \to \mathrm{D}^{**}\ell^-\overline{\nu}_\ell$ decays [10]. The most important advantage of measuring the moments at the Z energy is that one has access to nearly all the lepton energy spectrum. D^{**} are exclusively reconstructed in the decay channels $\mathrm{D}^0\pi^+$, $\mathrm{D}^+\pi^-$ and $\mathrm{D}^{*+}\pi^-$. The signal is isolated using a discriminant variable which depends on several event topology informations. A fit is performed to extract the D^{**} mass distribution by considering resonant and non-resonant states. Moments of the D^{**} mass distribution are then obtained from the fitted spectrum. The moments of the total hadronic mass are obtained by adding the contributions from the D and D^* mesons: $\langle m_H^n \rangle = p_D m_D^n + p_{D^*} m_{D^*}^n + p_{D^{**}} \langle m_{D^{**}}^n \rangle$, where the $\mathrm{D}^{(*)}$ masses and relative branching fractions (p_D and p_{D^*}) are known. Moreover, the constraint $p_D + p_{D^*} + p_{D^{**}} = 1$ is imposed. Results of the moments of the hadronic mass distribution are given in Table 3.

The first three moments of the inclusive lepton energy spectrum have also been measured by DELPHI [11]. Values of these six moments can be combined in a fit to extract the theoretical parameters describing the inclusive b semileptonic decay width [8]. In the kinetic mass scheme, these parameters are the quark masses m_b(1GeV), m_c(1GeV), the b quark kinetic energy inside the heavy hadron, μ_π^2(1 GeV), and the leading coefficient of the $1/m_b^3$ term in the heavy quark expansion, ρ_D^3(1GeV). Results of the fit are given in Table 4, where the following constraints: $m_b(1\mathrm{GeV}) = 4.57 \pm 0.10\,\mathrm{GeV}$, $m_c(1\mathrm{GeV}) = 1.05 \pm 0.30\,\mathrm{GeV}$, $\mu_G^2(1\mathrm{GeV}) = 0.35 \pm 0.05\ \mathrm{GeV}^2$, and $\rho_{LS}^3(1\mathrm{GeV}) = -0.15 \pm 0.15\,\mathrm{GeV}^3$, have been imposed. Figures 1 and 2 show the projection of the six measured moments of the lepton energy spectrum ($M_{i=1,3}(E_l)$) and hadronic mass distribution ($M_{i=1,3}(M_X)$) in both the m_b(1GeV)-μ_π^2(1GeV) and m_b(1GeV)-ρ_D^3(1GeV) planes, respectively.

The measured value for μ_π^2 is very similar to the μ_G^2 value. This result may open a challenging development to extract $|V_{cb}|$ from $\overline{\mathrm{B}} \to \mathrm{D}\ell^-\overline{\nu}_\ell$ as advertised in [9]. It has been experimentally verified that the ρ_D^3 value is about

Table 3. Measured moments of the hadronic mass distribution in b-hadron semileptonic decays

$M_1 =< m_H^2 - \overline{m}_D^2 > = 0.647 \pm 0.046 \pm 0.093\ (\mathrm{GeV/c^2})^2$
$M_2 =< (m_H^2 - \overline{m}_D^2)^2 > = 1.98 \pm 0.23 \pm 0.29\ (\mathrm{GeV/c^2})^4$
$M_2' =< (m_H^2 - < m_H^2 >)^2 > = 1.56 \pm 0.18 \pm 0.17\ (\mathrm{GeV/c^2})^4$
$M_3' =< (m_H^2 - < m_H^2 >)^3 > = 4.05 \pm 0.74 \pm 0.31\ (\mathrm{GeV/c^2})^6$

Table 4. Fitted parameters from inclusive moments. The systematic contribution has been split in two parts, the first one coming from the systematics of the moments and the se-cond one from theory

$m_b^{kin}(1\mathrm{GeV}) = 4.570 \pm 0.082 \pm 0.010 \pm 0.005\ \mathrm{GeV}$
$m_c^{kin}(1\mathrm{GeV}) = 1.133 \pm 0.134 \pm 0.019 \pm 0.020\ \mathrm{GeV}$
$\mu_\pi^2(1\mathrm{GeV}) = 0.382 \pm 0.070 \pm 0.031 \pm 0.020\ \mathrm{GeV}^2$
$\rho_D^3(1\mathrm{GeV}) = 0.089 \pm 0.039 \pm 0.004 \pm 0.010\ \mathrm{GeV}^3$

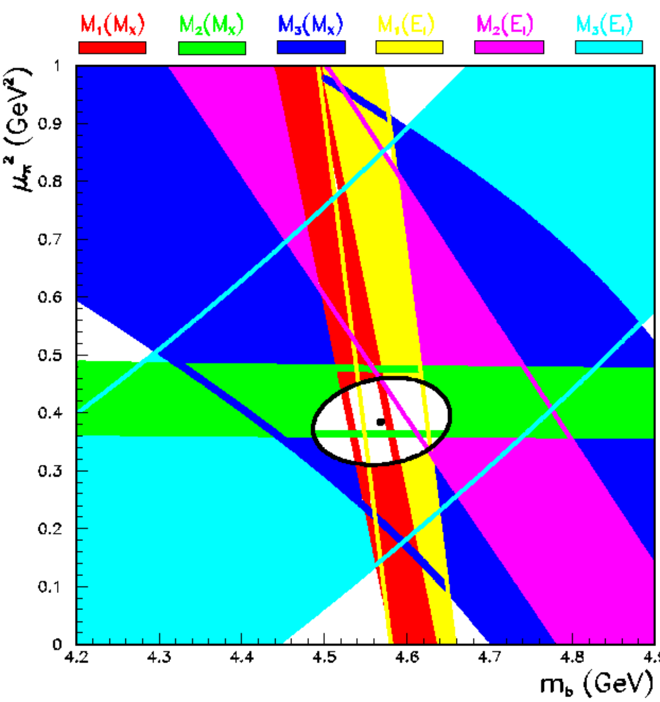

Fig. 1. m_b(1 GeV)-μ_π^2(1 GeV) projections of the constraints resulting from the measurement of moments. The ellipse represents the 1σ contour of the fitted parameters

[1] A detailed explanation of this formalism can been found in reference [8].

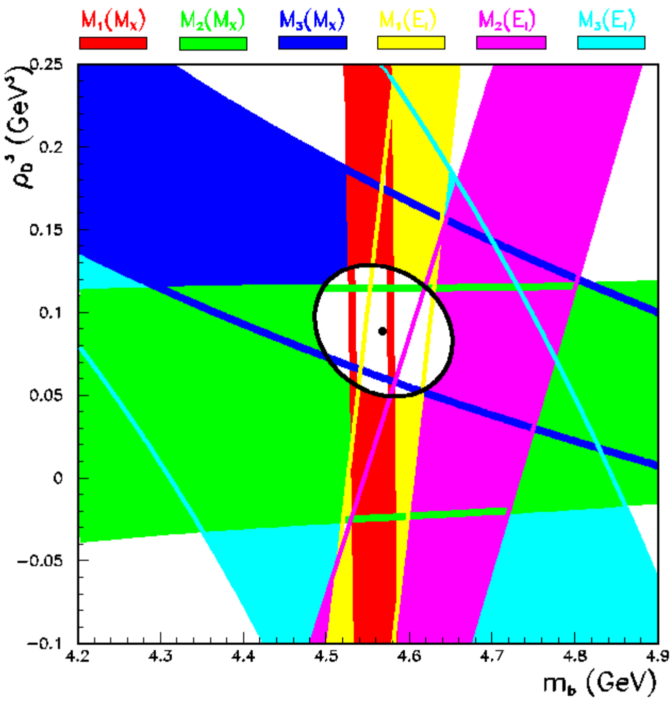

Fig. 2. m_b(1 GeV)-ρ_D^3(1 GeV) projections of the constraints resulting from the measurements of moments. The ellipse represents the 1σ contour of the fitted parameters

$0.1\,\mathrm{GeV}^3$, confirming that $1/m_b^3$ corrections are well under control.

Values extracted for heavy quark masses can be expressed in terms of $\overline{\mathrm{MS}}$ running masses. They yield:

$$\overline{m_b}(\overline{m_b})^{\overline{MS}} = 4.21 \pm 0.14 \text{ GeV}$$
$$\overline{m_c}(\overline{m_c})^{\overline{MS}} = 1.25 \pm 0.10 \text{ GeV}.$$

It must be noted that the present formalism does not rely on the hypothesis that the charm quark is heavy. Also, no external constraint linking m_b and m_c has been utilized.

Inserting the fitted parameters in the inclusive semileptonic decay width as described in [8], the extracted value for $|V_{cb}|$ results in:
$|V_{cb}| = 42.4 \times (1 \pm 0.015_{exp.} \pm 0.019_{fit} \pm 0.010_{theo.}) \times 10^{-3}$.
The first error is coming from the experimental accuracy of lifetime and branching ratio LEP measurements, and the second one from the fitted parameters. The last error comes from an estimate of $1/m_b^4$ corrections [12] and from the perturbative corrections due to the uncertainty in the energy scale used in the heavy quark expansion, $\alpha_s(m_b/2, 2m_b)$.

5 Conclusions

B semileptonic decays have been widely studied at DELPHI. Precise measurements of the τ_{B^+} and τ_{B^0} lifetimes, and the most accurate measurement of the average b-hadron lifetime have been achieved. The CKM matrix element $|V_{cb}|$ has been determined from exclusive $\overline{\mathrm{B}}_d^0 \to \mathrm{D}^{*+}\ell^-\overline{\nu}_\ell$ decays. Measurements of inclusive moments of the hadronic mass distribution and of the lepton energy spectrum have allowed the determination of the OPE parameters entering in the inclusive b semileptonic decay width. From them, $|V_{cb}|$ has also been extracted with high accuracy in the kinetic mass scheme which enables the control of non-perturbative corrections up to $1/m_b^3$ order.

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