Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Physics B (Proc. Suppl.) 142 (2005) 167–172

NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS

www.elsevierphysics.com

OPE parameter determinations from semileptonic B decays at DELPHI

L. Salmi [a]
For the DELPHI Collaboration

[a]Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland

The values of Operator Product Expansion (OPE) parameters m_b, m_c, μ_π^2, and ρ_D have been determined using first three moments of lepton energy spectrum and hadron mass spectrum in semileptonic B hadron decays by the DELPHI Collaboration at LEP. The measurement improves the accuracy of the inclusive determination of the value of $|V_{cb}|$. It also tests the consistency of theoretical predictions and the underlying assumptions of the model.

1. Introduction

The value of the $|V_{cb}|$ element of the CKM mixing matrix can be evaluated from the inclusive semileptonic width,

$$\Gamma_{\rm sl} = |V_{cb}|^2 \gamma_{\rm th} = {\rm BR}(\bar{\rm B} \to X_c \ell \bar{\nu})/\tau_{\rm B}. \quad (1)$$

The current experimental accuracy of the measurements of the semileptonic branching ratio ${\rm BR}(\bar{\rm B} \to X_c \ell \bar{\nu})$ and the B lifetime $\tau_{\rm B}$ result in an uncertainty of the order of 1% in the semileptonic width. However, uncertainties related to the factor $\gamma_{\rm th}$, including the uncertainty on the values of non-perturbative parameters and the assumption of quark-hadron duality, are a significant source of uncertainty in the value of $|V_{cb}|$.

When the non-perturbative QCD contribution to $\gamma_{\rm th}$ is expanded in inverse powers of the b-quark mass m_b, the term $1/m_b$ is absent. The $1/m_b^2$ terms contain the expectation values of the kinetic (μ_π^2) and chromo-magnetic (μ_G^2) operators. The $1/m_b^3$ terms introduce parameters corresponding to the Darwin (ρ_D^3) and spin-orbit (ρ_{LS}^3) operators. Of these four parameters, the value of μ_G^2 has been measured to be 0.35 GeV^2 using the B$^* -$ B mass difference.

The values of the non-perturbative parameters μ_π^2 and ρ_D^3, together with the quark masses m_b and m_c, can be extracted from other inclusive distributions in semileptonic B decays.

DELPHI has, as the only Z^0 experiment, determined the OPE parameter values using the first three statistical moments of the lepton energy (E_ℓ^*) distribution and hadronic mass (M_X) squared distribution. The analysis is presented in a forthcoming publication[1].

Performing the measurement at the Z^0 pole benefits from the large boost of the b-quark, which enables the measurement of leptons also in the low region of the lepton energy spectrum. Due to this the results are easier to interpret and complementary to the other measurements[2], where an explicit lower limit on the lepton energy is applied. On the other hand, at LEP the reconstruction of the B system is more challenging.

The DELPHI measurement is based on 2.0 million hadronic Z^0 decays in the case of the leptonic moments, and 3.4 million decays in the case of the hadronic moments. Decays $Z^0 \to b\bar{b}$ were selected using the standard DELPHI b-tagging algorithm, and semileptonic events were selected by requiring at least one identified lepton (electron or muon) in the event.

2. Lepton Energy Spectrum

Because of the large boost at LEP ($< E_{\rm B} > \approx$ 30 GeV), the lepton energy in the laboratory is much larger than its energy in the B rest frame. Thanks to this, the full lepton energy spectrum can be measured. The natural drawback is that a full reconstruction of the B system is necessary in order to be able to determine the E_ℓ^*. The size

0920-5632/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nuclphysbps.2005.01.033

of the available data sample does not allow to use only di-lepton events, where the lepton charges enable clean separation of signal and background events.

2.1. B **Reconstruction**

Hemispheres containing a single identified lepton are selected for the analysis. In this hemisphere, a charm decay vertex is reconstructed iteratively, starting with energetic charged particles with large impact parameters with respect to the main vertex of the event. At the last stage neutral particles are considered as well.

The neutrino momentum is estimated from the missing momentum and the missing mass in both hemispheres of the event.

The energy of the B is obtained from the sum of the energies of the lepton, the charm system and the estimated neutrino energy. The momentum of the B is estimated from the flight direction of the vertex formed by the charm system with the lepton, and from the sum of the momenta of the lepton, the charm system and the neutrino.

Only events with reconstructed B mass between 3.9 GeV/c^2 and 9 GeV/c^2 The achieved energy resolution for E_ℓ^* is 170 MeV for 82% of selected events (Figure 1).

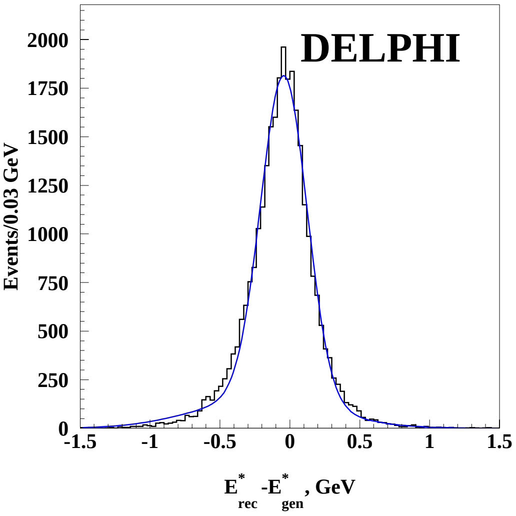

Figure 1. Lepton energy resolution for the selected event sample.

2.2. Backgrounds

The main source of background are cascade decays, where the lepton is produced in the decay of the c quark produced in the b decay. The methods normally used to separate signal events from background rely on the fact that the cascade leptons tend to have lower energies than the signal leptons. In this case that would introduce a bias. It would reject the signal leptons at the low edge of the lepton spectrum that are only accessible at LEP. Instead a number of variables sensitive to the event topology or the charge of the lepton, but independent of the lepton energy, were chosen.

The selected variables related to the topology were the lepton impact parameter with respect to the reconstructed charm vertex, the charm vertex mass and χ^2, the topology of the hemisphere, and the number of particles in the hemisphere not associated with the charm vertex. The charge variables used the correlations of the lepton charge with the charge of the reconstructed charm vertex, charges of other vertices in the same and the opposite hemisphere, the jet charge of the opposite hemisphere, and the leading kaon candidate charge. After combining the variables, samples enhanced in signal or background events can be selected (Figure 2).

2.3. Leptonic moments

After the subtraction of background, an unfolding is performed to account for resolution effects. The unfolded spectrum is shown in Figure 3. Corrections for efficiency, electromagnetic radiation, and B species are then applied. The first three moments of the spectrum are

$$M_1^\ell = (1.380 \pm 0.007 \pm 0.009)\ \mathrm{GeV}$$
$$M_2^{\prime\ell} = (0.179 \pm 0.006 \pm 0.006)\ \mathrm{GeV}^2$$
$$M_3^{\prime\ell} = (-0.028 \pm 0.002 \pm 0.004)\ \mathrm{GeV}^3,$$

where the first uncertainty is statistical and the second systematical.

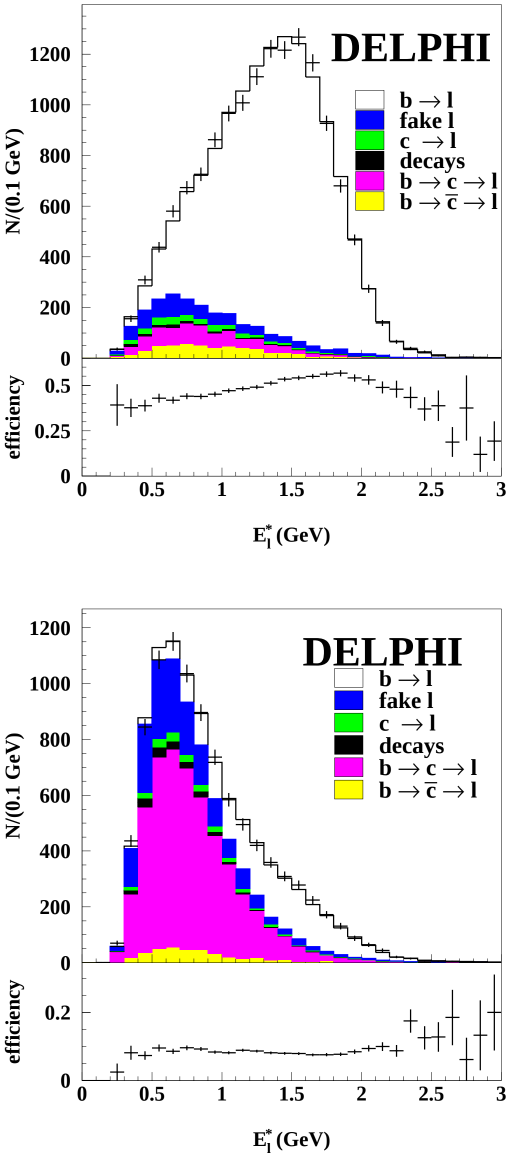

Figure 2. The lepton energy spectra of signal (top) and background (bottom) enhanced samples with their compositions estimated from simulation. Also shown are the selection efficiencies of the two samples as a function of E_ℓ^*.

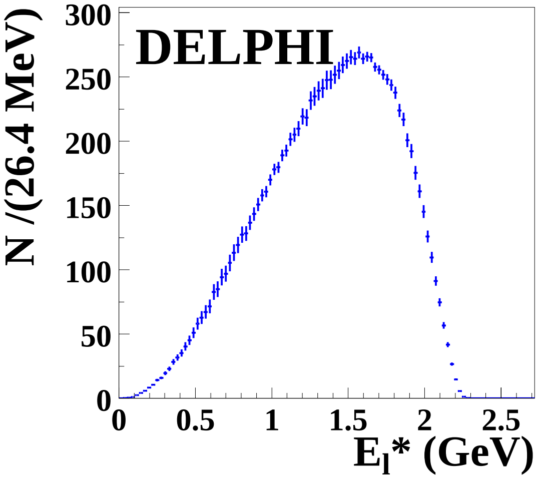

Figure 3. The lepton energy spectrum after background subtraction and unfolding for resolution.

3. Hadron Mass Spectrum

The measurement of the hadronic mass spectrum benefits from not placing a lower limit on lepton energy. Another advantage at DELPHI is that the B systems are back-to-back in opposite hemispheres of the event, facilitating a full event reconstruction.

The hadronic mass spectrum consists of sharp peaks corresponding to the D^0 and D^* masses, and broader contributions from heavier states (D^{**}). In order to measure the moments of the distribution, the shape of the D^{**} component needs to be measured. This is achieved by exclusive reconstruction of D^0, D^+ and D^* decays with a D^{**} decay pion, π^{**}, compatible with being emitted at the B decay vertex. In addition to the shape of the mass distribution, the D^{**} production rate is measured.

3.1. Hadronic decay reconstruction

The decay of the $D^{(*)}$ is reconstructed using only charged decay products. The event is selected as a signal event, if the reconstructed mass is close to the nominal mass. The sidebands of the mass distribution are used to study the combinatorial background.

The B decay vertex is reconstructed from the $D^{(*)}$ trajectory and the identified lepton. A π^{**} candidate compatible with having been emitted at the B vertex is searched for.

3.2. Backgrounds in $D^{**} \to D^{(*)}\pi(\pi)$

There are two kinds of background in the sample, combinatorial background and background that contains a genuine $D^{(*)}$. Background with a genuine $D^{(*)}$ include charm events, events where the π^{**} candidate in fact originates from the main vertex of the event, and events where leptons are mis-identified hadrons or come from cascade decays or τ decays. The combinatorial background can be estimated from the sidebands of the mass distributions.

To separate the background and the signal, a discriminating variable R is built. It contains information on the impact parameter of the π^{**} candidate with respect to the main vertex and the D decay vertex, the decay distance between the B and D decay vertices, the cosine of the π^{**} candidate in the B rest frame, the χ^2 of the D vertex, and the presence of other charged particles at the D decay vertex.

3.3. D^{**} mass distribution and production rates

The event sample can be divided into two categories: right sign ($D^0\pi^+$, $D^+\pi^-$, $D^{*+}\pi^-$) and wrong sign ($D^0\pi^-$, $D^+\pi^+$, $D^{*+}\pi^+$) combinations. The only signal components in the wrong sign sample are decays $b \to D^{(*)}\pi^+\pi^-\ell^-\bar{\nu}_\ell$.

The D^{**} production rates are estimated by fitting the signal and background components to the R distributions, separately for right and wrong sign events.

The branching fractions (right sign) are

$$\mathrm{BR}(b \to D^0\pi^+\ell^-X) = (0.089 \pm 0.18 \pm 0.07)\%$$
$$\mathrm{BR}(b \to D^+\pi^-\ell^-X) = (0.31 \pm 0.10 \pm 0.03)\%$$
$$\mathrm{BR}(b \to D^{*+}\pi^-\ell^-X) = (0.40 \pm 0.09 \pm 0.03)\%.$$

The branching fractions to two pions (wrong sign) are compatible with 0 within their uncertainties.

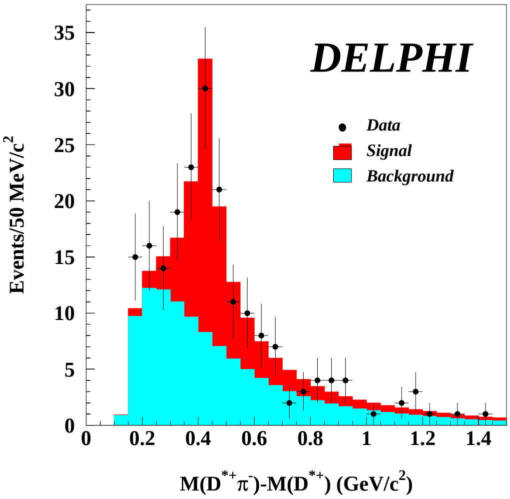

Figure 4. Mass difference distribution for $D^{*+}\pi^-$ sample, with fitted signal contribution superimposed.

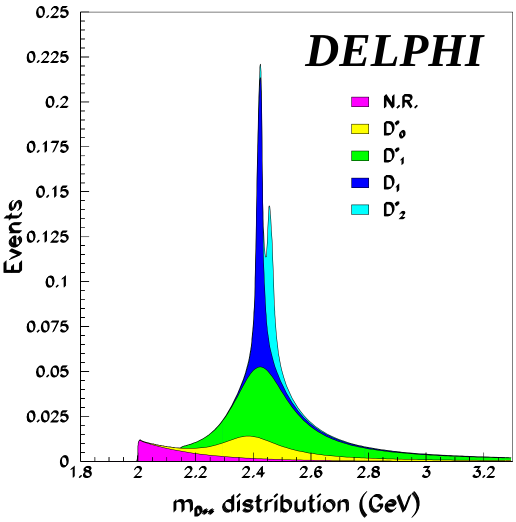

Figure 5. Fitted D^{**} mass distribution.

Table 1
Measurements of the mass and the width of the broad D_1^* state.

	$m_{D_1^*}$ (MeV/c^2)	$\Gamma_{D_1^*}$ (MeV/c^2)
DELPHI	$2445 \pm 34 \pm 10$	$234 \pm 74 \pm 25$
CLEO[3]	$2461^{+41}_{-34} \pm 10 \pm 32$	$290^{+101}_{-79} \pm 26 \pm 36$
BELLE[4]	$2427 \pm 26 \pm 20 \pm 15$	$384^{+107}_{-75} \pm 24 \pm 70$

For the D** mass distribution measurement only right sign events are used. The observed number of events in each bin of the two-dimensional distribution of R vs mass difference is compared to the expected number. The result of the fit in the $D^{*+}\pi^-$ sample is shown in Figure 4. The full fitted D** mass distribution with all the components is shown in Figure 5.

The accuracy of the measurement of the broad D_1^* mass and width is comparable to that of CLEO and BELLE (Table 1).

The total D** production rate was measured to be $(2.7 \pm 0.7 \pm 0.2)\%$.

3.4. Hadronic moments

The moments of hadronic mass distribution are obtained from

$$< m_H^n >= p_D m_D^n + p_{D^*} m_{D^*}^n + p_{D^{**}} < m_{D^{**}}^n >, \quad (2)$$

where p_i are the production fractions of each component. For the first three moments this gives

$$M_1^H = (0.647 \pm 0.046 \pm 0.090)\ (\mathrm{GeV}/c^2)^2$$
$$M_2^{'H} = (1.56 \pm 0.18 \pm 0.16)\ (\mathrm{GeV}/c^2)^4$$
$$M_3^{'H} = (4.05 \pm 0.74 \pm 0.32)\ (\mathrm{GeV}/c^2)^6.$$

4. Results

The values of OPE parameters m_b, m_c, μ_π^2 and ρ_D^3 can be determined using the three leptonic and three hadronic moments. The terms containing ρ_{LS}^3 are numerically suppressed. The expressions relating the moments and the parameters are given in Ref. [5]. A multiparameter fit is performed in two different formalisms, in the kinetic mass scheme and the pole mass scheme.

Table 2
Results of the fit.

	Fit Values	Fit Uncert.	Syst. moments	Syst. theory
m_b	4.575	$\pm$ 0.069	$\pm$ 0.043	$\pm$ 0.005 GeV
m_c	1.144	$\pm$ 0.106	$\pm$ 0.071	$\pm$ 0.020 GeV
μ_π^2	0.399	$\pm$ 0.047	$\pm$ 0.039	$\pm$ 0.020 GeV^2
ρ_D^3	0.054	$\pm$ 0.017	$\pm$ 0.010	$\pm$ 0.010 GeV^3

Some constraints are needed when the fit is done in the kinetic mass scheme. The constraints implemented are

$$m_b = 4.57 \pm 0.10\,\mathrm{GeV}/c^2$$
$$m_c = 1.05 \pm 0.30\,\mathrm{GeV}/c^2$$
$$\mu_G^2 = 0.35 \pm 0.05\,\mathrm{GeV}^2$$
$$\rho_{LS}^3 = -0.15 \pm 0.15\,\mathrm{GeV}^3.$$

The constraint on m_b is largely equivalent to including the mean energy of photon in $b \to s\gamma$ decays in the fit.

The results of the fit are given in Table 2. The projections, to the $m_b - \mu_\pi^2$ and $m_b - \rho_D^3$ planes, of the bands given by the six measured moments, with the fit result and its 1 σ contour, are shown in Figure 6, illustrating the common intersection of the six bands on these planes.

Without constraining the value of m_b, the fit gives $m_b = 4.57 \pm 0.10$ GeV/c^2.

Also in the pole mass scheme the six bands given by the six moments define a common intersection region in the four-parameter space.

The value of $|V_{cb}|$ is obtained from the formula of Ref. [6]. The values measured at LEP for semileptonic branching ratio and B lifetime are

$$\mathrm{BR}(b \to X\ell^-\nu) = (10.65 \pm 0.23)\%$$
$$\mathrm{BR}(b \to X_u\ell^-\nu) = (0.17 \pm 0.05)\%$$
$$\tau_B = 1.573 \pm 0.007\,\mathrm{ps}.$$

The fitted values of m_b, m_c, μ_π^2, ρ_D^3 are incorporated, giving

$$|V_{cb}| = 0.0421 \times (1 \pm 0.014_{\mathrm{meas}} \pm 0.014_{\mathrm{fit}} \pm 0.015_{\mathrm{th}}). \quad (3)$$

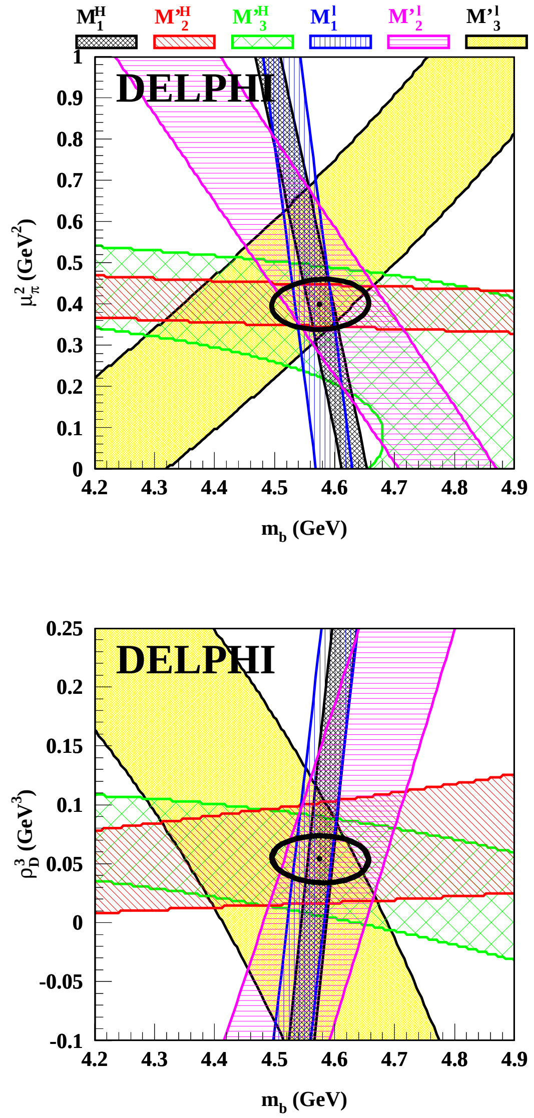

Figure 6. The six bands defined by the first three moments of lepton energy spectrum and hadronic mass spectrum and the result of the fit to the bands with its 1σ contour, projected onto the $m_b - \mu_\pi^2$ (top) and $m_b - \rho_D^3$ (bottom) planes.

5. Summary

Measuring the OPE parameters is important for two reasons. Firstly, precise knowledge of their values improves the theoretical accuracy of determination of $|V_{cb}|$. Secondly, it allows to study assumptions in the theoretical description of heavy quark decays, most importantly the assumption of parton-hadron duality.

The parameter values have been measured by the DELPHI collaboration, by measuring the first three moments of lepton energy spectrum and the hadronic mass spectrum in semileptonic B decays. These altogether six measurements yield a common intersection in the four-parameter space in the two commonly used formalisms. The obtained parameter values are also consistent with results obtained by other collaborations[2], while the measurements are complementary due to the different kinematical environment and analysis methods.

Incorporating the measured values of the OPE parameters, the accuracy of inclusive measurement of $|V_{cb}|$ is improved.

Within the accuracy of the measurement, there are no hints of a possible parton-hadron duality violation.

ACKNOWLEDGEMENTS

I wish to thank my collaborators M. Calvi, A. Oyanguren and P. Roudeau for their contribution.

REFERENCES

1. DELPHI Collaboration, in preparation
2. S.E. Csorna *et al.* (CLEO Collaboration), Phys. Rev. **D70**(2004)032002, 032003; B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. **D69**(2004)111103, 111104, Phys. Rev. Lett. **93**(2004)011803.
3. S. Anderson *et al.* (CLEO Collaboration), Nucl. Phys. **A663**(2000)650.
4. K. Abe *et al.* (BELLE Collaboration), Phys. Rev. **D69**(2004)112002.
5. M. Battaglia *et al.*, Phys. Lett. **B556**(2003)41
6. D. Benson, I.I. Bigi, T. Mannel and N. Uraltsev, Nucl. Phys. **B665**(2003)367.