Study of spectral moments in semileptonic decays of the b hadron with the DELPHI detector at LEP.

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The measurement of the moments of hadronic mass spectrum and of lepton energy spectrum based on a sample of semileptonic decays of the b hadron selected from $Z^0 \to b\bar{b}$ events recorded with the DELPHI detector at LEP, are presented. These results are interpreted in terms of constraints on the quark masses and on the b-quark kinetic energy value.

1. Introduction

Moments of hadronic mass spectrum and of lepton energy spectrum are sensitive to the masses of the b and c quarks as well as to the non-perturbative parameters of the Heavy Quark Expansion. They allow to improve the determination of the $|V_{cb}|$ element of the CKM quark coupling matrix which can be measured from inclusive semileptonic B decays by using the relation:

$$\Gamma(b \to c\ell\nu) = |V_{cb}|^2 f(par.) = BR(b \to c\ell\nu)/\tau_b$$

The current experimental accuracy on the semileptonic branching ratio and B lifetime is about 1%, while the evaluation of the function f, based on Operation Product Expansion, brings an uncertainty of the order of several percent, making it the dominant error contribution.

Moreover, the comparison of these results with different measurements of the same parameters provides a test of the consistency of the theoretical predictions for inclusive semileptonic B decays and of the underlying assumptions.

Previous measurements of spectral moments have been performed at the $\Upsilon(4S)$ [1], DELPHI has performed the first measurement in b hadron semileptonic decays at the Z^0. There are several advantages in the Z^0 kinematics, mainly the large boost acquired by the b quark ($E_B \sim 30$ GeV) which gives access in the laboratory frame to the low region of the lepton energy spectrum. The challenge in this case is the complete reconstruction of the B system. The lepton energy acceptance extending down to the lower end of the spectrum makes these results both easier to interpret and complementary to those obtained at the $\Upsilon(4S)$.

In this study two different formulations, using different mass definitions for deriving the constraints on the OPE parameters, are used.

2. Moments of hadronic mass distribution in b hadron semileptonic decays

The hadronic mass distribution of $\bar{B}^0_d \to D^{**}\ell\bar{\nu}$ events have been studied [2]. D^{**} events have been reconstructed in the three channels: $D^0\pi^+$, $D^+\pi^-$, $D^{*+}\pi^-$ with the D^0, D^+ and D^{*+} mesons fully reconstructed. Leptons have been required to have a momentum greater than 2 GeV/c in the laboratory frame. The separation of the signal from the background has been achieved by means of a discriminant variable based on the topological properties of the secondary vertex such as the presence of additional charged particles in addition to the D, the lepton and the neutrino.

Dπ candidates have been separated in “right sign” and “wrong sign”, considering the charge correlation between the D and the pion, and the discriminant variable distributions have been fitted to the simulation expectation in the two samples separately. Only $D^{(*)}\pi^+\pi^-$ events, with one missing pion, can contribute to “wrong sign” candidates and no evidence of signal have been found in this sample. The following upper limits have been derived at 90% C.L.:

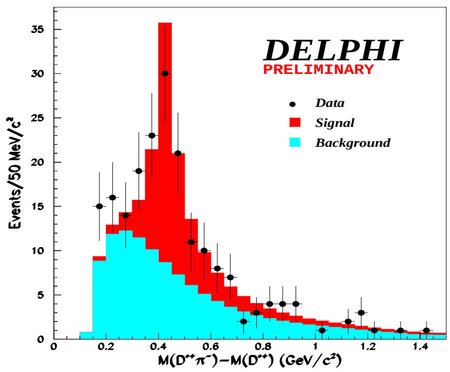

Figure 1. *ΔM distributions in the $D^{*+}\pi^-$ reconstructed decay channel.*

$BR(b \to D^0\pi^+\pi^-\ell^-\bar{\nu}) = BR(b \to D^+\pi^+\pi^-\ell^-\bar{\nu}) < 0.18\%$ and $BR(b \to D^{*+}\pi^+\pi^-\ell^-\bar{\nu}) < 0.17\%$.

Therefore only $D\pi$ states have been considered in the following analysis of the hadronic mass distribution of the D^{**} states. A fit to the variable $\Delta M = m(D^{(*)}\pi) - m(D^{(*)})$ has been performed, considering the contributions of narrow and broad resonant states D_0^{*+}, D_1^{*+}, D_1^+ and D_2^+ as well as non resonant $D\pi$ states. An example of ΔM distribution is shown in Figure 1.

The total rate for D^{**} production amounts to: $\bar{B}_d^0 \to D^{**}\ell\bar{\nu} = (2.6 \pm 0.5 \pm 0.6)\%$ and the broad D_1^{*+} is the dominant contributing channel.

Moments of the D^{**} mass distribution have been evaluated from the fitted mass distributions. To determine the moments of the complete hadronic mass distribution, in b-hadron semileptonic decays, the $b \to D\ell\bar{\nu}$ and $b \to D^*\ell\bar{\nu}$ components have been included using the relation $\langle m_H^n \rangle = p_D m_D^n + p_{D^*} m_{D^*}^n + p_{D^{**}} \langle m_{D^{**}}^n \rangle$ where p_D and p_{D^*} are the relative branching fractions derived from published results and $p_{D^{**}}$ is obtained by imposing the constraint $p_D + p_{D^*} + p_{D^{**}} = 1$ and using the above measurement.

The following preliminary DELPHI results have been obtained:

$$\langle m_H^2 - m_{\bar{D}}^2 \rangle = (0.534 \pm 0.041 \pm 0.074)\ GeV/c^2$$
$$\langle (m_H^2 - m_{\bar{D}}^2)^2 \rangle = (1.51 \pm 0.20 \pm 0.23)\ (GeV/c^2)^2$$
$$\langle (m_H^2 - \langle m_H^2 \rangle)^2 \rangle = (1.23 \pm 0.16 \pm 0.15)\ (GeV/c^2)^2$$
$$\langle (m_H^2 - \langle m_H^2 \rangle)^3 \rangle = (2.97 \pm 0.67 \pm 0.48)\ (GeV/c^2)^3$$

where the first uncertainty is statistic and the second is systematic.

3. Moments of lepton energy spectrum in b hadron semileptonic decays

The moments of the lepton energy spectrum provide constraints similar to those of the hadronic mass. Further they offer an important consistency test of the theory.

An inclusive reconstruction of the semileptonic decays has been performed [3]. Muons and electrons with a momentum greater than 2.5 and 3.0 GeV/c, respectively, have been tagged in a sample of $Z^0 \to b\bar{b}$ events. Secondary vertices have been reconstructed using an iterative procedure. The B energy has been reconstructed adding to the charm vertex energy, the lepton energy and the neutrino energy, evaluated from the event missing energy. The B direction has been estimated from both the reconstructed B momentum and the B decay flight direction. Boosting the leptons in the B reconstructed rest frame provides a typical energy resolution of 250 MeV. In order to separate signal $b \to \ell$ events form $b \to c \to \ell$ and other backgrounds without introducing significant biases to the lepton energy distribution, two probabilistic variables have been defined based on charge correlation and event topology. The measured energy spectrum after background subtraction is shown in Figure 2. For this preliminary result only 1994 and 1995 statistics have been used, corresponding to a sample of 18,300 leptons. After unfolding the resolution smearing, the first, second and third moments have been calculated. The relevant corrections for distortions due to electromagnetic radiation, contamination

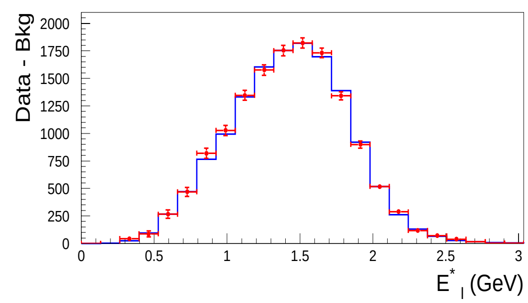

Figure 2. *Lepton energy spectrum after background subtraction. Points are data and histogram is the result of the fit.*

of $b \to u\ell\nu$ decays and contribution of B_s^0 and Λ_b hadrons in the events sample have been applied. The following preliminary DELPHI results have been obtained:

$$\langle E_\ell^* \rangle = (1.383 \pm 0.012 \pm 0.008)\ GeV$$
$$\langle (E_\ell^* - \langle E_\ell^* \rangle)^2 \rangle = (0.192 \pm 0.005 \pm 0.010)\ GeV^2$$
$$\langle (E_\ell^* - \langle E_\ell^* \rangle)^3 \rangle = (-0.029 \pm 0.005 \pm 0.005)\ GeV^3$$

where the first uncertainty is statistic and the second is systematic.

4. Interpretation of the results

Two different approaches have been followed in order to obtain constraints on the non-perturbative parameters of OPE from the measured spectral moments. The first [4] is based on an expansion on the pole masses m_b and m_c and expresses the b-energy parameter as λ_1, while the second [5] uses running heavy quark masses $m_b(\mu)$ and $m_c(\mu)$ and the kinetic energy expectation value μ_π^2, corresponding to λ_1.

Results obtained from the measured values of the first two moments of the hadronic mass spectrum and lepton energy spectrum have been found to be compatible. An exemplification is given in Figure 3 showing constraints extracted in the $\bar{\Lambda}$ - λ_1 plane which give:

$$\bar{\Lambda} = (\ 0.44 \pm 0.04 \pm 0.05 \pm 0.07)\ GeV$$
$$\lambda_1 = (-0.23 \pm 0.04 \pm 0.05 \pm 0.08)\ GeV^2$$

where the quoted uncertainties are statistic, systematic and related to the power corrections and α_s uncertainties, respectively.

Another way to express these results exploits the correlation in the expected values for the charm and beauty quark masses to extract the charm quark mass m_c by using an independently determined value of m_b. Using the first two moments of the lepton energy spectrum and m_b=(4.60±0.05) GeV, with the second theoretical formulation we find:

$$m_c(1\ \text{GeV}) = (1.19 \pm 0.05 \pm 0.05 \pm 0.07 \pm 0.04)\ GeV$$

where the quoted uncertainties are statistic, systematic ± 0.050 GeV on m_b and $1/m_b^3$ corrections, respectively.

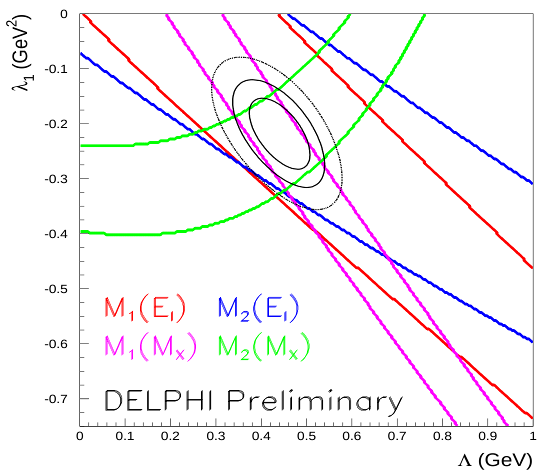

Figure 3. *The constraints on the $\bar{\Lambda}$ - λ_1 plane obtained from the combination of the first two moments of the lepton energy ($M_1(E_\ell)$,$M_2(E_\ell)$) and hadronic mass ($M_1(M_X)$,$M_2(M_X)$). The bands represents the regions selected by each moment within $\pm 1\sigma_{stat+syst}$. The ellipsis show the 1σ, 68% and 90% C.L. respectively.*

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