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Semileptonic B decays and CKM elements at LEP

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Abstract: The latest measurements of the semileptonic b branching ratios at LEP will be reported, which allow the determination of $|V_{cb}|$ and $|V_{ub}|$ CKM matrix elements.

1. Introduction

The large statistics of b hadrons collected by the four LEP Collaborations during the first phase of LEP activity, together with their peculiar kinematic characteristic, offer one of the best environments for the determination of the semileptonic branching ratios of the b hadrons.

The measurement of the inclusive semileptonic b branching ratio is an important quantity for many of the Heavy Flavour analyses. Within the context of the Heavy Quark Theory its value can be used together with the average lifetime of the b mesons to extract the value of the $|V_{cb}|$ CKM matrix element. The study of the kinematical properties of the hadronic system accompaining hard leptons in b hadron decays allows the determination of the $|V_{ub}|$ CKM matrix element.

2. Measurements of $|V_{cb}|$

The magnitude of V_{cb} can be measured from the measurement of the inclusive semileptonic branching ratio $B(b \to X\ell\nu)$, after subtracting the contribution from $b \to u\ell\nu$. The method used to relate the measured width to $|V_{cb}|$ is the so called Heavy Quark Theory (HQT), which computes the inclusive transition rates as an expansion in the inverse powers of the heavy quark masses [1]. In this approach, the semileptonic width is expressed in terms of the b quark mass m_b and a parameter μ_π, related to the average kinetic energy of the b quark inside the b hadron, yelding[2]:

$$
\begin{aligned}
|V_{cb}| = 0.0411 &\sqrt{\frac{B(b\to c\ell\nu)}{0.105} \cdot \frac{1.55\mathrm{ps}}{\tau_b} \times \left(1 - 0.024\left[\frac{\mu_\pi^2 - 0.5\mathrm{GeV}/c^2}{0.2\mathrm{GeV}/c^2}\right]\right)} \\
&\times (1 \pm 0.015(\mathrm{pert}) \pm 0.010(\mathrm{m}_b) \pm 0.012(1/\mathrm{m}_b^3))
\end{aligned}
\tag{2.1}
$$

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assuming $m_b(1\ \mathrm{GeV}) = (4.58 \pm 0.06)\ \mathrm{GeV}/c^2$.

The ALEPH Collaboration has presented a new measurement of the inclusive b branching ratio for this Conference [3]. The measurement uses LEP1 data reprocessed with a refined version of the reconstruction program, which allows for an improved tracking performance and a better particle identification.

Leptons are searched for opposite to hemispheres tagged in three different ways.

The first analysis uses a sample in which one hemisphere is tagged to contain b hadrons by means of the same lifetime-mass based variable used by the ALEPH R_b analysis[4]. A very high b purity sample is then selected, containing about 340,000 events.

In the opposite hemisphere a lepton is searched for, and its transverse momentum, relative to the jet to which it belongs, allows to discriminate direct $b \to \ell$ from cascade $b \to c \to \ell$ decays. The branching ratio is determined by a binned likelihood fit to the number of events in each transverse lepton momentum interval.

The second analysis uses two indipendent samples in which the b hemispheres are selected either by a loose cut on the lifetime-mass based variable or by a high p_T lepton in a randomly chosen hemisphere. In the hemisphere which tags the event as coming from a b decay, a charge is determined: for the high p_T lepton it is just the lepton charge, while in the other sample a combination of jet charges based on both momentum and impact parameter weights. Similarly to the first analysis a lepton then is searched for in the opposite hemisphere. The discrimination between direct and cascade lepton, in this analysis is achieved by the charge correlation between the two hemisphere charges: leptons coming from direct decays tend to have opposite charge correlation, diluted by mixing effects. The branching ratio is determined by a fit to the number of events with opposite and same charge hemispheres.

The probability to correctly tag the charge of the tagging hemisphere can be determined directly from data using a double tag technique, by measuring the fraction of opposite charge and same charge tagged hemispheres in the data sample, once corrected for the backgrounds and for correlations in the tag.

A detailed list of the systematic errors has been investigated. An important effect is coming from the modelling of the different semileptonic decays of the b hadrons. The leptons coming in the B meson decays into D, D^* and D^{**} final states have a different momentum spectrum. In this measurement, a different approach with respect to the past has been used to assess this systematic, by using the measured fractions of D, D^*, D_1, D_2^*. The B meson momentum spectrum measured in [5] is used, which also estimates the systematic errors coming from the decay modelling using the same recipe, therefore taking the correlation between the two analyses into account.

The two measurements have different sensitivities to the different systematic effects. For the p_T spectrum, the main error is coming from the modelling, while for the charge correlation measurement the main sources of systematics come from the evaluation of the charge tagging estimate: in particular, the mixing and the $B(b \to W \to \bar{c}\ell)$.

The two methods give compatible results, the charge correlation analysis having the largest weight in the average, due to the smaller systematic error. The ALEPH final result is:

$$B(b \to X\ell\nu) = (10.70 \pm 0.10(stat) \pm 0.23(syst) \pm 0.26(model))\%. \tag{2.2}$$

This measurement is then given in input to a global fit to the Heavy Flavour results[6] produced by the LEP Collaborations which combines the measurements of R_b, the $B(b \to \ell)$, $B(b \to c \to \ell)$, $B(c \to \ell)$, and $\bar{\chi}$, after being rescaled to common input paremeter values and systematic definitions, and taking into account correlated systematics.

The average LEP value for $B(b \to \ell)$ and $B(b \to c \to \ell)$ is

$$\begin{aligned} B(b \to X\ell\nu) &= (10.65 \pm 0.09(\mathrm{stat}) \pm 0.15(\mathrm{syst}) \pm 0.15(\mathrm{model}))\% \\ B(b \to c \to X\ell\nu) &= (8.04 \pm 0.12(\mathrm{stat}) \pm 0.13(\mathrm{syst}) \pm 0.09\ (\mathrm{model}))\%. \end{aligned} \tag{2.3}$$

Experimentally, the semileptonic width can be determined relating the measured branching ratio to the average b hadron lifetime, assuming that the semileptonic width for all b hadrons to be the same. This last statement is supported by direct measurements[7]. The value of $|V_{cb}|$ can be extracted by using equation 2.1, assuming an average b-hadron lifetime of $\tau_b = (1.561 \pm 0.014)$ ps [8] and adding theoretical uncertainties linearly, giving the result:

$$|V_{cb}|_{incl} = (40.9 \pm 0.5(\mathrm{exp}) \pm 2.4(\mathrm{theo})) \times 10^{-3} \tag{2.4}$$

where the first error is experimental and the second is theoretical.

Another determination of the $|V_{cb}|$ value can also be extracted by the measurement of the $B^0 \to D^{*+}\ell\nu$ decay rate as a function of the recoil energy w of the D^{*+} meson in the B rest frame. The differential decay rate is predicted in HQET[9] as

$$\frac{d\Gamma(B^0 \to D^{*+}\ell\nu)}{dw} = K(w)F^2_{D^*}(w)|V_{cb}|^2 \tag{2.5}$$

where $K(w)$ is the shape function and $F(w)$ is the hadronic form factor. At zero recoil ($w = 1$) in the infinite b quark mass limit, the heavy-quark symmetry predicts the form factor to be exactely equal to unity and allows to approximate the shape around $w = 1$ with an expansion, parameterised in terms of the variable ρ^2 which is the slope at zero recoil. The symmetry breaking corrections to the form factor are computable and the dependence on the finite size of the b quark mass is only inversely quadratic.

The main difficulty in measuring the decay rate, is coming from the fact that the B^0 mesons are not produced with fixed energy, requiring the reconstruction of the neutrino momentum. This makes the reconstruction of w problematic and leads to the difficulty of rejecting the poorly known $D^{**}\ell\nu$ decays, which represents the main background source. Experimentally, both the slope and the intercept at zero recoil are fitted simultaneously, and the different experiments averaged, taking into account correlations between the two parameters and systematics.

Using the average measured value of the product $|V_{cb}|F(1) = (35.6 \pm 1.7) \times 10^{-3}$ and $F(1) = 0.88 \pm 0.05$ [2] allows the determination of $|V_{cb}|$ to be

$$|V_{cb}|_{excl} = (40.5 \pm 1.9(\mathrm{exp}) \pm 2.3(\mathrm{theo})) \times 10^{-3}. \tag{2.6}$$

This measurement can be averaged with the inclusive determination taking into account common theoretical, modelling and experimental errors, yielding

$$|V_{cb}|_{LEP} = (40.7 \pm 1.9) \times 10^{-3}. \tag{2.7}$$

In the average, the largest weight is taken from the inclusive determination.

An important to test the predictions of the HQET is represented by the measurement of the $b \to X\tau\nu$, since the ratio with respect to the $b \to c\ell\nu$ is controlled only by the lepton masses. Two new measurements have been presented by ALEPH[10] and OPAL[11] to this Conference. They are based on the search for an excess of missing energy in b selected events, due to the presence of two neutrinos in the final state. The two above results have been averaged with the ones from DELPHI and L3, taking into account common systematics, giving the following result:

$$B(b \to X\tau\nu) = (2.44 \pm 0.14(\text{stat}) \pm 0.27(\text{syst}))\%. \tag{2.8}$$

3. Determination of $|V_{ub}|$

Similarly to $|V_{cb}|$, the measurement of the inclusive semileptonic branching ratio $b \to u\ell\nu$ allows the determination of the $|V_{ub}|$ CKM matrix element. In this case, the experimental difficulty is linked to the 100-fold larger background due to the $b \to c\ell\nu$ transition. The measurement relies upon the fact that nearly 80% of the $b \to u$ decays are expected to have an invariant mass of the hadronic system below the charm threshold. By contrast, the inclusive determination based on the lepton momentum endpoint, performed at the $Y(4S)$[12] have only access to 10% of the total $b \to u$ decay rate.

The techniques to extract the signal are quite mature and robust, and rely upon the inclusive reconstruction of the hadronic system, optimised in minimising the $b \to c$ contributions, whose normalisation is directly measured in signal depleted regions. A careful understanding of the background topologies allows to limit the systematic uncertainties.

For this Conference OPAL[13] has presented a new measurement of this quantity. Firstly, leptons coming from direct b decays are selected by means of a neural network to remove $b \to c \to \ell$ contributions. Seven variables are used to train an artificial neural network to separate the $b \to u$ from the $b \to c$ decays. They are based on lepton properties as well as on the hadronic invariant mass. The signal is extracted from a fit to the neural network output in the signal enriched region, taking care to measure the background in the signal depleted region. The result of the fit is

$$B(b \to u\ell\nu) = (1.63 \pm 0.57(\text{stat})^{+0.55}_{-0.62}(\text{syst})) \times 10^{-3}. \tag{3.1}$$

This result is averaged with similar ones from the other LEP Collaborations, taking into account common systematic errors. It is worth noticing that since the various experiments use different techniques to suppress the $b \to c$ background, they result in different systematic uncertainties for this common source of error. For instance ALEPH, OPAL and L3 are more sensitive to the b hadron fragmentation function due to the kinematical variables used to distinguish $b \to c$ from $b \to u$ transitions. DELPHI, on the contrary is more sensitive to the different b hadron species due to the use of kaon antitagging to reject $b \to c$, thus rejecting also B_s and Λ_b decays.

The LEP average is then

$$B(b \to u\ell\nu) = (1.71 \pm 0.31(\text{stat+exp}) \pm 0.37(b \to c) \pm 0.21(b \to u)) \times 10^{-3} \tag{3.2}$$

where the first error takes into account statistics and experimental uncertainties, the second and the third the modelling errors of $b \to c$ and $b \to u$ transitions, respectively. Similarly to Eq.2.1, the measured branching ratio is used to extract $|V_{ub}|$ according to the following formula:

$$|V_{ub}| = 0.0445\sqrt{\frac{B(b \to u\ell\nu)}{0.002} \cdot \frac{1.55\text{ps}}{\tau_b}}(1 \pm 0.010(\text{pert}) \pm 0.035(\text{m}_b) \pm 0.030(1/\text{m}_b^3)) \tag{3.3}$$

yielding

$$|V_{ub}|_{LEP} = \left(4.09^{+0.36}_{-0.39}(\text{stat+exp})^{+0.42}_{-0.47}(b \to c)^{+0.24}_{-0.26}(b \to u) \pm 0.17(\text{theo})\right) \times 10^{-3} \tag{3.4}$$

where the first error accounts for limited statistics and detector effects, the second and the third for the uncertainties on the modelling of $b \to c$ and $b \to u$ transitions, respectively, while the last is coming from the theoretical errors in Eq. 3.3

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