Lifetimes, Semileptonic Branching Ratios of B-Hadrons and $|V_{cb}|$ Estimation

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The lifetimes and the semileptonic branching ratios of the different b-hadrons are reviewed. The different methods to measure the lifetimes and the branching ratios are compared. The branching ratio for $b \rightarrow \nu + X$ from the L3 experiment is presented. These measurements result in an update of the KM - matrix element $|V_{cb}|$.

1. Introduction

The determination of the $|V_{cb}|$ element of the Kobayashi-Maskawa matrix can be done from the measurement of the semileptonic branching ratio and the inclusive lifetime of the b-hadron. The Heavy Quark Effective Theory (HQET) provides the following expression :

$$\Gamma(B \rightarrow X_c l\nu) = \frac{G_F^2 m_b^5}{192\,\pi^3} |V_{cb}|^2 F_{\mathrm{theo}} \qquad (1)$$

where G_F is the Fermi coupling constant, m_b the b-quark mass and F_{theo} a factor different from one determined by perturbative QCD, phase space and non-perturbative corrections. The semileptonic partial width

$$\Gamma(B \rightarrow X_c l\nu) = Br(b \rightarrow l\nu X)/\tau_b, \qquad (2)$$

is the input from experiment. That means one has to measure τ_b the average b-hadron lifetime and $Br(b \rightarrow l\nu X)$ the inclusive semileptonic branching ratio of the b-quark. The assumption that the contribution from $b \rightarrow ul\nu$ decays is negligible is supported by the values measured by CLEO [1].

A more complete theoretical discussion on inclusive $|V_{cb}|$ measurements can be found in [2].

The value of the theoretical uncertainty of the $|V_{cb}|$ determination is not unique in the literature. We will use a conservative theoretical error of $\Delta|V_{cb}|(\mathrm{theo}) = \pm 0.0040$, as suggested also in Reference [2].

2. Semileptonic Branching Ratios of B-Hadrons

Measurements of the semileptonic branching ratios of b-hadrons have been performed at two different

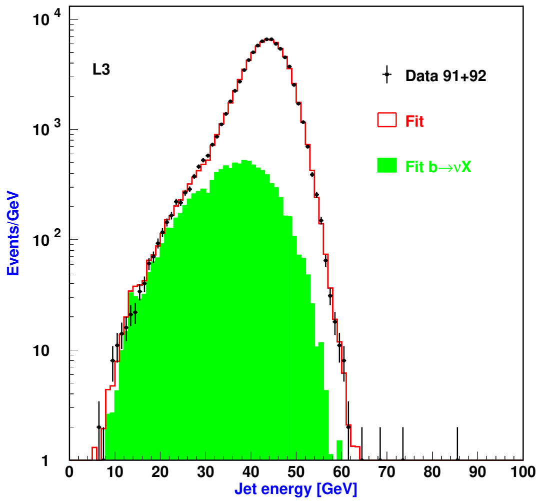

Figure 1. Fit to the total semileptonic branching fraction $Br(b \rightarrow l\nu X)$ from L3 Collaboration.

centre-of-mass energy regions : the $\Upsilon(4S)$ [3,4] and the LEP1 [5–7]. The physical conditions are completely different :

- At the $\Upsilon(4S)$ only B mesons are produced in pairs almost at rest leading to uncorrelated decay directions and a nearly isotropic distribution of the decay particles. No clustering in jets or hemispheres is observed. The production of B_s^0 and Λ_b hadrons is kinematically not allowed.

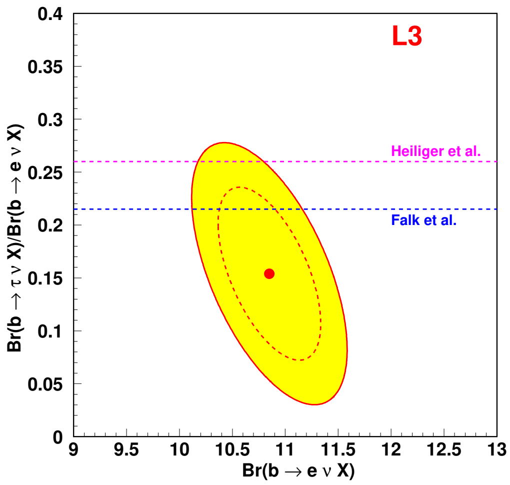

Figure 2. Comparison of theoretical predictions [16] with the L3 measurements [6]. The ellipses are the confidence level contours : solid ellipse 68% , dashed ellipse 39%

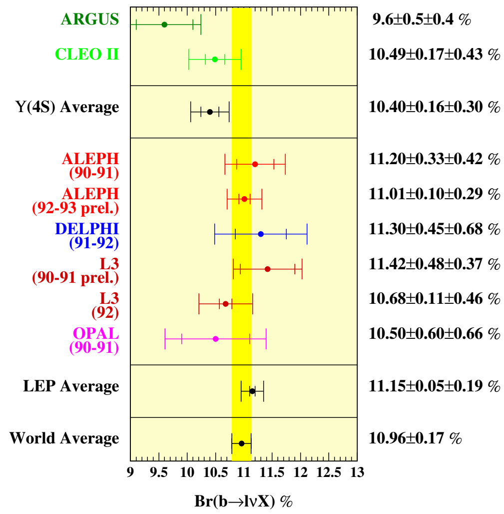

Figure 3. $Br(b \to l\nu X)$ measurements at the $\Upsilon(4S)$ and at LEP

The background from the continuum is small and under control.

- At the Z^o pole, $B^{\pm}$, B^0_d, B^0_s and Λ_b decays are all allowed. B-hadrons are produced in pairs together with other particles from the b-quark fragmentation in jets. Each jet defines its own hemishere and a back-to-back topology is observed. Large missing energy can be present due to energetic neutrinos. The background from ordinary quarks can be large and needs further reduction by lifetime tags. A good lepton identification over a large energy range is as essential as the understanding of the jet properties.

CLEO has published recently a new measurements at the $\Upsilon(4S)$ relying on the integration of the leptonic spectrum over the full momentum range [3]. It follows an original analysis performed by ARGUS [4].

The $B\overline{B}$ event is tagged by requiring one very energetic lepton. A second lepton in the event is used to analyse the momentum spectrum of the decay. Charge correlations and the well-known kinematics of the event help to identify the contributions : non-back-to-back leptons come usually from different B decays and same-charged leptons come from cascade decays $b \to c \to l$. Systematic uncertainties due to the modelling of the leptonic decay are extremely small (0.5% in the missing fraction for the CLEO measurement). Averaging the ARGUS and CLEO analyses leads to $Br(b \to l\nu X) = (10.40 \pm 0.16(\mathrm{stat}) \pm 0.30(\mathrm{syst}))\%$, where an absolute correlated systematic error of 0.10% was assumed.

At LEP the momentum and transverse momentum distributions of leptons with respect to the closest jet are studied. Again events with two leptons are used to decrease systematic uncertainties. Selected events are normalised in most analyses to the total number of hadronic decays. That leads to an interference with $R_b \equiv \Gamma_b/\Gamma_h$ assumptions. Other parameters in the fit are $Br(b \to l\nu X)$, $Br(b \to c \to l)$, χ (the B^o mixing parameter) and the mean value of the energy fraction of the b-hadron $< x_E >$.

Common systematic errors in the LEP analyses are the the b-semileptonic decay model and the lepton spectra at rest as simulation input from CLEO measurements. Further difficulties are caused by different background processes like $c \to l$ and a nonsatisfying knowledge about jet properties and QCD effects. The L3 collaboration has published a new analysis [6] using only the 2-jet topology. A consistent treatment of electrons, muons and neutrinos is performed. Neutrinos are taken into account by the measuring the missing energy in each hemisphere. Control subsamples are built using lifetime tags, high-p_t tags and light-quark tags (events containing particles with a very large momentum fraction of the beam energy). A measurement of the total semileptonic branching ratio $b \to \nu X = (23.08 \pm 0.77(\mathrm{stat}) \pm 1.24(\mathrm{syst}))\%$ has been obtained for the first time (Figure 1) assuming a ratio of $e : \mu : \tau$ as $1 : 1 : 0.25$. This allows also a determination of the branching ratio $b \to \tau\nu X$. As can be seen from figure 2 a reasonable agreement with the theoretical prediction is reached. The current L3 value for the branching ratio $b \to \tau\nu X$ is $(1.7\pm0.5\pm1.1)\%$.

Some features of the study are interesting. A harder fragmentation ($< x_E >= 0.72 \pm 0.02$) was required in the simulation to get a simultaneous agreement in the momentum distributions of muons, electrons and neutrinos. A detailed analysis of the systematical uncertainties is included in this paper. One important systematics was found in the definition of the jet sample. Adding three jet events leads to a slightly different value for the branching ratio.

Figure 3 shows all $Br(b \to l\nu X)$ measurements that have been included in the average. The average has been performed with the standard procedure described in Reference 14. The average presented here takes into account the new L3 result. A 2σ inconsistency between $\Upsilon(4S)$ and LEP is observed. The reason for difference is not fully understood. Different hadron composition of the two samples can not be the only motive.

Averaging the branching ratios one has to take into account that all measurement [14] used in the fit are correlated. The highest correlation of -12% is assigned to R_b. On the other hand no correction for the different $< x_E >$ values of the different experiments

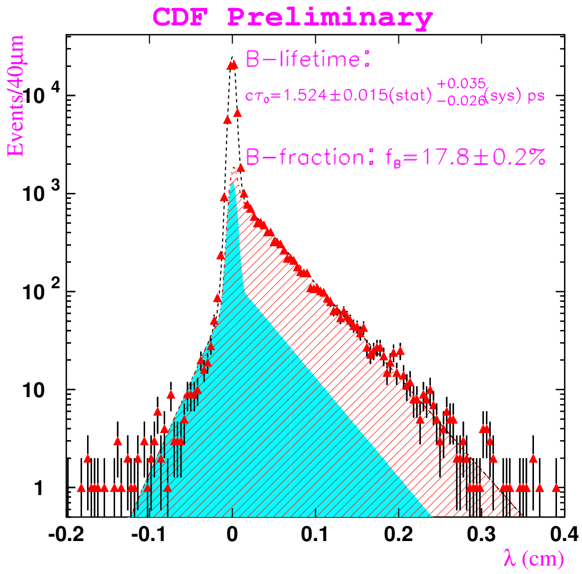

Figure 4. Average b-hadron lifetime from CDF using J/ψ decays.

was done. A higher $< x_E >$ parameter would result in a lower $Br(b \to l\nu X)$ value.

3. B-Lifetimes

Different methods for the determination of the average B lifetime are used in the different experiments. All of them are using the charged tracks coming from the B decay. Good tracking devices are the key for these analyses. All experiments use currently silicon microvertex detectors with resolutions of < 10 μm in the direction perpendicular to the beam and < 30 μm in beam direction. This allows a measurement of the impact parameters (δ) and decay lengths (L) with very high accuracy ($\sigma(\delta) < 30$ μm, $\sigma(L) < 500$ μm). This is one order of magnitude better than the typical values for weakly decaying B-hadrons ($\delta \sim 200$ μm, $L \sim 3$ mm at LEP).

Two variables are used for the lifetime measurement :

- **The decay length** [10–12] is directly proportional to the lifetime ($L = p_B/m_B\ \tau_b$). Because of large p_B it is the most sensitive method. Dedicated vertex algorithms developed by the different collaborations allow to optimize the resolution and the reliability. The decay length is defined as the distance between the primary and the secondary vertex The main systematic error comes from the b-fragmentation functions.

- **The impact parameter** δ [8,9] is not sensitive to the b-fragmentation function due to its independence from the hadron boost p_B/m_B. In most of these analyses a high-purity sample of tracks from weakly decaying B-hadrons is obtained by selecting high p, p_t leptons [8]. The relevant systematic errors come from the limited knowledge of the semileptonic decay process.

Figure 4 shows the decay length distribution from the CDF experiment at FERMILAB. They collected 62500 J/ψ decays. Their preliminary value was reported at the Warsaw Conference [10]. As can be seen from figure 4 the b-component is dominant after a few hundred microns. The slope is proportional to the value of τ_B. The fraction of J/ψ decays coming from b quarks is a free parameter in the fit. L3 [11] has also presented a new preliminary measurement of τ_B at the Warsaw Conference using the new silicon microvertex detector. . The decay length has been built by projecting all tracks onto the jet direction. An iterative procedure was used to determine the tracks to the corresponding vertices. Figure 5 presents the preliminary L3 data. In figure 6 are summerized all inclusive b-hadron lifetimes. All available inclusive B lifetime measurements have been combined by the LEP B Lifetime Working Group [13] (Figure 6). All systematic errors of the different measurements due to fragmentation, decay models, branching ratios, lifetimes and charged multiplicities are considered as fully correlated. The current updated average including the two new values is $\tau_B = 1.55 \pm 0.02$ ps. The final uncertainty is dominated by fragmentation and decay model effects.

In [13] are summarized also the exclusive lifetimes of the different b-hadrons. Figure 7 presents the status of the summer of this year. From the spectator model one expects

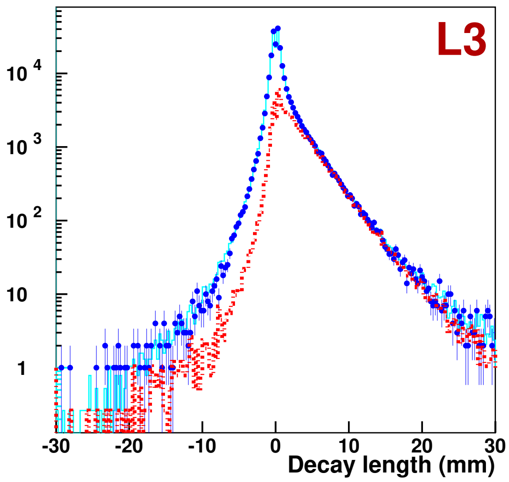

Figure 5. Average b-hadron lifetime from L3 using hadronic decays collected in 1994. The decay length has been built by projecting all tracks onto the jet direction. The secondary vertex is determined in an iterative procedure where tracks are associated to the primary vertex or to the new vertex in an exclusive way.

$$\tau(B^-) = \tau(B^o) = \tau(B_s).$$

The ratio of these lifetimes is always approximately 1. For the b-baryons the spectator model again predicts equal lifetimes. Including gluon corrections a slightly smaller lifetime for the Λ_b is expected

$$\tau(\Lambda_b) \leq 0.9 * \tau(B^-).$$

The world average of the $\tau(\Lambda_b)$ is 0.78 ± 0.04. [13]. This value is significantly shorter as predicted by any model.

4. $|V_{cb}|$ from inclusive measurements

In Table 1 the present status of $|V_{cb}|$ measurements is summarized. Formula (1) has been applied and an

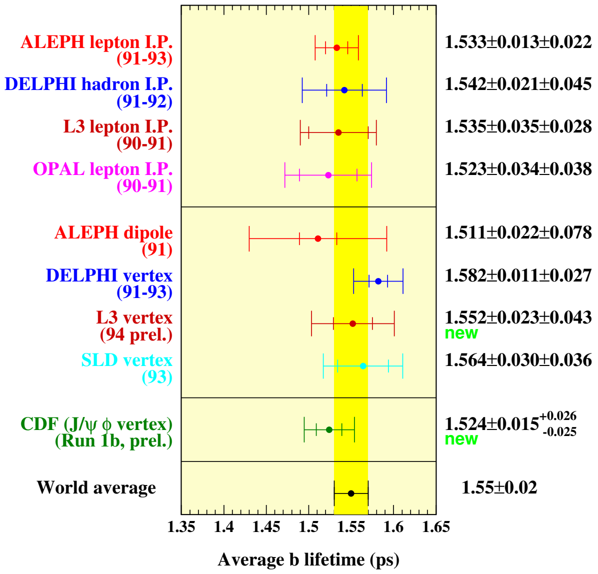

Figure 6. Combination of LEP, SLD and CDF average b-hadron lifetimes by the LEP B Lifetime Working Group.

inclusive b-lifetime of $\tau_b = 1.60 \pm 0.03$ has been assumed to be the average lifetime of B_d^0 and $B^{\pm}$ mesons [13] at the $\Upsilon(4S)$. Positive correlations between τ_b and $Br(b \to l\nu X)$ measurements (due to fragmentation effects) decreasing the experimental uncertainty are neglected.

Measurements at the $\Upsilon(4S)$ and at LEP are found to be consistent within the theoretical uncertainty. More experimental input is needed to understand the origin of the experimental discrepancy between the maesurements at these two energies. The final average is in agreement with $|V_{cb}|$ values from exclusive measurements [15].

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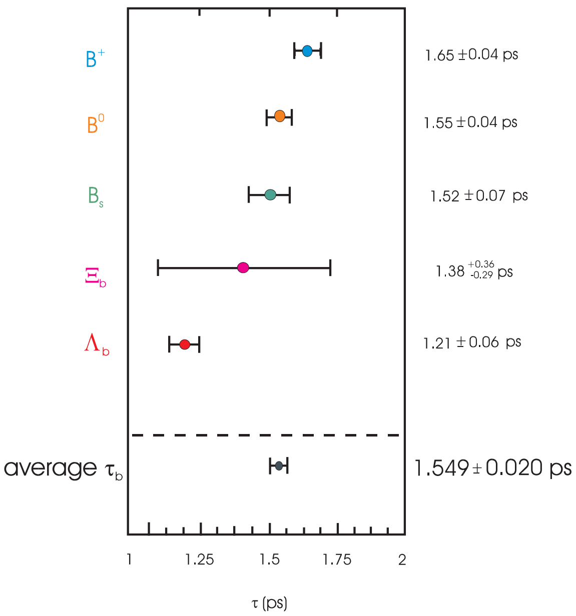

Figure 7. B-hadron lifetimes from the LEP B Lifetime Working Group.

Table 1
Average of inclusive $|V_{cb}|$ measurements.

	$\|V_{cb}\|$
$\Upsilon(4S)$	$0.0391 \pm 0.0007(\mathrm{exp}) \pm 0.0040(\mathrm{theo})$
LEP	$0.0408 \pm 0.0004(\mathrm{exp}) \pm 0.0040(\mathrm{theo})$
Average	$0.0404 \pm 0.0003(\mathrm{exp}) \pm 0.0040(\mathrm{theo})$

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