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B PHYSICS AT LEP

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B physics results from LEP are reviewed. The focus is put on recent results from DELPHI, results which serve as important input for hadron colliders and results which will still significantly contribute in the future.

1 b-hadron production

Measurements of b-hadron production properties at LEP are important for several reasons. Many of these properties serve as important input for the physics at hadron colliders, where many of the corresponding measurements cannot be done with similar precision. It is also interesting to compare b-hadron production properties for different environments (e^+e^-, $p\overline{p}$, ep), where one expects universal behaviour for many of them. Furthermore, their precise knowledge is needed for many other measurements in the heavy flavour sector (e.g. B-oscillations, CKM elements, b-hadron lifetimes) where they enter as a source of systematic uncertainty.

1.1 b-hadron production fractions

At e^+e^- and $p\overline{p}$ colliders with $\sqrt{s} \gg m_b$, all kinds of b-hadrons can be produced, either in the ground or excited states (e.g. orbital excitation). Since the production of b-hadrons takes place in the fragmentation process, the rates of individual types of b-hadrons can not be calculated perturbatively. Precise knowledge of these production fractions are e.g. very important to extract b-hadron branching fractions in analyses which measure product branching fractions of the kind $f_{B_i} \cdot BR(B_i \to X)$. DELPHI has published the most precise measurement of a single b-hadron production fraction [1] by reconstructing in an inclusive way the charge of the secondary b-hadron decay vertex (Figure 1). It is the first measurement of the fraction of charged b-hadrons in a sample of weakly-decaying b-hadrons produced in $Z^0 \to b\overline{b}$ decays, $f^+ = BR(\overline{b} \to X_B^+) = BR(b \to X_B^-) = (42.09 \pm 0.82(\text{stat.}) \pm 0.89(\text{syst.}))\%$. f_{B_u} can be extracted from f^+ with small additional uncertainties: $f_{B_u} = (40.99 \pm 0.82(\text{stat.}) \pm 1.11(\text{syst.}))\%$. Combination of all available data sensitive to b-hadron production fractions gives [2]: $f_{B_s} = (10.5 \pm 1.5)\%$, $f_{b-baryon} = (9.9 \pm 1.7)\%$, $f_{B_u} = f_{B_d} = (39.8 \pm 1.0)\%$, where the following assumptions have been used as constraints: $f(Z\text{-decays}) = f(\text{TEVATRON})$, $\sum_i f_i = 1$, $f_{B_u} = f_{B_d}$. In the future, b-hadron production fractions will be combined separately for LEP and TEVATRON to be able to test quantitatively the equality of these quantities in Z^0 decays and

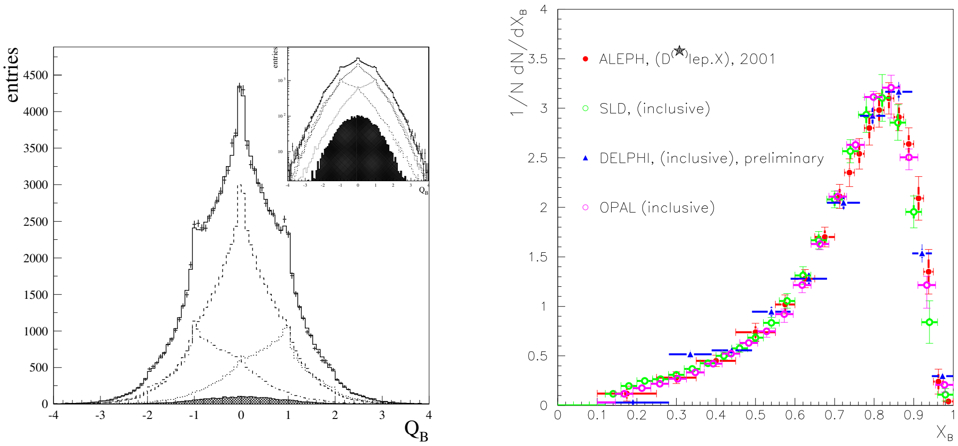

Figure 1. Left: the secondary vertex charge of the weakly decaying b-hadron from DELPHI for the data (points with error bars) with the result of the fit superimposed (solid histogram) on a linear scale and on a logarithmic scale (as inlay). The shapes for neutral (dashed histogram), negatively (dashed-dotted) and positively (dotted) charged b-hadrons obtained from the simulation are also shown. The hatched histogram shows the contribution of non-$b\overline{b}$ events. Right: the measured, unfolded distribution for x_B^{weak} from ALEPH, DELPHI, OPAL and SLD.

high p_t $p\overline{p}$ collisions.

1.2 The b-fragmentation function

Measuring the b-fragmentation function provides essential tests of hadronisation models, both of the perturbative and non-perturbative part. Their knowledge is crucial for heavy flavour processes at hadron colliders, e.g. the measurement of the total b-quark production cross section. The observable quantity measured by experiments operating at e^+e^- colliders is the scaled energy of the b-hadron, $x_B = 2E_B/\sqrt{S}$, with E_B being the energy of the b-hadron and $\sqrt{s}$ the centre of mass energy, where x_B can refer either to the primary or weakly decaying b-hadron (x_B^{prim}, x_B^{weak}). The measurements performed by the LEP experiments and SLD offer good sensitivity also to the shape of the fragmentation function and are shown in Figure 1. ALEPH used semi-exclusive $B \to D^{(*)} l \nu X$ decays, and is thus mainly sensitive to B-mesons. DELPHI, OPAL and SLD performed fully inclusive analyses a-priori not selecting specific b-hadrons. For $\langle x_B^{weak} \rangle$ they get (the first error is statistical, the second systematic, possibly including model uncertainties): ALEPH [3]: $\langle x_B^{weak} \rangle = 0.716 \pm 0.006 \pm 0.006$; DELPHI [4]: $\langle x_B^{weak} \rangle = 0.7153 \pm 0.0007^{+0.0049}_{-0.0052}$; OPAL [5]: $\langle x_B^{weak} \rangle = 0.7193 \pm 0.0016^{+0.0036}_{-0.0031}$; SLD [6]: $\langle x_B^{weak} \rangle = 0.709 \pm 0.003 \pm 0.004$.

Several fragmentation models [7] describing the non-perturbative part of the fragmentation function have been tested by the experiments. These tests favour the LUND and Bowler models which give the best description of the data. The commonly used Peterson model is disfavoured.

Table 1. Left: The $l=0$ and $l=1$ states of $\mathrm{B}_{u,d}$ mesons. (s) and (d) denote s-wave and d-wave decays, respectively. Right: Results on $B^{**}_{u,d}$ masses and production rates from analyses using inclusive (row 1-4), partial (5) and exclusive B reconstruction (6). Some numbers have been recomputed using updated values for input parameters and a similar set of assumptions.

l	j_q	J^P	state	dom. decay	
0	$\frac{1}{2}$	0^-	B		
		1^-	B^*	$\mathrm{B}\gamma$	
1	$\frac{1}{2}$	0^+	B_0^*	$\mathrm{B}\pi$	(s)
		1^+	B_1^*	$\mathrm{B}^*\pi$	(s)
1	$\frac{3}{2}$	1^+	B_1	$\mathrm{B}^*\pi$	(d)
		2^+	B_2^*	$\mathrm{B}^{(*)}\pi$	(d)

	$M(\mathrm{B}^{**})[MeV/c^2]$	$\sigma_{B^{**}_{u,d}}/\sigma_{b-jet}$
OPAL [18]	5712 ± 11	0.22 ± 0.05
DELPHI [19]	$5734 \pm 5 \pm 17$	$0.27 \pm 0.02 \pm 0.06$
ALEPH [20]	$5734 \pm 3 \pm 16$	$0.14 \pm 0.01 \pm 0.03$
L3 [21]	$\mathrm{B}_2^* : 5768 \pm 5 \pm 6$	$0.32 \pm 0.03 \pm 0.06$
CDF [24]	$\mathrm{B}_1 : 5710 \pm 20$	$0.22 \pm 0.05 \pm 0.02$
ALEPH [22]	$\mathrm{B}_2^* : 5739^{+8}_{-11}{}^{+6}_{-4}$	$0.25 \pm 0.07^{+0.05}_{-0.04}$

1.3 b-hadron spectroscopy

Heavy Quark Effective Theory (HQET) [8] predicts the multiplet structure for mesons with $l=0$ and $l=1$ shown in Table 1.3. The orbitally excited states, commonly labelled B^{**}, are grouped in doublets with same j_q and are degenerate in mass in the heavy quark limit $m_Q \to \infty$. The dominant decay mode of $B^{**}_{u,d}$ mesons is into the $B^{(*)}\pi$ final state. For B_s^{**} mesons, isospin conservation forbids $B_s^{**} \to B_s^{(*)}\pi$, thus $B_s^{**} \to B^{(*)}K$ should dominate if above threshold. The $j_q = 1/2$ $(3/2)$ states are expected to be broad (narrow) because the strong decay proceeds via s-wave (d-wave) transitions. Several theoretical predictions for the masses of B^{**} mesons exist [9–17]. Some of the models predict the mass of the narrow doublet ($j_q = 3/2$) to be above the broad doublet ($j_q = 1/2$), whereas others predict the opposite, called 'spin-orbit-inversion'. $B^{**}_{u,d}$ mesons have been identified by all four LEP Collaborations [18–23] and CDF [24] using different analysis methods (Table 1.3). The results show some disagreement on the production rates. Up to now, the composition of the signals could not been clearly resolved, and no final conclusions can be drawn on the mass hierarchy. OPAL [18] had also published an excess in the $B^{(*)}K$ spectrum, interpreted as stemming from B_s^{**} decays. DELPHI has performed new analyses [25] to overcome the main limitation of the old analyses causing the biggest systematic error, the description of the background under the signal. Both analyses are based on an inclusive reconstruction of the weakly decaying B-meson. The 'High Efficiency Analysis' aims for optimal background control by fitting the background on the data, the 'High Purity Analysis' (see Figure 2) aims for optimal background suppression by using Neural Networks in the different steps of reconstruction. A component compatible with the detector resolution can be isolated and is thus interpreted as stemming from narrow B^{**} states. This favours a small mass splitting within the narrow doublet and a small contribution from the decay $B_2 \to B\pi$. Results have been combined for the two analyses taking into account correlated errors. The results for the masses of these narrow states are: $m(B_2^*) = 5738 \pm 14 MeV/c^2$, $m(B_1) = 5732 \pm 20 MeV/c^2$. Their production rate has been measured to be $\left(\frac{(\sigma(B_d^{**})+\sigma(B_u^{**}))}{\sigma_{b-jet}}\right)_{narrow} = 0.090 \pm 0.007(\text{stat.})^{+0.013}_{-0.008}(\text{syst.}) \pm 0.011(\text{model})$. The total production rate follows then by assuming either state or spin counting for the individual production rates (1:1:1:1 or 1:3:3:5 for $B_0^* : B_1^* : B_1 : B_2^*$) to be

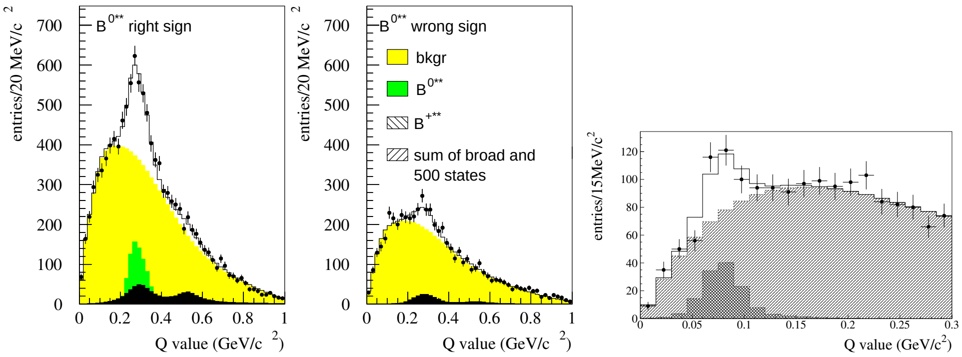

Figure 2. Left: The observed Q-value spectra ($Q = m(B^{(*)}\pi) - m(B^{(*)}) - m(\pi)$) in the $B_d^{**} \to B^{(*)+}\pi^-$ channel for the 'High Purity Analysis'. Right: The observed Q-value spectrum ($Q = m(B^{(*)}K) - m(B^{(*)}) - m(K)$) for $B^{(*)}K$ final states for the 'High Purity Analysis'.

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$\frac{(\sigma(B_d^{**})+\sigma(B_u^{**}))}{\sigma_{b-jet}} = 0.157 \pm 0.011(\text{stat.})^{+0.022}_{-0.014}(\text{syst.}) \pm 0.019(\text{model})$. The uncertainty labelled 'model' includes the variation corresponding to either the state or spin counting scheme as well as including or not in the fit a resonance at a Q-value of about 500 MeV which improves the fit quality but has no straight-forward interpretation.

To search for B_s^{**} mesons, the pion from the primary vertex is replaced by an identified kaon. Figure 2 shows the $B^{(*)}K$ Q-value spectrum. One narrow resonance compatible with the experimental resolution is observed, with parameters: $\langle Q \rangle = 79.0 \pm 4.0(\text{stat.}) \pm 3.7(\text{syst.}) MeV/c^2$, $\frac{(\sigma(B_s^{**}) \cdot BR(B_s^{**} \to B^{(*)}K))}{\sigma_{b-jet}} = 0.0093 \pm 0.0020(\text{stat.}) \pm 0.0013(\text{syst.})$.
The most likely interpretation is that the observed peak is from the decay $B_{s2}^* \to BK$. Under this hypothesis, the measured Q-value corresponds to $m(B_{2s}^*) = 5852 \pm 5 MeV/c^2$.

2 The CKM matrix element V_{cb}

The CKM element V_{cb} can be measured either in exclusive or inclusive semileptonic b-hadron decays. In exclusive decays $\overline{B}_d^0 \to D^{*+}l^-\overline{\nu}$, the differential decay rate is given through $\frac{d\Gamma(\overline{B}_d^0 \to D^{*+}l^-\overline{\nu})}{d\omega} = \frac{G_F^2}{48\pi^3} \cdot |V_{cb}|^2 \cdot F^2(\omega) \cdot K(\omega)$, with $\omega = v_B \cdot v_{D^*} = \frac{m_b^2 + m_{D^*}^2 - q^2}{2 \cdot m_B \cdot m_{D^*}}$. $F(\omega)$ can be computed in HQET [26], $F(\omega) = 0.91 \pm 0.04$, and is the dominating theoretical error for this method.

Precise knowledge of the b-lifetime and its semileptonic branching ratio are the main experimental ingredients to extract V_{cb} from inclusive semileptonic decays. This method is discussed in more detail in the following.

2.1 Leptonic and hadronic moments

In the Operator Product Expansion (OPE) formalism [27], the semileptonic b-decay width is related to V_{cb} through: $\Gamma_{sl}(b \to cl^-\overline{\nu}) \propto |V_{cb}|^2 \cdot [c_3\langle B|O_3|B\rangle + c_5\frac{\langle B|O_5|B\rangle}{m_b^2} + c_6\frac{\langle B|O_6|B\rangle}{m_b^3} + \mathcal{O}(\frac{1}{m_b^4})]$ In the 'kinetic mass scheme' (the alternative 'pole mass scheme' cannot be discussed here because of limited space) the quantities μ_π^2, μ_G^2 (at $\mathcal{O}(1/m_b^2)$), ρ_D^2 and ρ_{LS}^3 (at $\mathcal{O}(1/m_b^3)$) appear. They are the expectation values of the kinetic, chromomagnetic, Darwin and Spin-Orbit operators, respectively.

Moments of the lepton energy spectrum and hadronic mass spectrum in semileptonic b-decays are sensitive to these quantities. Measuring precisely these spectra can thus significantly reduce the uncertainties on $|V_{cb}|$.

DELPHI [28] has measured three lepton energy moments: $M_1^l = \langle E_l^* \rangle = 1.3782 \pm 0.0073 \pm 0.0093 GeV$, $M_2^{'l} = \langle (E_l^* - \langle E_l^* \rangle)^2 \rangle = 0.1838 \pm 0.0058 \pm 0.0055 GeV^2$, $M_3^{'l} = \langle (E_l^* - \langle E_l^* \rangle)^3 \rangle = -0.0301 \pm 0.0015 \pm 0.0039 GeV^3$, where E_l^* is the lepton energy in the b-hadron rest frame, and six hadron mass moments: $\langle m_{D^{**}} \rangle = 2.483 \pm 0.033 \pm 0.033 GeV/c^2$, $\langle m_{D^{**}}^2 \rangle = 6.22 \pm 0.16 \pm 0.15 (GeV/c^2)^2$, $\langle m_{D^{**}}^4 \rangle = 40.1 \pm 2.0 \pm 1.7 (GeV/c^2)^4$, $\langle m_{D^{**}}^6 \rangle = 271 \pm 21 \pm 16 (GeV/c^2)^6$, $\langle m_{D^{**}}^8 \rangle = (19.3 \pm 2.1 \pm 1.4) \cdot 10^2 (GeV/c^2)^8$, $\langle m_{D^{**}}^{10} \rangle = (14.7 \pm 2.0 \pm 1.2) \cdot 10^3 (GeV/c^2)^{10}$.

The first three leptonic and hadronic moments have been used to determine the parameters introduced before. Constraints have been imposed on μ_G^2, ρ_{LS}^3, $m_b(1GeV)$ and $m_c(1GeV)$. This gives: $m_b(1GeV) = 4.575 \pm 0.069 \pm 0.043 \pm 0.005 GeV/c^2$, $m_c(1GeV) = 1.144 \pm 0.106 \pm 0.071 \pm 0.020 GeV/c^2$, $\mu_\pi^2(1GeV) = 0.399 \pm 0.047 \pm 0.039 \pm 0.020 GeV^2$, $\tilde{\rho}_D^3 = 0.054 \pm 0.017 \pm 0.010 \pm 0.010 GeV^3$ ($\tilde{\rho}_D^3$ is related to ρ_D^3 through $\tilde{\rho}_D^3 \approx \rho_D^3(1GeV) - 0.1GeV^3$), where the first error is the uncertainty from the fit, the second from the systematic uncertainties on the measured moments (correlations have been taken into account) and the third from theoretical uncertainties.

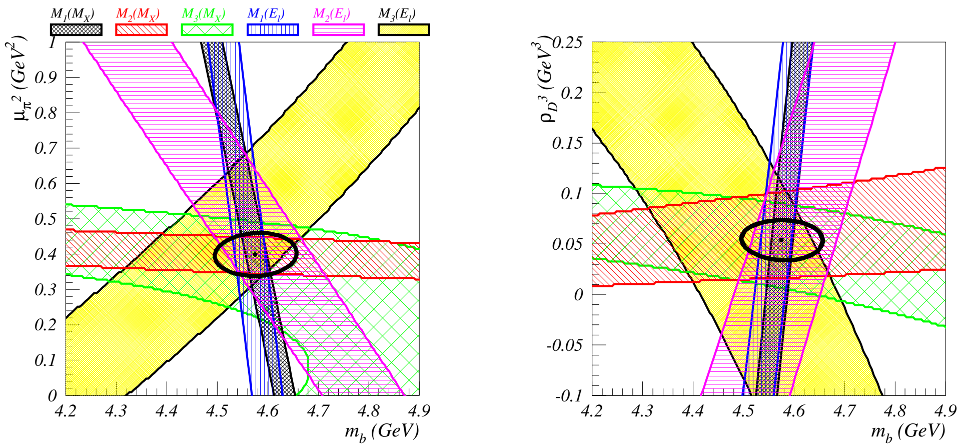

Figure 3. The projection of the constraints on the $m_b - \mu_\pi^2$ (left) and $m_b - \tilde{\rho}_D^3$ planes. The ellipses represent the 1 σ contours.

Using the expression for $|V_{cb}|$ from [29] then gives: $|V_{cb}| = 0.0421 \cdot (1 \pm 0.014(\text{meas.}) \pm 0.014(\text{fit}) \pm 0.015(\text{theory}))$. For the measurement of the inclusive b-hadron lifetime and the semileptonic branching fraction, leading to the first error indicated, only measurements from LEP have been considered. If results obtained by b-factories operating at the $\Upsilon(4S)$ are included, this error can be reduced to 1%. The uncertainty denoted 'fit' corresponds to the uncertainties of the parameters obtained before, not including theoretical errors. The theoretical uncertainty has been taken from [29].

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