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A REVIEW OF B PHYSICS AT LEP

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Abstract

A review of B hadron physics at LEP is presented. Following a brief description of the LEP accelerator and experiments, an overview of B tagging methods and analysis topics is given. Results for time dependent B_d and B_s meson mixing, rare decays, Λ_b polarisation and V_{cb} determination follow.

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1 Introduction

The first phase of LEP data taking, at a centre-of-mass energy $\sqrt{s} \sim 91.26$ GeV, began in 1989 and ended last year. Each of the four LEP experiments recorded about four million Z^0 decays and performed many precision tests of Standard Model physics. This review aims to provide a general overview of the B hadron physics that has been performed on the data.

Section 2 summarises the advantages of performing B physics analyses at LEP and briefly describes the four experiments. A review of the methods used to isolate B events follows in section 3. The variety of B physics topics pursued at LEP is summarised in section 4. Two of these, time dependent B meson mixing and rare decays, are treated in more detail and most recent results are presented. Results are also given from Λ_b polarisation and V_{cb} determination analyses. Conclusions are presented in section 5.

2 B Physics at LEP

There are three main advantages for studying B physics at LEP:

- The large centre-of-mass energy allows all types of B hadrons to be produced with a high boost. This translates into a typical B hadron flight distance of 3 mm, which can be measured and used to tag B hadrons with high purity and efficiency;
- The LEP luminosity is high. The design luminosity $\mathcal{L} \sim 1.5 \cdot 10^{-31}$ pb^{-1} [1] has been exceeded on several occasions. As the Z^0 boson couples strongly to $b\bar{b}$ quark pairs, a large B hadron sample is available;
- LEP is an $e^+ - e^-$ collider. It provides a clean environment with which to reconstruct B events. The large data sample available to the LEP experiments can therefore be used to its full potential.

The four LEP experiments ALEPH [2], DELPHI [3], L3 [4], and OPAL [5] record Z^0 events with high efficiency. ALEPH, DELPHI and OPAL are similar, and specialise in the detection and identification of charged pions, kaons, protons and leptons. They are each composed of a high precision silicon microvertex detector surrounded by larger drift chambers for tracking, with electron, hadron and muon calorimeters at larger radii to identify leptons. Pions, kaons and protons are identified by measurements of their energy loss dE/dx and momenta. Pions and kaon dE/dx expectations are separated by at least two standard deviations for momenta between 2 and 20 GeV/c. DELPHI can also identify charged particles using Cerenkov counters, which extend the separation between pions and kaons to 25 GeV/c. Electrons and muons are identified by a combination of shower profile, dE/dx, calorimetric and muon chamber information. L3, with a smaller

Quantity	Resolution
ALEPH, DELPHI, OPAL	
Track impact parameter (at Si microvertex) Momentum resolution Calorimetric energy resolution	$\sigma(d_0) \sim 15 - 25\mu m$ $\sigma(z_0) \sim 17 - 35\mu m$ $\sigma(1/p) \sim (0.5 - 1.5) \cdot 10^{-3}$ (GeV/c)$^{-1}$ 6 – 18% (electrons at 1 GeV) decreasing as $1/\sqrt{E}$ with E
L3	
Calorimetric energy resolution Calorimetric angular resolution	< 2% (electrons at 1 GeV or more) < 0.5 degree

Table 1: *Typical tracking and calorimetric resolutions for the four LEP experiments.*

tracking volume and refined calorimetry, complements these experiments by specialising in neutral particle and electron and muon identification. It can therefore reconstruct B decays to neutral particles. Typical resolutions for all experiments are given in table 1.

3 Methods to Isolate B decays

B hadron events must be separated from other Z^0 decays after the data have been recorded. Four properties of B decays can be used as a basis for isolating events: decay distance (typically 3 mm for B and 1.0 to 2.5 mm for charm hadrons); charged multiplicity (typically 5 for B and 2 for charm hadron decays); mass (typically 5.3 GeV/c^2 for B and 1.8 GeV/c^2 for charm hadrons); average energy after fragmentation (typically 32 GeV for B and 23 GeV for charm hadrons).

- A separated secondary vertex (figure 1) can be used to isolate an inclusive sample of B hadrons. The higher multiplicity of B decays ensures that sufficient tracks are reconstructed to form a decay vertex with high efficiency, and the longer decay distance ensures a greater separation between primary and decay verticies.
- A large impact parameter (figure 1) can be used to isolate an inclusive sample, due to the larger mass and decay distance of B hadrons.
- The requirement that decay products have large total and transverse momentum can be used to isolate an inclusive sample of B hadrons, due to the large B hadron mass and hard B fragmentation. For example, high momentum leptons from semileptonic B decay are often used to isolate events.
- Event shape information, reliant on the larger mass and harder fragmentation of

B events, can also be used to isolate an inclusive sample. However, the method is not as successful at LEP as at lower energy experiments because of the higher boost of the events.

- The reconstruction of a particular decay chain can be used to isolate an exclusive sample of B hadrons (ie. those of a given type).

A fuller discussion of these techniques can be found in [6]. Typical efficiencies and purities for all tagging methods are given in table 2.

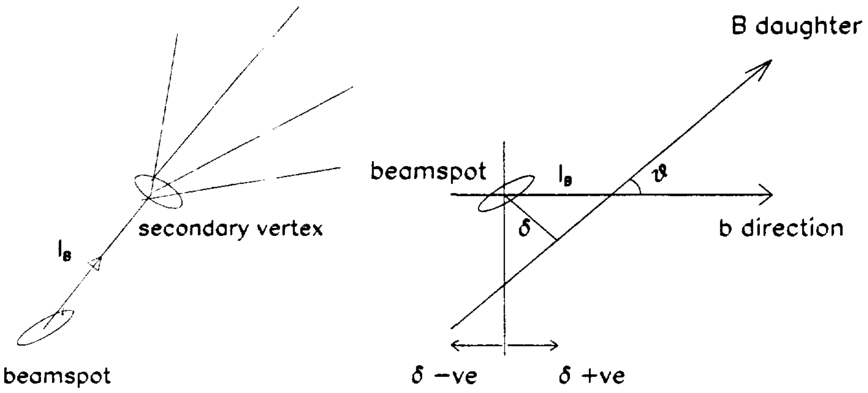

Figure 1: *Schematic diagrams of a separated secondary vertex (left), and track impact parameter δ (right).*

Tagging Method	Purity (%)	Efficiency (%)
Separated secondary vertex	95	20
Track impact parameter	90-95	25
High momentum lepton	90	6
Event shape information	70	20
Exclusive tag	70-90	0.05

Table 2: *Typical purities and efficiencies for different B tagging methods.*

4 B Physics Analyses at LEP

4.1 Overview

A full description of B physics is beyond the scope of this review, and can be found elsewhere [7]. The main analysis topics pursued at LEP are listed in table 3, together with the motivation for performing each analysis. In this section time dependent B mixing, rare decays, Λ_b polarisation and V_{cb} determination will be examined in further detail. Descriptions of analyses determining the partial width of the Z^0 to decay to b quark pairs, and B hadron masses and lifetimes can be found in other reviews given in this conference, and reviews of forward-backward asymmetry, b quark fragmentation, and b hadron branching ratio measurements can be found elsewhere, for example in [8, 9, 10].

Forward-backward asymmetry	Gives vector and axial coupling coefficients Standard Model test.
Partial width of Z^0 to decay to $b\bar{b}$ quarks	Standard Model test.
Neutral B meson mixing	Places limits on V_{ts}, V_{td}.
B hadron lifetimes	Test of heavy quark effective theory.
B hadron masses	Test of heavy quark effective theory.
Studies of rare decays	Window on possible physics beyond the Standard Model.
Studies of b quark fragmentation	Test of QCD models at Z^0 resonance.
B hadron branching ratios	Standard Model test.
Λ_b polarisation	Standard Model test.
V_{cb} determination	Input to Standard Model.

Table 3: *B physics topics currently under study at LEP, with their motivation.*

4.2 B mixing

Neutral B mesons, B^0, oscillate between conjugate states via the box diagrams shown in figure 2. The probability for a B^0 meson to decay as a $\overline{B^0}$ meson is time dependent and is given by the relation:

$$P(B^0 \rightarrow \overline{B^0}) = \frac{1}{\tau} e^{-t/\tau} \cos(\Delta m_q t) \tag{1}$$

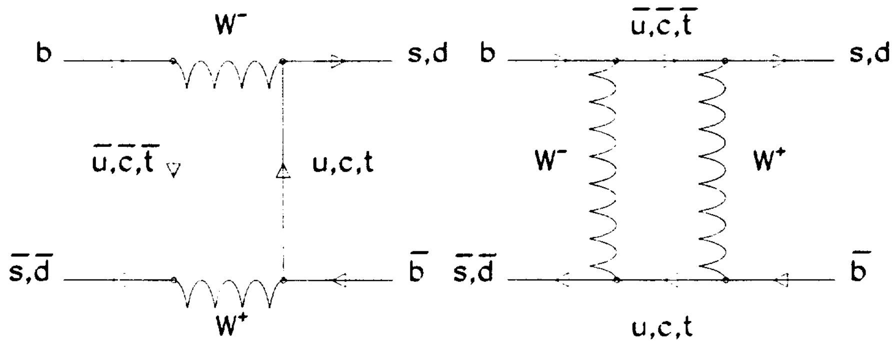

Figure 2: *Box diagrams which allow B^0 mixing to occur.*

where t is the decay time, τ the average lifetime of the CP eigenstates, and Δm_q their mass difference. If Δm_q can be measured for both B_d^0 and B_s^0 mesons, then a limit on the ratio of CKM matrix elements V_{tq} can be found. The mass differences are related [11] to the matrix elements by

$$\frac{\Delta m_s}{\Delta m_d} = (1.35 \pm 0.15) \cdot \left(\frac{V_{ts}}{V_{td}}\right)^2 . \tag{2}$$

Measurements of time dependent mixing usually proceed as follows.

- A sample enriched in B_d^0 and/or B_s^0 mesons is isolated.
- The b quark flavour at decay is determined from (for example) the sign of the decay product lepton, fast kaon, reconstructed charm meson, or the jet charge. Flavour at production is determined from equivalent quantities in the opposite hemisphere.
- The b decay time is formed from the reconstructed decay length and an estimate of the b boost.

Thus the only unknown remaining in equation 1 is Δm_q which can be fitted for taking background and flavour mistagging into account.

4.2.1 Δm_d results

B_d^0 mixing has been measured using a wide range of methods [12] to determine the mixing probability. As an example, consider a DELPHI analysis which tags b flavour at production by the sign of the decay product lepton or kaon, and b flavour at decay by the jet charge of tracks in the opposite hemisphere. A vertex is formed around the lepton or kaon candidate so that the b decay length can be reconstructed. This is convoluted with a fragmentation function to give the decay time, and Δm_d fitted. Figure 3 shows the asymmetry between unmixed and mixed events in the sample as a function of the b decay length ('flight estimator'). The full line (a) illustrates the result of the likelihood fit from which $\Delta m_d = 0.531^{+0.050}_{-0.046}$ ps^{-1}. The dashed line (c) gives the prediction for data if there were no time dependence in the oscillation, and the dashed line (d) gives the prediction for data if no oscillatory behaviour existed. It is clear that the data support the premise of time dependent mixing.

The most recent results from each experiment are summarised in figure 4. Results are given by mix-tagging method, and detail the years of data included in the analysis.

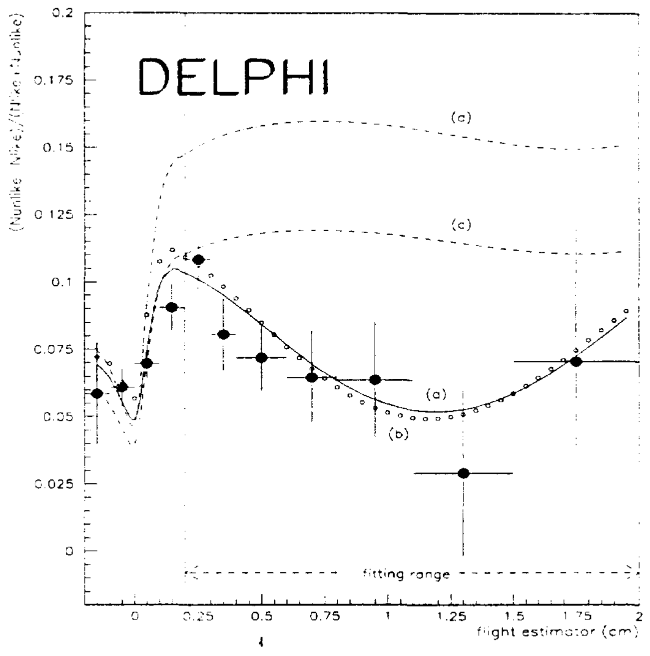

Figure 3: *The mixing asymmetry (fraction of unmixed - mixed events) as a function of the b decay length for the DELPHI lepton, kaon and jet charge analysis. The curves are the expected shapes for (a) the fitted mixing frequency, (b) the fitted mixing frequency without including detector resolution, (c) the time-independent mixing hypothesis with average mixing=0.17, (d) without mixing.*

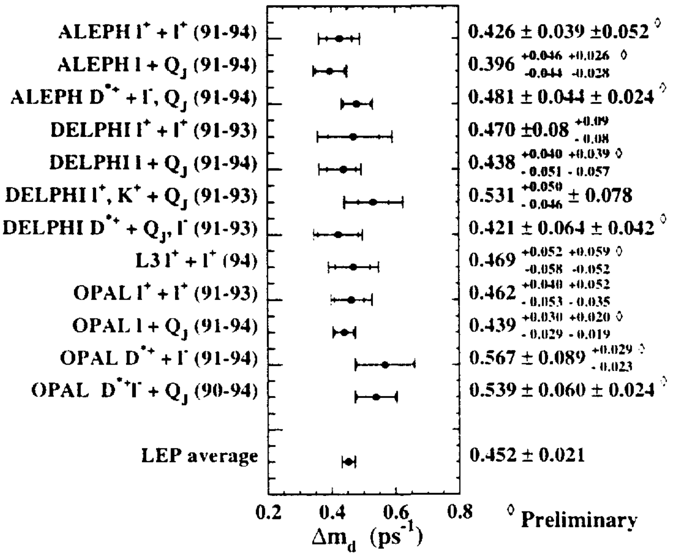

Figure 4: *Current LEP time dependent B_d^0 mixing results.*

4.2.2 Δm_s results

B_s^0 mixing analyses can be performed in two ways; either by scanning the likelihood that Δm_d produces the measured decay times for a given value of Δm_s, as a function of Δm_s [13] (B_s^0 forms approximately 10% of the dilepton event samples), or by isolating an exclusive sample of B_s^0 decays and measuring Δm_s directly [14]. It is only very recently that the second method has been used. For example, ALEPH isolates B_s^0 candidates by reconstructing D_s mesons (the sign of which tags the b decay flavour) through several decay modes. The flavour of the b quark at decay is determined by the sign of the lepton in the opposite hemisphere to the D_s candidate, an estimate is made of the decay time and Δm_s is fitted. The B_s^0 purity obtained using this analysis is around 60%. As statistics are fairly low (277 events are obtained using data taken between 1991 and 1995), care must be taken in extracting a value for Δm_s. Figure 5 shows the change in the likelihood that a given value of Δm_s produces the observed decay times, as a function of Δm_s, for the ALEPH analysis. It is not possible to distinguish between higher Δm_s values (these are equally likely), although a limit can be set on low values of Δm_s. A 95% confidence limit curve is calculated using a Monte Carlo technique and taking systematic errors into account. A 95% exclusion limit for the lower bound of Δm_s is found at the point where this curve intersects the Δlog(likelihood) curve and is found to be 6.6 ps^{-1}, the most stringent level to date.

Results from all experiments for Δm_s exclusion levels are given in figure 6.

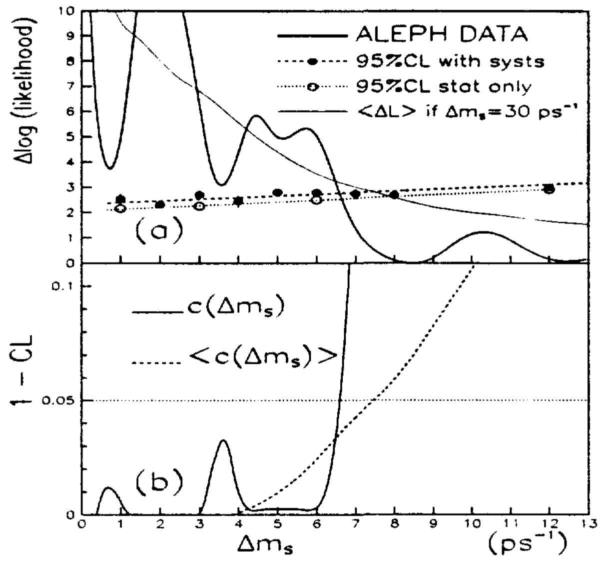

Figure 5: *Determination of the 95% exclusion level limit for the direct ALEPH method of determining* Δm_s *discussed in the text. (a) The change in log likelihood plotted as a function of* m_s *(solid line), with the 95% confidence level curve obtained from Monte Carlo with (dashed) and without (dotted) systematic errors included. The thin curve shows the expected log likelihood change if* $\Delta m_s = 30\ ps^{-1}$. *(b) The solid curve represents 1-confidence level. The dashed curve shows the average behaviour of the confidence level if* $\Delta m_s = 30\ ps^{-1}$.

4.2.3 Combining Δm_d and Δm_s results

If the LEP average result for Δm_d is combined with the best 95% confidence limit for Δm_s, a limit on the ratio $\left(\frac{V_{ts}}{V_{td}}\right)$ can be found;

$$\left(\frac{V_{ts}}{V_{td}}\right) > 2.97$$

(at 95% confidence level). This is in good agreement with predictions from the unitarity of the CKM matrix, which demands that $\left(\frac{V_{ts}}{V_{td}}\right) > 2.9$ [15].

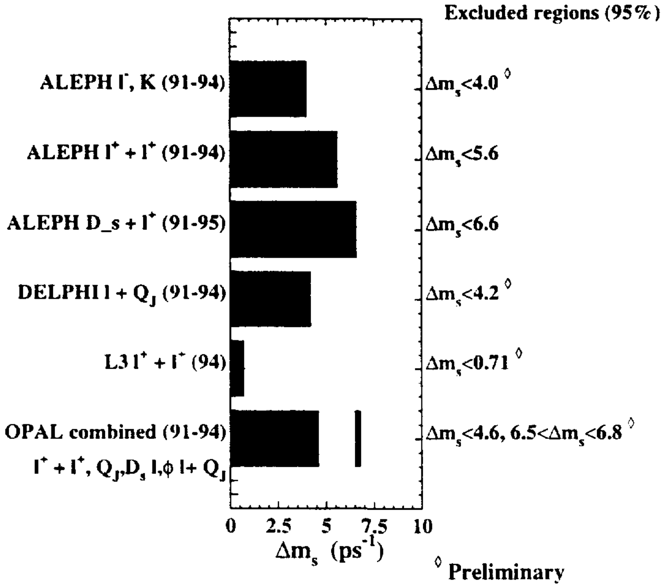

Figure 6: *Current exclusion levels for* Δm_s.

4.3 Rare decays

Observed rates of rare decays can test Standard Model predictions and thus give information on new physics. In addition parameters such as the CKM matrix elements can be found directly, given sufficient statistics. Three classes of rare and interesting decays (neutral charmless decays, charged charmless decays and decays to tau leptons) will now be described.

4.3.1 Neutral charmless decays

L3 have placed upper bounds on 90% confidence limits for the branching ratios of B_d^0 and B_s^0 mesons to two photons [16] or η and π^0 mesons [17]. Standard Model predictions for these branching ratios vary between 10^{-5} to 10^{-8}. Any deviation from these predictions would signal new physics, for example if the rate were enhanced then this could be ascribed to Higgs or superparticle exchange occurring in addition to Standard Model processes.

The results given in table 4 have been obtained using a data sample of three million Z^0 decays. Decays to two photons are isolated by applying a neural net based on event shape properties to first enrich the sample in B events, and then by requiring the decay products to be two isolated identified photons. Cuts are placed on the photon energies and opening angle to reduce background. For decays to η and π^0 a B sample is enriched by cutting on several kinematic quantities (for example the small opening angle between the two decay mesons, which must be of high energy). The invariant mass of the two

Branching ratio
$br(B_d^0 \to \gamma\gamma) < 3.9 \cdot 10^{-5}$ (*)
$br(B_d^0 \to \eta\eta) < 4.1 \cdot 10^{-4}$ (*)
$br(B_d^0 \to \eta\pi^0) < 2.5 \cdot 10^{-4}$
$br(B_d^0 \to \pi^0\pi^0) < 6.0 \cdot 10^{-5}$
$br(B_s^0 \to \gamma\gamma) < 14.8 \cdot 10^{-5}$ (*)
$br(B_s^0 \to \eta\eta) < 1.5 \cdot 10^{-3}$ (*)
$br(B_s^0 \to \eta\pi^0) < 1.0 \cdot 10^{-3}$ (*)
$br(B_s^0 \to \pi^0\pi^0) < 2.1 \cdot 10^{-4}$ (*)

Table 4: *Neutral charmless rare B decay branching ratios measured by L3. Measurements denoted by (*) have been made for the first time.*

photons from η decay, and the energy of the electromagnetic cluster from π^0 must also satisfy certain limits to reduce backgrounds. Some of these measurements have been made for the first time, while the others are competitive with existing measurements [18, 19]. It can be seen that more data are needed to test the Standard Model.

4.3.2 Charged charmless decays

Limits on exclusive two body decays have already been presented by the ALEPH [20] and DELPHI [21] collaborations. The ALEPH collaboration has recently updated its analysis to include all data taken between 1991 and 1995 [22], and results are given in table 5.

B decays are tagged by forming a secondary vertex, and requiring that this be significantly separated from the primary vertex. The two decay tracks must have an invariant mass higher than the charm kinematic limit. The mass and particle dE/dx measurements are used to calculate the consistency of each event with a given particle hypothesis, thus allowing limits to be placed on decays to pions, kaons and protons.

All results are preliminary, and are consistent with observations from CLEO [19].

4.3.3 B→ $\tau\nu$X decays

Although not strictly a rare decay (the Standard Model prediction for $br(b \to \tau\nu X)$ is 2.30 ± 0.25% [23]), study of this channel is interesting because the decay could proceed either by a W or a Higgs boson. Thus a measurement of this decay channel could be sensitive to new physics, for example supersymmetry where two Higgs doublet are introduced to couple to d-type and u-type quarks. The branching ratio $br(b \to \tau\nu X)$ limits

Branching ratio	90% confidence limit
$br(B_d^0 \rightarrow \pi^+\pi^-)$	$< 4.9 \cdot 10^{-5}$
$br(B_d^0 \rightarrow \pi^+K^-)$	$< 3.6 \cdot 10^{-5}$
$br(B_d^0 \rightarrow K^+K^-)$	$< 2.1 \cdot 10^{-5}$
$br(B_d^0 \rightarrow p^+p^-)$	$< 2.1 \cdot 10^{-5}$
$br(B_s^0 \rightarrow \pi^+\pi^-)$	$< 1.2 \cdot 10^{-4}$
$br(B_s^0 \rightarrow \pi^+K^-)$	$< 1.2 \cdot 10^{-4}$
$br(B_s^0 \rightarrow K^+K^-)$	$< 7.1 \cdot 10^{-5}$
$br(B_s^0 \rightarrow p^+p^-)$	$< 7.1 \cdot 10^{-5}$
$br(\Lambda_b \rightarrow p^+\pi^-)$	$< 1.1 \cdot 10^{-4}$
$br(\Lambda_b \rightarrow p^+K^-)$	$< 1.1 \cdot 10^{-4}$
Combined $br(b \rightarrow h^+h^-)$	$= (2 \pm 1) \cdot 10^{-5}$
CLEO $br(B_d^0 \rightarrow K\pi, \pi\pi)$	$= (1.8 \pm 0.7) \cdot 10^{-5}$

Table 5: *90% confidence level limits on charged charmless B decays from the ALEPH experiment. The total two body branching ratio is also compared to the current CLEO measurement; 'h' represents hadron.*

the ratio tan $\beta/m_{H^\pm}$, where tan β is the ratio of vacuum expectation values of the two Higgs doublets and $m_{H^\pm}$ is the mass of the charged Higgs. Further information on Higgs production can be obtained from the decay $br(b \rightarrow D^{*+}\tau\nu X)$. If scalar Higgs production occurs, then the b will decay preferentially to the S-wave channel $D^+\tau\nu$ rather than the P-wave $D^{*+}\tau\nu$. A limit on this can be inferred from a measurement of the branching ratio.

ALEPH [24] and L3 [25] have previously measured the branching ratio $br(b \rightarrow \tau\nu X)$. OPAL have since updated the measurement to include data taken between 1991 and 1994, and in addition have measured the branching ratio $br(b \rightarrow D^{*+}\tau\nu X)$ [26]. In order to isolate $b \rightarrow \tau\nu X$ decays high missing energy is required, with a b tag in the opposite hemisphere to that of the tau candidate. The missing energy spectrum of the decays is fitted to extract the branching ratio. $b \rightarrow D^{*+}\tau\nu X$ decays are isolated by reconstructing the D^{*+} meson, tagging the τ lepton by its decay to a hadron, and applying the previous cuts. Again, the missing energy spectrum (shown in figure 7) is fitted to extract the branching ratio.

A 90% confidence level limit for tan $\beta/m_{H^\pm} < 0.50$ GeV^{-1} has been set, using the OPAL results for $br(b \rightarrow \tau\nu X)$. No limit on the charged Higgs sector can be gained from the measurement of $br(b \rightarrow D^{*+}\tau\nu X)$, however an enhancement of the D^+ versus D^{*+} final state is not favoured.

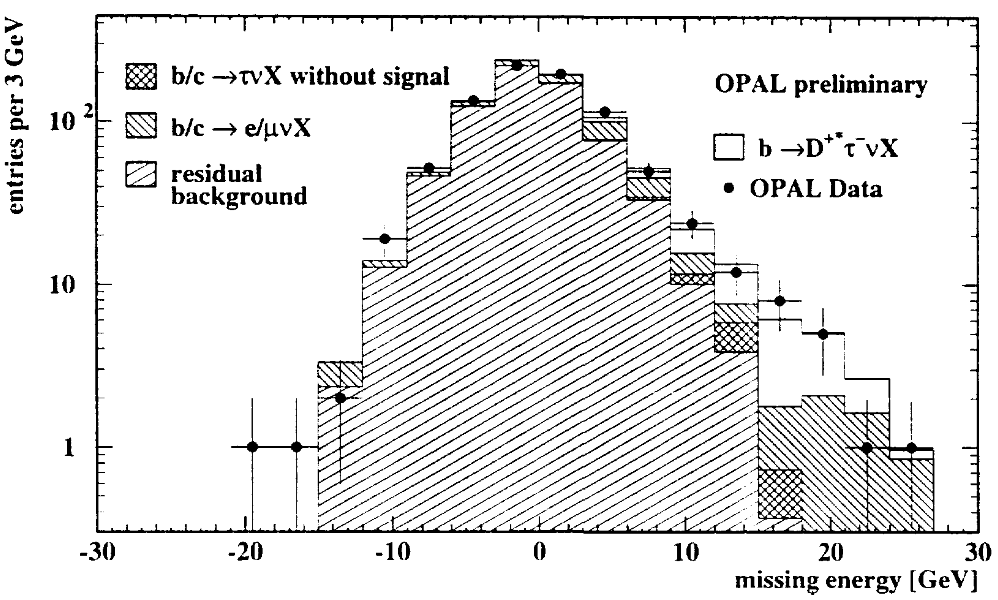

Figure 7: *Missing energy spectrum for* $b \rightarrow D^{*+}\tau\nu(X)$ *decays.*

4.4 Λ_b polarisation

Quarks produced in Z^0 decay are polarised. Although polarisation is lost from b quarks in mesons during fragmentation, it is expected to remain in baryons. Any polarisation remaining in the system will be manifested in the angular distribution, and therefore measured energies, of the decay products. The Standard Model prediction for the polarisation of the Λ_b baryon is $P_b = -(0.73 \pm 0.06)\%$.

ALEPH have measured this polarisation [27]. Λ_b baryons are tagged by reconstructing the semileptonic decay of the Λ_b to a fully reconstructed charm baryon. By measuring the ratio of the average lepton energy to the average neutrino energy (which is estimated as the difference in energy between the visible and total energy in the baryon candidate hemisphere), the polarisation is extracted. ALEPH find

$$P_b = -(0.23^{+0.24+0.08}_{-0.20-0.07})\%,$$

where the first error is statistical and the second systematic. This value is two standard deviations away from the prediction, which may imply the existence of extra depolarising mechanisms.

4.5 V_{cb}

ALEPH [28] and DELPHI [29] have measured the CKM matrix element V_{cb}. Semileptonic B meson decays to excited charm mesons (D^*) are tagged, and the differential decay rate $d\Gamma(B \to D^*\ell\nu)/dw$ fitted to extract V_{cb}. The results obtained are consistent with those from the CLEO experiment [30], and are listed in table 6.

Experiment	Measurement
ALEPH	$\mathcal{F}(1) \mid V_{cb} \mid = (31.4 \pm 2.3 \pm 2.5) \cdot 10^{-3}$
DELPHI	$\mathcal{F}(1) \mid V_{cb} \mid = (35.0 \pm 1.9 \pm 2.3) \cdot 10^{-3}$
CLEO	$\mathcal{F}(1) \mid V_{cb} \mid = (35.1 \pm 1.9 \pm 1.5) \cdot 10^{-3}$

Table 6: *Measurements of V_{cb} and the structure function $\mathcal{F}(1)$ by ALEPH, DELPHI and CLEO.*

5 Conclusions

LEP provides many advantages for studying B physics. The large amount of available data, highly efficient detectors, and good particle identification allow a wide range of B physics to be explored. This review has presented a general overview of LEP, its detectors, and the types of analyses that are pursued there. Time dependent mixing, rare decay analyses, Λ_b polarisation and V_{cb} determination have been described in more detail.

All measurements presented are in broad agreement with the Standard Model. However, it is worth noting that although LEP will no longer take data around the Z^0 pole, LEP analyses are far from over. Most measurements have not yet used the full dataset available, and so greater precision will be achieved in all analyses.

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