EFI-92-32
Fermilab Library
0 1160 0013750 9

EFI 92-32

HEAVY FLAVOUR PHYSICS AT LEP

Joseph Kroll
Enrico Fermi Institute
University of Chicago
Chicago, Illinois, 60637

ROUTE TO
NAME
SPALDING
LOCA
221
RETURN TO FERMI LIBRARY

Abstract

In the first three years of data taking, the four LEP experiments have collected 1.8 million hadronic Z^0 decays. About twenty percent of these events are $Z^0 \to b\bar{b}$. The measurements of the partial width of the Z^0 to $b\bar{b}$ pairs, $\Gamma_{b\bar{b}}$, and the b quark forward-backward charge asymmetry, $A_{FB}(b\bar{b})$, are discussed. These measurements are unique tests of the Electroweak Theory. In addition, this large sample of b quarks is used to study the properties of b hadrons. Measurements of neutral B meson mixing and the average b hadron lifetime are presented. Evidence of the production of the B_s^0 meson and baryons containing b quarks is shown.

Talk presented at the XXVII Rencontres de Moriond, 15–22 March 1992

FERMILAB
JUL 10 1992
LIBRARY

1. Introduction

In the first three years of operation, the four LEP experiments have collected 1.8 million hadronic Z^0 decays. About 20% of these events are $Z^0 \rightarrow b\bar{b}$, that is, about 400K $b\bar{b}$ pairs have been recorded. At the time of this presentation, the LEP collaborations have published nineteen papers[1-19] on b quark physics at the Z^0 resonance. The subjects of these papers include the partial width of the Z^0 to $b\bar{b}$ pairs ($\Gamma_{b\bar{b}}$)[1,6,8,9,12,14,19], the b quark forward–backward asymmetry ($A_{FB}(b\bar{b})$)[4,7,9,11,14], the mixing of neutral B mesons[3,10,17], the average lifetime of B hadrons[2,6,13,16], and evidence for the production of baryons containing b quarks[5,18]. In addition, there have been studies[20,21,22] of Quantum Chromodynamics based on tagging jets coming from b quarks.

Why has there been so much interest in b quark production at LEP? There are two reasons. First, as will be discussed later in this paper, there are unique tests of the Electroweak Theory that can be performed using b quarks. Second, some properties of hadrons containing b quarks can be measured more precisely at the Z^0 resonance than at lower energy e^+e^- colliders. Prior to the operation of LEP, most of our knowledge of the properties of b hadrons came from experiments at the $\Upsilon(4S)$. This knowledge was limited to B^0_d and $B^\pm$ mesons. At LEP, the B^0_s and b baryons are also produced (the first evidence of these particles in data collected at LEP is discussed in this paper). In addition, on the Z^0 resonance, the b quarks have a large Lorentz boost, which makes it possible to measure the the b hadron lifetime. This large boost also separates the decay products coming from the b quark from the decay products coming from the $\bar{b}$ quark. At the $\Upsilon(4S)$, the B mesons are produced with very little kinetic energy, so the decay products of the B meson and $\bar{B}$ meson are mixed rather than boosted in opposite directions. The cross-section on the Z^0 peak is large: $\sigma(b\bar{b}) = 6$ nb, compared to $\sigma(B\bar{B}) = 1$ nb on the peak of the $\Upsilon(4S)$, and $\sigma(b\bar{b}) \leq 0.03$ nb at the lower center-of-mass continuum e^+e^- colliders such as PEP, PETRA, and TRISTAN. Measurements of the average lifetime of b hadrons were made at these lower energy colliders, but already the lifetime measurements at LEP are more precise. This higher precision is due to the larger statistics and the higher purity of the b quark data samples at LEP. On the Z^0 peak, 20% of the hadronic events are predicted to be $b\bar{b}$ pairs, and the ratio of the number of $b\bar{b}$ pairs to $c\bar{c}$ pairs, which are the largest physics background in b quark studies, is $\sigma(b\bar{b})/\sigma(c\bar{c}) = 1.3$. At PEP and PETRA, only 9% of the hadronic events are $b\bar{b}$, and the ratio of cross-sections $\sigma(b\bar{b})/\sigma(c\bar{c}) = 0.25$.

There are several signatures of b quark production.

1. The semileptonic weak decays of b hadrons: the branching fractions for an electron or muon from b quark decay are known to be about 10% each. The leptons are produced with large momentum p and a large component of momentum, p_t, perpendicular to the line of flight of the decaying b hadron.

2. Secondary vertex tags: this signature exploits the long b hadron lifetime, which is about a picosecond. Since the average boost of the b hadrons is $\gamma \approx 6$ on the Z^0, the average decay length of the b hadrons is about 2 mm.

3. Event shape variables: the mass of the b quark is larger than the masses of the other quarks, and some event shape variables are sensitive to this larger mass. Often these event shape variables are based on dividing the event into two hemispheres.

4. A combination of signatures 1, 2, and 3 above: for example, vertex tags and lepton tags can be used simultaneously to get better statistics and to obtain the purity of b quark event samples from the data themselves.

Almost all the published results[1-19] are based on the semileptonic decay signature, so the discussion in this paper is limited to results based on these lepton tags. For an example of using event shapes to tag b quarks, see the talk by B. Brandl in these same proceedings, and the measurement[8] of $\Gamma_{b\bar{b}}$ using the boosted sphericity product.

The sources of leptons, ℓ, where ℓ = e or μ, in hadronic Z^0 decays are (in this paper, reference to a b or c quark decay implies the charge conjugate decay for $\bar{b}$ and $\bar{c}$ quarks)

1. primary b-flavoured hadron decays, $b \to \ell^- \bar{\nu}_\ell X$;
2. the secondary decay products of b-flavoured hadrons, $b \to c \to \ell^+ \nu_\ell X$, $b \to \bar{c} \to \ell^- \bar{\nu}_\ell X$, $b \to \tau^- \to \ell^- \bar{\nu}_\ell X$, and $b \to \psi \to \ell^+ \ell^- X$;
3. the direct production of charmed hadrons, $Z^0 \to c\bar{c}$, with $c \to \ell^+ \nu_\ell X$;
4. misidentified hadrons;
5. the decays of π and K mesons to muons, Dalitz decays, and photon conversions.

Leptons from the first three sources are referred to as prompt leptons. Leptons from primary b-flavoured hadron decays have a harder momentum spectrum than leptons from the other sources due to the hard b quark fragmentation. Leptons from primary b decays have a larger average momentum component perpendicular to the momentum of the decaying hadron than leptons from the other sources due to the large b-flavoured hadron mass. The transverse momentum p_t is measured with respect to the jet axis of the jet containing the lepton candidate. The maximum p_t value, not including the affects of detector resolution is approximately $m_b/2$. In some publications, the lepton momentum is removed from the jet-axis calculation; in this case, the maximum p_t value is approximately m_b. In this paper, unless explicitly stated otherwise, p_t refers to the case in which the lepton is included in the jet-axis definition. Figure 1 shows the muon p_t spectrum measured[14] by the OPAL collaboration. The points with error bars are the data, and the histograms are the spectrums of the different sources of muons predicted by Monte Carlo simulation. The muons from primary b hadron decay have a much harder p_t spectrum than the muons from the other sources. Typical kinematic cuts to enhance the fraction of primary b hadron decays are $p > 3$ GeV/c and $p_t > 1$ GeV/c; with these cuts, 80% of the prompt leptons come from primary b hadron decay.

The four collaborations have lepton identification procedures that are different in detail, but that use the same basic principles. Electron identification is based on dE/dx in the tracking chambers, the longitudinal and transverse shower shape in the electromagnetic calorimeter, and the comparison of the tracking chamber momentum with the energy in the electromagnetic calorimeter. In the angular range $|\cos\theta| < 0.8$ (θ is the polar angle with respect to the z-axis, which is the direction of the electron beam), for electrons with $p > 3$ GeV/c and $p_t > 1$ GeV/c, the electron identification efficiency ranges from 50% to 80%, depending on the experiment. This efficiency can be determined, in principle, from the data, although some experiments rely on Monte Carlo simulations. The errors on the efficiency are a minimum of 3% of the efficiency itself; in most analyses, this is the largest experimental systematic coming from the electrons. The backgrounds from misidentified pions, Dalitz decays, and photon conversions range from 4% to 33% of total number of candidates for $p > 3$ GeV/c and $p_t > 1$ GeV/c.

Muon identification is based on looking for a track that has penetrated a lot of material (at least 6 nuclear interaction lengths) to reach the outer muon detectors. The track in the inner tracking chamber and the track in the outer muon detector are required to agree in position, angle, or both. The outer muon track should point back to the nominal Z^0 decay point. Some collaborations use both muon chambers and their hadronic calorimeters as muon detectors. The muon identification efficiency is determined using $Z^0 \to \mu^+\mu^-$ data, and then making a small correction to this efficiency using Monte Carlo with full detector simulation to account for slight differences in efficiency due to the nonisolation of the muons in hadronic events. The identification efficiencies are typically 75% to 80% in the angular range $|\cos\theta| < 0.8$. The background due to hadron punchthrough, sailthrough, and decay is determined with Monte Carlo. For $p > 3$ GeV/c and $p_t > 1$ GeV/c, this background ranges from 11% to 30%, depending on the experiment; the knowledge of this background is the main systematic error coming from the muon channel.

2. $\Gamma_{b\bar{b}}$

The theoretical prediction for $\Gamma_{b\bar{b}}$ in the Standard Model is shown in Fig. 2 as a function of the mass of the t quark, m_t. The solid curve was calculated with the ZFITTER[23] program, with $m_Z = 91.174 \pm 0.020$ GeV/c^2, $m_H = 250$ GeV/c^2, and $\alpha_s = 0.116 \pm 0.008$. The dashed lines indicate the extremes due to varying the above parameters within the quoted errors and from varying the Higgs mass from 50 to 1000 GeV/c^2(the Higgs mass variation is the main contribution). The partial width of the Z^0 to d quarks, $\Gamma_{d\bar{d}}$, is also shown (dotted curve) in this figure. The dependence of $\Gamma_{d\bar{d}}$ on m_t comes from virtual t quark loops in the propagator. In b quark production, there are additional vertex corrections involving t quark exchange that cancel the effect of t quark loops in the propagator so that $\Gamma_{b\bar{b}}$ has very little dependence on m_t. A precise measurement of $\Gamma_{b\bar{b}}$ allows a strict test of the Standard Model without knowing the precise value of m_t; that is, a deviation of $\Gamma_{b\bar{b}}$ from the predicted value means there is something else beside the Standard Model with three families. Some new physics mainly affects $\Gamma_{b\bar{b}}$ (and consequently, Γ_{had}, but measuring $\Gamma_{b\bar{b}}$ would help pin down the source of the new physics), for example, exotic fermions[24] that mix with the lighter known fermions and extended technicolour theories[25]. In addition, the ratio of $\Gamma_{b\bar{b}}$ to the total hadronic width of the Z^0, Γ_{had}, is sensitive to m_t, but is not affected by other new physics that affects the propagator via vacuum polarization. (in principle, $\Gamma_{b\bar{b}}/\Gamma_{had}$ can be used to measure the top quark mass). These tests of the electroweak model are unique to the b quark.

The first determinations of $\Gamma_{b\bar{b}}$ from LEP data were based on the rate of leptons in hadronic events. To illustrate how these measurements were made, we now consider the hypothetical situation that the only source of leptons in hadronic events is b hadron decay. The number of $b\bar{b}$ pairs produced can be determined from counting the number of observed leptons, and correcting for the lepton detection efficiency and the b hadron semileptonic branching fraction. Usually some kinematic cuts are made on the leptons to enhance the primary b quark decay fraction. Typical cuts are $p > 3$ GeV/c and $p_t > 1$ GeV/c. The number of leptons observed, N_ℓ, is

$$N_\ell = 2 \cdot N_{had} \cdot \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} \cdot B(b \to \ell\bar{\nu}_\ell X) \cdot \varepsilon(b \to \ell\bar{\nu}_\ell X),$$

where N_{had} is the number of hadronic events, $B(b \to \ell\bar{\nu}_\ell X)$ is the average semileptonic branching fraction of the b hadrons produced on the Z^0 resonance, and $\varepsilon(b \to \ell\bar{\nu}_\ell X)$ is the efficiency for detecting the lepton, ℓ. The product $N_{had}\Gamma_{b\bar{b}}/\Gamma_{had}$ is the number of $b\bar{b}$ pairs produced; there is a factor 2 because either the b quark or the $\bar{b}$ quark can decay semileptonically. The efficiency, $\varepsilon(b \to \ell\bar{\nu}_\ell X)$, is the product of the efficiency of the lepton identification procedure, the kinematic acceptance of the p and p_t cuts (*e.g.* $p > 3$ GeV/c and $p_t > 1$ GeV/c), and the geometric acceptance (*e.g.* $|\cos\theta| < 0.7$). The kinematic and geometric acceptances are determined using Monte Carlo techniques.

From the measurement of N_ℓ, we can determine $\Gamma_{b\bar{b}}/\Gamma_{had}$:

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} = \frac{N_\ell}{2N_{had} \cdot B(b \to \ell\bar{\nu}_\ell X) \cdot \varepsilon(b \to \ell\bar{\nu}_\ell X)}.$$

If N_ℓ contains background, N_ℓ^{back}, then this background must be subtracted; that is, in the above formula, N_ℓ must be replaced by $N_\ell - N_\ell^{back}$. If the uncertainty in N_ℓ^{back} is ΔN_ℓ^{back}, then the fractional error on $\Gamma_{b\bar{b}}/\Gamma_{had}$ due to background subtraction is $\Delta N_\ell^{back}/(N_\ell - N_\ell^{back})$.

What should we use for the value of the branching fraction, $B(b \to \ell\bar{\nu}_\ell X)$? Before the operation of LEP, measurements of $B(b \to \ell\bar{\nu}_\ell X)$ were made at the $\Upsilon(4S)$ resonance and at PEP and PETRA. There are problems with using these branching fractions for LEP. At the $\Upsilon(4S)$, only $B_d^0\bar{B}_d^0$ pairs and B^+B^- pairs are known to be produced, (50% of the time each, as far as we know) so the measured semileptonic branching ratio measured at the $\Upsilon(4S)$ is the average of the semileptonic branching ratio of this mixture of B_d^0 and $B^\pm$ mesons produced at the $\Upsilon(4S)$. This same mixture is presumably produced at the Z^0, but in addition, so are

B_s^0 mesons and b baryons. Therefore the average semileptonic branching fraction at the Z^0 may be different than the average semileptonic branching fraction at the $\Upsilon(4S)$. There is a second difficulty with the measurements of $B(b \to \ell\bar{\nu}_\ell X)$ from the $\Upsilon(4S)$. Figure 3 illustrates how $B(b \to \ell\bar{\nu}_\ell X)$ is measured at the $\Upsilon(4S)$. The data are from the CLEO[26] collaboration. The same technique has been employed by the ARGUS[27], CRYSTAL BALL[28], and CUSB[29] collaborations.

The figure shows the momentum spectrum of electrons coming from $B\bar{B}$ events. On the $\Upsilon(4S)$, the B mesons are produced with a small boost ($\beta = 0.06$), so this spectrum is very close to the momentum distribution of the electrons in the B meson restframe. Above 1.2 GeV/c, the spectrum is dominated by primary B meson decay: $b \to c\ell\nu_\ell$, and $b \to u\ell\nu_\ell$. This second process contributes less than 2% of the total spectrum and will not be considered further. To determine the branching fraction, $B(b \to \ell\bar{\nu}_\ell X)$, it is necessary to use a model to extrapolate to low momentum where the cascade decays, $b \to c \to s\ell\nu_\ell$, dominate, and where the lepton spectrum is poorly measured. Different models predict different extrapolations, which give different branching fractions. The CLEO collaboration reports[26] a variation in $B(b \to \ell\bar{\nu}_\ell X)$ from 9.9% to 11.2% due to model variation alone.

Measurements of $B(b \to \ell\bar{\nu}_\ell X)$ have also been reported[30] by collaborations at the e^+e^- storage rings PEP and PETRA. The mixture of b hadrons produced at PEP and PETRA is probably similar to the mixture produced at the Z^0. These measurements should be limited by the same modelling uncertainties that affect the measurements at the $\Upsilon(4S)$, but none of these model variations have been reported, so the data are difficult to interpret.

Given these uncertainties from measurements made at lower center-of-mass energy, the LEP collaborations have been left with only one alternative: measure $B(b \to \ell\bar{\nu}_\ell X)$ at the Z^0 resonance themselves. The most promising method so far has been to compare the number of hadronic events with two leptons, $N_{\ell\ell}$, to N_ℓ, which is defined above. This method to determine $B(b \to \ell\bar{\nu}_\ell X)$ is not necessarily the only method that will be used in the future.

Extending the above illustration, the number of events with two leptons, $N_{\ell\ell}$, is

$$N_{\ell\ell} = N_{\rm had} \cdot \frac{\Gamma_{b\bar{b}}}{\Gamma_{\rm had}} \cdot (B(b \to \ell\bar{\nu}_\ell X) \cdot \varepsilon(b \to \ell\bar{\nu}_\ell X))^2 \cdot \eta,$$

where η is a correlation factor that is mainly geometric, *i.e.* if one lepton is in the geometric acceptance of the detector, then probably the other lepton is also in the geometric acceptance. This geometric correlation factor can be determined reliably with Monte Carlo calculations. The measured values of $N_{\ell\ell}$ and N_ℓ can be used to measure the product of the branching fraction times the efficiency:

$$B(b \to \ell\bar{\nu}_\ell X) \cdot \varepsilon(b \to \ell\bar{\nu}_\ell X) = 2 \cdot \eta \cdot \frac{N_{\ell\ell}}{N_\ell}.$$

The ratio of $N_{\ell\ell}$ to N_ℓ does not measure $B(b \to \ell\bar{\nu}_\ell X)$, it measures the product $B(b \to \ell\bar{\nu}_\ell X) \cdot \varepsilon(b \to \ell\bar{\nu}_\ell X)$. To measure $B(b \to \ell\bar{\nu}_\ell X)$, we have to assume a model to determine $\varepsilon(b \to \ell\bar{\nu}_\ell X)$, and the same modelling uncertainties that affect measurements at the $\Upsilon(4S)$ will affect this measurement. The uncertainty is even larger at LEP, since there is limited experimental information on the mass and decays of the B_s^0 meson and b baryons that are presumably produced on the Z^0. The product $B(b \to \ell\bar{\nu}_\ell X) \cdot \varepsilon(b \to \ell\bar{\nu}_\ell X)$ can be plugged into the above formula for $\Gamma_{b\bar{b}}/\Gamma_{\rm had}$ to determine

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{\rm had}} = \frac{{N_\ell}^2 \cdot \eta}{4 \cdot N_{\rm had} \cdot N_{\ell\ell}}.$$

The fractional error on $\Gamma_{b\bar{b}}/\Gamma_{\rm had}$ due to uncertainty in the background is $2\Delta N_\ell^{\rm back}/(N_\ell - N_\ell^{\rm back})$, which is twice the error when $\Gamma_{b\bar{b}}/\Gamma_{\rm had}$ is determined using N_ℓ alone. The other limitation of this method is that there is a large statistical error on $N_{\ell\ell}$. Extending this simplified case to take into account the cascade decays is straightforward: the product $B(b \to \ell\bar{\nu}_\ell X) \cdot \varepsilon(b \to \ell\bar{\nu}_\ell X)$

is generalized to $B(b \to \ell\bar{\nu}_\ell X)\cdot\varepsilon(b \to \ell\bar{\nu}_\ell X) + B(b \to c \to \ell\nu_\ell X)\cdot\varepsilon(b \to c \to s\ell\nu_\ell)$. The cascade decay is not a physics background, rather it adds to the statistics. This is because in this measurement, the sign of the charge of the lepton is not important.

Instead of counting leptons, most of the results are based on fits to the measured momentum and transverse momentum spectra of the leptons. The fits allow for a reduction of the statistical error and reduce some of the uncertainties associated with fragmentation and misidentification background. For example, at low p_t, the muon spectrum is dominated by background. If the shape of the background is well-understood, then the normalization is fixed by the rate of muons at low p_t and can be extrapolated reliably to large p_t, where the b signal dominates.

The most recent results on $\Gamma_{b\bar{b}}/\Gamma_{had}$ are summarized here; previously published results that are not mentioned here can be found in the References. The ALEPH Collaboration has measured $\Gamma_{b\bar{b}}/\Gamma_{had}$ using both electrons and muons using a fit to the variables[31] *momentum cross product* and *minimum transverse momentum* used by the MARKII Collaboration at PEP. This fit is described in the talk by B. Brandl at this conference and is used to determine $\Gamma_{b\bar{b}}/\Gamma_{had}$, $\Gamma_{c\bar{c}}/\Gamma_{had}$, $B(b \to \ell\bar{\nu}_\ell X)$, $B(c \to \bar{\ell}\nu_\ell X)$, $\langle x_E\rangle_b$, $\langle x_E\rangle_c$, and χ, where $\langle x_E\rangle_b$ is the mean fraction of the beam energy of the b hadrons, $\langle x_E\rangle_c$ is the same quantity for c hadrons, and χ is the B meson mixing parameter, which is discussed later in this paper. The result for $\Gamma_{b\bar{b}}/\Gamma_{had}$ is

$$\Gamma_{b\bar{b}}/\Gamma_{had} = 0.211 \pm 0.007 \pm 0.008 \text{ (ALEPH preliminary, e and } \mu \text{ combined)},$$

and the resulting branching ratio is $B(b \to \ell\bar{\nu}_\ell X) = 0.110 \pm 0.004 \pm 0.004$ (ALEPH preliminary). The first error is statistical and the second error is systematic. The DELPHI Collaboration reports a preliminary measurement of the product $\Gamma_{b\bar{b}}/\Gamma_{had}\cdot B(b \to \ell\bar{\nu}_\ell X)$, which is the combined result of their electrons and muons:

$$\Gamma_{b\bar{b}}/\Gamma_{had}\cdot B(b \to \ell\bar{\nu}_\ell X) = 0.0222 \pm 0.0014 \text{ (DELPHI preliminary, e and } \mu \text{ combined)},$$

where the error is the combined statistical and systematic error. All four collaborations choose to report their first measurements of $\Gamma_{b\bar{b}}/\Gamma_{had}$ in this form to eliminate the uncertainty due to the branching fraction. The uncertainty due to the modelling of b hadron decay is still important. The DELPHI result does not include an error due to this uncertainty. The L3 Collaboration has published a value of $\Gamma_{b\bar{b}}/\Gamma_{had}$,

$$\Gamma_{b\bar{b}}/\Gamma_{had} = 0.221 \pm 0.004 \pm 0.006 \pm 0.011 \text{ (L3 published[12], e and } \mu \text{ combined)},$$

where the first error is statistical, the second error is due to their experimental systematics, and the third error is due to the error in the semileptonic branching fraction. They determine $B(b \to \ell\bar{\nu}_\ell X) = 0.113 \pm 0.010 \pm 0.006$ using the same fit to their e and μ p and p_t spectra, and then they combine this result with an average from PEP and PETRA experiments in order to reduce the uncertainty on the measured branching fraction. This reduction in error is not necessarily justified, since it is not clarified whether the L3 branching fraction and the branching fraction determined at PEP and PETRA were derived using the same models of b hadron decay. The OPAL Collaboration has published the product $\Gamma_{b\bar{b}}/\Gamma_{had}\cdot B(b \to \ell\bar{\nu}_\ell X)$ separately for electrons and muons:

$$\Gamma_{b\bar{b}}/\Gamma_{had}\cdot B(b \to \ell\bar{\nu}_\ell X) = 0.0226 \pm 0.0007 \pm 0.0013 \text{ (OPAL published[14], } \mu \text{ only)},$$

$$\Gamma_{b\bar{b}}/\Gamma_{had}\cdot B(b \to \ell\bar{\nu}_\ell X) = 0.0238 \pm 0.0008 \pm 0.0020 \text{ (OPAL published[19], e only)}.$$

The result based on electrons includes modelling uncertainties (about 5%) in the systematic error. These uncertainties were neglected in the muon result, so the two results have not been combined. The OPAL Collaboration also reports[19] a value of $\Gamma_{b\bar{b}}/\Gamma_{had} = 0.226 \pm 0.008 \pm 0.018$, assuming that the semileptonic branching fraction of the mixture of b hadrons at the $\Upsilon(4S)$ is the same as the semileptonic branching fraction of the mixture of b hadrons at the Z^0. This

measurement makes use of the CLEO data to reduce uncertainties due to the modelling of b hadron decay.

The preliminary results from the ALEPH Collaboration are encouraging. These results are based on approximately 500 000 hadronic Z^0 decays; the statistical error is 3% and the systematic error is 4%. With an increase in statistics of a factor of ten, the combined systematic and statistical error could reach 2%. Other methods of measuring $\Gamma_{b\bar{b}}/\Gamma_{had}$, such as vertex tags, may reach this precision as well.

3. The b quark Forward-Backward Asymmetry: $A_{FB}(b\bar{b})$

On the peak of the Z^0 resonance, the forward-backward charge asymmetry for b quarks is predicted[32] to be approximately 10%. This asymmetry is much larger than the 1% asymmetry predicted for muon pairs. In principle, a more precise value of $\sin\theta_W$ can be determined from the b quark forward-backward asymmetry than the lepton pair forward-backward asymmetry. Of course, it is much easier to identify $\ell^+\ell^-$ pairs than it is to identify $b\bar{b}$ events, and determining whether the lepton is in the forward or backward hemisphere is much more straightforward than determining whether the b quark is in the forward or backward hemisphere.

The b quark angular distribution is proportional to

$$d\sigma/d\cos\theta \propto 1 + \frac{8}{3}A_{FB}\cos\theta + \cos^2\theta,$$

where θ is the angle of between the b quark momentum and the electron beam momentum, and A_{FB} is the forward-backward asymmetry. The angle θ is defined by the b quark at production, not by the momentum vector of the b hadron, which may be different due to final state gluon or photon radiation and hadronization. Leptons with large p and p_t are used to tag primary b quark decays. The event thrust axis is used to estimate the b quark production angle, θ, and the charge of the lepton is used to determine whether it is a b or $\bar{b}$ that decays. Primary b quark decays produce negative leptons. Figure 4 shows the distribution of $-q\cdot\cos\theta_T$, where q is the charge of the lepton, and θ_T is the angle of the thrust axis, measured by the ALEPH collaboration using data collected during the 1990 and 1991 runs of LEP. The plot is based on 434K hadronic Z^0 decays taken at the peak and ± 1 GeV away from the peak, only, since $A_{FB}(b\bar{b})$ varies with $\sqrt{s}$. Both electrons and muons with $p > 3$ GeV/c and $p_t > 1$ GeV/c are used to tag the b quarks. The data points have been corrected for acceptance, but have not been background subtracted. The curve is the above formula, with the value of $A_{FB}(b\bar{b})$ determined from the data. The value of $A_{FB}(b\bar{b})$ obtained in this way must be corrected for geometric acceptance (the data are observed from $-0.9 < |\cos\theta| < 0.9$), for nonprompt lepton backgrounds, for secondary b decays, and for B meson mixing. The last two corrections are not important in the measurement of $\Gamma_{b\bar{b}}/\Gamma_{had}$, since the sign of the charge of the lepton is irrelevant. In this measurement, the sign is used to distinguish b quarks from $\bar{b}$ quark decays. To account for B meson mixing, the observed asymmetry must be corrected by $1/(1-2\chi)$, where χ is the mixing parameter defined in the next section. For $\chi = 0.14$, this correction factor is 1.4; that is, the observed asymmetry must be increased by 40% to account for the dilution of mixing.

The individual measurements of $A_{FB}(b\bar{b})$ by the four LEP collaborations are reported in the talk by J. Nash at this conference. The value for $A_{FB}(b\bar{b})$ averaged over the four LEP experiments, and corrected for mixing using $\chi = 0.139 \pm 0.013$ is

$$A_{FB}(b\bar{b}) = 0.094 \pm 0.014 \text{ (average of the four LEP experiments).}$$

The error is the combined statistical and systematic error; the statistical contribution is dominant. The dominant systematic uncertainties are the knowledge of the mixing, χ, and the secondary branching fraction, $B(b \to c \to \ell\nu_\ell X)$. These two systematic uncertainties will probably be the ultimate limitation of the determination of $A_{FB}(b\bar{b})$.

4. Neutral B Meson Mixing

The transformation of a neutral B meson via second order weak interactions to a neutral $\bar{B}$ antimeson is known as B meson mixing. The mixing is quantified by χ, which is defined by

$$\chi \equiv \frac{\Pr(B \to \bar{B} \to \ell^-)}{\Pr(B \to \bar{B} \to \ell^-) + \Pr(B \to \ell^+)}.$$

The B meson contains a $\bar{b}$ quark, which decays to an ℓ^+. With this definition, the maximum value of χ is 0.5. This maximum value occurs when the period of oscillation of meson to antimeson is much shorter than the B meson lifetime. That is, if you start out with a B meson, there is 50% chance it will decay as a $\bar{B}$ antimeson and 50% chance it will decay as a B meson.

Both the B_d^0 meson and B_s^0 meson can mix. Presumably the mixing probabilities are different, and each is quantified by a different χ: χ_d and χ_s. At LEP, the measured χ is related to χ_d and χ_s by

$$\chi = f_d \cdot \chi_d + f_s \cdot \chi_s,$$

where f_d is the fraction of b quarks that form a $\bar{B}_d^0$ antimeson, and f_s is the fraction of b quarks that form a $\bar{B}_s^0$ antimeson. The precise values of these fractions are unknown, but are estimated[32] to be approximately $f_d \approx 0.40$ and $f_s \approx 0.12$.

The signature of mixing is an excess of large p and large p_t lepton pairs with like–sign on opposite sides of the event in hadronic decays of the Z^0. The physics background to this signal for mixing is events with one primary semileptonic decay, $b \to \ell^- \bar{\nu}_\ell X$, on one side of the event, and a secondary semileptonic decay, $\bar{b} \to \bar{c} \to \ell^- \bar{\nu}_\ell X$ on the other side of the event. Again, as in the measurement of $A_{FB}(b\bar{b})$, it is necessary to know the primary and secondary branching fractions.

To determine the mixing parameter χ, two methods have been used. The first is based on counting the number of like-sign lepton pairs and comparing it to the total number of lepton pairs:

$$R = \frac{N(++ \text{ or } --)}{N(++ \text{ or } --) + N(+-)},$$

where $N(++ \text{ or } --)$ is the number of events with an $\ell^+\ell^+$ or $\ell^-\ell^-$ lepton pair, and $N(+-)$ is the number of events with an $\ell^+\ell^-$ lepton pair. The lepton pairs are required to be separated by some minimum angle, which is 60° in the case of L3 and OPAL and 90° in the case of ALEPH. Minimum values are placed on the momenta and transverse momenta of the leptons to enhance the signal of double primary b hadron decays over the background of one primary b hadron decay plus one secondary b hadron decay. The mixing parameter χ is determined from the measurement of R. The lepton pairs that are on the same side of the event (*e.g.* the leptons separated at an angle of less than 60°) can be used to check the background from secondary b hadron decays. A b hadron that has both a primary and secondary semileptonic decay produces a lepton pair of opposite sign on the same side of the event. This check of the background can be made because the b quark and $\bar{b}$ antiquark are boosted to opposite sides of the events and their decay products are well separated. This is not the case at the $\Upsilon(4S)$.

The second method is based on fits to variables formed from p and p_t. Different collaborations use different combinations of these variables. As mentioned previously, the ALEPH collaboration uses the variables[31] used by the MARKII collaboration; the L3 collaboration fits[10] to the lepton p and p_t spectra (in this case p_t is defined with the lepton momentum removed in the definition of the jet axis); and the OPAL collaboration fits[17] to a single variable, p_{comb}, formed from p and p_t: $p_{comb} = \sqrt{(p/10\text{GeV}/c)^2 + p_t^2}$. Exploiting the full range of momentum and transverse momentum increases the statistical significance of the measurement of χ. The reported measurements of χ are

$$\begin{aligned}
\chi &= 0.134 \pm 0.013 \pm 0.008 \text{ (ALEPH preliminary)};\\
\chi &= 0.178^{+0.049}_{-0.040} \pm 0.02 \text{ (L3 published[10])};\\
\chi &= 0.145^{+0.041}_{-0.035} \pm 0.018 \text{ (OPAL published[17])}.
\end{aligned}$$

The statistical error on the ALEPH result is smaller because it is based on data collected during the 1990 and 1991 LEP runs. The L3 and OPAL results are based on 1990 data only. ALEPH has published[3] a result based on 1990 data alone. The above ALEPH result is an average of the value of χ determined using dileptons and the value determined using a technique called the jet-charge method. In this method, only one lepton tag is needed, so there is larger statistics than the dilepton sample. Since the time of this talk, ALEPH has published[33] a value of χ based on this jet-charge method.

The results on mixing are still statistics limited. The main systematic error is due to the uncertainty on $B(b \to c \to \ell\nu_\ell X)$.

5. The Average Lifetime of b hadrons

At LEP, all four collaborations have measured[2,6,13,16] the average lifetime of the mixture of b hadrons produced at the Z^0 resonance. These measurements are much more precise than previous measurements[30] by experiments at PEP and PETRA because the LEP experiments have much higher statistics and higher purity b quarks samples, a larger Lorentz boost ($\gamma \sim 6$), and a smaller beam spot ($\sigma_x \sim 150$ μm and $\sigma_y \sim 10$ μm). Despite this improved measurement of the lifetime, the measurement of V_{bc} has not been greatly improved, due to limitations[26,27] in our understanding of the semileptonic decays of b hadrons.

All four collaborations measure the lifetime using a maximum-likelihood fit to the lepton impact parameter distribution. Cuts are applied to the lepton p and p_t to enhance the fraction of leptons coming from b hadron decay. The impact parameter, δ, is depicted in Fig. 5. It is the distance of closest approach of the lepton trajectory to the beam spot in the plane perpendicular to the beam axis. The impact parameter has a sign convention, which is a crucial part of the sensitivity of δ to lifetime: δ is positive if the cosine of the angle Θ, depicted in Fig. 5 is positive.

The advantage of using the impact parameter to measure the lifetime as opposed to the decay distance is that the extraction of the lifetime from the measurement of the δ distribution is much less sensitive to the modelling of the fragmentation of the b hadrons. The impact parameter distribution, however, is dependent on the assumptions that are made about the polarization of b hadrons with spin that decay weakly, such as the Λ_b.

Figure 6[13] is the impact parameter distribution of electrons and muons in 115K hadronic decays of the Z^0 recorded with the L3 detector. The muons are required to have $p > 4$ GeV/c and $p_t > 1.5$ GeV/c, and the electrons are required to have $p > 4$ GeV/c and $p_t > 1.0$ GeV/c. The lepton is not included in the definition of the jet axis. The data points show a clear asymmetry favouring positive values of δ, and are mostly due to primary b hadron decay. The backgrounds from misidentified hadrons and meson decay have much more symmetric distributions in δ, since these backgrounds contain little lifetime information.

The average lifetime of the b hadrons produced at the Z^0 resonance measured by the four different LEP collaborations are

$$\tau_b = 1.29 \pm 0.06 \pm 0.10 \text{ psec (ALEPH published[2])};$$
$$\tau_b = 1.45 \pm 0.03 \pm 0.06 \text{ psec (ALEPH preliminary 1991 data only)};$$
$$\tau_b = 1.30 \pm 0.10 \pm 0.08 \text{ psec (DELPHI published[6])};$$
$$\tau_b = 1.32 \pm 0.08 \pm 0.09 \text{ psec (L3 published[13])};$$
$$\tau_b = 1.37 \pm 0.07 \pm 0.06 \text{ psec (OPAL published[16])}.$$

All of the published results are based on data taken during the 1990 LEP run and use both electrons and muons, except the DELPHI result, which is based on muons only. In each measurement, the statistical and systematic errors are about the same size. The largest systematic error is due to the uncertainty in the modelling of the detector resolution. Increased statistics will allow a better understanding of this detector resolution, so both the statistical and systematic errors should decrease with more Z^0's.

The average lifetime of b hadrons has also been measured from the decay length of the J/ψ observed in hadronic Z^0 decay. On the Z^0 resonance, J/ψ particles at large momentum are expected[15] to come primarily from b hadron decay. The J/ψ are detected in e^+e^- and $\mu^+\mu^-$ final states. The OPAL collaboration has published[15] a measurement of τ_b based on the decay length of J/ψ found in 163K hadronic Z^0 decays from their 1989 and 1990 data samples:

$$\tau_b = 1.32^{+0.31}_{-0.25} \pm 0.15 \text{ psec (OPAL published}^{15)} \text{ from b} \rightarrow J/\psi + \text{X}).$$

The ALEPH collaboration has a preliminary measurement of τ_b based on J/ψ found in 450K hadronic decays of the Z^0 from their 1990 and 1991 data samples:

$$\tau_b = 1.40^{+0.20}_{-0.18} \pm 0.07 \text{ psec (ALEPH preliminary from b} \rightarrow J/\psi + \text{X}).$$

Both of these measurements agree with the measurements of τ_b obtained from the lepton impact parameters.

6. Evidence for b-baryons and B_s^0

Now that the average lifetime of the b hadrons produced on the Z^0 resonance has been measured to better than 7% precision, the next step is to measure the individual lifetimes of the different b hadrons. The question we want to answer is whether or not these individual lifetimes are the same. To measure the individual lifetimes, we first need to isolate signals for the different b hadron species.

The ALEPH and OPAL collaborations have both published[5,18] evidence for baryons containing b quarks. This baryon is usually referred to as the Λ_b, but the signal need not be entirely due to a bound state of the u, d, and b quark; there could be, for example, some contribution from weak decays of a bound state of a u, s, and b quark.

The signal for b baryon production is the observation of a lambda and a lepton in the same jet ($\Lambda\ell^-$) or an antilambda and an antilepton in the same jet ($\bar{\Lambda}\ell^+$). These pairs are expected from the following decay chain: $\Lambda_b \rightarrow \Lambda_c^+\ell^-\bar{\nu}_\ell$, with $\Lambda_c^+ \rightarrow \Lambda + \text{X}$. This gives a high p and p_t lepton from a primary b quark semileptonic decay and a high momentum Λ. The decay of a $\bar{\Lambda}_b$ produces an antilambda-antilepton pair. The Λ ($\bar{\Lambda}$) is detected in the $p\pi^-$ ($\bar{p}\pi^+$) final state.

There are several sources of background to this signal. There can be accidental combinations of prompt leptons from b hadron decay with Λ from jet fragmentation. This background should produce equal numbers of the correct $\Lambda\ell^-$ combinations (and charge conjugate) as well as wrong $\Lambda\ell^+$ combinations (and charge conjugate). The number of wrong combinations can be used to estimate the amount of this background in the sample of correct combinations. Other sources of background are the decays of Λ_c^+: $\Lambda_c^+ \rightarrow \Lambda\ell^+\nu_\ell$, which gives the wrong combination; and the decay of $\bar{B}$ antimesons: $\bar{B} \rightarrow \Lambda_c^+\bar{N}\ell^-\bar{\nu}_\ell$, where $\bar{N}$ is an antibaryon, which gives the correct combination. These backgrounds can be suppressed to small levels with kinematic requirements such as the lepton momentum and transverse momentum, the lambda momentum, and the invariant mass of the lambda-lepton pair.

Figure 7a shows the invariant mass distribution of lambda candidates correlated with leptons (and antilambda candidates correlated with antileptons) published[18] by the OPAL collaboration. This plot is based on 459K hadronic Z^0 decays. The invariant mass distribution of lambda candidates correlated with antileptons (and antilambda candidates correlated with leptons) is shown in Fig. 7b. There is very little signal in the region of the lambda mass. The signal of correct combinations is $55 \pm 9^{+0.3}_{-3.1}$. The asymmetric systematic error is due to the subtraction of the background from $\bar{B}$ meson decays. The ALEPH collaboration has published[5] similar results based on their 1990 data sample, and has observed a signal of 117 ± 18 (preliminary) correct combinations in 451K Z^0 decays from their 1990 and 1991 runs combined.

Based on these observed signals, the following results have been obtained:

$$f(\text{b} \rightarrow \Lambda_b) \cdot \text{BR}(\Lambda_b \rightarrow \Lambda\ell^-\bar{\nu}\text{X}) = 7.5 \pm 1.1 \pm 1.8 \times 10^{-3} \text{ (ALEPH preliminary);}$$

$$\Gamma_{b\bar{b}}/\Gamma_{had} \cdot f(b \to \Lambda_b) \cdot BR(\Lambda_b \to \Lambda \ell^- \bar{\nu} X) = 1.2 \pm 0.2 \pm 0.3 \times 10^{-3} \text{ (OPAL published}^{18)}\text{)}.$$

These two results agree within errors, if you assume $\Gamma_{b\bar{b}}/\Gamma_{had} \approx 0.22$, To make the comparison easier, I have multiplied the OPAL result by two, since the OPAL result is the average of the two numbers obtained using electrons and muons separately, but the ALEPH result is the sum of the separate electron and muon results.

ALEPH has used the lepton impact parameter in these $\Lambda\ell^-$ combinations to get a first measurement of the b baryon lifetime:

$$\tau(\Lambda_b) = 1.12^{+0.29}_{-0.26} \pm 0.18 \text{ psec (ALEPH preliminary)}.$$

The systematic error includes a contribution of 0.06 psec that takes into account the uncertainty in the degree of Λ_b polarization.

In response to the reported signal[34)] by the UA1 collaboration of the observation of the signal $\Lambda_b \to J/\psi\Lambda$, the ALEPH collaboration has reported on a search for the same signature. They find no signal and put a limit on the branching ratio:

$$BR(\Lambda_b \to J/\psi\Lambda) < 1.15\% \text{ (ALEPH preliminary)}.$$

The branching ratio reported by UA1 is $BR(\Lambda_b \to J/\psi\Lambda) = 1.8 \pm 1.1\%$, assuming that b quarks form b baryons 10% of the time.

The ALEPH and DELPHI collaborations have reported evidence for the production of the B_s^0 meson. The signal is a large p and p_t lepton, ℓ^-, with a D_s^+ in the same jet. These particles come from the primary semileptonic decay of a $\bar{B}_s^0$ antimeson as depicted in Fig. 8. The background to this signal is also depicted in Fig. 8: the primary semileptonic decay of a $\bar{B}_d^0$ or a B^- can produce a D_s^+ and a lepton, ℓ^-, or these mesons can decay to a D_s^+D pair, and the D can decay semileptonically. Kinematic requirements on the lepton suppress this latter background, since the lepton comes from a secondary decay. The first background is not suppressed by kinematic cuts and must be estimated. It is not expected to be large. Unlike the Λ_b, no important background from accidental combinations of D_s^+ and lepton candidates is expected.

Figure 9 shows the D_s^+ (and charge conjugate) mass distribution from the DELPHI collaboration from hadronic events with a muon candidate with $p > 3$ GeV/c. Both the $\phi\pi^+$ and $K^{*0}K^+$ final states of the D_s^+ have been included in these plots, which are based on the analysis of 270K hadronic events. The DELPHI silicon vertex detector has been used to reduce combinatorial background. The lefthand plot in Fig. 9 shows the mass distribution when the muon is required to have $p_t > 0.8$ GeV/c. In this analysis, p_t is calculated without including the lepton in the jet definition. In the righthand plot in Fig. 9 the p_t cut is increased to 1.2 GeV/c. The signal is 7.5 ± 2.5 events[35)]. The fact that the signal remains when the p_t requirement is increased indicates that the D_s^+-lepton pair comes from primary $\bar{B}_s^0$ semileptonic decay rather than secondary $\bar{B}_d^0$ or B^- decay.

The ALEPH collaboration has searched[36)] for $D_s^+\ell^-$ pairs (and charge conjugate) in 450K hadronic events. They use both muons and electrons with $p > 3$ GeV/c. The $\phi\pi^+$ final state is used for the D_s^+, and the invariant mass of the $D_s^+\ell^-$ pair is required to be more than 3 GeV/c^2. The D_s^+ mass plots for both D_s^+ associated with ℓ^- (the correct combination) and with ℓ^+ (the wrong combination) are shown in Fig. 10. The correct charge combination (Fig. 10a) shows a signal of 16.0 ± 4.3 events. The wrong charge combination (Fig. 10b) shows no signal. After accounting for the backgrounds, a signal of $13.7 \pm 4.4^{+0.0}_{-2.0}$ is found. The systematic error is due to the estimate of the background from B_d^0 and $B^\pm$ decay, which is not subtracted, but could be as large as 2.0 ± 0.6.

Conclusions

The study of b quark production using high momentum and high transverse momentum leptons in hadronic Z^0 decays at LEP has allowed unique tests of the Electroweak Model and

has produced new results on the properties of hadrons containing b quarks. The precision of each of these measurements is limited by statistics. The determination of the partial width of the Z^0 to $b\bar{b}$, $\Gamma_{b\bar{b}}$, using lepton tags could reach a precision of 2%, if backgrounds from misidentified hadrons and $c\bar{c}$ production are well known. The ultimate precision of forward-backward charge asymmetry, $A_{FB}(b\bar{b})$, and neutral B meson mixing will depend how precisely the ratio of the primary branching fraction, $B(b \to \ell\bar{\nu}_\ell X)$, to the secondary branching fraction, $B(b \to c \to \ell\nu_\ell X)$is known. The first evidence for the production of the B_s^0 and the Λ_b on the Z^0 resonance has been seen. The next step is to isolate B_s^0 mixing and to measure the individual lifetimes of the b hadrons.

Acknowledgements

As always, the organizers of this conference, led by Professor J. Tran Thanh Van, have done an excellent job. I would like to thank them for a selection of interesting talks and an atmosphere that permitted fruitful discussion. I would like to thank my colleagues in the OPAL collaboration as well as Dr. P. Dornan and Dr. V. Sharma from the ALEPH Collaboration, Dr. J. E. Augustin, Dr. G. Myatt, Dr. P. Roudeau, and Dr. W. Venus from the DELPHI Collaboration, and Dr. B. Clare and Dr. P. McBride from the L3 Collaboration for assisting me with the content of this presentation. Dr. R. Van Kooten kindly provided me with Fig. 2. The CLEO collaboration provided Fig. 3. J. Kroll is supported by grant NSF PHY91–00690.

References

1. ALEPH Collaboration, D. Decamp et al., Phys. Lett. **B 244** (1990) 551.
2. ALEPH Collaboration, D. Decamp et al., Phys. Lett. **B 257** (1991) 492.
3. ALEPH Collaboration, D. Decamp et al., Phys. Lett. **B 258** (1991) 236.
4. ALEPH Collaboration, D. Decamp et al., Phys. Lett. **B 263** (1991) 325.
5. ALEPH Collaboration, D. Decamp et al., Phys. Lett. **B 278** (1992) 209.
6. DELPHI Collaboration, P. Abreu et al., Z. Phys. **C 53** (1992) 567.
7. DELPHI Collaboration, P. Abreu et al., Phys. Lett. **B 276** (1992) 536.
8. DELPHI Collaboration, P. Abreu et al., Phys. Lett. **B 281** (1992) 383.
9. L3 Collaboration, B. Adeva et al., Phys. Lett. **B 241** (1990) 416.
10. L3 Collaboration, B. Adeva et al., Phys. Lett. **B 252** (1990) 703.
11. L3 Collaboration, B. Adeva et al., Phys. Lett. **B 252** (1990) 713.
12. L3 Collaboration, B. Adeva et al., Phys. Lett. **B 261** (1991) 177.
13. L3 Collaboration, B. Adeva et al., Phys. Lett. **B 270** (1991) 111.
14. OPAL Collaboration, M. Z. Akrawy et al., Phys. Lett. **B 263** (1991) 311.
15. OPAL Collaboration, G. Alexander et al., Phys. Lett. **B 266** (1991) 485.
16. OPAL Collaboration, P. D. Acton et al., Phys. Lett. **B 274** (1992) 513.
17. OPAL Collaboration, P. D. Acton et al., Phys. Lett. **B 276** (1992) 379.
18. OPAL Collaboration, P. D. Acton et al., Phys. Lett. **B 281** (1992) 394.

19. OPAL Collaboration, P. D. Acton et al., *A Measurement of Electron Production in Hadronic Z^0 Decays and a Determination of* $\Gamma(Z^0 \to b\bar{b})$, submitted to Z. Phys. C, CERN–PPE/92-038.

20. OPAL Collaboration, M. Z. Akrawy et al., Phys. Lett. **B 261** (1991) 334.

21. OPAL Collaboration, G. Alexander et al., Phys. Lett. **B 265** (1991) 462.

22. L3 Collaboration, B. Adeva et al., Phys. Lett. **B 271** (1991) 461.

23. ZFITTER, Dubna-Zeuthen radiative correction group (based on the ZBIZON package): D. Yu. Bardin et al., Berlin-Zeuthen preprint 89–08, 1989;
R. Kleiss et al., in Z Physics at LEP1, CERN Yellow report 89-08, ed. G. Altarelli et al., Vol. 3, 1989.

24. A discussion of these models and other references can be found in P. Langacker and D. London, Phys. Rev. **D 38** (1988) 886.
The deviations from the Standard Model value of $\Gamma_{b\bar{b}}$ depend on the mixing angle between the ordinary and exotic fermions, and limits on these mixing angles based on LEP data have been published:
E. Nardi and E. Roulet, Phys. Lett. **B 248** (1990) 139;
E. Nardi, E. Roulet, and D. Tommasini, *Global analysis of fermion mixing with exotics*, FERMILAB PUB–91/207–A, July 1991.

25. R. S. Chivukula, S. B. Selipsky, and E. H. Simmons, *Non-Oblique Effects in the* $Zb\bar{b}$ *Vertex from ETC Dynamics*, BUHEP–92–12, HUTP–92/A017.

26. CLEO Collaboration, S. Henderson et al., Phys. Rev. **D 45** (1992) 2212.

27. ARGUS Collaboration, H. Albrecht et al., Phys. Lett. **B 249** (1990) 359.

28. Crystal Ball Collaboration, K. Wachs et al., Z. Phys. **C 42** (1989) 33.

29. CUSB Collaboration, C. Yanagisawa et al., Phys. Rev. Lett. **66** (1991) 2436.

30. J. J. Hernandez et al., Particle Data Book: Phys. Lett. **B 239** (1990) 1, and references therein.

31. MARKII Collaboration, A. J. Weir et al., Phys. Lett. **B 240** (1990) 289.

32. J. H. Kühn et al., *Heavy Flavours at LEP*, MPI–PAE/PTh 49/89, August 1989.

33. ALEPH Collaboration, D. Buskulic et al., *Measurement of* B–$\bar{B}$ *Mixing at the Z using a Jet–Charge Method*, submitted to Phys. Lett. B, CERN–PPE/92–048.

34. UA1 Collaboration, C. Albajar et al., Phys. Lett. **B 273** (1991) 540.

35. These results from the DELPHI collaboration have been updated since the time of the conference. The updated results are presented here.

36. The results presented here are the updated results that have been submitted for publication: ALEPH Collaboration, D. Buskulic et al., *Observation of the Semileptonic Decays of* B_s^0 *and* Λ_b *Hadrons at LEP*, submitted to Phys. Lett. B, CERN–PPE/92–073.

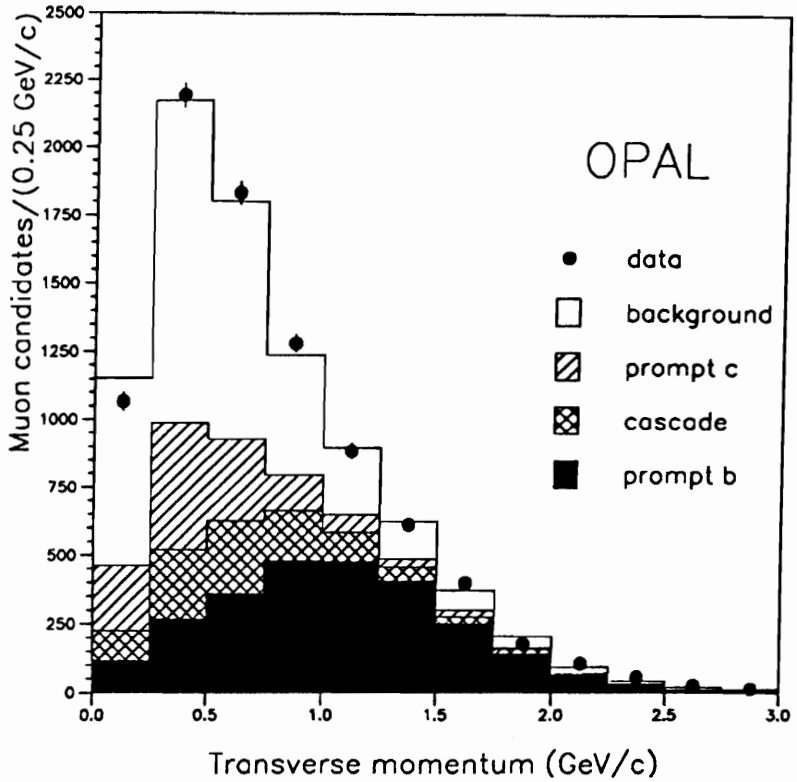

Figure 1: The transverse momentum spectrum for muon candidates with $p > 4.5$ GeV/c in hadronic Z decays measured[14] by the OPAL Collaboration. The points are the data, and the histograms are the composition predicted by Monte Carlo simulations: prompt b is primary b hadron decays; cascade refers to secondary b hadron decays; prompt c means the decays of directly produced charmed particles; and background refers to misidentified hadrons meson decays.

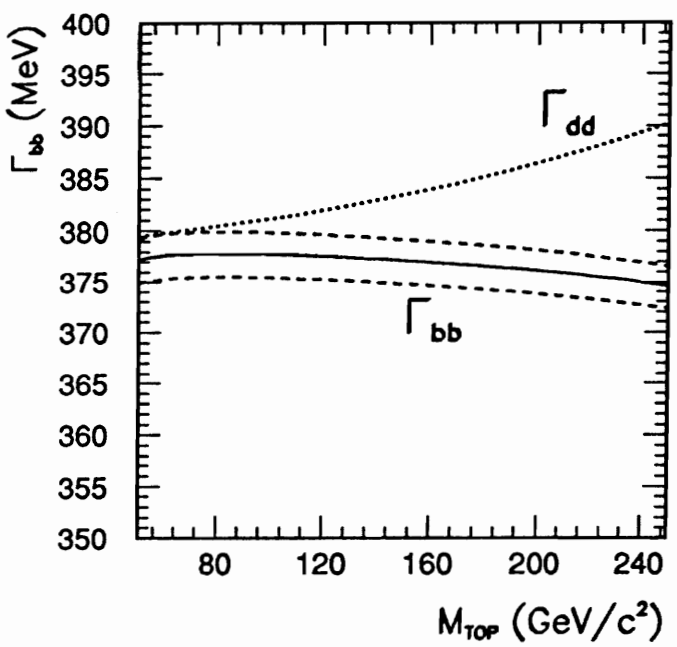

Figure 2: The prediction of the partial width of $Z^0 \rightarrow b\bar{b}$ as a function of the t quark mass.

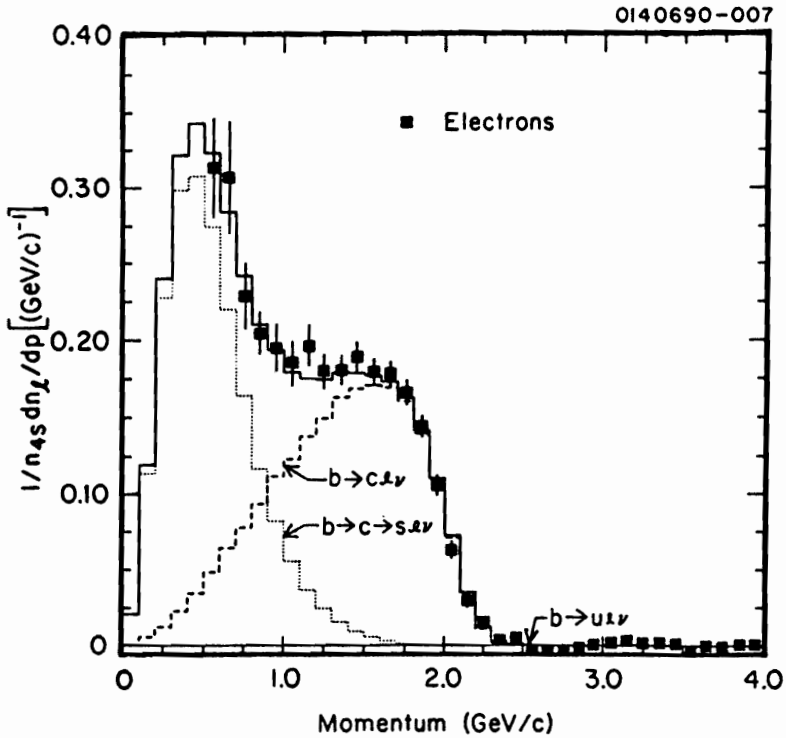

Figure 3: The momentum spectrum of electrons in $B\bar{B}$ events at the $\Upsilon(4S)$ measured[26] by the CLEO Collaboration.

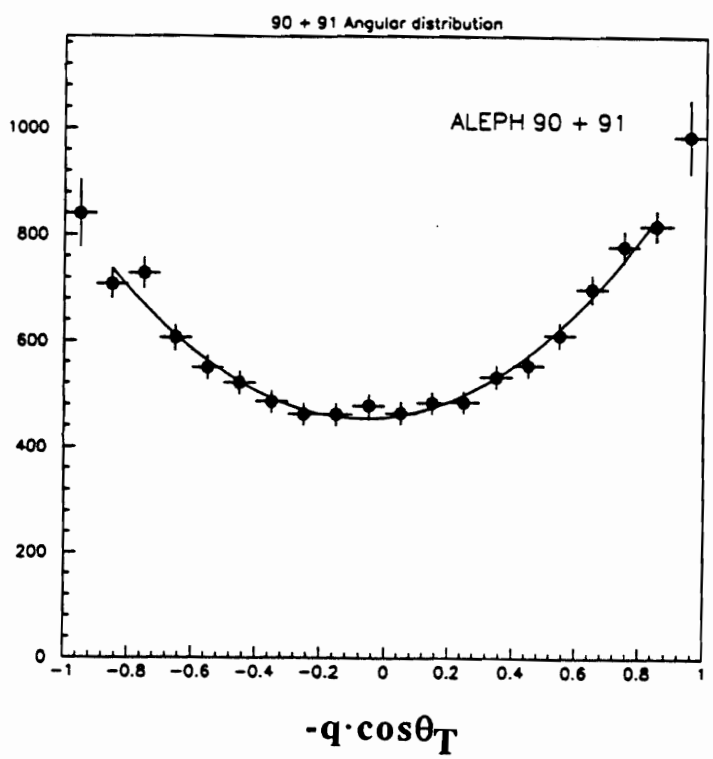

Figure 4: The distribution of $-\mathrm{q} \cdot \cos\theta_{\mathrm{T}}$ for electron and muon candidates with $p > 3$ GeV/c and $p_t > 1$ GeV/c measured by the ALEPH Collaboration.

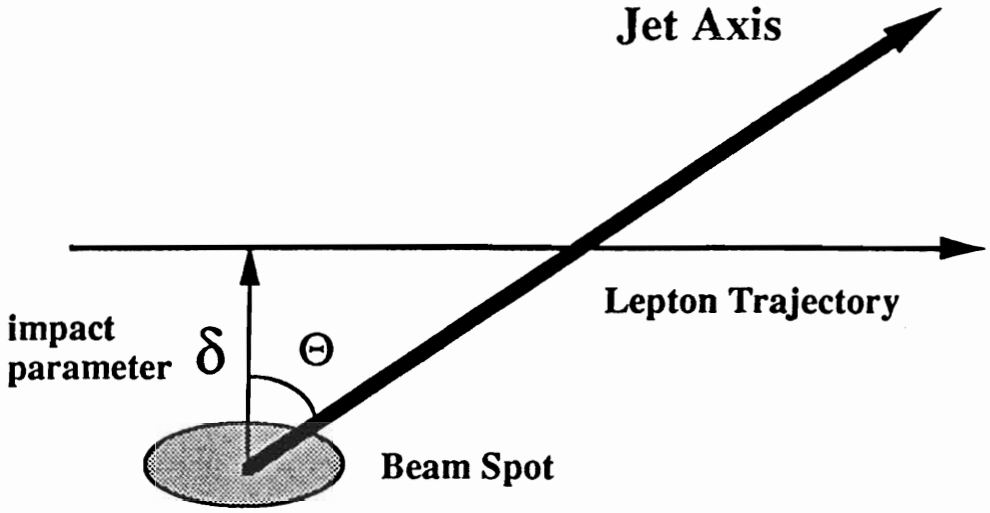

Figure 5: The definition of the impact parameter, δ, which is used to measure the lifetime of b hadrons.

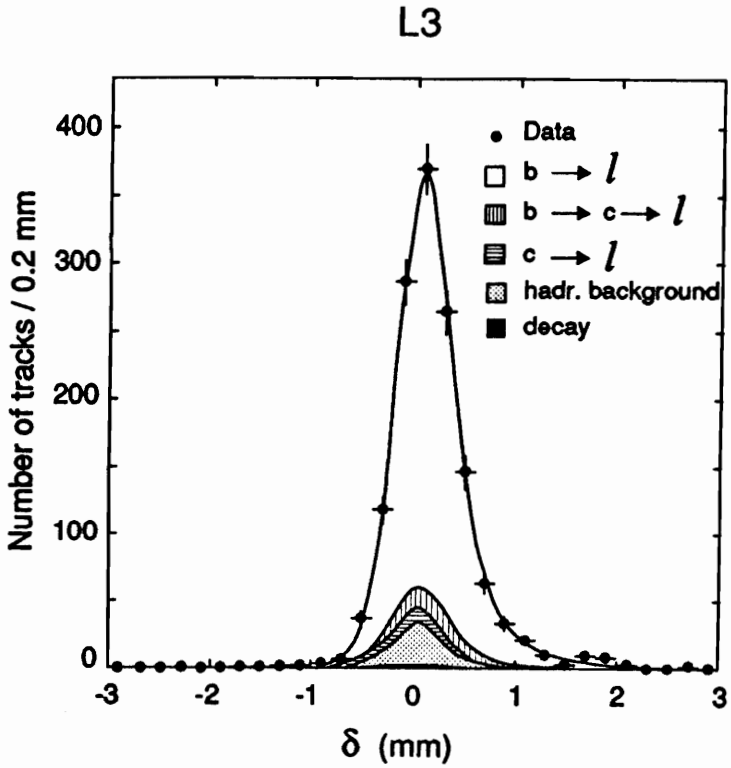

Figure 6: The impact parameter distribution of electron and muon candidates measured[13)] by the L3 Collaboration. The points are the data, and the curves are the composition of the data predicted by Monte Carlo simulations, which are fit to the data.

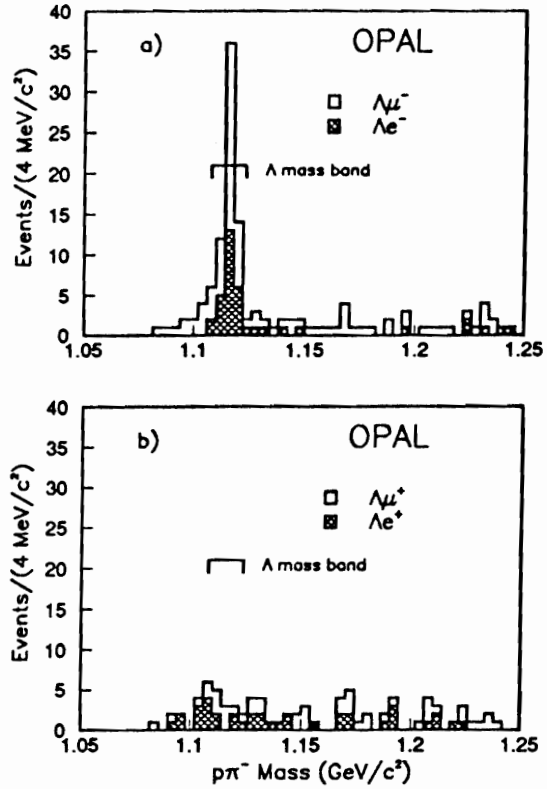

Figure 7: (a) The invariant mass distribution of lambda candidates correlated with a high p and p_t lepton candidate measured[18] by the OPAL Collaboration; (b) the invariant mass distribution for the wrong correlation: Lambdas correlated with antileptons and antilambdas correlated with leptons.

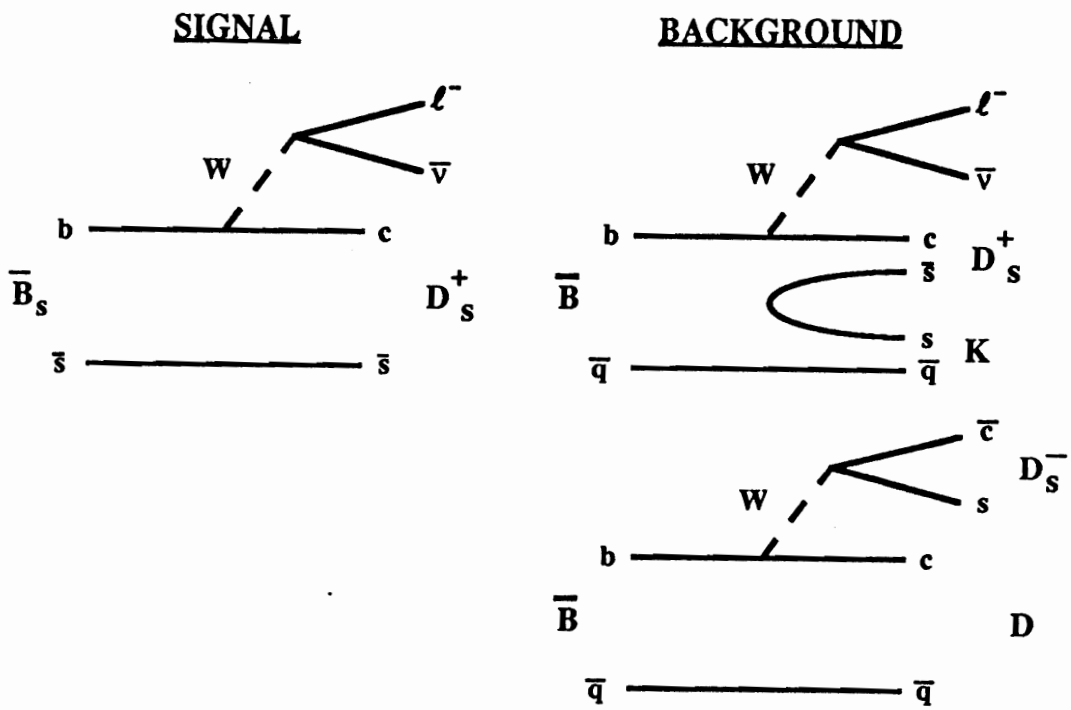

Figure 8: The signature for B_s^0 production and the backgrounds from B_d^0 and $B^{\pm}$ mesons.

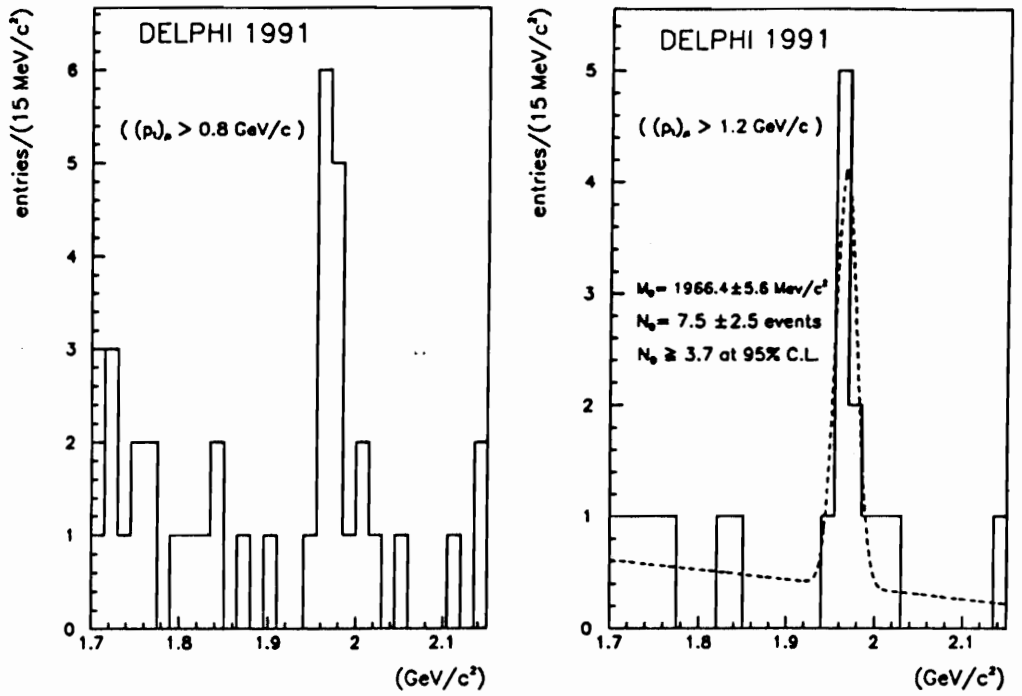

Figure 9: Evidence for the production of the B_s^0 meson seen by the DELPHI Collaboration.

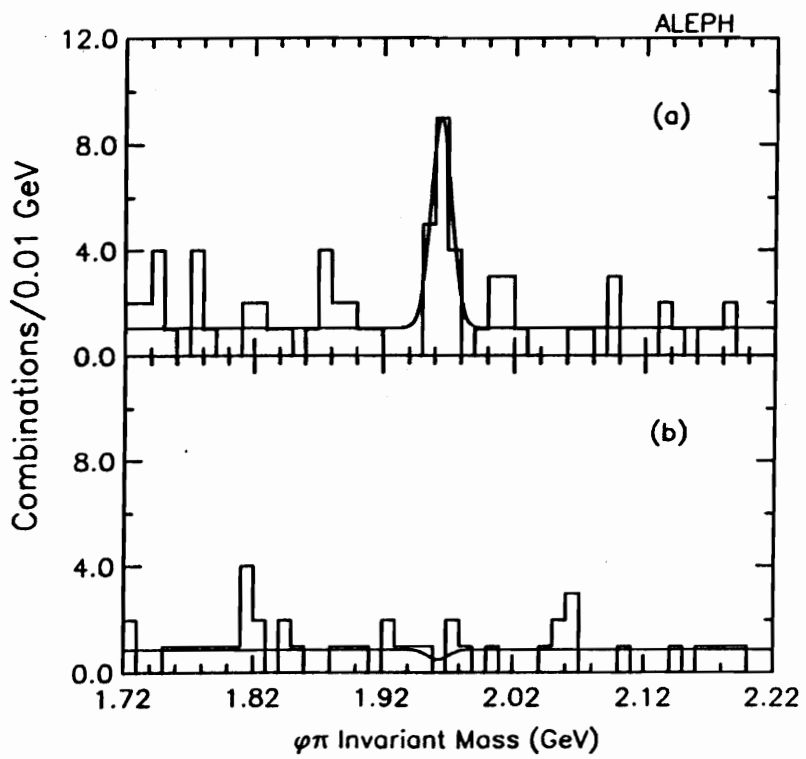

Figure 10: Evidence[36)] for the production of the B_s^0 meson seen by the ALEPH Collaboration.