LEP RESULTS
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Abstract
Recent LEP measurements are presented. Comparing them with the prediction of the Standard Model of the Electroweak Interaction, no discrepancy is found in the experiments’ precision which is often higher than 0.5%.

1. INTRODUCTION
Lep is the CERN Large Electron Positron collider. It is located between the Jura and the Geneva lake in a 26.7 km underground tunnel. It is used to produce electron positron collisions at a centre of mass energy close to the Z mass. There are 8+8 bunches of about $2 \times 10^{11}$ particles circulating with a revolution time of 88.92 μs. They collide at 4 interaction points producing a luminous region approximately $300 \times 60 \times 2000 \; \mu m^3$ where the three numbers $(\sigma_x, \sigma_y, \sigma_z)$ refer to the directions along bending radius, perpendicular to the bending plane and along the beams.

A typical LEP run goes through the following phases: 30' to fill the machine, 30' to ramp and squeeze the beams, 100' to correct the orbits, collide and cure the backgrounds followed by about 15 h of data taking at an average luminosity of about 30-35 nb⁻¹/h. Since the luminosity at high currents is dominated by beam-beam effects a careful trimming of the machine parameters results in an almost time-independent luminosity.

At the Z peak the total annihilation cross section is large: the hadronic cross section is about 30 nb and the cross section for annihilation into lepton pairs is about 1.5 nb. Typically 15,000 hadronic events and $3 \times 750$ leptonic events are collected by each experiment per day.

2. THE ENERGY CALIBRATION OF LEP
The absolute energy scale of LEP has been calibrated [1] using the measurements done with a controlled spin-depolarizing resonance on the vertically polarized beam[2] as a main tool.

In an ideal $e^+e^-$ storage ring the beams naturally polarize along the direction of the bending field (vertical) due to synchrotron radiation emission [3]:

$$P(t) = P_\infty \left(1 - e^{-t/T_p}\right)$$

(1)
where \( P_\infty = 92\% \) and \( \tau_p \) at LEP is 300 min.

In a real machine the polarization level is reduced by depolarization phenomena due to orbit imperfections and non vertical magnetic fields. Calling \( \tau_d \) the typical depolarization time, eqn.1 is modified as follows:

\[
P(t) = \frac{P_\infty}{1 + \frac{1}{\tau_d}} \left(1 - e^{-t/\tau}\right).
\]

where

\[
\frac{1}{\tau} = \frac{1}{\tau_d} + \frac{1}{\tau_p}.
\]

Careful control of the orbit and compensation of the effects of the solenoids of the experiments allows to reach \( \tau_d \sim \tau_p \) and measurable polarization. Polarization is measured scattering polarized laser light (few eV) on the beam and measuring the vertical distribution of the back scattered (22 GeV) photons at 250 m from the interaction point [4]. Reversing the incident photon polarization produces a shift of the distribution of about 50 \( \mu \)m for a 10\% beam polarization.

The spin of the electron rotates around the bending field direction with a precession frequency

\[
v_s f_{rev} = \gamma a f_{rev} = \frac{E_{beam}}{m_e} a f_{rev}
\]

where \( f_{rev} \) is the revolution frequency and \( a \) is the electron gyromagnetic anomaly (\( a = \frac{2}{3}\)). The spin tune \( \nu_s \) is about 105 for a beam energy of 46 GeV. It means that the electron spin precedes about 105 times during one revolution. Since the electron anomaly and the electron mass are known with very small errors, a precise measurement of \( \nu_s \) allows precise energy determination:

\[
E_{beam} = 0.4406486(1) \nu_s.
\]

A frequency-controlled radial RF magnetic field makes the electron spin precess away from the vertical axis. A depolarizing resonance occurs when the radial magnetic field oscillates at the spin precession frequency \( \omega_{dep} = 2\pi \nu_s f_{rev} \) (see Fig. 1). The intrinsic accuracy of the method is very high and allows a measurement of the average beam energy at the time of the experiment with an error of \( \sim 1 \) MeV. This calibration has to be then extrapolated at the time of the data taking introducing some additional uncertainties.

There are many effects that may change the energy of the beam for ideally identical settings. The most important one is the earth’s tide. The local radius of the earth and consequently the LEP radius change by a small relative amount \( (3 \times 10^{-8}) \) due to the tidal forces induced by the moon and by the sun. Since the length of the orbit is kept constant by the radiofrequency the beam position relative to the center of the quadrupole changes and the electrons see the strong magnetic field of the quadrupoles. The relative change of energy is linked to the change of radius by the so-called momentum compaction factor \( \alpha_c \)

\[
\frac{\Delta E}{E} = \frac{1}{\alpha_c} \frac{\Delta R}{R}
\]

that is small \((1/\alpha_c \sim 5200) \) [5] in LEP. The radius variation produces a change of the center of mass energy of \( \sim 15 \) MeV \((2 \times 10^{-4})\).
Figure 1: Polarization signal on 2 October 1991, showing the localization of the depolarizing frequency within the sweep. 
Top: display of data points, with the frequency sweep indicated with vertical dashed lines. The full line represents the result of a fit with starting polarization ($-4.9 \pm 1.1\%$), polarization rise-time ($60 \pm 13$) minutes, asymptotic polarization ($18.4 \pm 4.1\%$). 
Bottom: expanded view of the sweep period, with the individual data sets displayed (there are 10 sets per point). The frequency sweep lasted 7 data sets. The corresponding beam energy is shown in the upper box. Spin flip occurred between the two vertical dash-dotted lines.
This theory has been confirmed by a dedicated experiment performed on the 11th of November 1992 [6]. The energy measured by resonant depolarization is shown in Fig. 2 as a function of the day time. The prediction of the model fits the data very well. During this experiment the variation of the energy for a given change of radius was twice larger than during the scans performed in 1990 and 1991 because of the different optics implemented in the machine.

![Figure 2: LEP Tide experiment. Beam energy measured by the resonant depolarization is plotted as a function of the time and is compared with the prediction of the model.](image)

During the analysis of 1990 and 1991 scan data this correction was not applied. A comparison of the spread of different measurements performed at different times resulted in an error of ±3.7 MeV on the absolute calibration of the center of mass energy of LEP corresponding to a relative accuracy of $4 \times 10^{-3}$.

Other effects were taken into account transporting this calibration to the standard conditions of the physics runs, resulting in a relative accuracy of $5.7 \times 10^{-5}$. The main additional source of error was the change with the temperature of the integrated bending magnetic field seen by the electrons.

The absolute calibration was done at a single nominal energy setting (≈ 2 GeV above the Z mass). The error on the calibration at the other energy settings relative to this special setting depends on the accuracy of the relation between energy and dipole currents, which is determined by magnetic measurements. This error limits the relative accuracy on the measurement of the Z width to $1.8 \times 10^{-3}$.

The error on the Z parameters induced by the machine calibration is very relevant: the error on the mass is dominated by the calibration error, while the error on the width
due to calibration uncertainties is as large as the statistical one.

During the 1993 scan the energy has been calibrated at two different energy settings, below and above the peak, and particular care has been taken in monitoring the conditions of the machine. It should be possible to reach a systematic error below 3 MeV on both the Z mass ($3 \times 10^{-5}$) and width ($1.2 \times 10^{-3}$).

3. **Z LINESHAPE**

During 1990 and 1991 runs about 25 pb$^{-1}$ of integrated luminosity were delivered to each experiment out of which 8 pb$^{-1}$ were off peak for a precise measurement of the Z mass and width. During the 1992 run, 29 pb$^{-1}$ were delivered at the Z peak. The results reported here refer to these data sets. During 1993 40 pb$^{-1}$ additional - of which 20 pb$^{-1}$ were off peak- were delivered to improve the precision of the lineshape parameters but they have not yet been analyzed.

The triggers are highly redundant and their efficiency is essentially 100% for all channels resulting in negligible systematic errors. The event selections are similar to those performed with 1990 and 1991 data [7, 8, 9, 10] and better performances of the detectors allow a reduction in the systematic errors.

The number of selected events and the systematic errors on the event selections are shown in Table 1.

<table>
<thead>
<tr>
<th>Number of events</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q}$</td>
<td>1140K</td>
<td>1047K</td>
<td>1103K</td>
<td>1168K</td>
</tr>
<tr>
<td>$(\ell^+\ell^-)$</td>
<td>138K</td>
<td>101K</td>
<td>102K</td>
<td>147K</td>
</tr>
<tr>
<td>systematic error</td>
<td>$q\bar{q}$</td>
<td>0.17%</td>
<td>0.28%</td>
<td>0.14%</td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$</td>
<td>0.4%</td>
<td>0.6%</td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td>$\mu^+\mu^-$</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>$\tau^+\tau^-$</td>
<td>0.5%</td>
<td>0.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>experimental systematic error on luminosity</td>
<td>0.45%(0.15%)</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>common theoretical error</td>
<td>0.3%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The cross sections $e^+e^- \rightarrow f \bar{f}$ for hadronic($q\bar{q}$) and leptonic final ($\ell^+\ell^-$) states are measured at various energies around $\sqrt{s} \sim M_Z$ by comparing the number of selected Z decays ($N_{f\bar{f}}$) with the number of selected $e^+e^- \rightarrow e^+e^-$ (Bhabha) scattering events at very small angle ($N_B$).

$$\sigma_{f\bar{f}(s)} = \frac{N_{f\bar{f}}}{N_B} \frac{\epsilon_B}{\epsilon_{f\bar{f}}} \sigma_B$$

(3)

The systematic errors on the acceptance ($\epsilon_B$) of BHBHA events are given in Table 1. There are two numbers for ALEPH: the second refers to the last period of data taking when the new tungsten-silicon luminometer was installed. The uncertainty in the theoretical cross section of the Bhabha scattering used for the luminosity measurement is
reduced to the level of 0.3% by using the BHLUMI[11] computation of the visible cross section which is order $\alpha$ plus Leading Logs resummed. It is complemented with corrections taking into account the high-order terms of the $\gamma - Z$ interference[12].

The measured cross sections $\sigma^M$ are fitted to the expression

$$\sigma^M_{\ell\ell}(s) = \int H(s, s')\sigma^0_{\ell\ell}(s')ds'$$

where $H$ is the radiator function that takes into account the large ($\sim 30\%$) effects of the initial state radiation. $\sigma^0$ is the model independent formula of the cross section:

$$\sigma^0_{\ell\ell}(s) \equiv \sigma^\text{pole}_{\ell\ell}(s) = \frac{12\pi\Gamma_\ell \Gamma_f}{M_\ell^2 \Gamma_f^2}$$

Its first term contains the $Z$ exchange and defines the mass $M_\ell$ and the width $\Gamma_\ell$ of the $Z$ boson. The photon exchange and the interference terms are small and the Standard Model value is assumed within the fits without any loss in generality at the present level of precision.

Figure 3: Cross sections for $e^+e^- \rightarrow$ hadrons as functions of the centre-of-mass energy for the 1990 and 1991 data. The Standard Model predictions for $N_\nu = 2, 3,$ and 4 are shown. The lower plot shows the ratio of the measured points to the best fit values.
Two fitting programs are used to extract the lineshape parameters: ZFITTER[13] and MIZA[14]. They give the same result in 2% of the statistical errors of the fitted parameters.

Radiator function $H$ contains the contributions of multiple photon emission and lepton pair production. The error produced on the predicted cross sections by its theoretical uncertainties ($\Delta\sigma/\sigma \sim 4 \times 10^{-4}[15]$) is negligible at the present level of precision.

$e^+e^-$ final state contains additional contributions to the cross section from the $t$-channel diagrams and from the $s$-$t$-channel interference. They are taken into account using program ALIBABA[16] resulting in a systematic error smaller than 0.5%.

There are 4 independent parameters to be fitted: the mass and the width of the Z, the hadronic peak cross section and, assuming lepton universality, ratio $R_\ell$ between the hadronic and the leptonic partial widths. Fig. 3 shows hadronic cross section measured by the ALEPH experiment compared with the fitted lineshape.

The four LEP experiments give consistent results for all fitted quantities. They have been combined [17] to produce the best average values for the Z lineshape parameters, taking into account errors that are correlated among the experiments. The combination can be done following the procedure described in [17] by taking a simple weighted mean of the fit variables and using the correlation matrix of any of the experiments.

Systematic errors on efficiencies and $\sigma_B$ do not affect $M_Z$ and $\Gamma_Z$ determination provided they are $\sqrt{s}$ independent.

The error on the Z mass is dominated by the uncertainty on the energy calibration of LEP. The error on the Z width is still statistically limited but the systematic error due to the LEP energy calibration is not negligible. The systematic error on $R_\ell$ comes directly from the event selections. Fit results for $M_Z, \Gamma_Z$ and $R_\ell$ are shown in Fig.4.

The error on the hadronic peak cross section is dominated in each experiment by the systematic error on the luminosity measurement. Part of this error (0.3%) is due to the theory describing the Bhabha scattering and is completely correlated among the four measurements.

### 3.1 Luminosity measurement

Luminosity is measured counting Bhabha events at small scattering angle $\theta$. This is a calculable QED process:

$$\frac{d\sigma}{d\Omega} = \frac{16(\hbar c \alpha)^2}{s} \frac{1}{\hat{\theta}^4} \Rightarrow \sigma_B = \frac{1040 \text{ nb } GeV^2}{s} \left( \frac{1}{\hat{\theta}_{\text{min}}^2} - \frac{1}{\hat{\theta}_{\text{max}}^2} \right). \quad (6)$$

The measured Bhabha cross section $\sigma_B$ has to be larger than the hadronic cross section ($\sim 30$ nb) in order to minimize the effect of the luminosity statistical error: the minimum accepted angle must then satisfy $\theta_{\text{min}} \ll 30$ mrad.

Bhabha events are selected measuring the energy and the impact position of the scattered electron and positron in two calorimeters placed at small angle close to the beams. In ALEPH two silicon-tungsten calorimeters [18] 23.4 $X_0$ in depth, are placed symmetrically at a distance ($Z$) of about 250 cm from the interaction point. They fully contain showers of electrons hitting the calorimeter at a transverse distance ($R$) of 8 cm from the ideal beam-line.

Events are accepted if the electron (positron) is inside a precisely defined fiducial region of the calorimeter.
Figure 4: Fit results and Standard Model prediction as a function of $m_{top}$ for the ranges of $m_{higgs}$ and $\alpha_s$ indicated.
The main systematic error on the luminosity measurement is due to the definition of the acceptance. The dependence of the measured cross section on the acceptance can be computed using eqn. 6 and $\theta \simeq R/Z$:

$$\frac{\Delta \sigma_B}{\sigma_B} = \frac{2 \delta R}{R_{\text{min}}} \left(1 + \frac{R_{\text{min}}^2}{R_{\text{max}}^2 - R_{\text{min}}^2}\right) \simeq 2.5 \frac{\delta R}{R_{\text{min}}}$$

where the numerical coefficient is valid in ALEPH geometry.

In order to keep the relative error on $\sigma_B$ to the 0.1% level the average position of the collision point should be known with a precision $\delta R = 30\mu$m in the transverse direction and $\delta Z = 1$ mm in the longitudinal direction in the luminometer reference system. Moreover, also the beam direction should be known with a precision of $20 \times 10^{-3}$ mrad in the same reference system. This is not easily achievable and a special technique is used that minimizes the systematic error due to these effects [19]. Two geometrical fiducial regions are defined: a tight-side restricted selection and a loose-side less restrictive cut. The tight and the loose side are alternate between the positron and the electron side each event. This procedure makes the acceptance insensitive in the first order to the exact relative position of the calorimeter compared to the interaction point and to the beam directions.

Once this procedure is applied, the acceptance is defined by the dimensions of the tight fiducial region measured in the calorimeter reference system and by the relative distance of the two calorimeters that can be precisely measured.

The Bhabha events selection is easy and almost background free. Fig. 5 shows the energy and $\phi$ correlations of the detected electron and positron in the ALEPH luminometer. The small background at low energy and $\Delta \phi$ far from 180° is due to random coincidences of off momentum particles.

Figure 5: Left: Energy measured in the electron luminometer vs energy measured in the positron luminometer. Right: Difference between the reconstructed azimuthal angles of electron and positron. Data are compared with the Monte Carlo simulation (full line).

The main experimental sources of systematic error in the ALEPH luminosity mea-
measurement are given in table 2. The total systematic error is well below the theoretical error on the Bhabha cross section that has been estimated to be 0.25% [12] for this geometry.

Table 2. Systematic errors in the ALEPH luminosity measurement

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>0.010%</td>
</tr>
<tr>
<td>Mechanical precision (18 µm)</td>
<td>0.058%</td>
</tr>
<tr>
<td>Beam position-direction</td>
<td>0.045%</td>
</tr>
<tr>
<td>Cell to cell calibration</td>
<td>0.050%</td>
</tr>
<tr>
<td>Background</td>
<td>0.017%</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.120%</td>
</tr>
<tr>
<td>Total</td>
<td>0.15%</td>
</tr>
</tbody>
</table>

3.2 Number of light neutrinos

The partial width of the Z boson into undetectable states (like a neutrino anti-neutrino pair) is given by

\[ \Gamma_{\text{inv}} = \Gamma_Z - \Gamma_h - 3\Gamma_\ell \]

where \( \Gamma_h \) and \( \Gamma_\ell \) are the partial widths into hadrons and into a charged lepton pairs of a given flavour. The ratio between the invisible width and \( \Gamma_\ell \) can be rewritten in terms of the fitted quantities:

\[ \frac{\Gamma_{\text{inv}}}{\Gamma_\ell} = \frac{\Gamma_Z - \Gamma_h}{\Gamma_\ell} - 3 = \sqrt{\frac{12\pi R_\ell}{M_Z^2 \sigma_{\text{pole}}^h}} - R_\ell - 3 \] (8)

The error on this ratio is dominated by the relative error on the cross section measurement:

\[ \Delta \frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \approx 15 \frac{\Delta \sigma_{\text{pole}}^h}{\sigma_{\text{pole}}^h} + 4 \frac{\Delta R_\ell}{R_\ell} \]

The ratio between \( \Gamma_\ell \) and the width \( \Gamma_\nu \) into a neutrino anti-neutrino pair of a given flavour can be computed in the Standard Model:

\[ \frac{\Gamma_\ell}{\Gamma_\nu} = \frac{1}{2} \left( 1 + \left( \frac{g_\ell^2}{g_\nu^2} \right)^2 \right) \left( 1 + \frac{3\alpha}{4\pi} \right) (1 + \delta_\ell) = 0.5016 \pm 0.0007 \] (9)

where \( \delta_\ell \) is a small vertex correction and \( g_\ell, g_\nu \) are the vector and axial vector coupling constant of the lepton to the neutral current (see section 4). The number of neutrino species is derived combining eqn. 8 and 9:

\[ N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\nu} \]

Fig. 6 shows the results obtained by the four experiments. The error on the average takes into account the uncertainty on the Bhabha cross section that is common to the four measurements.
4. ASYMMETRIES

Because of the parity violation of the weak interaction the collision of unpolarized electrons and positrons produces longitudinally polarized Z particles. The amount of polarization depends on the ratio between the vector and axial vector coupling constant of the electron:

\[ A_e = \frac{2g_1^v g_1^a}{(g_1^v)^2 + (g_1^a)^2} \]  

(10)

These Z's decay violating the parity and emitting the fermion in a preferential direction with respect to the direction of their spin. The forward backward asymmetry for fully polarized Z is \(3/4A_f\) where \(A_f\) is given by Eqn. 10 and the factor \(3/4\) comes from the integration over the polar angle. Due to angular momentum conservation, the helicity of the fermion is correlated to the direction of the spin of the Z.

Ideally one can identify the fermion (using the measurement of the charge) for each Z decay and measure its direction and its helicity. Calling forward the hemisphere where the electron beam is pointing, the events can be subdivided into four categories
- \(N_1\): fermion with positive helicity in the forward direction
- \(N_2\): fermion with negative helicity in the forward direction
- \(N_3\): fermion with positive helicity in the backward direction
- \(N_4\): fermion with negative helicity in the backward direction

While the sum of the four \(N\)'s measures the total cross section, their differences measure the asymmetries:

\[ \frac{N_1 - N_2 + N_3 - N_4}{N_1 + N_2 + N_3 + N_4} = A_f \]  

(11)

\[ \frac{N_1 - N_2 - N_3 + N_4}{N_1 + N_2 + N_3 + N_4} = \frac{3}{4} A_e \]  

(12)

\[ \frac{N_1 + N_2 - N_3 - N_4}{N_1 + N_2 + N_3 + N_4} = \frac{3}{4} A_e A_f \]  

(13)
The first two asymmetries require the measurement of the helicity of the fermion. In practice it can be statistically measured only for the channel $Z \rightarrow \tau^+\tau^-$. The third asymmetry (usually called forward backward asymmetry) is the product of two parity violations, one in the production of the $Z$ and one in the decay. It is easier to measure because only the identification of the fermion and the measurement of its direction are needed.

### 4.1 Lepton forward-backward asymmetries

The identification of the fermion in leptonic decays is straightforward. The forward backward asymmetry $A_{FB}^L(s)$ is determined through a fit of the angular distribution of the cross section measured at each center of mass energy:

$$\frac{d\sigma(s)}{dcos \theta} \propto 1 + cos^2 \theta + \frac{s}{3} A_{FB}^L(s) cos \theta$$

(14)

The measured asymmetry $A_{FB}^L(s)$ is fitted to expression

$$A_{FB}^L(s) = \frac{\int H'(s, s') \sigma_{FB}^0(s') ds'}{\int H(s, s') \sigma_0(s') ds'}$$

where

$$\sigma_{FB}^0 = \int_0^1 \frac{d\sigma^0}{dcos \theta} dcos \theta - \int_{-1}^0 \frac{d\sigma^0}{dcos \theta} dcos \theta$$

and $\sigma^0$ is defined by eqn.5.

The forward backward cross section $\sigma_{FB}^0$ depends on the bare asymmetry $A_{FB}^L$:

$$\sigma_{FB}^0(M_t^2) = \sigma^0(M_t^2)(1 - \epsilon)(A_{FB}^0 + \delta)$$

where the small term $\epsilon (\sim 0.01)$ is due to the photon exchange and $\delta (\sim 0.002)$ is the contribution of the imaginary part of the propagator corrections.

This bare asymmetry $A_{FB}^L$ can be directly interpreted in terms of the ratio between the vector ($g_v$) and the axial vector ($g_a$) coupling constants of the neutral current to the fermions using equations 10 and 13:

$$\langle A_{FB}^L \rangle = \frac{3}{4} A_v A_a$$

### 4.2 $bb$ forward backward asymmetry

The forward backward asymmetry of the $b$ quark produced in the $Z$ decays at LEP has been measured by tagging the $bb$ production with the presence of a prompt lepton with high $p_T$ with respect to the parent jet direction [20, 21, 9, 22]. The thrust axis is taken to define the quark direction and the sign of the charge $Q_\ell$ of the lepton to distinguish $b$ from $\bar{b}$.

The raw asymmetry $A_M$ is measured by fitting the angular distribution

$$\frac{d\sigma}{dcos \theta_b} \propto 1 + cos^2 \theta_b + \frac{s}{3} A_M \cos \theta_b$$

$$cos \theta_b = -Q_\ell \cos \theta_{THRTST}$$

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Due to the mixing in the $B^0 - \bar{B}^0$ system, the observed $b$-quark asymmetry is smaller than the actual asymmetry by a factor $(1-2\chi_B)$, where $\chi_B$ is the probability that a hadron containing $b$-quark has oscillated into a hadron containing $\bar{b}$-quark at the time of its decay (see section 9).

The high $p_T$ lepton sample contains also non-prompt leptons from other sources: cascade decay of the $b$ ($b \rightarrow c \rightarrow \ell$, $b \rightarrow c \rightarrow \ell$), charm decay ($c \rightarrow \ell$) and background. The relation between the true ($A_{FB}^b$) asymmetry and the measured ($A_M$) one is:

$$A_M = (1 - 2\chi_B)A_{FB}^b [\eta_{\ell \rightarrow c} - \eta_{\ell \rightarrow \ell} + \eta_{\ell \rightarrow c}] - A_{FB}^b \eta_{\ell \rightarrow c} + A_{BKG} \eta_{BKG}.$$  \hspace{1cm} (15)

The fractions $\eta$ of each source of leptons are determined via Monte Carlo. The sensitivity of the measurement depends crucially on the purity of the sample $(\eta_{\ell \rightarrow c})$.

The forward backward asymmetry of the $b$ quark has also been measured by tagging the presence of the $b$ quark with a lifetime-tag and identifying the fermion from the momentum weighted average of the charges of the reconstructed particles [23, 24]. The advantage of this method is an increase of statistics at a price of a reduced sensitivity because the statistical measurement of the charge is less accurate.

Some corrections have to be made to convert the measured asymmetry $A_{FB}^b$ to the bare asymmetry $(A_{FB}^0)_b$ (cfr. eqn. 10) to take into account the effects of the photon exchange, of photons emission in the initial and final state and also gluon emission in the final state. They shift the central value of the measured quantity by $\approx 50\%$ of its error.

This bare asymmetry $(A_{FB}^0)_b$ can be directly interpreted in terms of the ratio between the vector ($g_v$) and the axial vector ($g_a$) coupling constants of the neutral current to the fermions using equations 10 and 13:

$$(A_{FB}^0)_b = \frac{3}{4} A_v A_a^0.$$  

4.3 Tau polarization asymmetry

The two asymmetries defined by equations 11 and 12 can be measured in $Z$ decays into $\tau$ pairs.

The angular dependence of the final state longitudinal polarization of the $\tau^-$ produced in the reaction $\epsilon^+ \epsilon^- \rightarrow \tau^+ \tau^-$ is:

$$P_\tau (\cos \theta) = \frac{d\sigma_R (\cos \theta) - d\sigma_L (\cos \theta)}{d\sigma_R (\cos \theta) + d\sigma_L (\cos \theta)}$$  \hspace{1cm} (16)

$$= - \frac{A_\tau + A_\epsilon \frac{2 \cos \theta}{1 + \cos^2 \theta}}{1 + A_\tau A_\epsilon \frac{2 \cos \theta}{1 + \cos^2 \theta}}$$

where $\sigma_R$ and $\sigma_L$ are the cross sections for the production of right-handed and left-handed $\tau^-$ and $\theta$ is the angle between the $\epsilon^-$ and the $\tau^-$ directions in the center of mass system and the $A$'s are defined by eqn. 10.

When averaged on all production angles $P_\tau$ is a measurement of $A_\tau$. Also $A_\epsilon$ can be extracted when the angular dependence is studied.

The $\tau$ polarization is measured by fitting the momentum distribution of its decay product. Particle identification is applied to select the $\tau$ decay channel. For each channel
the measured spectra are fitted with a linear combination of the Montecarlo predicted spectra for the two different helicities, including background and full detector simulation. V-A is assumed in the charged current $\tau$ decay to predict the momentum spectra.

The tau polarization averaged over production angles has been measured at LEP by the four collaborations using the $\tau^-$ decays into $e^-\nu\bar{\nu}$, $\mu^-\nu\bar{\nu}$, $\pi^-\nu\bar{\nu}$, $\rho^-\nu\bar{\nu}$ and $a_1\nu$. The analysis technique has been improved with respect to the already published results [25, 26, 9, 27], thus reducing systematic errors.

The polarizations obtained by each collaboration in each decay channel are consistent. Sensitivity is smaller for leptonic decay modes because part of the information is lost in the three body decay with undetectable neutrinos.

The ALEPH collaboration has also studied the angular dependence of the polarization. The polarization averaged over the four different channel is calculated in 9 different $\cos \theta$ bins. $A_\perp$ is measured from a fit of the angular dependence (cfr. eqn. 16).

Some corrections have to be made to convert the measured asymmetry $A_\perp$ to the bare asymmetry $A_\parallel^0$ (cfr. eqn. 10) to take into account the effects of the photon exchange and photons emission in the initial state. The effect of the final state radiation is taken into account in the fit procedure. These correction factors are small. They shift the central value of the measured asymmetry by a small amount compared to the error.

### 4.4 The effective sinus: $\sin^2 \theta_W^{eff}$

The effective sinus is defined in terms of the ratio between the vector and axial vector couplings of the lepton to the neutral current:

$$\frac{g_V}{g_A} = 1 - 4 \sin^2 \theta_W^{eff}$$

(17)

Assuming lepton universality, the measurements of the leptonic forward backward asymmetry and of $A_\parallel^0$ and $A_\perp^0$ from the $\tau$ polarization can be directly converted into $\sin^2 \theta_W^{eff}$ using eqn. 10 and 17.

The $b\bar{b}$ forward backward asymmetry can also be converted into $\sin^2 \theta_W^{eff}$ using the Standard Model to evaluate $A_\parallel^0$. This is a quite safe assumption since in the Standard Model $A_\parallel^0$ is almost independent from $\sin^2 \theta_W^{eff}$ [28].

Another determination of $\sin^2 \theta_W^{eff}$ can be obtained from the average quark charge asymmetry for all hadronic events [29, 30, 31, 32]. The charge of the primary quark is inferred from a momentum weighted average of the charges of the reconstructed particles. Montecarlo simulation is needed to interpret the measured asymmetry in terms of the effective sinus.

Fig. 7 shows the comparison among the different determinations of $\sin^2 \theta_W^{eff}$. They are all very consistent among each other and also with the Standard Model prediction. The average is:

$$\sin^2 \theta_W^{eff} = 0.2319 \pm 0.0007$$

### 5. STANDARD MODEL INTERPRETATION

The various measurements shown so far are all consistent with the Standard Model for a given range of the top mass and each of them can be used to constrain its value.

Fig. 8 shows the consistency among the different constraints: for any value of the top mass and for a fixed value of the Higgs mass (which here is assumed to be 300 GeV)
each electroweak measurement can be used to predict $\sin^2 \theta_W^{eff}$ within the framework of the Standard Model. The error on the prediction reflects the experimental error on the chosen quantity since all other input parameters have negligible relative error ($\alpha, G_F$) or are assumed ($m_{top}, m_{higgs}$). The prediction with its error can be plotted as a function of $m_{top}$ resulting in an allowed (68%) region in the plane $\sin^2 \theta_W^{eff}$ vs $m_{top}$.

Four different bands are shown in Fig. 8. They are calculated using the measurements of $M_\tau, \Gamma_\tau$ [11], the asymmetries and mass ratio $M_\tau/M_\ell$. The band produced by the asymmetries is horizontal since they are a direct measurement of $\sin^2 \theta_W^{eff}$. The mass ratio value is obtained by combining the results from the neutrino nucleon scattering [34, 35, 36] with those from the direct measurement of the W mass [37, 38] and the LEP value of $M_\ell$. The correlation between the constraint produced by the mass ratio and the very tight one produced by $M_\tau$ is negligible since the relative error on $M_\tau$ is very small compared to those on the other quantities.

All data are consistent with a top mass within the range 120-180 GeV and no discrepancy is seen from the Standard Model prediction.

### 6. MEASUREMENT OF $R_\ell$

In the Standard Model, the decay $Z \to b\bar{b}$ differs from other hadronic $Z$ decays because of final state electroweak interactions involving the top quark [39]. These corrections

---

1) The strong coupling constant $\alpha_s$ is needed to predict $\sin^2 \theta_W^{eff}$ from $\Gamma_\tau$. The value $\alpha_s = 0.123 \pm 0.006$ from LEP event shape is used [33] and the uncertainty induced on the prediction by its error is included in the width of the band.
The momentum spectrum of the leptons.

direction (refs. [41] to [45]). This method is limited by the knowledge of the shape of Tagg bb events with leptons at high transverse momentum respect to the parent jet.

Several methods have been used to measure $R_b$:

- Tagg bb events with leptons at high transverse momentum respect to the parent jet direction (refs. [41] to [45]). This method is limited by the knowledge of the shape of the momentum spectrum of the leptons.

are large for the $b\bar{b}$ final state (see Fig. 9) since $V_{tb} \sim 1$.

The effect of these vertex corrections is isolated by the ratio $R_b = \Gamma_b/\Gamma_h$ between the partial widths into $b\bar{b}$ and into hadrons, and is independent of theoretical uncertainties in final state strong interactions or higher-order propagator terms, which are cancelled in the ratio. The value of $R_b$ can be used to infer the standard model top mass through these vertex corrections, or to look for new processes which give rise to additional vertex corrections [40]. Assuming a top mass of 150 GeV one finds that $\Gamma_b$ differs from $\Gamma_h$ by only 2% (cfr. eqn.18).

$$R_b \simeq R_d \left[ 1 - \frac{20\alpha}{13\pi} \left( \frac{m_t^2}{m_Z^2} + \frac{13}{6} \ln \frac{m_t^2}{m_Z^2} \right) \right]$$

Thus, a precision measurement of $R_b$ is needed to observe the effect of the vertex corrections.

Figure 8: Constraints $\sin^2 \theta_W^{\text{eff}}$ versus $m_{\text{top}}$ from different measurements corresponding to 1 $\sigma$ limits. $m_{\text{higgs}} = 300$ GeV is assumed.
- Tagg $b\bar{b}$ events using the shape of the events [46, 47, 48]. Since the $b$ quark is heavy ($m_b \gg m_{uds}$), $b\bar{b}$ events are more fat. This method is somehow limited by the dependence on the Montecarlo or by the correlations between the two hemispheres.

- Tagg $b\bar{b}$ events using the lifetime information [49, 50, 51]. This is the most powerful method and is discussed in some detail.

In the lifetime tag measurement $b\bar{b}$ decays are identified by the long lifetime ($\simeq 1.5$ ps) of $b$ hadrons. Because all $b$ hadrons have long lifetimes, no statistical precision is lost through limited branching ratios. To be effective, this identification method requires precision tracking of the $b$ decay products. With the advent of silicon vertex detectors, lifetime effects in $b$ hadron decays become visible with a significance of several standard deviations per track [52], making such a lifetime tag practical. To avoid the large uncertainties in the $b$ hadron lifetimes, this technique is best applied in the double tag mode, where the tag efficiency is determined from the data.

The analysis [49] is organized as follows: jets are reconstructed and tracks are projected in the plane perpendicular to the jet. In this way lifetime information is lost. Projected tracks are combined with the beam spot position determined on the basis of $\sim 100$ events to find the $Z$ decay point. This technique has a resolution of $50 \times 10 \times 60$ $\mu$m$^3$ on the $Z$ decay point. The signed impact parameter $2) \delta$ is considered for each track with minivertex hits. The sensitivity $S$ of each track, defined as the ratio between the impact parameter and its error, is used to compute the probability that a given collection of tracks has no decay products from long lived particles. Typical values of the sensitivity are $S \sim 0$ for $uds$ events and $S \sim 4$ for $b$ events. This probability is computed separately for each hemisphere of the event.

As shown in Fig. 10 by applying a cut on this probability one can increase the $b$-purity of the sample of selected hadronic events: purities of 95% are reached still retaining $\sim 20\%$ of the $b\bar{b}$ events.

2) The impact parameter is defined as the distance of closest approach in space between a track and the estimated $Z$ decay point. It is signed positive (negative) if the point of closest approach between the track and the estimated $b$ hadron (jet) flight path is in front of (behind) the $Z$ decay point, along the direction of the $b$ momentum.
The first observation has been made by OPAL \cite{53} in the channel \( B_S \rightarrow J/\psi \phi \). The BS mass has been measured at LEP via a complete reconstruction of its decay framework of the standard model \cite{54}, \( m_{B_S} > 113 \) GeV. From this result alone it is possible to put a limit on the top quark mass within the boundaries of the standard model: \( m_{t_{\text{top}}} < 221 \) GeV at 95\% c.l. taking also into account the Tevatron limit \( m_{t_{\text{top}}} > 113 \) GeV.

\section{Measurement of \( B_s \) mass}

The \( B_s \) mass has been measured at LEP via a complete reconstruction of its decay final state. The first observation has been made by OPAL \cite{53} in the channel \( B_s \rightarrow J/\psi \phi \).
The most precise measurement at LEP has been made by the ALEPH collaboration [54] and is discussed here in some detail.

Aleph was lucky to identify and fully reconstruct one event in the rare decay channel $B_s \rightarrow \psi \phi$. This event is shown in Fig. 12.

The measured $B_s$ mass is $5.3684 \pm 0.0056$ GeV. There are two energetic tracks with momenta of 13.5 and 16.2 GeV which penetrate seven interaction lengths of iron and are well-identified as muons in the Hadron Calorimeter and the muon chambers. The $\mu^+\mu^-$ invariant mass is $3.692 \pm 0.020$ GeV, in good agreement with the known $\psi'$ mass of 3.686 GeV. The $\phi$ candidate is composed of two tracks with momenta 7.2 and 5.1 GeV respectively. Each of them has specific ionization in the time projection chamber (TPC) in good agreement with the kaon hypothesis. The $K^+K^-$ invariant mass is $1.0204 \pm 0.0008$ GeV. Each of the four tracks has at least one three-dimensional coordinate in the Vertex detector (VDET) and most track coordinate assignments in the Inner Chamber (ITC) and the TPC are unambiguous. These four charged tracks form a common vertex in three dimensions with a vertex $\chi^2$ probability of 43%. The $B_s$ decay vertex is displaced with respect to the interaction point by $4.53 \pm 0.14$ mm. The $B_s$ momentum is 41.7 GeV, close to the beam energy of 45.6 GeV. In the process of hadronization of the $b$ quark into a $B_s$ meson it is expected that the remaining most energetic track be a charged or neutral kaon. In this event, aside from the four tracks forming the $B_s$, the most energetic particle in the hemisphere containing the $B_s$ is a $K_S^0$ with a measured mass of $0.486 \pm 0.008$ GeV, momentum of 1.63 GeV and a decay length of $7.39 \pm 0.48$ with respect to the interaction point.

Several characteristics of this event can be used to dismiss any other plausible hypothesis. The large three dimensional impact parameter of these tracks imply that they come from a $b$ hadron decay. The event is well-contained in the detector and the lack of missing energy in the hemisphere containing the $B_s$ candidate excludes the possibility that the two muons making the $\psi'$ candidate were instead produced in the double semileptonic decay of a $b$ hadron ($b \rightarrow c\mu^-\nu, c \rightarrow X\mu^+\nu$). The $B^0$ hypothesis can be ruled out for this event by comparing the reconstructed mass with the precisely measured $B^0$ mass. The $B_s$ candidate tracks, when interpreted as $B^0 \rightarrow \psi'K^+\pi^-$ have a mass inconsistent to more than 10 standard deviations. The $\overline{B}^0 \rightarrow \psi'K^-\pi^+$ hypothesis was rejected on the basis of the observed mass at the five standard deviations level and also by the dE/dx information.

![Figure 11: Measurements of $R_b$.](image-url)
These observations on this event are substantiated by studies performed with a large sample of simulated $Z \rightarrow \psi' X$ events. From these studies the expected combinatorial background above 5.0 GeV was estimated to be less than 0.006 events at 95% confidence level. The expected background from reflections from $B^0$ and $\Lambda_b$ decays was estimated to be less than 0.0003 and 0.00008 events respectively.

The statistical error on the measured $B_s$ mass is due to tracking errors and is small because of the $\psi'$ mass constraint. The systematic error on the mass measurement has to be evaluated by studying the specific features of this event.

Processes such as decay in flight of kaons, multiple scattering, nuclear interaction in the tracking volume and misassignment of track coordinates (especially for the kaon tracks in the $\phi$ decay) can lead to a gross mismeasurement of the $B_s$ mass. This possibility was checked by generating 700 events with the topology of the observed event and simulating the response of the tracking system. The resulting $\mu^+\mu^-K^+K^-$ invariant mass distribution was fitted with a Gaussian. The observed mass was $5.3683 \pm 0.0008$ GeV with an r.m.s of $0.0050 \pm 0.0001$ GeV. No non-Gaussian tails were observed. Possible biases in the $\psi'$...
mass-constrained fit were checked by generating 1000 fully simulated \( B_s \rightarrow \psi' \phi \) events. The reconstructed mass was found to be in good agreement with the generated value.

From a comparison of the reconstructed mass of the \( D^0, D^+ \) and \( \psi \) hadrons with their known values, the mass scale of the detector is known to better than 0.12\%. Due to the \( \psi' \) mass constraint imposed in the fit, the effect of a 0.12\% scale error on the \( B_s \) mass measurement is 0.0011 GeV. The effects of possible misassignment of the track hit coordinates in the VDET, the ITC and the TPC were studied. It was not possible to interchange VDET coordinates on any of the four tracks from the \( B_s \) candidate without an unacceptably large increase in the \( \chi^2 \) of the track fit. Removing the ITC and the TPC coordinates which contributed most to the \( \chi^2 \) of the track fit changed the \( B_s \) mass by 0.0004 GeV. An interchange of the ambiguous hits in the ITC changed the \( B_s \) mass by 0.0001 GeV.

The alignment of the tracking system has been studied using the \( Z \rightarrow \mu^+ \mu^- \) data. Single helix fits to this dimuon data show that there is a possibility of a \( \phi \) dependent misalignment between the VDET and the ITC-TPC system. The amplitude of this effect is about 7 \( \mu \)m at the outer vdet layer. This could lead to an error on the track angle measurement of about 1.2 \( \cdot \) 10\(^{-4}\). Changing the measured \( \psi' \) and \( \phi \) angles in opposite directions by this amount led to a change in the \( B_s \) mass of 0.0008 GeV. Studies of \( Z \rightarrow \mu^+ \mu^- \) events have also shown a charge-dependent bias in momentum measurement of 0.3\% at 45 GeV. This offset contributes a mass measurement error of 0.0003 GeV. The sum, in quadrature, of all these sources of systematic error was 0.0015 GeV. Hence the \( B_s \) mass was measured to be

\[
M_{B_s} = 5.3686 \pm 0.0056({\text{stat.}}) \pm 0.0015({\text{syst.}}) \text{ GeV}.
\]

8. **Exclusive \( B \) lifetimes**

In the \( B \) system the spectator model is expected to give a good description of decays, due primarily to the larger mass of the \( b \) quark. Nevertheless, non-spectator effects are still expected in the hadronic decays. In the case of the \( B^+ \) standard spectator and internal spectator decays lead to the same final state and the interference between these amplitudes is expected to be destructive, leading to an increased lifetime. In the neutral \( B \) mesons and \( \Lambda_b \) (used as a shorthand for long-lived \( b \) baryons), \( W \)-exchange is possible, leading to a decreased lifetime. Such decays are, however, helicity suppressed for the mesons and one is left with an expected lifetime hierarchy

\[
\tau(B^+) > \tau(B_s) \geq \tau(B^0) > \tau(\Lambda_b)
\]

with lifetime differences of the order 10\% or less.

The \( B^+ \) and \( B^0 \) mesons produced can be identified from \( D^0 \) lepton and \( D^* \) lepton correlations\[55, 56, 57\], since \( B^+ \rightarrow D^0 l^+ \nu \) and \( B^0 \rightarrow D^{*-} l^+ \nu \). This assignment is confused by the further decay of the \( D^{*-} \) from \( B^0 \): \( D^{*-} \rightarrow D^{0} \pi^- \), but this occurs with a known branching fraction and can be corrected. However, to convert the effective \( D^0 \ell \) and \( D^* \ell \) lifetimes into \( B^+ \) and \( B^0 \) lifetime measurements, one must again make assumptions about the contribution from \( D^{*-} \) decays, and this leads to substantial systematic uncertainty. Eventually the best measurements for the individual lifetimes will come from fully reconstructed decays, and the first results of this type have been presented by CDF (using their \( J/\psi \) signal)\[58\].
The $B_s$ and $\Lambda_\circ$ are produced at LEP along with the $B^+$ and $B^0$, and partial reconstruction is used to measure their lifetimes. In the case of the $B_s$ this is done by looking for $D_s^+$ mesons correlated with a lepton. The $D_s^+$ are typically reconstructed in the $\phi\pi^+$ and $K^{*0}K^+$ decay modes. In $\Lambda_\circ$, the correlations of a $\Lambda$ or $\Lambda$ with a lepton are used; here a background is expected from the accidental correlation of a lepton with a $\Lambda$ from fragmentation, but this can be controlled by studying the wrong-sign combinations (since the background should be charge independent).

The averages of the results for the individual $B$ hadron lifetimes are shown in Fig. 13. As can be seen, the precision on the exclusive lifetimes is just reaching the interesting level of precision, and already the first signs of inequality are appearing, with the $\Lambda_\circ$ lifetime significantly lower than the average.

<table>
<thead>
<tr>
<th>$B$ hadron lifetimes (ps)</th>
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<tbody>
<tr>
<td>$B^+$</td>
</tr>
<tr>
<td>$B^0$</td>
</tr>
<tr>
<td>$B_s$</td>
</tr>
<tr>
<td>$\Lambda_\circ$</td>
</tr>
<tr>
<td>Inclusive</td>
</tr>
</tbody>
</table>

Figure 13: Exclusive lifetimes of $B$ hadrons. The inclusive measurement is also shown.

9. **Time dependent $B^0\bar{B}^0$ mixing**

The $B^0$ mass eigenstates $B_1$ and $B_2$ are linear combinations of the weak eigenstates: $B_{1,2} = (B^0 \pm \bar{B}^0)/\sqrt{2}$. Their difference in mass $\Delta m = m_1 - m_2$ leads to a time-dependent phase difference between their wavefunctions, and thus the probability to observe a $B^0$ or $\bar{B}^0$ oscillates as a function of proper time. For an initially pure $B^0$ state, the probability of observing the decay of a $B^0$ or $\bar{B}^0$ is given by

$$
\begin{align*}
\text{Prob}(B^0) &= \frac{1}{2} e^{-\Gamma t} (1 + \cos \Delta mt) \\
\text{Prob}(\bar{B}^0) &= \frac{1}{2} e^{-\Gamma t} (1 - \cos \Delta mt)
\end{align*}
$$

where the widths for the two states have been assumed equal (in contrast to the $K$ system). The total (time integrated) probability of mixing $B^0 \to \bar{B}^0$ is just given by

$$
\chi = \frac{1}{2} \frac{(\Delta m/\Gamma)^2}{1 + (\Delta m/\Gamma)^2}
$$

where the dimensionless mixing parameter $\Delta m/\Gamma$ has been introduced, which is essentially the oscillation frequency expressed in terms of the lifetime; $\chi$ lies between 0 (for no mixing) and 0.5 (maximal mixing).

To observe mixing one needs to tag the state of the $B^0$ both at its production and decay. The classical technique is to use dilepton events, where the leptons originate
from the semileptonic decay of the \( B \) hadrons. Normally \( B \rightarrow \ell^+ X \) and \( \bar{B} \rightarrow \ell^- X \), and thus for a \( B^0 \bar{B}^0 \) event with no mixing one would observe an unlike signed pair of leptons. Like-sign dileptons are thus a signature of mixing.

Since \( B \) hadrons are produced incoherently at LEP, an average mixing parameter is measured:

\[
\chi = f_d \chi_d + f_s \chi_s.
\]  

(22)

where \( f_d \) and \( f_s \) are the production fractions of \( B^0 \) and \( B_s \) and the extraction of the direct mixing parameters requires the knowledge of the fractions \( f \) that are not very well determined experimentally.

The mixing parameter \( \chi_d \) of the \( B^0 \) meson has been measured by Argus and Cleo \([59, 60]\) assuming almost equal probability for the decays of the \( \Upsilon(4S) \) into \( B^0 \bar{B}^0 \) and \( B^+ B^- \): \( \chi_d = 0.162 \pm 0.031 \).

The \( B^0 \) mixing has also been measured at LEP looking for the characteristic oscillatory behaviour and measuring directly its frequency. ALEPH has done this measurement studying \( D^* \) lepton correlations, where the \( D^* \) and lepton are on opposite side of the event [61].

![Figure 14: Schematic illustration of the event topology for the study of the time-dependent mixing using \( D^* \) lepton events. The shaded ellipses represent reconstructed vertices and the solid lines are charged tracks.](image)

After requiring that the lepton satisfies \( p_T > 0.75 \) GeV/c with respect to the jet axis, the \( D^* \) comes dominantly from the decay \( \bar{B}_0 \rightarrow D^{*+} X \). Reconstructing the \( D^* \) decay vertex in the channel \( D^{*+} \rightarrow D^0 \pi^+ \) is difficult due to the low momentum of the pion, so instead the \( D^0 \) vertex is used. The total decay length is then the combination of \( B^0 \) and \( D^0 \) decay lengths, but as the lifetime of the \( D^0 \) is well known and is much shorter than that of the \( B^0 \) (and the period of the oscillation under study) this is not troublesome. The event topology is illustrated in Fig. 14: mixed events will give a \( D^* \) and lepton of unlike sign. The charge asymmetry of the \( D^* \ell \) pairs is studied as a function of the reconstructed decay length, \( C = (N_{++} - N_{+-})/(N_{++} + N_{+-}) \). For a pure \( B^0 \) sample, with perfect tagging, this should give a sinusoidal dependence on proper time: \( C = \cos \Delta m_d t \); the effect of backgrounds and the fact that one measures decay length rather than time are illustrated in Fig. 15.

ALEPH has used the decay channels \( D^0 \rightarrow K^- \pi^+, K^- \pi^+ \pi^+ \pi^- \), \( K^- \pi^+ \pi^0 \), selecting 664 \( D^* \ell \) events. The charge asymmetry for these events is shown in Fig. 16. and clearly
Figure 15: Effect of reconstruction and backgrounds on the oscillation signal for the $D^*$ lepton analysis. (a) Expected charge asymmetry for a pure $B^0$ sample with perfect tagging; (b) using the $D^0$ instead of the $B^0$ vertex, and convoluting with the $B^0$ momentum distribution; (c) including the effects of lepton mistagging and backgrounds (from charm, $B^+$ and combinatorial). The dashed line shows the expectation for time-independent mixing.

demonstrates the time-dependent behaviour expected.

An unbinned fit to the like and unlike-sign events gives an (angular) frequency $\omega \sim 0.52 \text{ ps}^{-1}$, corresponding to a mass difference

$$\Delta m_d = \hbar \omega = (3.44 \pm 0.65 \pm 0.22) \times 10^{-4} \text{ eV}.$$ 

Using eqn.21 this value can be converted to $\chi = 0.75 \pm 0.15 \pm 0.07$.

The time dependence of the mixing has also been studied using dilepton events. Since both the $B^0$ and the $B_s$ contribute to the sample, one is looking for two frequency components in the time dependence and the fit is sensitive not only to $\chi$ but also to $\chi_s$ that is more difficult to measure.

10. Conclusion

In 1993 LEP has collected 40 pb$^{-1}$ of which 20 off peak. The frequent energy calibrations allow a precise measurement of the $Z$ mass and width. More data will be collected in 1994 when a long run at the $Z$ peak is expected to produce more than 2 millions hadronic decays per experiment. New and more precise results will be produced by LEP in the forthcoming years.
REFERENCES


L3 Collaboration, B. Adeva et al., CERN-PPE/93-31.


OPAL Collaboration, P.D. Acton et al., CERN-PPE/93-146.


The LEP Collaborations and the LEP electroweak working group, CERN-PPE/93-157.


[23] ALEPH Collaboration, A Preliminary Measurement of $\sin^2 \theta_W^{ff}$ from $b\bar{b}$ asymmetry in the 1992 lifetime tagged Heavy-Flavour sample. ALEPH 93-134 PHYSIC 93-115.

[24] DELPHI Collaboration, Inclusive measurement of the forward-backward asymmetry in $b\bar{b}$ events at LEP. DELPHI 93-78 PHYS 305.


[28] M. Bohm and W. Hollik, Forward-backward asymmetries, in Z physics at LEP 1, CERN 89-08.


[32] ALEPH Collaboration, Update of Hadronic forward/backward charge asymmetry using the 1991 data. ALEPH-Note 93-041 PHYSIC 93-032 (1993);
ALEPH Collaboration. Update of Hadronic forward/backward charge asymmetry systematic error. ALEPH-Note 93-042 PHYSIC 93-034 (1993);
ALEPH Collaboration. Determination of $sin^2\theta_{w}$ from the hadronic charge asymmetry. ALEPH-Note 93-044 PHYSIC 93-036 (1993).

[33] S. Bethke, Test of QCD. Talk given at the XXVII ICHEP Dallas.
R. Chivukula, R. Chivukula, B. Selipsky, Non-oblique Effects in the Zb\overline{b} Vertex from ETC Dynamics. BUHEP 92-12 (1992)
[41] ALEPH Collaboration. A measurement of $\Gamma_b/\Gamma_h$ using leptons, ALEPH Note 93-135 PHYSIC 93-116.
[42] DELPHI Collaboration. Determination of $\Gamma_b$ and $BR(b \rightarrow \ell)$ using semi-leptonic decays, DELPHI 93-74 PHYS 301.
DELPHI Collaboration. Direct measurement of the $b\overline{b}$ branching ratio at the Z by hemisphere double tagging. DELPHI 93-75 PHYS 302.
[51] OPAL Collaboration. P.D. Acton et al. CERN-PPE/93-79.
OPAL Collaboration. An Updated Measurement of $\Gamma_b/\Gamma_h$ Using Double Lifetime Tagging. OPAL Internal Physics Note PN104. 7 July 1993.
[57] OPAL Collaboration. P.D. Acton et al. CERN-PPE/93-33.