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FIRST RESULTS AT THE LEP $e^+ e^-$ COLLIDER

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LEP

The summer of 1989 saw the first collisions at LEP. Within a few months the four experiments: ALEPH, DELPHI, OPAL and L3 were able to produce results which a) demonstrated that the number of fermion families is three, b) measured the mass of the Z to 1 part in 3000, c) checked the validity of the electroweak theory with a sensitivity of $\sim 1\%$, and d) provided new upper limits on the masses of various postulated new particles, including the Higgs. As of this writing, more than sixty papers have been published, or submitted for publication. In these lectures some of these results are reviewed.

The LEP collider produces collisions between electrons and positrons up to energies of 55 on 55 GeV. This upper energy limit is expected to increase gradually to 90 on 90 GeV in 1994. The 27 km long tunnel is below the plane which separates Geneva, Switzerland from the French Jura, as shown in Fig. 1. It is the largest accelerator in the world but not the most energetic, by far. Even its final energy will be ten times less than that of the Tevatron, the present record holder for $p\bar{p}$ colliders, with only one-third the diameter of LEP. This is the price for accelerating electrons and positrons, which, because of their low mass, radiate heavily. The large radius is a compromise between construction cost and the cost of

FIGURE 1. Siting of the LEP 27 km long tunnel, between the Jura and the Geneva airport.

FIGURE 2. View into the LEP tunnel.

supplying the R.F. power to replenish the radiated energy. The machine is located in a tunnel 50 to 150 m underground (Fig. 2). Four bunches of electrons and positrons produce collisions at four intersection points, 40,000 times per second. The bunch size at collision is ~20 mm long, 300 μ transverse horizontally and 10 μ vertically. The luminosity is expected to be limited at $1.6 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ (up to now about one half of this has been reached at 50 GeV).

ALEPH

Fig. 3 shows one of the four experimental areas. The experiments are mounted in large underground vaults. On the surface, various buildings house the services, both for the accelerator and the experiment. The vaults measure about 20 m diam. x 60 m in length.

FIGURE 3. Cut-away view of one of the four underground experimental areas and associated.

The four detectors have much in common. They all try to cover as much of the total solid angle as possible, measure the momenta of the charged particles in track detectors, and the energies of all particles, neutral particles as well charged, in calorimeters. The calorimeters are in two layers: electromagnetic and hadronic and serve in a very important way in the identification of the electrons and muons. They are spatially subdivided to achieve as high a "granularity" as possible in order to localize the energy deposit, a feature also essential to the particle identification. The whole is surrounded by 2 or more layers of counters for muon detection and identification. Each experiment groups together upwards of three hundred physicists from thirty or more laboratories. The construction costs have varied between \$50 and 100 M.

In the following I concentrate on the ALEPH detector, and results obtained by the ALEPH collaboration, since I am associated with it; the results of the other collaborations are in general similar. When possible, I will give a combined LEP result. A cutaway view of the ALEPH detector [1] is shown in Fig. 4. Design studies began in 1980; the detector was

FIGURE 4. Cut-away view of the ALEPH detector. From the inside out, there are the silicon surface areas vertex chamber, the inner tracking chamber, the time projection chamber, the electromagnetic calorimeter, the superconducting solenoid, the hadron calorimeter, and the muon chambers.

essentially complete in 1989. Starting inside and moving out, there is the beam pipe, 16 cm in diameter (it will be reduced to 11 cm in 1991) of 0.5 mm Aluminium. This is followed by a 2 layer silicon strip vertex chamber with nominal $10\text{ }\mu\text{m}$ resolution in $r\phi$ and $20\text{ }\mu\text{m}$ in z , covering $\sim 70\%$ of the solid angle. This is not yet completely functional. The "Inner Tracking Chamber" (ITC) is a conventional drift chamber with 8 wire layers; it is used also to give tracking information in the first level trigger. The I.D. is 32 cm, the O.D. 52 cm, and the length 2 m. Resolution per wire in $r\phi$ is $\sim 100\text{ }\mu\text{m}$. In z it is $\sim 3\text{ cm}$, on the basis of the time difference of the signals on the two ends of each wire. The ITC is followed by a Time Projection Chamber (TPC) with I.D. 60 cm, O.D. 3.6 m and length 4.4 m. It is a gas filled cylinder. The ionization electrons produced in the traversal of charged particles are drifted to the two ends, in a homogeneous electric field, guided by the strong magnetic field. At the end, avalanches produced in proportional wire chambers are capacitively coupled to circular rows of small pads, in 21 evenly spaced rows, with altogether $\sim 50,000$ such pads for the two end plates (see Fig. 5). The transverse position of the track is measured by comparing the pulse heights of adjacent pads. The $r\phi$ resolution per pad row is $\sim 150\text{ }\mu\text{m}$; and the z position, obtained from the drift time, has a resolution of $\sim 1\text{ mm}$. The momentum resolution which is achieved in the combined tracking in the ITC and TPC is 4% at 45 GeV. For each track, also the pulse heights on the up to 300 traversed wires are recorded and furnish a measure of the specific ionization dE/dx , which is useful in the identification of electrons. The typical resolution in dE/dx is 4.5%. It is illustrated in Fig. 6.

The barrel of the electromagnetic calorimeter (ECAL) occupies the annular region between the TPC and the magnetization coil. It is a sandwich of lead sheets and multiwire proportional chambers, with 45 such layers, with a total thickness of 23 radiation lengths. ECAL consists of 12 barrel and 2×12 end-cap modules. The signals are read out for each wire plane, but the granularity is obtained from the 3 million capacitively coupled pads. These pads are arranged into 73'000 towers,

FIGURE 5. The Time Projection Chamber
 a) Cartoon of overall construction
 b) Layout of wire chambers and pads on each end.

FIGURE 6 Ionization density measured in the TPC for a sample of tracks, as function of track momentum.

FIGURE 7 Separation of electrons and hadrons in ECAL. R_T is a measure based on the ratio of track momentum and energy in the nearest four towers, R_L is a measure based on the longitudinal shower development in the three stories.

roughly 3 cm x 3 cm in cross section, each tower corresponding to an angular coverage of $0.8^\circ \times 0.8^\circ$. The geometry is a projection to the interaction point; each tower points to the interaction region and is read out in three "stories". The energy resolution for photons and electrons, $(1.7 + \frac{19}{\sqrt{E(\text{GeV})}})\%$, is not exceptional, but the angular granularity is unusually fine. The high granularity, matched to the size of electromagnetic showers, is useful in the identification of electrons imbedded in hadron jets. The separation achieved on the basis of comparing the energy in the four towers nearest the track with the track momentum, as well as on the longitudinal shower development, is illustrated in Fig. 7. The position resolution for an isolated electromagnetic shower is 1.5 mm in each direction.

The superconducting solenoid is a homogeneous winding of 1712 turns, 6.35 m long, carrying 5000 amperes. On each end there are compensating coils to achieve the field homogeneity imposed by the TPC drift requirements. The field is 1.5 T, the mean diameter 5.3 m, and the weight, including the cryostat is 55 tons. An important feature of the ALEPH design is the location of the ECAL inside the coil, so that the electromagnetic showers are not degraded by the material of the coil.

Continuing radially through the detector we find the combined hadron calorimeter (HCAL) and return yoke, with I.D. of ~ 6 m and O.D. ~ 9.4 m. It is a sandwich of iron plates, separated by gaps into which planes of streamer tubes are inserted. There are 22 inner layers of iron, each 5 cm thick, and an outer layer, 10 cm thick. The signals from the tubes are read out in projective towers as in ECAL, but the angular resolution is 4 times coarser, so that there are ~ 4500 towers. In addition, the 150,000 streamer tubes are read out digitally (yes or no) at intervals of one cm, so that tracks can be followed through HCAL in one of the two projections. This is useful in the identification of muons. The overall (ECAL + HCAL) energy resolution for hadronic jets is $\sim 60\%/\sqrt{E}$ (GEV).

Continuing outwards there are two double layers of streamer tubes, at diameters of ~ 9.5 and ~ 10.6 m for the purpose of identifying muons. These are readout digitally (yes or no) every 5 mm in both projections. Fig. 8 shows the assembled barrel, as it was in November of 1988, before the start of the cabling.

FIGURE 8 November 1988. The ALEPH barrel is assembled, the cabling of hundreds of thousands of channels is about to begin.

Essential for the determination of absolute cross sections are the luminosity calorimeters (LCAL). These are located around the beam pipe, at a distance of 2.7 m from the interaction point for the first lead layer, and with outer sensitive diameter ~ 95 cm. They are of the same basic construction as ECAL, with 768 projective towers on each side. An important requirement of the luminosity monitor is the systematic accuracy of the geometrical acceptance. This is accomplished here by means of the projective geometry, the precision of the mechanical construction, and a simple but effective selection which requires that the pulse height of an inner fiducial set of towers is larger than that outside of this boundary. The geometrical precision of the acceptance for Bhabha events is $\sim 0.4\%$.

Physics at LEP

The 100 GeV centre of mass energy available at LEP, eventually 200 GeV in 1994, is clearly much less than the 2000 GeV at the $p\bar{p}$ collider, even after allowance is made for the fact that the quark-antiquark centre of mass energy is only a fraction of the $p\bar{p}$ energy. The strength of the e^+e^- collider is the simplicity of the initial state which is carried over to the final state, so that in general, the rates for different channels can be calculated in the frame of present theories, and can be experimentally sorted out (except that the different quark flavour channels can only rarely be identified).

At collision energies near the Z mass, the cross section is enhanced through the Breit-Wigner resonance denominator by a factor of the order of $(m_Z/\Gamma_Z)^2 \sim 10^3$. Since the non-resonant cross section is very small, of the order of $\frac{4\alpha^2}{s}$, the resonance presents a very important experimental opportunity, by its magnitude alone. All the work at LEP up to now has been on or near the Z peak for this reason. The thrust of the work can be separated into three branches: a) studies of cross sections, branching ratios, lineshapes, forward-backward asymmetries, polarization asymmetries. These have given a precise value of m_Z , a strong argument that the number of fermion families are three, several checks on the

consistency of the electroweak theory much more precise than previously possible and which may still be substantially improved, and some understanding of the top mass through the radiative corrections;

b) Searches for new particles, such as Higgs, supersymmetric particles, and others. All these searches have been negative, but they have yielded better limits on the excluded mass domains; c) Work on the properties of heavy flavour quarks, especially b particles. The latter has just begun.

By 1994 it is expected that the LEP energy will exceed the threshold of ~ 160 GeV for $W^+ W^-$ pair production. This will open a new domain for the critical experimental check of the electroweak theory, although, because here there is no resonance enhancement, the rates will be painfully low.

The cross section studies we are concerned with are processes in which, in Born approximation, either a photon or a Z is exchanged, and a fermion pair is emitted:

The fermion f may be a charged lepton: e, μ or τ , a neutrino: ν_e, ν_μ, ν_τ , or one of five quark flavours: u, d, s, c or b . No other channels have been observed. For the process $e^+ e^- \rightarrow f \bar{f}$ the cross section in lowest order (born approx.) is:

$$\frac{d\sigma_f}{d\Omega} = \frac{\alpha^2 N_c^f}{4s} [F_1(s) (1 + \cos^2\theta) + 2(F_2(s) \cos \theta)] \quad (1)$$

where $s = (2E_{\text{beam}})^2$,

N_c^f is the colour factor, 3 for quarks, otherwise 1,

$$F_1(s) = Q_f^2 - 2 v_e v_f Q_f R_e \chi + (v_e^2 + a_e^2) (v_f^2 + a_f^2) |\chi|^2$$

$$F_2(s) = -2 a_e a_f Q_f R_e \chi + 4 v_e a_e v_f a_f |\chi|^2$$

$$\chi = \frac{s}{s - m_Z^2 + i m_Z \Gamma_Z} \quad \text{is the Breit-Wigner resonance denominator,}$$

$v_f = \frac{I_3^f - 2Q_f \sin^2 \theta_w}{2 \sin \theta_w \cos \theta_w}$ is the weak vector coupling,

$a_f = \frac{I_3^f}{2 \sin \theta_w \cos \theta_w}$ is the weak axial vector coupling

I_3 is the third component of weak isospin,

and $\Gamma_Z = \sum_{f_i=1}^n \Gamma_{f_i}$ is the total width of the Z.

The integrated cross section at and near the peak is dominated by the Z exchange, $|\chi|^2$ term:

$$\sigma_f = N_f^c \frac{4\pi}{3} \frac{\alpha^2}{s} (v_e^2 + a_e^2) (v_f^2 + a_f^2) |\chi|^2 \quad (2)$$

The partial widths are:

$$\Gamma_f = \frac{N_f^c}{3} \alpha m_Z \cdot (v_f^2 + a_f^2) = \frac{N_f^c G_F m_Z^3}{6\sqrt{2}\pi} (g_{V_f}^2 + g_{A_f}^2)$$

$$\text{where } g_{V_f}^2 = I_3^f - 2Q_f \sin^2 \theta_w \text{ and } g_{A_f}^2 = I_3^f. \quad (3)$$

$$\text{Then } \sigma_f = \frac{12\pi s}{m_Z^2} \frac{\Gamma_e \Gamma_f}{|s - m_Z^2 + i m_Z \Gamma_Z|^2} \quad (4)$$

and at the Z peak, the cross section for a final fermion pair $f\bar{f}$ is:

$$\sigma_{\text{peak}_f} = \frac{12\pi \Gamma_e \Gamma_f}{m_Z^2 \Gamma_Z^2} \quad (5)$$

It is useful to note that the peak cross sections are related only to ratios of partial to total widths.

The Born approximation is not adequate for the analysis of the LEP experiments; it is essential to include higher order radiative corrections. These include initial state photon radiation, final state photon and gluon radiation, vertex corrections and propagator corrections. They have been

the object of considerable study and are summarized and referenced in the publication "Z Physics at LEP" [2]. The initial state radiation can be factored out. The correction is substantial (see Fig. 9) but purely

FIGURE 9 Effect of initial state radiation on the Z lineshape. Solid line: born approximation. Dotted line: corrected lineshape.

electromagnetic, and calculated with adequate precision. The remaining corrections are small and calculable in the standard model. They depend however on the unknown Higgs and top masses, as well as the not yet very precisely known value of the strong coupling constant α_s . The dominant effect of these corrections can be summarized by replacing $\sin^2\theta_w$ by an "effective mixing angle" at the Z mass, $\sin^2\theta_w(m_Z^2)$, by replacing α by its renormalized value at the Z mass:

$$\alpha(m_Z^2) = \frac{\alpha}{1 - \Delta\alpha} = 1.064\alpha,$$

inserting the factor $\rho = \frac{1}{1-\Delta\rho}$ in the relationships between m_w and m_Z and G_F and m_Z :

$$m_w^2/m_Z^2 = \rho \cos^2\theta_w(m_Z^2)$$

$$\frac{\pi\alpha(m_Z^2)}{\sqrt{2} G_F} = \rho m_Z^2 \sin^2\theta_w(m_Z^2) \cos^2\theta_w(m_Z^2),$$

$$\begin{aligned} \text{with } \Delta\rho &\simeq 3G_F m_t^2 / 8\sqrt{2}\pi^2 - 11G_F m_Z^2 \sin^2\theta_W \ln(m_H/m_W)/12\pi^2\sqrt{2} \\ &= 0.0026 m_t^2/m_Z^2 - 0.0015 \ln((m_H/m_W), \end{aligned}$$

and, for the quark channels, including the second order QCD correction, replacing N_f by

$$N_c^f (1 + \alpha_s/\pi + 1.3 \alpha_s^2/\pi^2).$$

Finally, χ in (1) should be replaced by

$$\chi = \frac{s}{(s - m_Z^2) + i s \Gamma_Z/m_Z}.$$

These changes give the major radiative corrections for all channels $e^+ e^- \rightarrow f\bar{f}$, except the $b\bar{b}$ channel, which requires an additional correction which takes into account relatively large $t - b$ amplitudes in the vertex corrections. To give some feeling for the magnitude of the corrections, the top and Higgs mass dependence of Γ_l , Γ_b and Γ_Z are shown in Fig. 10.

FIGURE 10 Dependence on m_Z , m_H and α_s of a) Γ_Z , b) Γ_b , and c) Γ_l .

The electroweak predictions for the relative rates of the different channels are as follows:

each neutrino	6.7%
each charged lepton	3.35%
up or charm quark	12.0%
down or strange quark	15.4%
bottom quark	15.2%
total, all quarks	70%

The neutrino channel cannot be observed. Of the observed channels the quark (hadronic) channel is by far the most frequent, accounting for 86%; the charged leptons represent only 14%.

LEP Running

The first dozen or two events were observed in each of the four detectors in a five day "pilot run" in August 1989. After one month of improvements, data taking started in earnest in the middle of September. Of course, all four experiments share the same beam energy. A "fill" typically lasts ~ 12 hours before the luminosity has degraded sufficiently to warrant a new fill. For successive fills the energy was rotated in such a way that $1/2$ of the data were taken near the top of the Z peak, the other half were more or less equally divided between the points $m_Z \pm 1$, $m_Z \pm 2$, and $m_Z \pm 3$ GeV. The total number of hadronic events reported by ALEPH in 1989 was 28,000; for all four detectors combined it was 80,000. The luminosity of LEP improved during this period, and ended up with peak luminosities of $\sim 3 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$, about one-fifth of design.

After a 3 month shut-down, running resumed in March '90 with peak luminosities of $6 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$. At present the luminosity is limited to this value by beam - beam interaction. The integrated luminosity for all running at LEP up to July 1990 was ~ 5 per picobarn. At that time the ALEPH data sample consisted of $\sim 100,000$ hadronic and leptonic decays.

Lineshape and Number of Families

a) Introduction

The first analysis task is that of classifying the events according to channel. Event classification at LEP is, in general, rather easy (see Fig. 11). The dominant $q\bar{q}$, hadronic events are recognized by the large track multiplicity, the total energy and the wide distribution of calorimetric energy. Electronic and muonic decays both have back to back tracks of opposite electric charge, and momenta equal to one-half the center of mass

FIGURE 11 Typical events.

Top left: $e^+ e^- \rightarrow q\bar{q}$. Typically there are two jets of hadrons, each with an average of 10 charged particles. The total observed energy is near to the center of mass energy.

Top right: $e^+ e^- \rightarrow e^+ e^-$. The electrons are emitted back to back, each with one-half of the center of mass energy. They are identified by the shape and magnitude of the energy distribution in ECAL.

Bottom left: $e^+ e^- \rightarrow \mu^+ \mu^-$. Again there are two tracks, each with one-half of the center of mass energy. They are identified as muons by the small energy deposit in ECAL, and the penetration through HCAL.

Bottom right: $e^+ e^- \rightarrow \tau^+ \tau^-$. The τ 's decay within millimetres and are identified on the basis of missing energy and momentum (lost to neutrinos in their decay) and the visible decay products, usually one or three charged tracks in a narrow jet.

energy. The electrons are identified by the energy and shower shape seen in ECAL, the muons by their penetration in HCAL. The τ decays in the beam pipe, so only its decay products are seen. The decays result typically in one or three tracks, not strictly back to back and with missing energy, since in the τ decay at least one neutrino is emitted.

The determination of the number of families is based on the total Z width Γ_Z . Fermions with masses below $m_Z/2$ contribute to the width of Z decay. Their contribution can be calculated in the standard model with high precision. The particles which are expected to contribute are those belonging to the three known families, except for the top, since its mass is too high. From these, and other experiments it is known that there are no charged fermions from possible additional families with mass less than $m_Z/2$, since these would have been seen. But there may well be quarks and charged leptons with masses greater than $m_Z/2$. The neutrinos of these families however, although in the absence of a theory for the masses this cannot be proven, would be expected to have much smaller masses and would then contribute to the Z width:

$$\Gamma_Z = \Gamma_h + 3\Gamma_l + N_\nu \Gamma_\nu, \quad (6)$$

where Γ_h is the hadronic, $q\bar{q}$ width, Γ_l the width due to each charged lepton channel, and Γ_ν that due to each neutrino channel and N_ν the number of neutrino families contributing to the "invisible" width, Γ_{inv} . Each additional neutrino channel increases Γ_Z by 6.8%. It is therefore interesting to measure Γ_Z with much better precision than 6.8%. Γ_Z is determined most precisely from a measurement of the cross section of any of the fermion families at the Z peak, σ_f^{peak} . In practice the total hadronic channel is used since it is the most copious. From (5),

$$\Gamma_Z = \left[\frac{12\pi \Gamma_e \Gamma_h}{m_Z^2 \cdot \sigma_h^{peak}} \right]^{1/2}.$$

Here the initial state radiation has been unfolded. σ_{peak} refers to the cross section at the top of the resonance. Then

$$N_v = \frac{\Gamma_l}{\Gamma_v} \left[\sqrt{\frac{12\pi \cdot \Gamma_h}{m_z^2 \cdot \sigma_h^{peak} \cdot \Gamma_l}} - \frac{\Gamma_h}{\Gamma_l} - 3 \right]. \quad (7)$$

For the evaluation of (7), m_z is measured in the same experiment. Γ_h/Γ_l is also measured, or it may be taken from the standard model. Γ_l/Γ_v must be taken from the electroweak theory, it cannot be measured.

Precise measurement of the absolute cross section requires precise measurement of the absolute luminosity. This posed an interesting experimental challenge, already in the first weeks of experimentation.

In proceeding now to the experimental data, they are discussed using ALEPH as an illustration [3,4,5], but the results of the three other experiments [6,7,8,9,10,11,12,13] are included in the combined LEP results.

b) Trigger and trigger efficiency.

The acquisition of the data must be triggered. The basic problem is the early recognition of e^+e^- annihilation events as distinct from background events, which consist of electrons scattered in the residual gas, cosmic rays, and so called 2 photon processes. The latter are inelastic e^+e^- scatterings with creation of hadrons. It turns out that these backgrounds are sufficiently benign so that triggering at LEP is easy. In order to evaluate the efficiency of the trigger, it is essential to have redundancy in the trigger, that is two or more triggers which are independent and each adequate to trigger on the wanted events. This redundancy is the case in ALEPH for all event types. To trigger on hadronic Z decay, one trigger required only a certain minimum of ECAL energy, another, totally independent, required at least one charged particle with some penetration into HCAL. The trigger efficiency could be shown to be at least 99.9%.

c) Selection of hadronic events.

As we have already noted and illustrated in Fig. 11, the hadronic and the three charged leptonic channels have very different characteristics in the detector and event selection into the different channels with good efficiency

and purity is relatively simple. For the selection of hadronic events there were again two independent methods, one based on the calorimetric properties, requiring no tracks, the other based on having 5 or more tracks, independent of calorimetric energy. The selection efficiencies, respectively 99.4% and 97.5%, are determined on the basis of Monte Carlo simulation of the events and the detector. The near unity of the acceptance insures also that the uncertainty in the acceptance is small. The detailed agreement of Monte Carlo and data in the distributions of many observables reinforces confidence in the understanding of the events. In Fig. 12 the comparison is shown for the distribution in the total observed calorimetric energy. The contamination from background processes and unwanted decay channels is negligible (less than a few tenths of one per cent). Fig. 13 shows the

FIGURE 12
Comparison of data and MC simulation. Hadronic events selected calorimetrically. Distribution in the ratio of observed energy to beam energy.

FIGURE 13
Distribution in the track energy relative to the center of mass energy for events with more than five tracks. Acceptance into the hadronic event sample required in addition that this ratio exceeds 0.1. The rise at smaller values is due to $e^+ e^-$ inelastic scattering ($\gamma\gamma$ process).

FIGURE 14 Hadronic decays selected on the basis of the tracks. Distribution in the angle between beam and thrust axis. Comparison of data and simulation.

distribution in the track energy for track selected events, and Fig. 14 the thrust angle distribution, as determined using the charged momenta.

d) Luminosity determination.

The luminosity is determined on the basis of the observed small angle $e^+ e^-$ (Bhabha) elastic scattering, whose rate can be precisely calculated. The precision of the measurement is limited by the understanding of the acceptance of the luminosity detector. Since the cross section rises steeply with decreasing angle (as θ^{-4}), the precise knowledge of the effective inner cut off is especially critical. The best luminosity measurements reported from earlier, lower energy $e^+ e^-$ experiments are at the 3% level. However, the measurement becomes easier with increasing energy and the luminosity detectors of all 4 LEP experiments are substantially better than their predecessors. Most of the LEP luminosity measurements now report errors well below 3%; the systematic experimental luminosity uncertainty in the ALEPH experiments is now 0.4%. This is one of the more beautiful experimental accomplishments of this early work at LEP. Fig. 15 shows an ALEPH luminosity event, and Fig. 16 compares the observed and simulated polar angle distributions. The agreement is an essential element in the confidence in the precision of the luminosity determination.

FIGURE 15 Luminosity event in ALEPH. a) cut including beam direction. b) View along the beam of the two luminosity calorimeters. The two localized energy deposits can be seen to be due to particles 80° in azimuth, at small and opposite polar angles, and of comparable energy (since the scattered electron and positron are emitted at opposite angles, each with one half of the total energy).

FIGURE 16 Comparison of data and simulation for the polar angle distribution of luminosity events. Agreement is a measure of to the systematic understanding of the luminosity.

FIGURE 17 ALEPH results for the cross section as function of center of mass energy compared with the expectations of the Standard Model for hadronic events for 2, 3 and 4 neutrino families. The mass of the Z has been left free to achieve the best fit.

e) Results on the Z lineshapes from hadronic decays.

A recent ALEPH result on the lineshape of hadronic Z decays is shown in Fig. 17. The curves are the electroweak predictions for 2, 3 and 4 neutrino families, with only m_Z as free parameter. The data can also be fitted by a Breit-Wigner distribution of the form

$$\sigma_h(s) = \frac{\sigma_h^{\text{peak}} \cdot m_Z^2 \Gamma_Z^2}{\left| (s - m_Z^2) + i \frac{s \Gamma_Z}{m_Z} \right|^2}, \text{ with three free parameters, } m_Z,$$

Γ_Z and σ_h^{peak} . The most recent results of the four collaborations for these [13] are given in Table 1. They are in very good agreement with each other, as they are with the predictions of the Standard Model, also listed in the table.

The new precise value for the Z mass, $m_Z = 91.172 \pm 0.031$ GeV, is now one of the basic parameters of the electroweak theory, together with the fine structure constant α and the Fermi constant, G_F . Its remaining uncertainty is due principally to the 30 MeV uncertainty in the beam energy. Already this level of precision in the beam energy is a great

Table 1

Results on the lineshape of the hadronic channel, for each of the four collaborations, and the combined result.

	ALEPH	DELPHI	L-3	OPAL	LEP	Standard Model
Number of Hadronic Events	84'000	68'000	62'000	112'000	320'000	
m_Z , GeV	91'186 ± 0.013 ± 0.030	91'188 ± 0.014 ± 0.030	91'164 ± 0.013 ± 0.030	91'174 ± 0.011 ± 0.030	91'177 ± 0.031	
Γ_Z , MeV	2506 ± 26	2476 ± 26	2492 ± 25	2505 ± 20	2498 ± 12.5	2490 ± 15
σ_h^{peak} , nb	41.78 ± 0.63	42.38 ± 1.02	41.38 ± 0.71	41.88 ± 0.74	41.77 ± 0.42	41.42 ± 0.12

accomplishment. It is based on the comparison of the revolution frequencies of protons and electrons in the same beam orbit. In the future it is hoped to achieve an even smaller error with the use of polarized electrons.

The precise width provides, as we see later, a sensitive (at the moment, the most sensitive) check on the standard model. The peak cross-section is the basis of the argument on the number of neutrino families.

f) Results on the Z lineshape from the leptonic channels and partial decay widths of the Z.

The selection of the leptonic channels is more complex than that of the hadronic channel. Although, as we saw in Fig. 11, they are generally distinct, there are kinematic regions of confusion at the percent level, for instance if both electrons decide to go through cracks in the ECAL, or the muons in HCAL, or τ^+ and τ^- both choose to decay to electron and neutrino or to muon and neutrino. Assignment of these events to the correct channel requires adequate algorithms; these are understood and

checked with the help of simulation. In ALEPH systematic uncertainty in the separation and in the efficiencies is kept below the 1% level.

For the e^+e^- channel there is a complication at small angles, the t channel:

This contributes the large cross-section at small angles used in the luminosity determination. Its interference at larger angles with the s channel is an important and non trivial correction, especially for the asymmetry determination. It is therefore necessary in the case of the e^+e^- channel to exclude the small angles where the t channel is large, and to subtract it from the remaining angular range on the basis of a QED calculation. In the ALEPH analysis the excluded region is $\cos\theta > 0.7$.

The statistical accuracy of the leptonic channels is limited by the fact that each accounts for only ~5% of the observed events. It is therefore interesting to look also at the combined leptonic channels, assuming universality. This is done in ALEPH using an independent selection procedure which takes advantage of the fact that it is not necessary to distinguish the individual leptonic channels.

Fig. 18 shows the ALEPH leptonic cross sections at the Z resonance for the 3 separate, as well as for the combined leptonic channel [5].

The leptonic channels have been studied extensively at LEP [4,5,10,14,15,16,17,18,19,20]. The partial widths are obtained from the cross-sections and from Γ_Z on the basis of (5):

$$\Gamma_e = \Gamma_Z \sqrt{\frac{m_Z^2 \sigma_e^{\text{peak}}}{12 \pi}}$$

and $\Gamma_{\mu(\tau)} = \Gamma_Z \sigma_{\mu(\tau)}^{\text{peak}} m_Z / \sqrt{12 \pi \sigma_e^{\text{peak}}}$

FIGURE 18 ALEPH results for the cross sections a) $e^+ e^- \rightarrow e^+ e^-$, b) $e^+ e^- \rightarrow \mu^+ \mu^-$, c) $e^+ e^- \rightarrow \tau^+ \tau^-$ and d) the total leptonic channel $e^+ e^- \rightarrow l^+ l^-$, as function of the center of mass energy. The lines are the electroweak expectations, with $\sin^2 \theta_W(m_Z^2) = 0.232$.

or for the averaged leptonic channel, assuming universality:

$$\Gamma_l = \Gamma_Z \sqrt{\frac{m_Z^2 \sigma_l^{\text{peak}}}{12 \pi}}.$$

With $R = \Gamma_h / \Gamma_l = \sigma_h^{\text{peak}} / \sigma_l^{\text{peak}}$ the partial hadronic width is:

$$\Gamma_h = \Gamma_Z \sqrt{\frac{R m_Z^2 \sigma_h^{\text{peak}}}{12 \pi}}.$$

Finally, the invisible (neutrino) width is:

$$\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_h - 3 \Gamma_l.$$

Table 2

Results of the four collaborations and
combined result for the partial widths R , Γ_h and Γ_{inv} .

	ALEPH	DELPHI	L-3	OPAL	LEP	Standard Model
Number of Leptonic events	9'500	4'000	4'000	11'327	29'000	
Γ_e , MeV	84.9 ± 1.1	82.0 ± 1.7	84.3 ± 1.4	82.7 ± 1.3	83.4 ± 0.9	83.6 ± 0.3
Γ_μ , MeV	80.7 ± 2.2	87.2 ± 3.4	82.3 ± 2.9	85.9 ± 2.0	84.1 ± 1.4	83.6 ± 0.3
Γ_τ , MeV	81.8 ± 2.2	86.0 ± 3.9	83.5 ± 3.7	83.9 ± 2.3	83.25 ± 1.5	83.6 ± 0.3
Γ_l , MeV	84.2 ± 1.0	83.7 ± 1.4	83.2 ± 1.4	83.6 ± 0.9	83.7 ± 0.65	83.6 ± 0.3
$R = \Gamma_h/\Gamma_l$	20.95 ± 0.31	21.00 ± 0.48	21.02 ± 0.62	21.26 ± 0.32	21.08 ± 0.19	20.80 ± 0.15
Γ_h , MeV	1764 ± 24	1756 ± 32	1748 ± 35	1778 ± 26	1764 ± 16	1739 ± 14
Γ_{inv} , MeV	489 ± 22	469 ± 29	494 ± 32	476 ± 25	482 ± 13	500 ± 2

Recent results [13] of the four collaborations, as well as the combined LEP results and the electroweak prediction, are given in Table 2. Again, the experiments are in good agreement with each other and with the Standard Model predictions [2].

g) Number of neutrino families

The number of neutrino families N_ν is determined from Γ_{inv} by dividing by the width given in the electroweak theory for any neutrino family with mass much smaller than $m_Z/2$,

$\Gamma_\nu = 166.7 \pm 0.7$ MeV. N_ν includes, by definition, also other non-detectable decay channels of the Z, such as lowest mass supersymmetric particle, if these exist, are neutral, and their mass is less than $m_Z/2$. $\Gamma_{inv} = \Gamma_Z - \Gamma_h - 3 \Gamma_l$. Γ_Z is directly measured, but can also be obtained from the peak cross-section: $\Gamma_Z = \sqrt{\frac{12\pi \Gamma_l \Gamma_h}{m_Z^2 \sigma_h^{peak}}}$.

Table 3

Results of the four collaborations
for the number of neutrino families with $m_\nu \ll m_Z/2$.

	N_ν
ALEPH	2.91 ± 0.12
DELPHI	2.82 ± 0.17
L 3	3.01 ± 0.12
OPAL	2.86 ± 0.15

The error in N_ν can be minimized by using both. For Γ_e and Γ_h either the measured values or the Standard Model values can be used. Given the agreement between these, and the small errors now obtained in the measurements, the results are very similar. The results of the four experiments [Refs. 3 to 13] are given in Table 3.

A determination of N_ν , using the results of the four collaborations for σ_h^{peak} and Γ_Z , and the electroweak results for Γ_h and Γ_l , yields:

$$N_\nu = 2.92 \pm 0.08.$$

The "invisible" contribution to the Z width is in agreement with the standard model, with just three neutrinos, with an uncertainty of only 0.08 neutrino families. The integer nature of the result is a confirmation of the standard model. The fact that it is 3 and not 4 or 5 is a demonstration that, with the extremely unlikely caveat that there may be neutrinos in the frame of the standard model with masses greater than $0.45 m_Z$, the number of families of fermions is 3. Finally, the fact that N_ν is 3 and not 2 shows that the τ neutrino is distinct from the electron and muon neutrinos.

Asymmetries

Parity violating asymmetries are among the more sensitive observables for studying the electroweak theory. They can be divided into

two classes: forward-backward and polarization. For each of these there are two rather different domains: below and above the Z peak the asymmetry is due to the interference of the electromagnetic vector and the weak axial vector interactions, on the Z peak, and of greater physics interest, it is due to the interference between the weak vector and the weak axial vector interactions.

a) Forward-Backward Asymmetries.

This is the asymmetry in the angle between the outgoing fermion and the incident positron. The electroweak prediction is governed by the differential cross-section (1). The asymmetry at the Z peak is proportional to

$$\frac{(v/a)_e \cdot (v/a)_f}{[1 + (v/a)_e^2] \cdot [1 + (v/a)_f^2]}$$

Experiments usually report A_{FB} , defined as the difference in the cross sections integrated over forward and backward hemispheres, divided by their sum:

$$A_{FB} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}$$

In terms of F_1 and F_2 of (1), $A_{FB} = \frac{3}{4} F_2/F_1 = 3 v_e a_e v_f a_f / (v_e^2 + a_e^2) \cdot (v_f^2 + a_f^2)$. A_{FB} has been measured at lower energy (see e.g. the review by S.L. Wu [21]), but here, as already mentioned, it is dominated by the interference between photon and Z exchange. At the Z peak the asymmetry is sensitive to the ratio of vector to axial vector couplings v/a . In the electroweak theory, $v/a = 1 - 4|Q|\sin^2\theta_w(m_Z^2)$. The experimental results are just beginning to emerge, because of the as yet very limited statistics. The clearest channels, experimentally, are the three leptonic channels, however the rates are low. For the $e^+ e^-$ channel only, there is the

FIGURE 19 ALEPH measurement of the angular distribution of the reaction $e^+e^- \rightarrow l^+l^-$. The solid line is the calculated contribution of the t channel, which is subtracted. Acceptance is limited to $\cos\theta < 0.7$.

complication of the photon t channel - s channel interference at small angles which would produce huge asymmetries unless corrected. The procedure is to limit the acceptance region in the forward cone (in the case of ALEPH it is limited to $\cos\theta < 0.7$) and to subtract the remaining t channel contribution on the basis of the theory. This is shown for the ALEPH data [5] in Fig. 19. A_{FB} for leptons is small, very nearly equal to $(v/a)_l^2 = (1 - 4|Q|\sin^2\theta_w)^2$ which is small because $4\sin^2\theta_w$ is numerically close to unity. The fact that A_{FB} is quadratic in v/a , as well as small, makes it less sensitive in the measurement of $\sin^2\theta_w$.

In Fig. 20 the lepton asymmetry observed by ALEPH is shown as function of the centre of mass energy near the Z resonance peak.

The results for v_l^2/a_l^2 [7,19,20,5,13] are:

	v_l^2/a_l^2
ALEPH	0.0083 ± 0.0034
DELPHI	0.012 ± 0.009
L-3	0.012 ± 0.007
OPAL	0.0038 ± 0.0033
LEP	0.0069 ± 0.0022
E.W.	0.0052 ± 0.0008

FIGURE 20 ALEPH results for lepton forward-backward asymmetry A_{FB}^{l+l-} across the Z resonance.

The combined LEP result for the forward backward lepton asymmetry corresponds to $\sin^2\theta_w(m_Z^2) = 0.229 \pm 0.003$.

b) Polarization asymmetries

The asymmetry with respect to longitudinal polarization can, in principle, furnish very precise information on v/a , or equivalently, on $\sin^2\theta_w$. The simplest case is the one in which only the polarization of one of the incident particles, or one of the outgoing particles is observed. The basic expressions for these are the same, except for the reversal of the roles of electron and final state fermion. Here they are written for the case of final state polarization. In general, both Z and photon exchange must be considered, as well as their interference. For clarity, only polarization on the Z resonance peak, $s = m_Z^2$ is considered, where the photon exchange contribution is negligible.

$$\text{Then } \frac{d\sigma}{d\cos\theta}(\cos\theta, p) \propto (1 + \cos^2\theta) F_1 + 2 \cos\theta F_2 + p [(1 + \cos^2\theta) F_3 + 2 \cos\theta F_4]$$

where p is the longitudinal polarization, and

$$F_1 = (v_e^2 + a_e^2) (v_f^2 + a_f^2)$$

$$F_2 = 4 v_e a_e v_f a_f$$

$$F_3 = 2(v_e^2 + a_e^2) v_f a_f$$

$$F_4 = 2 v_e a_e (v_f^2 + a_f^2).$$

A_{Pol} and A_{Pol}^{FB} are defined:

$$A_{Pol} = \frac{\int_{-1}^1 d\cos\theta \frac{d\sigma(p=1)}{d\cos\theta} - \int_{-1}^1 d\cos\theta \frac{d\sigma(p=-1)}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\sigma(p=1)}{d\cos\theta} + \int_{-1}^1 d\cos\theta \frac{d\sigma(p=-1)}{d\cos\theta}} = \langle p \rangle.$$

Here $p = 1$ and $p = -1$ refer to positive and negative helicities respectively.

$$A_{Pol} = -F_3/F_1 = -\frac{2 v_f a_f}{v_f^2 + a_f^2}$$

$$A_{Pol}^{FB} =$$

$$\frac{\int_0^1 d\cos\theta \left[\frac{d\sigma(p=1)}{d\cos\theta} - \frac{d\sigma(p=-1)}{d\cos\theta} \right] - \int_{-1}^0 d\cos\theta \left[\frac{d\sigma(p=1)}{d\cos\theta} - \frac{d\sigma(p=-1)}{d\cos\theta} \right]}{\int_{-1}^1 \left[d\cos\theta \frac{d\sigma(p=1)}{d\cos\theta} + \frac{d\sigma(p=-1)}{d\cos\theta} \right]}$$

$$= -3/4 F_4/F_1 = -3/4 \cdot \frac{2 v_e a_e}{v_e^2 + a_e^2}$$

The polarization asymmetries, being linear rather than quadratic in v/a , provide eventually more sensitive possibilities to measure $\sin^2\theta_w$ than A_{FB} .

LEP as yet cannot provide polarized beams. It may in the future be possible to make modifications which will permit longitudinal beam polarization, but this is not yet certain and would be a major effort. At present, at LEP, polarization asymmetries can be studied in the τ channel, where the decays $\tau \rightarrow \nu_\tau + \pi$, $\tau \rightarrow \nu_\tau + l + \nu_l$ and $\tau \rightarrow \nu_\tau + \rho$ can serve as analyzers of the polarization. The work is only beginning. The first ALEPH result, presented at the Singapore conference, is [13]: $\langle p_\tau \rangle = A_{\text{pol}, \tau} = -0.151 \pm 0.087$. With $A_{\text{pol}, \tau} = \frac{-2 v_\tau/a_\tau}{(v_\tau/a_\tau)^2 + 1} \simeq -2 v_\tau/a_{\tau 1} = -2 (1 - 4 \sin^2\theta_w (m_w^2))$, this asymmetry corresponds to $\sin^2\theta_w(m_z^2) = 0.231 \pm 0.011$, in agreement with the other measurements, but with substantially larger error.

Comparison with the Standard Model, $\sin^2\theta_w$, Mass of the Top, and α_s

Table 4 lists the main LEP experimental results relevant to the critical confrontation with the predictions of the Standard Model [2]. For the model predictions, the new measurement of m_z , as well as the top mass constraints discussed below, have been used. The agreement is everywhere within the combined uncertainty, some at the $1/2$ to $1 1/2\%$ level of accuracy. Not all of the results are independent. If we consider the measurement of m_z , Γ_z , σ_h^{peak} and R as independent, the results for Γ_l , Γ_h , Γ_{inv} and N_ν , follow, and so add nothing new. In order to show the precision of the test, the value of $\sin^2\theta_w(m_z^2)$ derived from the particular measured quantity and its error are given in the table as well. For comparison, the most precise previous tests of the standard model were at best at the 4% level in $\sin^2\theta_w$.

The theoretical uncertainty will become more interesting as the experiments get more precise. In Γ_z , σ_h^{peak} and R this is dominated by the uncertainty in α_s (assumed here ± 0.02). The error in Γ_l is dominated by the uncertainty in the top mass. The latter also contributes the bulk of the uncertainty in $\sin^2\theta_w(m_z^2)$ as determined from m_z . If $\sin^2\theta_w$ were

defined directly in terms of m_Z , for instance as $\sin^2\theta_w \cos^2\theta_w = \frac{\pi\alpha}{\sqrt{2}G_F m_Z^2}$, instead of the effective $\sin^2\theta_w(m_Z^2)$ definition used here, the precision in $\sin^2\theta_w$ from the m_Z measurement would be 0.0002.

The relationship between $\sin^2\theta_w(m_Z^2)$ and m_Z is shown in Fig. 21 for the measured values of m_Z , Γ_Z and Γ_l . Here it is assumed that $m_H = 200$ GeV and $\alpha_s = 0.12$. In the same figure, the information from the measurements of m_w/m_Z is also shown. These are: the UA2 measurement of the ratio $\frac{m_w}{m_Z} = 0.8831 \pm 0.0055$ [22], the CDF measurement $m_w = 79.83 \pm 0.44$ GeV [23] and the result $1 - \frac{m_w^2}{m_Z^2} = 0.231 \pm 0.006$ [24] from the CDHS and CHARM measurements of the neutral to charged current ratio in neutrino deep inelastic scattering. These measurements of Fig. 21 taken together furnish the best value of the mass of the as yet undiscovered top, through its effect on the radiative corrections.

$$m_t = 127 \pm 34 \pm 17 \text{ (m Higgs) GeV.}$$

The last error covers an uncertainty in the Higgs mass from 40 to 1000 GeV.

The resultant value for $\sin^2\theta_w(m_Z^2)$ is:

$$\begin{aligned} \sin^2\theta_w(m_Z^2) &= 0.2325 \pm 0.0003 + 0.0043 \left(1 - \frac{m_t}{127 \text{ GeV}}\right) \\ &\quad + 0.0005 \log_{10} \frac{m_H}{200 \text{ GeV}} \\ &= 0.2325 \pm 0.0010 \pm 0.0005 (m_H). \end{aligned}$$

In the determination of m_t and $\sin^2\theta_w(m_Z^2)$ the m_Z and m_w/m_Z measurements are the most important ingredients; the Γ_Z and Γ_l measurements contribute less. This can be seen from Fig. 21. The agreement in $\sin^2\theta_w(m_Z^2)$ as determined from Γ_Z and Γ_l , as well as from the asymmetries, with the value determined from m_Z , illustrate the agreement of all experimental results with the Standard Model predictions.

Table 4

Combined LEP results and Standard Model predictions for m_Z , σ_h^{peak} , Γ_Z , Γ_h , Γ_l , R , N_ν and asymmetries. In the Standard Model predictions it is assumed that $40 < m_H < 1000$ GeV, $\alpha_s = 0.12 \pm 0.02$, and that $90 < m_Z < 170$ GeV. The column $\sin^2\theta_w(m_Z^2)$ lists the value which follows from the particular measurement.

	Experiment	Standard Model	$\sin^2\theta_w(m_Z^2)$
m_Z , GeV	91.177 ± 0.031		0.2325 ± 0.0010
Γ_Z , MeV	2498 ± 12.5	2490 ± 16	0.2313 ± 0.0023
σ_h^{peak} , nb	41.77 ± 0.42	41.42 ± 0.12	0.2350 ± 0.0035
Γ_h , MeV	1764 ± 14	1739 ± 14	0.2290 ± 0.0030
Γ_l , MeV	83.7 ± 0.65	83.6 ± 0.3	0.2318 ± 0.0034
$R = \Gamma_h/\Gamma_l$	21.08 ± 0.19	20.8 ± 0.15	0.215 ± 0.015
N_ν	2.92 ± 0.08	Integer	
$(v/a)_l^2 = 1/3 A_{\text{FB},l}$	0.0069 ± 0.0022	0.0052 ± 0.0008	0.229 ± 0.003
$(v/a)_\tau = -1/2 A_{\text{pol},\tau}$	0.075 ± 0.043	0.072 ± 0.006	0.231 ± 0.011
$A_{\text{FB},b}$	0.172 ± 0.076	0.098 ± 0.008	0.220 ± 0.013

FIGURE 21 Implications for $\sin^2\theta_w(m_Z^2)$ and m_t of the LEP results for m_Z , Γ_Z and Γ_l , as well as the UA2, CDF, CDHS and CHARM results for m_W/m_Z .

Finally, the radiative corrections to the hadronic width [2], $\Gamma_h = \Gamma_{h,ew} \times (1 + \alpha_s/\pi + 1.3\alpha_s^2/\pi^2)$ permit a determination of α_s , already at the present level of experimental accuracy. Two experimentally independent determinations are possible. From $\Gamma_Z = 2498 \pm 12.5$ GeV,

$$\alpha_s(m_Z^2) = 0.134 \pm 0.027$$

Here the error includes ± 0.012 due to the uncertainty in the top mass, taken to be $m_t = 127 \pm 34$ GeV, and ± 0.008 due to that in the Higgs mass, assumed $40 < m_H < 1000$ GeV. From $R = \Gamma_h/\Gamma_l = 21.08 \pm 0.19$ GeV,

$$\alpha_s(m_Z^2) = 0.162 \pm 0.031,$$

where the error is dominated by the experimental uncertainty. The combined value is

$$\alpha_s(m_Z^2) = 0.146 \pm 0.020.$$

The uncertainty is the experimental one only, the theoretical uncertainty is unknown to the author.

New Particle Searches at LEP

More than 20 publications have been produced by the four LEP collaborations on new particle searches. This is due to the obvious interest in new physics, and takes advantage of the general clarity of events in the LEP environment coupled with the detail and quality of the information produced by each event in the detectors. For many searches the background could be kept to zero, so that a single event would have been significant. The searches necessarily make use of the particular properties expected for the searched particles, including their expected production

cross-sections; that is to say, that they are usually based on theoretical models for the particle which is the object of the search. The negative results are stated in terms of mass limits.

The LEP new particle searches can be classified as follows:

1. Standard Higgs [25, 26,27,28,29,30,31,32]
2. Charged Higgs [33,34,35]
3. Neutral Higgs expected in minimal supersymmetry models [36]
4. Supersymmetric particles [37,38,39,40,41,42,43]
5. New quarks and leptons [44,45,46,47,48], and
6. Excited leptons [49, 50,51,52].

No evidence for any new particle has been found. Perhaps the most important results are the lower limits on the value of Higgs masses. The experimental problem of the individual searches is to find selection procedures, based on the kinematical properties of the process searched for and the qualities of the detector, which maximize the efficiency for the signal while excluding normal events as much as possible. These selection methods are tedious in their details and vary from detector to detector. Here I am very brief.

a) Search for the Higgs.

The production is through radiation by an intermediate Z:

If the beam energy is on the Z mass peak, the first intermediate Z is nearly on the mass shell, the second not. The Z-Higgs coupling is $\frac{m_Z^2}{v} Z^\mu Z_\mu \phi_H$, where $v = \frac{2m_Z \sin^2 \theta_w}{\sqrt{4\pi\alpha}} = 254 \text{ GeV}$. The production cross-section falls steeply with increasing Higgs mass, as shown in Fig. 22. It is the smallness of the production cross-section which limits the sensitivity of the present experiments.

FIGURE 22 Theoretical branching ratio $Z \rightarrow H + f\bar{f} / Z \rightarrow f\bar{f}$ as function of m_H .

The branching ratios for the decays of the Higgs into two fermions are proportional to the squares of the fermion masses, so the detection channel with highest rate is that into the heaviest fermion consistent with the Higgs mass.

The LEP Higgs searches have excluded the standard Higgs below a mass of 42 GeV. A Higgs of very low mass, $m_H < 50$ MeV, would be stable on the time scale of the LEP detectors. Such a Higgs would leave the apparatus without a track or energy deposit. Since the production cross-section for such a low mass Higgs would be very high, it could be detected as events with missing energy and transverse momentum. They were searched for using the decay of the Z^* into electron and muon pairs [29], with negative results. Higgs of slightly higher mass, $30 < m_H < 212$ MeV, live long enough so that they are likely to decay within the tracking region of the detectors. This decay could be detected by means of the secondary vertex. Also these have been excluded [25,28]. At higher masses the most useful channel has been $e^+ e^- \rightarrow H + Z^*$, $Z^* \rightarrow \nu\bar{\nu}$ [25,26,27,30,31,32]. The least useful decay channel of the Z^* is $Z^* \rightarrow$ hadrons, since the background of normal hadronic decays is difficult to deal with. We illustrate using the most recent result, which extended the lower mass limit

FIGURE 23 An example of an event $Z \rightarrow q + \bar{q} + \gamma$, with an energetic photon. This event, except for the photon, is typical of the events searched for in the process $Z \rightarrow H + \nu\bar{\nu}$, $H \rightarrow b\bar{b}$.

to 41.6 GeV [32]. The data sample consisted of 100'000 Z decays. The main search channel was $e^+ e^- \rightarrow H + Z^*$; $H \rightarrow b\bar{b}$; $Z^* \rightarrow \nu\bar{\nu}$ although $Z^* \rightarrow e^+ e^-$ and $Z^* \rightarrow \mu^+ \mu^-$ were also used, as were the channels $H \rightarrow \tau^+ \tau^-$, $Z^* \rightarrow \nu\bar{\nu}, l\bar{l}$. The main search therefore is for hadronic Higgs decays (5 or more tracks) and missing energy and momentum. Fig. 23 is an example of an event of the channel $Z \rightarrow q\bar{q} + \gamma$, with an energetic photon. Except for the photon, this is typical of the events searched for. The events are classified into monojets and two-jet events on the basis of an energy flow algorithm that uses all information, track as well as calorimetric. Fig. 24a shows the measured invariant mass distribution. These events are essentially all the hadronic Z decays, and are shown together with the distribution of simulated $Z \rightarrow q\bar{q}$ events. For the two-jet Higgs candidates, the jets are required to be non-colinear and non-coplanar. After the selection, there are no events with mass below 50 GeV

FIGURE 24 Distributions in the search for the Standard Higgs [30].
a) invariant mass of the observed energy flow, compared with simulation, before acoplanarity and acolinearity selection.
b) same, after selection.
c) shape of expected mass distribution for 40 GeV Higgs.

for data or simulation (Fig. 24b). The expected mass distribution for Higgs mass of 40 GeV is shown in Fig. 24c. For a Higgs mass of 41.6 GeV, 3 events within the acceptance would be expected, so a Higgs with lower mass is excluded with 95% confidence.

There exist minimal extensions of the Higgs sector [see Ref. 2, Vol. 2] with five Higgs particles, three neutral and two charged. The Z partial width for the charged members, $\Gamma(Z \rightarrow H^+ H^-)$ is predicted to be $\Gamma_{H^+ H^-} = \frac{G_F m_Z^3}{6\sqrt{2} \pi} (1 - \sin^2 \theta_W) \cdot (1 - 4 m_H^2/s)^{3/2}$. These have been searched on the basis of the decays $H^\pm \rightarrow \nu \tau$ and $H^\pm \rightarrow c \bar{b}$, $\bar{c} b$

[33,34,35]. The lower bound of the mass could be raised from the previous results obtained at Petra [53] to about 40 GeV.

b) Other searches.

There have been several searches at LEP for the particles predicted by supersymmetric theories [54]. The theory predicts bosonic siblings of the fermions, and fermionic partners of the gauge bosons. The masses are not predicted, however their partial widths in Z decay are predicted; these are comparable to their normal counterparts, if kinematically accessible. Gluinos and squarks have been excluded below masses of 70 GeV in $p\bar{p}$ collider experiments [55], so in the LEP searches it has been supposed that the photino is the lightest supersymmetric particle, and all other supersymmetric particles decay to photinos and their normal partners. Because of the relatively large expected branching ratios of the Z for sleptons and winos (the partners of the $W^\pm$) the search for these particles is straight forward, on the basis of missing energy, momentum, and acoplanarity, due to the missing photinos. Supersymmetric searches were reported by all four LEP collaborations [37,38,39, 40,41,42,43]. The mass bounds depend on the mass of the photino, as illustrated in Fig. 25. For a light photino, the lower mass limits are 40-45 GeV for $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$, $\tilde{W}$ and $\tilde{H}$.

FIGURE 25 Lower mass limit for the supersymmetric partner of the muon, as function of the assumed photino mass [38].

Other searches have excluded new quarks and leptons [44,45,46,47,48] below masses of ~ 45 GeV. Excited leptons which would decay to normal leptons by photon emission are predicted by theories in which the quarks and leptons are not elementary, but composite. These have been excluded below masses of 40 - 45 GeV [49,50,51,52]. Finally, supersymmetric partners of the neutral gauge bosons, the so-called neutralinos, have also been searched [40,43], and the parameter space of the theory much restricted for masses below 45 GeV.

Strong Interaction Physics at LEP

The $q\bar{q}$ events lend themselves to the study of the strong interaction. Here there is a history of important contributions from PETRA, PEP and TRISTAN (see e.g. the review of S.L. Wu [21]). Given the complexity of these events, the studies have centred on two aspects, one concerned with hadronization distributions: multiplicity, thrust, sphericity, oblateness, etc. [56,57,58,59], the other centres more on the perturbative aspects of QCD, trying to find as clear a confrontation of the theory with the experiment as possible, and precise values for λ and α_s [60,61,62,63,64,65]. It is for the latter that the increase of energy represented by LEP should permit some progress.

Given my personal lack of familiarity with the subject, I content myself with a few examples of the first results at LEP. As examples of hadronization, in Fig. 26 the acoplanarity distribution is compared with results at lower energy, as well as with some hadronization models. Fig. 27 shows the evolution of thrust with energy. As an example of QCD checks, in particular the study of gluon radiation, Fig. 28 shows an early OPAL result [60] on the fraction of events with 2, 3 or 4 jets depending on the variable y_c , which is basically the minimal fractional mass required in the definition of "jet". With this classification, for y_c sufficiently large, the predictions of perturbative QCD are modified relatively little by the hadronisation. Fig. 29 shows the dependence on the centre of mass

FIGURE 26 Aplanarity of hadronic events at LEP energy compared to previous results at lower energy, as well as some models of hadronization [56].

FIGURE 27 Energy evolution of the thrust variable for hadronic events [61].

FIGURE 28 Fraction of hadronic events with 2, 3, or 4 jets as function of the variable y_c [60]. y_c is essentially the minimum mass in units of the center of mass energy for a group of particles to be identified as a jet.

FIGURE 29 Variation with centre of mass energy of the fraction of 3 jet events, for $y_c = 0.08$ [60]. The decrease of multijet events with energy is in agreement with the "running" of α_s predicted in QCD [61].

energy of the fraction of events with a third jet for a particular y_c . The decrease with energy is in agreement with the QCD prediction and is a consequence of the effective decrease of the coupling constant with energy, the "running" of α_s . Such studies have also been used to measure α_s . The difficulties are connected with finding theoretical predictions for the event shapes not too much fuzzed by non-perturbative effects. $\alpha_s(m_Z^2)$ has been reported as follows:

$0.127^{+0.006}_{-0.017}$	ALEPH [13]
0.114 ± 0.012	DELPHI [64]
0.125 ± 0.012	L3 [65]
0.116 ± 0.016	OPAL [13]

The errors are dominated by the theoretical uncertainties common to all four determinations. The combined result is $\alpha_s(m_Z^2) = 0.120 \pm 0.013$.

Heavy Flavour Physics

a) b and c Partial Widths.

LEP is a prolific source of b quarks (22% of all hadronic Z decays), with a rate of the order of 10^6 b 's per year when and if full luminosity is achieved. Compared to symmetrical, low energy colliders which produce the $B\bar{B}$ systems in the $4s$ state, essentially at rest, LEP has the advantage that the particles are generated with sufficient velocity so that the two jets are well separated and the secondary vertices of the B meson decays can, in principle, be identified with suitable vertex chambers. The secondary vertices are expected to be a powerful tool in the identification of B_s and B_d mesons, in tagging individual decay modes, useful for instance in studies of $B_{s,d}\bar{B}_{s,d}$ mixing, and in the measurement of branching ratios and lifetimes. Another difference is that both B_s and B_d mesons are produced at LEP, whereas the $4s$ resonance is pure B_s .

No results using vertex chambers have as yet been reported. Results reported to date represent the bare beginnings of B research at LEP; they are on the $Z \rightarrow b\bar{b}$ branching ratio [66,67], $B\bar{B}$ mixing[13], forward backward asymmetry[13], and B lifetime [13]. The separation of the b from the other quark channels is based on an energetic lepton with high transverse momentum relative to the jet axis, from the decay $b \rightarrow c + l + \nu$. The background (see Fig. 30), consists of leptons from c decay either from

FIGURE 30 Momentum spectrum of leptons with transverse momentum with respect to the jet axis greater than 2 GeV for a) electron and b) muon selection. The estimated contributions from b decay, c decay, and non-prompt (hadrons simulating electrons or muons) are shown [67].

the cascade $b \rightarrow c \rightarrow l$, or from directly produced c quarks, and of hadrons simulating leptons. Depending on the severity of the selection, this remaining background tends to be between 10 and 30% of the signal. The tagging efficiency, even if both electrons and muons are used, is quite small, of the order of ten percent of all produced b 's.

The conversion of the event numbers to the partial b width Γ_b incurs substantial systematic errors. In addition to the understanding of the different backgrounds and the detection efficiency, which relies heavily on the simulation and hadronization models, the b branching ratio to leptons at LEP may not be the same as that measured in experiments on the $4s$ resonance. In the ALEPH analysis, the data with the lepton $P_T > 2$ GeV are used to find Γ_b . Comparison with the data below this P_T can be used to find Γ_c . The ALEPH results for Γ_b and Γ_c are [67].

Standard Model

$\Gamma_b/\Gamma_h = 0.215 \pm 0.0171 \pm 0.024$	$\Gamma_b = 374 \pm 51$ MeV
Standard Model	$\Gamma_b = 378$ MeV
$\Gamma_c/\Gamma_h = 0.148 \pm 0.044 \pm 0.041$	$\Gamma_c = 258 \pm 105$ MeV
Standard Model	$\Gamma_c = 298$ MeV

The uncertainties are many times larger than those for Γ_l and Γ_h . One can speculate if it will ever be possible to measure the interesting, $\sim 1.5\%$ differential effect due to the top radiative correction on Γ_b .

b) $B^0 - \bar{B}^0$ mixing.

Mixing in the B^0 system, just as in the K^0 system, is due to the mass difference between the two mass eigenstates (approximately CP eigenstates). In the leptonic b decay, the quark decays to the negative and the antiquark to the positive lepton. The charge of the lepton labels the

particle-antiparticle nature of the decaying B^0 meson. Mixing can be characterized by χ , where

$$\chi = \frac{\text{B.R. } (B^0 \rightarrow \bar{B}^0 \rightarrow l^+ + X)}{\text{B.R. } (B^0 \rightarrow l^\pm + X)}$$

In terms of the differences in mass and widths,

$$\chi \simeq \frac{1}{2} \left[\left(\frac{\Delta m}{\Gamma} \right)^2 + \left(\frac{\Delta \Gamma}{2\Gamma} \right)^2 \right] .$$

In the case of $Z^0 \rightarrow B^0 - \bar{B}^0$, with each B decaying to a lepton,

$$\chi = \frac{N^{++} + N^{--}}{N^{+-} + N^{++} + N^{--}} ,$$

where N^{++} denotes both leptons are positive, etc. Without mixing, no like sign leptons would be expected. There are, however, like sign events from background processes:

- leptons from the chain $b \rightarrow c \rightarrow l$
- hadrons mistaken as leptons.

In the ALEPH analysis [13], in 80'000 Z decays, using both electrons and muons, requiring minimum momenta of 5 GeV, and minimum transverse momenta relative to the jet axis of 1 GeV, 135 unlike and 67 like dilepton events were found. On the basis of simulation, 66% of these events are of the type primary b - primary b, 15% are primary b - secondary c, 2% are primary c - primary c, and 16% are background due to hadrons faking leptons (non-prompt). If the contribution of events other than primary b - primary b is subtracted,

$$\chi = 0.129 \pm 0.042 \text{ stat. } \pm 0.018 \text{ syst.}$$

The measured value of χ is diluted by the leptons due to B^+ and B^- decays, which of course do not mix. The B^0 which do contribute are

FIGURE 31 The Argus-Cleo result for B_d mixing [68,69] and the UA1 [70] and ALEPH [13] results for a mixture of B_d , B_s and $B^\pm$, on the assumption that the B_d fraction is 0.375 and the B_s fraction is 0.15, in the $\chi_s - \chi_d$ plane.

partly B_d mesons, partly B_s mesons. These are not expected to mix equally. Previous results are: $\chi_d = 0.17 \pm 0.04$ [68,69], for B 's produced in the $4s$ state and therefore B_d , and $\chi = 0.121 \pm 0.047$ from the UA1 $p\bar{p}$ collider experiment [70], where the mixture of B_s and B_d and $B^\pm$ which is produced can be expected to be similar to that at LEP. The ALEPH and UA1 results are in good agreement. The three results are shown in Fig. 31 in the $\chi_s - \chi_d$ plane under the assumption, based on hadronization models, that the fraction of B_d in the b mix is 0.375, and the B_s fraction is 0.15.

c) b -quark Forward-Backward Asymmetry A_{FB}^b .

The particle-antiparticle nature of the b is given by the sign of the electric charge of the lepton which is also used to select it: $b \rightarrow l^- + X$, and $\bar{b} \rightarrow l^+ + X$. This makes a measure of A_{FB}^b possible, [67,13]. The angular distribution of the 1630 ALEPH events with $p > 3$ GeV, and $p_T >$

FIGURE 32 ALEPH results for the efficiency corrected angular distribution of the Z decay to $b\bar{b}$. θ is the angle between the b jet and the incoming positron [13].

2 GeV is shown in Fig. 32. The interpretation is again complicated by the different processes which contribute. On the basis of Monte Carlo simulation, the basic process $b \rightarrow l$, accounts for 66%, the cascade $b \rightarrow c \rightarrow l$, for 6.7%, the direct c decay $c \rightarrow l$, for 13.5%, and the non-prompt background for 14%. It is also necessary to correct for $B - \bar{B}$ mixing using the measured χ . The raw asymmetry $A_{FB}^{b,diluted} = 6.9 \pm 2.7\%$ becomes, after corrections, $A_{FB}^b = 17.2 \pm 6.0(\text{stat}) \pm 4.7(\text{syst})\%$. The standard model prediction is $A_{FB}^b = 10 \pm 1\%$. The experimental result corresponds to $\sin^2\theta_w(m_Z^2) = 0.220 \pm 0.013$.

d) b lifetime.

ALEPH has made a determination of the b lifetime, using basically the same technique as was used at PEP[72,73,74]. The measurement is an average lifetime for all b states produced. In the near future, with the help of high resolution silicon strip vertex detectors, it is hoped that it will be possible to tag exclusive B channels.

FIGURE 33 ALEPH determination of the b lifetime. Distribution in the distance between the vertex and the lepton track which identifies the b [13].

The b mesons are selected on the basis of a high momentum, high transverse momentum lepton, $p > 5$ GeV and $p_T > 2$ GeV. The impact parameter, δ , of the lepton with respect to the beam collision center is measured, with a resolution of $\sim 110 \mu$, as determined from reconstructed $\mu^+ \mu^-$ and $e^+ e^-$ events. A sign is attributed to δ , depending on whether the lepton track projection crosses the thrust axis of the jet before (+) or behind (-) the beam spot. On the basis of the δ distribution of 1600 events (see Fig. 33), again taking into account the various backgrounds and uncertainties associated with them, the B lifetime is found to be $\tau_B = 1.33 \pm 0.08$ (stat) ± 0.11 (syst) ps [13]. This can be compared with previous results:

$$\tau_B = 1.17 \pm 30 \text{ ps [71]}$$

$$\tau_B = 1.29 \pm 0.29 \text{ ps [72]}$$

$$\tau_B = 0.98 \pm 0.18 \text{ ps [73]}$$

Summary

Less than a year after the start of LEP operation, of the order of 400,000 Z decays have been recorded. These have already furnished the demonstration that there are just three fermion families, and have provided a number of independent, precise checks of the Standard Model, at the percent level. The effective weak mixing angle has been measured with a new precision, $\sin^2\theta_W(m_Z^2) = 0.232 \pm 0.001$.

The mass of the Z has been measured to one part in 3000; together with other LEP results and the results on the W mass, the effects of radiative corrections furnish an indirect, coarse, measure of the top mass: $m_t = 127 \pm 38$ GeV.

All searches for new particles have been negative and new lower mass limits have been obtained for Higgs particles, supersymmetric particles and excited leptons. If a minimal Higgs exists, its mass must be larger than 42 GeV.

Studies of the hadronic events in the quark decay of the Z confirm basic predictions of QCD, and provide a measurement of $\alpha_s(m_Z^2)$.

Finally, LEP is an interesting source of b quarks, and work on Γ_b , A_{FB}^b , $B\bar{B}$ mixing, B lifetimes, etc. is beginning.

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