The Story of Large Electron Positron Collider

2. Experiments done at LEP

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We discuss the experiments carried out with LEP (large electron positron collider) that verified the standard model of the fundamental particles of nature. Some experiments planned for the future to detect Higgs particle are also discussed.

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LEP Detectors

Aims of the four detectors at LEP, surrounding the interaction points of e^+e^-, are to detect all the particles emerging from interactions (also called events) and these are: (a) particles with quark contents like pions, kaons, protons etc., called hadrons, (b) tau leptons, (c) photons, electrons, positrons, (d) muons and (e) neutrinos. The last mentioned particle neutrino has extremely weak interaction with matter and hence it escapes the detector without leaving any trace of itself. All these particles are detected mainly through their strong and electromagnetic interactions.

High energy electrons or positrons lose energy by bremsstrahlung process which is the emission of electromagnetic radiation due to scattering of electrons or positrons in the electric field of a nucleus ($e \to e+\gamma$), and high energy photons lose energy by e^+e^- pair-production in the presence of a nucleus ($\gamma \to e^+e^-$). Thus a high energy electron or photon, while passing through a thick absorber, initiates an electromagnetic cascade as bremsstrahlung and pair production generate more electrons and photons with lower energy (*Figure* 1). The detector that measures the electromagnetic energy deposited by the cascade is called electromagnetic calorimeter. The unit that is used to describe the characteristic electromagnetic shower development is the *radiation length*,

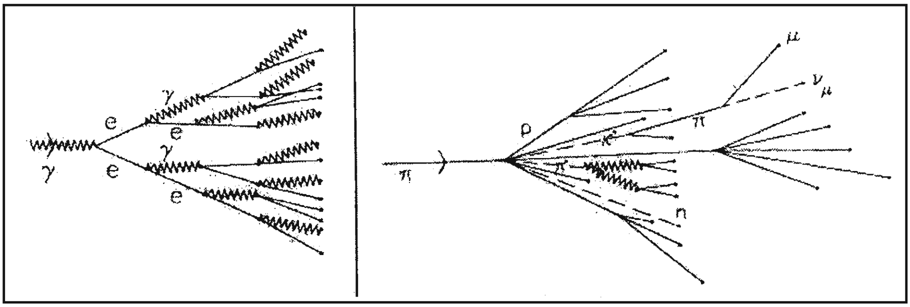


Figure 1 (left). Electromagnetic cascades.

Figure 2 (right). Hadronic shower.

X_0. The radiation length is defined as the distance over which a high energy electron loses on an average 63.2%, $(1 - 1/e)$, of its energy via bremsstrahlung. A high energy photon on an average travels a distance equal to $(9/7)X_0$ before converting to an e^+e^- pair. The radiation length scales as A/Z^2, and a convenient relation for radiation length is given by: $X_0 = \frac{716.4(\mathrm{gm.cm}^{-2}).A}{Z(Z+1)\ln(287/\sqrt{Z})}$, where A is the atomic mass and Z is the atomic number of the absorber.

When a high energy hadron (π, K, p, etc.) penetrates a block of matter, it will interact with nuclei of the matter resulting in production of several particles and this process repeats itself leading to the development of hadronic shower (*Figure* 2). The detector designed to detect the hadronic shower is called hadron calorimeter. The shower development is governed by the nuclear interaction length, λ_{int}, which scales with the nuclear radius as $A^{1/3}$, and it is given by: $\lambda_{\mathrm{int}} \sim 35(\mathrm{gm.cm}^{-2}).A^{1/3}$. It is important to note the differences in the characteristic pattern of energy deposition for high energy electrons (or photons) and hadrons. Since $\lambda_{\mathrm{int}} \propto A^{1/3}$ and $X_0 \propto A/Z^2$, the choice of high Z material would be best to separate electromagnetically interacting particles and hadrons, because one can then achieve the ratio $\lambda_{\mathrm{int}}/X_0$ as high as 30 or more, and hence one can put detector for hadrons behind that for electrons.

There are several components to a detector. As an example LEP-L3 detector is shown in *Figure* 3. Basic

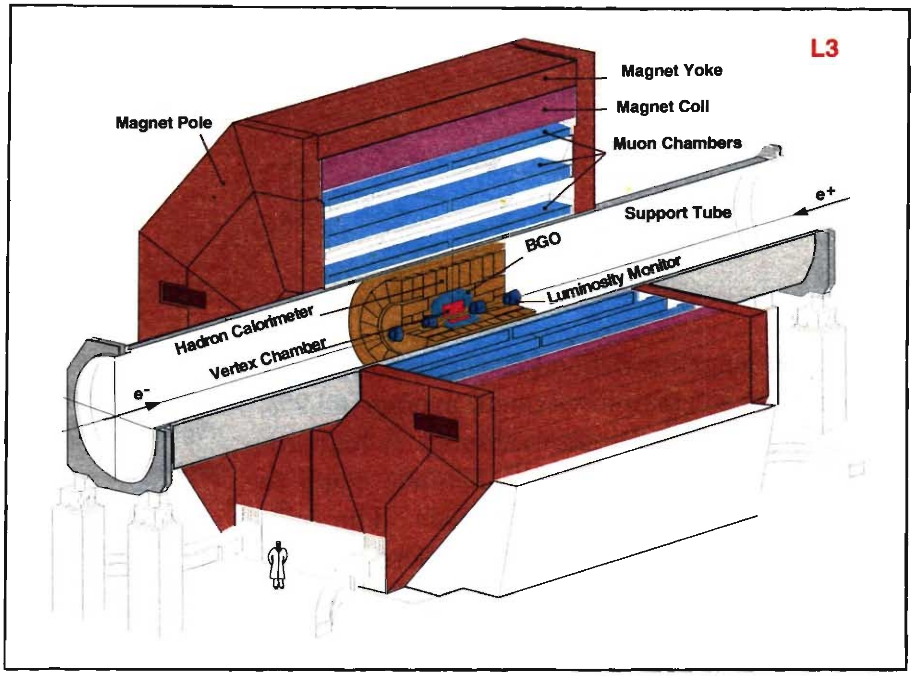


Figure 3. L3 detector: outermost part of the detector is a solenoidal magnet of 16 metre outer diameter and of length 12 metre.

components of these detectors are summarised briefly in the order of increasing radial distance from the collision point of electron-positron. The closest radial distance of a detector is about 5 cm and it is called vertex detector. These are silicon microvertex detectors with a fine spatial resolution of $\sim 10-20\mu$m which record hits of charged particles needed for reconstructing the event vertex. This is followed by a general tracking detector to measure momentum of charged particles from the curvature of the tracks in a magnetic field. Electrons, positrons and photons are then detected via their energy deposits in electromagnetic calorimeter (like crystals, lead-glass, lead-scintillators, etc.); these detectors have material thickness equivalent to about 20 X_0 (with effective interaction length less than one) and hence are expected to absorb completely the electromagnetic radiation. Surrounding the electromagnetic calorimeter there is hadron calorimeter to detect energy deposits by hadrons. In order to contain the hadronic shower the thickness of the calorimeter is equivalent to more than

$10\ \lambda_{\text{int}}$. Some of the examples of hadron calorimeters are copper-scintillator layers, layers of uranium-proportional tubes, iron-liquid argon, etc. To detect muons, which are weakly interacting as well as very penetrating particle, one places muon chambers behind the hadron calorimeter; muon chambers are in general wire drift tubes and one measures the momentum from the curvature of the track due to magnetic field. To detect tau leptons, which decay to electrons/muons with branching fraction of 35% and to hadrons in 65% of the cases, we need to use all components of the detector.

Muon chambers are in general wire drift tubes and one measures the momentum from the curvature of the track due to magnetic field.

Physics at LEP1

The first era of LEP physics, called LEP1, began from September 20, 1989, with electron beam of energy about 45 GeV colliding head-on with the positron beam from the opposite direction of energy about 45 GeV, such that the total centre of mass energy of collision was nearly 90 GeV ($\sqrt{s} \simeq 90$ GeV) (*Box* 1). This collision energy was chosen because of the indication of Z mass to be ≈ 90 GeV/c^2 from the $\bar{p}p$ collider experiments at CERN during early 1980s. In order to make a precision measurement of the Z mass, the collision energy was varied in step of 1 GeV from 88 GeV to 94 GeV. The purpose of LEP1 phase was to study the properties of Z bosons and to carry out precision test of the electroweak theory, which included physics with tau leptons and bottom quarks, study of quark and gluon jets forming part of QCD (quantum chromo-dynamics) physics, searches of new particles such as Higgs bosons and supersymmetric particles. These were successfully carried out by collecting over seventeen million Z decays in the four detectors. Some of the results are discussed below.

Annihilations of e^+e^- lead to pairs of fermions (lepton pairs or quark pairs). These interactions are understood in terms of exchanges of gammas (γ) and Z bosons (*Fig-*

Box 1. Centre of Mass Energy

Consider a two body collision $a + b \to c + d$, with energy and 3-momentum vectors of the two particles in the initial state as $\mathbf{P}_a = (E_a, \vec{p}_a)$ and $\mathbf{P}_b = (E_b, \vec{p}_b)$. The 4-momentum vectors $\mathbf{P}_a$ and $\mathbf{P}_b$ are related to the rest masses of the particles (m_a and m_b) by the following relations (we have used below the value for the speed of light as c=1):

$$\mathbf{P}_a^2 = E_a^2 - |\vec{p}_a|^2 = m_a^2, \text{ and } \mathbf{P}_b^2 = E_b^2 - |\vec{p}_b|^2 = m_b^2$$

From $\mathbf{P}_a$ and $\mathbf{P}_b$ we form another quantity called s, which remains invariant under Lorentz transformations and is known as square of centre of mass (CM) energy:

$$s = (\mathbf{P}_a + \mathbf{P}_b)^2 = (E_a + E_b)^2 - (\vec{p}_a + \vec{p}_b)^2$$

We now calculate $s$in two different collision systems. (i) **Lab system** (or fixed target experiments) in which the second particle 'b' is at rest (that is $\vec{p}_b$ and $E_b = m_b$) and the quantity s gets simplified to: $s = m_a^2 + m_b^2 + 2m_b.E_{a^{lab}}$. Since the energy E_a of the particle 'a' now refers to the energy in the lab system, we have denoted it by E_a^{lab} for the sake of clarity. If the energy $E_{a^{lab}}$ is reasonably large, we can write the CM energy as $\sqrt{s} \sim \sqrt{2m_b.E_{a^{lab}}}$. (ii) **CM system** (or collider experiments) in which both the particles collide head-on with each other with equal and opposite momenta (that is $\vec{p}_a + \vec{p}_b = 0$). For the sake of clarity let us define the energies of the two particles in this system as E_a^{cm} and E_b^{cm} instead of E_a and E_b. The expression for s gets simplified to: $s = (E_a^{cm} + E_b^{cm})^2$. We can thus write the CM energy as $\sqrt{s} = (E_a^{cm} + E_b^{cm})$. We thus see that the CM energy increases linearly with the energy of the beam for collider experiments, while it increases only as square root of the beam energy for fixed target experiments. For example in proton-proton collisions if we want to have $\sqrt{s} = 20$ GeV we would need $E^{cm} = 10$ GeV in collider case, whereas in the fixed target case we will need $E^{lab} \approx 212$ GeV. E^{lab} is much larger than E^{cm}, because in the former case most of the energy is wasted in balancing momentum. The CM energy of collisions dictates the particle production: their multiplicity as well as the feasibility of producing heavier particles. Threshold CM energy of a reaction can be obtained by simply adding the rest masses of the final state particles; as an example the minimum energy needed for the reaction $e^+e^- \to W^+W^-$ is $(\sqrt{s})_{min} = 2m_W c^2 \simeq 161$ GeV .

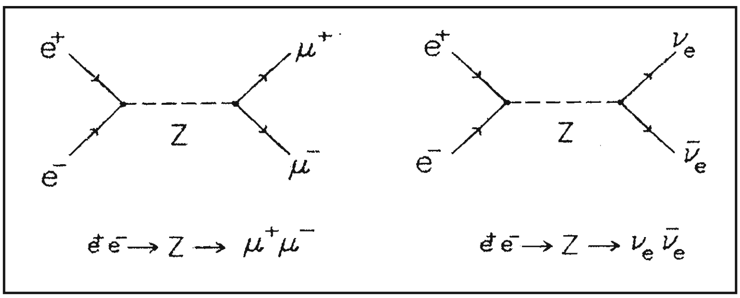


Figure 4. Exchanges of gammas and Z bosons.

ure 4); the contribution due to gamma exchange is negligible and at the peak it is only one event out of one thousand. One can describe the annihilation as a two step process. Firstly Z boson is produced in the reaction $e^+e^- \rightarrow$ Z, and then within about 10^{-25}sec it decays into leptons or hadrons. Nearly thirty Z bosons out of 100 decay to lepton pairs, while the rest 70 of them decay via quark pairs. Since quarks do not exist as free particles, they quickly fragment into several hadrons, called jets of hadrons or simply jets. Various decay channels of Z into fermion-antifermion pairs are summarised in *Table* 1. Since neutrinos escape detection, we have shown 'none' as observed particles against neutrinos.

Z Mass and Width

The mass and total width of the Z boson were determined by making precision measurements of cross-sections (σ) as a function of collision energy ($\sqrt{s}$) for the following four final states corresponding to Z decays: $e^+e^- \rightarrow$ hadrons, $e^+e^- \rightarrow e^+e^-$ (also called Bhabha scattering), $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ An illustration of the behaviour of cross-section as a function of $\sqrt{s}$ is shown in *Figure* 5. The shape of such distributions is characteristic of an unstable particle, in this case Z boson, and they are described by the Breit–Wigner distribution, first given by G Breit and E Wigner. Unstable particles are described by their lifetimes or decay widths (*Box* 2), which are related to each other via the

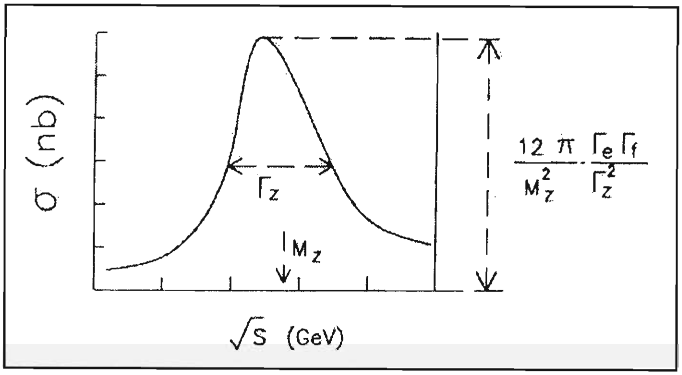


Figure 5. Illustration of cross-section vs collision energy.

Box 2. Lifetime vs Width of Unstable Particles

The lifetime of an unstable particle is calculated by making use of the uncertainty principle which states $\Delta E \times \Delta t \approx \hbar$, where $\hbar = h/2\pi$ with h as the Planck's constant; the value of $\hbar$ is 6.58×10^{-22} MeV.sec. Here ΔE represents the uncertainty in the mass of the particle, called decay width (Γ), and Δt as its mean lifetime (τ). With the width of the Z boson, as measured at LEP, $\Gamma = 2495$ MeV, one gets its lifetime from the relation $\tau = \hbar/\Gamma = (6.58 \times 10^{-22}$ MeV.sec)/(2495 MeV) $\approx 3 \times 10^{-25}$ sec. This lifetime is too short to measure and hence one measures experimentally the width of the Z. If the lifetime of a particle is greater than about 10^{-10}sec, the value of its decay width is too small (less than 7×10^{-12} MeV) to measure. What will be the distance traversed by such a particle? Let us consider a neutral kaon, whose mean-life is $\approx 10^{-10}$sec and its mass is nearly 500 MeV/c^2, moving with a momentum of 500 MeV/c. The mean distance travelled by this neutral kaon is: $x = c\tau(\frac{pc}{m_K c^2}) = 3 \times 10^{10} \times 10^{-10} \times (500/500) = 3$cm. Experimentally there is no difficulty in measuring this lifetime. Thus, one measures the width of a particle when its lifetime is very short, otherwise one measures the lifetime directly.

relation $\tau = \hbar/\Gamma$ The four partial widths of Z corresponding to its four visible decay modes (*Table* 1) are: Γ_{ee}, $\Gamma_{\mu\mu}$, $\Gamma_{\tau\tau}$ and Γ_{hadron}. Total width of Z, which includes contributions from all possible decay channels, is measured independent of the partial widths. The ratio of a partial width to the total width gives the fraction of time Z decays into a given final state, for example the ratio Γ_{hadron}/Γ_Z gives the fraction of Z decaying via the hadronic mode.

Now, let us examine the shape of the distribution of σ as a function of $\sqrt{s}$ (*Figure* 5). Three quantities can be determined: (i) the value of $\sqrt{s}$ corresponding to the maximum value of the cross-section and this fixes the mass of the Z boson, (ii) the width of the distribution at half the value of the peak cross-section which leads to the determination of the total width Γ_Z, and (iii) the height of the peak, or the maximum value of the cross-section, which is proportional to the product of the two partial widths $\Gamma_{ee}.\Gamma_{ff}$, where Γ_{ff} refers to the final state; for example it is proportional to $\Gamma_{ee}.\Gamma_{ee}$ for $e^+e^- \to e^+e^-$, to $\Gamma_{ee}.\Gamma_{\mu\mu}$ for $e^+e^- \to \mu^+\mu^-$ to $\Gamma_{ee}.\Gamma_{\tau\tau}$ for $e^+e^- \to \tau^+\tau^-$ and to $\Gamma_{ee}.\Gamma_{hadron}$ for $e^+e^- \to$ hadrons. From a simultaneous fit to all the four distributions in

Table 1. Z decay modes.

Decay channel	Observed particles	Branching fraction
(a)Z $\to$ leptons		
e^+e^-	e^+e^-	$\simeq 3.3\%$
$\mu^+\mu^-$	$\mu^+\mu^-$	$\simeq 3.3\%$
$\tau^+\tau^-$	low multiplicity final state	$\simeq 3.3\%$
$\nu_e\overline{\nu}_e, \nu_\mu\overline{\nu}_\mu, \nu_\tau\overline{\nu}_\tau$	none	$\simeq 20\%$
(b)Z $\to$ hadrons		
$u\overline{u}, d\overline{d}, s\overline{s}, c\overline{c}, b\overline{b}$	2,3,4 high multiplicity jets of hadrons	$\simeq 70\%$

σ versus $\sqrt{s}$ one determines the mass, partial widths and the total width of Z. The four experiments at LEP collected nearly 17 million Z events (out of which nearly 15 million events are due to Z $\to$ hadrons, and nearly 2 million events are due to Z $\to$ lepton – pairs). As an example, the LEP data for $e^+e^- \to \mu^+\mu^-$ is shown in *Figure* 6, and the results are summarised in *Table* 2. The mass of the Z particle is measured to a precision of two parts in hundred-thousand ($\Delta M_Z/M_Z \simeq 2 \times 10^{-5}$) and it is nearly hundred times heavier than a hydrogen atom.

Number of Neutrino Species

From the Z decays one gets an important information regarding its decay into invisible neutrino channels. Since the total width of Z is sum of all the partial widths of its decay channels, one determines the partial width of Z to all invisible particles, denoting it with $\Gamma_{\rm inv}$, from the relation: $\Gamma_{\rm inv} = \Gamma_Z - \Gamma_{\rm had} - (\Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau})$. From the measured values given in *Table* 2, one obtains:

Table 2. Mass and width of Z boson.

Parameters	Measurements
M_Z GeV	91.187 ± 0.002
Γ_Z GeV	2.495 ± 0.002
Γ_{ll} MeV	83.98 ± 0.09
$\Gamma_{\rm had}$ MeV	1744.4 ± 2.0

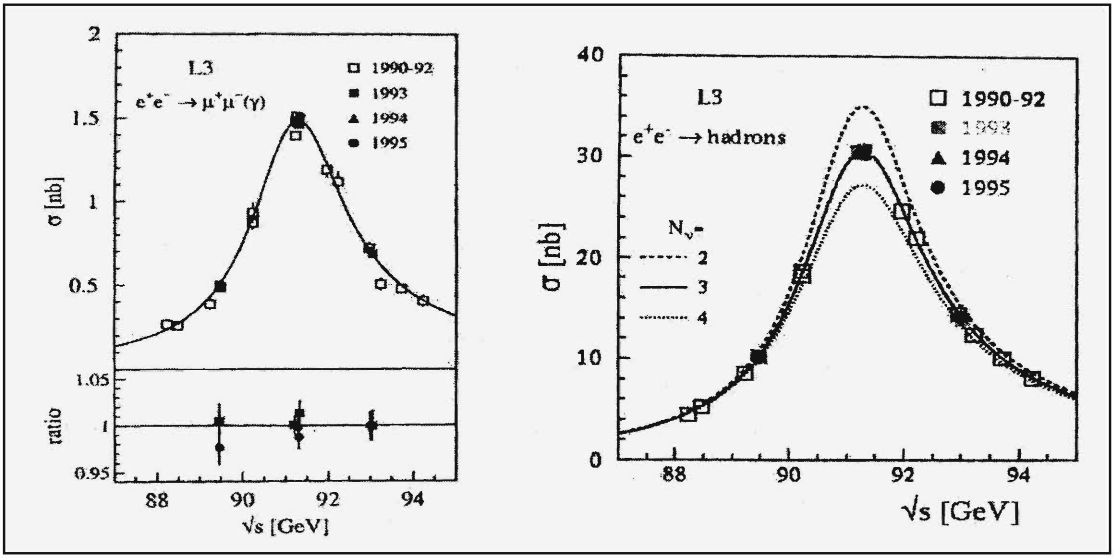


Figure 6 (left). Cross-section of e^+e^- $\mu^+\mu^- \rightarrow$ vs CM energy. The bottom part shows the ratio of the data and the fitted values.

Figure 7 (right). Cross-section of $e^+e^- \rightarrow$ hadrons vs CM energy.

$\Gamma_{\text{inv}} = 499.0 \pm 1.4$MeV. According to the standard model, the partial width of Z to one neutrino species ($\Gamma_{\nu\nu}$) is 166.9 MeV, and this then yields the number of light neutrino species as: $N_\nu = \Gamma_{\text{inv}}/\Gamma_{\nu\nu} = 2.98 \pm 0.01$. This determination confirms the number of generation to be 3 as assumed in the standard model. In *Figure* 7 is shown the sensitivity of N_ν to the Z production cross-section as a function of $\sqrt{s}$; it is clearly seen that $N_\nu = 2$ or 4 cannot represent the experimental data. It may be mentioned that the direct observation of the third neutrino, called tau-neutrino, was made several years later at Fermilab in 2000 by the DONUT experiment. The status of the number of neutrinos before the commissioning of LEP (*Box* 3) was: $N_\nu < 6$.

Electroweak Mixing Angle

The electroweak mixing angle, which measures the relative strengths of the electromagnetic and weak neutral force, is determined in several ways. Let us mention two of these methods. (i) Measurements of the forward-backward asymmetries of the three charged leptons, in which one counts the number of negatively charged leptons (e^-, μ^- or τ^-) in the forward (N_{F}) and backward

Box 3. Neutrinos from Cosmology

It was first noted by Shvartsman in 1969 that the abundance of primordial helium can constrain the number of possible neutrino flavours during nucleosynthesis in the early Universe. There are three factors involved in this conjecture and these are: (i) expansion rate of the Universe which depends directly on the number of light relativistic particles (like photons, electrons, neutrinos), (ii) the freeze out of neutron to proton ratio (n/p), and (iii) the abundance of helium. When the Universe was at a higher temperature ($T \geq 10^{10}$K), there was a thermal equilibrium with $n/p \approx 1$. As the temperature fell below this value, the equilibrium value of n/p could not be maintained because of the weak interaction processes: $n + e^+ \leftrightarrow p + \bar{\nu}_e$, $p + e^- \leftrightarrow n + \nu_e$, $n \rightarrow p + e^- + \bar{\nu}_e$. When the temperature dropped to about 10^9K, weak interaction processes, except for the free decay of neutrons, stopped (that is the freeze-out occurred) and the nucleosynthesis started: $n + p \rightarrow D + \gamma$, $D + D \rightarrow He^4 + \gamma$, where D stands for deuterium. Since there is no stable nuclei with atomic masses 5 and 8, heavier elements cannot be synthesised by Big Bang (heavier elements are produced in stellar nucleosynthesis). Since all the neutrons are used up in deuterium and all the deuterium in helium, the amount of helium produced depend exclusively on the ratio n/p and this is given by the mass fraction of helium as: $Y = \frac{2n/p}{n/p+1}$. Thus, if the N_ν increases the expansion rate becomes faster, which in turn makes the freeze out of n/p earlier. If the freeze out of p/n occurs early then the ratio n/p remains large leading to an increase in the abundance of helium. The value of Y has been measured from galaxies and they lie in the range 0.22-0.26. Besides Y one also needs to know the neutron half-life as well as the primordial abundances of deuterium and He^3. Several analyses have been carried out around 1985 and these analyses permit $N_\nu = 5$ or even $N_\nu = 6$ (the number of neutrinos as estimated from more recent analysis of cosmological data in 1999 is: $1.7 \leq N_\nu \leq 4.3$).

Neutrinos from accelerator experiments: At the $\bar{p}p$ collider at CERN, where W and Z bosons were discovered, the two experiments UA1 and UA2 from the decays of W and Z gave an upper limit on the number of neutrinos as: $N_\nu < 5.7$.

(N_B) directions with respect to the incident electron beam: $A_{FB} = (N_F - N_B)/(N_F + N_B)$ (*Figure* 8). (ii) Measurement of the left-right cross-section asymmetry, where one counts the number of Z bosons produced by the left (N_L) and the right (N_R) longitudinally polarised electrons: $A_{LR} = (N_L - N_R)/(N_L + N_R)$. This measurement was carried out at the SLD detector of the Stanford Linear Collider (SLC) where Z bosons were produced by longitudinally polarised electrons colliding on unpolarised positrons. These asymmetries are energy dependent and are expected to vanish at about $\sqrt{s} = M_Z$ for the value of $\sin^2\theta_w$ as 1/4. As an example we show in

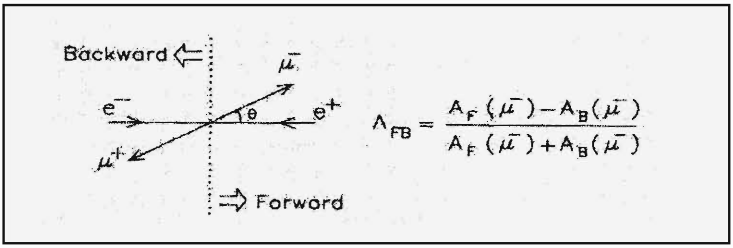


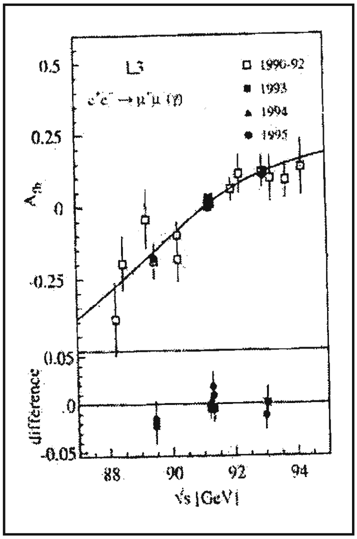
Figure 8. Illustration of forward-backward asymmetry.

Figure 9 the energy dependence of A_{FB} for the reaction $e^+e^- \to \mu^+\mu^-$. Combining all different kind of measurements, the best value for the electroweak mixing angle is: $\sin^2\theta_w = 0.2315 \pm 0.0002$.

Estimate of Top Quark Mass

One of the reasons for carrying out precision measurements of the properties of the Z particle at LEP1 and W particle at LEP2 are to measure quantum effects, also called radiative or loop corrections, on these results due to particles too heavy to be produced at LEP, such as the top quark and the Higgs boson. Radiative corrections are more sensitive to top quark mass (proportional to square of its mass) than that of the Higgs (proportional to logarithm of its mass). Thus using all the precision measurements at LEP, it was possible to predict by early 1990's the mass of the top quark to be about twice as heavy as the W particle, which was confirmed when it was discovered at Fermilab in 1995. The mass of the top quark measured by the two experiments, CDF and DZERO, is: $m_t = 174.3 \pm 5.1$ GeV The method to estimate the radiative corrections was shown by 't Hooft and Veltman and they were awarded the Nobel Prize in 1999.

Figure 9. Asymmetry of $e^+e^- \to \mu^+\mu^-$ vs CM energy. The bottom part shows the difference of the measured asymmetry and the fitted value.



Physics at LEP2

A new chapter of LEP started from June 1996 when the centre of mass energy of LEP was upgraded to cross the W pair production threshold by incorporating superconducting RF acceleration cavities in several stages. During the LEP2 phase which lasted till November 2000,

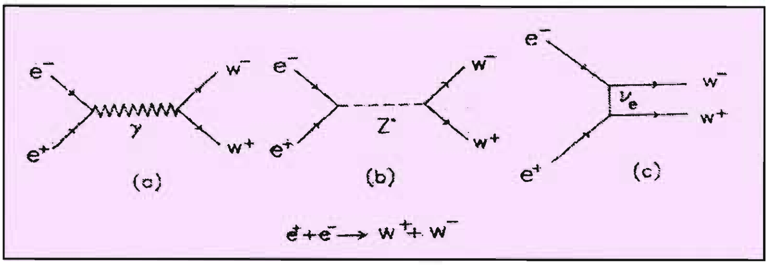


Figure 10.

LEP covered the energy range from 161 to 208 GeV. We will touch upon some of the results from LEP2.

W Mass and Width: W bosons at LEP are produced in pairs: $e^+e^- \rightarrow \mathrm{W^+W^-}$, (*Figure* 10), followed by decays of W within about 10^{-25}sec. W decays into leptons (examples: $\mathrm{W}^+ \rightarrow e^+\nu_e$, or $\mu^+\nu_\mu$, or $\tau^+\nu_\tau$) or quarks (examples: $\mathrm{W}^+ \rightarrow \mathrm{u\bar{d}, or c\bar{s}}$). Nearly 33 W particles out of 100 decay into lepton pairs, while the rest decay via quark pairs. The production cross-section of W pairs at $\sqrt{s} \simeq 180$ GeV is nearly 2000 times less than that of the Z particle at $\sqrt{s} \simeq 90$ GeV, and hence the four experiments could collect a total of about 40000 W pairs during the LEP2 phase.

By counting the number of W pair events, after subtracting the potential background events, and knowing the luminosity, the production cross-sections of W pair events for different collision energies were measured. These results are shown in *Figure* 11. We also show the theoretical prediction of the standard model (solid line) which fits the data very well. Before the realisation of the standard model, it was thought that the W pair production was due to neutrino exchange alone (*Figure* 10c) and the production cross-section was found to increase rapidly, which on general theoretical considerations turned out to be unphysical. This problem got solved with the introduction of the Z particle exchange in the standard model. The dash-dotted curve in the figure shows the cross-section due to neutrino exchange alone and the dashed curve due to neutrino plus gamma exchange. These measurements bring out the need of Z

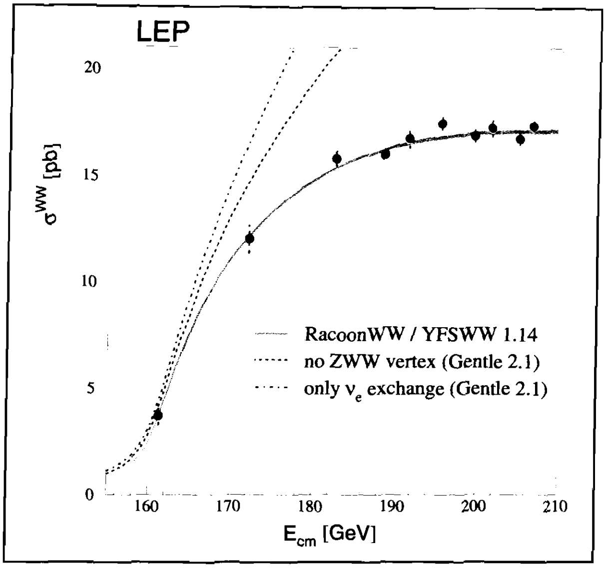


Figure 11. Cross-section of $e^+e^- \rightarrow W^+W^-$ vs CM energy. The solid curve refers to the prediction of the Standard Model as calculated using the programmes Racoon WW/YFSWW.

particles in understanding the production of W particles in e^+e^- annihilations.

The mass and width of W particle were measured by reconstructing all its decay products and carrying out energy and momentum conservation of the reaction. The values are: $M_\mathrm{W} = 80.45 \pm 0.04$ GeV and $\Gamma_\mathrm{W} = 2.15 \pm 0.06$ GeV. Two other experiments (CDF and DZERO) at the $\bar{\mathrm{p}}\mathrm{p}$ collider in Fermilab have also measured the mass and width of the W particle and these values are in good agreement with those of LEP.

Strong Coupling Constant

One of the dominant modes of annihilations in electrons and positrons is via the production of quark pairs:

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$e^+ + e^- \rightarrow$ quark + antiquark. As the quark (q) and antiquark ($\bar{\mathrm{q}}$) fly apart in opposite direction with large energies at LEP, the QCD confining forces, acting like a rubber band, releases the excess energy by emitting a gluon (q $\rightarrow$ q + gluon), which in turn gets converted into a new quark and a new antiquark (gluon $\rightarrow \mathrm{q} + \bar{\mathrm{q}}$). This process repeats itself and results in generation of many quarks and antiquarks pairs moving almost along

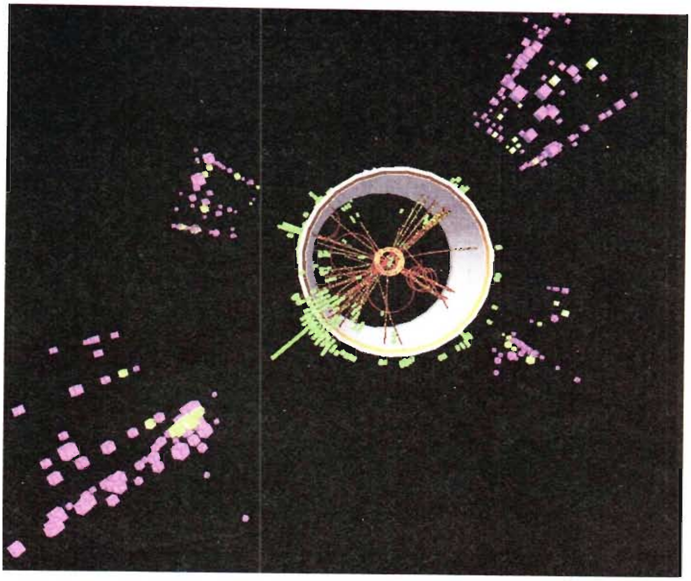

Figure 12. An event display of $e^+e^- \to 4$ jets (L3).

the direction of the original quark and antiquark; these quarks and antiquarks combine to form mesons and occasionally baryons. Final products are two back to back fast moving jets of hadrons (mesons and baryons). In some cases a third well separated jet of hadrons is also observed due to process: $e^+ + e^- \to \mathrm{q} + \bar{\mathrm{q}} + \mathrm{gluon}$. Such a process is called gluon bremsstrahlung and the third jet is due to gluon which also turns into a jet of hadrons. The number of jets in a collision depends on the total collision energy. As an example three jet events were first seen at the electron-positron collider PETRA, in Hamburg, Germany, operating at centre of mass energy of nearly 43 GeV. At LEP, because of its large collision energy, one is able to identify well separated six jets. An example of 4-jet event from L3-LEP is given in *Figure* 12.

There are various ways one has measured the force between quark and gluon interactions and this is denoted by the strong coupling α_s. Asymptotic freedom in QCD means that the interaction coupling is energy dependent and should decrease with increasing energy. At lower energies the values of α_s have been determined from decays of particles into hadronic final states like decays of tau

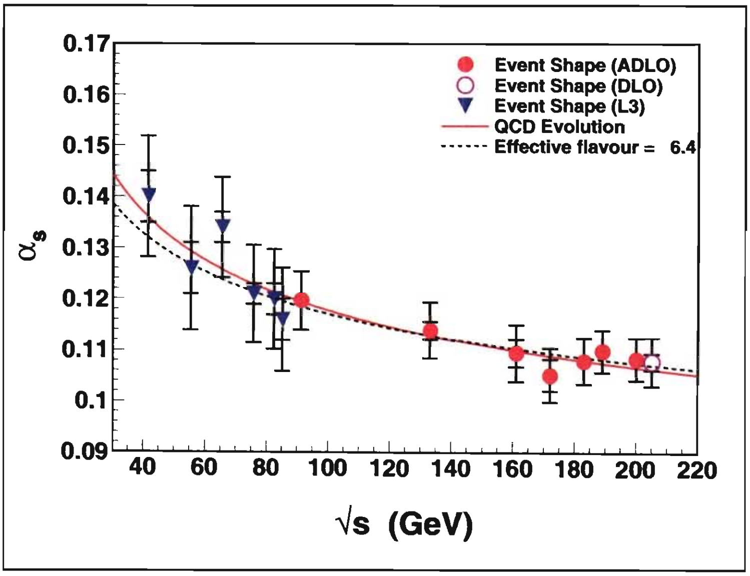

Figure 12. Strong coupling constant as measured at LEP.

leptons, J/Ψ particle of mass 3 GeV and Υ particle of mass 10 GeV. Measurements above 10 GeV are from electron-positron collider experiments. Precision determinations of α_s at LEP are in the energy region 90 to 200 GeV, and the measurements are based on the study of jets. Results are summarised in *Figure* 12. The values of α_s decrease with the increasing energy; it is about 0.30 at lower $\sqrt{s}$ values of a few GeV, while at LEP energies of 200 GeV it is about 0.10.

Higgs searches at LEP

The Higgs boson, in the standard model, is supposed to be responsible for the masses of the known particles. This unique Higgs particle is expected to couple more strongly to heavy particles than to the light ones; as a result it prefers to decay into a pair of heavy particles. Theoretically there is no prediction about its mass. If it is not very heavy (less than twice the mass of W particle) it will decay about 85% of the cases to a pair of b quarks ($H \to b\bar{b}$) and the rest 15% of the cases to c quarks and tau leptons. Two kinds of searches have been made at LEP: direct searches and indirect searches. Among the direct searches, the four LEP experiments have searched for Higgs production by the process known as higgsstrahlung: $e^+e^- \rightarrow$ HZ, where H decays to $b\bar{b}$ resulting in two b-quark jets, and Z will decay to one of the modes given in *Table* 1. If the Higgs bosons are produced, a peak should appear in the histograms of the two jet mass. Since the Z particle mass is known, the exploration of the Higgs mass depends on e^+e^- collision energy. At the highest energy of 208 GeV achieved at LEP2, these experiments have searched for Higgs boson and have not found any convincing evidence, and thereby setting a lower limit on the mass of the Higgs of 114 GeV.

An indirect estimate of Higgs is made by using all the available electroweak data and by studying quantum effects or radiative corrections as was done in the case of top mass, which proved to be very successful. Since the only missing quantity in the standard model now is the mass of the Higgs particle, all the available data is fitted in the standard model framework with the mass of the Higgs as the unknown quantity. The result of the fit yields an upper limit on the mass of the Higgs of approximately 222 GeV.

Conclusions and Outlook

Our attempts in these articles have been to give a flavour of physics that has come out from nearly eleven years of running of LEP with four detectors taking data and nearly two thousand scientists working round the clock. The performance of LEP has been exemplary and the credit goes to the excellent and hard work of a dedicated team of engineers and technicians of CERN. The precision measurements at LEP left no one in doubt that the understanding of physics through the standard model is in very good shape at the energy of LEP, and the only missing link at present is the neutral Higgs boson responsible for giving masses to particles. The standard model is based on three generations of matter particles and the exchange of elementary quanta of the force carriers: the photon for the electromagnetic interaction, gluons for the strong interaction and the $W^{\pm}$ and Z^0 for the weak interactions; the Higgs mechanism is expected to be responsible for giving masses to particles. However, it is generally believed that the standard model is incomplete and the physicists are pursuing the ultimate unification of all the four fundamental forces, that is including the gravity. On the experimental side the hunt is on for the elusive Higgs. After the LEP, the search is currently being undertaken at the antiproton-proton collider, Tevatron at Fermilab, with centre of mass energy of 2 TeV (1 TeV = 1000 GeV). If the Higgs is comparatively light with mass around 125 GeV or less, it may be seen at Tevatron in the next 4 to 5 years, otherwise one will have to wait for the commissioning of the large hadron collider (LHC) at CERN in 2007. At LHC two counter rotating proton beams will collide, each beam of energy 7 TeV yielding 14 TeV as centre of mass energy of collision – once commissioned it will be the world's highest energy accelerator (it may be mentioned for the sake of completeness that the LHC will also have colliding heavy ion beams at 5.5 TeV/nucleon). There will be two large-scale experiments, called ATLAS and CMS, specifically designed to search for Higgs or any other heavy new particles. It is expected that within two years of data taking at LHC these two experiments will be able to discover Higgs if its mass is not exceeding 1000 GeV, which is the expected upper limit on the mass of the Higgs from general theoretical considerations.

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Suggested Reading

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