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Five Years of LEP Experiments†

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†Presented at INS Workshop "Physics of e^+e^-, $e^-\gamma$ and $\gamma\gamma$ collisions at linear accelerators," December 20–22, 1994, and at YITP Workshop "Particle Physics and its Future Perspective," January 17–20, 1995.

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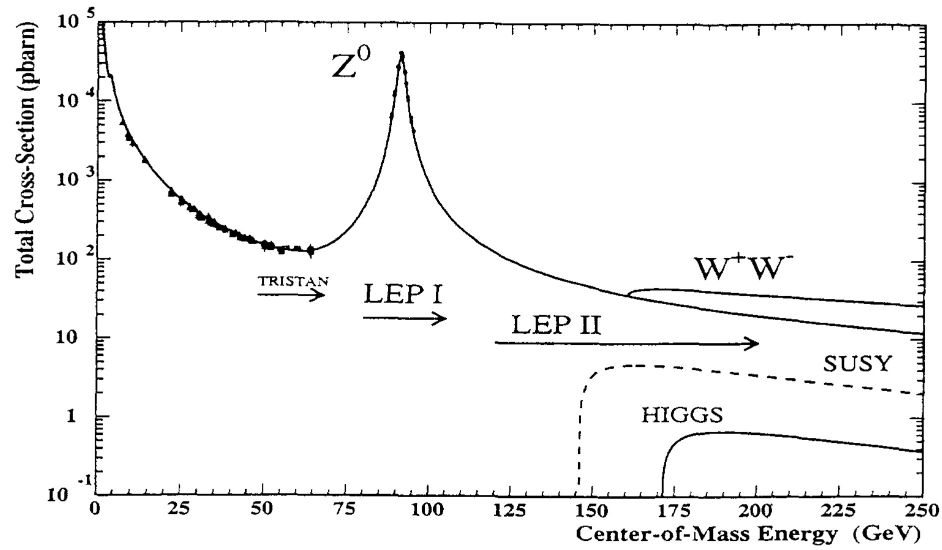

Figure 1: Total hadronic cross section of e^+e^- annihilation is plotted with the experimental data. Also shown are predicted cross sections for W-pair production, 80 GeV Higgs production, and an example of chargino-pair production (SUSY).

Standard Model and LEP

Most important concept in today's particle physics is, in no doubt, gauge interactions. Gauge symmetry is the very basis of the successful Standard Model, and all viable theories in the present particle physics are dependent on the gauge principle. It is therefore very important to examine this concept by experiments with best possible accuracies. Especially it needs to be proved that Z^0 and $W^\pm$ are really gauge bosons of electroweak interaction.

Equally important is the way the electroweak gauge symmetries are broken. They must be broken to give masses to the existing particles. At the moment there is no experimental clue to what mechanism is actually responsible for the symmetry breaking. The Standard Model and some of its extensions predict the existence of scalar particles called Higgs, which is a remnant of the symmetry breaking. Thus finding (or excluding) these remnant particles will open a gate to understanding of the symmetry breaking mechanism.

The Standard Model is known to have difficulty that Higgs obtains unnaturally large self-energy due to its new interaction. To avoid this, two ways of extending the Standard Model have been proposed: (1) No Higgs boson exists; instead a new strong interaction at an energy scale of around 1 TeV breaks the symmetries; (2) Other contributions cancel the large Higgs self-energy. Technicolor models are examples of the first scenario, while supersymmetric models are the only candidates for the second possibility. Looking for any signs of evidence for (or against) these extended models is also an important task of experiments.

LEP is the highest energy electron–positron collider, currently operating at CERN. Four international collaborations (ALEPH, DELPHI, L3, and OPAL) have been carrying out experiments at LEP since summer, 1989. The primary objective of the LEP experiments is to examine the gauge interactions by studying the properties and interactions of the heavy bosons

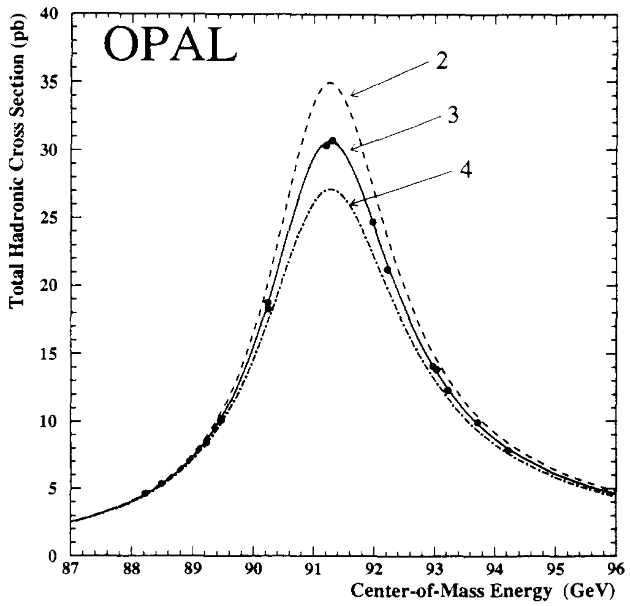

Figure 2: The total hadronic cross sections measured by the OPAL experiment are compared to the Standard Model predictions with 2, 3 or 4 light neutrino species.

(Z^0 and $W^{\pm}$). At the moment LEP is operating at the top of the Z^0 resonance (Fig. 1). With approximately 15 million Z^0 events recorded by the end of 1994, the properties of Z^0 are being extensively studied. These measurements probe radiative effects that are sensitive to top quark, Higgs boson, and effects of new physics at higher energy scales. In 1996 the LEP energy will be doubled to reach the threshold of W-pair production (LEP-II). Here the properties of W bosons and in particular the triple gauge boson couplings will be examined in detail.

Higgs bosons have also been searched for at LEP. Before the LEP experiments, most of the attempts to find Higgs bosons could not give definite conclusions, because Higgs production rates usually involve large uncertainties due to QCD corrections. On the other hand, the Higgs production via the Z^0 boson can be precisely calculated by the Standard Model. Its rate is high enough to allow the LEP experiments to discover or exclude its existence unambiguously, if the Higgs mass is around or below the Z^0 mass. Also there is possibility that new particles such as those predicted by supersymmetric models are produced at LEP.

In the following I summarize the major physics results of the LEP experiments [1] and briefly comment on the future prospects at the end.

Z^0 Lineshape — Only Three Generations

The shape of the Z^0 resonance ("lineshape") has been measured by scanning energy dependence of the total cross sections of Z^0 decays (Fig. 2). The hadronic and leptonic cross sections can be expressed by Breit-Wigner resonances with the following six parameters: the Z^0 mass, m_Z, the Z^0 total width, Γ_Z, the hadronic peak cross section, $\sigma^0_{\rm had}$, and the ratio of the hadronic width $\Gamma_{\rm had}$ to the leptonic width Γ_ℓ, $R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$, for each lepton species ($\ell = {\rm e}, \mu, \tau$). These parameters were chosen so that their experimental correlations are minimal. Other parameters, such as $\Gamma_{\rm had}$ and Γ_ℓ, can be derived from these parameters. The six parameters were obtained from the measured cross sections, taking correlated errors in the measurements into account. Among the major correlated errors are a 0.16% theoretical ambiguity in the luminosity calculation [2]†, and the center-of-mass energy uncertainty described below [3].

The Z^0 mass is one of the most fundamental parameters in the Standard Model and must be experimentally determined as precisely as possible. The experimental accuracy of m_Z is limited by our knowledge of the accelerator energies. During the 1993 runs, the status of the LEP storage ring was kept closely monitored and the beam energies were calibrated routinely about twice a week by using resonant depolarization technique. Elaborate work on systematics in energy variations and energy measurements has lead to a determination of the center-of-mass energies with a precision of 2 parts in 10^5 [3]. To understand the difficulty of the beam energy calibrations, it is worth noting that a few mm variations of LEP's 2.7 km circumference caused by the earth tides induce the beam energy changes of up to 1 part in 10^4. Finally the Z^0 mass was obtained as $m_Z = 91188.7 \pm 2.2$ MeV, where an error of 1.5 MeV from the LEP energy uncertainty is included.

The Z^0 total width measurement also benefited from the precise knowledge of the beam energies: $\Gamma_Z = 2497.1 \pm 3.3$ MeV. Here the error includes the LEP energy uncertainty ($\Delta\Gamma_Z =$ 1.7 MeV) and the uncertainty of the LEP energy spread ($\Delta\Gamma_Z = 1.0$ MeV).

In the Standard Model, the Z^0 total width is written as $\Gamma_Z = \Gamma_{\rm had} + 3\Gamma_\ell + \Gamma_{\rm inv}$,‡ where the invisible width $\Gamma_{\rm inv}$ is the sum of the contributions from N_ν generations of light neutrinos, $\Gamma_{\rm inv} = N_\nu \Gamma_\nu$. Using the values of Γ_Z, $\Gamma_{\rm had}$ and Γ_ℓ obtained from the cross section measurements, we can calculate the invisible width, $\Gamma_{\rm inv} = 499.5 \pm 2.7$ MeV; or assuming the Standard Model value of $\Gamma_\nu/\Gamma_\ell = 1.992 \pm 0.003$, the number of light neutrinos can be derived (Fig. 2):

$$N_\nu = 2.987 \pm 0.016.$$

This provides the strongest evidence that there are only three generations of particles, and that no exotic particle contributes to the invisible width. This result has been confirmed also by the direct measurements of the single photon (+ nothing) events [4].

Using the minimum values of the widths expected by the Standard Model for $m_t = 150-200$ GeV, $m_H = 65 - 1000$ GeV and $\alpha_S = 0.117 - 0.133$, the above width measurements yield the 95% C.L. maximum contributions from unknown particles to Γ_Z and $\Gamma_{\rm inv}$:§

$$\begin{aligned} \Delta\Gamma_Z &< 23.0 \text{ MeV} \\ \Delta\Gamma_{\rm inv} &< 7.6 \text{ MeV}. \end{aligned}$$

These limits eliminated the existence of various light ($< m_Z/2$) new particles such as light scaler neutrinos that might play an important role in early universe.

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†Experimental errors of luminosity measurements are generally better: for example, it is 0.076% for the OPAL experiment.

‡Small corrections due to the charged lepton masses were taken into account in the actual calculation.

§These limits are rather conservative. Assuming the Gaussian distributions of $m_t = 180 \pm 12$ GeV (a weighted average of [11]) and $\alpha_S = 0.123 \pm 0.006$ in the Standard Model prediction, the 95% C.L. limits become $\Delta\Gamma_Z < 13$ MeV and $\Delta\Gamma_{\rm inv} < 3.0$ MeV.

Universality of Weak Interaction

The interaction between Z^0 and lepton ℓ can be expressed in terms of the lepton's vector and axial vector couplings, $g_{V\ell}$ and $g_{A\ell}$. The partial decay width obtained from the cross section measurement is given by:

$$\Gamma_\ell \;=\; \frac{G_F m_Z^3}{6\pi\sqrt{2}}\left(g_{V\ell}^2 + g_{A\ell}^2\right)\left(1+\delta_\ell^{\mathrm{QED}}\right),$$

where $\delta_\ell^{\mathrm{QED}}$ is the final state QED correction.

In the experiments the angular distributions of the $\ell^+\ell^-$ pairs were also measured. The angular distribution is usually represented by forward–backward charge asymmetry, A_{FB}^ℓ. At the Z^0 resonance, because of the interference between the vector and the axial vector couplings, the asymmetry is generally not zero. The forward–backward asymmetry can be written in terms of the couplings:

$$A_{\mathrm{FB}}^\ell \;=\; \frac{3}{4}\mathcal{A}_e\mathcal{A}_\ell,$$

where $\mathcal{A}_\ell \equiv (2g_{V\ell}g_{A\ell})/(g_{V\ell}^2 + g_{A\ell}^2)$.

For τ leptons, using the five τ decay modes, $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, $\rho\nu$ and $a_1\nu$, the longitudinal polarization of final state τ pairs, $\mathcal{P}_\tau \equiv (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$, was also measured. It is given as a function of the angle θ between the initial e^- and the final τ^-:

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau + \mathcal{A}_e F(\cos\theta)}{1+\mathcal{A}_\tau\mathcal{A}_e F(\cos\theta)},$$

where $F(x) \equiv 2x/(1+x^2)$. The polarization averaged over $\cos\theta$ measures $\mathcal{A}_\tau$, while the forward–backward polarization asymmetry provides a measurement of $\mathcal{A}_e$.

Based on these measurements, the couplings of three charged leptons were obtained (Fig. 3). With the convention of $g_{Ae} < 0$, the signs of the couplings of all charged leptons are uniquely assigned. The good agreement of the couplings of three leptons provides strong confirmation that the Z^0 couplings to leptons are universal. Their values also agree with the prediction of the Standard Model, especially if the top quark is heavy (Fig. 3).

The Z^0 couplings of quarks were also studied. Among the five flavors of quarks produced in Z^0 decays, bottom and charm quarks can be identified by their decays. For example, since hadrons containing bottom quarks have relatively long life times, their displaced decay vertices are easily tagged by the Si vertex detectors. High momentum leptons from semi-leptonic decays and $D^{*\pm}$ and D mesons can be also tagged to identify the heavy quarks. The rates of the tagged hadronic events provide measurements of the ratios of the b and c partial widths to the total hadronic width, $R_q \equiv \Gamma_q/\Gamma_{\mathrm{had}}$ (q=b,c). For the forward–backward charge asymmetries, $A_{\mathrm{FB}}^{\mathrm{b}}$ and $A_{\mathrm{FB}}^{\mathrm{c}}$, the quark charge is implied from the lepton charge, the momentum-weighted hemisphere charge or the charge of the $D^{*\pm}$ meson. Because the measurements of R_q and A_{FB}^q are strongly correlated with the semi-leptonic branching ratios, BR(b$\to \ell$) and BR(b$\to$c$\to \ell$), and the average $B^0\overline{B}^0$ mixing $\bar{\chi}$, all of these quantities were simultaneously determined from the measurements, by using correlation matrices derived from a detailed breakdown of common

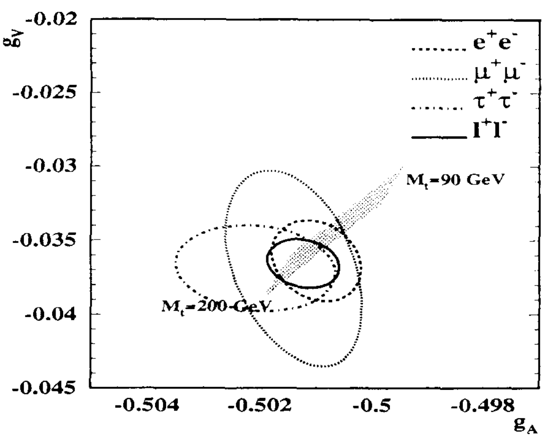

Figure 3: The measured vector (g_V) and axial-vector (g_A) couplings for each charged lepton species. The 68% C.L. contours are plotted. The combined result (denoted by $\ell^+\ell^-$) is also shown. The shaded area represents the Standard Model prediction, where its dependence on the top quark mass is shown.

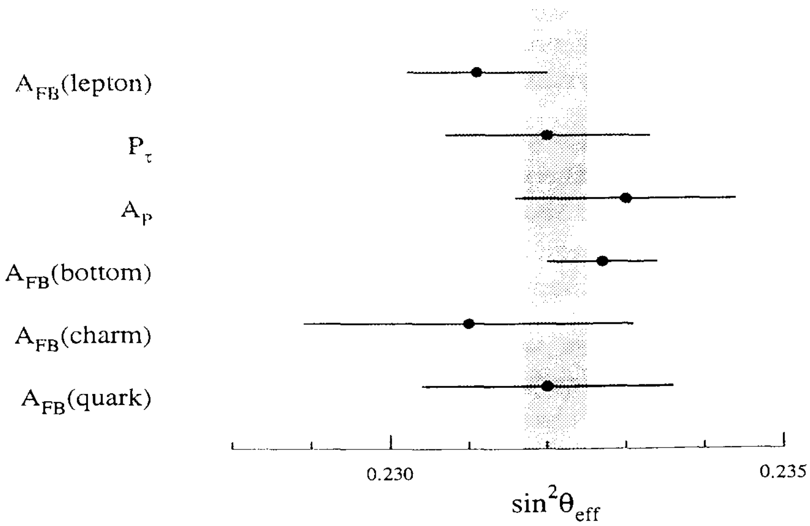

Figure 4: The effective Weinberg angles $\sin^2\theta_{\rm eff}$ obtained from various measurements at LEP are compared. The shaded band indicates the average value ($\pm 1\sigma$) of all the measurements.

uncertainties. The couplings of the heavy quarks, obtained this way, are in agreement with the Standard Model predictions.

In addition, using the hemisphere charge technique, the average forward–backward charge asymmetry of the five flavors of quarks was also measured.

To compare the hadron asymmetry results with those of leptons, the effective Weinberg angles, $\sin^2\theta_{\rm eff} \equiv (1/4)(1 - g_{V\ell}/g_{A\ell})$, † were calculated from all the asymmetry measurements. The results are plotted in Fig. 4. They agree quite well, thus providing the evidence that the Z^0 couplings are universal for both leptons and quarks. The average value of $\sin^2\theta_{\rm eff} = 0.2318 \pm 0.0004$ marks the most precise determination of the couplings of the weak interaction.

Top Quark and Higgs

The LEP measurements described in the previous sections are in excellent agreement with the Standard Model predictions. However, this good agreement is only obtained with the quantum corrections with relatively heavy top quarks (Fig. 3). The effects of heavy top quarks enter the corrections to the gauge boson propagators. The quantum corrections also have weak dependence on the Higgs boson mass $m_{\rm H}$. Thus there is no apparent deviation due to new physics beyond the Standard Model. Especially, deviations expected for simple technicolor models are not observed. This effectively make these models unlikely as realistic extensions of the Standard Model.

Assuming that the Standard Model is correct, we can then calculate the top quark mass, $m_{\rm t}$, from the LEP measurements. Values of the top quark mass calculated from the various LEP measurements are shown in Fig. 5. All the measurements (with a possible exception of $R_{\rm b}$, which is about 2σ away) give consistent values. Combining all the LEP measurements results in $m_{\rm t} = 176 \pm 10$ GeV for $m_{\rm H} = 300$ GeV. A variation of $m_{\rm H}$ from 60 to 1000 GeV gives an additional ambiguity of 18 GeV in $m_{\rm t}$.

As a comparison, the $m_{\rm t}$ values evaluated from other experiments are also plotted in Fig. 5. While the W mass measurements at the Tevatron collider [5] and the neutrino scattering experiments [6] give consistent values, the left-right asymmetry measurement at the SLC [7] is more than 2σ away from the LEP average. Combining all of them together with the LEP results, we obtain essentially the same result: $m_{\rm t} = 179 \pm 9$ GeV.

The above calculations include a theoretical error of 4 GeV in $m_{\rm t}$ due to the uncertainty of the contribution of light quarks to the photon vacuum polarization in the evaluation of $\alpha(m_{\rm Z}^2)$. Recently there have been several attempts to re-evaluate $\alpha(m_{\rm Z}^2)$ [8, 9, 10] giving a large range of values from $1/(129.08 \pm 0.10)$ [8] to $1/(128.896 \pm 0.090)$ [10]. All the above calculations used the value of $1/(128.896 \pm 0.090)$; if instead $1/129.08$ is used, the $m_{\rm t}$ values will shift by -9 GeV.

Recently the CDF and the DØ experiments at the Tevatron collider reported the direct observation of the top quark [11]. Their estimates of $m_{\rm t} = 176 \pm 8 \pm 10$ GeV (CDF) and $m_{\rm t} = 199^{+19}_{-21} \pm 22$ GeV (DØ) are in perfect agreement with the LEP results. This is a great success

†There are small corrections to the quark vertex.

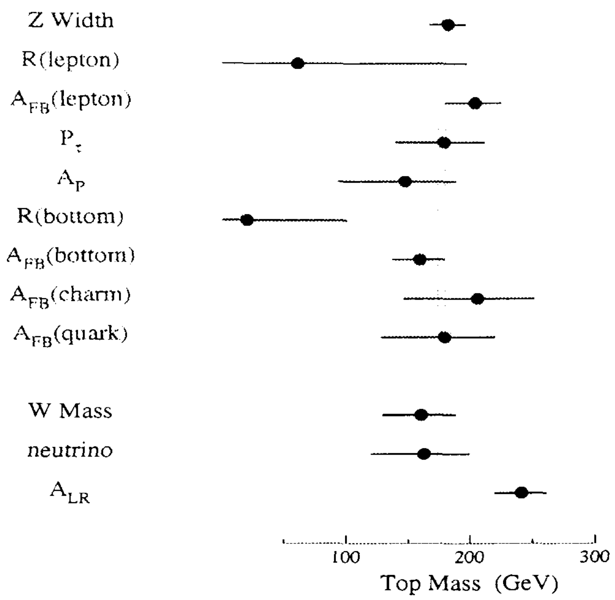

Figure 5: The top quark mass is estimated from various LEP measurements. Results from other experiments (W Mass, neutrino and A_{LR}) are also shown. The shaded band represents the average of the LEP measurements ($\pm 1\sigma$). The Higgs mass m_H and the strong coupling constant $\alpha_S(m_Z)$ are assumed to be 300 GeV and 0.123.

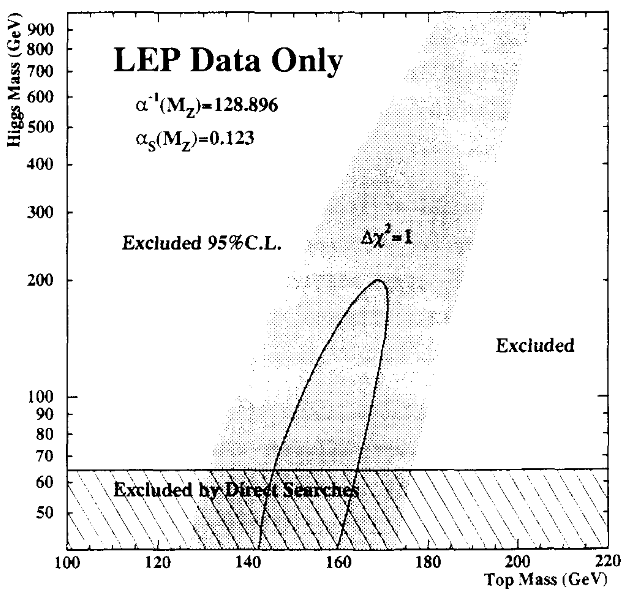

Figure 6: The masses of top quark and Higgs are strongly constrained by the LEP measurements. Indicated by the shaded area is the 95% C.L. contour. The 1σ contour ($\Delta\chi^2 = 1$) is also shown.

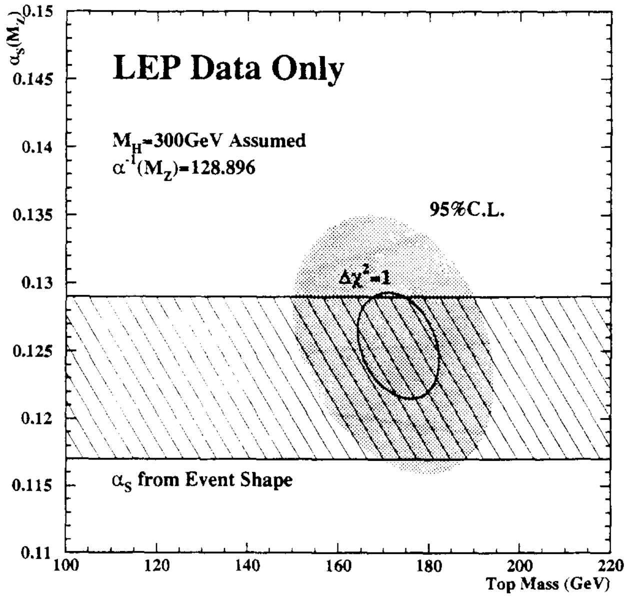

Figure 7: The strong coupling constant $\alpha_S(m_Z)$ is fitted together with the top quark mass using the LEP electroweak measurements. The $\alpha_S(m_Z)$ value ($\pm 1\sigma$) obtained from the event shape analysis of hadronic Z^0 decays is also shown.

of the Standard Model: all the measurements are consistently described down to radiative corrections by the Standard Model with top quarks of about 180 GeV.

As the experimental precision becomes better than the uncertainty due to m_H, it is now possible to extract constraints on the values of m_H from the LEP measurements. Fig. 6 shows the result of a simultaneous fit of m_t and m_H to the LEP data. The data slightly tend to prefer lighter Higgs bosons, mainly due to the measurements of R_ℓ and R_b (see also Fig. 5).

If the Higgs bosons are light enough, they are copiously produced in the Z^0 decays via the process $Z^0 \rightarrow Z^{0*}H^0$ at LEP. None of such decays have been found in spite of the extensive searches since the start of the experiments. This has placed a 95% C.L. lower limit of 65.1 GeV on the Higgs mass, which is also indicated in Fig. 6. Heavier Higgs bosons with a mass up to m_Z are expected to be discovered at LEP-II.

Strong Interaction

Various "event shape" variables of hadronic events have been systematically analyzed to determine the QCD coupling constant $\alpha_S(m_Z)$ at LEP. The obtained α_S value of 0.123 ± 0.006 [12] is, however, dominated by the theoretical uncertainties due to unknown higher order corrections ($\mathcal{O}(\alpha_S^3)$ or higher).

On the other hand, the QCD corrections to the rate of hadronic Z^0 decays are known up to $\mathcal{O}(\alpha_S^3)$. Thus the theoretical uncertainties are believed to be small on this variable. The total width of Z^0 also contains the same QCD corrections. Since these observables depend on the top quark mass, $\alpha_S(m_Z)$ and m_t were simultaneously fitted to the LEP electroweak measurements. The result of the fit is shown in Fig. 7. The obtained value of $\alpha_S = 0.125 \pm 0.004$ agrees well

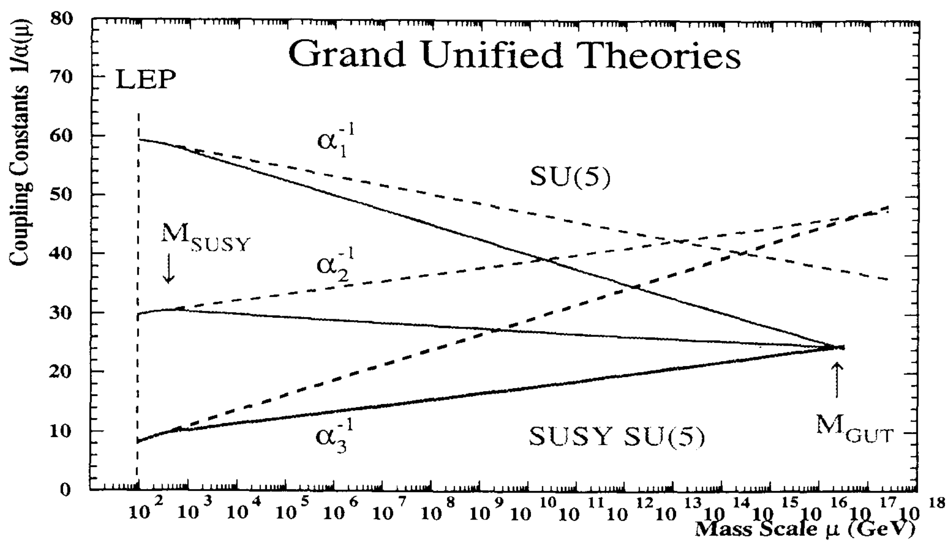

Figure 8: The coupling constants measured at LEP are extrapolated to higher energy regions according to the renormalization group equations. With a grand unification scenario of supersymmetric $SU(5)$, they all meet at around 10^{16} GeV, provided that the supersymmetric energy scale (M_{SUSY}) is below 10^3 GeV.

with the result from the event shape analysis.

Similarly, from the rate of hadronic decays of τ leptons, the QCD coupling constant at the energy scale of τ mass was obtained as $\alpha_{\mathrm{S}}(m_\tau) = 0.367 \pm 0.007$ [13]. A comparison of this value with the above $\alpha_{\mathrm{S}}(m_{\mathrm{Z}})$ values affirms the asymptotic freedom of QCD. If extrapolated to the Z^0 mass according to the renormalization group equations, it leads to $\alpha_{\mathrm{S}}(m_{\mathrm{Z}}) = 0.1222 \pm 0.0023$, which is in excellent agreement with the other results. This is the most accurate measurement of $\alpha_{\mathrm{S}}(m_{\mathrm{Z}})$, though uncertainties due to non-perturbative effects could be large [14].

Grand Unified Theories

In the framework of the Standard Model, three gauge interactions, being independent of each other, have independent gauge couplings, although the weak and the electromagnetic interactions are mixed. A group of models called grand unified theories (GUT) regard these interactions as originated from a single gauge interaction with a larger gauge symmetry. According to these models, apparently different gauge coupling constants will become the same at higher energy scales. Since leptons and quarks in the same generation are treated in a unified way, the assignments of the quantum numbers of these particles are naturally explained in these models.

To verify the possibility of the grand unification of the gauge couplings, the coupling constants measured accurately by the LEP experiments were extrapolated to higher energies according to the renormalization group equations (Fig. 8). The three coupling constants do not meet for the simplest grand unified theory with $SU(5)$ gauge symmetry. However, if the theory is made supersymmetric, they all meet at an extremely high energy of 10^{16} GeV (Fig. 8), provided that the scale of supersymmetric particles are set below 1 TeV.

Although this may be just a coincidence, it is intriguing to imagine that there might exist an energy scale of new physics (supersymmetry) slightly above the Z^0, and that the investigation at this energy scale might lead to understanding of physics at 10^{16} GeV, which corresponds to the universe just 10^{-23} seconds after the Big Bang.

If this supersymmetric grand unification is correct, supersymmetric partners of the existing particles must exist below 1 TeV. Particularly a Higgs boson with a mass lighter than 150 GeV should be discovered. Different modes of productions and decays of Higgs bosons, in addition to those of the Standard Model Higgs, have been carefully searched for at LEP. Other supersymmetric particles have been similarly looked for. In spite of these elaborate efforts, the LEP experiments have only placed constraints on the possible supersymmetric theories so far.

Factory of Bottoms and Taus

At LEP, clean, high-statistics samples of bottom quark jets and τ leptons are obtained from a huge number of Z^0 decays. LEP is thus serving as a factory of the third generation particles. In the following a few examples of the on-going investigations in this field are described.

Decays of τ leptons, which proceed via virtual W, provide a good place to study interactions with W bosons. If τ and μ leptons interact with W bosons with the same couplings, the branching ratio of τ into electrons, B_e, and the τ lifetime, τ_τ, must satisfy the following relation: $B_e = (\tau_\tau/\tau_\mu)(m_\tau/m_\mu)^5$. Here τ_μ is the lifetime of μ, and m_τ and m_μ are the masses of τ and μ leptons. But the earlier measurements of these quantities did not satisfy the relation at 2–3σ level. However, as LEP's precise measurements of τ_τ and B_e became available, together with the accurate measurement of m_τ at the Chinese e^+e^- collider BEBC, it turned out that the relation actually holds. This can be expressed as the ratio of the W couplings to τ and μ, which is 0.9986 ± 0.0033. This confirms the universality of the W interaction.

Other important results from studies of τ decays include a new upper limit of τ neutrino mass of 23.8 MeV at 95% C.L. using a new 2-dimensional likelihood method for 5-prong decays [15].

In the field of bottom physics, in addition to the measurements of masses and lifetimes of bottom hadrons, there have been active investigations on the $B^0\overline{B}^0$ oscillations [16]. At LEP, a time oscillation between B^0_d and its anti-particle was observed for the first time. The measured period of oscillation provided a precise determination of the mixing ratio or the mass difference of $\Delta m_d = 0.513 \pm 0.036$ (ps^{-1}). A similar phenomenon is also expected for the daughter particles B^0_s. The $B^0_s\overline{B}^0_s$ mixing was found to be much larger than $B^0_d\overline{B}^0_d$ mixing: $\Delta m_s/\Delta m_d > 7.8$ (95% C.L.). These measurements will have an impact on the study of CP violation, as they constrain one of the Kobayashi-Maskawa matrix elements through the relation $\Delta m_s/\Delta m_d \propto |V_{ts}/V_{td}|^2$.

Future Look

In 1995 it is planned that LEP will carry out another Z^0 resonance scan which aims at a determination of Γ_Z with an accuracy of 2 MeV. This will reduce errors of various partial width measurements, leading to an overall improvement in the sensitivities of the electroweak measurements for testing the Standard Model. Then, toward the end of 1995, with additional super-conducting cavities installed, LEP may enter a new energy frontier of 120–140 GeV, where signatures of new physics will be looked for.

If the installation and the conditioning of the super-conducting cavities go well, it is foreseen that the center-of-mass energy of the LEP machine will reach the threshold of W-pair production in 1996 — This will be the start of LEP-II. Here, through the measurement of W-pair production, further examinations of gauge interactions will be made.

The current LEP data indicate that the W mass is 80.32 ± 0.06 GeV, which is in excellent agreement with the directly measured value of 80.26 ± 0.16 at the Tevatron collider [5]. At LEP-II, the W mass will be best measured by reconstructing the event kinematics and a precision of 0.03–0.04 GeV can be obtained [17]. Combined with the current LEP data, this measurement will strongly constrain the Standard Model parameters. If the top quark mass is measured with a good precision, it will enable us to evaluate the Higgs mass. The triple gauge boson couplings will be also studied by measuring the distributions of the production and decays of the W boson. This will provide precious information on the structure of the gauge boson couplings for a further examination of the gauge interactions.

In addition to these standard physics analyses, it is very important to make a comprehensive search for new particles such as Higgs bosons and supersymmetric particles at LEP-II. The long-awaited Higgs boson could be light enough for discovery at LEP-II as might be suggested by the LEP data. Especially, if supersymmetry is the correct extension of the Standard Model, just as the coupling unification might imply, one of the Higgs bosons must be light, making the discovery potential at LEP-II reasonably high. It has been demonstrated that, with a data sample of 300 pb^{-1}, a discovery of the Higgs at 5σ level is possible if its mass is lighter than $\sqrt{s} - 100$ GeV [18]. This is true even if the Higgs mass happens to be equal to the Z^0 mass.

As the LEP experiments have been providing more and more evidence that the gauge interaction framework of the Standard Model is correct, the next step will be to make experimental studies on the origin of the symmetry breaking. The experiments at LEP-II could become the first step forward in this direction. And the next-generation colliders, the LHC and the e^+e^- linear collider, together will make further steps towards full understanding of the symmetry breaking mechanism, on the firm basis of gauge interactions that are being established by the LEP experiments.

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