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LEP, the Laboratory for Electrostrong Physics, one year later

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Abstract

The year 1990 has been the harvest year for LEP and its four detectors. By now many reviews have been published. The present one has been written for those who, not working in the field, are interested in a general description of the main results. Three subjects were singled out. The measurement of the main parameters of the Z-resonance, explored at LEP by scanning through the cross-section peak in small energy steps. The (still unsuccessful) search for standard and supersymmetric neutral Higgs particles. The extrapolation to higher energies, now allowed by the LEP accurate measurements of the electroweak and strong coupling constants, together with some interesting consistency checks on Grand Unified Theories.

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1. Introduction

In August 1989, LEP, the CERN electron-positron collider, produced the first events in which Z - bosons were created at rest and then decayed. In September the energy of the machine was varied in steps of 1 GeV around the value of 45.5 GeV and data were collected by the four detectors : ALEPH, DELPHI, L3 and OPAL. In October 1989, the determination of the number of neutrino species, as obtained from a two parameter fit to the Z - resonance, was announced in a public meeting

$$N_\nu = 3.15 \pm 0.20. \quad (1)$$

The results of the four Collaborations, which have been averaged in Eq. 1, were published immediately afterwards. [1]

In 1990 the luminosity of LEP has been increasing up to a maximum value of

$$L \simeq 6 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}, \quad (2)$$

and beams have been costing in the 27 km long storage ring for up to a day. At such a luminosity, a Z-boson is produced about every five seconds. By the end of 1990, the four Collaborations had collected a total of 700'000 events, somewhat unevenly distributed because, due to a machine asymmetry discovered too late in the year, in the interaction regions occupied by L3 and DELPHI the luminosity was ~ 25 % lower than in the regions where ALEPH and OPAL are installed. The many results obtained in these first runs have been published in about hundred reports and reviewed recently for the Singapore Conference [2].

Seen from far away, two results stick out : the accurate measurement of the number of neutrino species and the fact that no standard Higgs particle (to be called "higgson" in the following) was found in the mass range explored until now ($0 < M \leq 50 \text{ GeV}$). In Sections 2 and 3 these two results, and only few others, are described. In Sections 4 and 5, I underline a *third* result which, in my mind, is not less important but was neglected until now : by using as input the LEP precision results on the electroweak and strong coupling constants (discussed in Sections 2 and 4) it is now possible to perform meaningful consistence checks of Grand Unified Theories (GUT). In this way some interesting conclusions can be drawn on the physics to be expected at energies ten times larger than the one available at present at LEP.

2. Around the Z - peak

The four LEP detectors have been described many times, and in particular the interested reader can find all the necessary details in Refs. [3].

Figure 1 shows as an example DELPHI, the experiment in which I am personally involved. ALEPH and OPAL have similar external dimensions ($10 \times 10 \times 10 \text{ m}^3$), while L3 is much larger because the penetrating muons are measured in an air solenoidal magnet having an inner diameter of about 20 meters.

The four detectors can easily distinguish the final states which are of importance for the measurement of the parameters of the shape of the Z - resonance. The final states are either *leptonic* (e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$) or *hadronic* (which are due to the Z decaying in a quark - antiquark pair). Leptonic decays are characterized by the very small number of charged tracks : typically two for the e^+e^- and $\mu^+\mu^-$ channels and two or four in the $\tau^+\tau^-$ channel. The hadronic events contain on average twenty charged hadrons grouped in two or more jets.

The main parameters of the Z-boson are its mass M_Z and its partial decay widths in the various channels, which sum up to the total width

$$\Gamma_Z = \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_h + \Gamma_\nu + \Gamma_{\text{unknown}} \quad (3)$$

The notations are self-evident. Γ_ν is, in particular, the partial width for the Z-boson to decay in the different types of "light" neutrino - antineutrino pairs, i.e. neutrinos having much smaller mass than $M_Z/2$ so that energy conservation does not prohibit the decay. Before LEP three types of neutrinos were known (ν_e , ν_μ and ν_τ) and the important question was : are other (light) neutrinos produced in Z-decays so to increase proportionally Γ_ν ? Moreover, any other decay process, not present in the generally accepted Standard Model (SM) of the weak, electromagnetic and strong interactions, would contribute to Γ_{unknown} .

Once M_Z is measured, the Standard Model predicts values for all the other quantities : some of them with very high accuracy, other less precisely, mainly because other not well known parameters intervene. Among them the *two* most important ones are the mass M_t of the yet undiscovered top quark and the mass M_h of the neutral higgson h^0 . In fact, the dependence is such that, by using precision measurements, one can reverse the argument and get from the data useful information on the top mass and eventually, when many million events will be collected, on M_h .

By "scanning", i.e. by varying the energy of LEP around the value at which the event rate is maximum because of the resonance production of Z-bosons, the four Collaborations have measured the energy dependence of the cross-sections for the production of hadrons (due to quark - antiquark creation) and of leptonic pairs. Some of the results of such a scanning are shown in **figure 2**. The measured cross-sections are plotted on the vertical axis and the energy, which is computed from the accurately known strength of the magnetic field bending the particles in LEP, on the horizontal one. To transform an observed event rate into a cross-

section, a detector has to register *at the same time* the rate of a process which has a well-known cross-section, so that the integrated luminosity can be measured. Electron-positron scattering events at angles around 1° are used for this purpose. In fact, at such small angles the cross-section for these so-called "Bhabha scattering" events can be computed with quantum electrodynamics (QED) to accuracies which are better than 1 %. The first great (positive) surprise is that the monitoring systems of the LEP experiments, designed for $\sim 2\%$ systematic accuracy, have been working much better than foreseen. Precisions in the range of 0.5 - 0.8 % were achieved after few months of running. This technical prowess is at the origin of the incredible accuracy with which the number of neutrinos has been determined in a short time.

Figures 3 to 6 summarize some of the results obtained in the 1989 and 1990 runs by the four Collaborations^[4]. For each quantity the horizontal bar represents the final result presented by the Collaboration, after unfolding the systematic error which is common to the four measurements. The weighted average and the $\chi^2/(\text{degree of freedom})$ of the four experimental results are computed by using these errors. The average value and its error are represented on the line below, (AVG.W.COM.SYST.ERROR = average with common systematic error) ; here the common systematic error is re-introduced. (A typical error of this kind is the $\sim 0.5\%$ error in the luminosity due to the theoretical calculation of the Bhabha cross-section mentioned above). The lowest line in each figure is the expectation of the Standard Model. For the mass of the Z-particle this entry does not exist because it is an input to the Standard Model and, at present, only experiment can tell what it is.

The most striking feature of these results, and of the many others which are not shown, is the agreement with the Standard Model, once the value of M_Z is known. The partial width Γ_l represented in **figure 4** is obtained by assuming universality of the leptonic couplings, i.e. by assuming $\Gamma_l = \Gamma_e = \Gamma_\mu = \Gamma_\tau$. From the average value of Γ_l , and other quantities, one can obtain a very accurate number for a most important parameter of the model, the *weak mixing angle*. One gets at present^[4]

$$\sin^2\Theta(M_Z) = 0.2320 \pm 0.0010, \quad (4)$$

where the exact definition of $\sin^2\Theta(M_Z)$ is somewhat complicated. With a certain degree of approximation one can say that Θ is an angle such that $\cos\Theta = M_W / M_Z$, where M_W is the mass of the charged weak boson W. Note that, before LEP, the error on $\sin^2\Theta$ was about three times larger. Combining this result with the outputs of lower energy experiments (in particular on neutrino scattering and direct measurements of M_W) one can obtain, in the framework of the SM, an estimate of the top mass : $M_t = (130 \pm 35) \text{ GeV}$.

The total width Γ_Z of the Z-boson is about 2.5 GeV which means that, according to the indetermination principle, a still-standing Z-particle, once produced in LEP, lives about 10^{-24} seconds. **Figure 6** shows the value of the invisible width Γ_{inv} , which, according to Eq. 3, equals the sum $\Gamma_v + \Gamma_{unknown}$. By making the SM hypothesis that $\Gamma_{unknown} = 0$, one can divide the measured invisible width by the SM expectation for the width of Z into *one* (light) neutrino - antineutrino pair and obtain the number of (light) neutrino species in a three-parameter fit :

$$N_v = 2.98 \pm 0.05 . \quad (5)$$

By comparing Eqs. 1 and 5, it appears that in one year of running the error was reduced by a factor of 4. By now the error is dominated by systematics effects, and in particular by the accuracy in the determination of the Bhabha scattering rate. Further improvements are possible with more statistics and better control of the systematics. By hard work in the coming years the error of Eq. 5 will be divided by a factor 2 - 3.

3. Searches for new particles

Searching for new particles is a must at the opening of a new energy frontier. LEP is no exception, with the additional advantage that the annihilation of an electron-positron pair is a very clean process. The about 90 GeV liberated in the annihilation are transferred in a resonant way uniquely to the Z-field. Moreover, the produced Z-boson couples democratically to all known and, presumably, also unknown particles, so that the search for new particles is limited only by the energy conservation law. For this reason, in about one year the four experiments have been able to exclude the existence of most of the particles – imagined by theorists – which, coupled to the Z-boson, have a mass which goes from zero to the kinematical limit of about $M_Z / 2 \simeq 45$ GeV. The list of exclusions is very long : new neutrinos, new quarks, heavy leptons, supersymmetric partners of the known matter particles (as sleptons and squarks), leptoquarks and so on. Here I discuss only the unsuccessful searches for neutral higgson(s), the spin zero boson(s) supposed to be responsible for the fact that both the matter-particles (leptons and quarks) and some of the force-particles (the intermediate bosons W and Z) have a mass different from zero.

Only the neutral higgson h^0 should exist in the minimal SM of the fundamental interactions, which is based on the gauge group $SU(3) \times SU(2) \times U(1)$ and contains *one* Higgs doublet which gives mass to all the particles. Before LEP, one had doubtful limits for the existence of the standard higgson with mass smaller than about 5 GeV. Nowadays we know for sure that a neutral h-boson with mass smaller than about 50 GeV does *not* exist. This is

enormous progress, even if many would have liked to see the discovery of such a fundamental particle. To those who think that because of this lack of discoveries, "nothing new came out from LEP", I want to remind the popperian view of science : advances come from the *falsification* of established theories. From this point of view, the negative results of about one year of running at LEP, by falsifying a number of possible theoretical models, have greatly restricted the still open possibilities.

The lower limits (at 95 % confidence level) on the mass M_h of the Standard Model higgson obtained by the four experiments are [5] :

48 GeV (ALEPH), 40 GeV (DELPHI), 41.8 GeV (L3), 45 GeV (OPAL).

Combining limits is not as easy as combining measured numbers. Still, the above results, taken together, certainly exclude at 95 % confidence level that the h^0 - boson of the SM has a mass smaller than 50 GeV.

The better limits achieved by ALEPH and OPAL are due to a combination of higher statistics (see section 1) with the hermeticity of the detectors. This is an essential aspect in this kind of experiments, which are based on the search for the decay of the Z-boson into a higgson h^0 and a pair of leptons. The higgson, once produced, decays immediately in a quark-antiquark pair, which appears as two jets of hadrons, so that one is looking for events which contain *two* leptons and *two* jets.

Before LEP start-up, it was thought that the only reactions which could be used to put limits on the production of Higgs particles would have been those in which either a pair of electrons or a pair of muons are produced together with the two jets coming from the higgson. The hermeticity of the LEP detectors has instead allowed the use of the much more frequent reaction in which the higgson is produced together with an invisible neutrino-antineutrino pair. In this case the process is characterized by a large missing energy, carried away by neutrinos, and it is very important to use detectors which – being "hermetic" – are able to accurately detect all the energy of the produced particles (apart neutrinos). This has been the second (positive) surprise : the results have surpassed the most optimistic expectations. Beforehand it was thought that each experiment had to collect more than 10^6 Z decays to put a limit as large as $M_h \geq 45$ GeV. By using the neutrino-antineutrino channel, this has been achieved with less than 200'000 events. In the next couple of years with more statistics the limit should be pushed to at least 60 GeV.

In the minimal supersymmetric (SUSY) model the spectrum of the higgsos is richer [6] than in the minimal SM : there are three neutral higgsos (usually indicated with the symbols h^0 , H^0 and A^0) and a pair of charged Higgs particles. This comes from the fact that the interaction with the Higgs fields has to give masses both to the matter-particles (leptons and quarks) and to their supersymmetric particles, the "sparticles", so that *two* Higgs doublets have to be introduced. The symmetry between particles and sparticles of all SUSY models has the much needed consequence of curing the divergences which push the mass of the only higgsos of the SM to unreasonably large values. Moreover SUSY has many other appealing features as, for instance, its compatibility with theories of quantum gravity. For these reasons, minimal SUSY is *the model* which subatomic physicists would really like to falsify. For the moment, LEP data have been able to exclude only a limited, though non negligible, fraction of its parameter space.

There are *two* independent parameters in the neutral Higgs sector of the minimal SUSY model : often the masses M_h and M_A of the lightest scalar and pseudoscalar higgsos are used. To lowest order the following very important inequalities hold [7] :

$$M_h \leq M_Z , \quad (6)$$

$$M_H \geq M_Z , \quad (7)$$

$$M_h \leq M_A \leq M_H , \quad (8)$$

which however are modified by recently calculated higher order corrections [8]. Before these calculations, Eq. (6) appeared to be *the equation* that would allow the falsification of the minimal SUSY model. Indeed, in the years 1994 - 1995 LEP will be upgraded from a total c.m. energy of ~ 100 GeV (LEP 100) to $\sim 180 - 190$ GeV, within the so-called "LEP 200" programme. At energies not smaller than 190 GeV a higgsos h^0 of mass ≤ 90 GeV would be seen either in the already discussed neutrino channel ($h^0 \nu \bar{\nu}$) or in the complementary process ($h^0 A^0$), which has 4 jets in the final state. The non-observation of the h-particle in the mass range up to M_Z would prove the minimal SUSY to be *wrong* if, and only if, Eq. (6) is valid. Higher order corrections smear this sharp prediction [8] and will force us to continue in the painful work of gradually eroding the parameters space of the model without coming to a firm conclusion with LEP 200.

The present status of the excluded region is such that the lightest higgsos of the minimal SUSY model has a mass $M_h \geq 40$ GeV at a 95 % confidence level and that, similarly, $M_A \geq 40$ GeV [2]. There is clearly still a long way to go before excluding masses as large as 90 GeV.

4. Measurements of the strong coupling constant

During the first year of LEP, the third positive surprise came from the relative easiness with which one could measure the quark-gluon coupling constant, usually expressed as α_s , the equivalent of the fine structure constant $\alpha = 1/137$ of electromagnetism. Unfortunately the subject is involved and here the arguments can only be sketched.

Figure 7 describes the electroweak creation of a quark-antiquark pair in the decay of a Z-boson, followed by the radiation of hard gluons and, then – at a distance of less than 10^{-13} cm – by the fragmentation of the virtual partons (quarks and gluons) and the hadronization, which lead to the hadrons observed in the detector. The cascade of processes is very complicated and it has to be well understood to obtain, from the measured final states, the coupling constant α_s which determines the initial radiation of gluons. A further complication is due to the fact that the strong coupling constant of quantum chromodynamics (QCD) α_s is not at all constant but "runs", i.e. has a value which depends on the energy scale at which the process takes place [9].

$$\alpha_s = \alpha_s(\mu) \quad (8)$$

The larger the energy scale μ , the smaller is the distance at which the coupling constant $\alpha_s(\mu)$ is measured, so that $\alpha_s(\mu)$ is roughly the coupling constant which is effective at a distance $\hbar/\mu$.

The inverse of the coupling constant $\alpha_s(\mu)^{-1}$ has a simple physical meaning: qualitatively it equals the number of times one has to observe a quark before finding – close to it – a gluon of energy larger than μ . Strong interactions are called "strong" because $\alpha_s^{-1} \approx 1/2$ at $\mu \approx 0.5$ GeV, so that at distances of the order of 10^{-13} cm there is no such a thing as a "bare" quark.

The main property of QCD is "asymptotic freedom", which is the prediction that, due to virtual effects, $\alpha_s(\mu)$ decreases logarithmically when the scale μ increases, so that the radiation of gluons by quarks is less probable at small distances than at large distances. QCD is based on the gauge group SU(3) of colored quarks and gluons and the running of the strong coupling constant can be computed with perturbative methods. For a given value of μ , the quarks which contribute to the running of the coupling are the "light" ones, i.e. those which have masses much smaller than μ . The number f of relevant quarks is thus a function of μ . For scales $\mu \leq 5$ GeV (below the beauty quark mass $M_b = 5$ GeV) $f = 4$ because the only active quarks are u , d , s , and c . At LEP ($\mu \approx 100$ GeV) also the b quark contributes and $f = 5$. In general in this energy range the asymptotic first order expression of the coupling constant is

$$\alpha_s(\mu) = \frac{12\pi}{(33-2f) \ln(\mu/\Lambda)^2}, \quad (9)$$

where $f = 5$ and Λ is the QCD parameter which has to be obtained from experiment. Its numerical value depends on the number of active quarks and on the scheme adopted in the definition of the coupling constant. The usual prescription [10] is the "modified minimal subtraction scheme" ($\overline{MS}$) so that, with $f = 5$, a better symbol for the parameter Λ appearing in Eq. (10) is $\Lambda^{(5)}_{\overline{MS}}$.

Before the start-up of LEP, in Ref. 9 Guido Altarelli summarized all the lower energy data on $\alpha_s(m)$ coming to the conclusion that $\Lambda^{(5)}_{\overline{MS}} = (140 \pm 60) \text{ MeV}$ so that:

"...the prediction for α_s to be measured at LEP is very precise : $\alpha_s (\mu = M_Z) \simeq 0.11 \pm 0.01$. Establishing that this prediction is experimentally true would be a very quantitative and accurate test of QCD, conceptually equivalent but more reasonable than trying to see the running (of α_s) in a given experiment".

To obtain $\alpha_s(M_Z)$ the main methods are based on the measurement of a quantity that is proportional to α_s , and thus is zero in lowest order (corresponding to a quark - antiquark pair in the final state). Such a quantity is sensitive directly to the quark - antiquark - gluon coupling. To determine α_s it is necessary to know the same quantity also to the next order (α_s^2). The most widely used quantities at lower energies and at LEP are the fraction (R_3) of events containing three jets (the so-called *three-jet rate*) and the asymmetry of the energy - energy correlation (*AEEC*), which compares the width of a quark jet with the width of the combination of a quark and a gluon jet and, of course, it is zero if there is no gluon radiation.

The four LEP Collaborations have published by now a number of papers on the determination of $\alpha_s(M_Z)$ with these and other methods. The overall conclusion is that the value (0.11 ± 0.01) certainly covers the totality of the results. However, there are qualifications which require a long and detailed discussion and divide the experts. For instance, the final results of two recent reviews [11] can be summarized by the following two numbers :

$$\begin{array}{ll} \text{W. de Boer :} & \alpha_s(M_Z) = 0.107 \pm .007, \\ \text{S. Bethke :} & \alpha_s(M_Z) = 0.118 \pm .008. \end{array} \quad (10)$$

Of the many ingredients which, according to the image of *figure 7*, enter in the determination of α_s , the most uncertain one is the choice of the scale m at which the hard radiation processes have to be computed. In fact, at LEP the number of events is large and statistics are not a problem. Even the non-perturbative fragmentation and hadronization processes taking place in the grey - box of *figure 7* at these high energies can be kept under control, and give errors on $\alpha_s(M_Z)$ which are typically 3 %.

As far as the choice of the scale μ , to be introduced in the second order matrix element describing the hard radiation processes, is concerned, because only α_s^2 calculations exist and there is no firm prescription, the rule of the game has been to vary it between $M_b \simeq 5$ GeV, the mass of the b-quark, and M_Z . A theoretical "scale" error is thus appended to the output value of $\alpha_s(M_Z)$, which turns out to be of the order of ± 0.010 for the three jet rates (R_3), but is about five times smaller for the asymmetry of the energy - energy correlation (AEEC), because in this case the second-order corrections are less important. One of the main arguments of debate is whether this is an indication of the fact that the AEEC is a better quantity than R_3 to derive $\alpha_s(M_Z)$. The difference of opinion reflects itself, together with a somewhat different choice of data to average, in the difference between the central values of Eq. 10. However, the quoted errors which – being a mixture of experimental and of (often maximal) theoretical errors – have *not* the usual meaning of a 68 % confidence level – are large enough to cover it.

In conclusion, all measured values agree with the extrapolation from lower energies, thus confirming QCD predictions. Moreover, they agree also with the most recent analysis of *all* deep inelastic data [12]

$$\alpha_s(M_Z) = 0.109 \begin{array}{c} + .004, \\ - .005. \end{array} \quad (11)$$

5. A LEP view of Grand Unified Theories

LEP has been seen since its inception as a laboratory for very accurate measurements of electroweak parameters. It has been often called "*the (g-2) of electroweak interactions*", and the accumulation of statistics will make this statement even more true : during 1992, the number of bunches will pass from 4 to 8 and, by the end of 1993, each Collaboration should have collected about $5 \cdot 10^6$ Z's, with a potential decrease of the statistical errors by a factor 5. Afterwards LEP will run at higher energy (LEP 200), and with polarized beams it will give further accurate informations on the electroweak parameters, as $\sin^2\theta$, the mass M_W of the W-boson (to less than 100 MeV), and the never observed Z-W-W coupling. Towards the end of the century, the number of electron and positron bunches could be increased from 8 to 18, with a further increase of luminosity : a total of $25 \cdot 10^6$ Z's could be collected in a couple of years. This will open the way to, for instance, studies of $B\bar{B}$ oscillations which cannot be performed with dedicated collider called "threshold beauty factories".

By combining the electroweak data with accurate measurements of the strong coupling constant $\alpha_s(M_Z)$, one can even glance at what happens at energies larger than the one available at LEP and perform meaningful consistency checks of the so-called Grand Unified Theories (GUT). (The name is pompous : Unified Theories would be a better one). These

theories reduce the number of independent coupling constants by embedding the $SU(3) \otimes SU(2) \otimes U(1)$ group of the Standard Model into a group G , in which there is only one underlying gauge coupling constant at the unification scale. If at the scale M_{GUT} the group G is broken into the three independent gauge groups, the evolution of the corresponding coupling constants with the scale μ depends only on the particle content of the $SU(3) \otimes SU(2) \otimes U(1)$ model, but not on the structure of the group G . By evolving the coupling constants, as measured at low energies, towards high energies one can check which particle content is consistent with unification.

The starting point of the analysis of Ref. [13] is the work performed in 1987 in Ref. [14]. Previous approaches to the same problem using LEP data have been done by Paul Langacker [15] and John Ellis et al. [16].

One of the results of Ref. [14] is summarized in **figure 8a** (figure 11 from Ref. [14]) where the *inverses* of the Standard Model couplings are plotted versus the energy. The usual definitions of the coupling constants are

$$\begin{aligned}\alpha_1(\mu) &= \frac{5 \alpha(\mu)}{3 \cos^2 \Theta_w}, \\ \alpha_2(\mu) &= \frac{\alpha(\mu)}{\sin^2 \Theta_w}, \\ \alpha_3(\mu) &= \alpha_s(\mu),\end{aligned}\tag{12}$$

where $\alpha(\mu)$ is the (running) fine structure constant, which for $\mu = 0$ has the well-known value $\alpha(0)^{-1} = 137$ and for $\mu = M_Z$ is $\alpha(M_Z)^{-1} = 128.8$.

According to the GUT hypothesis, there is an energy M_{GUT} such that $\alpha_1(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_3(M_{GUT})$. From Eq. 12 one obtains that $\sin^2 \Theta_w(M_{GUT}) = 3/8 \simeq 0.375$ at $\mu = M_{GUT}$. The energy dependence of the coupling constant is completely determined by the particle content of each theory and the evolution equations are known [17] up to second order in α_i . **Figure 8a** was computed in 1987 using for the values of α_1 , α_2 and α_3 at ~ 100 GeV the averages of *all* the available data and making the assumptions of the minimal Standard Model with three families of matter and one Higgs doublet (which give rise to a single standard neutral higgs h^0). Clearly, around 10^{15} GeV all couplings become of the same order of magnitude, but they do not meet exactly in a single unification point. The deviation from perfect crossing, as expected in the simplest unified theories, was only two standard deviations in 1987. It is now possible to perform the same analysis with data from LEP.

Either results from a single experiment or average values can be used. In **figure 8b** the evolutions of the three coupling constants with the published data of the DELPHI Collaboration are shown; again the Minimal Standard Model with 3 families and 1 Higgs

doublet is assumed [13]. Compared to the results of 1987, the errors, indicated by the width of the lines, are considerably smaller. It is clear that a single unification point cannot be obtained within the present errors : the α_3 coupling constant misses the crossing point of the other two by more than 7 standard deviations. Even if one would neglect the non-unification and take the center of the triangle, there is a problem because the unification scale would be $M_{\text{GUT}} \approx 10^{15}$ GeV. The proton lifetime is determined by M_{GUT} , since one expects the new heavy gauge bosons (X), which in GUT can transform a quark in a lepton, to have masses which are typically $M_X \approx 0.3 M_{\text{GUT}}$. If the proton decay is dominated by X-boson exchange, the proton lifetime for $M_X = 3 \times 10^{14}$ GeV can be estimated to be :

$$\tau_{\text{proton}} \approx \frac{1}{\alpha_{\text{GUT}}^2} \frac{M_X^4}{M_p^5} \approx 10^{29} \text{ years}, \quad (13)$$

where M_p is the proton mass. Such a proton lifetime does contradict the present experimental limits of $\tau_{\text{proton}} \geq 5.5 \cdot 10^{32}$ years [18].

Therefore, both the non-observation of proton decay and the non-unification of the coupling constants independently rule out any minimal GUT, which breaks to the Standard Model below the unification point. In the framework of GUT this non-unification implies new physics. Such new physics could come from supersymmetry (SUSY) which introduces, as discussed in Section 3, a symmetry between bosons and fermions. In SUSY GUT's the evolution equations are modified. Since one does not know at which scale the modifications start to be effective, in Ref. 13 both the unification scale M_{GUT} and the SUSY breaking scale M_{SUSY} were fitted. By definition, M_{SUSY} is a *phenomenological parameter* which determines the point in which the inverse of the coupling constants change slope. The fit was done by minimizing the χ^2 for a single unification point. The minimal SUSY contains two Higgs doublets. In the minimization the mass of the lightest Higgs doublet was chosen to be equal to M_Z and the mass of the heavier doublet was taken to be equal to M_{SUSY} . These choices have practically no influence on the conclusions as long as the Higgs masses are less than a few times M_{SUSY} .

The second order renormalization group equations give the results shown in **figure 9a**. It is apparent from the figure both the break due to the onset of SUSY (at $M_{\text{SUSY}} \approx 1000$ GeV) and the fact that the three coupling constants meet in a single point around 10^{16} GeV. The resulting χ^2 distributions for M_{SUSY} and M_{GUT} are shown in **figures 9b** and **9c**. The minimum χ^2 is obtained for

$$\begin{aligned} M_{\text{SUSY}} &= 10^{3.0 \pm 1.0} \text{ GeV} , \\ M_{\text{GUT}} &= 10^{16.0 \pm 0.3} \text{ GeV} , \\ \alpha_{\text{GUT}}^{-1} &= 25.7 \pm 1.7 . \end{aligned} \quad (14)$$

It is interesting that, by introducing these values in Eq. 13, one obtains $\tau_{\text{proton}} \approx 10^{33.2 \pm 1.2}$ years, which is compatible with the present experimental limits *if* the decays, that are not dominated by X-boson exchange and are theoretically possible, are suppressed. It has to be added that, in standard and SUSY GUT's, the mass of the b-quark can be computed [19]. If the number of neutrinos is $N_\nu = 3$, the computed value $M_b = (5.2 \pm 0.3)$ GeV agrees very well with experiment, thus closing nicely the circle with the determination of N_ν from astrophysics [20] and the more accurate direct measurement of Eq. (5) provided by LEP.

In the framework of GUT, present LEP data favour the minimal SUSY (with two Higgs doublets) with respect to the minimal SM (which has one Higgs doublet). One can ask whether, by having more Higgs doublets, the situation changes. Further fits show that if, in the SM, one adds five additional Higgs doublets, unification can be obtained at a scale $M_{\text{GUT}} = 4.10^{13}$ GeV. However, such a low scale is excluded by the limits on the proton lifetime. It has also been shown in Ref. 13 that non-minimal SUSY models with four or more Higgs doublets - having masses around or below the SUSY scale - yield unification. However, once more, the unification scale is below the limit allowed by the proton decay experiments. Therefore only the minimal SUSY model gives a unification scale which may be compatible with the proton lifetime limit.

It has to be stressed that all these arguments are not a *proof* of SUSY, but tell us that SUSY GUT's are *consistent* with present LEP data at 100 GeV.

The best fit to the allowed minimal SUSY model, shown in **figure 9**, is obtained for a SUSY scale around 1000 GeV or, more precisely, $M_{\text{SUSY}} = 10^{3.0 \pm 1.0}$ GeV, where the error originates mainly from the uncertainty in the strong coupling constant. Averaging more experiments and better controlling the scale and fragmentation errors, the overall uncertainty on $\alpha_s(M_Z)$ will decrease with time below the 5 % taken in Ref. 13, where the input value was $\alpha_1(M_Z) = 0.108 \pm .005$ (68% confidence level). This will require a large but worthwhile concentrated effort from the side of both theorists and experimentalists.

The conclusion of this consistency check is that, *if* a supersymmetric GUT describes nature, SUSY particles, which are expected to have masses of the order of M_{SUSY} , could be within reach of the present or next generation of accelerators. Moreover it is rewarding to find that the SUSY scale, which is obtained from the extrapolation of LEP data is, even with large errors, compatible with the value $M_{\text{SUSY}} \leq 1$ TeV. This is indeed what is required by theorists to solve in a natural way the "hierarchy problem" of the incredibly small ratio $M_Z / M_{\text{PLANCK}} \approx 10^{-17}$, which was the main reason for introducing SUSY models in the first place.

Independently of the numerical values derived for M_{SUSY} and M_{GUT} , the main result of this type of analysis is summarized in **figure 10**, where the relations between $\alpha_s(M_Z)$, M_{SUSY} and M_{GUT} are plotted. To draw the lines it is necessary to use $a(0) = 1/137$ and $\sin^2\theta$ from Eq. 4 and, moreover, to assume that :

- (i) the three coupling constants (defined as in Eq. 12 with a factor $5/3$ in α_1) pass through a single unification point ;
- (ii) the particle content of the theory is the one of the minimal SUSY model.

As underlined in Section 4, the "best" central value for $\alpha_s(M_Z)$ and its 68 % confidence level errors are subjects of debate among specialists. Eventually the subject will be cleared and the final value of $\alpha_s(M_Z)$, with its reduced error, will be introduced in graphs similar to the ones of **figure 10** to obtain some informations on phenomena which take place at energies not yet available.

6. Conclusions

The year 1990 has been for LEP and its four detectors the year of the first harvest. The Standard Model predictions have been checked to an unprecedented level in the electroweak sector and neutral higgsos of mass smaller than about 50 GeV have been excluded. The measurements performed on hadronic jets are in quantitative agreement with asymptotic freedom, a crucial property of Quantum Chromodynamics. Moreover, the combination of the measured electroweak and strong couplings have allowed a first glimpse into the energy domain which is not directly available to LEP, which in this way can justifiably be called the CERN "Laboratory for Electrostrong Physics".

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Figure Captions

- Fig. 1** Four detectors are taking data at LEP : ALEPH, DELPHI, L3 and OPAL. Here one of them is shown. Its overall height is about 12 m. The diameter of the tube in which the electrons and positrons circulate is 10 cm. Around it many subdetectors of cylindrical shape detect and tag the charged and neutral particles produced in the decay of the Z-bosons, which are created at the center of the detector by the annihilations of electron-positron pairs.
- Fig. 2** Typical results of the energy "scanning". The different figures correspond to different decay channels of the Z-boson. Each one has the characteristic bell-shape of a resonant phenomenon of width Γ_Z . The peak cross-sections are proportional to the quantity $\Gamma_e \Gamma_i / \Gamma_Z$, where Γ_i is the partial width for the decay in the i-th channel. With a fit to all the cross-sections one obtains M_Z , Γ_Z , Γ_h , Γ_e , Γ_μ and Γ_τ .
- Fig. 3** Summary of 1989 - 1990 results obtained by the four experiments on the mass M_Z of the Z-particle. See the text of the explanation of the error - treatment.
- Fig. 4** Summary of the results on the partial leptonic width Γ_l . Universality of the leptonic couplings is assumed.
- Fig. 5** Summary of the four measurements of the total width Γ_Z .
- Fig. 6** The invisible width Γ_{inv} is obtained essentially by subtraction with the assumption $\Gamma_{unknown} = 0$ (see Eq. 3).
- Fig. 7** Representation of the creation of a quark - antiquark pair in the decay of a Z-boson. The virtual "hard" particles (q and $\bar{q}$) radiate virtual gluons (g) and quarks which then fragment and hadronize giving eventually rise to the many hadrons observed in the detector.

- Fig. 8**
- a) Evolution of the inverse of the three fundamental coupling constants α_1 , α_2 and α_3 in the minimal Standard Model. Input data are the world averages known in 1987 [14].
 - b) As above, but using the data from one of the LEP experiments.

Fig. 9 Evolution of the inverse of the coupling constants in the minimal supersymmetric (SUSY) model with the requirement that they meet at a point at an energy M_{GUT} . The parameters of the fit are M_{GUT} and M_{SUSY} , the unknown energy at which the slopes of the curve change. The lower plots show the χ^2 - distribution for M_{SUSY} and M_{GUT} .

Fig. 10 By knowing $\alpha(0) = 1/137$ and $\sin^2\Theta(M_Z)$ one can determine the value of the phenomenological parameter M_{SUSY} as a function of $\alpha_Z(M_Z)$ (full line). The other lines correspond to varying the region of masses, around M_{SUSY} , where the slopes change, so to have a smoother transition between the regions below and above the break.

DELPHI

Z MASS (GeV)

[⊗] ± 20 MeV from LEP energy

Γ_I (MeV) - universality

Γ_Z (GeV)

Γ_{inv} (MeV)