Physics at LEP2

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Abstract

The main physics topics of interest at LEP2, the CERN electron-positron collider with center-of-mass energy in the range (161-192) GeV, are reviewed. Progresses in both the precision tests of the standard model and the field of discovery physics attainable at this machine are discussed. A few results of the analysis of data collected in the 1996 first runs of LEP2 are also presented.

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1 Introduction

After a short run at intermediate energy in the 1995 fall (the so called LEP1.5 phase), LEP2, the second phase of LEP, the CERN Large Electron-Positron collider with a centre-of-mass energy in the range $\sqrt{s} \simeq (161 - 192)\text{GeV}$, started operating. This follows the excellent performance of LEP1 during the years 1990-95. LEP1 collected about $145 \text{ pb}^{-1}$ of integrated luminosity, working most of the time on the $Z$ vector-boson peak, at $\sqrt{s} \simeq M_Z$. In particular, about 16 million of $Z$ events have been analyzed, mostly associated to the two-fermion processes:

$$e^+e^- \rightarrow Z^0 \rightarrow \ell^+\ell^-, \nu\bar{\nu}, q\bar{q},$$

where $\ell^\pm$ can be an electron, muon or tau lepton, and $\nu$ and $q$ are neutrinos and quarks, respectively. The fine structure of the standard model was tested at an unprecedented (and unexpected before the LEP performance) level at LEP1. A summary of the most important results on precision measurements at LEP1 can be found in Table 1, where the numbers quoted at the 1997 Moriond Conference \cite{1} are presented. Apart from the comparison between the measured LEP1 value and the SM expectation, for each quantity, the pull is shown, where the pull is defined as the ratio of the difference between the measured and the predicted values over the corresponding experimental errors. One can note that, on the one hand, the experimental relative error is very small in several cases (e.g., only $2 \cdot 10^{-5}$ on the $Z$ mass and about $1 \%_0$ on the $Z$ width $\Gamma_Z$, the hadronic cross section $\sigma_h$ and the $\sin^2 \theta_{\text{eff}}$ electroweak parameter). Furthermore, the pull is quite low (in absolute value) and points to an excellent agreement between the experimental results and the SM predictions in any single detail of the theory. As a result, LEP1 provided a beautiful and highly nontrivial consistency check of the theory. On the other hand, on the same basis, one can even put strong limitations on models predicting physics beyond the standard model.

Compared to LEP1, the LEP2 physics potential presents quite different features. First of all, LEP2 works far away the $Z$ peak, and beyond the $e^+e^- \rightarrow W^+W^-$ threshold (i.e., at $\sqrt{s} \gtrsim 2M_W$). The cross sections for interesting processes at LEP2 are in general a few 10-pb's, to be compared with the typical LEP1 cross section of $\sim 10 \, \text{nb}$. With the expected LEP2 final integrated luminosity of $500\, \text{pb}^{-1}$, this corresponds to a few $10^4$ events collected at the end of the operation of LEP2, to be compared with the 16 million of $Z$ events analyzed at LEP1. Hence, the typical LEP2 statistical error ($\sim 1/\sqrt{N}$) is of the order of 1 $\%$, instead of the corresponding $\sim 1 \%_0$ at LEP1. LEP2 is not expected to be, at least as much as LEP1 has been, a precision measurement tool, although in a couple of important cases, that we will consider below, LEP2 will produce new precision results.

The basic feature of LEP2 is instead that it enters for the first time into a new energy regime for electron-positron collisions. This implies the possibility of exploring direct new physics signals in the electroweak sector of the theory (the most difficult to test at hadron colliders), with typical masses for the new degrees of freedom as large as about $\sqrt{s}/2$ (i.e., $\lesssim 100\, \text{GeV}$), and sometimes even larger than that.
In these lectures, I will first present the standard model expectations for the physics at LEP2. This is, in a sense, a minimal scenario that we are confident to observe and study at the LEP2 experiments. I will start by the two-fermion processes and the radiative-return phenomenon. Then, the $WW$ production will be discussed both as a test of possible anomalies in the trilinear vector-boson ($WW\gamma$ and $WWZ$) vertices, and as a means to determine $M_W$ precisely. More generally, the whole class of four-fermion processes (i.e., $ee \to 4f$), whose accurate knowledge is crucial at LEP2, will be analyzed. Possible checks of the quantum chromodynamics (QCD) at the energy scale $Q \sim \sqrt{s} \sim 200$GeV will be also stressed. Then, I will present a few major topics on discovery physics. In particular, I will discuss the LEP2 potential in searching for the Higgs boson. Expected signals from a low-energy supersymmetric extension of the standard model will be also discussed.

When available, I will combine the theoretical predictions with the experimental results and analysis from the first 1996 runs of LEP2. In 1996, LEP2 collected about $11 \text{ pb}^{-1}$ of integrated luminosity on the $e^+e^- \to W^+W^-$ threshold (i.e., at $\sqrt{s} \simeq 2M_W \simeq 161$GeV), then about $0.4 \text{ pb}^{-1}$ and $1 \text{ pb}^{-1}$ during two short runs at $\sqrt{s} \simeq 164$ and 170 GeV, respectively, and, finally, about $11 \text{ pb}^{-1}$ at $\sqrt{s} \simeq 172$GeV. A year before, in 1995, LEP had also run at intermediate energy, $\sqrt{s} \simeq 130-136$ GeV, with a total luminosity of about $6 \text{ pb}^{-1}$. The machine is now expected to run at higher energy ($\sqrt{s} \simeq 188$GeV), starting from June ’97, and to reach the maximum energy of $\sqrt{s} \simeq 192$GeV by 1998. The expected integrated luminosity is about 100-150 pb$^{-1}$/year per experiment, in the three years ’97,’98 and ’99.

Further material, details and useful references on the topics treated in these lectures can be found in [2].

## 2 Standard model physics

In figure 1 [2], the cross sections for the main standard model processes relevant at LEP2 are reported (in pb) versus the center-of-mass energy. The final state associated to each curve is shown in the figure. The total number of the events expected at LEP2 for the corresponding channel, after the complete period of operation, can be straightforwardly obtained by multiplying $\sigma[(161 – 192)\text{GeV}]$ in pb by 500, corresponding to an integrated luminosity of 500 pb$^{-1}$. One can observe that there are many competing processes at the LEP2 center-of-mass energies, contrary to the LEP1 case. Getting further from the $Z$ peak, the fermion-pair production (represented for its hadronic component by the $\Sigma q\bar{q}$ curve) drops as $1/s$, while the $WW$ production has a comparable cross section for $\sqrt{s} \gtrsim 170$GeV. Other very important channels are the $\gamma\gamma$ reactions, where the two fermions are produced by the interaction of two almost-real photons radiated by forward-scattered electrons and positrons (see figure 2). This class of processes (although of higher order in the electroweak coupling) has a very large cross section, which nevertheless decreases when cutting on the low invariant-mass range of the produced fermion-pair. For instance, the cross section shown in figure 1 for $e^+e^- \to e^+e^-\tau^+\tau^-$ corresponds to
cutting away all the events with $m_{(\tau^+\tau^-)} < 20\text{GeV}$, and is still larger than 10 pb (i.e., it will give more than 5000 events) at LEP2. The associated production of one photon plus a $Z$ boson and of two photons at large angles (e.g., $|\cos \theta_{e\gamma}| < 0.9$ in figure 1) has also relevant rates. Lower rates characterize the production of one $\gamma$, $Z$, $W$ plus two leptons. Furthermore, above the $ZZ$ threshold, the two-$Z$ production has a cross section larger than 1 pb.

2.1 $Z$ radiative return

The curve named $\Sigma q\bar{q}(\text{ISR})$ in figure 1, corresponds to the inclusion of the Initial-State-Radiation effects in the two-quark production. The ISR gives the main contribution to the total QED corrections. Although the higher-order corrections should in general moderately alter the tree-level values, in this case one observes an increase of about a factor 4 in the total rate at LEP2 energies. This can be explained by what is usually called the $Z$ radiative return. It corresponds to the dominance in the radiative corrections of the $e^+e^- \rightarrow f\bar{f}\gamma$ channel at $\sqrt{s} > M_Z$ of a kinematical configuration where the invariant mass of the fermion pair $m_{f\bar{f}}$ is still about $M_Z$ and a real photon is radiated with energy

$$E_0^\gamma = \frac{s - m_{f\bar{f}}^2}{2\sqrt{s}} \simeq \frac{s - M_Z^2}{2\sqrt{s}}.$$  

The effect arises from the Breit-Wigner behavior of the two-fermion cross section for $s$ around the $Z$ peak, which makes the rate for off-shell fermion pair production, and in particular for $m_{f\bar{f}} > M_Z$, much smaller than on the $Z$ peak, and of the same order in the electroweak coupling of the process of a real-$Z$ production, accompanied by a real photon, that takes away the residual energy. The real $Z$ subsequently decays into a $f\bar{f}$ pair with $m_{f\bar{f}} \simeq M_Z < \sqrt{s}$. The consequent photon energy spectrum in the ISR corrected distribution shows a peak around the value $E_0^\gamma$. Correspondingly, the corrected $m_{f\bar{f}}(\equiv \sqrt{s'})$ distribution shows a reduced peak at $\sqrt{s'} \simeq \sqrt{s}$, while the bulk of the cross section is concentrated around $\sqrt{s'} \sim M_Z$ (see figure 3, for the quark pair production $e^+e^- \rightarrow q\bar{q}\gamma$ [3]). In figure 4 [4], the continuous lines show the theoretical predictions for the almost inclusive measurement with $m_{f\bar{f}} > 0.1\sqrt{s}$ (solid line) and the “real” LEP2 events (i.e., dropping off $Z$-radiative-return events) with $m_{f\bar{f}} > 0.85\sqrt{s}$ (dashed line). In the same figure, the results from LEP1, LEP1.5 and LEP2 (combining the four experiment data) are reported. The relative difference between the data and the SM predictions is reported in the lower plot of figure 4, that shows good agreement for both hadronic and leptonic data.

2.2 $W$ pair production

LEP2 was mainly designed to work above the $WW$ threshold. This allows to study for the first time in $e^+e^-$ collisions the direct production of $W$ vector bosons. At tree level, the $W$ pair production occurs via the three graphs in figure 5, i.e., through either $t$-channel neutrino
exchange or $s$-channel $\gamma$ and $Z$ exchange, the latter involving non-abelian three-vector-boson vertices. These two modes give separately divergent contributions to the total cross sections, violating unitarity at high energies with terms of the order $s/M_W^4$ (see the dashed lines in figure 6). An accurate gauge cancellation between the two terms ensures the good high-energy behavior of the cross section, with $\sigma_{\text{tot}} \sim \log \frac{s}{M_W^2}$ (solid line in figure 6).

As a consequence, the $WW$ cross section is very sensitive to any deviation from the exact gauge cancellation, and its measurement gives a good test of the non-abelian sector of the standard model. In particular, limits on possible anomalies in the $\gamma WW$ and $ZW W$ vertices can be set at LEP2, complementing and improving the corresponding limits worked out in $pp$ collisions at the Tevatron. Dedicated studies have shown that limits on gauge anomalous coupling attainable at LEP2 can be made stronger, if, apart from the $WW$ total cross section information, one exploits the full angular-distributions information on both the $W$ production angles and the $W \rightarrow \ell \nu, jj$ decay angles. For instance, in figure 7, the contours of limits on the two parameters $\delta \kappa_\gamma$ and $\lambda_\gamma$, parametrizing the possible C and P conserving $\gamma WW$ anomalies, are shown, for different cases of available angular information, at $\sqrt{s} = 176$ and 190 GeV [outermost contour uses only the $W$ production angle, while the innermost one uses all the available (production and decay) angular data from the semileptonic $\ell \nu jj$ state]. Here, one assumes the final integrated luminosity of the machine. Present LEP2 data on the $W$ anomalous couplings correspond to a luminosity still too low to improve the constraints on the $W$ vertices anomalies obtained at other machines.

The second basic aim of the study of the $WW$ production at LEP2, is the precise direct determination of the $W$ mass. Such a measurement complements the precision measurement results of LEP1. Indeed, from LEP1, one gets only an indirect determination of $M_W$ through the relation

$$G_\mu = \frac{\alpha \pi}{\sqrt{2}M_W^2 \left(1 - M_W^2/M_H^2\right)} \frac{1}{1 - \Delta r}$$

where the Fermi Constant $G_\mu$ is accurately known from muon decay, and $\Delta r$ is 0 at tree level, while is linearly dependent on $m_{\text{top}}^2$ and $\log m_H$, when the dominant loop corrections are included. Hence, at LEP1, the $M_W$ determination depends on the values of $m_{\text{top}}$ and $m_H$. At LEP2, the direct measurement of $M_W$ allows instead a consistency check of the standard model through the relation above. On the other hand, by inserting the $m_{\text{top}}$ value measured at Tevatron, one can get through the same relation some indication on the $m_H$ value. For instance, in Table 2, for two different assumptions on the final indetermination on $M_W$ (25 or 50 MeV) and $m_{\text{top}}$, the estimated error on $m_H$ for different “central” (in the logarithmic scale) values for $m_H$ are reported. One can see that, especially for low values of $m_H$, assuming a very good resolution on $M_W$, such as 25 MeV, is equivalent to an indirect measurement of $m_H$ with a precision of a few tenths of GeV’s.

On the experimental side, there are two main methods to determine $M_W$ at LEP2. The first consists in measuring the total cross section for $e^+e^- \rightarrow W^+W^-$ on the threshold (i.e., at $\sqrt{s} \simeq 161$ GeV). This exploits the fact that, although the cross section is not maximal at that energy ($\sigma_{\text{tot}}(WW)_{161} \simeq 3.7$ pb), the statistical experimental error is strongly reduced by its inverse dependence on $d\sigma/dM_W$, which is maximal at the threshold. The second method
consists in directly reconstructing the resonance $M_W$ peak in the invariant mass distributions of the $W$ decay products, by using either the semileptonic mode ($WW \to \ell\nu jj$) or the hadronic mode ($WW \to jjjj$). These measurements are carried out above the threshold (in particular, for $\sqrt{s} \gtrsim 170$ GeV), where the larger cross section ($\sigma_{\text{tot}}(WW)_{170} \approx 12$ pb) reduces the statistical error, that scales as the ratio of the $W$ width over the square root of the total number of the events. In figure 8 [4], the final results for the $M_W$ measurement on threshold are reported. The rather large final error (about 200 MeV) suffers from the reduced luminosity collected at $\sqrt{s} = 161$ GeV (about 11 pb$^{-1}$) with respect to the planned value (50 pb$^{-1}$), that would have given $\Delta M_W \sim 100$ MeV. In figure 9 [4], the results based on the direct reconstruction method at $\sqrt{s} = 172$GeV are shown. This kind of measurement will be much improved by the further runs of LEP2. The present error on the directly reconstructed $W$ mass is already comparable (about 190 MeV) to the measurement on threshold. By averaging the two measurements, one obtains the preliminary LEP2 result $M_W = 80.38 \pm 0.14$ GeV. One can then combine this result with the present $M_W$ measurement at the TeVatron ($M_W = 80.37 \pm 0.10$ GeV), and obtain the present world average

$$M_W = 80.37 \pm 0.08 \text{ GeV}.$$ 

One can notice that, although still in a preliminary stage, LEP2 already contributes in getting a precision in the direct $M_W$ determination as good as 80 MeV.

LEP2 will also be able to improve the present determinations of the $W$ branching fractions in the different decay channels. Although, with the present statistics, the LEP2 data allow the BR($W$) measurements only with a rather low accuracy with respect to the corresponding TeVatron determinations, the LEP2 complete run will quite improve this sector of the $W$ physics, too.

### 2.3 Four-Fermion Processes

At LEP2 centre-of-mass energies, four-fermion final states are produced with large cross sections. These are not only due to real $WW$ and $ZZ$ pair production with subsequent decays $W \to \bar{f}f'$ and $Z \to \bar{f}f$, but arise from several production mechanisms, each giving sizeable contributions to the four-fermion cross section in specific configurations of the final-particle phase space. In figure 10, all the possible classes of four-fermion production diagrams are shown. The largest total cross sections arise from the multiperipheral diagrams. Here, two quasi-real photons are exchanged in the $t$-channel, giving rise to forward (and undetected) electrons/positrons plus a $\bar{f}f$ pair with a non-resonant structure (the so-called “two-photon” processes). For instance, one has $\sigma(e^+e^- \to e^+e^-\tau^+\tau^-) \sim 10^2$ pb for $M_{\tau\tau} > 10$GeV. On the other hand, although interesting for QCD studies and as a main background for missing energy/momentum events, these classes of processes do not sizably contribute to final states that are of interest for the studies of $W$, $Z$ and Higgs boson production. In the latter case, the main contributions come from the double-resonant diagrams (conversion and nonabelian-annihilation diagrams in figure 10). Also single-resonant processes (proceeding through abelian-annihilation, bremsstrahlung, fusion and single-resonant conversion graphs) can give an important contribution to vector-boson physics,
when the invariant mass constraint on one of the final fermion pairs is relaxed. A particular example is given by the single $W, Z$ production, $e^+ e^- \rightarrow evW \rightarrow evf f'$ and $e^+ e^- \rightarrow eeZ \rightarrow eef f$.

In this case, most of the cross section is due to single-resonant $\text{bremsstrahlung}$ and $\text{fusion}$ diagrams, where an almost real photon is exchanged in the $t$-channel and one final electron escapes detection. In a sense, one could rename these channels as “three-(visible)fermion” processes.

Different aspects of the four-fermion processes have been analyzed in [2]. In the next section, we concentrate on the total cross sections and present the rates for all the four-fermion processes when some canonical cuts are imposed, as given by many available computer codes.

Before doing that, we discuss the relevance of effective approximations in studying four-fermions rates. When including all the tree-level diagrams for a four-fermion process in a computer program, one can lose some insight on which subsets of diagrams are really dominant and which are “sub-leading”. On the other hand, in order to treat correctly the phase-space integrations and to get a reliable result, one should distinguish the main/secondary groups of diagrams. At the same time, it is also useful to check the reliability of effective approximations that allow to evaluate given subsets of diagrams in a much simpler way. The natural way of forming subsets of diagrams is by isolating subgraphs that (with the in- and out-intermediate particles taken on mass shell) correspond to some gauge-invariant process of lowest order.

We illustrate such a procedure in the particular process $e^+ e^- \rightarrow e^+ e^- b\bar{b}$. This channel is important as a background for Higgs bosons searches. Figure 11 shows the 48 diagrams that make up the complete set (excluding the two that involve Higgs bosons): 8 multiperipheral, 16 bremsstrahlung (single or non resonant, with a $\gamma/Z$ in the $t$-channel), 8 conversion (single- or double-resonant) and 16 annihilation (single- or non-resonant) graphs. The first three classes of diagrams involve the subprocesses $\gamma\gamma \rightarrow b\bar{b}$, $\gamma e \rightarrow Ve$ ($V = \gamma, Z$) and $e^+ e^- \rightarrow VV$, respectively.

The contribution of each subset to the total cross section has been computed exactly at tree level by the computer package CompHEP [7], and then compared with the corresponding results obtained through appropriate effective approximations. These approximations involve a convolution of a simpler subprocess of the four-fermion process considered with either the equivalent photon spectrum in the Weizsäcker-Williams (WW) approximation or a conversion factor describing the decay of a virtual (or resonant) intermediate state. Further details on these approximations can be found in [2].

Note that, in general, the interferences between different subsets of graphs for $e^+ e^- \rightarrow e^+ e^- b\bar{b}$ are found to be negligible at LEP2 energies, with the exception of the interferences of the bremsstrahlung diagrams with the $Z \rightarrow b\bar{b}$ decay, and the conversion diagrams with the $\gamma^* \rightarrow e^+ e^-$ and $Z \rightarrow b\bar{b}$ decays (that gives $-24 \text{ fb}$ at $\sqrt{s} = 200\text{GeV}$). Then, apart from the interference between the bremsstrahlung diagram with $Z \rightarrow b\bar{b}$ and the one with $\gamma^* \rightarrow b\bar{b}$, which gives $-3.2 \text{ fb}$ at $\sqrt{s} = 200\text{GeV}$, all other interferences are found to be less than $1 \text{ fb}$ at the same energy [8].

In figure 12, one can see that the exact computation (solid) is always reasonably recovered by a proper approximation (dashes). Indeed, adding the approximate formulae for multiperipheral,
single and double conversion incoherently (i.e., with no interferences) the total cross section is reproduced within 5%.

2.4 Cross sections for all four-fermion final states

We now report on the results of a study of the tree-level cross sections for all possible four-fermion final states, as listed in Tables 3-5. The complete set of diagrams is taken into account in each case (the corresponding total number of diagrams ($N_d$) is shown in the same tables). Higgs-boson contributions are not included. This comparative study involves seven computer codes: ALPHA, CompHEP, EXCALIBUR, grc4f (a package for computing four-fermion processes based on GRACE), WWGENPV/HIGGSPV, WPHACT and WTO. For a detailed description of these codes see [2]. In this comparison ISR and gluon-exchange diagrams for the hadronic four-fermion final states (when implemented) are switched off. The effect of non-zero fermion masses for some of the processes has also been investigated by ALPHA and grc4f (see Tables 3-5). Total cross sections have been computed at the centre-of-mass energy $\sqrt{s} = 190\text{GeV}$, with the following cuts: $E_{\ell\pm} > 1\text{GeV}$, $E_q > 3\text{GeV}$, $\theta(\ell\pm - \text{beam}) > 10^\circ$, $\theta(\ell\pm - \ell'\pm) > 5^\circ$, $M_{qq'} > 5\text{GeV}$ (cuts on the fermion energy variables are loosened in the case of massive fermions). Furthermore, in order to better check the agreement among the different codes, a canonical set of input parameter has been agreed upon in all the computations, that is $M_Z = 91.1888\text{GeV}$, $\Gamma_Z = 2.4974\text{GeV}$, $M_W = 80.23\text{GeV}$, $\Gamma_W = \frac{3G_F M_W^2}{\sqrt{2}} = 2.0337\text{GeV}$, $\alpha^{-1}(2M_W) = 128.07$, $G_F = 1.16639 \times 10^{-5}\text{GeV}^{-2}$, $\sin^2 \theta_W$ from $\frac{\alpha(2M_W)}{2\sin \theta_W \cos \theta_W} = \frac{G_F M_W^2}{\pi v^2}$. In Table 3, the cross sections for all the four-lepton final states are shown, in Table 4 the ones for the semileptonic states and in Table 5 the ones for the hadronic four-fermion states. The error in the last one or two digits, corresponding to the Monte Carlo event generator, is also shown in parenthesis. One can see that the agreement among the different central values is in general at the level of a few per-mil, and even better in some cases. Note that, with the cuts above, the effect of the fermion masses can be not negligible, as can be seen, for instance, by comparing the rates for muons to those for $\tau$’s (cf. Tables 3-4).

2.5 QCD tests

LEP2 gives the possibility to test the QCD predictions for the $e^+e^-$ physics at an energy scale $Q \sim 180\text{GeV}$, which is about twice the one at LEP1. Scaling violations are predicted to depend on $\log Q$ in QCD, which unfortunately corresponds to a rather modest variation of the relevant phenomenology when going from LEP1 to LEP2. Furthermore, the hadronic cross section at LEP2 is penalized by being far away from the $Z$ resonance. One has $\sigma_{\text{had}} \sim 20\text{ pb}$ at LEP2 (i.e., about 3 order of magnitude less than at LEP1), that corresponds to a total of about $N \sim 10^4$ events (for 500 pb$^{-1}$), and a typical statistical error of $1/\sqrt{N} \sim 1\%$ on $\sigma_{\text{had}}$. On the other hand, if one wants to check the evolution of the strong coupling constant $\alpha_s$, one of the theoretically sounder method is given by the measurement of the total hadronic cross section.
Indeed, one has at the first order in $\alpha_s$

$$\sigma_{\text{had}} \simeq \sigma_{\text{had}}^0 (1 + \frac{\alpha_s}{\pi}).$$

Since at LEP2 energies QCD predicts $\alpha_s \simeq 0.107$ (on the basis of the LEP1 value and lower-energies determinations), this relation implies that a statistical error of 1% on $\sigma_{\text{had}}$ translates into an error of about 30% on $\alpha_s$. This error does not allow to appreciate experimentally the evolution of $\alpha_s$ from the LEP1 energy ($\alpha_s(M_Z) \simeq 0.122$) down to $\alpha_s(\simeq 180\text{GeV}) \simeq 0.107$, corresponding to a relative variation of only about 10%. Hence, the measurement of the hadronic cross section is not a useful method to determine $\alpha_s$ at LEP2.

The measurement of the jet fractions and different event-shapes variables offers a more sensitive procedure to determine $\alpha_s$, which is nevertheless a bit less solid theoretically due to the presence of non-negligible nonperturbative effects. The 3-jet fraction over a sample of about $10^4$ hadronic events is expected to be of the order $10^3$, depending directly on $\alpha_s$. This translates into a statistical error on $\alpha_s$ of about 3%, that is sufficient to disentangle a 10% evolution from the LEP1 $\alpha_s$ value. In figure 13 [9], the preliminary results on the $\alpha_s$ measurement at LEP2 energies by OPAL are reported along with lower-energy determinations and the next-to-leading order theoretical prediction (continuous curves). Even with the present moderate statistics collected, the QCD $\alpha_s$ evolution looks well reproduced by the LEP2 data.

Other QCD issues that can be explored at LEP2 are the fragmentation function evolution and the charged multiplicity distributions. The fragmentation functions can be well determined at LEP2, but, theoretically, little evolution is expected from LEP1. On the other hand, the charged multiplicity distributions can test the available predictions of QCD in the leading-log approximation combined with the local parton-hadron duality hypothesis.

### 3 Discovery Physics

LEP2 gives the opportunity to look for new particles that interact only electroweakly (hence, hard to disentangle in hadronic machines), with masses in the range $M_Z/2 \lesssim m_{\text{NEW}} \lesssim 200\text{GeV}$, or even heavier in case they can be singly produced.

In the standard model, the only (crucial) particle yet to be discovered is the Higgs boson, that is needed within the framework of the spontaneous breaking of the electroweak symmetry. This neutral (scalar) particle is in general hard to produce in ordinary collisions, since its coupling with other particles depends on the ratio of the particles masses over the $W$ mass. Hence, the Higgs is very weakly coupled to the electrons and quarks that interacts at high energies in a normal collider. In order to produce a Higgs with sufficient cross section, one has first to excite some heavy degree of freedom, such as $W$ and $Z$ bosons, from the initial beams. Then the Higgs can be produced, either by radiation from a $Z/W$ or by fusion of a pair of vector bosons. As a consequence, the typical cross section for Higgs production al LEP does not exceed the 1-pb level, and is in general just a few tenths of pb. This requires a sufficiently
high integrated luminosity $[\mathcal{O}(\infty\sqrt{s}\infty)]$ in order to eventually detect a reasonable signal. Before the start of LEP2, the best direct limit on $m_H$ was found at LEP1, where the range $m_H < 64.5$GeV was excluded [10]. Furthermore, by optimizing the fit to the standard model predictions of all the electroweak precision data at LEP1, one obtains an indirect upper bound on $m_H$ of about 300 GeV [11]. On the other hand, LEP2 can approximately explore the $m_H$ range $m_H \lesssim \sqrt{s} - 100$GeV, and either discover a Higgs or improve considerably the LEP1 $m_H$ limits.

At LEP2, one can also explore possible extensions of the standard model predicting new particles with masses lighter than about 100 GeV. A widely considered possibility is given by the models introducing SUperSYmmetry (SUSY) [12]. A supersymmetric extension of the standard model offers the only way to make natural a theory with fundamental scalar (Higgs) fields, such as the standard model. The Minimal Supersymmetric Standard Model (MSSM) is the simplest, phenomenological model with low-energy SUSY effectively broken at an energy scale not much larger than $M_W$, as required by the solution of the naturalness problem. It predicts the doubling of the particle spectrum, by associating to each ordinary particle a new particle with spin that differs by 1/2 from the ordinary particle’s spin, and with same remaining quantum numbers. For instance, for each left- and right-handed fermionic (quark’s and lepton’s) degree of freedom, a scalar degree of freedom with same quantum numbers is predicted [the squark ($\tilde{q}$) and the slepton ($\tilde{\ell}$)]. On the other hand, the partners of the spin-1 photon, gluon, W and Z are the spin-1/2 photino, gluino, w-ino and z-ino. Usually the mass-matrix eigenstates mix the photinos and z-inos, on the one side, and W-inos, on the other side, with the neutral and charged components, respectively, of the higgsinos (the fermionic partners of the neutral and charged higgs bosons, coming from the two Higgs doublets introduced in the MSSM). Then, one obtains four neutral fermions [the neutralinos ($\chi^0_i$, $i = 1, \ldots, 4$)], and two charged fermions [the charginos ($\chi^\pm_i$, $i = 1, \ldots, 2$)], which are predicted to be among the lightest SUSY particles. In particular, the lightest neutralino ($\chi^0_1$) could be the lightest SUSY particle. This has important phenomenological consequences. Due to the conservation of the R parity, the neutralino is then stable, and is present at the end of the decay chain of all the SUSY particles. Being also neutral and weakly interacting, it will show up inside a normal experimental apparatus just as a neutrino does, through some missing energy and momentum in the final state. Hence, in general, the production of any SUSY particle will be characterized by leptons and/or jets (and/or photons) accompanied by missing energy and momentum.

Apart from the two main issues above, LEP2 can also complement the TeVatron and HERA programs in the search for some signal from compositness and new interactions’ effects. For instance, after the 1996 runs, lower limits of 1-2 TeV’s on the energy scale $\Lambda$ of a possible new contact interaction of the type $eeqq$ have been already put by OPAL [9]. Similarly, OPAL

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\*The R parity is a new multiplicative quantum number introduced to avoid lepton and barion number violation in the SUSY lagrangian. Its value is +1 for ordinary particles and $-1$ for SUSY partners. If R parity is conserved, three important phenomenological consequences follow: a) SuSy partners are produced in pairs in ordinary matter collisions. b) a SUSY particle always decays into an odd number of SUSY particles. c) the lightest SUSY particle is stable.

\†The exact value depends on the helicity features of the particular model considered.
produced stronger limits on the mass of a possible new scalar particle (such as a leptoquark or a squark) exchanged in the \( t \)-channel in the process \( e^+e^- \rightarrow q\bar{q} \). These limits already improve the present bounds obtained at the Tevatron and HERA. Excited leptons \( \ell^* \) (with \( \ell^* = e^*, \mu^*, \tau^* \)) are also being investigated, mainly through the processes \( e^+e^- \rightarrow \ell\ell^* \rightarrow \ell^+\ell^-\gamma \).

There are presently a few anomalous events at LEP1.5 and LEP2, that, if confirmed, could be a signal of new physics. The ALEPH experiment observes a clear excess in the four-jet production, that is kinematically compatible with the production of two heavy particles (of mass \( m_1 \sim 48 \text{GeV} \) and \( m_2 \sim 58 \text{GeV} \)) each decaying into two jets. The distribution of the dijet mass sum (that is \( \Sigma M = (m_1 + m_2) \)) shows a clear peak around 106 GeV (see figure 14 [13]). In particular, ALEPH observes 18 events in the interval \((106 \pm 4) \text{GeV} \) for \( \Sigma M \), against a background of 3.1 events expected. The problem is that all the other LEP experiments presently do not observe such a signal. This seems to point more to some experimental issue to solve than to some new phenomenon.

### 3.1 Higgs search

In figure 15, the two Feynman diagrams contributing to the Higgs boson production at LEP2 are shown. The dominant contribution is given by the process \( e^+e^- \rightarrow HZ \), where the Higgs boson is radiated by a Z vector boson (the so-called Higgs-strahlung process). On the other hand, the \( WW \) fusion channel has smaller cross sections in general. It gives non-negligible contributions only when the Higgs mass is beyond the threshold for the Higgs-strahlung process, i.e., for \( \sqrt{s} - M_Z \lesssim m_H \lesssim \sqrt{s} \). The total cross section for Higgs production versus \( m_H \), for different values of \( \sqrt{s} \), is shown in figure 16 [2]. In figure 17, the branching ratio \( \text{BR} \) for the main Higgs decay channels is reported. One can see that the dominant decay is the Higgs decay into a \( b \) quark pair, with a corresponding \( \text{BR}>80\% \). Hence, the typical experimental signature for the \( e^+e^- \rightarrow HZ \) channel is a pair of \( b \)-jets plus a jet or lepton pair coming from the Z decay (therefore, with invariant mass around \( M_Z \)). The four LEP experiment have carried out extensive simulations in order to determine the exact potential of LEP2 for discovering the Higgs boson. The result of this study is summarized in figure 18 [4], where the minimum luminosity needed per experiment (in \( \text{pb}^{-1} \)) to discover (solid line) and to exclude (dashed line) a Higgs boson is shown, as a function of \( m_H \), for three values of \( \sqrt{s} \). On the other hand, in Table 6 [4], one can find the maximal \( m_H \) that can be excluded or discovered with a given integrated luminosity per experiment. All these results correspond to combining the data from the four experiments. One can see that reaching 150 \( \text{pb}^{-1} \) at \( \sqrt{s} = 192 \text{GeV} \) is sufficient to cover the mass range up to 95 GeV for discovery and up to 98 GeV for exclusion. Increasing further the luminosity improves the situation only marginally. A possible run at \( \sqrt{s} = 205 \text{GeV} \) (not yet approved at the moment), could exclude a Higgs as heavy as 112 GeV, with a luminosity of 200 \( \text{pb}^{-1} \).

After the 1996 LEP2 runs at \( \sqrt{s} = 161 \) and 172 GeV, with a total luminosity of only 20 \( \text{pb}^{-1} \), some improvement on the LEP1 limits on \( m_H \) have already been obtained. The best bound is the one by ALEPH [13], that gives \( m_H > 70.7 \text{GeV} \).
3.2 Supersymmetry searches

While Higgs searches, due to the moderate production rates, need a rather large luminosity in order to exploit the full LEP2 potential, the SUSY particles search is characterized by larger cross sections. Hence, a modest luminosity can be sufficient to either discover or exclude particle masses even near the kinematical limit. In fact, one expects new charged particles in the lower SUSY mass spectrum, such as charginos and charged sleptons. Their electromagnetic coupling guarantees cross sections of at least a few pb’s. This explains, for instance, the remarkable new LEP2 mass limit on charginos, obtained from the short 1996 runs. Charginos are expected to be pair produced at LEP via the reaction $e^+e^- \rightarrow \chi^+_1\chi^-_1$, whose cross section depends on the physical composition of the chargino in terms of W-inos and Higgsinos, and on the mass of the sneutrino that can be exchange in the t-channel. In particular for relatively light sneutrino, the negative interference between the s- and t- channel (mediated by a $\gamma/Z$ and a $\tilde{\nu}$, respectively) reduces the cross section, thus leading to worse limits. The effects of the variation in the physical chargino composition and of the sneutrino mass can be taken into account through a scatter plot for the production rate versus the chargino mass (see figure 19 [14]). In figure 19, the limits on $m_{\chi^+_1}$ found by DELPHI in the 1996 run at 172 GeV for a heavy (upper part) and a light (lower part) sneutrino are also shown. For a heavy (light) sneutrino a lower bound of 84.5 (67.8) GeV at 95 % of C.L. is found (cf. the LEP1 limit on $m_{\chi^+_1}$ of about 45 GeV). Also shown (dashed lines) are the bounds one obtains in alternative models, where the lightest neutralino is not stable, but decays into a light gravitino plus a photon.

By using unification conditions on the gaugino masses [12], one can also extract a new limit on the lightest neutralino mass from the LEP2 chargino mass bound. For instance, figure 20 [13] shows the ALEPH bounds on the lightest neutralino mass from the data collected at LEP1, LEP1.5 and LEP2, versus $\tan \beta$ (the ratio of the vacuum expectation values for the two Higgs doublets, which usually parametrizes the MSSM). At LEP1.5 and LEP2, one can finally exclude a massless neutralino for any value of $\tan \beta$. In particular, the mass range $m_{\chi^0_1} < 22\text{GeV}$ has been excluded by ALEPH at 95% of C.L.

Finally, figure 21 [13] presents the ALEPH 1996 limits on the charged slepton masses (separately, for each flavour, and combined). The combined bound is about 75 GeV, that is quite lower than the chargino bound. This is because of the threshold factor in the cross section for scalar pair production ($\sim \beta^2$, being $\beta$ the velocity of the produced scalars) that reduces the rates near the kinematic limit, with respect to the fermion pair production.

Another crucial part of the MSSM to test at LEP2 is the Higgs sector. In the MSSM, the lightest neutral higgs corresponding to the two doublets (which gives rise to two neutral scalar, one pseudoscalar and one charged Higgs bosons) should be lighter than the standard model higgs boson, and hence more likely to be produced at LEP2. An extensive analysis has been done in this field. The two main production channels are the Higgs-strahlung and the associated production of the lightest neutral scalar $h$ and the pseudoscalar $A$. Table 7 [12] (analogously to Table 6) summarizes the expectations for the discovery and exclusion of SUSY Higgs bosons at LEP2.
4 Conclusions

The second phase of LEP just started, and produced the first results both in the field of the standard model tests and on new physics bounds. Further crucial progresses are expected from the full machine operation in the years 1997-1999, especially in the $W$ boson physics and in the exploration of the Higgs sector of the standard model. With an optimistic view, one could wait for the discovery of new particles/interactions effects, that are indeed possible with the collision energy available at LEP2. A more conservative attitude is anyway assured of new results in the precision measurement of the standard model and in constraining possible new theories, that will nicely complement the experimental analysis from the TeVatron and HERA.

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