RESULTS FROM HIGH ENERGY $e^+e^-$ COLLISIONS

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ABSTRACT

We review some of the recent experimental results obtained at the high-energy
$e^+e^-$ colliders, LEP and SLC, with emphasis on LEP2 results.

1. Introduction

$e^+e^-$ collisions offer the possibility of studying in the simplest way the fundamental
particles and their basic interactions. The present highest energy $e^+e^-$ collider is
the LEP storage ring at CERN (LEP2). It is giving a wealth of informations at c.m.
energies of 130-189 GeV and it is scheduled to reach $\sqrt{s} \sim 200$ GeV in year 2000. LEP1
and the SLC linear collider at SLAC provided important results at energies around
the $Z^0$ mass, like the three families of fermions, and tested the Standard Model (SM)
of electroweak and strong interactions to unprecedented high precisions.

In these lecture notes the main recent results from LEP and SLC will be briefly
summarized and discussed; emphasis is given to LEP2 results.

In colliders the c.m. energy grows linearly with the beam energy: $\sqrt{s} = 2E_b$.
Fig. 1 shows the energy dependence of the cross-sections for $e^+e^- \to$ hadrons and
$e^+e^- \to \mu^+\mu^-$. Besides energy, the second important parameter of a collider is its luminosity $\mathcal{L}$,
which is defined as that number which multiplied by a cross-section $\sigma$ gives the collision
rate $N : N = \mathcal{L}\sigma$. Existing $e^+e^-$ colliders have luminosities in the range $10^{31} < \mathcal{L} <
10^{32}$ cm$^{-2}$ s$^{-1}$, which yield collision rates of $\sim 1$ event/s at LEP1 and 0.01 event/s at
LEP2. Present LEP2 luminosities are $\sim 6 \times 10^{31}$ cm$^{-2}$s$^{-1}$.

At $\sqrt{s} \sim m_Z$ the cross-sections are large, see Fig. 1. Since the $Z^0$ is a carrier of
the weak force, the precise measurements of its mass, width, and decay properties are
precision tests of the electroweak (EW) theory. In the SM the $Z^0$ decay width is related
to the number of fermion pairs into which the $Z^0$ can decay. The more ways in which
it can decay, the faster it decays and the wider the \(Z^0\) peak becomes. Measurements of the \(Z^0\) width constrain the number of generations, and deviations from an integer value may hint at new physics. Radiative corrections modify the Breit–Wigner shape of the \(Z^0\) resonance. The analyses of radiative corrections yielded a precise value for the top–quark mass, in excellent agreement with the directly measured value.

Since the \(Z^0\) decays predominantly into quark–antiquark pairs, it yields a clean data sample with which to test quantum chromodynamics (QCD), the theory of the strong interaction. The quark–antiquark pair is never observed directly, but it gives rise to two opposite jets of hadrons by a process called fragmentation. Before fragmentation takes place, one of the quarks may radiate a gluon by a process similar to bremsstrahlung. In this case, three jets of hadrons are produced. The ratio of the number of three–jet events to the number of two–jet events is one way of measuring \(\alpha_s\), the strong coupling constant, which is a fundamental parameter of QCD.

In addition to the vector bosons (carriers of the interactions), the quarks and the leptons, the SM requires at least one scalar Higgs particle (the \(H^0\)), which is needed for the hypothesized mechanism for the generation of masses\(^a\). The coupling of the Higgs particle is predicted by the theory, but not its mass. The precision measurements at the \(Z^0\), yield indirect values on the \(H^0\) mass. Direct limits are obtained at LEP1 and LEP2 via the reaction \(e^+e^- \rightarrow Z^0 \rightarrow Z^0 H^0\).

The higher energies and luminosities from LEP2 allow to study the triple boson vertex in \(e^+e^- \rightarrow Z^0 \rightarrow W^+W^-\), measure with precision the mass and the width of \(W^\pm\), perform searches for new particles with high sensitivity and at increasing masses. Besides the search for the SM Higgs boson, the searches for new physics include searches for supersymmetric particles, charged Higgs bosons, substructures of quarks and leptons, excited leptons and quarks, tests of various conservation laws, and so on.

2. LEP and the four detectors at LEP

LEP is located in an underground tunnel of about 27 km circumference at an average depth of about 100 m. Four large, \(4\pi\), general purpose detectors (ALEPH, DELPHI, L3, OPAL) are operating simultaneously. Each of them is made of many subdetectors, whose combined role is to measure, with high precision, the energy, direction, charge, and type of the particles produced. Apart from neutrinos, no particle should be able to escape a detector without leaving some sign of its passage. Each subdetector has a cylindrical structure, with a “barrel” and two “end-caps” and almost \(4\pi\) coverage. Tracking is performed by a central detector, whilst electron and photon energy measurements are carried out by a high–resolution electromagnetic calorimeter; the magnet iron yoke is instrumented as a hadron calorimeter; it is followed by a muon detector. A forward detector completes the e.m. coverage by tagging small–angle

\(^a\)A Glashow sentence: "If one compares the Standard Model with a house, the Higgs sector is the toilet".
electrons and photons, and is used as a precision luminosity monitor. In order to select and measure the cross-section for a specific channel, one needs: (i) a trigger, (ii) the required events \((N_i)\), (iii) the computation of the global efficiency \((\epsilon_i)\), and (iv) a luminosity determination \((\int L \, dt)\): 
\[
\sigma_i = \frac{N_i}{(\epsilon_i \int L \, dt)} .
\]

In the period 1989–1995, each of the four experiments at LEP1 recorded about 4.5 million events, corresponding to an integrated luminosity of about 160 pb\(^{-1}\). LEP2 running started in the second half of 1995. The energy and the integrated luminosities increased every year: 133, 161, 172 GeV, each with \(L \simeq 10 \text{ pb}^{-1}\); then 55 pb\(^{-1}\) at 183 GeV in 1997, over 180 pb\(^{-1}\) at 189 GeV in 1998. Higher luminosities and higher energies are expected for 1999 and 2000. At LEP2 energies there is a large probability for photon-radiation from the initial electron or positron; this radiation lowers the effective c.m. energy of the colliding \(e^+e^-\) and it leads to asymmetric situations whereby the two produced jets (or the produced lepton pair) are not produced back-to-back. The effective c.m. energy after radiation from the initial state shows a peak corresponding to the "radiative return" to the \(Z^0\) and the peak at \(\sqrt{s}\), Fig. 2. Events may be selected at the nominal c.m. energy (equal to twice the beam energy) with an appropriate cut in the reduced energy variable \(\sqrt{s'} \simeq \sqrt{s} - E_\gamma\).
3. Electroweak physics

At energies around the \( Z^0 \) peak the basic processes are

\[
e^+e^- \rightarrow Z^0, \gamma \rightarrow ff, \quad ff = q\bar{q}, \ell\bar{\ell},
\]

where \( q\bar{q} \) pairs are uu, dd, ss, cc, and bb (the tt has a higher energy). Each q or \( \bar{q} \) hadronizes in a jet of hadrons. Thus the \( q\bar{q} \) pairs are characterized by two opposite jets of hadrons. The q (or the \( \bar{q} \)) may radiate a gluon, which yields a third jet. The \( \ell\bar{\ell} \) pairs may be charged \( (e^+e^-, \mu^+\mu^-, \tau^+\tau^-) \) or neutral \( (\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau) \).

A fourth family of quarks and leptons with masses smaller than half the \( Z^0 \) mass would increase the number of open channels, increasing the width of the \( Z^0 \) and lowering the height of the peak cross-section. New physics (such as SUSY) may contribute a fraction of the width contributed by each of the three known families.

The behaviour of the cross-section around the \( Z^0 \) peak is typical of a resonant state with \( J = 1 \) and is well described by a relativistic Breit–Wigner formula with an \( s \)-dependent width. In the case of \( \gamma, Z^0 \) exchange one has

\[
\sigma(e^+e^- \rightarrow ff) = \frac{4}{3}\pi \frac{a(m_Z^2)}{s} + \frac{f_{\pi}^2}{m_Z^2} + \frac{12\pi}{m_Z^2} \Gamma_{\gamma}^e \Gamma_{\gamma}^\gamma \frac{s}{(s-m_Z^2)^2 + \frac{d_s^2}{m_Z^2}}
\]

electrom. interf. resonant

term term term

This formula has to be convoluted with initial state radiation. Around the \( Z^0 \), the first two terms of Eq. 2 are small corrections to the main term, which is the \( Z^0 \) Breit–Wigner. \( \Gamma_{\gamma}^e \) is the partial width for the decay of the \( Z^0 \) into a fermion–antifermion pair, \( Z^0 \rightarrow ff \). The total width \( \Gamma_Z \) is given by

\[
\Gamma_Z = \Gamma_h + \Gamma_e + \Gamma_\mu + \Gamma_\tau + N_\nu \Gamma_{\nu} = \Gamma_{\text{vis}} + \Gamma_{\text{inv}},
\]

where \( \Gamma_h \) is the hadronic width and \( \Gamma_e, \Gamma_\mu, \Gamma_\tau, \Gamma_{\nu} \) are the leptonic widths; it is customary to use \( R_e = \Gamma_h/\Gamma_e, R_\mu = \Gamma_h/\Gamma_\mu \) and \( R_\tau = \Gamma_h/\Gamma_\tau \). In the Standard Model

\[
\begin{align*}
\Gamma_h &= 1734 \text{ MeV} \\
\Gamma_e &= 300 \text{ MeV} \quad \Gamma_\mu = 380 \text{ MeV} \\
\Gamma_\tau &= 83.4 \text{ MeV} \\
\Gamma_{\nu} &= 166.5 \text{ MeV} \quad N_\nu = 3 \quad \Gamma_{\text{inv}} = 499 \text{ MeV} \\
\Gamma_Z &= 2487 \text{ MeV}.
\end{align*}
\]

In the electroweak theory each partial width \( \Gamma_{\gamma} \) may be expressed in terms of vector \( (g_\nu) \) and axial–vector \( (g_a) \) coupling constants

\[
g_a = I_M, \quad g_\nu = I_M - 2Q_f \sin^2 \theta_W,
\]

where \( I_M \) is the maximal isospin.
where $I_{3f}$ is the third component of the weak isospin, $Q_f$ is the electric charge of the fermion and $\theta_w$ is the weak mixing angle. At the lowest order (tree level) one has

$$\Gamma_f = N_c G_F m_Z^2 \sqrt{2} (g_\nu^2 + g_a^2) (1 - \delta_f^{\text{QED}})$$

(6)

where $N_c$ is the number of colours ($N_c = 1$ for leptons, $N_c = 3$ for quarks), $\delta_f^{\text{QED}} = 3g_f^2\alpha(m_Z^2)/4\pi$ accounts for final state photonic corrections. The angular distributions of the produced $f\bar{f}$ exhibit asymmetries, which at $m_Z$ may be written as

$$A_{\text{FB}}^0 = \frac{3}{4} A_e A_f, \quad A_f = \frac{2g_\nu g_a}{g_\nu^2 + g_a^2}.$$  

(7)

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![Graph](image)

**Fig. 2.** The number of multihadrons vs the ratio of the reduced energy $\sqrt{s'}$ to the nominal c.m. energy $\sqrt{s}$ for $e^+e^- \rightarrow q\bar{q}(\gamma)$ at 161 GeV. The points are the data, the histogram the Monte Carlo prediction.

**Fig. 3** shows the energy dependence of the $e^+e^- \rightarrow \text{hadrons(}\gamma\text{)}$ and of the $e^+e^- \rightarrow l^+l^- (\gamma)$ cross sections without removing and removing the radiative events; the SM predictions (lines) are in good agreement with the data (points) \(^1\)\(^2\)\(^3\).

At each energy around the $Z^0$ peak, measurements of the cross-sections have been carried out for $Z^0 \rightarrow \text{hadrons}$, $Z^0 \rightarrow e^+e^-$, $Z^0 \rightarrow \mu^+\mu^-$, $Z^0 \rightarrow \tau^+\tau^-$, the forward–backward lepton asymmetries $A_{\text{FB}}^e, A_{\text{FB}}^\mu, A_{\text{FB}}^\tau$, the $\tau$ polarization asymmetry $P_\tau$, the $b\bar{b}$ and $c\bar{c}$ partial widths and forward–backward asymmetries, and the $q\bar{q}$ charge asymmetry. Each experiment performs fits and obtains nine parameters $(m_Z, \Gamma_Z, \sigma^p_h, \Gamma_e, \Gamma_\mu, \Gamma_\tau, A_{\text{FB}}^e, A_{\text{FB}}^\mu, A_{\text{FB}}^\tau)$. One checks that $\Gamma_e = \Gamma_\mu = \Gamma_\tau$ and $A_{\text{FB}}^e = A_{\text{FB}}^\mu = A_{\text{FB}}^\tau$ (lepton universality). The fit is then repeated with five parameters $(m_Z, \Gamma_Z, \sigma^p_h, \Gamma_\tau, A_{\text{FB}}^\tau)$.

In order to combine results from the four LEP experiments, each experiment provides a set of 9 parameters (five if lepton universality is assumed) optimizing assuming a common systematic error. The present results, using lepton universality, are shown in Table 1. The procedure is in reality more complicated. In particular as time goes
Fig. 3. $e^+e^-$ cross sections vs c.m. energy.

on more parameters are added. The latest one is $m_W$, whose determination at LEP2 and at other accelerators improves every year (see Table 3).

From the results given in Table 1 and from those of SLD, of the Fermilab $p\bar{p}$ collider and from $\nu$-experiments, the EW parameters given in Table 2 have been computed. Note the precise determination of the number of light neutrino families $N_\nu$ and of the strong coupling constant $\alpha_s$ at $m_Z$. Note also that the value of $m_t$ obtained “below threshold” is in good agreement with the directly measured value. By feeding in the measured value of $m_t$ one obtains the $\chi^2$ curve of Fig. 4 for the Higgs boson mass $m_H$: the graph is suggestive of a small $m_H$.

Many measurements can be expressed in terms of the effective EW mixing angle

$$\sin^2 \theta_{\text{eff}} = \frac{1}{4} \left( 1 - \frac{g_v}{g_a} \right).$$

A precise determination of this parameter is given in Table 2.

4. Multihadronic events

Multihadron production in $e^+e^-$ annihilations proceeds via four distinct phases.

i) In the first phase the initial $e^+e^-$ pair annihilates into a virtual $Z^0/\gamma$, which decays into the primary $q\bar{q}$ pair. Before annihilation, a $\gamma$ may be emitted by the initial $e^+$ or $e^-$; this reduces the effective c.m. energy. The production of the primary $q\bar{q}$ pair, described by the EW perturbative theory, occurs at distances of the order of $10^{-17}$ cm.
Table 1. Average electroweak parameters from the results of the four LEP experiments, assuming lepton universality \(^2, 3\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average LEP</th>
<th>Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_Z)</td>
<td>91186.7 ± 2.1 MeV</td>
<td>91186.6</td>
</tr>
<tr>
<td>(\Gamma_Z)</td>
<td>2493.9 ± 2.4 MeV</td>
<td>2496.6</td>
</tr>
<tr>
<td>(\sigma_h^p)</td>
<td>41.491 ± 0.058 nb</td>
<td>41.468</td>
</tr>
<tr>
<td>(R_t = \Gamma_h / \Gamma_t)</td>
<td>20.765 ± 0.026</td>
<td>20.756</td>
</tr>
<tr>
<td>(A_t^{FB})</td>
<td>0.01683 ± 0.00096</td>
<td>0.0163</td>
</tr>
<tr>
<td>(A_r = - P_r)</td>
<td>0.1431 ± 0.0045</td>
<td>0.1475</td>
</tr>
<tr>
<td>(A_e)</td>
<td>0.1479 ± 0.0051</td>
<td>0.1475</td>
</tr>
<tr>
<td>(R_b)</td>
<td>0.21656 ± 0.00074</td>
<td>0.2159</td>
</tr>
<tr>
<td>(R_c)</td>
<td>0.1733 ± 0.0044</td>
<td>0.1723</td>
</tr>
<tr>
<td>(\Gamma_t)</td>
<td>83.91 ± 0.10 MeV</td>
<td>83.4</td>
</tr>
<tr>
<td>(\Gamma_h)</td>
<td>1743.2 ± 2.3 MeV</td>
<td>500.1 ± 1.8 MeV</td>
</tr>
<tr>
<td>(\Gamma_{inv})</td>
<td>500.1 ± 1.8 MeV</td>
<td>499</td>
</tr>
<tr>
<td>(BR_t = \Gamma_t / \Gamma_Z)</td>
<td>3.36 %</td>
<td></td>
</tr>
<tr>
<td>(BR_h)</td>
<td>69.9 %</td>
<td></td>
</tr>
<tr>
<td>(BR_{inv})</td>
<td>20.0 %</td>
<td></td>
</tr>
</tbody>
</table>

ii) In the second phase the \(q\) or the \(\bar{q}\) radiates a gluon, which may subsequently radiate a second gluon (forming a three-gluon vertex), or may radiate a \(q\bar{q}\) pair. This phase, described by perturbative QCD, occurs over distances of \(\sim 10^{-15}\) cm.

iii) In the third phase the coloured partons, i.e. quarks and gluons, fragment (hadronize) into colourless hadrons. This process cannot be analysed with perturbative methods; it is treated with models. Hadronization occurs over distances of \(\sim 1\) fm.

iv) In the fourth phase the produced hadron resonances decay quickly via strong interaction (SI) into “stable” hadrons (e.g. \(\rho^0 \rightarrow \pi^+\pi^-\)); other hadrons decay via the EM interaction (\(\Sigma^0 \rightarrow \Lambda^0\gamma, \pi^0 \rightarrow \gamma\gamma\)). A few (like the b-hadrons) decay via weak interaction with lifetimes of the order of \(10^{-12}\) s. This phase is described by models

Table 2. Results of the analyses based on the measurements at LEP, SLD, Fermilab and on \(\nu\)-experiments \(^2, 3\). Note the derived value of \(m_W\), which may be compared with the values from direct measurements of Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(g_t)</th>
<th>(g_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{\nu} = \Gamma_{inv} / \Gamma_{\nu}^{SM})</td>
<td>2.993 ± 0.011</td>
<td></td>
</tr>
<tr>
<td>(m_t) (GeV)</td>
<td>171.3 ± 4.9</td>
<td></td>
</tr>
<tr>
<td>(m_Z) (GeV)</td>
<td>0.119 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>(\sin^2 \theta_{eff}^\nu)</td>
<td>0.23156 ± 0.00019</td>
<td></td>
</tr>
<tr>
<td>(1 - m_W^2 / m_Z^2)</td>
<td>0.2230 ± 0.0005</td>
<td></td>
</tr>
<tr>
<td>(m_W) (GeV)</td>
<td>80.370 ± 0.027</td>
<td></td>
</tr>
<tr>
<td>(1 / \alpha_{EM})</td>
<td>128.894 ± 0.090</td>
<td></td>
</tr>
<tr>
<td>(m_{H}) (GeV)</td>
<td>84^{+51}_{-51}</td>
<td></td>
</tr>
</tbody>
</table>
which include the experimental information on lifetimes and branching ratios.

Fig. 5 shows the average charged multiplicity in $e^+e^-$ collisions plotted versus c.m. energy. At the $Z^0$ peak the average charged multiplicity is $\langle n \rangle = 20.8 \pm 0.2$; at $\sqrt{s} = 189$ GeV one has $\langle n \rangle (189 \text{GeV}) = 26.94 \pm 0.17 \text{ (stat)} \pm 0.41 \text{ (syst)}$.

A number of shape parameters (Sphericity, Aplanarity, Thrust, ...) have been introduced to characterize the global event structure of multihadronic final states. Their studies provide checks of QCD and allow optimization of the Monte Carlos, which play major roles for corrections and analyses. For each track $k$ of a multihadronic event, we define the rapidity, the transverse and longitudinal momenta and the variable $x_k = p_k / E_{\text{beam}}$.

$\alpha_s$. The coupling constant of the SI is a fundamental parameter which may be determined from many types of measurements: (i) from the ratio of 3-jet events to 2-jet events, (ii) from event topology (shape variables), (iii) from $\Gamma_t/\Gamma_\ell = R^2_\ell (1 + \delta_{\text{QCD}})$, and others. The LEP experiments established the flavour independence of $\alpha_s$ and the decrease of $\alpha_s$ with increasing energy. $\alpha_s(\mu)$ can be written as a function of $\ln(\mu^2/\Lambda^2)$, where $\Lambda$ is the QCD scale parameter and $\mu$ is the QCD renormalization scale

$$\alpha_s(\mu) = \frac{12\pi}{(33 - 2n_f)} \ln(\mu^2/\Lambda^2) \left[ 1 - \frac{6(153 - 19n_f)}{(33 - 2n_f)^2} \frac{\ln \left[ \ln \left( \mu^2/\Lambda^2 \right) \right]}{\ln \left( \mu^2/\Lambda^2 \right)} \right] + \ldots ,$$

where $n_f$, the number of quarks with mass smaller than the energy scale $\mu$, is 5. Eq. 9 predicts $\alpha_s \rightarrow 0$ as $\mu \rightarrow \infty$ (asymptotic freedom property). LEP provided the first complete experimental evidence for the running of $\alpha_s$, see Fig. 6. With increasing energy, $n_f$ and the terms that depend on $n_f$ change by discrete amounts as a new flavour threshold is crossed. If Eq. 9 should be valid for all values of $\mu$, then $\Lambda$ must also change discretely through a flavour threshold. This implies a different value
Fig. 5. Average charged multiplicity in $e^+e^-$ collisions vs. c.m. energy $^4$. The lines represent different fits to the data.

of $\Lambda$ for each range of $\mu$ corresponding to an effective number of massless quarks: $\Lambda \rightarrow \Lambda(n_f)$. The renormalization scale $\mu^2$ is usually chosen to be the global c.m. energy ($\mu^2 = E_{cm}^2$). A definition $\mu^2 = f \cdot E_{cm}^2$, with $0.001 < f < 0.01$, gives a better description of the jet production rates.

**Quark and gluon jet differences.** QCD predicts different coupling strengths for the radiation of an additional gluon from either a quark or a gluon. These coupling strengths are governed by the colour factors for gluon emission, which have the values $C_F = 4/3$ and $C_A = 3$ for radiation from a quark and a gluon, respectively. These are inclusive factors which need corrections to predict real jets. QCD predicts that a gluon is more likely to radiate a gluon than a quark, and that a gluon jet has a higher particle multiplicity, a softer particle spectrum and is broader than a quark jet of equal energy. Many studies have been done at LEP to establish the differences between a quark jet and a gluon jet. For this purpose one first selected three-jet events in a $Y$ configuration, where the low energy quark and gluon jets are at 150° with respect to the high energy quark jet (identified by tagging), and the “Mercedes events” where the three jets are at 120° from each other. From these measurements it was established that, with respect to the light quark jet, the gluon jet is broader, has a larger hadron multiplicity and yields hadrons with a softer energy spectrum. These conclusions were only qualitative and could not be compared with QCD calculations. The reaction $e^+e^- \rightarrow \gamma/Z \rightarrow q\bar{q}$ leads to a $q\bar{q}$ from a color singlet source and this situation cannot be obtained for gluons in the used geometries for three-jet events. The measurements were not inclusive, they used a jet finder algorithm and the gluon jet could not be a color singlet. QCD calculations stop at the parton level, while the experiments are at
the hadron level.

More recent measurements selected rare events for which inclusive measurements could be made, thus avoiding most of the above mentioned difficulties. The selected events contain two tagged light quarks in one hemisphere, say the left one: all hadrons in the left hemisphere are assumed to come from the two quarks, which at the limit are collinear. The gluon goes in the right hemisphere, and at the limit is collinear with the two quarks, and one attributes all the hadrons in the right hemisphere to the gluon jet. The measurements yield the right charged multiplicity distributions; for 39 GeV gluons and quarks the ratio of the average charged multiplicities is:

\[
\tau_{ch} = \frac{\langle n_{ch}^{\text{incl}} \rangle}{\langle n_{ch}^{\text{hemisphere}} \rangle} = \frac{14.5}{10.1} = 1.49 \pm 0.03 \pm 0.05
\]

The theoretical calculation using analytic NNLO with approximate energy conservation and corrected via Monte Carlo to go from the parton level to the hadron level predicts a value close to the measured one. Further work should yield an even better agreement. In any case, we conclude that the measurements at LEP have confirmed that gluon jets have softer particle spectra, higher multiplicities, and are broader than quark jets of the same energy.

5. **The reaction** $e^+e^- \rightarrow W^+W^-$

One of the main motivations for LEP2 at c.m. energies $\sqrt{s} > 2m_W$ is connected with the possibility of studying the $e^+e^- \rightarrow W^+W^-$ reaction. This allows to perform precision $W$-physics and to test the SM triple boson vertices $ZWW$ and $\gamma WW$. The most important diagrams for $W$-pair production are the $s$-channel $\gamma/Z$ exchange, and
the $t$-channel neutrino exchange. The first available LEP energy, 161 GeV, was just above the $W$-pair production threshold; here the cross section has a particularly strong dependence on the value of the mass of the $W$-boson; it is thus possible to extract $m_W$ from the data by measuring the cross-section and comparing its value with the theoretical SM prediction. At higher energies the measurement of the $W$ mass is made by direct reconstruction of the invariant mass of the fermion pair for each $W$ decay channel.

Fig. 7 shows the energy dependence of the $e^+e^- \rightarrow W^+W^-$ cross section measured at the c.m. energies of 161, 172, 183 and 189 GeV: it has the typical dependence of a reaction at its threshold. The measured values are consistent with the SM prediction. The most general Lorentz invariant Lagrangian which describes the triple gauge boson interactions involving $W$-bosons has 14 independent terms, 7 describing the $WW\gamma$ vertex and 7 describing the $WWZ$ vertex. Assuming that the Lagrangian satisfies electromagnetic gauge invariance, charge conjugation and parity, the number of parameters reduces to 5. Adding considerations related to SU$(2)\times U(1)$ gauge invariance reduces the independent trilinear gauge couplings to 3. Anomalous triple gauge couplings could affect both the total production cross section and the shape of the differential cross section as a function of the $W$ production angle. No deviations have been observed and one can thus place only upper limits for anomalous couplings. The results of the direct measurements of $m_W$ and $\Lambda_W$ are given in Table 3.

<table>
<thead>
<tr>
<th>pp colliders</th>
<th>80.41 ± 0.09 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP2</td>
<td>80.37 ± 0.09</td>
</tr>
<tr>
<td>Average</td>
<td>80.39 ± 0.06</td>
</tr>
</tbody>
</table>

6. Physics below threshold

Because of radiative corrections, the LEP precision measurements are sensitive to contributions from the top quark, the $W^\pm$ and the Higgs boson. The contributions depend on the masses $m_t$, $m_W$ and $m_H$. Using the data up to 1994, the measurements predicted $m_t = 173^{+15}_{-12}^{+18}_{-20}$ GeV, where the second error was mainly due to the uncertainty in $m_H$. With SLD measurements of $A_{LR}$, slightly larger values are preferred. The present recalculation is in good agreement with the measured value at Fermilab. The determination of $m_W$ is very precise, see Table 3. Checks were also made that the $b$-quark has $I = \frac{1}{2}$ and $I_3 = -\frac{1}{2}$, which require a $t$-quark with $I_3 = +\frac{1}{2}$.

The dependence on $m_H$ is weaker. Nevertheless, by fixing $m_t$ at the Fermilab measured value and using all available information on $m_W$, a first estimate of $m_H$ has been obtained, see Fig. 4. The predicted value is low, around 80 GeV, but with a large uncertainty.

Several authors pointed out the importance of precision measurements capable of
yielding information below threshold, as has already proven valuable for $W^\pm$, $Z^0$ and $t$. It may be that, for a long time, precision measurements will be the only source of information for particles with very large masses.

7. New particle searches

Particle searches at LEP include the search for the SM Higgs boson, searches for other missing items of the SM and searches for new physics beyond the SM $^{10,13}$.

The SM has some intrinsic inconsistencies and too many free parameters. The SM may thus be an effective theory valid in the presently explored energy scale. Searches for new physics beyond the SM concern: (i) Supersymmetry, (ii) Unification, (iii) Compositeness, etc. In the first two cases one considers the particles of the SM as fundamental and pointlike. In the third case the particles of the SM are composites.

7.1. Searches for missing items in the SM

**SM Higgs boson searches.** These are performed via the reaction $e^+e^- \rightarrow Z^0 \rightarrow Z^0 + H^0$, looking for all possible decay channels of $Z^0$, $H^0$. The present direct limits from each LEP experiment is $m_{H^0} > 94$ GeV at the 95% CL $^{11}$.

**Search for a fourth family in the SM.** The precision measurement of the $Z^0$ width fixes the number of light neutrino families to $3^3$. Direct searches for new charged heavy leptons have been performed with negative results $^{10}$.

7.2. Searches for SUSY particles at LEP2

In supersymmetry (SUSY) models, each normal particle has a supersymmetric partner whose spin differs by half a unit. A new multiplicative quantum number, $R$-parity = $(-1)^{2S+3B-L}$, is introduced, with value +1 for the SM particles and -1 for the SUSY partners. If $R$-parity is conserved, SUSY particles are produced in pairs and they decay to the lightest SUSY particles (LSP), which is normally considered to be the lowest mass neutralino $\tilde{\chi}_1^0$. In the Minimal Supersymmetric extension of the Standard Model (MSSM) all sparticle masses are determined by 5 parameters: $m_0$ = the common mass at the GUT scale, $M_2$ = the SU(2) gaugino mass at the EW scale, $\mu$ = the mixing parameter of the two Higgs doublets, $A =$ the SUSY trilinear coupling. In the MSSM model there are 5 scalar Higgs bosons, $h^0$, $H^0$, $A^0$, $H^+$, $H^-$; the neutral ones may be searched for with methods similar to those used for the SM Higgs boson. **Charginos.** The fermionic SUSY partners of the $W^\pm$ and of the charged Higgs bosons $H^\pm$ mix to form two mass eigenstates, the charginos $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$. They could be pair produced either through $\gamma$ or $Z^0$ exchange in the s-channel or through sneutrino exchange in the t-channel. The production cross section is expected to be fairly large. The decays yield a neutralino, $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + other particles$. The experimental signature for pair production and decay is therefore: (i) two acoplanar leptons, (ii) one lepton and one
jet, (iii) multi-jets, all with missing energy/momentum (carried by the neutralinos). The existing limits are about at the kinematical limit, $m_{\tilde{\chi}^\pm} > 94 \text{ GeV}$ \cite{12}. 

**Charged sleptons.** Each SM lepton has two scalar partners, the right and left–held sleptons, denoted $\tilde{\ell}_R$ and $\tilde{\ell}_L$. Sleptons could be pair produced through s-channel $\gamma$ or $Z^0$ exchange or through t-channel neutralino exchange. The dominant charged slepton decay mode is $\tilde{\ell}^\pm \rightarrow \tilde{\ell}^\pm + \tilde{\chi}_1^0$. The event topology is: two acoplanar leptons and missing energy/momentum. No evidence has been seen; mass limits at the 95\% CL are at $\sim 80 \text{ GeV}$ \cite{12}.

**Scalar quarks.** Because of the possible large mass splitting by left–right mixing, the lowest mass eigenstate of the stop scalar quark, $\tilde{t}_1 = \tilde{t}_L \cos \theta_{\text{mix}} + \tilde{t}_R \cos \theta_{\text{mix}}$, could be the lightest charged SUSY particle. The dominant decay mode would be $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$. The event topology would be two acoplanar jets with missing energy/momentum. The limits, assuming a large $\theta_{\text{mix}}$, are $m_{\tilde{t}_1} > 85 \text{ GeV}$.

**Neutralinos.** The fermionic partners of the $\gamma$, $Z^0$ and of $W^0$ neutral Higgs bosons mix to form 4 mass eigenstates, the neutralinos, $\tilde{\chi}_i^0$, $i=1,2,3,4$. The neutralinos could be pair produced through s-channel $Z^0$ exchange or t-channel scalar electron exchange. Since the lowest mass $\tilde{\chi}_1^0$ is experimentally unobservable, the only way to look for $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production is via the reaction $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$ or via $\tilde{\chi}_2^0\tilde{\chi}_1^0$ pair production with $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 l^+l^-$. The limits obtained are $m_{\tilde{\chi}_1^0} > 30 \text{ GeV}$ for any SUSY parameter. Higher mass limits are valid only for specific values of the SUSY parameters.

**R-Parity violation.** If R-parity is violated, sparticles could be produced either in pairs or singly and there are no constraints on the nature and on the stability of the LSP. If the LSP decays promptly the events final states would be characterized by a large fermion multiplicity. If the LSP has a sizeable lifetime one would be able to directly observe sparticles crossing the detector. Both types of searches have been performed and no positive indication was reported \cite{13}.

### 7.3. Searches for heavy charged leptons

**Heavy charged and neutral leptons.** The interest in the search for heavy neutral leptons has recently increased in view of the possibility that neutrinos have non–zero masses \cite{14}. Then the see–saw mechanism would predict heavy neutral leptons with masses $m_{\tilde{N}_i} = m_2^2/m_{\nu_l}$. The typical event topology for pair production and decay $(e^+e^- \rightarrow N_l\tilde{N}_l \rightarrow lW\tilde{W})$ of unstable heavy neutral leptons would be two isolated leptons and jets.

Searches for long–lived charged heavy leptons, $e^+e^- \rightarrow L^+L^-$, involve topologies with back–to–back charged tracks. For these searches one uses the central tracking detectors, and in particular the $dE/dx$ measurements.

The searches for long–lived neutral leptons proceed assuming $e^+e^- \rightarrow L^+L^-$, $L^\pm \rightarrow l^0W^\pm$. The signature is a pair of acoplanar particles and missing transverse momentum.
Present limits extend to masses of about 90 GeV.

7.4. Excited fermions

Composite models of the SM particles predict the existence of excited fermions, $F^*$. They are assumed to have the same electroweak SU(2) and U(1) gauge couplings to the vector bosons ($g, g'$) as the SM fermions; but they are expected to group into left and right–handed weak isodoublets.

Excited fermions could be produced in pairs, $e^+e^- \rightarrow F^{**}F^{**}$. For CC decays one has $F \rightarrow fW$; then the signature would be similar to that for heavy leptons. For photonic decays, $F^{*} \rightarrow f\gamma$, the final states involve two leptons and two photons. For the $\bar{\nu}^*\nu^*$ case, the final state involves $2\gamma$ plus missing energy/momentum. The present mass limits extend to $m \sim 93$ GeV.

In conclusion: no evidence has been found for particles beyond the SM. The searches will proceed at LEP2 and at other high energy colliders.

8. Conclusions

$e^+e^-$ interactions at energies around the $Z^0$ peak provided the first real evidence for the three families of leptons and quarks and of the running of $\alpha_s$, the precise determinations of many parameters of the SM, a wealth of information from multihadronic events, limits on new particles and new phenomena. LEP2 has opened up the study of the reaction $e^+e^- \rightarrow W^+W^-$, of the precise measurements of the $W^\pm$ parameters and the detailed study of the triple boson vertex. LEP2 also allows particle searches to considerably higher masses and higher sensitivities. Let us hope that the anticipated increases in energy and in luminosity will really open up a new field

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9. References

Fig. 7. Cross section for the reaction $e^+e^- \rightarrow W^+W^-$ plotted versus $\sqrt{s}$, the SM prediction. The dashed line is the prediction from the t-channel neutrino exchange diagram only.


9. TGC combination working group, *A combination of preliminary measurements*
of the triple gauge boson coupling parameters measured by the LEP and D0 experiments, LEPEWWG/TGC/98-01 (1998).


14. See the proceedings of the 4th School on Non Accelerator Particle Astrophysics, World Scientific (1996) and the Proceedings of the 5th School, in particular:

- S.Bottino, *Dark matter*;