Electroweak Physics at LEP2
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Abstract
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glorious running. With the 4 operating detectors, ALEPH, DELPHI, L3, and
OPAL, an enormous wealth of new data at the highest centre-of-mass energies
has been recorded. These lectures will focus on aspects of electroweak physics
within the energy span of LEP2, namely 130-209 GeV. All current data are
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ELECTROWEAK PHYSICS AT LEP2

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On 2 November 2000 the LEP machine was finally closed after 12 years of glorious running. With the 4 operating detectors, ALEPH, DELPHI, L3, and OPAL, an enormous wealth of new data at the highest centre-of-mass energies has been recorded. These lectures will focus on aspects of electroweak physics within the energy span of LEP2, namely 130-209 GeV. All current data are in very good agreement with the electroweak Standard Model.

1 Introduction

Without a shadow of doubt $e^+e^-$ annihilation has been the most productive environment for new physics during the last 20-30 years. The early experiments at Orsay, Novosibirsk, Frascati, and SLAC have clearly demonstrated the simplicity and cleanliness of $e^+e^-$ annihilation to fermion-pair final states. SPEAR and DORIS initiated charm spectroscopy in 1974-5, followed by DORIS and CESR with beauty spectroscopy in 1978. Experiments at PEP, PETRA, CESR, and TRISTAN have produced hundreds, if not thousands, of new results covering aspects of pure QED, weak interactions, strong interactions, 2-photon physics, spectroscopy of heavy quarks, particle lifetimes and decays, and precision tests of the Standard Model. In 1989 both SLC and LEP started operation on a higher energy scale to investigate the detailed properties of the $Z$ boson. LEP was able to raise the beam energy in 1996 to allow production of $W^+W^-$ boson pairs and, eventually, $ZZ$ boson pairs. By the time LEP ceased operation, the $e^+e^-$ centre-of-mass energy had reached 209 GeV, a factor of 3 above the previous generation of $e^+e^-$ accelerators.

1.1 Setting the Scene, LEP1 to LEP2

LEP was formally approved in 1981 and the 4 experiments (Aleph, Delphi, L3, and OPAL) selected in 1982. Construction of the accelerator began in 1983 and the very first $e^+e^-$ collisions were observed on 13 August 1989. The period 1989-1995, the LEP1 era, provided each experiment with approximately 5 million $Z$ events. With the addition of superconducting RF cavities the LEP energy was gradually increased above $W^+W^-$ threshold and heralded the LEP2 era (1996-2000) during which each experiment recorded approxi-
mately 10,000 $W^+W^-$ pairs. The major physics goals of the LEP2 program were (a) to continue the precision tests of the validity of the Standard Model, (b) to make precise measurements of the $W^+W^-$ final state (cross-section, $W$ branching ratios, triple-gauge couplings, and $m_W$), (c) to continue the direct search for the Standard Model Higgs boson, and (d) to explore the increased phase-space for evidence of new physics, e.g. SUSY. Only items (a) and (b) will be discussed in these lectures.

1.2 Major References

I invite you to access the following sources for basic details, newer results, and (as ever) the very latest results,


- Very Latest Results: see the website http://www.cern.ch/LEPEWWG/ for a continuously updated situation, reports, talks, figures, averages, and much more. Here you will find the LEP combinations which ultimately are accessed by the Particle Data Group. These combinations require sophisticated procedures and tests and involve many people from the 4 experiments. This is excellent work and we all owe them many thanks.

1.3 Basic Processes, Event Rates, and 2-f vs 4-f Diagrams

Figure 1 shows the Standard Model expectation for the cross-sections of the major processes at LEP2 over the centre-of-mass energy range 100-250 GeV ¹. Compared to the LEP1 era with $\sqrt{s} = m_Z$ giving a peak hadronic cross-section of approx 30 nb, all LEP2 cross-sections are several orders-of-magnitude smaller, with the more interesting ones in the range 1-20 pb. For example, at $\sqrt{s} = 196$ GeV with a luminosity of 100pb$^{-1}$, we would expect (with efficiency and purity both 100\%) $\sim 2,000 q\bar{q}$, $\sim 300 \mu^+\mu^-$ or $\tau^+\tau^-$, $\sim 2,000 W^+W^-$, $\sim 700 \gamma\gamma$ with $\cos\theta_\gamma < 0.9$, and $\sim 150$ ZZ events. With the same luminosity at the $Z$ we would record 3 million $q\bar{q}$.
One big difference between LEP1 and LEP2 physics is that the major processes of interest at LEP2 involve 4-fermion diagrams. This can be appreciated by looking at figure 2 which shows the different classes of 4-fermion diagrams involving neutral currents\(^3\). The dominant 2-fermion diagram of LEP1 will, as we shall see later, contribute a background to the 4-fermion channels.

1.4 Luminosity, Centre-of-Mass Energy, and Beam Energy

As mentioned above, the LEP2 era started with the introduction of superconducting RF cavities in 1995. Each winter shutdown more and more RF capability was installed, culminating in 2000 when a record centre-of-mass energy
of 209 GeV was achieved. Table 1 shows the integrated luminosity recorded by OPAL as a function of $\sqrt{s}$ for the period 1995-2000. These numbers are within a few % of those recorded by the other 3 experiments. In total, LEP delivered almost 1fb$^{-1}$ over the 12 years of operation, with 189pb$^{-1}$ recorded at LEP1 and 721pb$^{-1}$ at LEP2. The luminosity-weighted centre-of-mass energy above $W^+W^-$ threshold is $\approx$ 196 GeV. Each experiment had installed precision luminometers during the LEP1 era for the Z lineshape measurement and these provided typical luminosity uncertainties of $\sim$ 0.3% at LEP2.

Table 1. Summary of LEP2 integrated Luminosity during 1995-2000, as recorded by OPAL.

<table>
<thead>
<tr>
<th></th>
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<td>$\sqrt{s}$ GeV</td>
<td>130 136</td>
<td>161 172</td>
<td>130 136 183</td>
<td>189</td>
<td>192 196 200 202</td>
<td>205 207</td>
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<tr>
<td>Luminosity pb$^{-1}$</td>
<td>3.3</td>
<td>10 10</td>
<td>3.3 57</td>
<td>187</td>
<td>30 78 79 38</td>
<td>80 140</td>
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</table>

Figure 3 shows the luminosity recorded by OPAL as a function of $\sqrt{s}$ over the entire LEP era. In the lower part of the figure can be seen the data recorded during LEP’s final year. Also to be remarked is the 2-3pb$^{-1}$ of Z calibration data that was recorded each year during the LEP2 period.
This data was essential to maintain a well-calibrated detector for the lower-statistics LEP2 final states.

![Graph showing LEP2 and L3 data](image)

Figure 3. Total luminosity recorded by OPAL as a function of centre-of-mass energy.

Table 2 provides a summary of the exact statistics of the major channels analysed by OPAL. You will notice that the ZZ channel (where we quote candidates-background) is not overwhelming in statistics due, primarily, to its small cross-section.

To be able to determine $m_W$ with a precision of $\sim 25$ GeV we need to control the LEP beam energy to 1 part in $10^4$. Unfortunately the LEP1 technique of resonant depolarisation runs out of steam near $E_{beam}=65$ GeV when the beam polarisation drops to zero. However, it is hoped that a combination of the following techniques might just provide the needed precision:

- A combination of resonant depolarisation at $E_{beam} < 65$ GeV followed by magnetic extrapolation via NMR probes to higher energies has given $\Delta E_{beam} \sim 21$ MeV in 1999.

- A precision magnetic spectrometer in the LEP tunnel, with beam position monitors and accurately mapped Bi-field, is hoped to provide $\Delta E_{beam} \sim 15$ MeV.

- A machine physics relationship linking the synchrotron tune with applied
Table 2. Summary of actual event statistics, as recorded by OPAL. The 2-fermion  
final states require $\sqrt{s}/\sqrt{s} > 0.85$, the Bhabha events require $|\cos \theta| < 0.7$ and $\theta_{\text{col}} < 10^\circ$ to  
enhance s-channel contribution, the $\gamma \gamma$ final state requires $\cos \theta^* < 0.90$ (except for 183,189  
GeV that have $\cos \theta^* < 0.97$), and the ZZ final state is an estimate of the signal after  
background subtraction.

<table>
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<tr>
<th>Year</th>
<th>Lumi pb$^{-1}$</th>
<th>$\sqrt{s}$ GeV</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$\tau^+\tau^-$</th>
<th>$\gamma\gamma$</th>
<th>ZZ</th>
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<td>5.3</td>
<td>133</td>
<td>380</td>
<td>210</td>
<td>46</td>
<td>24</td>
<td>66</td>
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<td>1996</td>
<td>10.0</td>
<td>161</td>
<td>370</td>
<td>285</td>
<td>45</td>
<td>38</td>
<td>102</td>
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<td>1997</td>
<td>10.3</td>
<td>172</td>
<td>339</td>
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<td>183</td>
<td>1408</td>
<td>1260</td>
<td>174</td>
<td>123</td>
<td>620</td>
<td>4</td>
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<tr>
<td>1999</td>
<td>187.2</td>
<td>192</td>
<td>4072</td>
<td>3735</td>
<td>527</td>
<td>420</td>
<td>1740</td>
<td>50</td>
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<td>1999</td>
<td>29.6</td>
<td>196</td>
<td>1555</td>
<td>1448</td>
<td>208</td>
<td>149</td>
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<td>202</td>
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<td>81</td>
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<td>205</td>
<td>1515</td>
<td>1423</td>
<td>217</td>
<td>154</td>
<td>486</td>
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<td>140.0</td>
<td>207</td>
<td>2410</td>
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<td>353</td>
<td>267</td>
<td>767</td>
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<tr>
<td></td>
<td>TOTAL</td>
<td>14935</td>
<td>13623</td>
<td>1979</td>
<td>1560</td>
<td>5330</td>
<td>232</td>
<td>11336</td>
</tr>
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</table>

RF voltage can provide an alternative measure of $E_{\text{beam}}$. This promises  
an uncertainty comparable to other methods.

- Use the ‘radiative return’ (see next section) events to calibrate $E_{\text{beam}}$  
with $m_Z$. This method, pioneered by Aleph $^6$, may be subject to large  
systematics and currently suffers from small statistics. Nevertheless, a  
combination of the 4 experiments may provide a competitive $E_{\text{beam}}$  
determination.

2 2-Fermion Physics

Although the Standard Model has been shown to provide an excellent description  
of 2-fermion physics at LEP1, it is important to continue these measurements at  
energies well above the Z-pole. The data at LEP2 allow new measurements at  
several discrete energy points over the range $130 < \sqrt{s} < 209$ GeV.  
The data from the 4 experiments have been combined: for the methodology  
and results see LEP2FF/00-03 $^7$ and http://www.cern.ch/LEPEWWG/lep2.

2.1 Standard Model and Radiative Return

One major complication of $e^+e^-$ annihilation at LEP2 is the potential for  
Initial State Radiation (ISR) down to the Z-pole. If we wish to study full-
energy annihilation events, then we must select those events with little or no such radiation. Figure 4 shows several distributions of \( \sqrt{s} \), the effective energy of the annihilation as estimated from the data. The Z-pole is clearly visible, particularly in the \( q\bar{q} \) channel. Experiments typically choose \( \sqrt{s}/\sqrt{s} > 0.85 \) for full-energy events and \( \sqrt{s}/\sqrt{s} > 0.10 \) for inclusive measurements.

2.2 Cross-sections and F-B Asymmetries for hadrons and leptons

In general, cross-sections and angular distributions have been measured and averaged for \( q\bar{q} \), \( e^+e^- \), \( \mu^+\mu^- \), and \( \tau^+\tau^- \) final states. The \( e^+e^- \) Bhabha scattering has a dominant contribution from t-channel photon exchange and additional cuts (e.g. acolinearity and cms scattering angle) are made to enhance the s-channel. A compilation of the cross-section data from OPAL is shown in figure 5 together with Standard Model expectations. One sees a very good agreement for all channels at all energies.
OPAL preliminary

![Graph of cross-sections](image)

Figure 5. Compilation of measured 2-fermion cross-sections together with curves representing Standard Model predictions.

The combined LEP data on cross-sections for $q\bar{q}$, $\mu^+\mu^-$, and $\tau^+\tau^-$ are shown in figure 6, together with the forward-backward asymmetries from final states where the outgoing charge is easily identified, $\mu^+\mu^-$ and $\tau^+\tau^-$. The Standard Model expectations are superimposed. The theoretical uncertainties are estimated to be $\sim 0.2\%$ on $q\bar{q}$ and $\sim 0.7\%$ on $\ell^+\ell^-$. 

2.3 Cross-sections and F-B Asymmetries for heavy flavours

Heavy quark tagging allows cross-sections and asymmetries to be determined for both $c\bar{c}$ and $b\bar{b}$ final states. Figure 7 shows the ratio of the heavy flavour cross-sections to the total hadronic cross-section, $R_b$ and $R_c$, and the values
Cross section (pb)

\[ \sqrt{s} \cdot \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} > 0.85 \]

\[ e^+ + e^- \rightarrow \mu^+ + \mu^- (\gamma) \]

\[ e^+ + e^- \rightarrow \tau^+ + \tau^- (\gamma) \]

**LEP preliminary**

![Figure 6. Combined LEP results on 2-fermion cross-sections and forward-backward asymmetries as a function of centre-of-mass energy. The lower plot sections show the ratio (or difference) of data to the ZFITTER prediction (curves).](image)

![Figure 7. Combined LEP results on \( R_b \) and \( R_c \) and \( A_{FB}^b \) and \( A_{FB}^c \) as a function of centre-of-mass energy. The curves represent the Standard Model prediction of ZFITTER.](image)
of the forward-backward asymmetries, $A_{FB}^b$ and $A_{FB}^c$, together with Standard Model expectations. The data is in excellent agreement with the Standard Model.

In conclusion, although the combined hadronic cross-sections are on average 2.5σ above Standard Model predictions\(^7\), there is no significant evidence in the results for physics beyond the Standard Model.

3 Some Basic Checks

The excellent data on 2-fermion final states over such a large range of centre-of-mass energy has provided an opportunity to check the expected running of both the fine structure constant and the strong coupling constant, to check the size of the $\gamma - Z$ interference term, and to complete more neutrino counting tests.

![Graph showing the relationship between $\alpha(\sqrt{Q^2})$ and $10\log(\sqrt{Q^2}/\text{GeV}^2)$ for small and large angles.]

Figure 8. Measurements of the fine structure constant $\alpha_{em}$ from small angle and large angle Bhabha scattering. The curve represents the Standard Model expectation.

3.1 Running of Fine Structure Constant

In processes involving virtual photon exchange, vacuum polarisation effects lead to a $Q^2$ dependence (running) of $\alpha_{em}$. The leptonic contributions can
be calculated but the effect of quark loops (non-perturbative QCD) must be estimated. There are two recent results from LEP which support the running of $\alpha_{em}$. The L3 Collaboration has studied both small angle and large angle Bhabha scattering. In each case the data is divided into a small and large $Q^2$ sample and the change in $\alpha_{em}$ required to represent the data over the relevant $Q^2$ span is determined. The results, shown in figure 8, exhibit a 3.0sd and 2.9sd effect respectively, in agreement with the expected running of $\alpha_{em}$.

The OPAL Collaboration has taken the non-radiative cross-sections and asymmetries for $q\bar{q}$, $\mu^+\mu^-$, and $\tau^+\tau^-$ over the range $130-\sqrt{s}-207$ GeV and used ZFITTER to determine the best value of $\alpha_{em}$, keeping all other variables fixed. They obtain $\alpha_{em}^{-1} = 126.1^{+2.2}_{-2.1}$ at $\sqrt{s} = 190.7$ GeV which is 5.0sd below $\alpha_{em}^{-1}(0)$. Figure 9 shows this result together with values from lower energy experiments.

### 3.2 Running of Strong Structure Constant

Using precision event shape distributions from the $q\bar{q}$ final state, the combined LEP data has been fitted to theory that uses second order calculations in $\alpha_s$ and NLLA. The event shapes are $l-T$, $M_H$, $C$, $B_T$, $B_W$, and $y_2^H$ and

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Figure 9. Measurements of the fine structure constant $\alpha_{em}$ as a function of $Q$. The curves represent the Standard Model expectation (solid = running, dotted = fixed).
the derived values of $\alpha_s$ were presented at the LEP fes of October 2000: see http://lepqcd.web.cern.ch/LEPQCD/annihilations and are displayed in figure 10. Excellent agreement with the expected running of $\alpha_s$ is evident over a wide range of $E_{cm}$.

3.3 Photon/Z Interference

Because the photon/Z interference term is very small in the region of the $Z$ peak, the LEP1 lineshape fit uses its Standard Model value. Since the interference term becomes larger when one moves away from the $Z$ pole, experimentally we can verify its Standard Model value. A previous test, eg by the VENUS Collaboration 10 at $\sqrt{s} = 58$ GeV obtained a value for $j^{\text{had}} = 0.196 \pm 0.083$ compared to the Standard Model value of 0.220. A new test by the L3 Collaboration 11 using the $q\bar{q}$ channel has determined

$$j^{\text{had}} = 0.31 \pm 0.13 \pm 0.04(\text{theory})$$

over the range $130 \leq \sqrt{s} \leq 189$ GeV to be compared with the Standard Model value of 0.21. Their data is shown in figure 11.

Figure 12 shows that the inclusion of this new LEP2 data would significantly reduce the uncertainty on $m_Z$ if a lineshape fit were performed with $j^{\text{had}}$ free.
Cross section ($\text{pb}$)

$e^+e^- \rightarrow \text{hadrons}(\gamma)$

$L_3$

$\sqrt{s} > 0.85$

$\sigma_{\text{meas}} / \sigma_{\text{theo}}$

$10^2$

$10$

$1.11$

$0.93$

$1.00$

$0.31$

$0.62$

Figure 11. Hadronic cross-section as function of centre-of-mass energy together with theory predictions for different values of $J_{\text{had}}^{\text{tot}}$.

$\sqrt{s}$ (GeV)

$L_3$

$120$

$140$

$160$

$180$

$200$

$\sigma_{\text{meas}} / \sigma_{\text{theo}}$

$0.9$

$1$

$1.1$

$120$

$140$

$160$

$180$

$200$

$68\% \text{ CL}$

Figure 12. Allowed contours in the $m_Z - J_{\text{had}}$ plane showing the improvement with new LEP2 data. The vertical band shows the $m_Z$ range from a fit assuming the Standard Model value for $\gamma/Z$ interference.
3.4 Neutrino Counting

Although the LEP1 lineshape analysis estimates the number of light neutrino species indirectly via the measurement of the $Z$ invisible width (giving $N_\nu = 2.984 \pm 0.008$), a more direct but statistically less powerful technique is to measure the cross-section for $e^+e^- \rightarrow \nu\bar{\nu}$. These latter results have been summarised by Mnich and provide $N_\nu = 3.00 \pm 0.08$ from all 4 experiments at LEP1 and $N_\nu = 2.99 \pm 0.10$ from Delphi and L3 at LEP2. An example of the sensitivity of the $e^+e^- \rightarrow \nu\bar{\nu}$ cross-section to the number of light neutrino species is shown in figure 13 by the L3 Collaboration. The ratio of measured/Standard Model cross-section averaged over the 4 experiments is $0.965 \pm 0.028$, perfectly compatible with 3 neutrino species.

![Figure 13](image)

Figure 13. Cross-section measurements for $e^+e^- \rightarrow \nu\bar{\nu}$ compared to the Standard Model expectation for 2,3,4 neutrino species. The upper curve corresponds to the extrapolated full cross-section $e^+e^- \rightarrow \nu\bar{\nu}$.

4 Constraints on New Physics

LEP has measured cross-sections and angular distributions for $e^+e^- \rightarrow q\bar{q}$, $e^+e^- \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \tau^+\tau^-$, $e^+e^- \rightarrow W^+W^-$, and $ZZ$ and, within errors, everything agrees with the Standard Model expectations. We will now use this data to set limits on a variety of models incorporating new physics. In general, the
Standard Model Lagrangian is modified by the addition of a new contribution representing the new physics and incorporating model specific parameters. This new contribution will be multiplied by an effective coupling constant and divided by an effective scale. Typically, both the coupling constant and scale are unknown and, in general, an assumption is made for one of them when obtaining limits on the other. Thus, care should be taken when interpreting the results below.

4.1 Limits on \(Z'\)

![Graph](image.png)

Figure 14. Exclusion contours at 95\% CL in the \(Z'\) mass-mixing angle plane for specific models. Only the inner area is allowed.

An introduction to \(Z'\) physics can be found in a paper by Altsareli, Mele, and Ruiz-Altaba\(^{14}\) which should be consulted together with the mini-review in PDG 2000\(^{15}\). One motivation for \(Z'\) searches is that Grand Unified Theories, eg E(6), will contain extra \(U(1)\) gauge groups. Current analyses incorporate \(Z-Z'\) mixing into ZFITTER in which the couplings of the bare state \(Z''\) are model dependent. Analyses with LEP1 data only, eg by the Delphi Collaboration\(^{16}\), already limited the mixing angle to a few mrad. The LEP2 analyses generally extend the exclusion region in the \(Z'\) mass-mixing angle plane as demonstrated by the OPAL Collaboration\(^{17}\) in figure 14. The data
from the 4 LEP experiments has been combined (see LEP2FF/00-03 from the LEPEWWG ff subgroup), and with zero mixing, yields limits on possible Z' masses at 95% CL ranging from 400 GeV to 2260 GeV, depending on the specific model couplings.

4.2 4-f Contact Interactions

Eichten, Lane, and Peskin have demonstrated a method to detect possible quark or lepton substructure via the introduction of a Lagrangian representing 4-fermion contact interactions 19. The coupling constant \( (g^2/4\pi) \), which is unknown, is generally set to unity by convention. Results on the scale on the contact interactions are given by \( \Lambda^- \) and \( \Lambda^+ \), where the sign characterizes the chiral structure of the interaction. The LEP2 data have been fitted by the LEPEWWG (see LEP2FF/00-03) using (a) purely leptonic final states \( \mu^+\mu^- \) and \( \tau^+\tau^- \) and (b) heavy flavour b\( \bar{b} \) and c\( \bar{c} \) final states. The results are displayed in figures 15 and 16 respectively. In the leptonic case the limits range from 8.0-23.9 TeV, and in the hadronic case from 1.3-14.0 TeV.

![LEP Combined Preliminary](image)

Figure 15. Limits on \( \Lambda \) for contact interactions from \( \mu^+\mu^- \) and \( \tau^+\tau^- \) final states.

```plaintext
LEP Combined Preliminary

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<tr>
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```

\( \Lambda^- \) (TeV) \( \Lambda^+ \) (TeV)
4.3 Exchange of R-parity violating sneutrinos

Since scalar neutrinos can decay to lepton-pairs via direct R-parity violating transitions, they can contribute to $\ell^+\ell^-$ final states via both s-channel and t-channel 2-fermion exchange diagrams. The analysis of LEP2 data thus allows limits to be derived on several products of couplings $\lambda_{ijk}$ (where $ij,k$ represent generation indices) as a function of $\nu$ mass. A good example has been presented by the L3 Collaboration 19 at $\sqrt{s} = 189$ GeV and shown in figure 17.

4.4 Exchange of Leptoquarks

In the reaction $e^+e^- \rightarrow \bar{f}f$ a contribution of t(or u)-channel leptoquark exchange is possible. Analyses can provide limits on scalar or vector leptoquark masses as a function of the relevant coupling constant. With a value of $g^2/4\pi = \alpha$ the L3 Collaboration 19 has been able to derive lower bounds for the leptoquark mass within the range 55-560 GeV.

4.5 QED cut-off parameters

The reaction $e^+e^- \rightarrow \gamma\gamma$ is a pure QED process mediated by electron exchange in the t-channel. Figure 18 shows the cross-section data of the OPAL Collaboration over the entire LEP energy range together with SM expectation. No discrepancy is observed. Deviations from pure QED are typically determined from a fit of the differential cross-section and expressed in terms

Figure 16. Limits on $\Lambda$ for contact interactions from $e^+e^- \rightarrow b\bar{b}$ and $e^+e^- \rightarrow c\bar{c}$.
Figure 17. Upper limits at 95% CL on the coupling strengths $\lambda_{ijj}$ of scalar leptons to leptons as a function of scalar neutrino mass.

Figure 18. Measurements of the cross-section $e^+e^- \rightarrow \gamma\gamma$ as a function of centre-of-mass energy together with the Standard Model QED expectation. The upper box shows the data-Standard Model difference.
of cut-off parameters $\Lambda_\pm$. The sensitivity of this method improves as $\sqrt{s}$ increases, see for example the results of the L3 Collaboration \textsuperscript{20}. A recent analysis by the OPAL Collaboration \textsuperscript{9} using all data up to $\sqrt{s} = 207$ GeV gives limits on $\Lambda_\pm$ in the 325-350 GeV range.

4.6 Exchange of Excited Electrons

The $e^+e^- \rightarrow \gamma\gamma$ reaction can also be influenced by the exchange of an excited electron ($e^*$) in the t-channel. The effect will depend on the $e^*$ mass and on the coupling $g_{e^*\gamma\gamma}$. A recent analysis by the OPAL Collaboration \textsuperscript{9}, with the restriction $g_{e^*\gamma}\gamma=g_{e\gamma\gamma}$, has set a lower mass limit of 354 GeV at 95\% CL.

4.7 Models with Low-scale Gravity

![OPAL preliminary](image)

Figure 19. Log likelihood curves as a function of $\lambda/M_4^4$ for different final states together with the combined result (solid curve).

In string models involving extra dimensions, the possibility of spin=2 graviton exchange could influence the reactions $e^+e^- \rightarrow f\bar{f}$ and also the final states $\gamma\gamma$, $W^+W^-$, and $ZZ$, see Mele and Sanchez \textsuperscript{21} and a recent talk by P. Krieger at SUSY2K \textsuperscript{22}. The differential cross-sections are modified by the addition of a pure graviton term and an interference term. Only the latter is relevant at LEP energies and contributes inversely proportional to the 4th
power of $M_s$ (the effective Planck mass at the string scale). The coupling constant is unknown (can only be calculated with a full knowledge of the underlying quantum gravitational theory) and is usually set to either $\lambda = -1$ or +1. 95% CL lower limits on $M_s$ from an analysis of $\gamma \gamma$, ZZ, $W^+ W^-$ final states are 0.96 TeV and 0.92 TeV $^{21}$ and from $\mu^+ \mu^-$, $\tau^+ \tau^-$, $\gamma \gamma$, ZZ final states are 0.88 TeV and 0.89 TeV $^{22}$. The latter results by the OPAL Collaboration are derived from the likelihood curves shown in figure 19.

![Exclusion curves at 95% CL in the $\kappa_2$-$\kappa_7$ plane for different values of $m_1$. The region excluded by CDF is shown by the dashed box.](image)

**Figure 20.** Exclusion curves at 95% CL in the $\kappa_2$-$\kappa_7$ plane for different values of $m_1$. The region excluded by CDF is shown by the dashed box.

### 4.8 Limits on FCNC single top production

With a top quark mass of $174.3 \pm 5.1$ GeV, LEP2 cannot produce $t\bar{t}$ pairs. However, FCNC can produce a single top quark via a loop diagram leading to final states $t\bar{t}(T)$. Although Standard Model calculations of this process lead to impossibly small cross-sections $^{24}$, an investigation of this channel may provide surprises. Two current searches for such final states with $t \rightarrow bW$ decays have provided 95% CL upper limits of 0.48pb $^{25}$ and 0.35pb $^{26}$. The Aleph Collaboration has expressed its result in the form of exclusion limits in the couplings corresponding to $t \rightarrow cZ$ and $t \rightarrow c\gamma$ $^{25}$. This exclusion region is displayed in figure 20 together with a previous exclusion from CDF. The $\kappa_2$
limit is clearly improved and will continue to improve when all the LEP data are combined.

5 ZZ Physics

The reaction $e^+e^- \rightarrow ZZ$, with a threshold near $\sqrt{s} = 183$ GeV, proceeds via the Standard Model diagrams NC02 involving the exchange of an electron in the $t\bar{t}$ channel. The final state is of special interest because it constitutes an irreducible background to $e^+e^- \rightarrow H^0Z^0$. Some of the final state characteristics that are used to identify Z-pair candidates are listed in table 3 which is taken directly from a recent talk by G. Bella 27. Remember that the Z branching ratios are 70% to $f\bar{f}$, 10% to $\ell^+\ell^-$, and 20% to $\nu\bar{\nu}$. In general it is rather difficult to obtain ‘clean’ signals due to the large backgrounds, particularly those due to 2-fermion QCD and $W^+W^-$-pairs. The channel $q\bar{q}\ell^+\ell^-$ has the highest efficiency*purity. A beautiful $q\bar{q}\mu^+\mu^-$ event at $\sqrt{s} = 205$ GeV recorded by the OPAL Collaboration is shown in figure 21.

Table 3. Final States used to identify ZZ-pairs. ME represents missing energy, and leptons refers to electrons/positrons/taus.

<table>
<thead>
<tr>
<th>Final State</th>
<th>Fraction</th>
<th>Signature</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q}f\bar{f}$</td>
<td>45%</td>
<td>1 jets</td>
<td>30%</td>
<td>15 - 35%</td>
</tr>
<tr>
<td>$q\bar{q}f\bar{f}$</td>
<td>26%</td>
<td>2 jets + ME</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>$q\bar{q}\ell^+\ell^-$</td>
<td>14%</td>
<td>2 jets + 2 leptons</td>
<td>50 - 80%</td>
<td>80 - 90%</td>
</tr>
<tr>
<td>$\ell^+\ell^-\nu\bar{\nu}$</td>
<td>4%</td>
<td>2 leptons + ME</td>
<td>30%</td>
<td>45 - 55%</td>
</tr>
<tr>
<td>$\ell^+\ell^-\ell^+\ell^-$</td>
<td>1%</td>
<td>4 leptons</td>
<td>40 - 60%</td>
<td>60 - 80%</td>
</tr>
<tr>
<td>$\nu\bar{\nu}$</td>
<td>4%</td>
<td>invisible</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Analyses typically use many sequential cuts and/or multivariate techniques and impose mass constraints where possible (e.g. $Z \rightarrow f\bar{f}, \ell^+\ell^-$). The event rates are small, see table 2, and the channels are combined in a maximum likelihood fit that assumes Standard Model Z branching ratios to determine the reaction cross-section at each energy. Figure 22 shows the combined-LEP cross-section together with theory expectation from YFSZZ and ZZTO, which have a 2% uncertainty. The agreement is excellent. In fact, the ratio of measured/theory cross-section, averaged over all $\sqrt{s}$ is $0.99 \pm 0.06$ 28.

All LEP Collaborations have analysed the ZZ cross-sections and angular distributions to search for anomalous neutral-current triple gauge couplings which are forbidden at tree-level within the Standard Model. No evidence has been found for non-zero couplings.
6 \(W^+W^-\) Physics

The main focus of the LEP2 program has been a detailed study of the \(e^+e^- \rightarrow W^+W^-\) process to (a) confirm the presence of the non-abelian triple gauge couplings which are demanded by the Standard Model and to (b) make a precision measurement of \(m_W\).

6.1 Cross-section Determination

\(W^+W^-\)-pair production takes place via the Standard Model diagrams CC03 which are (a) a t-channel \(\nu_e\) exchange, (b),(c) s-channel \(\gamma, Z\) exchange involving the triple gauge couplings (TGCs) \(\gamma WW\) and \(ZWW\) respectively. Diagram...
Figure 22. Measurements of the ZZ-pair cross-section (points) compared to the Standard Model prediction (curves).

(a) is dominant near threshold and gives the forward $W^-$-peaking in the angular distribution. Some of the characteristics of the channels used to isolate $W^+W^-$-pair candidates are given in table 4, which is taken directly from a recent talk by G. Bella. Remember that the $W$ decays hadronically ($qar{q}$) 67.5% and semi-leptonically ($\ell\nu\ell\nu$) 32.5% of the time. The decay $W \rightarrow t\bar{b}$ is not kinematically allowed. In comparison to ZZ production (see table 3) the $W^+W^-$ efficiencies and purities are significantly higher. There are still sizeable QCD backgrounds, particularly in the fully-hadronic channel, and these must be estimated carefully from MonteCarlo.

Table 4. Final States used to identify $W^+W^-$-pairs. ME represents missing energy, and leptons refer to electrons/μons/τs.

<table>
<thead>
<tr>
<th>Class</th>
<th>Final State</th>
<th>Fraction</th>
<th>Signature</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully-hadronic</td>
<td>$q\bar{q}$</td>
<td>45.6 %</td>
<td>4 jets</td>
<td>85%</td>
<td>80%</td>
</tr>
<tr>
<td>Semi-leptonic</td>
<td>$q\bar{q}$</td>
<td>43.9 %</td>
<td>2 jets + isolated lepton + ME</td>
<td>85%</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>$q\bar{q}$</td>
<td>43.9 %</td>
<td>isolated lepton + ME</td>
<td>90%</td>
<td>98%</td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$</td>
<td>10.6 %</td>
<td>2 acollinear jets + ME</td>
<td>45 – 80%</td>
<td>90%</td>
</tr>
</tbody>
</table>
The candidate event samples are isolated after applying sequential data cuts and/or multivariate techniques. A beautiful $q\overline{q}q\overline{q}$ event at $\sqrt{s} = 208$ GeV recorded by the OPAL Collaboration is shown in figure 23.

![Figure 23](image)

Figure 23. A classic example of $e^+e^- \rightarrow W^+W^- \rightarrow q\overline{q}q\overline{q}$ as recorded by the OPAL Collaboration at $\sqrt{s} = 208$GeV.

The $W^+W^-$ signal is estimated by subtracting the Standard Model background and then applying a maximum likelihood fit to obtain the CC03 cross-section with/without a simultaneous extraction of the W branching ratios. If we assume Standard Model W branching ratios, the resulting all-LEP cross-section is displayed in figure 24 (see LEPEWWG/XSEC/2000-01-31). The figure also shows the current theoretical predictions from RaccoonWW/YFSWW3 and GENTLE that have inherent uncertainties of 0.4% and 0.7%, respectively. Clearly, the data are well-represented by the Standard Model predictions and provide a convincing case that all three CC diagrams are required, i.e., triple gauge couplings are needed. Figure 25 shows the latest LEP2 data in greater detail (see LEPEWWG/XSEC/2000-01).
Figure 24. Measurements of the $W^+W^-$-pair cross-section (points) compared to the Standard Model prediction (curves) with/without triple gauge couplings.

Figure 25. Measurements of the $W^+W^-$-pair cross-section (points) compared to the Standard Model prediction (curves).
6.2 Branching Ratios, Lepton Universality, and CKM Matrix

![W Leptonic Branching Ratios Diagram]

Figure 26. Measurements of the W leptonic branching ratios provided by the 4 LEP experiments together with the combined result. The solid vertical line represents the Standard Model expectation.

If the maximum likelihood fit does not assume Standard Model W branching ratios, then these can be determined from the fit to the channel data. Figure 26 shows the W-leptonic branching ratios as determined by each of the 4 LEP experiments and their combined values. For each leptonic channel the individual measurements are in good agreement and the 3 combined values are consistent within 3.3% of equality thus confirming the Standard Model expectation of universal lepton couplings. Assuming lepton universality, the W to $\ell\tau$ branching ratio is determined to be $10.74 \pm 0.10$% per lepton decay channel, and the W to $q\bar{q}$ branching ratio is determined to be...
67.78 ± 0.32%, in good agreement with Standard Model expectation (10.83% and 67.51% respectively). The precision is now better than that from the p+p collider experiments.

The determined branching ratios can now be used to set new values on specific terms of the CKM matrix (see LEPEWWG/XSEC/2000-01). The q$q^\prime$ branching ratio is related to a sum of 6 terms in the CKM matrix, of which $|V_{cb}|$ is the least well determined. Using PDGT 2000 for the sum of the other 5 terms, the LEP hadronic branching ratio (above), and $\alpha_b(m_W^2) = 0.121 \pm 0.002$, a value of $|V_{cb}| = 0.989 \pm 0.016$ has been extracted. It should be noted that this value does not assume unitarity of the CKM matrix and that the error is dominated by the branching ratio uncertainty.

A more direct determination of $|V_{cb}|$ follows from the measurement of $R_c^W$, the ratio of the charm to total hadronic branching ratio of the W. Since extra selections are needed to isolate the charm component, the resulting precision will be clearly inferior. The 4 experiments in combination have determined $R_c^W = 0.494 \pm 0.044$ and this leads to an extraction of $|V_{cb}| = 0.96 \pm 0.08$, significantly less precise than the value above. Nevertheless, the two determinations are in good agreement with each other, and with expectation.

![Figure 27](image_url)  

Figure 27. Measurements of the single-W cross-section (points) compared to Standard Model predictions (curves).

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*cr467: submitted to World Scientific on May 3, 2001*
6.3 \textit{TGC Determination and W-polarisation}

The $W^+ W^-$-pair cross-section measurements (see above) have already shown the necessity to include the two $s$-channel diagrams involving triple gauge couplings. These $W^+ W^- \gamma$ and $W^+ W^- Z$ couplings are demanded by the gauge structure of the Standard Model. There are other reactions involving the $W^+ W^- \gamma$ coupling, in particular the single-$W$ diagram leading to the $W\tau\bar{\tau}$ final state, and the single-$\gamma$ diagram leading to the $v\bar{v}W\gamma$ final state, both of which are accessible at LEP2. The form and strength of these vertex couplings are unambiguously predicted by the gauge structure of the Standard Model, see e.g. the paper of Bilenky et al. \cite{Bilenky} and also the Yellow report CERN 96-01. Although the most general Lorentz-invariant Lagrangian describing TGCs has 14 terms, after insisting on gauge invariance and C+P conservation, only 3 terms remain which, in the Standard Model, are $\kappa_\gamma = 1$, $g_0^\phi = 1$, and $\lambda_\gamma = 0$, i.e. only 2 terms non-zero. The term 'anomalous' TGC refers to any TGC, including the 2 non-zero Standard Model TGCs, with values different from Standard Model expectation. The measured cross-sections for $e^+ e^- \rightarrow W^+ W^-$, and $W\nu\bar{\nu}$, and the production/decay angular distributions for $W^+ W^-\text{-pair}$ production are sensitive to the form and strength of all possible TGCs. Figure 27 shows the LEP cross-section for the single-$W$ final...
state, for those cases with W hadronic decays. The data is seen to be in good agreement with the Standard Model expectation, albeit with a 5% theoretical uncertainty.

Figure 28, taken from a talk by A. Macchiolo at EPS-HEP99, shows the definition of the 5 angles needed to specify the complete production and decay distributions in the $W^+W^-$ final state. We remark in passing that the entire angular phase-space is not always accessible due to ambiguities resulting from quark flavour identification, or missing neutrinos in the fully-leptonic channels, and problems with imperfect jet pairing. Figure 29 gives some idea of the sensitivity of these angular distributions to anomalous values of $g_1^z$, taken from the OPAL Collaboration 33.

![Figure 29. Sensitivity of angular distributions to anomalous values of $g_1^z$ for data taken from semi-leptonic WW events at 189 GeV.](image)

There are two methods in common use for an extraction of the TGCs. The first is model-dependent and determines the TGCs from maximum-likelihood fits to the cross-sections and angular distributions. The second is more general and evaluates the $W^+W^-$ spin density matrix from which one can
extract the helicity structure and polarisation properties. Figure 30 shows the log-likelihood curves from method 1 using the combined LEP data (see LEPEWWG/TGC/2000-02 34) and table 5 summarises the values and limits obtained for $\Delta g_1^Z \equiv g_1^Z - 1$, $\Delta \kappa_\gamma \equiv \kappa_\gamma - 1$, and $\lambda_\gamma$. In each case, the fits vary 1 parameter at a time, the others being kept fixed at their Standard Model values (ie $=0$). The results show no evidence for anomalous values of the couplings. More complex analyses looking for the other 14-3=11 parameters also give no evidence for non-zero values (this is good because they would violate C, P, or CP conservation). When all the LEP data is analysed, the precision on $\Delta g_1^Z \equiv g_1^Z - 1$, and $\lambda_\gamma$ should be better than $\pm 0.02$, and on $\Delta \kappa_\gamma \equiv \kappa_\gamma - 1$ better than $\pm 0.05$ 35. Note that these direct determinations of the TGCs
contrast with previous indirect estimations using EW radiative corrections at the Z pole \(^{36}\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>95% CL limits</th>
<th>Standard Model expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta \eta \equiv \eta - 1)</td>
<td>-0.026(^{+0.074}_{-0.028})</td>
<td>[-0.074, +0.028]</td>
<td>0</td>
</tr>
<tr>
<td>(\Delta \kappa \equiv \kappa - 1)</td>
<td>-0.002(^{+0.019}_{-0.008})</td>
<td>[-0.13, +0.13]</td>
<td>0</td>
</tr>
<tr>
<td>(\lambda_{\gamma})</td>
<td>-0.036(^{+0.089}_{-0.020})</td>
<td>[-0.089, +0.020]</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 31. W helicity fractions \(f_0\) and \(f_\pm\) as a function of \(\cos \theta_W\). The Standard Model (KORALZ) predictions are represented by the histograms.

The more general approach leading to helicity structure and polarisation has been formulated by Hagiwara, Peccei, and Zeppenfeld \(^{37}\). W’s are expected in both transverse (helicity \(\pm 1\)) and longitudinal (helicity 0) polarisation states. One can employ the full 9\(^{th}\) spin density matrix for W\(^\pm\) or, more simply, just use the W-decay as a polarisation analyser to extract the fractional contributions of helicity -1, 0, and +1 (denoted by \(f_-, f_0, f_+\), respectively). Hagiwara et alia \(^{37}\) have predicted the transverse and longitudinal components as a function of the W production angle \(\cos \theta_W\) at \(\sqrt{s} = 190\) GeV. A recent study by the L3 Collaboration \(^{39}\), whose results are displayed in figure 31, shows that within the present level of statistics the data and Standard
Model expectations are in good agreement. Table 6 lists a summary of recent determinations\textsuperscript{39,38,40} of $f_0$ together with Standard Model expectations.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>Collaboration</th>
<th>$f_0$ data</th>
<th>SM expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>183</td>
<td>OPAL</td>
<td>0.247 ± 0.091 ± 0.023</td>
<td>0.272</td>
</tr>
<tr>
<td>183-189</td>
<td>L3</td>
<td>0.261 ± 0.051 ± 0.016</td>
<td>0.26</td>
</tr>
<tr>
<td>183-202</td>
<td>OPAL</td>
<td>0.210 ± 0.033 ± 0.016</td>
<td>0.257</td>
</tr>
<tr>
<td>183-202</td>
<td>L3</td>
<td>0.259 ± 0.035</td>
<td>0.248</td>
</tr>
</tbody>
</table>

6.4 Mass Determination

The determination of $m_W$ is perhaps the most important, and certainly the most challenging, of the LEP2 precision measurements. See LEPEWWG/MASS/2000-01\textsuperscript{41} for more details. There are two standard methods\textsuperscript{1} via the measurement of the cross-section ($e^+e^- \rightarrow W^+W^-$) variation near $W^+W^-$ threshold, and\textsuperscript{2} via the direct mass reconstruction from the $W$ decay products. In the latter case, as seen in table 4, there are three event categories: (a) the fully-hadronic channel $qq'q'q''$, (b) the semi-leptonic channel $q\ell\nu\ell'\ell''$, and the fully-leptonic channel $\ell\nu\ell'\ell''$. As discussed by R. Strohmer\textsuperscript{42}, this last channel, which represents only 10.6\% of all $W^+W^-$ decays, has 2 undetected neutrinos and there are not enough constraints to perform a kinematic fit. Nevertheless, one can look at either the charged lepton energy spectrum or at a pseudo-mass estimator (which assumes the neutrinos are in the same plane as the leptons) to try and determine $m_W$. However, the resulting error on $m_W$ ranges from 0.5 to 1.5 GeV and the channel is ignored for the time being.

The threshold method\textsuperscript{1} (see CERN-PPE/97-154) was historically the first method used by the LEP Collaborations in 1996 when the beam energy was raised above $W^+W^-$ threshold. Approximately 30 $W^+W^-$ events were observed by each experiment at $\sqrt{s} = 161$ GeV and the resulting LEP-combined C03 cross-section was determined to be 3.69 ± 0.45pb. Knowing the variation of cross-section with $W$ mass (see figure 32), this translates into $m_W = 80.40^{+0.22}_{-0.21} ± 0.03$ GeV, where the systematic error of 0.03 GeV comes from the LEP energy calibration. As we will see later, the statistical weight of this threshold measurement will be overshadowed by the more precise direct mass determinations.

The direct mass reconstruction\textsuperscript{2} utilises both the fully-hadronic and semi-leptonic $W^+W^-$ decay channels. The fully-hadronic channel, which con-
stitutes 45.6\% of all $W^+W^-$ decays, was discussed recently by S. Schmidt-Karst at Osaka 43. The events are forced into 4 jets, energy/momentum constraints are applied, and the two $W$s are constrained to have the same mass. Of the 3 possible 2-jet pair combinations, current methods to choose the correct pairing succeed in about 90\% of the cases. The resulting mass distribution is fitted with a variety of methods and systematics are evaluated. Currently there are two serious complications associated with potential final state interactions (FSI).

The first of these is associated with Bose-Einstein Correlations (BEC), see a recent talk by A. Valassi at Osaka 44. BEC produce an enhancement of identical bosons in regions of close proximity of phase-space, giving more $\pi^\pm \pi^\pm$ than $\pi^\pm$ at small values of $Q$. We already know that intra-$W$ BEC exist, but if inter-$W$ BEC were found to be present in the data then this could bias the determination of $m_W$. The Aleph Collaboration 45 has recently shown strong evidence for intra-$W$ BEC (see figure 33 for semi-leptonic WW events) but their current data do not strongly favour inter-$W$ BEC (see figure 34) in fully-hadronic WW events. It will take the combined-LEP data to make a more definite statement.

The second FSI complication is associated with Colour-Reconnection

Figure 32. Extraction of $m_W$ from the LEP measurement of the $W$-pair cross-section near threshold. The curve represents the Standard Model.

$\sqrt{s} = 161.33 \pm 0.05$ GeV

\begin{align*}
\sigma_{WW} &= 3.69 \pm 0.45 \text{ pb} \\
m_W &= 80.40 \pm 0.21 \text{ GeV} \\
\text{LEP Average}
\end{align*}
Figure 33. Bose-Einstein correlation function for semi-leptonic WW events. The solid curve represents a fit to the data.

Figure 34. Bose-Einstein correlation function for fully-hadronic WW events. The solid curve represents a fit to the data. The open circles represent the prediction of a model that incorporates inter-W Bose-Einstein correlations.
(CR), see a recent talk by P. DeJong at Osaka\textsuperscript{49}. CR involves the exchange of coloured gluons during the non-perturbative hadronisation phase and could, in principle, give a bias to $m_W$. Several Monte Carlo models predict differing CR behaviour and there is no firm conclusion yet from the 4 experiments. However, a new, promising, method involving a study of particle flow was presented by the L3 Collaboration at Osaka\textsuperscript{47} and this is shown in figure 35 together with the expectations of several CR models. It is hoped that, with the full statistics from all 4 experiments, several models of CR could be ruled out, thus limiting the size of the associated systematic error.

![Figure 35](image)

Figure 35. Ratio of particle flows between jets from the same W and between jets from different W's as a function of the rescaled angle. The histograms represent Monte Carlo predictions.

Direct mass reconstruction from the semi-leptonic channel has been discussed recently by R. Strohmer at Osaka\textsuperscript{42}. This channel represents 43.9\% of all $W^+W^-$ decays and comprises the 3 separate leptonic decays $e\nu_e$, $\mu\nu_\mu$, and $\tau\nu_\tau$, (see table 4). There is clearly no problem here with inter-W FSI, nor is there any difficulty with jet-choice. The semi-leptonic channel has good efficiency and high purity. Energy and momentum, and mass equality constraints are applied as for the fully-hadronic channel previously. However, the $\tau\nu_\tau$ decay channel has additional missing neutrinos and the tau energy cannot be determined. One uses the mass from the hadronic decay in this case.
Again, mass distributions are fitted with a variety of methods and systematic error contributions are evaluated.

Figure 36 shows some typical mass distributions from the 4 experiments. The shaded regions, which represents background contributions evaluated from MonteCarlo, are generally small and well-determined.

![Graphs showing mass distributions](image_url)

Figure 36. Examples of reconstructed $W$ mass distributions from the LEP experiments.
6.5 Combination of Mass Values

The LEP EWG (see LEPEWG/MASS/2000-01) has combined the results of the direct reconstruction from the fully-leptonic and semi-leptonic channels after carefully taking into account the correlations in the systematic errors. The results are summarised in table 7. One immediately notices the large values of systematic error associated with colour-reconnection and Bose-Einstein correlation in the fully-hadronic channel. We hope to reduce these by a substantial factor before the final analysis is complete. With the current values, the q̅q̅ q̅q̅ statistical weight in the combination is but 27%. Another systematic that may reduce in the future is that labelled ‘Hadronisation’. This is associated with the differing MonteCarlos currently employed and could benefit from improved ‘tuning’ of the models to data. One notices that the difference in M_w between the q̅q̅ q̅q̅ and the q̅q̅ lν̅ν̅̄ channels is only +5 ± 51 MeV, indicating that global FSI effects cannot be huge. This is somewhat reassuring. The current best measurement of M_w is the combination of all direct mass values together with the threshold mass value, and leads to a LEP result of M_w = 80.427 ± 0.046 GeV (see table 8). It is hoped that a final LEP2 result will have a total error of ~ 30 MeV.

Table 7. Tabulation of systematic and statistical errors in the determination of the W-mass. Units are MeV.

<table>
<thead>
<tr>
<th>Source of systematic error</th>
<th>q̅q̅ q̅q̅</th>
<th>q̅q̅ q̅q̅</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR/FSR</td>
<td>8</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Hadronisation</td>
<td>26</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Detector effects</td>
<td>11</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>LEP beam energy</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>0</td>
<td>50</td>
<td>13</td>
</tr>
<tr>
<td>Bose-Einstein correlations</td>
<td>0</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>Others</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Total systematic</td>
<td>35</td>
<td>64</td>
<td>36</td>
</tr>
<tr>
<td>Statistical error</td>
<td>38</td>
<td>34</td>
<td>30</td>
</tr>
<tr>
<td>Total error (MeV)</td>
<td>51</td>
<td>73</td>
<td>47</td>
</tr>
<tr>
<td>Mass M_w (GeV)</td>
<td>80.427</td>
<td>80.432</td>
<td>80.428</td>
</tr>
</tbody>
</table>

Table 8. Combination of LEP2 threshold and direct W-mass determinations.

<table>
<thead>
<tr>
<th>Source</th>
<th>Mass value (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold Method</td>
<td>80.400 ± 0.220 ± 0.030</td>
</tr>
<tr>
<td>Direct Mass Measurement</td>
<td>80.428 ± 0.030 ± 0.036</td>
</tr>
<tr>
<td>LEP2 combined</td>
<td>80.427±0.016</td>
</tr>
</tbody>
</table>
6.6 Comparison of Direct and Indirect Mass Estimates

We can now compare the direct $m_W$ measurement from LEP2 with (a) the
direct measurements from the $p\bar{p}$ colliders and (b) the indirect measurements
from the Standard Model fits to precision data of LEP1/SLD and neutrino
scattering data (see figure 37). Within the current level of statistics, there is
no difference between the separate measurements. It certainly looks as though
the Standard Model has no surprises, at least within the energy range over
which we are testing it. It is an experimental triumph that the direct and
indirect mass measurements agree so well.

![W-Boson Mass](image)

Figure 37. Comparison of W mass measurements. The direct measurements from LEP and
$p\bar{p}$ colliders are averaged and compared to indirect determinations.

Figure 38 shows the direct and indirect error ellipses in the 2-dimensional
plane of $m_W$ vs $m_t$ as a function of the Standard Model Higgs mass. One
notices two things: (a) the error ellipses overlap substantially and (b) the
overlap area indicates a strong preference for a low mass Higgs.

Finally, we show in figure 39 the chisquare behaviour of the complete
Standard Model fit as a function of the Standard Model Higgs mass in which
all precision electroweak data has been used (LEP1 lineshape, SLD asymme-
tries, neutrino scattering, tau polarisations, direct measurements of $m_W$ and
$m_t$, etc). For full details consult CERN-EP-2000-153 \cite{48} for the combination
procedures and CERN-EP-2001-021 \cite{49} for the combination results themselves.
Figure 38. Comparison of the indirect measurements of $m_W$ and $m_t$ (solid contour) and the direct measurements (dashed contour). Also shown is the Standard Model relationship as a function of Higgs mass.

In this figure the shaded region represents the area already excluded by direct LEP Higgs searches (up to approximately 113 GeV at 95% CL\textsuperscript{50}). The solid (dashed) curve provides a 95% CL upper limit for the Standard Model Higgs mass of 165 (206) GeV. This will provide a great incentive for dedicated searches at Tevatron\textsuperscript{2} and the LHC. Which laboratory will claim a discovery?

7 Conclusions

These two lectures have displayed the wealth and beauty of LEP2 electroweak physics. There is absolutely no evidence for any significant deviation from current Standard Model expectations. Long live the Standard Model of particle physics.

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Figure 39. Chisquare versus Higgs mass. The theory uncertainty band represents missing higher order corrections. The excluded region is from direct Higgs searches. The dashed curve is the result obtained with a new determination of the fine structure constant.
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