REVIEW OF LEP2 PHYSICS

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Abstract. In this short review I summarise some of the current results obtained by the ALEPH, DELPHI, L3 and OPAL experiments using data taken at LEP2 at collision energies between 160 and 209 GeV.

1 Introduction

This is a review of results obtained by the ALEPH, DELPHI, L3 and OPAL experiments using data recorded at energies above the threshold for WW production between 1996 and 2000 at the LEP2 accelerator at CERN. There were other talks at this conference describing LEP2 searches for Higgs and SUSY particles, anomalous gauge couplings and single top production. Recent results on fermion-pair production, W and Z pair production and measurement of the W boson mass form the main topics for this talk. A few results on other topics have been included to illustrate the wide range of physics that can be studied with the LEP2 data. The combined results from all four LEP experiments were presented where available. Most of these results were preliminary and had been prepared for the 2001 summer conferences. At LEP2 the collision energy was regularly increased up to a maximum of 209 GeV. In the last year of data-taking the delivered luminosity was very high even though the LEP design energy had been exceeded. This was an outstanding achievement by the LEP machine group.

2 Fermion-pair production

In fermion-pair production at collision energies above the Z mass, initial state radiation plays an important role. These final states include non-radiative events at the full collision energy with back to back fermions. There are also radiative collisions at a range of lower collision energies including a radiative return peak due to the large cross-section at the Z mass. The value of the collision energy is reconstructed from the measured angles of the final state fermions or from kinematic fits to the measured final states.

The fermion-pair channels are detected with high efficiency and relatively low background which is predominantly from four fermion and two photon processes. Precise measurement of the cross-sections and angular distributions for all fermion-pair channels have been made at all LEP2 energies by the four experiments and compared to the predictions of the Standard Model (SM). This comparison for the hadronic and lepton-pair cross-sections is shown in

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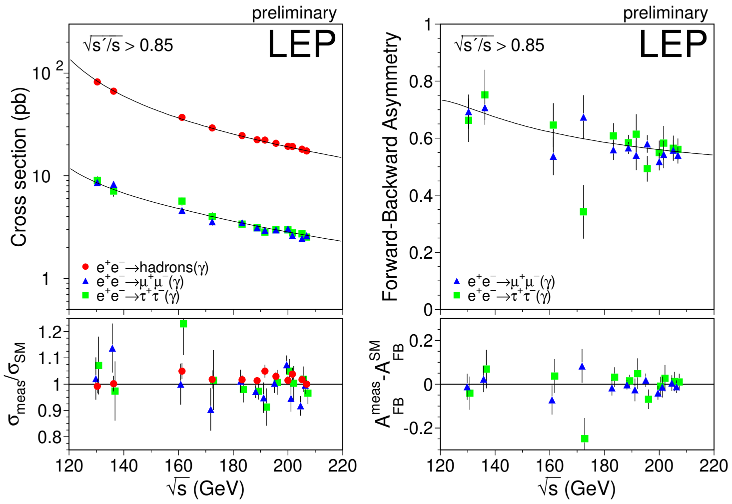


Figure 1: (a) LEP averaged cross-sections for $q\bar{q}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states as a function of energy [1] . (b) LEP averaged forward-backward asymmetries for $\mu^+\mu^-$ and $\tau^+\tau^-$ as a function of energy [1] . The curves on both figures are SM predictions.

Fig. 1. There is generally good agreement between the data and the predictions. The measured forward-backward asymmetries of lepton pairs also shows good agreement with SM predictions up to the highest LEP2 energy as shown in Fig. 1.

Many possible contributions to physics beyond the Standard Model eg extra Z bosons, lepto-quarks, contact interactions and hidden dimensions could modify these two-fermion cross-sections and angular distributions. The level of the agreement between the data and the SM predictions can therefore be used to place strong constraints on some of these models. The LEP-wide constraints on additional Z bosons produce lower mass limits which range from 0.45 to 2.1 TeV and lepto-quark lower mass limits range from 0.17 to 1.1 TeV. Limits extracted from the LEP2 data for the smallest allowed energy scale for various forms of new lepton-lepton contact interactions are summarised in Fig. 2. These limits, which depend on the type of coupling assumed, are typically around 10 TeV or above.

3 QED, QCD and two photon physics

Many new QED, QCD and two photon measurements have been made at LEP2 and a few examples are included here. The angular distribution of photons from

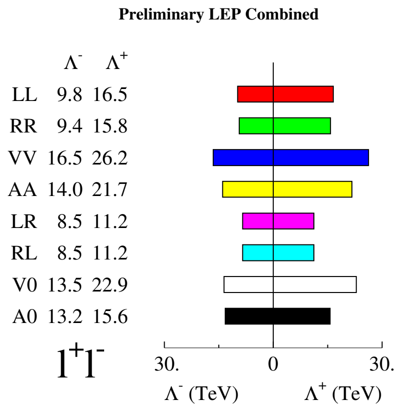


Figure 2: Contact interaction lepton-lepton limits from the combined LEP results [1].

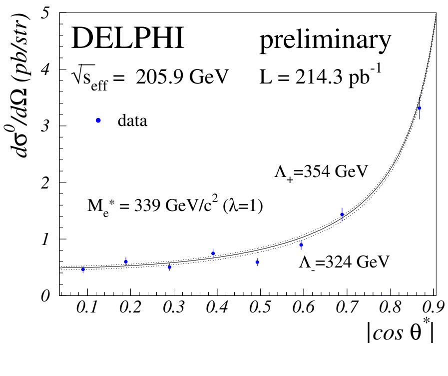


Figure 3: Two photon angular distribution from the DELPHI experiment

the reaction e^+e^- to $\gamma\gamma(\gamma)$ can be predicted from QED calculations and compared to the experimental measurements as shown in Fig. 3. The difference between the predicted and measured distribution has been parameterised in terms of a cutoff scale Λ which defines the energy scale at which a new interaction may contribute. The lower limit on Λ from the data currently exceeds 300 GeV for a single LEP experiment.

At each of the LEP energies the jet production rates and event shape variables in multi-hadronic events have been used to determine α_s . These results, together with others from lower energies, are shown in Fig. 4 and show clear evidence for the running of α_s with energy. The observed variation is in very good agreement with the predictions of NLLA QCD which is also shown on this figure.

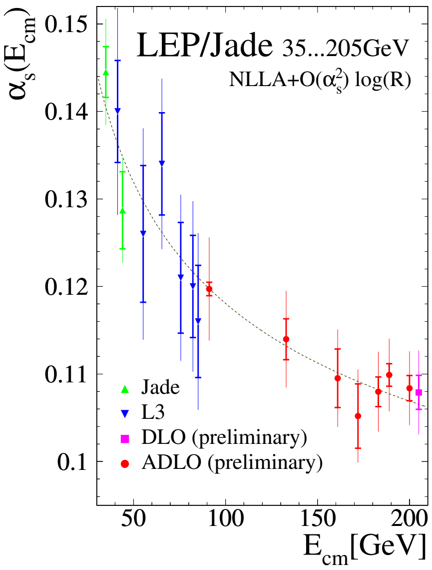


Figure 4: Variation of α_s with energy as measured by the listed experiments [2] together with the QCD predictions in the Next to Leading Log approximation (NLLA) at second order in α_s.

Two photon processes, where the two photons are radiated by the beam particles, produce the highest cross-sections at LEP2. Measurements allow the extraction of photon structure functions as a function of x and Q^2 and these are summarised in Fig. 5. These data show clear evidence for scaling violation consistent with the leading order predictions of QCD [4].

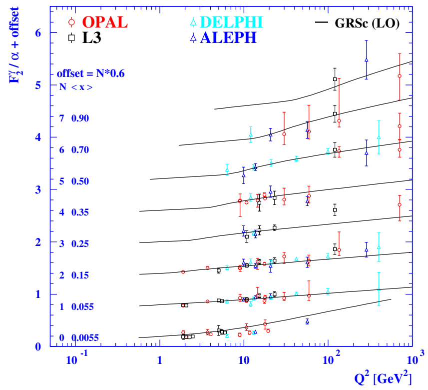


Figure 5: The photon structure function as measured by the LEP experiments [3] as a function of Q^2 for various x ranges together with the leading order QCD predictions [4].

4 WW and ZZ production

A primary reason for the construction of LEP2 was to allow a precise measurement of the W boson properties, particularly its mass, which is a crucial input to the SM precision electroweak fits. The cross-section and production and decay angular distributions of W pairs also provide a direct measurement of the triple gauge coupling which is predicted by the SM. At LEP2 W^+W^- pairs are expected to be produced by a mixture of s channel γ/Z and t channel ν exchange diagrams. The W bosons can decay into a charged lepton and a ν or a quark and antiquark with decay branching ratios of 1/3 and 2/3 respectively. This leads to three classes of W^+W^- final states being observed in the detectors namely fully leptonic (1/9), fully hadronic (4/9) and finally a leptonic and hadronic decay (4/9). The detection efficiency and background levels for these events vary somewhat for the different lepton species and between the different experiments. However the typical detection efficiency exceeds 80 % and increases to 90 % for events where at least one of the W decays is leptonic. The fully leptonic channel is very pure but because of the two missing neutrinos and its low production rate it has only limited impact on the W mass measurement.

The events with fully hadronic final states contain at least four jets and there can be pairing ambiguities in the reconstruction of the two W bosons. In addition as the two W bosons decay when they are separated by much less than one fermi, there is the possibility of final state interactions between the decay products of different W bosons. These colour reconnection and Bose-Einstein effects could in principle influence the W mass measurement and need to be carefully studied. The W^+W^- events with one hadronic and one leptonic decay are the cleanest and most useful sample. In this case the single missing neutrino can be reconstructed from energy and momentum conservation in a constrained fit.

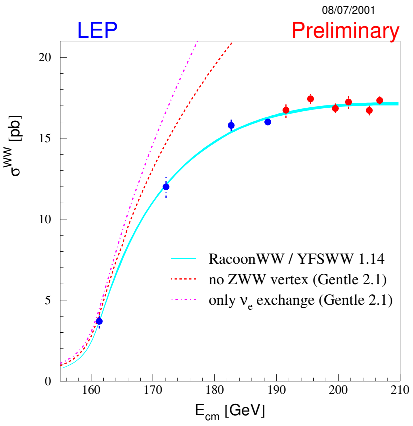


Figure 6: The LEP averaged WW cross-section as a function of energy [7] . The solid curve shows the SM prediction [5] [6] The other curves show the effect of removing various triple gauge coupling contributions.

The measured WW cross-section as a function of energy is shown in Fig. 6 together with the predictions of the RacoonWW [5] and YFSWW [6] Monte Carlo programmes. These include full order α corrections to the W pair production diagrams. The other curves on this figure, which are clearly excluded by the data, indicate the dramatic increase in the cross-section that would be predicted if the contributions from various diagrams with triple gauge couplings were removed. For the WW cross-section measurement the W decay branching ratios from the SM have been assumed. However these can also be determined from the LEP data and these measurements, which are more precise than current measurements from hadron colliders, are shown in Fig. 7. These agree well with the SM predictions.

The CKM matrix element V_{cs} , which is poorly known, has been directly measured at LEP from W decays into hadrons by using charm tagging of the jets. A much more precise indirect measurement of V_{cs} can be extracted from the LEP2 data by measuring the ratio of W decays to hadrons and leptons and by assuming the PDG values for all other CKM elements. From this approach

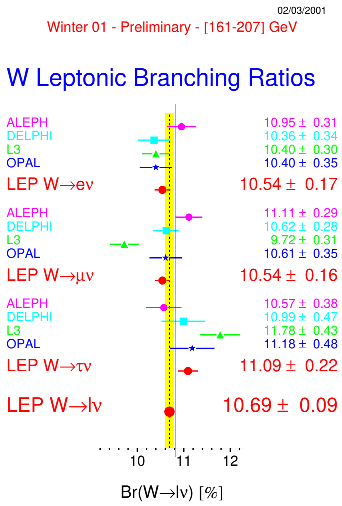


Figure 7: The W boson leptonic branching ratio measurements from the four LEP experiments [7] .

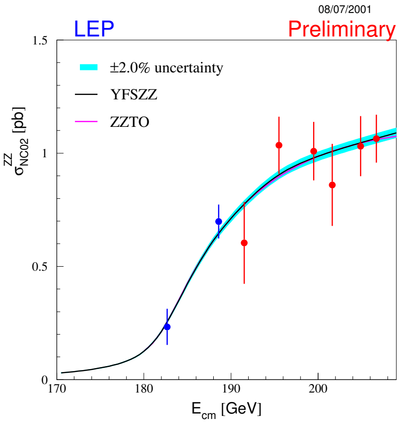


Figure 8: The LEP averaged ZZ cross-section as a function of energy [7]. The curves indicate the range of current SM predictions [8].

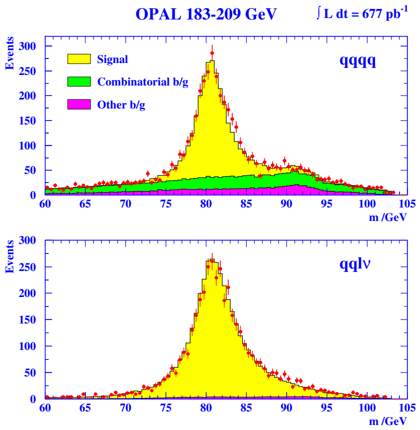


Figure 9: (a) Mass plot for preliminary data on qq pairs from the qqqq channel in the OPAL experiment. (b) Corresponding plot for qq pairs from the qqlν channel. In both plots the fitted curve is superimposed and the predicted background contributions are indicated.

a value of $V_{cs} = 0.996 + -0.013$ has been obtained without any direct unitarity assumptions.

The measured W decay angular distributions have also been used to verify the SM predictions for the helicity fractions and the the production rate of longitudinally polarised W bosons. The most important measurements of triple gauge couplings are made by measuring the production and decay properties of the W boson in WW production as described in a separate talk at this conference. However the production rate for single W bosons can also be used to constrain the charged triple gauge coupling as the incoming beams can exchange a W and a photon which then interact to produce the detected W boson. The LEP combined cross-section for single W production has a large statistical error but it agrees with the SM prediction.

At the higher LEP2 energies the production of Z pairs is also possible although the cross-section is much lower than for W pairs. These events are more difficult to isolate than W^+W^- events but the use of neural networks and likelihood methods allow a sample of such events to be selected. The ZZ production proceeds via both t channel electron exchange and s channel neutral triple gauge coupling diagrams. The energy dependence and size of this cross-section is well reproduced by theoretical predictions as shown in Fig. 8 .

5 W mass measurement

The first W mass measurements at LEP2 were extracted by measuring the cross-section for W pair production close to threshold. Although the statistics were very limited this yielded a W mass value of 80.40 ± 0.22 GeV which was the most precise measurement available at that time. At higher LEP2 energies the W mass is extracted from direct reconstruction of the events. Some examples of the observed quark-quark mass distributions for the qqqq and qqlν final states are shown in Fig. 9. For the qqqq channel the predicted contributions from background processes and events where the wrong jet pairing has been chosen are also indicated on the plot. The background in the qqlnu channel is also shown but it is negligible.

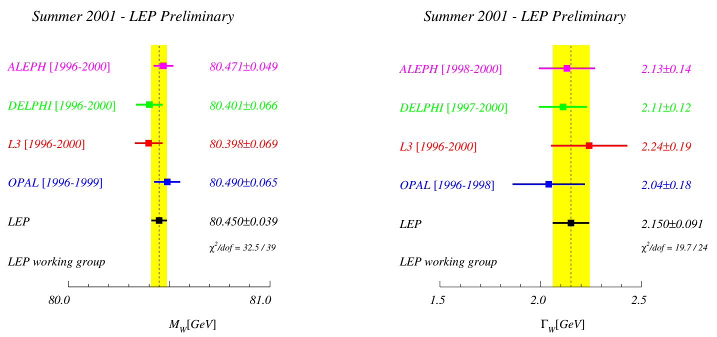
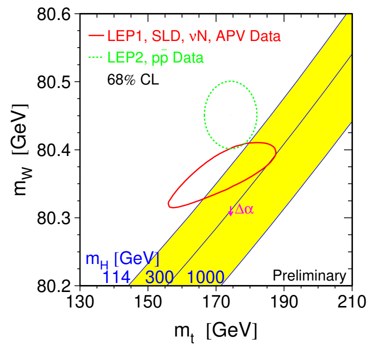


Figure 10: (a) The W mass as measured by the four LEP experiments [9]. (b) The W width as measured by the four LEP experiments.

Various methods are adopted by the collaborations to extract the W mass but all involve the use of constrained kinematic fits to improve the mass resolution. The W mass can then be calculated from direct Breit-Wigner fits or by performing likelihood or convolution fits to the mass distribution. These fits all require input from the Monte Carlo for the detector resolution but in the convolution fits the dependence on other features of the Monte Carlo is reduced. The preliminary results for the W mass and width extracted by the four LEP experiments are shown in Fig. 10.

These LEP2 results for the W mass are used to make a comparison between the direct and indirect measurements of the W and top quark masses in Fig. 11. These results are consistent with each other and favour a low mass Higgs boson within the context of the SM. The W mass measurements are also used together with many other precision electroweak measurements, performed at LEP and by SLD, CDF, D0, NuTeV and others as a function of the Higgs-boson mass assuming the Standard Model. The $\Delta\chi^2$ curve derived from these precision electroweak measurements is shown in Fig. 11 and this favours a relatively low mass Higgs. Some of this low mass region, up to a mass of 115 GeV, has been excluded by direct searches at LEP2 as also shown on this figure. As LEP running has now been completed the search for the Higgs boson at higher masses is being continued at FNAL and the LHC.

The LEP experiments continue to make a number of precise measurements which provide direct experimental tests of the predicted radiative corrections of the Standard Model. Currently much effort is going into converting the mainly preliminary LEP2 results presented here into final publications. The excellent working relationship between the accelerator staff and the experimental collaborations has contributed significantly to the final precision of these measurements. The LEP combined working groups have also been a very successful way of optimising the physics extracted from the many different measurements performed by the four experiments. It has been a pleasure to be a part of this venture over the past decade and more.



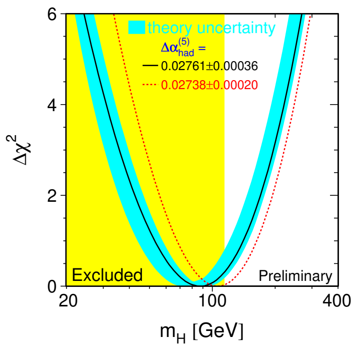


Figure 11: (a) A comparison between the direct and indirect measurements of the W and top quark masses. The predictions of the SM for a range of Higgs boson masses are also shown. (b) The $\Delta\chi^2$ curve derived from the precision electroweak measurements, performed at LEP and by SLD, CDF, D0, NuTeV and others, as a function of the Higgs-boson mass, assuming the Standard Model. The shaded band shows an estimate of the theoretical uncertainty. The light shaded region has been excluded by direct searches.

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