Experimental Aspects

Martin W. Grünewald
Institut für Physik, Humboldt-Universität zu Berlin, Germany

The year 2000 is the 12th and, as currently foreseen, last year of operation for the large $\mathrm{e^+e^-}$ collider LEP at CERN. By all standards, both the performance of the LEP machine and the wealth and precision of experimental results obtained by the four LEP experiments ALEPH [1], DELPHI [2], L3 [3] and OPAL [4] constitute an exciting success story in high-energy physics.

Operation of LEP started in summer 1989 at centre-of-mass energies around 91 GeV, corresponding to the mass of the Z boson (LEP1). Six years and 17 million Z events later, the second phase of LEP running boosted the centre-of-mass energy by a factor of 1.5. During the years 1996 until 2000, the energy of LEP increased further, from 161 GeV, the threshold of $\mathrm{W^+W^-}$ production, up to 209 GeV at the time of writing this report (LEP2).

Doubling the centre-of-mass energy opens up interesting new areas in electron–positron physics [5, 6]. In particular, while two-fermion production at LEP1 [7, 8] is analysed to study the Z boson [9], four-fermion production at LEP2 allows us to measure precisely the properties of the W boson [9]. More than 500 $\mathrm{pb^{-1}}$ of luminosity above the W-pair production threshold is collected by each LEP experiment, exceeding the original goal of the LEP2 programme [5]. These data sets correspond to a combined sample of about 30 000 $\mathrm{W^+W^-}$ events. The increase in energy also pushes the sensitivity to new particles, for example the Higgs boson or SUSY particles, towards higher and higher particle masses.

Now, a few weeks into the last data-taking period at LEP, it is crucial to prepare both the final months of LEP running for an optimal search for new particles, and the final precision analyses of the data collected at LEP2. A year ago the LEP2 Monte Carlo Workshop was initiated with these goals in mind. Clearly there is no end to the list of specific processes and phase-space regions accessible at LEP2 energies. The important Standard Model physics topics studied at LEP2 are fermion-pair production, four-fermion production, quantum chromodynamics (QCD), and two-photon collision processes.

- Two-fermion production has the highest cross-section of all hard processes. At LEP1 it serves as the unique reaction to study the properties of the Z boson. At centre-of-mass energies far above the Z pole, the radiative tail of the Z develops where QED radiative corrections are several times as large as the Born cross-sections. The production of secondary fermion–antifermion pairs due to the radiation of off-shell photons and Z bosons from the initial- or final-state need to be accounted for. This ties in with the signal definition, i.e., the separation between radiative corrections to two-fermion production and genuine four-fermion production.

- Four-fermion production through resonant gauge bosons, in particular W bosons, constitutes an exciting new process at centre-of-mass energies far above the Z pole. A main aspect of the LEP2 physics programme is given by the measurements of the properties of the W boson, such as its mass, decay width, and branching fractions. In addition, triple and quartic electroweak gauge boson couplings are studied, testing the non-Abelian nature of the electroweak Standard Model. Improved predictions need to take into account radiative corrections to four-fermion processes, including the radiation of photons, in a more complete manner. This is rather complex due to the number of Feynman diagrams involved, but important as it also affects the W-mass analysis due to photons visible in the detector.

- Hard QCD processes in quark-pair production allow tests of QCD at higher energy scales than before. Their understanding is also needed as QCD four-jet production constitutes a background to electroweak four-jet production via Z and W bosons but also Higgs bosons. The rate of QCD multijet final states must be well known, thus higher-order QCD corrections in multijet production need to be taken into account in the calculations.

- The two-photon collision process is viewed as a soft process but it has the highest cross-section in large regions of phase space at LEP2. In particular, the interest lies in predictions and simulations for hadronic two-photon collision processes, including heavy quark production. Also, for many new-particle searches with signatures involving large missing energy, two-photon collision processes form an important background which must be well modelled, including radiative corrections.

In each case, not only improvements in the predictions and Monte Carlo simulations are needed but also the size of the remaining theoretical uncertainties associated with the predictions. In particular the uncertainties were rarely estimated quantitatively in the past. Already now, the accuracy of the LEP2 measurements is so high that uncertainties on predictions can no longer be neglected. One prominent example out of many is given by the total W-pair production cross-section: while the theoretical uncertainty of previous calculations was estimated to be 2% [6], the experimental accuracy at LEP2, combining all measurements, is well below 1% [9]. Too large a theoretical uncertainty is therefore equivalent to a large loss in collected luminosity, which weakens the corresponding test of the theory. This must be avoided through improved predictions.

Accurate theoretical predictions are, however, not only crucial to confront the theory with the experimental result, but also in looking for the effects of new physics – new particles – beyond the Standard Model. In order to find such new physics effects as quickly as possible – and thus know how to plan the data taking – the collected data is continuously compared to the predictions in order to find deviations in distributions. The significance of such deviations depends on the uncertainties both in the measurement and in the prediction, which thus must be known.

To this extent an assessment of the prediction of Standard Model processes and their accuracies is mandatory also as the basic ingredient in the search for physics beyond the Standard Model: only if the Standard Model physics together with its uncertainty is precisely known, will the experiments find reliably and early the – at first small – indications for new physics, such as the production of Higgs or SUSY particles [6], or put tight limits on new physics beyond the Standard Model.

An effort such as this workshop requires very close collaboration between many people from theoretical and experimental high-energy physics. Based on the needs arising in and developed during the experimental analyses, many problems and detailed questions have been formulated, discussed, re-formulated and mostly solved. Improved predictions and quantitative estimates of the theoretical uncertainty on the prediction of a large variety of observables are now available. In many but still not all cases discussed in detail in this report, the theoretical uncertainty is smaller than the projected experimental uncertainty on the measurement combining all LEP2 data. As an example, for the W-pair cross-section discussed above, new calculations exist with a theoretical uncertainty of 0.4% on the W-pair cross-section at 200 GeV. By summarizing all results this report serves the intended purpose and will be very useful for the final analyses of the LEP2 data.

References

[1] D. Decamp *et al.* [ALEPH Collaboration], ALEPH: A Detector for Electron–Positron Annihilations at LEP, *Nucl. Instrum. Meth.* **A294** (1990) 121.

[2] P. Aarnio *et al.* [DELPHI Collaboration], The DELPHI Detector at LEP, *Nucl. Instrum. Meth.* **A303** (1991) 233.

[3] B. Adeva *et al.* [L3 Collaboration], The Construction of the L3 Experiment, *Nucl. Instrum. Meth.* **A289** (1990) 35.

[4] K. Ahmet *et al.* [OPAL Collaboration], The OPAL Detector at LEP, *Nucl. Instrum. Meth.* **A305** (1991) 275.

[5] A. Böhm and W. Hoogland (eds.), ECFA Workshop on LEP 200, Aachen, 1986, CERN Report 87–08 (2 vols.), ECFA 87–108,1987.

[6] G. Altarelli, T. Sjöstrand and F. Zwirner (eds.), Physics at LEP2, CERN Report 96–01 (2 vols.), 1996.

[7] G. Altarelli, R. Kleiss and C. Verzegnassi (eds.), Z Physics at LEP1, CERN Report 89–08, 1989.

[8] G. Bardin, W. Hollik and G. Passarino, Reports of the Working Group on Precision Calculations for the Z Resonance, CERN Report 95–03, 1995.

[9] D. Abbaneo *et al.* [the LEP Collaborations, ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavour Group and Electroweak Groups], A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model, CERN-EP/2000–016 and update for 2000 winter conferences, 2000.