LEP2 PHYSICS AND EVENT GENERATORS

R. PITTAU

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

The present status of four-fermion calculations and event generators for LEP2 physics is reviewed. Perspectives for future improvements are given.

1 Introduction

At LEP2, both Standard and New physics can be studied. On one hand, precision tests of the Standard Model are possible, first of all by measuring the W mass, but also by studying two-fermion processes off-resonance, $\gamma\gamma$ physics and QCD. On the other hand, the possibility of new physics discoveries exists. For example, searches for supersymmetric and/or new particles can be performed and the trilinear gauge boson vertex investigated in detail. Higgs physics lies somehow between those two categories: in case of discovery at LEP2, it could be hard to decide on the standard or non-standard nature of a neutral Higgs.

Due to the small cross sections, the number of collected events at LEP2 will be limited and two different attitudes can be adopted. One could think that, because of the low statistics, precise theoretical calculations are unimportant, but also -on the contrary- that, just because of the limited data, accurate theoretical knowledge is necessary in order to reduce the systematic error and extract as much information as possible. The choice between those two strategies is not matter of taste, but depends on the type of physics one is interested in. In fact, for discovery physics, one does not need very sophisticated tools. On the contrary, performing precision physics at LEP2 requires a dedicated effort. Forgetting that can easily lead to an bad underestimation of the systematic error in the precision measurements.

At LEP1 the enormous statistics allowed a strong interplay theory-experiment, which is not possible at LEP2. Therefore, at least for precision physics, theory must take over. As a consequence, when performing precision measurements, LEP2 Event Generators must be dedicated codes including loop corrections and all kind of backgrounds, while, for discovery physics, tree level signal programs are in general sufficient, unless the effects induced by new physics are expected to be tiny.

In the following, I shall concentrate on four-fermion physics in $e^+e^-$ collisions, by reviewing the present knowledge on the topic. I shall analyze the various contributions, pointing out what is still missing and should be computed for LEP2 experiments.

2 Four-fermion physics and codes

2.1 Tree level

Calculations involving four fermions in the final state are unavoidable at LEP2. In $M_W$ measurement the relevant process is the $W^+W^-$ production mechanism of fig. 1, but, since $\Gamma_W \neq 0$, the actual measured signal is a four-fermion final state. Therefore, one is led to consider decaying W's together with all contributing four-fermion background diagrams.

![Figure 1: $W^+W^-$ signal diagrams.](image)

Analogously, a four-fermion final state is the measured signal for Higgs physics and trilinear anomalous couplings studies (see fig. 2). Disregarding fermion masses, there are in total 27 leptonic four-fermion final states, 42 semileptonic processes and 17 hadronic channels.

---

*aFor example, a consistent study of the anomalous couplings has necessarily to be performed at the level of a four-fermion Event Generator.*
Neglecting fermion masses is a good approximation at LEP2 energies except for Higgs production (couplings $\propto m_f$) and studies involving electrons in the very forward region (t-channel photon diagrams become singular in the limit $m_e \to 0$).

Detailed comparison among codes can be found in ref. [4]. In fig. 3, I show the typical result of a tuned comparison among dedicated programs, namely codes including both signal and background diagrams.

A last comment is in order. Giving by hand a width to the bosons in tree level calculations breaks gauge invariance. A solution to this is the fermion loop (FL) approach of ref. [5], in which the imaginary part of the relevant one-loop diagrams is included to restore gauge independence. The deviation among the naive running width prescription, the FL result and the fixed width approach (constant complex masses in all propagators) is given in figure 4. One convinces oneself that the fixed width scheme - although without theoretical justification - numerically agrees with the FL result.

### 2.2 Electroweak radiative corrections

At LEP2, radiative corrections turn out to be extremely important for precision physics. In $M_W$ measurement, the expected shift in the reconstructed mass is

$$\Delta M_W = \frac{<E_{\gamma}>}{\sqrt{s}} M_W$$

where $<E_{\gamma}>$ is the average energy lost by QED radiation. To have control on $<E_{\gamma}>$ requires, in principle, an evaluation of the one-loop QED corrections to $e^+e^-\rightarrow 4$ fermions, namely, computing objects like the six-point diagram in fig 5. Furthermore, unlike at LEP1, QED and weak corrections are not separately gauge invariant. Therefore, for the sake of consistency, one should also include the full set of one-loop weak corrections.

At the moment, what is available is the implementation of the resummed (universal) leading log (LL) part of the initial state QED radiation in all programs of table 1. Some of them can include LL final state radiation and models for the generation of

$$\sigma(e^-\bar{\nu}_e u \bar{d})$$

at $\sqrt{s} = 190$ GeV. ADLO/TH cuts as in ref. [4], ISR included.
of 1 photon with finite \( p_T \). One code (\textit{Gentle}) also computes part of the subleading (non universal) QED corrections, by using the splitting techniques of ref. \((7)\).

As for the pure weak corrections, full one-loop calculations are available for on-shell \( W \)'s only \((8)\) and for the factorizable weak part in off-shell \( W^+W^- \) production \((9)\). At present, a full four-fermion electroweak calculation seems to be out of reach (although some promising techniques have been recently introduced \((10)\)). A gauge invariant and modular approach to the problem is the pole scheme described in ref. \((12)\).

2.3 \textbf{QCD contributions and loop corrections}

QCD enters the game in two different ways. Firstly, diagrams like those in fig. 6 contribute to four-quarks or four-jets final states as a background (for example) in \( M_W \) reconstruction \((4)\). All dedicated codes in table 1 can easily include them, when computing four-quark processes.

Secondly, radiative QCD corrections are present. Typical QCD loop diagrams for semi-leptonic final states, are shown in fig. 7. They have to be considered together with real gluonic emission to give the physical (infrared safe) cross section in 2 leptons + 2 jets.

\[
\Gamma_W \rightarrow \Gamma_W \left(1 + \frac{2}{3} \frac{\alpha_s}{\pi}\right), \quad \sigma \rightarrow \sigma \left(1 + \frac{\alpha_s}{\pi}\right). \quad (1)
\]

Strictly speaking, the above replacements give the correct result for \( W^+W^- \) production diagrams only, without cuts. Recently, an exact QCD one-loop calculation has been worked out for the channel \( \mu^+\bar{\nu}_\mu ud \). With ADLO/TH cuts \((4)\) a good agreement between the naive QCD approach and the exact calculation has been found, except for angular distributions (see fig. 8).

When dealing with QCD one also faces non perturbative phenomena. Most of the knowledge on hadronization, collected at LEP1, can be directly translated to LEP2 physics, with the exception of color reconnection and Bose-Einstein effects in four-jet production \((13)\), for which information will
have to be extracted from the LEP2 data. That may require a deep knowledge of the perturbative QCD contributions in order to disentangle the non-perturbative part. While all ingredients for computing $O(\alpha_s)$ loop corrections to four-jet production via electroweak interactions are already available\cite{13}, a calculation of the pure gluonic part (namely loop corrections to diagrams in fig. 6) is still missing.

3 Conclusions

Tree level four-fermion physics is in good shape. All processes can be computed including, where necessary, fermion masses and a gauge invariant solution exists for dealing with unstable particles. The available codes have been successfully cross-checked, reaching high technical precision. However, the latter does not imply small theoretical errors. Reducing theoretical uncertainties means incorporating new contributions in the calculations, namely including the loop corrections. While progress has been recently made in QCD (at least for semileptonic processes), our knowledge of the electroweak loop corrections in four-fermion production is, at present, at the LL level only.

A deeper understanding of the electroweak loop effects has to be reached, especially to meet the task $\Delta M_W = 50$ MeV. A first step in that direction could be employing the techniques in ref. \cite{10} to compute the photonic loop corrections in off-shell $W^+W^-$ production, that are anyway one of the basic ingredients of the full calculation. A different contribution will be soon provided by the authors of ref. \cite{5}, that are working out the fermionic set of loop corrections for $e^-\bar{\nu}_e u\bar{d}$.

Joining the forces of all peoples working on radiative corrections in four-fermion physics, will soon become desirable to overcome the technical difficulties and reach a satisfactory understanding of this very complicated subject.

Acknowledgment

I wish to thank G. Passarino for supplying me with Figure 4 and for useful discussions.

References

1. Physics at LEP2, G. Altarelli, T. Sjostrand and F. Zwirner eds., CERN 96-01.
2. F. A. Berends, R. Kleiss and R. Pittau, Nucl. Phys. B424 (1994) 308.
3. D. Bardin, A. Leike and T. Riemann, Phys. Lett. B353 (1995) 513.
4. Report on Event Generators for $WW$ physics in ref. \cite{1}.
5. E. N. Argyres et al., Phys. Lett. B358 (1995) 339.
6. S. Katsanevas et al., DELPHI internal report 92-166 Phys. 250.
7. D. Bardin et al., Phys. Lett. B308 (1993) 403.
8. J. Fleisher et al., Comp. Phys. Comm. 85 (1995) 29.
9. $WWFTSHV$, available on request from G. J. van Oldenborgh.
10. R. Pittau, A simple method for multi-leg loop calculations, PSI-PR-96-19.
11. R. Pittau, Phys. Lett. B335 (1994) 490.
12. Report on $WW$ cross sections and distributions in ref. \cite{1}.
13. E. Maina, R. Pittau and M. Pizzio, in preparation.