DEUTSCHES ELEKTRONEN – SYNCHROTRON

INSTITUT FÜR HOCHENERGIEPHYSIK

DESY 92-144
October 1992

ZFITTER
An Analytical Program for Fermion-Pair Production

T. Riemann

Deutsches Elektronen-Synchrotron DESY
Institut für Hochenergiephysik IfH, Zeuthen

ISSN 0418-9833

PLATANENALLEE 6 · O-1615 ZEUTHEN

DESY 92-144
October 1992

ISSN 0418-9833

$_{ZF}I^{T}T_{ER}$

AN ANALYTICAL PROGRAM FOR FERMION-PAIR PRODUCTION

Tord Riemann

DESY – Institut für Hochenergiephysik
Platanenallee 6
Zeuthen, Germany, O–1615

Abstract

I discuss the semi-analytical codes which have been developed for the Z line-shape analysis at LEP I. They are applied for a model-independent and, when using a weak library, a Standard Model interpretation of the data. Some of them are applicable for New Physics searches. The package $_{ZF}I^{T}T_{ER}$ serves as an example, and comparisons of the codes are discussed. The degrees of freedom of the line shape and of asymmetries are made explicit.

Talk held at the International Conference on High Energy Physics, August 1992, Dallas, Texas, USA

– to appear in the Proceedings –

INTRODUCTION

Among the most important results from LEP I experiments are the precise values of mass and width of the Z boson, $\delta M_Z/M_Z = 7\,MeV/91.187\,GeV = 0.008\%$, $\delta\Gamma_Z/\Gamma_Z = 7\,MeV/2.492\,GeV = 0.3\%$ [1]. Although their structure is much richer, the weak loop corrections may be properly described by a single number: the effective weak mixing angle $\sin^2\theta_W^{eff} = 0.2324 \pm 0.0011$. The corresponding on mass shell weak mixing angle is $\sin^2\theta_W \approx 0.226$. Their difference is a measure of the relevance of weak loop corrections.

The consistency of predictions and measurements for the Z line shape, i.e. the total cross section of the reaction

$$e^+e^- \to (\gamma, Z) \to f\bar{f}(n\gamma), \qquad (1)$$

heavily relies on the exact treatment of the radiative corrections; for a model-independent analysis, these are the photonic corrections which are potentially large and apparatus dependent. If cross sections are to be interpreted in the Standard Model, a weak library has to be used in addition in order to describe the hard-scattering process.

All the relevant line-shape codes rely on an ansatz of the following type:

$$\sigma_{T,pol}(s) = \int ds' \sigma^o_{T,pol}(s') \rho_T(\frac{s'}{s}, \cos\theta_{\max}), \quad (2)$$

$$\sigma_{FB}(s) = \int ds' \sigma^o_{FB}(s') \rho_{FB}(\frac{s'}{s}, \cos\theta_{\max}), \quad (3)$$

where the σ^o describe the hard-scattering process and the radiator functions ρ the QED corrections. The latter are result of a three-fold integration and may cover some cuts on the photon phase space and an acceptance cut $\cos\theta_{\max}$. In the simplest case, it is $\rho_T^{hard} = \frac{\alpha}{\pi}(L_e - 1)(1 + s'^2/s^2)/(1 - s'/s)$ [2]. Further, due to the soft photon dominance at LEP I the relation $\rho_T \approx \rho_{FB}$ holds with good accuracy.

At LEP I, the measurable asymmetries are

$$A_{FB} = \frac{\sigma_{FB}}{\sigma_T}, \quad A_{pol} = \frac{\sigma_{pol}}{\sigma_T}. \qquad (4)$$

They are important for the determination of additional parameters besides mass and width of the Z in a so-called global fit to (1).

SEMI-ANALYTICAL PROGRAMS

Stimulated by the great success of the LEP I collaborations in their aim to perform measurements with unpreceded accuracy, a variety of semi-analytical programs has been developed and updated by several groups of authors, some of them realizing the model-independent (MI) approach, others using the Standard Model (SM), and some of them both. In an obvious notation, I give here a list which, of course, cannot be exhaustive:

- `ALIBABA` [3] (σ_T, A_{FB}; SM)
- `CALASY` [4] (σ_T, A_{FB}; MI, SM)
- `BCMS` [5] (σ_T; MI, SM)
- `CMNPPP` [6] (σ_T, A_{FB}; MI, SM)
- `MIZA` [7] (σ_T, A_{FB}; MI)
- $_{ZF}I^{T}T_{ER}$ [8, 9, 10, 11] (σ_T, A_{FB}; MI, SM)
- `ZSHAPE` [12] (σ_T; SM)

Details on the above programs, especially on the treatment of the photonic corrections, may be found in the references.

THE PROGRAM $_{ZF}I^{T}T_{ER}$

For the line-shape analysis, the DELPHI, L3, and OPAL collaborations use $_{ZF}I^{T}T_{ER}$, and ALEPH uses `MIZA`. The $_{ZF}I^{T}T_{ER}$ is a flexible code with many options. These are described in [8]. In particular, the photonic corrections may be taken into account with three different sets of radiator functions $\rho_{T,FB}$ [9]:

- no cut
- cuts on the fermion scattering angle $\cos\theta$ and on the photon energy (i.e. s')
- cuts on the fermion scattering angle $\cos\theta$, on the acollinearity ξ of the fermions, and on the fermion energy.

They may be combined with several treatments of the hard-scattering process (with different sets of free parameters):

- Standard Model [10, 11] $(M_Z, m_t, M_H, \alpha_s)$
- Effective Couplings [8] $(M_Z, \Gamma_Z, g_v, g_a)$
- Partial Widths [10] $(M_Z, \Gamma_Z, \Gamma_e, \Gamma_f)$
- S-Matrix Approach [13] $(M_Z, \Gamma_Z, R(ZZ), J(\gamma Z))$.

The resulting flexibility, enhanced by some flags in the weak library DIZET, enables the user to simulate closely the experimental set-up. Further, detailed comparisons with other line-shape codes are possible.

EXTENSIONS

Due to the modular structure of ZFITTER, extensions for a covering of New Physics are possible with not too much effort. For the example of Z' physics, I refer to ZEFIT [14]. The determination of the parameters $\epsilon_{1,2,3}$, which are related to S, T, U, is possible with ZFEPSLON [15].

COMPARISONS

Comparisons between the different codes are extremely important since some radiative corrections are large (those from photonic bremsstrahlung reaching the order of 30%), while the quantum effects which we are searching for are much smaller (1 - 2.5 per mille). Assuming the validity of the Standard Model, there are different levels of complexity which may be gone through step by step in a comparison. With fixed input $(M_Z, m_t, M_H, \alpha_s)$, one may look at several quantities:

On mass shell mixing angle $\sin^2\theta_W$

Since $\sin^2\theta_W = 1 - M_W^2/M_Z^2$, this mixing angle contains for known M_Z a prediction of the W mass (or of Δr). As an example, we quote from table 11 of [8] the following numbers: $\sin^2\theta_W = 0.22681, 0.22690, 0.22695$. They are calculated for $M_Z = 91.170$, $m_t = 150$, $M_H = 500$ GeV from three independent programs (Hollik [16], ZFITTER, Degrassi et al. [17]). The deviations are of the order of fractions of a per mille (under well-defined, adjusted assumptions).

Total and partial widths Γ_Z, Γ_f

The total width is sum of the partial widths $\Gamma_f \sim \rho_f[g_v^{eff}(f)^2 + g_a^{eff}(f)^2]$. With presently yet sufficient accuracy, a 'universal' effective weak mixing angle may be derived from the effective couplings: $g_v^{eff}/g_a^{eff} = 1 - 4|Q_f|\sin^2\theta_W^{eff}$. For definiteness, this effective weak mixing angle is calculated from Γ_e. Evidently, the on mass shell weak mixing angle and the effective one contain qualitatively different physical information. The relation between them may be described by a weak form factor κ, $\sin^2\theta_W^{eff} = \kappa\sin^2\theta_W$. Again from table 11 of [8]: $\sin^2\theta_W^{eff} = 0.23291, 0.23300, 0.23306$ (from Hollik, ZFITTER, Degrassi et al.). These numbers correspond to a mean value of $\kappa \approx 1.0269$.

Improved Born approximation σ^o

The effective (or improved) Born cross sections contain the complete weak corrections. These corrections are covered by four weak

form factors ρ, $\kappa_e \approx \kappa_f$, $\kappa_{ef} \approx \kappa_e\kappa_f$. The indicated relations between the κ_i are fulfilled at LEP I energies by their leading contributions (e.g. the leading top quark corrections). In the same approximation, the κ_i of the cross sections agree *at the Z resonance* with those introduced in the Z partial widths. This may be understood intuitively from the relation $\sigma^o(Z,Z) \sim \Gamma_e\Gamma_f/[(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2]$.

The cross section σ

Finally, the ultimate test of a program concerns the cross-section prediction including the photonic corrections (and perhaps not at the same time the weak loops: in case of programs with a model-independent ansatz).

For a comparison of σ between ZFITTER and ZSHAPE and ALIBABA, I again refer to [8]. The agreement is at the per mille level. The BCMS program and ZFITTER have similar agreement for σ at LEP I energies [18], as do ZFITTER and the CMNPPP program [6] (where in addition σ^o is compared). For ZFITTER and MIZA, a comparative fit has been performed [19]. Some measured cross sections (from preliminary 1991 ALEPH data) have been fitted with the following results from ZFITTER, MIZA: $M_Z = 91.19142, 91.19148$ GeV; $\Gamma_Z = 2.5109, 2.5109$ GeV; $\sigma^o_{had} = 41.637, 41.650$ nb; $\Gamma_{had}/\Gamma_l = 20.688, 20.692$; $A^o_{FB,l} = 0.0114, 0.0106$.

Summarizing this section, one may conclude that the different programs agree with each other - within their assumptions on the underlying theory - at a level of one or several per mille. Taking into account the uncertainty of the assumptions, especially on the effects of higher orders, the uncertainty of the predictions will amount to several per mille. They safely allow to determine the Z boson parameters within the errors quoted above. In case of a reduction of the experimental errors by a factor of two, one should re-investigate the potential theoretical errors induced by the line-shape programs.

DEGREES OF FREEDOM

In model-independent fits to the line-shape data, often the following set of variables, or a similar one, is used for a parametrization [20]: $M_Z, \Gamma_Z, \sigma_{had}^{o,peak}, R_{had} = \sigma_{had}^{o,peak}/\sigma_{lept}^{o,peak}, A_{FB}^{lept}$. Here, I will discuss the question of a truly model-independent parametrization. In [5, 13], it has been shown that there exists exactly one, unique cross-section formula which is valid at LEP I with extremely high accuracy (and which can be improved if necessary); I quote it here in the form as derived from an S-matrix ansatz [13]:

$$\sigma^{o,S}(s) = \frac{r_\gamma}{s} + \frac{sR + (s - M_Z^2)J}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2} + \frac{r_0}{M_Z^2} + \ldots \qquad (5)$$

Since r_γ is predicted by QED and r_0, being non-resonating and arizing from quantum corrections, is strongly suppressed, the cross section depends on only four real constants: M_Z, Γ_Z, R, J. Here, the R describes the pure Z exchange cross section, and J the γZ interference. One should mention that the definitions of mass and width of the Z boson will slightly deviate from the values which became common in recent years since in (5) a constant width function is introduced [21].

Due to correlations, the knowledge of R, J (or a combined fitting together with M_Z, Γ_Z) is substantial for a precise determination of mass and width of the Z. So, the peak position, whose uncertainty is a measure of the uncertainty of M_Z, depends on J_T/R_T:

$$\delta\sqrt{s_{peak}} = \delta M_Z + (QED corrs.) + \frac{1}{4}\delta\frac{\Gamma_Z^2}{M_Z}\frac{J_T}{R_T}. \qquad (6)$$

Taking the ratio of two cross-section formulas, one can derive a simple, universal formula for asymmetries at LEP I [22]:

$$\left.\begin{array}{c} A_{FB} \\ A_{pol} \end{array}\right\} = A_0\left[1 + C_{QED}(s)\frac{A_1}{A_0}\left(s - M_Z^2\right)\right]. \tag{7}$$

In leading order, it is

$$A_0 = \frac{R_A}{R_T}, \qquad \frac{A_1}{A_0} = \frac{J_A}{R_A} - \frac{J_T}{R_T}. \tag{8}$$

The smooth function C contains QED corrections, including the radiative tail for energies beyond the resonance. Any asymmetry contains only two unknown real constants R_A, J_A. Here one should have in mind that the M_Z, Γ_Z, R_T, J_T are known from the corresponding line shape. Of course, the discussion applies to the leptonic and hadronic channels separately. This doubles the number of constants to be determined, if no additional model-dependent assumptions are introduced (e.g. the effective, universal weak mixing angle, or a prediction of the J_T from the quark parton model). A first application of the described formalism to L3 data of 1990 and 1991 may be found in [23].

The S-matrix parameters are related to those introduced above; e.g. $A_{FB}^{lept} \approx A_{0,FB}^{lept}$, $\sigma_{had}^{o,peak} \approx r_\gamma/M_Z^2 + R_{T,had}/\Gamma_Z^2$. The exact relations are slightly more involved. Strictly speaking, the so-called model-independent approaches to σ^o with a parametrization in effective couplings or in partial Z widths are (quite efficient) approximations to the unique model-independent cross section [5, 13].

SUMMARY

Basically, there are two languages for a line-shape description:

- Standard Model and extensions
- Model-independent ansatz

The semi-analytical programs realize them both in several ways, and in combination with one or the other approach to the QED corrections. They agree with each other within 1 - 2.5 per mille. The perhaps most flexible (and nevertheless fast) program is $_{ZF}I^{T}T_{ER}$.

The Z line shape allows to determine four physical parameters:

$$M_Z, \Gamma_Z, R_T, J_T.$$

Thus, a serious line-shape fit is based on at least five different beam energies.

Global fits to reaction (1) at LEP I include asymmetries. These depend each on two additional parameters:

$$R_A, J_A.$$

A serious fit needs asymmetry data from at least three different beam energies.

If the LEP collaborations will aim at an experimental error for Γ_Z as small as 3 MeV [1], a new round of careful checks and, possibly, improvements of the existing line-shape programs would be recommended.

Acknowledgements

First of all, I would like to thank all my collegues, theorists and experimentalists, who contributed, in one way or the other, to $_{ZF}I^{T}T_{ER}$. Much of the results covered in this contribution would not have been possible without the long collaboration with Dima Bardin. Thanks also to S. Kirsch and S. Riemann who prepared codes and performed tests, comparisons and fits. Finally, I acknowledge the kind hospitality at the Theory Division of CERN where much work on the Z line shape has been initiated and performed.

REFERENCES

1. L. Rolandi, these proceedings.
2. G. Bonneau, F. Martin, Nucl. Phys. B27 (1971) 381.
3. W. Beenakker, F.A. Berends, S.C. van der Marck, Nucl. Phys. B349 (1991) 323.
4. S. Jadach, Z. Was, in *Z Physics at LEP 1*, CERN 89-08, 1989 (G. Altarelli et al., eds.).
5. A. Borrelli, M. Consoli, L. Maiani, R. Sisto, Nucl. Phys. B333 (1990) 357.
6. M. Cacciari, G. Montagna, O. Nicrosini, G. Passarino, R. Pittau, to appear in Phys. Lett B (1992); F. Piccinini, R. Pittau, INFN Pavia prepr. (1992); and references therein.
7. M. Martinez, L. Garrido, R. Miquel, J. Harton, R. Tanaka, Z. Physik C49 (1991) 645.
8. D. Bardin, M. Bilenky, A. Chizhov, A. Olshevsky, S. Riemann, T. Riemann, M. Sachwitz, A. Sazonov, Yu. Sedykh, I. Sheer, program $_{ZF}I^{T}T_{ER}$; D. Bardin et al., CERN-TH. 6443/92 (1992).
9. D. Bardin et al., Nucl. Phys. B351 (1991) 1; Phys. Lett. B255 (1991) 290; M. Bilenky, A. Sazonov, Dubna prepr. E2-89-792 (1989).
10. A. Akhundov, D. Bardin, T. Riemann, Nucl. Phys. B276 (1986) 1.
11. D. Bardin, M. Bilenky, G. Mitselmakher, T. Riemann and M. Sachwitz, Z. Physik C44 (1989) 493.
12. F.A. Berends, G.J.H. Burgers, W.L. van Neerven, Nucl. Phys. B297 (1988) 429.
13. A. Leike, T. Riemann, J. Rose, Phys. Lett. B273 (1991) 513.
14. A. Leike, S. Riemann, T. Riemann, CERN-TH. 6545/92 (1992), to appear in Phys. Lett. B.
15. A. Gurtu, unpublished.
16. W. Hollik, Fortran package DELTAR; Fortschr. Physik 38 (1990) 165; prepr. MPI-Ph/92-116(1992).
17. G. Degrassi, S. Fanchiotti, A. Sirlin, Nucl. Phys. B351 (1991) 49.
18. D. Bardin, private information.
19. M. Martinez, private information.
20. The LEP Collaborations, Phys. Lett. B276 (1992) 247.
21. D. Bardin, A. Leike, T. Riemann, M. Sachwitz, Phys. Lett. B206 (1988) 539.
22. T. Riemann, CERN-TH. 6590/92 (1992), to appear in Phys. Lett. B.
23. S. Kirsch, S. Riemann, L3 note # 1233 (1992).