Four-Fermion Production with Anomalous Couplings at LEP2 and NLC

Jochen Biebel
Deutsches Elektronen-Synchrotron DESY–Zeuthen,
Platanenallee 6, D-15738 Zeuthen
Germany

Abstract

I give a short report on the semi-analytical approach to off-shell W pair production. In particular, I show the effects of irreducible background diagrams of the `CC11` class in the differential cross-section. Further, I study the influence of potential anomalous couplings at a future linear collider and investigate the sensitivity of the forward-backward asymmetry to anomalous couplings.

1 Introduction

Since the start of LEP2 in 1996 the production of W pairs in e^+e^- annihilation is observed in the process $e^+e^- \to W^+W^- \to 4f$ [1, 2, 3, 4]. This offers a good possibility to measure the mass and the couplings of the W boson [5, 6, 7, 8]. In this context, it is also a good probe of the standard model predictions for non-Abelian gauge couplings and one way to find new physics.

Additionally, the high energy and high luminosity of a future linear collider will deliver a good basis for a precise determination of anomalous couplings [9]. However, at a future collider, with a center-of-mass energy of 500 GeV or more, the process of W pair production is also regarded as a large background for particle searches and should be known as exactly as possible.

Therefore, it is inevitable to take certain corrections into account. The finite width of the W bosons [10], irreducible background processes [11, 12], and radiative corrections [13, 14, 15, 16, 17, 18, 19] must be considered.

To make theoretical predictions for the cross-section, a semi-analytical approach [12, 20, 21] is advantageous in two ways. First of all, semi-analytical programs, like the Fortran program `GENTLE` [22], allow a fast and precise prediction of total and differential cross-sections. This can be used directly in the analysis of data[1]. On the other hand, the precise predictions of a semi-analytical calculation can be used to test the reliability of the various existing Monte Carlo programs [23, 24].

In section 2, I study the background effects for processes of the `CC11` class, which is defined by the final state fermions:

- `CC09`: $(\mu\bar{\nu}_\mu, \bar{\tau}\nu_\tau)$
- `CC10`: $(\mu\bar{\nu}_\mu, \bar{d}u)$, $(\mu\bar{\nu}_\mu, \bar{s}c)$, $(\tau\bar{\nu}_\tau, \bar{d}u)$, $(\tau\bar{\nu}_\tau, \bar{s}c)$
- `CC11`: $(d\bar{u}, \bar{s}c)$

and their charge conjugates. A more detailed description of the classification scheme for four fermion production can be found in [12]; see also [23].

The non-Abelian gauge structure of the standard model was subject of theoretical interest for many years and a general expression for the three-gauge boson couplings was developed in 1979 [25]. Potential new physics was parameterized in an effective theory with anomalous couplings [26]. The current limits for the couplings from the LEP2 measurement are [27]:

$$\begin{aligned} \alpha_{B\phi} &= 0.45^{+0.56}_{-0.67} \\ \alpha_{W\phi} &= 0.02^{+0.16}_{-0.15} \\ \alpha_{W} &= 0.15^{+0.27}_{-0.27} \end{aligned} \tag{1}$$

A definition for the parameters in (1) is given in section 3. There, I study also the potential for measuring anomalous couplings at a future linear collider.

[1] `GENTLE` was used e. g. in the search for anomalous couplings [3].

2 The Differential Cross-Section for CC11

The semi-analytical results for the total cross-section for $e^+e^- \to W^+W^- \to 4f$ including the background of the CC11 class are presented and discussed in detail in [21]. The differential cross-section for the CC03 process, i. e. only the signal diagrams, is also given there.

Here, I will shortly sketch the results for the differential cross-section.

I write the threefold differential cross-section at a center-of-mass energy squared s as follows:

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}s_1\mathrm{d}s_2\mathrm{d}\cos\theta} = \frac{\sqrt{\lambda}}{\pi s^2}\sum_k \mathcal{C}_k \cdot \mathcal{G}_k(s, s_1, s_2, \cos\theta) \tag{2}$$

with

$$\lambda = \lambda(s, s_1, s_2) = s^2 + s_1^2 + s_2^2 - 2ss_1 - 2ss_2 - 2s_1s_2 \tag{3}$$

The invariant masses of the produced fermion pairs are s_1 and s_2.

In (2) I introduced the coefficient functions $\mathcal{C}_k$ and the kinematical functions $\mathcal{G}_k$. While the $\mathcal{C}_k$'s are trivial and contain only the coupling constants and the s-channel propagators, the $\mathcal{G}_k$'s describe the kinematics of the process and depend on $\cos\theta$. All $\mathcal{C}_k$'s and $\mathcal{G}_k$'s for the CC11 class will be presented in [28].

To include the effects of initial state radiation using the structure function approach the Born cross-section is convoluted with two structure functions $D(x)$ [29, 6]. I have to change eq. (2) to

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}s_1\mathrm{d}s_2\mathrm{d}\cos\theta_{\mathsf{lab}}} = \int\mathrm{d}x_+\int\mathrm{d}x_-\, D(x_+)D(x_-)\sum_i \left|\frac{\partial\cos\theta_i}{\partial\cos\theta_{\mathsf{lab}}}\right| \frac{\mathrm{d}^3\sigma}{\mathrm{d}s_1\mathrm{d}s_2,\mathrm{d}\cos\theta_i}. \tag{4}$$

Because of the radiation of photons, the electron and the positron change their energy and momentum. This leads to a Lorentz boost and the scattering angle in the center-of-mass system of the W bosons is shifted compared to the scattering angle measured in the detector. In the calculation I correct this by a transformation of the angles. Since the transformation is not always unique, the number of solutions depends on x_- and x_+. This is reflected in the sum over i.

Note, that for a bin-wise integration of (4) the relatively complicated Jacobean can be substituted by a transformation of the bin limits. This allows an analytical integration over $\cos\theta$.

As an application I study the different background effects for the various final states of the CC11 class in fig. 1. They are shown for a center-of-mass energy of 190 GeV as the ratio of the cross-section calculated for signal plus background diagrams over the cross-section of signal diagrams only.

Although the final state fermions have different coupling constants and there are even different numbers of diagrams for the CC09, CC10, and CC11 processes, the effects due to the irreducible background are almost the same.

3 Anomalous Couplings

Since 1979 there was much attention to the subject of anomalous couplings, see for example [25, 26, 30, 31, 32, 33, 34, 35]. As a recent overview [8] might be useful.

To introduce anomalous couplings into the calculation I add three terms to the standard model Lagrangian. The new terms are operators of dimension 6 and conserve both C *and* P. They are [8]:

$$\Delta\mathcal{L} = g'\frac{\alpha_{B\phi}}{m_W^2}\left(D_\mu\Phi\right)^\dagger B^{\mu\nu}\left(D_\nu\Phi\right) + g\frac{\alpha_{W\phi}}{m_W^2}\left(D_\nu\Phi\right)^\dagger \vec{\tau}\cdot\vec{W}^{\mu\nu}\left(D_\nu\Phi\right) + g\frac{\alpha_W}{6m_W^2}\vec{W}^\mu_{\ \nu}\cdot\left(\vec{W}^\nu_{\ \rho}\times\vec{W}^\rho_{\ \mu}\right) \tag{5}$$

In the unitary gauge these operators lead to the following effective Lagrangian for the WWV vertex:

$$\mathcal{L}_{\mathrm{eff}}^{WWV} = \mathrm{i}g_{WWV}\left[g_1^V\left(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu}\right)V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho\right], \tag{6}$$

where V can be a γ or a Z.

Electromagnetic gauge invariance requires $g_1^\gamma = 1$.

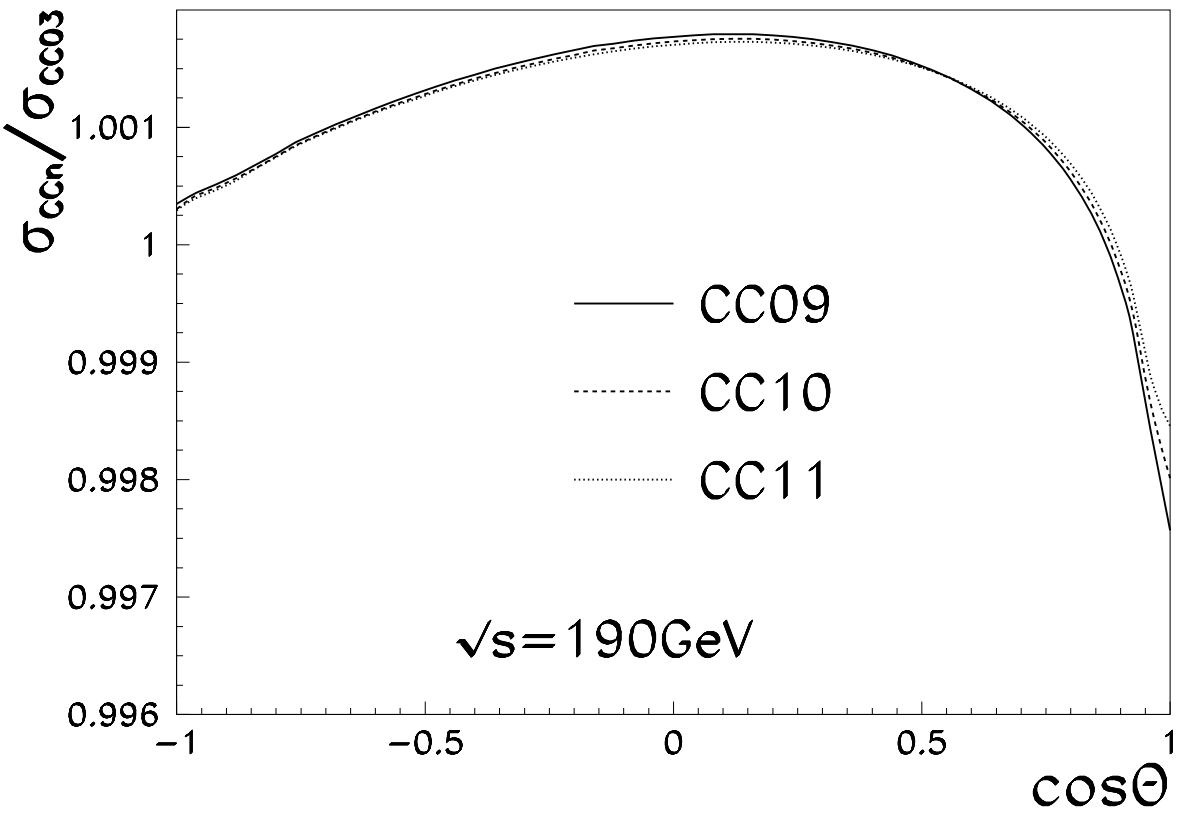

Figure 1: The ratio of background to signal processes in Born approximation.

For the WWZ vertex, I add also the term

$$\mathcal{L}_Z = -\frac{ez_Z}{m_W^2}\,\partial_\alpha \hat{Z}_{\rho\sigma}\left(W^{+\alpha}\overset{\leftrightarrow}{\partial^\rho}W^{-\sigma} - W^{+\sigma}\overset{\leftrightarrow}{\partial^\rho}W^{-\alpha}\right) \tag{7}$$

with

$$\hat{Z}_{\rho\sigma} = \frac{1}{2}\epsilon_{\rho\sigma\alpha\beta}Z^{\alpha\beta}. \tag{8}$$

This coupling is odd under both C *and* P transformation, therefore, it is invariant under a CP transformation.

In the standard model, we have $\kappa_\gamma = \kappa_Z = g_1^Z = 1$ and $\lambda_\gamma = \lambda_Z = z_Z = 0$.

With the couplings κ_γ and λ_γ the magnetic dipole moment and the electric quadrupole moment of the W are [36]:

$$\mu_W = \frac{e}{2m_W}(1+\kappa_\gamma+\lambda_\gamma) \tag{9}$$

$$q_W = -\frac{e}{m_W^2}(\kappa_\gamma-\lambda_\gamma) \tag{10}$$

It is useful to choose a different set of anomalous couplings in which all of the anomalous parameters vanish in the standard model. This is done with the transformation [8]:

$$\begin{aligned} x_\gamma &= \kappa_\gamma - 1 & x_Z &= (\kappa_Z-1)\cot\theta_W - \delta_Z \\ y_\gamma &= \lambda_\gamma & y_Z &= \lambda_Z\cot\theta_W \\ z_Z &= z_Z & \delta_Z &= (g_1^Z-1)\cot\theta_W \end{aligned} \tag{11}$$

The effects of the anomalous couplings defined in (11) are shown in fig. 2. To give an impression of the relative change in the cross-section the ratio $\sigma_{\rm ANO}/\sigma_{\rm SM}$ is plotted. The curves demonstrate nicely the sensitivity of the differential cross-section to anomalous couplings for large scattering angles, i. e. $\cos\theta < 0$.

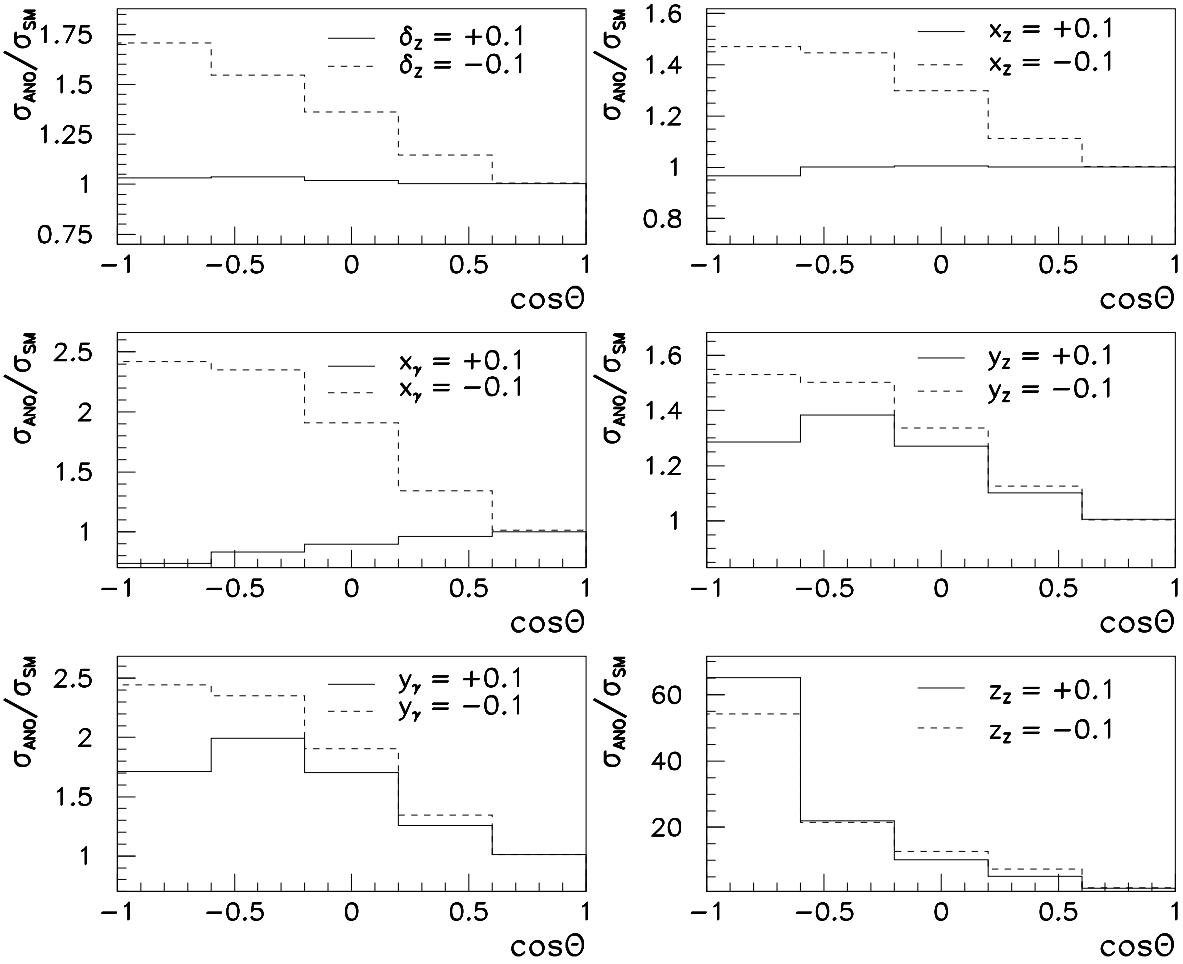

Figure 2: Ratio of cross-sections at $\sqrt{s} = 500$ GeV. Only one parameter differs from 0 in each figure.

In addition, the plots in fig. 2 are suitable for comparisons with output of Monte Carlo event generators. For 190 GeV the `GENTLE` results were in excellent agreement with the data published in [34] and for an energy of 500 GeV a comparison with the Monte Carlo program `WOPPER` [37] was also successful.

Of course, it is also worthwhile and more realistic[2] to study several couplings simultaneously. In fig. 3 I simulate the discriminative power of the forward-backward asymmetry to detect anomalous couplings. For a more detailed description of this analysis see [39]. The two rings shown in each picture correspond to the cross-section measured in the range $-1 < \cos\theta < 0$ (backward) and $0 < \cos\theta < 1$ (forward). The rings represent the allowed region for a pair of anomalous couplings, if we assume that the standard model cross-section is measured.

Although the statistics for forward scattering is much higher[3], the narrow rings, which give more

[2]There is absolutely no reason why only one of the anomalous parameters in (11) should appear in Nature. To decrease the number of new parameters it is more natural to require additional constraints for the operators in eq. (5), like in the "HISZ scenario" [31, 38], where $\alpha_{B\phi} = \alpha_{W\phi}$ is assumed.

[3]At 500 GeV about 94% of the produced W bosons go into the forward direction.

stringent limits, correspond to the measurement of the backward cross-section. This proves again the strong influence of anomalous couplings in the region of backward scattering [30].

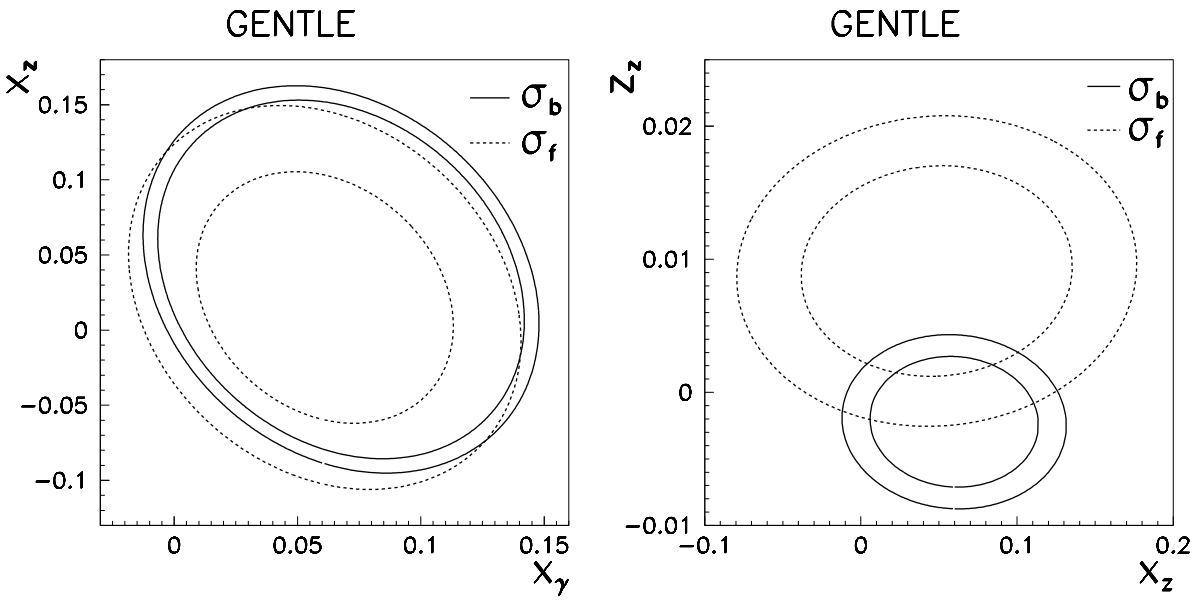

Figure 3: 1σ-bounds at 500 GeV for $\mathcal{L} = 50 fb^{-1}$.

Fig. 3 shows also that the allowed regions do not overlap so much, if the parameter z_Z is non-vanishing. It is not surprising that parity violating couplings are stronger constrained by the forward-backward asymmetry than parity conserving couplings.

4 Conclusions

I discussed some problems in connection with the use of W pair production at a linear collider in the search for new physics. Especially in the region of backward-scattering, anomalous couplings have a strong effect. However, only if precise predictions for the cross-sections exist, there is a chance to find deviations of the standard model.

To achieve such a high precision semi-analytical programs are useful. With the capability to produce bin-wise integrated cross-sections and to consider the effects of anomalous couplings, `GENTLE` provides a good base for comparisons with Monte Carlo event generators.

Acknowledgement

I would like to thank the organizers of the conference for their kind hospitality and the warm atmosphere they provided. Further, it is a pleasure for me to thank the other authors of `GENTLE`: D. Bardin, D. Lehner, A. Leike, A. Olchevski, and T. Riemann. Especially, I am grateful to Tord Riemann for collaboration on this topic. Further I thank T. Ohl for useful discussions and hints.

References

[1] ALEPH Collaboration, R. Barate *et. al.*, *Phys. Lett.* **B401** (1997) 347–362.

[2] DELPHI Collaboration, P. Abreu *et. al.*, *Phys. Lett.* **B397** (1997) 158–170.

[3] L3 Collaboration, M. Acciarri *et. al.*, *Phys. Lett.* **B398** (1997) 223–238.

[4] OPAL Collaboration, K. Ackerstaff *et. al.*, *Phys. Lett.* **B397** (1997) 147–157.

[5] G. Altarelli, T. Sjöstrand, and F. Zwirner (eds.), "Physics at LEP2", preprint CERN, CERN 96–01 (1996).

[6] W. Beenakker *et. al.*, "WW cross-sections and distributions", in [5], Vol. 1, p. 79, `hep-ph/9602351`.

[7] Z. Kunszt *et. al.*, "Determination of the mass of the W boson", in [5], Vol. 1, p.141, `hep-ph/9602352`.

[8] G. Gounaris *et. al.*, "Triple gauge boson couplings", in [5], Vol. 1, p. 525, `hep-ph/9601233`.

[9] ECFA/DESY LC Physics Working Group, E. Accomando *et. al.*, "Physics with e^+e^- linear colliders", preprint DESY, DESY 97-100 (1997), `hep-ph/9705442,` subm. to Phys. Repts.

[10] T. Muta, R. Najima, and S. Wakaizumi, *Mod. Phys. Lett.* **A1** (1986) 203.

[11] F. A. Berends, R. Pittau, and R. Kleiss, *Nucl. Phys.* **B424** (1994) 308–342.

[12] D. Bardin, M. Bilenky, D. Lehner, A. Olchevski, and T. Riemann, "Semi-analytical approach to four-fermion production in e^+e^- annihilation", in *Proc. Zeuthen Workshop on Elementary Particle Theory – Physics at LEP200 and Beyond, Teupitz, Germany, April 10-15, 1994, Nucl. Phys. (Proc. Suppl.) 37B* (T. Riemann and J. Blümlein, eds.), pp. 148–157, Elsevier, Amsterdam, 1994.

[13] M. Böhm *et. al.*, *Nucl. Phys.* **B304** (1988) 463.

[14] J. Fleischer, F. Jegerlehner, and M. Zralek, *Z. Phys.* **C42** (1989) 409.

[15] A. Denner and T. Sack, *Z. Phys.* **C46** (1990) 653.

[16] W. Beenakker, K. Kolodziej, and T. Sack, *Phys. Lett.* **B258** (1991) 469–474.

[17] S. Dittmaier, M. Böhm, and A. Denner, *Nucl. Phys.* **B376** (1992) 29–51.

[18] W. Beenakker, A. P. Chapovskii, and F. A. Berends, "Nonfactorizable corrections to W pair production: Methods and analytic results", preprint CERN-TH/97-158 (1997), `hep-ph/9707326`.

[19] A. Denner, S. Dittmaier, and M. Roth, "Nonfactorizable photonic corrections to $e^+e^- \to WW \to$ four fermions", preprint CERN-TH/97-258 (1997), `hep-ph/9710521`.

[20] D. Bardin, A. Olshevsky, M. Bilenky, and T. Riemann, *Phys. Lett.* **B308** (1993) 403–410, E: ibid., B357 (1995) 725.

[21] D. Bardin and T. Riemann, *Nucl. Phys.* **B462** (1996) 3–28.

[22] D. Bardin, J. Biebel, D. Lehner, A. Leike, A. Olchevski, and T. Riemann, *Comput. Phys. Commun.* **104** (1997) 161.

[23] D. Bardin *et. al.*, "Event generators for WW physics", 1997, in [5], Vol. 2, p. 3, `hep-ph/9709270`.

[24] T. Ohl, *Acta Phys. Polon.* **B28** (1997) 847.

[25] K. J. F. Gaemers and G. J. Gounaris, *Zeit. Phys.* **C1** (1979) 259.

[26] K. Hagiwara, R. D. Peccei, D. Zeppenfeld, and K. Hikasa, *Nucl. Phys.* **B282** (1987) 253.

[27] T. Saeki, contributions to this conference.

[28] J. Biebel and T. Riemann, in preparation.

[29] E. A. Kuraev and V. S. Fadin, *Sov. J. Nucl. Phys.* **41** (1985) 466–472.

[30] C. L. Bilchak and J. D. Stroughair, *Phys. Rev.* **D30** (1984) 1881.

[31] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, *Phys. Rev. D* **48** (1993) 2182–2203.

[32] M. Diehl and O. Nachtmann, *Z. Phys.* **C62** (1994) 397–412.

[33] F. Jegerlehner, "Search for anomalous gauge boson couplings", in *Proc. Zeuthen Workshop on Elementary Particle Theory – Physics at LEP200 and Beyond, Teupitz, Germany, April 10-15, 1994, Nucl. Phys. (Proc. Suppl.) 37B* (T. Riemann and J. Blümlein, eds.), pp. 129–140, Elsevier, Amsterdam, 1994.

[34] F. A. Berends and A. I. van Sighem, *Nucl. Phys.* **B454** (1995) 467–484.

[35] G. J. Gounaris and C. G. Papadopoulos, "Studying trilinear gauge couplings at next linear collider", preprint DEMO-HEP-96/04 (1996), `hep-ph/9612378`.

[36] H. Aronson, *Phys. Rev.* **186** (1969) 1434–1441.

[37] H. Anlauf, P. Manakos, T. Ohl, and H. D. Dahmen, "WOPPER, version 1.5: A Monte Carlo event generator for $e^+e^- \to (W^+W^-) \to 4f + n\gamma$ at LEP-2 and beyond", Darmstadt preprint IKDA 96/15 (1996), `hep-ph/9605457`.

[38] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, *Phys. Lett.* **B 283** (1992) 353–359.

[39] J. Biebel and T. Riemann, "Semi-analytic predictions for W pair production at 500-GeV", preprint DESY 97-167 (1997), `hep-ph/9709207`, to appear in the ECFA/DESY LC Workshop Report DESY 97-123E.