UTHEP-96-0702
July 1996

Gauge Invariant YFS Exponentiation of (Un)stable Z-Pair Production At and Beyond LEP2 Energies†

S. Jadach
Institute of Nuclear Physics, ul. Kawiory 26a, Kraków, Poland
CERN, Theory Division, CH-1211 Geneva 23, Switzerland,
W. Płaczek⋆
Department of Physics and Astronomy,
The University of Tennessee, Knoxville, Tennessee 37996-1200,
B.F.L. Ward
Department of Physics and Astronomy,
The University of Tennessee, Knoxville, Tennessee 37996-1200,
SLAC, Stanford University, Stanford, California 94309

Abstract

We present the theoretical basis and sample Monte Carlo data for the YFS exponentiated calculation of $e^+e^- \to ZZ \to f_1\bar{f}_1 + \bar{f}_2 f_2$ at and beyond LEP2 energies, where the left-handed part of f_i is a component of an SU_{2L} doublet, $i = 1, 2$. The calculation is performed for both SM couplings and for anomalous ZZV triple gauge boson couplings in the conventions of Hagiwara *et al.*. Our formulas, which are gauge invariant, are illustrated in a proto-typical YFS Monte Carlo event generator YFSZZ.

To be submitted to Phys. Rev. D

---

† Work partly supported by the Polish Government grant KBN 2P30225206 by the US Department of Energy Contracts DE-FG05-91ER40627 and DE-AC03-76ER00515.

⋆ On leave of absence from Institute of Computer Science, Jagiellonian University, Kraków, Poland.

UTHEP-96-0702

July 1996

The problem of the precision calculation of the processes $e^+e^- \rightarrow ZZ + n(\gamma) \rightarrow 4fermions + n(\gamma)$ at the higher energy range of LEP2 and at NLC ($>$ 300 GeV) type energies is the subject of our paper. We are motivated to investigate this problem for a number of reasons, the most important of which is its role in connection with the verification and tests of the $SU_{2L} \times U_1$ model of Glashow, Salam and Weinberg [1] of the electroweak interaction. Indeed, at the NLC these and related processes are expected to play the primary role in such physics studies [2, 3] as precision tests of the fundamental non-Abelian triple and quartet gauge field self-interactions in principle, for example. In this paper, we present and illustrate, via sample Monte Carlo data, the rigorous Yennie-Frautschi-Suura (YFS) [4] exponentiated Monte Carlo approach [5] to these processes. The respective Monte Carlo event generator which realizes the calculation is exact in the infrared regime and is of leading logarithmic accuracy through $\mathcal{O}(\alpha^2)$ in the initial state QED hard radiative regime. A higher precision realization of our methods and results is in progress [6].

We recall at this time the current state of the art insofar as Monte Carlo event generators for the processes $e^+e^- \rightarrow ZZ + n(\gamma) \rightarrow 4fermions + n(\gamma)$ are concerned. In ref. [7, 8], both semi-analytical and Monte Carlo event generator results in the literature have been reviewed. What is new in our work in this paper is that we present for the first time the results of a calculation of theese processes in which all of the following are simultaneously featured:

- realistic, finite p_T, simulation of the respective multiple photon radiative effects on an event-by-event basis in which infrared singularities are cancelled to all orders in α

- YFS exponentiated $\mathcal{O}(\alpha^2)$ LL initial state radiation (ISR)

- anomalous triple gauge boson couplings.

Thus, our work represents the first realistic multi-photon radiative effects simulation of the processes under study in which the interplay between the $n(\gamma)$ radiation and possible anomalous coupling effects can be systematically investigated. We illustrate this point in what follows.

Our work is organized as follows. We first build on the recent application of the YFS exponentiated Monte Carlo algorithm in ref. [9] to the W-pair production process by extending it to the Z-pair production process of interest to us here. We then present some sample MC data and discuss their implications for Z-pair production studies at high energy e^+e^- colliding beam devices. Finally, we present some summary remarks.

Specifically, in this paper, we extend the result in ref. [10] to the process $e^+ + e^- \to Z+Z+n(\gamma) \to 4fermions+n(\gamma)$, as it is illustrated in fig. 1. We start with the respective master formula.

Referring to our master formula in ref. [10], eq.(9) in this last reference, for the process $e^+ + e^- \to W^+ + W^- + n(\gamma) \to 4fermions\ + n(\gamma)$ and to the kinematics in fig. 1, we arrive at the corresponding initial state YFS exponentiated $\mathcal{O}(\alpha^2)$ leading log (LL) master formula for the process $e^+ + e^- \to Z + Z + n(\gamma) \to 4fermions\ + n(\gamma)$ by substituting the respective Born level differential distribution for the latter process for the former, yielding

$$d\sigma = e^{2\alpha Re B + 2\alpha\tilde{B}} \sum_{n=0}^{\infty} \frac{1}{n!} \int \prod_{j=1}^{n} \frac{d^3 k_j}{k_j^0} \int \frac{d^4 y}{(2\pi)^4}\, e^{iy(p_1+q_1-p_2-q_2-\sum_j k_j)+D}$$
$$\bar{\beta}_n(k_1,\ldots,k_n) \frac{d^3p_{f_1} d^3p_{\bar{f}_1} d^3p_{f_2} d^3p_{\bar{f}_2}}{p^0_{f_1} p^0_{\bar{f}_1} p^0_{f_2} p^0_{\bar{f}_2}}, \quad (1)$$

where we have introduced the same notation as that used in ref. [10] for the YFS infrared functions $B, \tilde{B}, D$ and for the YFS hard photon residuals $\bar{\beta}_n$. Thus, at the $\bar{\beta}_0$ level to which we work (i.e. $\bar{\beta}_1$ and $\bar{\beta}_2$ are included here in the LL approximation only), we may identify $\frac{1}{2}\bar{\beta}_0$ with $d\sigma_{Born}/d\Omega_1 d\Omega_2$ where $d\Omega_{1(2)}$ is the differential decay solid angle of

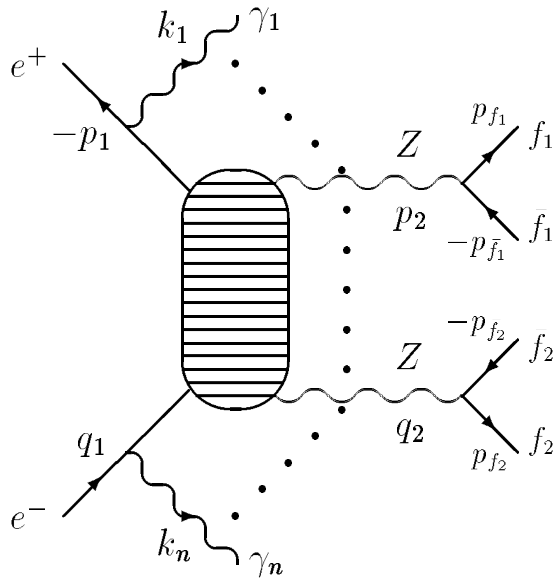

Figure 1: The process $e^+e^- \to ZZ + n(\gamma) \to f_1 + \bar{f}_1 + \bar{f}_2 + f_2 + n(\gamma)$.

$f_1(f_2)$ in the respective Z's rest frame. Our respective Born cross section $d\sigma_{Born}$ is taken from ref. [11], where we allow for anomalous couplings gauge boson couplings f_4, f_5 in the notation of this latter reference. We have realized the result (1) using MC methods of two of us (S.J. and B.F.L.W. [5, 9, 12]), in complete analogy with our work in ref. [10]. The resulting program is called YFSZZ 1.0 and it is available from the authors [13]. We will now illustrate some of its applications. Such multiple photon radiative effects in the process under study here have not appeared elsewhere.

Specifically, in fig. 2, we show the results for 10^6 simulated (weighted) events for the case that $f_1 = e, f_2 = \mu$ in fig. 1. We show this for the NLC type CMS energy $E_{CM} = 500$ GeV. To illustrate the interplay of the $n(\gamma)$ radiation and the anomalous gauge boson couplings f_4, f_5, we calculate five different scenarios, $f_i = 0$, $i = 4, 5$ (SM gauge boson couplings) at the Born level; $f_i = 0$, $i = 4, 5$ (SM gauge boson couplings) at the $\mathcal{O}(\alpha^2)$ LL

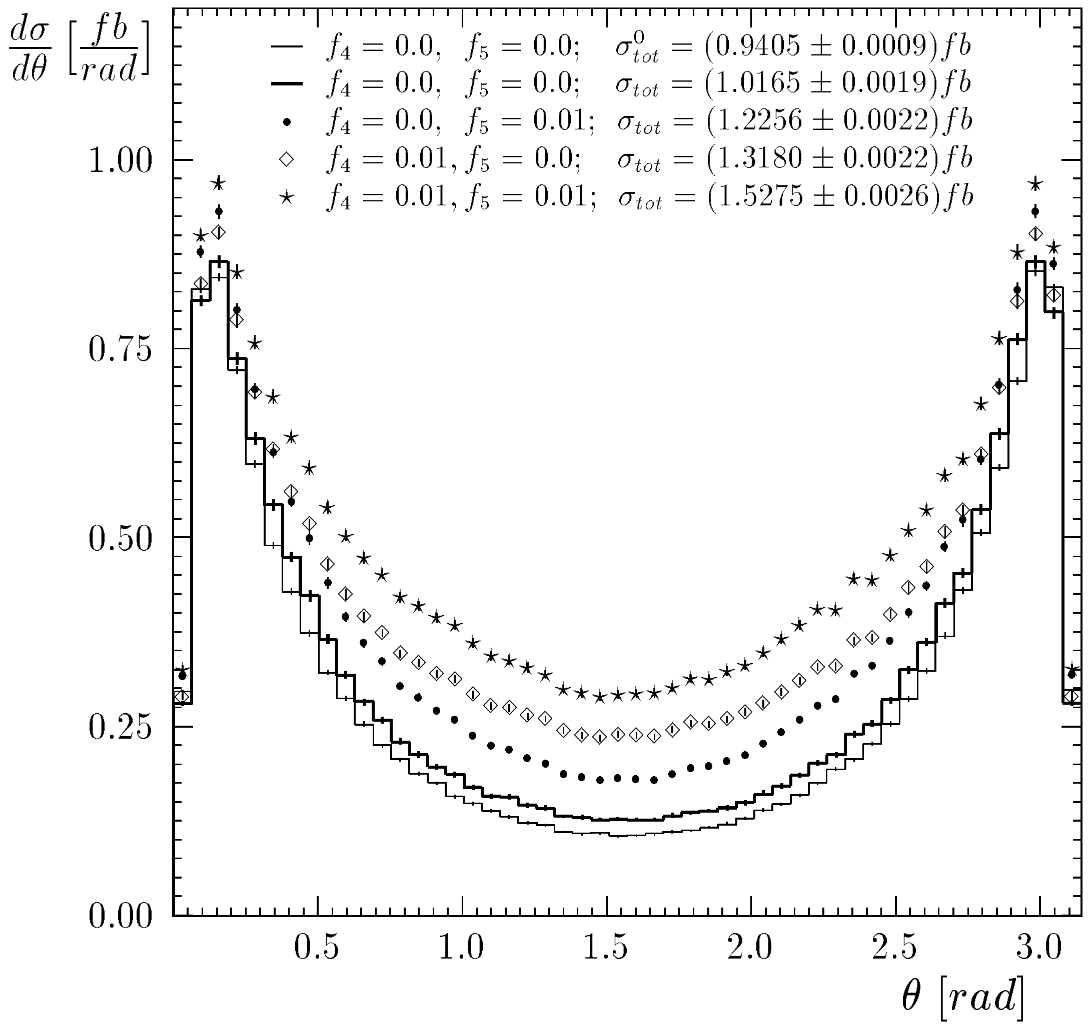

Figure 2: Total cross sections and angular distributions for the process in fig. 1 for $f_1 = e, f_2 = \mu$ at $E_{CM} = 500$ GeV. σ^0_{tot} corresponds to the respective Born total cross section. The light solid curve, dark solid curve, solid dot, open diamond, and solid star correspond respectively to the differential distributions the polar angle (θ) of one of the Z's relative to the incoming e^- direction for example for the Standard Model Born cross section, for the SM $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, for the $f_4 = 0.0, f_5 = 0.01$ $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, for the $f_4 = 0.01, f_5 = 0.0$ $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, and for the $f_4 = 0.01, f_5 = 0.01$ $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, respectively.

YFS exponentiated $\bar{\beta}_0$ level; $f_4 = .01$, $f_5 = 0$; $f_4 = 0$, $f_5 = .01$; and, finally, $f_4 = f_5 = .01$, where the last three scenarios are all done at the $\mathcal{O}(\alpha^2)$ LL YFS exponentiated $\bar{\beta}_0$ level. The respective total cross sections, along with the Born cross section denoted by σ^0_{tot}, are given in the top of the figure whereas the differential cross section in the polar production angle of one of the Z's is plotted in the figure for each case as indicated. The figure illustrates that these anomalous couplings give angular distributions with general shapes similar to that of the SM couplings but that they make a significant increase in the cross section normalization. In this last regard, the coupling f_4 produces a stronger effect than does the same strength of the coupling f_5; and, when both are present with the same strength, the effects essentially add linearly insofar as the total cross sections are concerned. This approximate additive linearity is consistent with the fact that f_4 is CP violating and f_5 is not. At the level of the differential cross sections, there is a more detailed interplay between the radiative corrections and the anomalous couplings so that there are regions near the forward and backward directions where the effect of f_5 exceeds that of f_4 whereas in the complementary region the effect of f_4 exceeds that of f_5, for the same strength of the respective couplings. Evidently, the multiple photon character of the radiative effects, affecting as it does the normalization and the detailed angular profile of the cross sections in the figure for example, must be taken into account in any precision analysis of such anomalous gauge boson effects. YFSZZ 1.0 allows one to do this on an event-by-event basis.

In ref. [14], semi-analytical results are presented for the process in fig. 1 which feature the exact $\mathcal{O}(\alpha)$ ISR correction with soft photon exponentiation. Indeed, the authors in ref. [14] have isolated both the complete $\mathcal{O}(\alpha)$ correction and the so-called universal part of this correction associated with structure function evolution of the incoming $e^{\pm}$ beams. For the process which we present in fig. 2, we may therefore compare directly the ratio the

$\sigma_{tot}/\sigma^0_{tot}$ for the case of SM couplings, 1.081 ± 0.002, with the analogous ratio in ref. [14] for the respective universal correction, which is 1.0798. The excellent agreement between these two numbers gives us an important cross check on our work.

In summary, we have developed and illustrated the first ever multiple photon, finite p_T, amplitude based Monte Carlo event generator, YFSZZ 1.0, for the process $e^+e^- \rightarrow ZZ + n(\gamma) \rightarrow f_1\bar{f}_1 + \bar{f}_2 f_2 + n(\gamma)$ in which infrared singularities are cancelled to all orders in α. We find that there is an interplay between the $n(\gamma)$ radiation and the presence of possible anomalous couplings in the gauge boson sector. We look forward with excitement to further applications of our calculation in high energy e^+e^- colliding beam devices.

Acknowledgements

Two of us (S. J. and B.F.L. W.) acknowledge the kind hospitality of Prof. G. Veneziano and the CERN Theory Division while this work was completed.

References

[1] S.L. Glashow, Nucl. Phys. **22** (1961) 579;
S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264;
A. Salam, in *Elementary Particle Theory*, ed. N. Svartholm (Almqvist and Wiksells, Stockholm, 1968), p 367.

[2] See for example S. Kuhlman *et al.*, SLAC-R-0485, 1996, and references therein.

[3] T. Barklow *et al.*, "Anomalous Gauge Boson Couplings", to appear in Proc. 1996 Snowmass Workshop, in press.

[4] D. R. Yennie, S. Frautschi and H. Suura, Ann. Phys. **13** (1961) 379.

[5] S. Jadach and B.F.L. Ward, Phys. Rev. **D38** (1988) 2897.

[6] S. Jadach, W. Płaczek, and B.F.L. Ward, in preparation.

[7] D. Bardin et al., "Event Generators for WW Physics", in Physics at LEP2, vol. 2, CERN-96-01, eds. G. Altarelli et al., (CERN, Geneva, 1996), p. 3.

[8] T. Ohl, preprint IKDA-96-21, 1996, to appear in Proc. 1996 Cracow Int. Symp. Rad. Corr., ed. S. Jadach, (Institute of Physics of the Polish Academy of Sciences, Cracow, 1997), in press.

[9] S. Jadach and B.F.L. Ward, Comput. Phys. Commun. **56** (1990) 351.

[10] S. Jadach, W. Płaczek, M. Skrzypek and B.F.L. Ward, Phys. Rev. **D54** (1996) 5434.

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

[12] S. Jadach and B.F.L. Ward, Phys. Rev. **D40** (1989) 3582.

[13] S. Jadach, W. Płaczek, and B.F.L. Ward, *The MC Event Generator YFSZZ 1.0*, available at the WWW URL http://enigma.phys.utk.edu/pub/YFSZZ/.

[14] D. Bardin *et al.*, Nucl. Phys. **B477** (1996) 27.

Figure Captions

Fig. 1. The process $e^+e^- \to ZZ + n(\gamma) \to f_1 + \bar{f}_1 + \bar{f}_2 + f_2 + n(\gamma)$.

Fig. 2. Total cross sections and angular distributions for the process in fig. 1 for $f_1 = e, f_2 = \mu$ at $E_{CM} = 500$ GeV. σ^0_{tot} corresponds to the respective Born total cross section. The light solid curve, dark solid curve, solid dot, open diamond, and solid star correspond respectively to the differential distributions the polar angle (θ) of one of the Z's relative to the incoming e^- direction for example for the Standard Model Born cross section, for the SM $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, for the $f_4 = 0.0, f_5 = 0.01$ $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, for the $f_4 = 0.01, f_5 = 0.0$ $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, and for the $f_4 = 0.01, f_5 = 0.01$ $\mathcal{O}(\alpha^2)$ LL YFS exponentiated cross section, respectively.