TESTING THE $WW\gamma$ COUPLING AT $e^+e^-$ COLLIDERS*

Jan Kalinowski†
Institute of Theoretical Physics, Warsaw University
Hoża 69, 00681 Warsaw, Poland

ABSTRACT

The production of single photons plus missing energy at future $e^+e^-$ colliders can provide a testing ground for non-standard $WW\gamma$ couplings. We show that even with conservative estimates of systematic errors there is still considerable sensitivity to anomalous couplings.

In spite of many experimental successes certain aspects of the standard model still await for direct tests. Among them is the non-abelian sector of the model and, in fact, a detailed investigation of gauge boson self-couplings will constitute one of the primary physics goals of the next linear colliders. The processes with production of gauge bosons in the final state at future colliders should provide such crucial tests of electroweak theory. In particular, they should allow to improve LEP bounds on non-Yang-Mills like triple gauge boson vertices.

In this talk we suggest that the process $e^+e^-\rightarrow\nu\nu\gamma$ containing a single isolated photon and missing energy may be used to study the precise structure of the $WW\gamma$ vertex. Such final states have been studied at PETRA and at LEP as a means of determining the number of light neutrini. At these energies though, not much sensitivity to anomalous $WW\gamma$ form-factors should be expected, as s-channel processes mediated by virtual $Z$ exchange also play an important role. However, at Next Linear Collider (NLC) energies ($\sqrt{s}=500$ GeV), s channel contributions become less important and the bulk of the cross-section comes from t channel $W$ exchange. The process $e^+e^-\rightarrow\nu\nu\gamma$ from the point of view of $WW\gamma$ studies has been considered earlier. The novel feature of our analysis, as we will show, is that it is possible to choose cuts which enhance the sensitivity of the observed cross-sections and differential distributions to the $WW\gamma$ form-factor.

The advantage of the process $e^+e^-\rightarrow\nu\nu\gamma$ over the most studied reaction $e^+e^-\rightarrow W^+W^-$ is that the latter, in spite of being a sensitive probe of non-standard $WW\gamma$ and $WWZ$ couplings, suffers from the drawback that there is no obvious way to disentangle the effects of $WW\gamma$ and $WWZ$ form-factors. Hence it is desirable to investigate other channels where such $\gamma-Z$ interference effects are not present.

The deviations of non-abelian vertices from the standard model couplings, as was shown by Hagiwara et al., can be parametrized by seven possible Lorentz and

---

*Presented at the Joint US-Polish Workshop "Physics from Planck Scale to Electroweak Scale", Warsaw, September 21-24, 1994
†Supported in part by the Polish Committee for Scientific Research Grant 2 P302 095 05
\(U(1)_{\text{em}}\) invariant triple gauge boson form-factors. Requiring C and P invariance (in the absence of beam polarisation there is no way to detect CP violating asymmetries if the only particle detected is a photon of unknown polarisation) then only two, traditionally denoted by \(\kappa\) and \(\lambda\), remain. In the standard model we have \(\kappa = 1\) and \(\lambda = 0\). Deviations from the standard model are then parameterised by \(\delta \kappa = \kappa - 1\) and \(\lambda\). The modified Feynman rules for the \(WW\gamma\) vertex may be obtained from Ref.\[8\].

All other Feynman rules are standard ones.

Due to the complexity of the Feynman rules for the non-standard couplings it turns out to be convenient to calculate the matrix-element using the helicity amplitude formalism\[9,10\]. The results are presented in Ref.\[2\].

As a further check we evaluated the helicity amplitudes using the formalisms of Ref.\[11\] and Ref.\[10\] and find excellent numerical agreement for various values of \(\kappa\) and \(\lambda\).

Since we assume the electron to be massless we need to impose a minimum angle cut on the direction of the outgoing photon to avoid collinear singularities as well as a minimum energy cut to avoid IR problems. Setting \(\theta_{\text{min}} = 20^\circ\) and \(E_{\text{min}} = 10\) GeV we find for the standard model a cross-section of \(\sim 1.6\) pb, which at projected NLC luminosities (\(\sim 10\) fb\(^{-1}\)) represents a sizable number of events. However, with these cuts alone the sensitivity to non-standard couplings is rather small because the bulk of the cross-section comes from initial state soft photon bremsstrahlung which is independent of the non-abelian couplings. It is clear that only the more energetic photons will be sensitive to the anomalous form-factors which are associated with higher dimensional operators containing derivative interactions. Therefore we require that the minimum energy of the photon be 80 GeV. Further improvement can be obtained by eliminating the background from the \(Z\) exchange graphs, \(e^+e^- \rightarrow Z\gamma \rightarrow \nu\nu\gamma\). This can easily be achieved by means of a simple kinematical cut because in this case the photon is essentially monochromatic (in the limit that the \(Z\) width is negligible) with an energy close to half the centre of mass energy. Hence we require that the energy of the photon be less than 180 GeV in order not to reduce the signal from the \(W\) exchange graphs too much.

With these cuts on the photon energy, 80 – 180 GeV, the cross-section for the standard model is 0.21 pb, which still leads to an appreciable number of events at NLC luminosities. Cross-sections for non-standard values of \(\delta \kappa\) and \(\lambda\) with the cuts mentioned above are presented in Fig.1, where we have varied \(\delta \kappa\) and \(\lambda\) individually and not simultaneously in order to keep the analysis simple.

As we can see, the process \(e^+e^- \rightarrow \nu\nu\) is quite sensitive to the deviations from the standard model. The experimental limits that can be derived for \(\delta \kappa\) and \(\lambda\) depend however on possible experimental and theoretical uncertainties. Statistical errors are probably quite small given the large number of events \(\mathcal{O}(2000)\). Assuming that there are no experimental systematic errors, the main source of theoretical systematic errors lies in unknown higher order corrections. Note that the higher order corrections discussed in Ref.\[4\] are those which are dominant on the \(Z\) pole, and are therefore not adequate for our purposes. It is reasonable to assume that the bulk of the corrections are real and virtual QED corrections which integrated over the the phase space are probably quite small. However we are restricting ourselves to a limited region of the
total phase space where radiative corrections may be sizable even though the total radiative corrections themselves are small. Making the conservative assumption that the overall systematic uncertainties are $O(20\%)$ it is possible to put the following discovery bounds $-0.6 < \lambda < 0.6$ and $-0.6 < \delta\kappa < 2.2$ using the cross-section with the cuts mentioned above as only sensitive variable.

If higher luminosity can be achieved ($\sim 50 \text{ fb}^{-1}$) one can be more optimistic about the systematic uncertainties and assuming errors to be $O(5\%)$ better limits can be derived $-0.3 < \lambda < 0.3$ and $-0.2 < \delta\kappa < 0.2$ or $1.2 < \delta\kappa < 1.6$. The discovery limits derived by Couture and Godfrey where similar issues are discussed, are even more stringent than ours due to very optimistic assumptions about the size of theoretical systematic errors.

The total cross section measurement alone will not allow to determine the parameters $\delta\kappa$ and $\lambda$ unambiguously. Further refinement is possible if one considers differential distributions. This is illustrated in Fig.2a where we have plotted the differential distribution with respect to photon energy for the standard model and for two values of $\delta\kappa$.

Although the cross-sections are almost the same the differential distributions are different. For the angular distribution, Fig.2b, the sensitivity to different values of $\delta\kappa$ is weaker. Similar effects are observed for $\lambda$ keeping $\delta\kappa = 0$. However, to derive further discovery bounds on the basis of differential distributions, a detailed consideration of detector acceptances and higher order radiative corrections is necessary.

It is interesting to note that even our conservative results compare favourably with the bounds obtained by McKellar and He on the basis of the recent CLEO measurement of $b \rightarrow s \gamma$. Referring to $e^+e^- \rightarrow W^+ W^-$ at LEP II at 190 GeV more stringent bounds of the order of $\pm 0.5$ for $\lambda$ and $\delta\kappa$ can be obtained based on theoretically favored three-parameter fits provided polarization properties of produced $W$ bosons are fully measured. Errors can be further reduced either by imposing additional constraints and performing fits with only one or two free parameters or employing initial beams polarization. Considerably weaker bounds are deduced from unconstrained multi-parameter fits. However these bounds are set knowing that one-loop corrections are small leading to smaller theoretical systematic errors than what we have assumed. It is also worth pointing out that $W$ pair production is sensitive to the time-like triple gauge boson form-factors, whereas the process we are studying probes the same form-factors in the space-like region. Therefore both measurements are in some sense complementary.

To conclude, we have demonstrated that $\sigma(e^+e^- \rightarrow \nu\nu\gamma)$ at projected NLC energies and luminosities is sensitive to anomalous $WW\gamma$ couplings. Making conservative estimates for systematic errors involved it is possible to constrain $\lambda$ and $\kappa$ to lie within the regions $-0.6 < \lambda < 0.6$ and $-0.6 < \delta\kappa < 2.2$. These bounds can be improved through knowledge of currently unknown radiative corrections.

---

$^1$I thank R. Settles for discussion on this point
Acknowledgements

I would like to thank J. Abraham for many discussions and enjoyable collaboration.

References

1. For a review and references see "$e^+e^- \text{ Collisions at 500 GeV: The Physics Potential }"$, Proc. Munich, Annecy, Hamburg Workshop, 1991-1993, DESY Reports 92-123A+B, 93-123C.
2. J.K. Abraham, J. Kalinowski, P. Ściepko, Phys. Lett. B339 (1994) 136.
3. K.J.F. Gaemers, R. Gastmans, F.M. Renard, Phys. Rev. D19 (1979) 1605.
4. F.A. Berends et al., Nucl. Phys. B301 (1988) 583.
5. OPAL Collab., R. Akers et al., CERN-PPE/94-105.
6. G.V. Borisov, V.N. Lin, F.F. Tikhonin, Z. Physik C41 (1988) 287.
7. K. Hagiwara et al., Nucl. Phys. B282 (1987) 253.
8. E. Yehudai, SLAC preprint, SLAC-383 (1991).
9. F.A. Berends, W. Giele, Nucl. Phys. B294 (1987) 700.
10. J.F. Gunion, Z. Kunszt, Phys. Lett. B161 (1985) 333.
11. K. Hagiwara, D. Zeppenfeld, Nucl. Phys. B274 (1986) 1.
12. G. Couture, S. Godfrey, preprint OICP/C 94-4, UQAM-PHE-94-09.
13. X.G. He, B.H.J. McKellar, preprint UM-P-93/53, OZ-93/14.
14. E. Thorndike (CLEO Collab.), in Proc. of the American Physical Society Meeting, Washington DC, April 1993.
15. M. Bilenky, J.L. Kneur, F.M. Renard, D. Schildknecht, Nucl. Phys. B409 (1993) 22.
16. A.A. Likhoded et al., preprint IC/93/288, UTS-DFT-93-22, hep-ph 9309322
Fig. 1. Cross section for the process $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$ at $\sqrt{s} = 500$ GeV (a) as a function of $\delta \kappa$ for $\lambda = 0$ and (b) as a function of $\lambda$ for $\delta \kappa = 0$.

Fig. 2. (a) Energy spectrum and (b) angular distribution of the photon at $\sqrt{s} = 500$ GeV for the standard model and for $\delta \kappa = -0.6$ and $2$. 
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9501237v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9501237v1
