Single W-boson production in $e^- \gamma$ colliders

K. Huitu$^a$, J. Maalampi$^b$ and M. Raidal$^c$

$^a$Research Institute for High Energy Physics, University of Helsinki
$^b$Department of Theoretical Physics, University of Helsinki
$^c$Department of Theoretical Physics, University of Valencia

Single W-boson production in $e^- \gamma$ collisions with polarized beams is investigated. In the framework of the Standard Model the updated estimates for the measurement precision of photon anomalous coupling parameters $\kappa_\gamma$, $\lambda_\gamma$ at the Next Linear Collider with $\sqrt{s_{e\gamma}} = 420$ GeV are obtained. The production of right-handed gauge bosons $W^-_2$ in this collision mode is also analysed. If the associated neutrino is light, the channel would give the best discovery reach for $W^-_2$ in the Next Linear Collider.

1 Introduction

In addition to the electron-positron option, the electron-electron and electron-photon collision modes of the Next Linear Collider (NLC) are also technically realizable [1]. During the recent years the physics potential of the latter options has been under intense study. While $e^-e^-$ collisions have been found to be particularly suitable for the study of possible lepton number violating phenomena [2], the $e^-\gamma$ operation mode will also be well motivated from the point of view of new physics.

So far, the $e^-\gamma$ collisions have been studied using the photon spectrum of classical Bremsstrahlung. In the linear collider it will be possible to obtain high luminosity photon beams by backscattering intensive laser pulses off the electron beam [3] without considerable losses in the beam energy and with very high polarizability and monochromaticity [4]. This possibility makes the $e^-\gamma$ collisions ideal for studying heavy gauge boson pro-

\[1\] Talk given by M. Raidal in the workshop "Physics with Linear Colliders," Gran Sasso, 1995.
production processes \[5, 6, 7\], since the initial state photon provides us with a possibility to probe directly the gauge boson self-interactions.

We will consider a single massive vector boson production in $e^-\gamma$ collision,

$$e^-\gamma \rightarrow W^-N,$$  \hfill (1)

for any combination of beam polarization. Here $W^-$ may stand for the ordinary SM charged vector boson $W^-_1$ and $N$ for the massless Dirac electron neutrino $\nu_e$. However, we do not restrict ourselves only to this case, since a wide class of models beyond the SM predicts a existence of new heavy vector bosons and massive neutrinos. For example, in the left-right symmetric model (LRM) \[8\] the vector boson may also be a heavy right-handed weak boson $W_2$. The present lower limit for the mass of $W_2$ coming from high energy experiment is $M_{W_2} \geq 652$ GeV \[9\], so that the right-handed boson production will be kinematically forbidden at least in the initial phase of the NLC. At the final phase of the NLC, however, the reaction (1) may be kinematically allowed and even favoured compared with, e.g., the $W_2$ pair production in $e^-e^+$ collisions, since the mass of the associated neutrino could be smaller than the mass of $W_2$. In the case of a sizeable mixing between the light, predominantly left-handed and the heavy, predominantly right-handed neutrinos the study of the process (1) may extend the kinematical discovery range of $W_2$ almost up to the energy $\sqrt{s_{e\gamma}}$.

2 Anomalous triple boson coupling in the Standard Model

There are two Feynman diagrams contributing at the tree level to the reaction (1) (see Fig. 1). One of them, the t-channel diagram, involves a triple gauge boson coupling making the process suitable for testing the non-Abelian gauge structure of the theory. A particularly interesting feature of the process (1) is that it is sensitive only to the possible anomalous coupling of the photon, allowing one to discriminate between the photon anomalous coupling and the anomalous coupling of massive neutral gauge boson $Z^0$. Since the deviation from the SM coupling is expected to be small, one can use of polarization of the initial state particles to enhance these effects.

The most general $CP$-conserving $\gamma WW$ interaction allowed by the electromagnetic gauge invariance is of the form \[10\]

$$\mathcal{L}_{\gamma WW} = -ie(W_{\mu}^\dagger W^\mu A^\nu - W_{\mu}^\dagger A_{\nu}W^{\mu\nu} + \kappa_{\gamma}W_{\mu}^\dagger W_{\nu}F^{\mu\nu} +$$
where $W_{\mu\nu} = (\partial_\mu - ieA_\mu)W_\nu - (\partial_\nu - ieA_\nu)W_\mu$ and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The coefficients $\kappa_\gamma$ and $\lambda_\gamma$ are related to the magnetic moment $\mu_W$ and the electric quadrupole moment $Q_W$ of $W$ according to

$$\mu_W = \frac{e}{2M_W}(1 + \kappa_\gamma + \lambda_\gamma), \quad Q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma).$$

In a gauge theory at tree level the coefficients have the values $\kappa_\gamma = 1$ and $\lambda_\gamma = 0$.

The scattering of linearly polarized laser light off the electron beam produces a polarized photon beam with very hard spectrum strongly peaked at the maximum energy, which is about 84% of the electron beam energy [3]. There are two different collision schemes of the photon colliders possible [4]. In the first case the photon conversion region is very close to the interaction point and the entire photon spectrum interacts with the electron beam. From the physics point of view this realization of the $e^-\gamma$ collisions is undesired because of the high rate of the background processes initiated by the electrons which have been used for creating the photon beam and also because of the low monochromaticity of the photon beam.

In the case of the second collision scheme the distance between the conversion and interaction points is longer. The electrons used for producing the photon beam are removed by applying strong magnetic field and therefore the $e^-\gamma$ collisions are clean. Since the electron beam probes only the hardest photons of the $\gamma$ beam the collisions are highly monochromatic. The achievable luminosities in this case are found to vary from 30 fb$^{-1}$ at VLEPP to 200 fb$^{-1}$ at TESLA per year [4]. Therefore, we have carried out our analysis for the center of mass energy $\sqrt{s_{ee\gamma}} = 420$ GeV corresponding to the peak value of the photon spectrum, assuming that the relatively small nonmonochromaticity effects of the
photon beam as well as the nonmonochromaticity effects of the electron beam due to the energy losses in beamstrahlung (both at the level of a few percent) will be taken into account in the analysis of experimental data. The other relevant NLC parameters which we have used are the following: integrated luminosity $L_{\text{int}} = 50 \text{ fb}^{-1}$, the covering region of a detector $|\cos \theta| \leq 0.95$ and $W^-$ reconstruction efficiency of 0.1.

We have used five observables for testing the parameters $\kappa_\gamma$ and $\lambda_\gamma$. Obviously, the differential cross section $d\sigma_{\tau_1 = \pm 1}/d\cos \theta$ and the total cross section $\sigma_{\tau_1 = \pm 1}^{\text{tot}}$ for different photon beam polarization $\tau_1 = \pm 1$ can be analysed. Since the differential cross sections are strongly peaked in the backward direction one would expect that also the forward backward asymmetries

$$A_{FB}^{\pm} = \frac{\sigma_{\tau_1 = \pm 1}(\cos \theta \geq 0) - \sigma_{\tau_1 = \pm 1}(\cos \theta \leq 0)}{\sigma_{\tau_1 = \pm 1}(\cos \theta \geq 0) + \sigma_{\tau_1 = \pm 1}(\cos \theta \leq 0)}$$

(3)

could be sensitive to the anomalous coupling. The quantity, which reflects the effects of the beam polarization, is the polarization asymmetry $A_{\text{pol}}$ defined as

$$A_{\text{pol}}(\cos \theta) = \frac{d\sigma_{\tau_1 = +1} - d\sigma_{\tau_1 = -1}}{d\sigma_{\tau_1 = +1} + d\sigma_{\tau_1 = -1}}.$$ 

(4)

We have also studied whether the measurement of the final state $W$-boson polarization could offer sensitive tests for $\kappa_\gamma$ and $\lambda_\gamma$. The information about the polarization of $W$-boson can be obtained by measuring the angular distribution of its decay products. A suitable quantity would be the forward-backward asymmetry of the leptons produced in $W^-$ decay, which is related to the cross sections corresponding to the different $W^-$ polarization states $\tau_2 = \pm 1$ as follows (see e.g. ref. [11]):

$$\chi_{FB}^{\pm} = \frac{3}{4} \frac{\sigma_{\tau_2 = -1, \tau_1 = \pm 1} - \sigma_{\tau_2 = +1, \tau_1 = \pm 1}}{\sigma_{\tau_1 = \pm 1}^{\text{tot}}}. $$

(5)

We have carried out a $\chi^2$ analysis by comparing the SM prediction of the observables with those corresponding ones to the anomalous $\kappa_\gamma$ and $\lambda_\gamma$. The limits are calculated at 90% confidence level, which corresponds to $\Delta \chi^2 = 4.61$. The statistical errors are computed assuming the NLC parameters given above. The systematic errors are estimated by assuming the uncertainty of the cross section measurement to be at the level of $\sim 2\%$ [14], coming mainly from the errors in the luminosity measurement, the acceptance, the background subtraction and the knowledge of branching ratios.

Both forward-backward asymmetries, $A_{\tau_1}^{FB}$ and $\chi_{\tau_1}^{FB}$, turned out to be several times less sensitive to the anomalous coupling than the other three observables. Polarization asymmetry $A_{\text{pol}}$ and the total cross sections $\sigma_{\tau_1 = \pm 1}^{\text{tot}}$ are more sensitive to the deviations
from the SM but still do not allow to constrain couplings sufficiently. The most sensitive observable to the photon anomalous coupling is the differential cross section. The contours of allowed regions in \((\kappa_\gamma, \lambda_\gamma)\) space obtained from its analysis are plotted in Fig. 2. The curves for the different photon polarization states \(\tau_1 = \pm 1\) are indicated in the figure. The contour resulting from the combined analysis is denoted by \(a\). As can be seen from Fig. 2 the most stringent constraints for the anomalous coupling are obtained in the case of left-handedly polarized electron and right-handedly polarized photon beams. This is an expected result, since the s-channel diagram in Fig. 1 does not contribute in this case and the entire cross section comes from the t-channel diagram, which probes the triple boson coupling.

As a result, by studying the reaction (1) in the NLC with the assumed set of parameters, one could constrain the anomalous triple boson coupling parameters \(\kappa_\gamma\) and \(\lambda_\gamma\) to the following regions:

\[-0.01 \leq 1 - \kappa_\gamma \leq 0.01, \quad -0.012 \leq \lambda_\gamma \leq 0.007.\]

At this level of precision the radiative corrections are expected to start to play a role \([15]\). Since the size of the SM radiative corrections depends crucially on the beam polarization, the use of polarized beams allows one to discriminate between the the radiative corrections and corrections from the new physics.

We have repeated the analysis with the integrated luminosity of \(10 fb^{-1}\) which gives \(\sim 1.4\) times weaker bounds for parameter \(\kappa_\gamma\) and \(\sim 1.6\) times weaker bounds for parameter \(\lambda_\gamma\). This shows that the measurement uncertainties are largely dominated by the systematic errors. In order to see the relevance of the beam polarization and to compare our results with the earlier works with unpolarized beams we also repeated the analysis using the NLC parameters of ref.\([6]\) \(i.e.\) \(|\cos \theta| \leq 0.7\) and the integrated luminosity of \(10 fb^{-1}\). It turned out that the beam polarization (together with the monochromaticity of the photon beam) gives an improvement of a factor of 3 in the measurement precision of the anomalous coupling parameters \(\kappa_\gamma\) and \(\lambda_\gamma\).

### 3 Single heavy vector boson production in left-right model

The LRM \([8]\) is an extension of the SM, in which the gauge interactions of left-handed and right-handed fundamental fermions are treated on equal basis. The LRM is based on the
gauge symmetry $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$, and there are hence two new weak bosons, $W_2$ and $Z_2$, in addition to the ones known in the SM. The left-right symmetry, not present in the low energy world, is broken by a SU(2)$_R$ triplet Higgs field $\Delta = (\Delta^+, \Delta^+, \Delta^0)$. The only new fermions the model predicts are the right-handed neutrinos.

The energy scale $v_R = <\Delta^0>$ of the breaking of the LRM symmetry to the SM symmetry, which also sets, up to coupling constants, the mass scale of the new weak bosons and right-handed neutrinos, is not given by the theory itself. In the Tevatron one has made a direct search of $W_2$ in the channel $pp \to W_2 \to eN$. The bound they give is $M_{W_2} \geq 652$ GeV \cite{9}. The result is based on several assumptions on the LRM: the quark-$W_2$ coupling has the SM strength, the CKM matrices for the left-handed quarks and the right-handed quarks are similar and the right-handed neutrino does not decay in the detector but appears as missing $E_T$. If one relaxes the first two assumptions, the mass bound will be weakened considerably, as was pointed out in ref.\cite{10}. The third assumption is also crucial; if the right-handed neutrino is heavy, with a mass of say 100 GeV or more, it will decay in the detector into charged particles with no missing energy. For this case, which is natural in the LRM, Tevatron search would be ineffective. Therefore, it was argued in ref.\cite{10}, that the lower limit for $M_{W_2}$ could be as low as 300 GeV.

The mass dependence of the total cross section of the process $e_R \gamma \to W_2^- N$ can be seen in Fig. 3, where we plot the cross section as a function of $W_2^-$ mass for the center of mass energy $\sqrt{s_{e\gamma}} = 1.5$ TeV, expected to be possible to achieve in the final stage of NLC, assuming the left- (Fig. 3 (I)) and right-handedly (Fig. 3 (II)) polarized photon beams. The curves denoted by $a$ and $b$ correspond to the neutrino masses $M_N = 300$ GeV and $M_N = 600$ GeV, respectively. The cross sections are found to be reasonably large for almost the entire kinematically allowed mass region, decreasing faster with $M_{W_2}$ for the $\tau_1 = 1$ photons. At low $W_2$ masses the difference between $a$ and $b$ curve is small but for heavy $W_2$ masses the cross section depends strongly on the neutrino mass. If $M_N \leq M_{W_2}$, the reaction \eqref{1} enables us to study heavier vector bosons than what is possible in the $W_2^-$ pair production in $e^-e^+$ or $e^-e^-$ collisions.

The reaction would be even more useful in this respect if the mixing between the heavy and the light neutrino is large enough to give observable effects. In Fig. 4 we plot the cross section of the reaction $e_R^- \gamma \to W_2^- \nu$ for different photon polarizations assuming a vanishing mass of $\nu$ and the neutrino mixing angle of $\sin \theta_N = 0.05$. For this set of parameters the process should be observable up to $W$-boson mass $M_W = 1.2$ TeV.
4 Summary

We have studied usefulness of the reaction $e^−γ \rightarrow W_2N$ in the NLC for finding signals of the physics beyond the SM. The NLC with $\sqrt{s} = 420$ GeV $e^−γ$ option will be able to probe $γWW$ interaction at the level of the SM quantum corrections. We have also pointed out the possibility to test the left-right symmetry of electroweak interactions at the energies of the final phase of the NLC through the same reaction. If the right-handed neutrino is light, this reaction offers a much better discovery reach for $W_2$ than the pair production in $e^+e^−$ or $e^−e^−$ collisions.

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Figure 1: Feynman diagrams for the process $e^- \gamma \to W^- N$.

Figure 2: The allowed domains of the photon anomalous coupling parameters $\kappa_\gamma, \lambda_\gamma$ obtained by analysing the SM differential cross sections of different photon polarization states (as indicated on figure). The curve of combined analysis of the differential cross sections is denoted by $a$. 
Figure 3: The total cross section of the process $e_R^-\gamma \rightarrow W_2^- N$ as a function of heavy gauge boson mass for the left- (figure (I)) and right-handedly (figure (II)) polarized photon beams. The masses of heavy neutrino are taken to be $M_N = 300$ GeV and $M_N = 600$ GeV for curves a and b, respectively.

Figure 4: The total cross section of the process $e_R^-\gamma \rightarrow W_2^- \nu$ as a function of heavy gauge boson mass for the left- and right-handedly polarized photon beams. The neutrino mixing angle is taken to be $\sin \theta = 0.05$. 