The Study of Triple Gauge Boson Anomalous Interactions via the Process $e^-\gamma \to W^-\nu$. Leptonic W Decay Mode.

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Abstract

We study possibilities to measure the triple anomalous W-boson couplings to photon in the $e\gamma \to W\nu$ process via its lepton decay channel (with the simplest signature). We found that in the study of the W quadruple momentum λ one can consider a small region of phase space. A way to find this region is proposed. The obtained estimates for λ at TESLA project are roughly two times than those anticipated for e^+e^- mode. For W anomalous magnetic moment the discussed mode gives no improvements as compared to e^+e^- mode.

Study of anomalous interactions of gauge bosons (beyond the Standard Model – SM) is an essential part of the program of Linear Colliders (LC), both in e^+e^- and $e\gamma$, $\gamma\gamma$ modes (Photon Colliders) [1],[2]. The e^+e^- mode of the LC has been studied thoroughly [3]. The process $e\gamma \to W\nu$ was considered in respect to Photon Collider program in 1984 [4] first. Anomalous gauge boson interactions in $e^+e^- \to WW$, $\gamma\gamma \to WW$, $e\gamma \to W\nu$ processes have been studied in papers [5],[7] with backgrounds neglected , W-boson decay and resulting initial particles' spectra, polarizations and luminosities are far from modern understanding.

The $e\gamma \to W\nu$ process has the following advantages as compared to $e^+e^- \to WW$:

(a) much larger cross-section not decreasing at high energies, as compared to $\sigma(e^+e^- \to WW)$, which decreases with energy;

(b) only γWW anomalies contribute here, making analysis more definite comparing with $e^+e^- \to WW$ case where ZWW anomalies contribute as well.

We use the standard effective lagrangian parameterization with anomalous parameters Δk and λ – anomalous magnetic and quadruple momenta of W–boson respectively as

$$e[W^\dagger{}_{\mu\nu}W^\mu F^\nu - W^\dagger{}_\mu F_\nu W^{\mu\nu} + (1+\Delta k)W^\dagger{}_\mu W_\nu F^{\mu\nu} + \frac{\lambda}{m_W^2}W^\dagger{}_{\lambda\mu}W^\mu{}_\nu F^{\nu\lambda}]\,.$$

Some important features of the $e\gamma \to W\nu$ reaction can be seen before numerical simulations:

• Since only left-hand polarized fermions interact in the $We\nu$ vertex, the cross-section is proportional to $(1-2\lambda_e)$ where λ_e stands for the degree of electron longitudinal polarization. Thus, varying the mean electron helicity, one can measure the right current admixture in this vertex in the new region of W virtualities.

• In our problem we assume anomalous effects to be relatively weak. Therefore, in the observable variations of cross sections only linear in Δk and λ effects should be considered to be experimentally observable. The structure of helicity amplitudes for $e\gamma \to W\nu$ process (without decay) shows that for the left-hand or right-hand polarized initial photons both anomalies (Δk and λ) contribute to the cross-sections, while for unpolarized photons linear in λ effects are canceled. Therefore, the analysis with unpolarized photons is incomplete.

To analyze the process we considered observable channels after W decays. Note that the description of these channels contains additional diagrams (not only $e\gamma \to W\nu$ with subsequent decay). For example, the muon decay channel contains a diagram in which an initial photon interacts with muon after W decay.

We classify **the observable channels of the reaction** by the observable particle

muon(electron) channel		τ – channel	quark channel
1	2		
$e\gamma \to W^-\nu_e$ $\downarrow$ $\mu(e)\bar{\nu}_\mu$	$e\gamma \to W^-\nu_e$ $\downarrow$ $\tau\bar{\nu}_\tau$ $\downarrow$ $\mu(e)\bar{\nu}_\mu\nu_\tau$	$e\gamma \to W^-\nu_e$ $\downarrow$ $\tau\bar{\nu}_\tau$ $\downarrow$ $\nu_\tau + hadrons$	$e\gamma \to W^-\nu_e$ $\downarrow$ $q\bar{q}$

Table 1: *W decay channels.*

and its origin (Table 1). We distinguish, for example, two muon channels, where channel 1 corresponds to direct W decay into $\mu\bar{\nu}$, and channel 2 corresponds to cascading decay to muon and neutrinos with intermediate τ state.

We consider first only muon channel.

Event selection cuts. We impose two constraints on muon escape angle θ and its transverse momentum $p_\perp$ (for operations with $\sqrt{s} \leq 1$ TeV):

$$\boxed{1.\ \pi - \theta_0 \geq \theta \geq \theta_0 = 10 \text{ mrad}; \qquad 2.\ p_\perp > p_{\perp 0} = 10 \text{ GeV}.}$$

Condition 1 corresponds to the TESLA detector expected angular limitation. The second cut allows to exclude or suppress many background processes. We found that reasonable (not excessive) increase of θ_0 and $p_{\perp 0}$ influences our results weakly.

Background processes are those where either muon is the only particle that can be observed or where other charged particles and photons cannot be detected due to their small escape angles. These are:

1. *Processes in which all the final particles can potentially be observed in principle* — $e\gamma \to e\mu^+\mu^-$, $e\gamma \to eZ\gamma$ ($Z \to \mu\bar{\mu}$).

2. *Processes including neutrinos in the final state* — $e\gamma \to e\bar{\tau}\tau$ ($\tau \to \mu$), $e\gamma \to eZZ$ ($Z \to \nu\bar{\nu}$, $Z \to \mu\bar{\mu}$), $e\gamma \to \nu WZ$ ($Z \to \nu\bar{\nu}$, $W \to \mu\nu$), $e\gamma \to eW^-W^+$ ($W^+ \to \ell^+\nu_\ell$, $W^- \to \mu\bar{\nu}_\mu$).

3. *Processes caused by deviation of the state from ideal due to conversion mechanism.* There are $e^-e^- \to \nu W^-e^-$ collisions with residual electrons in the photon beam and $\gamma\gamma \to W^-W^+$ process with beamsstrahlung photons. We consider in this group also the process $e\gamma \to W\nu$ with photons from multiple electron scattering on laser photons.

Transverse momentum conservation along with the cuts imposed exclude processes of the first group (it is impossible that with the energy and angular cuts given only one observed particle has transverse momentum higher than 10 GeV).

Of the third group processes, $e\gamma \to W\nu$ collisions with low energy photons from multiple electron scattering have been simulated and analyzed in detail. As for other processes, they cannot be excluded only by cuts. But it follows from our analysis that the anomalies considered can be extracted with good efficiency from the regions of muon momentum plane $(p_L, p_\perp)$ close to boundaries of the phase space permissible in the reaction. These regions are either beyond the reach of some background processes or their estimated cross sections are relatively small in these regions. Therefore, at the first analysis most of the backgrounds should not have been simulated.

Main parameters. In our analysis the electron longitudinal polarization was taken as $2\lambda_e = -0.85$, luminosity in $e\gamma$ mode was considered 1/4 of its magnitude in e^+e^- mode [2] $\int \mathcal{L}_{e\gamma} dt = \frac{1}{4} \int \mathcal{L}_{e^+e^-} dt$. Different signs of photon circular polarization have been considered. W parameters were taken from [6].

We assume the main parameter for $e \to \gamma$ conversion $x = 4.8$ (corresponding to $E_e = 500$ GeV). The shape of the high energy part of the photon spectrum depends weakly on details of conversion, the beam size and laser flash energy. We used here spectra from papers [4],[10] with parameter $\rho = 1$. On the contrary, the shape of the low-energy part does depend strongly on interaction details and cannot reliably be determined in advance. In addition, low-energetic photons are almost unpolarized. To imitate this part of the spectrum, we used the low-energy part of back-scattered photons' energy spectrum, given in the conversion point with completely unpolarized photons. It has been found that these low-energy photons do not influence the results significantly.

To take into account the electron initial state radiation we used the effective electron spectrum from refs. [8],[9].

Calculations. We calculated distribution of final muons over components of their momentum $\partial^2\sigma/(\partial p_{||} \partial p_\perp)$ in SM and with anomalies, using CompHEP package [11] for symbolic and numerical calculations. For the second μ-channel distribution over τ momenta was calculated using CompHEP (the same as for channel 1), the result was numerically convoluted with distribution (which is simple to calculate) of muons from τ decay with τ decay branching ratio from [6]. This procedure allowed us to avoid analyzing the multiparticle final phase space (after integration over neutrino momenta and averaging over muon spin this distribution becomes independent of polarization of intermediate τ. Indeed, this distribution is determined by two 4-momenta p_τ and p_μ and one pseudovector of τ spin s_τ, but one cannot form a scalar value, including s_τ and both momenta). This approximation is acceptable since τ–lepton width is rather small. We found that final distributions on muon momentum for these two channels are similar.

Computed distributions in SM and with anomalous interactions were used to calculate **Statistical Significance** (SS) defined as:

$$SS = \frac{N_{(SM+anom)} - N_{SM}}{\sqrt{N_{SM}}}$$

The quantity $\sqrt{N_{SM}}$ in denominator corresponds to the situation where relative influence of anomalies on cross section is small.

At the first step we put values $\lambda = \lambda_{sim} = 0.1$ or $\Delta k = \Delta k_{sim} = 0.1$ and calculated SS in separate cells of phase space. These SS vary strongly in the $(p_{||}, p_{\perp})$ plane (example

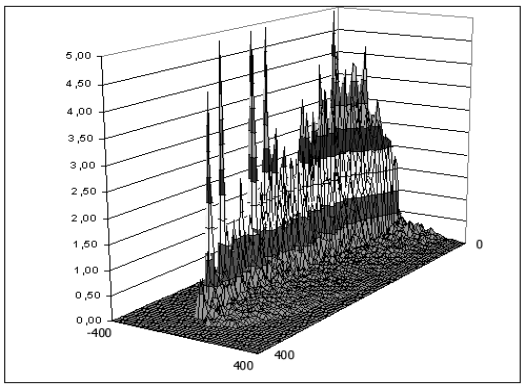


Figure 1: *A map of SS in* $p_{\perp}$, $p_{||}$ *plane for* $\sqrt{s} = 800GeV, \lambda_{\gamma} = -1$, $\Delta k = 0.1$, $\lambda = 0$.

on Figure 1).

The best estimates can be obtained using not the entire phase space, but a region limited by suitable cuts. To find *natural cuts*, i.e. regions of phase space providing the maximal SS value (examples are shown at Figure 2), the following iterative procedure was used.

At each step the current region is modified by the following rule, starting with empty region:

1. On each step we choose a random phase space cell (no matter belonging or not to the region found up to the moment),
2. SS value is re-calculated for the area with this cell included (or excluded, if it was already included to the area),
3. If SS increases, this area change is accepted.

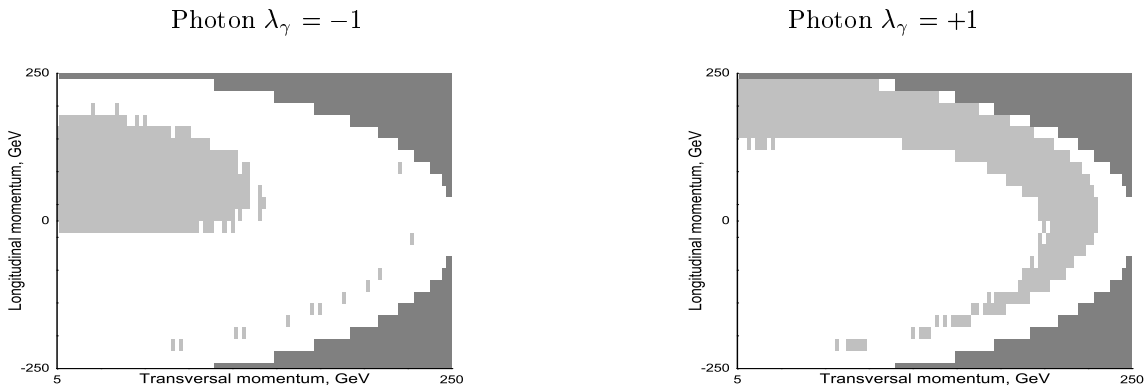
This process converges relatively fast (thousands of steps for our lattice) and results of this procedure are independent of the choice of the starting cell. The obtained areas are different for Δk and λ and depend on energy and photon helicity.

The areas responsible for λ detection belong to a small phase space region. One of the essential features is that reduction of the region to the borders of the phase space reduces SS slightly (by 10-20% with momentum cut at $0.7p_{max}$). With this reduction the intersection of areas, responsible for two considered anomalies, becomes small. That means Δk and λ can be measured practically independently.

At the second step we obtain the final values of the anomalous parameters in this process by linear extrapolation with signal level SL (values of signal measured in $\sqrt{N_{SM}}$ units, fixed by convention) from the equations

$$\lambda_{exp} = \lambda_{sim}(SL/SS),...$$

In the final estimates we also take into account contribution of e-channel as well. For this channel, some new background processes should be added not present in the μ–channel. However, their effect is estimated as small in the areas responsible for anomalies. Therefore, in preliminary estimates we can account for both e and μ channels by doubling the number of events found for μ channel.



$\sqrt{s}_{ee} = 500$ GeV, $\lambda = \lambda_{sim}, \Delta k = 0$

Figure 2: *Phase space areas (in muon $p_\perp$, $p_{||}$ plane), bringing the best SS value, – in gray. Dark are kinematically forbidden regions.*

In the Table 2 we compare the results for $e^+e^- \to W^+W^-$ in all possible channels [3] with muon and electron channels of $e\gamma \to W\nu$ process. For this comparison we use $SL = 1$, as used in [3]. Left column represents here the C.M.S. energy for the initial ee system. Numerical inaccuracy of the shown results is less than 5%.

$\sqrt{s}_{ee}$, GeV		$\int \mathcal{L}dt, fb^{-1}$	λ	Δk
130	$\mathbf{e}\gamma$	100	$3.3 \cdot 10^{-2}$	$1.2 \cdot 10^{-3}$
500	$\mathbf{e}\gamma$	125	$2.5 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$
	$\mathbf{e^+e^-}$	500	$5.9 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$
800	$\mathbf{e}\gamma$	250	$1.7 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$
	$\mathbf{e^+e^-}$	1000	$3.3 \cdot 10^{-4}$	$1.9 \cdot 10^{-4}$

Table 2: *Final values of Δk and λ which can be obtained from $e\gamma \to W\nu$ reaction (e and μ channels) and from $e^+e^- \to WW$*

These results can be improved by the factor 0.88 accounting the τ hadron channel, with branching ratios from [6]. Here the same approach may be used as for simulating μ channel 2. Since muon distributions in μ-channels 2 and 1 are similar and $m_\tau \ll M_W$, one can also use here the data obtained for muon channels. τ hadron decay products should have low multiplicity and small effective mass. Experimentally these events can be extracted by corresponding cuts ($M_{eff} < m_\tau$), and distribution over total momentum of hadrons should be similar to those for μ channels 1 and 2. Additional background processes are not likely to appear under the imposed event selection conditions.

Let us summarize our results.

1. Lepton modes of the process $e\gamma \to \mu\nu$ potentially can provide better opportunities for extracting λ, than the process $e^+e^- \to W^+W^-$; Δk is better measured in the process $e^+e^- \to WW$ (compared to lepton modes for $e\gamma \to \mu\nu$).
2. In most cases, estimates obtained with unpolarized photons are irrelevant to the problem.

3. The small part of final particles' phase space is responsible for the best statistical significance for λ anomaly. This part is located near the kinematically allowed border. This allows one to suppress or even exclude contribution of some background processes.
4. The measured values of Δk and λ are correlated weakly.

The following steps of the analysis are planned:

1. Due to estimated small influence of backgrounds on the result, their description can be simplified by approximations like one used for simulating of the second muon channel (convolution of production and decay distributions). Even though the estimates show that backgrounds influence the results weakly, these processes will be simulated. That will lead to more precise predictions and will provide useful experience for analyzing more complicated processes.

2. W-boson quark decay mode should be simulated. We hope this will also influence the results significantly.

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