Measurement of Trilinear Gauge Couplings at a $\gamma\gamma$ and $e\gamma$ Collider

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Abstract

The processes $\gamma\gamma \rightarrow W^+ W^-$ and $e\gamma \rightarrow \nu W$ are sensitive to triple gauge boson interactions. Both reactions have been simulated for hadronically decaying W-bosons and the sensitivity to anomalous couplings has been estimated.

Talk presented at LCWS2002, August 2002, Jeju Island, Korea
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1 Introduction

If no light Higgs boson exists weak interactions become strong at high energies and for example $WW$ scattering finally violates unitarity at $\sqrt{s} = 1.2$ TeV. First signs of this effect should be seen in a modification of the triple gauge-boson couplings already at lower energies. If, on the contrary, the model remains perturbative up to very high energies triple gauge couplings are modified by loop corrections making them sensitive to new physics at high energy in the same way as the weak mixing angle $\sin^2\theta$, measured at LEP and SLD, is sensitive to the Higgs boson mass.

The cross sections $\gamma\gamma \rightarrow W^+W^-$ and $e\gamma \rightarrow \nu W$ are about an order of magnitude larger than $e^+e^- \rightarrow W^+W^-$ and the dominating Feynman diagrams, shown in figure 1, contain the triple gauge coupling. Also in $e^+e^-$ the $WW\gamma$ and $WWZ$ couplings are mixed. They can, however, be separated, if beam polarization is available.

A $\gamma\gamma$ collider can be realized if a linear collider is run in the $e^-e^-$ mode and a high power laser beam is collided with the electron beam a few mm in front of the interaction point. By Compton scattering photons of up to 80% of the beam energy...
can be obtained and the luminosity in the high energy part of the spectrum can be as high as a third of the $e^+e^-$ luminosity. For $e\gamma$ one can either switch off one laser or one can use the parasitic $e\gamma$ luminosity in the $\gamma\gamma$ mode using unconverted electrons. In the latter case it is, however, not possible to distinguish from which of the two directions the electron was coming and one has additional background from $\gamma\gamma$ collisions.

In this note the processes $\gamma\gamma \rightarrow W^+W^-$ and $e\gamma \rightarrow W\nu$ are analyzed requiring hadronic decays of the Ws. This ensures that the events can be fully reconstructed. In the $\gamma\gamma$ fully hadronic mode in general the $W^+$ and the $W^-$ cannot be distinguished. This is, however, no problem since the cross section has to be symmetric in the production angle $\cos\theta$. Also for hadronically decaying Ws it is not possible in general to distinguish the quark from the antiquark. This leaves a twofold ambiguity in the decay angles. One can still separate longitudinally from transversely polarized Ws, but the two transverse states cannot be separated.

$\gamma\gamma$ and $e\gamma$ colliders allow a high degree of beam polarization. For $\gamma\gamma$ one has two distinct polarization states $J_z = 0$ and $J_z = 2$. For $e\gamma$ the electron has to be left-handed in order to couple to W-bosons. The cross section then depends on the helicity of the photon, $J_{\gamma}$.

Both processes proceed via t-channel exchange of a W and are strongly forward peaked, as can be seen from figure 2 for the $e\gamma$ case. The anomalous couplings, which are parameterized with the usual parameters $\kappa_\gamma$, $\lambda_\gamma$ [1] manifest themselves with modifications of the total and differential cross section and of the polarization structure as seen in figure 3.
2 Event Selection

The processes $\gamma\gamma \rightarrow W^+W^-$ and $e\gamma \rightarrow \nu W$ and the relevant background processes have been simulated with PYTHIA [2] using the correct $\gamma$ energy spectra. The detector has been simulated with SIMDET [3], assuming in addition that no particles below 7° are accepted. For $\gamma\gamma$ the only background is $\gamma\gamma \rightarrow q\bar{q}$. For $e\gamma$ the relevant backgrounds are $e\gamma \rightarrow eZ$ and $e\gamma \rightarrow eq\bar{q}$. The additional backgrounds to $e\gamma \rightarrow \nu W$ in the $\gamma\gamma$ mode have not yet been studied. As shown for two examples in figure 4 the backgrounds can be rejected efficiently with kinematic cuts. In $\gamma\gamma$ a signal/background ratio of 15 for $J_z = 2$ can be reached. For $J_z = 0$ it is much higher. In $e\gamma$ only some background is left at extreme polar angles that can easily be cut without a significant loss in the efficiency. The efficiency for both processes is around 90% over most of the solid angle with a drop to about 80% in the very forward region. In the forward region the Pythia efficiencies might be somewhat optimistic since the polarization structure of the Ws is not included. However in the final analysis a multi-dimensional acceptance function is used binned in the production angle and the polar decay angles of the Ws. In this way only some small effects stemming from the azimuthal decay angles are lost. The acceptance functions have been cross checked at a fixed beam energy with WHIZARD [4] that includes the full polarization structure.
Figure 3: a) Variation of the differential cross section $d\sigma(e\gamma \rightarrow \nu W)/d \cos \theta$ with the anomalous coupling $\kappa_\gamma$. b) variation of the fraction of longitudinal Ws in $e\gamma \rightarrow W\nu$ as a function of the W production angle.

3 Sensitivity Estimate

To estimate the sensitivity of the two processes to anomalous couplings helicity amplitudes for stable Ws have been used [5]. The center of mass energy has been taken to be $0.8\sqrt{s}$ for $\gamma\gamma$ and $0.9\sqrt{s}$ for $e\gamma$ which corresponds to the maximum energy for these modes. The beam polarization has been assumed to be 100%. The events have been binned in the production angle and the polar decay angle of the one or two Ws. The azimuthal decay angles, which are sensitive to the interference of the different helicity amplitudes are neglected for the moment. Using these amplitudes event rates are predicted without anomalous couplings in the different bins in the production and decay angles assuming a given luminosity. These event rates are then multiplied by the acceptance function to obtain rates of measured events which are taken as “data”. These “data” are fitted with a $\chi^2$ fit using the same helicity amplitudes multiplied by the acceptance function allowing for anomalous couplings. To allow for a possible normalization uncertainty from the luminosity and efficiency calculation, a free normalization factor has been included in the fit which has been constrained with the assumed accuracy on the normalization. The fits have been repeated with the normalization fixed to unity.
Figure 4: Acollinearity and 2-jet mass for signal (left) and background (right) in $\gamma\gamma \rightarrow W^+W^-$

Table 1 shows the results for $\sqrt{s_{ee}} = 500\text{ GeV}$, $\mathcal{L} = 110\text{ fb}^{-1}$ and $J_z = 2$ for $\gamma\gamma$ and $J_\gamma = 1$ for $e\gamma$. For the results shown, only one anomalous coupling has been left free in the fit while the other has been fixed to its Standard Model value. In a fit with both couplings left free the correlations for $e\gamma$ are small so that the errors practically don’t change. For $\gamma\gamma$ the correlations are large and the errors increase by a factor four. For the not shown polarization states the errors are up to a factor four larger than for the shown ones, where the difference increase with larger normalization uncertainty. Between $\sqrt{s_{ee}} = 500\text{ GeV}$ and $\sqrt{s_{ee}} = 800\text{ GeV}$ the sensitivity dependence on the center of mass energy is very small.

The $e\gamma$ results are given for the dedicated running mode. In the parasitic mode during $\gamma\gamma$ running, the same sensitivity can be reached for $\kappa_\gamma$ while the expected uncertainty for $\lambda_\gamma$ is a factor two larger, if the same efficiency and purity can be reached.

The sensitivity estimates don’t include yet the azimuthal decay angles which are sensitive to the interference of the helicity amplitudes. Some improvement can be expected from the inclusion of these angles. On the contrary, apart from the normalization no systematic uncertainties have been included up to now. Both studies are planned in the near future.
Table 1: Estimated sensitivity to $\kappa_\gamma$ and $\lambda_\gamma$ in $\gamma\gamma$ and $e\gamma$ with $\sqrt{s}_{ee} = 500$ GeV and $L = 110$ fb$^{-1}$.

|           | $\gamma\gamma, J_z = 2$ | $e\gamma, J_\gamma = 1$ |
|-----------|--------------------------|----------------------------|
| $\Delta \mathcal{L}$ | 1% 0.1% accurate | 1% 0.1% accurate |
| $\Delta \kappa_\gamma \cdot 10^{-4}$ | 8.5 6.7 4.2 | 34 10 5 |
| $\Delta \lambda_\gamma \cdot 10^{-4}$ | 6.3 6.0 5.0 | 16 15 15 |

4 Conclusion

According to preliminary estimates the WW$\gamma$ triple gauge couplings can be measured in $\gamma\gamma$ and $e\gamma$ collisions with an accuracy about a factor two worse than in $e^+e^-$ [6]. However the measurements in $\gamma\gamma$ and $e\gamma$ are in the spacelike region at lower scales, so that they are complementary to the $e^+e^-$ measurements, in case deviations from the Standard Model predictions are found.

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