Measurement of the $WW\gamma$ coupling in the process $e\gamma \to \nu q\bar{q}$ off the W-boson resonance

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We study the $WW\gamma$ gauge boson coupling in the process $e\gamma \to \nu q\bar{q}$ off the W-boson resonance by evaluating the helicity amplitudes of all contributing Feynman diagrams. We examine this process for 500 GeV and 1 TeV e^+e^- colliders including the photon spectra obtained from both a backscattered laser and from beamstrahlung radiation. The couplings could best be measured using the backscattered laser photons with $|\delta\kappa_\gamma| \leq 0.08$ and $-0.07 < \lambda_\gamma < 0.10$ at a 500 GeV collider and $|\lambda_\gamma| \leq 0.03$ at a 1 TeV collider, all at 95% C.L. Except for the relatively weak limits on $\delta\kappa$ at $\sqrt{s}=1$ TeV, these sensitivities are the same order of magnitude as can be obtained from real single W-production demonstrating that additional information can be obtained from non-resonant final states. [S0556-2821(99)01811-1]

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I. INTRODUCTION

Despite the fact that the standard model of the electroweak interactions [1] agrees extraordinarily well with all existing measurements [2] there is a widespread conviction that it is nothing more than a low energy limit of a more fundamental theory [3]. An approach to probe for new physics is to represent new physics by additional terms in an effective Lagrangian expansion and then to constrain the coefficients of the effective Lagrangian by precision experimental measurements [3–6]. The bounds obtained on the coefficients can then be related to possible theories of new physics. In particular, the trilinear gauge boson couplings have been described by effective Lagrangians [7–9]. In one commonly used parametrization, for on shell photons, the CP and P conserving γWW vertex is parametrized in terms of two parameters, κ_γ and λ_γ [8]. Although bounds can be extracted from high precision low energy measurements and measurements at the Z^0 pole [10], there are ambiguities and model dependencies in the results [11]. In contrast, gauge boson production at colliders can measure the gauge boson couplings directly and unambiguously. The current world average on these parameters from direct measurement of gauge boson production at the Fermilab Tevatron $p\bar{p}$ collider and the CERN e^+e^- collider LEP are $\delta\kappa_\gamma = 0.13 \pm 0.14$ and $\lambda_\gamma = -0.03 \pm 0.07$ [2]. In the future, the CERN Large Hadron Collider (LHC) [12] and the Next Linear Collider (NLC), a high energy e^+e^- collider [13], are expected to make more precise direct measurements to the percent level or better.

The idea of constructing $e\gamma$ and $\gamma\gamma$ colliders using either high energy photons from lasers backscattered from a high energy electron beam or photons arising from beamstrahlung radiation has received serious attention. The physics possibilities of $e\gamma$ colliders are the subject of a growing literature. In particular, the properties of W bosons, including the γWW coupling, has been examined in numerous publications [14,15] and the measurement of the γWW vertex via single W production is well established [16]. Our purpose here is to point out that one can obtain additional useful information in other kinematic regions, in particular by studying the cross section off the W-boson resonance in the process $e\gamma \to \nu q\bar{q}$. Our calculation includes both contributions from virtual single W boson production and its decay to final state fermions and the contributions to the final state that do not proceed via an intermediate W boson. The interference of the various diagrams provides additional information off the W resonance. In our analysis we considered the various backgrounds that may obscure results for hadronic W decay. We focus on W production at 500 GeV and 1 TeV e^+e^- colliders and compare the sensitivities achievable using a backscattered laser photon spectrum and a beamstrahlung photon spectrum.

II. THE $WW\gamma$ EFFECTIVE VERTEX

Within the standard model the $WW\gamma$ vertex is uniquely determined by $SU(2)_L \times U(1)$ gauge invariance so that a precise measurement of the vertex poses a severe test of the gauge structure of the theory. The most general $WW\gamma$ vertex, assuming CP conservation and Lorentz invariance for on shell photons and when the W bosons couple to essentially massless fermions (which effectively results in $\partial_\mu W^\mu = 0$) is commonly parametrized as [8,9]

$$\mathcal{L}_{WW\gamma} = -ie\left\{ (W^\dagger_{\mu\nu} W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu}) + \kappa_\gamma W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda_\gamma}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu F^{\nu\lambda} \right\} \quad (1)$$

where A^μ and W^μ are the photon and W^- fields, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$ and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ denote the W and

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photon field strength tensors, and M_W is the W boson mass. The vertex given by Eq. (1) is, technically, only valid for on-shell gauge bosons; the possibility of off-shell bosons would lead to additional terms in the vertex. For the purposes of this analysis, we will assume that these possible additional terms (which must be identically zero for on-shell bosons), remain much smaller than the ''leading'' terms we do consider here. A more careful analysis should include the off-shell terms. At tree level the standard model predicts $\kappa_\gamma = 1$ and $\lambda_\gamma = 0$. Other parametrizations exist in the literature such as the chiral Lagrangian expansion and one can map the parameters we use to those used in other approaches [4,5]. One expects that $\delta\kappa_\gamma \sim O(10^{-2})$ and λ_γ is suppressed by an additional factor of 100 [4]. These order of magnitude estimates are confirmed by explicit calculation. Technicolor theories give $\delta\kappa_Z = -0.023$ and $\delta\kappa_\gamma = 0$ [6] and supersymmetric theories give $\delta\kappa_{\max} \simeq 7\times 10^{-3}$ and $\lambda_{\max} \simeq 10^{-3}$ [17]. A deviation of more than several percent would therefore signal something very radical such as composite gauge bosons [18].

Deviations from the standard model ($a = \delta\kappa = \kappa - 1, \lambda$) lead to amplitudes which grow with energy and therefore violate unitarity at high energy. As one approaches the scale at which new physics becomes important additional contributions from non-standard model dynamics will, of course, prevent an actual violation of unitarity. However, it is common to introduce momentum dependence in the form factors, $a(q_W^2, \overline{q}_W^2, q_\gamma^2 = 0)$, so that the deviations vanish when either $|q_W^2|$ or $|\overline{q}_W^2|$, the absolute square of the four momentum of the vector bosons, becomes large [19]. We therefore included the form factors

$$a(q_W^2, \overline{q}_W^2, 0) = a_0[(1 + |q_W^2|/\Lambda^2)(1 + |\overline{q}_W^2|/\Lambda^2)]^{-n} \quad (2)$$

where Λ represents the scale at which new physics becomes important, which we take to be $\Lambda = 1$ TeV, and n is chosen as the minimum value compatible with unitarity, which we take to be $n = 1$. We find our results to be quite insensitive to the inclusion of the form factor for the energies and q_W^2 considered in our analysis.

III. CALCULATION AND RESULTS

The Feynman diagrams contributing to the process $e^-\gamma \to \nu f\overline{f}$ are given in Fig. 1, though the $WW\gamma$ vertex we are studying contributes only via diagram 1b. To obtain the cross sections and distributions we used the CALKUL helicity amplitude technique [20]. The helicity amplitudes corresponding to Fig. 1 are given in Ref. [15]. We treat the photon distributions as structure functions and integrate them with the $e\gamma$ cross sections to obtain our results. For our numerical results we take $\alpha(M_Z) = 1/128$, $M_W = 80.22$ GeV, $\Gamma_W = 2.0$ GeV, $\sin^2\theta_w = 0.23$.

The signal we are studying consists of two hadronic jets and large missing transverse momentum ($\not{p}_T$) due to the neutrino from the initial electron beam. We impose the kinematic cut that visible particles in the final state be at least 10° from the beam direction to account for the limited detector acceptance. Our conclusions are not sensitive to the exact value of this cut. We also impose a cut on the minimum $\not{p}_T$ to suppress backgrounds. We do not include fragmentation and hadronization effects and identify the hadron jet momenta with that of the quarks. The signal we are considering is therefore

$$e^- + \gamma \to j + j + \not{p}_T. \quad (3)$$

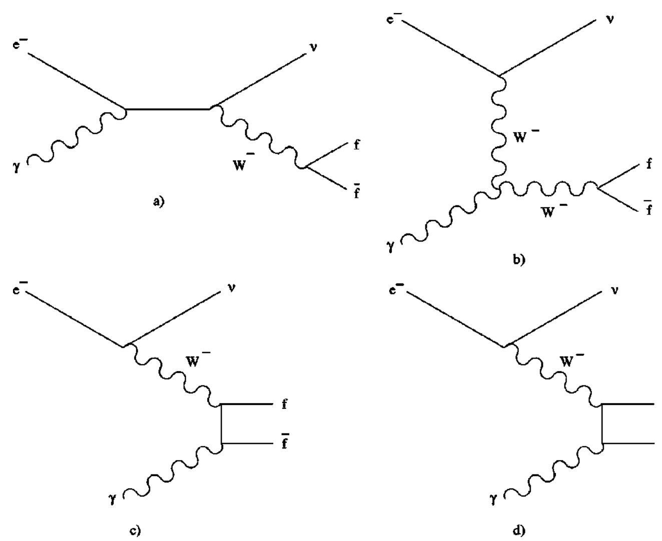

FIG. 1. The Feynman diagrams contributing to the process $e\gamma \to \nu q\overline{q}$.

A. Backgrounds

The potential backgrounds [21] to the process we are studying can be divided into 3 categories: *Direct* which are $e^-\gamma \to e^- Z^0 \to e^- q\overline{q}$ where the outgoing e^- is not observed and $e^-e^+ \to \gamma Z^0 \to \gamma q\overline{q}$ where the outgoing γ is not observed. *Once resolved* and *twice resolved* processes with parton level subprocesses such as $\hat{\sigma}(\gamma q \to qg)$ and $\hat{\sigma}(gg \to q\overline{q})$ respectively, in which the hadronic structure of the photon acts as partons in the subprocesses.

The $e^-e^+ \to Z^0\gamma$ is easily removed by imposing the constraint that the photon not be observed while at the same time there is significant missing p_T in the event. We show the jet–jet invariant mass for the signal and remaining backgrounds for the backscattered laser case with $\sqrt{s} = 500$ GeV in Fig. 2. These results include the detector acceptance cuts of $10° < \theta_{e-jet} < 170°$ and $p_T(\text{jet}) > 5$ GeV plus the cut $\not{p}_T > 10$ GeV. These remaining backgrounds can be removed by requiring large $\not{p}_T$ such that the $\not{p}_T$ is greater than the maximum possible for the unobserved electron (~ 40 GeV for $\sqrt{s} = 500$ GeV).

B. Results

We are interested in the sensitivity of the process $e\gamma \to \nu q\overline{q}$ for $\sqrt{s} = 500$ GeV and 1 TeV. In particular, we studied the effect of anomalous couplings on the cross section of the hadronic modes for $M_{q\overline{q}} > M_W$. In general, deviations of

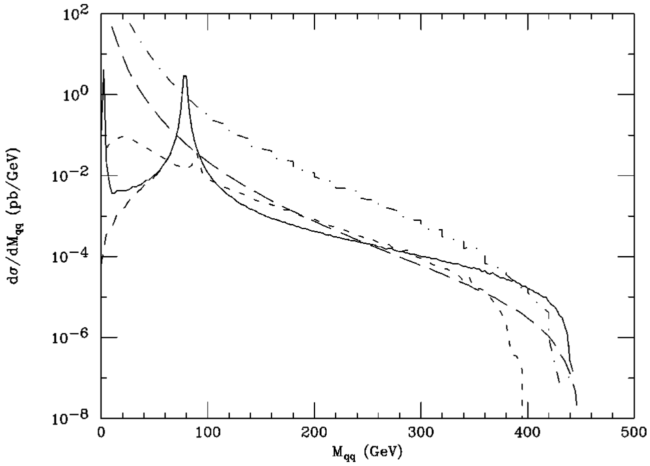

FIG. 2. Dijet invariant mass for the signal and backgrounds. The solid line is the signal, while the dashed line is the signal with the detector resolution p_T cut given in the text. The short dashed curve is the $e\gamma\to eZ$ background, the long dashed curve is the total of the singly resolved backgrounds and the dotdashed curve is the total of the doubly resolved backgrounds.

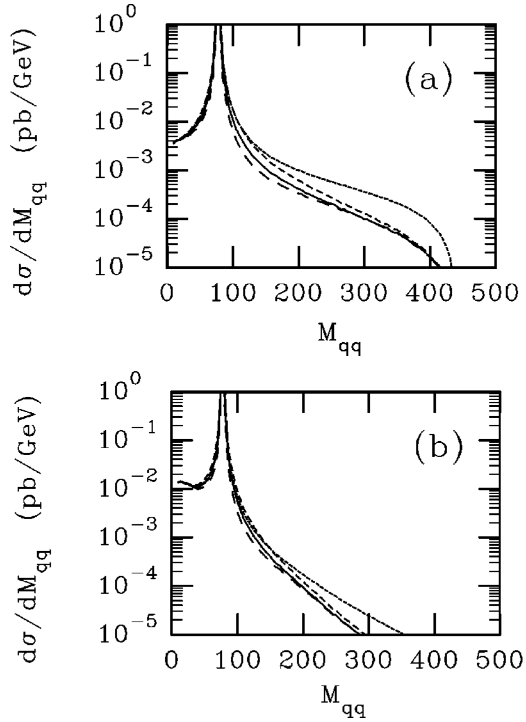

FIG. 3. The hadron jet invariant mass ($M_{q\bar{q}}$) distribution for $\sqrt{s}=500$ GeV. (a) For the backscattered laser photon spectrum and (b) for the beamstrahlung photon spectrum. In both cases the solid line is the standard model prediction, the long-dashed line is for $\kappa_\gamma=0.6$, $\lambda_\gamma=0$, the short-dashed line is for $\kappa_\gamma=1.4$, $\lambda_\gamma=0$, and the dotted line is for $\kappa_\gamma=1$, $\lambda_\gamma=0.4$.

the gauge boson couplings have a substantial effect on the cross section off the W resonance although, once the reduced cross section is taken into account, the statistical significance is not really enhanced. Nevertheless this measurement does point out that there is useful information to be obtained not just from the study of on-shell gauge boson production.

We considered two possibilities for the photon spectrum; that arising from laser backscattering from one of the electron beams and beamstrahlung, which is the radiation which arises when intense beams of electrons pass through one another. For the results using the beamstrahlung photon spectrum we concentrate on the beam spectrum resulting from the G set of parameters of Ref. [22]. The results are not sensitive to the specific choice of beam parameter set. Weizacker-Williams contributions were included in the beamstrahlung results.

The NLC is envisaged as a very high luminosity collider, with integrated luminosities for a Snowmass year (10^7 sec) expected to be ~ 60 fb^{-1} for a $\sqrt{s}=500$ GeV collider and ~ 200 fb^{-1} for a $\sqrt{s}=1$ TeV collider. The cross sections for the process $e\gamma\to W\nu\to q\bar{q}\nu$ at $\sqrt{s}=500$ GeV is 16.6 pb for the backscattered laser mode and 10.8 pb for the beamstrahlung mode, leading to $\sim 10^6$ events per year, while at $\sqrt{s}=1$ TeV the cross sections are 19 pb and 31 pb, respectively, leading to $\sim 6\times 10^6$ events/year.

We, however, are interested in the cross section off the W-resonance. The $q\bar{q}$ invariant mass distribution is plotted in Fig. 3 for $\sqrt{s}=500$ GeV. Very clearly, the cross section off the W-resonance is seen to be sensitive to anomalous couplings so that the $q\bar{q}$ invariant mass distribution above the W mass provides useful information. If, for example, we integrate the $M_{q\bar{q}}$ spectrum from 100 GeV up, we obtain a cross section of 0.25 pb for the backscattered laser mode which offers considerable statistics. For $M_{q\bar{q}}>300$ GeV, $\sigma=0.006$ pb which yields ~ 400 events/year. More importantly, this high $M_{q\bar{q}}$ region shows a higher sensitivity to anomalous couplings than the M_W pole region.

In general, the experimental errors are not limited by statistics, but rather by systematic errors. Estimating systematic errors requires detailed detector Monte Carlo studies which we do not attempt. For cross sections we assume a systematic error of 5% [23] which is combined in quadrature with statistical errors based on the integrated luminosities given above.

To quantify the measurement sensitivity of the gauge boson couplings cross sections we compare the cross section for the kinematic region defined by $M_{q\bar{q}}>M_{\rm min}$ with nonstandard vector boson couplings to the standard model expectations. As pointed out above, we eliminate backgrounds by the kinematic cut $\not{p}_T>40$ GeV, which has little effect on the signal. For $\sqrt{s}=500$ GeV we find that for $M_{q\bar{q}}>100$ GeV we obtain the 95% C.L. sensitivity of $-0.09<\delta\kappa_\gamma<0.08$ $(-0.1<\delta\kappa_\gamma<0.08)$ and $-0.1<\lambda_\gamma<0.16$ $(-0.16<\lambda_\gamma<0.24)$ for the back scattered (beamstrahlung) cases.

For $\sqrt{s}=1$ TeV we use an integrated luminosity of 200 fb^{-1}. The invariant mass distributions of the $q\bar{q}$ pair is very similar to the 500 GeV except that it extends out about a factor of two further. For $M_{q\bar{q}}>600$ GeV we obtain the 95% C.L. sensitivity of $|\lambda_\gamma|<0.03$ $(|\lambda_\gamma|<0.05)$ for the back scattered (beamstrahlung) cases. The κ_γ sensitivities are relatively weak and are therefore not given. Because of the relatively small cross section once the $M_{q\bar{q}}$ cut has been imposed statistical errors dominate, so that these results are not very sensitive to the exact value of the systematic error we assumed.

IV. CONCLUSIONS

We studied the process $e\gamma\to\nu q\bar{q}$ which proceeds via a number of processes, including an intermediate W boson, for both backscattered laser and beamstrahlung photon spectrums with NLC energies of $\sqrt{s}=500$ GeV and 1 TeV. Our purpose was to point out that at high energy, off resonance kinematic regions can provide additional information to real gauge boson production since interference effects between these other diagrams and the W production diagrams enhance the significance of anomalous couplings. For $\sqrt{s}=500$ GeV using the cross section for $M_{q\bar{q}}>M_{\min}$ we find $-0.09<\delta\kappa_\gamma<0.08$ and $-0.1<\delta\lambda_\gamma<0.16$ and for $\sqrt{s}=1$ TeV, $\delta\lambda_\gamma\simeq\pm0.03$ using the backscattered laser approach. The beamstrahlung photon spectrum results in only slightly less sensitive results. These numbers are the same order of magnitude (although slightly larger) as the sensitivities obtained from single W production which demonstrates that useful information can be obtained from the measurement of off-mass-shell W production in $e\gamma$ collisions. To be sure, measurements can be made using W-pair production at the NLC that are at least an order of magnitude better [13] but it is difficult to disentangle the $WW\gamma$ vertex from the WWZ vertex in that process, so that if deviations are observed measurements such as those described here could be important in disentangling the physics.

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