CERN-TH.5362/89
MAD/PH/486
April 1989

MEASURING THE $WW\gamma$ VERTEX IN SINGLE W PRODUCTION AT ep COLLIDERS

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ABSTRACT

A detailed analysis of single W production in ep collisions via $ep \rightarrow eW^\pm X$ is presented by using helicity amplitudes for general $WW\gamma$ couplings. Analytic expressions are given for the $\gamma q \rightarrow W^\pm q'$ helicity amplitudes which describe $ep \rightarrow eWX$ in Weizsäcker - Williams approximation and provide a semiquantitative understanding of the results obtained with the full matrix elements. Possibilities to test the gauge theory structure of the $WW\gamma$ vertex at HERA ($\sqrt{s} = 314$ GeV) and at an ep collider in the LEP tunnel ($\sqrt{s} \approx 1.4$ TeV) are explored. It is found that at HERA the $WW\gamma$ vertex can be measured with 30 - 50% accuracy after a few years of running.

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1. Introduction

One of the prime targets for experiments at future colliders is the measurement of the $WW\gamma$ and WWZ couplings. These couplings are a manifestation of the non abelian gauge symmetry upon which the standard electroweak theory (SM) is based. The observation of the vector boson self interactions is a crucial test of the theory.

A suitable process to study $WW\gamma$ and WWZ couplings is W pair production at LEP200¹⁾ ($\sqrt{s} \approx 190$ GeV). At the tree level $e^+e^- \rightarrow W^+W^-$ proceeds via s -channel photon and Z exchange, and via t -channel neutrino exchange. The interference between these graphs and in particular the gauge cancellations between them make this reaction sensitive to deviations of the three vector boson vertices from the SM. Since LEP200 will produce W pairs close to threshold, its sensitivity to anomalous $WW\gamma$ and WWZ couplings is limited because the full strength of the gauge theory cancellations can only be exploited at much higher energies. Moreover, both the WWZ and the $WW\gamma$ vertex contribute roughly equally to W pair production. Hence only a linear combination of the two will effectively be measured at LEP200, unless longitudinal or transverse beam polarization is available.²⁾

An independent measurement of the anomalous $WW\gamma$ and/or WWZ couplings from other colliders would thus be a valuable input for the analysis at LEP200. A possibility for such a measurement is offered by single W production at the ep collider HERA ($\sqrt{s} = 314$ GeV) which presently is under construction at DESY. By the time LEP200 will go into operation HERA should have accumulated data over several years.

In this paper we study the ability of future high energy ep colliders, in particular of HERA (30 GeV electrons on 820 GeV protons; $\mathcal{L} \approx 2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$) and an ep collider in the LEP tunnel, LEP-LHC, with $E_e = 60$ GeV and $E_p = 8$ TeV ($\sqrt{s} \approx 1.4$ TeV; $\mathcal{L} \approx 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$), to probe the three vector boson self interactions via single W production. Charged weak bosons can either be produced together with neutrinos or with electrons in ep collisions. Because the cross section for νW production is much smaller than the one for eW production³⁾ (about a factor 100 (25) at HERA (LEP-LHC) energies) we shall concentrate on the process $ep \rightarrow eWX$.

This process has been considered by several authors in the past³⁻⁸⁾ usually with emphasis on the anomalous magnetic moment of the W as a non gauge theory contribution. In this paper we go a step further and parametrize the most general $WW\gamma$ vertex which is accessible in $ep \rightarrow eW^\pm X$ (Section 2). Since the dominant contributions arise from γ -exchange graphs, $ep \rightarrow eWX$ is quite insensitive to anomalous WWZ couplings. Apart

from anomalous contributions to the $WW\gamma$ vertex we assume the SM to be valid. In particular we assume the coupling of W - and Z -bosons to quarks and leptons to be given by the SM.

Our analysis of the process $ep \rightarrow eW^\pm X$ is based on the calculation of helicity amplitudes for the complete process

$$eq \rightarrow eW^\pm q', \quad W^\pm \rightarrow \ell^\pm \nu \quad (1.1)$$

with $\ell = e, \mu$. A semiquantitative understanding of the results obtained with these amplitudes is provided by the matrix elements for the subprocess $\gamma q \rightarrow W^\pm q'$ which describes the reaction $ep \rightarrow eW^\pm X$ in Weizsäcker - Williams approximation. Analytic expressions for these matrix elements are presented in Section 3. In Section 4 we discuss the signatures for anomalous $WW\gamma$ couplings at HERA and LEP-LHC. In order to obtain realistic results, cuts which simulate the finite acceptance of detectors are imposed on the final state fermions. Already at present, severe constraints on anomalous contributions to the $WW\gamma$ vertex exist, either derived from low energy experiments,⁹⁻¹⁴⁾ or from unitarity considerations.^{10,15)} To avoid confusion we shall first discuss the expected signals in $ep \rightarrow eW^\pm X$ without taking into account the low energy bounds. In Section 5 we then compare the sensitivity to anomalous couplings, expected at HERA and LEP-LHC, with the low energy bounds and with the sensitivity which is expected from $e^+e^- \rightarrow W^+W^-$ at LEP200 and $W^\pm\gamma$ production at the Tevatron. In Section 5 we also give our conclusions.

2. Three Vector Boson Couplings

At the parton level the reaction $ep \rightarrow eWX$ proceeds via the Feynman graphs shown in Fig. 1a-1e. The three vector boson vertex that we are interested in enters via diagram 1c. The dominant contributions arise from the photon exchange graphs in Fig. 1a-1c due to the t -channel pole induced by the photon propagator. The Z -exchange diagrams in Fig. 1a-1c are strongly suppressed by the large mass of the Z -boson. Hence, $ep \rightarrow eWX$ is quite insensitive to anomalous WWZ couplings, and subsequently we shall only consider anomalous contributions to the $WW\gamma$ vertex. In the process (1.1) both the virtual W and the decaying onshell W couple to essentially massless fermions, which ensures that effectively $\partial_\mu W^\mu = 0$. This restricts the tensor structure of the WW photon vertex to allow

for seven free parameters, which are conveniently described by the effective Lagrangian^{1,16)}

$$\begin{aligned}
\mathcal{L}_{WW\gamma} = & -ie \left\{ g_1 (W_{\mu\nu}^\dagger W^\mu A^\nu - W_\mu^\dagger A_\nu W^{\mu\nu}) + \kappa W_\mu^\dagger W_\nu F^{\mu\nu} \right. \\
& + \frac{\lambda}{M_W^2} W_{\lambda\mu}^\dagger W^\mu{}_\nu F^{\nu\lambda} + ig_4 W_\mu^\dagger W_\nu (\partial^\mu A^\nu + \partial^\nu A^\mu) \\
& - ig_5 \epsilon^{\mu\nu\rho\sigma} (W_\mu^\dagger \tilde{\partial}_\rho W_\nu) A_\sigma + \tilde{\kappa} W_\mu^\dagger W_\nu \tilde{F}^{\mu\nu} \\
& \left. + \frac{\tilde{\lambda}}{M_W^2} W_{\lambda\mu}^\dagger W^\mu{}_\nu \tilde{F}^{\nu\lambda} \right\} .
\end{aligned} \tag{2.1}$$

Here W_μ denotes the W^- field, A_ν is the photon field, $W^{\mu\nu} = \partial^\mu W^\nu - \partial^\nu W^\mu$, $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$, $C\tilde{\partial}_\rho D \equiv C(\partial_\rho D) - (\partial_\rho C)D$, and $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\sigma\rho}F_{\sigma\rho}$. e is the charge of the proton and M_W represents the W -boson mass. In Eq. (2.1) g_4 violates CP and C , g_5 violates C and P but is CP even, while $\tilde{\kappa}$ and $\tilde{\lambda}$ are P odd and CP violating. Within the SM they all vanish at tree level and so does λ . The only nonzero couplings within the SM are

$$\begin{aligned}
g_1 &= 1 , \\
\kappa &= 1 .
\end{aligned} \tag{2.2}$$

The $\kappa(\tilde{\kappa})$ and $\lambda(\tilde{\lambda})$ terms are related to the magnetic (electric) dipole moment $\mu_W(d_W)$ and the electric (magnetic) quadrupole moment $Q_W(\tilde{Q}_W)$ of the W^+

$$\mu_W = \frac{e}{2M_W} (1 + \kappa + \lambda) , \tag{2.3a}$$

$$Q_W = -\frac{e}{M_W^2} (\kappa - \lambda) , \tag{2.3b}$$

$$d_W = \frac{e}{2M_W} (\tilde{\kappa} + \tilde{\lambda}) , \tag{2.3c}$$

$$\tilde{Q}_W = -\frac{e}{M_W^2} (\tilde{\kappa} - \tilde{\lambda}) . \tag{2.3d}$$

It is well known that tree level unitarity, *e.g.* for the process $e^+e^- \rightarrow W^+W^-$, uniquely restricts the $WW\gamma$ couplings to their (SM) gauge theory values at asymptotically high energies¹⁷⁾. This implies that any deviation $a = g_1 - 1, \dots, \tilde{\lambda}$ from the SM expectation has to be described by a form factor $a(q^2, \bar{q}^2, q_\gamma^2)$ which vanishes when one of the arguments, the square of the four momentum of one the W -bosons, q^2 or $\bar{q}^2$, or the square of the four momentum of the photon, q_γ^2 , becomes large. Electromagnetic gauge invariance puts an

additional constraint on $g_1 - 1$, g_4 and g_5 : for onshell photons these anomalous couplings are forbidden and the corresponding form factors must hence be proportional to some positive power of q_γ^2 . $g_1 - 1$, g_4 and g_5 are therefore all of $O(q_\gamma^2/\Lambda^2)$, where Λ represents the scale at which new physics becomes important in the weak boson sector, *e.g.* due to a composite structure of the W boson. Present experimental data suggest that Λ is at least of the order of a few hundred GeV.¹⁸⁾ Computing the cross section for $ep \rightarrow eWX$ one integrates over $t = q_\gamma^2$. Due to the $1/t$ pole induced by the photon propagator, the dominant part of the cross section arises from very small $|t|$ -values and $g_1 - 1$, g_4 and g_5 effectively vanish.

As a result, single W production in ep collisions only probes the anomalous $WW\gamma$ couplings κ , λ , $\tilde{\kappa}$ and $\tilde{\lambda}$. Since the energy region covered by HERA and LEP-LHC is smaller than what is typically expected for Λ we may assume the form factors $a = \kappa - 1, \dots, \tilde{\lambda}$ to be approximately constant in the following.

3. Helicity Amplitudes

The effective Lagrangian (2.1) with $g_1 = 1$, $g_4 = g_5 = 0$ leads to cross section formulas for the W production and decay process (1.1), including the effect of anomalous $WW\gamma$ couplings. When the decay of the W into a massless fermion antifermion pair $f\bar{f}'$ and a finite width W -propagator are taken into account, all the Feynman graphs of Fig. 1 have to be included in the calculation in order to preserve electromagnetic gauge invariance. In particular the contributions from diagrams 1f and 1g are needed for off-shell W 's. For our numerical simulations we have calculated these complete matrix elements for the process (1.1) by making use of the helicity techniques described in Ref. 19.

For our later phenomenological discussion it is useful to derive approximate forms of the $ep \rightarrow eWX$ production amplitudes. This is achieved by using the Weizsäcker - Williams approximation²⁰⁾ (WWA), for the quasireal incoming photons in Fig. 1 and by neglecting the W decay. The WWA is found to be accurate at the 20% level in our case. Hence the cross section for the real photon process $\gamma q \rightarrow W^\pm q'$, including the anomalous couplings discussed before, allows for a good understanding of the salient features of W production in ep collisions.

The calculation of the $\gamma q \rightarrow Wq'$ helicity amplitudes is straightforward. Only three diagrams contribute, which are shown in Fig. 2. Neglecting the mass of the quarks, their helicity is fixed to be $-\frac{1}{2}$ by the $V - A$ structure of the $Wq\bar{q}$ coupling. This means that the

$\gamma q \rightarrow W^\pm q'$ amplitudes only depend on the photon and W helicities λ_γ and λ_W . Denoting the helicity amplitudes by $\mathcal{M}_{\lambda_\gamma \lambda_W}$ one can write

$$\mathcal{M}_{\lambda_\gamma \lambda_W} = \frac{e^2}{\sqrt{2} \sin \theta_W} \frac{\hat{s}}{\hat{s} + M_W^2} \sqrt{\beta} \mathcal{A}_{\lambda_\gamma \lambda_W}, \quad (3.1)$$

where

$$\beta = 1 - \frac{M_W^2}{\hat{s}}, \quad (3.2)$$

θ_W is the Weinberg angle and $\hat{s}$ denotes the square of the γq invariant mass. From Eq. (2.1) with $g_1 = 1$, $g_4 = g_5 = 0$ we find the reduced amplitudes $\mathcal{A}_{\lambda_\gamma \lambda_W}$ in the γq center of mass frame to be

$$\begin{aligned} \mathcal{A}_{--} &= \mp 2 \left[-\frac{2M_W^2}{\hat{s}} + 1 + \kappa - i\tilde{\kappa} + (\lambda - i\tilde{\lambda}) \frac{1 - \cos \Theta}{2} \right] \frac{1}{1 - \beta_W \cos \Theta} \cos \frac{\Theta}{2} \\ &\quad + 2(e_q \mp 1) \left(1 + \frac{M_W^2}{\hat{s}} \right) \frac{2}{1 + \cos \Theta} \cos \frac{\Theta}{2}, \\ \mathcal{A}_{-+} &= \pm \frac{\hat{s}}{M_W^2} (\lambda - i\tilde{\lambda}) \frac{1 - \cos \Theta}{1 - \beta_W \cos \Theta} \cos \frac{\Theta}{2}, \\ \mathcal{A}_{-0} &= \pm \sqrt{2} \frac{\sqrt{\hat{s}}}{M_W} \left[\kappa - 1 - i\tilde{\kappa} - (\lambda - i\tilde{\lambda}) \cos \Theta \right] \frac{1}{1 - \beta_W \cos \Theta} \sin \frac{\Theta}{2}, \\ \mathcal{A}_{+-} &= \mp \left[\frac{2M_W^2}{\hat{s}} + \kappa - 1 + i\tilde{\kappa} - (\lambda + i\tilde{\lambda}) \frac{\hat{s} - M_W^2}{M_W^2} \right] \frac{1 - \cos \Theta}{1 - \beta_W \cos \Theta} \cos \frac{\Theta}{2} \\ &\quad + (e_q \mp 1) \frac{2}{\beta_W} \frac{M_W^2}{\hat{s}} \frac{1 - \cos \Theta}{1 + \cos \Theta} \cos \frac{\Theta}{2}, \\ \mathcal{A}_{++} &= \mp \left[1 + \kappa + i\tilde{\kappa} \right] \frac{1 + \cos \Theta}{1 - \beta_W \cos \Theta} \cos \frac{\Theta}{2} + (e_q \mp 1) \frac{2}{\beta_W} \cos \frac{\Theta}{2}, \\ \mathcal{A}_{+0} &= \mp \frac{1}{\sqrt{2}} \frac{M_W}{\sqrt{\hat{s}}} \left[4 + \left(1 + \frac{\hat{s}}{M_W^2} \right) \left\{ \kappa - 1 + i\tilde{\kappa} - (\lambda + i\tilde{\lambda}) \beta_W \right\} \right] \frac{1 + \cos \Theta}{1 - \beta_W \cos \Theta} \sin \frac{\Theta}{2} \\ &\quad + \sqrt{2} (e_q \mp 1) \frac{2}{\beta_W} \frac{M_W}{\sqrt{\hat{s}}} \sin \frac{\Theta}{2}, \end{aligned} \quad (3.3)$$

where

$$\beta_W = \frac{\hat{s} - M_W^2}{\hat{s} + M_W^2} \quad (3.4)$$

and e_q is the charge of the incoming quark q in units of e . Θ denotes the scattering angle of the W with respect to the incoming photon direction.

From Eqs. (3.1) and (3.3) we observe that, in the SM,

$$\mathcal{M}_{-+} = \mathcal{M}_{-0} = 0 . \quad (3.5)$$

In the high energy limit the remaining four amplitudes behave like

$$\begin{aligned} \mathcal{M}_{--} &\sim \text{const.} , \\ \mathcal{M}_{+-} &\sim \frac{M_W^2}{\hat{s}} , \\ \mathcal{M}_{++} &\sim \text{const.} , \\ \mathcal{M}_{+0} &\sim \frac{M_W}{\sqrt{\hat{s}}} . \end{aligned} \quad (3.6)$$

Thus, only $\mathcal{M}_{--}$ and $\mathcal{M}_{++}$ survive for $\hat{s} \gg M_W^2$ and finite scattering angles, and the final state W is predominantly transverse. However, $\mathcal{M}_{--}$ and $\mathcal{M}_{++}$ do not contribute to the cross section equally in this limit. The $(\lambda_\gamma, \lambda_W) = (--)$ amplitude dominates because the u -channel fermion propagator (see Fig. 2b) produces a singularity at $\cos \Theta = -1$. $\mathcal{M}_{++}$, on the other hand, vanishes at $\Theta = \pi$. These characteristics can be seen in Fig. 3a where the $\gamma d \rightarrow W^- u$ cross section

$$\frac{d\hat{\sigma}(\lambda_\gamma, \lambda_W)}{d \cos \Theta} = \frac{\beta}{64\pi\hat{s}} |\mathcal{M}_{\lambda_\gamma \lambda_W}|^2 \quad (3.7)$$

for each helicity state at $\sqrt{\hat{s}} = 300$ GeV is shown.

At threshold the situation is quite different. Here the amplitudes behave like

$$\begin{aligned} \mathcal{M}_{--} &\sim \beta^{1/2} , \\ \mathcal{M}_{+-} &\sim \beta^{-1/2} , \\ \mathcal{M}_{++} &\sim \beta^{-1/2} , \\ \mathcal{M}_{+0} &\sim \beta^{-1/2} , \end{aligned} \quad (3.8)$$

and $\mathcal{M}_{--}$ is suppressed compared with the $\lambda_\gamma = +1$ amplitudes which contribute about equally to the cross section. This is illustrated in Fig. 3b where $d\hat{\sigma}(\lambda_\gamma, \lambda_W)/d \cos \Theta$ is plotted for $\sqrt{\hat{s}} = 100$ GeV.

While the SM contribution to the $\gamma q \rightarrow Wq'$ scattering amplitudes is bounded from above for fixed scattering angle Θ (see Eq. (3.6)), the anomalous contributions in (3.3) rise without limit as $\hat{s}$ increases, eventually violating unitarity. This is the reason, of course, why the anomalous couplings have to show a form factor behaviour at very high energies. Anomalous values of λ or $\tilde{\lambda}$ are enhanced by $\hat{s}/M_W^2$ in the amplitudes $\mathcal{M}_{\pm\mp}$, whereas terms containing κ and $\tilde{\kappa}$ mainly contribute to $\mathcal{M}_{\pm 0}$ and grow only with $\sqrt{\hat{s}}/M_W$. Terms in (3.3) containing λ and $\tilde{\lambda}$ (κ and $\tilde{\kappa}$) differ only by a factor $\pm i$. The CP violating couplings $\tilde{\kappa}$ and $\tilde{\lambda}$ contribute imaginary parts to the helicity amplitudes. Because the SM amplitudes are real, all interference effects between the SM and the $\tilde{\kappa}$ and $\tilde{\lambda}$ terms vanish identically. This is also true for the full $ep \rightarrow eWX$, $W \rightarrow e\nu, \mu\nu$ amplitudes.

4. Signals for Anomalous $WW\gamma$ Couplings

The signal we are investigating consists of a jet produced by the quark struck inside the proton, an onshell W , and possibly the original beam electron. Since the dominant contributions to the cross section arise from the exchange of an almost real photon, the scattered electron will in general be lost in the beam pipe. The W may either decay leptonically or hadronically. The hadronic decay modes of the W will be difficult to observe at HERA and LEP-LHC due to the QCD two- and three-jet background.²¹⁾ By considering leptonic W decay modes only, about 20% of all W decays are still observable (we neglect the decay $W \rightarrow \tau\nu$ in the following). We include the leptonic branching fraction

$$B = \text{Br}(W \rightarrow e\nu, \mu\nu) = 0.182 \quad (4.1)$$

in all subsequent figures. This corresponds to a top quark mass of $m_t = 45$ GeV, which is around the present lower limit on m_t .²²⁾ For larger values of m_t B increases and reaches its upper limit of $B = 0.217$ for $m_t > M_W$. Hence, our results for the $ep \rightarrow eWX$ cross sections will be conservative.

The signal we are considering thus is

$$e^-p \rightarrow \ell^\pm + \text{jet} + \cancel{p}_T (+e^-) \quad (4.2)$$

with $\ell^\pm = e^\pm, \mu^\pm$. If the scattered electron is observed, the missing transverse momentum, $\cancel{p}_T$, is due to the neutrino associated with $\ell^\pm$ in the W decay. The p_T spectra of the neutrino and of the $\ell^\pm$ show the familiar Jacobian peak at $p_T \approx \frac{1}{2}M_W \approx 40$ GeV, smeared

by the W 's transverse momentum $p_{TW} \approx p_{Tj}$. If the electron is lost in the beam pipe, it will on the average contribute a mere $O(1 \text{ GeV})$ or less to the $\cancel{p}_T$, which is of the same order or smaller than the error on the p_T measurement of the balancing jet-charged lepton system. Hence the $\cancel{p}_T$ which is observed is almost identical to the p_T of the neutrino even when the scattered electron is lost in the beam pipe. This is important in order to be able to reconstruct the four momentum of the W .

In the following we identify a quark with a jet of the same direction. Energy mis-measurements in the detector are taken into account by gaussian smearing of the quark four momentum with $\sigma = 0.35\sqrt{E_{quark}}$ and of the charged lepton four momenta with $\sigma = 0.15\sqrt{E_{lepton}}$, corresponding to the resolution of the ZEUS detector at HERA.²³⁾ Finite detector acceptance is simulated by requiring the $\ell^\pm$ and jet pseudorapidities to be $|\eta_{\ell,j}| < 3.5$ which corresponds to scattering angles between about 4° and 176° . Furthermore we require a missing transverse momentum $\cancel{p}_T > 10 \text{ GeV}$ and a transverse momentum for the $\ell^\pm$ and the jet of $p_{T\ell^\pm}, p_{Tj} > 5 \text{ GeV}$ at HERA and $p_{T\ell^\pm}, p_{Tj} > 10 \text{ GeV}$ at LEP-LHC. Finally, we demand the charged lepton and the jet to be well separated in the pseudorapidity-azimuthal angle plane by imposing

$$\Delta R_{\ell j} = \left[(\Delta\phi_{\ell j})^2 + (\Delta\eta_{\ell j})^2 \right]^{1/2} > 0.5 . \quad (4.3)$$

The effects of the cuts on the cross section for $ep \rightarrow eW^\pm X$ at HERA and LEP-LHC are summarized in Table 1. The most severe cut obviously is the p_{Tj} cut and we will discuss below to which extent it limits the measurement of the $WW\gamma$ couplings. In fact, without a finite p_{Tj} cut the cross section for $ep \rightarrow eWX$ in the WWA would diverge logarithmically, due to the u -channel singularity in the $\gamma q \rightarrow Wq'$ amplitudes $\mathcal{M}_{\pm-}$ (see Eq. (3.3)). In the matrix elements for the complete process (1.1) this singularity is regulated by the non-zero value of q_γ^2 , which is bounded by the nonzero value of the electron mass. However, relying on this regularization of the u -channel pole is questionable, because momenta much smaller than the QCD scale Λ_{QCD} will be integrated over in the small p_{Tj} region, and QCD corrections are expected to be large. Hence the ‘no cuts’ row of Table 1, which was derived using this calculational procedure, should only be taken as a rough estimate of the total W production rate.

Among the other cuts the pseudorapidity cut reduces the rate significantly only at LEP-LHC whereas the $\cancel{p}_T$ and $p_{T\ell}$ cuts almost have no effect. This happens because the corresponding distributions show the familiar Jacobian peak at $p_T \approx \frac{1}{2}M_W$. Also the

isolation requirement for the charged lepton is almost always fulfilled because the parent W and the jet are back to back in the transverse plane.

The SM parameters used in Table 1 and all subsequent calculations are $\alpha = \alpha(m_e) = 1/137$ (m_e is the electron mass), $M_Z = 93$ GeV, $M_W = 82$ GeV and $\sin^2 \theta_W = 0.23$. For the parton distribution functions we use set 1 of Duke and Owens²⁴⁾ with the scale Q^2 given by the four-momentum transfer to the scattered quark, $Q^2 = -(p_q - p_{q'})^2$, where p_q ($p_{q'}$) is the four momentum of the initial (final) state quark. Within our cuts the constraint $Q^2 > 4$ GeV² is automatically fulfilled and the structure functions of Ref. 24 can be applied without imposing additional restrictions.

Since the charged lepton ℓ and the jet are in general well separated, backgrounds from heavy quark (c, b) semileptonic decays are expected to pose no problem. For $\ell = \mu^\pm$ and e^+ (in case of e^-p collisions) the signal of Eq. (4.2) should thus be virtually background free. For $\ell = e^-$ neutral current deep inelastic scattering (DIS) events are a potential source of background, when allowing for mismeasurements leading to missing p_T above our cut of 10 GeV. However, the x and Q^2 values calculated from the electron and the observed jet will in general not agree thus eliminating a DIS hypothesis. Since the neutral current events only affect 25% of the signal we have not pursued the analysis of the DIS background in detail.

From Table 1 we observe that, after cuts, the expected event rates at HERA are rather small. For an integrated luminosity of 10^3 pb⁻¹, which corresponds to five years of running at the nominal luminosity of 200 pb⁻¹/year, HERA will provide about 90 clean $W^\pm j$ events. At LEP-LHC on the other hand one year of operation with the projected luminosity of $\mathcal{L} \approx 10^{32}$ cm⁻² s⁻¹ will yield about 1600 Wj events.

At HERA most of the W 's will be produced close to threshold because of the rapidly decreasing quark luminosity inside the proton. This is evident from Fig. 4 where the normalized distribution $(1/\sigma) \cdot (d\sigma/d\sqrt{\hat{s}})$ of the Wj invariant mass $\sqrt{\hat{s}}$ is plotted: at HERA energies almost all of the cross section is concentrated in the threshold region while the $\sqrt{\hat{s}}$ spectrum is much broader for LEP-LHC. Thus the higher energies of LEP-LHC are needed to probe the high energy behaviour of the process $\gamma q \rightarrow Wq'$.

The dominant contribution to $ep \rightarrow eWX$ arises from the graph in Fig. 1a, which at the level of the $\gamma q \rightarrow Wq'$ subprocess is a u -channel quark exchange. The associated u -channel pole leads to a singularity in the $(--)$ and $(+-)$ amplitudes for $\cos \Theta = -1$ (see Eq. (3.3)) where Θ is the W scattering angle in the Wj center of mass frame. Thus a strong peaking of the cross section at small p_{Tj} values results. Since the $WW\gamma$ vertex does

not enter this diagram, the signal at low p_{Tj} is insensitive to anomalous $WW\gamma$ couplings and no sensitivity is lost by requiring $p_{Tj} > 5$ GeV (10 GeV) so that the jet is actually observed in the detector. As far as a measurement of the $WW\gamma$ vertex is concerned, the only use of the low p_{Tj} data is to provide a check on the normalization of the W production cross section (see below).

The p_{Tj} spectrum $B \cdot d\sigma/dp_{Tj}$ above 5 GeV (10 GeV) is shown in Fig. 5 for the SM (solid line) and anomalous values of κ and λ . It is obvious that the transverse momentum distribution of the jet is quite sensitive to anomalous $WW\gamma$ couplings. At large p_T it directly reflects the different high energy behaviour of the various anomalous contributions to the $\gamma q \rightarrow Wq'$ amplitudes in Eq. (3.3). Since terms proportional to λ grow much faster ($\sim \hat{s}/M_W^2$) than κ terms ($\sim \sqrt{\hat{s}}/M_W$) for $\hat{s} \gg M_W^2$, the p_{Tj} spectrum for anomalous values of λ is much harder than the one for a non-standard κ .

$B \cdot d\sigma/dp_{Tj}$ depends quadratically on the deviation $a = \kappa - 1, \dots, \tilde{\lambda}$ from the SM:

$$B \cdot \frac{d\sigma}{dp_{Tj}} = \left(B \cdot \frac{d\sigma}{dp_{Tj}} \right)_{SM} + a \cdot \left(B \cdot \frac{d\sigma}{dp_{Tj}} \right)_{Int} + a^2 \cdot \left(B \cdot \frac{d\sigma}{dp_{Tj}} \right)_{An}. \quad (4.4)$$

For $\tilde{\kappa}$ and $\tilde{\lambda}$ the interference term $(B \cdot d\sigma/dp_{Tj})_{Int}$ vanishes because the CP violating couplings contribute imaginary parts to the amplitude whereas the SM part is real. At HERA as well as at LEP-LHC energies the sensitivity to anomalous couplings in $ep \rightarrow eWX$ effectively stems from regions in phase space where the anomalous contributions to the cross section are considerably smaller than the SM expectation. As a result one expects that, for κ and λ , interference effects between the SM amplitude and the anomalous contributions to the amplitude dominate over the squared non-standard terms, *i.e.* $(B \cdot d\sigma/dp_{Tj})_{Int} \gg (B \cdot d\sigma/dp_{Tj})_{An}$. Indeed this effect is clearly visible in Fig. 5 for anomalous values of κ . The cross section for $\kappa = 2$ is always considerably bigger than for $\kappa = 0$. For $p_{Tj} \lesssim 100$ GeV the $\kappa = 0$ rate is even smaller than the SM cross section. This is reversed only at large p_{Tj} where the $\sqrt{\hat{s}}$ values are large enough so that the growth of the longitudinal W amplitudes with $\sqrt{\hat{s}}/M_W$ (see Eq. (3.3)) becomes noticeable and the $\kappa = 0$ cross section exceeds the SM result.

In contrast to the situation for κ and to the naive expectation, interference effects play only a minor role for anomalous values of λ (see Fig. 5a). This can be easily understood from the $\gamma q \rightarrow Wq'$ amplitudes. Computing the interference terms of the SM and the λ contributions to the amplitudes in Eq. (3.3), one finds that they vanish after the sum over

the photon and W polarizations has been taken. Thus

$$\left(B \cdot \frac{d\sigma}{dp_{Tj}} \right)_{Int} = 0 \quad \text{for} \quad a = \lambda \quad (4.5)$$

in the WWA. The small interference effect visible in Fig. 5a originates from the diagrams in Fig. 1 which in the complete tree level calculation for $ep \rightarrow eW^\pm X$, $W^\pm \rightarrow \ell^\pm \nu$ contribute in addition to the ones relevant in the WWA (see Fig. 2).

As we shall see in the next Section, existing low energy bounds limit $|\tilde{\kappa}|$ to be less than $O(10^{-3})$ and no visible effects of $\tilde{\kappa}$ are possible in $ep \rightarrow eWX$ at either HERA or LEP-LHC. Because the contributions to the $\gamma q \rightarrow Wq'$ helicity amplitudes containing λ and $\tilde{\lambda}$ differ only by a factor $\pm i$ and $\tilde{\lambda}$ terms do not interfere with the SM amplitudes, cross sections for the same values of λ and $\tilde{\lambda}$ are almost identical. Results for anomalous $\tilde{\kappa}$ and $\tilde{\lambda}$ values are therefore not included in Fig. 5 and all subsequent figures.

Since the interference effects for λ are very small, a rather large anomalous coupling is necessary in order to produce a measurable effect in $ep \rightarrow eWX$ at HERA. This is apparent in Fig. 6a where the integrated cross section $B \cdot \sigma$ above a minimum transverse momentum cutoff p_{Tmin} for the jet is shown for HERA. For $p_{Tmin} = 5$ GeV, for example, the cross section increases by $\approx 63\%$ for $\Delta\kappa = \kappa - 1 = +1$ whereas $\lambda = +2$ only leads to an increase of $\approx 33\%$. Consequently κ can be measured at HERA much more precisely than λ . In the helicity amplitudes the terms proportional to λ rise quite fast with increasing $\sqrt{s}$. Hence the chances for obtaining a stringent limit on λ will be considerably better at LEP-LHC where much higher $\sqrt{s}$ values are available than at HERA (compare Fig. 4). This is clearly demonstrated in Fig. 6b where $B \cdot \sigma$ versus p_{Tmin} is shown for the proposed ep collider in the LEP tunnel. For $p_{Tmin} = 10$ GeV a value of $\lambda = 0.5$ results in almost the same deviation from the SM prediction as $\lambda = 2$ at HERA.

These qualitative statements can be quantified by deriving those values of κ , λ and $\tilde{\lambda}$ which would give rise to a deviation from the SM at the 90% (69%) confidence level (CL) in the p_{Tj} spectrum for an integrated luminosity of $\int \mathcal{L} dt = 10^3 \text{ pb}^{-1}$, calculated within our cuts. $\tilde{\kappa}$ is omitted since, as already mentioned, low energy data constrain this quantity to be less than $O(10^{-3})$. The confidence level is calculated by splitting the p_{Tj} distribution into 8 (7) bins at HERA (LEP-LHC) with, typically, more than 5 events. In each bin the Poisson statistics is approximated by a gaussian distribution. In order to achieve a sizable counting rate in each bin, all events with $p_{Tj} > 40$ GeV (250 GeV) are collected into a single bin at HERA (LEP-LHC). This procedure guarantees that in our calculation a high

confidence level cannot arise from a single event at high p_T where the SM predicts, say, only 0.01 events.

An important point in such an analysis is the normalization uncertainty $\Delta\mathcal{N}$ of the W production cross section predicted within the SM. For the purpose of minimizing this error experimentally, W events in which the accompanying jet cannot be resolved will still be useful, since their rate is determined by the well measured $Wf\bar{f}$ coupling alone. However, in the low p_{Tj} region, close to the u -channel fermion exchange pole, QCD corrections are expected to be large and W production can be thought of as $q\bar{q} \rightarrow W$ where one of the quarks is regarded as a constituent of the photon. Thus contact is made with parton structure functions inside the photon and a careful merging of the two pictures is required. Knowledge of the next order QCD corrections would also help to fix the value of Q^2 which should be used to evaluate the structure functions. As is well known the choice of Q^2 is ambiguous in lowest order perturbation theory. Q^2 values different from our choice of $Q^2 = -(p_q - p_{q'})^2$ may easily result in rates which are $O(10\%)$ larger (*e.g.* for $Q^2 = p_{Tj}^2$) or smaller (*e.g.* for $Q^2 = \hat{s}$) than our results. Modulo these uncertainties W events where the jet cannot be resolved will provide an important check on the normalization of the W production rate within the SM.

An additional uncertainty is introduced in the SM cross section by the present limited knowledge of the structure functions in the large Feynman- x region in which most of the W 's at HERA are produced. Of course, this situation will improve once HERA is operating, and by the time enough W 's have been collected so that the p_{Tj} spectrum can be analyzed, the structure functions at large Feynman- x should be accurately known.

The resulting minimal anomalous couplings, which would give rise to a 90% or 69% CL effect are given in Table 2 for HERA and LEP-LHC. Only one coupling at a time is assumed to be different from the SM value. The sensitivity bounds are given for two choices of the SM normalization uncertainty, $\Delta\mathcal{N} = 30\%$ and a somewhat more optimistic value of $\Delta\mathcal{N} = 10\%$. These two values were chosen in order to display the effect that $\Delta\mathcal{N}$ has on the limits that can be achieved. For anomalous values of κ the bounds depend indeed significantly on $\Delta\mathcal{N}$, while this is not the case for λ and $\tilde{\lambda}$. This is a reflection of the powers of $\sqrt{\hat{s}}/M_W$ multiplying the various anomalous contributions to the amplitudes (3.3). Since terms proportional to $\Delta\kappa$ do not grow as fast as λ terms, deviations from the SM cross section arising from $\Delta\kappa$ do not dramatically change the shape of the transverse momentum spectrum of the jet and can more easily be misinterpreted as a normalization error than is the case for λ and $\tilde{\lambda}$. This also is apparent from Fig. 5. The values of Table 2 clearly demonstrate the need of minimizing the normalization error of the SM rate and thus the

need of a calculation of the QCD corrections to $ep \rightarrow eWX$, in order to be able to derive stringent limits on κ .

Table 2 shows that HERA can measure κ with 30-50% accuracy with an integrated luminosity of 10^3 pb^{-1} if the normalization of the SM rate is known to better than 10%. These errors become larger by roughly a factor of 2 for an integrated luminosity of 200 pb^{-1} . $|\lambda|$ and $|\tilde{\lambda}|$, on the other hand, can only be constrained to be less than 0.9-1.3, due to the small (vanishing) interference effects for λ ($\tilde{\lambda}$). The absence of interference effects is also responsible for the insensitivity of the λ and $\tilde{\lambda}$ bounds to the sign of the anomalous coupling. The limits which could be achieved with LEP-LHC are of course much better. For κ they roughly improve by a factor 2, and for λ and $\tilde{\lambda}$ by about a factor 10.

So far we have concentrated on ep collisions with unpolarized beams and on the p_T spectrum of the jet in WjX production. At HERA, and hopefully also at LEP-LHC, longitudinal polarization of the electron beam will be possible. If a substantial degree of polarization P_e can be achieved and Wj invariant masses much larger than M_W are accessible, one may study quantities which directly reflect those helicity amplitudes which survive in the high energy limit. As the best example we shall consider now the angular distribution $B \cdot d\sigma/d\cos\bar{\theta}$ of the charged lepton arising from the W decay. Here $\bar{\theta}$ is the $\ell^\pm$ polar angle in the W rest frame with respect to the W direction in the Wj rest frame.

In the WWA the probability that a photon with helicity λ_γ is emitted from an electron with helicity $\sigma_e/2$ is given by²⁵⁾

$$P_{\gamma/e}^{(\lambda_\gamma, \sigma_e)}(x) = \frac{\alpha}{2\pi} \frac{(1 + \sigma_e \lambda_\gamma) + (1 - \sigma_e \lambda_\gamma)(1-x)^2}{x} \ln\left(\frac{E_\gamma}{m_e}\right), \quad (4.6)$$

where $\alpha = e^2/4\pi$, E_γ is the photon energy and x is the fraction of the electron momentum which is carried by the photon. For $\sigma_e \lambda_\gamma = -1$ ($\sigma_e \lambda_\gamma = +1$) the first (second) term in the numerator of Eq. (4.6) vanishes. Thus,

$$P_{\gamma/e} \sim \frac{1}{x} \quad \text{if } \lambda_\gamma = \sigma_e \quad (4.7a)$$

$$P_{\gamma/e} \sim \frac{(1-x)^2}{x} \quad \text{if } \lambda_\gamma = -\sigma_e. \quad (4.7b)$$

If $\hat{s}$ is large enough ($\sqrt{\hat{s}} > M_W$ at HERA and $\sqrt{\hat{s}} \gg M_W$ at LEP-LHC), x is forced to be big also, and the photon is predominantly emitted with the same helicity as the electron: lefthanded (righthanded) polarized electrons produce approximately lefthanded (righthanded) polarized photons.

As we have discussed in the last Section, the only $\gamma q \rightarrow Wq'$ helicity amplitudes in the SM which survive in the high energy limit are $\mathcal{M}_{--}$ and $\mathcal{M}_{++}$. Thus the final state W has, in the SM, the same helicity as the incoming electron. For anomalous values of λ and $\tilde{\lambda}$, on the other hand, $\mathcal{M}_{-+}$ and $\mathcal{M}_{+-}$ dominate for $\hat{s} \gg M_W^2$ and the W usually has a helicity which is *opposite* to the one of the electron beam. Finally anomalous values of κ and $\tilde{\kappa}$ primarily lead to longitudinally polarized weak bosons.

The charged lepton angular distribution $B \cdot d\sigma/d\cos\bar{\theta}$ acts as an effective spin analyzer of the W . Due to the $V - A$ structure of the $W\ell\nu$ coupling transverse W 's of helicity $\lambda_W = \pm 1$ produce a $(1 + Q_W \lambda_W \cos\bar{\theta})^2$ distribution where $Q_W = \pm 1$ is the W -charge, while longitudinal W 's result in a $\sin^2\bar{\theta}$ distribution.

In reality the expected effects in the $\cos\bar{\theta}$ distribution are somewhat obscured by the fact that a complete polarization of the lepton beam cannot be achieved. Figure 7 shows $B \cdot d\sigma/d\cos\bar{\theta}$ for $ep \rightarrow eW^+jX$ at LEP-LHC and a 50% lefthanded ($P_e = -0.5$) and a 50% righthanded ($P_e = +0.5$) polarized electron beam. The region $\hat{s} \gg M_W^2$ was selected by a $p_{Tj} > 100$ GeV cut which translates into $\sqrt{\hat{s}} > 230$ GeV. This value was chosen as a compromise between the $\hat{s} \gg M_W^2$ requirement and the constraint of retaining enough rate so that the $\cos\bar{\theta}$ distribution still is a meaningful observable. Above $p_{Tj} > 100$ GeV approximately 100 W^+ and 100 W^- events are generated for $\int \mathcal{L} dt = 10^3 \text{ pb}^{-1}$ (see also Fig. 6b). Only W^+ events are shown in Fig. 7. At HERA where events are completely concentrated in the threshold region (see Fig. 4) the expected cross section at large p_{Tj} is too small to make $B \cdot d\sigma/d\cos\bar{\theta}$ a useful quantity.

The $\cos\bar{\theta}$ distributions of Fig. 7 clearly exhibit the dominance of W 's with polarization opposite to the one of the electron beam for large anomalous values of λ and of longitudinal W 's for large non-standard values of κ . For $P_e = -0.5$ the SM polar angle spectrum of the charged W decay lepton clearly resembles a $(1 - \cos\bar{\theta})^2$ distribution whereas for $P_e = +0.5$ the expected shape of a $(1 + \cos\bar{\theta})^2$ distribution is much less obvious. This can be explained by the dominance of the $\gamma q \rightarrow Wq'$ amplitude $\mathcal{M}_{--}$ over $\mathcal{M}_{++}$ in the high energy region so that the influence of the $(\lambda_\gamma, \lambda_W) = (--)$ amplitude is not negligible for $P_e = +0.5$.

In order to measure the $\cos\bar{\theta}$ distribution, the direction of the W in the Wj rest frame has to be reconstructed and hence the Wj invariant mass has to be known. Due to the nonobservation of the neutrino arising from W -decay it can not be determined unambiguously. Identifying the p_T of the neutrino with the missing transverse momentum of a given Wj event, the unobservable longitudinal neutrino momentum can be reconstructed, albeit with a twofold ambiguity, by imposing the constraint that the neutrino and the

charged lepton four momenta combine to form the W rest mass.^{26,27)} What is shown in Fig. 7 is the “reconstructed” $\cos \bar{\theta}$ distribution obtained by using the two solutions for the neutrino longitudinal momentum for each event. From the long dashed line in Fig. 7, which shows the “true” polar angle spectrum for the SM case, it is obvious that, for the parameters used, the reconstruction works quite well.

Although the $\cos \bar{\theta}$ distribution apparently is very sensitive to deviations from the SM, we have not included this quantity to derive the sensitivity bounds in Table 2 for the following reason. The effects displayed in Fig. 7 depend to a large extent on the assumption that a significant longitudinal polarization of the electron beam can be realized for a machine like LEP-LHC. Presently there is no guarantee for that. Even if one takes into account the $\cos \bar{\theta}$ distribution in addition to the p_{Tj} spectrum, the sensitivity bounds for LEP-LHC in Table 2 do not improve significantly since the counting rate for $p_{Tj} > 100$ GeV is rather small. The $\cos \bar{\theta}$ distribution will be more useful to discriminate between anomalous values of κ and λ once deviations in the p_{Tj} spectrum have been found and to crosscheck that the effect in the transverse momentum distribution cannot be explained *e.g.* by an error in the normalization of the SM rate.

5. Discussion and Conclusions

We have described, in the last Section, the signatures which anomalies in the $WW\gamma$ vertex will produce in single W production at ep colliders. In particular we have determined how large deviations from the SM have to be in order to yield visible effects at HERA and LEP-LHC. Naturally the question arises how the sensitivity of ep colliders compares with existing low energy limits on anomalous couplings and with the sensitivity to non gauge theory terms in the $WW\gamma$ vertex reachable via $e^+e^- \rightarrow W^+W^-$ at LEP200, and via $W\gamma$ production from $q\bar{q}$ annihilation, or radiative W -decays, at the Tevatron.

Low energy bounds on κ and λ are quite model dependent at present.²⁸⁾ From loop contributions to $(g-2)_\mu$ ⁹⁻¹¹⁾ one estimates

$$\left| (\kappa - 1) \ln \frac{\Lambda^2}{M_W^2} + \lambda \right| < 4.4 , \quad (5.1)$$

where Λ is the scale where weak bosons show novel strong interactions. Bounds derived from the photon propagator as measured at PETRA¹¹⁾ and the W/Z mass ratio^{10,11)} are more stringent, but also more controversial because loop corrections are particularly

ill-defined in these cases. From Table 2 it is clear that experiments at HERA and LEP-LHC can significantly improve the present low energy bounds derived from $(g-2)_\mu$. The situation is quite different for the CP violating coupling $\tilde{\kappa}$ which would contribute to the electric dipole moment of the neutron. From the present experimental limit on the neutron electric dipole moment one finds¹³⁾

$$\left| \tilde{\kappa} \ln \frac{\Lambda^2}{M_W^2} \right| < 10^{-3} \quad (5.2)$$

which clearly excludes any observable effect at ep colliders. Curiously, as was observed in Ref. 14, no such bound exists for the other CP violating coupling $\tilde{\lambda}$. Contributions of $\tilde{\lambda}$ to the neutron electric dipole moment are suppressed by at least another factor $(M_N^2/M_W^2) \approx 1.3 \cdot 10^{-4}$ (M_N being the neutron mass) as compared to the $\tilde{\kappa}$ bound (5.2) and hence a constraint $|\tilde{\lambda}| < O(1)$ results at best. Comparison with Table 2 shows that HERA can reach this level of accuracy while LEP-LHC would be able to explore more than one order of magnitude in $\tilde{\lambda}$. The LHC (pp collisions at $\sqrt{s} = 16$ TeV), which would operate at the same time as LEP-LHC, will however be even more sensitive to λ and $\tilde{\lambda}$. At hadron supercolliders such as the LHC or the SSC $\lambda(\tilde{\lambda})$ values as small as $O(10^{-3})$ can be probed.²⁹⁾

Experiments at the Tevatron, studying either $q\bar{q} \rightarrow W\gamma$, $W \rightarrow \ell\nu$ or $q\bar{q} \rightarrow W \rightarrow \ell\nu\gamma$ will also be able to probe the $WW\gamma$ vertex.²⁶⁾ In $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, for an integrated luminosity of 10 pb^{-1} , one expects about 25 $W^\pm\gamma$ events with $W \rightarrow e\nu, \mu\nu$ which satisfy the cuts $p_{T\ell,\gamma} > 10$ GeV and $|y_{\ell,\gamma}| < 3$. To discriminate genuine $W\gamma$ events from radiative W decay events, an additional cut on the $\gamma\ell$ cluster transverse mass of $m_T(\gamma\ell, \cancel{p}_T) > 90$ GeV was applied.

It turns out that the sensitivity of $W\gamma$ production with respect to non gauge contributions to the $WW\gamma$ vertex at the Tevatron is mainly limited by the potentially dangerous background arising from photon jet misidentification.²⁶⁾ For a misidentification probability of 1/200 for $p_{T\gamma} > 10$ GeV one obtains sensitivity bounds of $|\Delta\kappa| \lesssim 3$ and $|\lambda|, |\tilde{\lambda}| \lesssim 1$. Radiative W decays ($W \rightarrow \ell\nu\gamma$) are much less plagued by background problems²⁶⁾ but are also far less sensitive to anomalous $WW\gamma$ couplings, in particular for λ and $\tilde{\lambda}$. HERA will thus be able to put a much better limit on $\Delta\kappa$ than the Tevatron, mainly because single W production in ep collisions is virtually background free, in contrast to $q\bar{q} \rightarrow W\gamma$ at $p\bar{p}$ colliders. For λ and $\tilde{\lambda}$ HERA appears to compete in sensitivity with the Tevatron, although details depend on the photon-jet misidentification probability which can be achieved at the latter.

The reaction $ep \rightarrow eWX$ at HERA will thus yield the most precise direct measurement of the $WW\gamma$ vertex before W pair production can be studied at LEP200. Even in $e^+e^- \rightarrow W^+W^-$ at $\sqrt{s} = 190$ GeV an accuracy of $|\Delta\kappa|, |\lambda|, |\tilde{\lambda}| \approx 0.2$ only is expected²⁾ and in W^+W^- production it is actually a linear combination of $WW\gamma$ and WWZ couplings which will be measured. In view of our present poor knowledge of the values of κ , λ and $\tilde{\lambda}$, the direct measurement of the $WW\gamma$ couplings via $ep \rightarrow eWX$ at HERA will clearly constitute major progress. It will be very helpful in disentangling $WW\gamma$ and WWZ anomalous couplings in W pair production at LEP200 in the mid 1990's.

ACKNOWLEDGEMENTS

We would like to thank Ch. Berger, H. Meyer, G. Schuler and P. Zerwas for stimulating discussions. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the U. S. Department of Energy under contract DE-AC02-76ER00881.

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TABLE 1

Effects of increasingly stringent cuts on the $ep \rightarrow eW^\pm X$, $W^\pm \rightarrow e^\pm \nu, \mu^\pm \nu$ cross section in the SM. In each line the indicated cut is imposed in addition to all the previous ones. The values in the first line ('no cuts') are indicative only of the total W production rate (see text for details).

HERA		LEP-LHC	
cut	$B \cdot \sigma$ [pb]	cut	$B \cdot \sigma$ [pb]
no cuts	≈ 0.24	no cuts	≈ 4.6
$p_{Tj} > 5$ GeV	0.104	$p_{Tj} > 10$ GeV	2.66
$ \eta_{\ell,j} < 3.5$	0.098	$ \eta_{\ell,j} < 3.5$	1.78
$p_{T\ell} > 5$ GeV	0.097	$p_{T\ell} > 10$ GeV	1.73
$\cancel{p}_T > 10$ GeV	0.094	$\cancel{p}_T > 10$ GeV	1.66
$\Delta R_{\ell j} > 0.5$	0.092	$\Delta R_{\ell j} > 0.5$	1.64

TABLE 2

Sensitivities achievable at the 90% and 69% CL for the anomalous $WW\gamma$ couplings $\Delta\kappa = \kappa - 1$, λ and $\tilde{\lambda}$ at HERA and LEP-LHC for an integrated luminosity of 1000 pb^{-1} . The bounds are given for a normalization uncertainty of the SM rate of $\Delta\mathcal{N} = 10\%$ and $\Delta\mathcal{N} = 30\%$. Only one coupling at a time is assumed to be different from the SM value.

a	CL	HERA		LEP-LHC	
		$\Delta\mathcal{N} = 10\%$	$\Delta\mathcal{N} = 30\%$	$\Delta\mathcal{N} = 10\%$	$\Delta\mathcal{N} = 30\%$
$\Delta\kappa$	90%	+0.51	+0.72	+0.20	+0.38
		-0.72	-1.15	-0.23	-0.43
	69%	+0.33	+0.46	+0.16	+0.21
		-0.39	-0.59	-0.19	-0.26
λ	90%	+1.22	+1.24	+0.11	+0.11
		-1.28	-1.30	-0.12	-0.12
	69%	+0.86	+0.86	+0.08	+0.08
		-0.91	-0.92	-0.08	-0.08
$\tilde{\lambda}$	90%	+1.25	+1.28	+0.12	+0.12
		-1.25	-1.28	-0.12	-0.12
	69%	+0.89	+0.91	+0.08	+0.08
		-0.89	-0.91	-0.08	-0.08

FIGURE CAPTIONS

1. Feynman graphs for the parton level processes contributing to $ep \rightarrow eWX$, including the subsequent decay $W \rightarrow f\bar{f}'$. Diagrams (f) and (g) have to be included for offshell W 's in order to preserve electromagnetic gauge invariance.
2. Feynman diagrams contributing to $\gamma q \rightarrow W^\pm q'$.
3. Angular distribution $d\hat{\sigma}(\lambda_\gamma, \lambda_W)/d\cos\Theta$ for $\gamma d \rightarrow W^-u$ in the SM at (a) $\sqrt{\hat{s}} = 300$ GeV and (b) $\sqrt{\hat{s}} = 100$ GeV, averaged over the initial quark polarization. Shown in parantheses are the photon and W helicities in the γd center of mass frame.
4. Normalized distribution $(1/\sigma) \cdot (d\sigma/d\sqrt{\hat{s}})$ of the Wj invariant mass $\sqrt{\hat{s}}$ in $ep \rightarrow eW^\pm jX$ at HERA (solid line) and LEP-LHC (dashed line) in the SM, imposing the cuts described in the text.
5. Transverse momentum spectrum of the jet in $ep \rightarrow eW^\pm jX$ at (a) HERA and (b) LEP-LHC for the SM (solid line) and various anomalous values of κ and λ . Cuts are specified in the text. The curve for $\lambda = -0.5$ in (b) almost coincides with the one for $\lambda = +0.5$ (dash dotted line) and, therefore, is not shown.
6. The total cross section $B \cdot \sigma(p_{Tj} > p_{T\min})$ for $ep \rightarrow eW^\pm jX$ versus the minimum jet p_T cutoff $p_{T\min}$ at (a) HERA and (b) LEP-LHC. The anomalous couplings and cuts are the same as in Fig. 5.
7. Polar angle distribution of the charged decay lepton from W^+ decay in $ep \rightarrow eW^+ jX$ at LEP-LHC for $p_{Tj} > 100$ GeV and a) $P_e = -0.5$, b) $P_e = +0.5$, obtained from reconstructing the longitudinal momentum of the neutrino. See text for a description of $\bar{\theta}$. The anomalous couplings and all other cuts are the same as in Fig. 5b. For comparison, also the true $\cos\bar{\theta}$ distribution is shown for the SM case (long dashed line).

Fig. 1

Fig. 2

Fig. 3a

Fig. 3b

Fig. 4

Fig. 5a

Fig. 5b

Fig. 6a

Fig. 6b

Fig. 7a

Fig. 7b