Measuring the *WWZ* coupling at the Fermilab Tevatron

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Hadroproduction of weak-boson pairs $W^{\pm}Z$ and W^+W^- is studied quantitatively at Fermilab Tevatron energies. Although the cross sections are expected to be small in the standard model, they grow substantially with nonstandard WWZ and $WW\gamma$ couplings even after careful consideration of unitarity constraints. With 4.7 pb^{-1} of data at hand, the Collider Detector at Fermilab Collaboration may already be sensitive to nonstandard WWZ couplings if $|\kappa_Z - 1| > 1.3$ or $|\lambda_Z| > 1.0$ (90% C.L.) from Z ($\rightarrow l^+l^-$) plus dijet and W ($\rightarrow l\nu$) plus dijet event rates or from leptonic decays of both weak bosons. With 100 pb^{-1} of data, purely leptonic modes can be used to extend the sensitivity to $|\lambda_Z| > 0.4$ (90% C.L.), which is comparable and complementary to the $e^+e^- \rightarrow W^+W^-$ experiments at the CERN collider LEP II.

I. INTRODUCTION

In the standard theory of electroweak interactions, the weak bosons and the photon are the gauge bosons of a local $SU(2)\times U(1)$ symmetry. Although W and Z bosons acquire masses due to the spontaneous breakdown of this local symmetry, the interactions among themselves and with the photon are completely dictated by the gauge symmetry. Since most novel theoretical ideas about the fundamental laws of nature rely on the validity of this picture, it is of utmost importance to test these vector-boson self-couplings experimentally.

It has been shown that the process $e^+e^- \rightarrow W^+W^-$ to be measured at the CERN collider LEP II is sensitive to a linear combination of $WW\gamma$ and WWZ couplings,[1] whereas single-W production processes at the DESY *ep* collider HERA (Ref. 2) and at LEP II (Ref. 3) measure the $WW\gamma$ coupling. At hadron colliders, both $W\gamma$ production and W radiative decay processes are shown to be sensitive to the $WW\gamma$ couplings.[4]

In this paper, we show that the Collider Detector at Fermilab (CDF) Collaboration, with their 4.7 pb^{-1} of data accumulated at the Tevatron, should already be sensitive to some of the $WW\gamma$ and WWZ couplings from weak-boson pair production processes.[5,6] Our basic observations can be summarized as follows. Even though the W^+W^- and WZ production cross sections are expected to be small in the standard model (SM), about 8.4 pb and 2.5 pb at $\sqrt{s} = 1.8$ TeV, they can be enhanced significantly in the presence of nonstandard couplings. This fact was already exploited in Ref. 6 to discuss bounds on particular combinations of nonstandard couplings. Since the large cross sections result from spin-one partial-wave amplitudes that grow with energy, the produced weak bosons tend to have high transverse momenta, which facilitates their detection against the QCD background. Such growing partial-wave amplitudes signal the onset of new strong interactions among weak bosons, whose effect should be taken into account by energy-dependent form factors[7] to avoid apparent violation of unitarity already at Tevatron energies. We find that the study of Z ($\rightarrow l^+l^-$) plus dijet events as well as W ($\rightarrow l\nu$) plus dijet events can already lead to interesting constraints on the WWZ and $WW\gamma$ couplings. The latter mode may be useful only when the top quark is sufficiently heavy so as not to produce many W^+W^- pairs. Information from these single-leptonic modes would be complemented by the nonobservation of double-leptonic decays of weak-boson pairs, which already can lead to significant constraints on nonstandard three-boson couplings.

The remainder of this paper is organized as follows. In Sec. II we describe the deviations from the SM three-vector-boson couplings to be used later within the framework of an effective Lagrangian. We argue that particular dimension-6 operators, which preserve the electroweak $SU(2)\times U(1)$ gauge symmetry, should be the focus of an experimental search. In Sec. III we give helicity amplitudes for the production of WZ pairs including the effects of anomalous couplings. Tree-level unitarity is invoked to limit the size of the form factors which correspond to these anomalous couplings. Section IV contains our major results. Cross sections at the Tevatron are discussed including decay branching fractions and correlations of the weak-boson decay products, the visibility of the WZ and WW signal in the leptons plus dijet mode is established, provided the anomalous couplings are sufficiently large, and present and future sensitivities (with 100 pb^{-1}) of the Tevatron are estimated. Finally Sec. V gives our conclusions and we discuss to what extent measurements are complementary to those at HERA and LEP II.

II. EFFECTIVE LAGRANGIAN FOR *WWV* COUPLINGS

The most general WWV coupling ($V=\gamma$ or Z) consistent with Lorentz invariance may be parametrized in terms of seven form factors if we exclude terms proportional to $\partial_\mu W^\mu$ and $\partial_\mu V^\mu$. These terms vanish if the vector bosons are on mass shell or are coupled to massless fermions, which, to a good approximation, is the case in the processes we are considering. Following Ref. 1, we write the effective Lagrangian

$$\mathcal{L}_{WWV}/g_{WWV}=ig_1^V(W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu})+i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu}+\frac{i\lambda_V}{M_W^2}W_{\lambda\mu}^\dagger W^\mu{}_\nu V^{\nu\lambda}-g_4^V W_\mu^\dagger W_\nu(\partial^\mu V^\nu+\partial^\nu V^\mu)$$
$$+g_5^V\epsilon^{\mu\nu\rho\sigma}(W_\mu^\dagger \overleftrightarrow{\partial}_\rho W_\nu)V_\sigma+i\tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu}+\frac{i\tilde{\lambda}_V}{M_W^2}W_{\lambda\mu}^\dagger W^\mu{}_\nu \tilde{V}^{\nu\lambda}\ , \tag{1}$$

where W^μ denotes the W^- field, $W_{\mu\nu}=\partial_\mu W_\nu-\partial_\nu W_\mu$, $V_{\mu\nu}=\partial_\mu V_\nu-\partial_\nu V_\mu$, $\tilde{V}_{\mu\nu}=\frac{1}{2}\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$, and $(A\overleftrightarrow{\partial}_\mu B)=A(\partial_\mu B)-(\partial_\mu A)B$. Without loss of generality we choose the overall coupling constants g_{WWV} as in the SM:

$$g_{WW\gamma}=-e,\quad g_{WWZ}=-e\cot(\theta_W)\ . \tag{2}$$

In Eq. (1) g_4 is odd under CP and C, g_5 is odd under C and P, while $\tilde{\kappa}$ and $\tilde{\lambda}$ are odd under CP and P. Within the SM they all vanish at the tree level and so does λ. The only nonzero couplings within the SM are

$$g_1^V=1,\quad \kappa_V=1\ , \tag{3}$$

for $V=\gamma,Z$. Here we note that among these 14 couplings (7 each for $WW\gamma$ and WWZ), there are just two independent couplings which are invariant under the gauge group $SU(2)_L\times U(1)_Y$,

$$\lambda=\lambda_\gamma=\lambda_Z\ , \tag{4}$$

which is even under C and P, and

$$\tilde{\lambda}=\tilde{\lambda}_\gamma=\tilde{\lambda}_Z\ , \tag{5}$$

which is even under C but odd under P. This easily follows from

$$-e\cot\theta_W\lambda_Z W_{\rho\mu}^\dagger W^\mu{}_\nu Z^{\nu\rho}-e\lambda_\gamma W_{\rho\mu}^\dagger W^\mu{}_\nu A^{\nu\rho}=-\frac{e\lambda}{\sin\theta_W}W_{\rho\mu}^\dagger W^\mu{}_\nu W^{3\nu\rho}\ , \tag{6}$$

where the replacement $\cos\theta_W Z^{\nu\rho}+\sin\theta_W A^{\nu\rho}=W^{3\nu\rho}$ has been made. On the other hand, using the full non-Abelian field strengths for the triplet of SU(2) gauge bosons, the combination

$$\mathrm{Tr}(\boldsymbol{\sigma}\cdot\mathbf{W}_{\rho\mu}\boldsymbol{\sigma}\cdot\mathbf{W}^\mu{}_\nu\boldsymbol{\sigma}\cdot\mathbf{W}^{\nu\rho})=12iW_{\rho\mu}^1 W^{2\mu}{}_\nu W^{3\nu\rho}=12W_{\rho\mu}^\dagger W^\mu{}_\nu W^{3\nu\rho} \tag{7}$$

is manifestly gauge invariant, and the three-vector-boson coupling derived from Eq. (7) agrees with Eq. (6). The corresponding CP-odd term proportional to $\tilde{\lambda}$ is also gauge invariant since it is obtained from Eq. (6) by replacing $\lambda W^{3\nu\rho}$ by $\tilde{\lambda}\tilde{W}^{3\nu\rho}$.

These two gauge-invariant couplings play a distinguished role among all nonstandard couplings. Unlike the $\kappa-1$ coupling, the λ coupling leads to a finite correction to the electron anomalous magnetic moment.[8] Also the $\tilde{\lambda}$ contribution to the electron and neutron electric dipole moment seems to be suppressed[9] as compared to the $\tilde{\kappa}$ contribution.[10] Because of the gauge invariance, they cannot give rise to weak-boson mass shifts.[11] Accordingly, there are almost no constraints from low-energy experiments on λ and $\tilde{\lambda}$ couplings. If the new strong interactions among weak bosons which are responsible for generating these nonstandard couplings respect the electroweak gauge symmetry, then it is only these two couplings that can be generated.

This is the reason why in the following we somewhat concentrate on the λ and $\tilde{\lambda}$ couplings. In addition we shall discuss anomalous values of $\kappa=\kappa_\gamma=\kappa_Z$. This limit of equal anomalous couplings of the W to the photon and the Z is no constraint for WZ production but relevant for interference effects between the photon and Z-exchange graphs in W^+W^- production. Since electromagnetic gauge invariance forbids any deviations of g_1^γ, g_4^γ, and g_5^γ from their SM values 1, 0, and 0, respectively, for on-shell photons this assumption of equal photon and Z couplings allows us to discard anomalies in g_1^V, g_4^V, and g_5^V altogether. (For a discussion of these particular anomalous couplings for virtual photons, see Ref. 1.) The same applies for $\tilde{\kappa}^V$ since $\tilde{\kappa}^\gamma$ is severely limited by measurements of the electric dipole moment of the neutron.[10] Imposing the photon constraints on both the photon and the Z couplings actually is a natural consequence of any model in which mixing of the SU(2) and U(1) neutral gauge bosons occurs.[12] In the following we shall restrict ourselves to a discussion of nonstandard values of $\kappa=\kappa_\gamma=\kappa_Z$, $\lambda=\lambda_\gamma=\lambda_Z$, and $\tilde{\lambda}=\tilde{\lambda}_\gamma=\tilde{\lambda}_Z$.

III. HELICITY AMPLITUDES AND FORM FACTORS

Helicity amplitudes for the processes $q\bar{q}\to WZ$ and WW have been obtained in Ref. 7 for the most general couplings (1). Here we reproduce the helicity amplitudes for WZ production with just three nonstandard couplings, $\kappa-1$, λ, and $\tilde{\lambda}$ for illustration. Amplitudes for W^+W^- production can be found in Ref. 1. The amplitudes for the process

$$d_L+\bar{u}_R\to W^-(\lambda_1)+Z(\lambda_2) \tag{8}$$

from the nonstandard couplings read

$$\Delta\mathcal{M}(\lambda_1,\lambda_2) = -\frac{e^2\cos\theta_W}{\sin^2\theta_W}\,\frac{s}{s-M_W^2} \times \beta\mathcal{A}(\lambda_1,\lambda_2)\, d^{\,1}_{-1,\lambda_1-\lambda_2}(\theta)\ , \tag{9}$$

where θ is the scattering angle of the W^- with respect to the incoming d-quark direction in the parton rest frame, $\beta = 2|\mathbf{p}_w|/\sqrt{s}$, and the dependence on the scattering angle is absorbed in the conventional d functions.[13] The reduced amplitudes $\mathcal{A}(\lambda_1,\lambda_2)$ are given by

$$\begin{aligned}
\mathcal{A}(0,\pm) &= \frac{\sqrt{s}}{2M_W}\left[\kappa - 1 + \lambda \mp i\frac{\tilde{\lambda}}{\beta}\left[1 + \frac{M_Z^2 - M_W^2}{s}\right]\right],\\
\mathcal{A}(\pm,0) &= \frac{\sqrt{s}}{2M_Z}\,\frac{M_Z^2}{M_W^2}\left[\lambda \mp i\frac{\tilde{\lambda}}{\beta}\left[1 - \frac{M_Z^2 - M_W^2}{s}\right]\right],\\
\mathcal{A}(\pm,\pm) &= \frac{\kappa-1}{2} + \frac{s}{2M_W^2}\left[\lambda \mp i\frac{\tilde{\lambda}}{\beta}\left[1 - \frac{M_Z^2 + M_W^2}{s}\right]\right],\\
\mathcal{A}(0,0) &= \frac{M_W^2 + M_Z^2}{4M_W M_Z}(\kappa - 1) + \frac{(M_W^2 - M_Z^2)^2}{4M_W^3 M_Z}\lambda\ .
\end{aligned} \tag{10}$$

Inspection of these amplitudes shows, that the λ and $\tilde{\lambda}$ terms mainly affect transverse W's and Z's rather than the longitudinal ones. Indeed the amplitude for two longitudinal bosons, $\mathcal{A}(0,0)$, does not grow with energy as one might naively expect from the wave-function factors and the dimensionality of the operators in the Lagrangian (1). The amplitudes for the CP-conjugate process $u_L + \bar{d}_R \to W^+(-\lambda_1) + Z(-\lambda_2)$ are identical to the above amplitudes apart from an overall sign and the sign of $\tilde{\lambda}$ which should be reversed.

For finite and constant values of λ the reduced amplitudes $\mathcal{A}(\pm,\pm)$ in Eq. (10) grow with energy as s/M_W^2, eventually violating tree-level unitarity. A consistent description of anomalous couplings hence requires λ to be actually a form factor which vanishes in the $s \to \infty$ limit. A general analysis of these unitarity constraints has been performed in Ref. 7. Using dipole form factors for all anomalous couplings, e.g.,

$$\lambda(s) = \frac{\lambda}{(1 + s/\Lambda^2)^2} \tag{11}$$

with some cutoff scale Λ, the scale where the novel strong interactions giving rise to the anomalous behavior of the WWV vertices set in, one finds that the cutoff scale is bounded by the low-energy values of the anomalous couplings. Tree-level unitarity is satisfied provided[7]

$$\Lambda \le \left[\frac{6.88}{(\kappa-1)^2 + 2\lambda^2 + 2\tilde{\lambda}^2}\right]^{1/4} \text{TeV}\ . \tag{12}$$

For instance, if $\lambda = 3$ then the form factor should have a scale of about 0.8 TeV, where the weak bosons start interacting strongly.

IV. SIGNALS FOR ANOMALOUS COUPLINGS

While the amplitudes of Eq. (10) give a qualitative description of the effects of anomalous couplings, a complete calculation of vector-boson pair production cross sections is needed, including finite-width effects and correlations of the decay products of W's and/or Z, in order to obtain realistic estimates of the signals which may be observed at the Tevatron. We use the tree-level formulas given in Refs. 1 and 14, which are valid for arbitrary anomalous $WW\gamma$ and WWZ couplings. In our signal calculations we include a K factor $1 + \frac{8}{9}\pi\alpha_s$ as obtained for WW and WZ production.[15] Duke-Owens structure functions[16] (set I) are used throughout.

The resulting total cross sections for $p\bar{p} \to W^\pm Z$ and $p\bar{p} \to W^+W^-$ at $\sqrt{s} = 1.8$ TeV are shown in Fig. 1 as a function of the anomalous coupling λ for three different values of κ: $\kappa = -1$, 1, and 3. For the SM values of the couplings ($\kappa = 1$ and $\lambda = 0$) strong gauge theory cancellations lead to relatively small cross sections of 2.5 pb for $W^\pm Z$ production and 8.4 pb for W^+W^- production. Even for relatively small anomalous couplings these cancellations are spoiled and lead to dramatic increases of the predicted cross sections, in particular at large values of $\sqrt{\hat{s}}$, the parton center-of-mass energy.

Because of the large energies available at the Tevatron the inclusion of form factors in the calculation is important in order to avoid unitarity violation and hence unphysically large cross sections in the calculation. In Fig. 1 the lower set of curves, labeled FF, is obtained by using dipole form factors with the scale Λ given by the unitarity limit of Eq. (12) for any set of anomalous couplings $(\kappa - 1, \lambda)$. These form factors result in a reduction of cross sections by almost a factor 3 for the largest anomalies displayed and hence cannot be neglected at Tevatron energies. In the following we shall always use dipole form factors with the maximum scale Λ allowed by Eq. (12).

In Fig. 1 the $W^\pm Z$ and W^+W^- cross sections approach rather similar values in the SU(2) limit of large values of λ. In this limit the parton level cross sections

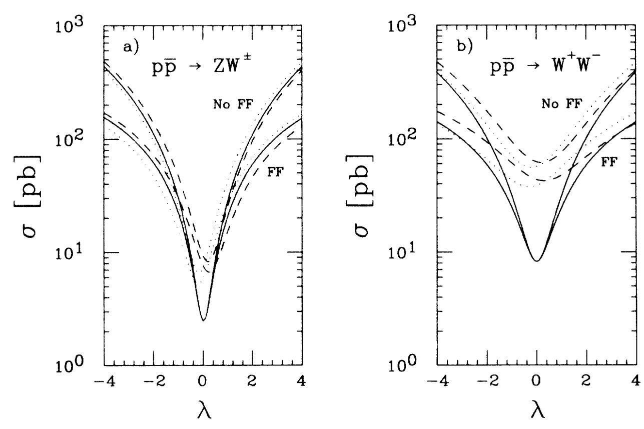

FIG. 1. Total production cross sections at $\sqrt{s} = 1.8$ TeV for (a) $p\bar{p} \to ZW^\pm$ and (b) $p\bar{p} \to W^+W^-$ as a function of λ for $\kappa = -1$ (dashes), $\kappa = 1$ (solid), and $\kappa = 3$ (dots). In the set of three curves labeled by "FF" the anomalous couplings are suppressed by a form factor which ensures that the cross section does not surpass the limit imposed by unitarity. The curves labeled by "No FF" have no form factor suppression.

are dominated by $W^{\pm}$ and W^3 s-channel exchange, respectively, and one finds

$$\hat{\sigma}(W^{\pm}Z)/\hat{\sigma}(W^+W^-) \xrightarrow{\lambda \gg 1} 2\cos^2\theta_W \ .$$

This enhancement of the WZ cross section is partially offset by the smaller parton luminosities for WZ production: $2ud/(uu+dd)<1$. In the SM (at $\lambda=0$ and $\kappa=1$), WZ production is somewhat suppressed compared to W^+W^- production due to the smaller Z couplings to quarks in the dominating quark-exchange graphs. This results in the larger sensitivity of the WZ cross section to the SU(2)-symmetric λ couplings which is obvious in Fig. 1.

W pair production is not only less sensitive to λ but also any observed enhancement in the W^+W^- production cross section would most likely be attributed to top production with subsequent decay to real W's (Ref. 17) $p\bar{p}\to t\bar{t}X\to bW^+\bar{b}W^-X$. One has to keep in mind that the expected $t\bar{t}$ cross section is larger than the SM direct W^+W^- rate of 8.4 pb for $m_t \lesssim 150$ GeV (Ref. 18). Even disregarding the possibility to distinguish top and direct W-pair events by the larger jet activity in top events, the W^+W^- channel will nevertheless be very useful in putting bounds on anomalous $WW\gamma$ and WWZ couplings: as long as no excess of W^+W^- events is seen (and hence top remains undiscovered) a small W^+W^- cross section directly translates into bounds on λ and also $\kappa-1$. In particular anomalous values of κ are most easily seen in W pair production, where they give rise to amplitudes[1] which grow as s/M_W^2, while from Eq. (10) we read off an enhancement factor of only $\sqrt{s}/M_W$ for WZ production. Summarizing the situation, WZ production is the cleaner channel for tests of the three-boson couplings, but W pair production will provide additional valuable information as long as the signal is not swamped by the $t\bar{t}$ background.

In order to observe either vector-boson pair signal the decay products of W's and Z's have to be observed above possible backgrounds. While leptonic decays of both vector bosons provide for a virtually background-free signal, branching ratios for this double-leptonic mode are tiny and amount to 1.4% for WZ decay and 4.7% for W^+W^- double-leptonic decay, even when adding up electron and muon decay channels. This leads to double leptonic signal cross sections of 0.035 pb for WZ production and 0.4 pb for W^+W^- production, within the SM. On the other extreme, purely hadronic decays of both vector bosons which amount to branching ratios of almost 50% in both cases are expected to be unobservable in view of the large four-jet QCD background.

One is led, hence, to look for a dilepton plus dijet, or semileptonic, decay signature for the vector-boson pairs. The corresponding branching ratios are

$$B(W\to e\nu, Z\to jj)=7.6\% \ , \tag{13a}$$

$$B(W\to jj,\ Z\to ee)=2.3\% \tag{13b}$$

for the WZ signal and

$$B(W\to e\nu,\ W\to jj)=14.6\% \tag{14}$$

for the W pair signal. Another factor of 2 is gained by looking for muon signals as well, and hence the useful cross section, even for WZ production within the SM, rises to 0.5 pb, at the price, of course, of a large competing $(W\to e\nu)+jj$ and $(Z\to ee)+jj$ QCD background.

We calculate the W,Z +two-jet background with a parton level Monte Carlo program using the full tree-level QCD matrix elments, as described in Refs. 19 and 20. Jet definition and lepton-isolation cuts are imposed, both to regularize the infrared and collinear singularities of the QCD tree-level cross sections and in order to roughly simulate the CDF acceptance:

$$\begin{aligned} &p_T(j)>15 \text{ GeV}, \quad p_T(e)>15\,\text{GeV}, \quad \not{p}_T>15 \text{ GeV} \ , \\ &|\eta(j)|<2.5, \quad |\eta(e)|<2.5 \ , \\ &\Delta R_{jj}>1, \quad \Delta R_{ej}>0.7 \ . \end{aligned} \tag{15}$$

Here p_T denotes the transverse momentum and η the pseudorapidity of jets and electrons, $\not{p}_T$ is the missing p_T of the event and $\Delta R=[(\Delta\eta)^2+(\Delta\phi)^2]^{1/2}$ is the separation of two jets and electrons and jets in the pseudorapidity-azimuthal angle plane. In determining these cuts the energy resolution in the CDF calorimeter has been roughly simulated by Gaussian smearing of jet energies with $\sigma=0.8\sqrt{E_{\text{parton}}}$. For W and Z identification we further require

$$M_T(e,\nu)>50 \text{ GeV} \tag{16}$$

and

$$M(ee)>50 \text{ GeV} \ , \tag{17}$$

respectively, for the transverse mass and the invariant mass of the decay leptons.

Within these cuts the QCD background overwhelms the SM signal, even when requiring the dijet invariant mass to be compatible with a W or Z hadronic decay. Large anomalous couplings are needed to obtain signal and background rates which are comparable at best. However, the jets in QCD events tend to be produced at small transverse momenta with large dijet invariant masses arising from large rapidity differences between the two jets. On the other hand, the two jets from vector boson decays, which already receive an intrinsic p_T of order $M_{W,Z}/2$ each in the decay process, in addition share the transverse momentum of the parent W or Z.

In the case of anomalous couplings the parent electroweak bosons are produced at large transverse momenta, due to the $\hat{s}^{1/2}/M_W$ enhancement factors in the production amplitudes of Eq. (10), and also because the anomalous couplings lead to vector-boson production in the $J=1$ partial wave, corresponding to s-channel vector boson exchange, which prefers production at large scattering angles. This renders the scalar sum of the jet transverse energies, $\sum E_T$, an excellent tool to distinguish the WW and ZW signals from the QCD background. In Fig. 2 the $\sum E_T$ distributions are shown for both the signal (at an anomalous coupling of $\lambda=3$, $\kappa=1$ and a scale $\Lambda=0.8$ TeV in the dipole form factor) and the background for $(Z\to e^+e^-)+jj$ and $(W^{\pm}\to e^{\pm}\nu)+jj$ events, where the dijet invariant mass has been restricted to 70

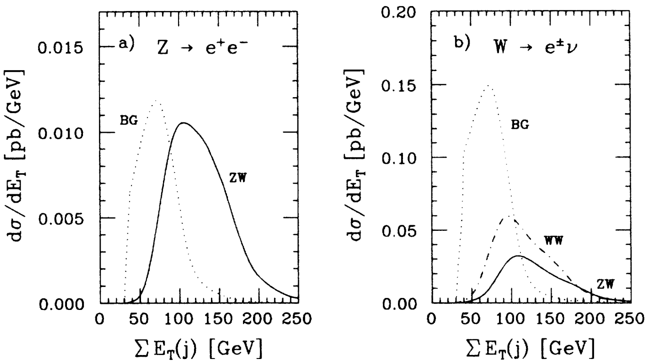

FIG. 2. Distributions at $\sqrt{s}=1.8$ TeV and $\lambda=3$, $\kappa=1$ for the summed scalar E_T of the two jets in the following signal and background processes. (a) Signal: $p\bar{p}\to ZW^{\pm}$, $Z\to e^+e^-$, $W\to$two jets. Background: $p\bar{p}\to Z+$two jets, $Z\to e^+e^-$. (b) Signal: $p\bar{p}\to ZW^{\pm}$, $Z\to$two jets, $W\to e\nu$, and $p\bar{p}\to W^+W^-$, $W\to e\nu$, $W\to$two jets. Background: $p\bar{p}\to W^{\pm}+$two jets, $W\to e\nu$. The distributions are subject to the cuts described in the text [see Eqs. (15)–(17)].

GeV $< M_{jj} <$ 90 GeV for the ZW signal of Fig. 2(a) and 70 GeV $< M_{jj} <$ 100 GeV for the combined ZW and WW signal in Fig. 2(b). Requiring $\sum E_T > 100$ GeV will clearly achieve an acceptable signal-to-background ratio in both cases.

Because of remaining normalization uncertainties of the background calculation[20] an experimental determination of the background off the W,Z peak is desirable. Imposing $\sum E_T > 100$ GeV will force even the background to peak around $M_{jj}\approx 80$ GeV. By scaling the $\sum E_T$ cut with the dijet invariant mass, we find that the effect of the cut on the dijet-invariant-mass distribution can be made small. Hence we suggest a cut

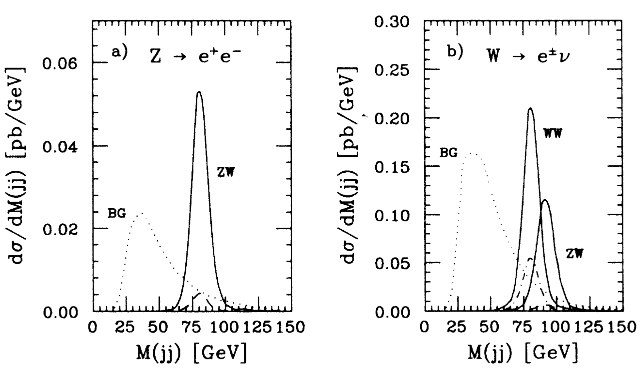

FIG. 3. Dijet-invariant-mass distributions at $\sqrt{s}=1.8$ TeV and $\lambda=3$, $\kappa=1$ for signal and background. (a) Signal: $p\bar{p}\to ZW^{\pm}$, $Z\to e^+e^-$, $W\to$two jets. Background: $p\bar{p}\to Z+$two jets, $Z\to e^+e^-$. Also shown (dashed curve) is the standard-model result for the signal ($\lambda=0$, $\kappa=1$) multiplied by a factor of 10. (b) Signal: $p\bar{p}\to ZW^{\pm}$, $Z\to$two jets, $W\to e\nu$, and $p\bar{p}\to W^+W^-$, $W\to e\nu$, $W\to$two jets. Background: $p\bar{p}\to W^{\pm}+$two jets, $W\to e\nu$. The standard-model results times a factor 10 are also shown for the two signal processes, $ZW^{\pm}$ (dashed curve) and W^+W^- (dotted-dashed curve). Cuts are as in Fig. 2 with an additional $\sum E_T > (100\text{ GeV})M_{jj}/M_W$ imposed.

$$\left[\sum E_T\right]\frac{M_W}{M_{jj}} > 100\,\text{GeV} \tag{18}$$

to allow for a background measurement in the experiment.

The resulting dijet-invariant-mass distributions are shown in Fig. 3. The background distributions are smooth, as promised, in the relevant region around $M_{jj}\approx 80$ GeV. For anomalous couplings as large as $\lambda=3$ clear W and Z peaks would be observable. At this point it should be noted that the cut value of 100 GeV in Eq. (18) is not optimal for WZ and WW production within the SM, because of the lower vector-boson transverse momenta as compared to the anomalous coupling case. For the SM the cut needs to be lowered to 80–90 GeV in order to retain a good fraction of signal events, at the price of substantially increasing the background.

The resulting signal and background cross sections are given in Fig. 4 as a function of the anomalous couplings λ for the three values $\kappa=-1$, 1, and 3. The $\sum E_T$ cut of Eq. (18) is imposed and the dijet invariant mass is restricted to a bin of $M_{jj}=70$–90 GeV for $Z\to ee$ events and $M_{jj}=70-100$ GeV for $W\to e\nu$ events. Assuming that 1 background event $(Z\to e^+e^-)+$two jets is seen in the 4.7 pb^{-1} of CDF data (we expect 0.5 events within our cuts for the SM) a 90%-C.L. bound on $\sigma(p\bar{p}\to WZ;\ Z\to e^+e^-,\ W\to jj)<0.83$ pb could be set and hence a bound on λ of $|\lambda|\leq 3.3$ would result. Similarly observation of 4 $(W\to e\nu)+jj$ events within cuts, which would be consistent with our background estimate, would imply a combined signal-plus-background cross section smaller than 1.7 pb and hence a 90%-C.L. bound $|\lambda|\leq 1.5$, even when neglecting the background contribution. Analogously κ could be constrained to $-1.3\lesssim\kappa\lesssim 3.6$ from an $e\nu+$dijet event rate consistent with the QCD background.

Once an integrated luminosity of 100 pb^{-1} is reached at the Tevatron and small deviations of the WZ and WW rates are being searched for, the QCD background consti-

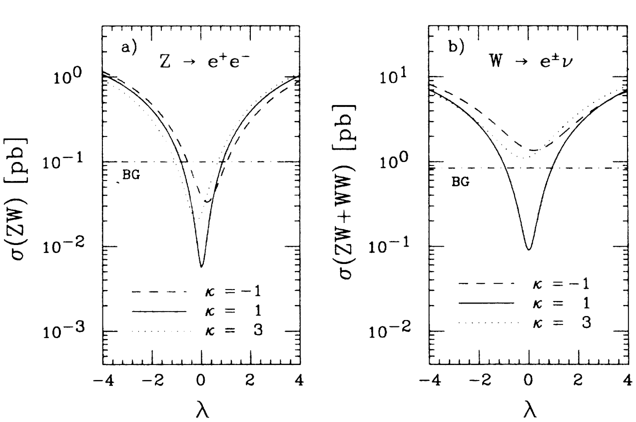

FIG. 4. Total cross sections for the dilepton plus dijet signal and background at $\sqrt{s}=1.8$ TeV. The signal curves are given as a function of λ for $\kappa=-1$ (dashes), $\kappa=1$ (solid), and $\kappa=3$ (dots) and include form-factor suppression at the unitarity limit of Eq. (12). Signals and background are as in Figs. 2 and 3. The cuts are as in the previous figure.

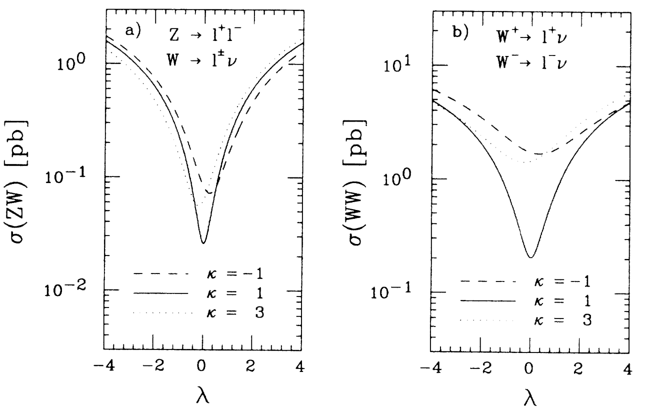

FIG. 5. Total cross sections for double leptonic decay modes at $\sqrt{s} = 1.8$ TeV, including cuts and form-factor suppression at the unitarity limit. Results are given as a function of λ for $\kappa = -1$ (dashes), $\kappa = 1$ (solid), and $\kappa = 3$ (dots). In (a) $ZW^\pm$ production and in (b) W^+W^- production with subsequent decay into electrons and/or muons is shown. The cuts are described in the text.

tutes the major limitation in the semileptonic decay channel. Nevertheless a sensitivity to $|\lambda| \gtrsim 0.6$ and $|\kappa - 1| \gtrsim 3$ may be achievable in the $(Z \to e^+e^-)$+dijet channel while the sensitivity in the $(W \to e\nu)$+dijet channel depends on the size of the $t\bar{t}$ background.

In contrast to the semileptonic decays of the vector boson pairs, the double leptonic modes, in particular $Z \to l^+l^-$, $W \to l\nu$ $(l = e,\mu)$, should be virtually background-free. Merely imposing the lepton acceptance cuts of Eq. (15) we obtain the total cross sections depicted in Fig. 5, where we have included the branching ratios for decays into both electrons and muons. In Fig. 5(b) for $(W^+ \to l^+\nu)(W^- \to l'^-\bar{\nu})$ we require the azimuthal angle between the two charged leptons to be less than 150° in order to suppress the background from $Z \to \tau\bar{\tau}$ decays.

By comparing Figs. 4. and 5 one finds that for small anomalous couplings the double leptonic decay modes of WZ and W^+W^- events give a larger cross section than the semileptonic ones, even when multiplying the curves of Fig. 4 by another factor 2 in order to take into account the muon decay channel of the W and the Z. This strong suppression of the semileptonic channel is due to the severity of the cuts which needed to be imposed to reduce the W,Z +2 jet background.

On the basis of Fig. 5 we estimate a 90%-C.L. sensitivity of the Tevatron, with the present 4.7 pb^{-1} of data, to $|\lambda| \gtrsim 1.7$ from double leptonic ZW events (assuming no event is observed) and $|\lambda| \gtrsim 1.0$, $|\kappa - 1| \gtrsim 1.3$ from double leptonic decays of W pairs (assuming one event is observed). For 100 pb^{-1} of data the ZW double leptonic decays should allow one to put 90%-C.L. limits of $|\lambda| \lesssim 0.4$ and $|\kappa - 1| \lesssim 2$ while the size of the W-pair signal again crucially depends on the $t\bar{t}$ background.

In Sec. II we saw that there are two anomalous couplings which respect SU(2)×U(1) gauge invariance, $\lambda = \lambda_\gamma = \lambda_Z$ which has been discussed above, and the CP-violating analogue $\tilde{\lambda} = \tilde{\lambda}_\gamma = \tilde{\lambda}_Z$. Inspection of the explicit production amplitudes of Eq. (10) shows a remarkable symmetry in the λ and $\tilde{\lambda}$ dependence: apart from threshold effects it is always the combination $\lambda \pm i\tilde{\lambda}$ which enters in the production amplitudes (here we neglect the tiny contribution of λ in the case of two longitudinally polarized vector bosons). From the total cross section Figs. 1, 4, and 5 it is obvious that interference effects with the SM amplitude are unimportant for λ and they are absent for $\tilde{\lambda}$ which contributes only to the imaginary part of the production amplitudes. Hence the enhancement of the production cross sections for anomalous values of λ and $\tilde{\lambda}$ are very similar and one obtains almost identical sensitivities to $\tilde{\lambda}$ and λ in Tevatron experiments, $|\tilde{\lambda}| \lesssim 1$ from 4.7 pb^{-1} and $|\tilde{\lambda}| \lesssim 0.4$ from 100 pb^{-1} of data.

In principle, $p\bar{p}$ experiments are well suited to study CP-odd asymmetries, which could distinguish λ and $\tilde{\lambda}$, because the initial state is a CP eigenstate. (For W^+W^- production a listing of CP-odd observables can be found in Ref. 1.) However, from the bound of order $|\tilde{\lambda}| \lesssim 1$, which is expected from the present CDF data, it is clear already that too few events will be observed even with an integrated luminosity of 100 pb^{-1} to study such CP-odd distributions: with 100 pb^{-1} less than 20 double leptonic $W^\pm Z$ decays and less than 80 double leptonic W^+W^- decays are expected for $|\tilde{\lambda}| < 1$ at the Tevatron.

Even if an enhancement of the total vector boson pair cross sections due to anomalous couplings is observed in future high-luminosity runs of the Tevatron, the study of possible CP violation in vector-boson-pair physics remains a task for LEP II.

V. CONCLUSIONS

With the 4.7 pb^{-1} of data accumulated so far at the Tevatron weak-boson pair production (W^+W^- and $W^\pm Z$) starts to become accessible to experimental examination. While SM predictions for the rates would still be marginal, deviations from the gauge theory prediction for the three-vector-boson vertices generally lead to largely enhanced cross sections. Nonobservation of excess W^+W^- or $W^\pm Z$ events may already allow the CDF Collaboration to put bounds on possible deviations of roughly $|\lambda| < 1$ and $|\kappa - 1| < 1.3$.

In a future run collecting 100 pb^{-1} of data these bounds can be improved to $|\lambda| \lesssim 0.4$, using the WZ mode only. (We have assumed that the W^+W^- mode will have a substantial background from $t\bar{t}$ decays.)

These bounds have to be compared to low-energy and unitarity constraints and what can be achieved in single-W production at HERA and in W^+W^- production at LEP II. Low-energy constraints restrict $|\kappa_\gamma - 1|$ and $|\kappa_Z - 1|$ to be smaller than 1, with a strong correlation between the two, while essentially no low-energy constraints exist for the SU(2)-symmetric situation $\lambda_\gamma = \lambda_Z$ (Ref. 11). Hence the Tevatron will mainly provide new information on λ. Single-W production at HERA (Ref. 2) is mainly sensitive to $\kappa_\gamma - 1$, which can eventually be measured with an accuracy of ± 0.4 (at the 1σ level) while the sensitivity to λ_γ is worse by a factor 2 to 3, and HERA is not sensitive at all to anomalous WWZ couplings.

W pair production at LEP II is sensitive to $\kappa_\gamma - 1$, $\kappa_Z - 1$, λ_γ, and λ_Z at the ± 0.1 to ± 0.2 level (1σ) (Ref.

21); however it is only a linear combination of WWZ and $WW\gamma$ couplings which is measured in W^+W^- production, and separating the two requires polarized beams.[21] The separate measurement of κ_γ at HERA and λ_Z and λ_γ at the Tevatron in WZ and $W\gamma$ production[4] will hence be very useful in interpreting the LEP II data.

One finds, hence, that experiments to measure the $WW\gamma$ and WWZ couplings at the Tevatron, at HERA and at LEP II are largely complementary and they all go beyond the bounds implied by tree-level unitarity [see Eq. (12)]. Measuring the W^+W^-, $W^\pm Z$, and $W^\pm\gamma$ cross sections at the Tevatron is an important task at present and in the future.

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