Boson Pair Production and Triple Gauge Couplings

H.T. Diehl
For the DØ and CDF Collaborations

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

June 1997

Proceedings of the 5th Topical Seminar on The Irresistible Rise of the Standard Model,
San Miniato al Todesco, Italy, April 21-25, 1997
Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Distribution

Approved for public release; further dissemination unlimited.
Boson Pair Production and Triple Gauge Couplings

H. T. Diehl

Fermi National Accelerator Laboratory, Batavia, IL 60510

1. Introduction

The Standard Model (SM) of electroweak interactions makes precise predictions for the couplings between gauge bosons due to the non-abelian gauge symmetry of SU(2)_L \otimes U(1)_Y. These self-interactions are described by the triple gauge boson (trilinear) WWγ, WZW, Zγγ, and ZZγ couplings and the quartic couplings. Vector boson pair production provides sensitive ground for direct tests of the trilinear couplings. The CDF and DØ Collaborations have studied WW, WZ, and ZZ events produced in pp collisions at \( \sqrt{s} = 1.8 \text{ TeV} \) during the 1992-1995 Tevatron run (Run I) [1]. This paper describes the results of those studies.

1.1. WWγ and WWZ Couplings

A formalism has been developed to describe the WWγ and WWZ interactions for models beyond the SM [2]. The effective Lorentz invariant Lagrangian, after imposing C, P, and CP symmetry, is:

\[
\frac{iL_{WWV}}{g_{WWV}} = g_{V} \left( W_{\mu\nu}^{\dagger} W_{\mu\nu} - W_{\mu\nu} W_{\mu\nu}^{\dagger} \right) + \kappa_{V} W_{\mu\nu}^{\dagger} W_{\mu\nu} + \frac{\lambda_{V}}{m_{W}^{2}} W_{\mu\nu}^{\dagger} W_{\mu\nu} V_{\mu\nu},
\]

where V means γ or Z. The factor g_{WWγ} is e; g_{WWZ} is e cot θ_W. The couplings g_{V}^{1}, κ_{V}, and λ_{V} are to be determined by experiment. In the SM, g_{V}^{1} = g_{V}^{2} = κ_{V} = κ_{Z} = 1 and λ_{V} = λ_{Z} = 0.

1.2. ZZγ and ZZZγ Couplings

The trilinear ZZγ and ZZγγ couplings are all expected to be zero in the SM at tree level. Deviations from the SM are characterized [3] by momentum dependent form factors h_{V}^{1} (i = 1, 4), where V means γ or Z. h_{V}^{1}\gamma and h_{V}^{2}\gamma are CP odd, while h_{V}^{1}\gamma and h_{V}^{2}\gamma are CP even. Anomalous ZZγ and ZZγγ couplings enhance the cross section and harden the photon \( E_{T} \) spectrum.

Electromagnetic gauge invariance restricts g_{V}^{1} to 1; however, g_{V}^{2} could be different from the SM prediction. The coupling parameters are related to the magnetic dipole moments (\( \mu_{W} \)) and electric quadrupole moments (\( Q_{W} \)) of the W boson:

\[
\mu_{W} = \frac{e}{2m_{W}} \left( 1 + \kappa + \lambda \right) \text{ and } Q_{W} = -\frac{e}{3m_{W}} \left( \kappa - \lambda \right),
\]

where e and M_{W} are the charge and the mass of the W boson [3].

The effective Lagrangian leads to vector boson pair production cross sections which grow with \( \sqrt{s} \), the square of the invariant mass of the diboson system, for non-SM values of the couplings. In order to avoid unitarity violation, the anomalous couplings are parameterized as form factors with a scale, Λ (e.g., Δκ/1 + \( \delta/\Lambda^{2} \)) [4]. The cross section is enhanced, particularly at high \( \delta \), because the delicate cancellation of some SM amplitudes is destroyed. The total cross section depends quadratically on the anomalous couplings. Furthermore, the transverse momentum of the bosons is larger.
2. $W\gamma$ Production

2.1. Results from CDF

The CDF Collaboration has previously published [6] the results of the Run Ia analysis. Here we report on the analysis of 67 pb$^{-1}$ of the Run Ib data, last updated in July 1995 [7]. $W\gamma$ events are identified by the presence of an isolated muon with $|\eta| < 0.6$ or electron with $|\eta| < 1.1$ and $E_T > 20$ GeV. Missing transverse energy $E_T > 20$ GeV is required. A photon with $E_T > 7$ GeV is required within $|\eta| < 1.1$. The angular separation $\Delta R(\ell\gamma) = \sqrt{\Delta \phi^2 + \Delta \eta^2}$ between the lepton and the photon is required to be greater than 0.7. The $\Delta R$ selection criterion reduces the contribution from events where the photon has radiated from the lepton. CDF found 109 $W\gamma$ candidates.

The background, mainly from $W + \text{jet(s)}$ where a jet mimics a photon, is expected to be $26.4 \pm 2.7$ events. Limits on anomalous $WW\gamma$ couplings [8], from a fit to the photon $E_T$ spectrum, are as follows. For $\Lambda = 1.5$ TeV, $-1.8 < \Delta \kappa < 2.0$ and $-0.7 < \lambda_\gamma < 0.7$ at 95% CL.

SM $W^+\gamma$ production has a radiation zero [9] at $\cos \theta^* = \pm 1/3$, where $\theta^*$ is the angle between the incoming quark and photon in the $W\gamma$ rest frame. Requiring $\Delta R(\ell\gamma) > 1.5$ and that the invariant mass of the lepton and $E_T$ is close to the $W$ boson mass reduces the final state bremsstrahlung. A hint of a radiation zero is observed [7].

2.2. Results from DØ

The DØ Collaboration has previously published the results of the Run Ia (14 pb$^{-1}$) analysis [10]. Here we report on the Run I (93 pb$^{-1}$) combined analysis published recently [11]. $W\gamma$ events are identified by the presence of a high-$p_T$ lepton, either an isolated muon with $|\eta| < 1.0$ or electron with $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. $E_T$ indicative of the decay of a $W$ boson is required. A photon with $E_T > 10$ GeV is required within the same fiducial limits as the electron. As in the CDF analysis, requiring $\Delta R(\ell\gamma) > 0.7$ reduces the number of events where the photon radiated from the lepton.

The combined data sample contains 127 events with a background, due mainly to $W + \text{jet(s)}$ and $Z\gamma$, of $43 \pm 5$ events. The cross section times branching ratio, $\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow \ell\nu)$, with $E_T > 10$ GeV and $\Delta R(\ell\gamma) > 0.7$ is $11.3_{-1.2}^{+1.3}$ (stat) $\pm 1.4$ (sys) $\pm 0.6$ (lum) pb, in agreement with the SM prediction $12.5 \pm 1.0$ pb. Limits on anomalous $WW\gamma$ couplings for $\Lambda = 1.5$ TeV are $-0.93 < \Delta \kappa < 0.94$ and $-0.31 < \lambda < 0.29$ at 95% CL (the limits on CP-violating couplings $\tilde{\kappa}$ and $\tilde{\lambda}$ are similar). These are the tightest limits presently available for $WW\gamma$ couplings.

One particularly interesting result is the exclusion, at 96% CL, of the $U(1)_{EM}$—only point $\kappa = 0, \lambda = 0$. Exclusion of this point is direct evidence that the photon couples to more than just the electric charge of the $W$ boson. This is a triumphant confirmation of the SM gauge theory prediction.

3. $WW$ and $WZ$ Production

3.1. Results from DØ

The DØ Collaboration has studied the channels $pp \rightarrow WW \rightarrow b\tau\tau\nu\nu$, $(t, t' = e, \mu)$ and $pp \rightarrow WW(WZ) \rightarrow ev\text{jet} + X$. The background from $W + \text{jet(s)}$ makes it difficult to extract a SM signal for the latter. Results of a search for a $WW \rightarrow$ dileptons signal in the Run Ia data, leading to limits on $WW\gamma$ and $WZW$ anomalous couplings, has been previously published [12]. The results of a search for a non-SM signal in the Run Ia data of the $WW(WZ) \rightarrow ev\text{jet}$ decay mode have also been previously published [13]. All of the Run Ia analyses (including the $W\gamma$, $WW/WZ$, and $Z\gamma$ analyses) are described in detail in a previous publication [14]. The combined Run Ia $W\gamma$ and $WW/WZ$ analyses provide anomalous coupling limits (assuming the $WW$ and $WW\gamma$ couplings are equal) of $-0.71 < \Delta \kappa < 0.89$ and $-0.44 < \lambda < 0.44$ for $\Lambda = 1500$ GeV [14]. These analyses have been extended into Run Ib data.

The signature of the dilepton decay of a $WW$ is two high-$p_T$ charged leptons along with large $E_T$. The $E_T$ and $E_{\text{T}T}$ cuts depend on the particular decay mode $ee, e\mu, or \mu\mu$, because of the difference in the $p_T$ resolution of the DØ electron and muon detectors. In order to reduce the background from $Z$ boson decays, cuts are made on the azimuthal angle between the $E_{\text{T}T}$ and leptons. Fur-
ther rejection of $Z \to ee$ is obtained by requiring that $|M_{\gamma} - M_Z| > 15$ GeV/c$^2$. For the $e\mu\nu$ decay channel, it was required that $\Delta R(\mu, e) > 0.5$ to reject $W$ bosons with a tracked-matched photon due to bremsstrahlung radiation from the muon. The background due to $t\bar{t}$ production was reduced by requiring $|E_{T}^{miss}| < 40$ GeV. Four $(2 e\mu, 1 ee, 1 e\mu)$ candidates were found in the Run Ib data with an expected background of $2.6 \pm 0.4$ events. The 95% CL upper limit for $\sigma(WW + X)$ is 43 pb. Limits on anomalous couplings for $\Lambda = 1$ TeV are $|\Delta \kappa| < 1.2$ and $|\lambda| < 1.0$ at 95% CL, assuming the $WW\gamma$ and $WWZ$ couplings are equal, from the upper limit on the cross section. DØ expects to have substantially improved anomalous coupling limits from a 2-dimensional fit to the two lepton $p_T$'s in the near future.

DØ has extended the search for a non-SM signal of the semileptonic decay modes of $WW$ and $WZ$ to the Run Ib data. An electron with $(E_T > 25 \text{ GeV})$ and $(E_T > 25 \text{ GeV})$ which combine to form a transverse mass, $M_T(e\nu) > 40$ GeV/c$^2$, indicate the presence of a $W$ boson decay. In addition, two jets (formed with a cone radius of 0.5 in $p_T$ space) with $E_T > 20$ GeV are required; they must form an invariant mass $M(\text{dijet})$ between 50 and 110 GeV/c$^2$. This provides the $W$ or $Z$ decay to jets. It is required that $|E_T(\text{jet jet}) - E_T(e\nu)| < 40$ GeV. Requiring that the two bosons have nearly the same $E_T$ reduces the background from $t\bar{t}$. In a data sample comprising 82.3 pb$^{-1}$, 399 candidates are found. Of these, only $17.5 \pm 3.0$ are expected to be $WW$ or $WZ$ events. The remainder are principally $W +$ jets and QCD fake events.

Limits on anomalous $WW\gamma$ and $WWZ$ couplings are made by fitting the $E_T(e\nu)$ spectrum with the data with that expected of the background plus signal as a function of anomalous couplings. Combining the Run Ia and Run Ib semileptonic decay analyses yields limits, for $\Lambda = 2000$ GeV, of $-0.33 < \lambda < 0.36$ and $-0.43 < \Delta \kappa < 0.59$ under the assumption that $\lambda = \lambda_Z$ and $\Delta \kappa = \Delta \kappa_Z$. Limits using a different assumption, that the $WW\gamma$ have the SM values (so as to contribute minimally to the cross section), shows the exclusion at more than 95% CL of the point $\kappa_Z = 0$ $\lambda_Z = 0$. Exclusion of this point is direct evidence that the $W$ boson couples directly to the $Z$ boson. This is an important confirmation of the electroweak gauge theory first noted in a CDF publication [16]. This result has been submitted for publication [18].

3.2. Results from CDF

CDF has studied the dilepton and semileptonic decay modes of $WW$ and $WZ$ production. The $WW(WZ) \to \ell\nu$ jet jet $(\ell = e, \mu)$ analysis from Run Ia is long since published [16].

CDF has recently published [17] a study of $pp \to WW \to b\bar{b}P_{\nu}\nu$ $(\ell, \ell' = e, \mu)$ based on the Run I data. Two isolated charged leptons with $E_T > 20$ GeV and $E_T > 25$ GeV are required. In order to reduce background from $Z$ boson decays, events with $ee$ or $\mu\mu$ invariant mass in the range $75 - 105$ GeV/c$^2$ are rejected and, similar to the DØ analysis, events with $\Delta \phi(E_T, \ell)$ are rejected if $E_T < 50$ GeV. Finally, events with any jet with $E_T > 10$ GeV are rejected in order to reduce the background from $t\bar{t}$ production. Five $(3 e\mu, 2 ee, 0 \mu\mu)$ candidates were found in a data sample with an integrated luminosity of 108 pb$^{-1}$. The background, mainly from Drell-Yan lepton pair production and events with fake leptons, is $1.2 \pm 0.3$ events. From this, CDF has enough evidence to quote a cross section $\sigma(WW) = 10.2^{+6.3}_{-5.1} \pm 1.6$ pb. This is the first measurement of $WW$ production and it is consistent with the SM prediction [18] of $9.5 \pm 1.0$ pb. Limits on anomalous couplings for $\Lambda = 1$ TeV are $-1.1 < \Delta \kappa < 1.3$ and $-0.8 < \lambda < 0.9$ at 95% CL, assuming the $WW\gamma$ and $WWZ$ couplings are equal, from the upper limit on the cross section. CDF is in the process of extending the search for a non-SM signal of the semileptonic decay modes of $WW$ and $WZ$ to the Run Ib data. A high-$p_T$ electron or muon $(> 20 \text{ GeV/c})$ and $E_T > 20$ GeV which combine to form a transverse mass, $M_T(\ell\nu) > 40$ GeV/c$^2$, indicate the presence of a $W$ boson decay. In addition, two jets (formed with a cone radius of 0.4) with $E_T > 25$ GeV are required; they must form an invariant mass $M(\text{dijet})$ between 60 and 110 GeV/c$^2$. This provides the $W$ or $Z$ decay to jets. Unlike the DØ analysis, CDF requires that the jet-pair has
an $E_T > 200$ GeV. This eliminates the need for a background estimate but limits the sensitivity of the analysis by pinching the acceptance to a region between $200 < p_T(W) < 350$ GeV/c. The upper bound comes from the merging of the two jets at high $p_T(W)$.

No candidate events are seen in a 110 pb$^{-1}$ Run IA + Run Ib sample. Preliminary results for the anomalous coupling limits at $\Lambda = 2000$ GeV are $-0.49 < \Delta \kappa < 0.54$ and $-0.35 < \lambda < 0.32$ at 95% CL, assuming the $WW\gamma$ and $WWZ$ couplings are equal. These results are comparable to those from the D$\bar{\Omega}$ analysis. The two analyses have the tightest available limits for $\Delta \kappa$. The limits on $\lambda$ are close to those obtained from the D$\bar{\Omega}$ $WW\gamma$ analysis noted above.

4. $Z\gamma$ Production

4.1. Results from CDF

The CDF Collaboration has previously published the results of the Run IA $Z\gamma \rightarrow ee\gamma(\mu\mu\gamma)$ analysis [19]. An analysis [7] based on a 67 pb$^{-1}$ subsample of the Run Ib data is presented here.

$Z\gamma$ candidates are identified by the presence of two charged leptons with large $E_T$ and a photon. The $E_T$ threshold is decreased from 20 GeV to 10 GeV for the lower $E_T$ electron. The muon thresholds remain at 20 GeV. The pseudorapidity range is increased from $|\eta| < 1.1$ (6.8) to $|\eta| < 4.2$ (1.2) for the lower $E_T$ electron (muon). The photon has the same selection requirements, including $\Delta R(\ell, \gamma)$, as in the $W\gamma$ analysis described above. 31 Candidates are found with 18 in the $ee\gamma$ and 13 in the $\mu\mu\gamma$ decay modes. The background is expected to be $1.4 \pm 0.3$ events, dominated by $Z + \text{jet(s)}$ where the jet mimics a photon. The predicted number of events, including background, from the SM is $26.3 \pm 2.6$ events. This is in agreement with the observed number. The highest $E_T$ photons are 39 and 64 GeV. An event in the remaining (unanalyzed) part of the Run Ib data has a $Z\gamma$ candidate with a photon of $E_T = 182$ GeV. A fit of the observed $E_T^\gamma$ to that expected from the SM + background yields limits on anomalous $ZZ\gamma$ couplings. They are: $|h^Z_{30}(h^Z_{10})| < 1.6$ and $|h^Z_{50}(h^Z_{10})| < 0.4$. The $Z\gamma\gamma$ limits are similar.

4.2. Results from D$\bar{\Omega}$

The D$\bar{\Omega}$ collaboration previously published the results of the Run IA (14 pb$^{-1}$) analysis of the $Z\gamma \rightarrow ee\gamma(\mu\mu\gamma)$ (charged lepton) decay modes [20]. The analysis of the Run Ib charged lepton decay mode was updated for this conference and presented for the first time including both the $ee\gamma$ and $\mu\mu\gamma$ channels. The analysis of the Run Ia data for the $Z\gamma \rightarrow \nu\nu\gamma$ decay channel was recently published [14,21] and will also be summarized below.

In the Run Ib analysis, $Z\gamma \rightarrow ee\gamma$ candidates are identified by the presence of two electrons with $E_T > 25$ GeV and a photon with $E_T > 10$ GeV. The electrons and photons are required to fall with the pseudorapidity range $|\eta| < 1.0$ or $1.5 < |\eta| < 2.5$. $Z\gamma \rightarrow \mu\mu\gamma$ events are identified using either of two selection criteria. For the "tight" selection, two isolated muons with $|\eta| < 1$ and $p_T^\mu > 15$ (6) GeV/c must be identified using the muon tracking detectors. For the "loose" selection, one muon with $|\eta| < 1$ and $p_T^\mu > 15$ GeV/c is identified using the muon tracking detectors; the second muon is identified by the coincidence of the isolated energy deposition left by the muon through the longitudinal layers of the calorimeter with the azimuthal direction of the $E_T$ corrected only for the "tracked" muon. The photon must have $E_T > 10$ GeV and be in the same fiducial region as those from the $W\gamma$ analysis. In both the electron and muon analyses, the photons are isolated from the electrons by requiring $\Delta R > 0.7$ to remove final state bremsstrahlung photons. 29 Candidates are identified, 14 in the $ee\gamma$ and 15 in the $\mu\mu\gamma$ channels. The total expected background is $5.4 \pm 1.0$ events, primarily from $Z + \text{jet(s)}$ with a jet that mimics a photon and (muon channel only) $W + \gamma$ events with an second, fake muon. The number of candidates agrees with the SM prediction of 29 $\pm$ 3 events. The photon spectrum, shown in Fig. 1, shows qualitative agreement with the SM prediction. Two events in the $ee\gamma$ channel have $E_T^\gamma > 75$ GeV, dielectron invariant mass $M_{e\gamma} \sim M_Z$, and $M_{e\gamma} \sim 200$ GeV/c$^2$. The probability for the SM signal + background to have two or more events with $E_T^\gamma > 60$ GeV is 16%, including the $\mu\mu\gamma$ decay mode. Anomalous coupling limits, formed
with $\Lambda = 500$ GeV, are $|h^Z_{20}(h^Z_{10})| < 1.36$ and $|h^Z_{40}(h^Z_{20})| < 0.26$ at 95% CL. The $Z\gamma\gamma$ limits are similar.

Run Ia anomalous coupling limits for $\Lambda = 500$ GeV are $|h^Z_{20}(h^Z_{10})| < 0.78$ and $|h^Z_{40}(h^Z_{20})| < 0.19$ at 95% CL. For $\Lambda = 750$ GeV the limits are $|h^Z_{20}(h^Z_{10})| < 0.44$ and $|h^Z_{40}(h^Z_{20})| < 0.06$. The $Z\gamma\gamma$ limits are similar. These are the most restrictive $ZZ\gamma$ and $Z\gamma\gamma$ limits available.

5. Prospects

There will be substantial improvements in the anomalous coupling limits in the near future as CDF and DØ continue to analyze the Run Ib data. Ultimately, the two experiments will combine their results to produce Tevatron limits for Run I.

Presently DØ and CDF are working on their detector upgrades for Run II. The Main Injector will allow the Tevatron to provide 2 fb$^{-1}$ data samples to each detector at $\sqrt{s} = 2000$ GeV. For DØ, the addition of a solenoid magnet and new tracking system will improve the muon resolution. The CDF detector will have improved electron and photon acceptance in the forward direction.

Limits on anomalous couplings scale by approximately the $1/4$ root of the luminosity for fixed $\Lambda$ and assuming no improvement in technique. The large luminosity will provide upwards of 3000 $W\gamma \rightarrow \ell\nu\gamma$ events, 700 $Z\gamma \rightarrow ee\gamma + \mu\mu\gamma$ events, 100 $WW \rightarrow$ dileptons events, some 30 $WZ \rightarrow$ trileptons and a handful of $ZZ \rightarrow e^+e^-\mu^+\mu^-$ and $\mu^+\mu^-\mu^+\mu^-$ events. CDF has already observed a $ZZ \rightarrow e^+e^-\mu^+\mu^-$ event during Run I. Figure 2 shows their $ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$ event. This is the first $Z$ boson pair candidate recorded. Qualitatively, the $W\gamma$, and perhaps, the $WZ$ radiation zeroes will be unambiguously observed. Anomalous coupling limits will begin to probe the theoretical expectations.

6. Conclusions

In summary, the Tevatron continues to dominate observation of vector boson pair production. All of the pair production decay modes are accessible. Limits on anomalous coupling $WW\gamma$, $WWZ$, $ZZ\gamma$, and $Z\gamma\gamma$ couplings remain, by a large margin, the tightest available. The prospects for Run II indicate the situation will
Figure 2. The $ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$ candidate from the Run I CDF data.

remain so for some time.

I am grateful to the Tevatron Collider staff, to both collaborations, and particularly to Gerry Guglielmo, Chris Murphy, Greg Landsberg, Mike Tuts, and Larry Nodulman.

REFERENCES

1. Run I was divided into three time periods. The initial period, consisting of $\sim 20$ (14 pb$^{-1}$) recorded at CDF (DØ), is generally named “Run Ia.” The second time period, “Run Ib,” consisted of $\sim 90$ (93 pb$^{-1}$) recorded at CDF (DØ). A short “Run Ic” occurred in early 1996.


8. Limits on anomalous couplings are typically 2-dimensional contours (e.g. $\lambda$ vs. $\Delta k$). Throughout this paper I quote the intersections of the contours with the coordinate axes.


