Abstract

Direct measurements of vector boson pair production processes and trilinear gauge boson couplings have been conducted by the CDF and DØ Collaborations. Preliminary results from searches for anomalous $WW/WZ \to \mu\nu$ jet jet and $WZ \to ee\nu\nu$ production are presented. 95% CL anomalous coupling limits from previously published DØ results are $-0.20 < \lambda < 0.20$ ($\Delta\kappa = 0$) and $-0.30 < \Delta\kappa < 0.43$ ($\lambda = 0$) for $\Lambda = 2000$ GeV where the $WW\gamma$ couplings are assumed to equal the $WWZ$ couplings. Combined DØ + LEP experiment anomalous coupling limits are presented for the first time. 95% CL limits are $-0.16 < \lambda_\gamma < 0.10$ ($\Delta\kappa = 0$) and $-0.15 < \Delta\kappa_\gamma < 0.41$ ($\lambda = 0$) under the assumption that the couplings are related by the “HISZ” constraints. 95% CL anomalous $ZZ\gamma$ and $Z\gamma\gamma$ coupling limits from DØ are $|h_{50}^Z| < 0.36$ ($h_{30}^Z = 0$) and $|h_{50}^Z| < 0.05$ ($h_{30}^Z = 0$) for $\Lambda = 750$ GeV. CDF reports the first observation of a $ZZ$ event. Prospects for Run II are discussed.
VECTOR BOSON PAIR PRODUCTION AND TRILINEAR GAUGE BOSON COUPLINGS - RESULTS FROM THE TEVATRON

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Direct measurements of vector boson pair production processes and trilinear gauge boson couplings have been conducted by the CDF and DØ Collaborations. Preliminary results from searches for anomalous WW/WZ → µν jet jet and WZ → eee jet production are presented. 95% CL anomalous coupling limits from previously published DØ results are −0.20 < λ < 0.20 (∆κ = 0) and −0.30 < ∆κ < 0.43 (λ = 0) for λ = 2000 GeV where the WWγ couplings are assumed to equal the WWZ couplings. Combined DØ + LEP experiment anomalous coupling limits are presented for the first time. 95% CL limits are −0.16 < λ < 0.10 (∆κ = 0) and −0.15 < ∆κ < 0.41 (λ = 0) under the assumption that the couplings are related by the “HISZ” constraints. 95% CL anomalous ZZγ and Zγγ coupling limits from DØ are |h_{Z0}| < 0.36 (h_{Z0} = 0) and |h_{Z0}| < 0.05 (h_{Z0} = 0) for λ = 750 GeV. CDF reports the first observation of a ZZ event. Prospects for Run II are discussed.

1 Introduction

The Standard Model of electroweak interactions makes precise predictions for the couplings between gauge bosons due to the non-abelian gauge symmetry of SU(2)L ⊗ U(1)Y. These self-interactions are described by the triple gauge boson (trilinear) WWγ, WWZ, Zγγ, and ZZγ couplings and the quartic couplings. Deviations of the couplings from the Standard Model (SM) values would indicate the presence of new physical phenomena.

The WWV (V = γ or Z) vertices are described by a general effective Lagrangian \( \mathcal{L} \) with two overall couplings, \( g_{WWV} = -e \) and \( g_{WWZ} = -e \cdot \cot \theta_W \), and six dimensionless couplings \( g_i^V, \kappa_V \), and \( \lambda_V \) (V = γ or Z), after imposing C, P and CP invariance. Electromagnetic gauge invariance requires that \( g_i^V = 1 \), which we assume throughout this paper. The SM Lagrangian is obtained by setting \( g_i^V = g_i^Z = 1, \kappa_V = 1(\Delta \kappa_V = \kappa_V - 1 = 0) \) and \( \lambda_V = 0 \).

A different set of parameters, motivated by SU(2) x U(1) gauge invariance, has been used by the LEP collaborations. This set consists of three independent couplings \( \alpha_{B\phi}, \alpha_{W\phi} \) and \( \alpha_W \): \( \alpha_{B\phi} = \Delta \kappa_Z - \Delta g_1^Z \cos^2 \theta_W, \alpha_{W\phi} = \Delta g_2^Z \cos^2 \theta_W, \) and \( \alpha_W = \lambda_W \). The remaining WWZ coupling parameters \( \lambda_Z \) and \( \Delta \kappa_Z \) are determined by the relations \( \lambda_Z = \lambda_{W\phi} \) and \( \Delta \kappa_Z = -\Delta \kappa_V \tan^2 \theta_W + \Delta g_2^Z \). The HISZ relations have been used by the DØ and CDF collaborations, and our approach is based on this set with the additional constraint \( \alpha_{B\phi} = \alpha_{W\phi} \).

The cross section with non-SM couplings grows with \( \lambda \). In order to avoid unitarity violation, the anomalous couplings are modified as form factors with a scale \( \Lambda \): \( \lambda_V(\hat{s}) = \frac{\lambda_V}{(1 + \hat{s}/\Lambda^2)}, \) and \( \Delta \kappa_V(\hat{s}) = \frac{\Delta \kappa_V}{(1 + \hat{s}/\Lambda^2)} \).

The ZγV (V = γ or Z) vertices are described by a general vertex function \( \mathcal{V}(\lambda, \Delta \kappa) \) with eight dimensionless couplings \( h_i^V (i = 1, 4; V = \gamma \text{ or } Z) \). In the SM, all of \( h_i^V \)'s are zero. The form factors for these vertices, similar to the WWV vertices, are \( h_i^V(\hat{s}) = \frac{h_i^{V_i}}{(1 + \hat{s}/\Lambda^2)}, \) where \( n = 3 \) for \( i = 1, 3 \) and \( n = 4 \) for \( i = 2, 4 \).

Vector boson pair production provides sensitive ground for direct tests of the trilinear couplings. This paper provides a description of recent results from DØ and CDF, including preliminary results from searches for anomalous couplings in WW/WZ → µν jet jet and WZ → eee final states at DØ, a description of a recently published, combined analysis, anomalous WWγ and WWZ coupling result from DØ, combined DØ + LEP anomalous WWγ and WWZ couplings results (presented for the first time), limits on anomalous Zγγ and ZZγ couplings from studies of Zγ final states at DØ, and report of the observation of a ZZ → µµµµ event at CDF in Run I. Prospects for Run II are discussed.

2 Preliminary Results from DØ

2.1 Search for anomalous WW/WZ → µν jet jet Production

This analysis searches for anomalous WW or WZ production using the decay signature \( W \rightarrow \mu\nu \) and \( W/Z \rightarrow jj \). We cannot distinguish between W and Z decays to jets. Further, because SM WW and WZ production is swamped by backgrounds having this same signature, the analysis is sensitive only to production with anomalous couplings.

We selected events with an isolated, central muon with \( p_T > 20 \text{ GeV/c} \) and with \( E_T > 20 \text{ GeV} \) where the transverse mass \( M_T(\mu\nu) > 40 \text{ GeV}/c^2 \), indicative of a W boson decay. We required that the event contain at least two jets with \( E_T > 20 \text{ GeV} \). For 224 of the 372
candidates which survived those selection criteria, the invariant mass of the two highest $E_T$ jets was between 50 and 110 GeV/$c^2$, as expected from the hadronic decay of a $W$ or $Z$ boson. From Monte Carlo simulation, we expected $4.04^{+0.54}_{-0.68}$ WW events and $0.49^{+0.10}_{-0.11}$ WZ events, given SM trilinear couplings. Of course, if the couplings are non-SM, there will be an excess of events with high-$p_T$ W bosons.

The background consists principally of $W^+ + W^- > 2$ jets (117 ± 24 events expected) and multijet events with an accidentally isolated muon from a heavy quark decay (105 ± 19 events expected). Small contributions to the background arise from $t\bar{t}$ production. The total expected background is 224 ± 31 events. Figure 1 shows the dijet invariant mass and $p_T(\mu\nu)$ for the data and expected background.

Since we observed no excess of events in the high-$p_T(\mu\nu)$ region, we place upper limits on anomalous $WW\gamma$ and $WWZ$ couplings. This is performed using a binned likelihood fit of the observed $p_T(\mu\nu)$ spectrum to the expected $p_T(\mu\nu)$ spectrum, given anomalous couplings plus the expected background. The 1-D 95% CL coupling limits are $-0.45 < \lambda < 0.46$ ($\Delta\kappa = 0$) and $-0.62 < \Delta\kappa < 0.78$ ($\lambda = 0$) for $\Lambda = 1500$ GeV, assuming the $WW\gamma$ couplings equal the $WWZ$ couplings. While previous analyses have produced more restrictive anomalous coupling limits, these results will ultimately contribute to the DØ combined results.

2.2 Search for $WZ \rightarrow eee\nu$ Events

Searches for anomalous $WZ$ production enable the possibility of constraining the $WWZ$ couplings independent of the $WW\gamma$ couplings. DØ has searched for the process $WZ \rightarrow eee\nu$. Two electrons with $E_T > 25$ GeV, one more electron with $E_T > 10$ GeV, and $E_T > 15$ GeV are required in candidate events. The transverse mass of one electron and the $E_T$ must be greater than 30 GeV/$c^2$. The invariant mass of the other two electrons must be between 81 and 101 GeV/$c^2$. One candidate survives the selection criteria.

Based on SM Monte Carlo, $0.146 \pm 0.011$ WZ events are expected. The background, principally due to $Z+\text{jet}$ events where the jet mimicks an electron and there is accidental $E_T$, amounts to $0.38 \pm 0.14$ events. Figure 2 shows the candidate’s event display. One pair of electrons has invariant mass of 93.6 GeV/$c^2$; the transverse mass of the other electron and the missing $E_T$ is 74.7 GeV/$c^2$.

$WZ$ production is more sensitive to the value of $\lambda_Z$ and $\Delta g_\gamma^Z$ than $\Delta\kappa_Z$. Given one observed event and taking into account the expected background, 95% CL limits are $|\lambda| < 2.07$ ($\Delta g_\gamma^Z = 0$) and $|\Delta g_\gamma^Z| < 2.56$ ($\lambda_Z = 0$) for $\Lambda = 1000$ GeV. Although the limits are looser than those previously measured, they are independent of any assumptions on the relation between $WW\gamma$ and $WWZ$ couplings. Ultimately, these results will help constrain $\Delta g_\gamma^Z$ in DØ’s combined limits.

3 Combined $WW\gamma$ and $WWZ$ Anomalous Coupling Limits from DØ

We have combined previously published limits on $WW\gamma$ couplings obtained from a fit to the photon $E_T$ spectrum in $W\gamma$ events, limits on $WWZ$ and $WW\gamma$ couplings obtained from a fit to the $E_T$ of the two charged leptons in $WW \rightarrow $ dilepton events, and limits on $WWZ$ and
of new LEP results.

Table 1: Limits at 95% C.L. from a simultaneous fit to the DØ $W\gamma$, $WW \rightarrow$ dilepton and $WW/WZ \rightarrow e\nu jj$ data samples. The four sets of limits apply the same assumptions as the four components (a), (b), (c) and (d), respectively, of Fig. 3. The HISZ results include the additional constraint $\alpha_{B\phi} = \alpha_{W\phi}$.

| Coupling | $\Lambda = 1.5$ TeV | $\Lambda = 2.0$ TeV |
|----------|---------------------|---------------------|
| $\lambda = \lambda_Z (\Delta \kappa_Z = \Delta \kappa = 0)$ | $-0.21, 0.21$ | $-0.20, 0.20$ |
| $\Delta \kappa = \Delta \kappa_Z (\lambda = \lambda_Z = 0)$ | $-0.33, 0.46$ | $-0.30, 0.43$ |
| $\lambda_Z (\text{HISZ}) (\Delta \kappa_Z = 0)$ | $-0.21, 0.21$ | $-0.20, 0.20$ |
| $\Delta \kappa_Z (\text{HISZ}) (\lambda = 0)$ | $-0.39, 0.61$ | $-0.37, 0.56$ |

Table 2: Limits at 95% C.L. on $\alpha$ parameters from a simultaneous fit to the DØ $W\gamma$, $WW \rightarrow$ dilepton and $WW/WZ \rightarrow e\nu jj$ data samples.

**4 Combined DØ and LEP Anomalous $WW\gamma$ and $WWZ$ Couplings**

The published results from DØ and the four LEP experiments (see the summary by Hywel Phillips) were combined to produce the tightest available $WW\gamma$ and $WWZ$ coupling limits. The procedure, documented in detail in preprint form [1], is to add the negative log-likelihoods presented as a function of trilinear coupling from the several LEP analyses and the combined DØ analysis described above. The one standard deviation limits are obtained directly from the curves by taking the values of the coupling where $\Delta \log \mathcal{L} = +0.5$ from the minimum. The 95% CL limit is given by the values of the coupling where $\Delta \log \mathcal{L} = +1.92$. The dependencies on correlated systematic errors and on $\Lambda$ are negligible. Figures 3 and 4 show log-likelihoods and one $\sigma$ limits on $\lambda_\gamma$ and $\Delta \kappa_\gamma$ where one coupling is varied at a time and the $WWZ$ couplings are related to the $WW\gamma$ couplings through the HISZ equations (without the extra constraint $\alpha_{B\phi} = \alpha_{W\phi}$).

The 95% CL limits are $-0.16 < \lambda_\gamma < 0.10$ ($\Delta \kappa = 0$) and $-0.15 < \Delta \kappa_\gamma < 0.41$ ($\lambda = 0$). These limits provide an update to the original analysis [3] due to the inclusion of new LEP results.

![Figure 3](image_url)
5 \(Z\gamma\) and \(ZZ\) Production and Anomalous \(ZZ\gamma\) and \(Z\gamma\gamma\) Couplings from DØ and CDF

DØ has recently published studies of \(Z\gamma\) production using the \(\nu\nu\gamma\), \(ee\gamma\), and \(\mu\mu\gamma\) final states. The two neutrino final state makes up for its smaller integrated luminosity by having a larger branching fraction than the charged lepton mode and has the advantage that there are no photons radiating from the \(Z\)'s decay products. On the other hand, in the charged-lepton decay mode the backgrounds are smaller and the final state can be completely reconstructed.

The \(Z\gamma \to \nu\nu\gamma\) analysis, with a minimum photon \(E_T\) of 40 GeV, yielded 4 candidates with an expected background of 5.8±1.0 events in an integrated luminosity of 14 pb\(^{-1}\). The analysis of the charged-lepton decay mode yielded 29 candidates with an expected background of 5.4±1.0 events in 97 pb\(^{-1}\). It is interesting that there were two events in the charged-lepton sample with an \(\sim 75\) GeV photon and with an \(\ell^+\ell^-\gamma\) invariant mass of \(\sim 200\) GeV/c\(^2\). SM \(Z\gamma\) production would yield two or more events with \(E_T^{\gamma} > 60\) (70) GeV in 15% (7.3%) of repeats of the experiment. Also, SM Monte Carlo indicates the most likely \(Z\gamma\) mass for events with \(E_T^{\gamma}\) in the range 70 to 79 GeV is 200 GeV/c\(^2\). CDF noted a \(Z\gamma\) event with \(E_T^{\gamma} \sim 64\) GeV and \(M(\mu\mu\gamma) \sim 188\) GeV/c\(^2\) in their 20 pb\(^{-1}\) sample from Run Ia. While there is no evidence of non-SM physics here, it is something to keep one’s eye on in the future.

The tightest limits on anomalous \(ZZ\gamma\) and \(Z\gamma\gamma\) couplings are those from the combined DØ analyses. At 95% CL, the \(Z\gamma\gamma\) limits are \(|h^{Z\gamma}_{30}(h^{Z\gamma}_{10})| < 0.37\) and \(|h^{30}_{10}(h^{30}_{20})| < 0.05\) with \(\Lambda = 750\) GeV. The \(ZZ\gamma\) limits are similar.
6 Prospects for the Near Future and for Run II

In the immediate future, DØ will combine the two new analyses with the previous, finalizing the Run I anomalous WWγ and WWZ coupling limits. Perhaps CDF will finish its Run I Wγ and Zγ analyses soon.

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. These modifications strengthen the detectors’ ability to study diboson final states.

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 data samples will provide upwards of 3000 Wγ → ℓνγ events, 700 Zγ → $ee\gamma + \mu\mu\gamma$ events, 100 WW → dileptons events, some 30 WZ → trileptons and a handful of ZZ → $e^+e^-$ events and $\mu^+\mu^-$ per experiment.

CDF has already observed a ZZ event during Run I. Figure 7 shows their ZZ → $\mu^+\mu^-\mu^+\mu^-$ event. This is the first Z boson pair candidate recorded. They expected slightly less than one such event in Run I.

Qualitatively, the Wγ, and perhaps, the WZ radiation zeroes will be unambiguously observed. Anomalous trilinear coupling limits will begin to probe the theoretical expectations. The first measurements of quadrilinear couplings will be available.

7 Summary

Direct measurements of vector boson pair production processes and trilinear gauge boson couplings have been conducted by the CDF and DØ Collaborations. Preliminary results from searches for anomalous WW/WZ → $\mu\nu$ jet jet and WZ → $eee\gamma$ production from DØ were presented. 95% CL anomalous coupling limits from previously published DØ results are $-0.20 < \lambda < 0.20$ ($\Delta\kappa = 0$) and $-0.30 < \Delta\kappa < 0.43$ ($\lambda = 0$) for $\Lambda = 2000$ GeV where the WWγ couplings are assumed to equal the WWZ couplings. Combined DØ + LEP experiment anomalous coupling limits were presented for the first time. 95% CL limits are $-0.16 < \lambda < 0.10$ ($\Delta\kappa = 0$) and $-0.15 < \Delta\kappa < 0.41$ ($\lambda = 0$) under the assumption that the couplings are related by the “HISZ” constraints.

95% CL anomalous ZZγ and Zγγ coupling limits from DØ are $h_{ZZ0}^0 < 0.36$ ($h_{ZZ0} = 0$) and $h_{ZZ0}^0 < 0.05$ ($h_{ZZ0} = 0$) for Λ = 750 GeV. CDF reports the first observation of a ZZ event.

Run II, with upgrades to the CDF and DØ detectors and larger integrated luminosities due primarily to the Main Injector, will provide even more tantalizing opportunities for studying gauge boson couplings.

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