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Vector Boson Pair Production and Trilinear Gauge Boson Couplings - Results from the Tevatron

H.T. Diehl
For the CDF and D0 Collaborations

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

October 1998

Published Proceedings of the *ICHEP98, XXIX International Conference on High Energy Physics,* Vancouver, B.C., Canada, July 23-29, 1998

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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HEP-EX/9810006

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H. T. Diehl
For the CDF + DØ Collaborations
Fermi National Accelerator Laboratory, Batavia, IL 60510
(September 25, 1998)

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 $WW/WZ \rightarrow \mu\nu$ jet jet and $WZ \rightarrow$ eeeν 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 $|h^Z_{30}| < 0.36$ ($h^Z_{40} = 0$) and $|h^Z_{40}| < 0.05$ ($h^Z_{30} = 0$) for $\Lambda = 750$ GeV. CDF reports the first observation of a ZZ event. Prospects for Run II are discussed.

Submitted to the Proceedings of
ICHEP 98 XXIX International Conference on High Energy Physics
UBC, Vancouver, B.C.
Canada
July 23-29, 1998

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H. T. DIEHL

M.S. 357,
Fermi National Accelerator Laboratory,
Batavia, IL 60510, USA
E-mail: DIEHL@FNAL.GOV

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 $WZ \to$ eeeν 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 $|h^Z_{30}| < 0.36$ ($h^Z_{40} = 0$) and $|h^Z_{40}| < 0.05$ ($h^Z_{30} = 0$) for $\Lambda = 750$ 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 $SU(2)_L \otimes U(1)_Y$. These self-interactions are described by the triple gauge boson (trilinear) $WW\gamma$, WWZ, $Z\gamma\gamma$, and $ZZ\gamma$ 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 ($V = \gamma$ or Z) vertices are described by a general effective Lagrangian [1] with two overall couplings, $g_{WW\gamma} = -e$ and $g_{WWZ} = -e \cdot \cot\theta_W$, and six dimensionless couplings g_1^V, κ_V, and λ_V ($V = \gamma$ or Z), after imposing C, P and CP invariance. Electromagnetic gauge invariance requires that $g_1^\gamma = 1$, which we assume throughout this paper. The SM Lagrangian is obtained by setting $g_1^\gamma = g_1^Z = 1$, $\kappa_V = 1 (\Delta\kappa_V \equiv \kappa_V - 1 = 0)$ and $\lambda_V = 0$.

A different set of parameters, motivated by $SU(2) \times U(1)$ gauge invariance, has been used by the LEP collaborations [2]. This set consists of three independent couplings $\alpha_{B\phi}$, $\alpha_{W\phi}$ and α_W: $\alpha_{B\phi} \equiv \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$, $\alpha_{W\phi} \equiv \Delta g_1^Z \cos^2\theta_W$ and $\alpha_W \equiv \lambda_\gamma$. The remaining WWZ coupling parameters λ_Z and $\Delta\kappa_Z$ are determined by the relations $\lambda_Z = \lambda_\gamma$ and $\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_1^Z$. The HISZ relations [3] which have been used by the DØ and CDF collaborations are also based on this set with the additional constraint $\alpha_{B\phi} = \alpha_{W\phi}$.

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

The $Z\gamma V$ ($V = \gamma$ or Z) vertices are described by a general vertex function [4] with eight dimensionless couplings $h_i^V (i = 1,4\ ; V = \gamma$ 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 $h_i^V(\hat{s}) = \frac{h_{i0}^V}{(1+\hat{s}/\Lambda^2)^n}$, 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 $WW/WZ \to \mu\nu$ jet jet and $WZ \to ee e\nu$ final states at DØ, a description of a recently published, combined analysis, anomalous $WW\gamma$ and WWZ coupling result from DØ, combined DØ + LEP anomalous $WW\gamma$ and WWZ couplings results (presented for the first time), limits on anomalous $Z\gamma\gamma$ and $ZZ\gamma$ couplings from studies of $Z\gamma$ final states at DØ, and report of the observation of a $ZZ \to \mu\mu\mu\mu$ event at CDF in Run I. Prospects for Run II are discussed.

2 Preliminary Results from DØ

2.1 *Search for anomalous* $WW/WZ \to \mu\nu$ jet jet *Production*

This analysis searches for anomalous WW or WZ production using the decay signature $W \to \mu\nu$ and $W/Z \to$ 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 $p_T > 20$ GeV/c and with $\not\!\!E_T > 20$ GeV where the transverse mass $M_T(\mu\nu) > 40$ GeV/c^2, indicative of a W boson decay. We required that the event contain at least two jets with $E_T > 20$ GeV. For 224 of the 372

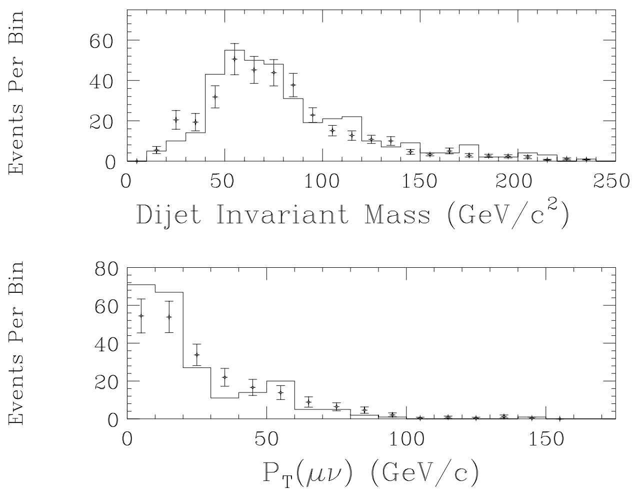

Figure 1: DØ $WW/WZ \to \mu\nu$ jet jet analysis. The upper plot is the dijet invariant mass. The lower plot is $p_T(\mu\nu)$ for events which pass the dijet mass selection criteria. The histogram is the data. The points are the background and it's uncertainty.

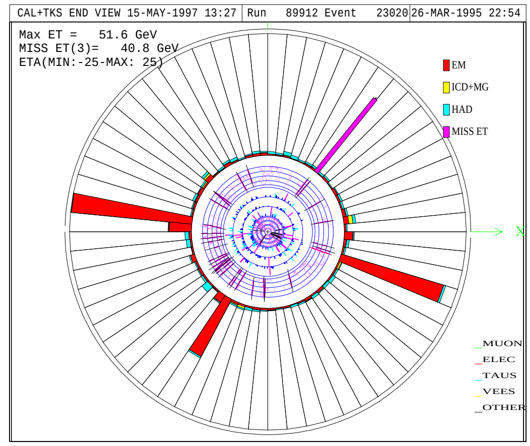

Figure 2: $WZ \to ee e\nu$ candidate from DØ. The figure shows the E_T, represented by the height of the column, deposited in the central calorimeter. The three largest towers are the three electrons. The narrow tower shows the direction and magnitude of the missing transverse energy.

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 $W+\geq 2$ 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 likelyhood 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 $WZ \to eee\nu$ Events*

Searches for anomalous WZ production enable the possibility of constraining the WWZ couplings independant of the $WW\gamma$ couplings. DØ has searched for the process $WZ \to eee\nu$. Two electrons with $E_T > 25$ GeV, one more electron with $E_T > 10$ GeV, and $\not{E}_T > 15$ GeV are required in candidate events. The transverse mass of one electron and the $\not{E}_T$ must be greater the 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 ± 0.011 WZ events are expected. The background, principally due to $Z+$jet events where the jet mimicks an electron and there is accidental $\not{E}_T$, amounts to 0.38 ± 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 λ_Z and Δg_1^Z than $\Delta\kappa_Z$. Given one observed event and taking into account the expected background, 95% CL limits are $|\lambda| < 2.07$ ($\Delta g_1^Z = 0$) and $|\Delta g_1^Z| < 2.56$ ($\lambda_Z = 0$) for $\Lambda = 1000$ GeV. Although the limits are looser than some of those previously measured, they are independant of any assumptions on the relation between $WW\gamma$ and WWZ couplings. Ultimately, these results will help constrain Δg_1^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 [5], limits on WWZ and $WW\gamma$ couplings obtained from a fit to the E_T of the two charged leptons in $WW \to$ dilepton events [6], and limits on WWZ and

Coupling	$\Lambda = 1.5$ TeV	$\Lambda = 2.0$ TeV
$\lambda_\gamma = \lambda_Z$ ($\Delta\kappa_\gamma = \Delta\kappa_Z = 0$)	$-0.21,\ 0.21$	$-0.20,\ 0.20$
$\Delta\kappa_\gamma = \Delta\kappa_Z$ ($\lambda_\gamma = \lambda_Z = 0$)	$-0.33,\ 0.46$	$-0.30,\ 0.43$
λ_γ(HISZ) ($\Delta\kappa_\gamma = 0$)	$-0.21,\ 0.21$	$-0.20,\ 0.20$
$\Delta\kappa_\gamma$(HISZ) ($\lambda_\gamma = 0$)	$-0.39,\ 0.61$	$-0.37,\ 0.56$
λ_Z(SM $WW\gamma$) ($\Delta\kappa_Z = \Delta g_1^Z = 0$)	$-0.33,\ 0.37$	$-0.31,\ 0.34$
$\Delta\kappa_Z$(SM $WW\gamma$) ($\lambda_Z = \Delta g_1^Z = 0$)	$-0.46,\ 0.64$	$-0.42,\ 0.59$
Δg_1^Z(SM $WW\gamma$) ($\lambda_Z = \Delta\kappa_Z = 0$)	$-0.56,\ 0.86$	$-0.52,\ 0.78$
λ_γ(SM WWZ) ($\Delta\kappa_\gamma = 0$)	$-0.27,\ 0.25$	$-0.26,\ 0.24$
$\Delta\kappa_\gamma$(SM WWZ) ($\lambda_\gamma = 0$)	$-0.63,\ 0.75$	$-0.59,\ 0.72$

Table 1: Limits at 95% C.L. from a simultaneous fit to the DØ $W\gamma$, $WW \to$ dilepton and $WW/WZ \to e\nu jj$ 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 $\alpha_{B\phi} = \alpha_{W\phi}$.

$WW\gamma$ couplings obtained from a fit to the p_T spectrum of the electron-neutrino system in $WW/WZ \to e\nu jj$ events [7]. The results [8] are shown in Tables 1 and 2 and in Figures 3 and 4.

Coupling	$\Lambda = 1.5$ TeV	$\Lambda = 2.0$ TeV
$\alpha_{B\phi}$ ($\alpha_{W\phi} = \alpha_W = 0$)	$-0.81,\ 0.61$	$-0.77,\ 0.58$
$\alpha_{W\phi}$ ($\alpha_{B\phi} = \alpha_W = 0$)	$-0.24,\ 0.46$	$-0.22,\ 0.44$
α_W ($\alpha_{B\phi} = \alpha_{W\phi} = 0$)	$-0.21,\ 0.21$	$-0.20,\ 0.20$
Δg_1^Z ($\alpha_{B\phi} = \alpha_W = 0$)	$-0.31,\ 0.60$	$-0.29,\ 0.57$

Table 2: Limits at 95% C.L. on α parameters from a simultaneous fit to the DØ $W\gamma$, $WW \to$ dilepton and $WW/WZ \to e\nu jj$ 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 [9] by Hywel Phillips) were combined to produce the tightest available $WW\gamma$ and WWZ coupling limits. The procedure, documented in detail in preprint form [10], is to add the negative log-likelyhoods 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 Λ are negligible. Figures 5 and 6 show log-likelihoods and one σ limits on λ_γ 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 [10] due to the inclusion of new LEP results.

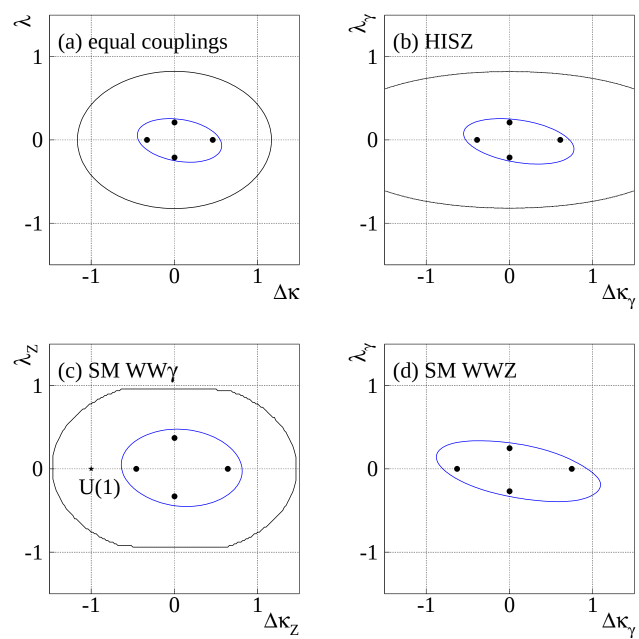

Figure 3: Contour limits on anomalous couplings from a simultaneous fit to the DØ data sets of $W\gamma$, $WW \to$ dilepton, and $WW/WZ \to e\nu jj$ final states for $\Lambda = 1.5$ TeV: (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z, \lambda \equiv \lambda_\gamma = \lambda_Z$; (b) HISZ relations; (c) SM $WW\gamma$ couplings; and (d) SM WWZ couplings. (a), (c), and (d) assume that $\Delta g_1^Z = 0$. The solid circles correspond to 95% C.L. one-degree of freedom exclusion limits. The inner and outer curves are 95% C.L. two-degree of freedom exclusion contour and the constraint from the unitarity condition, respectively. In (d), the unitarity contour is located outside of the boundary of the plot. The HISZ results include the additional constraint $\alpha_{B\phi} = \alpha_{W\phi}$.

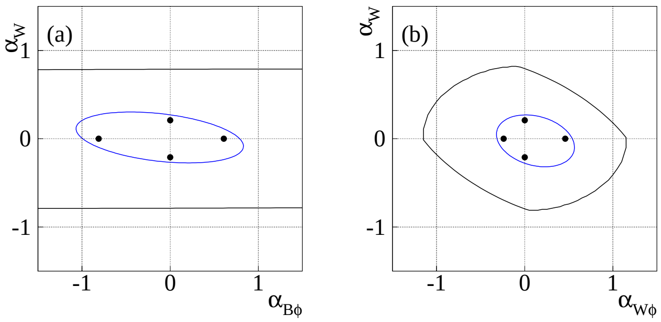

Figure 4: Contour limits on anomalous couplings from a simultaneous fit to the DØ data sets of the $W\gamma$, $WW \rightarrow$ dilepton, and $WW/WZ \rightarrow e\nu jj$ final states for $\Lambda = 1.5$ TeV: (a) α_W vs $\alpha_{B\phi}$ when $\alpha_{W\phi} = 0$; and (b) α_W vs $\alpha_{W\phi}$ when $\alpha_{B\phi} = 0$. The solid circles correspond to 95% C.L. one-degree of freedom exclusion limits. The inner and outer curves are 95% C.L. two-degree of freedom exclusion contour and the constraint from the unitarity condition, respectively.

5 $Z\gamma$ and ZZ Production and Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ Couplings from DØ and CDF

DØ has recently published [11,12] 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 it's 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 $Z\gamma \rightarrow \nu\nu\gamma$ 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^γ in the range 70 to 79 GeV is 200 GeV/c^2. CDF noted [13] 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 [12] DØ analyses. At 95% CL, the $Z\gamma\gamma$ limits are $|h_{30}^\gamma\ (h_{10}^\gamma)| < 0.37$ and $|h_{40}^\gamma\ (h_{20}^\gamma)| < 0.05$ with $\Lambda = 750$ GeV. The $ZZ\gamma$ limits are similar.

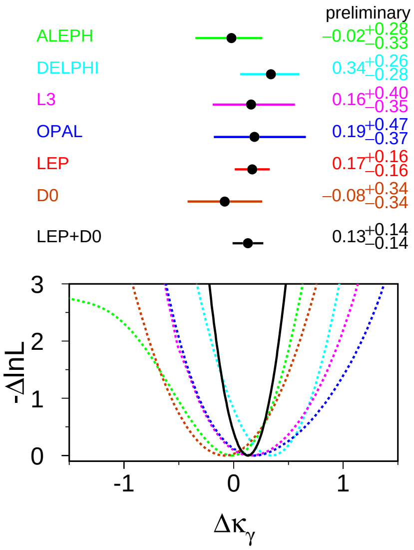

Figure 5: Limits on $\Delta\kappa_\gamma$ and the log-likelyhood curves for the LEP experiments, DØ, and the combination, assuming $\lambda_\gamma = \lambda_Z = \Delta g_1^Z = 0$ and that $\Delta\kappa_Z$ is determined from the HISZ relations. At 95% CL, the combined limit is $-0.15 < \Delta\kappa_\gamma < 0.41$.

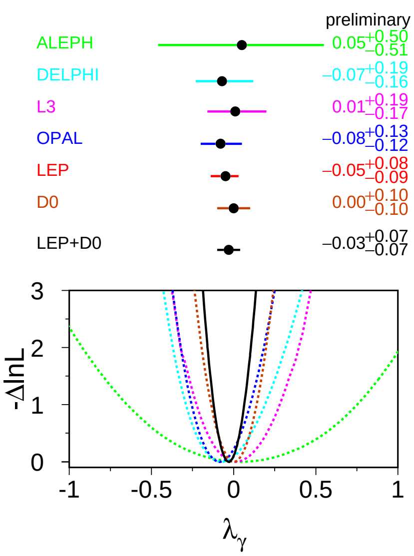

Figure 6: Limits on λ_γ and log-likelyhood curves for the LEP experiments, DØ, and the combination, assuming $\lambda_\gamma = \lambda_Z$, and $\Delta\kappa_\gamma = \Delta\kappa_Z = 0$. The limits are 68% CL. At 95% CL, the combined limit is $-0.16 < \lambda_\gamma < 0.10$.

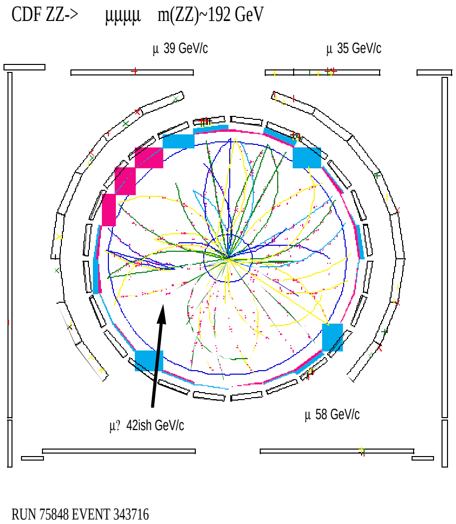

Figure 7: $ZZ \to \mu\mu$ event observed at CDF in Run I. The E_T and locations of the muons are shown.

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 $WW\gamma$ and WWZ coupling limits. Perhaps CDF will finish it's Run I $W\gamma$ and $Z\gamma$ 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 Λ and assuming no improvement in technique. The large data samples will provide upwards of 3000 $W\gamma \to \ell\nu\gamma$ events, 700 $Z\gamma \to ee\gamma + \mu\mu\gamma$ events, 100 $WW \to$ dileptons events, some 30 $WZ \to$ trileptons and a handful of $ZZ \to e's$ and $\mu's$ per experiment.

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

Qualitatively, the $W\gamma$, 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 $WW/WZ \to \mu\nu$ jet jet and $WZ \to ee e\nu$ 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 $WW\gamma$ 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 $-0.16 < \lambda_\gamma < 0.10$ ($\Delta\kappa = 0$) 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 $|h_{30}^Z| < 0.36$ ($h_{40}^Z = 0$) and $|h_{40}^Z| < 0.05$ ($h_{30}^Z = 0$) for $\Lambda = 750$ 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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