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CDF and DØ

Tevatron Results on Gauge Boson Couplings

T. Yasuda

For the CDF and DØ Collaborations

*Northeastern University
Boston, Massachusetts 02115*

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

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Tevatron Results on Gauge Boson Couplings

T. Yasuda

Northeastern University, Boston, MA 02115

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Abstract

Direct measurements of the trilinear gauge boson couplings by the CDF and DØ collaborations at Fermilab are reviewed. Limits on the anomalous couplings were obtained at a 95% CL from four diboson production processes: $W\gamma$ production with the subsequent W boson decay to $e\nu$ or $\mu\nu$, WW production with both the W boson decaying to $e\nu$ or $\mu\nu$, WW/WZ production with one of the gauge bosons decaying leptonically and the other gauge boson decaying to two jets, and $Z\gamma$ production with the subsequent Z boson decay to ee , $\mu\mu$, or $\nu\nu$. Limits were also obtained by a combined fit to $W\gamma$, $WW \rightarrow$ dileptons and WW/WZ semileptonic data samples.

Introduction

The gauge boson self-interactions are a direct consequence of the non-Abelian $SU(2) \times U(1)$ gauge symmetry of the Standard Model (SM). The trilinear gauge boson couplings can be measured by studying the gauge boson pair production processes. The determination of the couplings is one of a few remaining crucial tests of the SM. Deviations of the couplings from the SM values signal new physics. Measurements of the anomalous couplings have been previously reported by the UA2[1], CDF[2],[3],[4] and DØ[5],[6],[7],[8] collaborations.

The WWV ($V = \gamma$ or Z) vertices are described by a general effective Lagrangian[9] 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 , where $V = \gamma$ or Z , after imposing C , P and CP invariance. g_1^V is restricted to unity by electromagnetic gauge invariance. 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 $\lambda_V = 0$. The cross section with the 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[10] 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 couplings, similar to the WWV couplings, 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 $i = 2, 4$.

The characteristic that the production cross section of a gauge boson pair with anomalous couplings grows with \hat{s} is an advantage for the Tevatron experiments over LEP II. The increase of the cross section is greater at higher gauge boson p_T . This is exploited to set limits on the anomalous couplings in all of the analyses presented here.

In this report, the measurements of trilinear gauge boson couplings by the CDF and DØ experiments at Fermilab are reviewed. Limits on the anomalous couplings were obtained at a 95% CL from four processes: $W\gamma$ production with the subsequent W boson decay to $e\nu$ or $\mu\nu$, WW production with both the W boson decaying to $e\nu$ or $\mu\nu$, WW/WZ production with one of the gauge bosons decaying leptonically and the other gauge boson decaying to two jets, and $Z\gamma$ production with the subsequent Z boson decay to ee , $\mu\mu$, or $\nu\nu$. Limits were also obtained by a combined fit to $W\gamma$, $WW \rightarrow$ dileptons and WW/WZ semileptonic data samples.

$W\gamma$ production

The $W(\ell\nu)\gamma$ candidates were selected by searching for events containing an isolated electron or muon with high transverse energy, E_T , large missing transverse energy, \cancel{E}_T , and an isolated photon. The major sources of background for this process are W + jets production with a jet misidentified as a photon and $Z\gamma$ production with an electron or a muon from Z decay undetected. The signal to background ratio for this process is 1 to 0.2 – 0.3 for both CDF and DØ experiments. CDF and DØ previously reported the results with the 1992 – 1993 data [2], [5].

CDF has reported the preliminary results based on a partial data set of 1993 – 1995 Tevatron collider run ($\sim 67 \text{ pb}^{-1}$) [11]. The candidate events were required to have an electron or a muon with $E_T > 20 \text{ GeV}$, a photon with $E_T > 7 \text{ GeV}$, and $\cancel{E}_T > 20 \text{ GeV}$. A requirement on the transverse mass $M_T > 40 \text{ GeV}/c^2$ was applied to insure the detection of a W boson. The electrons and photons had to be in the fiducial region of $|\eta| < 1.1$ and the muons in $|\eta| < 0.6$. In addition, the separation in $\eta - \phi$ space between a photon and a lepton ($\mathcal{R}_{\ell\gamma}$) had to be greater than 0.7. This requirement suppressed the contribution of the radiative W decay process, and minimized the probability for a photon cluster to merge with a nearby calorimeter cluster associated with an electron or a muon. A total of 75 $e\nu\gamma$ and 34 $\mu\nu\gamma$ candidate events was observed.

DØ completed the analysis of the data set of the 1993 – 1995 run, and the results from the two Tevatron runs were combined. The total data sample corresponds to an integrated luminosity of 92.8 pb^{-1} [12]. For the electron channel, the candidate events were required to have an electron with $E_T > 25 \text{ GeV}$ in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$ and to have $\cancel{E}_T > 25 \text{ GeV}$. A requirement on the transverse mass $M_T > 40 \text{ GeV}/c^2$ was also applied. For the muon channel, the events were required to have a muon with $p_T > 15 \text{ GeV}/c$ in the fiducial region of $|\eta| < 1.0$ and to have $\cancel{E}_T > 15 \text{ GeV}$. The requirement for the photon was common to both the channels. The candidate events were required to have a photon with $E_T > 10 \text{ GeV}$ in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. The same cut as CDF on the separation between the lepton and the photon

was applied. The above selection criteria yielded 57 $W(e\nu)\gamma$ and 70 $W(\mu\nu)\gamma$ candidates.

The backgrounds were estimated from Monte Carlo simulation and data. The estimated total backgrounds are listed in Table 1. The detection efficiency was estimated as a function of anomalous couplings using the Monte Carlo program of Baur and Zeppenfeld[13] and a fast detector simulation program. The $W\gamma$ cross section times the leptonic branching ratio $Br(W \rightarrow \ell\nu)$ (for photons with $E_T^\gamma > 7$ GeV (CDF) or > 10 GeV (DØ) and $\mathcal{R}_{\ell\gamma} > 0.7$) was obtained from the number of candidate events and the estimated numbers of background events, as listed in Table 1. The results from the two experiments agree with the SM

	DØ ($\int \mathcal{L}dt = 92.8 \text{ pb}^{-1}$)		CDF ($\int \mathcal{L}dt \sim 67 \text{ pb}^{-1}$)	
	$e\nu\gamma$	$\mu\nu\gamma$	$e\nu\gamma$	$\mu\nu\gamma$
N_{data}	57	70	75	34
N_{BG}	15.2 ± 2.5	27.7 ± 4.7	16.1 ± 2.4	10.3 ± 1.2
N_{Signal}	41.8 ± 8.9	42.3 ± 9.7	58.9 ± 9.4	23.7 ± 6.0
$\sigma \cdot \text{BR}$	$11.3_{-1.5}^{+1.7} \pm 1.4 \pm 0.6 \text{ pb}$		$20.7 \pm 2.9 \pm 0.7 \text{ pb}$	
$\sigma \cdot \text{BR(SM)}$	$12.5 \pm 1.0 \text{ pb}$		$18.6 \pm 2.9 \text{ pb}$	

Table 1: Summary of $W\gamma$ analyses

prediction within errors.

To set limits on the anomalous couplings, a binned maximum likelihood fit was performed on the E_T spectrum of the photon. Form factors with a scale $\Lambda = 1.5$ TeV were used in the Monte Carlo event generation. The 95% CL limit contour for the CP-conserving anomalous couplings $\Delta\kappa_\gamma$ and λ_γ by DØ are shown in Fig. 1. The SM point and the point for the models with $U(1)$ couplings only are also indicated in Fig. 1. The 95% CL limits on the anomalous couplings are listed in Table 2. The $U(1)$ only couplings of the W boson

	$\lambda_\gamma = 0$	$\Delta\kappa_\gamma = 0$
DØ	$-0.93 < \Delta\kappa_\gamma < 0.94$	$-0.31 < \lambda_\gamma < 0.29$
CDF (preliminary)	$-1.8 < \Delta\kappa_\gamma < 2.0$	$-0.7 < \lambda_\gamma < 0.6$

Table 2: 95 % CL limits on the anomalous $WW\gamma$ couplings

to a photon, which correspond to $\kappa_\gamma = 0$ ($\Delta\kappa_\gamma = -1$) and $\lambda_\gamma = 0$ are excluded at a 96% CL by the DØ results. The DØ limit on λ_γ is the tightest to date among the individual analyses of gauge boson pair final states.

$WW \rightarrow$ dileptons

The W boson pair production candidates were obtained by searching for events containing two isolated leptons ($e\mu$, ee , or $\mu\mu$) with high E_T and large \cancel{E}_T . The major sources of background for this process are Drell-Yan production of a Z boson or a virtual photon,

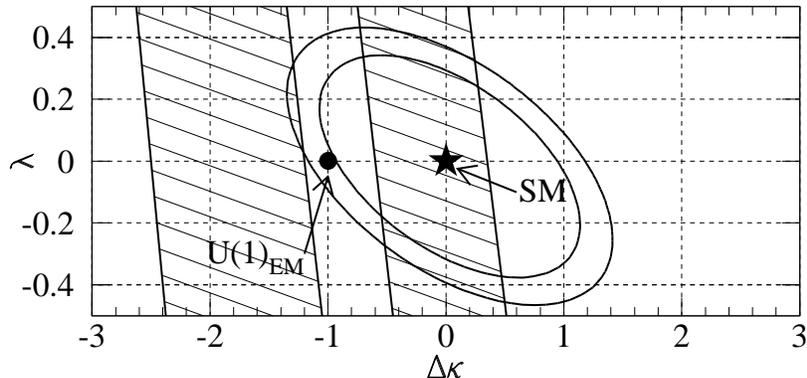


Figure 1: 95 % CL limits on the anomalous $WW\gamma$ couplings from the $D\bar{O}$ $W\gamma$ analysis. The shaded bands are the constraints from CLEO.

$t\bar{t}$ production, $W\gamma$ production with a γ misidentified as an electron, $Z \rightarrow \tau\tau$ with the subsequent τ decays to $e\nu\nu$ or $\mu\nu\nu$, and $W+$ jets production with a jet misidentified as an electron or a muon. The signal to background ratio for this process is 1 to 0.5(1) for CDF($D\bar{O}$). $D\bar{O}$ previously reported the results with the 1992 – 1993 data [6].

CDF analysed the full data set of 1992 – 1993 and 1993 – 1995 Tevatron collider runs, corresponding to an integrated luminosity of 108 pb^{-1} [14]. The candidate events were required to have two electrons, two muons, or one electron and one muon with each having $E_T > 20 \text{ GeV}$ and $\cancel{E}_T > 20 \text{ GeV}$. An invariant mass cut, $75 < m < 105 \text{ GeV}/c^2$, was applied to ee and $\mu\mu$ candidate events, in order to reduce the background from the Z boson production. The background contribution from the $t\bar{t}$ production was suppressed by rejecting the events with one or more jets with $E_T > 10 \text{ GeV}$. CDF observed five candidate events with an estimated background of 1.2 ± 0.3 events, as listed in Table 3. From this, the WW production cross section was calculated to be

$$\sigma(\bar{p}p \rightarrow W^+W^-) = 10.2_{-5.1}^{+6.3} \text{ (stat)} \pm 1.6 \text{ (syst) pb.}$$

The probability that the observed events corresponds to a fluctuation of the background is 1.1%. The measured cross section is consistent with the SM prediction of 9.5 pb.

$D\bar{O}$ also completed the analysis of the data set of the 1993 – 1995 Tevatron collider run, and the results from the two Tevatron runs were combined. The total data sample corresponds to an integrated luminosity of 96.6 pb^{-1} . For the ee channel, the candidate events were required to have two electrons, one with $E_T \geq 25 \text{ GeV}$ and another with $E_T \geq 20 \text{ GeV}$. The \cancel{E}_T was required to be $\geq 20 \text{ GeV}$. The Z boson background was reduced by removing events with the dielectron invariant mass between 76 and $106 \text{ GeV}/c^2$. For the $e\mu$ channel, an electron with $E_T \geq 25 \text{ GeV}$ and a muon with $p_T \geq 15 \text{ GeV}/c$ were required.

	DØ ($\int \mathcal{L} dt = 96.6 \text{ pb}^{-1}$)	CDF ($\int \mathcal{L} dt = 108 \text{ pb}^{-1}$)
N_{data}	5	5
N_{BG}	3.3 ± 0.4	1.2 ± 0.3
N_{SM}	2.10 ± 0.15	3.5 ± 1.2

Table 3: Summary of $WW \rightarrow$ dileptons analyses

\cancel{E}_T was required to be ≥ 20 GeV. For the $\mu\mu$ channel, two muons were required, one with $p_T \geq 25$ GeV/ c and another with $p_T \geq 20$ GeV/ c . In order to reduce the background from the Z boson events, it was required that the \cancel{E}_T projected on the dimuon bisector in the transverse plane be greater than 30 GeV. The $t\bar{t}$ background was suppressed by applying a cut on the hadronic energy in the event. It was required that the vector sum of hadronic energy in the event be ≤ 40 GeV in magnitude in all three channels. For the three channels combined, the expected number of events for the SM W boson pair production, based on a cross section of 9.5 pb, is 2.10 ± 0.15 . DØ observed five candidate events. A maximum likelihood fit to the electron E_T and the muon p_T of the five candidate events was performed and limits on the anomalous couplings were obtained. The preliminary 95% CL limits from the fit are:

$$\begin{aligned}
-0.62 < \Delta\kappa < 0.75 \quad (\lambda = 0) \\
-0.50 < \lambda < 0.56 \quad (\Delta\kappa = 0)
\end{aligned}$$

where the $WW\gamma$ couplings are assumed to be equal to the WWZ couplings and $\Lambda = 1.5$ TeV is used. These limits are comparable to the limits obtained from the $WW/WZ \rightarrow$ semileptonic mode analyses.

$WW/WZ \rightarrow \ell\nu jj, \ell\ell jj$

The WW/WZ candidates were obtained by searching for events containing an isolated electron or muon with high E_T and large \cancel{E}_T , indicating a W boson decay, or two high E_T electrons or muons, indicating a Z boson decay, and two high E_T jets. The transverse mass of the electron or muon and neutrino system was required to be $M_T > 40$ GeV/ c^2 for $e\nu jj$ and $\mu\nu jj$ candidates. The invariant mass of ee or $\mu\mu$ system was required to be $70 < m_{\ell\ell} < 110$ GeV/ c^2 for $eejj$ and $\mu\mu jj$ candidates. There were two major sources of background for this process: QCD multijet events with a jet misidentified as an electron or a muon and W or Z boson production associated with two jets. The signal to background ratio for this process is 1 to 20 – 30 with a low p_T cut on the W or Z boson. CDF and DØ both previously reported the results from the 1992 – 1993 data [3], [7].

CDF completed the analysis of the data set of the 1993 – 1995 Tevatron collider run, and the results from the two Tevatron collider runs were combined. The total data sample corresponds to an integrated luminosity of 110 pb $^{-1}$ [15]. The background was eliminated by imposing a high p_T cut ($p_T^{jj} > 200$ GeV) on the hadronically decaying W or Z boson.

This cut also significantly reduced the signals from the SM WW/WZ production, but it enabled one to set limits on the anomalous couplings that enhance the cross section for high p_T gauge bosons. The invariant mass of the two jet system was required to be $60 < m_{jj} < 110 \text{ GeV}/c^2$, as expected for a W or Z boson decay. Before the invariant mass cut on the two jet system, 294 $\ell\nu jj$ and 47 $\ell\ell jj$ candidates were observed. After the invariant mass cut, no events remained. The limits on the anomalous couplings from this analysis are listed in Table 5.

DØ completed the analysis of $e\nu jj$ channel using the data set of the 1993 – 1995 Tevatron collider run, and the results from the two Tevatron runs were combined. The total data sample corresponds to an integrated luminosity of 96 pb^{-1} [16]. The candidate events were required to have an electron with $E_T > 25 \text{ GeV}$, two or more jets each with $E_T > 20 \text{ GeV}$ and $\cancel{E}_T > 25 \text{ GeV}$. The transverse mass of the electron and \cancel{E}_T system was required to be $M_T > 40 \text{ GeV}/c^2$. The invariant mass of the two jet system was required to be $50 < m_{jj} < 110 \text{ GeV}/c^2$. The estimated numbers of background events are listed in Table 4. The SM predicted 20.7 ± 3.1 events for the above requirements. No significant deviation from the SM prediction was seen. The p_T spectrum of W boson calculated from the E_T of electron and \cancel{E}_T , $p_T^{e\nu}$, which is more precise than the value from E_T of two jets, is shown in Fig 2. The solid circles and the solid histogram indicate the data and the background estimate plus SM prediction, respectively. A maximum likelihood fit to the $p_T^{e\nu}$ spectrum was performed to set limits on the anomalous couplings. The limits on the anomalous couplings are listed in Table 5.

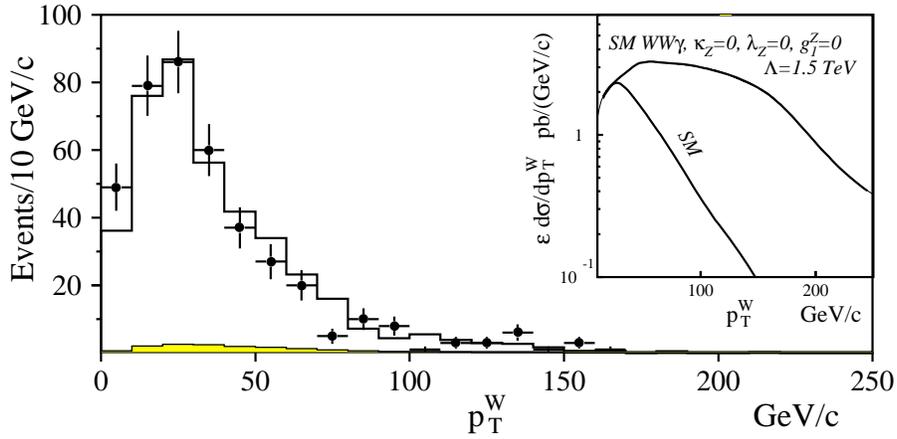


Figure 2: p_T distribution of the $e\nu$ system from the DØ 1993 – 1995 data set.

Different assumptions for the relationship between the WWZ couplings and the $WW\gamma$ couplings were also examined. The limit contour in Fig. 3b was obtained using the HISZ[17] relations. In Figs. 3c and 3d limit contours on the WWZ couplings are shown under the assumption that the $WW\gamma$ couplings take the SM values. These plots indicate that this

D \emptyset	1992 – 1993	1993 – 1995
Luminosity	13.7 pb ⁻¹	82.3 pb ⁻¹
Backgrounds		
$W + \geq 2$ jets	62.2 \pm 13.0	279.5 \pm 36.0
Multijet	12.2 \pm 2.6	104.3 \pm 12.3
$t\bar{t} \rightarrow e\nu jjX$	0.9 \pm 0.1	3.7 \pm 1.3
Total	75.3 \pm 13.3	387.5 \pm 38.1
Data	84	399
SM $WW + WZ$ prediction	3.2 \pm 0.6	17.5 \pm 3.0

Table 4: Summary of D \emptyset $WW/WZ \rightarrow e\nu jj$ analysis

analysis is more sensitive to WWZ couplings as expected from the larger overall couplings for WWZ than $WW\gamma$ and that it is complementary to the $W\gamma$ analysis which is sensitive to the $WW\gamma$ couplings only. The $U(1)$ point in the anomalous WWZ couplings plane, $\kappa_Z = 0$ ($\Delta\kappa_Z = -1$), $\lambda_Z = 0$ and $g_1^Z = 0$ ($\Delta g_1^Z = -1$), is excluded at a 99% CL. The CDF and D \emptyset limits on $\Delta\kappa$ are the tightest limits to date among the individual analyses of gauge boson pair final states.

Couplings \ Λ (TeV)	D \emptyset		CDF	
	1.5	2.0	1.0	2.0
$\Delta\kappa_\gamma = \Delta\kappa_Z$	-0.47, 0.63	-0.43, 0.59	-0.67, 0.85	-0.49, 0.54
$\lambda_\gamma = \lambda_Z$	-0.36, 0.39	-0.33, 0.36	-0.51, 0.51	-0.35, 0.32
Δg_1^Z (SM $WW\gamma$)	-0.64, 0.89	-0.60, 0.81	-0.91, 1.05	-0.61, 0.68
$\Delta\kappa_Z$ (SM $WW\gamma$)	-0.60, 0.79	-0.54, 0.72	-0.95, 1.01	0.58, 0.68
λ_Z (SM $WW\gamma$)	-0.40, 0.43	-0.37, 0.40	-0.60, 0.58	-0.37, 0.40
$\Delta\kappa_\gamma$ HISZ	-0.56, 0.85	-0.53, 0.78	-0.83, 1.02	-0.61, 0.67
λ_γ HISZ	-0.36, 0.38	-0.34, 0.36	-0.51, 0.52	-0.34, 0.33

Table 5: Summary of preliminary 95 % CL limits on $WW\gamma$ and WWZ couplings from WW/WZ semileptonic mode analyses

Limits on $WW\gamma/WWZ$ couplings from combined fit

The limits on $WW\gamma$ couplings were obtained from a fit to the photon E_T spectrum of the $W\gamma$ candidate events. The limits on $WW\gamma$ and WWZ couplings were obtained from a fit to the E_T of two leptons of the $WW \rightarrow$ dileptons candidate events (D \emptyset) and a fit to the p_T of electron – neutrino system of the $WW/WZ \rightarrow e\nu jj$ candidate events (D \emptyset) or the limit on the cross section with a high p_T cut on the hadronically decaying gauge bosons (CDF). Since these analyses measure the same couplings, D \emptyset performed a combined fit to

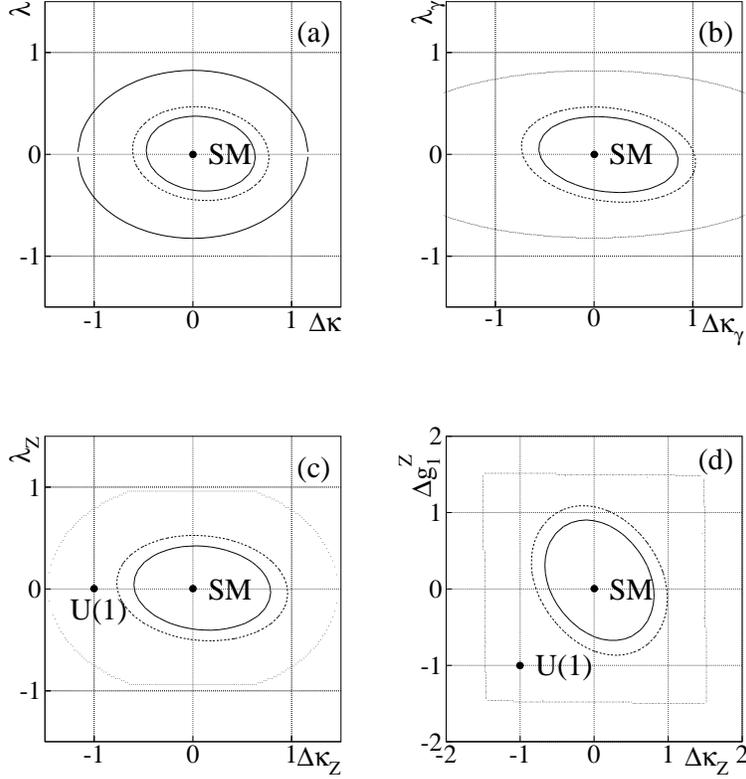


Figure 3: DØ 95 % CL limits on CP -conserving anomalous couplings: (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda \equiv \lambda_\gamma = \lambda_Z$; (b) HISZ relations; (c) and (d) SM $WW\gamma$ couplings.

all three data sets [18] from the 1992 – 1993 and 1993 – 1995 Tevatron collider runs, yielding a significantly improved limits from the individual analyses. The preliminary limits are:

$$-0.33 < \Delta\kappa < -0.45 \quad (\lambda = 0) ; \quad -0.20 < \lambda < 0.20 \quad (\Delta\kappa = 0),$$

where the WWZ couplings and the $WW\gamma$ couplings are assumed to be equal. In the fit, correlated uncertainties such as the uncertainties on the integrated luminosities and theoretical prediction of the cross section were properly taken into account. The 95% CL contour limit is shown in Fig. 4. These limits represent a significant progress in constraining the $WW\gamma/WWZ$ couplings in the past several years and are competitive limits to those expected from the LEP II experiments.

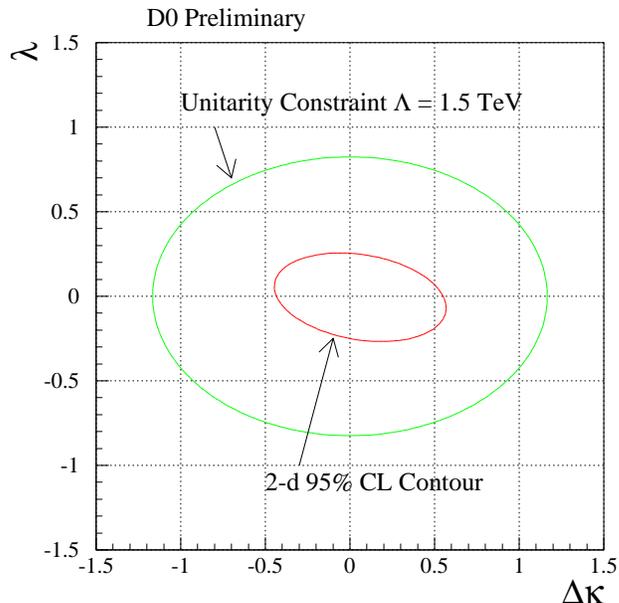


Figure 4: 95 % CL limits on the anomalous couplings from a combined fit to $W\gamma$, $WW \rightarrow$ dileptons, and $WW/WZ \rightarrow e\nu jj$ data samples.

$Z\gamma$ production

$$Z\gamma \rightarrow ee\gamma, \mu\mu\gamma$$

The $Z\gamma$ candidates were selected by searching for events containing two isolated electrons or two isolated muons with high E_T and an isolated photon. The major sources of background for this process are Z + jets production with a jet misidentified as a photon and multijet and direct photon production events with two jets misidentified as electrons or muons and a jet misidentified as a photon. The signal to background ratio for this process is 1 to 0.1 for both CDF and DØ experiments. CDF and DØ both previously reported the results from the 1992 – 1993 data [4], [8].

CDF reported the preliminary results based on a partial data set of the 1993 – 1995 Tevatron collider run ($\sim 67\text{pb}^{-1}$). The candidate events were required to have two electrons, one with $E_T > 20$ GeV in $|\eta| < 1.1$ and another with $E_T > 20$ GeV if $|\eta| < 1.1$, $E_T > 15$ GeV if $1.1 < |\eta| < 2.4$ or $E_T > 10$ GeV if $|\eta| > 2.4$, or two muons with $p_T > 20$ GeV/c, one in $|\eta| < 0.6$ and another in $|\eta| < 1.2$, and a photon with $E_T > 7$ GeV. The separation in $\eta - \phi$ space between a photon and a lepton ($\mathcal{R}_{\ell\gamma}$) had to be greater than 0.7. This requirement suppressed the contribution of the radiative Z decay process, as in the $W\gamma$ analysis. A total of 18 $e\nu\gamma$ and 13 $\mu\nu\gamma$ candidate events were observed.

DØ completed the analysis of the data set of the 1993 – 1995 run, and the results from

the two Tevatron runs were combined. The total data sample corresponds to an integrated luminosity of 103 pb^{-1} . For the electron channel, the candidate events were required to have two electrons with $E_T > 20 \text{ GeV}$ in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. For the muon channel, the candidate events were required to have two muons, one with $p_T > 15 \text{ GeV}/c$ in the fiducial region of $|\eta| < 1.0$ and another with $p_T > 8(10) \text{ GeV}/c$ in the fiducial region of $|\eta| < 1.1(2.4)$ for the 1992 – 1993(1993 – 1995) data samples. The muon η coverage for the 1993 – 1995 data was extended by a track finding method using the calorimeter hits. The requirement for the photon was common to both the channels. The candidate events were required to have a photon with $E_T > 10 \text{ GeV}$ in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. The same cut as CDF on the separation between the lepton and the photon was applied. The above selection criteria yielded 18 $Z(ee)\gamma$ and 17 $Z(\mu\mu)\gamma$ candidates.

The backgrounds were estimated from Monte Carlo simulation and data. The estimated total backgrounds are listed in Tables 6 and 7. The detection efficiency was estimated as a function of anomalous couplings using the Monte Carlo program of Baur and Berger[10] and a fast detector simulation program. Form factors with a scale $\Lambda = 0.5 \text{ TeV}$ were used in the Monte Carlo event generation.

CDF ($\int \mathcal{L} dt \sim 67 \text{ pb}^{-1}$)		
	$ee\gamma$	$\mu\mu\gamma$
N_{data}	18	13
N_{BG}	0.9 ± 0.3	0.5 ± 0.1
N_{Signal}	17.1 ± 5.7	12.5 ± 3.6

Table 6: Summary of CDF $Z\gamma \rightarrow ee\gamma, \mu\mu\gamma$ analysis

	DØ 1a ($\int \mathcal{L} dt = 14 \text{ pb}^{-1}$)		DØ 1b ($\int \mathcal{L} dt = 89 \text{ pb}^{-1}$)	
	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$
N_{data}	4	2	14	15
N_{BG}	0.43 ± 0.06	0.05 ± 0.01	1.8 ± 0.6	3.6 ± 0.8
N_{Signal}	$3.6^{+3.1}_{-1.9}$	$1.9^{+2.6}_{-1.3}$	12.1 ± 1.2	17.3 ± 2.0

Table 7: Summary of DØ $Z\gamma \rightarrow ee\gamma, \mu\mu\gamma$ analysis

To set limits on the anomalous couplings, the observed E_T spectrum of the photon was fitted using a maximum likelihood method. The preliminary 95% CL limits on the anomalous couplings are listed in Table 8.

$Z\gamma \rightarrow \nu\nu\gamma$

DØ completed an analysis of $Z\gamma \rightarrow \nu\nu\gamma$ process using the 1992 – 1993 data sample, taking advantage of its hermetic calorimeters[19]. This process has a significantly higher branching

	$h_{40}^Z(h_{20}^Z) = 0$	$h_{30}^Z(h_{10}^Z) = 0$
DØ 1a	$-1.9 < h_{30}^Z(h_{10}^Z) < 1.8$	$-0.5 < h_{40}^Z(h_{20}^Z) < 0.5$
DØ 1b preliminary	$-1.3 < h_{30}^Z(h_{10}^Z) < 1.3$	$-0.26 < h_{40}^Z(h_{20}^Z) < 0.26$
CDF preliminary	$-1.6 < h_{30}^Z(h_{10}^Z) < 1.6$	$-0.4 < h_{40}^Z(h_{20}^Z) < 0.4$

Table 8: 95 % CL limits on $ZZ\gamma$ and $Z\gamma\gamma$ couplings

ratio than the charged lepton decay modes of Z boson and no contributions from the radiative process of the final state leptons. The major sources of background are $W \rightarrow e\nu$ decay with the electron misidentified as a photon and the bremsstrahlung photon from the cosmic or Tevatron beam halo muons. The candidate events were required to have a photon with $E_T > 40$ GeV in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. This high E_T cut eliminated most of the $W \rightarrow e\nu$ background. The $Z \rightarrow \nu\nu$ decay was identified by $\cancel{E}_T > 40$ GeV. The signal to background ratio for this process is 1 to 3 with the above cuts. DØ observed four candidate events. The numbers of candidate events, background estimates and the SM prediction are listed in Table 9.

DØ 1a ($\int \mathcal{L} dt = 13.5 \text{ pb}^{-1}$)	
$N_{\text{candidate}}$	4
Muon background	1.8 ± 0.6
$W \rightarrow e\nu$ background	4.0 ± 0.8
$jj + j\gamma$ background	< 0.6
Total background	5.8 ± 1.0
N_{SM}	1.8 ± 0.2

Table 9: Summary of DØ $Z\gamma \rightarrow \nu\nu\gamma$ analysis

To set limits on the anomalous couplings, the observed E_T spectrum of the photon was fitted using a maximum likelihood method. The 95% CL limits on the anomalous couplings are listed in Table 10 for $\Lambda = 0.5$ TeV and $\Lambda = 0.75$ TeV. The limit contours are shown in Fig. 5. These are the tightest limits to date among the $Z\gamma$ analyses and the limits on h_{40}^V are better than those expected from LEP II experiments.

Summary

The CDF and DØ experiments at Fermilab set limits on anomalous trilinear gauge boson couplings using four diboson final states, $W\gamma \rightarrow e\nu\gamma, \mu\nu\gamma, WW \rightarrow$ dileptons, $WW/WZ \rightarrow \ell\nu jj, \ell\ell jj$ and $Z\gamma \rightarrow ee\gamma, \mu\mu\gamma, \nu\nu\gamma$. The tightest limits on the anomalous $WW\gamma$ couplings with no assumptions on the WWZ couplings were obtained from the DØ $W\gamma$ analysis:

$$-0.98 < \Delta\kappa_\gamma < -0.94 \ (\lambda_\gamma = 0) ; \ -0.31 < \lambda_\gamma < 0.29 \ (\Delta\kappa_\gamma = 0).$$

	$h_{40}^Z = 0$	$h_{30}^Z = 0$	$h_{40}^\gamma = 0$	$h_{30}^\gamma = 0$
$\Lambda = 0.5 \text{ TeV}$				
$\nu\nu$	$ h_{30}^Z < 0.87$	$ h_{40}^Z < 0.21$	$ h_{30}^\gamma < 0.90$	$ h_{40}^\gamma < 0.22$
1a ($ee, \mu\mu, \nu\nu$)	$ h_{30}^Z < 0.78$	$ h_{40}^Z < 0.19$	$ h_{30}^\gamma < 0.90$	$ h_{40}^\gamma < 0.22$
$\Lambda = 0.75 \text{ TeV}$				
$\nu\nu$	$ h_{30}^Z < 0.49$	$ h_{40}^Z < 0.07$	$ h_{30}^\gamma < 0.50$	$ h_{40}^\gamma < 0.07$
1a ($ee, \mu\mu, \nu\nu$)	$ h_{30}^Z < 0.44$	$ h_{40}^Z < 0.06$	$ h_{30}^\gamma < 0.45$	$ h_{40}^\gamma < 0.06$

Table 10: $D\bar{O}$ 95 % CL limits on $ZZ\gamma$ and $Z\gamma\gamma$ couplings

The tightest limits on the anomalous $WW\gamma$ and WWZ couplings, with the assumption that the two sets of couplings are equal, were obtained from a combined fit to $W\gamma$, $WW \rightarrow$ dileptons and $WW/WZ \rightarrow e\nu jj$ data samples by $D\bar{O}$:

$$-0.33 < \Delta\kappa < -0.45 \quad (\lambda = 0) ; \quad -0.20 < \lambda < 0.20 \quad (\Delta\kappa = 0).$$

CDF measured the production cross section of W boson pair using dilepton decay modes:

$$\sigma(\bar{p}p \rightarrow W^+W^-) = 10.2_{-5.1}^{+6.3} \text{ (stat)} \pm 1.6 \text{ (syst) pb.}$$

The tightest limits on the anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings were obtained from a $Z\gamma \rightarrow \nu\nu\gamma$ analysis by $D\bar{O}$ using the 1992 – 1993 Tevatron collider run data:

$$\begin{aligned} |h_{30}^Z| < 0.44 \quad (|h_{40}^Z| = 0) & ; \quad |h_{40}^Z| < 0.06 \quad (|h_{30}^Z| = 0) \\ |h_{30}^\gamma| < 0.45 \quad (|h_{40}^\gamma| = 0) & ; \quad |h_{40}^\gamma| < 0.06 \quad (|h_{30}^\gamma| = 0). \end{aligned}$$

The CDF and $D\bar{O}$ experiments plan to combine the limits on the anomalous trilinear gauge boson couplings and improve the limits on the couplings.

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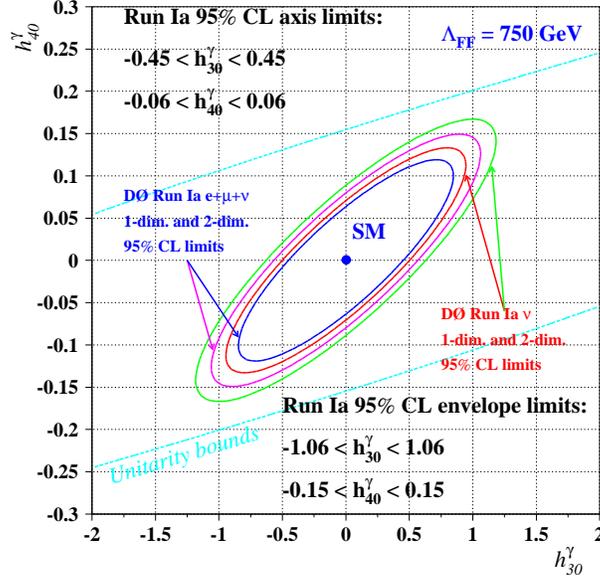


Figure 5: 95 % CL limits on the anomalous $Z\gamma\gamma$ couplings from $Z\gamma \rightarrow \nu\nu\gamma$ analysis for $\Lambda = 0.75$ TeV.

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