Measurements of Trilinear Gauge Boson Couplings

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Abstract

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

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I. 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 measurement 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.

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, where $V = \gamma$ or Z, after imposing C, P and CP invariance. g_1^γ 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 [2] 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 $i = 2, 4$.

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 DØ collaboration at Fermilab are reviewed. Limits on the anomalous couplings were obtained at a 95% CL from four processes: $W\gamma$ production with the W boson decaying to $e\nu$ or $\mu\nu$, WW production with both of the W bosons decaying to $e\nu$ or $\mu\nu$, WW/WZ production with one W boson decaying to $e\nu$ and the other W or Z boson decaying to two jets, and $Z\gamma$ production with the Z boson decaying to ee, $\mu\mu$, or $\nu\nu$. Limits were also obtained from a combined fit to $W\gamma$, $WW \rightarrow$ dileptons and $WW/WZ \rightarrow e\nu jj$ data samples.

II. $W\gamma$ PRODUCTION

Limits on the anomalous $WW\gamma$ couplings using the $W\gamma$ production events by DØ was reported previously, based on the data sample of the 1992 – 1993 Tevatron collider run [3]. The analysis of the 1993 – 1995 data sample was recently completed and the results from the two Tevatron runs were combined. The total data sample corresponds to an integrated luminosity of 92.8 pb^{-1} [4]. The $W(\ell\nu)\gamma$ candidates were selected by searching for events containing an isolated lepton with high transverse energy, E_T, large missing transverse energy, $\not{E}_T$, and an isolated photon. For the electron channel, the candidate events were required to have an electron with $E_T > 25$ GeV in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$ and to have $\not{E}_T > 25$ GeV. A requirement on the transverse mass $M_T > 40$ GeV/c^2 was applied to insure the detection of a W boson. For the muon channel, the events were required to have a muon with $p_T > 15$ GeV/c in the fiducial region of $|\eta| < 1.0$ and to have $\not{E}_T > 15$ GeV. The requirement for the photon was common to both the channels. The candidate events were required to have a photon with $E_T > 10$ GeV in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. 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. The above selection criteria yielded 57 $W(e\nu)\gamma$ and 70 $W(\mu\nu)\gamma$ candidates.

The major sources of background for this process are $W+$ jets production with a jet misidentified as a photon and $Z\gamma$ production events with an electron or a muon from Z decay undetected. The backgrounds were estimated from Monte Carlo simulation and data. The estimated total backgrounds are listed in Table I. The detection efficiency was estimated as a function of anomalous couplings using the Monte Carlo program of Baur and Zeppenfeld [5] and a fast detector simulation program. The $W\gamma$ cross section times the leptonic branching ratio $Br(W \to \ell\nu)$ (for photons with $E_T^{\gamma} > 10$ GeV and $\mathcal{R}_{\ell\gamma} > 0.7$) was obtained from the number of candidate events and the estimated number of background events, as listed in Table I. The results agree with the SM prediction within errors.

	$e\nu\gamma$		$\mu\nu\gamma$
$\mathrm{N_{data}}$	57		70
$\mathrm{N_{BG}}$	15.2 ± 2.5		27.7 ± 4.7
$\mathrm{N_{Signal}}$	41.8 ± 8.9		42.3 ± 9.7
$\sigma \cdot$ BR		$11.3^{+1.7}_{-1.5} \pm 1.4 \pm 0.6$ pb	
$\sigma \cdot$ BR(SM)		12.5 ± 1.0 pb	

TABLE I. Summary of $W\gamma$ analyses

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 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:

$$-0.93 < \Delta\kappa_\gamma < 0.94 \ (\lambda_\gamma = 0); \ -0.31 < \lambda_\gamma < 0.29 \ (\Delta\kappa_\gamma = 0)$$

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

III. $WW \to$ DILEPTONS

A search for the W boson pair production and decay in the dilepton mode was reported previously, based on the data sample of the 1992 – 1993 Tevatron collider run [7]. The

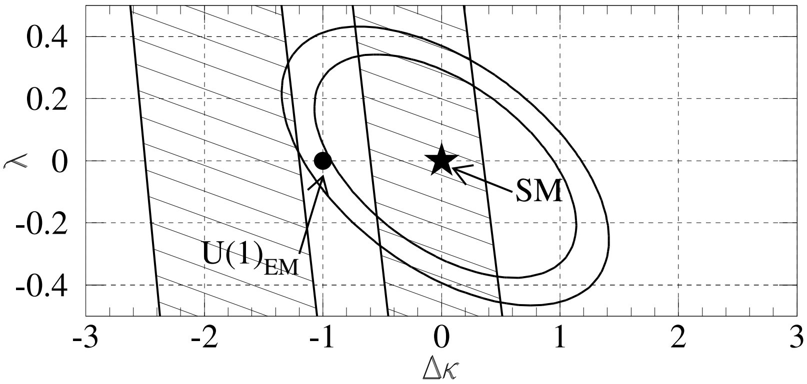

FIG. 1. Limits on the anomalous $WW\gamma$ couplings from the DØ $W\gamma$ analysis. The shaded bands are the constraints from CLEO [6].

analysis of the 1993 – 1995 data sample was completed recently and the results from the two Tevatron runs were combined. The total data sample corresponds to an integrated luminosity of 96.6 pb^{-1}. The W boson pair candidates were obtained by searching for events containing two isolated leptons ($e\mu$, ee, or $\mu\mu$) with high E_T and large $\not\!\!E_T$. The major sources of background for this process are Drell-Yan production of a Z boson or a virtual photon, $t\bar{t}$ production, $W\gamma$ production with a γ misidentified as an electron, $Z \to \tau\tau$ 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. For the ee channel, the candidate events were required to have two electrons, one with $E_T \geq 25$ GeV and another with $E_T \geq 20$ GeV. $\not\!\!E_T$ was required to be $\geq$ 20 GeV. The Z boson background was reduced by removing events with the dielectron invariant mass between 76 and 106 GeV/c^2. For the $e\mu$ channel, an electron with $E_T \geq 25$ GeV and a muon with $p_T \geq 15$ GeV/c were required. $\not\!\!E_T$ was required to be $\geq$ 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 $\not\!\!E_T$ 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 $\leq$ 40 GeV in magnitude in all three channels. For the three channels combined, the expected number of events for SM W boson pair production, based on a cross section of 9.5 pb, is 2.10 ± 0.15. DØ observed five candidate events. The numbers of events for the candidate, the estimated background and the SM prediction are listed in Table II.

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 95% CL limits from the fit are:

$$-0.62 < \Delta\kappa < 0.75 \ (\lambda = 0) \ ; \ -0.50 < \lambda < 0.56 \ (\Delta\kappa = 0)$$

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 $WW/WZ \to$

	$\int \mathcal{L}dt = 96.6$ pb^{-1}
N_{data}	5
N_{BG}	3.3 ± 0.4
N_{SM}	2.10 ± 0.15

TABLE II. Summary of $WW \to$ dileptons analyses

semileptonic mode analyses.

IV. $WW/WZ \to e\nu jj$

Limits on the $WW\gamma/WWZ$ couplings from a study on the $WW/WZ \to e\nu jj$ candidate events were reported previously by DØ, based on the data sample of the 1992 – 1993 Tevatron collider run [8]. The analysis of the 1993 – 1995 data sample was recently completed and the results from the two Tevatron runs were combined, corresponding to an integrated luminosity of 96 pb^{-1} [9]. The WW/WZ candidates were obtained by searching for events containing an isolated electron with high E_T and large $\not\!\!E_T$, indicating a W boson decay, and two high E_T jets. The candidate events were required to have an electron with $E_T > 25$ GeV, two or more jets each with $E_T > 20$ GeV and $\not\!\!E_T > 25$ GeV. The transverse mass of the electron and $\not\!\!E_T$ system was required to be $M_T > 40$ GeV/c^2. The invariant mass of the two jet system was required to be $50 < m_{jj} < 110$ GeV/c^2, as expected for a W or Z boson decay. There were two major sources of background for this process; QCD multijet events with a jet misidentified as an electron and W boson production associated with two jets. The estimated numbers of background events are listed in Table III. 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 $\not\!\!E_T$, $p_T^{e\nu}$, 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 IV.

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 [10] 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 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 $W\gamma$ production process 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 limits on $\Delta\kappa$ are the tightest limits to date among the individual analyses of gauge boson pair final states.

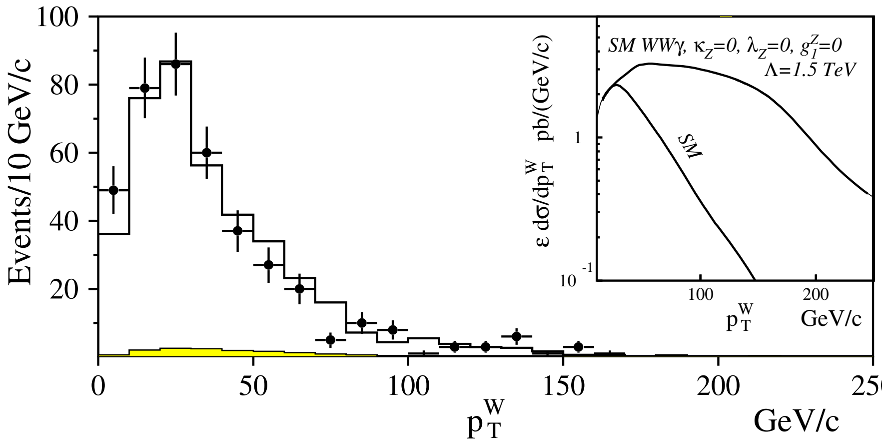

FIG. 2. p_T distribution of the $e\nu$ system from the DØ 1993 – 1995 data set.

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

TABLE III. Summary of $WW/WZ \rightarrow e\nu jj$ analysis

V. LIMITS ON $WW\gamma/WWZ$ COUPLINGS FROM COMBINED FIT

Limits on $WW\gamma$ couplings were obtained from a fit to the photon E_T spectrum of the $W\gamma$ candidate events. 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 and a fit to the p_T of electron – neutrino system of the $WW/WZ \rightarrow e\nu jj$ candidate events. Since these analyses measure the same couplings, DØ performed a simultaneous fit to all three data sets [11] from the 1992 – 1993 and 1993 – 1995 Tevatron collider runs, yielding significantly improved limits from the individual analyses. The preliminary limits are:

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

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 significant progress in constraining

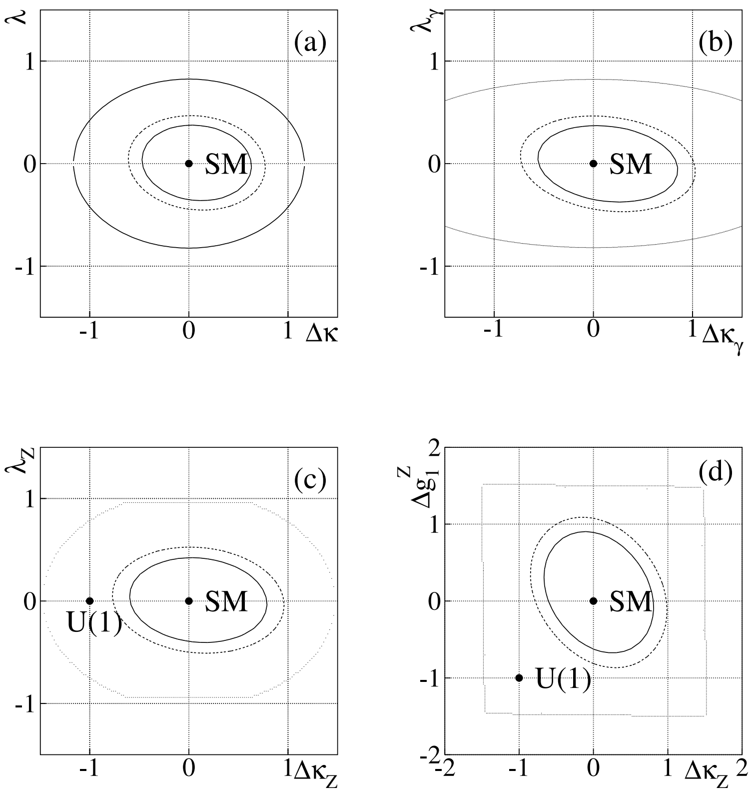

FIG. 3. Limits on $CP-$conserving anomalous couplings: (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z,\ \lambda \equiv \lambda_\gamma = \lambda_Z$; (b) HISZ relations; (c) and (d) SM $WW\gamma$ couplings.

Couplings $\backslash\Lambda$(TeV)	1.5	2.0
$\Delta\kappa_\gamma = \Delta\kappa_Z$	-0.47, 0.63	-0.43, 0.59
$\lambda_\gamma = \lambda_Z$	-0.36, 0.39	-0.33, 0.36
Δg_1^Z(SM $WW\gamma$)	-0.64, 0.89	-0.60, 0.81
$\Delta\kappa_Z$(SM $WW\gamma$)	-0.60, 0.79	-0.54, 0.72
λ_Z(SM $WW\gamma$)	-0.40, 0.43	-0.37, 0.40
$\Delta\kappa_\gamma$ HISZ	-0.56, 0.85	-0.53, 0.78
λ_γ HISZ	-0.36, 0.38	-0.34, 0.36

TABLE IV. Summary of preliminary limits on $WW\gamma$ and WWZ couplings from $WW/WZ \to e\nu jj$ analysis

the $WW\gamma/WWZ$ couplings in the past several years and are competitive limits to those expected from the LEP II experiments.

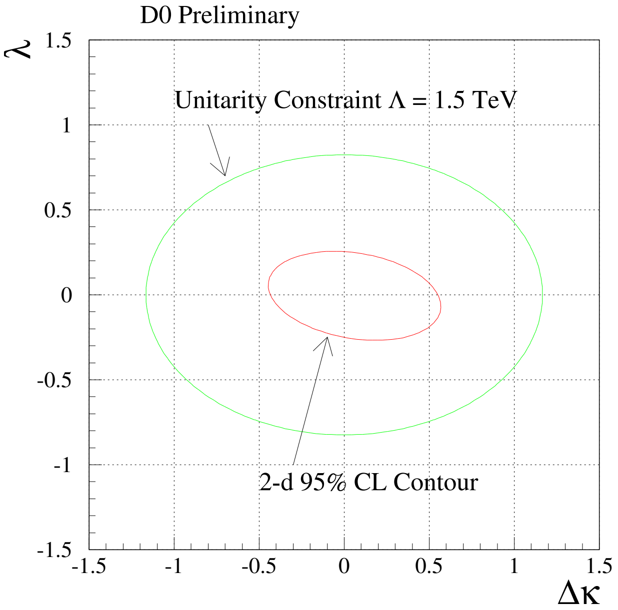

FIG. 4. Limits on the anomalous couplings from a combined fit to $W\gamma$, $WW \to$ dileptons, and $WW/WZ \to e\nu jj$ data samples.

VI. $Z\gamma$ PRODUCTION

A. $Z\gamma \to ee\gamma, \mu\mu\gamma$

Limits on the $ZZ\gamma/Z\gamma\gamma$ couplings using $Z\gamma$ production events were reported previously by DØ, based on the data sample of 1992 – 1993 Tevatron collider run [12]. The analysis of the 1993 – 1995 data sample, corresponding to an integrated luminosity of 89 pb^{-1}, was recently completed. 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. For the electron channel, the candidate events were required to have two electrons with $E_T > 20$ 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 $p_T > 15$ GeV/c in the fiducial region of $|\eta| < 1.0$ and another with $p_T > 10$ GeV/c in the fiducial region of $|\eta| < 2.4$. 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 $E_T > 10$ GeV in the fiducial region of $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. 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. The above selection criteria yielded 18 $Z(ee)\gamma$ and 17 $Z(\mu\mu)\gamma$ candidates.

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 backgrounds were estimated from Monte Carlo simulation and data. The estimated total backgrounds are listed in Table V. The detection efficiency was estimated as a function of anomalous couplings using the Monte Carlo program of Baur and Berger [2] and a fast detector simulation program. Form factors with a scale $\Lambda = 0.5$ TeV were used in the Monte Carlo event generation.

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

TABLE V. Summary of $Z\gamma \to ee\gamma, \mu\mu\gamma$ analysis

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

	$h^Z_{40}(h^Z_{20}) = 0$	$h^Z_{30}(h^Z_{10}) = 0$
DØ 1a	$-1.9 < h^Z_{30}(h^Z_{10}) < 1.8$	$-0.5 < h^Z_{40}(h^Z_{20}) < 0.5$
DØ 1b preliminary	$-1.3 < h^Z_{30}(h^Z_{10}) < 1.3$	$-0.26 < h^Z_{40}(h^Z_{20}) < 0.26$

TABLE VI. Limits on $ZZ\gamma$ and $Z\gamma\gamma$ couplings

B. $Z\gamma \to \nu\nu\gamma$

DØ completed an analysis of $Z\gamma \to \nu\nu\gamma$ process using the 1992 – 1993 data sample, taking advantage of its hermetic calorimeters [13]. This process has a significantly higher branching ratio than 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 $W \to e\nu$ decay with the electron misidentified as a photon and the bremsstrahlung photon from the cosmic or 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 $W \to e\nu$ background. The $Z \to \nu\nu$ decay was identified by $\not{E}_T > 40$ GeV. DØ observed four candidate events. The numbers of candidate events, background estimates and the SM prediction are listed in Table VII.

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 VIII 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^V_{40}

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

TABLE VII. Summary of $Z\gamma \to \nu\nu\gamma$ analysis

are better than those expected from LEP II experiments when they accumlulate their full integrated luminosity of 500 pb^{-1}.

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

TABLE VIII. Limits on $ZZ\gamma$ and $Z\gamma\gamma$ couplings

VII. SUMMARY

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

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

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 $W\gamma$, $WW \to$ dileptons and $WW/WZ \to e\nu jj$ data samples:

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

The tightest limits on the anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings to date were obtained from a $Z\gamma \to \nu\nu\gamma$ analysis using the 1992 – 1993 Tevatron collider run data:

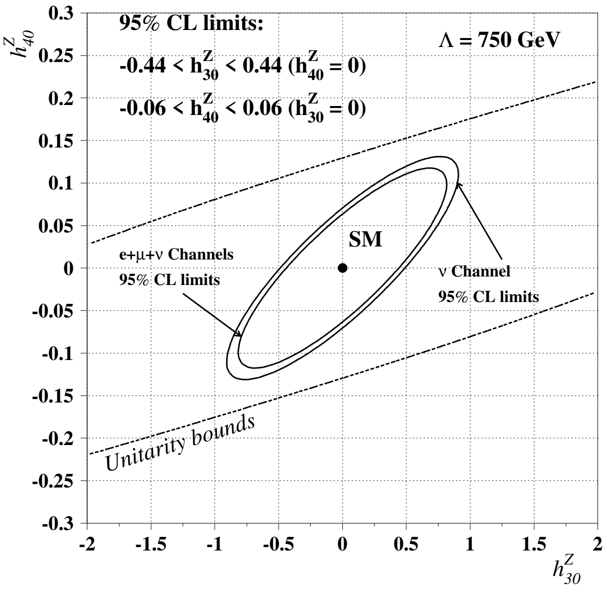

FIG. 5. Limits on the anomalous $ZZ\gamma$ couplings from $Z\gamma \to \nu\nu\gamma$ analysis for $\Lambda = 0.75$ TeV.

$$|h^Z_{30}| < 0.44 \ (|h^Z_{40}| = 0); \ \ |h^Z_{40}| < 0.06 \ (|h^Z_{30}| = 0)$$
$$|h^\gamma_{30}| < 0.45 \ (|h^\gamma_{40}| = 0); \ \ |h^\gamma_{40}| < 0.06 \ (|h^\gamma_{30}| = 0).$$

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