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Trilinear Gauge Couplings at the Fermilab Tevatron

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Recent trilinear gauge boson couplings measurements by the CDF and DØ Collaborations at the Fermilab Tevatron are presented. The measurements were done by analyzing diboson production in multiple decay channels and final states. No deviations from the Standard Model description of the WWZ, $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ vertices were found. Limits on anomalous gauge couplings set by these analyses are the tightest available to date.

The existence of trilinear gauge boson couplings (TGC) is one of the explicit predictions of the Standard Model (SM) of electroweak interactions [1]. Since the SM is based on $SU(2)_{\rm Y} \times U(1)_{\rm EM}$ symmetry, properties of these couplings differ from pure electromagnetic. Therefore, precision measurement of the couplings offers a crucial test of the gauge sector of the SM.

From the form of the gauge part of the SM Lagrangian, only $WW\gamma$ and WWZ TGC are nonzero. All other couplings allowed by charge conservation and EM gauge invariance ($ZZ\gamma$, $Z\gamma\gamma$, ZZZ) are zero at tree level [1].

The most direct way to study TGC is to measure pair production of vector gauge bosons in fermion-antifermion ($f\bar{f}$) collisions. Because of its high energy and luminosity, the Fermilab Tevatron is an excellent machine for such measurements. With a center of mass energy $\sqrt{s} =$ 1800 GeV and an accumulated integrated luminosity of about 100 pb^{-1} per experiment, it is possible to measure $W\gamma$, WW, $Z\gamma$ and even WZ production, with a possibility to study ZZ production in the future. Both the CDF and DØ experiments have extensively studied diboson production over the past few years.

1. $Z\gamma$ PRODUCTION

Measurement of $Z\gamma$ production allows one to probe both $ZZ\gamma$ and $Z\gamma\gamma$ (in what follows called $ZV\gamma$) couplings. Since the Z boson is observed only by its decay products, a $f\bar{f}$ pair, the measurements are done in the $f\bar{f}\gamma$ final state. Even though the $ZV\gamma$ vertex does not exist in the SM, there is SM background to the above final state from t-channel production of the Z and photon, as well as from radiative Z decays: $q\bar{q} \to Z \to f\bar{f}\gamma$. Anomalous couplings, if they exist, not only would increase total $f\bar{f}\gamma$ production cross section, but also would result in a much harder p_T spectrum of the produced photons. This is an excellent experimental signature.

The most general anomalous coupling Lagrangian contains four different anomalous $ZV\gamma$ couplings, traditionally called h_i^V, $i = 1,\ldots,4$. The $i = 1,2$ couplings are CP-odd, while the other pair conserves CP. In order to respect partial wave unitarity it is necessary to turn off the couplings at high energy. We use a form-factor ansatz in which couplings at high energy are related to their static limits h_{i0}^V as $h_i^V = h_{i0}^V/(1 + \hat{s}/\Lambda^2)^n$, where Λ is a form-factor scale closely related to the mass scale of the new physics responsible for anomalous couplings, and $n = 3$ for $h_{1,3}^V$ couplings and 4 for $h_{2,4}^V$ ones.

Both CDF and DØ have published [2] the results of their searches for anomalous couplings in dielectron and dimuon decay channels of the Z in the data collected during the 1992–1993 Tevatron run with integrated luminosity of ≈ 15 pb^{-1} per experiment. Preliminary results of similar searches in the much larger 1994–1995 data set are now available. The analysis strategy and the cuts are similar to the published ones: both experiments require two good isolated electrons or muons in the final state and a photon with transverse energy (E_T^γ) above 7 (10) GeV for CDF (DØ). In 67 pb^{-1} of data CDF observed 18 (13)

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Table 1
95% CL limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings

Data set and channel	CDF $c^V \equiv h^V_{10,30}$	CDF $c^V \equiv h^V_{20,40}$	DØ $c^V \equiv h^V_{10,30}$	DØ $c^V \equiv h^V_{20,40}$
1992–1993 $Z(\nu\nu)\gamma$	N/A	N/A	$\|c^V\| < 0.9$	$\|c^V\| < 0.2$
1992–1993 $Z(ee+\mu\mu+\nu\nu)\gamma$	N/A	N/A	$\|c^V\| < 0.8$	$\|c^V\| < 0.2$
1994-1995 $Z(ee+\mu\mu)\gamma$	$\|c^V\| < 1.6$	$\|c^V\| < 0.4$	$\|c^{Z(\gamma)}\| < 1.3$ (1.4)	$\|c^V\| < 0.3$

$ee\gamma$ ($\mu\mu\gamma$) candidates with estimated background of 0.9 ± 0.3 (0.5 ± 0.1) events, dominated by $Z + j$ and QCD multijet production. The observed signal agrees with the SM prediction of 16.2 ± 1.8 (8.7 ± 0.7) events. DØ analyzed 97 (87) pb^{-1} of $ee\gamma$ ($\mu\mu\gamma$) data and observed 14 (15) candidate events with an expected background of 1.8 ± 0.5 (3.6 ± 0.7) events, consistent with SM prediction of 12.8 ± 1.3 (16.3 ± 2.0) events. (Backgrounds are similar to that in the CDF analysis, except in the dimuon decay channel where an additional $W(\mu\nu)\gamma$ background arises from fake muons because of loose ID cuts on one of the muons.) Both experiments set limits on anomalous couplings by performing a binned likelihood fit to the E_T^γ spectrum. These limits are summarized in Table 1 (a form-factor scale $\Lambda = 500$ GeV was used for easy comparison with other experiments).

DØ has recently performed [3] a unique search for anomalous couplings in the "invisible" neutrino decay channel of the Z in 1992–1993 data set. The advantages of the $\nu\bar{\nu}\gamma$ final state are a high branching ratio (factor of six higher than that in a charged lepton channel) and the absence of radiative Z-decay background. Other backgrounds, however, are quite large in this channel and are dominated by $W(e\nu)$ production with electron misidentified as a photon due to tracking chamber inefficiencies, and cosmic or beam muon bremsstrahlung in the EM calorimeter. Special techniques [3] were developed to suppress these backgrounds; also the E_T^γ cut used in this analysis was much higher (40 GeV). As a result, 4 candidate events were observed with an expected background of 5.8 ± 1.0 events, in agreement with the SM prediction of 1.8 ± 0.2 events. Despite higher backgrounds, the sensitivity to anomalous couplings in this channel is very high since, unlike the anomalous coupling signal, the background falls rapidly with E_T^γ. A fitting technique similar to that used in dilepton analysis yields limits on anomalous couplings which are a factor of two better than that in charged lepton channels (see Table 1). Combined anomalous couplings limits from published DØ 1992–1993 data set analyses are the most restrictive limits available today.

2. $W\gamma$ PRODUCTION

$W\gamma$ production is similar to that of $Z\gamma$, except that the contribution of the $WW\gamma$ vertex is not zero. Analogous to the $Z\gamma$ case there are four general $WW\gamma$ couplings which are called κ_γ, λ_γ, $\tilde{\kappa}_\gamma$, and $\tilde{\lambda}_\gamma$. The first two are CP-conserving; the second pair violates CP. The SM predicts $\kappa_\gamma = 1$ and all other couplings to be zero. In what follows we will use $\Delta\kappa_\gamma = \kappa_\gamma - 1$ in order to describe deviations from the SM. The four couplings are related to the EM multipole moments of the W, e.g. W magnetic dipole moment equals $\frac{e}{2M_W}(2 + \Delta\kappa_\gamma + \lambda_\gamma)$. The anomalous $WW\gamma$ couplings are also modified with a form-factor in order to ensure partial wave unitarity. A dipole form-factor with scale Λ is used. Unlike the $Z\gamma$ case, the form-factor scale dependence of the $WW\gamma$ production is small. As in the $Z\gamma$ case there are SM backgrounds from $W\gamma$ production in t-channel and from radiative W decays.

Both experiments have published [4] the results of their $W\gamma$ production measurements in the electron and muon decay channels of the W from the data collected during the 1992-1993 Tevatron run. DØ has recently published [5] final results from the entire 1992–1995 Tevatron run, and CDF has preliminary results for the 1994–1995 data set. The analysis strategy and the cuts are similar to the $Z\gamma$ analysis in the dilepton channels: both experiments require one good isolated electron

Table 2
95% CL limits on anomalous $WW\gamma$ couplings from 1992–1995 data sets

Channel	CDF		DØ	
$W(e\nu+\mu\nu)\gamma$	$-1.8<\Delta\kappa_\gamma, \tilde{\kappa}_\gamma<2.0$	$-0.7<\lambda_\gamma, \tilde{\lambda}_\gamma<0.6$	$\lvert\Delta\kappa_\gamma\rvert, \lvert\tilde{\kappa}_\gamma\rvert<0.9$	$\lvert\lambda_\gamma\rvert, \lvert\tilde{\lambda}_\gamma\rvert<0.3$
WW, leptonic	$-1.1<\Delta\kappa_\gamma<1.3$	$\lvert\lambda_\gamma\rvert<0.9$	$-0.6<\Delta\kappa_\gamma<0.8$	$-0.5<\lambda_\gamma<0.6$
WW/WZ,	$-0.4<\Delta\kappa_\gamma<0.6$	$-0.3<\lambda_\gamma<0.4$	$-0.5<\Delta\kappa_\gamma<0.5$	$-0.4<\lambda_\gamma<0.3$

or muon in the final state, significant amount of missing transverse energy (signature for neutrino), and a photon with transverse energy above 7 (10) GeV for CDF (DØ). In 67 pb^{-1} of data CDF observes 75 (34) $e\nu\gamma$ ($\mu\nu\gamma$) candidates with estimated background of 16.1 ± 2.4 (10.3 ± 1.2) events, dominated by W+jets production. In the muon decay channel there is an additional background from $Z(\mu\mu)\gamma$ production with one of the muons being lost by the reconstruction program and therefore contributing to the missing transverse energy. The observed signal agrees with the SM prediction of 53.5 ± 6.8 (21.8 ± 4.3) events. In the same 1993–1994 data set (79 pb^{-1}) DØ observed 46 (58) $e\nu\gamma$ ($\mu\nu\gamma$) candidate events with an expected background of 13.2 ± 2.3 (23.3 ± 4.6) events, consistent with SM prediction of 39.7 ± 4.5 (34.6 ± 4.2) events. (Backgrounds are similar to those in the CDF analysis.) Both experiments set limits on anomalous couplings by performing a binned likelihood fit to the E_T^γ spectrum. They are summarized in Table 2 (a form-factor scale $\Lambda = 1500$ GeV was used.)

Combined DØ Run I limits exclude the EM-only couplings of the W to photons ($\kappa_\gamma = \lambda_\gamma = 0$) at 96% CL. That means that DØ has explicitly shown that W weak isospin is not zero. These are the most stringent model independent limits on anomalous $W\gamma$ couplings as of today.

3. WW AND WZ PRODUCTION

Both experiments have also searched for anomalous WWZ couplings in WW/WZ production. There are seven possible WWZ couplings (only two of them, $\kappa_Z = g_1^Z = 1$ are non-zero in the SM), so in order to reduce the number of free parameters some additional assumptions are usually made [1]. First of all, CP-violating WWZ couplings are assumed to be 0, which leaves only 4 couplings: κ_Z, λ_Z, $g_{1,5}^Z$. It is often further assumed that WWZ and $WW\gamma$ couplings are equal (equal coupling scenario). Alternatively, in the HISZ model [6] (based on $SU(2) \times U(1)$ invariance with a Higgs doublet) a different relation between $WW\gamma$ and WWZ couplings is used: $\Delta g_Z^1 \equiv g_Z^1 - 1 = \frac{\Delta\kappa_\gamma}{2\cos^2\theta_W}$, $\Delta\kappa_Z \equiv \kappa_Z - 1 = \Delta\kappa_\gamma \frac{1-\tan^2\theta_W}{2}$, $\lambda_Z = \lambda_\gamma$, $g_5^Z = 0$. Both scenarios leave only two independent parameters: $\Delta\kappa_\gamma$ and λ_γ, similar to the $W\gamma$ production case.

WW production is sensitive to both $WW\gamma$ and WWZ couplings, so the limits on each type of couplings obtained from the WW production measurement are model dependent. In what follows all limits will be presented in the equal coupling scenario. HISZ-based limits are also available from both experiments. The studies of WW production were performed in the electron and muon decay channels of the W which correspond to $ee\nu\nu$, $e\mu\nu\nu$, and $\mu\mu\nu\nu$ final states. CDF has recently published [7] final 1992–1995 results. DØ has published [8] the results of this analysis for 1992–1993 data set and has preliminary results from 1994–1995 data set. Both experiments require two good isolated leptons and significant amount of missing transverse energy in the event. Additional cuts are introduced to decrease dominant QCD, Drell-Yan and $t\bar{t}$ backgrounds. CDF observed 2, 3, and 0 candidate events in the $ee\nu\nu$, $e\mu\nu\nu$, and $\mu\mu\nu\nu$ final states in 108 pb^{-1} of data with an overall background of 1.2 ± 0.3 events, consistent with SM expectation of 3.5 ± 1.2 events. The measured WW production cross section is $10.2\,^{+6.3}_{-5.1} \pm 1.6$ pb (the NLO theoretical cross section [9] is 9.5 ± 2.9 pb). Limits on anomalous couplings are extracted from the total cross section measurement and summarized in Table 2. DØ observed 1, 2, and 1 candidates in $ee\nu\nu$, $e\mu\nu\nu$, and $\mu\mu\nu\nu$ channels with respective backgrounds of 0.9 ± 0.2, 1.1 ± 0.2, and 0.7 ± 0.2 events, which agrees with SM predictions of 0.52 ± 0.04, 0.86 ± 0.10, and 0.09 ± 0.01 events. Limits on anomalous couplings were obtained by performing a binned likelihood fit to the lepton transverse momentum spectra (see Table 2). A form-factor scale $\Lambda = 1$ TeV (1.5 TeV) was used in CDF (DØ) analysis (the Λ-dependence is small). DØ results exclude EM-only $WW\gamma$ couplings at $> 99\%$ CL in the equal coupling scenario.

Both experiments also measured WW/WZ production in semihadronic final states. CDF analyzed $l\nu +$jets and $l\bar{l} +$jets channels, where l is either an electron or muon. DØ performed measurements only in the $e\nu +$jets channel. Both experiments published [10] the results from 1992–1993 data set. DØ recently published [11] final 1992–1995 run results, and CDF has preliminary results from 1994–1995 data. Due to poor jet energy resolutuion the W and Z bosons decaying hadronically can not be distinguished by the dijet invariant mass. Consequently, both experiments measure a mixture of WW and WZ production in the $l\bar{l}$+jets final state. CDF $l\bar{l}$+jets measurement which explicitly selects WZ final state unfortunately has low sensitivity due to small branching fraction of $Z \to l\bar{l}$ decay. Therefore neither experiment can disentangle WWZ and $WW\gamma$ couplings in the semihadronic channel.

The event selection requires at least two energetic jets with invariant mass between 60 (50) and 110 GeV for CDF (DØ). Leptons are required to be isolated and have significant transverse energy. An additional requirement in the $l\nu +$jets final state is missing transverse energy above 20 (25) GeV. To increase sensitivity to anomalous couplings the CDF analysis requires the transverse momentum of the dijet system (p_T^{jj}) to exceed 200 GeV. DØ, instead, performs a binned likelihood fit of the $p_T^{e\nu}$ spectrum, so no explicit cut is made. CDF observed no candidate events with an expected background of 0.8 events and SM expectation of 0.1 event. DØ has observed 399 candidates with an expected background of 388 ± 38 events and SM prediction of 17.5 ± 3.0 events. For both experiments the dominant background is from associated vector boson production with two or more jets, QCD fakes and in CDF case an additional $t\bar{t}$ background. Limits are summarized in Table 2 for $\Lambda = 2$ TeV. The EM-only $WW\gamma$ couplings are excluded at $> 99\%$ CL by both experiments.

Both experiments are working on finalizing the analyses and combining final results which are expected to be comparable with final results anticipated from LEP II [1]. Space restrictions preclude discussion of other interesting TGC results from both experiments, such as search for radiation zero from CDF, or combined $W\gamma/WW/WZ$ limits from DØ. These results, as well as the figures are available at http://www-cdf.fnal.gov/physics/ewk/ewk.html and http://www-d0.fnal.gov/public/wz/ewk_public.html. Both experiments will continue the TGC studies in the next run, and the opportunities in this field are exciting.

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