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Trilinear Gauge Boson Couplings and Vector Boson Pair Production[1]

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Abstract. The trilinear couplings appear as the three gauge boson vertices and can be measured by studying the gauge boson pair production processes. The measurement of the coupling parameters is one of the few remaining crucial tests of the Standard Model. DØ has studied $W\gamma$, $Z\gamma$, WW, and WZ production and found no evidence of anomalous production. In this paper we review all the current results from DØ data.

INTRODUCTION

Over the past two decades, experiments have beautifully confirmed the predictions of the Standard Model (SM). However two crucial sectors remain poorly tested: The symmetry breaking sector, and the self-interactions of gauge bosons. The self-couplings of the gauge bosons are completely fixed by the $SU(2) \times U(1)$ symmetry of the SM. The trilinear couplings appear as the three gauge boson vertices and can be measured by studying the gauge boson pair production processes. Deviations of the couplings parameters values from the SM ones signal new physics.

The WWV ($V = \gamma$ or Z) vertices are described by a generalized effective Lagrangian [1] with two overall couplings parameters ($g_{WW\gamma} = -e$ and $g_{WWZ} = -e \cdot \cot\theta_W$) and six dimensionless coupling parameters g_1^V, κ_V and λ_V, where $V = \gamma$ or Z, after imposing C, P and CP invariance. Furthermore g_1^γ is restricted to unity by electromagnetic gauge invariance. The general Lagrangian is reduced to the SM Lagrangian by setting $g_1^\gamma = g_1^Z = \kappa_V = 1$ ($\Delta\kappa_V \equiv \kappa_V - 1 = 0$) and $\lambda_V = 0$. The amplitudes for gauge boson pair production with the non-SM coupling parameters grows with energy ($\hat{s}$). In order to avoid unitarity violation, the coupling parameters are modified by form factors with a cutoff scale Λ; $\lambda_V(\hat{s}) = \frac{\lambda_V}{(1+\hat{s}/\Lambda^2)^2}$ and

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$\Delta\kappa_V(\hat{s}) = \frac{\Delta\kappa_V}{(1+\hat{s}/\Lambda^2)^2}$. Λ is physically interpreted as the mass scale where the new phenomenon which is responsible for the anomalous couplings would be directly observed.

In an analogous manner, the $Z\gamma V$ ($V = \gamma$ or Z) vertices are described by a general vertex function [2] with eight dimensionless coupling parameters h_i^V ($i = 1,4; V = \gamma$ or Z). In the SM, all h_i^V's are zero. The form factors for these vertices, which are required to constrain the cross sections amplitudes within the unitarity limit, 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 DØ collaboration has performed several searches for anomalous trilinear gauge boson couplings. In this paper we review all measurements of trilinear gauge boson couplings based on the direct observation of diboson final states produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV during the 1992-1996 data taking period using the DØ detector at Fermilab. Limits on the anomalous coupling parameters were obtained at a 95% CL from the following processes: $p\bar{p} \rightarrow Z\gamma + X \rightarrow l\bar{l}\gamma + X$ ($l = e, \mu, \nu$), $p\bar{p} \rightarrow W\gamma + X \rightarrow l\nu\gamma + X$ ($l = e, \mu$), $p\bar{p} \rightarrow WW/WZ + X \rightarrow l\nu jj + X$ ($l = e, \mu$), $p\bar{p} \rightarrow WW + X \rightarrow l\nu l\nu + X$ ($l = e, \mu$), and $p\bar{p} \rightarrow WZ + X \rightarrow l\nu ll + X$ ($l = e, \mu$). Combined limits with LEP experiments have also been obtained.

$W\gamma$ ANALYSIS

The DØ collaboration has studied $W\gamma$ production from two decay modes of the W boson: $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$, reported in Ref. [3]. In each case the photon was required to have a minimum transverse momentum of 10 GeV/c and to be spatially separated from the charged lepton by at least 0.7 units of $\mathcal{R}_{l\gamma}$, $\mathcal{R} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ ($\eta = -\log\tan(\theta/2)$). We have observed $84.4^{+12.3}_{-11.3} \pm 8.7$ signal events from $\sim$ 89pb^{-1} of data taken during 1992-1993 and 1993-1995 Tevatron collider runs. The asymmetrical error is the 1σ uncertainty due to Poisson statistics, and the second error is due to the uncertainties in the background estimates.

From this observation we calculated the $W\gamma$ cross section times branching ratio of W bosons to leptons, for our photon requirements, to be: $\sigma(p\bar{p} \rightarrow W\gamma + X) \times$ BR($W \rightarrow l\nu$) $= 11.3^{+1.7}_{-1.5} \pm 1.6(syst)$ pb. This is in agreement with the SM prediction of 12.5 ± 1.0 pb. A combined likelihood analysis of the p_T^γ spectra from the individual $W(e\nu)$ and $W(\mu\nu)$ analyses allowed us to set 95% CL limits on the anomalous $WW\gamma$ coupling parameters of $-0.98 < \Delta\kappa < 0.94$ and $-0.31 < \lambda < 0.29$. These are the 95% CL limits when only one of the couplings is allowed to vary at a time.

$Z\gamma$ ANALYSIS

Measurements of $Z\gamma$ production through the $ee\gamma$, $\mu\mu\gamma$, and $\nu\nu\gamma$ decay channels with the DØ detector were previously reported in Ref. [4]. Here we briefly describe those analyses. The measurements of $ee\gamma$, and $\mu\mu\gamma$ channels are based on $\sim$ 100 pb^{-1} of data collected in 1993-1995 Tevatron collider run, while the measurement of the $\nu\nu\gamma$ production is based on 13.5 pb^{-1} of data collected in the 1992-1993 run. Event selection for the $ee\gamma(\mu\mu\gamma)$ analysis required two electrons (muons) with high E_T and a photon with $E_T > 10$ GeV. We additionally required that the photon was separated from either electron (muon) by at least 0.7 units in $\eta - \phi$ space. These channels are dominated by $Z + j$ and multijet production with jets faking the photon or electrons (muons). This background was derived from data. The observed yield events agree well with the SM predictions and background estimates.

For the $\nu\nu\gamma$ analysis, we required a much tighter cut on the photon energy: $E_T > 40$ GeV which was forced by a dominant background from $W \to e\nu$ decays with the electron being misidentified for a photon due to inefficiency of the central tracker. Additional cuts were applied to the shape of the photon EM shower in transverse and longitudinal directions to ensure that it was consistent with a photon originating from a real vertex. The residual background, which had roughly equal contributions from $W \to e\nu$ decays and *bremsstrahlung* photons from cosmic and beam halo muons, was derived from data. The observed yield is consistent with the SM prediction and brackground estimates. Combined limits on anomalous couplings were set at 95% CL by the E_T^γ fit: $|h_{10,30}^Z| < 0.36$, $|h_{10,30}^\gamma| < 0.37$, and $|h_{20,40}^V| < 0.05$ using a cutoff scale of $\Lambda = 750$ GeV. This represents the most stringent limits available today.

WW ANALYSIS

DØ has searched for W pair production in the dilepton decay modes: $e\nu e\nu$, $e\nu\mu\nu$, and $\mu\nu\mu\nu$ [5]. The analyses require two isolated leptons plus mising transverse energy. In order to remove the background coming from top quark pair production, DØ require the vector sum of the E_T from hadrons to be less than 40 GeV. This cut reduces the this background by a factor of more than four, while is 95% efficient for SM W^+W^- events. A cut in the transverse missing energy in introduced to avoid backgrounds from $Z \to \tau^+\tau^-$ and Drell–Yan processes $\gamma/Z \to e^+e^-, \mu^+\mu^-$. Events are also rejected if the transverse missing energy vector points along or opposite the direction of a lepton. Also, events with a dilepton mass greater than 75 GeV/c^2 or less than 110 GeV/c^2 are rejected. 5 events pass the above selection criteria while the estimated background is 3.1 ± 0.4 events. This leds to an upper limit on the cross section for $p\bar{p} \to W^+W^-$ of 37.1 pb at the 95% CL. Using a binned likelihood to the measured p_T spectra of the two leptons the limits at 95% CL and a cutoff scale of 1.5 TeV are: $-0.62 < \Delta\kappa < 0.77$ and $-0.52 < \lambda < 0.56$ varing only one coupling at a time.

WZ ANALYSIS

WZ production have also been studied using the $e\nu ee$ and $\mu\nu ee$ decay modes at DØ [6]. In that analysis we searched for unusual signature of three charged high–

E_T leptons and the missing transverse energy due to the high–E_T neutrino. We use about 92 pb^{-1} of data. One event was found which passed the selection criteria (an $e\nu ee$ candidate). The SM prediction for both channels combined was found to be 0.25 ± 0.02 events, with a estimated backgound of 0.50 ± 0.17 events. Based on these the 95% CL upper limit on the cross section was 47 pb, consistent with the SM. Since no excess of events, which would be an indication of non-SM WWZ couplings, was seen, DØ set limits on anomalous couplings. The analysis is most sensitive to the λ_Z and g_1^Z parameters because the helicity amplitudes have larger factors multiplying λ_Z and g_1^Z compared with $\Delta\kappa_Z$. Due to WZ production is sensitive only to the WWZ couplings, the results are independent on any assumption on $WW\gamma$ couplings. Using a cutoff scale of $\Lambda = 1.0$ TeV, the one-dimensional 95% CL limits were: $|\lambda_Z| < 1.42$ and $|\Delta g_1^Z| < 1.63$.

WW/WZ ANALYSIS

The WW/WZ candidates were selected by searching for events containing an isolated electron (muon) with high E_T, large missing transverse energy $\not{E}_T$ and two high E_T jets. The transverse mass of the electron and neutrino system was requiered to be consistent with a W boson decay ($M_T > 40$ 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 decay. Additionally for the electron channel, it was also required that the p_T of the two gauge bosons was balanced ($|p_T(jj) - p_T(e\nu)| < 40$ GeV/c) as expected for WW/WZ production. The number of events that satisfied all of the requirements were 483 for the electron channel and 224 for the muon one. There were two major sources of background for these processes, QCD multijet events with a jet misidentified as an electron or muon and W boson production with two associated jets. Total number of background events was estimated to be 463 ± 40 and 224 ± 55 respectively. The SM predicts 21 ± 3 events and 5 ± 1 respectively for the above requirements and thus no significant deviation from the SM prediction was seen.

A maximum likelihood fit to the p_T^W spectrum, calculated from the E_T of electron (muon) and missing E_T, was performed to set limits on the anomalous couplings. Using a cutoff scale of $\Lambda = 2.0$ TeV, the 95% confidence level (CL) limits were: $-0.43 < \Delta\kappa < 0.59$ (with $\lambda = 0$) and $-0.33 < \lambda < 0.36$ (with $\Delta\kappa = 0$) for the electron channel, and $-0.60 < \Delta\kappa < 0.74$ (with $\lambda = 0$) and $-0.43 < \lambda < 0.44$ (with $\Delta\kappa = 0$) for the muon channel. These results were reported in Ref. [6,7].

COMBINED ANALYSIS

The DØ experiment has performed combined limits on the parameters of the $WW\gamma$ and WWZ couplings using a simultaneous fit to the p_T distribution in the $W\gamma$ data, the lepton $p_T^{(l\nu)}$ distribution in the $WW \to l\nu l'\nu'$, and $WW/WZ \to l\nu jj$ data, and the number of observed event in $WZ \to l\nu ll$. This exercise is reported in Ref. [6]. There, the limits on the $WW\gamma$ and WWZ coupling parameters are extracted from that fit. Correlations between the uncertainties due the integrated luminosity, the selection efficiencies and the background estimates are properly taken into account. In these exercise $\Delta\kappa$, λ, and g_1^Z parameters are used, as well as the LEP ones: $\alpha_{B\phi}$, $\alpha_{W\phi}$, and α_W.

The results obtained on $WW\gamma$ and WWZ coupling parameters have comparable sensitivity to those from the LEP experiments. The limits on the $\alpha_{B\phi}$, α_W parameters obtained by DØ are also the most stringent constraints. However, the LEP measurements are most sensitive to $\alpha_{W\phi}$. The LEP limits are complementary to the Tevatron ones because they are obtained from a different process ($e^+e^- \rightarrow W^+W^-$) exploting the behavior of the angular distributions of the decay products. Table 1 shows limits on λ, $\Delta\kappa$, and where applicable on Δg_1^Z, $\alpha_{B\phi}$, $\alpha_{W\phi}$, and α_W, for $\Lambda = 1.5$ and 2.0 TeV.

Couplings	$\Lambda = 1.5$ TeV	$\Lambda = 2.0$ TeV
$\lambda_\gamma = \lambda_Z (\Delta\kappa_\gamma = \Delta\kappa_Z = 0)$	-0.20, 0.20	-0.18, 0.19
$\Delta\kappa_\gamma = \Delta\kappa_Z = 0 (\lambda_\gamma = \lambda_Z = 0)$	-0.27, 0.42	-0.25, 0.39
λ_γ(HISZ [8])$(\Delta\kappa_\gamma = 0)$	-0.20, 0.20	-0.18, 0.19
$\Delta\kappa_\gamma$ (HISZ) $(\lambda_\gamma = 0)$	-0.31, 0.56	-0.29, 0.53
λ_Z (SM $WW\gamma$)$(\Delta\kappa_Z = \Delta g_1^Z = 0)$	-0.26, 0.29	-0.24, 0.27
$\Delta\kappa_Z$ (SM $WW\gamma$)$(\lambda_Z = \Delta g_1^Z = 0)$	-0.37, 0.55	-0.34, 0.51
Δg_1^Z (SM $WW\gamma$)$(\lambda_Z = \Delta\kappa_Z = 0)$	-0.39, 0.62	-0.37, 0.57
λ_γ (SM WWZ) $(\Delta\kappa_\gamma = 0)$	-0.27, 0.25	-0.25, 0.24
$\Delta\kappa_\gamma$ (SM WWZ) $(\lambda_\gamma = 0)$	-0.57, 0.74	-0.54, 0.69
$\alpha_{B\phi}$ $(\alpha_{W\phi} = \alpha_W = 0)$	-0.73, 0.59	-0.67, 0.56
$\alpha_{W\phi}$ $(\alpha_{B\phi} = \alpha_W = 0)$	-0.19, 0.38	-0.18, 0.36
α_W $(\alpha_{B\phi} = \alpha_{W\phi})$	-0.20, 0.20	-0.18, 0.19
Δg_1^Z $(\alpha_{B\phi} = \alpha_W = 0)$	-0.25, 0.49	-0.23, 0.47

TABLE 1. One-dimensional limits at 95% CL. from a simultaneos fit to the DØ $WW\gamma$, $WW \rightarrow$ dilepton, $WW/WZ \rightarrow l\nu jj$, and $WZ \rightarrow$ trilepton data samples.

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