

## Limits on anomalous trilinear gauge couplings from $WW \rightarrow e^+e^-$ , $WW \rightarrow e^\pm\mu^\mp$ , and $WW \rightarrow \mu^+\mu^-$ events from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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(Received 7 August 2006; published 8 September 2006; corrected 14 September 2006)

Limits are set on anomalous  $WW\gamma$  and  $WWZ$  trilinear gauge couplings using  $W^+W^- \rightarrow e^+\nu_e e^-\bar{\nu}_e$ ,  $W^+W^- \rightarrow e^+\nu_e\mu^+\nu_\mu$ , and  $W^+W^- \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$  events. The data set was collected by the Run II D0 detector at the Fermilab Tevatron Collider and corresponds to approximately  $250\text{ pb}^{-1}$  of integrated

luminosity at  $\sqrt{s} = 1.96$  TeV. Under the assumption that the  $WW\gamma$  couplings are equal to the  $WWZ$  couplings and using a form factor scale of  $\Lambda = 2.0$  TeV, the combined 95% C.L. one-dimensional coupling limits from all three channels are  $-0.32 < \Delta\kappa < 0.45$  and  $-0.29 < \lambda < 0.30$ .

DOI: [10.1103/PhysRevD.74.057101](https://doi.org/10.1103/PhysRevD.74.057101)

PACS numbers: 14.70.Fm, 13.85.Qk

Within the standard model (SM), interactions between the bosons of the electroweak interaction are entirely determined by the gauge symmetry. Any deviation from the SM couplings is therefore evidence of new physics.

The most general Lorentz invariant effective Lagrangian which describes the triple gauge couplings has 14 independent coupling parameters, seven for each of the  $WW\gamma$  and  $WWZ$  vertices [1]. With the assumption of electromagnetic gauge invariance and  $C$  and  $P$  conservation, the number of independent couplings is reduced to five, and the Lagrangian takes this form:

$$\begin{aligned} \frac{\mathcal{L}_{WWV}}{g_{WWV}} = & ig_1^V (W_{\mu\nu}^\dagger W^{\mu\nu} V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}) \\ & + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W^\mu V^\nu W^{\nu\lambda} \end{aligned} \quad (1)$$

where  $V = \gamma$  or  $Z$ ,  $W^\mu$  is the  $W^-$  field,  $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$ ,  $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ , and  $g_1^\gamma = 1$ . The overall couplings are  $g_{WW\gamma} = -e$  and  $g_{WWZ} = -e \cot\theta_W$ .

The five remaining parameters are  $g_1^Z$ ,  $\kappa_Z$ ,  $\kappa_\gamma$ ,  $\lambda_Z$ , and  $\lambda_\gamma$ . In the SM,  $g_1^Z = \kappa_Z = \kappa_\gamma = 1$  and  $\lambda_Z = \lambda_\gamma = 0$ . The couplings  $g_1^Z$ ,  $\kappa_Z$ , and  $\kappa_\gamma$  are often written in terms of their deviation from the SM values as  $\Delta g_1^Z = g_1^Z - 1$ , and similarly for  $\Delta\kappa_Z$  and  $\Delta\kappa_\gamma$ .

One effect of introducing anomalous coupling parameters into the SM Lagrangian is an increase of the cross section for the  $q\bar{q} \rightarrow Z/\gamma \rightarrow W^+W^-$  process, particularly as parton center-of-mass energies rise to infinity. Thus, constant finite values of the anomalous couplings produce unphysically large cross sections, violating unitarity. To keep the cross section from diverging, the anomalous coupling must vanish as  $s \rightarrow \infty$ . This is done by introducing a dipole form factor for an arbitrary coupling  $\alpha$  [ $g_1^Z$ ,  $\kappa_V$ , or  $\lambda_V$  from Eq. (1)]:

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1 + \hat{s}/\Lambda^2)^2} \quad (2)$$

where the form factor scale  $\Lambda$  is set by new physics. For a

TABLE I. Predicted numbers of signal and background events, with statistical error, and number of candidate events for each decay channel.

Channel	Signal	Background	Candidates
$e^+e^-$	$3.26 \pm 0.05$	$2.30 \pm 0.21$	6
$e^\pm\mu^\mp$	$10.8 \pm 0.1$	$3.81 \pm 0.17$	15
$\mu^+\mu^-$	$2.01 \pm 0.05$	$1.94 \pm 0.41$	4

given value of  $\Lambda$ , there is an upper limit on the size of the coupling, beyond which unitarity is exceeded.

Limits on the  $WW\gamma$  and  $WWZ$  anomalous couplings are set using the data, event selection, and background calculations from the recent  $WW$  cross section analysis published by the D0 Collaboration [2]. The cross section analysis measures the  $p\bar{p} \rightarrow WW$  cross section to be  $13.8_{-3.8}^{+4.3}(\text{stat})_{-0.9}^{+1.2}(\text{syst}) \pm 0.9(\text{lum})$  pb, compared with a SM next-to-leading order prediction of  $13.0 - 13.5$  pb [3].

The leptonic channels  $WW \rightarrow \ell^+\nu\ell^-\bar{\nu} (\ell = e, \mu)$  were used to measure the cross section, with integrated luminosities of  $252 \text{ pb}^{-1}$  for the  $e^+e^-$  channel,  $235 \text{ pb}^{-1}$  for the  $e^\pm\mu^\mp$  channel, and  $224 \text{ pb}^{-1}$  for the  $\mu^+\mu^-$  channel. Table I summarizes the predicted numbers of signal and background events and the number of observed candidate events in each channel. Details of selection cuts and efficiencies can be found in Ref. [2].

Four anomalous coupling relationships are considered. In the first relationship, the  $WW\gamma$  parameters are equal to the  $WWZ$  parameters:  $\Delta\kappa_\gamma = \Delta\kappa_Z$  and  $\lambda_\gamma = \lambda_Z$ . The second relationship, the HISZ parametrization [4], imposes  $SU(2) \times U(1)$  symmetry upon the coupling parameters. For the final two relationships, either the SM  $WW\gamma$  or  $WWZ$  interaction is fixed, while the other parameters are allowed to vary. In all cases, parameters which are not constrained by the coupling relationships are set to their SM values.

Anomalous coupling limits must be set for a given coupling relationship and form factor scale. Setting limits on a pair of anomalous couplings simultaneously requires a grid of Monte Carlo (MC) events, generated specifically for that coupling relationship and form factor scale. The likelihood of getting the actual measured events is calculated at each of the grid points and the limits for the couplings are then extracted from a fit to the likelihood distribution across the grid.

The leading order MC generator by Hagiwara, Woodside, and Zeppenfeld (HWZ) [1] is used to generate events for a grid in  $(\Delta\kappa, \lambda)$  space. The central area of each grid has a finer spacing of generated coupling parameters to ensure that the likelihood surface is well defined inside the area where limits are expected to be set.

The generated events for each grid point are passed through a parametrized simulation of the D0 detector that is tuned using  $Z$  boson events. The outputs for each grid point are the simulated  $p_T$  spectra for the two leptons in the event scaled to match the luminosity of the data. Eight  $p_T$  bins are used to calculate the likelihood at each grid point: three bins plus an overflow bin for each of the two leptons. Figure 1 shows the data for the leading lepton in the  $e^\pm\mu^\mp$

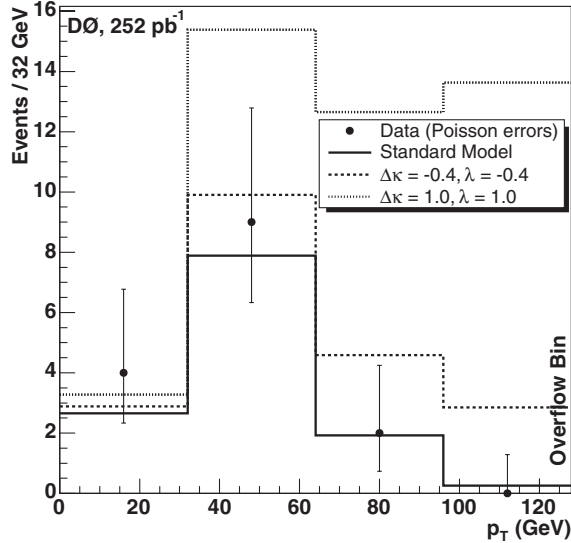


FIG. 1. Leading lepton  $p_T$  distributions for data (points), SM MC (solid line), and two anomalous coupling MC scenarios (dashed lines), from the  $WW \rightarrow e^\pm \mu^\mp$  channel, binned as used to calculate likelihood.

channel with MC estimations for the SM and two sample anomalous coupling grid points.

The simulated signal from the HWZ generator and the background, taken from the cross section analysis, are compared to the  $p_T$  distribution of the data by calculating a bin-by-bin likelihood. Each bin is assumed to have a Poisson distribution with a mean equal to the sum of the signal and background. The uncertainties on the signal and background distributions are accounted for by weighting with Gaussian distributions. Correlations between the signal and background uncertainties for each channel are small, so they are handled separately. The uncertainty on the luminosity is 100% correlated, and so varies the same way for all channels. The likelihood,  $L$ , is calculated as

$$L = \int \mathcal{G}_{f_l} P_{ee}(f_l) P_{e\mu}(f_l) P_{\mu\mu}(f_l) df_l \quad (3)$$

$$P_{\ell\ell'}(f_l) = \int \mathcal{G}_{f_n} \int \mathcal{G}_{f_b} \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}[N_{\ell\ell'}^i; (f_l f_n n_{\ell\ell'}^i + f_l f_b b_{\ell\ell'}^i)] df_n df_b \quad (4)$$

where  $\mathcal{P}(a; \alpha)$  is the Poisson probability of obtaining  $a$  events if the mean expected number is  $\alpha$ ;  $n_{\ell\ell'}^i$  and  $b_{\ell\ell'}^i$  are the simulated numbers of signal and background events for the  $\ell\ell'$  channel in bin  $i$ ;  $N_{\ell\ell'}^i$  is the measured number of events for this channel in this bin; and  $f_l$ ,  $f_n$ , and  $f_b$  are the luminosity, signal, and background weights drawn from the Gaussian distributions  $\mathcal{G}_{f_l}$ ,  $\mathcal{G}_{f_n}$ , and  $\mathcal{G}_{f_b}$  respectively.

To extract the limits, a 6th order polynomial is fitted to the grid of negative log likelihood values. The one- and two-dimensional 95% C.L. limits are determined by inte-

TABLE II. One-dimensional limits at the 95% C.L. with various assumptions relating the  $WW\gamma$  and  $WWZ$  couplings at various values of  $\Lambda$ . Parameters which are not constrained by the coupling relationships are set to their SM values.

Coupling		95% C.L. Limits	$\Lambda$ (TeV)
$WW\gamma = WWZ$	$\lambda$	-0.31, 0.33	1.5
	$\Delta\kappa$	-0.36, 0.47	
$WW\gamma = WWZ$	$\lambda$	-0.29, 0.30	2.0
	$\Delta\kappa$	-0.32, 0.45	
HISZ	$\lambda$	-0.34, 0.35	1.5
	$\Delta\kappa_\gamma$	-0.57, 0.75	
SM $WW\gamma$	$\lambda_Z$	-0.39, 0.39	2.0
	$\Delta\kappa_Z$	-0.45, 0.55	
SM $WWZ$	$\lambda_\gamma$	-0.97, 1.04	1.0
	$\Delta\kappa_\gamma$	-1.05, 1.29	

grating the likelihood curve or surface, respectively. In the one-dimensional case, the 95% C.L. limits represent the pair of points of equal likelihood that bound 95% of the total integrated area between the ends of the MC grid. The two-dimensional 95% C.L. contour line is the set of points of equal likelihood that bound a region containing 95% of the total integrated volume between the MC grid boundaries.

One-dimensional 95% C.L. limits are summarized in Table II, and two-dimensional 95% C.L. contours are shown in Figs. 2 and 3. Under the assumption that the

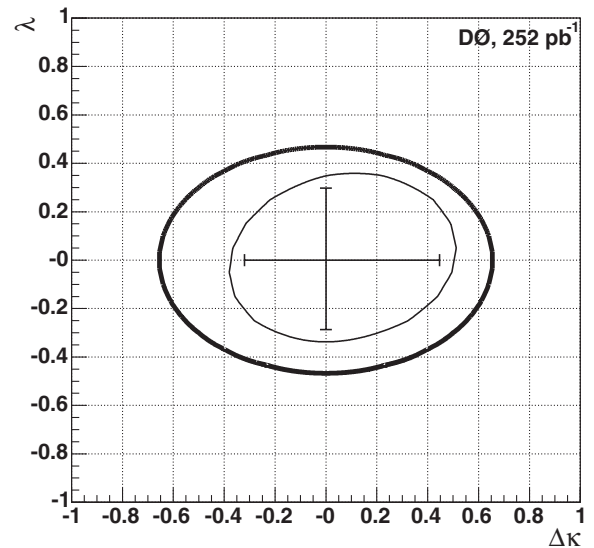


FIG. 2. One- and two-dimensional 95% C.L. limits when  $WWZ$  couplings are equal to  $WW\gamma$  couplings, at  $\Lambda = 2.0$  TeV. The bold curve is the unitarity limit, the inner curve is the two-dimensional 95% C.L. contour, and the ticks along the axes are the one-dimensional 95% C.L. limits.

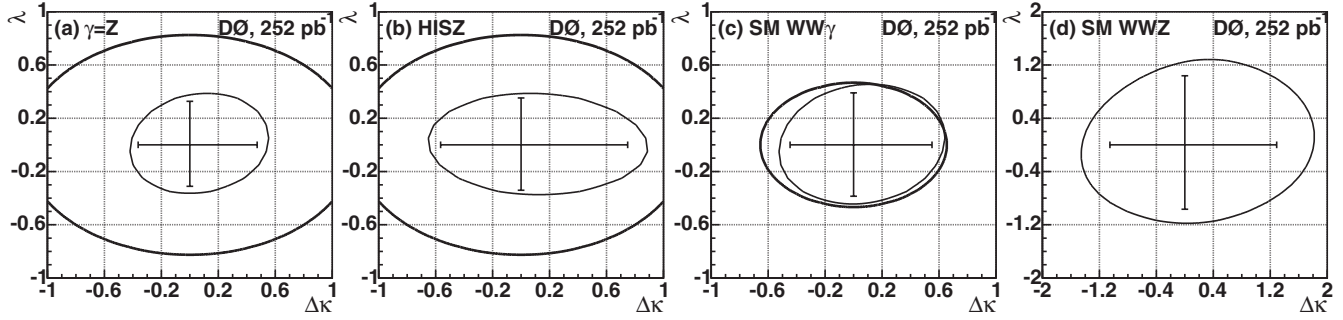


FIG. 3. One- and two-dimensional 95% C.L. limits for (a)  $WW\gamma = WWZ$  at  $\Lambda = 1.5$  TeV, (b) HISZ at  $\Lambda = 1.5$  TeV, (c) SM  $WW\gamma$  at  $\Lambda = 2.0$  TeV, and (d) SM  $WWZ$  at  $\Lambda = 1.0$  TeV. The bold curve is the unitarity limit (where it fits within the plot boundaries), the inner curve is the two-dimensional 95% C.L. contour, and the ticks along the axes are the one-dimensional 95% C.L. limits.

$WW\gamma$  and  $WWZ$  couplings are equal and using a form factor scale of  $\Lambda = 2.0$  TeV, the 95% C.L. limits obtained are  $-0.32 < \Delta\kappa < 0.45$  and  $-0.29 < \lambda < 0.30$ . This significantly improves upon the previous limits from the D0 Collaboration,  $-0.62 < \Delta\kappa < 0.77$  and  $-0.53 < \lambda < 0.56$ , set in Run I at the Fermilab Tevatron Collider for the same channels under the same assumption using an integrated luminosity of  $100 \text{ pb}^{-1}$  [5]. Although the combined anomalous coupling limits from the CERN  $e^+e^-$  Collider (LEP) collaborations are tighter [6], the hadronic collisions at the Fermilab Tevatron Collider explore a range of parton center-of-mass energies not explored at LEP.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); PPARC (United Kingdom); MSMT (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); Research Corporation; Alexander von Humboldt Foundation; and the Marie Curie Program.

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used are  $\Delta\kappa_Z = \Delta\kappa_\gamma(1 - \tan^2\theta_W)$ ,  $\Delta g_1^Z = \Delta\kappa_\gamma/(2\cos^2\theta_W)$ , and  $\lambda_Z = \lambda_\gamma$ .

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