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

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

250 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 $-0.29 < \lambda < 0.30$.

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 fourteen 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:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu V^{\nu\lambda} \tag{1}$$

where $V = \gamma$ or Z, W^μ 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, κ_Z, κ_γ, λ_Z, and λ_γ. In the SM, $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ and $\lambda_Z = \lambda_\gamma = 0$. The couplings g_1^Z, κ_Z, and κ_γ 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 $q\bar{q} \to Z/\gamma \to W^+W^-$ 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 $s \to \infty$. This is done by introducing a dipole form factor for an arbitrary coupling α (g_1^Z, κ_V, or λ_V from Eq. 1):

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

where the form factor scale Λ is set by new physics. For a given value of Λ, 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 DØ Collaboration [2]. The cross section analysis measures the $p\bar{p} \to WW$ cross section to be $13.8^{+4.3}_{-3.8}(\mathrm{stat})^{+1.2}_{-0.9}(\mathrm{syst}) \pm 0.9(\mathrm{lum})$ pb, compared with a SM next-to-leading order prediction of $13.0 - 13.5$ pb [3].

The leptonic channels $WW \to \ell^+\nu\ell^-\bar{\nu}$ ($\ell = e,\ \mu$) were used to measure the cross section, with integrated luminosities of 252 pb^{-1} for the e^+e^- channel, 235 pb^{-1} for the $e^\pm\mu^\mp$ channel, and 224 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].

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

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

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 parameterization [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 parameterized simulation of the DØ 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 $e^\pm\mu^\mp$ channel with MC estimations for the SM and two sample anomalous coupling grid points.

The simulated signal from the HWZ generator and the

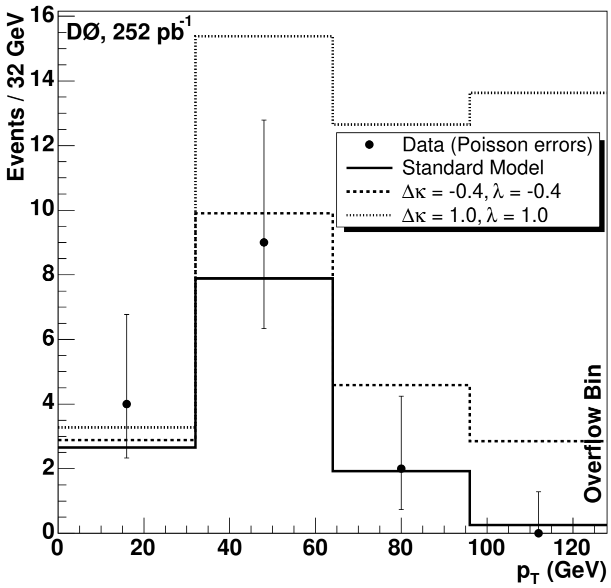

FIG. 1: Leading lepton p_T distributions for data (points), SM MC (solid line), and two anomalous coupling MC scenarios (dashed lines), from the $WW \to e^{\pm}\mu^{\mp}$ channel, binned as used to calculate likelihood.

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

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

$$P_{\ell\ell}(f_l) = \int \mathcal{G}_{f_n} \int \mathcal{G}_{f_b} \prod_{i=1}^{N_{\rm bins}} \mathcal{P}\left[N^i_{\ell\ell}; (f_l f_n n^i_{\ell\ell} + f_l f_b b^i_{\ell\ell})\right] df_n df_b \tag{4}$$

where $\mathcal{P}(a;\alpha)$ is the Poisson probability of obtaining a events if the mean expected number is α; $n^i_{\ell\ell'}$ and $b^i_{\ell\ell'}$ are the simulated numbers of signal and background events for the $\ell\ell'$ channel in bin i; $N^i_{\ell\ell'}$ 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.

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

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

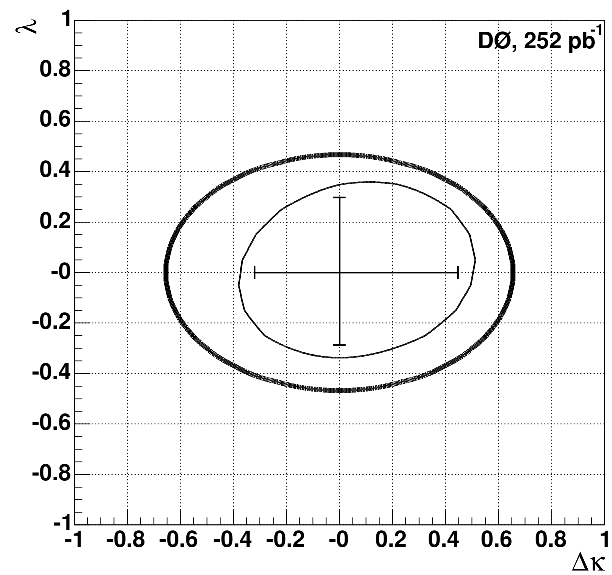

FIG. 2: One- and two-dimensional 95% C.L. limits when WWZ couplings are equal to $WW\gamma$ couplings, at $\Lambda = 2.0$ TeV. The bold curve is the unitarity limit, the inner curve is the two-dimensional 95% C.L. contour, and the ticks along the axes are the one-dimensional 95% C.L. limits.

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 integrating 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. countour 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

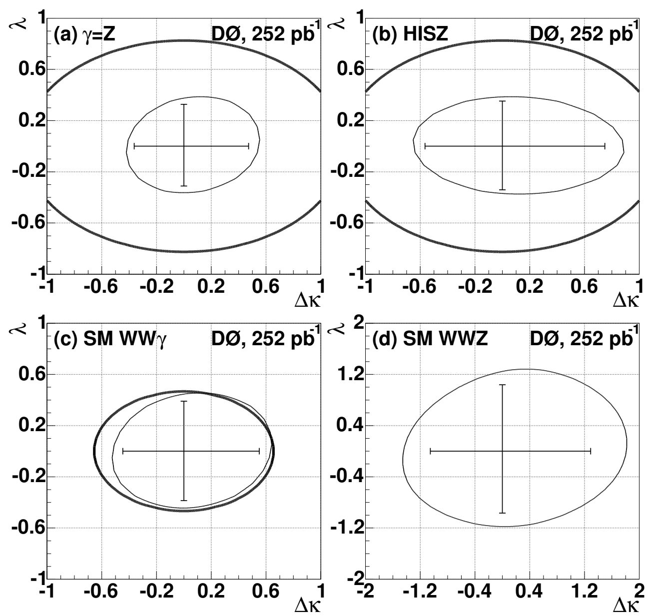

FIG. 3: One- and two-dimensional 95% C.L. limits for (a) $WW\gamma = WWZ$ at Λ=1.5 TeV, (b) HISZ at Λ=1.5 TeV, (c) SM $WW\gamma$ at Λ=2.0 TeV, and (d) SM WWZ at Λ=1.0 TeV. The bold curve is the unitarity limit (where it fits within the plot boundaries), the inner curve is the two-dimensional 95% C.L.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

Table II, and two-dimensional 95% C.L. contours are shown in Figs. 2 and 3. Under the assumption that the $WW\gamma$ 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 DØ 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 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.

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