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Electroweak Boson Pair Production at the Tevatron

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The CDF and DØ Collaborations

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Abstract

Preliminary results from CDF and DØ on $W\gamma$, $Z\gamma$ and WW, WZ, ZZ boson pair production in $\sqrt{s}$ = 1.8 TeV p̄-p collisions from the 1992-93 collider run are presented. Direct limits on $\mathcal{CP}$-conserving and $\mathcal{CP}$-violating $WW\gamma$, WWZ, $ZZ\gamma$ and $Z\gamma\gamma$ anomalous couplings have been obtained. The results are consistent with Standard Model expectations. In the static limit, the direct experimental limits on $WW\gamma$ and $ZZ\gamma$ anomalous couplings are related to bounds on the higher-order static (transition) EM moments of the W (Z) bosons. Expectations from the on-going and future Tevatron collider runs are discussed.

1. Introduction

During the 1992-93 Tevatron collider run, CDF (DØ) accumulated $\sim$ 20 (13) pb^{-1} integrated luminosity. The inclusive W/Z data samples obtained during this run are sufficiently large that studies of rare and/or semi-rare exclusive processes such as $W\gamma$, $Z\gamma$, WW, WZ and ZZ-pair production are now becoming feasible.

The observation and detailed study of these processes provide important new tests of the Standard Model (SM) of electroweak (EWK) interactions through the investigation and study of tri-linear gauge boson couplings of the W, Z and γ. Strong gauge cancellations are predicted to occur in the $W\gamma$, WW and WZ processes, while no such cancellations are expected for the $Z\gamma$ or ZZ processes. The tri-linear gauge boson couplings associated with the $WW\gamma$ and WWZ vertices (s-channel Feynman diagrams) are a consequence of the non-Abelian $SU_L(2) \times U_Y(1)$ symmetry of the EWK theory [1]. They are the *only* non-zero tree-level tri-vector boson vertices allowed in the SM. The corresponding u and t-channel diboson processes depend only on the coupling between quarks and EWK bosons. However, the fermion-gauge boson couplings are now well-tested in the production and decay of single bosons, and are considered as known. Diboson production is therefore primarily a test of the strength and nature of the tri-linear gauge boson couplings.

In various non-standard models of the electroweak interactions, the V = W, Z and γ are viewed as composite, rather than fundamental particles [2]. In such scenarios, non-standard $WW\gamma$, WWZ, $ZZ\gamma$, $Z\gamma\gamma$ and ZZZ anomalous couplings may exist. New physics must be introduced at large $\hat{s}$ [3] in order to avoid violation of tree-level S-matrix unitarity [4]. The anomalous couplings are modified via the introduction of generalized dipole form factors [5, 6] $a(\hat{s}) = a_o/(1+\hat{s}/\Lambda_V^2)^n$ where $a_o = \Delta\kappa$, λ... which force the anomalous boson couplings to approach their SM values at large $\hat{s}$. The form factor scale Λ_V is presumed to be significantly larger than the typical $\hat{s}$ values seen at the Tevatron. A signature of the existence of non-zero anomalous couplings is an excess rate of production of diboson pairs, particularly at high transverse energies. The absence of an excess of such events can therefore be used to obtain *direct* experimental limits on such anomalous couplings for each diboson process.

2. Diboson Pair Production at the Tevatron

CDF (DØ) extract $W\gamma/Z\gamma$ data samples from inclusive e/μ channel W/Z samples by requiring an isolated photon in a fiducial region of their central (central + endcap) EM calorimeters with $E_T^\gamma \geq 7$ (10) GeV. A minimum lepton $-$ photon angular separation of $\Delta R_{\ell\gamma} = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.7$ suppresses final-state QED bremsstrahlung. Background from W/Z+jets is suppressed by requiring isolated photons and transverse/longitudinal EM shower development consistent with a single photon. The level of W/Z+jet background in each of the $W\gamma/Z\gamma$ data samples is determined by use of QCD jet data samples to obtain a jet fragmentation probability $\mathcal{P}_{J\rightarrow\gamma}(E_T)$ which is then convoluted with the jet E_T spectrum in each of the inclusive W/Z data samples. The $Z\gamma$ background in the $W\gamma$ data arising from non-observation of one of the Z decay leptons is estimated from MC simulations. The contributions to $W\gamma$ and $Z\gamma$ from tau W/Z decay channels are also estimated from MC simulations and found to be small.

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WW, WZ and ZZ data samples are also extracted from inclusive e/μ W/Z data. CDF has analyzed the $WW, WZ \rightarrow \ell\bar{\nu}\ jj$ and $ZW, ZZ \rightarrow \ell^+\ell^-\ jj$ ($\ell = e$ or μ) channels using standard W/Z lepton selection cuts, and requiring $60 < M_{jj} < 110$ GeV/c^2. For leptonic W (Z) events, CDF eliminates W/Z+jets background by requiring $P_T^{jj} > 130$ (100) GeV/c, which also eliminates the SM signal but retains good sensitivity for non-zero $WW\gamma/WWZ$ anomalous couplings. DØ has analyzed the $WW \rightarrow e\nu_e\ \ell\nu_\ell$ channel using standard lepton cuts for selection of W pairs. The Z mass region in the ee channel is excluded and $M_T(ee,\not{E}_T) > 100$ GeV/c^2 is required. Backgrounds from Z decay and fake electrons are estimated from data and MC simulations.

SM and anomalous coupling predictions for the $W\gamma$ and $Z\gamma$ processes are obtained via use of the Baur/Berger MC event generators [5, 6] and detailed MC detector simulations. MRSD−′ structure functions are used for event generation as they best match the recent W lepton asymmetry measurements from CDF [7]. SM and anomalous coupling predictions for the WW, WZ and ZW processes are obtained via use of the Zeppenfeld MC event generator [8] and MC detector simulations.

Preliminary CDF and DØ results from the 1992-93 collider run for event yields and SM predictions for $W\gamma$, $Z\gamma$, WW, WZ and ZZ production are summarized in Table 1, along with UA2 $W\gamma$ [9] and preliminary CDF $W\gamma$, $Z\gamma$ results from the 1988-89 collider run [10]. All results are in good agreement with SM expectations.

Table 1. Diboson pair event yields and SM comparison. UA2 and DØ (CDF) quote SS (DS) $\pm 1\sigma$ stat+syst uncertainties.

	N_{obs}	ΣN_{bkgnd}	N_{signal}	N_{pred}^{SM}
UA2 '90 $W\gamma_e$	16	6.8 ± 1.0	$9.2^{+5.2}_{-3.2}$	11.9 ± 1.1
CDF '88 $W\gamma_{e+\mu}$	13	6.2 ± 1.7	6.8 ± 4.0	7.0 ± 1.0
CDF '92 $W\gamma_{e+\mu}$	25	8.5 ± 2.4	16.5 ± 5.5	23.3 ± 3.4
DØ '92 $W\gamma_{e+\mu}$	19	$5.5^{+3.0}_{-2.3}$	$13.5^{+5.3}_{-3.0}$	13.8 ± 2.1
CDF '88 $Z\gamma_{e+\mu}$	4	0.4 ± 0.1	3.6 ± 2.0	2.0 ± 0.2
CDF '92 $Z\gamma_{e+\mu}$	8	0.5 ± 0.2	7.5 ± 2.8	7.1 ± 0.8
DØ '92 $Z\gamma_{e+\mu}$	6	0.2 ± 0.1	$5.8^{+3.6}_{-2.4}$	4.2 ± 0.9
CDF '92 WW/WZ	1	–	1	0.08
CDF '92 ZW/ZZ	0	–	0	0.01
DØ '92 WW	2	2.2 ± 1.0	2	0.55

Table 2. 95% CL limits on $WW\gamma$ anomalous couplings. Only one coupling is allowed to deviate from its SM value at a time.

$\mathcal{CP}$-conserving	$\Delta\kappa^\gamma$	λ^γ
UA2 '90 $W\gamma_e$	$-4.5 < \Delta\kappa^\gamma < 4.9$	$-3.6 < \lambda^\gamma < 3.9$
CDF '88 $W\gamma_{e+\mu}$	$-6.0 < \Delta\kappa^\gamma < 6.4$	$-2.4 < \lambda^\gamma < 2.3$
CDF '92 $W\gamma_{e+\mu}$	$-2.3 < \Delta\kappa^\gamma < 2.2$	$-0.7 < \lambda^\gamma < 0.7$
DØ '92 $W\gamma_{e+\mu}$	$-2.3 < \Delta\kappa^\gamma < 2.3$	$-0.7 < \lambda^\gamma < 0.7$
CDF '92 WW/WZ	$-1.0 < \Delta\kappa^\gamma < 1.1$	$-0.8 < \lambda^\gamma < 0.8$
DØ '92 WW	$-3.3 < \Delta\kappa^\gamma < 3.5$	$-2.6 < \lambda^\gamma < 2.7$
$\mathcal{CP}$-violating	$\tilde{\kappa}^\gamma$	$\tilde{\lambda}^\gamma$
UA2 '90 $W\gamma_e$	$-4.7 < \tilde{\kappa}^\gamma < 4.7$	$-3.7 < \tilde{\lambda}^\gamma < 3.7$
CDF '88 $W\gamma_{e+\mu}$	$-6.2 < \tilde{\kappa}^\gamma < 6.2$	$-2.4 < \tilde{\lambda}^\gamma < 2.4$
CDF '92 $W\gamma_{e+\mu}$	$-2.2 < \tilde{\kappa}^\gamma < 2.2$	$-0.7 < \tilde{\lambda}^\gamma < 0.7$
DØ '92 $W\gamma_{e+\mu}$	$-2.3 < \tilde{\kappa}^\gamma < 2.3$	$-0.7 < \tilde{\lambda}^\gamma < 0.7$
CDF '92 WW/WZ	$-3.4 < \tilde{\kappa}^\gamma < 3.4$	$-0.8 < \tilde{\lambda}^\gamma < 0.8$

3. Direct Limits on W/Z Anomalous Couplings

Direct experimental limits on $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ anomalous couplings for the $W\gamma/Z\gamma$ processes are obtained via binned maximum likelihood fits to the E_T^γ distribution. The observed E_T^γ distribution is compared to the sum of expected signal plus background(s) prediction, calculating the Poisson likelihood that this sum would fluctuate to the observed number of events in each E_T bin, and convoluting with a Gaussian distribution to take into account systematic uncertainties associated with backgrounds, luminosity normalization, structure function choice, Q^2-scale and uncertainties in the shape of the $P_T(W\gamma/Z\gamma)$ distribution, efficiencies, *etc.*

CDF extracts direct experimental limits on $WW\gamma$ and WWZ anomalous couplings for the WW/WZ processes via comparison of observed events to the expected signal, including systematic uncertainties due to luminosity normalization, jet energy scale and resolution, structure function choice and higher order QCD corrections, *etc.* DØ extracts direct experimental limits on $WW\gamma/WWZ$ anomalous couplings via comparison of their background non-subtracted 95% CL upper limit on $\sigma \cdot B(WW)_{expt} < 133$ pb with $\sigma \cdot B(WW)_{pred}$ as a function of anomalous couplings.

Table 2 summarizes the results from hadron colliders on 95% CL, direct limits on $WW\gamma$ anomalous couplings. Figure 1 shows the 95% CL limit contours for $\mathcal{CP}$-conserving $WW\gamma$ anomalous couplings. The limit contours for $\mathcal{CP}$-violating $WW\gamma$ anomalous couplings (not shown) are similar. For the WW/WZ boson pair processes, $\Delta\kappa^\gamma = \Delta\kappa^Z$ and $\lambda^\gamma = \lambda^Z$ have been assumed. The maximum value of the form factor scale Λ_W where the combined $W\gamma$+WW unitarity constraint contour lies outside the anomalous couplings limit contour for each experiment is indicated. Table 3 summarizes the results on 95% CL, direct limits on $ZZ\gamma$ and $Z\gamma\gamma$ anomalous couplings from CDF, DØ and L3 at LEP [11]. The Tevatron limits on $Z\gamma\gamma$ anomalous couplings are the first *direct* test of these couplings. Figure 2 shows the 95% CL limit contours for $\mathcal{CP}$-conserving/violating $ZZ\gamma$ anomalous couplings. The Tevatron limit contours for $Z\gamma\gamma$ anomalous couplings (not shown) are similar. The different orientation of limit contours in each figure is due to the $\hat{s}$-dependencies of the anomalous couplings.

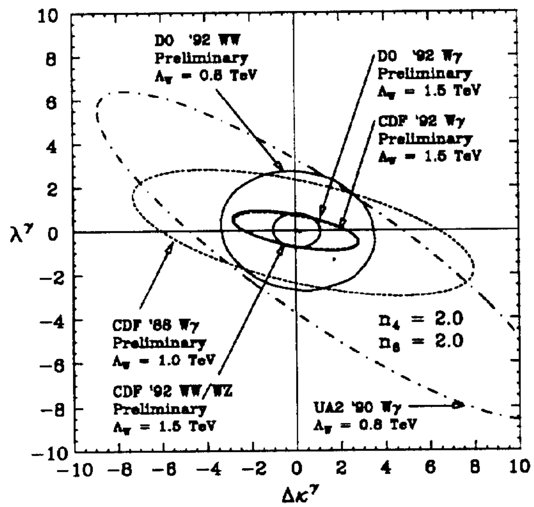

Figure 1. 95% CL limits on $\mathcal{CP}$-conserving $WW\gamma$ anomalous couplings.

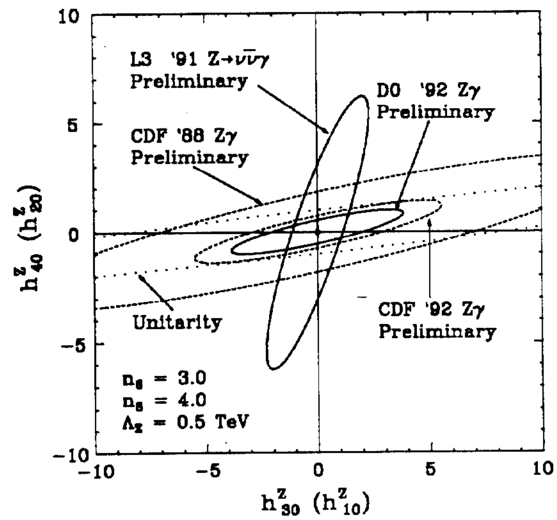

Figure 2. 95% CL limits on $\mathcal{CP}$-conserving ($\mathcal{CP}$-violating) $ZZ\gamma$ anomalous couplings.

Table 3. 95% CL limits on $ZZ\gamma/Z\gamma\gamma$ anomalous couplings for $\Lambda_Z = 500$ GeV. Only one coupling is allowed to deviate from its SM value at a time.

$\mathcal{CP}$-conserving	$h_{30}^{Z,\gamma}$	$h_{40}^{Z,\gamma}$
CDF '88 $Z\gamma_{e+\mu}$	$-7.1 < h_{30}^Z < 7.1$	$-1.8 < h_{40}^Z < 1.8$
CDF '92 $Z\gamma_{e+\mu}$	$-3.0 < h_{30}^Z < 2.9$	$-0.7 < h_{40}^Z < 0.7$
DØ '92 $Z\gamma_{e+\mu}$	$-2.1 < h_{30}^Z < 2.1$	$-0.5 < h_{40}^Z < 0.5$
L3 '91 $Z \rightarrow \nu\bar{\nu}\gamma$	$-1.1 < h_{30}^Z < 1.1$	$-3.0 < h_{40}^Z < 3.0$
CDF '88 $Z\gamma_{e+\mu}$	$-7.4 < h_{30}^\gamma < 7.4$	$-1.9 < h_{40}^\gamma < 1.9$
CDF '92 $Z\gamma_{e+\mu}$	$-3.1 < h_{30}^\gamma < 3.1$	$-0.8 < h_{40}^\gamma < 0.8$
DØ '92 $Z\gamma_{e+\mu}$	$-2.2 < h_{30}^\gamma < 2.1$	$-0.5 < h_{40}^\gamma < 0.5$
$\mathcal{CP}$-violating	$h_{10}^{Z,\gamma}$	$h_{20}^{Z,\gamma}$
CDF '88 $Z\gamma_{e+\mu}$	$-7.1 < h_{10}^Z < 7.1$	$-1.8 < h_{20}^Z < 1.8$
CDF '92 $Z\gamma_{e+\mu}$	$-2.9 < h_{10}^Z < 2.9$	$-0.7 < h_{20}^Z < 0.7$
DØ '92 $Z\gamma_{e+\mu}$	$-2.1 < h_{10}^Z < 2.1$	$-0.5 < h_{20}^Z < 0.5$
L3 '91 $Z \rightarrow \nu\bar{\nu}\gamma$	$-1.1 < h_{10}^Z < 1.1$	$-3.0 < h_{20}^Z < 3.0$
CDF '88 $Z\gamma_{e+\mu}$	$-7.4 < h_{10}^\gamma < 7.4$	$-1.9 < h_{20}^\gamma < 1.9$
CDF '92 $Z\gamma_{e+\mu}$	$-3.1 < h_{10}^\gamma < 3.1$	$-0.8 < h_{20}^\gamma < 0.8$
DØ '92 $Z\gamma_{e+\mu}$	$-2.2 < h_{10}^\gamma < 2.2$	$-0.5 < h_{20}^\gamma < 0.5$

4. Direct Limits on W/Z Boson EM Moments

In the static limit (photon energy $k \rightarrow 0$), the $WW\gamma$ anomalous couplings, which are relativistic quantities, are related to the higher-order classical EM moments of the W boson (with $\hbar = c = 1$) via [12]:

$$
\begin{aligned}
\mu_W &= \frac{e}{2M_W}(2 + \Delta\kappa_\gamma + \lambda_\gamma) &&\equiv \frac{e}{2M_W} g_W \\
Q_W^e &= -\frac{e}{M_W^2}(1 + \Delta\kappa_\gamma - \lambda_\gamma) &&\equiv -\frac{e}{M_W^2} q_W^e \\
d_W &= \frac{e}{2M_W}(\tilde{\kappa}_\gamma + \tilde{\lambda}_\gamma) &&\equiv \frac{e}{2M_W} \delta_W \\
Q_W^m &= -\frac{e}{M_W^2}(\tilde{\kappa}_\gamma - \tilde{\lambda}_\gamma) &&\equiv -\frac{e}{M_W^2} q_W^m \\
<R_W^2> &= \frac{1}{M_W^2}(1 + \Delta\kappa_\gamma + \lambda_\gamma) &&\equiv \frac{1}{M_W^2} r_W^2
\end{aligned}
$$

The sign associated with each of these quantities indicates their orientation relative to the spin direction of the W^+ boson. The $ZZ\gamma$ anomalous couplings are

Table 4. 95% CL limits on W boson EM moments. Only one EM moment is allowed to deviate from its SM value at a time.

$\mathcal{CP}$-conserving	$g_W\text{-}2 = \Delta\kappa^\gamma + \lambda^\gamma$	$q_W^e\text{-}1 = \Delta\kappa^\gamma - \lambda^\gamma$
UA2 '90 $W\gamma_e$	$-4.4 < g_W\text{-}2 < 4.0$	$-12.3 < q_W^e\text{-}1 < 16.3$
CDF '88 $W\gamma_{e+\mu}$	$-3.7 < g_W\text{-}2 < 3.7$	$-5.5 < q_W^e\text{-}1 < 5.8$
CDF '92 $W\gamma_{e+\mu}$	$-1.2 < g_W\text{-}2 < 1.1$	$-1.6 < q_W^e\text{-}1 < 1.7$
DØ '92 $W\gamma_{e+\mu}$	$-1.2 < g_W\text{-}2 < 1.1$	$-1.6 < q_W^e\text{-}1 < 1.7$
CDF '92 WW/WZ	$-1.2 < g_W\text{-}2 < 1.3$	$-1.3 < q_W^e\text{-}1 < 1.3$
DØ '92 WW	$-3.5 < g_W\text{-}2 < 3.7$	$-3.8 < q_W^e\text{-}1 < 4.2$
$\mathcal{CP}$-violating	$d_W = \tilde{\kappa}^\gamma + \tilde{\lambda}$	$q_W^m = \tilde{\kappa}^\gamma - \tilde{\lambda}$
UA2 '90 $W\gamma_e$	$-4.2 < d_W < 4.2$	$-14.3 < q_W^m < 14.3$
CDF '88 $W\gamma_{e+\mu}$	$-3.7 < d_W < 3.7$	$-5.6 < q_W^m < 5.6$
CDF '92 $W\gamma_{e+\mu}$	$-1.1 < d_W < 1.1$	$-1.6 < q_W^m < 1.6$
DØ '92 $W\gamma_{e+\mu}$	$-1.1 < d_W < 1.1$	$-1.6 < q_W^m < 1.6$
CDF '92 WW/WZ	$-1.6 < d_W < 1.6$	$-1.4 < q_W^m < 1.4$

related to the higher-order EM transition moments of the Z boson in the static limit via [13]:

$$
\begin{aligned}
d_{Z_T} &= -\frac{e}{M_Z}\frac{1}{\sqrt{2}}\frac{k^2}{M_Z^2}(h_{30}^Z - h_{40}^Z) &&\equiv -\frac{e}{2M_Z}\frac{k^2}{M_Z^2}\delta_{Z_T}^* \\
Q_{Z_T}^m &= \frac{e}{M_Z^2}\sqrt{10}\,(2h_{30}^Z) &&\equiv \frac{e}{M_Z^2} q_{Z_T}^m \\
\mu_{Z_T} &= -\frac{e}{M_Z}\frac{1}{\sqrt{2}}\frac{k^2}{M_Z^2}(h_{10}^Z - h_{20}^Z) &&\equiv -\frac{e}{2M_Z}\frac{k^2}{M_Z^2} g_{Z_T}^* \\
Q_{Z_T}^e &= \frac{e}{M_Z^2}\sqrt{10}\,(2h_{10}^Z) &&\equiv \frac{e}{M_Z^2} q_{Z_T}^e
\end{aligned}
$$

The 95% CL limits on W (Z) boson EM static (transition) moments are summarized in Tables 4 (5), and shown in Figures 3 (4). The 95% CL limit contours for $\mathcal{CP}$-violating W boson EM moments (not shown) are similar to the $\mathcal{CP}$-conserving moments. Note that the relative signs of μ_W and Q_W^e are now known to >95% CL, in agreement with the SM prediction.

5. Summary and Future Prospects

CDF and DØ have obtained preliminary results on $W\gamma$, $Z\gamma$ and WW, WZ and ZZ boson pair production,

Table 5. 95% CL limits on Z boson EM transition moments for $\Lambda_Z = 500$ GeV. Only one EM moment is allowed to deviate from its SM value at a time.

$\mathcal{CP}$-conserving	$\delta^*_{Z_T} = \sqrt{2}(h^Z_{30} - h^Z_{40})$	$q^m_{Z_T} = \sqrt{10}(2h^Z_{30})$
CDF '88 $Z\gamma_{e+\mu}$	$-2.6 < \delta^*_{Z_T} < 2.6$	$-14.5 < q^m_{Z_T} < 14.4$
CDF '92 $Z\gamma_{e+\mu}$	$-1.1 < \delta^*_{Z_T} < 1.1$	$-6.0 < q^m_{Z_T} < 6.0$
DØ '92 $Z\gamma_{e+\mu}$	$-0.7 < \delta^*_{Z_T} < 0.7$	$-4.6 < q^m_{Z_T} < 4.6$
L3 '91 $Z \to \nu\bar{\nu}\gamma$	$-4.6 < \delta^*_{Z_T} < 4.6$	$-10.3 < q^m_{Z_T} < 10.3$
$\mathcal{CP}$-violating	$g^*_{Z_T} = \sqrt{2}(h^Z_{10} - h^Z_{20})$	$q^e_{Z_T} = \sqrt{10}(2h^Z_{10})$
CDF '88 $Z\gamma_{e+\mu}$	$-2.6 < g^*_{Z_T} < 2.6$	$-14.4 < q^e_{Z_T} < 14.4$
CDF '92 $Z\gamma_{e+\mu}$	$-1.1 < g^*_{Z_T} < 1.1$	$-6.0 < q^e_{Z_T} < 6.0$
DØ '92 $Z\gamma_{e+\mu}$	$-0.7 < g^*_{Z_T} < 0.7$	$-4.6 < q^e_{Z_T} < 4.6$
L3 '91 $Z \to \nu\bar{\nu}\gamma$	$-4.6 < g^*_{Z_T} < 4.6$	$-10.3 < q^e_{Z_T} < 10.3$

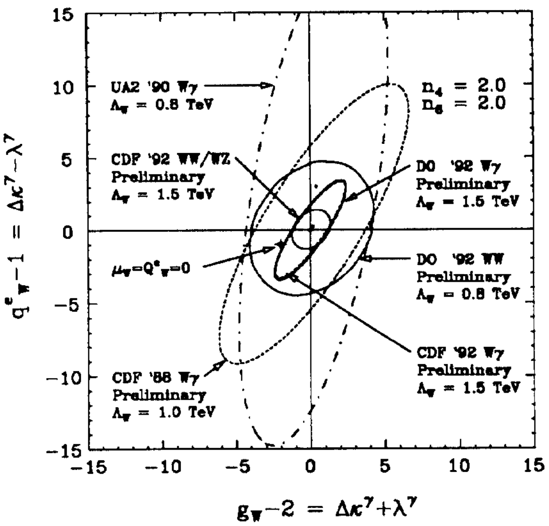

Figure 3. 95% CL limits on $\mathcal{CP}$-conserving W boson EM moments. The point where $\mu_W = Q^e_W = 0$ is indicated.

direct limits on $WW\gamma$, WWZ, $ZZ\gamma$ and $Z\gamma\gamma$ anomalous couplings and higher-order static (transition) EM moments of the W (Z) bosons. All results are in good agreement with SM expectations. An increase of $\sim 10\times$ more data is anticipated from the present collider run. With the commissioning of the Main Injector by the end of the decade, ~ 1 fb^{-1} data samples are envisioned. Detailed studies of EWK boson pair production at the Tevatron will continue throughout this era, providing evermore stringent tests of the SM on the nature of the mutual interactions of the W, Z and γ at each stage.

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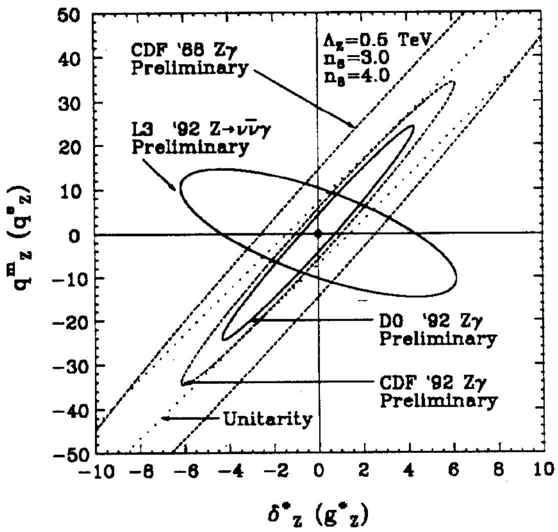

Figure 4. 95% CL limits on $\mathcal{CP}$-conserving ($\mathcal{CP}$-violating) Z boson EM transition moments for $\Lambda_Z = 500$ GeV.

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