Diboson Production at the Tevatron

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I present the latest results for diboson production at a center of mass energy of $\sqrt{s} =$ 1.96 TeV with the CDF and D0 detectors at the Fermilab Tevatron Collider.[a]

1 Diboson Production at the Tevatron

The study of diboson production provides an opportunity to perform fundamental tests of the nature of the electroweak sector of the standard model (SM), by studying the triple gauge-boson couplings (TGCs) associated with each process. An overarching goal of the Tevatron program is the discovery of the Higgs boson, which may itself decay into diboson pairs or share the same final state as diboson production when produced in association with a weak boson. Dibosons are therefore very important for understanding all aspects of the electroweak theory.

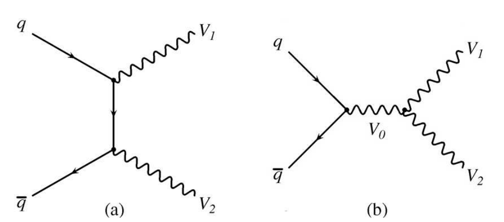

Figure 1: Vector boson pair production via (a) t-channel and (b) s-channel diagrams. For $V_1 = W$ and $V_2 = \gamma/Z$, $V_0 = W$. For $V_1 = V_2 = W$, $V_0 = \gamma/Z$.

The SM includes two charged triple gauge-boson vertices, $WW\gamma$ and WWZ, which contribute directly to $W\gamma$, WW, and WZ production, through tree-level s-channel Feynman diagrams, as shown in Figure 1.

While the most general Lorentz invariant effective Lagrangian for these vertices include seven couplings for each vertex, these couplings are generally studied while preserving electromagnetic gauge invariance and CP conservation [2]. These constraints reduce the number of free couplings from fourteen to five:

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

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 $g_{WWZ} = -e\cot\theta_W$, where e is the electron charge and θ_W is the weak mixing angle. In the SM, $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ and $\lambda_Z = \lambda_\gamma = 0$. The couplings that are non-zero in the SM are often expressed in terms of their deviation from the SM values, e.g. $\Delta g_1^Z \equiv g_1^Z - 1$.

[a]The slides presented on April 28, 2009, at the XVII International Workshop on Deep-Inelastic Scattering and Related Subjects can be found in [1].

In some analyses, additional constraints between the couplings are introduced. Enforcing $SU(2)_L \otimes U(1)_Y$ symmetry introduces two relationships between the remaining parameters: $\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W$ and $\lambda_Z = \lambda_\gamma$, reducing the number of free parameters to three [3]. Alternatively, enforcing equality between the $WW\gamma$ and WWZ vertices such that $\kappa_\gamma = \kappa_Z$, $\lambda_\gamma = \lambda_Z$, and $g_1^Z = 1$ reduces the number of free parameters to two.

Equivalent triple gauge-boson vertices do not exist in the SM for $Z\gamma$ or ZZ production. A general Lagrangian containing eight terms (h_i^V, where $i = 1,...,4$ and $V = \gamma, Z$) is usually used to describe the theoretical $Z\gamma\gamma$ and $ZZ\gamma$ vertices that could contribute to $Z\gamma$ production [4]. In this framework, the $h_{1,2}^V$ couplings are CP-odd and the $h_{3,4}^V$ couplings are CP-even.

Anomalous values of any of these TGCs lead to divergence in the production cross section as the partonic center of mass energy, $\sqrt{\hat{s}}$, increases. In order to preserve partial wave unitarity, each coupling, A, must be introduced as a form factor:

$$A(\hat{s}) = \frac{A_0}{(1 + \hat{s}/\Lambda^2)^n} \tag{2}$$

where Λ sets the energy scale for new physics, $n = 2$ for $WW\gamma$ and WWZ couplings, $n = 3$ for h_1^V and h_3^V, $n = 4$ for h_2^V and h_4^V, and coupling limits are set in terms of A_0.

2 $Z\gamma$ Production

Only initial state radiation from an annihilating quark contributes to $Z\gamma$ production at tree level in the SM. If the Z boson subsequently decays into neutrinos, then only the photon is observed, with a significant amount of missing transverse energy, $\not\!\!E_T$. A recent study by the D0 Collaboration observes this process using data corresponding to 3.6 fb^{-1} of integrated luminosity [5]. The D0 detector is described in [6].

Event selection requires a photon candidate with transverse energy $E_T > 90$ GeV and $\not\!\!E_T > 70$ GeV. A pointing algorithm uses the cluster position reconstructed by the calorimeter in four EM layers to confirm the interaction vertex and estimate backgrounds from non-collision events and misreconstructed jets. Events are rejected if they contain a jet or a second electromagnetic object with $E_T > 15$ GeV, a reconstructed muon, or an isolated high-p_T track. The total background expectation is 17.3 ± 0.6 (stat) ± 2.3 (syst) events, with 33.7 ± 3.4 expected signal and 51 events observed in data, consistent with $\sigma(p\bar{p} \to Z\gamma) = 32 \pm 9$ (stat+syst) $\pm$ 2 (lumi) fb at a significance of 5.1σ.

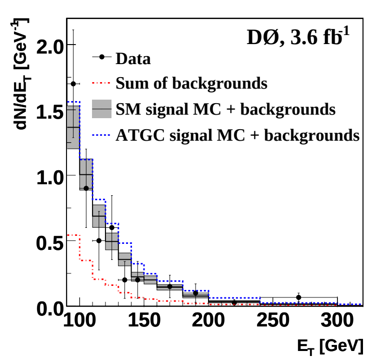

Figure 2: The photon E_T spectrum of $Z\gamma \to \nu\nu\gamma$ events.

The photon E_T spectrum, shown in Figure 2, is used to study anomalous TGCs in combination with $Z\gamma \to \ell\ell\gamma$ events [8]. This analysis is not sensitive to the differences between the CP-odd and CP-even couplings, and sets 95% C.L. limits of $|h_{1,3}^V| < 0.033$ and $|h_{2,4}^V| < 0.0017$ for $\Lambda = 1.5$ TeV. This is a factor of three improvement beyond the

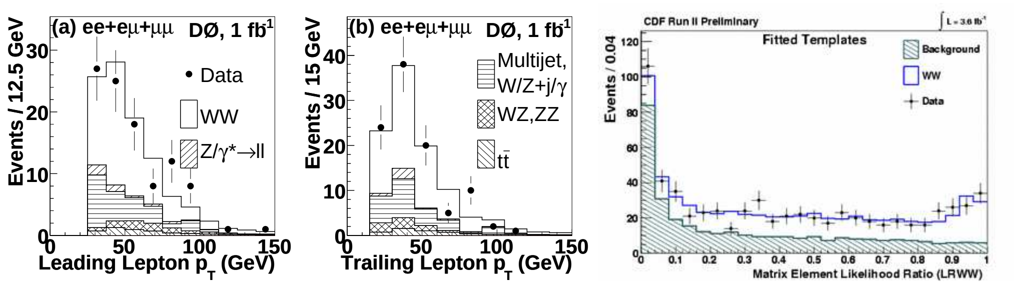

Figure 3: The leading (left) and trailing (center) lepton p_T distributions in selected events form the D0 WW analysis, and the result of the CDF matrix element likelihood ratio fit for WW signal (right).

$Z\gamma \to \ell\ell\gamma$ alone, and all but h_3^γ are improvements upon the limits from the CERN e^+e^- Collider (LEP) [7].

3 $WW \to \ell\nu\ell\nu$ Production

The most precise measurement of the WW cross section at a hadronic collider was improved twice in April, 2009, after successive announcements of preliminary results from each of the D0 and CDF collaborations.

The D0 analysis uses data corresponding to 1.0 fb^{-1} of integrated luminosity, and focused on optimizing cuts in each of the ee, $e\mu$, and $\mu\mu$ channels to produce the most precise cross section measurement possible [9]. A total of 22 (ee), 64 ($e\mu$), and 14 ($\mu\mu$) events were observed in each channel from data, corresponding to a combined cross section measurement of $\sigma(p\bar{p} \to WW) = 11.5 \pm 2.1$ (stat+syst) $\pm\, 0.7$ (lumi) pb.

The lepton p_T distributions, shown in Figure 3a and b, are used to set anomalous TGC limits. For $\Lambda = 2$ TeV, the $SU(2)_L \otimes U(1)_Y$-symmetric 95% C.L. coupling limits are $-0.54 < \Delta\kappa_\gamma < 0.83$, $-0.14 < \lambda_\gamma = \lambda_Z < 0.18$, and $-0.14 < \Delta g_1^Z < 0.30$, while the equal-coupling limits are $-0.12 < \Delta\kappa_\gamma = \Delta\kappa_Z < 0.35$ and $-0.14 < \lambda_\gamma = \lambda_Z < 0.18$.

The CDF analysis, corresponding to 3.6 fb^{-1} of data, uses event kinematics to assign a probability based on a leading-order matrix-element cross section calculation for the WW, WZ, ZZ, $W\gamma$ and W+jet processes [10]. The CDF detector is described in [11]. The likelihood ratio output, which is used to fit for the signal estimation, is shown in Figure 3c. The measured cross section is $\sigma(p\bar{p} \to WW) = 12.1 \pm 0.9$ (stat) $\pm\, ^{+1.6}_{-1.4}$ (syst) pb.

4 WW, WZ Semi-leptonic Production

A multivariate discriminant is used to separate $WW + WZ$ production from W+jet background in this D0 analysis, which uses data corresponding to 1.1 fb^{-1} of integrated luminosity [12]. A fit to the multivariate output determines the amount of signal present in the data, as shown in Figure 4. The observed cross section is $\sigma(p\bar{p} \to WW + WZ) = 20.2 \pm 2.5$ (stat) $\pm\, 3.6$ (syst) $\pm\, 1.2$ (lumi) pb, with a significance of 4.4σ, which makes this the first evidence for $WW + WZ \to \ell\nu jj$ production at a hadronic collider.

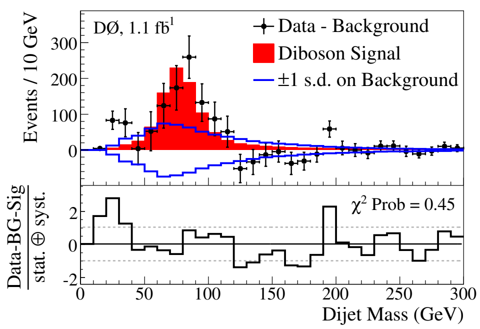

Figure 4: The background-subtracted dijet mass spectrum for selected events in the D0 $WW + WZ \to \ell\nu jj$ analysis.

The dijet mass spectrum is used to set limits on anomalous TGCs, yielding the smallest allowed range of values at 95% C.L. of these values from the Tevatron. For $\Lambda = 2$ TeV, the $SU(2)_L \otimes U(1)_Y$-symmetric 95% C.L. coupling limits are $-0.44 < \Delta\kappa_\gamma < 0.55$, $-0.10 < \lambda_\gamma = \lambda_Z < 0.11$, and $-0.12 < \Delta g_1^Z < 0.20$, while the equal-coupling limits are $-0.16 < \Delta\kappa_\gamma = \Delta\kappa_Z < 0.23$ and $-0.11 < \lambda_\gamma = \lambda_Z < 0.11$.

The CDF Collaboration has announced preliminary results based on studies of $WZ \to \ell\ell jj$ events using data corresponding to 1.9 fb^{-1} of integrated luminosity [13]. Three bins in Z boson p_T are used to study $\sigma(p\bar{p} \to WZ)$ and anomalous TGCs. The control bin, $105 < Z\ p_T < 140$ GeV, is dominated by high p_T Drell-Yan production and is used to test event modeling. Two medium p_T bin, $140 < Z\ p_T < 210$ GeV, and the high p_T bin, $Z\ p_T > 210$ GeV, are used to perform m_{jj} fits to set limits on the WZ production cross section and anomalous TGCs. The 95% C.L. limits on $\sigma(p\bar{p} \to WZ)$ are 234 fb for the medium bin and 135 fb for the high bin. Limits are set on individual TGCs, with the other couplings set equal to their SM values. For $\Lambda = 2$ TeV, the 95% C.L. coupling limits are $-1.01 < \Delta\kappa_Z < 1.27$, $-0.16 < \lambda_\gamma = \lambda_Z < 0.17$, and $-0.20 < \Delta g_1^Z < 0.29$.

5 ZZ Production

The D0 Collaboration has produced studies of both $ZZ \to \ell\ell\nu\nu$ and $ZZ \to \ell\ell\ell\ell$ production, which when combined provided a 5.7σ significance observation of ZZ production, the first observation of this process at a hadronic collider [14].

The 2.7 fb^{-1} $ZZ \to \ell\ell\nu\nu$ analysis uses a special "corrected $\not\!\!E_T$" discriminant, shown in Figure 5, that minimizes the effect of mismeasured jets and muons on the event selection. Missing transverse energy is deconstructed into components parallel and perpendicular to the thrust axis of the leptons. The $\not\!\!E_T$ component perpendicular to the thrust axis is given more weight in the "corrected $\not\!\!E_T$" discriminant, since it is more likely to be from authentic missing energy. A total of 7.4 ZZ events were expected, with 26.5 ± 0.5 background events, and 43 events were observed in data. This corresponds to an observed cross section of $\sigma(p\bar{p} \to ZZ) = 2.01 \pm 0.93$ (stat) $\pm\, 0.29$ (syst) pb, with a significance of 2.6σ.

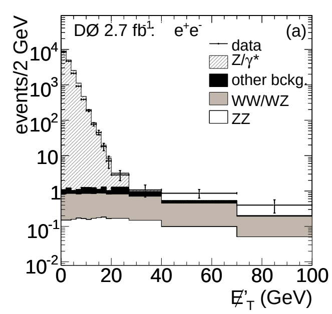

Figure 5: The D0 $ZZ \to \ell\ell\nu\nu$ "corrected $\not\!\!E_T$" distribution.

The $ZZ \to \ell\ell\ell\ell$ analysis focused on the optimization of lepton selection. A previous D0 result, based on 1 fb^{-1} of data, expected $1.71 \pm 0.15 ZZ$ events with 0.13 ± 0.03 background events and observed a single event in data.

A new independent data sample, totaling 1.7 fb^{-1}, was studied using tighter kinematic and lepton identification cuts, leading to an increase in the expected ZZ yield to 1.89 ± 0.08 events while maintaining a low background expectation of 0.14 ± 0.03 events. Three events are observed in the independent data sample, as shown in Figure 6.

The combined observations across all three of these ZZ analyses yields a cross section of $\sigma(p\bar{p} \to ZZ) = 1.60 \pm 0.63$ (stat)$^{+0.16}_{-0.17}$ (syst) pb, with a significance of 5.7σ. The CDF collaboration reported 4.4σ evidence for ZZ production in 2008 [15].

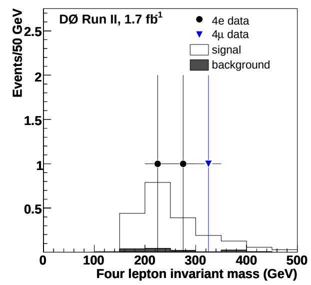

Figure 6: Selected events from the D0 $ZZ \to \ell\ell\ell\ell$ analysis.

6 Summary

The CDF and D0 Collaborations have measured the cross section of diboson processes in many final states, and observations have been consistent with SM expectations. No evidence has been found for anomalous values of TGCs from charged or neutral electroweak vertices. Recent Tevatron results have pushed the boundaries of hadron collider based results, including evidence for $WW + WZ \to \ell\nu jj$ production (4.4σ), the observation of $Z\gamma \to \nu\nu\gamma$ (5.1σ), the observation of ZZ production (5.7σ), the most precise $WW \to \ell\nu\ell\nu$ cross section measurement, increasingly stringent limits on the charged vertex TGCs (κ_γ, λ_γ, g_1^Z), and the most stringent limits on h_3^Z and h_4^V.

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