

## Diboson Production at D0

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We present recent diboson production measurements from the D0 experiment at Fermilab's Tevatron collider. The production of  $ZZ$  was observed using leptonic final states.  $Z\gamma \rightarrow \nu\nu\gamma$  was observed and used to set the most stringent limits from a hadron collider on anomalous  $Z\gamma\gamma$  and  $ZZ\gamma$  trilinear gauge couplings (TGCs).  $WW$  events with leptonic final states and  $WW + WZ$  events with semi-leptonic final states were used to set limits on anomalous  $WWZ$  and  $WW\gamma$  TGCs. Finally, limits on anomalous  $WWZ$  and  $WW\gamma$  TGCs were obtained from a combination of the fully-leptonic  $W\gamma$ ,  $WW$ , and  $WZ$  channels and the semi-leptonic  $WW$  and  $WZ$  channels, giving the most stringent limits from a hadron collider.

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## 1. Introduction

Diboson productions provides a probe for new physics that may reside beyond some high energy scale  $\Lambda_{NP}$ . In this case, the Standard Model (SM) of particle physics is simply the low energy limit of a more general theory. Such new physics could result in anomalous trilinear gauge-boson couplings (TGCs) that would affect the production rates and kinematics of diboson processes. Measuring TGCs could give clues to the new physics and the mechanism for electroweak symmetry breaking.

The most general Lorentz-invariant Lagrangian for  $\gamma WW$  and  $ZWW$  TGCs has 14 coupling parameters. However, the theory simplifies to a more manageable five coupling parameters by assuming EM gauge invariance and C, P, and CP symmetry conservation. These five couplings,  $g_1^Z$ ,  $\kappa_\gamma$ ,  $\kappa_Z$ ,  $\lambda_\gamma$ , and  $\lambda_Z$ , are measured by analyzing the production of  $WW$ ,  $WZ$ , and  $W\gamma$ .  $\gamma ZZ$  and  $\gamma\gamma Z$  TGCs are probed by analyzing  $ZZ$  and  $Z\gamma$  production. For  $ZZ\gamma$  and  $Z\gamma\gamma$  TGCs in  $Z\gamma$  production we consider the four coupling parameters  $h_3^\gamma$ ,  $h_3^Z$ ,  $h_4^\gamma$ , and  $h_4^Z$  from the most general Lorentz-invariant Lagrangian that conserves CP symmetry. In the SM,  $g_1^Z = \kappa_\gamma = \kappa_Z = 1$  and  $\lambda_\gamma = \lambda_Z = h_3^\gamma = h_3^Z = h_4^\gamma = h_4^Z = 0$  with any deviation defined as an anomalous TGC.

## 2. $ZZ \rightarrow \ell\ell\ell\ell$

The  $ZZ \rightarrow \ell\ell\ell\ell$  analysis [1] selected events in  $1.7 \text{ fb}^{-1}$  of D0 data with four energetic leptons ( $e^+e^-e^+e^-$ ,  $\mu^+\mu^-\mu^+\mu^-$ , or  $e^+e^-\mu^+\mu^-$ ). The leptons were grouped into oppositely charged, same flavor pairs required to have an invariant dilepton mass  $M_{\ell\ell} > 70 \text{ GeV}$  for one pair and  $M_{\ell\ell} > 50 \text{ GeV}$  for the other. There was a small background from  $Z/\gamma^* + \text{jets}$  events, in which two jets were incorrectly reconstructed as electrons; however, there are no SM backgrounds with four energetic leptons. As a result, this final state is extremely clean with only  $0.14_{-0.02}^{+0.03}$  background and  $1.89 \pm 0.08$  signal events expected. Three events were observed in the data resulting in a measured cross section of  $\sigma(ZZ) = 1.75_{-0.86}^{+1.27}(\text{stat}) \pm 0.13(\text{syst}) \text{ pb}$ , which is consistent with the SM NLO prediction of  $\sigma(ZZ) = 1.4 \pm 0.1 \text{ pb}$ . The observed significance of the measurement was  $5.3\sigma$  and represents the first observation of  $ZZ$  production at the Tevatron.

To further improve the measurement, this result was combined with the  $ZZ \rightarrow \ell\ell\ell\ell$  analysis using a previous dataset of  $1 \text{ fb}^{-1}$  and the  $ZZ \rightarrow \ell\ell\nu\nu$  analysis with  $2.7 \text{ fb}^{-1}$  of data. The combined measurement yields  $\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})_{-0.17}^{+0.16}(\text{syst}) \text{ pb}$  with an observed significance of  $5.7\sigma$ .

## 3. $Z\gamma \rightarrow \nu\nu\gamma$

The  $Z\gamma \rightarrow \nu\nu\gamma$  analysis [2] selected events in  $3.6 \text{ fb}^{-1}$  of data with “missing transverse energy”  $\cancel{E}_T > 70 \text{ GeV}$  from the undetected neutrinos and a single high energy photon having a “transverse energy” of  $E_T^\gamma > 90 \text{ GeV}$ . Backgrounds from  $W \rightarrow \ell\nu$  and  $Z \rightarrow \ell\ell$  were reduced by vetoing events with muons, additional EM objects, and isolated tracks. Non-collision backgrounds (e.g., bremsstrahlung from beam halo) were reduced by using the EM shower in the calorimeter to determine the origin of the photon and require that it be consistent with coming from the  $p\bar{p}$  collision point. Finally, mis-measured  $\cancel{E}_T$  was minimized by requiring zero jets. With this selection, there were  $17.3 \pm 2.4$  background and  $33.7 \pm 3.4$  signal events expected and 51 candidate events observed. The measured cross section times branching ratio was

$\sigma(Z\gamma; E_T^\gamma > 90 \text{ GeV}) \cdot \text{BR}(Z \rightarrow \nu\nu) = 32.9 \pm 9(\text{stat+syst}) \pm 2(\text{lumi}) \text{ fb}$ , which is consistent with the SM NLO prediction of  $\sigma(Z\gamma; E_T^\gamma > 90 \text{ GeV}) \cdot \text{BR}(Z \rightarrow \nu\nu) = 39 \pm 4 \text{ fb}$ . The observed significance of this measurement was  $5.1\sigma$  and was the first observation of  $Z\gamma \rightarrow \nu\nu\gamma$  at the Tevatron.

The  $E_T^\gamma$  spectrum is highly sensitive to the  $\gamma ZZ$  and  $\gamma\gamma Z$  couplings and was used to set limits on anomalous TGCs for  $\Lambda_{NP} = 1.5 \text{ TeV}$ . The 95% confidence level (CL) limits are  $|h_3^\gamma| < 0.036$ ,  $|h_3^Z| < 0.0019$ ,  $|h_4^\gamma| < 0.035$ ,  $|h_4^Z| < 0.0019$ . When combined with the  $Z\gamma \rightarrow ee\gamma$  and  $Z\gamma \rightarrow \mu\mu\gamma$  channels using  $1 \text{ fb}^{-1}$  of data, the 95% CL limits become  $|h_3^\gamma| < 0.033$ ,  $|h_3^Z| < 0.0017$ ,  $|h_4^\gamma| < 0.033$ ,  $|h_4^Z| < 0.0017$ , which are the world best for  $h_3^\gamma$ ,  $h_4^\gamma$ , and  $h_4^Z$ .

#### 4. $WW/WZ \rightarrow \ell\nu q\bar{q}$

The  $WW/WZ \rightarrow \ell\nu q\bar{q}$  analysis [3] selected events in  $1.1 \text{ fb}^{-1}$  of data with one high  $p_T$  isolated lepton, large  $\cancel{E}_T$  (indicating a neutrino), and two high  $p_T$  jets. Background from multijet events, in which a jets was mistakenly identified as a lepton, were reduced by requiring that the invariant mass reconstructed from the lepton  $\vec{p}_T^\ell$  and  $\cancel{E}_T$  be greater than  $35 \text{ GeV}$ .  $W$ +jets and other backgrounds were separated from the signal using a ‘‘Random Forest’’ multivariate discriminant. The output distribution of the Random Forest discriminant was fit to reveal a signal cross section of  $\sigma(WW + WZ) = 20.2 \pm 4.4(\text{stat+syst}) \pm 1.2(\text{lumi}) \text{ pb}$ , which is consistent with the SM NLO prediction of  $\sigma(WW + WZ) = 16.1 \pm 0.9 \text{ fb}$ . The significance of this measurement was  $4.4\sigma$ , representing the first evidence for this process at the Tevatron.

The  $p_T$  spectrum of the dijet system was used to set limits [4] on anomalous  $\gamma WW$  and  $ZWW$  TGCs. The limits were measured for  $\Lambda_{NP} = 2 \text{ TeV}$  assuming two different scenarios. The first scenario, also used by the LEP experiments, requires  $\text{SU}(2) \times \text{U}(1)$  symmetry. This so-called LEP parametrization requires  $\lambda_\gamma = \lambda_Z$  and  $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan(\theta_W)$ ; where  $\Delta\kappa_V \equiv \kappa_V - 1$  and  $\Delta g_1^Z \equiv g_1^Z - 1$ . The 95% CL limits on the three free parameters were measured to be  $-0.44 < \Delta\kappa_\gamma < 0.50$ ,  $-0.10 < \lambda < 0.11$ , and  $-0.12 < \Delta g_1^Z < 0.20$ . The second scenario assumes equal couplings for  $\gamma WW$  and  $ZWW$  resulting in  $\lambda_\gamma = \lambda_Z$ ,  $\kappa_Z = \kappa_\gamma$ , and  $g_1^Z = g_1^\gamma = 1$ . For the two free parameters in the equal couplings scenario we measured 95% CL limits of  $-0.16 < \Delta\kappa < 0.23$  and  $-0.11 < \lambda < 0.11$ .

#### 5. $WW \rightarrow \ell\nu\ell\nu$

The  $WW \rightarrow \ell\nu\ell\nu$  analysis [5] selected events in  $1.0 \text{ fb}^{-1}$  of data with two isolated high  $p_T$  leptons of opposite charge ( $e^+e^-$ ,  $e^\pm\mu^\mp$ , or  $\mu^+\mu^-$ ). A cut on  $\cancel{E}_T$  was optimized for each channel to reduce  $Z \rightarrow \ell\ell$  backgrounds.  $W$ +jets and  $t\bar{t}$  backgrounds were reduced by requiring the  $\vec{p}_T$  of the two leptons to be balanced with the  $\cancel{E}_T$ . The cross section measured for  $WW$  production was  $\sigma(WW) = 11.5 \pm 2.1(\text{stat+syst}) \pm 0.7(\text{lumi}) \text{ pb}$ , consistent with the NLO SM prediction of  $\sigma(WW) = 12.0 \pm 0.7 \text{ pb}$ .

Limits on anomalous TGCs for both the LEP parametrization and equal couplings scenario with  $\Lambda_{NP} = 2 \text{ TeV}$  were determined from the two-dimensional distribution of the lepton  $p_T$ s. In the LEP parametrization, we measured 95% CL limits of  $-0.54 < \Delta\kappa_\gamma < 0.83$ ,  $-0.14 < \lambda < 0.18$ , and  $-0.14 < \Delta g_1^Z < 0.30$ . For the equal couplings scenario, the 95% CL limits were  $-0.12 < \Delta\kappa < 0.35$  and  $-0.14 < \lambda < 0.18$ .

## 6. $WV$ Combination

Four analyses with approximately  $1 \text{ fb}^{-1}$  of data were combined to improve the measurement of anomalous  $\gamma WW$  and  $ZWW$  TGCs. Along with the  $WW/WZ \rightarrow \ell\nu q\bar{q}$  and  $WW \rightarrow \ell\nu\ell\nu$  analyses, the combination [6] incorporated previous analyses of  $WZ \rightarrow \ell\nu\ell\ell$  and  $W\gamma \rightarrow \ell\nu\gamma$ . The combined measurement yielded 95% CL limits for the LEP parametrization of  $-0.29 < \Delta\kappa_\gamma < 0.38$ ,  $-0.08 < \lambda < 0.08$ , and  $-0.07 < \Delta g_1^Z < 0.16$  with  $\Lambda_{NP} = 2 \text{ TeV}$ . For the equal couplings scenario with  $\Lambda_{NP} = 2 \text{ TeV}$ , we measured 95% CL limits of  $-0.11 < \Delta\kappa < 0.18$  and  $-0.08 < \lambda < 0.08$ . These are the most stringent limits from the Tevatron and are approaching the sensitivity of the individual LEP2 experiments.

## 7. Conclusions

The recent diboson measurements from the D0 experiment represent many first and best diboson measurements from the Tevatron.  $ZZ$  production was observed for the first time;  $Z\gamma \rightarrow \nu\nu\gamma$  was observed and used to set the world best limits on  $h_3^Z$ ,  $h_4^\gamma$ , and  $h_4^Z$ ;  $WW \rightarrow \ell\nu\ell\nu$  and  $WW/WZ \rightarrow \ell\nu q\bar{q}$  were measured and used to set limits on anomalous TGCs; and the best Tevatron limits on anomalous  $WWZ$  and  $WW\gamma$  TGCs were obtained from a combination of four diboson analyses. So far, all diboson measurements from D0 are consistent with SM predictions. The future of diboson physics at D0 looks bright as we collect more data each year and increase our sensitivity to new physics lurking beyond the SM.

## References

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