At the Fermilab Tevatron, the CDF and DØ detectors are used to study diboson production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We summarize recent measurements of the $W\gamma$, $Z\gamma$, and $WW$ cross sections and limits on $WZ$ and $ZZ$ production. Limits on anomalous trilinear gauge couplings are also presented.

1 Introduction

The self-couplings of gauge bosons are a striking consequence of the SU(2)$_L \otimes$ U(1)$_Y$ structure of the Standard Model (SM). Detailed study of diboson production provides a stringent test of SM trilinear gauge couplings (TGC), which are sensitive to new physics (NP) effects. These NP effects are parametrized as deviations from SM couplings in an effective Lagrangian which, for TGC involving two $W$ bosons, is given by

$$\mathcal{L}_{WWV}/g_{WWV} = i g_1^V (W^\mu W^\nu V^\nu - W^\mu V^\nu W^\nu) + i \kappa V W^\mu W^\nu V^\nu + \frac{i \lambda V}{M_W^2} W^\mu W^\nu V^\nu,$$

where $V \equiv Z, \gamma$. This involves 5 C- and P-conserving coupling parameters ($g_1^V = 1$ by EM gauge invariance) with SM values at tree level given by $\Delta \kappa_Z = \Delta \kappa_\gamma = 0$ ($\Delta \kappa \equiv \kappa - 1$) and $\Delta g_1^Z = 0$ ($\Delta g_1^Z \equiv g_1^Z - 1$). Non-SM couplings increase the cross section at high $E_T$. A form factor ansatz is introduced to avoid unitarity violation at large $\tilde{s}$ such that $\alpha \rightarrow \alpha(\tilde{s}) = \alpha_0/(1 + \tilde{s}/\Lambda_{FF}^2)^2$ for a given parameter $\alpha$. The NP causing non-SM couplings enter at a scale $\Lambda_{FF}$ assumed to be $\sim$1-2 TeV in the analyses presented here.

In these proceedings, a brief summary of the current diboson results from the CDF and DØ Collaborations at the Tevatron Run II are presented. The diboson physics program at the Tevatron is complementary to LEP since $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV probe different combinations of TGC couplings at higher $\tilde{s}$, where NP effects might become evident.
2 \ W\gamma

The $W\gamma$ final state observed at hadron colliders provides a direct test of the $WW\gamma$ TGC. Anomalous $WW\gamma$ leads to an enhancement in the production cross section and an excess of large $E_T$ photons. Both CDF and DØ have made measurements of the $W\gamma$ cross section using leptonic decays of the $W$ bosons. The signature of the $W\gamma$ signal is an isolated high $E_T$ lepton, an isolated high $E_T$ photon, and large missing transverse energy ($E_T^\text{miss}$) from the $W$ neutrino. The dominant background is from $W+\text{jets}$ where a jet mimics an isolated photon. A lepton-photon separation requirement in $\eta−\phi$ space of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 0.7$ is made by both CDF and DØ to suppress events with final-state radiation of the photon from the outgoing lepton and to avoid collinear singularities in theory calculations. A kinematic requirement on photon $E_T$ of $E_T > 7(8)$ GeV$/c^2$ is made by CDF (DØ ) in the analysis.

CDF has published a measurement with $\int \mathcal{L} \, dt = 200$ pb$^{-1}$ of $\sigma(p\bar{p} \rightarrow W\gamma + X) \times BR(W \rightarrow l\nu) = 18.1 \pm 1.6$(stat.) $\pm 2.4$(syst.) $\pm 1.2$(lum.) pb, to be compared with the NLO theoretical expectation of $19.3 \pm 1.4$ pb. DØ published a measurement with $\int \mathcal{L} \, dt = 162$ pb$^{-1}$ of $\sigma(p\bar{p} \rightarrow W\gamma + X) \times BR(W \rightarrow l\nu) = 14.8 \pm 1.6$(stat.) $\pm 1.0$(syst.) $\pm 1.0$(lum.) pb to be compared with the NLO expectation of $16.0 \pm 0.4$ pb.

Both results are consistent with the SM expectations at NLO. DØ sets limits on anomalous $WW\gamma$ TGC based upon the observed photon $E_T$ spectrum. The one-dimensional limits at 95% C.L. are $0.88 < \Delta\kappa_\gamma < 0.96$ and $-0.20 < \lambda_\gamma < 0.20$ for $\Lambda_{\text{FF}} = 2$ TeV.

3 \ Z\gamma

In the SM, photons do not directly couple to $Z$ bosons at lowest order. Therefore, observation of such a coupling would constitute evidence for NP. The $Z\gamma$ final state at hadron colliders involves a combination of $ZZ\gamma$ and $Z\gamma\gamma$ couplings. Both CDF and DØ have made measurements of the $Z\gamma$ cross section in leptonic decay channels of the $Z$ boson. The signature of the $Z\gamma$ signal is two isolated high $E_T$ leptons having the same flavor and opposite charge with invariant mass consistent with decay of a $Z$ boson and an isolated high $E_T$ photon. The dominant background is from $Z+\text{jets}$ where a jet mimics an isolated photon. As in the $W\gamma$ analyses, a lepton-photon separation requirement of $\Delta R > 0.7$ is made by both CDF and DØ. A kinematic requirement on photon $E_T$ of $E_T > 7(8)$ GeV$/c^2$ is made by CDF (DØ ) in the analysis.

CDF has published a measurement with $\int \mathcal{L} \, dt = 200$ pb$^{-1}$ of $\sigma(p\bar{p} \rightarrow Z\gamma + X) \times BR(Z \rightarrow ll) = 4.6 \pm 0.5$(stat.) $\pm 0.2$(syst.) $\pm 0.3$(lum.) pb, to be compared with the NLO theoretical expectation of $4.5 \pm 0.3$ pb. DØ published a measurement with $\int \mathcal{L} \, dt = 300$ pb$^{-1}$ of $\sigma(p\bar{p} \rightarrow Z\gamma + X) \times BR(Z \rightarrow ll) = 4.2 \pm 0.4$(stat. + syst.) $\pm 0.3$(lum.) pb, to be compared with the NLO expectation of $3.9 \pm 0.2$ pb.

Both results are consistent with the SM expectations. DØ sets anomalous coupling limits based upon the observed photon $E_T$ spectrum. The one dimensional limits at 95% C.L. are $|h_{10,30}| < 0.23$, $|h_{20,40}^Z| < 0.019$, $|h_{10,30}^Z| < 0.23$, and $|h_{20,40}^Z| < 0.020$ for $\Lambda_{\text{FF}} = 1$ TeV. The limits on $|h_{20,40}^Z|$ and $|h_{20,40}^Z|$ are the most stringent limits currently available.

4 \ WW

Production of $W$ boson pairs involves both $WW\gamma$ and $WWZ$ couplings. At LEP, $WW$ production has been extensively studied and stringent limits on anomalous TGC were determined. However, at the Tevatron much higher $WW$ invariant masses are probed compared to LEP because of the higher accessible energies. Also, the $WW$ final state is a promising discovery channel for the Higgs boson at both the Tevatron and the LHC. The signature of the $WW$ signal in leptonic decay is two isolated high $E_T$ leptons with opposite charge and large missing
transverse energy ($E_T$) from the W neutrinos. Events are required to have minimal jet activity to reduce contamination from $t\bar{t}$ events. After the selection cuts, the dominant backgrounds are from Drell-Yan, other diboson decays, and $W$+jets where the jet fakes an isolated lepton.

CDF published a preliminary result in the dilepton channel with $\int L\ dt = 240\ pb^{-1}$ of $\sigma(p\bar{p} \rightarrow WW + X) = 13.8^{+4.3}_{-3.8}\ (\text{stat.})^{+1.2}_{-0.9}\ (\text{syst.})\ pb$. CDF has a new preliminary measurement with $\int L\ dt = 825\ pb^{-1}$ of $\sigma(p\bar{p} \rightarrow WW + X) = 13.6 \pm 2.3\ (\text{stat.}) \pm 1.6\ (\text{syst.}) \pm 1.2\ (\text{lum.})\ pb$. In this analysis, 95 events are observed with an expected signal (background) of $52.4 \pm 4.4\ (37.8 \pm 4.8)\ events$. Some kinematic distributions of WW candidate events are shown in Figure 1. The CDF measurement is the most precise measurement of the WW cross section available from the Tevatron. Both measurements are consistent with the NLO expectation of $12.4 \pm 0.8\ pb$.

5 \textit{WZ/ZZ}

Production of WZ involves the WWW TGC. The production is unavailable at LEP and has not been conclusively observed. The study of WZ production allows one to search for anomalous WZW coupling independent of the WW$\gamma$ coupling, in contrast to WW production. The NLO cross section for WZ production at $\sqrt{s} = 1.96$ is $3.7 \pm 0.1\ pb$. CDF published a search for the sum of WZ and ZZ production in 2, 3, and 4 lepton channels with $\int L\ dt = 194\ pb^{-1}$ and set a limit of $\sigma(p\bar{p} \rightarrow WZ + ZZ) < 15.2\ pb$ at 95\% C.L. The SM expectation for $\sigma(p\bar{p} \rightarrow WZ + ZZ)$ is $5.0 \pm 0.4\ pb$.

CDF and DØ have made direct searches for WZ production in the trilepton + $E_T$ channel, assuming SM ZZ production. The dominant backgrounds are from $Z$+X, where X is a $Z$, $\gamma$, or jet faking a lepton. The published DØ analysis used $\int L\ dt \approx 300\ pb^{-1}$ and observed three events (1 eee, 2$\mu\mu\mu$) with an expected signal of $2.0 \pm 0.2$ events and background of $0.71 \pm 0.08$ events. Based upon these results, they quoted both an upper limit of $\sigma(p\bar{p} \rightarrow WW) < 13.3\ pb$ at 95\% C.L. and a measurement of the cross section of $\sigma(p\bar{p} \rightarrow WZ) = 4.5^{+3.8}_{-2.0}\ (\text{stat.} + \text{syst.})\ pb$. They also set limits on WZW anomalous TGC: one-dimensional 95\% C.L. are $-2.0 < \Delta\kappa_{WW} < 2.4$ for $\Lambda_{FF} = 1.0\ TeV$ and $-0.48 < \lambda_{Z} < 0.48$, $-0.49 < \Delta g_{\gamma}^Z < 0.66$ for $\Lambda_{FF} = 1.5\ TeV$. CDF has a new preliminary result in the same decay channel with $\int L\ dt = 825\ pb^{-1}$ where they observe two events (both eee) with an expected signal of $3.7 \pm 0.3$ events and background of $0.9 \pm 0.2$ events. Based upon these results, they quote an upper limit of $\sigma(p\bar{p} \rightarrow WZ) < 6.34\ pb$ at 95\% C.L. Figure 2 shows the $E_T$ and dilepton mass for candidates both inside and outside the WZ signal region.
6 \(WW + WZ\) in \(l\nu jj\)

CDF has a new preliminary search for the sum of \(WW\) and \(WZ\) production in the decay channel \(l\nu jj\) with \(\int L\ dt = 350 \text{ pb}^{-1}\). The advantage of this mode over the purely leptonic channels is the larger branching fraction to jets, at the expense of larger backgrounds, mainly from \(W+\text{jets}\). Fitting the expected signal and background dijet mass shape to data, the result shows no statistically significant evidence for \(WW + WZ\) production. A 95% C.L. limit on the \(WW + WZ\) cross section of 36 pb is determined from these results. Using the observed \(W p_{T}\) spectrum, which is sensitive to anomalous TGC, 95% C.I. limits of \(-0.51 < \Delta \kappa < 0.44\) and \(-0.28 < \lambda < 0.28\) for \(\Lambda_{\text{FF}} = 1.5 \text{ TeV}\) are obtained.

7 Summary

Figure 3 summarizes the single boson and diboson cross section measurements from the Tevatron. No deviation from the SM is observed. With 4-8 \(fb^{-1}\) expected by the end of Run II, the electroweak sector of the SM will be put to more stringent tests in the search for NP.

References