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DIBOSON PHYSICS AT THE TEVATRON

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At the Fermilab Tevatron, the CDF and D0 detectors are being 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 $\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$ 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 to W bosons, is given by [1]

$$\mathcal{L}_{\mathrm{WWV}}/\mathrm{g_{WWV}} = i\mathrm{g}_1^{\mathrm{V}}(\mathrm{W}_{\mu\nu}\mathrm{W}^{\mu}\mathrm{V}^{\nu} - \mathrm{W}_{\mu}\mathrm{V}_{\nu}\mathrm{W}^{\mu\nu}) + i\kappa_{\mathrm{V}}\mathrm{W}_{\mu}\mathrm{W}_{\nu}\mathrm{V}^{\mu\nu} + \frac{i\lambda_{\mathrm{V}}}{\mathrm{M}_{\mathrm{W}}^2}\mathrm{W}_{\lambda\mu}\mathrm{W}_{\nu}^{\mu}\mathrm{V}^{\nu\lambda} \qquad (1)$$

where V$\equiv Z, \gamma$. This involves 5 C and P conserving coupling parameters ($\mathrm{g}_1^{\gamma} = 1$ 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 $\mathrm{E_T}$. A form factor anzatz is introduced to avoid unitarity violation at large $\hat{s}$ such that $\alpha \to \alpha(\hat{s}) = \alpha_0/(1+\hat{s}/\Lambda_{\mathrm{FF}}^2)^2$ for a given parameter α. The NP causing non-SM couplings enters at a scale Λ_{FF} assumed to be ~1-2 TeV in the analyses presented here.

In these proceedings, a brief summary of the current diboson results from the CDF and D0 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 $\hat{s}$ 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 excess of large E_T photons. Both CDF and D0 have made measurements of the $W\gamma$ cross section using leptonic decay 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 ($\not{E}_T$) from the W neutrino. The dominant background is from W+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 D0 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 (D0) in the analysis.

CDF has published a measurement [2] using 200 pb^{-1} in integrated luminosity of $\sigma(p\bar{p} \to W\gamma + X) \times BR(W \to l\nu) = 18.1 \pm 1.6(\text{stat.}) \pm 2.4(\text{syst.}) \pm 1.2(\text{lum.})$ pb compared with the NLO theoretical expectation [3] of 19.3 ± 1.4 pb. D0 published a measurement [4] using 162 pb^{-1} of $\sigma(p\bar{p} \to W\gamma + X) \times BR(W \to l\nu) = 14.8 \pm 1.6(\text{stat.}) \pm 1.0(\text{syst.}) \pm 1.0(\text{lum.})$ pb compared with the NLO expectation [3] of 16.0 ± 0.4 pb.

Both results are consistent with the SM expectations at NLO. D0 sets limits on anomalous $WW\gamma$ TGC based upon the observed photon E_T spectrum. The one dimensional limits at 95% C.I. are $-0.88 < \Delta\kappa_\gamma < 0.96$ and $-0.20 < \lambda_\gamma < 0.20$ for $\Lambda_{FF} = 2$ 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 D0 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+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 D0. A kinematic requirement on photon E_T of $E_T > 7(8)$ GeV/c^2 is made by CDF (D0) in the analysis.

CDF has published a measurement [2] using 200 pb^{-1} in integrated luminosity of $\sigma(p\bar{p} \to Z\gamma + X) \times BR(Z \to ll) = 4.6 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.}) \pm 0.3(\text{lum.})$ pb compared with the NLO theoretical expectation [3] of 4.5 ± 0.3 pb. D0 published a measurement [5] using 300 pb^{-1} of $\sigma(p\bar{p} \to Z\gamma + X) \times BR(Z \to ll) = 4.2 \pm 0.4(\text{stat.} + \text{syst.})0.3(\text{lum.})$ pb compared with the NLO expectation [3] of 3.9 ± 0.2 pb.

Both results are consistent with the SM expectations. D0 sets anomalous coupling limits based upon the observed photon E_T spectrum. The one dimensional limits at 95% C.I. are $|h^\gamma_{10,30}| < 0.23$, $|h^\gamma_{20,40}| < 0.019$, $|h^Z_{10,30}| < 0.23$, $|h^Z_{20,40}| < 0.020$ for $\Lambda_{FF} = 1$ TeV.. The limits on $|h^\gamma_{20,40}|$ and $|h^Z_{20,40}|$ are the best 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 determined. However, at the Tevatron much higher WW invariant mass is 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 $WW\gamma$ signal in leptonic decay is two isolated high E_T leptons with opposite charge and large missing transverse energy

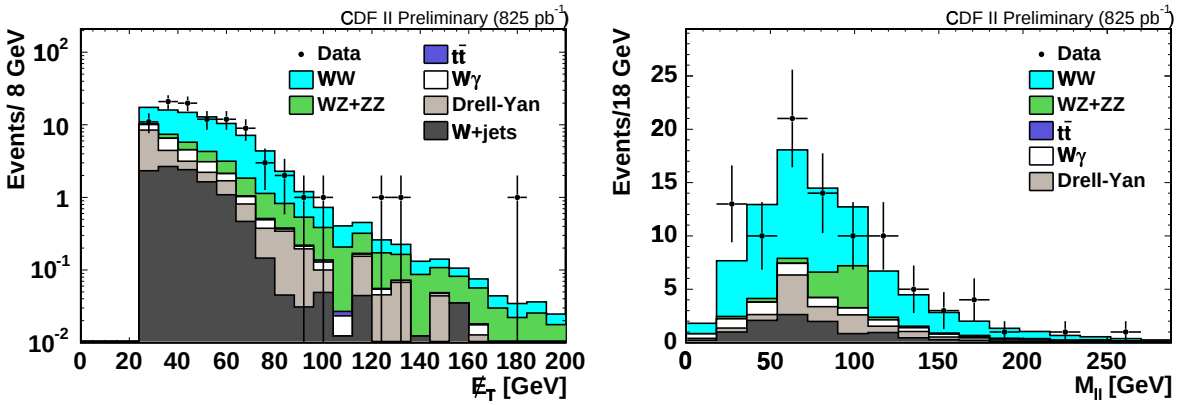

Figure 1: (left) $\not{E}_T$ and (right) dilepton mass for WW candidates.

($\not{E}_T$) 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.

D0 published a measurement[6] in the dilepton channel using 240 pb^{-1} of $\sigma(p\bar{p} \to WW+X) = 13.8^{+4.3}_{-3.8}$ (stat.)$^{+1.2}_{-0.9}$ (syst.)0.9 (lum.) pb. CDF has a new preliminary measurement using 825 pb^{-1} of $\sigma(p\bar{p} \to WW+X) = 13.6 \pm 2.3$(stat.) ± 1.6(syst.) ± 1.2(lum.) pb. In this analysis, 95 events are observed with an expected signal (background) of 52.4 ± 4.4 (37.8 ± 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 at the time of presentation. Both measurements are consistent with the NLO expectation[7] of 12.4 ± 0.8 pb.

5 WZ/ZZ

Production of WZ involves the WWZ TGC. The production is unavailable at LEP and has not been conclusively observed. The study of WZ production allows one to search for anomalous WWZ 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 ± 0.1 pb[7]. CDF published[8] a search for the sum of WZ and ZZ production in 2, 3, and 4 lepton channels using 194 pb^{-1} of integrated luminosity and set a limit of $\sigma(p\bar{p} \to WZ + ZZ) < 15.2$ pb at 95% C.I. The SM expectation for $\sigma(p\bar{p} \to WZ + ZZ)$ is 5.0 ± 0.4 pb.

CDF and D0 have made direct searches for WZ production in the trilepton + $\not{E}_T$ channel, assuming SM ZZ production. The dominant backgrounds are from Z+X, where X is a Z, γ, or jet faking a lepton. The published D0 analysis[9] used approximately 300 pb^{-1} and observed three events (1 eee, $2\mu\mu\mu$) with an expected signal of 2.0 ± 0.2 events and background of 0.71 ± 0.08 events. Based upon these results, they quoted both an upper limit of $\sigma(p\bar{p} \to WZ) < 13.3$ pb at 95% C.I. and a measurement of the cross section of $\sigma(p\bar{p} \to WZ) = 4.5^{+3.8}_{-2.6}$(stat. + syst.) pb. They also set limits on WWZ anomalous TGC: one-dimensional 95% C.I. limits are $-2.0 < \Delta\kappa_Z < 2.4$ for $\Lambda_{\rm FF} = 1.0$ TeV and $-0.48 < \lambda_Z < 0.48$, $-0.49 < \Delta g_1^Z < 0.66$ for $\Lambda_{\rm FF} = 1.5$ TeV. CDF has a new preliminary result in the same decay channel using 825 pb^{-1} where they observe two events (both eee) with an expected signal of 3.7 ± 0.3 events and background of 0.9 ± 0.2 events. Based upon these results, they quote an upper limit of $\sigma(p\bar{p} \to WZ) < 6.34$ pb at 95% C.I. Figure 2 shows the $\not{E}_T$ and dilepton mass for candidates both inside and outside the WZ signal region.

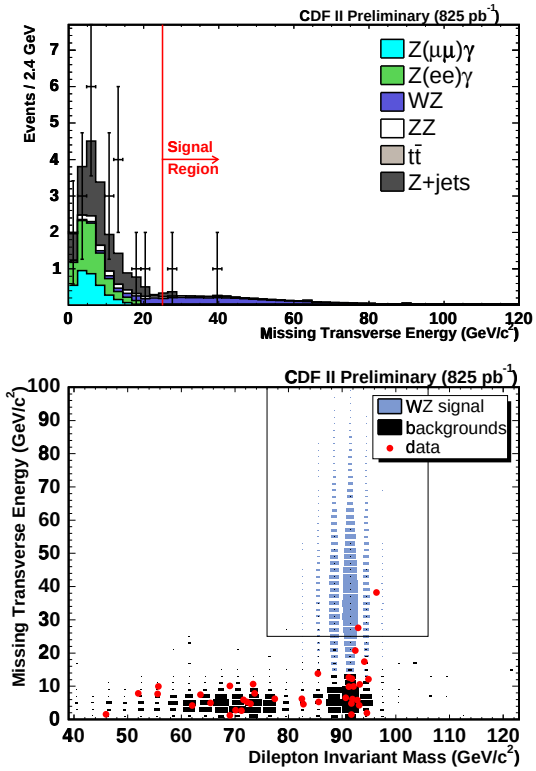

Figure 2: (top) $\not\!\!E_T$ and (bottom) $\not\!\!E_T$ vs. dilepton mass for trilepton candidates.

6 $WW + WZ$ in lνjj

CDF has a new preliminary search for the sum of WW and WZ production in the decay channel $l\nu$jj. 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+jets. Fitting the expected signal and background di-jet mass shape to data, the result is consistent with no $WW + WZ$ production. A 95% C.I. 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 $\Lambda_{FF} = 1.5$ 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 stringent tests in the search for NP.

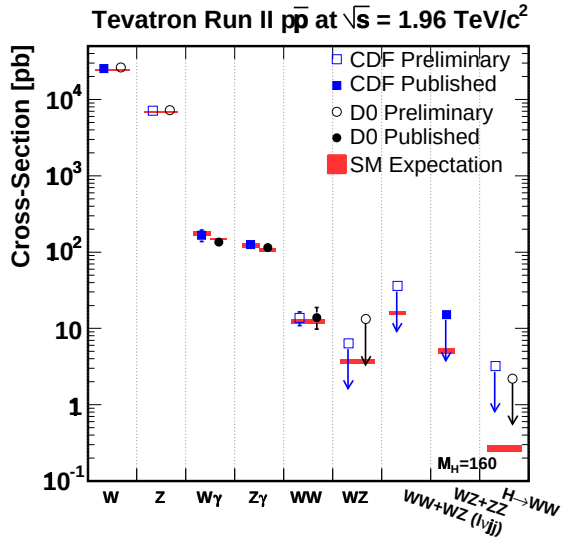

Figure 3: Electroweak cross section measurements from CDF and D0.

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