Diboson measurements at the Tevatron

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Recent measurements of diboson production from the CDF and D0 experiments at the Tevatron are presented. Agreement with Standard Model predictions is observed in all measurements, and some are used to set limits on new physics. Searches in high-background topologies are also briefly described.

1 Introduction

Measurements of diboson production cross sections and other properties of diboson events are probes of the electroweak sector of the Standard Model (SM). Several models of new physics predict enhancements in the production rates of diboson events via anomalous triple gauge boson interactions [1] or from new resonances decaying to pairs of bosons. Diboson events are also relevant to the search for the Higgs boson at the Tevatron, as several sensitive channels in the Higgs search have topologies similar to those in diboson events. Therefore diboson events present a good place to test strategies employed in the Higgs search.

The cross sections of diboson ($Z\gamma$, $W\gamma$, WW, WZ, and ZZ) as well as other electroweak processes have been measured at the Tevatron by both the CDF and D0 experiments, and are summarized in Fig 1. The measurements, spanning orders of magnitude in production rates, agree both between the two experiments and with theoretical predictions. Recent work uses large data samples, sophisticated analysis techniques, and new decay topologies to improve the statistical and systematic precision of the measurements.

The measurements presented in these proceedings are performed based on data collected by the CDF [2] and D0 [3] experiments in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Tevatron. The integrated luminosity used in the measurements ranges up to 7.0 fb^{-1}.

2 Measurements of the ZZ production cross section

The production of ZZ events at the Tevatron is rare, with a predicted cross section of $\sigma(p\bar{p} \to ZZ) = 1.4 \pm 0.1$ pb at next-to-leading order [4]. In events where both Z bosons decay to charged leptons ($ZZ \to l^+l^-l^+l^-$), there is a very clean final state signature with two pairs of opposite-charge, same-flavor leptons. The backgrounds to this signal are negligible. Because of the low branching fraction for $Z \to l^+l^-$ and limited detector acceptance, the rate of detection of these events is extremely low. As a result, a large part of the experimental work in measurement of $ZZ \to l^+l^-l^+l^-$ consists of improving the lepton detection efficiency.

The D0 collaboration has analyzed 6.4 fb^{-1} of integrated luminosity, finding 10 events consistent with $ZZ \to l^+l^-l^+l^-$ where 9 signal events and 0.4 background events were expected [5].

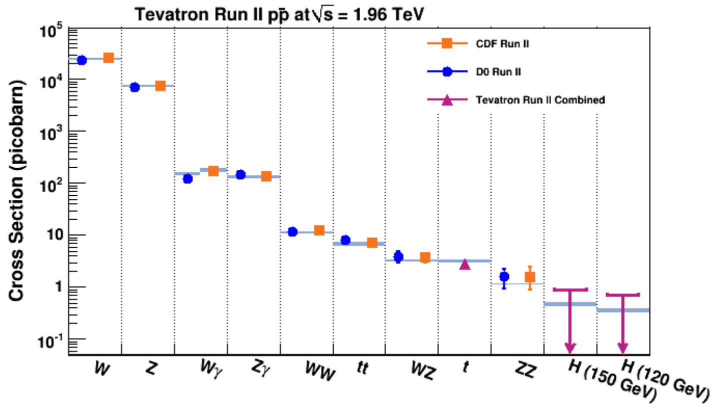

Figure 1: Measured and predicted production cross sections for several processes at the Tevatron.

Figure 2 (left) shows that the invariant mass of the two lepton pairs in the events is consistent with the decays of two Z bosons. The cross section for ZZ production was measured to be $1.33^{+0.50}_{-0.40}$(stat)$\pm$0.12(syst)$\pm$0.09(lumi) pb.

The CDF collaboration measured the ZZ cross section in $ZZ \to l^+l^-l^+l^-$ events using a data sample corresponding to 4.8 fb^{-1} of integrated luminosity [6]. Five events were observed, while 4.7 signal and < 0.1 background events were expected. The measured cross section was $1.56^{+0.80}_{-0.63}$(stat.)$\pm$0.25(syst) pb. Figure 2 (right) shows the correlation between the dilepton masses, with the signal region marked by the blue line.

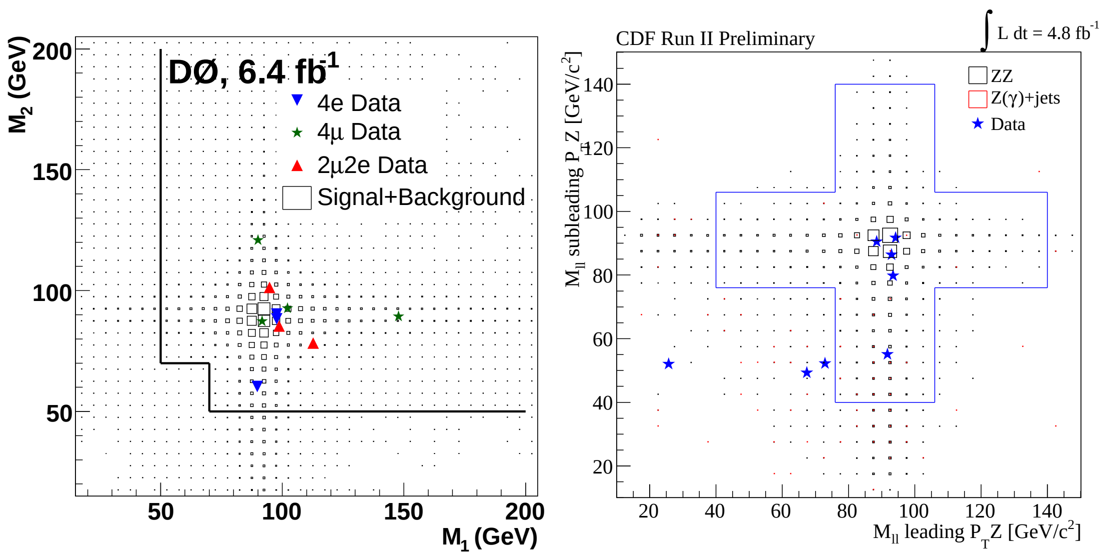

Figure 2: Scatter plots of the invariant mass distribution of two-lepton pairs in $ZZ \to l^+l^-l^+l^-$ candidate events at D0 (left) and CDF (right).

The CDF collaboration also recently presented a result for $ZZ \to l^+l^-\nu\nu$, detected in events with two opposite-charge leptons and large missing transverse energy ($\not\!\!E_T$) [7]. This final state topology suffers from a large background due to Drell-Yan production where an imbalance in the measurement leads to $\not\!\!E_T$. A requirement that the $\not\!\!E_T$ is nearly back-to-back with the Z boson in the transverse plane reduces the Drell-Yan background while retaining most of the signal. Even with this technique used to reduce the backgrounds, about 1100 background events and 50 signal events were expected in 5.9 fb^{-1}. A neural network, relying on variables like the

$\not\!\!E_T$ significance, is used to build a discriminant to separate signal from background. The neural network output for backgrounds and signal, with data superimposed, is shown in Figure 3. Using a fit to the neural network discriminant, the ZZ production cross section is measured to be $1.45^{+0.45}_{-0.42}$(stat.)$^{+0.41}_{-0.30}$(syst.) pb. This result agrees with theoretical prediction as well as with the measured cross section in $ZZ \to llll$.

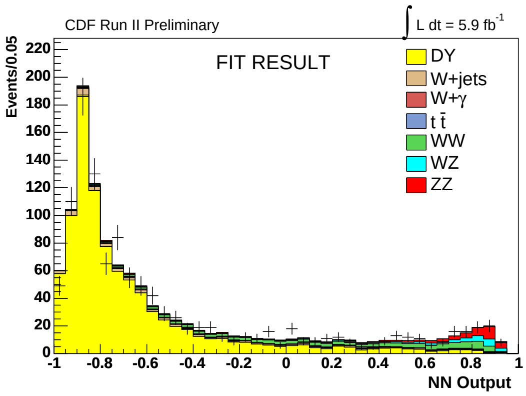

Figure 3: Fit to neural network output discriminant to determine the ZZ cross section in events with two charged leptons and large missing transverse energy.

3 $WZ \to l\nu ll$

The D0 collaboration measured the WZ production cross section with 4.1 fb^{-1} of integrated luminosity [8]. The measurement is based on the decay $WZ \to l\nu ll$, characterized by three high-p_T isolated leptons and missing transverse energy. The charged leptons from the Z boson decay are identified by finding the pair of opposite-charge, same-flavor leptons with an invariant mass closest to the mass of the Z boson. The backgrounds to WZ production in this final state topology are fairly small: six background and 23 signal events are expected. 34 candidate events are observed, leading to a measured cross section of $3.90^{+1.06}_{-0.90}$ pb. Anomalous WWZ couplings would enhance this cross section and lead to more W and Z bosons at high p_T. The distribution of the p_T of the Z boson matches the SM prediction well, as shown in Fig. 4(left), allowing stringent limits to be set on the WWZ coupling.

CDF also recently performed a measurement of the WZ production cross section in events with three charged leptons and $\not\!\!E_T$. The measurement was performed with 6 fb^{-1} and improved charged lepton acceptance with respect to previous measurements [9]. Figure 4 (right) shows the transverse mass of the W boson candidate formed from the non-Z lepton and the $\not\!\!E_T$. The shape is consistent with W decays in WZ events as described by simulation. The cross section is measured both with respect to the inclusive Z boson production cross section: $\sigma(p\bar{p} \to WZ)/\sigma(p\bar{p} \to Z) = (5.5 \pm 0.9) \times 10^{-4}$ and as an absolute number: $\sigma(p\bar{p} \to WZ) = 4.1 \pm 0.7$ pb. Both of these results are in good agreement with theoretical predictions. The systematic uncertainty on the WZ cross section is reduced when it is measured with respect to the inclusive Z production cross section.

4 $W\gamma \to \mu\nu\gamma$

The D0 collaboration used events with a muon, a photon, and large $\not\!\!E_T$ to study $W\gamma$ production [10]. The cross section for events with $p_T^\gamma > 8$ GeV/c and $\Delta R_{\mu\gamma} > 0.7$ was measured to be 15.2 ± 0.4(stat) ± 1.6(syst) pb, in agreement with the SM prediction of 16.0 ± 0.4 pb. In addition, the SM prediction of a radiation amplitude zero (RAZ) resulting from interference between

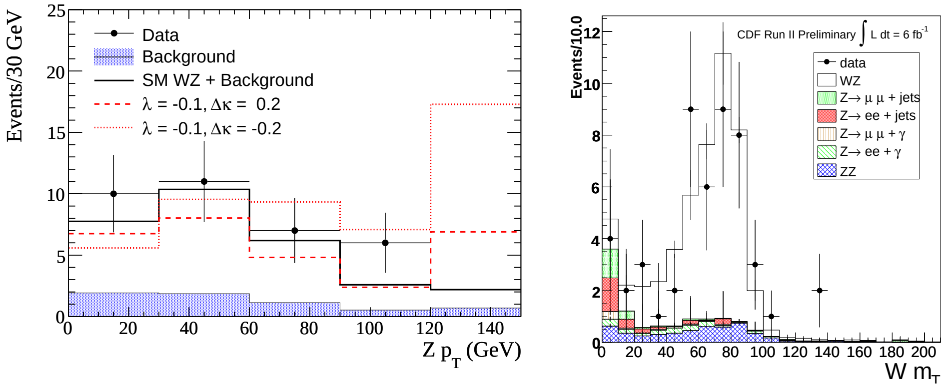

Figure 4: Distribution of transverse mass of the W boson in $WZ \to l\nu ll$ events at CDF (left). Distribution of the Z p_T in $WZ \to l\nu ll$ at D0.

production diagrams was tested by considering the distribution of $Q_\mu \times (\eta_\gamma - \eta_\mu)$, as shown in Fig. 5 (left). The distribution of the data matched the expected shape due to the RAZ. Finally, a limit on anomalous $WW\gamma$ couplings was placed by analyzing the distribution of the p_T of the photon, shown in Fig. 5 (right). The resulting limits on the anomalous coupling parameters are $-0.14 < \Delta\kappa_\gamma < 0.15$ and $-0.02 < \lambda_\gamma < 0.02$. These limits are the best limits on the $WW\gamma$ coupling achieved at a hadron collider and have similar sensitivity to that achieved at LEP.

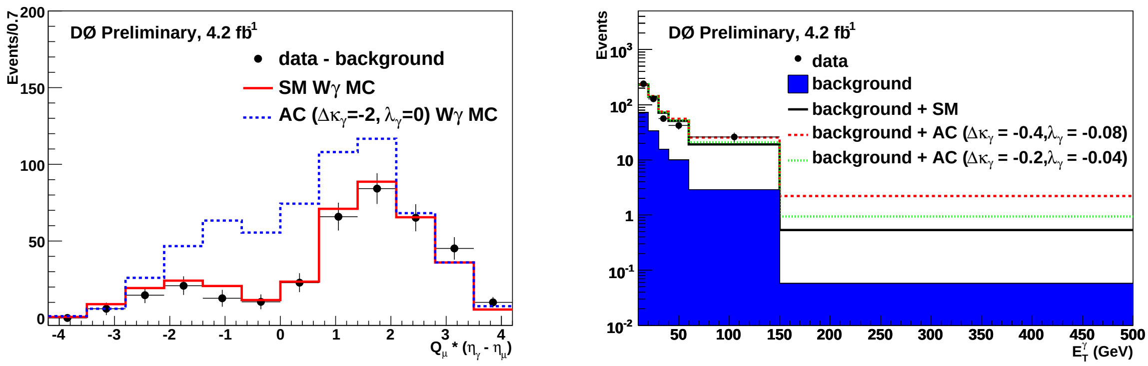

Figure 5: Distribution of the photon p_T in $W\gamma$ events at D0.

5 Measurements with hadronic decays

Diboson events where one boson decays to quarks are difficult to detect at a hadronic collider because of the large backgrounds from W/Z+jet production. Diboson events with a hadronic decay are topologically similar to events with associated Higgs boson production (WH and ZH) in the mass range where the Higgs boson decays primarily to two b quarks. The sophisticated analysis techniques applied in the Higgs searches, which optimize the separation between signal Higgs events and backgrounds from W/Z+jets, can thus be tested and improved in the context of measuring diboson production in events with a hadronic decay.

The D0 collaboration found strong evidence for $WW+WZ \to l\nu jj$ in events with a charged lepton, two jets, and $\not{E}_T$ [11]. The CDF collaboration subsequently observed and measured the cross section of $WW + WZ$ in events with the same final state signature, both using a matrix element technique and fitting the dijet invariant mass [12].

CDF also observed $WW+WZ+ZZ$ production in events with large $\not\!\!E_T$ nad two jets with 3.5 fb^{-1} [13]. Using the same techniques, a more recent measurement searches for the rarer process $WZ + ZZ \rightarrow \not\!\!E_T + b\bar{b}$ [14]. This search requires two jets and $\not\!\!E_T > 50$ GeV, resulting in large backgrounds from multi-jet events and from W/Z+jets events. Data-driven techniques are used to understand these backgrounds and reduce the systematic uncertainty on their normalization and shape. A neural network tagger is used to identify jets from b quark decays. Using a fit to the invariant mass of the two jets, the signal is extracted with a significance of 2σ with respect to a hypothesis with no $WZ + ZZ$ production. The measured cross section is $\sigma(WZ + ZZ) = 5.0^{+3.6}_{-2.6}$ pb, consistent with SM predictions.

6 Conclusions

The CDF and D0 experiments at the Tevatron collider have performed a wide variety of measurements of diboson processes. They are tests of the electroweak sector of the SM, and have thus far demonstrated excellent agreement with predictions. The properties of diboson events are also used to set some of the world's best limits on anomalous triple gauge boson couplings, providing constraints on models of new physics.

Sophisticated experimental techniques have been developed and used in the diboson measurements in order to increase the acceptance for the low-rate signal processes and to improve the discrimination from higher-rate background processes. The measurements are done and compared in a variety of decay channels. In all cases, agreement between different methods of measurement and between the two experiments are observed. This demonstrates the good understanding that CDF and D0 have of their detectors and of the physics modeling at the Tevatron, and builds confidence in the tools used in the search for the Higgs boson.

The larger data samples available to both experiments will lead to further improvement in the precision of the measurements. In addition, combinations between experiments and channels promises to reduce uncertainties and further strengthen the limits set on new physics.

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