Diboson Production and Couplings

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We present the most recent cross section measurements for $WW$ and $WZ$ production in proton-antiproton collisions with $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron in final states with two or three leptons, respectively, along with limits on $WWZ$ triple gauge couplings. We also present the combined search for $WW$ and $WZ$ production in the lepton, neutrino, and dijet final state. Finally, we present $ZZ$ cross section measurements in both the fully leptonic and the two lepton, two neutrino final states along with limits on anomalous couplings $ZZZ$ and $ZZ\gamma$. All results presented are based on data collected with the Run II DØ and CDF II detectors.

1. INTRODUCTION

Diboson production at the Tevatron can proceed directly from quark-antiquark annihilation or from the boson self-interactions or Triple Gauge Couplings (TGCs) that are a consequence of the non-Abelian structure of the electroweak symmetry group $SU(2)_L \otimes U(1)_Y$. Measuring diboson production provides an important test of Standard Model (SM) predictions for these mechanisms. In particular, observing TGCs not permitted in the SM, or anomalous TGCs, would be a clear sign of new physics. Understanding diboson production is also critical for Higgs searches where dibosons are a major source of background in several important channels.

These proceedings summarize the most recent cross section measurements by the CDF and DØ collaborations for $WW$, $WZ$, and $ZZ$ production, as well as limits on the corresponding TGCs. This includes a new $5.7\sigma$ observation of $ZZ$ production by DØ and the world’s best limits on anomalous $ZZZ$ and $ZZ\gamma$ production by CDF.

2. $WW \rightarrow l\nu l\nu$

The simultaneous production of two $W$ bosons at the Tevatron is extremely rare with a predicted SM next-to-leading order (NLO) cross section of only $12.4 \pm 0.8$ pb \cite{1}. DO reported the first Tevatron observation of $WW$ production in events where each $W$ boson decays into an electron or a muon and a neutrino \cite{2}. After selecting events with two leptons that have high transverse momenta ($p_T$) and significant missing transverse energy ($E_T$) from the neutrino, 25 candidate events are found in approximately 250 pb$^{-1}$ of data. $8.1 \pm 1.0$ of these events are expected to be background. The measured cross section is $\sigma(WW) = 13.8^{+4.3}_{-3.8}(\text{stat})^{+1.2}_{-0.9}(\text{syst}) \pm 0.9(\text{lum})$ pb, which is consistent with the SM prediction. A similar measurement by CDF using approximately 825 pb$^{-1}$ of data finds 95 candidate events, $37.8 \pm 4.8$ of which are expected to be background \cite{3}. The corresponding cross section measurement is $\sigma(WW) = 13.6 \pm 2.3(\text{stat}) \pm 1.6(\text{syst}) \pm 1.2(\text{lum})$ pb, which is again consistent with the SM prediction.

3. $WZ \rightarrow l\nu l\nu$

$WZ$ production at the Tevatron is even more rare with a SM NLO production cross section of $3.7 \pm 0.3$ pb \cite{1}. Unlike $WW$ production, which was well studied at LEP, $WZ$ production was first observed by the CDF collaboration using approximately 1.1 fb$^{-1}$ of data in the $WZ \rightarrow l\nu l\nu$ channel where $l$ is either an electron or a muon \cite{4}. DO and CDF have both made more recent measurements in this channel by selecting events with three high $p_T$ leptons, high $E_T$, and at least one pair of leptons with a combined invariant mass consistent with the mass of a $Z$ boson. Background processes include $Z + \text{jets}$, $Z\gamma$, $ZZ$, and $t\bar{t}$ production. DO finds 13 candidates in approximately 1 fb$^{-1}$ of data, $4.5 \pm 0.6$ of which are expected to be background. The corresponding measured cross section is $\sigma(WZ) = 2.7^{+1.7}_{-1.3}(\text{stat} + \text{syst})$ pb \cite{5}. CDF finds 25 candidates using approximately 1.9 fb$^{-1}$ of data with an expected
4. **WWZ Triple Gauge Couplings**

In addition to measuring the cross section, both CDF and DØ set limits on $WZ$ production from the triple gauge coupling $WWZ$. This coupling can be described in terms of three parameters that are typically expressed as differences from their SM values, $\Delta g_1^Z$, $\Delta \kappa_Z$, and $\lambda_Z$. To set the limits, both experiments perform one- and two-dimensional fits to their $WZ$ candidates on the $p_T$ distribution of the $Z$ boson, which is sensitive to the coupling parameters as shown in Figure 1. No excess of $WWZ$ production over the SM prediction is found. The one-dimensional, 95% CL limits set by DØ assuming a form factor $\Lambda = 2.0 \text{ TeV}$ are:

- $-0.17 < \lambda_Z < 0.21$,
- $-0.14 < \Delta g_1^Z < 0.34$, and
- $-0.12 < \Delta \kappa_Z = \Delta g_2^Z < 0.29$.

The limits set by CDF for $\Lambda = 2.0 \text{ TeV}$ are:

- $-0.13 < \lambda_Z < 0.14$,
- $-0.13 < \Delta g_1^Z < 0.23$, and
- $-0.76 < \Delta \kappa_Z < 1.18$.

5. **WW/WZ → $l\nu jj$**

CDF has also reported a search for combined $WW$ and $WZ$ production in the partially hadronic decay channel $WW/WZ → l\nu jj$ using approximately $1.2 \text{ fb}^{-1}$ of data. Although this process has a higher branching ratio than the fully leptonic decay channel, it has not yet been observed at a hadron collider due to the large $W + jets$ background.

Initial selection includes requiring exactly one high $p_T$ electron or muon, significant $E_T^{miss}$, at least two jets, and a leptonic transverse mass consistent with a $W$ boson. A neural network is utilized to reduce the background. The signal yield, extracted from a fit to data on the dijet invariant mass distribution shown in Figure 2, is found to be $410 \pm 212 \text{ (stat)} \pm 102 \text{ (syst)}$. Assuming this signal (1.7$\sigma$ significance including systematics) is from WW and WZ production, the measured cross section is $\sigma(WW/WZ) \times BR(W \rightarrow l\nu, W/Z \rightarrow jj) = 1.47 \pm 0.77 \text{ (stat)} \pm 0.38 \text{ (syst)} \text{ pb}$. A 95% CL limit is also set on the cross section: $\sigma(WW/WZ) \times BR(W \rightarrow l\nu, W/Z \rightarrow jj) < 2.88 \text{ pb}$.

6. **ZZ Production**

With a predicted NLO cross section of $1.4 \pm 0.1 \text{ pb}$, ZZ production is the most rare SM diboson process apart from associated Higgs production \cite{1}. The channels with the best sensitivity at the Tevatron are $ZZ \rightarrow ll\nu\nu$ and $ZZ \rightarrow lll$. 

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**Figure 1:** $p_T(Z)$ distribution for $WZ$ events (DØ). The dotted lines depict possible non-SM values for $WWZ$ coupling parameters.

**Figure 2:** Dijet invariant mass spectrum for $WW/WZ$ events with the background shape subtracted from data (CDF).
CDF published a search for ZZ production using approximately 1.9 fb⁻¹ of data earlier this year [8]. Initial selection in the ZZ → llνν channel requires two high p_T, opposite sign electrons or muons, a cut on the dilepton invariant mass, and a maximum number of allowed high p_T jets. Additional E_T cuts are used to reduce the dominant Z + jets background. 276 candidate events are observed, 14 ± 2 of which are expected to be from ZZ production. To distinguish this signal from the large WW background, a likelihood ratio, shown in Figure 3, is constructed from event-by-event probability density functions that take into account the full event kinematics. The resulting signal has a significance of 1.2σ [8]. DO’s new search for ZZ → llνν production using 2.7 fb⁻¹ uses similar initial selection requirements. However, in order to maximize discriminating power against the Z + jets background, DO creates a novel E_T-like variable that represents the minimum possible E_T in the event given the measurement uncertainties on lepton energies and hadronic recoil, shown in Figure 4. After cutting on this distribution, 28(15) eee ν (μμνν) events are found with an expected background of 15.6 ± 0.4 (10.9 ± 0.3) events. A multivariate likelihood is used to distinguish ZZ production from the remaining backgrounds. The resulting signal has a significance of 2.6σ [9].

Although its branching ratio is six times smaller than ZZ → llνν, the fully leptonic decay channel is the most sensitive channel to search for ZZ production at the Tevatron because few processes have four leptons in the final state. The dominant background, Z + jets, is effectively suppressed by selecting two high p_T pairs of electrons or muons that have a dilepton invariant mass consistent with the mass of the Z boson. In order to maximize sensitivity, the published 1.9 fb⁻¹ CDF analysis separates events into higher and lower background categories based on whether the event includes an electron that is outside of the detector’s central tracking system. One such candidate is found with an expected background of 0.082±0.009(stat) ± 0.016(syst). Two candidates are found in the lower background category where the expected background yield is only 0.014±0.010(stat) ± 0.003(syst). This results in a signal with a significance of 4.2σ. Combined with the ZZ → llνν channel, CDF finds a 4.4σ signal for ZZ production and measures a cross section of \( \sigma = 1.4^{+0.7}_{-0.6}(\text{stat} + \text{syst}) \) pb, which is consistent with the SM prediction [9]. DO’s new search for ZZ → llll using 1.7 fb⁻¹ also separates candidates into higher and lower purity samples. Seven separate categories are considered based on the number of electrons in the central calorimeter region. In total, one μμμμ candidate and two ee μμ ν candidates are found for a total expected background of 0.14±0.03 events. The observed significance of this result is 5.3σ. Combined with the 2.7 fb⁻¹ llνν search and an earlier llll search on an independent 1 fb⁻¹ dataset [10], DO observes ZZ production with a significance of 5.7σ [11]. DO’s measured cross section, \( \sigma = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.15}(\text{syst}) \) pb, is also consistent with the SM prediction [12].

7. ZZ and ZZγ Anomalous Couplings

The simultaneous production of two Z bosons from the triple gauge couplings ZZZ and ZZγ is not permitted by the SM. Both DO and CDF have set limits on these anomalous couplings, described in terms of parameters \( f_A^Z \), \( f_A^γ \), \( f_B^Z \), \( f_B^γ \). DO’s published result based on approximately 1 fb⁻¹ of data set one- and two-dimensional limits on
the anomalous coupling parameters using $ZZ \rightarrow llll$ candidates. The 1-dimensional 95% CL limits assuming a form factor $\Lambda = 1.2$ TeV are: $-0.28 < f_4^Z < 0.28$, $-0.31 < f_5^Z < 0.29$, $-0.26 < f_4^\gamma < 0.26$, $-0.30 < f_5^\gamma < 0.28$. CDF has new preliminary limits based on 1.9 fb$^{-1}$ of data in the channel where one $Z$ boson decays to a pair of electrons or muons and the other $Z$ boson decays hadronically to jets. Although this channel suffers from a large $Z + jets$ background, the background falls away at high values of the $p_T$ of the $Z$ boson candidate formed from the two leptons. The dijet mass spectrum, shown in Figure 6, is fit in this high $p_T(Z)$ region to constrain potential contributions from anomalous couplings. No excess $ZZ$ production is found, and the world’s tightest 95% CL limits are set on the anomalous coupling parameters. For $\Lambda = 1.2$ TeV, these are: $-0.12 < f_4^Z < 0.12$, $-0.13 < f_5^Z < 0.12$, $-0.10 < f_4^\gamma < 0.10$, $-0.11 < f_5^\gamma < 0.11$.

8. SUMMARY

The two Tevatron experiments, CDF and DØ, have become increasingly sensitive to rare processes and have now measured the cross section for all SM diboson processes apart from associated Higgs production. This report summarized the most recent Tevatron cross section measurements for $WW$, $WZ$, and $ZZ$ production as well as limits on the corresponding TGCs. DØ’s 5.7$\sigma$ observation of $ZZ$ production is the first such Tevatron measurement to cross 5$\sigma$, and CDF set the world’s best limits on anomalous $ZZZ$ and $ZZ\gamma$ production.

References

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