DIBOSON PRODUCTION CROSS SECTIONS AT $\sqrt{s} = 1.96$ TeV

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The increasing size of the data recorded by the CDF and DØ experiments at the Tevatron collider at $\sqrt{s} = 1.96$ TeV makes the diboson physics program more accessible for probes of the electroweak gauge structure in the Standard Model. Here we summarize the most recent measurements of the diboson cross sections and limits on the trilinear gauge boson couplings.

1 Introduction

The diboson production plays an important role in electroweak precision measurements and searches for the New Physics (NP) which may exist at some energy scale $\Lambda$. The search for the NP is often related to the precision measurements such those of the cross sections and the trilinear gauge boson couplings (TGCs). More discussions about these TGC parameters can be found in [1]. Depending on the NP scenario, these observables are expected to deviate from their SM predictions. The charged TGCs studied in $WW$ and $W\gamma$ production are $(\Delta g^Z_{1}, \Delta \kappa_{\gamma,Z}, \lambda)$ and $(\Delta \kappa_{\gamma}, \lambda)$, respectively, and $(\Delta g^Z_{1}, \Delta \kappa_{Z}, \lambda)$ in $WZ$ production, where $\Delta$ represents the deviation from the SM prediction. In the SM, $\Delta g^Z_{1} = \Delta \kappa_{\gamma,Z} = \lambda = 0$. The neutral TGCs $h_{30,40}^\gamma, Z$ studied in $Z\gamma$ production are not allowed in the SM and their values are predicted to be zero. Besides, the diboson production is an important background to studies of the top quark and searches for the Higgs boson and SUSY particles. The most precise knowledge of background processes and their proper modeling is highly valuable for current and future studies.

2 Diboson Production

2.1 $Z\gamma \rightarrow \nu \nu \gamma$

The $Z\gamma$ events are reconstructed from 3.6 fb$^{-1}$ of DØ data. Candidate events are required to have one isolated central photon ($|\eta_{\text{det}}| < 1.1$) with $E_T > 90$ GeV and $E_T > 70$ GeV. The pointing algorithm [3] is used in order to reduce the contribution from bremsstrahlung photons. After all selection criteria were applied 51 $\nu \nu \gamma$ candidate events are observed. The predicted numbers of signal and background events are $3.7 \pm 3.4$ and $17.3 \pm 2.4$, respectively. The dominant background events are $W \rightarrow e \nu$ in which the electron is misidentified as a photon and it contributes with $9.7 \pm 0.6$ events. The measured cross section is $\sigma_{ZZ} \times BR(Z \rightarrow \nu \nu) = 32 \pm 9(\text{stat} + \text{syst}) \pm 2(\text{lumi})$ fb, [4] which is in agreement with the next-to-leading (NLO) cross section of $(39 \pm 4)$ fb [4]. The observed signal significance is 5.1 standard deviations (s.d.).
Furthermore, the photon $E_T$ spectrum shown in Fig. 1 is used to set the limits on $ZZ\gamma$ and $Z\gamma\gamma$ TGCs. The 95\% C.L one-dimensional limits for $h_{30,40}^{\gamma,Z}$ at $\Lambda = 1.5$ TeV are $|h_{30}^{\gamma,Z}| < 0.036$, $|h_{30}^{\gamma,Z}| < 0.035$ and $|h_{40}^{\gamma,Z}| < 0.0019$. The combination with the previous results in the most restrictive limits on these couplings at 95\% C.L. of $|h_{30}^{\gamma,Z}| < 0.033$ and $|h_{40}^{\gamma,Z}| < 0.0017$ of which three of them ($h_{30}^{\gamma,Z}$, $h_{40}^{\gamma,Z}$ and $h_{30}^{\gamma,Z}$) are world’s best to date.

2.2 $ZZ \to \nu\nu l^+l^-$

For the first time, the $ZZ$ production in the $\nu\nu ll$ ($l = e, \mu$) final states has been studied at the DO using 2.7 fb$^{-1}$ of data. The analysis builds up a new variable $E'_T$, highly discriminating against the $Z \to ll$ background events. Its purpose is to minimize the mismeasurement of the transverse momentum of either the charged leptons or the hadronic recoil system which contributes to the reconstructed $E'_T$. In the electron channel $E'_T$ is required to be $> 27$ GeV, and in the muon channel $E'_T > 30(35)$ GeV for data collected during 2002-2006 (2006-2008). In addition, each channel requires that there are only two oppositely charged isolated leptons with $p_T > 15$ GeV with the dilepton invariant mass is $(70 < M_{ll} < 110)$ GeV. Events with additional lepton of the same family are vetoed. Further separation between the signal and $WW$, $WZ$, $W+$jets, $ZZ \to l^+l^-$ backgrounds uses the likelihood discriminant. The total number of 43 candidate events has been selected of which 26.5 ± 0.5 are predicted to be the background. The observed signal significance is 2.6 s.d. and the measured cross section is $\sigma_{ZZ} = 2.01\pm0.93(stat)\pm0.29(syst)$ pb which is consistent with the NLO SM predicted cross section of 1.4 ± 0.1 pb.

2.3 $ZZ \to l^+l^-l'^+l'^-$

Sensitivity to single lepton cuts plays an important role when selecting $l^+l^-l'^+l'^-$ events ($l,l' = e$ or $\mu$). Application of tighter selection criteria such as lepton $p_T$, dilepton invariant mass and lepton isolation, relative to the previous DO analysis results in the first observation of the $ZZ$ production at a hadron collider. The analysis uses 1.7 fb$^{-1}$ of DO data in which four isolated leptons with $p_T > 15$ GeV are required to be within $|\eta_{det}| < 2$ if muons and $|\eta_{det}| < 1.1$ or $1.5 < |\eta_{det}| < 3.2$ if electrons. Two most energetic leptons in the $\mu\mu\mu\mu$ or $eeee$ channel are required to have $p_T > 30(25)$ GeV. Events are required to have at least one $Z$ with an invariant mass greater than 70 GeV and the other greater than 50 GeV. In the $ee\mu\mu$ channel the two most energetic electrons or muons must have $p_T > 25(15)$ GeV. Lepton candidates are required to be spatially separated by $R > 0.2$ ($R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) to reduce $Z \to \mu\mu$ background. The total of 3 events, two in the $eeee$ channel and one in the $\mu\mu\mu\mu$ channel, were observed. The SM signal and background are expected to contribute with $1.89 \pm 0.08$ and $0.14^{+0.03}_{-0.02}$ events, respectively. The observed signal significance is 5.3s and the measured cross section $\sigma_{ZZ} = 1.75^{+1.27}_{-0.86}(stat) \pm 0.13(syst)$ pb is in agreement with the SM prediction. The combination with previous analyses results in the observed signal significance of 5.7s and the measured cross section is $\sigma_{ZZ} = 1.60 \pm 0.63(stat) \pm 0.17(syst)$ pb.

2.4 $WZ \to j\ell ll$

A search for anomalous $ZWW$ TGCs in the $j\ell ll$ final states results in setting the 95\% C.L. limits on $\Delta h_{Z,\lambda}$ and $\Delta g_T^Z$ using the $p_T^j$ distribution, and the 95\% C.L. limits on the cross section for the $WZ$ production. This preliminary result is obtained using 1.9 fb$^{-1}$ of CDF data selecting events with two high $p_T$ leptons and two jets. The $p_T^j$ phase space is divided in three regions: control region used to validate the data modeling (105 – 140 GeV), medium (140 – 210 GeV) and high (> 210 GeV) regions. The medium and high $p_T^j$ regions are used to perform the measurements. Total number of observed (predicted) events is 97 (71.4 ± 0.5) and
12 (9.74 \pm 0.18) in the medium and high region, respectively. The observed 95% C.L. limits on TGCs are
-1.09 < \Delta \kappa_Z < 1.40, -0.18 < \lambda < 0.18 and -0.22 < \Delta g_T^Z < 0.32 for \Lambda = 1.5 \text{ TeV},
and -1.01 < \Delta \kappa_Z < 1.27, -0.16 < \lambda < 0.17 and -0.20 < \Delta g_T^Z < 0.29 for \Lambda = 2 \text{ TeV}. Unbinned
MC fit to data in the dijet mass distribution results in the 95% C.L. cross section limits of 234
fb and 135 fb for medium and high region, respectively.

2.5 WW \rightarrow ll'\nu

The most precise WW cross section measurement at a hadron collider is performed analyzing the
ll'\nu (l,l' = e,\mu) final states with 1.0 fb^{-1} of DØ data. In each ll' final state (ee, \mu\mu or e\mu) the two most energetic leptons are required to have
p_T > 25 (15) GeV, to be of opposite charge and to be spatially separated from each other by
R > 0.8 (ee) and R > 0.5 (e\mu). The Z/\gamma^* \rightarrow ll background is effectively removed requiring \E_T > 45 (ee), 20 (e\mu) or 35 (\mu\mu) GeV, \E_T > 50 GeV if |M_Z - m_ee| < 6 GeV (ee), \Delta \phi_{\mu\mu} < 2.45 and \E_T > 40 GeV if \Delta \phi_{e\mu} > 2.8.
Imposing the upper cut on the transverse momentum of the WW system, of 20 (ee), 25 (e\mu) and 16 (\mu\mu) GeV minimizes the tf background. After all selection criteria were applied, all three
combined channels yield 100 candidate events, 38.19 \pm 4.01 predicted background events and
64.70 \pm 1.12 predicted signal events. The cross section measurements in the individual channels are
combined, yielding \sigma_{WW} = 11.5 \pm 2.1(stat + syst) \pm 0.7(lumi) \text{pb} which is in agreement with
the SM NLO prediction of 12.4 \pm 0.8 \text{pb}. The pt distributions of the leading and trailing leptons
were used to set limits on anomalous TGCs considering two different parameterizations between
the couplings. The one-dimensional 95% C.L. limits for \Lambda = 2 \text{ TeV} are -0.54 < \Delta \kappa_\gamma < 0.83,
-0.14 < \lambda_\gamma = \lambda_Z < 0.18 and -0.14 < \Delta g_T^Z < 0.30 under the SU(2)_L \times U(1)_Y-conserving
constrains, and -0.12 < \Delta \kappa_\gamma = \Delta \kappa_Z < 0.35 and -0.14 < \lambda_\gamma = \lambda_Z < 0.18 under the
assumption that \gamma WW and ZWW couplings are equal.

2.6 WW + WZ \rightarrow lljj

This analysis results in the first evidence for the WW/WZ production in the lljj final states at
the hadron collider with 1.1 fb^{-1} of DØ data. Selected lljj (l = e,\mu) candidate events are
required to have a single isolated lepton with \pt > 20 GeV and |\eta| < 1.1 (2.0) for electrons
(muons), \E_T > 20 GeV and at least two jets with \pt > 20 GeV. The jet of highest \pt must
have \pt > 30 GeV and the transverse mass of leptonically decaying W boson must be > 35 GeV
to reduce the multijet background. Because of the small signal-to-background ratio (3%), an
accurate modeling of the dominant W+jets background is essential and therefore, studied in
great detail. After all selection criteria were applied, the signal and the backgrounds are further
separated using a multivariate classifier, Random Forest (RF). The signal cross section
is determined from a fit of signal and background RF templates to the data with respect to
variations in the systematic uncertainties, and is measured to be \sigma_{WW+WZ} = 20.2 \pm 2.5(stat) \pm
3.6(syst) \pm 1.2(lumi) \text{pb} which is consistent with the SM NLO prediction of \sigma(WW + WZ) =
16.1 \pm 0.9 \text{pb}. The observed signal significance is 4.4 s.d.. Fig. 2 shows the WW/WZ dijet
mass peak extracted from data compared to the MC prediction.

3 Summary

The recent results in diboson production at the Tevatron, using 1.0–3.6 pb^{-1} of data, have been
presented. Measured cross sections for the Z\gamma, ZZ, WZ and WW processes and TGCs at the
\gamma ZZ, \gamma WW and ZWW vertices are in agreement with the SM predictions. The DØ experiment
sets the world’s tightest limits on the h_{40}^\gamma, h_{40}^Z and h_{30}^Z TGCs and reports the first evidence of
WW/WZ production in semi-leptonic final states at a hadron collider.

Figure 1: Photon $E_T$ spectrum of $\nu\nu\gamma$ data candidate events compared to the SM signal and background, and the expected distribution in the presence of anomalous TGCs. The systematic and statistical uncertainties on the SM MC events are included as shaded bands.

Figure 2: A comparison of the extracted signal (filled histogram) to background-subtracted data (points), along with the ±1 standard deviation (s.d.) systematic uncertainty on the background. The residual distance between the data points and the extracted signal, divided by the total uncertainty, is given at the bottom.

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