Diboson Production at D0

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Abstract. New data set recorded by DØ experiment at the Tevatron collider at $\sqrt{s} = 1.96$ TeV makes the diboson physics program an attractive probe of electroweak gauge structure in the Standard Model. Here we present the most recent diboson production cross section measurements at DØ for $W\gamma$, $Z\gamma$, $WZ$ and $ZZ$ and report on the tightest limits to date on the neutral trilinear gauge boson couplings in $Z\gamma$ production. Depending on the analysis the size of utilized RunIIa data collected during 2002-2006 by the DØ detector is 0.8-1.0 pb$^{-1}$.

1. Introduction

Diboson production and interactions provide a test of the electroweak sector of the Standard Model (SM). Diboson production can be studied by measuring production cross sections and their interactions can be studied by measuring trilinear gauge boson couplings (TGCs) [1]. The available TGCs are $g_{1}^{\gamma,Z}$, $\Delta\kappa_{\gamma,Z}$, $\Delta\lambda_{\gamma,Z}$ in WW production and $g_{1}^{\gamma}$, $\Delta\kappa_{\gamma}$, $\Delta\lambda_{\gamma}$ in WW and $W\gamma$ production. In the SM, $g_{1}^{\gamma,Z} = \Delta\kappa_{\gamma,Z} = 1$ and $\Delta\lambda_{\gamma,Z} = 0$. The neutral TGCs $h_{1-4}^{\gamma,Z}$ and $f_{1-5}^{\gamma,Z}$ in ZZ and $Z\gamma$ production are not allowed in the SM and so their values are predicted to be zero. Any deviation of TGC or production cross section values from their SM predictions is a possible indication for New Physics and could give us some clues about the electroweak symmetry breaking mechanism. Though if diboson production cross sections in $p\bar{p}$ collisions are up to $10^{4}$ times smaller than those for single boson production, the DØ data provides enough statistics to obtain significant improvement in precision measurements relative to earlier results [2]. Channels previously limited in statistics such as WZ and ZZ are now available. The WZ and ZZ events are reconstructed using only the leptonic final states, while $W\gamma$ and $Z\gamma$ final states are leptonic with an associated photon.

Diboson production is also an important background to studies of the top quark and searches for the Higgs boson and SUSY particles, where detailed understanding of all backgrounds is important.

2. Diboson Production

2.1. The process $W\gamma \rightarrow l\nu\gamma$

Negative interference among the tree-level diagrams the amplitude for $W\gamma$ production in the SM is expected to decrease in some regions of phase space [3] and it is known as the Radiation Amplitude Zero (RAZ). This effect is evident in the charge-signed lepton-photon rapidity difference as a dip around -0.3, shown in Fig.1. An anomalous TGC value may cancel the...
interference and obscures the dip. However, final state radiation, backgrounds and higher order corrections also reduce the effect. Thus, this measurement provides a probe of WWγ TGCs but more statistics are needed to unambiguously establish the RAZ. The analyzed data correspond to 933 pb⁻¹ (878 pb⁻¹) in the electron (muon) channel. An isolated electron (muon) is required to be in the region $|\eta_e| < 1.1$ or $1.5 < |\eta_e| < 2.5$ ($|\eta_\mu| < 2$) with $E_T > 25$ GeV (20 GeV). In both channels, the photon must be detected in $|\eta_\gamma| < 1.1$ or $1.5 < |\eta_\gamma| < 2.5$ with $E_T > 7$ GeV and be separated from the lepton by $\Delta R_{l\gamma} > 0.7$ where $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$. The event is required to have $E_T > 25$ GeV and a three-body transverse mass greater than 110 GeV. The total number of selected candidate events is 634. We observe 335 ±44 signal events after background subtraction in both channels [4]. According to the number of selected signal events the measured cross sections correspond to $3.1 \pm 0.5$ (stat+syst)±0.2 (lumi) pb in the electron channel and to $3.2 \pm 0.5$ (stat+syst)±0.2 (lumi) pb in the muon channel. The results are in agreement with the SM prediction which gives $3.21 \pm 0.08$ (PDF) pb in the single lepton channel for the same set of cuts. Data and Monte Carlo shapes shown in Fig.2 are consistent with RAZ.

![Figure 1.](image1.png)  

**Figure 1.** Monte Carlo prediction of the charge-signed rapidity difference in SM $W\gamma$ events and in the presence of an anomalous TGC $\kappa_\gamma$ ($\Delta \kappa_\gamma = -1$).

![Figure 2.](image2.png)  

**Figure 2.** DØ RunIIa Preliminary: Charge-signed rapidity difference of combined candidates, background subtracted.

2.2. *The process $Z\gamma \rightarrow l\nu\gamma$*

The $Z\gamma$ events are reconstructed from 1109 pb⁻¹ (1009 pb⁻¹) of data in the electron (muon) channel. In the electron channel at least one electron is required to have $E_T > 25$ GeV and a second electron with $E_T > 15$ GeV. At least one of the two electrons must be reconstructed within $|\eta_e| < 1.1$. In the muon channel one muon is required to have $p_T > 20$ GeV and the second must have $p_T > 15$ GeV. If the opening angle between two muon candidates is less than 0.05 the events are rejected as possible cosmic ray contamination. In both channels an event is selected if the invariant mass of the $ll$ pair is larger than 30 GeV. As in the $W\gamma$ case, photon identification is of particular importance for the quality of the analysis. A photon candidate with $E_T > 7$ GeV must be reconstructed in the central region and separated from the lepton by $\Delta R_{l\gamma} > 0.7$. After all selection criteria are applied 453 $ee\gamma$ and 515 $\mu\mu\gamma$ candidate events are observed. The main source of background, $Z+\text{jets}$, contributes with 55.2 ± 8.3 (61.3 ± 9.0) events in the electron (muon) channel as estimated from data. With the previously mentioned cuts on $\Delta R_{l\gamma}$, $M_{ll}$ and photon $E_T$ the combined $ll\gamma$ cross section is measured to be $4.96 \pm 0.30$ (stat+syst)±0.30 (lumi) pb which is in agreement with $4.74 \pm 0.22$ pb as predicted by the NLO event generator [5]. Furthermore, the $E_T$ spectrum of photon candidates shown in Fig.4 is used to set the limits on neutral ZZγ and $Z\gamma\gamma$ TGCs for the form-factor $\Lambda=1.2$ TeV. The one-dimensional limits for
\( h^\gamma Z \) are \(-0.085 < h_3^{\gamma 0} < 0.084, -0.083 < h_3^{Z 0} < 0.082 \) and \(-0.053 < h_4^{\gamma Z} < 0.054 \) for \( \Lambda = 1.2 \) TeV at the 95\% C.L. [6].

2.3. The process \( ZZ \rightarrow llll \)

Due to the small SM cross section of \( 1.6 \pm 0.1 \) pb, \( ZZ \) production at a hadron collider was not observed until recently [7]. The sensitivity to single lepton cuts plays an important role in selection efficiency. The \( Z/\gamma^* \) analysis uses 944 pb\(^{-1}\) for the \( \mu\mu\mu\mu \) channel, 1070 pb\(^{-1}\) for the \( eee\mu \) channel and 1020 pb\(^{-1}\) for the \( ee\mu\mu \) channel. Four isolated leptons with \( E_T > 15 \) GeV are required to be within \( |\eta_\mu| < 2 \) for muons and \( |\eta_e| < 1.1 \) or 1.5 \(< |\eta_e| < 3.2 \) for electrons. Beam halo is reduced by requiring \( |\Delta z_{\text{vtx}}| \) between muon track vertices to be less that 3 cm. The muon pair originating from the same vertex is required to have an opening angle of \( \cos \theta < 0.96 \) to remove cosmic ray background. To avoid photons radiated off the muon faking an electron, the separation between electrons and muons is required to be \( \Delta R > 0.2 \). In addition, the invariant \( ee \) and \( \mu\mu \) masses must be greater than 30 GeV. After all selection criteria have been applied one \( ee\mu\mu \) candidate event with invariant \( ee \) mass of 93.4 GeV and invariant \( \mu\mu \) mass of 33.4 GeV remains. This is in agreement with the SM prediction of \( 1.71 \pm 0.11 \) ZZ events. According to dilepton invariant masses it is very probable that this is a \( Z/\gamma^* \) event shown in Fig.5. The cross section limit for ZZ to decay into leptons (muons and electrons) set by \( \text{DØ} \), is \( \sigma_{ZZ} < 4.3 \) pb at 95\% C.L. [8].

2.4. The process \( WZ \rightarrow ll\tau \)

A \( \text{DØ} \) search for \( WZ \) to leptons events has been made using 860 pb\(^{-1}\) of data for \( ee \) final states, 830 pb\(^{-1}\) for \( ee\mu \) final states and 760 pb\(^{-1}\) for \( \mu\mu \) final states. The events are selected by
requiring 3 isolated leptons with $p_T > 15$ GeV and $E_T > 20$ GeV. Leptons are also required to be separated from each other by $\Delta R > 0.2$ in order to avoid being reconstructed using the same track. The $Z$ candidates are selected if the invariant mass of a like lepton pair is within a mass window 71 GeV to 111 GeV for $Z \rightarrow ee$ and 51 GeV to 131 GeV for $Z \rightarrow \mu\mu$. In order to minimize cosmic background $Z$ candidates in the muon channel are accepted if the angle between them is larger than 0.05. To reduce the $t\bar{t}$ background, the vector sum of the leptons’ $E_T$ and the $E_T$ is required to be less than 50 GeV. A total of $7.54 \pm 1.21$ WZ events and $3.61 \pm 0.20$ background events are expected. 12 candidate events were observed. This is the first evidence for WZ at DØ with 3.3 $\sigma$ significance. The measured WZ production cross section of $3.98^{+1.0}_{-0.91}$ pb is determined from the likelihood distribution shown in Fig.6 [9].

3. Conclusions
The diboson results presented here were obtained by analyzing leptonic final states in $\approx 1$ fb$^{-1}$ DØ of data. They are consistent with NLO SM predictions and no deviation from the SM has been found. The $W\gamma$ analysis shows an indication of the RAZ. The first evidence of WZ production at DØ has been found with 3.3 $\sigma$ significance and one ZZ candidate event is observed in the $ee\mu\mu$ channel with a SM prediction of $1.71 \pm 0.11$ events. Using the latest $Z\gamma$ measurement we set the world’s tightest limits on the neutral couplings $h_4^{\gamma}$ and $h_4^{Z}$. 

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