$ZZ \to \ell\ell\nu\nu$ production at DØ

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This papers describes a search for Z boson pair production in $p\bar{p}$ collisions at $\sqrt{s}$= 1.96 TeV with the D0 detector at the Fermilab Tevatron Collider. The search for $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (where $\ell = e$ or μ) is performed in a data sample corresponding to an integrated luminosity of 2.7 fb^{-1}. We observe ZZ production in the combination of DØ results in this channel as well as in $ZZ \to \ell^+\ell^-\ell^{'+}\ell^{'-}$ with a 5.7 standard deviations significance (4.8 expected) corresponding to a cross section of $1.60 \pm 0.63(\text{stat.})^{+.16}_{-.17}(\text{syst.})$ pb.

1 Introduction

We describe a search for Z boson pair production in $p\bar{p}$ collisions in the case where one Z boson decays into two charged leptons (either electrons or muons) and the other decays into two neutrinos. Special attention will be given to the development of an instrumental variable used to reduce the contribution from events with artificially inflated missing transverse momentum ($\not\!\!E_T$).

Observation of the ZZ process is an essential stepping stone for Standard Model (SM) Higgs searches. In the SM, ZZ production is the double gauge boson process with the lowest cross section, making it an ideal testing ground for Higgs searches. Additionally, it is a background to some of these very same searches, such as the $ZH \to \ell^+\ell^- b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$ and $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ channels. Unlike the WW and WZ processes, there are no expected SM contributions from triple gauge boson couplings involving two Z bosons, an unexpectedly high cross section measurement could indicate the presence of anomalous couplings.

2 Event Selection

The signal is characterized by two leptons, missing transverse energy and little jet activity. In each of the two channels we require that there be exactly two oppositely charged leptons with transverse momentum $p_T > 15$ GeV and dilepton invariant mass $70 < M_{\ell\ell} < 110$ GeV.

WZ production is suppressed by vetoing events with one or more leptons (e, μ, or τ) in addition to those forming the Z candidate. Events with relatively large calorimeter activity are rejected by vetoing on the presence of more than two jets in the detector with ΔR(jet, lepton)> 0.3, where ΔR is the distance between two objects in (η, ϕ) space, and jet $E_T > 15$ GeV. This requirement significantly reduces background from $t\bar{t}$ production.

3 Instrumental Background Rejection

The primary background after the initial selection is inclusive $Z/\gamma^* \rightarrow \ell^+\ell^-$ production in which mismeasurement results in a mistakenly large $\not{E}_T$value. Rather than attempt to make an unbiased or accurate estimate of the $\not{E}_T$ we devise a new variable ($\not{E}'_T$) in five steps which is a representation of the minimum feasible $\not{E}_T$ given the measurement uncertainties of the leptons and the hadronic recoil. This is not intended to be the best estimator of true $\not{E}_T$, but rather to be variable which is robust against reconstruction mistakes. The approach is inspired by the OPAL collaboration which used a similar variable to search in final states similar to that of this analysis [1].

3.1 Decomposition

First, the $\vec{p}_T$ of the lepton pair is decomposed into two components, one of which is almost insensitive to lepton p_T resolution for Z candidates with moderate values of transverse momentum. In the transverse plane a dilepton thrust axis is defined as the p_T of the leading lepton minus the p_T of the second lepton. For the rest of this paper, a subscript l or t denotes the component in the longitudinal ($\hat{a}_l$) or transverse ($\hat{a}_t$) direction.

The dilepton system p_T is decomposed into components parallel to $\hat{a}_l$ ($a_l^{\ell\ell}$) and to $\hat{a}_t$ ($a_t^{\ell\ell}$). The decomposition is performed only for events in which $\Delta\phi^{\ell\ell} > \pi/2$, where $\Delta\phi^{\ell\ell}$ is the angle between the two charged leptons in the transverse plane. For the case $\Delta\phi^{\ell\ell} \leq \pi/2$ the direction of the dilepton transverse momentum $\vec{p}_T^{\,\ell\ell}$ is used to define $\hat{a}_t$, and all components in the $\hat{a}_l$ direction are set to zero.

3.2 Calorimeter Recoil Activity

Two measures of net calorimeter transverse energy are considered: (a) a vector sum of the E_T of selected reconstructed jets in the hemisphere opposite the dilepton pair and (b) the calorimeter missing transverse energy $\not{E}_T$. Along each of the two axes we use the one with the largest projected magnitude pointing away from the dilepton pair.

$$\delta a_t^{cal} = 2 \times \min(\Sigma \vec{p}_T^{\,jets} \cdot \hat{a}_t, -\vec{\not{E}}_T \cdot \hat{a}_t, 0) \qquad \delta a_l^{cal} = 2 \times \min(\Sigma \vec{p}_T^{\,jets} \cdot \hat{a}_l, -\vec{\not{E}}_T \cdot \hat{a}_l, 0)$$

in which a jet is used in the $\hat{a}_l(\hat{a}_t)$ component sum only if it satisfies $\vec{p}_T \cdot \hat{a}_l < 0$ ($\vec{p}_T \cdot \hat{a}_t < 0$).

3.3 Recoiling Tracks

The third step identifies events in which the recoil activity is not observed in the calorimeter as jets. We consider tracks that are $\Delta R > 0.5$ away from all calorimeter jets, $\Delta R > 0.5$ from the candidate leptons, have a fit satisfying $\chi^2/\text{NDF} < 4.0$, and $p_T > 0.5$ GeV and use these to build track jets using a cone algorithm. The track jet transverse momentum ${p_T}^{tjet}$ is the vector sum of the p_T values of all tracks forming the track jet.

$$\delta a_t^{trk} = (\Sigma \vec{p}_T^{\,tjet}) \cdot \hat{a}_t \qquad \delta a_l^{trk} = (\Sigma \vec{p}_T^{\,tjet}) \cdot \hat{a}_l.$$

As with the calorimeter jets, a track jet is included in the correction for the $\hat{a}_l(\hat{a}_t)$ direction only if it satisfies $\vec{p}_T^{\,tjet} \cdot \hat{a}_l < 0$ ($\vec{p}_T^{\,tjet} \cdot \hat{a}_t < 0$).

3.4 Lepton p_T Uncertainty

The fourth step accounts for the resolution of the lepton p_T measurement. The lepton transverse momenta are fluctuated by one standard deviation of their uncertainty so as to minimize, separately, the $\hat{a}_l$ and $\hat{a}_t$ components of the dilepton ${p_T}^{\ell\ell}$. The transverse component, $a_t^{\ell\ell}$, is minimized by decreasing the transverse momenta of both leptons to give the modified quantity:

$$a_t^{\ell\ell\prime} = \vec{p}_T^{\,\ell\ell\prime} \cdot \hat{a}_t{}'.$$

Here $\vec{p}_T^{\,\ell\ell\prime}$ and $\hat{a}_t{}'$ correspond, respectively, to $\vec{p}_T^{\,\ell\ell}$ and $\hat{a}_t$, redefined using $\vec{p}_T^{\,(1)} \times (1 - \sigma_1)$ and $\vec{p}_T^{\,(2)} \times (1 - \sigma_2)$ in place of the unscaled quantities. The longitudinal component, $a_l^{\ell\ell}$, is minimized by decreasing $\vec{p}_T^{\,(1)}$ and increasing $\vec{p}_T^{\,(2)}$ using their fractional uncertainties σ_1 and σ_2:

$$\delta a_t^{\ell\ell} = a_t^{\ell\ell\prime} - a_t^{\ell\ell}. \qquad \delta a_l^{\ell\ell} = (-\sigma_1 \vec{p}_T^{\,(1)} + \sigma_2 \vec{p}_T^{\,(2)}) \cdot \hat{a}_l$$

If the fractional uncertainty on either of the lepton transverse momenta is larger than unity, then the fractional uncertainties on both $a_t^{\ell\ell}$ and $a_l^{\ell\ell}$ are set to unity. Electrons falling at the calorimeter module boundaries risk being significantly under measured. If the lower p_T electron is within this region, the fractional uncertainty on $a_l^{\ell\ell}$ is set to unity.

3.5 Combination

In the fifth and final step, the variable $\not{E}_T'$ is computed from the quantities calculated in the previous steps. We compute components:

$$a_t = a_t^{\ell\ell} + \delta a_t^{cal} + k' \times \delta a_t^{trk} + k \times \delta a_t^{\ell\ell} \qquad a_l = a_l^{\ell\ell} + \delta a_l^{cal} + k' \times \delta a_l^{trk} + k \times \delta a_l^{\ell\ell},$$

The values of k and k' were optimized by maximizing $S/\sqrt{B}$ in a background dominated sample. Recall that by construction the δa_i (where $i = t$ or l) terms are always zero or negative while $a_i^{\ell\ell}$ is positive. For events with significant transverse energy from neutrinos and no mismeasurements, the a_i variables are large and positive. If $a_i \leq 0$, then there is no significant missing transverse momentum along direction i and that component is ignored in the subsequent analysis. The final discriminating variable is then calculated as a weighted quadrature sum of the two components:

$$a_t' = \max(a_t, 0) \qquad a_l' = \max(a_l, 0).$$

$$\not{E}_T' = \sqrt{a_l'^2 + (1.5 a_t')^2}.$$

The rejection of instrumental background events using this method and a simple $\not{E}_T$ cut is shown in Figure 1.

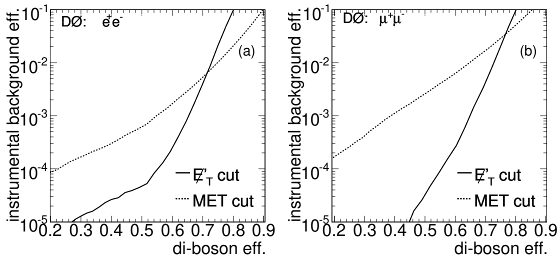

Figure 1: The efficiency of WW, WZ, and ZZ events vs instrumental background events using the $\not\!\!E_T$ (labeled as MET in the figure) and $\not\!\!E'_T$ variables in the dielectron (a) and dimuon (b) channels.

	dielectron		dimuon	
Sample	dilepton selection	$\not\!\!E'_T$ requirement	dilepton selection	$\not\!\!E'_T$ requirement
$Z \to \ell^+\ell^-$	1.18×10^5	0.5 ± 0.2	1.30×10^5	0.1 ± 0.1
$Z \to \tau^+\tau^-$	48.3	0.35	53.3	0.09
W+Jets	18.2	2.7 ± 0.4	–	< 0.01
$t\bar{t}$	16.4	0.34	16.0	0.21
Diboson	47.2	11.68 ± 0.1	50.3	10.52 ± 0.1
$W\gamma$	2.0	0.03	–	–
Predicted Background	1.19×10^5	15.6 ± 0.4	1.30×10^5	10.9 ± 0.3
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	2.9	0.02	2.89	0.00
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	8.9	4.03	9.48	3.39
Predicted Total	1.19×10^5	19.6 ± 0.4	1.30×10^5	14.3 ± 0.3
Data	118,850	28	127,960	15

Table 1: Predicted events and data yield after the dilepton selection and after the requirement on $\not\!\!E'_T$. The uncertainties in the final column are statistical only. If not present, the statistical uncertainty is negligible.

4 Final Selection, Likelihood and Yields

The events come from two data taking periods. The $\not\!\!E'_T$ cut is optimized for each of these in the two dilepton channels. After cutting on $\not\!\!E'_T$, we observe 28 events (19.6 expected) in the dielectron channel and 15 events (14.3 expected) in the dimuon. The yields are listed in Table 4.

The ZZ signal is separated from the remaining backgrounds using a likelihood with the following input variables: the dilepton invariant mass (for the dielectron channel), the χ^2 probability from a refit of the measured lepton momenta under the constraint that their dilepton mass gives the Z mass (for the dimuon channel), the p_T of the leading lepton, the opening angle between the dilepton pair and the leading lepton, and the cosine of the negative lepton scattering angle in the dilepton rest frame.

5 Results

After considering the systematic uncertainties associated with our various object reconstructions and analysis methods, the search yields an observed significance of 2.6 standard deviations (2.0 expected) [2]. This result is combined with an independent DØ search for $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ [3]. After the combination we observe a significance of 5.7 standard deviations (4.8 expected). The SM cross section for $p\bar{p} \to ZZ + X$ is 1.4 ± 0.1 pb [4] at $\sqrt{s} = 1.96$ TeV, we find:

$$\sigma(ZZ) = 1.6 \pm 0.64(stat.)^{+0.16}_{-0.17}(sys.)\ \text{pb}.$$

References

1. K. Ackerstaff *et al.* (OPAL Collaboration), Eur. Phys. J C**4**, 47 (1998).
2. V. Abazov *et al.* (DØ Collaboration), Phys. Rev. D **78**, 072002 (2008),
3. V. Abazov *et al.* (DØ Collaboration), Phys. Rev. Lett. **101**, 171803 (2008),
4. J. M. Campbell and R.K. Ellis, Phy. Rev. D **60**, 113006 (1999).