A measurement of the $WZ$ and $ZZ$ production cross sections using leptonic final states in 8.6 fb$^{-1}$ of $p\bar{p}$ collisions

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We study the processes $p\bar{p} \rightarrow WZ \rightarrow \ell\nu\ell\ell$ and $p\bar{p} \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$, where \(\ell = e \) or \(\mu\). Using 8.6 fb\(^{-1}\) of integrated luminosity collected by the D0 experiment at the Fermilab Tevatron collider, we measure the WZ production cross section to be $4.50^{+0.63}_{-0.66}$ pb which is consistent with, but slightly above a prediction of the standard model. The ZZ cross section is measured to be $1.64 \pm 0.46$ pb, in agreement with a prediction of the standard model. Combination with an earlier analysis of the ZZ \(\rightarrow \ell^+\ell^-\ell^+\ell^-\) channel yields a ZZ cross section of $1.44^{+0.35}_{-0.31}$ pb.

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I. INTRODUCTION

This Article reports a study of $WZ \rightarrow \ell\nu\ell\ell$ and $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ production in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. When not stated otherwise, we denote as $Z$ the full $Z/\gamma^*$ propagator, with the requirement of $60 < M_{\ell\ell} < 120$ GeV on the dilepton invariant mass $M_{\ell\ell}$ for the decay $Z \rightarrow \ell^+\ell^-$. The pair production of $W$ and $Z$ gauge bosons probes the electroweak component of the standard model (SM) as these cross sections are predicted to be significantly larger in the presence of new resonances or anomalous triple-gauge-couplings [1, 2]. Diboson production is a major source of background in many search channels for Higgs bosons. For example, ZZ decays correspond to some of the dominant backgrounds in searches for $ZH$ production at the Tevatron. Understanding diboson production is therefore crucial for demonstrating sensitivity to the presence of a SM Higgs boson at the Tevatron.

Production of WZ pairs was first reported by the CDF Collaboration, in 1.1 fb\(^{-1}\) of integrated luminosity in the $\ell\nu\ell\ell$ channel [3]. Evidence for $WZ \rightarrow \ell\nu\ell\ell$ production was also presented by the D0 Collaboration in 1.0 fb\(^{-1}\) of integrated luminosity [4]. The D0 Collaboration studied the same process with 4.1 fb\(^{-1}\) [5], measuring a production cross section of $3.90^{+1.06}_{-0.90}$ pb. The production of ZZ was first observed by D0 in the $\ell^+\ell^-\ell^+\ell^-$ final state with 2.7 fb\(^{-1}\) [6]. Combination with an analysis of the $\ell^+\ell^-\nu\bar{\nu}$ final state with 2.7 fb\(^{-1}\) [7], increased the significance from 5.3 to 5.7 standard deviations [8]. Evidence for ZZ production was also presented by CDF in 1.9 fb\(^{-1}\) [9] of integrated luminosity. D0 has recently analyzed 6.4 fb\(^{-1}\) of integrated luminosity in the $\ell^+\ell^-\ell^+\ell^-$ final state [10]. Combination with the earlier 2.7 fb\(^{-1}\) analysis [7] of the $\ell^+\ell^-\nu\bar{\nu}$ channel yields a ZZ cross section of $1.44^{+0.35}_{-0.31}$ pb.
final state yielded a $ZZ$ production cross section of $1.40^{+0.44}_{-0.27}{(\text{stat})} \pm 0.14{\text{(syst)}}$ pb$^{10}$. The CDF Collaboration recently measured a cross section of $1.64^{+0.44}_{-0.38}$ pb for $ZZ$ production using 6 fb$^{-1}$ in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states$^{11}$. The ATLAS Collaboration has recently studied the $WZ \rightarrow \ell\nu\ell\nu$ and $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ processes in $pp$ collisions at $\sqrt{s} = 7$ TeV using 1.1 fb$^{-1}$ of integrated luminosity$^{[12, 13]}$.

Following the approach of the previous D0 analysis$^{7}$ of the $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ signal, we measure the ratios of signal cross sections relative to the inclusive $Z$ cross section. This has the advantage of cancelling the uncertainty on the luminosity, while other systematic uncertainties related to lepton identification and trigger efficiencies, are also largely cancelled.

All selection requirements and analysis techniques are optimized based on Monte Carlo (MC) simulation, or on data in signal-free control regions. The data are examined in the region expected for signal only after all selection criteria are defined through simulation.

II. APPARATUS

The D0 detector$^{[14-16]}$ has a central-tracking system, consisting of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 1.9 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities$^{[17]}$ $|\eta| < 3$ and $|\eta| < 2.5$, respectively. A liquid-argon and uranium calorimeter has a central section (CC) covering $|\eta|$ up to $\approx 1.1$ and two end calorimeters (EC) that extend coverage to $|\eta| \approx 4.2$, with all three housed in separate cryostats. The inter-cryostat (IC) region (1.1 $< |\eta| < 1.5$) has little electromagnetic (EM) calorimetry, and reduced hadronic coverage. Additional scintillating tiles covering the region 1.1 $< |\eta| < 1.4$ provide improved energy resolution for hadronic jets. An outer muon system, covering $|\eta| < 2$, consists of a layer of wire chambers and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two similar layers after the toroids.

III. DATA AND INITIAL EVENT SELECTION

The data used in this analysis were collected with the D0 detector at the Fermilab Tevatron $pp$ collider at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. An integrated luminosity of 8.6 fb$^{-1}$ is available for analysis, following application of data quality requirements.

Unlike the previous D0 analyses of these channels, we do not restrict the offline event selection to events satisfying specific trigger conditions. Rather, we analyse all recorded data in order to maximise the event yields. The analyzed events are mostly recorded by triggers that require one or two electrons or muons with high transverse momentum, $p_T$.

Since both signal processes involve the decay $Z \rightarrow \ell^+\ell^-$, a natural starting point is to select an inclusive sample of dilepton events. In addition to the $e^+e^-$ and $\mu^+\mu^-$ dilepton channels, the $ZZ$ analysis makes extensive use of the $e^+\mu^-$ channel for verifying modelling of dominant backgrounds (mostly $WW \rightarrow \ell^+\nu\ell^-\bar{\nu}$). In all channels we require that there are two oppositely charged leptons with an invariant mass $M_{\ell\ell}$ between 60 and 120 GeV. The regions $40 < M_{\ell\ell} < 60$ GeV and $M_{\ell\ell} > 120$ GeV are used as control regions. The two leptons are required to originate from a common vertex that is located within $\pm 80$ cm of the detector center along the z axis, defined by the beam direction.

We define three different qualities for electrons and muons and refer to electrons or muons satisfying the corresponding selection criteria, discussed below, as loose, medium, and tight, respectively. Electrons are treated differently when they are reconstructed in the CC, EC, and IC regions of the calorimeter. Loose CC/EC electron candidates are reconstructed using EM energy clusters in the calorimeter that satisfy minimal shower shape and isolation requirements and that are spatially matched to central tracks. A boosted decision tree (BDT)$^{[18]}$ is trained to separate electrons from jets, based on tracking, isolation, and shower shape information. Medium and tight CC/EC electrons must satisfy increasingly stringent requirements on the output from this BDT.

In the IC region, there is no dedicated reconstruction of electrons. However, electrons traversing this region are identified using an algorithm that searches for hadronic decays of tau leptons. A neural network is trained to use shower shape, isolation, and tracking information to recover electrons from reconstructed taus while rejecting hadronic jets. Electrons found in the IC region must be matched to a central track with at least one hit in the SMT and ten hits in the CFT. Loose, medium, and tight IC electrons must satisfy increasingly stringent requirements on the neural network output. In addition, medium(tight) IC electrons must satisfy $T_{\text{elec}}^{\text{trk}}/p_T < 0.2(0.1)$, where $T_{\text{elec}}^{\text{trk}}$ is the scalar $p_T$ sum of all tracks within an annulus of radius 0.05 $< \Delta R < 0.4$ around the candidate electron. IC electrons are placed into two sub-categories: type-2(1) IC electrons do (not) contain a cluster of energy in the EM layers of the calorimeter. For type-2 IC electrons the momentum is determined from the calorimeter energy, whereas for type-1 IC electrons, we rely on the central track, which provides a relatively poor momentum resolution.

Loose muons are required to have a track segment that has wire and scintillator hits in at least one layer of the muon spectrometer and a spatially matched track in the central detector. Loose muons must also satisfy a calorimeter isolation requirement of $T_{\text{cal}}^{\text{mono}}/p_T < 0.4$, where $T_{\text{cal}}^{\text{mono}}$ is the scalar sum of transverse energies of all calorimeter cells within an annulus of radius $0.1 < \Delta R < 0.4$ around the candidate muon. A track isolation requirement, $T_{\text{trk}}^{\text{mono}}/p_T < 0.4$, is also imposed on loose muons, where $T_{\text{trk}}^{\text{mono}}$ is the scalar $p_T$ sum of
all tracks within a cone of radius $\Delta R < 0.5$ relative to the candidate muon. Medium(tight) muons must satisfy $T^{\mu \text{muon}}_{\text{cal}}/p_T < 0.2(0.1)$ and $T^{\mu \text{muon}}_{\text{trk}}/p_T < 0.2(0.1)$.

The number of events that pass an inclusive dilepton selection is used as the denominator for the purposes of measuring the ratio of $WZ$ and $ZZ$ cross sections to the $Z$ cross section. The $WZ$ dilepton selection requires two opposite charge medium quality leptons of the same flavor. Hard and soft electron(muon) $p_T$ requirements are defined as $p_T > 20(15)$ GeV and $p_T > 15(10)$ GeV, respectively. IC electrons are considered only if they satisfy $p_T > 20$ GeV. The $\ell^+\ell^-$ and $\mu^+\mu^-$ channels require that both leptons satisfy the appropriate soft $p_T$ requirement, and that at least one lepton satisfies the appropriate hard $p_T$ requirement.

The $ZZ$ dilepton selection requires tight rather than medium leptons, and also includes the $e^\pm\mu^\mp$ control channel. The lepton $p_T$ requirements are the same as in the $WZ$ analysis. Since a reliable energy/momentum measurement is needed to suppress background from misreconstructed $Z \rightarrow \ell^+\ell^-$ events, type-1 IC electrons are excluded. In the $e^\pm\mu^\mp$ channel, electrons are considered only in the CC and EC regions. Figure 1 compares the $M_{\ell\ell}$ distribution in data and simulation (described in Section IV) after the $ZZ$ dilepton selection, prior to any additional requirements. The data are well described by the simulation apart from the region of large $M_{\ell\ell}$ in the dielectron channel where the simulation yields more events than the data due to a mis-modelling of the resolution tails. This is shown not to have a significant effect on the analysis.

The $Z \rightarrow \ell^+\ell^-$ selections used as denominators in the cross section ratio measurements include some further requirements that are detailed in Sections V and VII.

IV. PREDICTION FOR BACKGROUND AND SIGNAL

Background yields are estimated using a combination of control data samples and MC simulation. The signal processes and certain backgrounds ($WW \rightarrow \ell^+\ell^-\nu\bar{\nu}$, $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$, $Z \rightarrow \ell^+\ell^-$, $tt \rightarrow \ell^+\ell^-\nu\bar{\nu}bb$, $Z\gamma \rightarrow \ell^+\ell^-\gamma$ and $W\gamma \rightarrow \ell\nu_\gamma$) are estimated based on simulations using the PYTHIA 20 event generator and leading order CTEQ6L1 21 parton distribution functions (PDF). Events are passed through a GEANT 22 based simulation of the D0 detector response. In addition, randomly triggered bunch crossings from data are added to the simulated events to model the effect of additional $p\bar{p}$ collisions. The GEANT based simulation does not include efficiency of the trigger. Instead, the efficiencies of certain triggers (single-electron and single-muon) are measured using $Z \rightarrow \ell^+\ell^-$ candidate events from data. A parameterization of these efficiencies is applied to the simulated events, with a correction determined from data for the additional efficiency that is gained from the remaining triggers (mostly dilepton and lepton-plus-jet triggers). The MC simulation does not accurately describe the dilepton $p_T$ distribution in $Z$ production. Weights are therefore assigned to the simulated events as a function of their generated dilepton $p_T$, based on a comparison with more accurate predictions from RESBOS 23. The diboson events are similarly corrected as a function of diboson $p_T$ to match predictions from the next-to-leading order (NLO) event generator POWHEG 24 22. The simulation of $WZ$ production by PYTHIA does not include diagrams with $\gamma^* \rightarrow \ell^+\ell^-$. Weights are assigned to the generated events based on comparison of the $Z \rightarrow \ell^+\ell^-$ invariant mass distribution with POWHEG, which does include these diagrams. The simulated events are further corrected for inaccuracies in reconstruction efficiency and energy/momentum resolution for leptons. The MC predictions are normalized to match the observed event yield after the inclusive dilepton selection, such that knowledge of the integrated luminosity is not required.

Instrumental backgrounds arise from the misreconstruction of hadronic jets as isolated electron and muon candidates. These backgrounds are estimated from data using the so-called “Matrix Method” 26, since their rates cannot be modelled sufficiently well by the MC. We select a sample of events in which a high $p_T$ jet satisfies the trigger conditions for the event and is back-to-back in $\phi$ with an electron or muon that satisfies the loose requirements. We measure the efficiency ($\epsilon_{\text{jet}}$) for a jet that is mis-reconstructed as a loose lepton to also satisfy the medium or tight lepton requirements. The equivalent efficiency for genuine electrons and muons ($\epsilon_{\text{sig}}$) is measured in a sample of $Z \rightarrow \ell^+\ell^-$ candidate events. The $Z$+jets background in the $WZ \rightarrow \ell\nu\ell^+\ell^-$ sample is estimated by selecting a sample of events in which the lepton assigned to the $W \rightarrow \ell\nu$ decay is of loose rather than tight quality. Given the estimates of $\epsilon_{\text{sig}}$ and $\epsilon_{\text{jet}}$, we solve a set of simultaneous equations to estimate the amount of background in the tight sample. A sample of $Z$+jets events generated with PYTHIA is normalized to the estimate from data. The $W$+jets background in the $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ sample is estimated in a similar way, with a sample of MC events normalized to an estimate from data. In the inclusive dilepton sample, there is a small background from multijet events in the $e^+e^-$ channel. This background is estimated by fitting the observed $M_{\ell\ell}$ distribution with the sum of simulated contributions and a multijet template that is obtained by inverting the electron quality cuts in real data.

V. SELECTION OF WZ CANDIDATES

Four channels are considered for $WZ$ decay: $e^+e^-\ell\pm$, $\mu^+\mu^-\ell\pm$, $\mu^+\mu^-e\pm$, $\mu^+\mu^-\mu\pm$. Events must contain two oppositely charged medium quality leptons satisfying the $p_T$ requirements described earlier and with $M_{\ell\ell}$ between 60 and 120 GeV. The selection of $WZ$ candidates further requires an additional electron (CC or EC) or muon.
with $p_T > 15$ GeV, and tight quality. This lepton must originate from a common vertex with the lepton pair that is assigned to the $Z \to \ell^+\ell^-$ decay. If there are three like flavor leptons, there are two possible combinations of opposite charge leptons. In this case, the pair with smallest $|M_{\ell\ell} - m_Z|$, where $m_Z$ is the Z boson mass [27], is assigned to the $Z \to \ell^+\ell^-$ decay. Simulation shows that this assignment is correct in 93% of cases in the three electron channel, and 87% of cases in the three muon channel. In order to suppress the contribution from $ZZ \to \ell^+\ell^-\ell^+\ell^-$ decays, no additional reconstructed muons for the $\ell^+\ell^-\mu^\mp$ selection are allowed for the $\ell^+\ell^-\mu^\pm$ selection. The additional EM clusters must satisfy $E_T > 5$ GeV. Clusters that are not matched to a central track must satisfy loose shower shape requirements. There are no explicit $p_T$ or isolation requirements imposed on the additional muons. Events that satisfy these requirements, excluding the requirement of a third lepton, are considered as $Z$ candidates, to be used in the denominator when measuring the ratio of $WZ$ and $Z$ cross sections. We choose to include a veto on more than two leptons in the $Z$ selection, such that uncertainties in the veto efficiency are mostly cancelled in the ratio of $WZ$ to $Z$ cross sections.

The $WZ$ events are characterised by large missing transverse energy, $E_T$, defined as the magnitude of a vector sum of the transverse energies of cells in the calorimeter. The $E_T$ is corrected for muons, which only deposit a small fraction of their energy in the calorimeter, and for the energy loss of electrons. The variable $E_T'$ is defined by recalculating the $E_T$ after rescaling the transverse momenta of the leptons that are assigned to be $Z$ daughters within 3 standard deviations of their resolution $\sigma(p_T^i)$, through a fit that minimises the $\chi^2$ function:

$$\chi^2 = \left(\frac{M_{\ell\ell} - m_Z}{\Gamma_Z}\right)^2 + \left(\frac{\delta p_T^1}{\sigma(p_T^1)}\right)^2 + \left(\frac{\delta p_T^2}{\sigma(p_T^2)}\right)^2,$$

where $\Gamma_Z$ is the total width of the $Z$ boson [27], and $\delta p_T^i$ is the amount by which the $p_T$ of lepton $i$ is shifted. This kinematic constraint is only used for the purposes of calculating the variable $E_T'$. The requirement of $E_T' > 20$ GeV is imposed in order to reject $Z$+jets and $Z\gamma$ backgrounds. A background to the sub-channels with a $W \to \ell\nu$ decay is the radiation of a high $p_T$ photon from a lepton in a $Z \to \ell^+\ell^-$ decay. We therefore require that $|M_{\ell\ell\ell} - 91.2| > |M_{\ell\ell} - 91.2|$, where $M_{\ell\ell\ell}$ is the invariant mass of the three leptons. In addition, at least one of the leptons from the $Z \to \ell^+\ell^-$ decay is required to have $p_T > 25$ GeV.

Tables [I] and [II] list the observed and predicted event yields after all $WZ$ selection requirements. The yields are also listed for the samples that exclusively fail the $E_T$ or $M_{\ell\ell}$ requirements, but satisfy all other requirements. Figure [2] shows the $E_T$, $M_{\ell\ell}$, and $M_W^T$ distributions for $WZ \to \ell\ell\ell\nu$ candidate events, before imposing the requirement on each variable. The transverse mass is defined as $M_W^T = \sqrt{2p_T E_T(1 - \cos \Delta\phi)}$, with $p_T$ being the transverse momentum of the charged lepton that is assigned as the $W$ daughter, and $\Delta\phi$ being the azimuthal angle between this lepton and the $E_T$ vector. Figure [3] shows the distributions of various kinematic quantities after combining the four sub-channels.

**VI. Missing Transverse Momentum Estimators**

The basic signature for the $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ analysis is a pair of charged leptons with invariant mass close to $m_Z$, produced in association with significant imbalance in transverse momentum, $p_T$, due to the neutrinos from the $Z \to \nu\bar{\nu}$ decay. A substantial background corresponds to inclusive $Z \to \ell^+\ell^-$ production in which either the leptons and/or any hadronic recoil is mis-reconstructed. Stringent selection requirements are necessary to suppress this background, since (i) the production cross sec-
TABLE I: $WZ \to \ell\ell \ell\ell^-$ selection: Predicted and observed yields in the $Z \to e^+e^-$ sub-channels. The systematic uncertainties are provided for the predictions.

<table>
<thead>
<tr>
<th>Process</th>
<th>Accepted</th>
<th>fail $E_T$</th>
<th>fail $M_{\ell\ell}$</th>
<th>Predicted</th>
<th>fail $E_T$</th>
<th>fail $M_{\ell\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to \ell^+\ell^-$</td>
<td>0.3 ± 0.1</td>
<td>9 ± 1</td>
<td>0.0 ± 0.0</td>
<td>3 ± 1</td>
<td>7 ± 2</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>$Z\gamma \to \ell^+\ell^-\gamma$</td>
<td>0.6 ± 0.2</td>
<td>10.1 ± 0.6</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.2 ± 0.0</td>
</tr>
<tr>
<td>$ZZ \to \ell^+\ell^- \ell^+\ell^-$</td>
<td>0.6 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>0.0 ± 0.0</td>
<td>1.5 ± 0.0</td>
<td>0.7 ± 0.0</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>$t\bar{t} \to \ell^+\ell^- \nu\bar{\nu}$</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$ZZ \to \ell^+\ell^- \nu\bar{\nu}$</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$WW \to \ell^+\ell^- \bar{\nu}\nu$</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
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</tr>
<tr>
<td>Predicted background</td>
<td>1.5 ± 0.4</td>
<td>20 ± 1</td>
<td>0.1 ± 0.0</td>
<td>5 ± 1</td>
<td>7 ± 2</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>$WZ \to \ell\ell\ell\ell^-$</td>
<td>9.9 ± 0.2</td>
<td>1.7 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>13.9 ± 0.3</td>
<td>2.2 ± 0.1</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>Predicted total</td>
<td>11.4 ± 0.4</td>
<td>21 ± 1</td>
<td>0.2 ± 0.1</td>
<td>19 ± 1</td>
<td>9 ± 2</td>
<td>0.8 ± 0.2</td>
</tr>
</tbody>
</table>

TABLE II: $WZ \to \ell\ell\ell\ell^-$ selection: Predicted and observed yields in the $Z \to \mu^+\mu^-$ sub-channels. The systematic uncertainties are provided for the predictions.

<table>
<thead>
<tr>
<th>Process</th>
<th>Accepted</th>
<th>fail $E_T$</th>
<th>fail $M_{\ell\ell}$</th>
<th>Predicted</th>
<th>fail $E_T$</th>
<th>fail $M_{\ell\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to \ell^+\ell^-$</td>
<td>1.5 ± 0.4</td>
<td>12 ± 2</td>
<td>0.5 ± 0.2</td>
<td>4 ± 2</td>
<td>3 ± 1</td>
<td>0.1 ± 0.5</td>
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<tr>
<td>$Z\gamma \to \ell^+\ell^-\gamma$</td>
<td>1.6 ± 0.4</td>
<td>13.0 ± 0.5</td>
<td>0.3 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$ZZ \to \ell^+\ell^- \ell^+\ell^-$</td>
<td>0.9 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>0.1 ± 0.0</td>
<td>1.6 ± 0.0</td>
<td>0.7 ± 0.0</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>$t\bar{t} \to \ell^+\ell^- \nu\bar{\nu}$</td>
<td>0.3 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$ZZ \to \ell^+\ell^- \nu\bar{\nu}$</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
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<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$WW \to \ell^+\ell^- \bar{\nu}\nu$</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Predicted background</td>
<td>4.3 ± 0.8</td>
<td>26 ± 2</td>
<td>1.0 ± 0.3</td>
<td>6 ± 2</td>
<td>4 ± 1</td>
<td>0.2 ± 0.5</td>
</tr>
<tr>
<td>$WZ \to \ell\ell\ell\ell^-$</td>
<td>14.0 ± 0.2</td>
<td>2.1 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>15.1 ± 0.4</td>
<td>2.0 ± 0.1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Predicted total</td>
<td>18.3 ± 0.8</td>
<td>29 ± 2</td>
<td>1.9 ± 0.4</td>
<td>21 ± 2</td>
<td>6 ± 1</td>
<td>0.5 ± 0.6</td>
</tr>
<tr>
<td>Observed</td>
<td>26</td>
<td>23</td>
<td>3</td>
<td>25</td>
<td>12</td>
<td>5</td>
</tr>
</tbody>
</table>

The terms, $p_T^{\ell\ell}$, $p_T^{\text{recoil}}$, and $p_T^{\text{trkjets}}$ (and similarly for $a_T^{\ell\ell}$ and $a_T^{\ell\ell}$) are corrections for lepton $p_T$ mis-measurement, hadronic recoil measured in the calorimeter, and remaining hadronic recoil measured in the tracking system, respectively. These terms are described in more detail in the following sections. The factor of two is found to be optimal based on MC simulations.
A. Dilepton mis-measurement

A correction for possible lepton $p_T$ mis-measurement is determined by varying each individual lepton $p_T$ within one standard deviation of its estimated uncertainty in order to separately minimise $a^{e+e-}_L$, $a^{e+e-}_L$ and $p^{e+e-}_T$. Electrons that are reconstructed close to module boundaries in the CC or in the IC have relatively poor energy resolution and are given special treatment. The estimated uncertainty may be inflated to cover the difference between the calorimeter based $p_T$ measurement and the alternative measurement from the central track. This is only
FIG. 3: Kinematic distributions for the $WZ \rightarrow \ell \ell \ell$ signal candidates after combining the different sub-channels. The following variables are shown: (a) the $E_T'$; (b) the invariant mass of the $Z \rightarrow \ell^+ \ell^-$ decay; (c) the $W$ transverse mass; the transverse momenta of the (d) leading and (e) subleading leptons from the $Z \rightarrow \ell^+ \ell^-$ decay and (f) the charged lepton from the $W$ decay; the transverse momenta of the reconstructed (g) $Z \rightarrow \ell^+ \ell^-$ and (h) $W \rightarrow l\nu$ decays. The vertical dashed lines indicate the requirements on $E_T'$ and $M_{\ell\ell}$. The signal normalization is as described in Section IV.

FIG. 4: Illustration of the decomposition of the dilepton $p_T$ into $a_T$ and $a_L$ components.
are calculated for each jet in the event, e.g.,

$$a_T^{\text{jet}(i)} = \vec{p}_T^{\text{jet}(i)} \times \hat{t},$$

(8)

where $\vec{p}_T^{\text{jet}(i)}$ is the $p_T$ vector of the $i$th jet. An individual jet that has a positive value (i.e., increases the momentum imbalance) is ignored. This approach ensures that jets which are not genuinely associated with the recoil system (e.g., from additional $p\bar{p}$ collisions or the underlying event) are not allowed to generate a fake imbalance in an otherwise well reconstructed event. The sum of contributions from the jets is denoted, e.g., for the $a_T$ component, $a_T^{\text{jets}}$.

The $E_T$ estimate subtracts any contribution from the two leptons and then tests how well the remaining $E_T$ balances the dilepton system. Between the jet and $E_T$ based corrections we choose (separately for the $a_T$, $a_L$ and $p_T$ components) the one that best balances the dilepton system. This correction term is denoted, e.g., $E_T^{\text{recoil}}$.

C. Track recoil

As a protection against events in which at least one hadronic jet fails to be reconstructed in the calorimeter, we attempt to recover any remaining activity in the tracker. Track jets are reconstructed by merging together reconstructed tracks within cones of size $\Delta R = 0.5$. These tracks must satisfy $p_T > 1$ GeV. Track jets must have at least two tracks within the cone, and be separated by at least $\Delta R = 0.3$ from the leptons, and by at least $\Delta R = 0.5$ from any calorimeter jets. Corrections to each of the ($p_T$, $a_T$, and $a_L$) components are determined in the same way as for calorimeter jets.

D. Performance

Figure 5 shows the $Z \to \ell^+\ell^-$ background efficiency versus the $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ signal efficiency for a range of requirements on each of the variables: $p_T'$, $\phi_L'$, $\phi_T'$, and $E_T'$. The decays of $Z \to \tau^+\tau^-$ into $e^+e^-$, $\mu^+\mu^-$, and $e^+\mu^\pm$ final states produce a genuine missing $p_T$ along the $a_L$ direction. Our $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ candidate selection requirements therefore include a “soft” requirement of $p_T' > 5$ GeV. The curves in Fig. 5 correspond to the combination of this requirement and a varying requirement on the variable under study. The $p_T'$ variable has the best performance over the range of background efficiencies of interest. The efficiency for the requirement $p_T' > 30$ GeV (and $p_T' > 5$ GeV) is indicated explicitly by a star symbol. This is the requirement that is made in selecting $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ candidates. The optimisation of the $p_T'$ requirement is discussed later.

VII. SELECTION OF ZZ CANDIDATES

Decays of $ZZ$ into the following final states are considered: $e^+e^-, \mu^+\mu^-$. Events must contain two oppositely charged tight quality leptons satisfying the $p_T$ requirements described earlier and with $M_{\ell\ell}$ between 60 and 120 GeV. To reject events in which the missing transverse momentum estimators defined in Section VII are poorly reconstructed, we require that there are no more than two jets with $p_T > 15$ GeV and separated by at least $\Delta R = 0.3$ from the leptons. In order to reject $WZ \to t\nu\ell^+\ell^-$ and $ZZ \to \ell^+\ell^-\ell^+\ell^-$ events, there must be no additional EM clusters or muons according to the criteria in Section VII. In addition, there must be no isolated tracks or hadronic taus with $p_T > 5$ GeV. This requirement is not necessary in the $WZ$ analysis.
for which the $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ background is less significant. These four types of objects are only considered if they are separated by at least $\Delta R = 0.3$ from the leptons. The jet and additional lepton vetoes are also effective in suppressing the background from $t\bar{t} \rightarrow \ell^+\ell^-\nu\bar{\nu}b\bar{b}$ decays. The number of events that satisfy these requirements is used as the denominator in the measurement of the $ZZ/Z$ cross section ratio. Including the jet and lepton vetoes in the $Z$ selection helps to reduce the impact of uncertainties in the corresponding efficiencies.

Events are considered as $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ candidates if they further satisfy $p_T' > 5$ GeV (to reject $Z \rightarrow \ell^+\ell^-$) and $y_T' > 30$ GeV (to reject $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$). Tables VI and VII list the sources of systematic uncertainty on the measured dilepton invariant mass. The following sources of systematic uncertainty are considered.

- **Beam conditions**
  The differential distributions of the instantaneous luminosity and vertex $z$ position are varied to cover any disagreement with the data.

- **Physics modelling**
  The value of the $g_2$ parameter in RESBOS is varied when determining the corrections that are applied to the simulated $Z \rightarrow \ell^+\ell^-$ events. This is a model parameter that describes the intrinsic transverse momentum of the partons within the colliding hadrons. As a test of sensitivity to the diboson $p_T$ modelling, the reweighting in this variable is switched off.

- **Jet reconstruction**
  The jet energy scale, resolution, and reconstruction efficiencies are varied within their uncertainties. The simulation requires additional corrections to the energy response for jets in the IC region. An additional systematic uncertainty is assigned to these corrections. The track jet reconstruction efficiency is also varied to cover an observed disagreement with the data.

- **Lepton momentum scale and resolution**
  The lepton momentum scales and resolutions are varied within their uncertainties, as are the reconstruction and identification efficiencies. Non-Gaussian tails in the lepton momentum resolution are also considered.

- **Instrumental backgrounds**
  The $W+$jets and $Z+$jets background normalizations are varied within the uncertainties of the estimate from data. All other variations on the simulation (e.g., lepton momentum scales and resolutions) are allowed to vary the shape of these backgrounds. Since PYTHIA does not include the matrix element for wide angle photon emission in $W\gamma$ production, the normalization of this process is varied by a factor of two, which is considered to be an overestimate but introduces no significant uncertainty on the $ZZ$ cross section measurement.

- **Trigger efficiencies**
  The trigger efficiencies are estimated to introduce a negligible uncertainty into the cross section measurements.
FIG. 6: (a-c) The $p_T'$ distribution of the $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ candidate events before imposing the $p_T'$ requirement. (d-f) The $M_{ll}$ distribution of the $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ candidate events before imposing the $M_{ll}$ requirement. (g-i) The neural network output distribution of the accepted $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ candidate events. For the $e^+\mu^-$ channel, the neural network trained in the $e^+e^-$ channel is shown. The vertical dashed lines indicate the requirements on $p_T'$ and $M_{ll}$. The signal normalization is as described in Section IV.

TABLE III: Table of predicted signal and background yields for the $ZZ \to e^+e^-\nu\bar{\nu}$ signal and control regions. The systematic uncertainties are provided for the predictions.

<table>
<thead>
<tr>
<th>Process</th>
<th>Accepted</th>
<th>$p_T'$</th>
<th>Rejected by requirement on</th>
<th>$\ell\ell$</th>
<th>Extra lcp.</th>
<th>Charge</th>
<th>Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>0.6 ± 0.3</td>
<td>11666 ± 1665</td>
<td>0 ± 1</td>
<td>0.3 ± 0.2</td>
<td>3 ± 2</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0.1 ± 0.1</td>
<td>8 ± 2</td>
<td>1.4 ± 0.2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$WW \rightarrow \ell^+\ell^-\ell^+\ell^-$</td>
<td>35 ± 1</td>
<td>35 ± 1</td>
<td>1.7 ± 0.1</td>
<td>0.33 ± 1</td>
<td>9 ± 5</td>
<td>0.3 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$</td>
<td>2.3 ± 0.1</td>
<td>1.9 ± 0.1</td>
<td>0.2 ± 0.0</td>
<td>0.2 ± 0.1</td>
<td>14 ± 2</td>
<td>0.2 ± 0.1</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>6 ± 2</td>
<td>13 ± 2</td>
<td>0.3 ± 0.1</td>
<td>5 ± 1</td>
<td>2 ± 1</td>
<td>4 ± 1</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$W \rightarrow \gamma e\gamma$</td>
<td>3.3 ± 0.3</td>
<td>5.5 ± 0.5</td>
<td>0.0 ± 0.1</td>
<td>2.8 ± 0.5</td>
<td>0.6 ± 0.5</td>
<td>3.3 ± 0.4</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>1.3 ± 0.2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \ell^+\ell^-\nu\bar{b}b$</td>
<td>1.0 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>0.4 ± 0.1</td>
<td>1.2 ± 0.1</td>
<td>7 ± 1</td>
<td>0.0 ± 0.0</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Predicted background</td>
<td>48 ± 2</td>
<td>11749 ± 1668</td>
<td>4 ± 1</td>
<td>43 ± 2</td>
<td>37 ± 11</td>
<td>8 ± 1</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>Predicted total</td>
<td>62 ± 3</td>
<td>11756 ± 1668</td>
<td>6 ± 1</td>
<td>43 ± 2</td>
<td>41 ± 13</td>
<td>8 ± 1</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>Observed</td>
<td>61</td>
<td>10560</td>
<td>12</td>
<td>50</td>
<td>63</td>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>
FIG. 7: Distributions of (a) $\cos(\theta^*)$, (b) $(M_{l\ell} - m_Z)/\sigma(M_{l\ell})$, (c) $E_T$, transverse momenta of the (d) leading and (e) subleading lepton, (f) the azimuthal angle between the leading lepton and the dilepton system $\Delta\phi(l_1, l_\ell)$ for the combination of $ZZ \to e^+e^-\nu\bar{\nu}$ and $ZZ \to \mu^+\mu^-\nu\bar{\nu}$ candidates. The signal normalization is as described in Section IV.

FIG. 8: Variation of the predicted uncertainties on the measured $ZZ$ cross section with the choice of $p'_T$ requirement in the (a) $e^+e^-$ and (b) $\mu^+\mu^-$ channels.

IX. MEASUREMENT OF CROSS SECTIONS

The ratios of the signal ($WZ$ or $ZZ$) cross sections to the inclusive $Z$ cross section are determined as follows:

$$R = \frac{N_{\text{obs}}^{\text{sig}}/(A_{l\ell} \times B_{l\ell} \times \mathcal{L})}{N_{ll}^{\text{obs}}/(A_{ll} \times B_{ll} \times \mathcal{L})},$$

where $\mathcal{L}$ is the integrated luminosity; $B_{l\ell}$ and $B_{ll}$ are the known branching fractions for $Z \to l^+l^-$ and the signal decay, respectively [27]. We choose an acceptance window of $60 < M_{l\ell} < 120$ GeV.

The number of observed signal events, $N_{\text{obs}}^{\text{sig}}$, is determined by allowing the predicted signal yield to float such that the following likelihood function is maximized:

$$L = \prod_{i=0}^{\text{bins}} P(N_i^{\text{obs}}; N_i^{\text{pred}}),$$

where $P$ is the Poisson probability to observe $N_i^{\text{obs}}$ events.
in the $i$th bin, given a prediction of $N_i^{\text{pred}}$. In the WZ analysis, the $M_T$ distribution is used, while the neural network output distribution is used in the $ZZ$ analysis. The 68% C.L. interval on the signal yield is defined by $\delta(\ln L) = 0.5$, with respect to the maximum of $\ln L$.

Table VIII lists, for the six different sub-channels, the ratios of inclusive $Z$ and signal acceptances that are estimated from the simulation. Table IX lists the measured $R$ values. The $p$-values for consistency of the different sub-channels are 54% and 11% for the WZ and $ZZ$ analyses, respectively, evaluated using a $\chi^2$ test. For the combination of respective sub-channels, we measure:

$$R(WZ) = 0.593 \pm 0.080 \text{(stat)} \pm 0.017 \text{(syst)} \times 10^{-3},$$

$$R(ZZ) = 0.216 \pm 0.058 \text{(stat)} \pm 0.017 \text{(syst)} \times 10^{-3}.$$ 

A theoretical calculation of the $Z$ cross section can be used to translate these into signal cross section measurements. The product of the cross section and branching fraction for $Z \to \ell^+\ell^-$ (one lepton flavor) is calculated using a modified version of the next-to-NLO (NNLO) code of Ref. [31] with the MRST2004 NNLO PDFs [32]. Since this code excludes the $\gamma^*$ and $Z/\gamma^*$ interference, a correction factor is determined using PYTHIA and the NLO event generator MC@NLO [33]. For $60 < M_{\ell\ell} < 120$ GeV, the result is,

$$\sigma(p\bar{p} \to Z/\gamma^*) \times B_{\ell\ell} = 255.8^{+5.1}_{-12.0} \text{ pb},$$

where the uncertainties arise from variations in the PDFs and the renormalization and factorization scales, and with $B_{\ell\ell} = 3.3658 \pm 0.0023$ %. [27]. The measured WZ cross section with $60 < M_{\ell\ell} < 120$ GeV is

$$\sigma(p\bar{p} \to WZ) = 4.50 \pm 0.61 \text{(stat)}^{+0.16}_{-0.25} \text{(syst)} \text{ pb}.$$ 

This result is slightly higher than, but still consistent with a prediction of $3.21 \pm 0.19$ pb from the NLO program MCFM [34] with the MSTW2008 NLO PDFs [35], and
setting the renormalization and factorization scales equal to $m_W + m_Z$. The measured $ZZ$ cross section with $60 < M_{ll} < 120$ GeV is

$$\sigma(p\bar{p} \rightarrow ZZ) = 1.64 \pm 0.44^{+0.13}_{-0.12} \text{(stat)} \pm 0.05 \text{(syst)} \text{ pb.}$$

This can be compared to a prediction of $1.30 \pm 0.10$ pb from MCFM. Setting the renormalization and factorization scales equal to $2m_Z$. For comparing to and combining with previous measurements it is more convenient to correct the cross sections for the presence of diagrams involving $\gamma^*$. A correction of $+3.4\%$ is obtained by comparing $ZZ$ cross sections with and without $\gamma^*$ and $Z/\gamma^*$ interference from mcfm [34]. Combining this corrected $ZZ$ cross section with a previous D0 measurement [9] in the $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ channel yields

$$\sigma(p\bar{p} \rightarrow ZZ) = 1.44^{+0.31}_{-0.28} \text{(stat)}^{+0.17}_{-0.19} \text{(syst)} \text{ pb.}$$

X. CONCLUSIONS

We measure the production cross sections for the processes $p\bar{p} \rightarrow WZ \rightarrow \ell\nu\ell^+\ell^-$ and $p\bar{p} \rightarrow ZZ \rightarrow \nu\ell\nu\ell^-$, using 8.6 fb$^{-1}$ of integrated luminosity collected by the D0 experiment at the Fermilab Tevatron collider. For decay channels involving electrons and muons, we observe agreement between the different sub-channels as can be seen in Fig. Combining the sub-channels yields a $WZ$ cross section of $4.50^{+0.63}_{-0.66}$ pb, which is slightly above, but still consistent with a standard model prediction of $3.21 \pm 0.19$ pb. The $ZZ$ cross section is measured to be $1.64 \pm 0.46$ pb, which is also in agreement with a standard model prediction of $1.30 \pm 0.10$ pb. These are the most precise measurements to date of the $WZ$ and $ZZ$ cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Correcting for the contribution from $\gamma^*$ and $Z/\gamma^*$ interference and combining with a previous measurement in the $\ell^+\ell^-\ell^+\ell^-$ channel yields a $ZZ$ cross section of $1.44^{+0.35}_{-0.34}$ pb.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF....
We define \((\Delta \mathcal{R})^2 = (\Delta \phi)^2 + (\Delta \eta)^2\), where \(\Delta \phi\) and \(\Delta \eta\) are the differences between two objects in azimuth and pseudorapidity, respectively.

TABLE IX: Table of \(\mathcal{R}\) values measured for each of the subchannels, where the uncertainties correspond to statistical and systematic components added in quadrature.

<table>
<thead>
<tr>
<th>Sub-channel</th>
<th>(\mathcal{R}(\times 10^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(WZ \rightarrow e \nu e^{-})</td>
<td>(0.70 \pm 0.20)</td>
</tr>
<tr>
<td>(WZ \rightarrow \mu e^{-})</td>
<td>(0.40 \pm 0.14)</td>
</tr>
<tr>
<td>(WZ \rightarrow e \nu \mu^{-})</td>
<td>(0.66 \pm 0.17)</td>
</tr>
<tr>
<td>(WZ \rightarrow \mu \nu \mu^{-})</td>
<td>(0.61 \pm 0.16)</td>
</tr>
<tr>
<td>(ZZ \rightarrow e^{+}e^{-}\nu \bar{\nu})</td>
<td>(0.13 \pm 0.07)</td>
</tr>
<tr>
<td>(ZZ \rightarrow \mu^{+}\mu^{-}\nu \bar{\nu})</td>
<td>(0.33 \pm 0.10)</td>
</tr>
</tbody>
</table>

References:
[10] This cross section is corrected for the \(\gamma^*\) contribution.
[17] Rapidity is defined by \(y = (1/2) \ln[(E - p_z)/(E + p_z)]\), where \(E\) is the energy and \(p_z\) is the momentum component parallel to the proton beam direction. Pseudorapidity is defined by \(\eta = -\ln[\tan(\theta/2)]\), where \(\theta\) is the polar angle measured relative to the center of the detector.
[19] We define \((\Delta \mathcal{R})^2 = (\Delta \phi)^2 + (\Delta \eta)^2\), where \(\Delta \phi\) and \(\Delta \eta\) are the differences between two objects in azimuth and pseudorapidity, respectively.
FIG. 9: Comparison of the measured ZZ and WZ cross sections with SM predictions, and with previous measurements in leptonic final states. The ZZ cross section measured by D0 in the $ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ channel has been corrected to the same dilepton invariant mass range as considered in this analysis.