We describe a search for $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the DØ detector at the Tevatron collider. An integrated luminosity of 2.2 fb$^{-1}$ is used. Using the final state decay $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ (where $\ell$ are either electrons or muons) we observe a signal with a $+2.4\sigma$ significance ($+1.8\sigma$ expected) and measure a cross section $\sigma(p\bar{p} \rightarrow ZZ) = 2.1 \pm 1.1(\text{stat.}) \pm 0.4(\text{sys.})$ pb.
I. INTRODUCTION

We perform a search for $Z$ boson pair production in $p\bar{p}$ collisions in the decay channel where one $Z$ decays into two charged leptons (either electrons or muons) and the other $Z$ decays into two neutrinos (see Fig. 1). At the Tevatron, aside from associated production of the Higgs boson, $ZZ$ production is the diboson process with the lowest cross section and is the last remaining unobserved diboson process. Unlike other diboson processes, there are no standard model triple boson couplings involving two $Z$'s. Additionally, this process forms an irreducible background to Higgs searches in the $ZH$ channel. The data for this analysis was collected at the D detector at the Fermilab Tevatron collider, at a center-of-mass energy $\sqrt{s} = 1.96$ TeV. An integrated luminosity of $2.2$ fb$^{-1}$ is used. The D collaboration has a previous search for the reaction $p\bar{p} \rightarrow ZZ \rightarrow \ell\ell\ell'$ with $\ell, \ell' = e$ or $\mu$ [1]. The CDF collaboration has recently produced a result using both the $\ell\ell\ell'$ and the $\ell\ell\nu\nu$ channels [2].

![FIG. 1: Leading order Feynman diagram for the process $ZZ \rightarrow \ell\ell\nu\nu$](image)

II. THE D DETECTOR

The D detector has a central-tracking system, consisting of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet [3], with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively. Central and forward preshower detectors are positioned just outside of the superconducting coil. 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 [4]. An outer muon system, covering $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers after the toroids [5]. Luminosity is measured using plastic scintillator arrays placed in front of the EC cryostats. The trigger and data acquisition systems are designed to accommodate the high luminosities of Run II.

III. EVENT SELECTION

A. Preselection

Data is selected using an OR of all single electron or all single muon triggers for the di-electron and di-muon channels respectively. The selection criteria for di-electron events require two electromagnetic (EM) clusters in the calorimeter which pass requirements on shower shape and have a high fraction of the energy deposited in the EM layers. These electrons must both have transverse momentum $p_T > 15.0$ GeV and pass tight cuts on isolation and on a seven parameter multivariate discriminator which compares the energy deposited in each layer of the calorimeter and the total shower energy to average distributions. Electrons must be within the central or forward calorimeter regions of $|\eta| < 1.1$ and $1.5 < |\eta| < 2.5$ respectively.

Di-muon events require two muons reconstructed from scintillator and wire hits in the muon system with a central track match. Muons are required to have $p_T > 15.0$ GeV and must have an associated track with at least one hit in the Silicon Microstrip Tracker (SMT). A distance of closest approach of $< 0.02$ cm is required for the track. Additional calorimeter isolation requirements are made using the scaled calorimeter halo, defined as $|\Sigma^{\text{cells}}E_T/p_T(\mu)|$ in the annulus $0.1 < \Delta R < 0.4$ and the scaled track halo, defined as $|\Sigma^{\text{tracks}}p_T/p_T(\mu)|$ in the cone $\Delta R < 0.5$.

Events must have exactly two charged leptons with a dilepton mass $70 < M_{ll} < 110$ GeV.
In order to optimize the determination of the missing momentum in $Z$ boson pair events and suppress certain sources of background events (such as $WZ$ and $t\bar{t}$), additional vetoes discussed below are applied.

**B. Veto on additional charged leptons**

The presence of additional charged leptons other than those from the charged leptonic $Z$ decay is vetoed by looking for soft, non-isolated or poorly reconstructed objects which did not satisfy the tight lepton requirements described above. The following classes of events are therefore discarded:

- Events with one or more extra isolated EM clusters, with transverse energy $E_T > 5$ GeV with $\Delta R > 0.2$ from both of the tight leptons and either a central track match or a requirement on the shower shape.
- Events with additional muons satisfying looser quality criteria, with $\Delta R > 0.2$ from both of the tight leptons.
- Events with reconstructed multi-prong hadronic tau leptons identified using the standard DØ algorithms [6] and with $\Delta R > 0.2$ from both of the tight leptons.
- Events with isolated tracks with $p_T > 5$ GeV and $\Delta z$ (primary vertex) < 1 cm and with $\Delta R > 0.2$ from both of the tight leptons.

**C. Veto on jet activity**

Events with relatively low calorimeter activity are selected by vetoing on the presence of more than two jets in the detector. Jets used in the veto are reconstructed using a cone algorithm with $\Delta R < 0.5$ and must satisfy $\Delta R$ (jet, lepton) > 0.3 and jet $E_T > 10$ GeV.

**IV. SELECTION OF EVENTS WITH SIGNIFICANT MISSING TRANSVERSE MOMENTUM**

The basic aim of this analysis is to select events containing a high mass pair of charged leptons (from the decay of one $Z$) produced in association with significant missing $p_T$. A potential source of very substantial background to this signature is inclusive $Z$ production in which a fake missing $p_T$ is reconstructed. Fake missing $p_T$ can arise from a mismeasurement of the $p_T$ of the individual charged leptons or a mismeasurement of the hadronic recoil in such events. Because the relevant cross section times branching ratios differ by a factor of more than 13000, very stringent selection criteria against inclusive $Z$ production are required. All previous searches at DØ for the di-lepton plus missing $p_T$ final state have excluded events in which the mass of the pair of charged leptons is close to the $Z$ mass. Clearly, such a cut is not appropriate in the search for $ZZ$ events.

We present below a novel approach to this challenge, which is outlined in the following two paragraphs. In particular, we do not attempt to make an unbiased or accurate estimate of the missing $p_T$ in the candidate events. Rather our approach is to examine each event and ask the question “Is it conceivable that the missing $p_T$ could have been caused by a mismeasurement of the $p_T$ of the individual charged leptons or a mismeasurement of the hadronic recoil?” Only if the answer to this question is negative is an event accepted as a candidate. This approach is inspired by that employed in searches at OPAL for the anomalous production of events containing a pair of charged leptons and missing $p_T$ [7].

The principal discriminating variable $E_T^d$ is defined below with this approach in mind. In order to minimize the sensitivity to mismeasurement of the $p_T$ of the individual leptons, the net $p_T$ of the lepton pair is decomposed into two components, one of which is almost insensitive to lepton $p_T$ resolution for moderate boosts. The decomposition is performed only for events in which $\Delta \phi^{d\text{-lept}}>\pi/2$, where $\Delta \phi^{d\text{-lept}}$ is the angle between the two charged leptons in the transverse plane. For the case $\Delta \phi^{d\text{-lept}} < \pi/2$, the single variable $p_T^{d\text{-lept}}$, the net $p_T$ of the lepton pair, is used instead. In addition, the charged lepton transverse momenta are varied within two standard deviations of their measurement uncertainties so as to minimize the two components of the di-lepton $p_T$. In this process particular care is taken in cases where the measurement uncertainties calculated in the event reconstruction may not be reliable. $E_T^d$ is formed by a weighted quadrature sum of the two $p_T$ components, giving greater weight to the component that is less sensitive to mismeasurements.

The next step in the process is to examine any visible additional activity in the event in order to assess whether or not it might conceivably account for the apparent di-lepton $p_T$ as calculated above. An essential element of this process is to consider jets only if their $p_T$ is in the direction opposite to that of the di-lepton system. In this way we try to minimize the possibility that a well-balanced event acquires an apparently significant net missing momentum...
due to calorimeter noise or a jet with a grossly overestimated energy. The particularly low threshold on jets of $E_T > 10$ GeV, together with the fact that no quality requirements are imposed on the selected jets is important; ignoring such activity might otherwise generate a fake imbalance in $p_T$. In order to catch inclusive $Z$ events in which recoiling hadronic activity is observed, but is not reconstructed into jets we also consider the net $p_T$ of the entire calorimeter activity in the event (excluding the leptons). However, it is not unlikely for the energy of a recoiling hadronic system to be significantly underestimated in the calorimeter. We conservatively allow for the possibility that only 50% of the actual recoiling energy is measured by multiplying the $p_T$ of the recoil system by a factor of two when considering whether or not it balances the di-lepton $p_T$. In order to catch events in which the recoil activity is not observed in the calorimeter we then take into account track jets if their $p_T$ is in the opposite direction to that of the di-lepton system. Only tracks that are $\Delta R > 0.5$ away from any calorimeter jets contribute to building these track jets.

Having given an overview of the strategy we now describe the specific procedures used to calculate the discriminating variable $E_T'$. In order to minimize the sensitivity to mismeasurement of the $p_T$ of the individual leptons the following approach is taken. For events with $\Delta \phi > \frac{\pi}{2}$ the net $p_T$ of the lepton pair ($p_{di-lept}^T$) is decomposed into two components, one of which ($a_{di-lept}^t$) is almost insensitive to lepton $p_T$ resolution and the other of which ($a_{di-lept}^l$) is highly sensitive to lepton $p_T$ resolution. This decomposition is achieved as follows. In the transverse plane a di-lepton thrust axis is defined (see Fig. 2). This is the axis which maximizes the scalar sum of the longitudinal components of the $p_T$ of the two leptons. Its direction is found as follows:

$$\vec{t} = \vec{p}_1^T - \vec{p}_2^T ,$$

where $\vec{p}_1^T$ and $\vec{p}_2^T$ are the transverse momenta of the leading and trailing leptons respectively. This axis is used to decompose $p_{di-lept}^T$ into transverse ($a_{di-lept}^t$) and longitudinal ($a_{di-lept}^l$) components.

In order further to reduce the sensitivity to mismeasurement of the $p_T$ of the individual leptons an additional step is performed. Treating separately the two components $a_{di-lept}^t$ and $a_{di-lept}^l$, the individual transverse momenta of the two leptons are fluctuated independently by up to two standard deviations of their measurement uncertainty such as to minimize the magnitudes of $a_{di-lept}^t$ and $a_{di-lept}^l$. The maximum effect of these fluctuations in the direction of reducing the momentum imbalance determines a correction $\delta p_T$. Although cleanly identified, electrons reconstructed in regions of the central calorimeter close to module boundaries have a non-zero probability to have significantly underestimated energies. If the lower $E_T$ electron is in a module boundary, $a_{di-lept}^l$ is effectively set to

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**FIG. 2:** Simple representation of the transverse plane of the event and of the decomposition of the di-lepton $p_T$ along the di-lepton thrust axis.
FIG. 3: Corrected momentum imbalance $\hat{E}_T$ for the di-electron (left) and di-muon (right) final states.

zero by significantly increasing the uncertainty.

Additional activity in the event (i.e., activity not associated with either of the leptons) is taken into account in correcting $a_{\mathrm{di-lept}}^t$ and/or $a_{\mathrm{di-lept}}^l$ only if it is recoiling against the di-lepton system. Two types of recoil activity are taken in consideration: calorimeter and tracking recoil activity.

The calorimeter recoil activity is defined as:

\[ a_{\mathrm{recoil}}^t = 2 \min(a_{\mathrm{total \ recoil}}^t, a_{\mathrm{jets}}^t), \]

\[ a_{\mathrm{recoil}}^l = 2 \min(a_{\mathrm{total \ recoil}}^l, a_{\mathrm{jets}}^l). \]

where both jet transverse momenta and the total recoil against the lepton pair are decomposed with respect to the thrust axis into transverse and longitudinal components. As discussed above, the factor of 2 conservatively allows for the possibility that only 50% of the actual recoiling energy is measured.

Note on sign conventions: since the direction of the thrust axis is chosen such that $a_{\mathrm{di-lept}}^t$ and $a_{\mathrm{di-lept}}^l$ are positive definite and only jets recoiling against the di-lepton system are taken into account, $a_{\mathrm{jets}}^t$ and $a_{\mathrm{jets}}^l$ must be less than or equal to zero.

The track recoil activity is defined in a similar way to the calorimeter recoil activity but it uses track jets recoiling against the lepton pair. The amount by which this recoil can reduce the momentum imbalance is used to determine a correction $\delta_{\mathrm{trackjets}}$.

We correct for the calorimeter and track recoil activity against the di-lepton momentum considering the two components separately:

\[ \hat{E}_T = a_{\mathrm{di-lept}}^t + a_{\mathrm{recoil}}^t, \]

\[ \hat{E}_L = a_{\mathrm{di-lept}}^l + a_{\mathrm{recoil}}^l. \]

The final corrected momentum imbalance is:

\[ \hat{E}_{T\ell} = \sqrt{\hat{E}_T^2 + (1.5\hat{E}_L)^2 - \delta_m - \delta_{\mathrm{trackjets}}}. \]

The factor of 1.5 is included to give more weight to the component less sensitive to lepton momentum uncertainties. The distribution of this corrected momentum imbalance is shown in Fig. 3 for the two final states.

When $\Delta \phi < \frac{\pi}{2}$ the decomposition into $a_{\mathrm{di-lept}}^t$ and $a_{\mathrm{di-lept}}^l$ makes no sense and the single variable $p_T^{\mathrm{di-lept}}$ is used in each of the above steps to calculate $\hat{E}_T$. In order to reject the background from inclusive $Z$ production, a cut on $\hat{E}_T$ is applied requiring $\hat{E}_T > 30$ GeV in the di-electron channel and $\hat{E}_T > 35$ GeV in the di-muon one. Fig. 3 indicates that very few $Z \rightarrow ll$ events survive these cuts and that the simulation models the data well.
V. BACKGROUND ESTIMATES

In order to study the various backgrounds, as well as the modelling of the signal, Monte Carlo samples are used. The samples were generated using Pythia[8], except for $W+$jets, which uses Alpgen[9] for generation and Pythia for fragmentation. The $Z$ $p_T$ spectrum of the $Z$ inclusive Monte Carlo is reweighted to match the data and a muon and electron momentum smearing are applied to all Monte Carlo samples to match the $p_T$ resolution observed in data. All background and signal samples, except for $W+$jets, are normalized to the luminosity of the data. The matrix inversion method described below is used to normalize the $W+$jets to the predicted QCD background contribution.

A. Instrumental backgrounds

The techniques used to reduce the backgrounds arising from a mis-measurement of the missing transverse momentum in $Z$ events have been described in detail in the previous section. Here we discuss backgrounds that arise from events containing a leptonically decaying $W$ boson with a mis-identified second charged lepton candidate.

1. Fake lepton contributions in the di-electron channel

Given the signature under consideration these backgrounds result mainly from the production of leptonically decaying $W$ bosons in association with a photon or a jet that fakes the second lepton.

- $W\gamma$: The $W\gamma$ background cross section is taken from the Baur Leading Order Monte Carlo generator[10], which correctly handles all the final state, trilinear vertex, and initial state radiation diagrams. We select $W\gamma$ events and apply the probability for a photon to fake an electron as measured in control data samples. We use the Monte Carlo to extract the kinematic distributions. The probability for a photon to fake an electron selected with the criteria described in Section III has been estimated from data. A sample of $Z\gamma \rightarrow \ell\ell\gamma$ radiative events is used for this purpose; when looking at the three body mass region of events around the $Z$ pole a very pure photon sample can be selected. The probability for a simple isolated electromagnetic object with $E_T > 15$ GeV to pass the cut on the electron likelihood of 0.85 has been measured to be $0.012 \pm 0.008$. Note that no requirement was imposed on the $p_T$ of the track matched to the electromagnetic cluster. This estimate can therefore be considered conservative, although the effect of the $p_T$ cut is expected to be small. The measured fake rate is used for the normalization of the background. In order to avoid double counting with the $W+$jets only electromagnetic clusters matched to a particle level photon are considered as fake electrons: the contribution from $W+$jets is estimated with the procedure described below. The $W\gamma$ events passing this selection are then treated as all the other backgrounds, propagating the weights to the following stages of the analysis. The estimated $W\gamma$ is very small and it has almost no impact on the analysis. It is therefore not reported in Table I and Table II.

- $W+$jets: Hadronic jets can fake electrons thus contributing to the background. When the jet is produced in association with a $W$ boson the signature becomes very similar to our signal. With the large cross section for $W+$jets production, this process is the second most important background in the analysis. The total number of $W+$jets to the final sample is estimated using data using the matrix inversion method. Two samples are defined: a sample passing all selection cuts (“tight”) and a sample where a looser isolation requirement is applied to one of the leptons (“loose”). The efficiencies for “loose” background and signal events making it to the “tight” sample are $\epsilon_{\text{fake}}$ and $\epsilon_{\text{real}}$ respectively.

$$N_l = \epsilon_{\text{fake}} N_{\text{bkg}} + \epsilon_{\text{real}} N_{\text{sig}}$$

Solving these equations for $N_{\text{sig}}$ (the number of real di-lepton pairs) and $N_{\text{bkg}}$ (the number of pairs containing a mis-identified lepton) permits the calculation of the number of signal and background events in the tight sample, along with associated uncertainties. The results are determined for each $M_{\ell\ell}$ bin. The estimated number of $W+$jets events in the mass window $70 < M_{\ell\ell} < 110$ GeV after all other cuts have been applied is $3.2 \pm 0.8$ in the electron channel. This number is used to normalize the $W+$jets Monte Carlo. The shape of the relevant kinematic quantities is estimated using Monte Carlo.
2. **Fake lepton contributions in the di-muon channel**

- **$W\gamma$:** The contribution is negligible in the muon channel.

- **$W^{+}$jets:** The same method of estimating the normalization (from data, with the matrix inversion method) and the kinematics (from Monte Carlo) of the $W^{+}$jets background is used for the di-muon channel. The loose sample is selected by relaxing the muon isolation requirement. The estimated number of $W^{+}$jets events in the mass window $70 < M_{ll} < 110$ GeV after all other cuts have been applied is $0.2 \pm 0.2$.

The number of Monte Carlo and data events passing each major step of the selection chain are listed in Table I and Table II. The number of Monte Carlo events is normalized to the number of data under the $Z$ peak.

### Table I: Number of Monte Carlo and data events after the major steps of the selection chain for the di-electron final state.

<table>
<thead>
<tr>
<th>Sample</th>
<th>di-lepton selection</th>
<th>Jet veto</th>
<th>Extra activity</th>
<th>$E_T^*$ cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ll$</td>
<td>103583</td>
<td>94712</td>
<td>78364</td>
<td>0.40 ± 0.32</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>42.4</td>
<td>37.7</td>
<td>31.1</td>
<td>0.36 ± 0.05</td>
</tr>
<tr>
<td>$ZZ \rightarrow ll\ell\ell$</td>
<td>2.72</td>
<td>2.16</td>
<td>0.15</td>
<td>0.010 ± 0.001</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>14.11</td>
<td>7.70</td>
<td>1.33</td>
<td>0.25 ± 0.03</td>
</tr>
<tr>
<td>$WZ \rightarrow ll\ell\nu$</td>
<td>16.78</td>
<td>14.47</td>
<td>2.65</td>
<td>1.05 ± 0.06</td>
</tr>
<tr>
<td>$W + jets$</td>
<td>12.20</td>
<td>11.13</td>
<td>8.61</td>
<td>3.22 ± 0.77</td>
</tr>
<tr>
<td>$WW \rightarrow ll\ell\ell$</td>
<td>25.01</td>
<td>22.89</td>
<td>19.59</td>
<td>9.67 ± 0.68</td>
</tr>
<tr>
<td>Tot MC bckg</td>
<td>103697</td>
<td>94808</td>
<td>78427</td>
<td>14.87 ± 1.08</td>
</tr>
<tr>
<td>$ZZ \rightarrow ll\ell\nu$</td>
<td>8.22</td>
<td>7.56</td>
<td>6.42</td>
<td>3.81 ± 0.19</td>
</tr>
<tr>
<td>Tot MC</td>
<td>103705</td>
<td>94816</td>
<td>78434</td>
<td>18.68 ± 1.09</td>
</tr>
<tr>
<td>data</td>
<td>100989</td>
<td>94261</td>
<td>78433</td>
<td>25</td>
</tr>
</tbody>
</table>

### Table II: Number of Monte Carlo and data events after the major steps of the selection chain for the di-muon final state.

<table>
<thead>
<tr>
<th>Sample</th>
<th>di-lepton selection</th>
<th>Jet veto</th>
<th>Extra activity</th>
<th>$E_T^*$ cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ll$</td>
<td>114230</td>
<td>102220</td>
<td>84564</td>
<td>0.45 ± 0.25</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>47.7</td>
<td>43.2</td>
<td>36.8</td>
<td>0.18 ± 0.04</td>
</tr>
<tr>
<td>$ZZ \rightarrow ll\ell\ell$</td>
<td>2.73</td>
<td>1.73</td>
<td>0.14</td>
<td>0.010 ± 0.001</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>14.47</td>
<td>7.06</td>
<td>1.29</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>$WZ \rightarrow ll\ell\nu$</td>
<td>16.29</td>
<td>13.26</td>
<td>2.39</td>
<td>0.77 ± 0.06</td>
</tr>
<tr>
<td>$W + jets$</td>
<td>3.33</td>
<td>2.13</td>
<td>1.57</td>
<td>0.23 ± 0.15</td>
</tr>
<tr>
<td>$WW \rightarrow ll\ell\ell$</td>
<td>28.90</td>
<td>26.16</td>
<td>22.32</td>
<td>8.67 ± 0.62</td>
</tr>
<tr>
<td>Tot MC bckg</td>
<td>114340</td>
<td>102310</td>
<td>84628</td>
<td>10.44 ± 0.69</td>
</tr>
<tr>
<td>$ZZ \rightarrow ll\ell\nu$</td>
<td>9.09</td>
<td>8.21</td>
<td>7.04</td>
<td>3.30 ± 0.17</td>
</tr>
<tr>
<td>Tot MC</td>
<td>114350</td>
<td>102320</td>
<td>84635</td>
<td>13.73 ± 0.71</td>
</tr>
<tr>
<td>data</td>
<td>110792</td>
<td>100900</td>
<td>84635</td>
<td>17</td>
</tr>
</tbody>
</table>

### B. Physics backgrounds

#### 1. Likelihood discriminant

While the cut on $E_T^*$ suppresses most of the instrumental backgrounds, the $WW$, $WZ$, and $W +$jets backgrounds still represent an important contribution to the final sample. The discrimination of the signal therefore requires a further selection. A likelihood discriminant is used for this task, using the following variables:

- invariant mass of the di-lepton system $M_{ll}$;
- transverse momentum of the leading lepton $p_T^{lead-\ell}$;
- cosine of the scattering angle of the negative lepton in the di-lepton rest frame $\cos(\theta^*)$;
• opening angle between the di-lepton system and the leading lepton $\Delta \phi (l_{\text{lead}}, \text{di}\ell)$.

The fit to the ratio of the signal and background distribution for the four variables has been used to build the likelihood discriminant. The distribution of the likelihood discriminant is shown in Fig. 6 for both the di-electron and di-muon final states.

![Graphs showing distributions of variables](image)

**Fig. 4:** Distribution of the input variables of the likelihood discriminant for data and MC in the di-electron channel. Clockwise from the top left: Invariant $p_T$ of the di-lepton system, $p_T$ of the leading lepton, the cosine of the scattering angle of the negative lepton in the di-lepton rest frame, and the opening angle between the lead lepton and the di-lepton system.

The output of the likelihood is used to estimate the significance of the signal in the selected data sample using a semi-frequentist confidence level evaluator. The results are presented in the next section.

**VI. SYSTEMATIC UNCERTAINTIES**

Since the Monte Carlo samples are normalized to data after the veto on the extra activity and the $ZZ$ cross section is estimated measuring the ratio of $ZZ$ events with respect to $Z$ events, any uncertainty which would result in a
Overall scale factor of the Monte Carlo sample (e.g. the uncertainties in the luminosity measurement) does not affect the results of the analysis. This is not the case for the theoretical uncertainty on the inclusive $Z$ cross section which must be propagated to the final result on the $ZZ$ cross section.

Below is a description of the sources of systematics which are propagated into the likelihood and affect the predicted and observed significance. Additional uncertainties taken into account in the determination of the cross-section are listed last.

The largest sources of uncertainty to the determination of the significance and the cross-section are the normalization of the $W+\text{jets}$ background, the uncertainty on the $WW$ cross-section and the lepton resolution.
FIG. 6: Output of the likelihood discriminant for the di-electron (left) and di-muon (right) final states (two data taking periods combined).

<table>
<thead>
<tr>
<th>Channel</th>
<th>Normalization</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>di-electron</td>
<td>3.2 ± 0.8</td>
<td>25%</td>
</tr>
<tr>
<td>di-muon</td>
<td>0.2 ± 0.2</td>
<td>100%</td>
</tr>
</tbody>
</table>

TABLE III: Uncertainties on the $W+$jets normalization.

A. Uncertainties on the $WW$, $WZ$ production cross-sections

A 7% scale uncertainty on the theoretical cross section for the $WW$ and $WZ$ [11] production processes has been considered in the computation of the significance and of the cross-section.

B. Normalization of the $W+$jets background from the matrix method

The uncertainties on the normalization of the $W+$jets background, coming mainly from the uncertainties on the lepton-to-fake rate used in the matrix method, are propagated to the significance and cross-section computation. Since the statistics available after the $E_T$ requirement is very limited, these uncertainties are among the most relevant for the analysis. The values of these uncertainties are listed in Table III.

C. Lepton resolution

The effect of the lepton resolution is studied by varying the parameters of the electron and muon smearing in the Monte Carlo. The effect of this uncertainty on the di-electron final state is within the statistical uncertainties in almost all bins while it is more important in the di-muon final state. In both cases the uncertainty is propagated as an uncertainty in the shape of the likelihood.

D. Estimate of the background after the $E_T$ requirement

Three estimates of the number of events expected after the cut on the corrected energy are obtained. The first two are determined by integrating an exponential function which is fit to the falling edge of the $E_T$ distribution for the
TABLE IV: Estimated significance for the di-electron and di-muon channels and for the combination of the two.

<table>
<thead>
<tr>
<th></th>
<th>di-electron</th>
<th></th>
<th>di-muon</th>
<th></th>
<th>combined</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>expected</td>
<td>observed</td>
<td>expected</td>
<td>observed</td>
<td>expected</td>
<td>observed</td>
</tr>
<tr>
<td>p-value</td>
<td>0.0753</td>
<td>0.1140</td>
<td>0.1100</td>
<td>0.0052</td>
<td>0.0387</td>
<td>0.0082</td>
</tr>
<tr>
<td>significance</td>
<td>+1.44</td>
<td>+1.21</td>
<td>+1.23</td>
<td>+2.57</td>
<td>+1.77</td>
<td>+2.40</td>
</tr>
</tbody>
</table>

data and the Monte Carlo. The third is calculated by summing the predicted Monte Carlo events above the cut. The central value of the Z contribution is computed from the number of surviving MC events while the uncertainty on this number is estimated comparing the extrapolation of the Monte Carlo and data fits.

E. Jet related systematics

None of the variables used to build the likelihood for the signal discrimination are directly related to jets, therefore these uncertainties (absolute value of the jet energy scale, jet energy resolution, and jet reconstruction efficiency) do not affect the shape of the final distribution. The only contribution considered for these uncertainties is therefore the relative normalization of each background. Note that absolute variations in the normalization are re-absorbed by the normalization to data.

F. Uncertainties affecting the cross-section computation

In addition to all the systematic uncertainties listed above, the cross section computation is also affected by the following uncertainties:

- **Uncertainties on the $Z/\gamma^* \rightarrow \ell\ell$ theoretical cross-section.** The $Z/\gamma^* \rightarrow \ell\ell$ cross-section is used in the computation of $\sigma^{ZZ} \times BR(\ell\ell\nu\nu)$. The uncertainties on this number are therefore propagated in the cross-section measurement.

- **Uncertainty on the $A_{ZZZ}^{Z\gamma}$ ratio due to PDF uncertainties.** The $Z/\gamma^*$ and ZZ production mechanisms probe different regions of the PDF distributions. Variations in the PDF distributions can affect the lepton pseudorapidity of the two processes in different ways. The corresponding uncertainty on the $A_{ZZZ}^{Z\gamma}$ ratio used to compute the cross section was estimated to be 1.7%.

- **Uncertainty on the $A_{ZZZ}^{Z\gamma}$ ratio due to modeling of the veto efficiency.** A systematic uncertainty is assigned to the ratio $A_{ZZZ}^{Z\gamma}$ to account for the modeling of the veto efficiency in the Monte Carlo. The size of the uncertainty is estimated to be 3% based on the measured difference in efficiency between data and Monte Carlo.

- **Uncertainty on the $A_{ZZZ}^{Z\gamma}$ ratio due to modeling of the ZZ $p_T$ spectrum.** We apply a reweighting function on the ZZ $p_T$, derived by fitting the $p_T$ spectra of $WW$ in Sherpa [12] and Pythia. A 3.6% uncertainty is estimated from the effect on the ZZ acceptance.

VII. RESULTS

A. Significance calculation

A negative log-likelihood ratio (LLR) test statistic is used to evaluate the significance of the result, taking as input the binned outputs of the di-electron and di-muon likelihood discriminants divided into two data taking periods. A modified frequentist calculation is used [13] which returns the probability of background-only fluctuating to give the observed yield or higher (p-value) and the corresponding Gaussian equivalent significance. The expected and observed results in the di-electron and di-muon channels are reported in Table IV. The resulting LLR distribution for the combination of the di-electron and di-muon channels is shown in Fig. 7 and the numerical results are reported in the last column of Table IV.
FIG. 7: LLR distribution in many pseudo-experiments for the signal plus backgrounds (S+B) and background only (B only) hypothesis combining the di-electron and di-muon final states. The red vertical line is the median of the S+B distribution, which can be considered as the expected value for the test statistic. The observed value is indicated by the black vertical line.

B. Cross section measurement

The relative normalization among the Monte Carlo processes has been computed using the theoretical cross sections. To reduce the effect of multiplicative scale uncertainties and systematics related to the modeling of the efficiencies of the cut applied, the absolute normalization of the Monte Carlo samples has been obtained scaling to the number of events in the data surviving the extra activity veto. At this point, the sample is dominated by inclusive $Z \rightarrow \ell \ell$ production. The measurement of the $ZZ \rightarrow \ell^+\ell^- \nu\bar{\nu}$ production cross section can be therefore expressed in terms of relative number of events with respect to the $Z \rightarrow \ell \ell$ sample.

To determine the cross section the likelihood distribution in the data has been fitted without constraining the signal. The scale factor $f$ with respect to the Standard Model cross section and its error are determined by the fit. The corresponding cross section can be computed scaling the number of events foreseen by the Monte Carlo:

$$\sigma_{ZZ} = \sigma_{Z} \frac{A_{Z}}{A_{ZZ}} \frac{f N_{MC}^{MC}}{N_{Z}}$$  \hspace{1cm} (7)

in which $A_{Z}$ is the acceptance times efficiency for $Z \rightarrow \ell \ell$ and $A_{ZZ}$ is the acceptance times efficiency for our $ZZ$ signal. We assume the theoretical cross section for $Z/\gamma^* \rightarrow \ell \ell$ in the mass window $60 < M_{\ell\ell} < 130$ GeV: $\sigma_{Z} = 256.6^{+5.1}_{-12.0}$ pb\cite{14, 15}.

The resulting cross section for the production of $ZZ \rightarrow \ell^+\ell^- \nu\bar{\nu}$ is:

$$\sigma_{ZZ} = 2.1 \pm 1.1(\text{stat.}) \pm 0.4(\text{sys.}) \text{ pb}$$  \hspace{1cm} (8)

This can be compared with the predicted Standard Model cross section of $1.6 \pm 0.1$ pb\cite{11}.

The major contribution to the systematic uncertainty on the cross section ($\sim 18\%$) come from the uncertainties considered in the fitting procedure (mainly the uncertainty on the $WW$ cross-section, the $W+$jets normalization and the lepton resolution) which are listed in Sections VI A to VI E. Further contributions come from the uncertainty on the $Z/\gamma^* \rightarrow \ell \ell$ cross-section and from the uncertainties on the $A_{Z}/A_{ZZ}$ ratio described in Section VI F.
VIII. CONCLUSIONS

We performed a measurement of the production cross-section of $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ using 2.2 $fb^{-1}$ of data collected by the D0 experiment at a center of mass energy of 1.96 TeV. We observe a signal with a +2.4 $\sigma$ significance (+1.8 $\sigma$ expected) and measure a cross-section $\sigma(pp \rightarrow ZZ) = 2.1 \pm 1.1(stat.) \pm 0.4(sys.)$ pb.

Acknowledgments

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); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Co条评论(哥伦比亚); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBAcYt (Argentina); STFC (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); the Alexander von Humboldt Foundation; and the INFN (Italy).

[6] The D0 Collaboration, Measurement of $\sigma(pp \rightarrow Z)B(Z \rightarrow \tau\tau)$, D0 Conference note 5484, in preparation for submission to Phys. Rev. Lett.
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/EW/E21/