Strong Evidence for ZZ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report the first evidence of Z boson pair production at a hadron collider with a significance exceeding 4 standard deviations. This result is based on a data sample corresponding to 1.9 fb^{-1} of integrated luminosity from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron. In the $\ell\ell\ell'\ell'$ channel, we observe three ZZ candidates with an expected background of $0.096^{+0.092}_{-0.063}$ events. In the $\ell\ell\nu\nu$ channel, we use a leading-order calculation of the relative ZZ and WW event probabilities to discriminate between signal and background. In the combination of $\ell\ell\ell'\ell'$ and $\ell\ell\nu\nu$ channels, we observe an excess of events with a probability of 5.1×10^{-6} to be due to the expected background. This corresponds to a significance of 4.4 standard deviations. The measured cross section is $\sigma(p\overline{p} \to ZZ) = 1.4^{+0.7}_{-0.6}$ (stat.+syst.) pb, consistent with the standard model expectation.

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Measurements of heavy vector boson pair production (WW, WZ, ZZ) are of great importance because they test the electroweak sector of the standard model (SM). Diboson production provides a sensitive probe of new physics, including anomalous trilinear gauge couplings [1], new particles such as the Higgs boson [2], and large extra dimensions [3]. Important tests of electroweak physics have been made recently at the Fermilab Tevatron with the first observation of WW production in hadron collisions [4, 5] and the first observation of WZ production [6]. The production of Z pairs has been observed in e^+e^- collisions at LEP [7], but not in hadron collisions. As a window to new physics, ZZ production is particularly interesting because of the absence of $ZZ\gamma$ and ZZZ couplings in the SM, and because of the very low backgrounds in the four charged-lepton channel.

The full process that we consider in this search is $p\overline{p} \rightarrow Z/\gamma^*\ Z/\gamma^*$. For brevity, we denote $Z/\gamma^*\ Z/\gamma^*$ as ZZ throughout this Letter. The most sensitive previous search for ZZ production in hadron collisions was reported by the DØ Collaboration using data corresponding to 1 fb^{-1} of integrated luminosity. That search used only the four charged-lepton channel and set a limit on the cross section of $\sigma(ZZ) < 4.4$ pb at 95% C.L. [8]. The next-to-leading order (NLO) ZZ cross section for $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV is 1.4 ± 0.1 pb in the zero-width Z boson approximation [9].

In this Letter, we report a signal for ZZ production in hadron collisions which has a probability of 5.1×10^{-6} to be due to the expected background. The production is observed in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV using a data sample corresponding to 1.9 fb^{-1} of integrated luminosity collected by the CDF II detector. We consider both $ZZ \rightarrow \ell\ell\ell'\ell'$ and $ZZ \rightarrow \ell\ell\nu\nu$ decays, where ℓ and ℓ' are electrons or muons directly from Z decay or from the leptonic decay of τ's when one or both Z bosons decay to τ leptons. In the $ZZ \rightarrow \ell\ell\ell'\ell'$ channel, we have a small sensitivity to the γ^* contribution and its interference with the Z boson, while this sensitivity is negligible for the $ZZ \rightarrow \ell\ell\nu\nu$ channel.

The CDF II detector [10] geometry is described using the azimuthal angle ϕ and the pseudo-rapidity $\eta \equiv -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the proton beam axis (positive z-axis). The pseudo-rapidity of a particle assumed to originate from the center of the detector is referred to as $\eta_{\rm d}$.

The trajectories of charged particles (tracks) are reconstructed using silicon micro-strip detectors [11, 12] and a 96-layer open-cell drift chamber (COT) [13] inside a 1.4 T solenoid. A particle with $|\eta_{\rm d}| \leq 1$ traverses all 96 COT radial layers. The number of traversed layers decreases to zero as $|\eta_{\rm d}|$ approaches 2. The silicon system provides coverage with 6 (7) layers with radii between 2.4 cm and 28 cm for $|\eta_{\rm d}| < 1.0$ ($1.0 < |\eta_{\rm d}| < 2.0$). Outside of the solenoid are electromagnetic (EM) and hadronic (HAD) sampling calorimeters, segmented in a projective tower geometry, and constructed of layers of lead and iron absorber, respectively, and scintillator. The EM section is the first 19-21 radiation lengths, corresponding to one hadronic interaction length (λ), and contains electromagnetic showers. The HAD section of the calorimeter extends to 4.5-7 λ and contains the majority of a hadronic shower. The calorimeters are divided into central ($|\eta_{\rm d}| < 1.1$) and forward ($1.1 < |\eta_{\rm d}| < 3.6$) regions. Outside of the central calorimeters are muon detectors consisting of scintillators and drift chambers.

The branching fraction of the ZZ state to four e or μ leptons, including those from leptonic τ decays, is only 0.51%. When coupled with the small SM cross-section, only a small number ($\sim$14) of $ZZ \rightarrow \ell\ell\ell'\ell'$ are expected to be produced in 1.9 fb^{-1} at the Tevatron. The finite CDF II acceptance further reduces the expected number of observed $ZZ \rightarrow \ell\ell\ell'\ell'$ events.

To maximize the acceptance, we construct lepton candidates out of all reconstructed tracks and energy clusters in the EM section of the calorimeter. This is done with the same lepton identification criteria used in a previous CDF measurement of WZ production [6]. The lepton candidates are divided into seven exclusive categories: three for muons, three for electrons, and one for "track-only leptons" which are tracks extrapolating to detector regions that are inactive for energy measurement because they are either not covered, or are only partially covered, by calorimeter components. The three muon categories include one that uses the muon detectors and two that use different types of minimum ionizing tracks, central ($|\eta_{\rm d}| < 1.1$) and forward ($1.2 < |\eta_{\rm d}| < 2.0$). The three electron categories are central ($|\eta_{\rm d}| < 1.1$), forward ($1.2 < |\eta_{\rm d}| < 2.0$) with a matched silicon-based track, and forward ($1.2 < |\eta_{\rm d}| < 2.8$) without a matched silicon-based track (see Ref. [6] for more detail).

The transverse energy E_T of an EM cluster or calorimeter tower is $E\sin\theta$, where E is the associated energy. Similarly, p_T is the component of track momentum transverse to the beam line. To suppress jets being misidentified as leptons, all lepton candidates are required to pass a calorimeter-based isolation requirement such that the sum of the E_T for the calorime-

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ter towers not associated with the lepton in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the lepton direction is less than 10% of the E_T for electrons or p_T for muons and track lepton candidates.

To detect the presence of neutrinos in $ZZ \to \ell\ell\nu\nu$ decay, we use missing transverse energy $\vec{\not\!E}_T = -\sum_i E_i\ \hat{n}_{T,i}$, where $\hat{n}_{T,i}$ is the transverse component of the unit vector pointing from the interaction point to calorimeter tower i. The $\vec{\not\!E}_T$ calculation is corrected for muons and track-only lepton candidates, which do not deposit all of their energy in the calorimeter. We analogously define the scalar sum $\Sigma E_T = \sum_i E_{T,i}$ applying the same corrections.

The events we consider must pass at least one of four trigger selection criteria. The central electron trigger requires an EM energy cluster with $E_T > 18$ GeV matched to a track with $p_T > 8$ GeV/c. For the $ZZ \to ee\nu\nu$ channel only, a trigger for forward electrons requires an EM energy cluster with $E_T > 20$ GeV and an uncorrected, calorimeter-based measurement of $\not\!E_T > 15$ GeV. Two muon triggers are based on stubs from the corresponding muon detectors matched to a track with $p_T > 18$ GeV/c. Trigger efficiencies are measured in leptonic W and Z boson data samples [14].

The $ZZ \to \ell\ell\ell'\ell'$ candidates are selected from events with exactly four charged-lepton candidates using requirements that were optimized with Monte Carlo simulation without reference to the data. At least one lepton is required to satisfy the trigger criteria and have $E_T > 20$ GeV ($p_T > 20$ GeV/c) for electrons (muons). We loosen this requirement to 10 GeV (GeV/c) for the other leptons to increase the ZZ kinematic acceptance. We require at least two same-flavor, opposite-sign lepton pairs in the event. Trackless electrons are considered to have either charge, and track-only leptons either flavor. One pair must have invariant mass $M_{\ell^+\ell^-}$ in the range [76, 106] GeV/c^2, while the requirement for the other pair is extended to [40, 140] GeV/c^2 to increase the acceptance for off-shell Z decays.

The acceptance for the ZZ process is determined using PYTHIA [15] Monte Carlo calculations followed by a GEANT-based simulation [16] of the CDF II detector. An efficiency correction, of up to 10% per lepton, is applied to the simulation based on measurements of the lepton reconstruction and identification efficiencies using observed $Z \to \ell^+\ell^-$ events.

The dominant backgrounds to the $ZZ \to \ell\ell\ell'\ell'$ selection are the Drell-Yan Z/γ^* process (DY) with two jets misidentified as leptons (Z+jets) and DY with an additional photon and a jet, both misidentified as leptons ($Z\gamma$+jets). The Z+jets and $Z\gamma$+jets background contributions are estimated from data by extrapolating from a sample of events that contain three identified leptons and a jet j_l containing a track or EM energy cluster similar to those required in the lepton identification. The contribution of each event to the total yield is scaled by the probability that the j_l is identified as a lepton. This probability $p(j_l)$ is determined from multijet events collected with jet-based triggers and is a function of the j_l p_T and type of lepton. A correction to $p(j_l)$ is applied for the small real lepton contribution using Monte Carlo simulation of single W and Z boson processes. In this background sample, one of the three identified leptons is likely to be either a jet or a photon misidentified as a lepton. An event with two leptons and two j_l jets enters the three lepton plus j_l sample if either of the j_l jets is misidentified as a lepton, but will enter the four identified lepton sample only if both j_l jets are misidentified as leptons. Therefore, the contribution from this category of events is double counted. A correction for this is made by subtracting the yield of two leptons plus two j_l jets scaled by $p(j_{l,1}) \times p(j_{l,2})$. As the three lepton plus j_l sample has significant contributions from the $ZZ \to \ell\ell\ell'\ell'$ signal itself when one of the leptons is not fully identified but is counted as a j_l, an anti-isolation requirement of >20% (see previous definition of calorimeter-based isolation) is applied to the j_l selection.

As a cross-check, we estimate the $Z\gamma$+jet background contribution in an alternative way using the yield of three lepton plus j_l events in simulated $Z\gamma$+jet data scaled by $p(j_l)$. We correct this with the ratio of data to simulation for an analogous calculation of two identified leptons and one j_l scaled by $p(j_l)$ in Z+jets events. This estimate of the $Z\gamma$+jet background is in good agreement with the nominal estimate based solely on the data.

We separate the $ZZ \to \ell\ell\ell'\ell'$ candidates into two exclusive categories based on whether or not they contain at least one forward electron without a track because the background from $Z\gamma$+jets is much larger in candidates with a forward trackless electron. The expected signal and background yields, assuming $\sigma(ZZ) = 1.4 \pm 0.1$ pb, and the observed yields are shown in Table I.

The statistical significance of the $ZZ \to \ell\ell\ell'\ell'$ yield is determined using a maximum likelihood fit with two bins, one for each of the $ZZ \to \ell\ell\ell'\ell'$ categories. We define $\Delta \ln \mathcal{L}$ as the logarithm of the likelihood ratio between this fit and the no signal hypothesis. In 10^7 background-only Monte Carlo experiments, only 109 have larger $\Delta \ln \mathcal{L}$ than that observed in data. This corresponds to a background-only probability (p-value) of 1.1×10^{-5} and a signal significance equivalent to 4.2 standard deviations.

The $ZZ \to \ell\ell\nu\nu$ candidates are selected from events with exactly two lepton candidates excluding events with forward electrons without a track which are contaminated by large $W\gamma$ backgrounds. At least one lepton is required to satisfy the trigger and have $E_T > 20$ GeV ($p_T > 20$ GeV/c) for electrons (muons). This requirement is loosened to 10 GeV (GeV/c) for the other lepton. We apply a track-based isolation selection in which the sum of the p_T of the tracks not associated with the lepton within a cone of $\Delta R < 0.4$ around the lepton is required to be less than 10% of the momentum of the

TABLE I: Expected and observed number of $ZZ \to \ell\ell\ell'\ell'$ candidate events. The first uncertainty is statistical and the second one is systematic.

Category	Candidates without a trackless electron	Candidates with a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	**2**	**1**

track associated with the lepton.

Aside from ZZ production, other SM processes that can lead to two high-p_T leptons include events from DY, a W decay with photon ($W\gamma$) or jet (W+jets) misidentified as a lepton; and $t\bar{t}$, WW, and WZ production. The $t\bar{t}$ contribution is suppressed by requiring fewer than two reconstructed jets with $E_T > 15$ GeV and $|\eta_d| < 2.5$ in the event. The DY background is suppressed by requiring sufficiently large $\not{E}_T$ in the event to remove contributions from mismeasured leptons and/or jets. This is achieved by requiring $\not{E}_{T,rel} > 25$ GeV, where

$$\not{E}_{T,rel} \equiv \left\{ \begin{array}{ll} \not{E}_T & \text{if } \Delta\phi_{\not{E}_T,(\ell,\text{jet})} > \frac{\pi}{2} \\ \not{E}_T \sin\Delta\phi_{\not{E}_T,(\ell,\text{jet})} & \text{if } \Delta\phi_{\not{E}_T,(\ell,\text{jet})} < \frac{\pi}{2} \end{array} \right\} \quad (1)$$

and $\Delta\phi_{\not{E}_T,(\ell,\text{jet})}$ is the angle between the $\vec{\not{E}}_T$ direction and the nearest lepton or jet. To suppress events with $\not{E}_T$ from mismeasured unclustered energy, we require significant $\not{E}_T$ such that $\not{E}_T/\sqrt{(\Sigma E_T)} > 2.5$ GeV$^{1/2}$. We require the lepton pair to be consistent with the same-flavor, opposite-sign property of Z decay and have dilepton invariant mass $M_{\ell^+\ell^-} > 16$ GeV$/c^2$ to suppress QCD backgrounds.

The acceptances for the WW, WZ, ZZ, $W\gamma$, and $t\bar{t}$ processes are determined using the same detector simulation as described for the $ZZ \to \ell\ell\ell'\ell'$ channel. Events are simulated with the MC@NLO program for WW [17], PYTHIA for WZ, ZZ, and $t\bar{t}$ [15], and the generator described in [18] for $W\gamma$. An additional correction is applied to the $W\gamma$ background estimate based on a measurement of the photon conversion veto efficiency in data. The background from W+jets is estimated from the yield of one identified lepton plus one j_l scaled by $p(j_l)$. As the sample size is sufficiently large, a loose calorimeter-based isolation cut ($< 30\%$) is applied to the j_l samples to reduce the magnitude of the extrapolation from the j_l to the fully-identified lepton.

We observe 276 events in the selected region which is expected to contain 256 ± 21 events of which only 14 ± 2 are from the $ZZ \to \ell\ell\nu\nu$ process in the SM. Approximately half of the yield is due to the WW process. However, $ZZ \to \ell\ell\nu\nu$ and WW have different kinematic properties which are exploited to statistically separate the contribution of these two processes to the dataset.

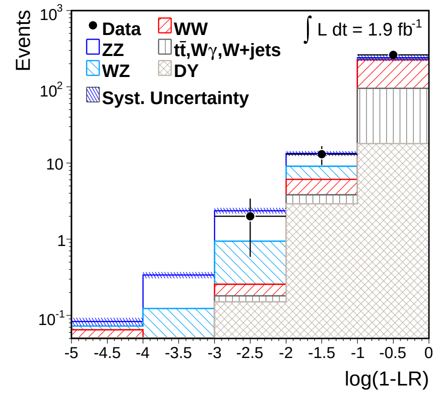

FIG. 1: Distribution of the discriminating variable $\log_{10}(1 - LR)$ for the $ZZ \to \ell\ell\nu\nu$ search.

We calculate an event-by-event probability density for the observed lepton momenta and $\not{E}_T$ using leading order calculations of the differential decay rate for the processes [9]. The event probability density is

$$P(x_{obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{LO}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy, \quad (2)$$

where the elements of y (x_{obs}) are the true (observed) values of the lepton momenta and $\not{E}_T$, $\frac{d\sigma_{LO}}{dy}$ is the parton level cross section differential in those observables, $\epsilon(y)$ is the detector acceptance and efficiency function, and $G(x_{obs}, y)$ is the transfer function representing the detector resolution. The constant $\langle\sigma\rangle$ normalizes the total event probability to unity. The missing information due to the fact that we have two neutrinos in the final state is integrated over in this calculation. We then form a likelihood ratio discriminant LR which is the signal probability divided by the sum of signal and background probabilities $LR = P_{ZZ}/(P_{ZZ} + P_{WW})$. The distribution of $\log_{10}(1 - LR)$ for the data compared to the summed signal and background expectation is shown in Figure 1.

For both $\ell\ell\ell'\ell'$ and $\ell\ell\nu\nu$ channels, the systematic uncertainties associated with the Monte Carlo simulation affect the WW, WZ, ZZ, $W\gamma$, and $t\bar{t}$ expectations similarly. The uncertainties from the lepton selection and trigger efficiency measurements are propagated through the analysis, giving uncertainties from 1.0% to 1.4% and 2.1% to 6.1% for the respective efficiencies of the different signal and background processes. The detector acceptance variation due to PDF uncertainties is assessed to be in the range 1.9% - 4.1% using the 20 pairs of PDF sets described in [19]. We assign a 6% luminosity uncertainty to signal and background estimates obtained from simulation [20]. The cross-section uncertainties are 10% for WW [9], WZ [9], and $W\gamma$ [21], and 15% for $t\bar{t}$ [22, 23].

The systematic uncertainty on the W+jets background to $ZZ \to \ell\ell\nu\nu$ candidates and the Z+jets and $Z\gamma$+jets background to the $ZZ \to \ell\ell\ell'\ell'$ is estimated to be 20%

from differences in the observed probability that a jet is identified as a lepton for jets collected using different jet E_T trigger thresholds. These variations correspond to changing the parton composition of the jets and the relative amount of contamination from real leptons.

For the $ZZ \to \ell\ell\nu\nu$, the systematic uncertainty on the DY background yield due to the $\not\!\!E_T$ resolution modeling is estimated to be 20% from comparisons of the data and Monte Carlo simulation in a sample of dilepton events. For the $W\gamma$ background contribution, there is an additional uncertainty of 20% from the detector material description and conversion veto efficiency.

We define four independent control samples based on the $ZZ \to \ell\ell\nu\nu$ selection where one of the cuts is removed or inverted to test our modeling of background-dominated data. Removing the $\not\!\!E_T$ requirement produces a DY-dominated sample which tests luminosity accounting, lepton reconstruction efficiency, and non-$\not\!\!E_T$ related trigger efficiencies that apply to both the $\ell\ell\ell'\ell'$ and $\ell\ell\nu\nu$ final states; we observe (expect) 160980 (160000 ± 18000) events, where the uncertainty combines statistical and systematic contributions. Inverting the charge sign requirement to select same-sign dilepton events tests our modeling of photons and jets misidentified as leptons; we observe (expect) 161 (138 ± 19) events. Inverting the $\not\!\!E_T/\sqrt(\Sigma E_T)$ requirement but selecting $\not\!\!E_{T,rel} > 25$ GeV events tests our modeling of the effect of unclustered energy on the $\not\!\!E_T$; we observe (expect) 55 (59 ± 9) events. Finally, inverting the $\not\!\!E_{T,rel} > 25$ GeV requirement but selecting $\not\!\!E_T > 25$ GeV events tests our modeling of mismeasured leptons or jets at high $\not\!\!E_T$; we observe (expect) 151 (178 ± 30) events. The observed yields are in good agreement with the expectations in each selection set.

We combine the $ZZ \to \ell\ell\nu\nu$ with the $ZZ \to \ell\ell\ell'\ell'$ results by extending the likelihood fit previously described to include the $\log_{10}(1 - LR)$ distribution. The p-value for the $ZZ \to \ell\ell\nu\nu$ alone is 0.12 and the combined p-value is 5.1×10^{-6} corresponding to a significance equivalent to 4.4 standard deviations. This is the first evidence of ZZ production at a hadron collider with a significance exceeding 4 standard deviations. We determine the ZZ cross section by fitting the data for the fraction of the expected SM yield in the full acceptance and scaling the zero-width Z boson approximation cross section by that fraction. The measured cross section is $\sigma(p\overline{p} \to ZZ) = 1.4^{+0.7}_{-0.6}$ pb, consistent with the SM expectation. This is the first measurement of the ZZ cross section in hadron collisions.

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