Observation of ZZ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present an observation for $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ (ℓ, $\ell' = e$ or μ) production in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. Using 1.7 fb^{-1} of data collected by the D0 experiment at the Fermilab Tevatron Collider, we observe three candidate events with an expected background of $0.14^{+0.03}_{-0.02}$ events. The significance of this observation is 5.3 standard deviations. The combination of D0 results in this channel, as well as in $ZZ \to \ell^+\ell^-\nu\bar{\nu}$, yields a significance of 5.7 standard deviations and a combined cross section of $\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{syst})$ pb.

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Studies of the pair production of electroweak gauge bosons provide an interesting test of the electroweak theory predictions [1]. In contrast with other diboson processes, Z boson pair production (ZZ) does not involve trilinear gauge boson interactions within the standard model (SM). The observation of an unexpectedly high cross section could indicate the presence of anomalous ZZZ or $ZZ\gamma$ couplings [2]. The SM prediction for the total ZZ production cross section in $p\bar{p}$ collisions at the Fermilab Tevatron Collider at $\sqrt{s} = 1.96$ TeV is $\sigma(ZZ) = 1.4 \pm 0.1$ pb [3]. The requirement of leptonic Z boson decays reduces the observable cross section, making its measurement rather challenging. The accumulation of integrated luminosities in excess of 3 fb^{-1} at the Fermilab Tevatron Collider and the development of highly optimized event selection criteria has now made possible the direct observation of ZZ production.

Previous investigations of ZZ production have been performed both at the Fermilab Tevatron $p\bar{p}$ and the CERN e^+e^- (LEP) [4] Colliders. The D0 collaboration reported a search for $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ (ℓ, $\ell' = e$ or μ) with 1 fb^{-1} of data that provided a 95% C.L. limit of $\sigma(ZZ) < 4.4$ pb [5]. The CDF collaboration reported a signal for ZZ production with a significance of 4.4 standard deviations from combined $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ and $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ searches, and measured a production cross section of $\sigma(ZZ) = 1.4^{+0.7}_{-0.6}$ pb [6].

In this Letter, we present a search for Z boson pairs where the Z bosons have decayed to either electron or muon pairs, resulting in final states consisting of four electrons ($4e$), four muons (4μ), or two muons and two electrons ($2\mu 2e$). Data used in this analysis were collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider at $\sqrt{s} = 1.96$ TeV between June 2006 and May 2008. The integrated luminosities [7] for the three analyzed channels are about 1.7 fb^{-1}. This result is later combined with that from an earlier similar analysis [5] using data collected from October 2002 to February 2006 and corresponding to an integrated luminosity of 1 fb^{-1}.

The D0 detector [8] consists of a central tracking system, comprised of a silicon microstrip tracker (SMT), and a central fiber tracker (CFT), providing coverage to pseudorapidity $|\eta| < 3$ [9], both located within a 2 T superconducting solenoidal magnet. Three liquid argon and uranium calorimeters provide coverage to $|\eta| < 4$. Electromagnetic objects are well reconstructed in the regions of the central calorimeter (CC) with coverage to $|\eta| < 1.1$ and the end calorimeters (EC) with coverage of $1.5 < |\eta| < 3.2$. A muon system surrounds the calorimetry, consisting of three layers of scintillators and drift tubes and 1.8 T iron toroids, with a coverage of $|\eta| < 2$.

This analysis employs a combination of single and dielectron triggers for the $4e$ channel. Similarly, single and dimuon triggers are used for the 4μ channel. The $2\mu 2e$ channel uses a combination of all these triggers, and additional specific electron-muon triggers. The triggering efficiency for events with four leptons having high transverse momentum (p_T) that satisfy all offline selection requirements exceeds 99%.

For the $4e$ channel, we require four electrons with ordered transverse energies $E_T > 30$, 25, 15, and 15 GeV, respectively. Electrons must be reconstructed either in the CC region or in the EC region, and be isolated from other energy clusters in the calorimeter. Electrons in the CC region are required to satisfy identification criteria based on a multivariate discriminant derived from calorimeter shower shape and a matched track reconstructed in the SMT and CFT. Electrons in the EC are not required to have a matched track, but must satisfy more stringent shower shape requirements. At least two electrons must be in the CC region. With no requirement applied on the charge of the electrons at this stage to increase selection efficiency, three possible ZZ combinations can be formed for each $4e$ event. Events are required to have a solution for which one ee combination has an invariant mass >70 GeV and the other >50 GeV. Finally, events are split into three categories, depending on the number of electrons in the CC region. Subsamples with two electrons, with three electrons, and with four or more electrons in the CC region are denoted as $4e_{2C}$, $4e_{3C}$, and $4e_{4C}$, respectively. The three exclusive subsamples contain significantly different levels of background contamination and thus the separation of the subsamples provides more sensitivity to the search.

For the 4μ channel, each muon must satisfy quality criteria based on scintillator and wire chamber information from the muon system, and have a matched track in the central tracker. We require that the four most energetic muons have ordered transverse momenta $p_T > 30$, 25, 15, and 15 GeV, respectively. At least three muons in the event must be isolated, each passing a requirement of less than 2.5 GeV of transverse energy deposited in the calorimeter in the annulus $0.1 < \Delta R < 0.4$ centered around the muon track [10]. Finally, the muon is required to be well reconstructed and to originate from the primary event vertex. Of the three possible ZZ combinations per event that can be formed without considering muon charge at this stage, a solution is required where one $\mu\mu$ combination has an invariant mass >70 GeV and the other >50 GeV.

For the $2\mu 2e$ channel, the two most energetic electrons and muons in an event must have $E_T(p_T) > 25$, 15 GeV. All muons and electrons must satisfy the single lepton selection criteria defined for the $4e$ and 4μ final states. In addition, electrons and muons are required to be spatially separated by $\Delta R > 0.2$ to remove $Z \to \mu\mu$ background with muons radiating photons giving events with two muon and two trackless electron candidates. At least one muon must satisfy the same calorimeter isolation requirement imposed in the 4μ final state. A solution is required where one pair of same flavor leptons has an invariant mass >70 GeV, and the other >50 GeV.

Finally, events are split into three categories depending on the number of electrons in the CC region. Subsamples with no electron, with one electron, and with two or more electrons in the CC are denoted as $2\mu 2e_{0C}$, $2\mu 2e_{1C}$, and $2\mu 2e_{2C}$, respectively. As in the $4e$ channel, these subsamples have significantly different levels of background contamination.

A Monte Carlo (MC) simulation is used to determine the expected number of signal events in each subchannel. The small contribution from ZZ events with at least one Z boson decaying into tau pairs is also included in the signal. Simulated events are generated using PYTHIA [11] and passed through a detailed GEANT-based simulation [12] of the detector response. Differences between MC simulations and data in the reconstruction and identification efficiencies for electrons and muons are corrected using efficiencies derived from large data samples of inclusive $Z \to \ell\ell$ ($\ell = e$, or μ) events. The systematic uncertainty in the signal is dominated by the uncertainty in the theoretical cross section (6.25%), the uncertainty on the lepton identification and reconstruction efficiencies ($\approx$4% for the $4e$ and 4μ subchannels and $\approx$2.5% for the $2\mu 2e$ subchannels), and a 6.1% uncertainty on the luminosity measurement [7]. Additional smaller sources of systematic uncertainty arise from energy and momentum resolutions and MC modeling of the signal process.

Backgrounds to the ZZ signal originate from top quark pair ($t\bar{t}$) production and from events with W and/or Z bosons that decay to leptons and additional jets or photons. The jets can then be misidentified as leptons or contain true electrons or muons from in-flight decays of pions, kaons, or heavy-flavored hadrons.

The background from $t\bar{t}$ production is estimated from MC calculations, assuming the cross section of $\sigma(t\bar{t}) = 7.9$ pb [13] for a top quark mass of 170 GeV. The systematic uncertainty includes a 10% uncertainty on $\sigma(t\bar{t})$, as well as contributions from the variation in cross section and acceptance originating from uncertainties on the mass of the top quark.

To estimate the misidentified lepton background, we first measure the probability for a jet to produce an electron or muon that satisfy the identification criteria from data using a "tag and probe" method [5]. The probability for a jet to mimic an electron, parametrized in terms of jet E_T and η, is equal to 4×10^{-4} for the case of CC electrons with a matched track and 5×10^{-3} in the case of EC electrons for which no track matching is applied. The probability for a 15 GeV (100 GeV) jet to produce a muon of $p_T > 15$ GeV is $10^{-4}(10^{-2})$ without requiring muon isolation, and it is $10^{-5}(10^{-4})$ when the muon is required to be isolated. A systematic uncertainty of 30% on the jet-to-lepton misidentification probabilities is estimated by varying the selection criteria of the control samples used.

The probabilities for jets to be misidentified as electrons are then applied to jets in eee + jets and $\mu\mu e$ + jets data to determine the background to the $4e$ and $2\mu 2e$ channels, respectively. This method takes into account contributions from Z + jets, $Z + \gamma$ + jets, WZ + jets, WW + jets, W + jets, and events with ≥ 4 jets. However, this method double counts the contribution from Z + jets. A correction is measured, amounting to $\approx 20\%$, to correct for the double counting. The probabilities for jets to contain a muon are applied to jets in $\mu\mu$ + jets data to determine a background estimate for the 4μ channel. Systematic uncertainties on this background arise from the 30% uncertainty in measured misidentification rates, and from the limited statistics of the data remaining in the samples after selection.

Table I summarizes the expected signal and background contributions to each subchannel, as well as the number of candidate events in data. The total signal and background expectations are 1.89 ± 0.08 events and $0.14^{+0.03}_{-0.02}$ events, respectively. We observe a total of three candidate events in the data, two in the $4e_{4C}$ subchannel and one in the 4μ subchannel. Table II summarizes some of their kinematic characteristics. The quoted dilepton masses in the table correspond to one out of the three possible combinations having opposite charge within the pairs and having a dilepton mass closest to that of the Z boson. Figure 1 shows the distribution of the four lepton invariant mass for data and for the expected signal and background.

We extract the significance of the observed event distributions using a negative log-likelihood ratio (LLR) test statistic [14]. As input, we use the expected yields (number of events) from signal and background, separated into the seven subchannels compared to the observed yields. The

TABLE I. The integrated luminosity, expected number of signal ($Z/\gamma^* \ Z/\gamma^*$) and background events [$t\bar{t}$ and $Z(\gamma)$ + jets which includes all $W/Z/\gamma$ + jets contributions], and the number of observed candidates in the seven $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ subchannels. Uncertainties reflect statistical and systematic contributions added in quadrature.

Subchannel	$4e_{2C}$	$4e_{3C}$	$4e_{4C}$	4μ	$2\mu 2e_{0C}$	$2\mu 2e_{1C}$	$2\mu 2e_{2C}$
Luminosity (fb^{-1})	1.75 ± 0.11	1.75 ± 0.11	1.75 ± 0.11	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10
Signal	0.084 ± 0.008	0.173 ± 0.015	0.140 ± 0.012	0.534 ± 0.043	$0.058^{+0.007}_{-0.006}$	0.352 ± 0.040	$0.553^{+0.045}_{-0.044}$
$Z(\gamma)$ + jets	$0.030^{+0.009}_{-0.008}$	$0.018^{+0.008}_{-0.007}$	$0.002^{+0.002}_{-0.001}$	0.0003 ± 0.0001	$0.03^{+0.02}_{-0.01}$	0.05 ± 0.01	$0.008^{+0.004}_{-0.003}$
$t\bar{t}$	...	...	...	...	$0.0012^{+0.0016}_{-0.0009}$	0.005 ± 0.002	$0.0007^{+0.0009}_{-0.0005}$
Observed events	0	0	2	1	0	0	0

TABLE II. Characteristics of the observed candidate events. η and ϕ values are measured relative to the location of the $p\bar{p}$ collision. M_{ll} is the mass of the lepton pair.

		e_1^+	e_2^+	e_3^-	e_4^-
4e candidate 1	p_T (GeV)	107	59	52	16
	η	0.66	0.25	-0.64	-0.85
	ϕ	4.10	1.08	0.46	2.62
	$M_{\ell\ell}$ (GeV)	$e_1^+e_4^-$		$e_2^+e_3^-$	
		89 ± 3		61 ± 2	

		e_1^+	e_2^+	e_3^-	e_4^-
4e candidate 2	p_T (GeV)	83	75	35	26
	η	0.64	0.40	0.85	1.17
	ϕ	6.16	3.80	3.83	1.40
	$M_{\ell\ell}$ (GeV)	$e_1^+e_3^-$		$e_2^+e_4^-$	
		99 ± 3		90 ± 4	

		μ_1^+	μ_2^-	μ_3^-	μ_4^+
4μ candidate	p_T (GeV)	115	77	42	24
	η	0.04	-1.01	0.77	-1.93
	ϕ	1.69	4.26	5.29	0.36
	$M_{\ell\ell}$ (GeV)	$\mu_1^+\mu_3^-$		$\mu_2^-\mu_4^+$	
		148^{+32}_{-18}		90^{+12}_{-8}	

modified frequentist method returns the probability (p-value) of the background-only fluctuating to give the observed yields or higher. In 5×10^9 background pseudoexperiments, we find 213 trials with an LLR value smaller or equal to that observed in data. This gives a p-value of 4.3×10^{-8} which corresponds to a 5.3 standard deviation (σ) observed significance (3.7σ expected). The probability for the signal plus background hypothesis to give less signal-like observations than the observed one is 0.87. A correction factor of 0.93, derived using PYTHIA, is used to convert the measured cross section for $(Z/\gamma^*) \times (Z/\gamma^*)$ into that for ZZ production. Minimizing the LLR function we obtain a cross section of $\sigma(ZZ) = 1.75^{+1.27}_{-0.86}$(stat) $\pm$ 0.13(syst) pb for this analysis.

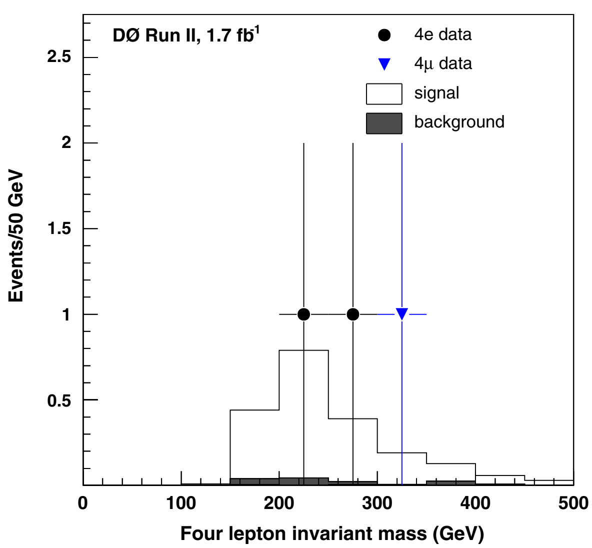

FIG. 1 (color online). Distribution of four lepton invariant mass in data, expected signal, and expected background.

This result is combined with the results from an independent $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ search [15], and the previous $(Z/\gamma^*)(Z/\gamma^*) \to \ell^+\ell^-\ell'^+\ell'^-$ analysis [5] which used a separate data sample with a looser mass requirement $M(\ell\ell) > 30$ GeV. The earlier search contributes no signal events, and we have scaled its background estimate to the tighter kinematic range used in the recent analysis. The combination of the three analyses is performed taking into account the correlations of systematic uncertainties between subchannels and among analyses. The resulting p-value is 6.2×10^{-9}, and the significance for observation of ZZ production increases to 5.7σ (4.8σ expected). The probability for the signal plus background hypothesis to give less signal-like observations than the observed one is 0.71. We therefore report the observation of a ZZ signal at a hadron collider with a combined cross section of $\sigma(ZZ) = 1.60 \pm 0.63$(stat)$^{+0.16}_{-0.17}$(syst) pb, consistent with the standard model expectation.

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