

## Search for Exclusive Z-Boson Production and Observation of High-Mass $p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow pl^+l^-\bar{p}$ Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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This Letter presents a search for exclusive  $Z$  boson production in proton-antiproton collisions at  $\sqrt{s} = 1.96$  TeV, using the CDF II detector. No exclusive  $Z \rightarrow l^+l^-$  candidates are observed and the first upper limit on the exclusive  $Z$  cross section in hadron collisions is found to be  $\sigma_{\text{excl}}(Z) < 0.96$  pb at 95% confidence level. In addition, eight candidate exclusive dilepton events from the process

$p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow pl^+l^-\bar{p}$  are observed, and a measurement of the cross section for  $M_{ll} > 40 \text{ GeV}/c^2$  and  $|\eta_l| < 4$  is found to be  $\sigma = 0.24_{-0.10}^{+0.13} \text{ pb}$ , which is consistent with the standard model prediction.

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At the Tevatron  $p\bar{p}$  collider it is possible to produce  $Z$  bosons exclusively, in association with no other particles except the  $p$  and  $\bar{p}$ :  $p\bar{p} \rightarrow pZ\bar{p}$ . The colliding hadrons emerge intact with small transverse momenta,  $p_T$  [1]. The process is predicted by the standard model (SM) to proceed via photoproduction. A radiated virtual photon fluctuates to a  $q\bar{q}$  loop which scatters elastically by two-gluon exchange on the (anti)proton and materializes as a  $Z$ , as shown in Fig. 1(a). The same mechanism gives photoproduction of the vector mesons  $J/\psi$ ,  $\psi(2S)$  and  $\Upsilon$ , which have been studied in  $ep$  collisions at HERA [2] and recently observed in  $p\bar{p}$  collisions by CDF [3]. The SM cross section for exclusive  $Z$  production is predicted to be  $\sigma_{\text{excl}}(Z) = 0.3 \text{ fb}$  by Ref. [4] and  $0.21 \text{ fb}$  by Ref. [5], and is thus below the threshold for detection in the  $\sim 2 \text{ fb}^{-1}$  data set used in this analysis. An observation at the Tevatron would therefore be evidence for beyond SM (BSM) physics. A BSM theory of the pomeron [6] predicts a much larger cross section, possibly orders of magnitude larger, but without a quantitative estimate. In this theory the pomeron couples strongly to the electroweak sector through a pair of color sextet quarks which contribute to the quark loop shown in Fig. 1(a).

This Letter presents a search for exclusive  $Z$  production with the  $Z$  decaying to a  $\mu^+\mu^-$  or  $e^+e^-$  pair, and a measurement of the cross section for exclusive  $\mu^+\mu^-$  and  $e^+e^-$  production with dilepton invariant mass  $M_{ll} > 40 \text{ GeV}/c^2$  and  $|\eta_l| < 4$ . We used the CDF II detector at the Tevatron with  $p\bar{p}$  collisions at a center of mass energy  $\sqrt{s} = 1.96 \text{ TeV}$ . The exclusive dilepton process is expected in quantum electrodynamics (QED) through  $p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow pl^+l^-\bar{p}$ , as shown in Fig. 1(b). For the remainder of this Letter this process will be referred to as  $\gamma\gamma \rightarrow l^+l^-$  for convenience. We have previously observed  $\gamma\gamma \rightarrow e^+e^-$  with  $10 < M_{ee} < 40 \text{ GeV}/c^2$  [7] and  $\gamma\gamma \rightarrow \mu^+\mu^-$  with  $3 < M_{\mu\mu} < 4 \text{ GeV}/c^2$  [3] and measured cross sections in agreement with expectations. The final state particles in exclusive dilepton events are identical to those in exclusive  $Z$  production with leptonic decay, the only difference in the signature being the  $M_{ll}$  distribution and other kinematics. Agreement with the precise theoretical prediction therefore gives us confidence in our sensitivity to selecting exclusive  $Z$  bosons.

CDF II is a general purpose detector which is described in detail elsewhere [8]. Surrounding the collision region is a tracking system consisting of silicon microstrips and a cylindrical drift chamber, the central outer tracker (COT), in a 1.4 Tesla solenoid. The tracking system tracks particles with  $p_T \gtrsim 0.3 \text{ GeV}/c$  and pseudorapidity  $|\eta| \lesssim 2$  [1]. Central and end-plug calorimeters cover the range  $|\eta| < 1.3$  and  $1.3 < |\eta| < 3.6$ , respectively, with separate elec-

tromagnetic (EM) and hadronic (HAD) compartments. Outside the calorimeters, drift chambers measure muons in the region  $|\eta| < 1.0$ . The regions  $3.6 < |\eta| < 5.2$  are covered by lead-liquid scintillator calorimeters called the miniplugs [9]. At higher pseudorapidities,  $5.4 < |\eta| < 7.4$ , scintillation counters called beam shower counters (BSC) are located along the beam pipe. Gas Čerenkov detectors covering  $3.7 < |\eta| < 4.7$  measure the luminosity with a 6% uncertainty [10]. Tracking detectors in a Roman pot spectrometer [11] can detect antiprotons with small  $p_T$  and  $0.03 \lesssim \xi(\bar{p}) \lesssim 0.08$ , where  $\xi(\bar{p})$  is the fractional momentum loss of the antiproton [12]. These detectors were operational for approximately 30% of the data set used in this analysis.

For the  $\gamma\gamma \rightarrow l^+l^-$  event selection a sample of  $l^+l^-$  pairs was selected in a kinematic region where this process has not previously been observed, with  $M_{ll} > 40 \text{ GeV}/c^2$  and lepton transverse momenta  $p_T^l > 20 \text{ GeV}/c$ . For the exclusive  $Z$  search a subsample was selected with an invariant mass close to the  $Z$  mass,  $82 < M_{ll} < 98 \text{ GeV}/c^2$ , and  $p_T^l > 25 \text{ GeV}/c$ . The  $\mu^+\mu^-$  events were collected with a trigger requiring one muon with  $p_T > 18 \text{ GeV}/c$ . Offline two candidate muons were required. One muon was required to have been detected in the COT, the central calorimeter, and the muon chambers, and therefore to have  $|\eta_\mu| < 1.0$ . To increase the acceptance the second muon was only required to be detected in the COT and therefore to have  $|\eta_\mu| < 1.5$ . Events consistent with cosmic rays were eliminated with an identification algorithm [13] that used the timing of the COT drift chamber hits. The muon kinematics were found from the COT track momentum measurement. The  $e^+e^-$  events were collected with a trigger requiring one central electron with  $p_T > 18 \text{ GeV}/c$ . Offline we required one candidate electron to be reconstructed in the central EM calorimeter and matched to a COT track, and a second electron to be reconstructed either in the same way or in the end-plug EM calorimeter where no matching COT track was required, since the tracking efficiency is lower in this region. The central electrons have  $|\eta_e| < 1.3$  and the end-plug elec-

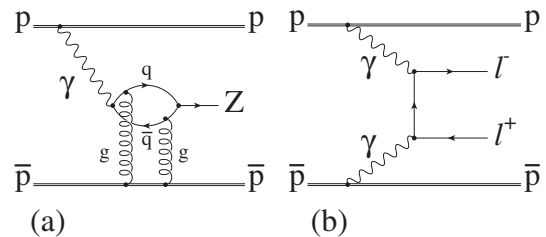


FIG. 1. (a) Exclusive photoproduction of a  $Z$  boson and (b) exclusive dilepton production via two-photon exchange.

trons have  $1.3 < |\eta_e| < 3.6$ . The electron kinematics were found from the calorimeter energy measurement, but if a track was matched to the calorimeter cluster it was used to determine the electron direction. If no track was matched the  $z$  position of the interaction was measured from the other electron track, and was used to determine the kinematics. With an integrated luminosity of  $2.20(2.03) \text{ fb}^{-1}$  in the electron (muon) channels we found a total of 317712 candidate dileptons with  $M_{ll} > 40 \text{ GeV}/c^2$ , of which 183332 were in the  $Z$  region  $82 < M_{ll} < 98 \text{ GeV}/c^2$ .

Starting with the dilepton samples, events that were consistent with arising from exclusive production were selected by requiring that no other particles were produced in the collision. We vetoed events with any additional tracks reconstructed in the COT or the silicon tracker, or in which any of the calorimeters had a total energy deposition above that expected from noise. For this purpose the calorimeters were divided into five subdetectors (the central EM, the plug EM, the plug HAD, and the East and West miniplug) and the energy of all towers was summed, excluding those traversed by and surrounding the charged leptons, to give five  $\Sigma E$  values. Each  $\Sigma E$  was required to be less than a threshold, which was determined by studying two control samples: (1) events selected with a random bunch-crossing (zero bias) trigger with no tracks in the event, which should give distributions dominated by noise and (2)  $W \rightarrow l\nu$  events with no detected tracks other than that of the charged lepton, which should give the distributions expected for nonexclusive  $Z \rightarrow l^+l^-$  events with no additional tracks. The production mechanism for nonexclusive  $W$  bosons is very similar to that for  $Z$  bosons and the cross section for exclusive  $W$  production ( $p\bar{p} \rightarrow nW\bar{p}$ ) is negligible, making them an excellent control sample.

These exclusivity cuts rejected exclusive events that were in coincidence with additional inelastic  $p\bar{p}$  collisions. It was therefore necessary to define an effective integrated luminosity  $\int \mathcal{L}_{\text{eff}}$ , for single interactions. The fraction of bunch crossings, selected from the zero bias trigger, that passed the exclusivity cuts was used to establish that  $\int \mathcal{L}_{\text{eff}} = 20.6\%$  of the total integrated luminosity. The fraction was found from distributions reweighted to account for the difference in the instantaneous luminosity profiles between the zero bias events and the  $Z$  events. This method properly accounts for events with no interactions that failed the cuts due to noise in the calorimeters and fake reconstructed tracks, and events with a very soft interaction that passed the exclusivity cuts. We found  $\int \mathcal{L}_{\text{eff}} = (403 \pm 45) \text{ pb}^{-1}$  and  $(467 \pm 50) \text{ pb}^{-1}$  for the  $\mu^+\mu^-$  and  $e^+e^-$  samples, respectively. The uncertainty includes a contribution of 9% obtained from an independent determination of  $\int \mathcal{L}_{\text{eff}}$  (to be 18.7% of the total integrated luminosity) using Poisson statistics and the mean number of expected interactions per bunch crossing as a function of instantaneous luminosity, and a contribution of 6% from the uncertainty on the CDF luminosity measurement.

In order to reduce the background from  $\gamma\gamma \rightarrow l^+l^-$  events where the proton dissociates into forward-going hadrons, we also made cuts on hits in the BSC detectors. An event was vetoed if any photomultiplier had hits above threshold. The inefficiency of this requirement was included in the acceptance.

A total of eight events passed the  $\gamma\gamma \rightarrow l^+l^-$  selection criteria and no events passed the tighter exclusive  $Z \rightarrow l^+l^-$  criteria. We used these events to measure the cross section for the  $\gamma\gamma \rightarrow l^+l^-$  process and we set an upper limit on the cross section for exclusive  $Z$  production. To do this it was necessary to determine the acceptance for reconstructing the events, and the expected number of background events.

We calculated the acceptance for reconstructing  $\gamma\gamma \rightarrow l^+l^-$  events using the LPAIR [14] Monte Carlo (MC) event generator together with a GEANT [15] simulation of the CDF detector. We applied corrections to account for changes in the acceptance due to internal bremsstrahlung from the leptons, using the PHOTOS [16] MC event generator. The acceptance for the exclusive  $Z$  search was found from the PYTHIA [17] MC event generator, which simulates nonexclusive  $Z/\gamma^* \rightarrow l^+l^-$  events. Corrections were applied to account for the difference in kinematics between nonexclusive and exclusive production. We considered the  $Z p_T$  distribution, which was assumed to be between 0 and 2 GeV/ $c$  for exclusive  $Z$  production, the  $Z$  rapidity  $y_Z$  distribution, obtained from Ref. [4], and the angular distribution of the leptons.

The backgrounds to the  $\gamma\gamma \rightarrow l^+l^-$  events were nonexclusive  $Z/\gamma^* \rightarrow l^+l^-$  events that pass the exclusivity cuts, and  $\gamma\gamma \rightarrow l^+l^-$  events where the proton or antiproton dissociates and the products were not detected in the forward detectors. The former was found to be  $0.28 \pm 0.19$  events by assuming the fraction of nonexclusive  $Z/\gamma^* \rightarrow l^+l^-$  events passing the exclusivity cuts to be the same as that for nonexclusive  $W \rightarrow l\nu$  events. This fraction was found from  $W \rightarrow l\nu$  data samples, selected by requiring a high  $p_T$  lepton and large missing transverse energy, to be  $(9 \pm 6) \times 10^{-7}$ , where the uncertainty is from the statistics of the samples. The latter was found from the LPAIR event generator, which also simulates  $\gamma\gamma \rightarrow l^+l^-$  events where either the proton or antiproton or both dissociate. We used the minimum bias Rockefeller MC [18], which fragments the excited (anti)proton into a nucleon and pions, to predict the fraction of dissociation events that failed our exclusivity cuts due to particles in the region  $|\eta| < 7.4$ , which is the edge of the BSC acceptance. We predicted a total background of  $1.45 \pm 0.61$  events, where the uncertainty came from varying the exclusivity cuts and observing how the number of events changes.

The backgrounds to exclusive  $Z$  events were nonexclusive  $Z/\gamma^* \rightarrow l^+l^-$  events that passed the exclusivity cuts and exclusive  $\gamma\gamma \rightarrow l^+l^-$  events with  $M_{ll}$  in the  $Z$  mass window. The former was found to be  $0.163 \pm 0.099$  events

TABLE I. Properties of the eight exclusive dilepton events, in order of  $M_{ll}$ .

Final state	$M_{ll}$ (GeV/ $c^2$ )	$p_T^l(1)$ (GeV/ $c$ )	$p_T^l(2)$ (GeV/ $c$ )	$180^\circ - \Delta\phi_{ll}$ (degrees)	$p_T(ll)$ (GeV/ $c$ )
$e^+e^-$	40.9	20.4	20.1	0.38	0.26
$e^+e^-$	49.3	24.5	24.6	0.37	0.21
$e^+e^-$	50.4	20.5	20.2	0.05	0.31
$e^+e^-$	56.3	24.8	24.9	0.48	0.24
$\mu^+\mu^-$	58.6	24.1	24.4	0.17	0.32
$\mu^+\mu^-$	66.0	31.8	31.3	0.75	0.65
$e^+e^-$	67.1	24.1	24.0	0.51	0.24
$e^+e^-$	75.6	34.1	33.1	0.23	1.01

using the method described above, and the latter was found from the LPAIR MC samples to be  $0.492 \pm 0.061$  events. We did not include a dissociation background for the exclusive  $Z$  search; instead we quote an upper limit on the cross section for a  $Z$  produced with no other particles with  $|\eta| < 7.4$ .

From a study of the acolinearity and timing of the tracks it was deduced that none of the candidate events were consistent with being induced by cosmic rays.

We calculated a cross section for each final state using the formula

$$\sigma = \frac{N - N_{\text{bck}}}{\alpha \int \mathcal{L}_{\text{eff}}},$$

where  $N$  is the number of candidate events,  $N_{\text{bck}}$  is the expected number of background events, and  $\alpha$  is the acceptance. Assuming equal rates for the  $\mu^+\mu^-$  and  $e^+e^-$  processes, a combined cross section was found by forming a joint likelihood for the final states, which is the product of the Poisson probabilities to observe  $N$  events in each final state. The method is described in Ref. [19]; a prior that is flat for positive cross sections was assumed. The combined cross section for one lepton flavor was found to be  $\sigma(p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow pl^+l^-\bar{p}) = 0.24_{-0.10}^{+0.13}$  pb for  $M_{ll} > 40$  GeV/ $c^2$  and  $|\eta_l| < 4$ , which is in good agreement with the LPAIR prediction of 0.256 pb.

Some of the kinematic properties of the candidate events are given in Table I, where  $p_T^l(1)$  and  $p_T^l(2)$  are the lepton transverse momenta,  $\Delta\phi_{ll}$  is the difference in the azimuthal lepton angles (i.e.,  $180^\circ$  minus  $\Delta\phi_{ll}$  is the deviation from back-to-back in the transverse plane) and  $p_T(ll)$  is the  $p_T$  of the lepton pair. The resolution of the lepton transverse momenta is approximately 3.5 (1.4)% for electrons (muons). All of the events have lepton pairs that are back-to-back in azimuth with low  $p_T(ll)$  values, which is expected for  $\gamma\gamma \rightarrow l^+l^-$  events. Figures 2(a) and 2(b) show the dilepton invariant mass and  $180^\circ$  minus  $\Delta\phi_{ll}$  distributions for the data together with the QED spectrum from LPAIR and the GEANT detector simulation. A good agreement with the data is observed.

No events passed our exclusive  $Z \rightarrow l^+l^-$  selection criteria, therefore we place an upper limit on the cross section of exclusive  $Z$  production at the Tevatron. We summed the

final states to give  $\sum N = 0$ ,  $\sum N_{\text{bck}} = 0.66 \pm 0.11$ , and  $\alpha \int \mathcal{L}_{\text{eff}} \times \text{BR}(l^+l^-) = 3.22 \pm 0.38$  pb $^{-1}$ . Here we have used  $\text{BR}(l^+l^-) = 3.37\%$  as the branching fraction of the  $Z$  to decay to one lepton flavor pair. We used a Bayesian limit technique to set an upper limit on the exclusive  $Z$  cross section of  $\sigma_{\text{excl}}(Z) < 0.96$  pb at 95% confidence level. We also set an upper limit on the differential cross section with respect to  $y_Z$  at  $y_Z = 0$  ( $\frac{d\sigma}{dy}|_{y=0}$ ) using the theoretical prediction of the  $y_Z$  distribution [4]. We took 0.257 as the ratio of  $\frac{d\sigma}{dy}|_{y=0}$  to  $\sigma_{\text{excl}}(Z)$  and find  $\frac{d\sigma}{dy}|_{y=0} < 0.25$  pb at 95% confidence level.

At hadron colliders the lepton kinematics in  $\gamma\gamma \rightarrow l^+l^-$  events determine the momenta of the forward (anti)protons through the relation  $\xi(p_{1(2)}) = \frac{1}{\sqrt{s}} \sum_{i=1,2} p_T^i e^{+(-)\eta_i}$  [1,12], where  $\xi(p_{1(2)})$  is the fractional momentum loss of the forward (backward) hadron. In principle this relation could be used to calibrate both the momentum scale and resolution of forward proton spectrometers. In our eight candidate events, only one—that with  $M_{\mu\mu} = 66.0$  GeV/ $c^2$ —was from a period when the Roman pot spectrometer was operational and with  $\xi(\bar{p})$  in its acceptance; a track is observed, as expected for exclusive dilepton production. This is an encouraging sign that exclusive dilepton events at the large hadron collider (LHC) may be used to calibrate forward proton spectrometers [20].

In conclusion, we have observed exclusive production of high mass ( $M_{ll} > 40$  GeV/ $c^2$ )  $e^+e^-$  and  $\mu^+\mu^-$  pairs and

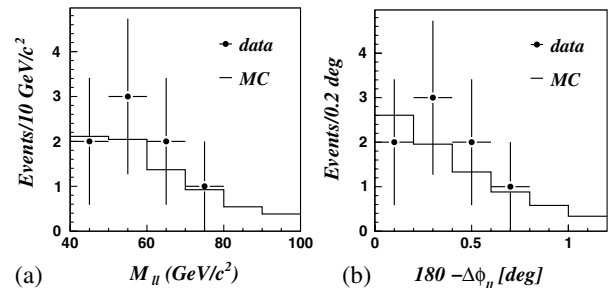


FIG. 2 (color online). (a) The dilepton invariant mass distribution, and (b) the distribution of  $180^\circ$  minus the difference in the azimuthal lepton angles for the data and the LPAIR prediction with the GEANT detector simulation, scaled to account for acceptance and luminosity.

measured a cross section that agrees with QED expectations. We observed no candidates for exclusive Z production and put an upper limit on the photoproduction of Z at a level  $\approx 3,000$  times higher than SM predictions.

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- [1] A cylindrical coordinate system is used with the  $z$  axis along the proton beam direction;  $\theta$  is the polar angle and  $\phi$  is the azimuthal angle. The transverse momentum  $p_T$  is the momentum perpendicular to the  $z$  axis. We define rapidity as  $y = \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$  where  $E$  and  $p_z$  are the energy and momentum parallel to the  $z$  axis, pseudorapidity as  $\eta = -\ln \tan(\theta/2)$  and transverse energy as  $E_T = E \sin\theta$ .
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- [12] A forward  $\bar{p}$  has fractional momentum loss  $\xi(\bar{p}) = 1 - \frac{p_z}{980}$ , where  $p_z$  is the  $\bar{p}$  momentum (GeV/ $c$ ) after an interaction.
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