Search for New High-Mass Particles Decaying to Lepton Pairs in \( p \bar{p} \) Collisions at \( \sqrt{s} = 1.96 \) TeV

A search for new particles (X) that decay to electron or muon pairs has been performed using approximately 200 pb$^{-1}$ of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected by the CDF II experiment at the Fermilab Tevatron. Limits on $\sigma(p\bar{p}\rightarrow X)BR(X\rightarrow \ell \ell)$ are presented as a function of dilepton invariant mass $m_{\ell\ell} > 150$ GeV/$c^2$, for different spin hypotheses (0, 1, or 2). The limits are approximately 25 fb for $m_{\ell\ell} > 600$ GeV/$c^2$. Lower mass bounds for X from representative models beyond the standard model including heavy neutral gauge bosons are presented.

A search for new particles (X) has been performed in the dilepton ($ee$ and $\mu\mu$) decay channel using $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected by the upgraded Collider Detector at Fermilab (CDF II) at the Tevatron. The observed dilepton invariant mass ($m_{\ell\ell}$) distribution is compared with that expected from standard model (SM) processes for $m_{\ell\ell} > 150$ GeV/$c^2$. Many models beyond the SM predict such particles with masses at or below the TeV scale [1]. Generic searches for spin 0, 1, and 2 particles are performed, taking into account the dependence of the experimental acceptance on the spin-dependent angular distributions of the lepton pair. While this approach provides sensitivity to broad classes of new models, the spin 1 result addresses an issue of fundamental importance in particle physics: the possible existence of extra neutral gauge bosons expected in many models with a higher...
gauge structure than that of the SM. A generic SM-like (sequential) $Z'$ boson ($Z'_{\text{SM}}$) is defined to have the same coupling strengths to fermions as those of the SM $Z^0$ boson and its mass bound provides a convenient reference indicating the experimental sensitivity. The previous best $Z'_{\text{SM}}$ lower mass bounds from direct searches are 690 GeV/$c^2$ by the CDF collaboration [2] and 670 GeV/$c^2$ by the D0 collaboration [3] at the 95% confidence level (C.L.) [4]. Increased integrated luminosity and center-of-mass energy for Run II are expected to provide a significant improvement over these previous results. Indirect limits on the mass of $Z'$ bosons have been set by the LEP II experiments [5]. A more detailed discussion of the LEP results and the advantages of the Tevatron search can be found in Ref. [6]. In addition to $Z'_{\text{SM}}$, we consider $Z'$ bosons (spin 1) from the $E_6$ model ($Z_\chi, Z_\phi, Z_\eta, Z_\ell$) [7] and the littlest Higgs model ($Z_H$) [8], technicolor (TC) particles (spin 1) [9], sneutrinos ($\tilde{\nu}$) in an $R$-parity violating supersymmetric model (spin 0) [10], and gravitons in the Randall-Sundrum (RS) warped extra dimension model (spin 2) [11]. Independent of specific models, the limits on $\sigma(X\ell\ell) \equiv \sigma(p\bar{p} \rightarrow X)BR(X \rightarrow \ell\ell)$ presented here can be used to set lower bounds on the mass of $X (m_X)$ in many classes of models with a narrow width resonance. Using the spin 1 $\sigma(X\ell\ell)$ limit result, bounds on the couplings in more generalized $Z'$ models [6] have been derived and are presented.

The CDF II detector is a forward-backward and azimuthally symmetric detector with a tracking system immersed in a 1.4 T solenoidal magnetic field, calorimetry for measuring the energies of particles, and detectors to identify deeply penetrating muons [12]. The tracking system consists of an open-cell drift chamber, the central outer tracker (COT), surrounding an eight layer silicon tracker. The fiducial coverage of the COT is $|\eta| < 1.0$ and the silicon extends this coverage forward to $|\eta| < 1.8$ [13]. The tracking system is surrounded by electromagnetic (EM) and hadronic calorimeters that are divided into a central calorimeter ($|\eta| < 1.1$) and two forward, or “plug,” calorimeters ($1.2 < |\eta| < 3.6$). Drift chambers, located outside the hadronic calorimeters and also outside an additional 60 cm of iron shield, detect muons having $|\eta| < 1.0$.

Candidate events are selected from data collected during 2002–2003, corresponding to an integrated luminosity ranging from 173 to 200 pb$^{-1}$, depending upon the detector elements required for the analysis. Dielectron events with a central candidate are collected using a single-electron trigger requiring a loosely selected electron in the central EM calorimeter with $E_T > 18$ GeV and a matching COT track with $p_T > 9$ GeV/$c$. Dielectron events without a central candidate are collected using a trigger requiring two loosely selected electron candidates in the plug EM calorimeter with $E_T > 18$ GeV and no tracking requirement. Additional triggers with higher $E_T$ thresholds but looser electron-selection requirements are used to ensure full efficiency for high-mass events.

Together, these triggers are essentially 100% efficient for the $ee$ decay mode for $m_{\ell\ell} > 150$ GeV/$c^2$. Dimuon candidate events are collected with single-muon triggers which require a muon-chamber track with a matching track measured by the COT with $p_T > 18$ GeV/$c$. The overall trigger efficiency for the $\mu\mu$ decay mode is above 90%.

The dilepton event selection requires at least two electron or two muon candidates with no charge requirement. Both electron and muon candidates are required to be isolated with a cut on the energy found within a cone of angular radius $R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4$ around the lepton candidate. Electron candidates require an EM cluster with $E_T > 25$ GeV and longitudinal and transverse shower profiles consistent with electrons [14]. At least one of the two electrons is required to have a matching track, except...
for events with two central electrons, which both require matching tracks. The inclusion of events with two forward electrons is possible due to a calorimeter-seeded forward tracking algorithm [13]. Events with a significant amount of $E_T$ are rejected to remove $W +$ jets and other backgrounds with unreconstructed particles. All muon candidates are required to have a COT track with $p_T > 20$ GeV/c and calorimeter energy deposition consistent with a minimum-ionizing particle signal, where at least one candidate must also have a matching track in the muon chambers. To reject cosmic-ray events, muon candidates are required to have COT hit timing consistent with outward-moving particles [16].

The selected data contain 14 799 $ee$ and 7775 $\mu\mu$ candidate events with the dilepton invariant mass distributions shown in Fig. 1. These samples are dominated by events in the $Z^0$ peak. In this region the dielectron sample has a larger acceptance; however, in the high-mass search region the two channels have similar sensitivity. The lepton identification efficiencies are estimated using a purified sample of dilepton events from $Z^0$ decays [2]. Since leptons from the decay of high-mass objects typically have higher $p_T$ than this sample, the lepton identification efficiency is studied as a function of $p_T$, and the selection criteria are chosen to ensure high efficiencies throughout the relevant $p_T$ range [17, 18]. The geometric and kinematic acceptance as a function of resonance mass is estimated using Monte Carlo (MC) samples: the PYTHIA event generator [19] with CTEQ5L parton distribution functions (PDFs) [20] and the CDF II detector simulation are used except as noted. Signal samples for the heavy Higgs (spin 0), $Z_{SM}^\text{SM}$ (spin 1), and RS Graviton (spin 2) are generated to model each spin hypothesis. The product of acceptance and selection efficiency is approximately 50% for $m_X > 400$ GeV/c$^2$ for $ee$ and $\mu\mu$ for all spins.

The primary and irreducible SM background results from Drell-Yan production of $ee$ and $\mu\mu$ pairs. It is estimated using MC simulation normalized to fit to the data in the $Z^0$ peak, after the other background contributions have been subtracted. This reduces the effect of the luminosity uncertainty on the background estimate. The other contributions such as $t\bar{t}$ (generated with HERWIG [21]), $\tau^+\tau^-, W^-W^+$, and $W^\pm Z^0$ are estimated using MC simulation. Some accepted $ee$ events come from nondilepton sources, predominantly misidentified QCD dijet events. This background is estimated by extrapolating from events where the leptons are not isolated. The QCD background in the $\mu\mu$ channel is estimated using same-sign events that pass the selection criteria and is found to be small. The cosmic-ray background in the $\mu\mu$ channel is estimated by applying the signal selection criteria to a sample of cosmic-ray data collected by the CDF II detector and is non-negligible at high mass ($m_{\ell\ell} > 400$ GeV/c$^2$).

Figure 1 compares the estimated background distributions to the $ee$ and $\mu\mu$ data. Table I shows the integrated number of events observed and expected above a given $m_{\ell\ell}$.

Systematic uncertainties on the acceptance, efficiency, and luminosity result in a relative uncertainty on the scale of $\sigma(X_{\ell\ell})$ of approximately 10%. The largest contributions

![FIG. 2 (color online). The $\sigma(X_{\ell\ell})$ limits from $ee$, $\mu\mu$, and the combined channels as a function of $m_X$ for spin 0 (a), spin 1 (b), and spin 2 (c). For the combined channel, $BR(X \rightarrow ee) = BR(X \rightarrow \mu\mu) \frac{1}{(1 + BR(X \rightarrow \ell\ell))}$ is assumed. Also shown are theoretical cross-section predictions of some representative models [22].]
are from the uncertainties on luminosity, energy and momentum scales and resolutions, and the choice of PDF as estimated by comparison of different PDF parametrizations. Background uncertainty in the $ee$ channel ranging from 40–80% due to misidentified jets results in absolute uncertainties on values of $\sigma(X_{\ell\ell})$ that are large for $m_{\ell\ell} < 350\text{ GeV}/c^2$ but negligible at the higher mass region. Background uncertainties in the $\mu\mu$ channel are $\approx 30\%$ and $\approx 20\%$ due to fake muons and cosmic rays, respectively. The relative uncertainty with respect to the scale of $\sigma(X_{\ell\ell})$ on the electroweak backgrounds is $\approx 5\%$ in both channels.

Since no significant excess of events is observed, limits on $\sigma(X_{\ell\ell})$ are extracted using a Bayesian, binned likelihood method. For combined dilepton results assuming $BR(\ell\ell) = BR(X \rightarrow \ell\ell)$, a joint likelihood is formed from the product of the individual-channel likelihoods accounting for the correlations among systematic uncertainties. When the nuisance parameters are integrated out, uncertainties on PDF, luminosity and common selection efficiencies are taken as 100% correlated among the different components of the acceptance. This joint likelihood is converted to a posterior density in the signal cross section acceptance. This joint likelihood is computed to a posterior density in the signal cross section acceptance.

The two dashed lines show the range between which the values of $\lambda^2$ are obtained from the combined channel: 825, 690, 675, 720, and 615 GeV$/c^2$ from $ee$ channel and 665, 590, and 450 GeV$/c^2$ from $\mu\mu$ channel are obtained for $\bar{\nu}$ for the coupling strength squared times branching fraction $(\lambda^2 \cdot BR) = 0.01, 0.005, \text{and } 0.001$, respectively. For spin 1 [Fig. 2(b)] the following mass bounds are obtained from the combined channel: $825, 690, 675, 720, \text{and } 615$ GeV$/c^2$ for $Z_{SM}, Z_{X}, Z_{\psi}, Z_{\eta}, \text{and } Z_{\ell}$, respectively, and $885, 860, 805, \text{and } 725$ GeV$/c^2$ for $Z_{H}$ with the mixing parameter $\cot\theta_H = 1.0, 0.9, 0.7, \text{and } 0.5$, respectively. Similarly, the lower mass limits of 280 GeV$/c^2$ (270 GeV$/c^2$) are set for $\rho_{TC}$ and $\omega_{TC}$ in the TC model [9] with corresponding values of Technicolor-scale mass parameters $M_\nu = M_A$ of 500 GeV$/c^2$ (400 GeV$/c^2$). From the spin 2 $\sigma(X_{\ell\ell})$ limit shown in Fig. 2(c), the lower mass bounds of 710, 510, and 170 GeV$/c^2$ are obtained for the first excited state of the RS graviton for dimensionless coupling parameter $(k/M_{Pl}) = 0.1, 0.05, \text{and } 0.01$, respectively, where $k$ is the relative strength of the warped dimension’s curvature scale and $M_{Pl}$ is the effective Planck scale. A method of factorizing the couplings, charges, and $1/s$ dependence of $Z'$ cross sections from kinematic factors that depend upon PDF parametrizations allows more general constraints on possible $Z'$ models [6]. In this formalism, a generic $Z'$ is described by two parame-

![FIG. 3 (color online). Limit contours in the $(c_d, c_u)$ plane [6] for a given $Z'$ mass derived from the spin 1 $\sigma(X_{\ell\ell})$ limit. All possible models for the $U(1)_{\eta-xu}$ group are on the diagonal solid line, and those for the $U(1)_{\eta+su}$ group are below the dotted line. The two dashed lines show the range between which the values for the $U(1)_{\eta-xu}$ group must fall. The values for the $U(1)_{\eta-xu}$ group may fall anywhere on the plane. The parameters of the $E_6$-model $Z'$ bosons are indicated.](image-url)
ters, $c_d$ and $c_u$, that define the coupling of down and up-type quarks to the resonance. Figure 3 shows the bounds set by the spin 1 limits in the $(c_d, c_u)$ plane along with the parameters describing the four $E_6$-model $Z'$ bosons.

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[4] All the limits presented in this paper are at the 95% C.L.
[13] CDF uses a cylindrical coordinate system in which $\phi$ is the azimuthal angle, and $+z$ points in the direction of the proton beam and is zero at the center of the detector. The pseudorapidity $\eta = -\ln (\tan (\theta / 2))$, where $\theta$ is the polar angle relative to the $z$ axis. Calorimeter energy (track momentum) measured transverse to the beam is denoted as $E_T (p_T)$, and the total calorimetric transverse energy imbalance is denoted as $\delta E_T$.
[22] The Refs. [17,18] show all the cross-section predictions of theoretical models which are used to derive the lower mass bounds.
[23] A constant $K$ factor of 1.3 is used to be consistent with the previous analyses making comparison of the $Z'$ mass limits easier. The NLO calculation is used for the RPV $\nu$ case. The dependence on the higher order corrections for the $\sigma(X_{\ell\ell})$ limits is negligible.