

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

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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 $\sqrt{s} = 1.96 \text{ TeV}$ 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 $m_{\ell\ell} > 150 \text{ GeV}/c^2$, for different spin hypotheses (0, 1, or 2). The limits are approximately 25 fb for $m_{\ell\ell} > 600 \text{ GeV}/c^2$. Lower mass bounds for X from representative models beyond the standard model including heavy neutral gauge bosons are presented.

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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 $\sqrt{s} = 1.96 \text{ TeV}$ 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 $m_{\ell\ell} > 150 \text{ GeV}/c^2$. 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'_{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'_{SM} lower mass bounds from direct searches are $690 \text{ GeV}/c^2$ by the CDF collaboration [2] and $670 \text{ GeV}/c^2$ 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'_{SM} , we consider Z' bosons (spin 1) from the E_6 model ($Z_\chi, Z_\psi, Z_\eta, Z_I$) [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 $E_T > 18 \text{ GeV}$ and a matching COT track with $p_T > 9 \text{ GeV}/c$. Dielectron events without a central candidate are collected using a trigger requiring two loosely selected electron candidates in the plug EM calorimeter with $E_T > 18 \text{ GeV}$ 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 $m_{\ell\ell} > 150 \text{ GeV}/c^2$. Dimuon candidate events are collected with single-muon triggers which require a muon-chamber track with a matching track measured by the COT with $p_T > 18 \text{ GeV}/c$. 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 $E_T > 25 \text{ GeV}$ 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

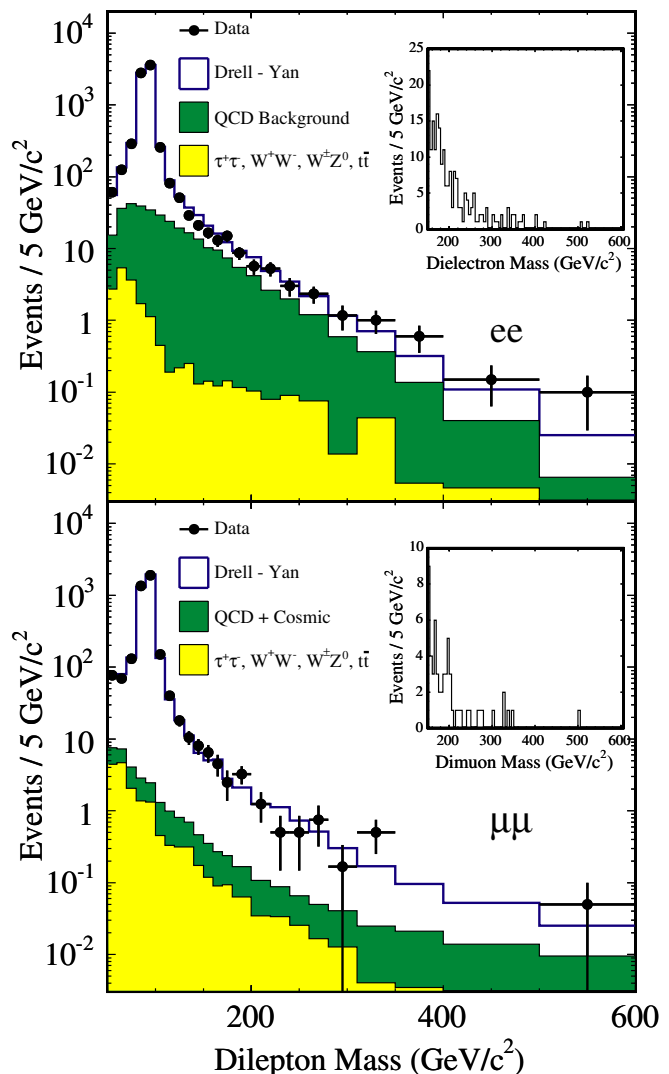


FIG. 1 (color online). The ee (top panel) and $\mu\mu$ (bottom panel) invariant mass distributions of the observed data (points) with the background prediction (solid line). The background is corrected for acceptance and efficiency. The insets show the data with a fixed bin width of $5 \text{ GeV}/c^2$ for $m_{\ell\ell} > 150 \text{ GeV}/c^2$.

TABLE I. Integrated number of events above a given $m_{\ell\ell}$ for the observed data and estimated background.

$m_{\ell\ell}$ (GeV/ c^2)	ee		$\mu\mu$	
	Observed	Expected	Observed	Expected
>150	205	212.9 ± 99.3	58	55.3 ± 2.5
>200	84	78.2 ± 33.4	18	20.9 ± 1.0
>300	22	13.6 ± 4.4	6	5.2 ± 0.3
>400	5	2.9 ± 0.7	1	2.3 ± 0.2
>500	2	0.8 ± 0.1	1	1.2 ± 0.1

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 [15]. Events with a significant amount of \cancel{E}_T are rejected to remove W + jets and others 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 14799 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} (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 nondielectron 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

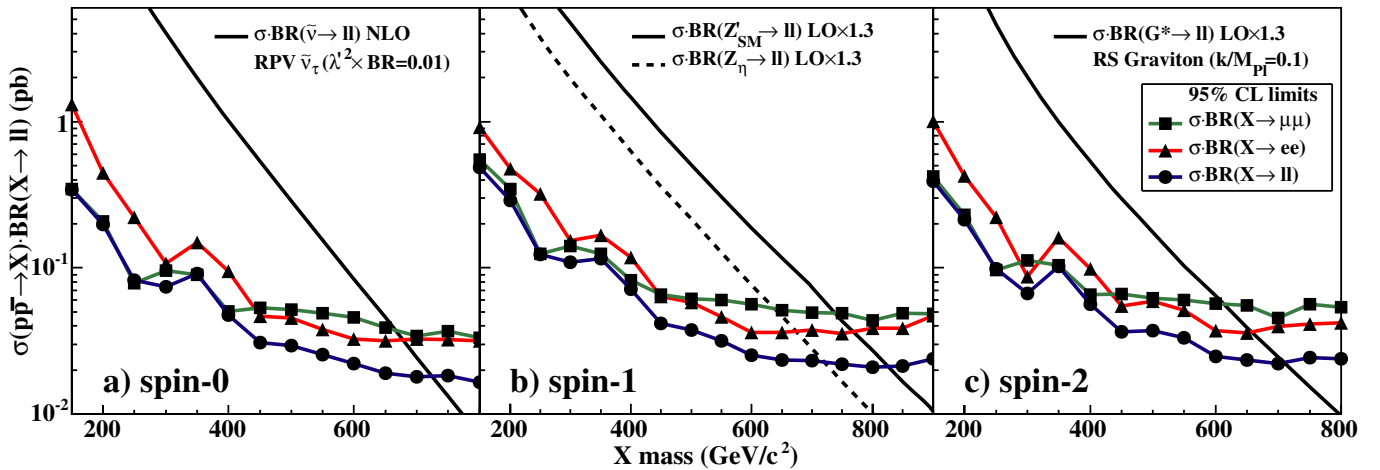


FIG. 2 (color online). The $\sigma(X_{\ell\ell})$ limits from ee , $\mu\mu$, and the combined channels as a function of m_X for spin 0 (a), spin 1 (b), and spin 2 (c). For the combined channel, $BR(X \rightarrow ee) = BR(X \rightarrow \mu\mu)$ [$\equiv BR(X \rightarrow \ell\ell)$] is assumed. Also shown are theoretical cross-section predictions of some representative models [22].

TABLE II. 95% C.L. upper limits on $\sigma(p\bar{p} \rightarrow X)BR(X \rightarrow \ell\ell)$ (in fb) for a given m_X (in GeV/c^2). Spin 1 limits are computed to $900 \text{ GeV}/c^2$ to accommodate Z' models with large predicted cross sections.

Spin \ m_X	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900
Spin 0	340	200	83	74	91	48	31	29	26	22	19	18	18	17
Spin 1	490	290	120	110	120	72	42	38	32	25	24	23	22	21	21	24
Spin 2	390	210	98	67	100	56	37	37	33	25	24	22	24	24

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 $BR(X \rightarrow ee) = BR(X \rightarrow \mu\mu)$, 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 and numerically integrated to obtain the 95% C.L. limits on $\sigma(X_{\ell\ell})$. Figure 2 and Table II show the $\sigma(X_{\ell\ell})$ limits as a function of m_X with spins 0, 1, and 2. At high mass ($m_X > 600 \text{ GeV}/c^2$) the limits are approximately 25 fb for all spins (but best for spin 0) and are consistent with expected limits in the absence of signal. The corresponding CDF Run I limit was 40 fb [2]. The sensitivity of these searches is enhanced compared to the Run I searches by the addition of the plug-plug dielectrons (10% relative gain in ee acceptance), an increase in muon trigger coverage and the use of muons without muon-chamber tracks (50% relative gain in $\mu\mu$ acceptance). Figure 2 also shows the predictions from some representative models [22] with higher order corrections [23]. The particle X is assumed to decay only to the known fermions in the mass range examined. From the spin 0 $\sigma(X_{\ell\ell})$ limit shown in Fig. 2(a), the lower mass bounds of 680, 620, and 460 GeV/c^2 from ee channel and 665, 590, and 450 GeV/c^2 from $\mu\mu$ channel are obtained for $\tilde{\nu}$ for the coupling strength squared times branching fraction $(\lambda^2 \cdot \text{Br}) = 0.01, 0.005, \text{ and } 0.001$, respectively. For spin 1 [Fig. 2(b)] the following mass bounds are obtained from the combined channel: 825, 690, 675, 720, and 615 GeV/c^2 for $Z'_{\text{SM}}, Z'_X, Z'_\psi, Z'_\eta,$ and Z'_I , respectively, and 885, 860, 805, and 725 GeV/c^2 for Z'_H with

the mixing parameter $\cot\theta_H = 1.0, 0.9, 0.7,$ and $0.5,$ respectively. Similarly, the lower mass limits of 280 GeV/c^2 (270 GeV/c^2) are set for ρ_{TC} and ω_{TC} in the TC model [9] with corresponding values of Technicolor-scale mass parameters $M_V = M_A$ 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, 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 param-

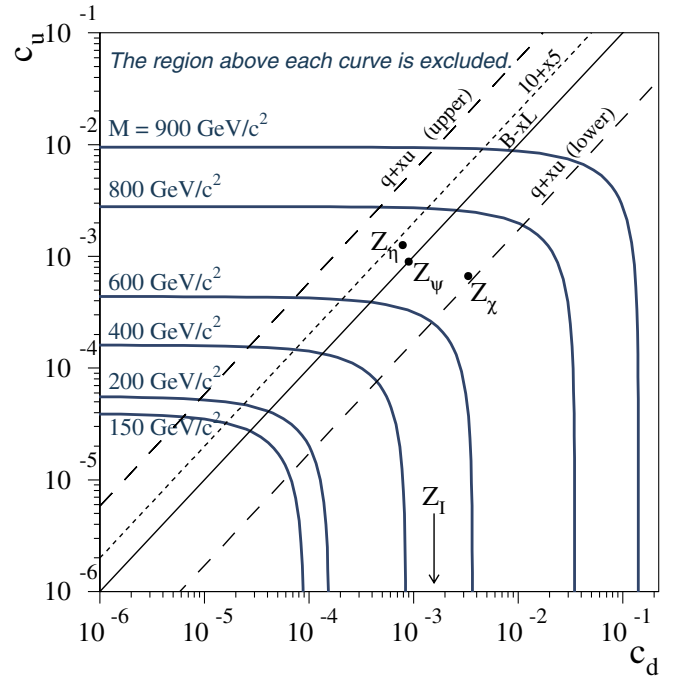


FIG. 3 (color online). Limit contours in the (c_d, c_u) plane [6] for a given Z' mass derived from the spin 1 $\sigma(X_{\ell\ell})$ limit. All possible models for the $U(1)_{B-XL}$ group are on the diagonal solid line, and those for the $U(1)_{10+X5}$ group are below the dotted line. The two dashed lines show the range between which the values for the $U(1)_{q+Xu}$ group must fall. The values for the $U(1)_{d-Xu}$ group may fall anywhere on the plane. The parameters of the E_6 -model Z' bosons are indicated.

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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