

# 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  $200 \text{ pb}^{-1}$  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  $\sigma(p\bar{p} \rightarrow X) \cdot BR(X \rightarrow \ell\ell)$  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  $25 \text{ fb}$  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 ( $Z'_{\text{SM}}$ ) 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 (CL) [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 Reference [6]. In addition to  $Z'_{\text{SM}}$ , 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 (RPV SUSY) 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  $\sigma(X_{\ell\ell}) \equiv \sigma(p\bar{p} \rightarrow X) \cdot BR(X \rightarrow \ell\ell)$  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 (HAD) 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 (CEM) 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 (PEM) 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 [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 contains 14,799  $ee$  and 7,775  $\mu\mu$  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 (PDF) [20] and the CDF II detector simulation are used except as noted. Signal samples for the heavy Higgs (spin-0),  $Z'_{\text{SM}}$  (spin-1) and RS Graviton (spin-2) are generated to model each spin hypothe-

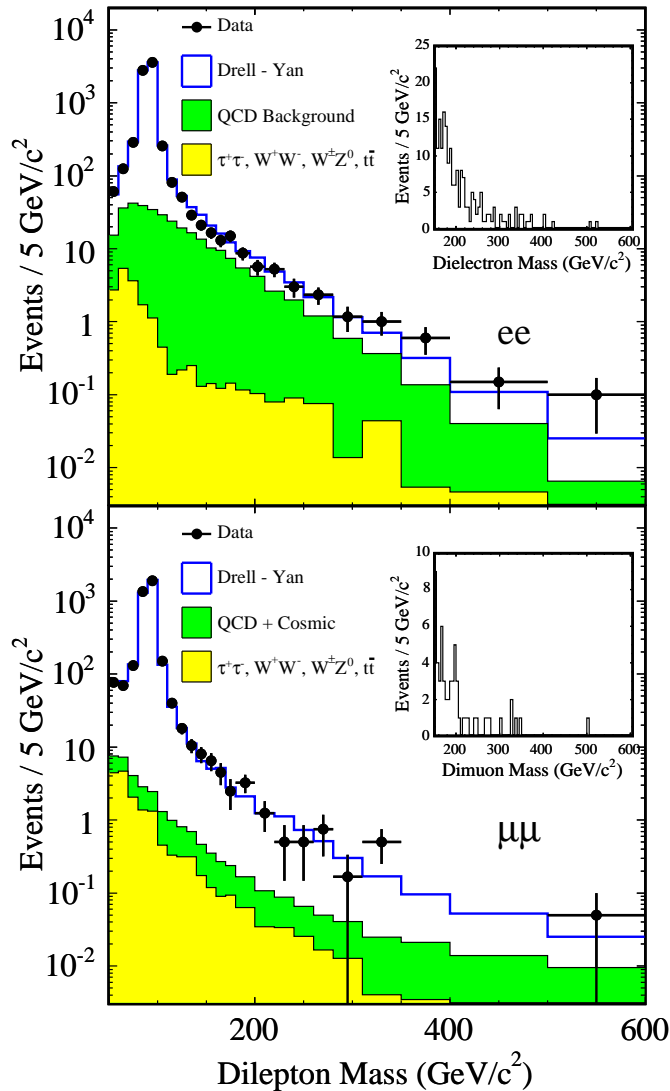


FIG. 1: The  $ee$  (top) and  $\mu\mu$  (bottom) invariant mass distributions of the observed data (points) with the background prediction (solid line). The background is corrected for acceptance and efficiency. The insets show the data with a fixed bin width of  $5 \text{ GeV}/c^2$  for  $m_{\ell\ell}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

sis. The product of acceptance and selection efficiency is approximately 50% for  $m_X > 400 \text{ GeV}/c^2$  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 non-dielectron sources, predominantly misidentified QCD dijet events. This background is estimated by ex-

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

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

trapolating 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 ( $m_{\ell\ell} > 400 \text{ GeV}/c^2$ ). Fig. 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 are from the uncertainties on luminosity, energy/momentum scales and resolutions, and the choice of PDF as estimated by comparison of different PDF parameterizations. 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 the 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% CL limits on  $\sigma(X_{\ell\ell})$ . Fig. 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

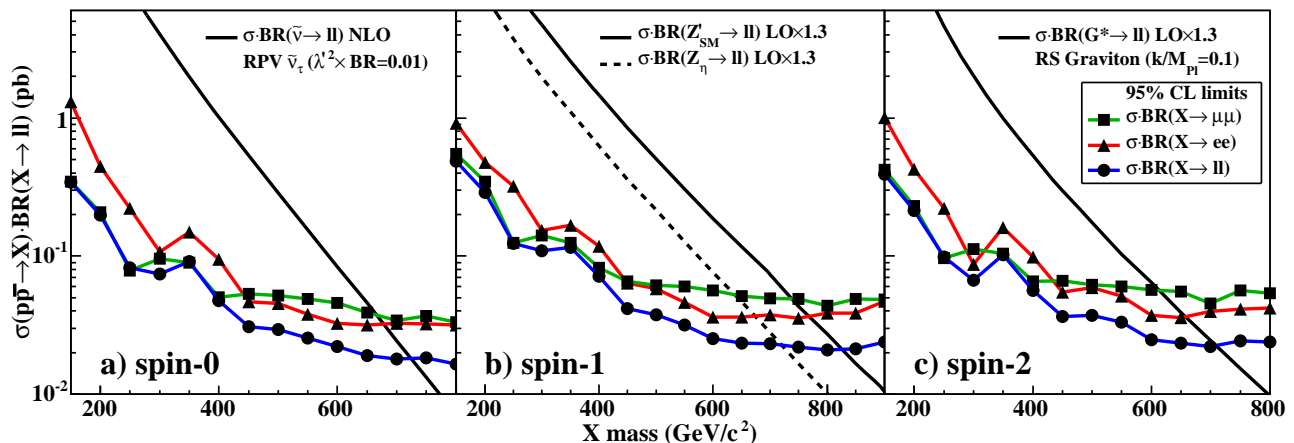


FIG. 2: The  $\sigma(X_{\ell\ell})$  limits from  $ee$ ,  $\mu\mu$  and the combined channels as a function of  $m_X$  for spin-0 (a), spin-1 (b), and spin-2 (c). For the combined channel,  $BR(X \rightarrow ee) = BR(X \rightarrow \mu\mu) (\equiv BR(X \rightarrow \ell\ell))$  is assumed. Also shown are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

TABLE II: 95% CL upper limits on  $\sigma(pp\bar{p} \rightarrow X) \cdot BR(X \rightarrow \ell\ell)$  (in fb) for a given  $m_X$  (in  $\text{GeV}/c^2$ ). 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	—	—

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). Fig. 2 also shows the predictions from representative models with higher order corrections [22]. 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  $\text{GeV}/c^2$  from  $ee$  channel and 665, 590, and 450  $\text{GeV}/c^2$  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, 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  $\text{GeV}/c^2$  for  $Z'_{\text{SM}}$ ,  $Z'_\chi$ ,  $Z'_\psi$ ,  $Z'_\eta$  and  $Z'_I$  respectively and 885, 860, 805 and 725  $\text{GeV}/c^2$  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  $\text{GeV}/c^2$  (270  $\text{GeV}/c^2$ ) are set for  $\rho_{TC}$  and  $\omega_{TC}$  in the TC model [9] with corresponding values of Technicolor-scale mass parameters  $M_V = M_A$  of 500  $\text{GeV}/c^2$  (400  $\text{GeV}/c^2$ ). From the spin-2  $\sigma(X_{\ell\ell})$  limit shown in Fig. 2(c), the lower mass bounds of 710, 510, and 170  $\text{GeV}/c^2$  are obtained for the first excited state of the RS graviton for dimensionless coupling parameter ( $k/M_{\text{PL}}$ ) 0.1, 0.05, and 0.01 respectively, where  $k$  is the relative strength of the warped dimension's

curvature scale and  $M_{\text{PL}}$  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 parameterizations allows more general constraints on possible  $Z'$  models [6]. In this formalism, a generic  $Z'$  is described by two parameters,  $c_d$  and  $c_u$ , that define the coupling of down and up-type quarks to the resonance. Fig. 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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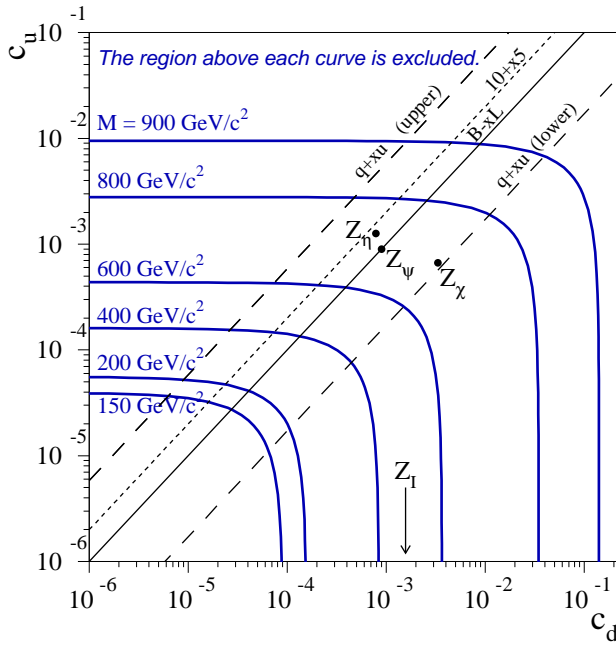


FIG. 3: Limit contours in the  $(c_d, c_u)$  plane [6] for a given  $Z'$  mass derived from the spin-1  $\sigma(X_{\ell\ell})$  limit. The solid and dotted diagonal lines show all possible models for the  $U(1)_{B-xL}$  and  $U(1)_{10+x5}$  groups respectively. The two dashed lines show the range between 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.

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