Search for New High Mass Particles Decaying to Lepton Pairs in $pp$ 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 $\sigma(p\bar{p} \to X) \cdot BR(X \to \ell\ell)$ 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.

PACS numbers: 13.85.Rm, 12.38.Qk, 13.85.Qk, 14.70.Pw, 12.60.Cn

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
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 [13]. 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 $E_T$ 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. [14]. 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 [10] 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), $Z'_{SM}$ (spin-1) and RS Graviton (spin-2) are generated to model each spin hypothe-
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 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 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 (\( m_{\ell\ell} > 400 \text{ GeV/c}^2 \)). 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 \( BR(X \to ee) = BR(X \to \mu\mu) \), 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. 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 GeV/c^2 for \( m_{\ell\ell} > 150 \text{ GeV/c}^2 \).](image)

<table>
<thead>
<tr>
<th>( m_{\ell\ell} ) (GeV/c^2)</th>
<th>Observed</th>
<th>Expected</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 150</td>
<td>205</td>
<td>212.9 ± 99.3</td>
<td>58</td>
<td>55.3 ± 2.5</td>
</tr>
<tr>
<td>&gt; 200</td>
<td>84</td>
<td>78.2 ± 33.4</td>
<td>18</td>
<td>20.9 ± 1.0</td>
</tr>
<tr>
<td>&gt; 300</td>
<td>22</td>
<td>13.6 ± 4.4</td>
<td>6</td>
<td>5.2 ± 0.3</td>
</tr>
<tr>
<td>&gt; 400</td>
<td>5</td>
<td>2.9 ± 0.7</td>
<td>1</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>2</td>
<td>0.8 ± 0.1</td>
<td>1</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>

TABLE I: Integrated number of events above a given \( m_{\ell\ell} \) for the observed data and estimated background.
was 40 fb. 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 acceptance). Fig. 2 also shows the predictions from representative models with higher order corrections. 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. 2a), 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 $\bar{\nu}$ 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. 2b)) the following mass bounds are obtained from the combined channel: 825, 690, 675, 720 and 615 GeV/c$^2$ for $Z_{SM}^\prime$, $Z_X$, $Z_\phi$, $Z_\eta$ 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 $\rho_{TC}$ and $\omega_{TC}$ in the TC model 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. 2c), 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 parameterizations allows more general constraints on possible $Z'$ models. 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.

We thank D. Choudhury, A. Daleo, H. Logan, and S. Mrenna for their useful contributions. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; in part by the European

![Diagram](image-url)
The region above each curve is excluded.

\[ M = 900 \text{ GeV/c}^2 \]

\[ 800 \text{ GeV/c}^2 \]

\[ 600 \text{ GeV/c}^2 \]

\[ 400 \text{ GeV/c}^2 \]

\[ 200 \text{ GeV/c}^2 \]

\[ 150 \text{ GeV/c}^2 \]

\[ 100 \text{ GeV/c}^2 \]

\[ 60 \text{ GeV/c}^2 \]

\[ 40 \text{ GeV/c}^2 \]

\[ 20 \text{ GeV/c}^2 \]

\[ 10 \text{ GeV/c}^2 \]

\[ 5 \text{ GeV/c}^2 \]

\[ 2 \text{ GeV/c}^2 \]

\[ 1 \text{ GeV/c}^2 \]

The region above each curve is excluded.

FIG. 3: Limit contours in the \((c_d, c_u)\) plane 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 \(U(1)_{B-L}\) and \(U(1)_{10+5}\) groups respectively. The two dashed lines show the range between which the values for the \(U(1)_{10+5}\) group must fall. The values for the \(U(1)_{d-x\bar{u}}\) group may fall anywhere on the plane. The parameters of the \(E_6\)-model \(Z'\) bosons are indicated.

[4] All the limits presented in this paper are at the 95% CL.
[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 \(\eta \equiv -\ln(\tan(\theta/2))\), 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 calorimeter transverse energy imbalance is denoted as \(\not{E}_T\).

[22] 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 \(\tilde{\nu}\) case. The dependence on the higher order corrections for the \(\sigma(X\ell\ell)\) limits is negligible.

Community’s Human Potential Programme under contract HPRN-CT-2002-00292; and the Academy of Finland.