Search for Heavy Particles Decaying into Electron-Positron Pairs in $p\bar{p}$ Collisions

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We present results of searches for technirho (ρ_T), techniomega (ω_T), and Z' particles, using the decay channels $\rho_T, \omega_T, Z' \to e^+e^-$. The search is based on 124.8 pb^{-1} of data collected by the DØ detector at the Fermilab Tevatron during 1992–1996. In the absence of a signal, we set 95% C.L. upper limits on the cross sections for the processes $p\overline{p} \to \rho_T, \omega_T, Z' \to e^+e^-$ as a function of the mass of the decaying particle. For certain model parameters, we exclude the existence of degenerate ρ_T and ω_T states with masses below about 200 GeV. We exclude a Z' with mass below 670 GeV, assuming that it has the same couplings to fermions as the Z boson.

Historically, studies of lepton-antilepton pair production — in particular e^+e^- and $\mu^+\mu^-$ — have been important discovery channels for new particles. The J/ψ, Υ, and Z resonances were all found in this way. Many extensions of the standard model predict the existence of particles that decay to lepton-antilepton pairs. Examples are heavy gauge bosons (Z') and technihadrons (ρ_T, ω_T). The lepton-antilepton signature is a preferred channel for particle searches in strong interactions because of the relatively low backgrounds compared to hadronic decay channels. Electrons and muons permit a relatively straightforward trigger and their momenta can be measured precisely. Thus particles that decay to e^+e^- or $\mu^+\mu^-$ can be identified as resonances in the dilepton mass spectrum.

In this Letter, we describe a search for resonances in the dielectron mass spectrum in data collected by DØ during 1992–1996 at the Fermilab Tevatron. We first describe the data sample, background sources, acceptance, and efficiency. We then set limits on the product of the cross section and branching fraction for the production of such resonances and their subsequent decay to e^+e^- as a function of the resonance mass. Finally, we compare this limit to predictions for hypothesized particles.

The DØ detector [1] is a multi-purpose particle detector. It tracks charged particles in tracking detectors located around the interaction region. The energy of particles is measured in uranium/liquid-argon calorimeters that surround the tracking detectors. The calorimeters are housed in three cryostats. In the central calorimeter (CC) we accept electrons with pseudorapidity $|\eta| < 1.1$ and in the end calorimeters (EC) with $1.5 < |\eta| < 2.5$. Pseudorapidity is defined in terms of the polar angle θ relative to the proton beam direction as $\eta = -\ln\tan\frac{\theta}{2}$. Electrons are identified as narrow showers in the electromagnetic section of the calorimeters, with a matching track in the drift chambers. The electron energy E is measured with a resolution σ_E, given by $(\sigma_E/E)^2 = \left(15\%/\sqrt{E/\mathrm{GeV}}\right)^2 + (1\%)^2$. No distinction can be made between electrons and positrons, because the tracking detectors are not in a magnetic field.

The data sample, background predictions, event selection, and electron identification criteria used for this analysis are identical to those described in Ref. [2]. We require at least two electrons [3] with $E\sin\theta > 25$ GeV. To maximize the signal efficiency, one electron in the CC fiducial region is not required to have a matching track.

The dielectron invariant mass spectra for events with both electrons in the central region (CC/CC) and with one electron in the central region and the other in the forward region (CC/EC) are shown in Figs. 1 and 2. The data correspond to an integrated luminosity of 124.8±5.1 pb^{-1}, taken at $\sqrt{s}$=1.8 TeV. The superimposed histograms represent the estimated spectrum from standard model processes and instrumental effects. This is dominated by two sources:

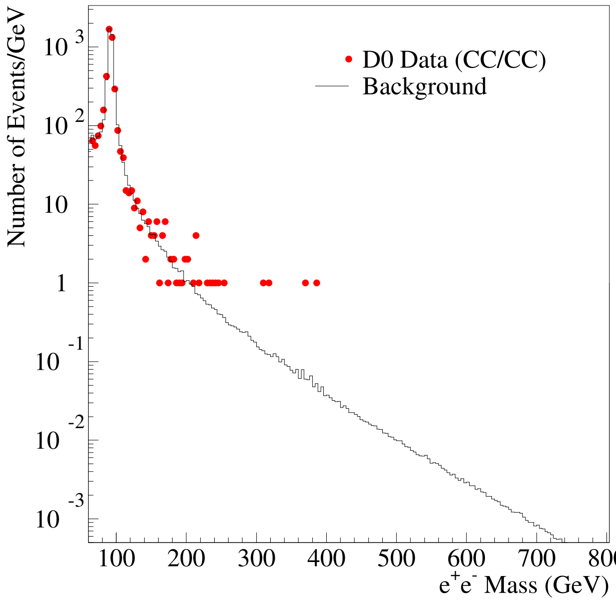

FIG. 1. Dielectron invariant mass spectrum for CC/CC events.

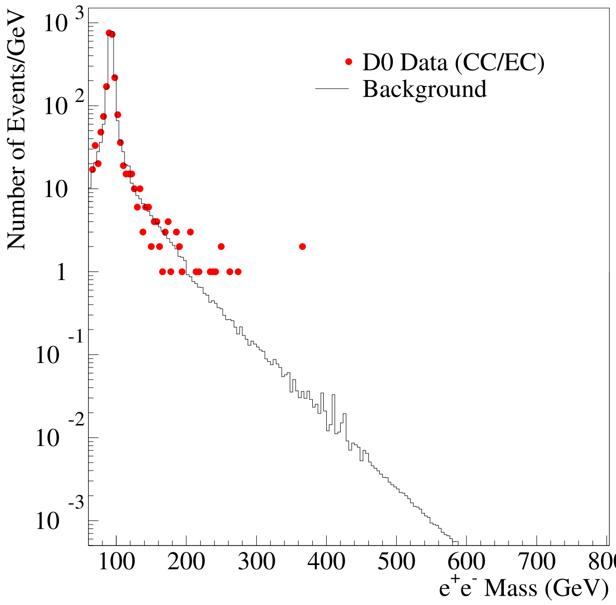

FIG. 2. Dielectron invariant mass spectrum for CC/EC events.

- Drell-Yan process (via intermediate γ^* and Z^*)
- Jets misidentified as electrons. This includes contributions from:
  - Dijet events in which both jets are misidentified as electrons
  - $W(\to e\nu)$+jets events in which one of the jets is misidentified as an electron

– γ+jets events in which a jet and the photon are misidentified as electrons

Other processes ($W\gamma$, $Z\gamma$, $t\bar{t}$, WW, and $\gamma^*/Z \to \tau\tau$), that can in principle also contribute to dielectron final states, have not been included in this analysis because these are at least an order of magnitude smaller than the two main backgrounds, as shown in Ref. [2].

The Drell-Yan spectrum is estimated using the PYTHIA Monte Carlo generator [4]. A K-factor is applied, as a function of dielectron mass, in order to normalize the cross sections from PYTHIA to next-to-leading-order calculations [5], as described in Ref. [2]. The uncertainty in the K-factor is 5%.

The efficiencies for identification of electron-positron pairs are [2]:

$$\epsilon = 0.814 \pm 0.014 \text{ for CC/CC events;}$$
$$\epsilon = 0.479 \pm 0.010 \text{ for CC/EC events.} \quad (1)$$

The acceptance for an e^+e^--resonance signal is about 50%, roughly independent of dielectron mass. The larger the dielectron mass, the larger is the fraction of CC/CC events, and thus the larger the total overall efficiency. This efficiency varies between 30% (at a mass of 140 GeV) and 40% (at a mass of 450 GeV). The apparent width of the resonance (dominated by the detector resolution) increases with the mass of the particle.

In Table I, we compare the observed number of events with standard model expectations. There is no significant excess in cross section, nor do we see any significant accumulation of events at one mass value, as expected for the decay of a narrow resonance. In the absence of a signal, we set an upper limit on the product of the cross section and branching fraction as a function of dielectron invariant mass.

TABLE I. Comparison of observed and expected number of events, for combined CC/CC and CC/EC samples.

mass region	expected	observed
> 100 GeV	609±73	571
> 200 GeV	26±3.4	32
> 300 GeV	4.7±0.6	6
> 400 GeV	1.1±0.1	0

We calculate the limit in a way similar to that described in Ref. [6]. We bin the spectra shown in Figs. 1 and 2 in 4 GeV wide bins. In bin i, we expect to see μ_i events, where

$$\mu_i = f_i \times \sigma \times \epsilon \times \mathcal{L} + b_i^1 + b_i^2 \times \mathcal{L}. \quad (2)$$

Here f_i is the signal acceptance for bin i, σ is the signal cross section multiplied by the branching fraction into e^+e^-, ϵ is the signal efficiency, $\mathcal{L}$ is the integrated luminosity, b_i^1 is the expected number of events with misidentified jets in bin i, and b_i^2 is the Drell-Yan cross section, corrected for acceptance and efficiency, integrated over bin i. The acceptance f_i depends somewhat on the process under consideration (but not the detailed model parameters), and has been evaluated using Monte Carlo simulations for the specific final states considered below. The only unknown of these parameters is σ. We use Poisson statistics to calculate the probability $p_i(n_i|\mu_i)$ to see the n_i events observed in the data given the expected value μ_i. To account for the uncertainties in the values of the parameters that determine μ_i, we average this probability over prior distributions for the parameters. The joint probability for all bins, as a function of σ, is then

$$P(\sigma) = \int\int G_{\mathcal{L}} G_{\epsilon} \prod_{i=1}^{n} \int\int G_{b_i^1} G_{b_i^2} p_i(n_i|\mu_i) db_i^2 db_i^1 d\epsilon d\mathcal{L}. \quad (3)$$

The priors G are Gaussians with means equal to the most probable parameter values and variances given by the square of the uncertainties. We calculate this probability for the CC/CC data sample ($P_{CC}(\sigma)$) and for the CC/EC data sample ($P_{EC}(\sigma)$) separately. We determine a Bayesian 95% confidence level upper limit on the product of the signal cross section and branching fraction (σ_{95}) from the definition:

$$\frac{\int_0^{\sigma_{95}} P_{CC}(\sigma) * P_{EC}(\sigma) d\sigma}{\int_0^{\infty} P_{CC}(\sigma) * P_{EC}(\sigma) d\sigma} = 0.95. \quad (4)$$

This definition does not account for correlations in the uncertainties between the CC/CC and CC/EC samples because their effect on the limit is negligible. The resulting limits are represented by the data points in Figs. 3 and 4 for ρ_T and ω_T and in Fig. 5 for Z'.

Topcolor-assisted technicolor models with walking gauge coupling [7] predict the existence of many technihadron states. The lightest of these technihadrons are the scalar mesons, technipions ($\pi_T^\pm$ and π_T^0), and the vector mesons (ρ_T and ω_T). These are bound states of the members of the lightest technifermion doublet, U and D. They are expected to be produced with substantial rates at the Fermilab Tevatron [8]. The vector mesons decay to $\gamma\pi_T$, $W\pi_T$, or fermion-antifermion pairs. No large isospin-violating technicolor interactions are needed to explain the mass difference between the top and bottom quarks. Therefore, the ρ_T and ω_T states can be (and are assumed to be) degenerate in mass. As shown in Ref. [9], most of the rate to dilepton final states originates from ω_T decays, so that our conclusions for the mass of the ω_T do not depend strongly on this assumption.

The predicted products of cross sections and branching fractions for the processes $p\overline{p} \to \rho_T, \omega_T$, $\rho_T, \omega_T \to \ell^+\ell^-$) depend on the masses of ρ_T (M_ρ) and ω_T (M_ω) and the mass difference between the vector mesons (ρ_T, ω_T) and the technipions. The latter determines the spectrum of accessible decay channels. In addition, the ω_T production cross section is sensitive to the charges of the technifermions (taken to be $Q_U = Q_D - 1 = 4/3$), as well as to a mass parameter M_T that controls the rate for

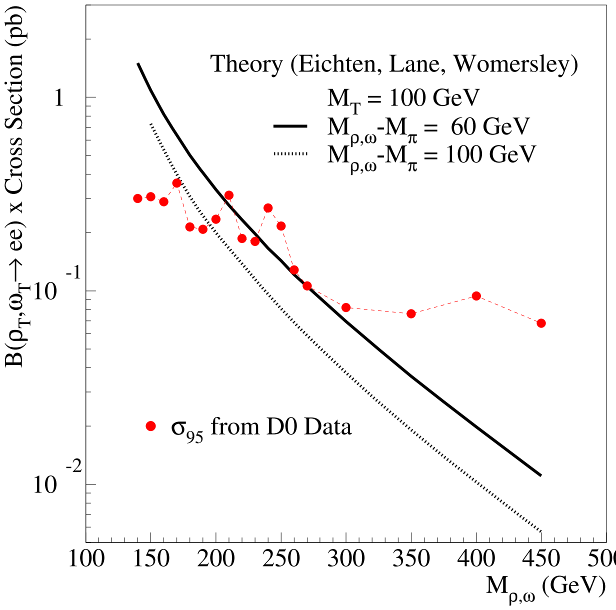

FIG. 3. Experimental upper limits at 95% confidence level for $\rho_T, \omega_T \rightarrow e^+e^-$ production compared with predictions from Refs. [9,11]. $M_{\rho,\omega}$ and M_π denote technihadron masses.

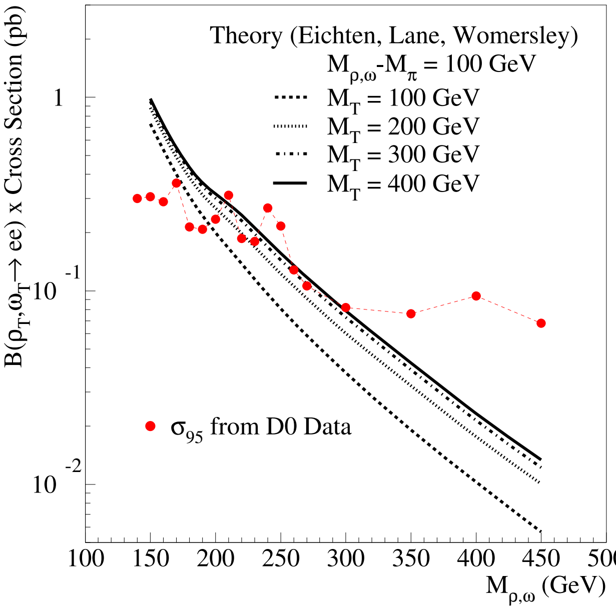

FIG. 4. Experimental upper limits at 95% confidence level for $\rho_T, \omega_T \rightarrow e^+e^-$ production compared with predictions from Refs. [9,11]. $M_{\rho,\omega}$ and M_π denote technihadron masses.

$\omega_T \rightarrow \gamma + \pi_T^0$ [10]. The value of this mass parameter is unknown. Scaling from the QCD decay $\omega \rightarrow \gamma + \pi^0$, Ref. [9] suggest a value of several hundred GeV. For all other parameters, we use the default values quoted in Table 2 of Ref. [11].

We use recently updated calculations for the processes $p\overline{p} \rightarrow \rho_T \rightarrow \ell^+\ell^-$ and $p\overline{p} \rightarrow \omega_T \rightarrow \ell^+\ell^-$, and include a K-factor of 1.3. Previously published searches for technicolor particles [12] use an older calculation that predicted larger branching fractions for the dilepton decay modes. When comparing limits, this must be taken into account. Two predictions [9,11] for the product of cross section and branching fraction for the process $p\overline{p} \rightarrow (\rho_T \text{ or } \omega_T) \rightarrow e^+e^-$ are plotted in Fig. 3. The two predictions shown differ in the assumed mass difference between the vector and scalar mesons. For a mass difference smaller than the mass of the W boson (e.g., 60 GeV), the decay $\rho_T \rightarrow W + \pi_T$ is forbidden and the branching ratio to dielectrons is enhanced compared to the case of a mass difference of 100 GeV, for which the $W\pi_T$ mode is allowed. We rule out ρ_T and ω_T with masses below 207 GeV, if the mass difference between ρ_T and $\pi_T^\pm$ is smaller than the W-boson mass.

The limit depends on the choice of the parameter M_T, as illustrated in Fig. 4. In this figure, the experimental limit is compared to predictions in which the parameter M_T, which controls the ω_T decay rate, is varied. For sufficiently large values of M_T ($M_T > 200$ GeV) we can rule out the existence of ρ_T and ω_T with masses below 203 GeV, even when the competing $W\pi_T$ decay mode of the technirho is open.

There is no unique prediction for the couplings of a heavy neutral gauge boson (Z') to fermions. We assume as a benchmark that the Z' has the same couplings to fermions as the Z boson of the standard model. Thus, the width of the Z' scales proportional to $M_{Z'}$. We determine the product of the cross section and branching ratio using PYTHIA and adjust for the K-factor [13].

We set an upper limit on the product of the cross section and branching fraction using the same algorithm as for the technicolor particles. Figure 5 shows the experimental limit together with the theoretical cross section. For the assumed couplings, we exclude the existence of a Z' boson below a mass of 670 GeV at the 95% confidence level. The previous search by DØ [14], using a smaller data sample, set a lower limit at 490 GeV. A search by CDF in both the dielectron and dimuon channels [15] set a lower limit at 690 GeV.

To summarize, based on 124.8 pb^{-1} of data collected by the DØ detector at the Fermilab Tevatron during 1992–1996, we set new limits on the production of technirho (ρ_T), techniomega (ω_T), and Z' particles in $p\overline{p}$ collisions using their decays to e^+e^-. The 95% C.L. lower limits on the particle masses are 207 GeV for ρ_T and ω_T states, assuming that they have equal mass and that the decay $\rho_T \rightarrow \pi_T + W$ is kinematically forbidden, and 670 GeV for Z' bosons with standard model couplings to fermions.

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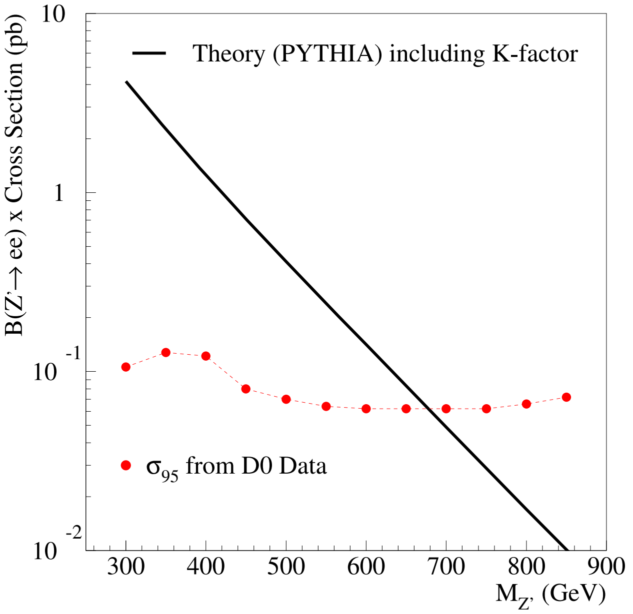

FIG. 5. Experimental upper limit at 95% confidence level for $Z' \to e^+e^-$ production compared with predictions.

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