We search for the technicolor process $p\bar{p} \rightarrow \rho_T/\omega_T \rightarrow W_T$ in events containing one electron and two jets, in data corresponding to an integrated luminosity of 390 pb$^{-1}$, recorded by the D0 experiment at the Fermilab Tevatron. Technicolor predicts that technipions, $\rho_T$, decay dominantly into $b\bar{b}$, $b\bar{c}$, or $b\bar{c}$, depending on their charge. In these events $b$ and $c$ quarks are identified by their secondary decay vertices within jets. Two analysis methods based on topological variables are
Technicolor (TC), first formulated by Weinberg and Susskind [1, 2], provides a dynamical explanation of electroweak symmetry breaking through a new strong $SU(N_{TC})$ gauge interaction acting on new fermions, called “technifermions.” Technicolor is a non-Abelian gauge theory modeled after Quantum Chromodynamics (QCD). In its low-energy limit, a spontaneous breaking of the global chiral symmetry in the technifermion sector leads to electroweak symmetry breaking. The Nambu-Goldstone bosons produced in this process are called technipions, $\pi_T$, in analogy with the pions of QCD. Three of these technipions become the longitudinal components of the $W$ and $Z$ bosons, making them massive.

An additional gauge interaction, called extended technicolor [3, 4], couples standard model fermions and technifermions to provide a mechanism for generating quark and lepton masses. By limiting the running of the technicolor coupling constant, walking technicolor [5] avoids flavor-changing neutral currents. To generate masses as large as the top quark mass, another interaction, topcolor, seems to be necessary, thereby giving rise to topcolor-assisted technicolor models [6].

Extensions of the basic technicolor model tend to require the number $N_D$ of technifermion doublets to be large. In general, the technicolor scale $\Lambda_{TC} \approx O(1) \times F_{TC}$, where $F_{TC}$ is the technipion decay constant, depends inversely on the number of technifermion doublets: $F_{TC} \approx 246 \text{ GeV}/\sqrt{N_D}$. For large $N_D$, the lowest lying technihadrons have masses on the order of few hundred GeV. This scenario is referred to as low-scale technicolor [7]. Low-scale technicolor models predict the existence of scalar technimesons, $\pi_T^\pm$ and $\pi_T^0$, and vector technimesons, $\rho_T$ and $\omega_T$. General features of low-scale technicolor have been summarized in the technicolor strawman model (TCSM) [8, 9]. The analysis presented in this paper is based on Ref. [9].

Vector technimesons are expected to be produced with substantial rates at the Fermilab Tevatron Collider via the Drell-Yan-like electroweak process $p\bar{p} \rightarrow \rho_T + X$ or $\omega_T + X$. In walking technicolor, it is expected that vector technimesons decay to a gauge boson ($\gamma, W, Z$) and a technipion or to fermion-antifermion pairs. The production cross sections and branching fractions depend on the masses of the vector technimesons, $M(\rho_T)$ and $M(\omega_T)$, on the technicolor-charges of the technifermions, on the mass differences between the vector and scalar technimesons, which determine the spectrum of accessible decay channels, and on two mass parameters, $M_A$ for axial-vector and $M_V$ for vector couplings. The parameter $M_A$ controls the rate for the decay $\rho_T, \omega_T \rightarrow \gamma + \pi_T$ and is unknown a priori. Scaling from the QCD decay $p, \omega \rightarrow \gamma + \pi^0$, the authors of Ref. [9] suggest a value of several hundred GeV. We set $M_A = M_V$, and evaluate the production and decay rates at two different values: 100 and 500 GeV. For all other parameters, we use the default values quoted in Table III of Ref. [9].

In this Letter, we describe a search for the decay of vector technimesons to $W\pi_T$, followed by the decays $W \rightarrow e\nu$ and $\pi_T \rightarrow bb, bc$, or $cb$. In the D0 detector, which is described in detail in Ref. [10], the signature of this process is an isolated electron and missing transverse momentum ($p_T$) from the undetected neutrino from the decay of the $W$ boson, and two jets of hadrons coming from the fragmentation of the quarks from the decay of the technipion. Jets are reconstructed using the Run II cone algorithm [11] with a cone size of 0.5. We search for events with this signature in the data collected with a single electron trigger until July 2004 and corresponding to an integrated luminosity of $388 \pm 25 \text{ pb}^{-1}$ [12].

There are a number of standard model processes that can result in the same final state signature as $W\pi_T$ production. Vector boson production in association with jets is the dominant background. $Z$ boson production can be suppressed by vetoing on a second electron and requiring significant $p_T$. Most of the jets in W+jets events originate from the fragmentation of light quarks or gluons and therefore requiring the explicit identification of at least one jet from the fragmentation of a $b$ or $c$ quark suppresses most of this background, leaving only $W + bb$, $W + b$, $W + c$, and $W + c$ events. Top quark production followed by the decay to $e\nu b$ is another background. Top-antitop quark pair production typically results in either an additional lepton or a higher jet multiplicity from the decay of the second top quark, and this background can be reduced by selecting events with exactly two jets. Single top quark production is an irreducible background, but it has a smaller cross section. We simulate all these processes using either PYTHIA [13] or ALPGEN [14] Monte Carlo (MC) generators, followed by the D0 detector simulation based on GEANT [15]. Quark hadronization and fragmentation is simulated using PYTHIA.

The multijet background is due to events with poorly measured jets, resulting in missing momentum and a jet that is misidentified as an electron. Background from the mistagged $W+jets$ process originates from events in which a light-quark or gluon jet is incorrectly identified as a $b$ jet. These instrumental background contributions are estimated from the same data sample before requiring...
the identification of a $b$ jet.

We select events in which there is exactly one well-
identified electron based on tracking and calorimeter data
with transverse momentum $p_T > 20$ GeV and pseudo-
rapidity $|\eta| < 1.1$ [16]. There must be significant $p_T$,
measured in two ways: $p_T^{(\text{jet})} > 20$ GeV computed as the
negative sum of the jet momentum vectors and the electron
momentum vector and $p_T > 20$ GeV which also
includes the calorimeter energy deposit not assigned to
the electron or the jets. We require the transverse mass
$M_T(e\nu) > 30$ GeV. We further require the presence of
equally two jets with $p_T > 20$ GeV and $|\eta| < 2.5$.

To further reduce backgrounds, we take advantage of the
long lifetime of $b$ flavored hadrons. Tracks from the decay
products of $b$ hadrons may not project back to the
proton-antiproton collision, but have a significant impact
parameter. They can therefore be identified and used to
reconstruct the decay vertex of the $b$ hadron. A jet is
tagged as a $b$ jet if there is a secondary decay vertex
within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.5$ of the jet axis. We
require at least one of the jets to be $b$-tagged. This leaves us
with 117 events in our final data sample.

The expected background event yields are listed in Table I. When estimating these yields, each Monte Carlo
event is weighted by the probability that at least one jet
is tagged as a $b$ jet. The tagging probability is parameter-
ized as a function of jet flavor, jet $p_T$, and $\eta$. The
efficiency of tagging a jet from the fragmentation of a $b$
quark is derived from collider data which were enriched
in their $b$ jet contents by requiring a muon to be recon-
structed within at least one jet to preferentially select jets
with semileptonic $b$ decays. The probability of tagging
a $c$ jet is derived from the tagging probability for $b$ jets
by multiplying by the ratio of tagging probabilities for $c$
and $b$ jets derived from MC simulations. We derive the
probability to tag a light-quark or gluon jet from a set of
dijet events, corrected for contamination by $c$ and $b$ jets.
The Monte Carlo events are also weighted by the ratios
of jet and electron finding efficiencies in Monte Carlo and
collider data. Electron finding efficiencies are measured
in $Z \rightarrow ee$ events in both data and Monte Carlo.

We use the PYTHIA event generator to simulate sig-
nal events, modeling initial state and final state radi-
ation, fragmentation, and hadronization. To generate
$W\pi_T$ signal events for a range of values of the technime-
son masses, we use a fast, parameterized detector simula-
tion that was tuned to reproduce the kinematic distrib-
utions and acceptances from events simulated with the
detailed GEANT-based detector simulation. For the cross
section calculations, CTEQ5L [17] parton distribution
functions are used. Finally, as is appropriate for this
Drell-Yan-like process, the cross section is multiplied by
a $K$-factor of 1.3 to approximate NLO contributions to
the cross section [18]. We generate events with $p_T$ masses
from 160 GeV to 220 GeV and assume $M(\omega_T) = M(p_T)$.
The $\pi_T$ mass values start at the kinematic threshold for

<table>
<thead>
<tr>
<th>Final data sample</th>
<th>117</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal:</td>
<td></td>
</tr>
<tr>
<td>$\rho_T/\omega_T \rightarrow W + \pi_T \rightarrow evb\bar{b}$ ($M_V = 100$ GeV)</td>
<td>$11.1 \pm 0.1$</td>
</tr>
<tr>
<td>$\rho_T/\omega_T \rightarrow W + \pi_T \rightarrow evb\bar{b}$ ($M_V = 500$ GeV)</td>
<td>$17.1 \pm 0.2$</td>
</tr>
<tr>
<td>Physics background:</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow evq\bar{q}b$</td>
<td>$7.9 \pm 0.5$</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow e^+\nu\nu\nu\nu \bar{b}$</td>
<td>$14.1 \pm 0.3$</td>
</tr>
<tr>
<td>$W* \rightarrow t\bar{b} \rightarrow evb\bar{b}$ or $\tau\nu\bar{b}\bar{b}$</td>
<td>$3.5 \pm 0.1$</td>
</tr>
<tr>
<td>$tq\bar{b} \rightarrow evb\bar{b}$ or $\tau\nu\bar{b}\bar{b}$</td>
<td>$4.3 \pm 0.1$</td>
</tr>
<tr>
<td>$W(\rightarrow e\nu) +$ heavy flavor</td>
<td>$56.4 \pm 4.2$</td>
</tr>
<tr>
<td>$WZ \rightarrow evb\bar{b}$</td>
<td>$11.0 \pm 0.02$</td>
</tr>
<tr>
<td>$Z(\rightarrow e^+e^-)$</td>
<td>$0.5 \pm 0.4$</td>
</tr>
<tr>
<td>$Z(\rightarrow e^+e^-) + b\bar{b}$</td>
<td>$0.60 \pm 0.03$</td>
</tr>
<tr>
<td>Instrumental background:</td>
<td></td>
</tr>
<tr>
<td>multijet events</td>
<td>$16.3 \pm 3.2$</td>
</tr>
<tr>
<td>mistagged $W(\rightarrow ev) +$ jets</td>
<td>$10.3 \pm 0.3$</td>
</tr>
<tr>
<td>Total background</td>
<td>$115.1 \pm 5.4$</td>
</tr>
</tbody>
</table>

$W\pi_T$ production is $M(p_T) = M(\pi_T) - M(W)$ and go
down to $M(\pi_T) = M(p_T)/2 - 5$ GeV where the decay
channel $\rho_T^{(0)} \rightarrow \pi_T^{(\pm)}(0,\pm)\pi_T^{(0,\pm)}$ is accessible, reducing
the branching fraction of $\rho_T^{(0)} \rightarrow W\pi_T$.

At this point our data sample is still dominated by
background. We therefore use additional variables that
characterize the topology of the events to discriminate
between signal and background. These variables are the
azimuthal angle difference between the two jets $\Delta \phi(j,j)$,
the azimuthal angle difference between the electron and the
$p_T$, $\Delta \phi(e, p_T)$, the transverse momentum of the dijet
system $p_T(jj)$, the scalar sum of the transverse momenta
of the electron and the two jets $H_T$, the invariant mass of
the dijet system $M(jj)$, and the invariant mass of the
$W$ boson-dijet system $M(Wjj)$. The technicolor par-
ticles are expected to have narrow widths ($\approx 1$ GeV). We
should therefore see enhancements in the distributions of
$M(jj)$ and $M(Wjj)$, consistent in width with the detector
resolution. $M(jj)$ corresponds to the reconstructed
$\pi_T$ mass and $M(Wjj)$ corresponds to the reconstructed
$p_T$ mass. We reconstruct the $W$ boson from the electron
and the missing transverse momentum using the $W$ bo-
son mass constraint to solve for $p_z$ of the neutrino. If
there are two real solutions, we take the smaller value of
neutrino $p_z$. If there is only a complex solution, we take
the real part. Distributions of these variables are shown
in Figs. 1 and 2. We use two approaches to separate sig-
nal and background, a cut-based analysis and a neural
network analysis.

The cut-based analysis is optimized using Monte Carlo
simulations to maximize the ratio $S/\sqrt{B}$ for every set of
technimeson mass values. $S$ is the expected number of

$W\pi_T$. 

The Monte Carlo events are also weighted by the ratios
of jet and electron finding efficiencies in Monte Carlo and
collider data. Electron finding efficiencies are measured
in $Z \rightarrow ee$ events in both data and Monte Carlo.
The neural network analysis uses the topological variables $H_T^T$, $\Delta \phi(e, p_T)$, $\Delta \phi(jj)$, $p_T(jj)$, the transverse momenta of both jets and of the electron and $p_T$. A two-stage neural network based on the Multi Layer Perceptron algorithm [19] is used. The first stage consists of three independent networks which are trained to reject the three main backgrounds, top quark production, $W + b\bar{b}$ production, and all other $W +$jets production including heavy flavors. Each of these three networks has eight input nodes and one hidden layer with 24 nodes. The second stage network has three input nodes, connected to the outputs of the three networks in the first stage, and one hidden layer with six nodes. The second stage network is trained using all nine physics background processes. The networks are trained separately for each set of technicolor mass values. We then apply the trained neural networks to the collider data, technicolor signals, and physics and instrumental backgrounds to obtain the discriminator output spectra. We optimize the discriminator cut for every set of techniparticle masses to maximize $S/\sqrt{B}$.

There is no excess in our data over the expected background. We compute upper limits on the $\rho_T \rightarrow W\pi_T \rightarrow e\nu b\bar{b}(c)$ production cross section times branching fraction. In the cut-based analysis, which is a simple counting experiment, we compute an upper 95% C.L. limit on the signal using Bayesian statistics [20]. The neural network analysis performs a maximum likelihood fit of the data in the $M(p_T), M(\pi_T)$ plane to signal and background expectations. The backgrounds are constrained to their expected values within statistical and systematic uncertainties. The uncertainties in the background event yields total to 10–12% and the uncertainty in the signal selection efficiency is 10% for the cut-based analysis and 20% for the neural-net based analysis. The largest contributions to the systematic uncertainties are due to jet reconstruction efficiency, jet energy scale, $b$-tagging efficiency, and, only for the signal, from the difference between fast and fully simulated detector Monte Carlo. The 95% C.L. upper limit on the signal cross section is then determined by the number of signal events below which lies 95% of the integral over the resulting likelihood function.

The expected sensitivity and the regions excluded at 95% C.L. by both analyses in the $M(p_T), M(\pi_T)$ plane for $M_V = 500$ GeV are shown in Fig. 3. For $M_V = 100$ GeV, only a small region around $M(p_T) = 190$ GeV and $M(\pi_T) = 95$ GeV can be excluded. We note from Fig. 3(a), that the expected sensitivity of the neural network analysis is better than that of the cut-based analysis, as indicated by the larger 95% C.L. exclusion region.
FIG. 3: Expected region of exclusion (a) and excluded region (b) at the 95% C.L. in the $M(\rho_T), M(\pi_T)$ plane for $p_T \to W \pi T \to e\nu b\bar{b}(\bar{e})$ production with $M_V = 500$ GeV. Kinematic thresholds from $W \pi T$ and $\pi T \pi T$ are shown on the figures.

We quote the observed 95% C.L. exclusion region in the $M(\rho_T), M(\pi_T)$ plane in Fig. 3(b) by the neural network analysis as our measurement [21].

The results presented in this paper cannot be compared directly to those previously published [23]. The CDF experiment did not use Ref. [8] and [9], but rather the models described in the earlier paper of Ref. [7], a precursor to the TCSM. The LEP experiments used Ref. [8] in which the cross sections, while appropriate for narrow $\rho_T$ production in $q\bar{q}$ collisions, are incorrect for off-resonance production in $e^+e^-$ collisions such as at LEP (see Ref. [24]). Although differences in the employed TC models preclude a direct comparison with previous searches, the current search achieves a higher sensitivity to the considered physics process.

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[†] Visitor from Helsinki Institute of Physics, Helsinki, Finland.

[16] $\eta = -\ln[\tan(\theta/2)]$ and $\theta$ is the polar angle with respect to the proton beam direction.
[21] Consistent scaling of luminosity and background prior to optimization, using the new D0 luminosity [22] will lead to somewhat better limits. Nevertheless, we choose to keep the analysis consistent with the previous estimate of the luminosity value [12].