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Search for Color Singlet Technicolor Particles in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We search for color singlet technirho and technipion production in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV recorded with the Collider Detector at Fermilab. These exotic technimesons are present in a model of walking technicolor. The signatures studied are lepton plus two jets plus $\not\!\!E_T$ and multijet final states. No excess of events is seen in either final state. We set an upper limit on the technirho production cross section and exclude a region in the technipion mass versus technirho mass plane.

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In the standard model, electroweak symmetry breaking is responsible for giving rise to particle masses. The broken symmetry arises from a Higgs scalar field and an as yet unobserved Higgs boson. An alternative explanation for the broken symmetry is through a dynamical interaction known as technicolor [1], where the Higgs boson is replaced by states of two techniquarks, called technipions, bound by the technicolor force. In the walking technicolor (WTC) model [2] color singlet technirhos ($\rho_T^{\pm,0}$) can be produced in high energy s-channel $q\overline{q}$ annihilation. The decay modes of charged technirhos are $\rho_T^{\pm} \to W^{\pm}\pi_T^0$, $Z^0\pi_T^{\pm}$, $W^{\pm}Z^0$, $\pi_T^0\pi_T^{\pm}$, and fermion pairs. The decay modes of neutral technirhos are $\rho_T^0 \to W^{\pm}\pi_T^{\mp}$, $W^{\pm}W^{\mp}$, $\pi_T^{\pm}\pi_T^{\mp}$, and fermion pairs. The branching ratio of each decay mode depends on the mass of the technirho $[M(\rho_T)]$ and the technipion $[M(\pi_T)]$ and some other parameters of the model which we explain later. The $\rho_T^{\pm}$ and ρ_T^0 (also $\pi_T^{\pm}$ and π_T^0) are mass degenerate states. For $M(\pi_T) < \frac{1}{2}M(\rho_T)$, the $\rho_T \to \pi_T\pi_T$ decay dominates. For masses $M(\rho_T) \sim 180$ GeV$/c^2$ and $M(\pi_T) \sim 90$ GeV$/c^2$, $\rho_T \to W\pi_T$ is the dominant decay mode. The rates of these $\rho_T \to W\pi_T$ and $\rho_T \to \pi_T\pi_T$ decay modes are large enough that we might observe a WTC signal at the Tevatron [3]. We search for the WTC particles described in Ref. [3]. The W boson decays to leptonic or hadronic final states, with the leptonic (e or μ) channels having smaller backgrounds. The technipion decays to a pair of fermions. The coupling between a technipion and a fermion is stronger for larger fermion mass. Therefore, a π_T^0 decays mostly to $b\overline{b}$ pairs, and a $\pi_T^{\pm}$ to $\overline{b}c$ [4], producing at least one b jet. Consequently, the $\rho_T \to \pi_T\pi_T$ decay mode produces the only all-hadronic final state with at least two b jets in this model.

In this analysis, we search for technipions and technirhos in the lepton (e or μ) plus two jets plus $\not\!\!E_T(\ell + 2j)$ mode using an integrated luminosity of 109 ± 7 pb^{-1} [5] and in the multijet $(4j)$ mode using an integrated luminosity of 91 ± 7 pb^{-1} [6] collected with the Collider Detector at Fermilab (CDF) in 1992–1995. The processes which we include for the WTC particle search in the $\ell + 2j$ mode are $\rho_T^{\pm,0} \to W^{\pm}\pi_T^{0,\mp} \to \ell\nu b\overline{b}$ or $\ell\nu\overline{b}c$. The main processes we include in the $4j$ mode are $\rho_T^{\pm,0} \to \pi_T^{\pm}\pi_T^{0,\mp} \to \overline{b}cb\overline{b}$ or $\overline{b}c\overline{b}c$ as well as $\rho_T^{\pm,0} \to W^{\pm}\pi_T^{0,\mp} \to q\overline{q}'b\overline{b}$ or $q\overline{q}'\overline{b}c$. In both modes, we reconstruct technipions from the dijet system where one or both jets are identified ("tagged") as coming from a b hadron. Technirhos are reconstructed from the $W + 2$ jet system only in the $\ell + 2j$ mode [7]. The width of these particles is narrower than the experimental resolution. We perform a counting experiment applying Poisson statistics with background [8] using the $\ell + 2j$ mode, and we also perform a shape analysis of the dijet invariant mass distribution in both $\ell + 2j$ and multijet modes. Since we observe no excess of events in either final state, we obtain cross section limits from both methods. The leptonic channel analysis using the counting experiment method results in more stringent limits.

In this Letter, we describe details of the $\ell + 2j$ mode analysis followed by a brief summary of the multijet mode shape analysis. We show cross section limits and an excluded region in the $M(\pi_T)$ vs $M(\rho_T)$ plane from the $\ell + 2j$ mode. This Letter is the first published result in the direct search for color singlet technirho production [9].

The CDF detector [10] consists of a magnetic spectrometer surrounded by calorimeters and muon chambers. A four-layer silicon microstrip vertex detector (SVX) [11], located immediately outside the beam pipe, provides precise track reconstruction in the plane transverse to the beam and is used to identify secondary vertices from b and c hadron decays. The momenta of charged particles are measured in the central tracking chamber (CTC), which is located inside a 1.4-T superconducting solenoid. Outside the CTC, electromagnetic and hadronic calorimeters cover the pseudorapidity region $|\eta| < 4.2$ [12] and are used to identify electron and photon candidates and jets. The calorimeters are also used to determine the missing transverse energy ($\not\!\!E_T$), which can indicate the presence of energetic neutrinos. Outside the calorimeters, drift chambers in the region $|\eta| < 1.0$ provide muon identification.

The data selection criteria for the $\ell + 2j$ mode is the same as in the standard model Higgs boson search analysis in the $W + 2$ jet channel [13] plus additional criteria designed to further exploit the characteristics of the WTC signal [3]. We require either an isolated electron with $E_T > 20$ GeV or an isolated muon with $P_T > 20$ GeV$/c$ in the central region, $|\eta| < 1.0$. We also require $\not\!\!E_T > 20$ GeV, and exactly two jets with $E_T > 15$ GeV and $|\eta| < 2.0$. Jets are defined as localized energy depositions in the calorimeters and are reconstructed using an iterative clustering algorithm with a fixed cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ in $\eta - \phi$ space [14]. In order to reduce the large $W + 2$ jet background, we require that at least one of the jets be identified as a b-jet candidate. Identification of the b jet is done by reconstructing secondary vertices from b-quark decay using the SVX (SVX b tagging). The details of the SVX b-tagging algorithm are described in Ref. [15]. After the $W + 2$ jet with SVX b-tagging selection (Wbq), the observed number of

events is 42, while the expected number of background events is 31.6 ± 4.3 (syst) [13] which represents an excess of about 1.5σ. The major background contributions are $Wb\overline{b}$, $Wc\overline{c}$, and Wc productions. Other backgrounds are due to mistags (tagging a light quark as a b), $t\overline{t}$ and single t production, non-W processes, vector boson pairs, and Z boson plus heavy flavor production.

The acceptance and efficiencies of the signal are estimated using the PYTHIA Monte Carlo simulation [16]. We arbitrarily choose 47 mass combinations of the ρ_T and π_T, where the cross sections are larger than ~5 pb. The model parameters we use are $N_{TC} = 4$ (the number of technicolors, analogous to the three colors in QCD), $Q_D = Q_U - 1 = 0$ (techniquark charges), and $\sin\chi = \frac{1}{3}$ (the mixing angle). Details of the parameters are described in [2]. Generated events are passed through a simulation of the CDF detector. The total efficiency of the Wbq selection is approximately 1%, including the branching ratio of $W \to e\nu, \mu\nu$.

We reduce the background further by applying additional selection criteria on the azimuthal angle (ϕ) between the two jets, $\Delta\phi(jj)$, and on the P_T of the dijet system, $P_T(jj)$, which are unique to this analysis [3]. Our WTC signal search region in the $\ell + 2j$ mode is characterized by $M(\pi_T) + M(W) \simeq M(\rho_T)$. In this case, technipions are produced nearly at rest in the transverse plane, and consequently the $P_T(jj)$ is smaller and the two jets are more back-to-back than in background events. In order to obtain the optimum selection criteria, we apply $\Delta\phi(jj)$ and the $P_T(jj)$ requirements simultaneously and maximize the $S/\sqrt{B}$ (signal over square root of the background) values. We thus obtain $\Delta\phi(jj)$ and $P_T(jj)$ cut values for each mass combination. For example, at a mass combination of $M(\pi_T) = 90$ GeV/c^2 and $M(\rho_T) = 180$ GeV/c^2, the optimized selection criteria are $\Delta\phi(jj) > 2.1$ and $P_T(jj) < 40$ GeV/c. For each mass combination, the efficiency of these additional criteria ranges from 80% to 90% for the signal, and 20% to 40% for the background.

We reconstruct the invariant mass of the dijet system, $M(jj)$, which corresponds to the technipion mass, and the invariant mass of the $W + 2$ jet system, $M(Wjj)$, which corresponds to the technirho mass. A signal would appear as peaks in the two mass distributions. Jet energy is corrected for calorimeter gaps, nonlinear response, energy not contained in the jet cone, and underlying event energy. In order to reconstruct the $M(Wjj)$, we need to estimate the P_z of the neutrino $[P_z(\nu)]$ which is unknown since we measure only its transverse component. We solve for $P_z(\nu)$ using the W mass constraint in a lepton-neutrino system and take the smaller $|P_z(\nu)|$ of the two solutions [17]. If there is no real solution for the $P_z(\nu)$, we take the real part of the solution of the quadratic equation. Figure 1 shows the $M(jj)$ and $M(Wjj)$ distributions before and after the $\Delta\phi(jj)$ and $P_T(jj)$ requirements for data and simulation

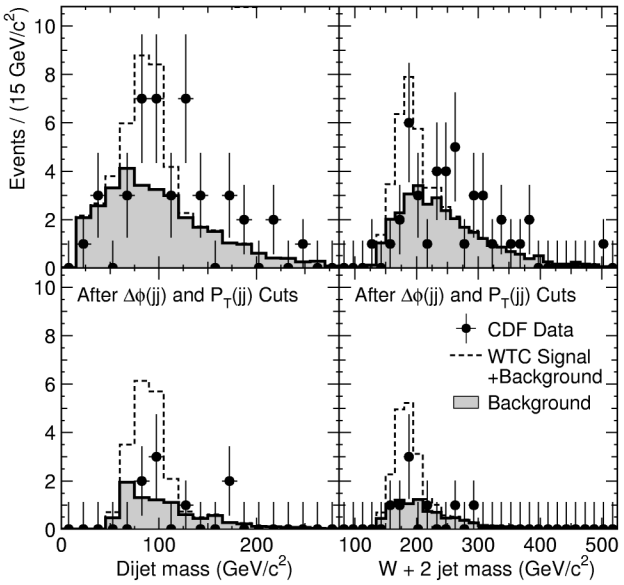

FIG. 1. The invariant mass of the dijet system and of the $W + 2$ jet system for the $\ell + 2j$ mode. Requirements of $\Delta\phi(jj) > 2.1$ and $P_T(jj) > 40$ GeV/c are applied in the bottom plots. The number of events of the background and the technicolor Monte Carlo signal are normalized to the expected number of events in 109 pb^{-1}. The mass combination shown is $M(\pi_T) = 90$ GeV/c^2 and $M(\rho_T) = 180$ GeV/c^2.

for $M(\pi_T) = 90$ GeV/c^2 and $M(\rho_T) = 180$ GeV/c^2. Finally, we apply mass window requirements. The signal Monte Carlo sample is used to estimate the mean and resolution (σ_m) for both $M(jj)$ and $M(Wjj)$. We define the mass window requirement to be within $\pm 3\sigma_m$ of the mean mass value. The typical mass resolutions for $M(jj)$ and $M(Wjj)$ are approximately 15 GeV/c^2 and 20 GeV/c^2, respectively.

Table I summarizes our results. The small excess seen in the $\ell + 2j$ mode after the Wbq selection is no longer present after the cuts designed to enhance a contribution from WTC. We set 95% C.L. upper limits on σ_{counting}, taking into account a total 27% and 14% systematic uncertainty in the signal efficiency and background estimation, respectively. The σ_{counting} is defined as $\sigma(p\overline{p} \to \rho_T \to W\pi_T)$ times the branching ratio (BR), where BR includes $\pi_T^0 \to b\overline{b}$ and $\pi_T^{\pm} \to \overline{b}c$. The dominant sources of systematic uncertainty are initial state radiation (10%) and final state radiation (19%). We exclude a region in the $M(\pi_T)$ vs $M(\rho_T)$ plane where the cross section is less than the predicted cross section for this model as shown in Fig. 2.

One could expect to improve this sensitivity with a shape analysis of the dijet mass distribution of the two b-tagged jets in the $\ell + 2j$ and $4j$ channels. The $4j$ channel is sensitive to both the $W\pi_T$ and $\pi_T\pi_T$ decays of the ρ_T, while the $\ell + 2j$ analysis described above searched for $\rho_T \to W\pi_T$ decays only. This allows us to explore a different region in the $M(\rho_T)$ vs $M(\pi_T)$ plane outside the

TABLE I. Summary of the $\ell + 2j$ mode counting experiment for various π_T and ρ_T mass combinations after all selection cuts have been applied. The $\sigma^{\text{theory}}_{\text{counting}}$ is the expected theoretical σ_{counting}. The ϵ_{tot} is the total efficiency, N_{exp} is the expected number of signal events, $N_{\text{B.G.}}$ is the estimated number of background events, N_{obs} is the observed number of events, and N_{lim} and $\sigma^{\text{lim}}_{\text{counting}}$ are the 95% C.L. limits, taking into account systematic uncertainties.

$M_{(\pi_T,\rho_T)}$ (GeV/c^2)	$\sigma^{\text{theory}}_{\text{counting}}$ (pb)	ϵ_{tot} (%)	N_{exp}	$N_{\text{B.G.}}$	N_{obs}	N_{lim}	$\sigma^{\text{lim}}_{\text{counting}}$ (pb)
80 170	3.7	0.64	2.6	5.4 ± 0.7	5	7.3	10.5
85 170	14.1	0.66	10.2	3.8 ± 0.5	5	8.4	11.7
90 180	15.7	0.69	11.8	5.7 ± 0.8	5	7.1	9.5
95 185	13.0	0.88	12.5	6.4 ± 0.9	6	7.9	8.1
100 190	10.9	0.92	10.9	6.5 ± 0.9	6	7.8	7.8
105 200	9.3	0.94	9.5	7.4 ± 1.0	8	9.5	9.2
110 210	7.4	0.97	7.9	9.8 ± 1.3	13	13.8	13.0
115 210	6.9	1.02	7.7	8.4 ± 1.2	10	11.2	10.0

region already excluded by the counting experiment. Our previous published CDF search for standard model Higgs boson production [18] suggests that searching for the WTC particles in the $4j$ channel may result in observing a signal or setting more stringent limits in certain mass regions. For that reason, we have performed a very similar analysis in $4j$ mode as [18] using the same data sample and the same shape analysis method to extract limits [19]. For details of this analysis, we refer the reader to Ref. [6]. The shape of invariant mass distribution of the b-tagged dijet system for data can be well explained with the predicted background shape. We place cross section limits by taking into account a 34% total systematic uncertainty. The $\ell + 2j$ data discussed above is incorporated into this technique.

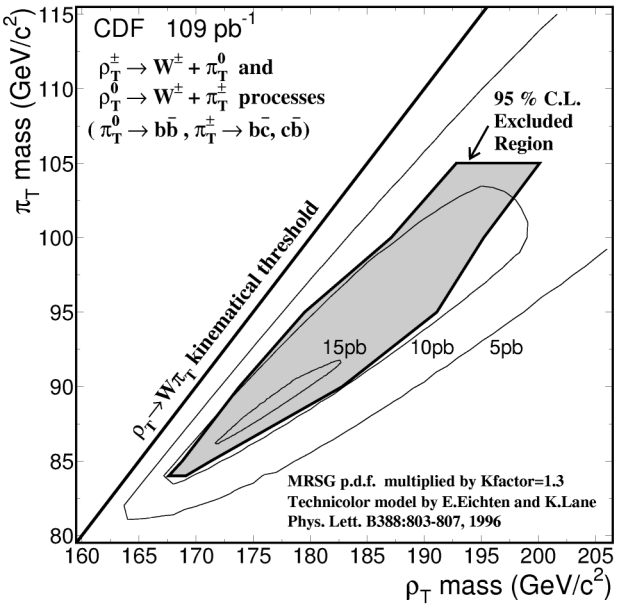

FIG. 2. The shaded region shows the excluded region in the $M(\pi_T)$, $M(\rho_T)$ plane. Three contours of $\sigma^{\text{theory}}_{\text{counting}}$ are also shown (5, 10, and 15 pb). PYTHIA v6.115 with MRSG parton distribution function and a K factor = 1.3 is used to calculate the cross section.

The result from these shape analyses provides no further constraint to the WTC model. However, in addition to the cross section limits from the shape analysis themselves, the results provide us with important guidance for the upcoming Tevatron run. Besides higher luminosity and significant detector improvements, we will have the ability to trigger on hadronic b decays by way of charged track impact parameter information. This hadronic b trigger along with lower trigger energy thresholds will significantly improve our sensitivity to technicolor models.

In summary, we have performed a search for technicolor particles, ρ_T and π_T. From the counting experiment in the $\ell + 2j$ mode with $\Delta\phi(jj)$, $P_T(jj)$, and mass window cuts, no excess over background estimation is observed, and we set production cross section limits. We exclude a region in the $M(\rho_T)$ and $M(\pi_T)$ plane at the 95% C.L. We also perform a search using the shape of the dijet invariant mass distributions in the $4j$ and the $\ell + 2j$ modes.

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