Search for Technicolor Particles Produced in Association with a W Boson at CDF

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Abstract

We present a search for the technicolor particles ρ_T and π_T in the process of $p\bar{p} \to \rho_T \to W\pi_T$ at a center of mass energy of $\sqrt{s} = 1.96\,\mathrm{TeV}$. The search uses a data sample corresponding to approximately $1.9\,\mathrm{fb}^{-1}$ of integrated luminosity accumulated in the CDF II detector at the Fermilab Tevatron. The event signature we consider is the $W \to \ell\nu$ and $\pi_T \to b\bar{b}, b\bar{c}$ or $b\bar{u}$ depending on the π_T charge. We select events consistent with a signature of a single high-p_T electron or muon, a large missing transverse energy, and two jets. Jets corresponding to bottom quarks are identified with multiple b-tagging algorithms. In the case of events with exactly one b- tagged jet, we apply a neural network flavor separator to reject contamination from charm and light quark jets. The observed number of events and the invariant mass distributions of dijet and $W + 2$ jets are consistent with the Standard Model background expectations, and we set 95% confidence level exclusion region in the ρ_T-π_T mass plane.

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The mechanism of electroweak symmetry breaking in the standard model is still unknown. The most popular mechanism to induce electroweak symmetry breaking of the gauge theory, resulting in massive gauge bosons and fermions, are the Higgs mechanism [1]. Alternatively, there is a theory that predicts the existence of a strong interaction of new fermions (technifermions) and gauge bosons at a scale of $\Lambda \sim 1TeV$, which arises as a result of spontaneous electroweak symmetry breaking through the new strong interaction, technicolor model [2, 3]. Technicolor interacts between technifermions to form the bound states (technihadrons) such as $\rho_T^{0,\pm}$, $\pi_T^{0,\pm}$ and ω_T^0, analogous to the mesons in QCD. In the techcnicolor theory, the technipions ($\pi_T^{0,\pm}$) act the same role as Higgs boson in the Standard Model. One of the most sensitive processes for technipion searches is $\rho_T \to W\pi_T \to l^{\pm}\nu b\bar{b}, b\bar{c}$ or $b\bar{u}$, depending on their charge. In this letter we report results of a search for technipion produced in association with W bosons from technirho decay in a context of the Technicolor Straw Man Model (TCSM) [4]. The resulting final state is identified by selecting events with exactly one high-energy electron or muon candidate, large missing transverse energy, and one or two b-tagged jets.

Previous searches at CDF [5] and D0 [6] were limited not only by smaller data samples, but also by contaminations from jets associated with charm or light flavor quarks which are falsely tagged as b-jets. The search described in this letter employs for multiple b-tagging strategies to improve the purity of the selected event sample. The data sample used here corresponds to $1.916 \pm 0.115\,\mathrm{fb}^{-1}$ of integrated luminosity, nearly five times the sample used in the previous searches. LEP [9] also performed the searches for technicolor particles, however the search mass region was constrained by beam energy.

The CDF II detector is a general purpose detector to study $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$ at Fermilab Tevatron. It consists of a cylindrical magnetic spectrometer surrounded by sampling calorimeters used to measure energies of electromagnetic showers and jets. Charged particle tracking is performed with microstrip silicon detectors surrounded by a large cylindrical multilayer drift chamber, both immersed in a 1.4 T solenoidal magnetic field parallel to the p and $\bar{p}$ beams. Jets are identified as a collection of hadronic and electromagnetic calorimeter towers, which are clustered using an iterative cone algorithm with a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ units in the azimuth-pseudorapidity space [8]. Planar drift chambers used for muon detection surround the calorimeters at least five interaction lengths from the interaction region.

Events are collected using high-p_T electron or muon triggers with a three-level selection filter. The first two level criteria ensure that purely electromagnetic calorimeter clusters exist or that track stubs in the muon chambers align with tracks in drift chamber having $p_T > 8\,\mathrm{GeV}/c$. The third-level trigger requires an electron (muon) with $E_T > 18\,\mathrm{GeV}$ ($p_T > 18\,\mathrm{GeV}/c$).

To select the $W + 2$ jets final state, events are selected by requiring exactly one electron or muon candidate, large missing transverse energy $\not\!\!E_T > 20\mathrm{GeV}$, and two high E_T jets. The electron or muon must be within the central part of the detector, in the pseudorapidity regions $|\eta| < 1.1$ or $|\eta| < 1.0$, respectively, and must have $E_T > 20\mathrm{GeV}$. The lepton must be isolated from the rest of the event by a cone of radius $\Delta R = 0.4$ containing no more than 10% of the lepton energy. It must also be no more than 5 cm in z away from the primary event vertex, which is defined by fitting a subset of charged particle tracks in the event to a single vertex. To reduce the background from Z boson, we reject the events with multiple high-p_T leptons, as well as events in which the lepton and another high-energy track of opposite sign form an invariant mass between $76 < M_{ll} < 106\,\mathrm{GeV}/c^2$. Jets used in the analysis must fall within the acceptance of the silicon detector ($|\eta| < 2.0$) for reliable b-tagging, and they must have transverse energy greater than 20 GeV. Even though the $W + 2$ jet final state is the target sample for this search, other sample with $W+$ 1 or $W + 3$, 4 jets are useful for cross-checks of the background estimates with similar topologies.

The $W + 2$ jets final states are dominated from QCD light flavor contribution, while the techni-pions' decay process include one or two b quark jets in final state. Identifying these b quark jets help to suppress the background from QCD light flavor. In this analysis, we use two b-tagging algorithms, secondary vertex finding algorithm [7] (SECVTX) and jet probability tagging algorithm [10] (JETPROB). In addition to the secondary vertex finding algorithm, a neural network (NN) filter has been trained to reject tagged jets originating from charm or light-quarks [7]. To improve the search sensitivity, we require that at least one jet is b-tagged by the SECVTX. Three b-tagged event categories are considered. The first category (ST+ST) are events with two SECVTX b-tagged jets. The second category (ST+JP) consists of events where only one of the jets is b-tagged by SECVTX and the second jet is only b-tagged by JETPROB. The third category (ST w/ NNtag) is for events which do not belong to the first two categories but contain exactly one SECVTX b-tagged jet that passes the NN filter as well. Because events with charm and light-flavor jets are unlikely to be double-tagged, the extra NN filter is not applied to double-tagged events. The selected event sample includes contributions from other Standard Model processes. The largest background rates are due to W+jets production, $t\bar{t}$ production, and non-W multijet production, with small contributions from single top and electroweak boson production WW, WZ, ZZ, or $Z \rightarrow \tau\tau$. These backgrounds are estimated using the same strategies used in the previous analysis [7].

The W+jets production include either with jets from b or c quarks or with jets mistagged by the b-tagging algorithm. The effect of true W+heavy-flavor production is estimated from a combination of data and simulation. We use the ALPGEN Monte Carlo program [11] to calculate the rate of $Wb\bar{b}, Wc\bar{c}$, and Wc production relative to inclusive W+jets production. Then this relative rate is applied to the observed W+jets sample, after non-W and $t\bar{t}$ contributions have been subtracted. Finally, we apply a b-tagging efficiency calculated using the appropriate ALPGEN event samples (corrected with the data-to-MC efficiency scale factor) and the NN filter rate.

Events from $t\bar{t}$ production followed by leptonic W decay typically have two b jets from t decay, significant missing transverse energy, and one or two high-energy leptons with two or zero additional jets, depending on whether one or both W bosons from the top quarks decay leptonically. The $t\bar{t}$ contribution to the $\ell\nu b\bar{b}$ final state is estimated using simulated PYTHIA events [12]. It is normalized to the NLO cross section $6.7^{+0.7}_{-0.9}$ pb calculated for $m_t = 175\mathrm{GeV/c}^2$ [13]. The small contribution from production of single top quarks is estimated using MADEVENT [14] and PYTHIA normalized to the NLO cross section [15].

Multijet events may have high-energy identified leptons or missing transverse energies, both mimicking the signature of W decay. These may be from semileptonic heavy flavor decay or from false reconstructions. The identified leptons from such events are rarely isolated in energy, as required by our event selection, and seldom yield large missing transverse energy. We therefore calculate the number of non-W events in our selected sample by extrapolating from sideband regions (defined in the space of lepton energy isolation and missing transverse energy) into the signal region [16].

Contributions from events with falsely tagged light-flavor jets (mistags) are estimated by measuring a mistag rate in generic jet data. The mistag rate is further modified by the NN filter efficiency. The resulting overall mistag rate is applied to the W+jets sample to yield the number of mistagged events present in the sample.

Small contributions from electroweak diboson backgrounds (WW, WZ, and ZZ) are estimated using the most recent theoretical cross section calculations [17] and $Z \to \tau\tau$ backgrounds are estimated using the CDF result [18], with acceptances calculated using fully simulated events from the PYTHIA Monte Carlo program.

The dominant uncertainty in the W + heavy flavor background is the production rate calibration factor for simulation derived from multijet data [16]. Different simulation inputs give different factors, and we find a 30% relative error on the background from heavy flavor. The background from mistags has major uncertainties on the rate correction due to particle interactions in detector material and on the NN rejection factor. Both are 15% relative errors. Cross-checks of sideband data yield a 17% relative uncertainty on the non-W multijet estimate. The electroweak background estimates for diboson and single top are subject to uncertainties in the b-tagging efficiency and the cross section predictions.

A summary of the estimated background contributions to the W + 2-jets final state is shown in Table I, along with the results from the data sample and expected technicolor signal.

The signal process in $\rho_T \to W\pi_T \to l\nu j_1 j_2$ is expected to show a resonant peak in the dijet and $W+2$-jet mass spectrums. Figure 1 shows the dijet mass spectrums in the double tagged (two SECVTX tagged and one SECVTX + one JETPROB tagged) and one SECVTX with NN filter tagged 2-jet samples for the estimated background as well as for the observed events. Figure 2 shows the Q-value (mass difference defined as $Q = m(\rho_T) - m(\pi_T) - m(W)$) spectrum in each b-tagging category where the p_z of the neutrino is taken by choosing the solutions from the quadratic equation of the W mass constraint with the smallest $|p_z|$ or set the imaginary part of solutions to zero if there is no real solution. A $\rho_T = 200\,\mathrm{GeV}/c^2$, $\pi_T = 115\,\mathrm{GeV}/c^2$ technicolor signal is also shown for comparison. There is no significant excess observed in both dijet mass and Q-value spectrums.

The acceptance for $\rho_T \to W\pi_T \to \ell\nu b\bar{b}, b\bar{c}, b\bar{u}$, including leptonic τ decays, is calculated from samples generated with the PYTHIA Monte Carlo program using ρ_T mass values between 180 and $250\,\mathrm{GeV}/c^2$ with a step of 10 GeV/c^2. We set the mass parameters as $M_V = M_A = 200\,\mathrm{GeV}/c^2$, the charge of up-type technifermion as $Q_U = 1$ and the mixing angle between isotriplet technipion interaction and mass eigenstates as $sin\chi = 1/3$ in TCSM. For this study, we focus on the π_T mass region as $m(W) + m(\pi_T) < m(\rho_T) < 2 \times m(\pi_T)$. Lower threshold is due to the kinematic allowed for $W\pi_T$ production, and upper threshold is to suppress the $\rho_T \to \pi_T\pi_T$ production.

Selection	double SECVTX	SECVTX + JETPROB	one SECVTX with NN filter
Mistag	3.88±0.35	11.73±0.92	107.1±9.38
$Wb\bar{b}$	37.93±16.92	31.15±14.03	215.6±92.34
$Wc\bar{c}$	2.88±1.25	7.87±3.43	167±62.14
$t\bar{t}$(6.7pb)	19.05±2.92	15.56±2.39	60.68±9.30
Single top(s-ch)	6.90±1.00	5.14±0.75	14.38±2.09
Single top(t-ch)	1.60±0.23	1.87±0.27	29.57±4.33
WW	0.17±0.02	0.93±0.11	15.45±1.91
WZ	2.41±0.26	1.84±0.20	7.59±0.81
ZZ	0.06±0.01	0.08±0.01	0.31±0.03
$Z- > \tau\tau$	0.25±0.04	1.29±0.20	7.27±1.12
nonW QCD	5.50±1.00	9.55±1.73	184.7±33.04
Total Bkg	80.62±18.75	86.99±17.99	809.61±159.38
m($\rho_T^{\pm}$,π_T^0)=(200,115) GeV/c^2	11.24±0.98	7.69±0.87	20.74 ± 1.61
m(ρ_T^0,$\pi_T^{\mp}$)=(200,115) GeV/c^2	1.50±0.16	2.85±0.34	22.96±1.78
Observed Events	83	90	805

TABLE I: Background estimation of W+2-jet events for each b-tag category.

The acceptances for double SECVTX, one SECVTX + one JETPROB and one SECVTX with NN filter events of $\pi_T^0 \to b\bar{b}$ ($\pi_T^{\pm} \to b\bar{c}, b\bar{u}$) are 0.40±0.05% (0.05±0.01%), 0.27±0.04% (0.10±0.02%) and 0.73 ± 0.06% (0.81 ± 0.07%) including the W branching ratio to lepton pairs, for a mass hypothesis of $\rho_T = 200\,\mathrm{GeV}/c^2$, $\pi_T = 115\,\mathrm{GeV}/c^2$. The dominant systematic uncertainty on the acceptance of $\pi_T^0 \to b\bar{b}$ ($\pi_T^{\pm} \to b\bar{c}, b\bar{u}$) process is the b-tagging scale factor uncertainty, which is a 8.4% (9.4%) relative error for the double SECVTX selection, a 9.2% (17.0%) relative error for the one SECVTX + one JETPROB selection and a 4.3% (4.3%) relative error for the one SECVTX with NN filter selection. This value is largely due to uncertainties in fitting the b/c ratio for the data sample in which the scale factor is measured. Additional sources of systematic error include the jet energy scale, the lepton identification efficiency, parton distribution function, and the initial and final state radiation models [19].

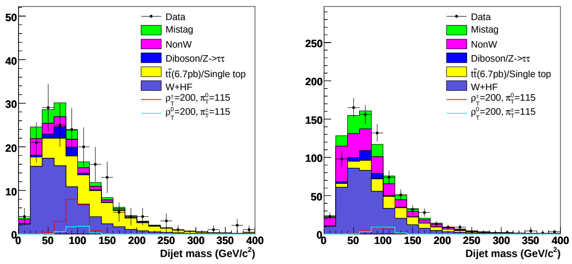

FIG. 1: Reconstructed dijet mass distributions for W+2-jet events. (Left) Two SECVTX tagged jets and one SECVTX + one JETPROB tagged jets. (Right) One SECVTX with NN filter tagged jets.

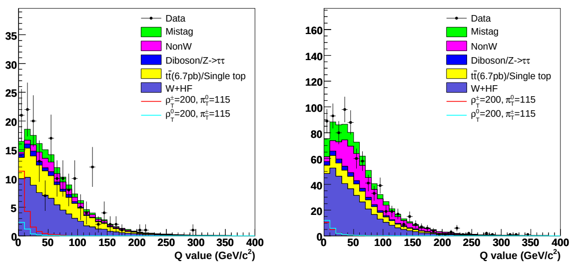

FIG. 2: Reconstructed Q-value distributions for W+2-jet events. Q-value is a mass difference defined as $Q = m(\rho_T) - m(\pi_T) - m(W)$. (Left) Two SECVTX tagged jets and one SECVTX + one JETPROB tagged jets. (Bottom) One SECVTX with NN filter tagged jets.

Since there is no significant excess of events in the data compared to the predicted background, we set the 95% C.L. excluded region on technicolor production as a function of the technicolor particles mass. A 2-dimensional binned maximum likelihood technique which assuming Poisson statistics is used on the 2-dimensional distribution of dijet invariant mass vs Q-value by constraining the number of background events within the uncertainties. To calculate the 95% C.L. excluded region, we use neutral and charged π_T signals simultaneously. A Bayesian interval is constructed from the cumulative likelihood distributions and a prior probability density function uniform in the number of technicolor signal events s. The 95% confidence level upper limit is defined to be the value $s_{\rm up}$ for which $\int_0^{s_{\rm up}} L(s)ds / \int_0^{\infty} L(s)ds = 0.95$. The number of signal events is then converted to a technicolor particles production cross section times branching fraction $\sigma(p\bar{p} \to W\pi_T^0(\pi_T^{\pm})) \cdot Br(H \to b\bar{b}(b\bar{c}, b\bar{u}))$.

The expected limits determined from pseudo-experiments and the observed limits com-

$m(\rho_T,\pi_T)$	Normalized Upper Limit		$m(\rho_T,\pi_T)$	Normalized Upper Limit	
GeV/c^2	Observed Limit	Expected Limit	GeV/c^2	Observed Limit	Expected Limit
(180,95)	0.30	0.22	(230,135)	0.72	0.49
(190,105)	0.44	0.28	(230,145)	1.61	0.79
(200,105)	0.37	0.30	(240,125)	0.71	0.57
(200,115)	0.59	0.37	(240,135)	0.65	0.56
(210,115)	0.42	0.33	(240,145)	0.86	0.58
(210,125)	0.88	0.47	(240,155)	1.94	1.03
(220,115)	0.59	0.42	(250,135)	0.76	0.66
(220,125)	0.52	0.39	(250,145)	0.69	0.65
(220,135)	1.22	0.59	(250,155)	1.02	0.72
(230,125)	0.60	0.48	(250,165)	2.01	1.31

TABLE II: Expected and observed upper limit on $\sigma(\rho_T \to \pi_T W^\pm) \times BR(\pi_T \to b\bar{q})/\sigma_{theory}(\rho_T \to \pi_T W^\pm) \times BR_{theory}(\pi_T \to b\bar{q})$ as a function of $m(\rho_T)$ and $m(\pi_T)$.

pared to the theoretical production rate are listed in Table II. The expected and observed 95% confidence level excluded region as function of technicolor particles mass is shown in Figure 3. Almost all the region which we focused on are excluded at 95% confidence level, except the region which are near the $W\pi_T$ production threshold with $m(\rho_T) \geq 220\,\mathrm{GeV}/c^2$ and $m(\pi_T) \geq 125\,\mathrm{GeV}/c^2$.

In summary, we have performed first analysis of search for technicolor production $p\bar{p} \to \rho_T^{\pm/0} \to W^\pm \pi_T^{0/\mp} \to \ell\nu b\bar{b}$, $\ell\nu b\bar{c}$ or $\ell\nu b\bar{u}$ with using the large dataset accumulated by CDF II detector. A large region of $m(\rho_T)$ = 180 - 250 GeV/c^2 and $m(\pi_T)$ = 95 - 145 GeV/c^2 are excluded at 95% confidence level, based on the technicolor Straw Man model.

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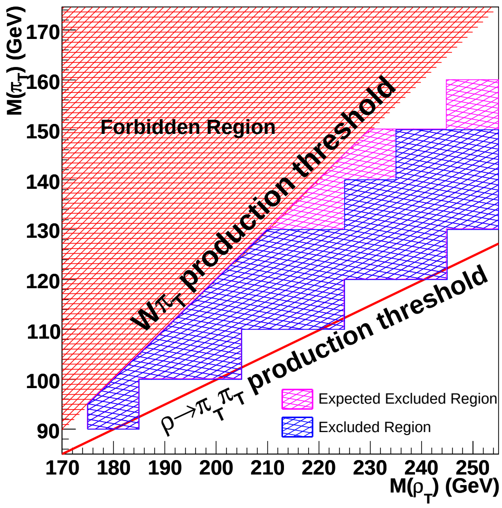

FIG. 3: 95% confidence level excluded region on technicolor particles production cross section times branching fraction as a function of $m(\rho_T)$ and $m(\pi_T)$ mass hypothesis. The expected excluded region from background-only pseudoexperiments are shown with the observed results from this analysis.

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