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A search for narrow resonances that decay into $t\bar{t}$ pairs has been performed using 130 pb^{-1} of data in the lepton + jets channel collected by the DØ detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. There is no significant deviation observed from the standard-model predictions at a top-quark mass of 175 GeV$/c^2$. We therefore present upper limits at the 95% confidence level on the product of the production cross section and branching fraction to $t\bar{t}$ for narrow resonances as a function of the resonance mass M_X. These limits are used to exclude the existence of a leptophobic top-color particle with mass $M_X <$ 560 GeV$/c^2$, using a theoretical cross section for a width $\Gamma_X = 0.012 M_X$.

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Narrow resonances decaying to $t\bar{t}$ pairs are predicted by several theories beyond the standard model. For instance, in the top-color-assisted technicolor model [1] which combines top-color [2] and technicolor [3] models, the technicolor interactions at the electroweak scale are responsible for electroweak symmetry breaking, and extended technicolor generates the masses of all quarks and leptons except that of the top quark. The strong top-color interactions, broken near 1 TeV, induce a massive dynamical $t\bar{t}$ condensate and all but a few GeV of the top-quark mass, and contribute little to electroweak symmetry breaking. The $t\bar{t}$ condensate, or the heavy Z' boson, couples preferentially to the third generation. In one of the scenarios of the top-color-assisted technicolor model the heavy Z' boson couples preferentially to the third quark generation, and not to leptons (leptophobic). The cross section for the Z' boson in this model is large enough for it to be observed over a wide range of masses and widths in data available from the 1.8 TeV $p\bar{p}$ Tevatron Collider at Fermilab.

In searches for such heavy particles or narrow resonances, we seek an excess of events beyond that predicted by the standard model in the distribution of the invariant mass of $t\bar{t}$ decay products. This excess of events would appear as a peak at the mass of the narrow resonance. Previous searches at the Tevatron have limited a leptophobic Z' boson to a mass higher than 480 GeV$/c^2$ [4]. In this paper, we describe a direct search for narrow $t\bar{t}$ resonances in the inclusive decay modes $t\bar{t} \rightarrow \ell\nu + \geq$ 4 jets, where $\ell =$ an electron (e) or a muon (μ), using 130 pb^{-1} of data recorded by the DØ experiment from 1992 to 1996. Having observed no significant deviation from the standard model, we present model-independent 95% confidence-level (C.L.) upper limits on the product of the cross section (σ_X) and branching fraction (B) to $t\bar{t}$, for a narrow resonance. We also present a lower limit on the resonance mass (M_X) of the Z' boson in a particular scenario of the top-color-assisted technicolor model [1].

The DØ detector is a multipurpose particle detector designed to study $p\bar{p}$ collisions at the Fermilab Tevatron Collider. The detector consists of three major systems: a nonmagnetic central tracking system, a uranium/liquid-argon calorimeter, and a muon spectrometer. A detailed description of the DØ detector can be found in Ref. [5].

The present search rests upon techniques developed for the measurement of the mass of the top quark at DØ in the lepton + jets channel [6]. Because of the large mass of the top quark (m_t), the $t\bar{t} \rightarrow \ell\nu + \geq 4$ jets final state is characterized by a high-p_T isolated lepton (e or μ) and large missing transverse energy ($\not{E}_T$) from the undetected neutrino. Additional soft muons (μ tags) from semileptonic decays of b and c quarks occur in $\approx 20\%$ of $t\bar{t}$ events but only in $\approx 2\%$ of non-$t\bar{t}$ events [7], and therefore offer discrimination between signal and background. We consider two orthogonal classes of events for this analysis: (i) a purely topological selection of lepton + jets events denoted as e + jets and μ + jets, where the jets are required not to contain a muon, and (ii) a selection based primarily on the presence of a muon contained within a jet (μ tag), and additional selections on the topology of the event. These events are denoted as e + jets$/\mu$ and μ + jets$/\mu$. Details of the trigger requirements, reconstruction of events, and identification of the e, μ, $\not{E}_T$, and jets can be found in Ref. [6]. The principal sources of background correspond to standard-model $t\bar{t}$ production, $W(\rightarrow \ell\nu)$ + jets production, and production of multijets ($N_j \approx 5$), in which one of the jets is misidentified as a lepton and $\not{E}_T$ stems from jet-energy mismeasurement. The contribution from all other physics sources is negligible.

In order to reduce the contribution from W + jets and multijets we apply the selections summarized in Table I. In the untagged channels, the cuts on $E_T^W (\equiv |E_T^l| + |\not{E}_T|)$ and η^W are applied to further reduce the background from multijets. The variable η^W is determined by using the smaller of the two solutions for p_z^ν, the longitudinal component of the neutrino momentum, obtained while performing a kinematic fit to $W \rightarrow l\nu$ decay using the W mass as a constraint. In the tagged channels, the multijet background is further reduced by applying selections on $\Delta\phi(\not{E}_T, \mu)$ which is the difference in the azimuthal angle between $\not{E}_T$ and the highest-p_T muon. We also apply a cut on the χ^2 from a kinematic fit to the $t\bar{t} \rightarrow \ell\nu$ + jets hypothesis described later.

The resonance signal $X \rightarrow t\bar{t}$ is modeled using the PHTHIA-6.1 [8] Monte Carlo (MC) event generator, with $m_t = 175$ GeV$/c^2$, and CTEQ3M [9] parton distribution functions. Initial- and final-state radiation (ISR/FSR) is included. About 10 000 events at eight resonance masses between 400 and 850 GeV$/c^2$ are generated, using a width $\Gamma_X = 0.012 M_X$. This width is significantly smaller than the $\approx 0.04 M_X$ mass resolution of the DØ detector for

TABLE I. Summary of event selections. Here $\not{E}_T^{\rm cal}$ is the missing transverse energy measured just in the calorimeter.

	e + jets	μ + jets	e + jets/μ	μ + jets/μ
Lepton (l)	$E_T^l > 20$ GeV $\lvert\eta\rvert < 2$	$p_T^l > 20$ GeV/c $\lvert\eta\rvert < 1.7$	$E_T^l > 20$ GeV $\lvert\eta\rvert < 2$	$p_T^l > 20$ GeV/c $\lvert\eta\rvert < 1.7$
$\not{E}_T$	$\not{E}_T > 20$ GeV $\not{E}_T^{\rm cal} > 25$ GeV	$\not{E}_T > 20$ GeV $\not{E}_T^{\rm cal} > 20$ GeV	$\not{E}_T > 20$ GeV	$\not{E}_T > 20$ GeV $\not{E}_T^{\rm cal} > 20$ GeV
Jets	≥ 4 jets $E_T > 15$ GeV $\lvert\eta\rvert < 2$	≥ 4 jets $E_T > 15$ GeV $\lvert\eta\rvert < 2$	≥ 4 jets $E_T > 15$ GeV $\lvert\eta\rvert < 2$	≥ 4 jets $E_T > 15$ GeV $\lvert\eta\rvert < 2$
μ tag	No	No	Yes	Yes
Other	$\lvert\not{E}_T\rvert + \lvert E_T^l\rvert > 60$ GeV $\lvert\eta^W\rvert < 2$	$\lvert\not{E}_T\rvert + \lvert p_T^l\rvert > 60$ GeV $\lvert\eta^W\rvert < 2$	$\not{E}_T > 35$ GeV if $\Delta\phi(\not{E}_T, \mu) < 25°$	$\Delta\phi(\not{E}_T, \mu) < 170°$ $\lvert\Delta\phi(\not{E}_T, \mu) - 90°\rvert/90°$ $<\not{E}_T/(45$ GeV)
Events passing above cuts and $\chi^2 < 10$	16	21	1	3

$t\bar{t}$ systems [10]. Hence, our upper limits on $\sigma_X B$ are dominated by the detector resolution and independent of Γ_X for such narrow resonances and are valid for all choices of Γ_X that are reasonably small compared to the detector resolution. The generated events are processed through the DØGEANT detector simulation package [11] and reconstructed using the DØ event-reconstruction program.

The background is estimated from a combination of Monte Carlo simulations and collider data [6]. Standard-model $t\bar{t}$ production is modeled using the HERWIG-5.7 [12] MC generator with a top mass $m_t = 175$ GeV/c^2. The W + jets background is modeled using the VECBOS [13] parton-level event generator whose output is passed through HERWIG for QCD evolution and fragmentation. The background from multijets is estimated using signal-suppressed data samples. The selections summarized in Table I are also applied to the Monte Carlo signal and background samples.

Each event in data, as well as in the Monte Carlo signal and background samples, is fitted to a three-constraint hypothesis for the $t\bar{t}$ production and decay:

$$t\bar{t} \to W^+ b W^- \bar{b}; \qquad W^\pm \to l^\pm \nu_l; \qquad W^\mp \to q\bar{q}'. \quad (1)$$

The inputs to the fit are the measured kinematic parameters of the lepton and the jets, and the missing transverse energy vector, $\vec{\not{E}}_T$. We minimize $\chi^2 = (\mathbf{x} - \mathbf{x}^m)^T \mathbf{G} (\mathbf{x} - \mathbf{x}^m)$, where $\mathbf{x}^m(\mathbf{x})$ is the vector for measured (fitted) variables, and $\mathbf{G}^{-1}$ is its error matrix [6]. The two reconstructed W boson masses are constrained to the pole mass M_W of the W boson, and the reconstructed t and $\bar{t}$ quark masses are set to $m_t = 173.3$ GeV/c^2 as measured by DØ [6]. The bias introduced due to the difference in the top-quark mass used in the fit and that in the MC simulation of signal and background is negligible. Only the four highest-E_T jets are used in the kinematic fit. All other jets are assumed to be due to initial-state radiation, and are ignored. There are six (12) possible assignments of these jets to quarks in the events with (without) a μ tag, each having two solutions for p_z^ν. For every possible permutation, we apply additional parton-level and η-dependent jet corrections derived using data and Monte Carlo simulations [6]. We apply a loose selection on the reconstructed mass, $M(q\bar{q})$, of the hadronically decaying W boson, $40 < M(q\bar{q}) < 140$ GeV/c^2, before the fit, to reduce computation. The results of the fit with the lowest χ^2 are used to reconstruct the invariant mass ($M_{t\bar{t}}$) of the $t\bar{t}$ system. It is observed that the jet permutation with the lowest χ^2 is the correct choice for $\approx$20% of all Monte Carlo $t\bar{t}$ events [6]. We require $\chi^2 < 10$ to further reduce non-$t\bar{t}$ background, whereupon summing all four classes of events 41 events are left in the data sample of which four are μ tagged.

For each M_X sample generated by Monte Carlo, we perform a fit based on Bayesian statistics [14] to determine the number of events expected from signal and background in the observed lepton + jets data sample. We fit [10] the data to a three-source model comprised of n_1 signal events ($X \to t\bar{t}$), n_2 background events from standard-model $t\bar{t}$ production, and n_3 events due to the combined backgrounds from W + jets and multijets in the ratio 0.78:0.22. That ratio is based on their relative proportions in the top-quark mass analysis at DØ [6]. We define [10] a likelihood (L) and a posterior probability $P(n_1, n_2, n_3, M_X|D)$ for obtaining n_1, n_2, and n_3 events from the three respective sources, for a model specified by M_X. Given the observed data set D, we can write

$$P(n_1, n_2 n_3, M_X|D) = \frac{L(D|n_1, n_2, n_3, M_X) w(n_1, n_2, n_2|M_X)}{\mathcal{N}'}, \quad (2)$$

where w denotes the joint prior probability for the three-source strengths, and $\mathcal{N}'$ is a normalization that is obtained from the requirement

TABLE II. The fitted number of events for signal, $\langle n_1 \rangle$, and background from standard-model $t\bar{t}$ production, $\langle n_2 \rangle$, and W + jets and multijets, $\langle n_3 \rangle$, for different M_X. After all selections, 41 events are observed in the $M_{t\bar{t}}$ distribution of lepton + jets data.

M_X (GeV/c^2)	$\langle n_1 \rangle$	$\langle n_2 \rangle$	$\langle n_3 \rangle$	Background $\langle n_2 \rangle + \langle n_3 \rangle$
400	9.0 ± 7.0	20.5 ± 10.8	13.9 ± 10.2	34.4 ± 14.9
500	4.9 ± 4.2	22.2 ± 11.5	15.3 ± 10.5	37.5 ± 15.6
600	4.2 ± 3.2	23.7 ± 11.6	15.4 ± 10.6	39.0 ± 15.7
750	1.6 ± 1.6	26.8 ± 11.7	12.6 ± 9.9	39.4 ± 15.3

$$\int P(n_1, n_2, n_3, M_X|D)dn_1dn_2dn_3 = 1. \tag{3}$$

We assume Poisson statistics for the likelihood and flat priors for each of the three sources. Bayesian integration [14] over possible signal and background populations in each bin i of the $M_{t\bar{t}}$ distribution yields the likelihood

$$L(D|n_1, n_2, n_3, M_X) = \prod_{i=1}^{M} \sum_{k_1,k_2,k_3=0}^{D_i} \prod_{j=1}^{3} \binom{A_{ji} + k_j}{k_j} \times \frac{p_j^{k_j}}{(1 + p_j)^{A_{ji}+k_j+1}}, \tag{4}$$

where D_i (A_{ji}) is the number of events in bin i for data (Monte Carlo source j); the indices k_j satisfy the multinomial constraint $\sum_{j=1}^{3} k_j = D_i$, and $p_j = n_j/(M + \sum_{i=1}^{M} A_{ji})$ is an estimate of the strength of the jth source ($j = 1, 2, 3$), where M is the number of bins. The expected number of counts from any source j can be obtained from the fit as

$$\langle n_j \rangle = \iiint n_j P(n_1, n_2, n_3, M_X|D)dn_1dn_2dn_3. \tag{5}$$

The fitted number of events for signal ($\langle n_1 \rangle$) and the two background sources ($\langle n_2 \rangle$ and $\langle n_3 \rangle$) are listed in Table II for several values of M_X. The observed $M_{t\bar{t}}$ distribution and the corresponding distributions from the three Monte Carlo sources normalized to $\langle n_1 \rangle$, $\langle n_2 \rangle$, and $\langle n_3 \rangle$, respectively, for $M_X = 400$ GeV/c^2, are shown in Fig. 1. There is no significant deviation from the standard-model prediction. Similar agreement is observed for other choices of resonance mass.

In the absence of a signal, we proceed to set upper limits on the product of the production cross section of X and branching fraction to $t\bar{t}$, $\sigma_X B$, by expressing $n_1 = \mathcal{A}\mathcal{L}\sigma_X B$ in Eq. (2), where $\mathcal{A}$ is the acceptance for $X \to t\bar{t}$ events and $\mathcal{L}$ is the integrated luminosity. Integrating over n_2 and n_3, we define for every M_X the upper limit on $\sigma_X B$ at the 95% confidence level as

$$\int_0^{(\sigma_X B)_{95}} P(\sigma_X B, M_X|D)d(\sigma_X B) = 0.95. \tag{6}$$

The expected shapes of distributions for background and signal, and the acceptance for signal, are subject to several sources of systematic uncertainty. The uncertainty due to the jet-energy scale is estimated by rescaling the jet energies by $\pm(2.5\% + 0.5$ GeV) [6] before applying any selections to the signal Monte Carlo events. For the contribution from ISR/FSR, we compare the acceptance for the signal with and without ISR/FSR (in PYTHIA). For the uncertainty from the choice of parton distribution functions, we compare the signal acceptance for the two

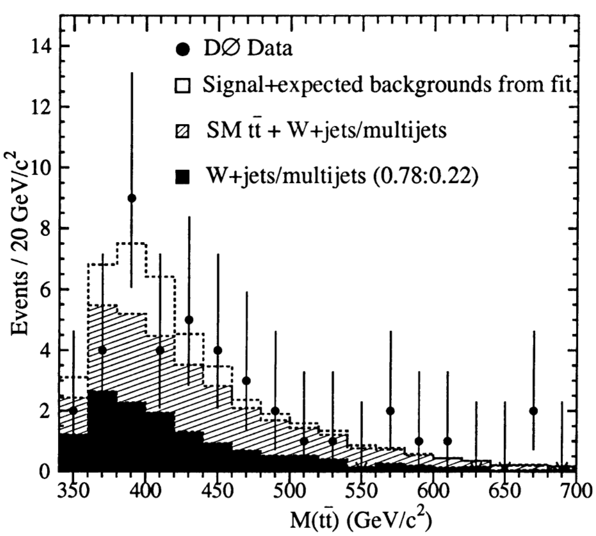

FIG. 1. Distributions of $M_{t\bar{t}}$ obtained from the fit, for the sum of signal ($X \to t\bar{t}$) and all standard-model backgrounds (open histogram), sum of all standard-model backgrounds (hatched histogram), and W + jets and multijets (solid histogram), for $M_X = 400$ GeV/c^2. The data correspond to the dots with their statistical errors.

TABLE III. The fractional uncertainty in the product $\mathcal{A}\mathcal{L}$ from different sources, for $M_X = 400$ GeV/c^2.

MC statistics	3.3%
Trigger efficiency	3.6%
e/μ identification	3.8%
Luminosity	4.3%
Jet energy scale	7.4%
ISR/FSR	16.0%
Parton distribution functions	15.0%
Total	24.3%

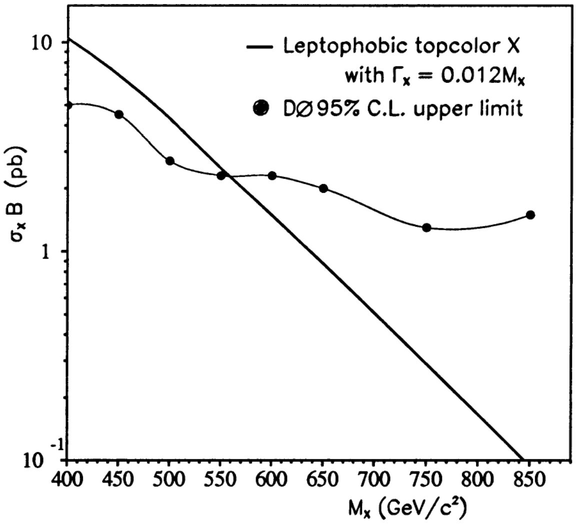

FIG. 2. The 95% C.L. upper limit on $\sigma_X B$ as a function of resonance mass M_X. Included for reference is the $\sigma_X B$ predicted by the top-color-assisted technicolor model for a width $\Gamma_X = 0.012 M_X$.

parton distribution sets CTEQ3M and GRV94L [15]. We also consider the uncertainties in trigger efficiency, lepton identification, and integrated luminosity. All the sources of statistical and systematic uncertainty in the product $\mathcal{A}\mathcal{L}$ are listed in Table III for $M_X = 400$ GeV$/c^2$ [10]. For each M_X, we convolute the posterior probability density $P(\sigma_X B, M_X|D)$ with a Gaussian prior for $\mathcal{A}\mathcal{L}$, with the estimated value of $\mathcal{A}\mathcal{L}$ as the mean of the Gaussian and its uncertainty as 1 standard deviation from the mean. The upper limits on $\sigma_X B$ at the 95% confidence level obtained using (6), and integrating over $\mathcal{A}\mathcal{L}$, vary between 5.0 pb at $M_X = 400$ GeV$/c^2$ and 1.5 pb at $M_X = 850$ GeV$/c^2$, as shown in Fig. 2. These limits are valid as long as the width of the resonance, Γ_X, is reasonably small compared to the DØ detector resolution. Also plotted in Fig. 2 is the theoretical prediction for $\sigma_X B$ for a leptophobic top color of width $\Gamma_X = 0.012 M_X$ [10], which we use to exclude at the 95% C.L. the existence of the leptophobic Z' boson with mass $M_X < 560$ GeV$/c^2$, for a width $\Gamma_X = 0.012 M_X$.

In conclusion, after investigating 130 pb^{-1} of data, we find no statistically significant evidence for a narrow $t\bar{t}$ resonance at $m_t = 175$ GeV$/c^2$, and establish upper limits on $\sigma_X B$ at the 95% C.L. for M_X between 400 and 850 GeV$/c^2$. We also exclude at the 95% C.L. the existence of a leptophobic Z' boson with mass $M_X < 560$ GeV$/c^2$, for a width $\Gamma_X = 0.012 M_X$.

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