Search for Narrow $t\bar{t}$ Resonances in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV.

V.M. Abazov,[21] B. Abbott,[55] A. Abdesselam,[11] M. Abolins,[48] V. Abramov,[24] B.S. Acharya,[17] D.L. Adams,[53] M. Adams,[35] S.N. Ahmed,[20] G.D. Alexeev,[21] A. Alton,[47] G.A. Alves,[2] E.W. Anderson,[40] Y. Arnoud,[9] C. Avila,[5] V.V. Babintsev,[24] L. Babukhadia,[52] T.C. Bacon,[26] A. Baden,[44] S. Baffioni,[10] B. Baldin,[34] P.W. Balm,[19] S. Banerjee,[17] E. Barberis,[46] P. Baringer,[41] J. Barreto,[2] J.F. Bartlett,[34] U. Bassler,[12] D. Bauer,[38] A. Bean,[41] F. Beaudette,[11] M. Begel,[51] A. Belyaev,[33] S.B. Beri,[15] G. Bernardi,[12] I. Bertram,[25] A. Besson,[9] R. Beuselinck,[26] V.A. Bezzubov,[24] P.C. Bhat,[34] V. Bhatnagar,[15] M. Bhattacharjee,[52] G. Blazey,[36] F. Blekman,[19] S. Blessing,[33] A. Boehnlein,[34] N.I. Bojko,[24] T.A. Bolton,[42] F. Borcherding,[34] K. Bos,[19] T. Bose,[50] A. Brandt,[57] G. Briskin,[56] R. Brock,[48] G. Brooijmans,[34] A. Bross,[34] D. Buchholz,[37] M. Buehler,[35] V. Buescher,[14] V.S. Burtovoi,[24] J.M. Butler,[45] F. Canelli,[51] W. Carvalho,[3] D. Casey,[48] H. Castilla-Valdez,[18] D. Chakraborty,[36] K.M. Chan,[51] S.V. Chekulaev,[24] D.K. Cho,[51] S. Choi,[32] S. Chopra,[53] D. Claes,[49] A.R. Clark,[28] B. Connolly,[33] W.E. Cooper,[34] D. Coppage,[41] S. Crépé-Renaudin,[9] M.A.C. Cummings,[36] D. Cutts,[56] H. da Motta,[2] G.A. Davis,[51] K. De,[57] S.J. de Jong,[20] M. Demarteau,[34] R. Demina,[51] P. Demine,[13] D. Denisov,[34] S.P. Denisov,[24] S. Desai,[52] H.T. Diehl,[34] M. Diesburg,[34] S. Doulas,[46] L.V. Dudko,[23] S. Duensing,[20] L. Duflot,[11] S.R. Dugad,[17] A. Duperrin,[10] A. Dyshkant,[36] D. Edmunds,[48] J. Ellison,[32] J.T. Eltzroth,[57] V.D. Elvira,[34] R. Engelmann,[52] S. Eno,[44] G. Eppley,[58] P. Ermolov,[23] O.V. Eroshin,[24] J. Estrada,[51] H. Evans,[50] V.N. Evdokimov,[24] D. Fein,[27] T. Ferbel,[51] F. Filthaut,[20] H.E. Fisk,[34] F. Fleuret,[12] M. Fortner,[36] H. Fox,[37] S. Fu,[50] S. Fuess,[34] E. Gallas,[34] A.N. Galyaev,[24] M. Gao,[50] V. Gavrilov,[22] R.J. 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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 in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. There is no significant deviation observed from the standard model, and upper limits at the 95% confidence level on the product of the production cross section and branching fraction to $t\bar{t}$ are presented for narrow resonances as a function of the resonance mass M_X. These limits are used to exclude the existence of a leptophobic topcolor particle with mass $M_X < 560$ GeV/c^2 and 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 [1,2]. For instance, one of the scenarios of the topcolor-assisted technicolor model in Ref. [2] predicts a heavy Z' boson that 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 the Fermi National Accelerator Laboratory.

In searches for such heavy particles or 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. Previous searches at the Tevatron have limited a leptophobic Z' boson to a mass higher than 480 GeV/c^2 [3]. In this paper, we describe a direct search for narrow $t\bar{t}$ resonances in the inclusive decay modes $t\bar{t} \to \ell\nu + \geq 4$ jets, where ℓ = 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 model [2].

The DØ detector is a multi-purpose particle detector designed to study $p\bar{p}$ collisions at the Fermilab Tevatron Collider. The detector consists of three major systems: a non-magnetic central tracking system, a uranium/liquid-argon calorimeter, and a muon spectrometer. A detailed description of the DØ detector can be found in Ref. [4].

The present search rests upon techniques developed for the measurement of the mass of the top quark at DØ in the lepton + jets channel [5]. Due to the large mass of the top quark (m_t), the $t\bar{t} \to \ell\nu + \geq 4$ 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 [6], and therefore offer discrimination between signal and background. We consider two orthogonal classes of events for this analysis: a) a purely topological selection of lepton+jets events denoted as $e + jets$ and $\mu + jets$, where the jets do not contain a muon, and b) 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 $\mu + jets/\mu$. Details of the trigger requirements, reconstruction of events, and identification of the e, μ, $\not\!\!E_T$, and jets can be found in Ref. [5]. The principal sources of background correspond to standard-model $t\bar{t}$ production, $W(\to l\nu)$ + 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. For the measurement of the top-quark mass, most selections were optimized to reduce the contribution from non-$t\bar{t}$ sources. We therefore use similar selections in the present analysis, and these are summarized in Table I.

The resonance signal $X \to t\bar{t}$ is modeled using the PYTHIA-6.1 [7] Monte Carlo event generator, with m_t = 175 GeV/c^2, and CTEQ3M [8] parton distribution functions. Initial and final-state radiation (ISR/FSR) is included. About 10,000 events at nine resonance masses between 400 and 1000 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 $t\bar{t}$ systems [9]. Hence, our results are dominated by the detector resolution and independent of Γ_X. The generated events are processed through the DØGEANT detector simulation package [10] and reconstructed using the DØ event-reconstruction program. A standard set of corrections is applied to electromagnetic objects and jets [5], and the missing transverse energy recalculated.

The backgrounds are estimated from a combination of Monte Carlo simulations and collider data [5]. The selections summarized in Table I are also applied to the Monte Carlo (MC) 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 (3C) hypothesis for the $t\bar{t}$ production and decay:

$$\begin{aligned} t\bar{t} &\to W^+ b\ W^- \bar{b}, \\ W^+ &\to l^+ \nu_l \ \ (\text{or } q\bar{q}'), \\ W^- &\to q\bar{q}' \ \ (\text{or } l^- \bar{\nu}_l). \end{aligned} \tag{1}$$

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

TABLE I. Summary of event selections. Here ${\not\!\!E_T}^{cal}$ is the missing transverse energy measured just in the calorimeter, η^W is the pseudorapidity of the W boson that decays leptonically, and $\Delta\phi(\not\!\!E_T, \mu)$ is the difference in the azimuthal angle between $\not\!\!E_T$ and the highest-p_T muon.

	e+$jets$	μ+$jets$	e+$jets/\mu$	μ+$jets/\mu$
Lepton (l)	E_T^l >20 GeV $\|\eta\|$ <2	p_T^l >20 GeV/c $\|\eta\|$ <1.7	E_T^l >20 GeV $\|\eta\|$ <2	p_T^l >20 GeV/c $\|\eta\|$ <1.7
$\not\!\!E_T$	$\not\!\!E_T$ >20 GeV ${\not\!\!E_T}^{cal}$ >25 GeV	$\not\!\!E_T$ >20 GeV ${\not\!\!E_T}^{cal}$ >20 GeV	$\not\!\!E_T$ >20 GeV	$\not\!\!E_T$ >20 GeV ${\not\!\!E_T}^{cal}$ >20 GeV
Jets	$\geq$ 4 jets E_T >15 GeV $\|\eta\|$ <2	$\geq$ 4 jets E_T >15 GeV $\|\eta\|$ <2	$\geq$ 4 jets E_T >15 GeV $\|\eta\|$ <2	$\geq$ 4 jets E_T >15 GeV $\|\eta\|$ <2
μ tag	No	No	Yes	Yes
Other	$\|\not\!\!E_T\| + \|E_T^l\| > 60$ GeV $\|\eta^W\|$ <2	$\|\not\!\!E_T\| + \|p_T^l\| > 60$ GeV $\|\eta^W\|$ <2	$\not\!\!E_T$ >35 GeV, if $\Delta\phi(\not\!\!E_T, \mu) < 25°$	$\Delta\phi(\not\!\!E_T, \mu) < 170°$ $\|\Delta\phi(\not\!\!E_T, \mu) - 90°\|/90°$ $< \not\!\!E_T/(45$ GeV)
Events passing above criteria	42	41	4	3
With $\chi^2 < 10$	16	21	1	3

$\chi^2 = (\mathbf{x} - \mathbf{x}^m)^T \mathbf{G}(\mathbf{x} - \mathbf{x}^m)$, where $\mathbf{x}^m(\mathbf{x})$ is the vector for measured (fitted) variables, and $\mathbf{G}^{-1}$ is its error matrix [5]. 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 [5]. 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 6 (12) possible assignments of these jets to quarks in the events with (without) a μ tag, each having two solutions for the longitudinal momentum of the neutrino (p_z^ν). For every possible permutation, we apply additional parton-level and η-dependent jet corrections derived using data and Monte Carlo simulations [5]. 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 [5]. We require $\chi^2 < 10$ to further reduce non-$t\bar{t}$ background, whereupon 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 [11] to determine the number of events expected from signal and background in the observed lepton+jets data sample. We fit [9] the data to a three-source model comprised of signal ($X \to t\bar{t}$), and backgrounds from standard-model $t\bar{t}$ production, W+jets, and multijets. We combine backgrounds from W+jets and multijets in the ratio 0.78:0.22, based on a measurement of their relative proportions in the top-quark mass analysis at DØ [5]. We define 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:

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

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

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

We assume Poisson statistics for the likelihood, and flat priors for each of the three sources. Bayesian integration [11] over possible signal and background populations in each bin i of the $M_{t\bar{t}}$ distribution yields the likelihood:

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

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 $\sum_{j=1}^{3} k_j = D_i$; $p_j = n_j/(M + \sum_{i=1}^{M} A_{ji})$ is an estimate of the strength of the j^{th} source ($j = 1, 2, 3$); and M is the number of bins. The expected number of counts from any source j can be obtained from the fit as:

$$< n_j >= \int\int\int n_j P(n_1, n_2, n_3, M_X|D) dn_1 dn_2 dn_3. \quad (5)$$

The fitted number of events expected from the signal ($< n_1 >$) and the two background sources ($< n_2 >$ and $< n_3 >$) 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 $< n_1 >$, $< n_2 >$ and $< n_3 >$, 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.

TABLE II. The fitted number of events expected from signal, $< n_1 >$, and background from standard model $t\bar{t}$ production, $< n_2 >$, and $W+$jets and multijets, $< n_3 >$, 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$/c^2$)	$< n_1 >$	$< n_2 >$	$< n_3 >$	Background $< n_2 > + < n_3 >$
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

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:

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

The expected shapes of distributions for background and signal, and the acceptance for signal,

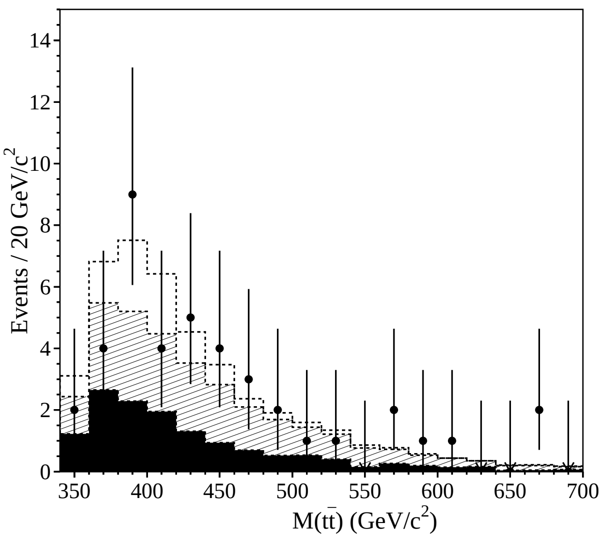

FIG. 1. Distributions of $M_{t\bar{t}}$ obtained from the fit, for the sum of signal ($X \to t\bar{t}$) and all standard-model backgrounds (open histogram), sum of all standard-model backgrounds (hatched histogram), and W+jets and multijets (solid histogram), for $M_X = 400$ GeV$/c^2$. The data correspond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

are subject to several sources of systematic uncertainty. The uncertainty due to the jet energy scale is estimated by re-scaling the jet energies by $\pm(2.5\% + 0.5$ GeV) [5] 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 parton distribution sets CTEQ3M and GRV94L [12]. 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$/c^2$ [9].

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 %
PDF	15.0 %
Total	24.3 %

For each M_X, we convolute the posterior probability density $P(\sigma_X B, M_X|D)$ with a Gaussian prior for $\mathcal{AL}$, with the estimated value of $\mathcal{AL}$ as the mean of the Gaussian and its uncertainty as one standard deviation from the mean. The upper limits on $\sigma_X B$ at the 95% confidence level obtained using Eq. (6), integrating over all possible values of $\mathcal{AL}$, are listed in Table IV. We use these limits to constrain [9] a model of topcolor-assisted technicolor, and exclude at the 95% C.L. the existence of a leptophobic Z' boson with mass $M_X < 560$ GeV/c^2, for a width $\Gamma_X = 0.012 M_X$, as shown in Fig. 2.

TABLE IV. The 95% C.L. upper limits on $\sigma_X B$ for narrow resonances of mass M_X decaying into $t\bar{t}$.

M_X (GeV/c^2)	95% C.L. upper limits on $\sigma_X B$ (pb)
400.	5.0
450	4.5
500	2.7
550	2.3
600	2.3
650	2.0
750	1.3
850	1.5
1000	2.0

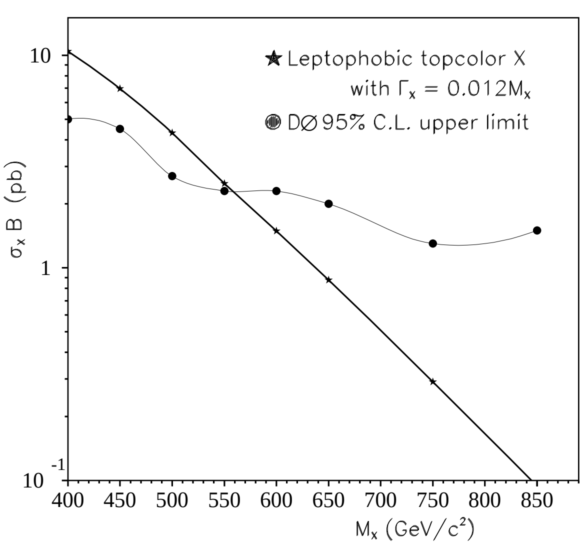

FIG. 2. The 95% C.L. upper limit on $\sigma_X B$ as a function of resonance mass M_X. Included for reference is the predicted topcolor-assisted technicolor cross section for a width $\Gamma_X = 0.012 M_X$.

In conclusion, after investigating 130 pb^{-1} of data, we find no statistically significant evidence for a $t\bar{t}$ resonance, and establish upper limits on $\sigma_X B$ at the 95% C.L. for M_X between 400 and 1000 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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