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This Letter reports a search for a narrow resonant state decaying into two W bosons and two b quarks where one W boson decays leptonically and the other decays into a quark-antiquark pair. The search is particularly sensitive to top-antitop resonant production. We use the full data sample of proton-antiproton collisions at a center-of-mass energy of 1.96 TeV collected by the CDF II detector at the Fermilab Tevatron, corresponding to an integrated luminosity of 9.45 fb^{-1}. No evidence for resonant production is found and upper limits on the production cross section times branching ratio for a narrow resonant state are extracted. Within a specific benchmark model, we exclude a Z' boson with mass, $M_{Z'}$, below 915 GeV/c^2 decaying into a top-antitop pair at the 95% credibility level assuming a Z' boson decay width of $\Gamma_{Z'} = 0.012\ M_{Z'}$. This is the most sensitive search for a narrow $q\bar{q}$-initiated $t\bar{t}$ resonance in the mass region below 750 GeV/c^2.

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The large mass of the top quark, compared to that of the other fundamental particles, gives it a special position within the standard model (SM). Since its discovery [1], the top quark has played an important role in theoretical extensions beyond the standard model (BSM) [2]. Recently, renewed interest has been directed toward searches including top quark final states for BSM physics due to discrepancies reported in the $t\bar{t}$ forward-backward asymmetry [3, 4]. Moreover, the most recent search for resonant $t\bar{t}$ production from D0 [5] reports an approximately 2σ excess of events at resonant-mass values around 950 GeV/c^2. Many BSM theories [6–10] predict heavy resonances that add a resonant component to the SM $t\bar{t}$ production mechanism.

Top quarks decay via the weak interaction, nearly always into a W boson and a b quark. The W boson then decays into lighter fermion-antifermion pair [11]. We search for resonant production of top quark pairs followed by decays into a final state with one charged

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lepton(electron or muon) and multiple jets, where one of the W bosons decays leptonically and the other W boson decays hadronically. This lepton+jets channel features a distinctive final state due to the presence of a charged lepton and has a branching ratio of 29% [12].

Unlike previous searches at CDF [13–16], we do not apply constraints based on the presence of top quarks in the event. While we focus the discussion on $t\bar{t}$ resonances, we construct the top-antitop mass $M_{t\bar{t}}$ used as a final search discriminant by taking the invariant mass of all objects (lepton, jets, and missing E_T) in the event including those that may not originate from top quark production. Other than the event selection defined below, which provides a sample primarily composed of $t\bar{t}$ events, there are no requirements that the event be consistent with $t\bar{t}$ production. This results in a more general search that is sensitive not only to $t\bar{t}$, but also to any heavy narrow resonance decaying into a final state with a W boson and three or more jets with one or two jets originating from a b quark.

As a benchmark model, we consider a specific SM extension, topcolor-assisted technicolor [17, 18]. This model explains the large mass of the top quark through the introduction of new strong dynamics and also predicts a vector particle (Z' boson), which couples primarily to the third generation of quarks and has no significant couplings to leptons. The existence of a narrow-width Z' boson resonance ($\Gamma_{Z'} = 0.012\ M_{Z'}$) decaying to $t\bar{t}$ pairs, using the leptophobic topcolor model [18, 19], has been searched for both by the CDF [13–16] and D0 [5, 20, 21] experiments at the Tevatron, and also by the ATLAS [22–24] and CMS [25, 26] experiments at the LHC. For resonance searches at the highest masses, the LHC experiments have superior sensitivity to the Tevatron due to the higher center-of-mass energy. However, in the lower-mass regions ($m_{Z'} < 750\ \mathrm{GeV}/c^2$) the Tevatron experiments have competitive sensitivity in searches for particles produced in $q\bar{q}$-initiated states, such as the Z' boson. While the production rate for the main background from SM $t\bar{t}$ is approximately 25 times larger at a center-of-mass energy of 7 TeV, no valence antiquarks are available in the LHC pp collisions, so the signal production rate increases by a smaller factor relative to the $p\bar{p}$ collisions of the Tevatron (between four and eight in the lower-mass region).

The collision events discussed in this Letter were produced at the Tevatron $p\bar{p}$ collider at a center-of-mass energy of 1.96 TeV and were recorded by the CDF II detector [27]. The data sample corresponds to the full data set of the Tevatron, which comes from an integrated luminosity of 9.45 fb^{-1}. The CDF II detector consists of high-precision tracking systems for vertex and charged-particle track reconstruction, surrounded by electromagnetic and hadronic calorimeters for energy measurement, and muon subsystems outside the calorimeter for muon detection. CDF II uses a cylindrical coordinate system with azimuthal angle ϕ, polar angle θ measured with respect to the positive z direction along the proton beam, and the distance r measured from the beamline. The pseudorapidity, transverse energy, and transverse momentum are defined as $\eta = -\ln\left[\tan(\frac{\theta}{2})\right]$, $E_T = E\sin\theta$, and $p_T = p\sin\theta$, respectively, where E and p are the energy and momentum of an outgoing particle. The missing transverse energy $\vec{\not\!\!E}_T$ is defined by $\vec{\not\!\!E}_T = -\sum_i E_T^i \hat{n}_i$, where $\hat{n}_i$ is a unit vector perpendicular to the beam axis that points to the ith calorimeter tower ($\not\!\!E_T = |\vec{\not\!\!E}_T|$).

The event selection and background estimation methods summarized below closely follow those that were employed in the observation of single top quark production [28] and in the search for the Higgs boson in the $WH \to \ell\nu b\bar{b}$ final state [29]. The main difference is that the single top and WH analyses select events consistant with W+ two or three jets and the current search requires three or more jets.

The data were collected using online event selections (triggers) requiring one of the following energetic-lepton signatures: a high transverse momentum (p_T) electron candidate, a high-p_T muon candidate, or large $\not\!\!E_T$. Significant $\not\!\!E_T$ can be produced when the neutrino from a leptonic W boson decay escapes detection.

Candidate events are selected by requiring a lepton candidate with $p_T^\ell > 20\ \mathrm{GeV}/c$, $\not\!\!E_T > 20$ GeV, and three or more jets with $|\eta| < 2.0$ and $E_T > 20$ GeV after correcting the jet energies for instrumental effects [30, 31]. One or two jets must be identified as being likely to have originated from a b quark according to the SECVTX [32] algorithm. This algorithm searches in the jet for a secondary vertex which results from the displaced decay of B hadrons. Events are rejected if more than one lepton candidate is reconstructed, or if they are kinematically inconsistent with leptonic W boson decays [33]. Events with severely misreconstructed jets or leptons are removed based on angular correlations between the jet or lepton candidate and the $\vec{\not\!\!E}_T$.

Models for background processes are derived from a mixture of simulation and data-driven techniques [28]. Important backgrounds in this final state include SM $t\bar{t}$ production and other processes that include a W or Z boson in association with three or more jets. The events can include true b-quark jets, as in W boson + $b\bar{b}j$ events, or jets that have been misidentified as b-quark jets, such as in W boson $+c\bar{c}j$ and W boson $+jjj$ events, where j refers to jets not originating from heavy-flavor quarks. Multijet events without W bosons also contribute to the sample composition. Additional small background contributions are included from Z boson production with additional jets, diboson production, and single top quark production.

The expected rate for the SM $t\bar{t}$ background is taken to be 7.04 ± 0.70 pb [34] as calculated at approximate next-to-next-to-leading order using MSTW 2008 parton distribution functions [35]. In order to predict the acceptance

Process	3-jet events	$\geq$ 4-jet events
$t\bar{t}$	1930 $\pm$ 200	2570 $\pm$ 270
W/Z boson + jets	2280 $\pm$ 610	570 $\pm$ 190
Multijets	150 $\pm$ 60	130 $\pm$ 100
Total background	4360 $\pm$ 870	3270 $\pm$ 560
Observed	4254	3049

TABLE I: Summary of the background prediction and observed data for three-jet and four-or-more-jet events. The uncertainties include statistical and systematic contributions.

for non-resonant SM $t\bar{t}$ events and their kinematic distributions, we use a sample of Monte Carlo (MC) events generated using POWHEG [36] and assuming a top quark mass of 172.5 GeV/$c^2$with parton showering provided by PYTHIA [38] followed by simulation of the CDF II detector [39, 40]. The detection efficiency predicted by the simulation is corrected based on measurements using data for lepton identification, trigger efficiencies, and b-jet tagging efficiencies. The normalization for the QCD multijet and W boson + jet processes is obtained from a fit to the $\not\!\!E_T$ distribution. The background from events with mistakenly b-tagged light-flavor jets, W boson $+jjj$ for example, is estimated by measuring the rate of such mistags in multijet data [32] and applying this rate to the W boson + jets data samples before b tagging. The contribution from true heavy-flavor production in the W boson + jets event sample is determined from measurements of the heavy-flavor event fraction in a W boson + 1 jet sample that is independent of the sample used in the resonance search. We model the kinematic distributions of W boson + jets events using a combination of ALPGEN [41] matrix-element generation and PYTHIA parton showering. The QCD multijet background is modeled using a sample of collision events in which one of the lepton identification requirements is inverted to obtain an enriched sample of QCD multijet events.

The background predictions are summarized in Table I. In this table and the following figures we have divided the sample into events that include three jets and events that include four or more jets. For the statistical interpretation of the data we further subdivide the events based on the number of b-tagged jets (one or two b tags) and based on the lepton type (lepton types that can be directly identified by the trigger, or leptons in events selected with the $\not\!\!E_T$-based trigger), yielding eight independent channels used to search for a resonance in the $M_{t\bar{t}}$ distributions. The sensitivity of the search benefits from this subdivision because the search subchannels have different background compositions, signal-to-background ratios, and invariant mass resolutions.

We use the invariant mass of all reconstructed objects in the event to discriminate between SM background and Z' boson signal events. For each event we calculate $M_{t\bar{t}}$ using the momenta of the three or more jets, the charged lepton, and the neutrino. The transverse momentum of the neutrino is estimated from the $\vec{\not\!\!E}_T$. However, because the z-component of the momenta of the scattering partons from the $p\bar{p}$ collision is unknown, the final-state reconstructed energy need not be balanced in the z direction. The longitudinal component of the neutrino momentum (p_z^ν) is determined by solving $M_W^2 = (p^l + p^\nu)^2$, where M_W, p^l, and p^ν are the W boson mass, the lepton momentum, and the neutrino momentum, respectively. The smaller solution of the resulting quadratic equation is chosen for the p_z^ν. If there is no real solution we set $p_z^\nu = 0$. This approach is found to select the correct p_z^ν in about 70% of simulated $t\bar{t}$ events.

For the benchmark model, the Z' boson cross sections times branching fraction are based on leading-order predictions from Ref. [19] with an additional scaling factor of 1.3 applied to account for next-to-leading-order effects [42]. Signal Z' boson events are modeled with simulated events generated by PYTHIA in order to study the signal acceptance and to predict the $M_{t\bar{t}}$ distributions.

A total of 4254 (3049) events survive the selection criteria for the three-jet (four-or-more-jet) category. The SM $t\bar{t}$ contribution is estimated to be 43% (78%) for three-jet (four-or-more-jet) events. The remaining events are contributed primarily from the W boson + jet and QCD multijet processes plus a potential signal contribution from Z' boson events. The $M_{t\bar{t}}$ distributions for the background model and events observed in the data are shown in Fig. 1. We fit the $M_{t\bar{t}}$ distributions to what is observed in the data, allowing the background predictions to float within their systematic uncertainties. The $M_{t\bar{t}}$ distribution for the Z' boson signal for the 600 GeV/c^2 mass hypothesis is also included in Fig. 1.

We calculate a Bayesian credibility level (C.L.) limit on resonant $t\bar{t}$ production for each mass hypothesis based on the binned observed $M_{t\bar{t}}$ spectrum using the combined likelihood which includes the priors, $\pi(\vec{\theta})$, on the systematic uncertainties, $\vec{\theta}$:

$$\mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta}) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_{\rm C}} \prod_{j=1}^{N_{\rm bins}} \mu_{ij}^{n_{ij}} \frac{e^{-\mu_{ij}}}{n_{ij}!} \times \prod_{k=1}^{n_{\rm sys}} e^{-\theta_k^2/2}. \quad (1)$$

In this expression, the first product is over the eight channels, $N_{\rm C}$, we consider in this analysis. The second product is over histogram bins containing n_{ij} events. The predictions for the bin contents are $\mu_{ij} = R \times s_{ij}(\vec{\theta}) + b_{ij}(\vec{\theta})$ for channel i and histogram bin j, where s_{ij} represents the potential resonant signal, b_{ij} is the expected background in the bin, and R is a scaling factor applied to the signal.

Systematic uncertainties are parametrized by the de-

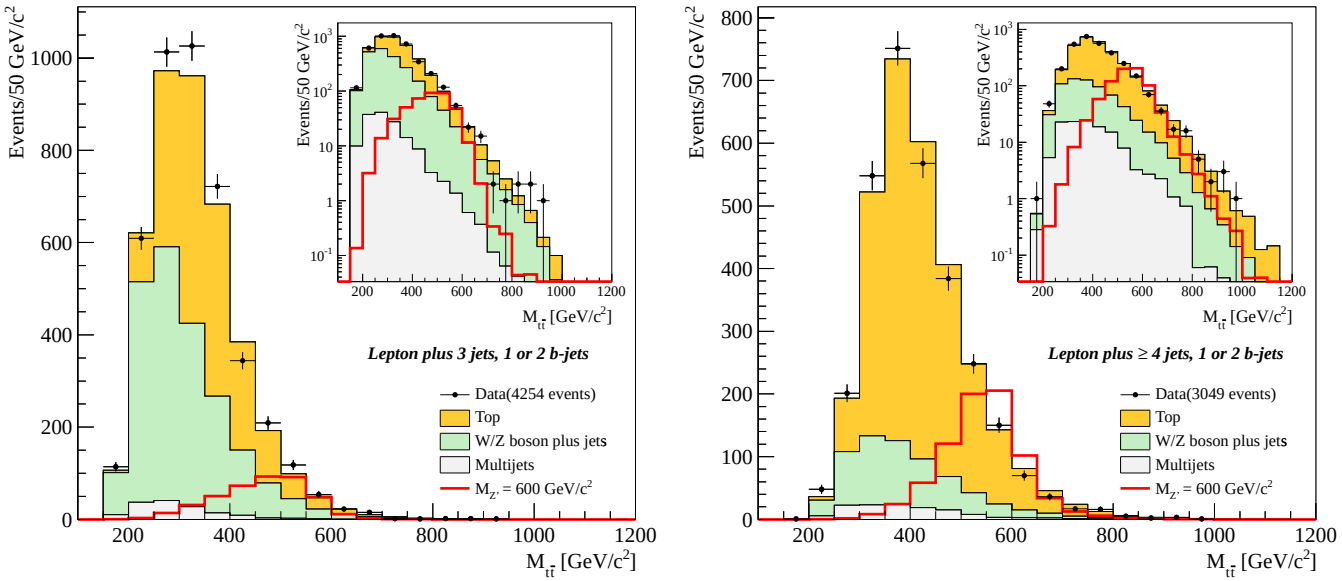

FIG. 1: Reconstructed $M_{t\bar{t}}$ for the three-jet events (left) and four-or-more-jet events (right). The distribution of $M_{t\bar{t}}$ spectrum is on a linear scale and the inset shows a logarithmic scale of the same distribution. The background expectation is normalized to the best fit to the data. The red histogram shows the expectation for a 600 GeV/c^2 mass hypothesis for the leptophobic topcolor resonance normalized to the predicted cross section.

pendence of s_{ij} and b_{ij} on $\vec{\theta}$. Each of the $n_{\rm sys}$ components of $\vec{\theta}$, θ_k, corresponds to a single independent source of systematic uncertainty. We account for correlations by allowing each parameter to have an impact on several sources of signal and background in different channels. Gaussian priors are assumed for the θ_k, which are truncated so that no prediction is negative. The likelihood function, multiplied by the θ_k priors, $\pi(\theta_k)$, is then integrated over θ_k including correlations [11]:

$$\mathcal{L}'(R) = \int \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta})\pi(\vec{\theta})d\vec{\theta}. \qquad (2)$$

We assume a uniform prior in R to obtain its posterior distribution. The observed 95% C.L. upper limit on R, $R_{95}^{\rm obs}$, satisfies $0.95 = \int_0^{R_{95}^{\rm obs}} \mathcal{L}'(\mathcal{R})\mathrm{d}\mathcal{R}$. The expected distribution of R_{95} is computed in an ensemble of pseudo experiments generated without signal. In each pseudo experiment, values of the nuisance parameters are drawn from their priors. The median expected value of R_{95} in this ensemble is quoted as the expected limit. This statistical procedure is repeated for each resonance mass hypothesis from 350 GeV/c^2 to 1200 GeV/c^2.

We consider uncertainties that affect the normalization as well as uncertainties that affect the $M_{t\bar{t}}$ distributions. The same set of uncertainties on the dominant background (SM $t\bar{t}$ production) and the resonant signal are considered: they arise from the uncertainty in the jet energy scale (JES) [31], the b-tagging efficiency, the luminosity measurement [43], the lepton identification and trigger efficiency, and the rate of initial- and final-state (IFSR) radiation from the parton shower model. The JES, b-tag, and IFSR variations also affect the shape of the $M_{t\bar{t}}$ distributions. The background normalizations for the QCD multijet background and for events with a W boson and heavy-flavor jet (b or c) are assigned uncertainties due to limitations in their data-driven estimations [28] . Uncertainties on the renormalization and factorization scale used in the ALPGEN sample affect the shape of the $M_{t\bar{t}}$ distributions from W boson + jets.

The resulting 95% C.L. upper limits on the cross section times the branching ratio for the leptophobic topcolor Z' [19] signal hypotheses, $\sigma_{Z'}BR(Z' \to t\bar{t})$, as a function of $M_{t\bar{t}}$ are shown in Fig. 2 and Table II together with expected limits derived from pseudo experiments that include the SM background hypothesis only. A benchmark leptophobic topcolor model [19] is excluded at 95% C.L. for Z' boson masses smaller than 915 GeV/c^2 assuming the width of the resonance is $\Gamma_{Z'} = 0.012\ M_{Z'}$. In addition, the limits reported here can be applied to any resonance producing the same final state as long as the decay width is significantly smaller than the reconstruction mass resolution ($\Gamma_{Z'} \ll 0.15\ M_{Z'}$).

In conclusion, we have performed a search for a heavy resonance decaying into $t\bar{t}$ using the lepton+jets decay channel in data from 9.45 fb^{-1} of integrated luminosity.

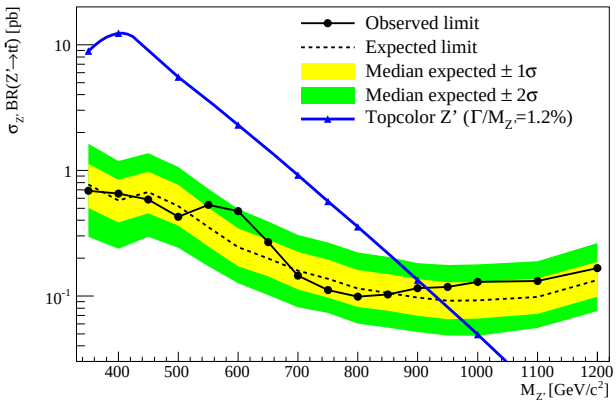

FIG. 2: Expected and observed upper limits on the production cross section times the branching ratio for a leptophobic topcolor Z' boson in 9.45 fb^{-1} of CDF data. The dashed line is the median expected upper limit with the assumption of no signal, the black points are the observed limit, and the blue line is the cross section prediction for leptophobic topcolor Z' boson [19] production.

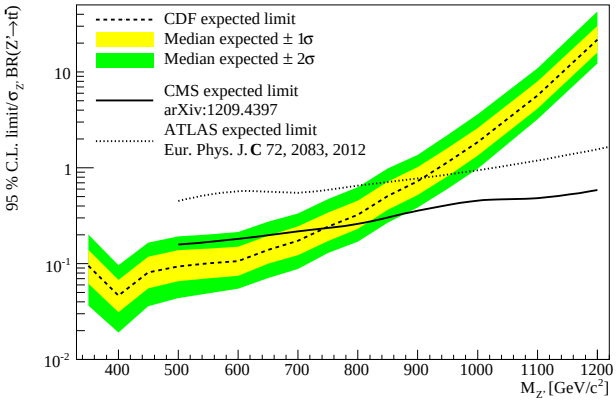

FIG. 3: Tevatron and LHC sensitivity comparison to new physics for narrow $t\bar{t}$ resonant final states, using the benchmark leptophobic topcolor Z' model. The figure shows the expected upper limits on $\sigma_{Z'}BR(Z' \to t\bar{t})$ divided by the theoretical prediction of $\sigma_{Z'}BR(Z' \to t\bar{t})$ as a function of $M_{t\bar{t}}$. Dashed, dotted, and solid lines correspond to the expected upper limits of the most sensitive analyses to date from CDF, ATLAS and CMS experiments respectively.

The data are found to be consistent with the background expectation and upper limits are set on the production cross section times branching ratio at the 95% C.L. For a specific benchmark model (leptophobic topcolor), we exclude Z' bosons with masses up to 915 GeV/c^2. As shown in Fig. 3, for masses smaller than approximately 750 GeV/c^2, this search yields the most constraining limits to date on $q\bar{q}$-produced narrow $t\bar{t}$ resonant states in the lepton+jets decay mode.

$M_{Z'}$ [GeV/c^2]	Expected [pb]	Observed [pb]	$\sigma_{Z'}BR(Z' \to t\bar{t})$ [pb]
350	0.772	0.687	8.91
400	0.575	0.652	12.3
450	0.670	0.585	8.24
500	0.520	0.427	5.53
550	0.354	0.530	3.51
600	0.245	0.472	2.30
650	0.199	0.269	1.43
700	0.159	0.145	0.917
750	0.137	0.112	0.566
800	0.115	0.099	0.355
850	0.106	0.103	0.208
900	0.097	0.116	0.134
950	0.091	0.118	0.080
1000	0.092	0.129	0.049
1100	0.098	0.132	0.017
1200	0.134	0.166	0.006

TABLE II: Expected, observed 95% C.L. upper limits and theoretical prediction for the production cross section times the branching ratio for a narrow $t\bar{t}$ resonance, given as a function of Z' boson mass.

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