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Search for resonant $t\bar{t}$ production in $p\bar{p}$ collisions at s=1.96TeV

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We report on a search for narrow-width particles decaying to a top and antitop quark pair. The data set used in the analysis corresponds to an integrated luminosity of 680 pb^{-1} collected with the Collider Detector at Fermilab in run II. We present 95% confidence level upper limits on the cross section times branching ratio. Assuming a specific top-color-assisted technicolor production model, the leptophobic Z' with width $\Gamma_{Z'} = 0.012 M_{Z'}$, we exclude the mass range $M_{Z'} < 725\ \mathrm{GeV}/c^2$ at the 95% confidence level.

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The discovery of the top quark in 1995 at Fermilab [1] concluded a long search that occupied particle physicists for about two decades. Nevertheless, a decade after the top quark discovery there is still much to investigate about this massive but fundamental particle. There are several ways in which new physics can make an appearance through the top quark. The large mass, in particular, suggests that the top quark may play a special role in the dynamics of electroweak symmetry breaking and act as a powerful probe in this physics sector.

Among the technicolor scenarios, Ref. [2] predicts the existence of a heavy meson η_T produced in gluon-gluon interactions ($gg \to \eta_T \to t\bar{t}$). Top-color models, later extended to top-color assisted technicolor [3,4], account for the spontaneous breaking of electroweak symmetry by introducing new strong dynamics, which would explain the large top quark mass. In this scheme the breaking of the $SU(3)_1 \times U(1)_1 \times SU(3)_2 \times U(1)_2$ gauge structure at a scale of 1 TeV results in colored "top gluons" and in a singlet vector Z', which couples to the third quark generation. A narrow leptophobic Z' decaying to $t\bar{t}$ has been predicted in [5] and searched for in Tevatron run I data [6]. Other $t\bar{t}$ production mechanisms can be found in universal extra dimensions theories. The Randall-Sundrum scenario with the standard model in the bulk predicts the existence of Kaluza-Klein excitations of the gluon, which decay primarily into top quarks [7].

In this Letter, we present a search for narrow resonances decaying to $t\bar{t}$ by looking for an anomalous peak in the $t\bar{t}$ invariant mass distribution. The search algorithm was developed for a narrow $t\bar{t}$ resonance, like a Z', before looking at the data. At the Tevatron, the Z' resonance can be produced via $q\bar{q}$ annihilation. The standard model (SM) predicts that the top quark decays more than 99% of the time into a Wb pair and then the W can decay either leptonically ($BR = 32.4\%$) or hadronically ($BR = 67.6\%$) [8].

The Collider Detector at Fermilab II (CDFII) [9] is an azimuthally and forward-backward symmetric apparatus designed to study $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Tevatron. The detector has a charged particle tracking system [10] in a 1.4 T magnetic field directed parallel to the proton beam direction. This system consists of a silicon microstrip detector, which covers the radial range from 1.35 cm to 28 cm, and an open-cell drift chamber in the radial range from 40 cm to 137 cm. Outside the tracking system are the electromagnetic and hadronic calorimeters, with projective segmentation in η-ϕ [11]. A set of drift chambers and scintillation counters detects muons in the central region ($|\eta| < 1$). The beam luminosity is determined by measuring the inelastic $p\bar{p}$ collision rate with gas Cherenkov detectors [12].

We search for events in which one W boson decays hadronically and one leptonically. The partonic final state for this decay channel is $\ell\nu_\ell b\bar{b}q\bar{q}'$ ($\ell = e, \mu$); therefore, the final state events have one high momentum charged lepton, large missing transverse energy ($\not{E}_T$) [11] due to the undetected neutrino, and four jets from the quarks' parton shower and hadronization processes ("lepton + jets" channel).

The data sample for this analysis has been collected using high-p_T triggers for electrons and muons [9]. The off-line selection requires an electron (or muon) candidate with $E_T(p_T) > 20$ GeV contained in the central detector region. A jet is defined as an energy cluster in the calorimeter and is reconstructed using a fixed cone algorithm with a cone of radius 0.4 in η-ϕ space. This cone size is chosen to minimize jet merging due to overlapping cones in these multijet events. After correcting the raw jet energies and $\not{E}_T$ to account for multiple $p\bar{p}$ interactions and inhomogeneities in the detector according to [13], we select events containing at least 4 jets with $|\eta| < 2$ and $E_T > 15$ GeV, and with $\not{E}_T > 20$ GeV. Jets originating from the hadronization of b quarks are identified (b tagged), with about 40% efficiency, by reconstructing their displaced vertices [14]. The tagging information is not used for event selection, but only to reduce jet combinatorics during event reconstruction.

Standard model processes that result in the same final state as the resonance are backgrounds to this search. The dominant components are W boson production in association with jets (W + jets), $t\bar{t}$ production, multijet events where a jet is misidentified as a charged lepton and missing energy is generated by jet energy mismeasurement, and diboson production (WW, WZ, ZZ) with extra jets from initial and final state radiation (ISR, FSR). The expected contributions in a data set corresponding to an integrated luminosity of 680 pb^{-1} are presented in Table I. Standard model $t\bar{t}$ and diboson expectations are calculated according to their theoretical cross sections [15,16] and their acceptances estimated from Monte Carlo simulations (see below). The quoted uncertainties include the uncertainties on the theoretical cross sections, integrated luminosity, and acceptances. Given the lack of precise theoretical predictions for W + jets (≥ 4 jets) and multijet production cross sections, the contributions from these backgrounds listed in Table I are obtained by constraining the total numbers to add up to the 450 events observed in data. The multijets to W + jets ratio in this sample is fixed at 10%, which is consistent with an estimate obtained in a previous CDF analysis [9]. The quoted uncertainties for these two backgrounds account for both the Poisson statistical uncertainty on the total number of observed events and the uncertainties on the $t\bar{t}$ and diboson predictions.

The signature for top-quark-pair resonant production is a peak in the invariant mass spectrum of the $t\bar{t}$ pair ($M_{t\bar{t}}$), while, in the mass range investigated here, all of the standard model backgrounds fall smoothly with increasing $M_{t\bar{t}}$. The resolution on the $t\bar{t}$ invariant mass is limited by the uncertainty on the jet energy and by the unmeasured longitudinal momentum of the neutrino. The approach adopted here is to use a matrix-element technique [17] to reconstruct $M_{t\bar{t}}$ for an event. We integrate the matrix-element for standard model $t\bar{t}$ production over unmeasured quantities, convoluted with detector resolution functions for the jet energies. The matrix-element implemented for the event reconstruction is the standard model leading order $t\bar{t}$ production and decay, $q\bar{q}(gg) \rightarrow t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q\bar{q}'b\ell\nu_\ell\bar{b}$, and it is used to derive the value of $M_{t\bar{t}}$ in the same way for events in simulated samples and in data.

The *a priori* probability density for producing a $t\bar{t}$ parton-level final state, $\pi_{\rm part}(\{\vec{p}\})$, relative to other $t\bar{t}$ final states, is the normalized differential cross section

TABLE I. Expected number of events from standard model processes in a data set corresponding to an integrated luminosity of 680 pb^{-1} of data, assuming the null hypothesis. The observed number of events on data is 450.

Background	Number of events
SM $t\bar{t}$	199 ± 24
Diboson	14 ± 1
Multijet	22 ± 10
$W(\rightarrow \ell\bar{\nu}_\ell) + 4j$	215 ± 30

$$\pi_{\text{part}}(\{\vec{p}\})\prod_i d^3\vec{p}_i = 1\Big/\sigma \int_0^1 \int_0^1 dz_a dz_b f_k(z_a) f_l(z_b) d\sigma_{kl}(\{\vec{p}\}, z_a\vec{P}, z_b\vec{\bar{P}}),$$

where f_k (f_l) are the proton (antiproton) parton distribution functions, $d\sigma_{kl}$ the $t\bar{t}$ differential cross section, $\vec{P}$ ($\vec{\bar{P}}$) the proton (antiproton) momentum, and $\{\vec{p}\}$ the set of six final state three-momenta. Indices k, l cover the parton types in the proton and antiproton, respectively, and a sum over both indices is implied. The *a priori* probability density for the parton-level final state $\{\vec{p}\}$ and the measured jet quantities $\{\vec{j}\}$ is given by the product

$$\pi_{\text{part,jets}}(\{\vec{p}\}, \{\vec{j}\}) = \pi_{\text{part}}(\{\vec{p}\}) \prod_{i=1}^{4} T(\vec{j}_i|\vec{p}_i),$$

where $T(\vec{j}|\vec{p})$ denotes the parton to jet transfer function, i.e., the probability that a parton of momentum $\vec{p}$ is measured as a jet of momentum $\vec{j}$. Transfer functions are parametrized in $|\eta|$ and momentum of the jet, and are derived from Monte Carlo simulated (PYTHIA) [18] events. Different sets of transfer functions are adopted for b quarks and lighter quarks. No transfer function is used for the charged lepton given its negligible momentum uncertainty. Also, the $\not{E}_T$ measurement is not used to constrain the neutrino transverse momentum.

From $\pi_{\text{part,jets}}(\{\vec{p}\}, \{\vec{j}\})$ we build $P(\{\vec{p}\}|\{\vec{j}\})$, the probability density for the parton momenta $\{\vec{p}\}$, given the observed quantities $\{\vec{j}\}$. From this distribution we derive probability distributions for the new variable, $M_{t\bar{t}}$, which is a function of the parton-level quantities $\{\vec{p}\}$, by calculating $P_f(x|\{\vec{j}\}) = \int P(\{\vec{p}\}|\{\vec{j}\})\delta[x - M_{t\bar{t}}(\{\vec{p}\})]d\{\vec{p}\}$. Having an event probability distribution for $M_{t\bar{t}}$, we choose the mean as the reconstructed value for that event, since Monte Carlo simulations showed it to be the best single value $M_{t\bar{t}}$ estimator. However, given that we do not know which jet matches which parton, we also sum over all possible permutations before extracting the mean. If the event contains jets identified as originating from b quarks we sum only over permutations with b-tagged jets assigned to b-quark partons.

To produce the $M_{t\bar{t}}$ templates, we apply the reconstruction algorithm to each signal and background sample. PYTHIA [18] was used to simulate both the Z' vector resonant production ($M_t = 175\ \text{GeV}/c^2$) and $t\bar{t}$ events. ALPGEN [19] was used for the simulation of the W boson plus parton production, with HERWIG [20] used to model parton showers. All generated events are passed through the CDF detector simulation. The multijet background template was obtained using CDF II data.

To allow direct comparison with the Tevatron run I results [6], we choose a resonance width $\Gamma_{Z'} = 0.012 M_{Z'}$; however, the measured signal cross section upper limits are insensitive to width values up to $\Gamma_{Z'} \approx 0.05 M_{Z'}$. The algorithm shows an intrinsic resolution on $M_{t\bar{t}}$ of about 25 GeV/c^2 when applied to standard model $t\bar{t}$ events, in case of correct partons to jet association. When applied to resonance samples, the mass is still correctly reconstructed in the case of proper parton-jet assignment; however, incorrect parton-jet assignment leads to a low tail in the reconstructed mass distribution as shown in the inset of Fig. 1. The spectra plotted are restricted to the search region ($M_{t\bar{t}} > 400\ \text{GeV}/c^2$) in which the standard model sources fall off exponentially in $M_{t\bar{t}}$.

To derive the posterior probability for $\sigma(p\bar{p} \to Z')BR(Z' \to t\bar{t})$ (we will refer to it simply as "signal cross section") given the observed $M_{t\bar{t}}$ spectrum, we build the likelihood $\mathcal{L}(\vec{n}|\sigma, \vec{\nu}) = \prod_{i\in\{\text{bins}\}} e^{-\mu_i}\mu_i^{n_i}/n_i!$. This is the prior probability of observing $\vec{n}$, where n_i is the number of observed events in $M_{t\bar{t}}$ mass bin i, $\mu_i = \sigma_s A_s T_{si} + \sum_j N_j T_{ji}$ is the number of expected events in the same bin, σ_s is the assumed signal cross section, A_s is the acceptance, N_j is the contribution from the jth background, and T_{si}, T_{ji} is the content of the ith bin of the normalized signal and background templates, respectively. The contributions from standard model $t\bar{t}$ and dibosons are weighted as in Table I, while the contributions due to W + jets and multijets are rescaled to account for the presence of signal and still match the total number of events observed ($N_{W+\text{jets}} + N_{\text{multijet}} = N_{\text{data}} - N_{\text{signal}} - N_{t\bar{t}} - N_{\text{diboson}}$). If one uses a flat prior distribution for the signal cross section and integrates over the nuisance parameters $\vec{\nu}$ (background

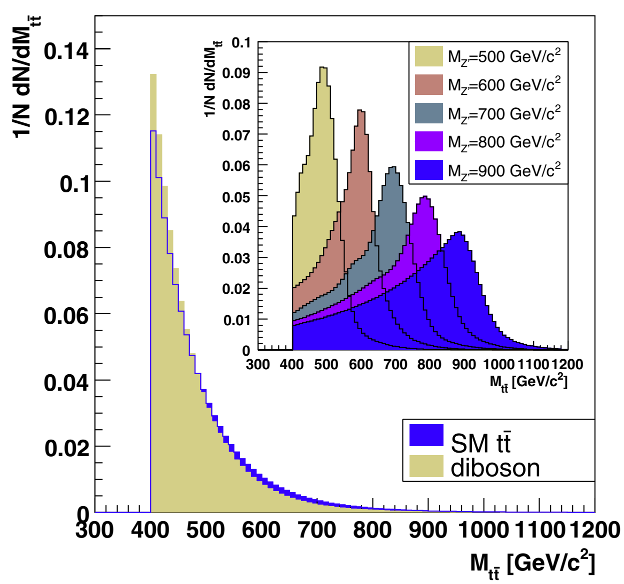

FIG. 1 (color online). Reconstructed $M_{t\bar{t}}$ distributions for two simulated standard model backgrounds. We plot the samples with the "hardest" ($t\bar{t}$) and the "softest" (diboson) spectrum (normalized to unity); all the others lie in between. The inset shows the reconstructed $M_{t\bar{t}}$ distributions for five signal samples.

contributions and signal acceptance) then Bayes's theorem gives the posterior probability density $P(\sigma|\vec{n})$. This is used to define upper limits at any given confidence level (C.L.), together with the most likely value, which is regarded as the measured cross section. This procedure is repeated for 10 resonance masses from 450 GeV/c^2 to 900 GeV/c^2, and 95% C.L. upper limits are established.

As mentioned previously, uncertainties on template weighting are incorporated in the prior probability by means of the prior densities of the nuisance parameters. In this way the marginalized posterior probability density for the signal cross section includes the acceptance and cross section uncertainties. However, the relative contribution of multijet and W + jet events has been kept fixed at 10%. To evaluate the impact of the uncertainty on this ratio, the multijet component has been either set to zero or increased by a factor of 3, in each case yielding negligible change on the cross section posterior distribution. This is because after the event selection the W + jet and multijet $M_{t\bar{t}}$ spectra are very similar above 400 GeV/c^2, as shown in Fig. 1. We assume a 10% acceptance uncertainty for all the resonant $t\bar{t}$ signals, consistent with the uncertainty from the SM $t\bar{t}$.

Other sources of systematic uncertainties can affect both the acceptances and the templates. These "shape systematics" are due to the imperfect knowledge in the modeling of (1) jet energy scale, (2) ISR and FSR, (3) the Q^2 scale for W + jets production, and (4) parton distribution functions (PDF). To account for these uncertainties, we convolute the cross section posterior probability with a Gaussian, whose width is estimated from a new set of templates and acceptances corresponding to a $\pm 1\sigma$ change for each systematic. For a resonance of mass $M_{Z'} =$ 700 GeV/c^2 the uncertainties due to sources (1), (2), and (3) translate into a relative increase of the expected upper limits of 5%, 5%, 2%, and 2%, respectively, for an overall impact of about 10%. The uncertainty due to the choice of the PDFs turned out to be negligible.

In the data sample used for this analysis, 450 events passed our event selection requirements, and 302 of them are found in the search region $M_{t\bar{t}} > 400$ GeV/c^2. The $M_{t\bar{t}}$ data spectrum is shown in Fig. 2, together with the background expectations (above 400 GeV/c^2) based on Monte Carlo studies. In order to establish an *a priori* sensitivity of the reconstruction algorithm we generated 1000 simulated experiments in the null hypothesis and extracted, for each mass point, the 95% C.L. expected upper limit, defined as the median of the upper limits distribution. We also calculated the central 1σ and 2σ frequentist coverage bands.

In the data, the posterior probability distributions for the signal cross section show no evidence of resonant $t\bar{t}$ production. The predicted and observed upper limits at 95% C.L. are shown in Fig. 3, together with the theoretical prediction for the cross section as a function of mass in

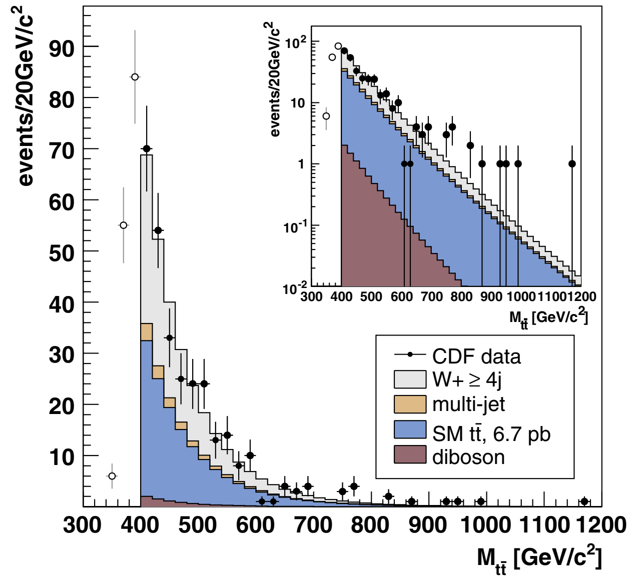

FIG. 2 (color online). The reconstructed $M_{t\bar{t}}$ spectrum (data) and the standard model prediction in the search region above 400 GeV/c^2. The inset shows the same distributions in logarithmic scale.

the leptophobic Z' model (with $\Gamma_{Z'} = 0.012 M_{Z'}$) [5]. Based on this model, we exclude a leptophobic top-color resonance candidate with a mass of 725 GeV/c^2 or less.

In conclusion, we performed a search for a narrow heavy resonance decaying into $t\bar{t}$ in the lepton + jets channel using 680 pb^{-1} of CDF run 2 data. We set upper limits on the production cross section times branching ratio at the

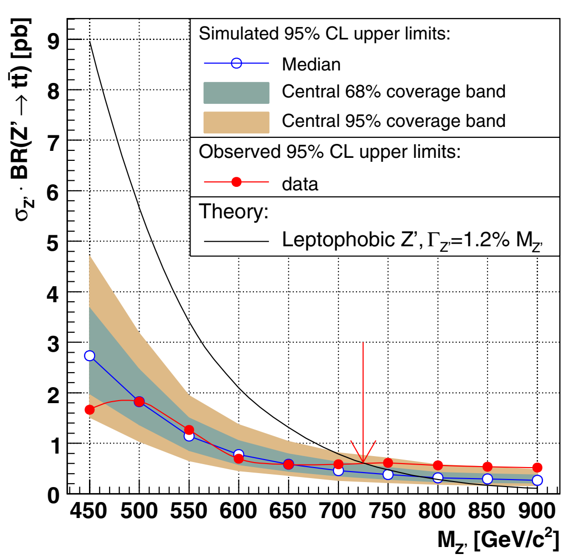

FIG. 3 (color online). Predicted and experimental 95% C.L. upper limits using data corresponding to 680 pb^{-1} of integrated luminosity, together with the leptophobic top-color Z' cross section prediction. Dark and light areas define the 1σ and 2σ ranges for the expected limits. The arrow marks the mass upper limit.

95% C.L. For one leptophobic top-color production mechanism we exclude masses up to 725 GeV/c^2, extending significantly the run I limit of 560 GeV/c^2 [6].

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