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Limits on the production of narrow $t\bar{t}$ resonances in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We search for evidence of resonant top quark pair production in 955 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} =$ 1.96 TeV recorded with the CDF II detector at the Fermilab Tevatron. For fully reconstructed candidate $t\bar{t}$ events triggered on leptons with large transverse momentum and containing at least one identified b-quark jet, we compare the invariant mass spectrum of $t\bar{t}$ pairs to the expected superposition of standard model $t\bar{t}$, non-$t\bar{t}$ backgrounds, and a simple resonance model based on a sequential Z' boson. We establish upper limits for $\sigma(p\bar{p} \to Z') \cdot Br(Z' \to t\bar{t})$ in the Z' mass interval from 450 GeV/c^2 to 900 GeV/c^2. A topcolor leptophobic Z' is ruled out below 720 GeV/c^2, and the cross section of any narrow Z'-like state decaying to $t\bar{t}$ is found to be less than 0.64 pb at 95% C.L. for $M_{Z'}$ above 700 GeV/c^2.

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Resonant top pair production in hadronic collisions has been discussed in the context of extended gauge theories with massive Z-like bosons [1–3], in theories with topcolor [4], or with axigluons [5]. Decays to $t\bar{t}$ are of special interest in leptophobic models that would evade detection in traditional searches based on dielectron or dimuon signatures. More recently, resonant top pairs have been suggested as signatures for Kaluza-Klein (KK) states of gluons, weak bosons, and gravitons [6–8]; in some of these models the KK excitation couples strongly to the top quark and $t\bar{t}$ is the dominant decay mode.

A $t\bar{t}$ resonance would appear as unexpected structure in the spectrum of the invariant mass of $t\bar{t}$ pairs $M_{t\bar{t}}$. Previous searches using ≈ 100 pb^{-1} samples from Fermilab Tevatron Run I have ruled out the production of a narrow leptophobic topcolor resonance with mass less than 480 GeV/c^2 [9,10]. Here, we search for resonant structure in the $M_{t\bar{t}}$ spectrum in 955 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} =$ 1.96 TeV recorded with the CDF II detector in Tevatron Run II. Modeling the resonance as a narrow massive vector boson Z', and calculating its mass with techniques used in precision measurement of the top quark mass [11], we set limits on the cross section times branching ratio $\sigma B = \sigma(p\bar{p} \to Z') \cdot Br(Z' \to t\bar{t})$ as a function of $M_{Z'}$. This study is complementary to Ref. [12], which uses a different event selection and reconstruction of the $t\bar{t}$ kinematics.

The CDF II detector comprises a spectrometer in a 1.4 T magnetic field surrounded by projective electromagnetic and hadronic calorimeters and muon detectors [13]. The spectrometer, consisting of silicon microstrip detectors surrounded by a large open cell drift chamber, provides precision track reconstruction and displaced secondary vertex detection. We use coordinates where ϕ is the azimuthal angle, θ is the polar angle with respect to the proton beam axis, transverse energy is $E_T = E\sin(\theta)$, and the pseudorapidity is $\eta = -\ln[\tan(\theta/2)]$. The data used here were recorded between March 2002 and January 2006.

We collect a sample of $t\bar{t} \to W^+bW^-\bar{b}$ candidate events with one leptonic W boson decay using triggers that require a central ($|\eta| \leq 1.0$) electron with $E_T > 18$ GeV or central muon with transverse momentum $p_T > 18$ GeV/c. After offline reconstruction, we select events with an isolated electron with $E_T \geq 20$ GeV or muon with $p_T \geq 20$ GeV/c, missing transverse energy $\not\!\!E_T \geq 20$ GeV consistent with a neutrino from W decay, and at least four hadronic jets with $|\eta| \leq 2.0$, of which three must have $E_T \geq 15$ GeV, and a fourth must have $E_T \geq 8$ GeV [14]. The jets are clustered in fixed cones of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$. At least one of the jets is required to be b-tagged, i.e. contain a reconstructed secondary vertex displaced from the primary event vertex as expected from the decay of a bottom hadron in the jet [15]. We find 347 events fulfilling these criteria.

The sample is dominated by s-channel $q\bar{q}$ annihilation into $t\bar{t}$ pairs [16,17]. The $t\bar{t}$ acceptance and efficiencies are calculated using the HERWIG generator [18] and a detector simulation, assuming a top mass $M_t = 175$ GeV/c^2. The simulated detector response, particularly with respect to lepton isolation, jet energies, and b-tagging, has been tuned in an earlier measurement of the top pair production cross section [14]. The total combined trigger and reconstruction efficiency is $3.5 \pm 0.5\%$. Non-$t\bar{t}$ backgrounds include W bosons produced in association with jets (W + jets), where a light flavor jet is incorrectly b-tagged; W + jets events with real heavy-flavor jets; mismeasured QCD multijet events with one jet identified as a lepton; and smaller contributions from electroweak processes such as diboson (WW, WZ, ZZ) and single-top production. The rates and kinematics of these processes are modeled with simulated and data control samples as employed in the top cross section measurement [14]. A total of 73 ± 9 non-$t\bar{t}$ background events are expected.

The final state of four jets, a high-p_T lepton, and $\not\!\!E_T$ allows an over-constrained (2C) reconstruction of the top pair kinematics. The assignment of jets to quarks most consistent with the $t\bar{t}$ hypothesis is determined using the χ^2 minimization algorithm employed in the measurement of the top mass [11]. Here, following [19], we include the known top mass as a constraint, which improves the accuracy of the parton assignments. The measured jet energies are corrected back to parton values using calibrations derived from photon-jet balancing and detector simulation [20]. In the χ^2 minimization the parton energies are varied

within their uncertainties and the W and top masses are constrained to the values $M_W = 80.4\ \mathrm{GeV}/c^2$ and $M_t = 175.0\ \mathrm{GeV}/c^2$ within their natural widths (2.1 and 1.5 GeV/c^2, respectively). The effect of variation in the central value of M_t is included later as a systematic uncertainty. Jets with b-tags must be associated with b quarks. The jet-quark assignment giving the lowest χ^2 consistent with these constraints is chosen as the solution. In simulated $t\bar{t}$ events we find a small number of poorly reconstructed events flagged by extreme χ^2. We find the sensitivity of the search is optimized by requiring $\chi^2 < 50$; this cut removes 4% of $t\bar{t}$ events and 9% of non-$t\bar{t}$ backgrounds.

We model the resonant $t\bar{t}$ production mechanism as a sequential Z', a heavy neutral boson with the same couplings as the Z, here including decay to $t\bar{t}$ with $M_t = 175\ \mathrm{GeV}/c^2$. This color-singlet resonance has no interference with the standard color-octet $t\bar{t}$ production processes and the model lineshape is purely Lorentzian. To facilitate comparison to other results [9,10,12] we assign the same narrow width used there, $\Gamma_{Z'} = 0.012 M_{Z'}$. A strictly sequential Z' with open $t\bar{t}$ decays has $\Gamma_{Z'} \simeq 0.03 M_{Z'}$. Since our reconstructed mass resolution is greater than 60 GeV/c^2 (see below) the analysis is insensitive to model dependent width differences at this level, and applies to any narrow $t\bar{t}$ state appearing as a single enhancement in the $M_{t\bar{t}}$ spectrum. Signal models are generated using the PYTHIA simulation [21] with Z' masses between 450 and 900 GeV/c^2 in increments of 50 GeV/c^2.

The inset of Fig. 1 shows the $M_{t\bar{t}}$ distribution reconstructed for a simulated 750 GeV/c^2 Z'. There is a peak near the expected value and a low mass tail which arises from the incorrect jet-parton assignments where a jet from initial or final state radiation has been used instead of a jet from top decay. The rms of the peak region is approximately 60 GeV/c^2 and the full rms is 137 GeV/c^2. Other Z' masses show similar behavior: the $M_{Z'}$ peak width is preserved and the low mass tail extends down to the kinematic threshold at 350 GeV/c^2. The full rms of the $M_{t\bar{t}}$ distribution varies between 67 and 178 GeV/c^2 over our Z' mass range. The fraction of Z' removed by the χ^2 cut varies between 4% and 9% over the Z' mass range.

We use a three-parameter binned likelihood maximization to fit the $M_{t\bar{t}}$ spectrum to a superposition of the expected shapes for $Z' \to t\bar{t}$, standard model $t\bar{t}$, and non-$t\bar{t}$ processes. In the ith bin, we expect

$$\mu_i = \left[\sigma B A \epsilon \int \mathcal{L} dt\right] P_{Z',i} + N_{t\bar{t}} P_{t\bar{t},i} + N_{\mathrm{bkg}} P_{\mathrm{bkg},i} \quad (1)$$

where $P_{Z',i}$, $P_{t\bar{t},i}$, and $P_{\mathrm{bkg},i}$ are the probabilities of observing a signal event, $t\bar{t}$ event or non-$t\bar{t}$ background event in bin i, respectively. $N_{t\bar{t}}$ and N_{bkg} are the number of nonresonant $t\bar{t}$ and the non-$t\bar{t}$ background events. The $\sigma B A \epsilon \int \mathcal{L} dt$ term contains the product of cross section and $t\bar{t}$ branching ratio, acceptance, and efficiency for the Z', and the luminosity.

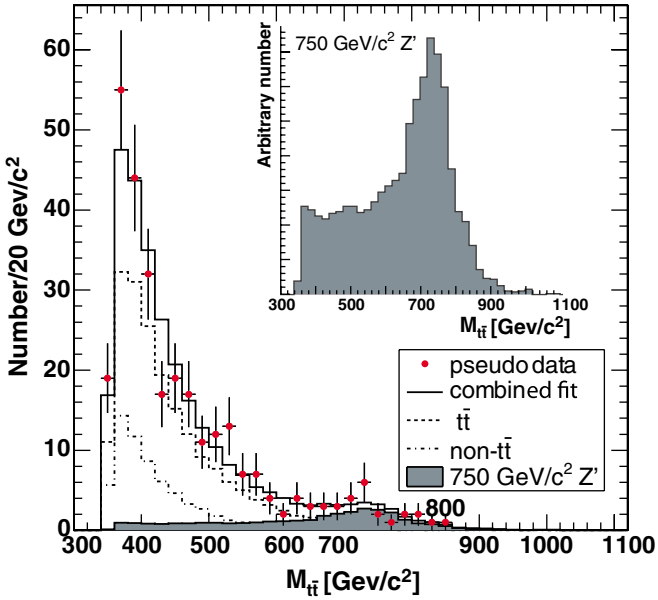

FIG. 1 (color online). Simulated $M_{t\bar{t}}$ spectrum for 955 pb^{-1} in presence of a 750 GeV/c^2 Z' with $\sigma B = 1$ pb (shaded curve). The points are a simulated data set. The solid line is the best fit to a superposition of the Z' signal (solid histogram) and the expected $t\bar{t}$ (dot line) and non-$t\bar{t}$ (dot-dash line) backgrounds. The inset shows the reconstructed $M_{t\bar{t}}$ spectrum in an arbitrarily large sample of simulated 750 GeV/c^2 Z'. The low mass tail arises from incorrect jet-parton associations.

A likelihood function L for the distribution can be written as

$$L = \prod_{i,k} \mathcal{P}_i(n_i|\mu_i) G(\nu_k|\bar{\nu}_k, \sigma_{\nu_k}). \quad (2)$$

The function $\mathcal{P}_i(n_i|\mu_i)$ is the Poisson probability for observing n_i events in a bin i where μ_i are expected. The functions $G(\nu_k|\bar{\nu}_k, \sigma_{\nu_k})$ constrain the nuisance parameters ν_k, which include the non-$t\bar{t}$ background normalization N_{bkg}, b-tag efficiency, acceptances and luminosities, with Gaussian probability around their central values $\bar{\nu}_k$ and uncertainties σ_{ν_k}. The $t\bar{t}$ and non-$t\bar{t}$ background values are taken from [14], and the Z' acceptances and efficiencies are determined from the PYTHIA simulation. We find σB, $N_{t\bar{t}}$, N_{bkg}, and ν_k that maximize the likelihood function for each $M_{Z'}$.

The algorithm is tested with simulated samples where the $t\bar{t}$, non-$t\bar{t}$, and Z' models are combined in the expected ratios and sampled with the expected level of statistical fluctuations. The points in the main part of Fig. 1 show the $M_{t\bar{t}}$ distribution for a simulated data sample corresponding to an integrated luminosity of 955 pb^{-1} in the case of a 750 GeV/c^2 Z' with $\sigma B = 1$ pb. The histograms show the components as resolved by the likelihood fit. The extrac-

tion of the Z' component uses shape information from the low mass part of the spectrum as well as the peak area.

The 95% C.L. upper limit on σB at a given mass is found by integrating the likelihood along σB, reoptimizing at each point, to find the value that contains 95% of the area. We measure our expected sensitivity using large ensembles of simulated samples like the one shown in Fig. 1. The main sources of systematic uncertainty are the acceptance change due to energy scale uncertainty on the jet thresholds, and the shape change in $M_{t\bar{t}}$ from the top mass uncertainty of 3 GeV/c^2. Model dependent shape effects associated with initial and final state gluon radiation and non-$t\bar{t}$ backgrounds are small. PDF uncertainties are evaluated using simulated samples generated with MRST [22] and the full set of eigenvectors from CTEQ6M [23]. Simulated samples with reasonable variations for systematic effects are used to measure the apparent shifts in the fitted σB as a function of the true value. The sum of the shifts in quadrature is used as the width of a Gaussian resolution function that is convolved with the likelihood as a function of σB. The systematic uncertainties worsen the limits by roughly 0.2 pb, independent of the Z' mass, with the increase dominated by the effects of jet energy scale and the top mass uncertainty in equal measure. The expected 95% C.L. upper limits including all sources of uncertainty are shown as a function of $M_{Z'}$ in the middle column of Table I. If no Z' is present our expected cross section limit at high $M_{Z'}$ is 0.55 pb.

The $M_{t\bar{t}}$ distribution measured in the data is shown in Fig. 2. A final sample of 327 candidates remains after the χ^2 requirement. In this figure we compare the observation to the expected spectrum in the case of no Z'. The non-$t\bar{t}$ component is fixed at the expected value and the $t\bar{t}$ normalization is scaled to match the total number of events. The inferred top production cross section is $\sigma(t\bar{t}) = 7.8 \pm 0.7$ pb (statistical error only), to be compared with the predicted standard model value of 6.7 pb for $M_t = 175$ GeV/c^2 [16,17]. The inset shows the measurement

TABLE I. Expected and observed limits (95% C.L.) on $\sigma(p\bar{p} \to Z') \cdot Br(Z' \to t\bar{t})$ as a function of $M_{Z'}$ for 955 pb^{-1}, including both statistical and systematic uncertainties.

$M_{Z'}$(GeV/c^2)	Expected Limit (pb)	Observed Limit (pb)
450	$2.27^{+0.79}_{-0.57}$	3.39
500	$1.92^{+0.63}_{-0.40}$	2.72
550	$1.37^{+0.45}_{-0.30}$	1.57
600	$0.97^{+0.33}_{-0.18}$	0.83
650	$0.78^{+0.24}_{-0.13}$	0.65
700	$0.70^{+0.14}_{-0.12}$	0.64
750	$0.64^{+0.15}_{-0.11}$	0.61
800	$0.58^{+0.15}_{-0.07}$	0.60
850	$0.55^{+0.10}_{-0.05}$	0.57
900	$0.55^{+0.08}_{-0.06}$	0.57

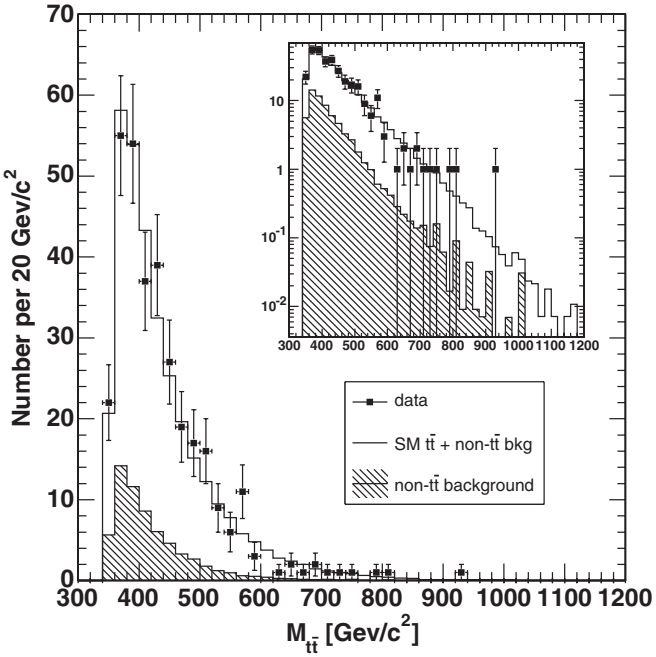

FIG. 2. The invariant mass of top quark pairs $M_{t\bar{t}}$ observed in the data is compared to the no Z' expectation. The non-$t\bar{t}$ backgrounds are constrained to the expected value and the sum of $t\bar{t}$ and non-$t\bar{t}$ equal the number of data events.

on a logarithmic scale. The simulated $M_{t\bar{t}}$ spectra for $t\bar{t}$ and non-$t\bar{t}$ describe the data well.

Applying the full limit procedure to the spectrum in Fig. 2 we find 95% C.L. upper limits on $\sigma(p\bar{p} \to Z') \cdot Br(Z' \to t\bar{t})$ as listed in the rightmost column of Table I. The limits at high mass are consistent with expectation. At lower masses our measurement shows an excursion above the expected value of approximately 1 standard deviation.

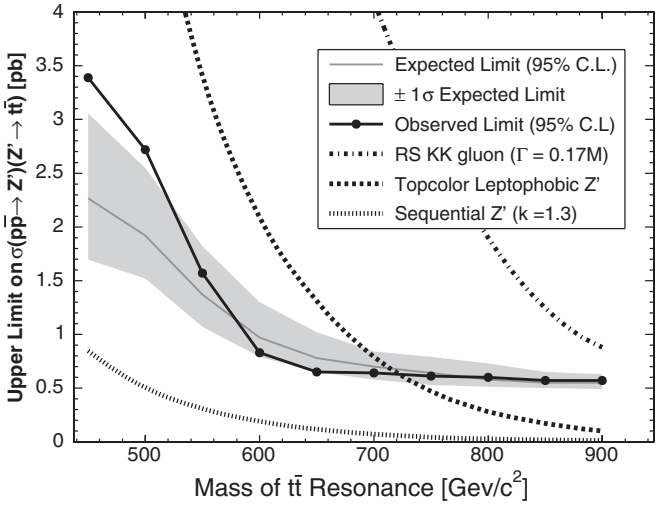

FIG. 3. Upper limits (95% C.L.) on the production cross section for $t\bar{t}$ resonance along with expected cross sections for several models.

The result is represented graphically and compared to some theoretical predictions in Fig. 3. The observed limit is the solid black line and the shaded band around the gray line denotes the $\pm 1\sigma$ uncertainties around the expected upper limit. A leptophobic Z' predicted by the top color theory [4], shown as a large-dotted line, is ruled out below 720 GeV$/c^2$ at 95% C.L. The small-dotted curve at the bottom of the figure is the expected cross section for a sequential Z', calculated with the HERWIG simulation using a multiplicative factor of 1.3 to account for NLO effects. A leptophobic Z' with these couplings would evade direct searches in dilepton final states, and because the $t\bar{t}$ detection efficiency is small, is still out of range of our sensitivity in the $t\bar{t}$ mode. The Tevatron cross section for the KK gluon excitation in the Randall-Sundrum model of Ref. [6] is shown as a dot-dash line [24]. Since the KK resonance is broad ($\Gamma \approx 0.17M$), our limits derived in the ''narrow width'' assumption are not strictly applicable; we show the curve here for qualitative comparison. The cross section of any narrow Z'-like state produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and subsequently decaying to $t\bar{t}$ is less than or equal to 0.64 pb (95% C.L) for all $M_{Z'}$ above 600 GeV$/c^2$.

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