CDF/PUB/EXOTIC/CDFR/10927

Search for Resonant $t\bar{t}$ Production in the Semi-leptonic Decay Mode Using the Full CDF Data Set

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(Dated: October 5, 2012)

Abstract

This Letter reports a search for a non-standard-model resonance decaying into $t\bar{t} \to W^+ b W^- \bar{b}$, where one W boson decays leptonically and the other decays into a quark-antiquark pair. We examine the top-antitop pair invariant mass spectrum for the presence of a narrow resonant state. The search uses the full data sample of $p\bar{p}$ 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} which is the full CDF II data set. No evidence for top-antitop pair resonant production is found. We place upper limits on the production cross section times branching ratio for a narrow resonant $t\bar{t}$ state. Within a specific benchmark model, topcolor-assisted technicolor, we exclude a Z' boson with masses below 915 GeV/c^2 at the 95% credibility level assuming a Z' boson decay width of $\Gamma_{Z'} = 0.012\ M_{Z'}$.

PACS numbers: 13.85.Rm, 14.65.Ha, 14.70.Pw, 14.80.Tt

The discovery of the top quark in 1995 [1] completed the third generation of quarks. Today, the top quark continues to play an important role in theoretical extensions of the standard model (SM). The large mass of the top quark, compared to that of the other quarks, gives it a special position within the SM; understanding its properties may shed light on the dynamics of electroweak symmetry breaking.

Recently, there has been renewed interest in searches in top-quark final states for physics beyond the SM (BSM) due to discrepancies reported in the $t\bar{t}$ forward-backward asymmetry [2]. Moreover, the most recent search for resonant $t\bar{t}$ production from D0 [3] reports an intriguing 2σ excess for resonant masses above approximately 800 GeV/c^2. Many BSM theories [4, 5] predict heavy resonances that add a resonant component to the SM $t\bar{t}$ production mechanism.

In many BSM extensions, top quarks decay via the weak interaction as in the SM, nearly always into a W boson and a b quark. W bosons decay into light fermion-antifermion pairs. A leptonic decay into a charged lepton and a neutrino occurs 32.4% of the time while a hadronic decay into an up-type quark and a down-type quark occurs the remaining 67.6% of the time. We search for resonant production of top quark pairs followed by decays into the lepton-plus-jets channel, where one of the W bosons decays leptonically (to an electron or a muon) and the other W boson decays hadronically. This channel features a clean signature due to the presence of a lepton in the final state, and has a branching ratio of 29%.

Unlike previous searches at CDF [6–9], we do not apply constraints based on the presence of top quarks in the event. While we focus the discussion of this letter on $t\bar{t}$ resonances, and denote the invariant mass used as the final discriminant by $M_{t\bar{t}}$, we construct this variable by taking the invariant mass of all of the objects in the event and these objects may not originate from top quarks. Other than the basic event selection, which already provides a sample primarily composed of $t\bar{t}$ events, there are no additional 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 W boson plus three or more jets final state.

As a benchmark model, we consider a specific SM extension, topcolor-assisted technicolor [10]. This model accounts for the spontaneous breaking of electroweak symmetry and 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 [11], has been searched for both by the CDF [6–9] and D0 [3, 12, 13] experiments at the Tevatron, and also by the ATLAS [14] and CMS [15, 16] experiments at the LHC. For resonance searches at the highest masses (> 1 TeV), the LHC experiments already have superior sensitivity to the Tevatron due increased center of mass energy. However, in the lower mass regions ($m_{Z'}$ <750 GeV/c^2) the Tevatron experiments still 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, SM $t\bar{t}$, is approximately 25 times larger at the LHC, no valence anti-quarks are available in the LHC collisions so the signal scales by a smaller factor relative to the Tevatron (between four and eight depending on the signal mass hypothesis).

The $p\bar{p}$ collision events analyzed in this Letter were produced at the Tevatron collider at a center of mass energy of 1.96 TeV and were recorded by the CDF II detector [17]. The data sample corresponds to the full data set of the Tevatron, which amounts to 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 from the beamline. The pseudorapidity, transverse energy, and 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 incident particle. The missing E_T ($\vec{\not\!\!E}_T$) 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 follows those that were employed in the single-top-quark discovery [18] and the Higgs boson search in the $WH \to \ell\nu b\bar{b}$ final state [19] and are described in more detail in those references. The main difference with respect to the current search is the jet multiplicity requirements.

The data were collected using online event selection (triggers) requiring one of the following energetic lepton signatures: a high-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 $p_T^\ell > 20$ 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 [20, 21]. At least one of the jets must be identified as being likely to have originated from a b quark according to the SECVTX [22] algorithm. SECVTX searches for tracks with non-zero impact parameter resulting from the displaced decay of B hadrons inside the jet, and fits the tracks to a common vertex. Events are rejected if more than one identified lepton is reconstructed or if they are kinematically inconsistent with leptonic W boson decays [23]. 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 MC simulation and data-driven techniques [18]. Important backgrounds in this final state include SM $t\bar{t}$ production and other processes that include a W or Z boson along 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 but non-negligible background contributions come 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 ± 0.50 pb [24] which is calculated at next-to-next-to-leading order using MSTW 2008 parton distribution functions [25]. To predict the acceptance and kinematic distributions of non-resonant SM $t\bar{t}$ events, we use a sample of Monte Carlo (MC) events generated using POWHEG [26] and assuming a top-quark mass of 172.5 GeV/c^2 [27] with parton showering provided by PYTHIA v6.2 [28] followed by simulation of the CDF II detector [29, 30]. The detection efficiency predicted by the MC is corrected based on measurements using data for lepton identification, trigger efficiencies, and b-jet tagging efficiencies. The normalization for the W boson + jet processes is obtained from a fit to the $\not\!\!E_T$ distribution before the b-tagging requirement is applied. 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 multi-jet data [22] 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

CDF run II preliminary (9.45 fb^{-1})		
Process	3-jet events	$\geq$ 4-jet events
$t\bar{t}$	1925.3 $\pm$ 204.8	2564.7 $\pm$ 270.5
W/Z boson + jets	2281.2 $\pm$ 607.2	569.2 $\pm$ 188.6
Multijets	147.2 $\pm$ 60.4	126.3 $\pm$ 104.0
Total background	4353.7 $\pm$ 872.0	3260.2 $\pm$ 563.0
Observed	4254	3049

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

determined from measurements of the heavy-flavor event fraction in a sample of W boson + jets events that is independent of the sample used in the resonance search (W boson + 1 jet sample). We model the kinematics of W boson + jets events using a combination of ALPGEN [31] matrix-element generation and PYTHIA parton showering. The rate of the QCD multijet background is obtained from a fit to the $\not\!\!E_T$ distribution, where the QCD multijet background is modeled using a data sample of collision events in which one of the lepton identification requirements is inverted to obtain a 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. In addition we subdivide the events based on the number of b-tagged jets (one or two b tags), and based on the lepton type (lepton directly identified by the trigger, central muons or electrons, or leptons selected with the $\not\!\!E_T$-based trigger) yielding eight non-overlapping 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.

As mentioned above, 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 tight 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 in the event need not be balanced in the z direction. The longitudinal component of the neutrino momentum (p_z) is determined by solving $M_W^2 = (p^l + p^\nu)^2$ and choosing the smaller solution of the resulting quadratic equation for the p_z of the neutrino. If there is no real solution we set neutrino $p_z = 0$. This approach is found to select the correct p_z of the neutrino in about 70% of $t\bar{t}$ events.

TABLE II. Table of cross sections, σ, and acceptances for the Z' boson signal hypothesis.

CDF run II preliminary (9.45 fb^{-1})			
	Acceptance		$\sigma_{Z'} \cdot BR(Z' \to t\bar{t})$
$M_{Z'}$ [GeV/c^2]	3 jets [%]	≥4 jets [%]	[pb]
350	2.75 ± 0.15	3.68 ± 0.21	8.91
400	2.82 ± 0.16	3.83 ± 0.21	12.3
450	2.35 ± 0.13	3.47 ± 0.19	8.24
500	2.29 ± 0.13	3.59 ± 0.20	5.53
550	2.16 ± 0.12	3.63 ± 0.21	3.51
600	1.93 ± 0.11	3.58 ± 0.21	2.30
650	1.71 ± 0.10	3.48 ± 0.20	1.43
700	1.52 ± 0.09	3.24 ± 0.19	0.917
750	1.37 ± 0.09	2.99 ± 0.18	0.566
800	1.19 ± 0.08	2.75 ± 0.17	0.355
850	1.10 ± 0.07	2.46 ± 0.15	0.208
900	0.96 ± 0.06	2.24 ± 0.14	0.134
950	0.92 ± 0.06	2.03 ± 0.12	0.080
1000	0.87 ± 0.06	1.91 ± 0.12	0.049
1100	0.86 ± 0.06	1.84 ± 0.11	0.017
1200	1.05 ± 0.07	2.01 ± 0.12	0.006

For the benchmark model, the Z' boson cross sections times branching fraction are based on leading order predictions from Ref. [32] with an additional K-factor of 1.3 applied to account for next-to-leading-order (NLO) effects [33]. Signal Z' boson events are modeled

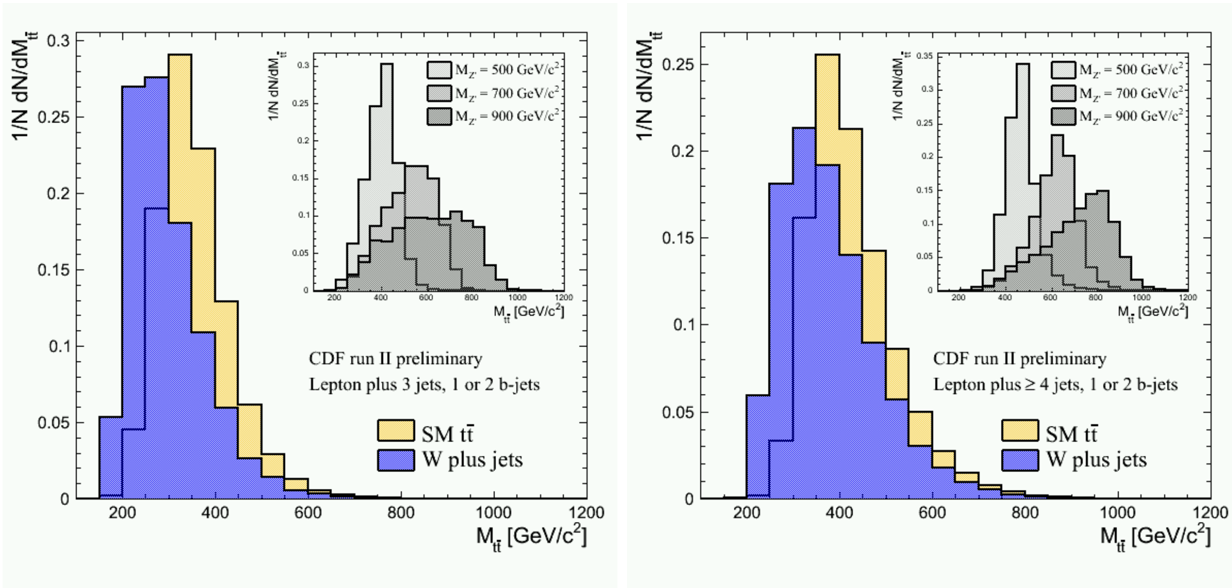

FIG. 1. Reconstructed $M_{t\bar{t}}$ for the three-jet events (left) and four-or-more-jet events (right). All histograms are unit normalized. The inset shows the expected $M_{t\bar{t}}$ distribution for three mass hypotheses of the Z' model.

with simulated events generated by PYTHIA in order to study the signal acceptance and to predict the $M_{t\bar{t}}$ distributions. Table II shows the selection efficiencies and cross sections for Z' boson events after the final event selection for each mass hypothesis considered in the analysis. The expected shape of the $M_{t\bar{t}}$ distributions for the Z' signal for a few representative mass hypothe ses can be compared to the predicted shape for the $t\bar{t}$ and W+jets backgrounds in Fig. 1.

There are 4254 (3049) events surviving the final selection criteria for the three-jet (four-or-more-jet) category. Of this sample, the SM $t\bar{t}$ contribution is estimated to be 43% (78%) for three-jet (four-or-more-jet) events. The remaining events are 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 split into three- and four-or-more-jet events and shown in Fig. 2. The $M_{t\bar{t}}$ distribution for the Z' boson signal for the 600 GeV/c^2 mass hypotheses is also included in Fig. 2.

We calculate a Bayesian credibility level (C.L.) limit on resonant $t\bar{t}$ production for each mass hypothesis based on the observed $M_{t\bar{t}}$ spectrum using the combined binned likelihood

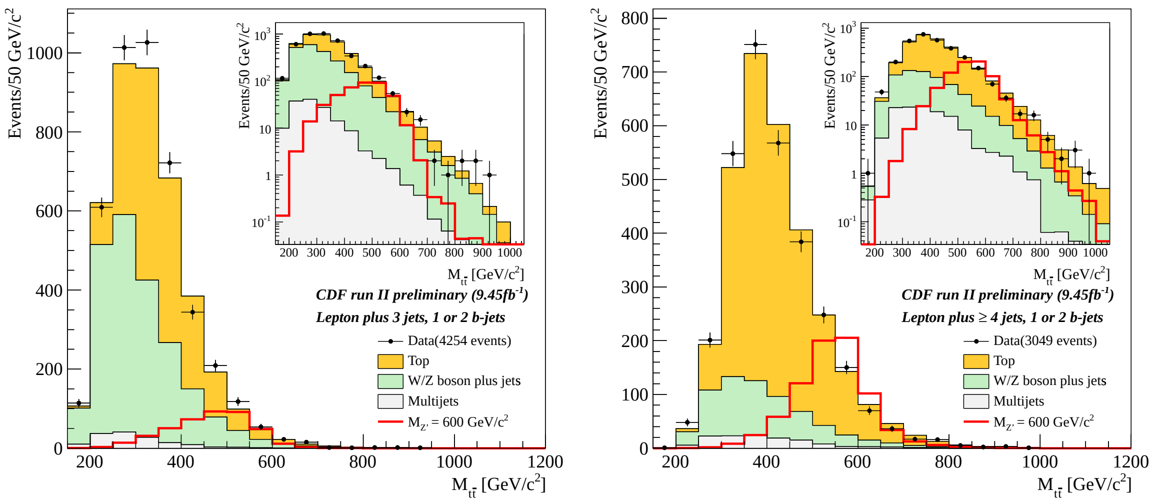

FIG. 2. Reconstructed $M_{t\bar{t}}$ for the three-jet events (left) and four-or-more-jet events (right). The full distribution is shown on a linear scale while the high-mass tail is shown in the inset drawn on a logarithmic scale.. The background expectation is shown normalized to the best fit from the data. The expectation for a 600 GeV$/c^2$ leptophobic topcolor resonance normalized to the predicted cross section is shown with the red line.

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

In this expression, the first product is over the number of channels (N_{C}), and 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} represents the expected background in the bin, and R is a scaling factor applied to the signal.

Systematic uncertainties are parametrized by the dependence of s_{ij} and b_{ij} on $\vec{\theta}$. Each of the n_{sys} components of $\vec{\theta}$, θ_k, corresponds to a single independent source of systematic uncertainty, and each parameter may have an impact on several sources of signal and background in different channels, thus accounting for correlations. 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 [34],

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

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 pseudoexperiments generated without signal. In each pseudoexperiment, random 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, which arise due to the uncertainty in the jet energy scale (JES) [21], the b-tagging efficiency, the luminosity measurement [35], the lepton identification and trigger efficiency (2-6%), parton distribution functions, 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 uncertainty on the rate of production for events with a W boson and heavy-flavor jet (b or c) is 30% due to limitations in the calibration of the fraction of heavy-flavor jets in the sample. 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 QCD multijet background normalization is assigned at least a 40% uncertainty due to statistical limitations from the fitting procedure and the definition of the multijet model [18].

The resulting 95% C.L. upper limits on $\sigma(p\bar{p} \to Z') \cdot BR(Z' \to t\bar{t})$ as a function of $M_{t\bar{t}}$ are shown in Fig. 3 and Tab. III together with expected limits derived from pseudoexperiments that include the SM background hypothesis only. These limits can be used to exclude the leptophobic topcolor model for resonant Z' boson masses less than 915 GeV/c^2 at 95% C.L., assuming the width of the resonance is $\Gamma_{Z'} = 0.012\ M_{Z'}$. We use the leptophobic top color model as a benchmark. However, the limits reported here can be applied to any narrow resonance producing the same final state as long as the difference in the acceptance with respect to the values quoted in Tab. II are taken into account.

In conclusion, we have performed a search for a heavy resonance decaying into $t\bar{t}$ using data with 9.45 fb^{-1} integrated luminosity in the semi-leptonic decay channel. The data

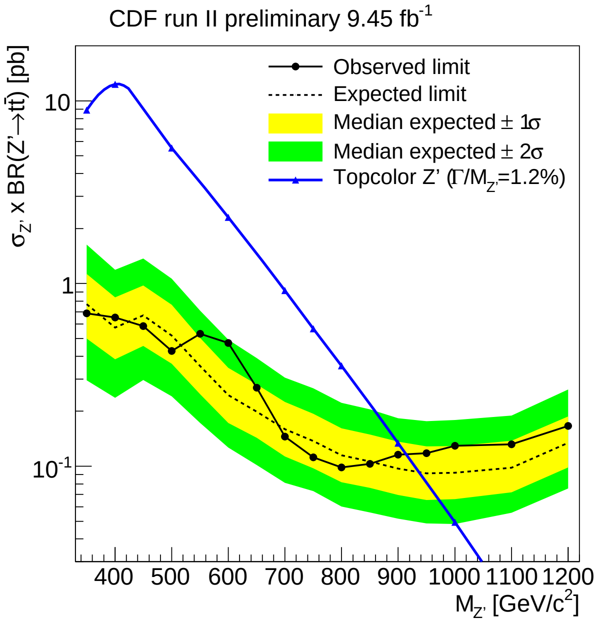

FIG. 3. Expected and observed upper limits on leptophobic topcolor Z' boson in 9.45 fb^{-1} of CDF II data. The dashed line is the median expected upper limit with the assumption of no signal, the black points are the observed limit, and the blue line is the cross section prediction for leptophobic topcolor Z' boson production.

are found to be consistent with the background expectation and we set upper limits on the production cross section times branching ratio at the 95% C.L. For one benchmark model (leptophobic topcolor), we exclude Z' bosons with masses up to 915 GeV/c^2. As show in Fig. 4, for masses below $\sim$ 750 GeV/c^2 this search produces the strongest limit to date on $q\bar{q}$-produced narrow $t\bar{t}$ resonant states in the semi-leptonic decay mode.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program,

CDF run II preliminary (9.45 fb^{-1})		
$M_{Z'}$ [GeV/c^2]	Exp [pb]	Obs [pb]
350	0.772	0.687
400	0.575	0.652
450	0.670	0.585
500	0.520	0.427
550	0.354	0.530
600	0.245	0.472
650	0.199	0.269
700	0.159	0.145
750	0.137	0.112
800	0.115	0.099
850	0.106	0.103
900	0.097	0.116
950	0.091	0.118
1000	0.092	0.129
1100	0.098	0.132
1200	0.134	0.166

TABLE III. Expected and observed limits as a function of Z' boson mass.

the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC).

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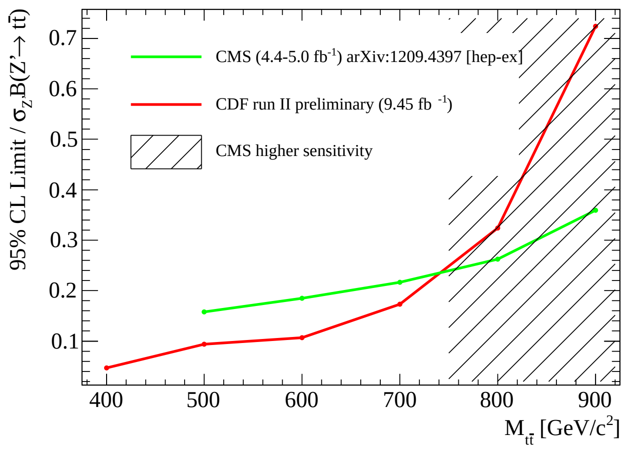

FIG. 4. Expected limits on leptophobic topcolor Z' boson are compared for the CDF result presented here and the most sensitive result to date from the LHC. The CDF result is more sensitive for Z' boson masses below about 750 GeV/c^2.

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