Search for a heavy vector boson decaying to two gluons in pp[over ¯] collisions at sqrt[s]=1.96 TeV

T. Aaltonen *et al.* (CDF Collaboration)

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in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for a new heavy vector boson Z' that decays to gluons. Decays to on-shell gluons are suppressed, leading to a dominant decay mode of $Z' \to g^*g$. We study the case where the off-shell gluon g^* converts to a pair of top quarks, leading to a final state of $t\bar{t}g$. In a sample of events with exactly one charged lepton, large missing transverse momentum and at least five jets, corresponding to an integrated luminosity of 8.7 fb^{-1} collected by the CDF II detector, we find the data to be consistent with the standard model. We set upper limits on the production cross section times branching ratio of this chromophilic Z' at 95% confidence level from 300 fb to 40 fb for Z' masses ranging from 400 GeV/c^2 to 1000 GeV/c^2, respectively.

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Various models of physics beyond the standard model (SM) predict new U(1) symmetries with an associated electrically neutral Z' gauge boson. Assuming coupling to charged lepton pairs, experiments at the LHC rule out such particles up to masses of several TeV [1, 2]. Strict limits are also set by D0, CDF, ATLAS and CMS in searches for Z' decaying to light quarks [3–6] or $t\bar{t}$ pairs [7–10]. If the new particle decays only to gluons (*chromophilic* Z'), such limits are evaded. If the new gauge boson is due to a new hidden sector, tree-level couplings to fermions may be suppressed, and the leading interactions would be with fields charged under the new U(1) and SU(2) or SU(3) groups; the SU(3) case leads to a chromophilic Z' that decays to pairs of gluons [11]. However, the Landau-Yang theorem [12] prevents a vector particle from decaying to two massless gauge bosons, and so the predominant decay mode is to one on-shell (massless) gluon and one off-shell (massive) gluon, the latter then decaying to a pair of quarks, giving $Z' \to g^*g \to q\bar{q}g$. For the same reason, the Z' boson can not be produced through the fusion of two on-shell
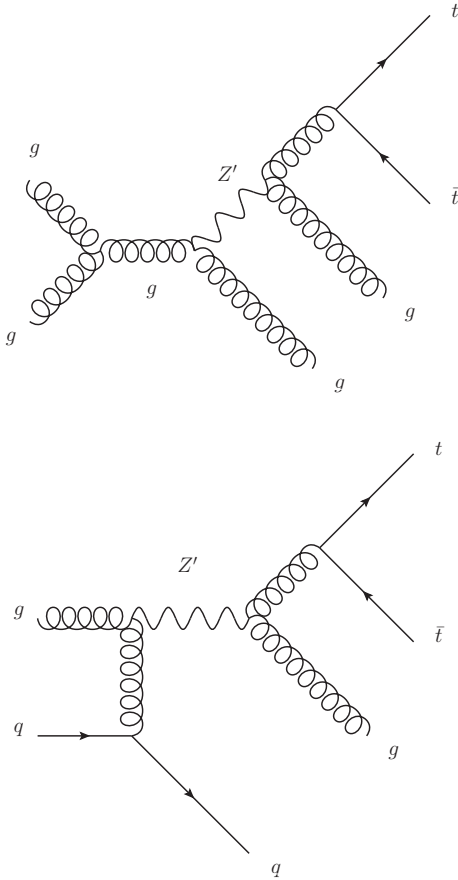
FIG. 1: Diagram for $Z'g$ (top) or $Z'q$ (bottom) production followed by $Z' \to gg^* \to gt\bar{t}$ decay giving a $t\bar{t}gg$ (top) or $t\bar{t}gq$ (bottom) final state.

gluons in the process $gg \to Z'$, but require at least one of the incoming gluons to be offshell, see Fig. 1.

If the $g^* \to q\bar{q}$ pair in the decay is below the top-quark pair mass threshold, it gives a four-jet final state; the usual constraints on Z' models from dilepton and dijet final states therefore do not apply to this model. However, the four-jet final state with a resonance in three jets would be challenging to see over the large multi-jet background. To extract the signal from the large background, we will look at signal events where the off-shell gluon decays to heavy flavor quarks. In this paper, we focus on the decay $Z' \to gt\bar{t}$ and consider the decay mode $Z' \to t\bar{t}g \to W^+bW^-\bar{b}g$ in which one W boson decays leptonically (including τ lepton decays) and the second W boson decays to a quark-antiquark pair. This decay mode features a large $t\bar{t}$ branching ratio and a distinctive experimental signature which allows the reduction to a manageable level of the backgrounds other than SM $t\bar{t}$ production. Such a signal is similar to SM top-quark pair production and decay, but with an additional jet coming from the on-shell gluon from $Z' \to g^*g$ decay.

We analyze a sample of events corresponding to an in-

tegrated luminosity of 8.7 ± 0.5 fb^{-1} recorded by the CDF II detector [13], a general purpose detector designed to study $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV produced by the Fermilab Tevatron collider. CDF's tracking system consists of a silicon microstrip tracker and a drift chamber that are immersed in a 1.4 T axial magnetic field [14]. Electromagnetic and hadronic calorimeters surrounding the tracking system measure particle energies, with muon detection provided by an additional system of drift chambers located outside the calorimeters.

Events are selected online (triggered) by the requirement of an e or μ candidate [15] with transverse momentum p_T [16] greater than 18 GeV/c. After trigger selection, events are retained if the electron or muon candidate has a pseudorapidity $|\eta| < 1.1$ [16], $p_T > 20$ GeV/c and satisfies the standard CDF identification and isolation requirements [15]. We reconstruct jets in the calorimeter using the JETCLU [17] algorithm with a clustering radius of 0.4 in $\eta - \phi$ space, and calibrated using the techniques outlined in Ref. [18]. Jets are required to have transverse energy $E_T > 15$ GeV and $|\eta| < 2.4$. Missing transverse momentum [19] is reconstructed using calorimeter and muon information [15]; in this experimental signature the missing transverse momentum is mostly due to the neutrino from the leptonically-decaying W boson.

The signature of $Z' \to t\bar{t}g \to W^+bW^-\bar{b}g \to \ell\nu bqq'\bar{b}g$ is a charged lepton (e or μ), large missing transverse momentum, two jets arising from b quarks, and three additional jets from the W-boson hadronic decay and the Z' decay gluon. We select events with exactly one electron or muon, at least five jets, and missing transverse momentum greater than 20 GeV/c. Since such a signal would have two jets originating from b quarks, we require (with minimal loss of efficiency) evidence of decay of a b hadron in at least one jet. This requirement, called b-tagging, makes use of the SECVTX algorithm, which identifies jets from b quarks via their secondary vertices [20].

We model the production of Z' bosons with $m_{Z'} = 400$–1000 GeV/c^2 in 100 GeV/c^2 intervals and subsequent decays $Z' \to gg^*$ and $g^* \to t\bar{t}$ with MAD-GRAPH [21]. Additional radiation, hadronization and showering are described by PYTHIA [22]. The detector response for all simulated samples is modeled by the GEANT-based CDF II detector simulation [23].

The dominant SM background to the $t\bar{t} + j$ signature is top-quark pair production with an additional jet due to initial-state or final-state radiation. We model this background using PYTHIA $t\bar{t}$ production with a top-quark mass $m_t = 172.5$ GeV/c^2 [24]. We normalize the $t\bar{t}$ background to the theoretical calculation at next-to-next-to-leading order (NNLO) in α_s [25]. In addition, events generated by a next-to-leading order generator, MC@NLO [26], are used in estimating an uncertainty in modeling the radiation of an additional jet.

The second-largest SM background process is the associated production of a W boson and jets. Samples of W-boson+jets events with light-flavor and heavy-flavor (b, c) quark jets are generated using ALPGEN [27], and inter-

faced with a parton-shower model using PYTHIA. The W-boson+jets samples are normalized to the measured W-boson production cross section, with an additional multiplicative factor for the relative contribution of heavy- and light-flavor jets, following the same technique utilized previously in measuring the top-quark pair-production cross section [20].

To check the quality of the W-boson+jets background modeling, we compare the model to the data in W-boson+four-jet events with zero b-tags. These events are expected to contain only 1% of signal, while W-boson+jets events are expected to account for 50% of the expected background yield. We find agreement between our total background estimate and the data to within 1%.

Backgrounds due to production of a Z boson with additional jets, where the second lepton from the Z-boson decay is not reconstructed, are small compared to the W-boson background and are modeled using events generated with ALPGEN, and interfaced with the parton-shower model using PYTHIA. The multi-jet background, in which a jet is misreconstructed as a lepton, is modeled using events triggered on jets below the selection threshold normalized to a background-dominated region at low missing transverse momentum where the multi-jet background is large.

The SM background due to single-top-quark is modeled using MADGRAPH interfaced with PYTHIA parton-shower models; backgrounds from diboson production are modeled using PYTHIA. Both are normalized to next-to-leading-order cross sections [28, 29].

We search for a signal as an excess of events above expectations from backgrounds in event distributions versus the mass of the $t\bar{t}j$ system ($Z' \rightarrow t\bar{t}j$). In $t\bar{t}+j$ events, we first identify the jets belonging to the $t\bar{t}$ system, using a kinematic fitter [30] to select from all available jets in the event the four jets most consistent with the $t\bar{t}$ topology. In the fit, the top-quark and W-boson masses are constrained to be 172.5 GeV/c^2 and 80.4 GeV/c^2, respectively. All remaining jets are considered candidates for the light-quark jet in the $t\bar{t}j$ resonance. Following the strategy proposed in Ref. [11], we choose the jet with the largest value of $\Delta R(j, t\bar{t}) \times p_{\mathrm{T}}^{\mathrm{jet}}$ to reconstruct the resonance mass $m_{t\bar{t}j}$, where $\Delta R(j, t\bar{t})$ is the distance between a jet and the $t\bar{t}$ system in $\eta - \phi$ space. Figure 2 shows distributions of the reconstructed mass for several choices of Z' mass; the width of these distributions is mostly due to jet energy resolution and the multiple combinations of jet-parton assignments, rather than the natural width of the Z', which is predicted to be much smaller [11]. Backgrounds, in which no resonance is present, have a broad, smoothly decreasing distribution at low $m_{t\bar{t}j}$, while a signal would be reconstructed near the resonance mass.

We consider several sources of systematic uncertainty on the predicted background rates and distributions, as well as on the expectations for a signal. Each systematic uncertainty affects the expected sensitivity to a signal,
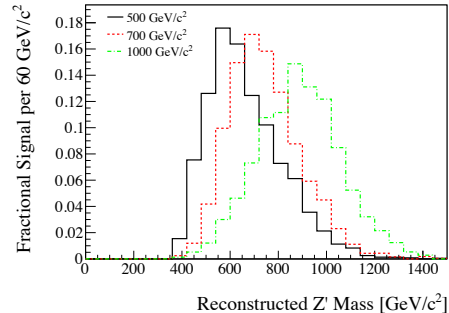

FIG. 2: Distribution of reconstructed Z' mass in simulated events for three choices of $m_{Z'}$.

expressed as an expected cross-section upper limit in the no-signal assumption. The dominant systematic uncertainty is the jet energy scale (JES) uncertainty [18], followed by theoretical uncertainties on the cross sections of the background processes. To probe the description of the additional jet, we compare our nominal $t\bar{t}$ model to one generated by MC@NLO and take the full difference as a systematic uncertainty. We also consider systematic uncertainties associated with the description of initial- and final-state radiation [30], uncertainties in the efficiency of reconstructing leptons and identifying b-quark jets, and uncertainties in the contribution from multiple proton interactions. In addition, we consider a variation of the Q^2 scale of W-boson+jet events in ALGPEN. In each case, we treat the unknown underlying quantity as a nuisance parameter and measure the distortion of the $m_{t\bar{t}j}$ spectrum for positive and negative fluctuations of the underlying quantity. Table I lists the contributions of each of these sources of systematic uncertainty to the yields.

TABLE I: Contributions to the systematic uncertainty on the expected numbers of events for the two main background processes, the total background yield, and an example 500 GeV/c^2 resonance signal with an assumed total cross section of 300 fb.

Process	$t\bar{t}$	W-boson+jets	Total bg.	Z'
Yield	550	79	670	102
JES	17%	15%	16%	9%
Cross section	10%	30%	12%	-
$t\bar{t}$ generator	6%	-	5%	-
Gluon radiation	6%	-	5%	4%
(e/μ, b-jet) ID eff.	5%	5%	5%	5%
Mult. interactions	3%	2%	3%	2%
Q^2 scale	-	19%	2%	-
Total syst. uncert.	22%	39%	22%	11%

We validate our modeling of the SM backgrounds in three background-dominated control regions. The $t\bar{t}$ background is validated in events with exactly four jets and at least one b tag. We validate W-boson+jets backgrounds in events with at least five jets and no b tags.

TABLE II: For each Z' mass hypothesis, the expected and observed limits at 95% C.L. on the production cross section times branching ratio, the theoretical prediction for coupling $g = 100 \text{ GeV}^{-2}$, and the limit on g.

Z' mass (GeV/c^2)	Exp (obs) limit on σ (pb)	Theory σ (pb)	Limit on g (GeV^{-2})
400	0.27 (0.30)	0.003	987
500	0.23 (0.26)	0.09	157
600	0.17 (0.18)	0.22	87
700	0.10 (0.11)	0.24	64
800	0.083 (0.085)	0.18	68
900	0.061 (0.061)	0.10	77
1000	0.041 (0.041)	0.05	94

Finally, modeling of SM $t\bar{t}$ events with an additional jet is validated by examining a signal-depleted region with at least five jets, at least one b tag and H_T, the scalar sum of lepton and jet transverse momenta, less than 350 GeV/c. As shown in Fig. 3, the backgrounds are well modeled within systematic uncertainties.

Figure 4 shows the observed distribution of events in the signal region compared to possible signals and estimated backgrounds. At each Z' mass hypothesis, we fit the most likely value of the Z' cross section by performing a binned maximum-likelihood fit of the $m_{t\bar{t}j}$ distribution, allowing for systematic and statistical fluctuations via template morphing [31] of the signal and background distributions. No evidence is found for the presence of top-quark-pair+jet resonances in $t\bar{t}j$ events, so we set upper limits on Z' boson production at 95% confidence level using the CLs method [32], without profiling the systematic uncertainties. The observed limits are consistent with expectation for the background-only hypothesis. The upper limits on the cross section are converted into limits on the coupling factor g in the Z' gluon vertex [11] (Fig. 5 and Table II) in order to relate the observed limits to the theoretical prediction. A coupling which is much larger than unity would make the theory non-perturbative.

In conclusion, we report on the first search for top-quark-pair+jet resonances in $t\bar{t}j$ events. Such resonances are predicted by various extensions [11] of the standard model and their existence is poorly constrained experimentally. For each accepted event, we reconstruct the resonance mass ($m_{t\bar{t}j}$), and find the data to be consistent with SM background predictions. We calculate 95% C.L. upper limits on the cross section of such resonance production from 300 fb to 40 fb for Z' masses ranging from 400 GeV/c^2 to 1000 GeV/c^2 and interpret the limits in terms of a specific physics model. These limits constrain a small portion of the model parameter space. Analysis of collisions at the Large Hadron Collider may further probe the remaining allowed regions.
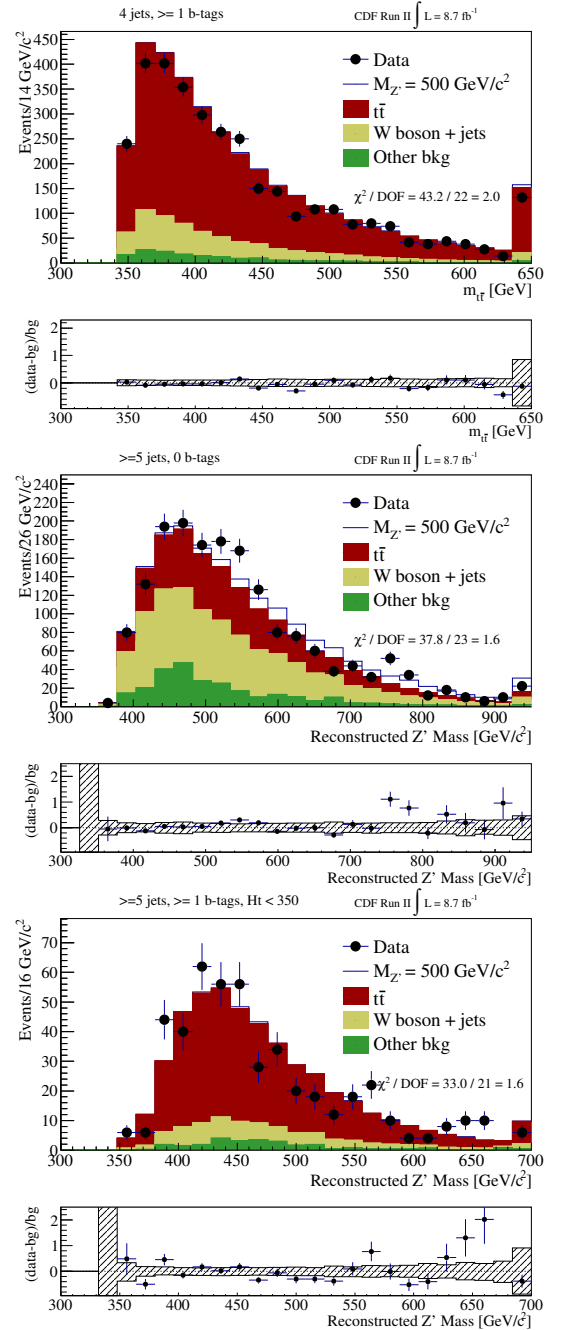
FIG. 3: Distribution of events versus reconstructed $t\bar{t}$ or $t\bar{t}j$ invariant mass for observed data and expected backgrounds in three control regions. Top, reconstructed $t\bar{t}$ invariant mass in events with exactly four jets and at least one b-tag. Center, reconstructed $t\bar{t}j$ invariant mass in events with at least five jets and exactly zero b-tags. Bottom, reconstructed $t\bar{t}j$ invariant mass in events with at least five jets at least one b-tag and $H_T < 350$ GeV. The lower panels give the relative difference between the observed and expected distributions; the hatched areas show the combined statistical and systematic uncertainties of the expected background. A comparison of the observed data and expected backround is provided by the χ^2 calculation.
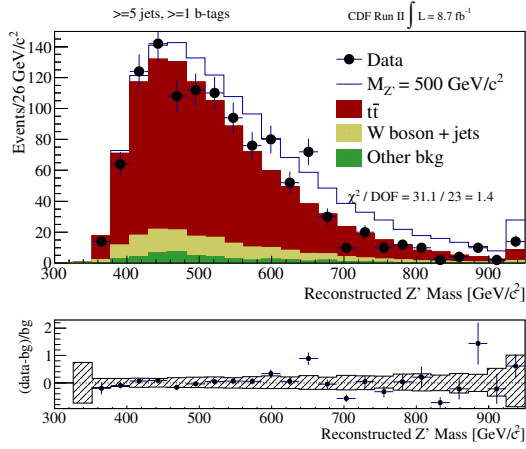
FIG. 4: Distribution of events versus reconstructed $t\bar{t}j$ invariant mass, $m_{t\bar{t}j}$, for observed data and expected backgrounds in the signal region. A signal hypothesis is shown, assuming a total cross section of 300 fb. The lower panel gives the relative difference between the observed and expected distributions; the hatched area shows the combined statistical and systematic uncertainties of the expected background. A comparison of the observed data and expected backround is provided by the χ^2 calculation.
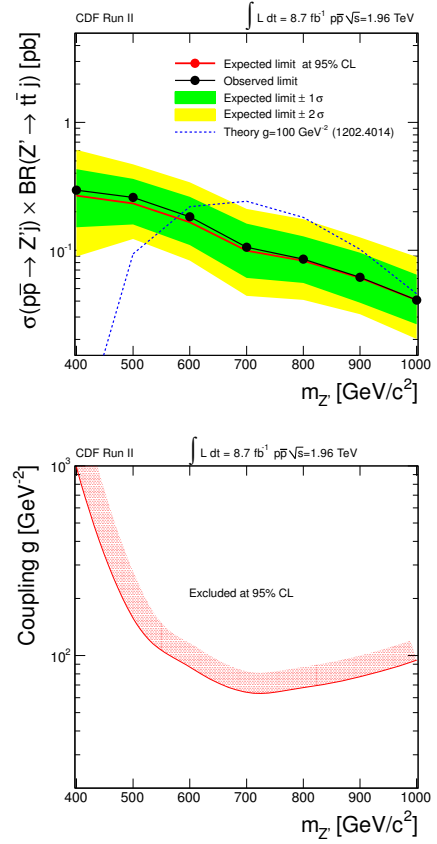
FIG. 5: Top, upper limits at 95% C.L. on $t\bar{t} + j$ production via a heavy new resonance Z', as a function of the resonance mass. Bottom, limits on the coupling g in the Z' theory [11] versus resonance mass.

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