Search for a Vectorlike Quark with Charge 2/3 in $t + Z$ Events from pp Collisions at $\sqrt{s} = 7$ TeV

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A search for pair-produced heavy vectorlike charge-2/3 quarks, T, in pp collisions at a center-of-mass energy of 7 TeV, is performed with the CMS detector at the LHC. Events consistent with the flavor-changing-neutral-current decay of a T quark to a top quark and a Z boson are selected by requiring two leptons from the Z-boson decay, as well as an additional isolated charged lepton. In a data sample corresponding to an integrated luminosity of 1.14 fb^{-1}, the number of observed events is found to be consistent with the standard model background prediction. Assuming a branching fraction of 100% for the decay $T \to tZ$, a T quark with a mass less than 475 GeV/c^2 is excluded at the 95% confidence level.

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Recently, there has been renewed interest in the search for fourth-generation particles [1] that could have escaped the stringent bounds set by precision measurements [2,3]. Searches for $b' \to tW$ [4,5] and $t' \to bW, qW$ [6] decays have been performed at the Tevatron and LHC, setting lower bounds on the masses of fourth-generation quarks b' and t'. The decays $b' \to bZ$ and $t' \to tZ$ are flavor-changing-neutral-current (FCNC) processes and, since they proceed through loop diagrams, they are expected [7] to have branching fractions of $\mathcal{O}(10^{-5}$–$10^{-4})$. Lower bounds on the mass of a b' decaying to bZ have been established [8]. If a vectorlike quark of charge 2/3 (denoted T) exists, however, as expected in several models of new physics [9–11], it would have tree-level FCNC couplings that could result in a large branching fraction for FCNC T decays. For example, for a vectorlike T with a new Yukawa coupling [12,13], the decays $T \to tZ$ and $T \to tH$ could be dominant, where H is the Higgs boson. If the Higgs decay channel is kinematically forbidden, the $T \to tZ$ branching fraction could be close to 100%.

In this Letter, we report the results of a first search for pair-produced T quarks that decay to top quarks and Z bosons, with the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC). The decay chain, $pp \to T\bar{T}X$, with $T\bar{T} \to tZ\bar{t}Z \to b\bar{b}W^+W^-ZZ$, can generate a very clean signature if at least one Z boson decays to $\ell^+\ell^-$, where ℓ is an electron or a muon, and the decay of one of the W bosons yields an additional isolated charged lepton. A search for singly produced vectorlike quarks has been performed by the D0 Collaboration [14].

The central feature of the CMS apparatus is a superconducting solenoid that provides an axial magnetic field of 3.8 T. Charged particle trajectories are measured within the field volume by a pixel and silicon strip tracker. The calorimeter enclosing the tracker includes a lead tungstate crystal electromagnetic calorimeter (ECAL), which is composed of a barrel part and two end caps, a lead and silicon preshower detector in front of the ECAL end caps, and a brass or scintillator hadron calorimeter (HCAL) that together provide an energy measurement for electrons, photons, and hadronic jets. Muons are identified and measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid. The detector is nearly hermetic, allowing accurate energy balance measurements in the plane transverse to the beam direction. The direction of particles measured inside the CMS detector is described using the azimuthal angle (ϕ) and the pseudorapidity (η), which is defined as $\eta \equiv -\ln[\tan\theta/2]$, where θ is the polar angle relative to the counterclockwise proton beam direction, as measured from the nominal interaction vertex. A more detailed description of the CMS detector can be found elsewhere [15].

This study is based on a sample of pp collisions at $\sqrt{s} = 7$ TeV recorded in March–June 2011, and corresponds to an integrated luminosity of (1.14 ± 0.05 fb^{-1}). The CMS trigger system consists of hardware and software triggers [16] that are used to select events for further analysis. Events selected for this search are required to pass one of several dilepton triggers. The efficiencies of the dilepton triggers are measured using an independent data sample collected with a jet-based trigger and containing at least two fully reconstructed leptons, and found to be 99% for two-electron, 89% for two-muon, and 97% for electron-muon triggers.

Muon candidates are required to have a transverse momentum $p_T > 15$ GeV/c and be within the fiducial range $|\eta| < 2.4$. The reconstructed muon track must be associated with signals in the pixel and silicon strip detectors, as well as track segments in the muon system, and have a high-quality global fit using the information of both the central tracker and the muon detector. The muon

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reconstruction is described in detail in Ref. [17]. The muon candidate is also required to be consistent with coming from the primary interaction vertex [18].

Electron candidates are reconstructed using clusters of energy deposits in the ECAL that are matched to a track reconstructed in the tracker. A candidate is required to have $p_T > 20$ GeV$/c$ and be within the fully instrumented barrel ($|\eta| < 1.44$) or end cap ($1.57 < |\eta| < 2.5$) regions. The track must also be consistent with originating from the interaction vertex. Electrons are identified based on the ratio between the energy depositions in the ECAL and the HCAL, the shower width in η, and the distance between the energy-weighted mean position in the ECAL and the extrapolated position of the associated track measured in both η and ϕ. The selection criteria are optimized to identify electrons from W- or Z-boson decays with an efficiency of 85%, while suppressing at least 98% of candidates originating from hadronic jets [19].

Leptons from W- or Z-boson decays tend to be isolated from other particles in the event. Several requirements are imposed on the sum of the transverse momentum or energy of particles (not including the lepton itself) surrounding the lepton within a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle between the lepton and the particle directions. The sum of the p_T of tracks surrounding a muon candidate must be less than 3 GeV$/c$. Similarly, an electron candidate in the barrel (end caps) is rejected if the sum of the p_T of tracks around it is greater than 9% (5%) of the electron's p_T, the sum of the E_T in the surrounding ECAL region is greater than 8% (5%) of that of the candidate, or if the sum of the E_T in the surrounding HCAL is greater than 10% (2.5%) of the electron's E_T. Electron candidates within a cone of $\Delta R = 0.1$ of a muon candidate are rejected in order to remove misidentified muon bremsstrahlung photons mistakenly associated with the muon-candidate track and misidentified as electrons. Electrons identified as resulting from photon conversions are also rejected.

Jets are reconstructed from particles whose identities and energies have been determined by a particle-flow technique [20,21]. All particles found by the particle-flow algorithm are clustered into jets using the anti-k_T algorithm with the distance parameter of 0.5 [22]. Jet energies are corrected for nonuniformity in calorimeter response and for differences found between jets in simulation and data [23]. Jet candidates are required to have $p_T > 25$ GeV$/c$, be within $|\eta| < 2.4$, and pass quality requirements that reject most misidentified jets arising from calorimeter noise. Jets must also be separated from all lepton candidates by a distance $\Delta R > 0.4$.

We select events that contain at least one well-reconstructed interaction vertex and a leptonic Z-boson decay, which is identified by requiring oppositely charged, same-flavor leptons (e or μ) having an invariant mass in the range $60 < M_{\ell^+\ell^-} < 120$ GeV$/c^2$. At least three leptons and at least two jets are required. An additional reduction of the standard model (SM) background is obtained by requiring

$$R_T \equiv \sum_{i\neq 1,2} p_T(\mathrm{jet}_i) + \sum_{j\neq 1,2} p_T(\mathrm{lepton}_j) > 80\ \mathrm{GeV}/c, \qquad (1)$$

where the $i, j \neq 1, 2$ indicates that the sum extends over all leptons and jets, except the two highest-p_T ones.

Simulated event samples are used to estimate the signal efficiencies. The $pp \to T\bar{T}X$ process, with up to two additional hard partons, is simulated using the MADGRAPH [24] event generator. The result is passed to PYTHIA(v6.420) [25] for parton showering and hadronization. Detector simulation is performed using GEANT4 [26]. The signal efficiencies, excluding the combined branching fractions of 5.4% from the W and Z leptonic decays, vary from $(14 \pm 3)\%$ to $(36 \pm 6)\%$ as the T mass increases from 250 to 550 GeV$/c^2$, where the uncertainties are

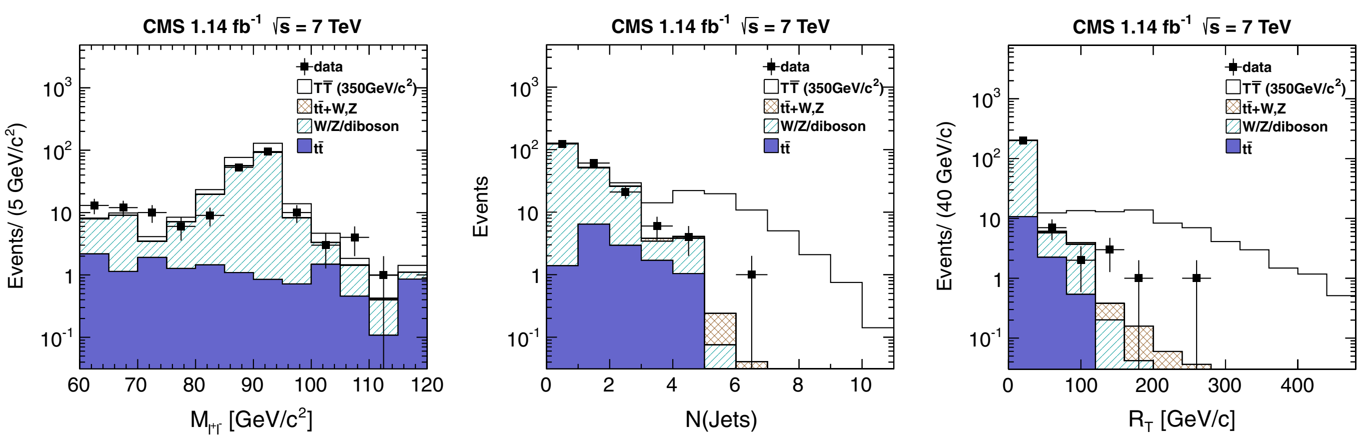

FIG. 1 (color online). The distributions of the invariant mass of two oppositely charged muons or electrons from data (points) and from Monte Carlo simulations of the backgrounds (colored histograms) and a 350 GeV$/c^2$ $T\bar{T}$ signal (open histograms), $M_{\ell^+\ell^-}$ (left), jet multiplicity (center), and R_T (right) for events with a reconstructed Z-boson candidate and a charged lepton.

systematic. The reduction of signal efficiency for events with a lower T-quark mass is due to the requirement on R_T and the minimum p_T threshold for lepton candidates. Contributions from cascade decays of τ leptons are negligible. The distributions of the dilepton invariant mass, jet multiplicity, and R_T for events with a Z-boson candidate and a charged lepton are displayed in Fig. 1. The expected distributions of a T signal with 350 GeV$/c^2$ mass also shown in Fig. 1 are normalized using the $T\bar{T}$ cross section calculated to approximately next-to-next-to-leading order (NNLO) in α_s [27].

After the full selection criteria are applied, two types of background sources remain in the signal sample: (a) events with two prompt leptons ($B_{2\ell}$) and a nonprompt lepton from a jet and (b) events with three prompt leptons ($B_{3\ell}$). To estimate the yield of the $B_{2\ell}$ background in data, a method using a sample of leptons passing looser selection criteria than those described above is introduced. This type of background is primarily from Z and $t\bar{t}$ processes. Electrons chosen with the full selection criteria defined above are called ''tight'' electrons. Electron candidates that are above the same p_T threshold, satisfy the online trigger selection, but fail the full selection criteria are called ''loose'' electrons. Similarly, muons chosen with the full selection criteria are tight muons, while muon candidates passing the selection criteria defined above except the requirement on the sum of the p_T of tracks surrounding the muon candidate are loose muons. A control sample is defined with selection criteria similar to those of the signal sample, except that the third lepton must only satisfy the loose lepton requirements. Z and $t\bar{t}$ production are the dominant processes also in the control sample, similarly to the signal sample. The background is estimated using the event yield observed in the control sample, multiplied by the probability of a loose lepton in background events passing the tight criteria. This probability is determined from data by taking the number of events in a multijet dominant control sample, and dividing the number of events with one loose and one tight lepton by the number of events with two loose leptons. For electrons this probability is $(2.00 \pm 0.02)\%$ and for muons it is $(18.7 \pm 0.1)\%$, where the uncertainties are statistical only. The background yield in the signal sample is estimated to be 3.0 ± 0.8 events. The data-based estimation has been validated with closure tests using the Monte Carlo simulation; in particular, the possible presence of signal events in the control sample has a negligible effect. The small contribution from QCD multijet processes is included in this estimation. The method described above predicts a background contribution in the signal sample that is consistent with the expectation from simulated standard model event samples.

The contribution of $B_{3\ell}$ background from processes such as $t\bar{t} + Z$ and diboson production is evaluated from simulations using the MADGRAPH and PYTHIA generators. These background processes are irreducible and their contribution amounts to 1.6 ± 0.5 events, where 42% of events comes from $t\bar{t} + Z$ production. As summarized in Table I, the total estimated background yield in the signal sample is 4.6 ± 1.0 events, including the systematic uncertainties described below. Seven events are observed in data, compatible with the SM expectation.

The systematic uncertainties on the signal efficiencies and the background estimation are summarized in Table II. The uncertainty on the integrated luminosity is estimated to be 4.5% [28], and is included in the limit calculations. An uncertainty of 2.1% in the trigger efficiency for signal events is obtained by comparing the trigger efficiency measured from data with that measured from the simulated signal sample. The lepton selection efficiencies computed from $T\bar{T}$ simulated events are checked in data using Z samples. The difference between the efficiencies measured in simulated Z boson and $T\bar{T}$ signal samples is taken into

TABLE I. Predicted number of background events having two prompt leptons ($B_{2\ell}$), estimated using data, three prompt leptons ($B_{3\ell}$), estimated using simulations, and their sum (B_{total}) in each of the trilepton channels, as well as the observed yield in data after applying the full selection criteria. The uncertainties shown include both statistical and systematic uncertainties.

Channel	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$	Total
$B_{2\ell}$	$0.2^{+0.3}_{-0.2}$	0.8 ± 0.5	0.9 ± 0.4	1.1 ± 0.5	3.0 ± 0.8
$B_{3\ell}$	0.3 ± 0.1	0.3 ± 0.1	0.5 ± 0.2	0.5 ± 0.2	1.6 ± 0.5
B_{total}	0.5 ± 0.3	1.1 ± 0.5	1.4 ± 0.5	1.7 ± 0.6	4.6 ± 1.0
Data	0	2	2	3	7

TABLE II. A summary of relative systematic uncertainties on the signal efficiencies ($\Delta\epsilon/\epsilon$) in percent and estimated background yield. The uncertainties on the signal efficiency vary with the T-quark mass and these variations are shown by the ranges given in the table. The uncertainties on the number of background events with two prompt leptons ($\Delta B_{2\ell}$), three prompt leptons ($\Delta B_{3\ell}$), and their sum (ΔB_{total}) are also summarized. In all cases, the uncertainties from different sources are summed in quadrature to obtain the total uncertainty, while the correlations between different background sources are taken into account.

Source	Signal $\Delta\epsilon/\epsilon$ [%]	Background $\Delta B_{2\ell}$	$\Delta B_{3\ell}$	ΔB_{total}
Luminosity	4.5	···	0.1	0.1
Trigger efficiency	2.1	···	···	···
Lepton selection	17	<0.01	0.3	0.3
Pileup	2.3	0.3	0.06	0.4
PDF	0.2–1.4	-	0.03	0.03
Jet energy scale/resolution	0.8–5.4	0.3	0.2	0.4
Simulated sample statistics	3.0–4.8	···	0.1	0.1
Control region statistics	···	0.7	···	0.7
Background normalization	···	0.2	0.4	0.4
Total	18–20	0.8	0.5	1.0

TABLE III. Summary of the predicted $T\bar{T}$ cross sections, selection efficiencies, and expected yields for various T masses, normalized to an integrated luminosity of 1.14 fb^{-1}, and the observed upper limits at the 95% confidence level on the cross section. The expected yields include the combined branching fraction of 5.4% from the W and Z leptonic decays.

$M(T)$ [GeV/c^2]	250	300	350	400	450	500	550
Cross section [pb]	22.6	7.99	3.20	1.41	0.662	0.330	0.171
Efficiency [%]	14.4 ± 2.8	24.0 ± 4.4	29.4 ± 5.3	32.8 ± 5.8	34.3 ± 6.1	32.7 ± 5.8	35.6 ± 6.3
Expected yield	200	118	57.8	28.3	13.9	6.6	3.7
Observed limit [pb]	1.09	0.65	0.53	0.48	0.45	0.48	0.44

account. The resulting uncertainties on the lepton selection efficiencies are 5.7% and 7.1% for electrons and muons, respectively, giving a total uncertainty of 17% on the signal selection efficiency, and an uncertainty of ± 0.3 events on the background estimation. The effects of multiple pp collisions per beam crossing (pileup) are tested with simulations. Weights are assigned to the simulated events so that the distribution of the number of pileup events matches the target distribution in data. The associated uncertainty is estimated by varying the weights for different distributions. The uncertainty on the parton distribution function (PDF) from CTEQ6 [29] and the jet energy scale [23] and resolution are also accounted for. The uncertainty on the background estimation due to the statistical size of the control samples is ± 0.7 events. The effect of uncertainties on the background cross sections is considered by varying the normalization of the relevant processes as follows: $\pm 11\%$ for $t\bar{t}$ [30], $\pm 3\%$ ($\pm 4\%$) for W (Z) [31], conservatively $\pm(27$–$42)\%$ for dibosons [32], and $\pm 50\%$ for $t\bar{t} + W/Z$.

For each T mass hypothesis from 250 to 550 GeV/c^2 we present the predicted cross section, selection efficiency,

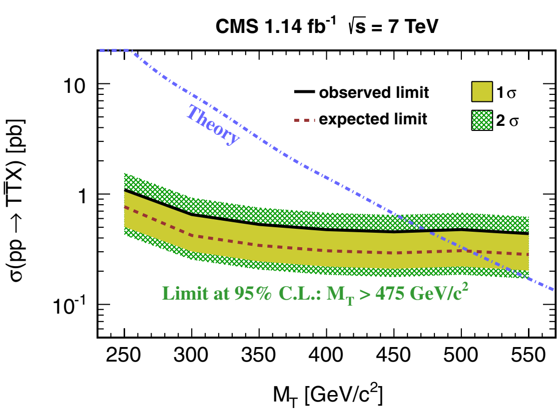

FIG. 2 (color online). The 95% confidence level (C.L.) upper limit on the cross section of the $pp \to T\bar{T}X$ process, as a function of the T-quark mass. The branching fraction of $T \to tZ$ is assumed to be 100%. The solid line shows the observed limit. The dotted line corresponds to the expected limit under a background-only hypothesis. The solid (hatched) area shows the ± 1 (± 2) standard deviation uncertainties on the expected limit. The dot-dashed line shows the value of the theoretical cross section [27] for the $T\bar{T}$ process.

and yield in Table III. Upper limits on the cross section are calculated using a Bayesian method [33] with a flat prior for the signal cross section, and a log-normal model for integration over the nuisance parameters. The observed upper limit at the 95% confidence level (C.L.) on the $T\bar{T}$ cross section as a function of the T-quark mass hypotheses is shown as a solid line in Fig. 2. The dotted line gives the expected upper limit on the cross section under a background-only hypothesis, and the solid and hatched areas around it show the ± 1 and ± 2 standard deviation uncertainties on the expected limit. These were found by producing a large sample of pseudoexperiments in which the expected number of background events was allowed to vary according to its statistical and systematic uncertainties, and the resulting upper limit was then determined. By comparing the observed $T\bar{T}$ upper limit with the approximate NNLO calculation of the $pp \to T\bar{T}X$ production cross section [27] and assuming a 100% branching fraction for $T \to tZ$ decays, a lower limit on the T-quark mass of 475 GeV/c^2 is derived at the 95% confidence level.

In conclusion, using a data sample corresponding to an integrated luminosity of 1.14 fb^{-1} collected by the CMS experiment, we have searched for a vectorlike charge-2/3 T quark that is pair produced in pp collisions at a center-of-mass energy of 7 TeV and decays to a top quark and a Z boson. Seven events are observed in data, consistent with 4.6 ± 1.0 events expected from SM processes. Assuming a 100% branching fraction for the decay $T \to tZ$, we exclude a T quark with a mass less than 475 GeV/c^2 at the 95% confidence level. This is the first search for a pair-produced T quark at hadron colliders.

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