Exclusion of an Exotic Top Quark with −4/3 Electric Charge Using Soft Lepton Tagging

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We present a measurement of the electric charge of the top quark using $p\bar{p}$ collisions corresponding to an integrated luminosity of 2.7 fb^{-1} at the CDF II detector. We reconstruct $t\bar{t}$ events in the lepton + jets final state. We use soft lepton taggers to determine the flavor of the b jets, which we use to reconstruct the top quark's electric charge and exclude an exotic top quark with $-4/3$ charge at 95% confidence level. This is the strongest exclusion of the exotic charge scenario and the first to use soft leptons for this purpose.

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Since the discovery of the top quark in 1995 [1], the CDF and D0 Collaborations have scrutinized its properties. Measurements of the properties of the top quark all present a consistent picture of the top quark as the third-generation standard model (SM) weak-isospin partner of the bottom quark [2]. However, a $+2/3$-electric-charged top quark has yet to be experimentally confirmed, and an exotic $-4/3$-charged scenario has been proposed [3]. In this theoretical scenario, the observed excess of events historically attributed to the top quark are instead attributed to an exotic particle, called "XM top quark," which is identical to the SM top quark except that it decays to W^-b rather than to the SM W^+b. In order to preserve anomaly cancellation, the weak-isospin partner of the bottom (i.e., the "true" top quark) is assumed to exist but is too massive to be observed experimentally.

In this Letter, we present a measurement of the electric charge of the top quark. We analyze data corresponding to an integrated luminosity, $\int \mathcal{L} dt = 2.7\ \text{fb}^{-1}$, collected from February 2002 to April 2008.

We measure the top-quark charge by reconstructing $t\bar{t}$ pairs in the $\ell\bar{\nu}\,\bar{b}\,q\bar{q}'b$ final state. The b quarks associated with the leptonically (hadronically) decaying W are called the "leptonic" ("hadronic") b quarks. Reconstructing the top-quark charge involves identifying either the leptonic or hadronic b quark and determining its flavor, either as b or $\bar{b}$. We use a soft electron tagger (SLT_e) [4] and a soft muon tagger (SLT_μ) [5] (collectively referred to as the SLT taggers) to identify the b jets. The charges of the soft leptons are used to infer the flavor of the b jets. A secondary vertex tagger (SecVtx) [6] is also used to identify the b jets and suppress SM backgrounds. A kinematic fitter [7] determines which b jet is leptonic and which is hadronic. An event is considered SM if the lepton from the W and the SLT lepton from the leptonic (hadronic) b jet have the opposite (same) charge sign. The event is considered to be XM otherwise. For the purposes of this measurement, we assume that the XM top quark has identical properties to the SM top quark, except for its electric charge.

This binary event reconstruction implies that if both the kinematic fitter and the SLT tagger are incorrect, then the correct top-quark charge is still reconstructed. From a Monte Carlo (MC) simulation of $t\bar{t}$ events, the fraction of b jets for which the SLT taggers give the correct flavor assignment is approximately 69%. The fraction of events for which the kinematic fitter properly determines whether a b jet is the leptonic or hadronic b is approximately 76%. This method reconstructs a SM (XM) charge in approximately 60% (40%) of simulated SM $t\bar{t}$ events.

This technique complements the measurement of the top-quark charge in Ref. [8] which uses the curvature and momentum of tracks within a b-jet cone to determine its charge. The SLT method is much less efficient than this technique since the semileptonic branching fraction for b jets is only $\sim$10% per lepton flavor; however, the b-jet flavor determination is much more reliable because of the higher b-jet flavor reconstruction purity. The overall reduction in sensitivity with the SLT technique is therefore only a factor of 2–3 lower.

The CDF II detector [9] is a general-purpose detector [10] with silicon and drift chamber tracking [11,12] immersed in a 1.4 T solenoidal magnetic field. Projective electromagnetic- and hadronic-sampling calorimeters [13] lie beyond the solenoid and provide jet and missing E_T ($\not{E}_T$) reconstruction. Muon chambers [14] lie beyond the calorimeter. Gaseous Cherenkov counters [15] measure the average number of inelastic $p\bar{p}$ collisions to determine the luminosity with a 6% relative uncertainty.

Events are identified with central ($|\eta| \lesssim 1$), high-p_T ($-E_T$) muon (electron) triggers. We select events with a $p_T > 20$ GeV$/c$ ($E_T > 20$ GeV) muon (electron), which we call the "primary" lepton. At least four jets [16] with corrected $E_T > 20$ GeV [17] and $|\eta| \leq 2.0$ must be present in the event. To increase our acceptance for $t\bar{t}$ events, we allow one of the four jets to pass a looser selection ($E_T > 12$ GeV and $|\eta| \leq 2.4$), but we do not consider the looser fourth jet for tagging, either by the SLT or SecVtx algorithms. We explicitly reject cosmic muons, electrons from photon conversions, leptons from Z boson decay, and events with more than one energetic and isolated lepton. We also require $H_T > 250$ GeV and $\not{E}_T > 30$ GeV, where H_T is the scalar sum of the transverse energy of the primary lepton, $\not{E}_T$, and jets.

We require each event to have ≥ 1 SLT (either e or μ) tag, and ≥ 1 SecVtx tag. In order to have a larger sample, we do not require that different jets in the same event are tagged by the different taggers. To suppress cascade decays of b jets (i.e., $b \to c \to \ell\nu X$) that result in flavor misidentification, we require the SLT track $p_T > 6$ GeV$/c$, since leptons from cascade decays tend to be softer than those from direct semileptonic decays. We further require $p_T^{\text{rel}} > 1.5$ GeV$/c$ where p_T^{rel} is the SLT_μ track p_T relative to the jet axis. This requirement makes the SLT_e and SLT_μ purities approximately equal.

We use a kinematic fitter described in detail in Ref. [7] which minimizes a reduced χ^2-like function to fit to the $t\bar{t}$ event hypothesis. Jets are assigned uniquely to each of the four final-state quarks, and those jets tagged by either the SLT or SecVtx algorithms are constrained to be either of the two b jets. All possible permutations are considered and the one which results in the lowest χ^2 value is chosen. If two different jets are both tagged, then we require that the lowest $\chi^2 < 27$; however, if only one jet in the event is tagged, by both SecVtx and the SLT, then we require $\chi^2 < 9$. The tighter requirement on the χ^2 enforces a higher top-quark charge reconstruction purity since there is a greater ambiguity when only one jet is identified as a b jet by the taggers.

The requirement on the χ^2, SLT track p_T, and SLT_μ p_T^{rel} variables is determined by optimizing on the total expected ϵD^2, where ϵ is the event-reconstruction efficiency, $D = 2P - 1$ is the dilution, where P is the purity, which is defined as the fraction of reconstructed events that are determined to have an SM charge. Table I presents the expected ϵD^2 using the PYTHIA MC generator [18] to model $t\bar{t}$ and assuming $\sigma_{t\bar{t}} = 6.7 \pm 0.8$ pb [19],

TABLE I. Expected efficiency (ϵ), purity (P), ϵD^2, and number of events reconstructed as SM and XM, assuming $\sigma_{t\bar{t}} = 6.7$ pb for $\int \mathcal{L} dt = 2.7$ fb^{-1} in PYTHIA simulation.

	ϵ (%)	P (%)	ϵD^2 (%)	$\langle N_{\rm SM}\rangle$	$\langle N_{\rm XM}\rangle$
Total	3.26	60.8	0.152	18.3	11.8
1 tagged jet	0.92	58.2	0.025	4.9	3.5
≥ 2 tagged jets	2.34	61.8	0.130	13.4	8.3
SLT$_e$ only	1.62	61.9	0.092	9.2	5.7
SLT$_\mu$ only	1.69	59.4	0.060	9.3	6.3

$M_t = 175$ GeV$/c^2$, and $\int \mathcal{L} dt = 2.7$ fb^{-1}. We (arbitrarily) choose the pretag expectation as the denominator of the efficiency. The figure of merit ϵD^2 is shown for the combined result, as well as separately for events with one or two tagged jets and with the SLT$_e$ or SLT$_\mu$ only. We expect 30.0 ± 5.9 events from $t\bar{t}$ in the tag sample, where the uncertainty is dominated by the theoretical cross section uncertainty and the jet energy scale uncertainty.

The contribution from non-$t\bar{t}$ backgrounds to the data is very small. The production of $W + b\bar{b}$ dominates, and the total expected contribution to the tag sample from all backgrounds is 2.4 ± 0.8 events, where the uncertainty is dominated by the jet energy scale. The background estimate uses the same technique as in Ref. [4].

The measurement of the b-jet flavor determination purity is estimated with simulation but is calibrated by comparing a sample of pure $b\bar{b}$ events in both data and MC calculations, by requiring that b quarks decay semileptonically and be SLT tagged. The sample is constructed from events with a $p_T > 8$ GeV$/c$ ($E_T > 8$ GeV) muon (electron) close to a jet. A recoiling jet must also be found in the event in which an SLT tag is present, and both jets must be tagged by SecVtx. We measure a dilution scale factor, $SF_D = \sqrt{D_{\rm data}/D_{\rm MC}}$ where $D = (\epsilon_{\rm OS} - \epsilon_{\rm SS})/(\epsilon_{\rm OS} + \epsilon_{\rm SS})$, and $\epsilon_{\rm OS/SS}$ is the tagging efficiency when the trigger lepton and the SLT have the opposite sign (OS) or same sign (SS) charge. The square root originates from the assumption that since both b jets decay semileptonically they are subject to the same dilution factor. This scale factor accounts for differences between the data and MC calculations such as misestimated branching ratios or mismodeling of neutral B mixing.

We measure SF_D to be 0.92 ± 0.11, where the uncertainty is statistically dominated. We use this to correct the simulation estimate for the $t\bar{t}$ charge reconstruction purity, for which our final estimate is $(60 \pm 3)\%$. The uncertainty in the purity is dominated by uncertainties in the simulation of the QCD radiation both in the initial (ISR) and final-state (FSR), the uncertainty in SF_D, and that arising when an alternate MC generator, HERWIG [20], is used. The background has a "purity" of $(50 \pm 6)\%$, where a conservative systematic uncertainty is applied to address potential background mismodeling.

We reconstruct 45 events in data, which is an upward fluctuation consistent with what is observed in Refs. [4,5]. Of these events, 29 are reconstructed as SM and 16 as XM, a ratio consistent with the SM hypothesis. Three events have two SLT tags, although only one of these events has both SLT tags close to jets identified as b jets by the kinematic fit (in this case, both SLT tags are consistent with the SM). Table II shows the number of tags by subsample, including the flavor of the primary lepton, the number of tagged b jets, and the SLT flavor. Note that one event has both SLT$_e$ and SLT$_\mu$ tags. There is no significantly different SM/XM admixture in any of the subsamples.

The statistical significance of the measurement is given by the p value for the test statistic

$$A \equiv \frac{1}{D_S} \frac{N_{\rm SM} - N_{\rm XM} - \langle B\rangle D_B}{N_{\rm SM} + N_{\rm XM} - \langle B\rangle}, \tag{1}$$

where $N_{\rm SM}$ ($N_{\rm XM}$) is the number of SM (XM) events, D_S and D_B are the signal and background dilution, respectively, and $\langle B\rangle$ is the total background expectation. This asymmetry A has been normalized so that the median expectation of the SM (XM) hypothesis is $+1.0$ (-1.0). In the data, we measure a normalized asymmetry $A_0 = 1.53 \pm 0.75$(stat), which clearly favors a SM hypothesis.

We use pseudoexperiments to determine the p value, where systematic uncertainties are treated as Gaussian distributions. We measure $p_{\rm SM} = p(A \leq A_0|{\rm SM}) = 0.69$ and $p_{\rm XM} = p(A \geq A_0|{\rm XM}) = 0.0094$ for the SM and XM hypotheses, respectively, while we expect $p_{\rm SM} = 0.50$ and $p_{\rm XM} = 0.028$, assuming the SM. Figure 1 shows the distribution of p values under the SM and XM hypotheses. We choose the type-I error rate α *a priori* by using the standard threshold for exclusion of exotica: $\alpha = 0.05$. From this we exclude the exotic $-4/3$-charged top quark at 95% confidence level. Table III shows the expected and observed XM p value with the significant systematic errors added cumulatively.

We can also quantify the result of this measurement with a Bayes Factor (BF), which can be interpreted as the posterior odds in favor of the SM when the prior odds

TABLE II. Tag configurations in various subsamples of the data, including divisions according to the primary lepton flavor, the number of tagged b jets, and the SLT flavor. Shown are the number of SM and XM tags as well as the total.

Subsample	N	$N_{\rm SM}$	$N_{\rm XM}$
Primary electron	25	16	9
Primary muon	20	13	7
1 tagged jet	7	4	3
≥ 2 tagged jets	38	25	13
SLT$_e$	25	15	10
SLT$_\mu$	21	15	6
All	45	29	16

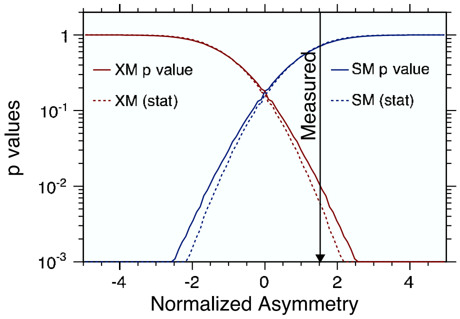

FIG. 1 (color online). The SM and XM p values for the normalized asymmetry test statistic A from pseudoexperiments shown with all uncertainties combined and statistical uncertainties only.

are neutral. This quantity is equal to the ratio, $p(A = A_0|\mathrm{SM})/p(A = A_0|\mathrm{XM})$. For this measurement the BF is 85.8, which is considered "strong" evidence [21] for a $+2/3$-charged top quark.

Figure 2 shows the distribution of the event H_T and the SLT tag p_T. Both the sum and difference of the events classified as SM and XM are shown. The total $t\bar{t}$ contribution (SM + XM) from simulation is normalized to the data and divided between SLT contributions from direct semileptonic b decay, cascade semileptonic decay, and other sources. The expected distribution assuming a $-4/3$ charge XM top quark is shown as a dotted line in the SM − XM plots. These figures demonstrate the preference of the asymmetry for the SM expectation as a function of the event kinematics.

In conclusion, we have presented the strongest exclusion of an exotic top quark with $-4/3$ charge to date (at 95% C.L.), while observing strong evidence for the SM $+2/3$ electric charge of the top quark. We improve on both the expected and measured p values reported in Ref. [8]. For purposes of comparison, we note that what is labeled as "expected C.L." in Ref. [8] corresponds to one minus the expectation value of our p_{XM} under the SM hypothesis. This is the first time an SLT algorithm has been used to accomplish this measurement.

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TABLE III. The p values obtained for the XM hypothesis and how they are affected by the cumulative addition of systematic uncertainties. Other sources of systematic uncertainties are negligible.

Source	Expected p value	Observed p value
Stat. only	0.020	0.0054
Dilultion scale factor	0.021	0.0058
ISR/FSR	0.022	0.0062
Cross sections	0.023	0.0069
Jet energy scale	0.026	0.0080
MC generator	0.028	0.0094

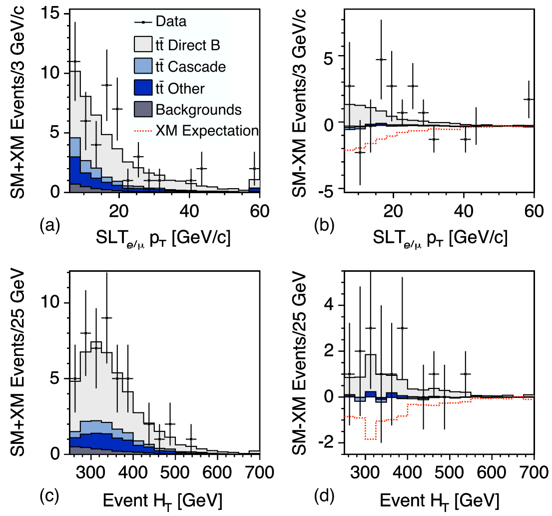

FIG. 2 (color online). Distribution of the SLT track p_T for SM + XM tags (a), track p_T for SM − XM tags (b), event H_T for SM + XM tags (c), and event H_T for SM − XM tags (d). The expectation for a hypothetical XM top quark is shown in the dotted line.

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[1] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **74**, 2626 (1995); S. Abachi *et al.* (D0 Collaboration), Phys. Rev. Lett. **74**, 2632 (1995).
[2] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **103**, 092002 (2009); V. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **103**, 092001 (2009).
[3] D. Chang, W. F. Chang, and E. Ma, Phys. Rev. D **59**, 091503 (1999).
[4] J. P. Chou, Ph.D. thesis, Harvard University [FERMILAB-THESIS-2008-93, 2008]; T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **81**, 092002 (2010).
[5] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **72**, 032002 (2005); T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **79**, 052007 (2009).
[6] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).
[7] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **73**, 032003 (2006).
[8] A. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **98**, 041801 (2007).
[9] A. Abulencia *et al.* (CDF Collaboration), J. Phys. G **34**, 2457 (2007).
[10] We use a transverse coordinate system, where $p_T = p\sin(\theta)$ and $E_T = E\sin(\theta)$ are the momentum and energy measured transverse to the beam line, respectively. We define the pseudorapidity variable, $\eta \equiv -\ln\tan(\theta/2)$. We define $\not{E}_T$ as the negative vector sum of the transverse energies in all the calorimeter cells, $-\Sigma E_T^i$.
[11] C. Hill *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **530**, 1 (2004); A. Sill, Nucl. Instrum. Methods Phys. Res., Sect. A **447**, 1 (2000); A. Affolder *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **453**, 84 (2000).
[12] T. Affolder *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **526**, 249 (2004).
[13] L. Balka *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **267**, 272 (1988); S. Bertolucci *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **267**, 301 (1988).
[14] G. Ascoli *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **268**, 33 (1988).
[15] D. Acosta *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **494**, 57 (2002).
[16] We reconstruct jets using a fixed-cone algorithm with a cone size of $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq 0.4$, where ϕ is the azimuthal angle.
[17] A. Bhatti *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **566**, 375 (2006). We correct jet energies for detector variation, multiple interactions, and uninstrumented regions of the detector.
[18] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026. We use PYTHIA version 6.216.
[19] M. Cacciari *et al.*, J. High Energy Phys. 09 (2008) 127; N. Kidonakis and R. Vogt, Phys. Rev. D **78**, 074005 (2008); S. Moch and P. Uwer, Nucl. Phys. B, Proc. Suppl. **183**, 75 (2008).
[20] G. Corcella *et al.*, J. High Energy Phys. 01 (2001) 010. We use HERWIG version 6.510.
[21] R. E. Kass and A. E. Raftery, J. Am. Stat. Assoc. **90**, 773 (1995).