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

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.

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 for its electric charge. The SM top quark, except for its electric charge. The event is considered to be SM if the lepton from the leptonic or hadronic jet is leptonic and which is hadronic.

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 leptonic or hadronic 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.


Events are identified with central ($|\eta| \leq 1$), 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 $|\eta| \leq 2.4$ 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 $E_T > 30$ GeV, where $H_T$ is the scalar sum of the transverse energy of the primary lepton, $E_T$, and jets.

We require each event to have $\leq 1$ SLT (either $e$ or $\mu$) tag, and $\geq 1$ 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., $b \rightarrow c \rightarrow (\ell \nu X)$ 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 $p_T^{1\ell} > 1.5$ GeV/c where $p_T^{1\ell}$ is the SLT$_\mu$ track $p_T$ relative to the jet axis. This requirement makes the SLT$_e$ and SLT$_\mu$ purities approximately equal.

We use a kinematic fitter described in detail in Ref. [7] which minimizes a reduced $\chi^2$-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 $\chi^2$ 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 $\chi^2$ 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 $\chi^2$, SLT track $p_T$, and SLT$_\mu$ $p_T^{1\ell}$ variables is determined by optimizing on the total expected $eD^2$, where $e$ 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 $eD^2$ using the PYTHIA MC generator [18] to model $t\bar{t}$ and assuming $\sigma_{t\bar{t}} = 6.7 \pm 0.8$ pb [19],
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

$$A = \frac{1}{D_S} \frac{N_{\text{SM}} - N_{\text{XM}} - \langle B \rangle D_B}{N_{\text{SM}} + N_{\text{XM}} - \langle B \rangle},$$

(1)

where $N_{\text{SM}}$ ($N_{\text{XM}}$) 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 $A_0 = 1.53 \pm 0.75\text{(stat)}$, which clearly favors a SM hypothesis.

We use pseudoexperiments to determine the $p$ value, where systematic uncertainties are treated as Gaussian distributions. We measure $p_{\text{SM}} = p(A \leq A_0|\text{SM}) = 0.69$ and $p_{\text{XM}} = p(A \geq A_0|\text{XM}) = 0.0094$ for the SM and XM hypotheses, respectively, while we expect $p_{\text{SM}} = 0.50$ and $p_{\text{XM}} = 0.028$, assuming the SM. Figure 1 shows the distribution of $p$ values under the SM and XM hypotheses. We choose the type-I error rate $\alpha$ 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 quantize 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 I

<table>
<thead>
<tr>
<th>$\epsilon$ (%)</th>
<th>$P$ (%)</th>
<th>$\epsilon D^2$ (%)</th>
<th>$\langle N_{\text{SM}} \rangle$</th>
<th>$\langle N_{\text{XM}} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3.26</td>
<td>60.8</td>
<td>0.152</td>
<td>18.3</td>
</tr>
<tr>
<td>1 tagged jet</td>
<td>0.92</td>
<td>58.2</td>
<td>0.025</td>
<td>4.9</td>
</tr>
<tr>
<td>$\geq 2$ tagged jets</td>
<td>2.34</td>
<td>61.8</td>
<td>0.130</td>
<td>13.4</td>
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<tr>
<td>SLT$_e$ only</td>
<td>1.62</td>
<td>61.9</td>
<td>0.092</td>
<td>9.2</td>
</tr>
<tr>
<td>SLT$_\mu$ only</td>
<td>1.69</td>
<td>59.4</td>
<td>0.060</td>
<td>9.3</td>
</tr>
</tbody>
</table>

We can also interpret the $p$ value from the Bayes Factor (BF), which can be interpreted as the posterior odds in favor of the SM when the prior odds

### Table II

<table>
<thead>
<tr>
<th>Subsample</th>
<th>$N$</th>
<th>$N_{\text{SM}}$</th>
<th>$N_{\text{XM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary electron</td>
<td>25</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>Primary muon</td>
<td>20</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>1 tagged jet</td>
<td>7</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>$\geq 2$ tagged jets</td>
<td>38</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>SLT$_e$</td>
<td>25</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>SLT$_\mu$</td>
<td>21</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>All</td>
<td>45</td>
<td>29</td>
<td>16</td>
</tr>
</tbody>
</table>
are neutral. This quantity is equal to the ratio, $p(A = A_0[SM]/p(A = A_0[XM])$. 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 $n$ 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

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected $p$ value</th>
<th>Observed $p$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stat. only</td>
<td>0.020</td>
<td>0.0054</td>
</tr>
<tr>
<td>Dilution scale factor</td>
<td>0.021</td>
<td>0.0058</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>0.022</td>
<td>0.0062</td>
</tr>
<tr>
<td>Cross sections</td>
<td>0.023</td>
<td>0.0069</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.026</td>
<td>0.0080</td>
</tr>
<tr>
<td>MC generator</td>
<td>0.028</td>
<td>0.0094</td>
</tr>
</tbody>
</table>

$^a$Deceased.

$^b$Visitor from University of Massachusetts Amherst, Amherst, MA 01003, USA.

$^c$Visitor from Universiteit Antwerpen, B-2610 Antwerp, Belgium.

$^d$Visitor from University of Bristol, Bristol BS8 1TL, U.K.

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On leave from J. Stefan Institute, Ljubljana, Slovenia.


[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, $\eta = -\ln(\tan(\theta/2))$. We define $E_T$ as the negative vector sum of the transverse energies in all the calorimeter cells, $-E_T$.


[16] We reconstruct jets using a fixed-cone algorithm with a cone size of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \leq 0.4$, where $\phi$ is the azimuthal angle.


