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Models of maximal flavor violation (MxFV) in elementary particle physics may contain at least one new scalar SU(2) doublet field $\Phi_{FV} = (\eta^0, \eta^+)$ that couples the first and third generation quarks (q_1, q_3) via a Lagrangian term $\mathcal{L}_{FV} = \xi_{13}\Phi_{FV}q_1q_3$. These models have a distinctive signature of same-charge top-quark pairs and evade flavor-changing limits from meson mixing measurements. Data corresponding to 2 fb^{-1} collected by the Collider Dectector at Fermilab II detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV are analyzed for evidence of the MxFV signature. For a neutral scalar η^0 with $m_{\eta^0} = 200$ GeV/c^2 and coupling $\xi_{13} = 1$, ~11 signal events are expected over a background of 2.1 ± 1.8 events. Three events are observed in the data, consistent with background expectations, and limits are set on the coupling ξ_{13} for $m_{\eta^0} = 180$–300 GeV/c^2.

Measurements of low energy flavor-changing (FC) transitions, such as neutral meson mixing and rare B and K decays [1], largely confirm the minimal flavor violation (MFV) ansatz of the standard model's quark-mixing matrix. This suggests that any new physics that couples quark flavors must either be well aligned with the standard model

couplings or mediated by particles that are too heavy to give observable deviations in current data. If the proposed new physics can be written in terms of a coupling matrix ξ_{ij} between quark flavors i and j, MFV imposes strict constraints on models that couple the top quark to lighter quarks, namely $\xi_{31}, \xi_{13}, \xi_{32}, \xi_{23} \sim 0$.

However, there is no strong theoretical motivation for an alignment between the flavor structure of the standard model and new physics. On the contrary, theories beyond the standard model typically predict large flavor-changing transitions if no additional symmetries are imposed. Moreover, new results on CP-violating asymmetries from $B_s \rightarrow J/\psi\phi$ [2,3] suggest that new flavor structure beyond that of the CKM may be required [4].

A new class of scalar-mediated models has recently been proposed with a Lagrangian describing a scalar SU(2) doublet field $\Phi_{FV} = (\eta^0, \eta^+)$ that couple left-handed quark fields of flavor i (Q_{iL}) to right-handed up-type quark fields of flavor j (u_{jR}) with a strength ξ_{ij} [5]

$$\mathcal{L}_{FV} = \xi_{ij}\bar{Q}_{iL}\tilde{\Phi}_{FV}u_{jR} + \text{H.c.} \qquad (1)$$

This departs maximally from the MFV ansatz by allowing real $\xi_{31}, \xi_{13} \sim 1$ or $\xi_{32}, \xi_{23} \sim 1$ with all other terms zero. Contrary to previous understanding, these models are not excluded by current measurements, which constrain the products of terms in the coupling matrix, e.g., $\xi_{32} \cdot \xi_{31}$ [5], even with a light η^0 mass of $\mathcal{O}(200)$ GeV/c^2.

In the model investigated here ($\xi_{31}, \xi_{13} \sim 1$, called MxFV$_1$ in Ref. [5]), the η^0 decays with equal probability to quark-antiquark pairs $t + \bar{u}$ and $\bar{t} + u$. This leads to production of same-charge top-quark pairs in association with light-quark jets through the processes $ug \rightarrow t\eta^0 \rightarrow tt\bar{u}$, $ug \rightarrow tt\bar{u}$ (η^0 exchange), $u\bar{u} \rightarrow \eta^0\eta^0 \rightarrow tt\bar{u}\bar{u}$, and $uu \rightarrow tt$ (η^0 exchange) and their Hermitian conjugates [6]. The predicted cross section is $\mathcal{O}(1)$ pb over a range of light η^0 masses, 180–300 GeV/c^2.

As suggested in Ref. [6], the case in which both W bosons decay leptonically ($t \rightarrow Wb \rightarrow l\nu b$) presents an

experimentally attractive signature of two same-charge leptons, missing transverse energy ($\not{E}_T$) [7,8], and at least one b jet ($\ell^\pm\ell^\pm\not{E}_T b$) accompanied by additional jets. Though CDF has examined its inclusive same-charge lepton data set in smaller data subsets [9], and has looked for new physics in exclusive final states [10] there has not been an experimental study of the inclusive $\ell^\pm\ell^\pm\not{E}_T b$ final state, where many of the contributions to a $\ell^\pm\ell^\pm$ final state are suppressed by the requirement of b jet identification or large missing transverse energy. Thus, there may be new flavor-violating processes which have large cross sections, low backgrounds, and no direct experimental constraints. In addition, this final state is sensitive to a broad array of new physics topics which give same-charge top quarks, such as heavy down-type quarks [11] or scalar gluons [12].

Reference [6] used a parametrized detector description to describe the signal and background rates. This Letter estimates the dominant backgrounds using data-driven models, validates those estimates in control samples, calculates the signal acceptance with a realistic GEANT-based detector simulation [13], and reports the results of the first experimental search for particles that couple up and top quarks in this generic manner.

We use data collected between 2002 and 2007 with the CDF II detector, corresponding to an integrated luminosity of 2.0 fb^{-1}. CDF II [8,14] is a general purpose detector designed to study $p\bar{p}$ collisions at the Fermilab Tevatron. The tracking system consists of a cylindrical open-cell drift chamber and silicon microstrip detectors in a 1.4 T magnetic field parallel to the beam axis; the momentum resolution is $\delta p_T/p_T^2 = 0.1\%$/GeV/c. The silicon detectors provide tracking information for pseudorapidity $|\eta| < 2$ and are used to reconstruct collision and decay points. The drift chamber surrounds the silicon detectors and gives full coverage in the central pseudorapidity region $|\eta| < 1$. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers and scintillators located outside the calorimeters detect muons in the central pseudorapidity region $|\eta| < 1$. The data used in this measurement are collected with

TABLE I. Cross sections $\sigma(tt)$, $\sigma(tt\bar{u})$, and $\sigma(tt\bar{u}\bar{u})$, acceptance (ϵ) and number (N) of selected $\ell^\pm\ell^\pm b\not{E}_T$ events expected in the sample [6].

	M_{η^0} [GeV/c^2]	180	190	200	225	250	300
	σ [pb]	0.50	0.45	0.41	0.33	0.27	0.19
tt	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	4.4	4.3	3.8	2.6	2.1	0.9
	σ [pb]	0.54	0.50	0.42	0.28	0.22	0.10
$tt\bar{u}$	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	4.7	3.9	3.9	3.0	2.4	1.7
	σ [pb]	0.68	0.45	0.38	0.17	0.06	0.02
$tt\bar{u}\bar{u}$	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	5.7	3.5	3.3	1.4	0.5	0.2
Total $N(l^\pm l^\pm b\not{E}_T)$		14.7	11.7	10.9	7.0	5.0	2.7

TABLE II. Number of expected events for each background process, and the observed same-charge lepton events with b-tag and missing transverse energy, see text.

Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
$Z \to \ell\ell$	0.01	0.02	0.02	0.1 ± 0.1
$t\bar{t}$	0.09	0.03	0.11	0.2 ± 0.1
MisID	0.6	0.71	0.50	1.8 ± 1.8
Total	0.7	0.8	0.6	2.1 ± 1.8
Data	0	1	2	3

FIG. 1 (color online). Following the prescriptions in Refs. [6,24], horizontal bands in measured ξ are shown which include 95% of simulated experiments, for various values of true ξ, with $m_{\eta^0} = 180$ GeV/c^2.

lepton triggers that require an electron or muon with $p_T > 18$ GeV/c.

To isolate the same-charge top-quarks signal we follow [6] to define the $\ell^\pm\ell^\pm b\not{E}_T$ signature by requiring two same-charge reconstructed leptons (electrons or muons) in the central region of the detector, each with $p_T > 20$ GeV/c, one of which must be isolated [15]; at least one jet with $|\eta| < 2.4$ and transverse energy of at least 15 GeV identified as a b jet by the SECVTX algorithm that searches for a displaced secondary vertex [16]; and at least 20 GeV of missing transverse energy, $\not{E}_T$ [7].

To calculate the expected number of tt and $\overline{tt}$ events, we generate events for each of the same-charge processes using CALCHEP [17] with CTEQ6M proton parton distribution functions [18] followed by parton fragmentation and hadronization by PYTHIA [19]. Detector resolution and acceptance are modeled using the GEANT-based detector simulation, CDFSIM [13]. Table I shows the number of expected events in our sample.

Backgrounds to same-charge lepton pairs come from two classes of processes. In the first class, a real lepton is paired with a jet, which is misidentified as a same-charge lepton. The second class of processes comes from a pair of real opposite-charge leptons which include an electron; a hard photon emission from an electron converts into an electron-positron pair with strongly asymmetric momenta so that only one leg is reconstructed.

Backgrounds in which the second lepton arises from a misidentified jet or the decay of a heavy quark are largely due to production of W + jets or semileptonic $t\bar{t}$ decays and are described using a model from jet data [20] in which the rate of lepton reconstruction in inclusive jets is measured and applied to W + jet events. The misidentification model is validated for light-quark jets by comparing the predicted and observed rates of same-charge events as a function of the missing transverse energy without a b-tag requirement. Discrepancies in rates in control regions motivate a 40% uncertainty. The selected sample may have a larger heavy-flavor fraction than the jets from which the lepton misidentification model was derived. Studies in simulated events show that the rate of misidentified leptons in a heavy-flavor enriched sample may be 50%–75% higher, and examination of the equivalent opposite-charge
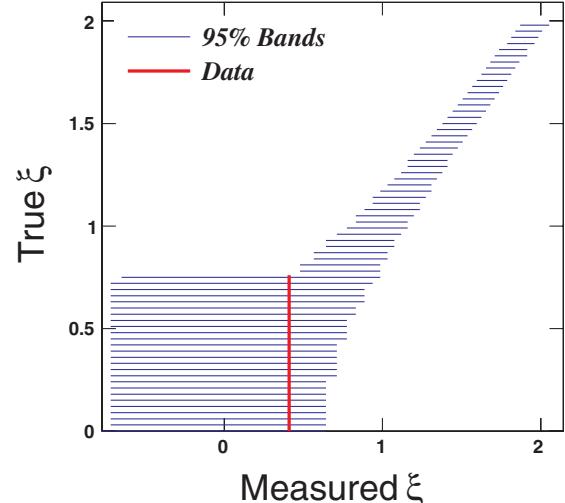
sample motivate a 100% total uncertainty on the background prediction from lepton misidentification.

Backgrounds in which the same-charge lepton is due to a hard photon emission come from Z/γ^* + jets and top-quark pairs with electron-positron decays. Estimates of the backgrounds from Z/γ^* + jets processes are made with the ALPGEN [21] simulation code matched with PYTHIA in the MLM scheme [21] for the hadronization and fragmentation and normalized to data in opposite-sign events. To validate the modeling of the rate of hard emission, we compare our prediction for the contribution of $Z \to e^+e^-$ to the observed sample of same-charge electrons or positron without a b-tag or missing transverse
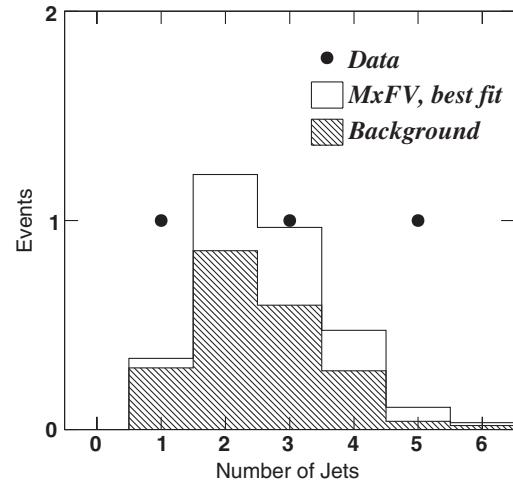
FIG. 2. Jet multiplicity for background, observed data, and MxFV$_1$ signal with best-fit value of $\xi = 0.41$ for $M_{\eta^0} = 180$ GeV/c^2.

TABLE III.   95% confidence level upper limits on the coupling ξ as a function of the mass of η^0.

Mass [GeV/c^2]	180	190	200	225	250	300
(95% C.L.) $\xi <$	0.78	0.81	0.87	1.03	1.11	1.39

energy requirement. The shape and yield of the observed signal at the Z mass agrees well with the prediction. The $t\bar{t}$ backgrounds are estimated using events generated in PYTHIA at $m_t = 172$ GeV/c^2. Modeling of the $t\bar{t}$ contribution is validated by comparing predicted and observed rates of opposite-sign leptons with $\not{E}_T$ and a b tag, where $t\bar{t}$ is expected to dominate. The detector response for both $Z +$ jets and $t\bar{t}$ processes is evaluated using CDFSIM, where, to avoid double-counting, the same-charge leptons are required to originate from the W or Z decays rather than from misidentified jets.

Backgrounds from charge mismeasurement are insignificant, as the charge of a particle with momentum of 100 GeV/c is typically determined with a significance greater than 5σ [22]. The largest potential source comes from top-quark pair events, in which the lepton momenta are typically softer. Charge mismeasurement is very rare in this range, confirmed by the absence of a significant signal near the Z mass in observed same-charge muon events.

Backgrounds from diboson production WW, WZ, ZZ, $W\gamma$, and $Z\gamma$ in association with b jets are modeled with PYTHIA and BAUR [23] generators. These have non-negligible contributions to the inclusive same-charge lepton pair sample, but in the final selection they are insignificant due to the requirement of a b tag.

The final background estimate, shown in Table II, is 2.1 events with an uncertainty of 1.8 events.

From the observed number of events, one could directly measure the value of the MxFV$_1$ coupling $\xi = \xi_{31} = \xi_{13}$. As suggested in [6], the precision of a coupling measurement can be enhanced by simultaneously fitting for the number of signal and background events in the data. This exploits the different number of jets expected in signal and background events (see Fig. 2). Our likelihood fit for the number of signal events is binned in the number of reconstructed jets and takes into account that $\sigma(ug \rightarrow t\eta^0 \rightarrow tt\bar{u}) \propto \xi^2$ while $\sigma(uu \rightarrow tt)$ and $\sigma(u\bar{u} \rightarrow \eta^0\eta^0 \rightarrow tt\bar{u}\,\bar{u}) \propto \xi^4$. The fitted number of signal events can be transformed into an estimated value for ξ.

Following the Feldman-Cousins prescription [24], we use simulated experiments to construct bands which contain 95% of the fitted values of ξ at various true values of ξ for a mass of η^0 (Fig. 1). The simulated experiments include fluctuations in the nuisance parameters, including the uncertainty in the jet energy scale, initial and final state radiation, parton distribution functions and signal and background normalization uncertainties. The confidence band in the space of the true ξ for an individual experiment is the intersection of a line drawn at the observed ξ.
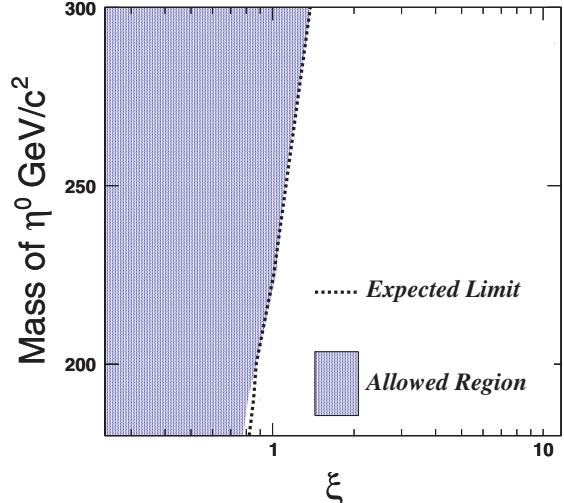
FIG. 3 (color online).   Observed 95% C.L. regions in the $\xi - m_{\eta^0}$ plane.

We observe 3 events, in good agreement with the background expectation. The distribution of jets can be seen in Fig. 2 for the data as well as for the signal and background for the best-fit value of $\xi = 0.41$ for $m_{\eta^0} = 180$ GeV/c^2. As shown in Fig. 1, this corresponds to an upper limit $\xi < 0.78$ at 95% C.L. Table III and Fig. 3 give upper limits on the value of the coupling ξ for $m_\eta^0 = 180$–300 GeV/c^2.

In conclusion, we find no evidence of the signature for maximal flavor violation, and set the first limits on the flavor-changing coupling between the top and up quark in such a model.

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[8] CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. Pseudorapidity is $\eta \equiv -\ln(\tan(\theta/2))$, where θ is the polar angle, and ϕ is the azimuthal angle relative to the proton beam direction, while $p_T = |p|\sin\theta$, $E_T = E\sin\theta$.

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