Collider Signals of Maximal Flavor Violation: 
Same-Sign Leptons from Same-Sign Tops at the Tevatron

Shaouly Bar-Shalom\textsuperscript{a,b} \thanks{Electronic address: shaouly@physics.technion.ac.il} \, Arvind Rajaraman\textsuperscript{b} \thanks{Electronic address: arajaram@uci.edu} \, Daniel Whiteson\textsuperscript{b} \thanks{Electronic address: daniel@uci.edu} \, and Felix Yu\textsuperscript{b} \thanks{Electronic address: felixy@uci.edu}

\textsuperscript{a} Physics Department, Technion-Institute of Technology, Haifa 32000, Israel
\textsuperscript{b} Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

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In models of maximal flavor violation (MxFV) suggested in \cite{MxFV} there is at least one new scalar $\Phi_{FV}$ which couples to the quarks via $\Phi_{FV} q_i q_j \propto \xi_{ij}$ where $\xi_{i3}, \xi_{i2} \sim V_{ij}$ for $i = 1, 2$ and $\xi_{i3} \sim V_{id}$ and $V$ is the CKM matrix. In this article, we explore the potential phenomenological implications of MxFV for collider experiments. We study MxFV signals of same-sign leptons from same-sign top-quark pair production at the Tevatron and at the LHC. We show that the current Tevatron dataset has strong sensitivity to this signature, for which there are no current limits. For example, if $m_{\Phi_{FV}} \sim 200$ GeV and the MxFV coupling $\xi$ has a natural value of $\sim 1$, we expect $\sim 12$ MxFV events to survive a selection requiring a pair of same-sign leptons, a tagged $b$-jet and missing transverse energy, over a background of approximately 4-5 events.

If there is New Physics (NP) around the TeV scale, as suggested by the hierarchy problem and the existence of dark matter, then flavor violating (FV) processes can in principle occur at large rates, but such processes are not observed. This implies that there is some structure to the new physics couplings. One such structure is the minimal FV (MFV) ansatz, which states that the NP is “aligned” with the SM, such that all FV transitions are governed by the nearly diagonal CKM matrix $V$. The MFV ansatz therefore imposes the couplings of any new scalar to a pair of top+light quark to satisfy $\xi_{3i}, \xi_{i3} \sim V_{id}$ for $i = 1, 2$.

In a previous paper \cite{MxFV}, two of the authors have presented a new class of scalar-mediated MxFV models which (as suggested by their name) maximally depart from the MFV ansatz in the sense that $\xi_{31}, \xi_{32} \sim O(1) \gg \xi_{33}$, and still satisfy all constraints from flavor physics even with a relatively light scalar with a mass of $O(m_W)$. In particular, let $\Phi_{FV} \equiv (\eta^+, \eta^0)$ be a new scalar doublet that mediates MxFV through \cite{MxFV}:

$$\mathcal{L}_{FV} = \xi_{ij} \tilde{Q}_{iL} \tilde{\Phi}_{FV} u_{jR} + h.c.,$$

(1)

where $\xi$ is a 3x3 matrix in flavor space. In \cite{MxFV}, it was shown that some substructures of the MxFV texture:

$$\xi \equiv \begin{pmatrix} 0 & 0 & \xi_{13} \\ 0 & 0 & \xi_{23} \\ \xi_{31} & \xi_{32} & 0 \end{pmatrix},$$

(2)

can potentially avoid constraints from low-energy flavor data such as meson mixings and K-decays. In particular, it was shown in \cite{MxFV} that there are no constraints if only one MxFV coupling is non-zero (e.g., the case $\xi_{31} \sim O(1) \gg \xi_{13}, \xi_{32}, \xi_{23}$ is not ruled out regardless of $m_{\eta^+}$ and $m_{\eta^0}$), and that the MxFV\textsuperscript{1} models (defined as models with $\xi_{31}, \xi_{13} \gg \xi_{32}, \xi_{23}$) are not ruled out even with $\xi_{31}, \xi_{13} \sim O(1)$, as long as $m_{\eta^+} \lesssim 600$ GeV (regardless of $m_{\eta^0}$).

A list of possible collider signals of MxFV models was given in \cite{MxFV}. In this paper we study in detail one possible signal: same-sign charged leptons from same-sign top quark pair production. For definiteness, in what follows we will study the case of MxFV\textsuperscript{1} models (defined above) under the assumptions that $\xi_{ij}$ are real and that $\xi \equiv \xi_{31} = \xi_{13}$. As was shown in \cite{MxFV}, in this case the only relevant (sizable) flavor changing couplings are:

$$\Gamma_{\eta^i \eta^a} = \Gamma_{\eta^a \eta^i} = -i \xi, \quad \Gamma_{\eta^+ \eta^-} = \Gamma_{\eta^\pm \eta^\mp} = \frac{i}{2} (1 - \gamma_5).$$

(3)

A particularly interesting limit which we will study in this paper is when the charged scalar $\eta^+$ is too heavy to be accessible at Tevatron and LHC energies, and decouples (the sensitivity of the LHC and the Tevatron to $\eta^+$ will be discussed in a separate paper). If the neutral scalar is light ($m_{\eta^0} \ll m_{\eta^+}$) it can still be probed at colliders. Note that in this case, there are essentially no constraints from low energy data.

The neutral scalar decays half the time to $t + \bar{u}$ and half the time to $\bar{t} + u$. This leads to a striking signal, because we can have production of same-sign top-quark pairs in association with light-quark jets through the processes:

$$u g \to t \eta^0 \to t \bar{t} u + h.c.,$$

(4)

$$u \bar{u} \to \eta^0 \eta^0 \to t \bar{t} u + h.c.,$$

(5)

$$uu \to t \bar{t} + h.c.,$$

(6)

where the last process comes from t-channel $\eta^0$
exchange. As we will see below, this same-sign top pair production signature will be an unambiguous signal of MxFV; indeed, there is no such process in the SM or any extension to the SM with natural flavor conservation like the MSSM. Note that $t\bar{t}$ production (with additional jets) from MxFV $\eta^0$ decays is less sensitive to the new physics because the SM background is larger.

Another important cross-check is that there is no s-channel resonance of the new MxFV scalar, see [1]. In particular, since only $\eta^+$ can be produced in resonance, the case of a decoupling $\eta^+$ leads to a very distinct Higgs phenomenology as one would observe a new scalar (i.e., $\eta^0$) produced in pairs or in association with a top-quark, but, contrary to the usual expectations, this new scalar would not be observed on resonance.

We now consider the production of same-sign top-quark pairs at the Tevatron through the processes mentioned above. We define the inclusive reaction:

$$pp \rightarrow tt + nj + X,$$

where $tt$ stands for both the $tt$ and $t\bar{t}$ production channels (as we will be interested in same-sign leptons signals either positively or negatively charged) and $n$ is the number of light-quark jets $j$, each with transverse energy $E_T > 15$ GeV. Note that, for $m_{\eta^0} > m_t$, $\sigma(ug \rightarrow t\bar{t} \eta^0 \rightarrow tt\bar{t}) \propto \xi^2$ while $\sigma(uu \rightarrow tt)$ and $\sigma(u\bar{u} \rightarrow \eta^0\eta^0 \rightarrow tt\bar{t}) \propto \xi^4$. Thus, for $\xi < 1$, $\sigma(pp \rightarrow tt + nj + X)$ is dominated by the $t\bar{t}\eta^0$ production channel.

When both top quarks decay leptonically ($t \rightarrow Wb \rightarrow l\nu b$), these processes have a striking low-background signature of two same-sign leptons, missing energy, and two $b$-jets ($l^\pm l^\pm E_Tbb$) accompanied by $n$ hard jets. Though CDF has examined its inclusive same-sign lepton dataset in small datasets [2], there has not been an experimental study of the $l^\pm l^\pm E_Tbb$ final state in which many of the same-sign contributions are suppressed by the requirement of a $b$-tag or missing transverse energy. In what follows we describe an event selection to isolate these same-sign lepton signatures, calculate the expected number of such events in the Tevatron data, estimate the contributions from background sources, and determine the sensitivity of a single Tevatron detector as a function of $\xi$ and $m_{\eta^0}$.

**Event Reconstruction and Selection**

To isolate the same-sign top quarks signal we define the $l^\pm l^\pm bE_T$ signature by requiring:

- Two same-sign reconstructed leptons (electrons or muons), each with $p_T > 20$ GeV/c.
- At least one secondary-vertex tag ($b$-tag) [5].
- At least 20 GeV of missing transverse energy, $E_T$.[2]

**Expected Yield and Backgrounds**

To calculate the number of $tt$ and $t\bar{t}$ events we expect at a single Tevatron experiment, we generate events for each of the three same-sign processes in [1]-[6] using Calchep [8] and shower them using PYTHIA [7]. Detector resolution and acceptance are modeled using a parametric detector simulation written to approximately describe the performance of a CDFII-like detector, including lepton acceptance and charge identification, missing energy resolution, misidentification of leptons from jets, $b$-tagging efficiency as well as mistagging of light-quark jets as $b$-jets. The performance of our parametric detector simulation was compared to several published CDFII results and found to agree to within 25%.

**TABLE I: Production cross-sections $\sigma(tt)$, $\sigma(tt\bar{t})$ and $\sigma(tt\bar{t})$, for each of the three same-sign top quark processes in [1]-[6], for $\xi = 1$ and various $\eta^0$ masses. Also given are the acceptance ($\epsilon$) of the event selection described in the text and expected number ($N$) of $l^\pm l^\pm bE_T$ events in 2 fb$^{-1}$ of data.**

| $M_{\eta^0}$ [GeV/c$^2$] | 180 | 190 | 200 | 225 | 250 | 300 |
|--------------------------|-----|-----|-----|-----|-----|-----|
| $\sigma$ [pb]            | 0.50 | 0.45 | 0.41 | 0.33 | 0.27 | 0.19 |
| $tt$ $\epsilon$ [%]     | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  | 0.5  |
| $N$                      | 4.8  | 4.4  | 4.1  | 3.3  | 2.6  | 1.8  |
| $tt\bar{t}$ $\epsilon$ [%] | 0.54 | 0.50 | 0.42 | 0.28 | 0.22 | 0.10 |
| $N$                      | 5.3  | 4.9  | 4.3  | 3.0  | 2.4  | 1.1  |
| $tt\bar{t}$ $\epsilon$ [%] | 0.68 | 0.45 | 0.38 | 0.17 | 0.06 | 0.02 |
| $N$                      | 6.4  | 4.7  | 4.1  | 1.8  | 0.7  | 0.2  |

Major backgrounds to the $l^\pm l^\pm bE_T$ signature come from:

- $Z +$jets $\rightarrow e^+e^-$+jets, in which the $e^+$ or $e^-$ emits a hard photon which later converts asymmetrically in the detector, giving a same-sign lepton pair.
- $W$+jets, where one jet is misidentified as a lepton, typically an electron
- $t\bar{t}$ events where $t\bar{t} \rightarrow b\nu b\gamma j$ and a second lepton comes from semi-leptonic decays of one of the $b$ quarks, or $t\bar{t} \rightarrow b\nu b\bar{\nu}e^-\nu$ with a same-sign $ee$ pair arising from a trident.

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[1] The $tt\bar{t}$ final state also receives an additional (sub-leading) contribution from the pure $2 \rightarrow 3$ $t$-channel $\eta^0$-exchange process $ug \rightarrow tt\bar{t}$ which is included in our analysis.

[2] Missing transverse energy, $E_T$, is defined as the magnitude of the vector, $-\sum_i E_T^i \vec{n}_i$, where $E_T^i$ are the magnitudes of transverse energy contained in each calorimeter tower $i$, and $\vec{n}_i$ is the unit vector from the interaction vertex to the tower in the transverse $(x,y)$ plane. $E_T$ is further corrected for reconstructed jets and muons.
Backgrounds from diboson production $WW, WZ, ZZ, Wγ$ and $Zγ$ that produce real same-sign leptons are found to be insignificant due to the requirement of a $b$-tag.

Backgrounds from $Z$+jets processes are estimated using ALPGEN [8] matched with PYTHIA for the showering. Kinematics of fake-lepton backgrounds are described using ALPGEN $W$+jet events for the hard process with showering and matching as with $Z$+jets. The $t\bar{t}$ backgrounds are estimated using events generated in PYTHIA at $m_t = 171$ GeV/c$^2$. As with the signal case, the efficiency of the selection after event reconstruction is described using a parametric detector simulation. Table II shows the number of expected background events in 2 fb$^{-1}$ of data.

**Sensitivity to $\xi$**

From the experimental data, one could measure directly the value of the MxFV coupling $\xi$, which is directly proportional to $\sigma(pp \rightarrow t\bar{t} + nj + X)$ at a specific $m_\eta^0$. The simplest method would be to transform the number of observed events over the expected background into a measurement of $\sigma(pp \rightarrow t\bar{t} + nj + X)$ and therefore of $\xi$. To improve sensitivity, we simultaneously fit for the number of signal and background events in the data by exploiting the difference between the number of expected jets in signal and background events, see Fig. 1; the fitted number of signal events can be transformed into a fitted value for $\xi$.

![Fig. 1: Top: distribution in reconstructed jets with $E_T > 15$ GeV for the signal process (each process is shown with unit area) with $m_\eta^0 = 200$ GeV/c$^2$ and after requiring same-sign leptons, 20 GeV of $E_T$ and at least one $b$-tagged jet. Bottom: expected number of reconstructed jets in 2 fb$^{-1}$ of data, for the signal processes with $\xi = 1$ and backgrounds.](image1)

**TABLE II: Expected number of background events for the $t\bar{t}l^+l^0bE_T$ signature in 2 fb$^{-1}$ of data including three categories of lepton flavors (ee, $\mu\mu, e\mu$), and the total background. Systematic uncertainties in the background are dominated by uncertainties in the normalization corrections.**

| Source | $N(l^\pm l^0 bE_T)$ |
|--------|---------------------|
| $Z\gamma, W\gamma, WW, WZ, WW$ | $< 0.2$ |
| $Z$+jets | $0.3 \pm 0.2$ |
| $W$+jets | $1.6 \pm 1.0$ |
| $t\bar{t}$ | $2.5 \pm 1.1$ |
| **Total** | $4.4 \pm 1.5$ |

Prior to any analysis of the Tevatron data, we can evaluate the expected sensitivity of the dataset, which indicates the strength of the measurement or exclusion that either Tevatron experiment could make. Following the Feldman-Cousins prescription [9], we use Monte Carlo experiments to construct bands which contain 95% of the fitted values of $\xi$ at various true values of $\xi$ for a specific mass of $\eta^0$, see Fig. 2. The confidence band in $\xi$ for an individual experiment is the vertical band at the fitted $\xi$. For example, a fit value of $\xi = 1$ would correspond to a

![Fig. 2: Horizontal bands in fitted (measured) $\xi$ which include 95% of the results of Monte Carlo experiments, for varying values of true $\xi$, with $m_\eta^0 = 200$ GeV/c$^2$, following the prescription in [9]. A 95% CL band in true $\xi$ for a given fit $\xi$ is a vertical band at the measured value (see text).](image2)
The expected sensitivity to $\xi$ is the mean vertical 95% CL band in $\xi$ from Monte Carlo experiments. We evaluate the expected sensitivity for both the background-only (using $\xi = 0$ for the Monte Carlo experiments) and the signal-plus-background hypothesis with $\xi = 1$, see Fig. 3.

In the case of the background-only hypothesis, the expected allowed region includes $\xi = 0$, so the result would be interpreted as an upper limit on $\xi$. In the case of the signal-plus-background hypothesis, $\xi = 0$ is expected to be excluded at greater than 95% CL, indicating strong sensitivity to the presence of $\eta^0 \rightarrow tu$ decays if they exist in the data.

To summarize, we have performed a detailed signal-to-background analysis of same-sign leptons signals at the Tevatron, originating from same-sign top quark pair production in models of MxFV. We have shown that the current Tevatron dataset has strong sensitivity to the same-sign lepton signature $l^\pm l^\pm bE_T$, for natural values of the MxFV coupling, i.e. $\xi \sim O(1)$, and a mass around 200 GeV of the scalar that mediates MxFV. In particular, after an event selection corresponding to an acceptance of 0.5% we expect 8-16 $l^\pm l^\pm bE_T$ events (from same-sign top quark pair production) for $m_{\eta^0} \approx 225 - 180$ GeV/c$^2$, respectively, over about 4-5 background events. As there are no current limits on this MxFV signals, we urge an analysis of the Tevatron data in this channel.

A similar analysis for the LHC is beyond the scope of this paper. We can, however, estimate the LHC sensitivity to the same-sign leptons $l^\pm l^\pm bE_T$ signal. In particular, for the LHC we find $\sigma(pp \rightarrow tt + nj + X) \sim O(100)$ pb for $\xi \sim 1$ and a several hundred GeV $\eta^0$. Thus, based on the present analysis, after an event selection with an acceptance around 0.5% and an early stage integrated luminosity of 10 fb$^{-1}$, we expect about 5,000 $l^\pm l^\pm bE_T$ signal events. The background at the LHC is expected to be dominated by the $tt$ production which has a cross-section about 1,000 times larger than at the Tevatron. Thus scaling the Tevatron $tt$ background by a factor of 1,000 (see Table II), we expect about 2,000 $l^\pm l^\pm bE_T$ background events. We hope to return to these questions in future work.

Finally, there are many other channels which are also worth analyzing, see [1]. For example, single top quark production in association with a wrong-sign b jet and a light jet, resonance production of $\eta^+$ (i.e., the charged component of $\Phi_{FV}$) and $tt$ production which occurs at a similar rate as the same-sign $tt$ production in these models, albeit with a larger background.

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