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Search for Maximal Flavor Violating Scalars in Same-sign Leptons

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In models of maximal flavor violation (MxFV) there is at least one new scalar Φ_{FV} which couples to the quarks via $\Phi_{FV} q_i q_j \propto \xi_{ij}$ where $\xi_{i3}, \xi_{3i} \sim V_{tb}$ for $i = 1, 2$ and $\xi_{33} \sim V_{td}$ 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 CDF. We show that the current 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 ξ has a natural value of ~ 1, we expect ~ 11 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 3 events.

We find 3 events in the data, consistent with background expectations and set limits on the coupling ξ. At $m_{\eta_0} = 200$, $\xi < 0.85$.

I. INTRODUCTION

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 $\xi_{3i}, \xi_{i3} (\sim V_{td}) \ll \xi_{33} (\sim V_{tb})$ for $i = 1, 2$.

A new class of scalar-mediated MxFV models [1] which (as suggested by their name) maximally depart from the MFV ansatz in the sense that $\xi_{31}, \xi_{32} \sim \mathcal{O}(1) \gg \xi_{33}$, and still satisfy all constraints from flavor physics even with a relatively light scalar with a mass of $\mathcal{O}(m_W)$.

In particular, let $\Phi_{FV} \equiv (\eta^+, \eta^0)$ be a new scalar doublet that mediates MxFV through [1]:

$$\mathcal{L}_{FV} \;=\; \xi_{ij} \bar{Q}_{iL} \tilde{\Phi}_{FV} u_{jR} + h.c. \;, \tag{1}$$

where ξ is a 3x3 matrix in flavor space. It was shown in [1] that there are no constraints if only one MxFV coupling is non-zero (e.g., the case $\xi_{31} \sim \mathcal{O}(1) \gg \xi_{13}, \xi_{32}, \xi_{23}$ is not ruled out regardless of m_{η^0} and m_{η^+}), and that the MxFV$_1$ models (defined as models with $\xi_{31}, \xi_{13} \gg \xi_{32}, \xi_{23}$) are not ruled out even with $\xi_{31}, \xi_{13} \sim \mathcal{O}(1)$, as long as $m_{\eta^+} \gtrsim 600$ GeV (regardless of m_{η^0}).

A list of possible collider signals of MxFV models was given in [1]. Here 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$_1$ models (defined above) under the assumptions that ξ_{ij} are real and that $\xi \equiv \xi_{31} = \xi_{13}$. As was shown in [1], in this case the only relevant (sizable) flavor changing couplings are:

$$\Gamma_{\eta^0 \bar{t} u} = \Gamma_{\eta^0 \bar{u} t} = -i\xi \;,\; \Gamma_{\eta^+ \bar{t} d} = \Gamma_{\eta^+ \bar{u} b} = \frac{i}{2} \xi \, (1 - \gamma_5) \,. \tag{2}$$

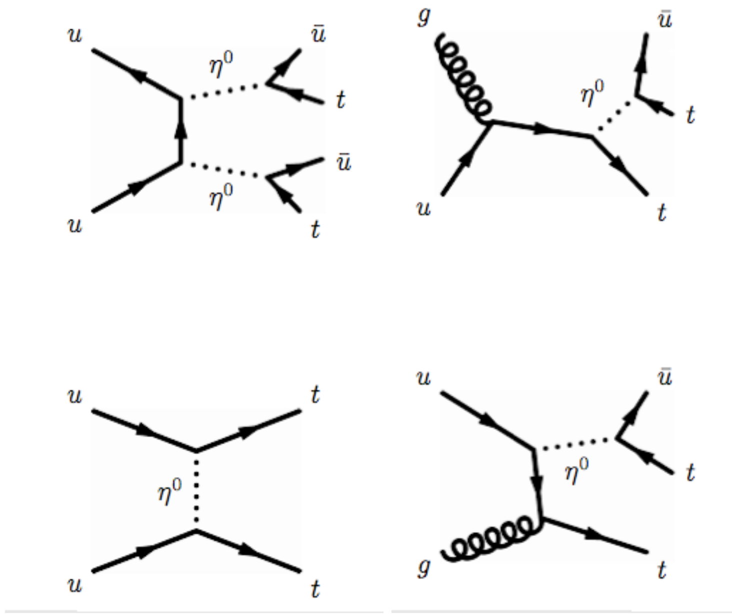
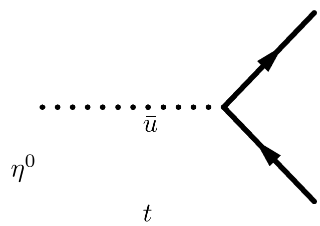


FIG. 1: Production diagrams for same-sign top quark pairs

II. PRODUCTION

A particularly interesting limit which we analyze is when the charged scalar η^+ is too heavy to be accessible at Tevatron and LHC energies, and decouples . 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 interaction vertex of interest is



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:

$$ug \to t\eta^0 \to tt\bar{u} + h.c. \ , \tag{3}$$

$$u\bar{u} \to \eta^0\eta^0 \to tt\bar{u}\bar{u} + h.c. \ , \tag{4}$$

$$uu \to tt + h.c. \ , \tag{5}$$

where the last process comes from t-channel η^0 exchange[1], see Figure 1.

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

$$p\bar{p} \to tt + nj + X \ , \tag{6}$$

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

where tt stands for both the tt and $\overline{tt}$ 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 $m_{\eta^0} > m_t$, $\hat{\sigma}(ug \to t\eta^0 \to tt\bar{u}) \propto \xi^2$ while $\hat{\sigma}(uu \to tt)$ and $\hat{\sigma}(u\bar{u} \to \eta^0\eta^0 \to tt\bar{u}\bar{u}) \propto \xi^4$. Thus, for $\xi < 1$, $\sigma(p\bar{p} \to tt + nj + X)$ is dominated by the $t\eta^0$ production channel.

When both top quarks decay leptonically ($t \to Wb \to l\nu b$), these processes have a striking low-background signature of two same-sign leptons, missing energy, and two b-jets ($\ell^\pm\ell^\pm \not{E}_T bb$) accompanied by n hard jets. Though CDF has examined its inclusive same-sign lepton dataset in small datasets[2], there has not been an experimenal study of the $\ell^\pm\ell^\pm \not{E}_T bb$ final state in which many of the same-sign contributions are supressed 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 data, estimate the contributions from background sources, and determine the sensitivity as a function of ξ and m_{η^0}.

III. EVENT SELECTION

To isolate the same-sign top quarks signal we define the $l^\pm l^\pm b \not{E}_T$ signature by requiring:

- Two same-sign reconstructed central leptons (electrons or muons), each with $p_T > 20$ GeV/c.
- At least one secondary-vertex tag (b-tag) [7].
- At least 20 GeV of missing transverse energy, $\not{E}_T$.[2]

IV. ACCEPTANCE

To calculate the number of tt and $\overline{tt}$ events we expect, we generate events for each of the three same-sign processes in (3)-(5) using Calchep[8] and shower them using PYTHIA [9]. Detector resolution and acceptance are modeled using the full simulation,CDFSIM. Table IV shows the number of expected events in 2 fb^{-1} of data.

CDF Run II Preliminary (2 fb^{-1})

	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	4.8	4.0	4.0	3.1	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	5.8	3.6	3.3	1.4	0.5	0.2
Total	$N(l^\pm l^\pm b \not{E}_T)$	14.9	11.9	11.0	7.1	5.0	2.7

TABLE I: Production cross-sections $\sigma(tt)$, $\sigma(tt\bar{u})$ and $\sigma(tt\bar{u}\bar{u})$ for each of the three same-sign top quark processes in (3)-(5), for $\xi = 1$ and various η^0 masses. Also given are the acceptance (ϵ) of the event selection described in the text and expected number (N) of $l^\pm l^\pm b \not{E}_T$ events in 2 fb^{-1} of data. The uncertainty on the cross-sections is estimated to be 10%, mainly due to the choice of the renormalization scale, the choice of PDF's and the numerical integration.

[2] Missing transverse energy, $\not{E}_T$, 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. $\not{E}_T$ is further corrected for reconstructed jets and muons.

V. BACKGROUNDS

Major backgrounds to the $l^{\pm}l^{\pm}b\not\!\!E_T$ signature come from:

- Z+jets $\rightarrow l^+l^-$+jets, in which the l^+ or l^- emits a hard photon which later converts asymmetrically in the detector, giving a same-sign lepton pair. Additionally, a lepton may come from semi-leptonic decays of a radiated b quark.
- W+jets, where one jet is misidentified as a lepton, typically an electron
- $t\bar{t}$ events where $t\bar{t} \rightarrow bl\nu bjj$ and a second lepton comes from semi-leptonic decays of one of the b quarks, or $t\bar{t} \rightarrow bl^+\nu bl^-\nu$ with a same-sign ll pair arising from photon radiation as above.

Backgrounds from diboson production $WW, WZ, ZZ, W\gamma$ and $Z\gamma$ are modeled with PYTHIA and BAUR generators. In the final selection, these are found to be insignificant due to the requirement of a b-tag.

The $t\bar{t}$ backgrounds are estimated using events generated in PYTHIA at $m_t = 172$ GeV/c^2. There is a 10% uncertainty on the prediction. Fake backgrounds are described using a fake lepton model from jet data [5]. Backgrounds from Z+jets processes are estimated using ALPGEN [10] matched with PYTHIA for the showering and normalized to data in opposite-sign events.

The final background estimate is 2.9 events, with an error of 1.8 events.

CDF Run II Preliminary (2 fb^{-1})

Source	ee	$\mu\mu$	$e\mu$	ll
$Z \rightarrow ll$	0.01	0.03	0.04	0.1 ± 0.1
tt	0.27	0.26	0.42	0.9 ± 0.1
$W + jets$	0.60	0.71	0.50	1.8 ± 1.8
Total	0.9	1.0	1.0	2.9 ± 1.8

VI. FITTING FOR ξ

From the experimental data, one could measure directly the value of the MxFV coupling ξ, which is directly proportional to $\sigma(p\bar{p} \rightarrow tt + nj + X)$ at a specific m_{η^0}. The simplest method would be to transform the number of observed events over the expected background into a measurement of $\sigma(p\bar{p} \rightarrow tt + nj + X)$ and therefore of ξ. 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. 2; the fitted number of signal events can be transformed into a fitted value for ξ.

We use a binned likelihood fit, which takes into account that the number of expected events from each signal process grows at different powers of xi due to the different number of vertices in the respective diagrams.

Prior to any analysis of the data, we can evaluate the expected sensitivity of the dataset, which indicates the strength of the measurement or exclusion that CDF could make. Following the Feldman-Cousins prescription [11], we use Monte Carlo experiments to construct bands which contain 95% of the fitted values of ξ at various true values of ξ for a specific mass of η^0, see Fig. 3. The confidence band in ξ for an individual experiment is the *vertical* band at the fitted ξ. For example, a fit value of $\xi = 1$ would correspond to a 95% CL band of $\xi \approx 0.7$ to $\xi \approx 1.2$.

The expected sensitivity to ξ is the mean vertical 95% CL band in ξ from Monte Carlo experiments. We evaluate the expected sensitivity for the background-only hypothesis (using $\xi = 0$ for the Monte Carlo experiments).

The expected allowed region includes $\xi = 0$, so the result would be interpreted as an upper limit on ξ.

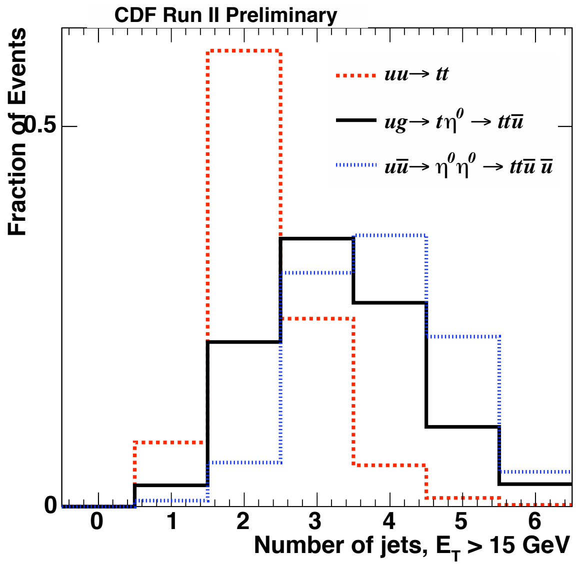

FIG. 2: Distribution in reconstructed jets with $E_T > 15$ GeV for the signal process (each process is shown with unit area) with $m_{\eta^0} = 200$ GeV/c^2 and after requiring same-sign leptons, 20 GeV of $\not\!\!E_T$ and at least one b-tagged jet.

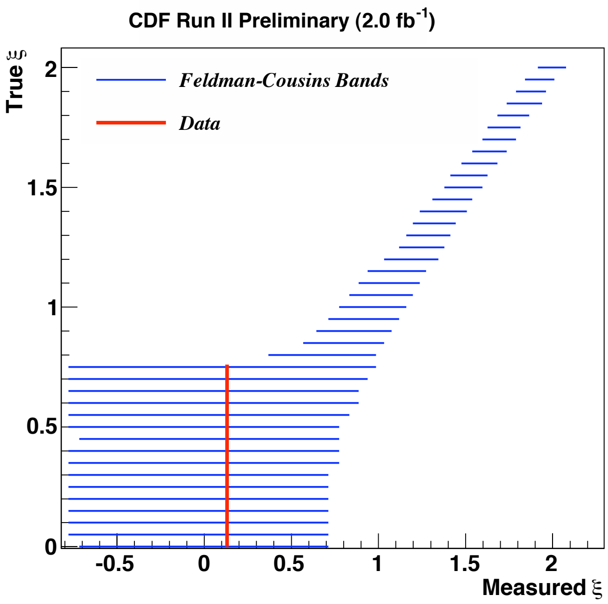

FIG. 3: Horizontal bands in fitted (measured) ξ which include 95% of the results of Monte Carlo experiments, for varying values of true ξ, with $m_{\eta^0} = 180$ GeV/c^2, following the prescription in [11]. A 95% CL band in true ξ for a given fit ξ is a vertical band at the measured value, shown in red for the data.

CDF Run II Preliminary (2 fb^{-1})						
Mass	180	190	200	225	250	300
$\xi <$ (95% CL)	0.79	0.85	0.85	1.11	1.12	1.32

TABLE II: Fit values and upper limits as a function of the mass of η_0.

VII. RESULT

In 2.0/fb of data, we expect a background of 2.9 ± 1.8 events, and a signal of 2.7-14.9 events depending on the mass of the neutral scalar.

We observe 3 events, in nearly perfect agreement with the backgrounds. The distribution of jets can be seen in Figure 5

CDF Run II Preliminary (2 fb^{-1})				
Source	ee	$\mu\mu$	$e\mu$	ll
$Z \to ll$	0.01	0.03	0.04	0.1 ± 0.1
tt	0.27	0.26	0.42	0.9 ± 0.1
$W + jets$	0.60	0.71	0.50	1.8 ± 1.8
Total	0.9	1.0	1.0	2.9 ± 1.8
Data	0	1	2	3

The fitted values of ξ are given in Table II, as well as the 95% CL upper limits which are shown in Figure 4

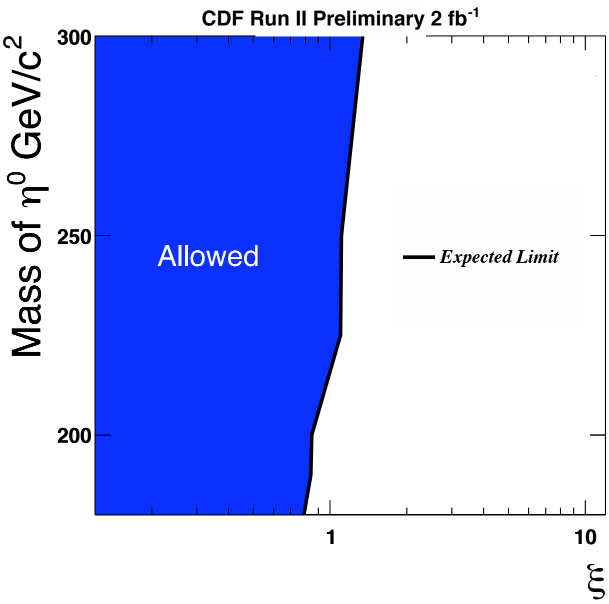

FIG. 4: Observed 95% CL allowed regions in the $\xi - m_{\eta^0}$ plane for 2 fb^{-1} data.

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[5] CDF 8741, CDF 9247

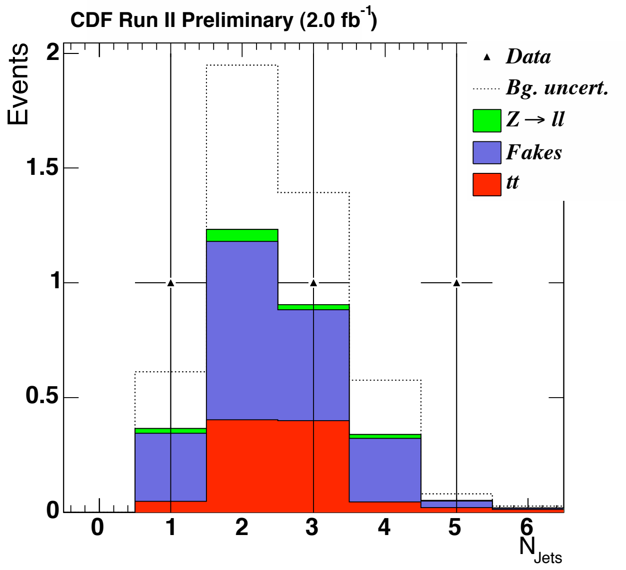

FIG. 5: Expected and observed number of jets.

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