FCNC production of same sign Top quark pairs at the LHC.

F. Larios and F. Peñuñuri

Departamento de Física Aplicada, CINVESTAV-Mérida,
AP 73 Cordemex, 97310 Mérida, Yucatán, México

We study the possibility of same sign top quark pair production at the LHC (and the VLHC) as a direct probe of FCNC processes. Besides the SM neutral Z boson, two other neutral bosons are considered, a top-Higgs type scalar and a Z' boson that appear in Topcolor assisted Technicolor models. We find that the FCNC couplings $tqV$ ($q=u,c;V=H,Z,Z'$) may produce an interesting signal of same sign top quark pairs that could be observed at the LHC (VLHC).

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I. INTRODUCTION

With an integrated luminosity of about 100 fb$^{-1}$ the CERN LHC is expected to produce several tens of millions of $tt$ pairs for each of the detectors, ATLAS and CMS per year[1]. Such a high rate of production will allow the LHC to look for new physics effects involving the top quark. In particular, Flavor Changing Neutral Current (FCNC) effects are a well known way to look for physics beyond the Standard Model (SM). The standard way to measure FCNC couplings is by searching for rare top quark decays like $t \rightarrow q\gamma, qZ$ ($q=u,c$)[2]. Also, the FCNC couplings $Vtq$, with $V=\gamma, Z, H$ and gluon can be probed via the associated $tZ, t\gamma$ and $tH$ production at the LHC[3,4], or at lepton colliders[5].

The appearance of FCNC in the quark sector occurs at the one loop level in the SM and is very suppressed by the GIM mechanism. However, some extensions of the SM can generate these couplings at tree level, like Topcolor assisted Technicolor[6,7]. At the LHC one can think of a process in which two incoming up type quarks exchange a neutral boson and then change to a pair of (same sign) top quark pairs, see Fig. (1). As expected from the fact that the anomalous coupling appears twice in the Feynman diagram, the rates predicted can become negligible for not very small coupling values. In this sense, the usual production process that involves only one anomalous coupling is usually a better probe. However, we believe that the production of same sign top quark pairs is an interesting way to confirm the existence of a FCNC with the top quark, and it should be considered in future runnings of the LHC. Apart from the standard backgrounds associated with a top quark pair there is no other SM process that can hide this signal. The SM process $pp \rightarrow b\bar{b}W^+W^-$ is negligible. Unfortunately, the only way to separate the $tt$ from the $t\bar{t}$ signal is by identification of same charges in the dilepton mode -a mode with very low efficiency. However, the size of the FCNC couplings could be large and as we shall see, the LHC could find many pairs of tops even during the first few years of running. Another interesting feature of this signal is that higher center-of-mass energies of the colliding beams would boost the production rates, which makes this process a very good possibility at a future VLHC.

Below, we will discuss separately this process via three intermediary bosons for the FCNC: the SM $Z$ boson, a $Z'$ boson and a scalar boson that couples strongly with the top quark. Then we will make a comment on the detection mode required to separate the $tt$ signal from the $t\bar{t}$ signal.

II. FCNC FOR THE TOP QUARK.

We will consider the two possibilities for the Flavor transition of the top quark with the two lighter up and charm quarks. We parameterize the FCNC couplings of the top quark with the following Lagrangian:

$$L = \bar{t} (y_{tq}^R P_R + y_{tq}^L P_L) q H + \bar{t} \gamma_{\mu} (a_{tq}^L P_L + a_{tq}^R P_R) q Z^\mu + g_3 \bar{t} \gamma_{\mu} (B_{tq}^L P_L + B_{tq}^R P_R) q Z'^\mu$$

(1)

where, $q = u, c$. Similar parameterizations have appeared in the literature; for instance, the couplings $a_{tq}^{L,R}$ are defined as $a_{tq}^{L,R} = \frac{g}{2c_{W}} X_{tq}^{L,R}$ in Ref. [8,9], and $y_{tq}^{L,R} = \frac{g_{tq}}{2} a_{tq}^{L,R}$ with $c_{a,v}=1/\sqrt{2}$ in Ref. [10]. In general, there can be dimension 5 (and higher) operators that generate transition magnetic dipole couplings $tq\gamma$, $tqZ$ and $tq$-gluon[11,12]. In this work we are only considering dimension 4 interactions.
A. FCNC with the Z boson.

There are three top quark FCNC couplings that involve existing gauge bosons $\gamma$, $Z$ and the gluon and that are currently considered at the Tevatron Run II\cite{10}. Here, we want to take the case of the Z boson. Similar results will hold for the other two bosons, as we shall see later. At LEP all the FCNC couplings of the Z boson with the fermions have been strongly constrained for all the charged leptons and the light quarks. However, the top quark cannot be a decay product of $Z$, and the only direct constraint of a $Z\ell\ell$ ($\ell = u, c$) coupling comes from the Tevatron\cite{11}:

\[ \sqrt{|X_R^{tu}|^2 + |X_L^{tu}|^2} \leq 0.8, \tag{2} \]

which translates to $|a_{tu}| \leq 0.3$ for the couplings defined here. The weakness of this bound is also evident from the associated upper bound on the branching ratio $Br(t \rightarrow cZ) \leq 33\%$\cite{11}. However, Run II of the Tevatron is expected to reach a level of 1.5\%, which would be translated in a much stronger bound on $X_R^{tu} \leq 0.04$\cite{11}. Actually, it has been shown that this coupling can be tested down to values of order $10^{-2}$ at the LHC via the associated production of a top and a $Z$ or $\gamma$\cite{12}. On the other hand, even the present weak bound can be made stronger by considering more specific models. In Ref.\cite{12} an extension of the SM with extra quark singlets or doublets was considered; it was found that present stringent constraints on the diagonal couplings imply an $X_{tu} \leq 0.2 (a_{tu} \leq 0.07)$ bound that is one fourth the size of the direct limit.

We show in Fig. 2 the production cross section for $pp \rightarrow tt$ for values of the $a_{tu}^{R/L}$ couplings below 0.15 ($X_{tu} \leq 0.4$). With an expected 100 fb$^{-1}$ of luminosity there could be a few hundreds pairs of same sign tops coming from this coupling. Notice that the scale of the plot Fig. 2 is logarithmic to accommodate the $a_{tu}^{R/L}$ dependence of the cross section. Because of the larger parton luminosity from the $u$ quark the process $uu \rightarrow tt$ is more sensitive to the size of the FCNC couplings. However, it is usually assumed that the top-charm transition coupling should be the larger one (as it turns out with the hierarchy of the CKM matrix elements). We could have run the values of $a_{tu}^{R/L}$ up to 0.3 but we have only considered values up to 0.14 to prove that indeed the production rate could be large enough. In fact, in Ref.\cite{8} the authors have used $a_{tu}^{R/L}$ of the order 0.4 and have obtained a huge rate of a couple tens of pb for the LHC.

To bear in mind, for the $cc \rightarrow tt$ process there is also the equivalent $c\bar{c} \rightarrow t\bar{t}$ like sign anti-top production process, because the parton luminosity of $c$ and $\bar{c}$ coincide. According to Fig. 2 if the bounds of Ref.\cite{12} apply for this case the production from charm quarks could be not higher than of order 1 fb. As we shall discuss later a rate of only a few fb’s may be too small to ever be identified at the LHC. We should consider rates of order 10 fb and higher the ones to look for to make the search of this signal feasible. In this sense, the production of same sign top quark pairs is not the best way to probe these FCNC couplings, in fact the associated production of a single top with a neutral boson like $Z$ or $\gamma$ is considerably more sensitive. However, $tt$ production is an interesting signal that clearly indicates the presence of significant FCNC.

To be consistent with the usual experimental limitations, in this work we have imposed the following cuts on the rapidity, transverse momentum and invariant mass of the top quarks:

| $y_t$ | $\leq 2$  
| $Pt_t$ | $\geq 40$ GeV  
| $M_{tt}$ | $\geq 380$ GeV  

These cuts reduce the total rate in about 40\%.

We have taken the factorization scale equal to the invariant mass of the $tt$ pair $\mu = M_{tt}$. The top quark mass we have used is $m_t = 175$ GeV. The Parton Distribution Function (PDF) used was the recent CTEQ6M\cite{13}. Our calculations are at tree level, obtained with the aid of the CompHEP program\cite{14}.

Please notice that for the process $uc \rightarrow tt$ it is understood that the other possibility $cu \rightarrow tt$ is already included in the figures shown.

B. FCNC with the $Z'$ boson

Now we want to consider a heavy $Z'$ boson, such as the one that appears in Topcolor assisted technicolor (TC2) models\cite{15}. In these models the heavy $Z'$ couples strongly with the third family of quarks and may induce FCNC. The coupling strength is given by $g_2 = e/c_W s_W c_\phi$ where $c_W$ is the cosine of the SM $SU(2)_L \times U(1)_Y$ mixing angle and $\phi$ is the mixing angle for the $Z_1$ and $Z_2$ neutral bosons of the TC2 model. As shown in Ref.\cite{15} electroweak data requires the mass of $Z'$ to be higher than 1-4 TeV for values of $\sin^2 \phi$ between 0.05 and 0.5 (this
range of values implies the diagonal coupling strength $g_2$ to be of order between 0.7 and 1.2). We show in Fig. 3 the production cross section of $pp \to tt$ for different values of $M_{Z'}$. We have chosen high values of the coupling $B_{tc}$ (between 0.5 and 0.7) but we have also assumed only the right handed current term $B_{tc}^R$ as different from zero. Given the assumption that the cross section must be at least of order 10 fb to become detectable we can see that $B_{tc}^R$ must be higher than 0.5 to yield this production rate. Again, other processes where the anomalous coupling appears only once in the Feynman diagram are more sensitive. For instance, from Ref. [16] a loop level induced rare top decay $t \to cV$ ($V = \gamma, Z$ or gluon) would require a smaller coupling size $B_{tc} = g_1 K_{tc} \sim 0.2$ to become of order $10^{-5}$ (for gluon) or $10^{-6}$ (for $\gamma$) for its branching ratio, which is already at detectable levels at the LHC. However, the rare top quark decay would be an indirect way to test the existence of $Z'$. Finding a $Z'$, or any heavy resonance, that couples preferentially to the third family is possible via $\tau$ lepton pair production [17], but it may not be possible at all at any future hadron collider (including the LHC) searching in the $tt$ mode [18]. This is because of the overwhelming QCD production of $tt$, which in contrast makes no background for a $tt$ signal. Therefore, either the single top production mode or the same sign $tt$ pair mode could be the way to test this kind of physics at the LHC.

C. Scalar FCNC

Next we want to consider a FCNC scalar coupling of the type $H_{tc}$. This coupling was also studied in Ref. [4, 15]. It is not expected that the $y_{tc}^L$ coupling could be very large, maybe of order $\lambda^2 m_t / f_{\pi}$ with $\lambda = 0.22$ in relation to the CKM mixing parameter (the Cabibbo angle). Also, $y_{tc}^R$ would be less than $\lambda^2 m_t / f_{\pi}$. However, there is no reason to believe the right handed $y_{tc}^R$ coupling couldn’t be much larger. In fact, the dynamical Top-color (TopC) model generally predicts $0.2 \leq y_{tc}^L \leq 0.7$ [20, 21]. For this size of the FCNC coupling the production of top pairs can be significant, see Fig. 4.

If the scalar Higgs mass is not very high, between 100 and 200 GeV, a coupling somewhat higher than $y_{tc}^L = 0.3$ could give enough rate to be observed at the LHC.

1. Scalar FCNC production at a VLHC

At this point it is interesting to compare with what would be expected at a VLHC machine with a center of mass (CM) energy of $\sqrt{s} = 100$ TeV for this same scalar coupling. In Figure 5 we show the much higher rates for even smaller values of the coupling size and for a heavier scalar boson.

D. Dependence on PDF set and factorization scale.

Throughout this work we have used CTEQ6M. We have checked the uncertainty due to the PDF by computing the production of $tt$ pairs with all the 41 sets of ctq61 PDFs provided by the CTEQ group. The variation amounts to only about 10%, we show our results in Figure 6. We have only shown the computations that are farther apart from each other, i.e. the results of any other PDF set will fall between the curves shown. Figure 6 applies to the $uu \to tt$ process; a similar graph would apply to the $cc \to tt$ process, except that the highest (lowest) curve would come from ctq61.09 (ctq61.10) instead of the ctq61.18 (ctq61.17) PDF set.

To compare different values of the factorization scale we have tried some fixed scale values, it turns out that the fixed value of 380 GeV yields almost the same cross section as the running $\mu = M_{tt}$ value. Also, there is some mild dependence on the (fixed) factorization scale,
we have found about less than 20% variation going from \( \mu = 190 \text{GeV} \) to \( \mu = 760 \text{GeV} \).

III. IDENTIFICATION OF TT PAIRS AT LHC

Compared with the number of \( t\bar{t} \) pairs that are expected every year at the LHC, of the order of 10 million, our \( tt \) signal is overwhelmed by many orders of magnitude. There are 3 modes of detecting a pair of top quarks depending on the decay products of the \( W \) bosons: dilepton, lepton plus jets and all jets mode. Separating these signals can only happen via the dilepton mode, in which the two same sign tops produce two same sign leptons. Unfortunately, this mode is associated with a small branching ratio, approximately 5%. Considering a 50% b-tagging efficiency, this mode will let us observe only a small 2% (or less) fraction of all the top quark pairs produced \[11, 22\]. Our assumption here is that it will be possible to identify the sign of top quark pairs via the dilepton mode with an overall efficiency of order 1% at the LHC. Then, we can expect to observe from a few to up to several tens of same sign top events every year for the parameters used in this paper.

A. SM background for \( tt \) production.

The SM background we have considered here is production of \( pp \to bbW^+W^+ \). In the SM there are 45 diagrams for the \( uu \to bbW^+W^+ \) process (49 for \( cc \to bbW^+W^+ \)), of which two give the most important contributions, see Figure 7. By taking only one diagram at a time we have found that the greatest contribution is less than of order \( 6 \times 10^{-6} \text{ fb} \). So, we can safely conclude that the total contribution must be well below the \( 10^{-4} \text{ fb} \) level. This is a negligible background.

IV. CONCLUSION

In this work we have shown that FCNC couplings of the top quark with either the SM gauge bosons or new bosons like the ones that appear in Top color assisted technicolor theories, could give rise to significant production of same sign top quark pairs at the LHC. Such a signal could be searched for in the dilepton mode. We have found that for FCNC top quark couplings, well within the present experimental constraints, we could have production cross sections of order several tens or a few hundred femtobarns at the LHC. In terms of sensitivity, the cross section is proportional to the fourth power of the FCNC coupling. In particular, a coupling size of order 0.05 (0.1) for \( tuZ \) (\( tcZ \)) would give rise to a few \( tt \) pairs detected in the dilepton mode at the LHC. In addition, in the case of a heavy resonance like \( Z' \) or a scalar \( H \), a coupling size of 0.15 (0.5) for \( tuZ' \) (\( tcZ' \)) along with a \( Z' \) mass between 1 and 1.6 TeV would be required for the same yield. A coupling size higher than 0.1 (0.3) for \( tuH \) (\( tcH \)) along with a 100-300 GeV mass range in the case of the scalar FCNC; in comparison, for even slightly smaller couplings
FIG. 8: Tevatron and LHC production via $uu \rightarrow tt$ from dimension 5 $tuZ$, $tu\gamma$ couplings. The factorization scale used is $\mu = M_t$, the invariant mass of $tt$. The couplings $\kappa^t$ and $\kappa^\mu$ are defined in Ref. [23]. No cuts on the $tt$ signal are applied in this case. The production rate from the dimension 4 couplings used by us is shown for comparison.

Upon the completion of this article, another work on

the production of top quarks via the FCNC anomalous dimension 5 $tq\gamma$ and $tqZ$ couplings has appeared. They have computed the cross section for $p\bar{p} \rightarrow tt$ at the Tevatron with NLO-NLL and NNLO-NLL corrections. They obtain a cross section of order a few femtobarns at the Born level with a 25% increase due to the higher order corrections.[23]. To compare with their analysis we show in Figure S the production of $tt$ at both the Tevatron and the LHC from either, the combination of dimension 5 $tu\gamma$ and $tuZ$ couplings used by them ($\kappa^t = \kappa^\mu$) or the dimension 4 $tuZ$ used by us ($\alpha_{tu}$).

Instead of the fixed value for the factorization scale $\mu = m_t = 175$ GeV, we have used $\mu = M_t$. That is why we have a somewhat lower (about 20% less) value for the Born level cross section. Otherwise, if we use $\mu = m_t$ we obtain the same rates. To be consistent with their calculations, we have applied no cuts in this figure. The dimension 5 operator requires a mass scale factor $1/\Lambda$ for which they have used a rather small value $\Lambda = m_t$. If we use the same scale $\Lambda = m_t$ for the LHC we would obtain a huge rate of order $10^4$ fb, and we could as well be violating unitarity constraints. For these operators, we think a higher mass scale $\Lambda = 1$ TeV is more realistic; we have used it for the LHC production in Figure S. Notice that the dimension 4 $tuZ$ coupling could yield even higher production rates than the dim 5 coupling. However, due to the much smaller range of luminosity of the Tevatron, as compared with the LHC, these rates may be too low to be detectable.

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