PROBING THE COUPLINGS OF THE TOP QUARK TO GAUGE BOSONS

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Abstract

We parameterize the non-universal couplings of $t-t-Z$ and $t-b-W$ in the electroweak chiral lagrangian approach, and examine the constraints on these parameters from the LEP data. We also study how the SLC, Tevatron, LHC and NLC can improve the measurement of these couplings. Different symmetry breaking scenarios imply different correlations among these couplings, whose measurement will then provide a means to probe the electroweak symmetry breaking sector.
1 Introduction

Studies on radiative corrections concluded that the mass ($m_t$) of a Standard Model (SM) top quark has to be less than 200 GeV \[1\]. From the direct search at the Tevatron, assuming a SM top quark, $m_t$ has to be larger than 131 GeV \[2\]. Recently, data were presented by the CDF group at the FNAL to support the existence of a heavy top quark with mass $m_t \sim 174 \pm 20$ GeV \[3\]. However, there are no compelling reasons to believe that the top quark couplings to other particles should be of the SM nature. Because the top quark is heavy relative to other observed fundamental particles, one expects that any underlying theory at high energy scale $\Lambda \gg m_t$ will easily reveal itself at low energy through the effective interactions of the top quark to other particles. Also, because the top quark mass is of the order of the Fermi scale $v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV, which characterizes the electroweak symmetry breaking scale, the top quark would be useful in probing the symmetry breaking sector.

In this paper we constrain the effective couplings of the top quark to gauge bosons using LEP data and discuss how the measurement of these couplings can be improved by direct detection of the top quark in either $e^-e^+$ ($e^-\gamma$) or hadron collisions. In section 2 we examine what we have learned about the top quark couplings from low energy data at LEP. In section 3 we study how to probe the couplings $\kappa_L^{CC}$ and $\kappa_R^{CC}$ at the Tevatron and the LHC from direct detection of the top quark. In section 4 we discuss how the NLC can contribute to the measurement of these couplings. Finally, in section 5 we discuss how to probe the symmetry breaking sector by examining the correlations among the couplings of the top quark to gauge bosons. Some conclusions are also given in that section.

2 Probing the Top Quark Couplings at LEP

Since the top quark contributes to low energy data through radiative corrections, one can indirectly probe the couplings of the top quark to gauge bosons at LEP. Taking the chiral lagrangian approach \[4-13\], we systematically parameterize the in-
interactions of the top quark to gauge bosons at low energy using an effective lagrangian with the non-linear realization of the symmetry $SU(2)_L \times U(1)_Y / U(1)_{em}$ \cite{14}. In the unitary gauge, it is

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{g}{4\cos\theta_W} \bar{t} \left( \kappa^{NC}_L \gamma^\mu(1 - \gamma_5) + \kappa^{NC}_R \gamma^\mu(1 + \gamma_5) \right) t Z_\mu$$

$$+ \frac{g}{2\sqrt{2}} \bar{t} \left( \kappa^{CC}_L \gamma^\mu(1 - \gamma_5) + \kappa^{CC}_R \gamma^\mu(1 + \gamma_5) \right) b W_\mu^+$$

$$+ \frac{g}{2\sqrt{2}} \bar{b} \left( \kappa^{CC}_L \gamma^\mu(1 - \gamma_5) + \kappa^{CC}_R \gamma^\mu(1 + \gamma_5) \right) t W_\mu^- , \quad (1)$$

where $\mathcal{L}_{SM}$ is the SM lagrangian, $\kappa^{NC}_L$ and $\kappa^{NC}_R$ are two arbitrary real parameters, $\kappa^{CC}_L$ and $\kappa^{CC}_R$ are two arbitrary complex parameters and the superscript $NC$ and $CC$ denote neutral and charged current respectively. In this work, we assume the vertex $b-b-Z$ is standard. The case where the vertex $b-b-Z$ has a non-standard effect comparable with the non-standard effect in the vertices $t-t-Z$ and $t-b-W$, as expected in some Extended Technicolor models \cite{15}, will not be discussed here, but in a more detailed study in Ref. \cite{14}.

The chiral lagrangian $\mathcal{L}$, as defined in Eq. (1), has six independent parameters ($\kappa$'s) to be constrained by low energy precision data. We will only consider the insertion of $\kappa$'s once in one-loop diagrams by assuming that these non-standard couplings are small, i.e., $\kappa^{NC,CC}_{L,R} < \mathcal{O}(1)$. At one loop level the imaginary parts of the couplings do not contribute in those LEP observables of interest. Thus, hereafter we drop the imaginary part of these couplings, which reduces the number of relevant parameters to four. To the order $\mathcal{O}(m_t^2 \log \Lambda^2)$, $\kappa^{CC}_R$ does not contribute to low energy data when ignoring the bottom quark mass, hence only the three parameters $\kappa^{NC}_L$, $\kappa^{NC}_R$ and $\kappa^{CC}_L$ can be constrained by LEP data.

A systematic approach can be implemented for such an analysis based on the scheme used in Refs. [16-18], where the radiative corrections can be parameterized by 4 independent parameters, three of those parameters ($\epsilon_1$, $\epsilon_2$, and $\epsilon_3$) are proportional to the variables $S$, $U$ and $T$ \cite{19}, and the fourth one ($\epsilon_b$) is due to the GIM violating contribution in $Z \rightarrow b\bar{b}$ \cite{16}. These parameters are derived from four basic measured observables, $\Gamma_\ell$ (the partial width of $Z$ to a charged lepton pair), $A_{FB}^\ell$ (the forward-
backward asymmetry at the $Z$ peak for the charged lepton $\ell$, $M_W/M_Z$ and $\Gamma_b$ (the partial width of $Z$ to a $b\bar{b}$ pair).

Non-renormalizability of the effective lagrangian presents a major issue of how to find a scheme to handle both the divergent and the finite pieces in loop calculations [20, 21]. Such a problem arises because one does not know the underlying theory, hence no matching can be performed to extract the correct scheme to be used in the effective lagrangian [22]. One approach is to associate the divergent piece in loop calculations with a physical cut-off $\Lambda$, the upper scale at which the effective lagrangian is valid [9]. In the chiral lagrangian approach this cut-off $\Lambda$ is taken to be $4\pi v \sim 3$ TeV [22]. For the finite piece no completely satisfactory approach is available [20].

Performing the calculations in the unitary gauge, we calculate the contribution to $\epsilon_1$ and $\epsilon_b$ due to the new interaction terms in the chiral lagrangian (see Eq. (1)) using the dimensional regularization scheme and taking the bottom quark mass to be zero. At the end of the calculation, we replace the divergent piece $1/\epsilon$ by $\log(\Lambda^2/m_t^2)$ for $\epsilon = (4 - n)/2$, where $n$ is the space-time dimension. Since we are mainly interested in new physics associated with the top quark couplings to gauge bosons, we shall restrict ourselves to the leading contribution enhanced by the top quark mass, i.e., of the order of $m_t^2 \log \Lambda^2$.

We find

$$\epsilon_1 = \frac{G_F}{2\sqrt{2}\pi^2} 3m_t^2 \left( -\kappa_L^{NC} + \kappa_R^{NC} + \kappa_L^{CC} \right) \log \frac{\Lambda^2}{m_t^2},$$  \hspace{1cm} (2)

$$\epsilon_b = \frac{G_F}{2\sqrt{2}\pi^2} m_t^2 \left( -\frac{1}{4}\kappa_R^{NC} + \kappa_L^{NC} \right) \log \frac{\Lambda^2}{m_t^2}.$$  \hspace{1cm} (3)

Note that $\epsilon_2$ and $\epsilon_3$ do not contribute at this order.

To constrain these non-standard couplings we need to have both the experimental values and the SM predictions of these $\epsilon$'s, which were obtained from Ref. [10].

Choosing $m_t = 150$ GeV, $m_H = 100$ GeV, and including both the SM and the new physics contributions, we span the parameter space defined by $-1 \leq \kappa_L^{NC} \leq 1$, $-1 \leq \kappa_R^{NC} \leq 1$ and $-1 \leq \kappa_L^{CC} \leq 1$. Within 95% confidence level (C.L.), the allowed region of these three parameters was found to form a thin slice in the specified volume.
The two-dimensional projections of this slice are shown in Figs. (1)-(3). These non-standard couplings ($\kappa$’s) do exhibit some interesting features:

1) As a function of the top quark mass, the allowed volume for the top quark couplings to gauge bosons shrinks as the top quark becomes more massive.

2) New physics prefers positive $\kappa_{LNC}$, see Figs. (1) and (2). $\kappa_{LNC}$ is constrained to be within $-0.3$ to $0.6$ ($-0.2$ to $0.5$) for a 150 (175) GeV top quark.

3) New physics prefers $\kappa_{LCC} \approx -\kappa_{RNC}$. This is clearly shown in Fig. (3) which is the projection of the allowed volume in the $\kappa_{LCC}$ and $\kappa_{RNC}$ plane.

In Ref. [23], a similar analysis has been carried out by Peccei et al. However, in their analysis they did not include the charged current contribution and assumed only the vertex $t-t-Z$ gives large non-standard effects. The allowed region they found simply corresponds, in our analysis, to the region defined by the intersection of the allowed volume and the plane $\kappa_{LCC} = 0$. This gives a small area confined in the vicinity of the line $\kappa_{LNC} = \kappa_{RNC}$. (This is obtained by setting $\kappa_{LCC} = 0$ in Eq. (2).) In this case we note that the length of the allowed area is merely determined by $\epsilon_b$.

To conclude, assuming $b-b-Z$ vertex is not modified, we found that $\kappa_{LNC}$ is already constrained at the 95% C.L. to be $-0.3 < \kappa_{LNC} < 0.6$ ($-0.2 < \kappa_{LNC} < 0.5$) by LEP data for a 150 (175) GeV top quark. Although $\kappa_{RNC}$ and $\kappa_{LCC}$ are allowed to be in the full range of $\pm 1.0$, the precision LEP data do impose some correlations among $\kappa_{LNC}$, $\kappa_{RNC}$ and $\kappa_{LCC}$. Note that $\kappa_{RCC}$ does not contribute to the LEP observables of interest in the limit of $m_b = 0$.

At the SLC, with expected better measurement of the left-right cross section asymmetry $A_{LR}$ in $Z$ production with a longitudinally polarized electron beam, one can further constrain these $\kappa$’s [14].

3 At the Tevatron and the LHC

In this section, we study how to constrain the non-standard couplings of the top quark to gauge bosons from direct detection of the top quark at hadron colliders.
At the Tevatron and the LHC, heavy top quarks are predominantly produced from the QCD process $gg, q\bar{q} \rightarrow t\bar{t}$ and the $W$-gluon fusion process $qg(Wg) \rightarrow t\bar{b}, \bar{t}b$. In the former process, one can probe $\kappa^{L\text{CC}}$ and $\kappa^{R\text{CC}}$ from the decay of the top quark to a bottom quark and a $W$ boson. In the latter process, these non-standard couplings can be measured by simply counting the production rates of signal events with a single $t$ or $\bar{t}$. More details can be found in Ref. \cite{24}.

To probe $\kappa^{L\text{CC}}$ and $\kappa^{R\text{CC}}$ from the decay of the top quark to a bottom quark and a $W$ boson, one needs to measure the polarization of the $W$ boson. For a massless $b$, the $W$ boson from top quark decay can only be either longitudinally or left-handed polarized for a left-handed charged current ($\kappa^{R\text{CC}} = 0$). For a right-handed charged current ($\kappa^{L\text{CC}} = -1$) the $W$ boson can only be either longitudinally or right-handed polarized. (Note that the handedness of the $W$ boson is reversed for a massless $\bar{b}$ from $\bar{t}$ decays.) In all cases the fraction of longitudinal $W$ from top quark decay is enhanced by $m_t^2/2M_W^2$ as compared to the fraction of transversely polarized $W$. Therefore, for a more massive top quark, it is more difficult to untangle the $\kappa^{L\text{CC}}$ and $\kappa^{R\text{CC}}$ contributions. The $W$ polarization measurement can be done by measuring the invariant mass ($m_{b\ell}$) of the bottom quark and the charged lepton from the decay of top quark \cite{25}. We note that this method does not require knowing the longitudinal momentum (with two-fold ambiguity) of the neutrino from $W$ decay to reconstruct the rest frame of the $W$ boson in the rest frame of the top quark.

Consider the (upgraded) Tevatron as a $p\bar{p}$ collider at $\sqrt{S} = 2$ or 3.5 TeV, with an integrated luminosity of 1 or 10 fb$^{-1}$. Unless specified otherwise, we will give event numbers for a 175 GeV top quark and an integrated luminosity of 1 fb$^{-1}$.

The cross section of the QCD process $gg, q\bar{q} \rightarrow t\bar{t}$ is about 7 (29) pb at a $\sqrt{S} = 2$ (3.5) TeV collider. In order to measure $\kappa^{L\text{CC}}$ and $\kappa^{R\text{CC}}$ we have to study the decay kinematics of the reconstructed $t$ and/or $\bar{t}$. For simplicity, let’s consider the $\ell^\pm + \geq 3$ jet decay mode, whose branching ratio is $Br = 2\frac{6}{27} = \frac{8}{27}$, for $\ell^+ = e^+$ or $\mu^+$. We assume an experimental detection efficiency, which includes both the kinematic acceptance and the efficiency of $b$-tagging, of 15% for the $t\bar{t}$ event. We further assume
that there is no ambiguity in picking up the right $b$ ($\bar{b}$) to combine with the charged lepton $\ell^+$ ($\ell^-$) to reconstruct $t$ ($\bar{t}$). In total, there are $7 \text{ pb} \times 10^3 \text{ pb}^{-1} \times \frac{8}{27} \times 0.15 = 300$ reconstructed $t\bar{t}$ events to be used in measuring $\kappa_L^{CC}$ and $\kappa_R^{CC}$ at $\sqrt{S} = 2$ TeV. The same calculation at $\sqrt{S} = 3.5$ TeV yields 1300 reconstructed $t\bar{t}$ events. Given the number of reconstructed top quark events, one can in principle fit the $m_{\ell\ell}$ distribution to measure $\kappa_L^{CC}$ and $\kappa_R^{CC}$. We note that the polarization of the $W$ boson can also be studied from the distribution of $\cos \theta^*_\ell$, where $\theta^*_\ell$ is the polar angle of $\ell$ in the rest frame of the $W$ boson whose $z$-axis is the $W$ bosons moving direction in the rest frame of the top quark \[25\]. For a massless $b$, $\cos \theta^*_\ell$ is related to $m_{\ell\ell}^2$ by

$$\cos \theta^*_\ell \simeq \frac{2m_{\ell\ell}^2}{m_t^2 - M_W^2} - 1. \tag{4}$$

However, in reality, the momenta of the bottom quark and the charged lepton will be smeared by the detector effects and the most serious problem in this analysis is the identification of the right $b$ to reconstruct $t$. There are two strategies to improve the efficiency of identifying the right $b$. One is to demand a large invariant mass of the $t\bar{t}$ system so that $t$ is boosted and its decay products are collimated. Namely, the right $b$ will be moving closer to the lepton from $t$ decay. This can be easily enforced by demanding lepton $\ell$ with large transverse momentum. Another is to identify the non-isolated lepton from $\bar{b}$ decay (with a branching ratio $Br(\bar{b} \to \mu^+ X) \sim 10\%$). Both of these methods will further reduce the reconstructed signal rate by an order of magnitude. How will these affect our conclusion on the determination of the non-universal couplings $\kappa_L^{CC}$ and $\kappa_R^{CC}$? This cannot be answered in the absence of detailed Monte Carlo studies.

Here we propose to probe the couplings $\kappa_L^{CC}$ and $\kappa_R^{CC}$ by measuring the production rate of the single-top quark events. A single-top quark event can be produced from either the $W$-gluon fusion process $qg (W^+ g) \rightarrow t\bar{b}X$, or the Drell-Yan type process $q\bar{q} \rightarrow W^* \rightarrow t\bar{b}$. Including both the single-$t$ and single-$\bar{t}$ events, for a $2$ ($3.5$) TeV collider, the $W$-gluon fusion rate is $2$ ($16$) pb; the Drell-Yan type rate is $0.6$ ($1.5$) pb. The Drell-Yan type event is easily separated from the $W$-gluon fusion event, therefore will not be considered hereafter \[26\]. For the decay mode of $t \rightarrow bW^+ \rightarrow b\ell^+ \mu$, with
= e^+ \text{ or } \nu^+\), the branching ratio of interest is \( Br = \frac{2}{9} \). The kinematic acceptance of this event at \( \sqrt{S} = 2 \text{ TeV} \) is found to be 0.55 \( [26] \). If the efficiency of b-tagging is 30\%, there will be \( 2 \text{ pb} \times 10^3 \text{ pb}^{-1} \times \frac{2}{9} \times 0.55 \times 0.3 = 75 \) single-top quark events reconstructed. At \( \sqrt{S} = 3.5 \text{ TeV} \) the kinematic acceptance of this event is 0.50 which, from the above calculation yields about 530 reconstructed events. Based on statistical error alone, this corresponds to a 12\% and 4\% measurement on the single-top cross section. A factor of 10 increase in the luminosity of the collider can improve the measurement by a factor of 3 statistically.

Taking into account the theoretical uncertainties, we examine two scenarios: 20\% and 50\% error on the measurement of the single-top cross section, which depends on both \( \kappa_L^{CC} \) and \( \kappa_R^{CC} \). (Here we assume the experimental data agrees with the SM prediction within 20\% (50\%).) We found that for a 175 GeV top quark \( \kappa_L^{CC} \) and \( \kappa_R^{CC} \) are well constrained inside the region bounded by two (approximate) ellipses, as shown in Fig. (4). These results are not sensitive to the energies of the colliders considered here.

The top quark produced from the W-gluon fusion process is almost one hundred percent left-handed (right-handed) polarized for a left-handed (right-handed) t-b-W vertex, therefore the charged lepton \( \ell^+ \) from \( t \) decay has a harder momentum in a right-handed t-b-W coupling than in a left-handed coupling. (Note that the couplings of light-fermions to W boson have been well tested from the low energy data to be left-handed as described in the SM.) This difference becomes smaller when the top quark is more massive because the W boson from the top quark decay tends to be more longitudinally polarized.

A right-handed charged current is absent in a linearly \( SU(2)_L \) invariant gauge theory with massless bottom quark. In this case, \( \kappa_R^{CC} = 0 \), then \( \kappa_L^{CC} \) can be constrained to within about \(-0.08 < \kappa_L^{CC} < 0.03 \) \((-0.20 < \kappa_L^{CC} < 0.08)\) with a 20\% (50\%) error on the measurement of the the single-top quark production rate at the Tevatron. This means that if we interpret \( (1 + \kappa_L^{CC}) \) as the CKM matrix element \( V_{tb} \), then \( V_{tb} \) can be bounded as \( V_{tb} > 0.9 \) (or 0.8) for a 20\% (or 50\%) error on the
measurement of the single-top production rate. Recall that if there are more than three generations, within 90% C.L., $V_{tb}$ can be anywhere between 0 and 0.9995 from low energy data [27]. This measurement can therefore provide useful information on possible additional fermion generations.

We expect the LHC can provide similar or better bounds on these non-standard couplings when detail analyses are available.

4 At the NLC

The best place to probe $\kappa_L^{NC}$ and $\kappa_R^{NC}$ associated with the $t$-$t$-$Z$ coupling is at the NLC through $e^-e^+ \rightarrow A, Z \rightarrow t\bar{t}$. (We use NLC to represent a generic $e^-e^+$ supercollider [28].) A detail Monte Carlo study on the measurement of these couplings at the NLC including detector effects and initial state radiation can be found in Ref. [29]. The bounds were obtained by studying the angular distribution and the polarization of the top quark produced in $e^-e^+$ collisions. Assuming a 50 fb$^{-1}$ luminosity at $\sqrt{s} = 500$ GeV, we concluded that within 90% confidence level, it should be possible to measure $\kappa_L^{NC}$ to within about 8%, while $\kappa_R^{NC}$ can be known to within about 18%. A 1 TeV machine can do better than a 500 GeV machine in determining $\kappa_L^{NC}$ and $\kappa_R^{NC}$ because the relative sizes of the $t_R(t_R)$ and $t_L(t_L)$ production rates become small and the polarization of the $t\bar{t}$ pair is purer. Namely, it’s more likely to produce either a $t_L(t_R)$ or a $t_R(t_L)$ pair. A purer polarization of the $t\bar{t}$ pair makes $\kappa_L^{NC}$ and $\kappa_R^{NC}$ better determined. (The purity of the $t\bar{t}$ polarization can be further improved by polarizing the electron beam.) Furthermore, the top quark is boosted more in a 1 TeV machine thereby allowing a better determination of its polar angle in the $t\bar{t}$ system because it is easier to find the right $b$ associated with the lepton to reconstruct the top quark moving direction.

Finally, we remark that at the NLC, $\kappa_L^{CC}$ and $\kappa_R^{CC}$ can be studied either from the decay of the top quark pair or from the single-top quark production process; W-photon fusion process $e^-e^+ (W\gamma) \rightarrow tX$, or $e^-\gamma (W\gamma) \rightarrow \bar{t}X$, which is similar to the $W$-gluon fusion process in hadron collisions.
5 Discussion and Conclusions

Different symmetry breaking scenarios will imply different correlations among the couplings of the top quark to gauge bosons. By examining these correlations one may be able to probe the electroweak symmetry breaking sector. To illustrate how a specific symmetry breaking mechanism might affect these couplings in the effective lagrangian, we consider the SM with a heavy Higgs boson as the full theory, and perform matching between the underlying theory (SM) and the effective lagrangian. We find \[ \kappa_L^{NC} = 2 \kappa_L^{CC} = \frac{G_F}{2\sqrt{2}\pi^2} \left( \frac{-1}{8} \right) m_t^2 \log \left( \frac{m_H^2}{m_t^2} \right), \] \[ \kappa_R^{NC} = \frac{G_F}{2\sqrt{2}\pi^2} \frac{1}{8} m_t^2 \log \left( \frac{m_H^2}{m_t^2} \right), \] \[ \kappa_R^{CC} = 0, \] at the scale \( m_t \). Note that due to the Ward identities associated with the photon field there can be no non-universal contribution to either the \( b-b-A \) or \( t-t-A \) vertex after renormalizing the fine structure constant \( \alpha \). This can be explicitly checked in this model. Furthermore, up to the order of \( m_t^2 \log m_H^2 \), the vertex \( b-b-Z \) is not modified.

From this example we learn that the effective non-standard couplings of the top quark to gauge bosons arising from a heavy Higgs boson are correlated in a specific way, namely
\[ \kappa_L^{NC} = 2 \kappa_L^{CC} = -\kappa_R^{NC} \] and \( \kappa_R^{CC} = 0 \).

Hence, if the couplings of a heavy top quark to gauge bosons are measured and exhibit large deviations from these relations, then it is likely that the electroweak symmetry breaking is not due to the standard Higgs mechanism with a heavy SM Higgs boson. This illustrates how one may be able to probe the symmetry breaking sector by measuring the effective couplings of the top quark to gauge bosons.

In conclusion, assuming the \( b-b-Z \) vertex is not modified, from LEP data, we found that \( \kappa_L^{NC} \) is already constrained to be \(-0.3 < \kappa_L^{NC} < 0.6 \) \((-0.2 < \kappa_L^{NC} < 0.5 \) at the 95\% C.L. for a 150 (175) GeV top quark. Despite the fact that \( \kappa_R^{NC}, \kappa_L^{CC} \)
and $\kappa_{R}^{CC}$ are not constrained in the range of $\pm 1.0$, LEP data does impose some correlations among the couplings $\kappa_{L}^{NC}$, $\kappa_{R}^{NC}$ and $\kappa_{L}^{CC}$. But, $\kappa_{R}^{CC}$ is not bounded because it does not contribute to the LEP observables at the order of $m_{t}^{2}\log \Lambda^{2}$.

Undoubtedly, direct detection of the top quark at the Tevatron, the LHC and the NLC is crucial to measuring the couplings of $t-b-W$ and $t-t-Z$. At hadron colliders, $\kappa_{L}^{CC}$ and $\kappa_{R}^{CC}$ can be measured by studying the polarization of the $W$ boson from top quark decay. They can also be measured simply from the production rate of the single-top quark event. The NLC is the best machine to measure $\kappa_{L}^{NC}$ and $\kappa_{R}^{NC}$ which can be measured from studying the angular distribution and the polarization of the top quark produced in $e^{-}e^{+}$ collisions.

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Figure Captions

Fig. 1.
Two-dimensional projection in the plane of $\kappa_L^{NC}$ and $\kappa_R^{NC}$, for $m_t = 150$ GeV, $m_H = 100$ GeV.

Fig. 2.
Two-dimensional projection in the plane of $\kappa_L^{NC}$ and $\kappa_L^{CC}$, for $m_t = 150$ GeV, $m_H = 100$ GeV.

Fig. 3.
Two-dimensional projection in the plane of $\kappa_R^{NC}$ and $\kappa_L^{CC}$, for $m_t = 150$ GeV, $m_H = 100$ GeV.

Fig. 4.
The allowed $|\kappa_R^{CC}|$ and $\kappa_L^{CC}$ are bounded within the two dashed (solid) lines for a 20% (50%) error on the measurement of the single-top production rate, for a 175 GeV top quark.
This figure "fig1-1.png" is available in "png" format from:

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