General Analysis of Single Top Production and
W Helicity in Top Decay

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We provide a framework for the analysis of the W boson helicity in the decay of the top quark that is based on a general effective tbW coupling. Four independent coupling coefficients can be uniquely determined by the fractions of longitudinal and transverse W boson polarizations as well as the single top production rates for the t-channel and the s-channel processes. The knowledge of these coefficients can be used to discriminate models of electroweak symmetry breaking.

I. INTRODUCTION

The top quark stands out as the heaviest elementary particle known to date. It lives very shortly and almost all of the time decays into a b quark and a W boson [1]. Because of the top quark mass being of order the electroweak symmetry breaking (EWSB) energy scale, studying the top quark interactions is of great interest. The knowledge of these interactions is required in order to discriminate mechanisms of EWSB. Moreover, because of the top's decay mode $t \to bW$, the tbW coupling plays a significant role in the physics of the top quark.

One of the main goals at the Fermilab Tevatron and at the CERN Large Hadron Collider (LHC) is to study the production and decay of top quarks. The measurement of single top production cross section has turned out to be a challenging task and no single top events have been observed so far [2]. This non-observation is translated into upper limits of order 5 pb (based on $230\,\mathrm{pb}^{-1}$ integrated luminosity) for each production channel [2], far above the predictions of the Standard Model (SM) which are of order $1-2$ pb. However, it is expected

that more luminosity and improved analysis methods will eventually achieve detection of SM single top events.

There are three modes in the $t \to bW$ decay, depending on the polarization state of the W boson. Each mode is associated with a fraction, f_0, f_+ or f_-, that corresponds to the longitudinal, right-handed or left-handed polarization, respectively. By definition, we have the constraint $f_0 + f_+ + f_- = 1$. Recent reports by the DØ and CDF collaborations at Fermilab give the following (95% C.L.) results for the longitudinal and right-handed fraction of $t \to bW$ in the $t\bar{t}$ pair events [3]:

$$f_0 = 0.91 \pm 0.38 \,(\text{CDF})\,, \quad f_0 = 0.56 \pm 0.32 \,(\text{DØ})\,,$$

$$f_+ \leq 0.18 \,(\text{CDF})\,, \qquad f_+ \leq 0.24 \,(\text{DØ})\,.$$

In this work we propose a new strategy to use the measurements on the single top production cross section and on the polarization of the W boson in the $t \to bW$ decay in order to determine the general effective tbW vertex. Our strategy consists of using four measurements: a) σ_s and σ_t, the cross sections of the two most important modes of single top quark production at the Tevatron, referred to as s-channel and t-channel [4], and b) two of the three decay ratios, f_0, f_- and f_+, to determine the four independent couplings that define the general effective tbW vertex. To emphasize the importance of measuring the tbW vertex, we will consider two different models of EWSB, and compare their predictions on tbW. In this manner, we show that the proposed analysis can help us to distinguish different models of EWSB.

II. THE GENERAL APPROACH TO STUDY TOP QUARK INTERACTIONS

Currently, the only missing ingredient of the SM is the Higgs boson. This is the agent that causes the breaking of the electroweak symmetry, and LEPII searches have concluded that its mass must be greater than $115\,\text{GeV}$ if such particle exists [5]. It is well known that the Higgs mechanism in the SM leaves many important questions unanswered; like what is the real origin of the fermion masses, or what is the explanation for a significant cancellation of higher order corrections to the Higgs mass. As a result, other theories of EWSB are given much attention in the particle physics community. Theories like the Minimal Supersymmetric Standard Model (MSSM), the Technicolor models, and theories

with new top quark interactions suggest some of the answers, but so far no indication of their validity has been found.

Another approach to study the physics that is responsible for EWSB is to focus our attention on the particles that we know exist. Whatever new physics interactions may exist, they must become apparent at an energy scale higher than what we have been able to probe so far. We do not know how high this scale may be. Maybe it lies much higher than the electroweak scale $(246\,\text{GeV})$ and if so, the only way we can begin to get information about these interactions is by looking at the effects they produce on the interactions appearing at lower energies. Because of their big masses, the top quark, the W and the Z bosons are the prime candidates to show these effects through their interactions.

In this paper we want to provide a general framework that describes all the possible effects from any physics beyond the SM. This framework is based on the non-linear electroweak chiral Lagrangian [6]. This Lagrangian satisfies the $SU(2)_L \times U(1)_Y$ symmetry by a non-linear realization, and it is the most general Lagrangian that is consistent with the SM gauge symmetry and that can contain all the possible effects (decoupled and non-decoupled) coming from the physics at higher energy scales. Concerning the tbW system, it has been shown that the leading dimension 4 and dimension 5 interaction terms that are independent from each other are [7]:

$$
\begin{aligned}
\mathcal{L}_{(tbW)} = &-\frac{1}{\sqrt{2}} \left((1 + \kappa_L^{(4)})\bar{t}\gamma^\mu P_L b + \kappa_R^{(4)}\bar{t}\gamma^\mu P_R b \right) \mathcal{W}_\mu^+ \\
&+\frac{\kappa_{R(L)}^\sigma}{\Lambda}\, \bar{b}\sigma^{\mu\nu} P_{R(L)} t\, D_\mu \mathcal{W}_\nu^- + i\frac{\kappa_{R(L)}^t}{\Lambda}\, \mathcal{W}^{-\mu}\bar{b}P_{L(R)}\, D_\mu t \\
&+i\frac{\kappa_{R(L)}^w}{\Lambda}\, \bar{b}P_{R(L)} t\, D^\mu \mathcal{W}_\mu^- \quad + h.c.\,,
\end{aligned}
$$

where $P_{R(L)}$ are the right-and left-handed chiral projectors $P_{R(L)} = (1 \pm \gamma_5)/2$, D_μ is the electromagnetic $U(1)$ covariant derivative and Λ is the energy scale at which the physics beyond the SM becomes apparent. The t, b and $\mathcal{W}^+$ fields are not the usual fermion and vector boson fields. Rather, they are *composite* fields that involve Goldstone boson fields and that transform non-linearly under the gauge group [7]. In the unitary gauge they become the usual fields (e.g., $\mathcal{W}^+ = -gW^+$). In the remainder of this letter, t and b denote the usual fermion fields for the top and bottom quarks. To simplify our analysis, the κ coefficients are taken to be real so that there are no CP violation effects.

The effective tbW coupling generated by this Lagrangian contains terms proportional

to γ_μ, $\sigma_{\mu\nu}q^\nu$, p_μ and q_μ, with p and q the momenta of the top quark and the W boson, respectively. We can make a simplification of this vertex that is valid for our study. First of all, since the $t \to bW$ decay involves quarks on-shell, we can use the well known Gordon identity:

$$(m_b + m_t)\bar{b}\gamma_\mu t = \bar{b}(p_\mu + p'_\mu - i\sigma_{\mu\nu}q^\nu)t \, ,$$

where $p' = p - q$ is the momentum of the b quark, and reduce the degrees of freedom to three terms: γ_μ, $\sigma_{\mu\nu}q^\nu$ and q_μ. Because of the on-shell condition of the W boson, the term proportional to q_μ will not contribute to the $t \to bW$ decay amplitude. Furthermore, this q_μ term will neither contribute to the single top production processes, because it will only generate a contribution proportional to the incoming state light quark masses which are usually taken as zero.

Therefore, the effects of our general effective Lagrangian to the processes considered here can be completely described by the following tbW vertex:

$$
\begin{aligned}
\mathcal{L}_{tbW} =\ & \frac{g}{\sqrt{2}} W_\mu^- \bar{b}\gamma^\mu \left(f_1^L P_L + f_1^R P_R\right) t \\
& - \frac{g}{\sqrt{2}M_W} \partial_\nu W_\mu^- \bar{b}\sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R\right) t \quad + h.c. \, ,
\end{aligned}
\tag{1}
$$

where we have changed the mass scale Λ to m_W to keep the same notation used in the literature [8, 9].

In the SM the values of the form factors are $f_1^L = V_{tb} \simeq 1$, $f_1^R = f_2^L = f_2^R = 0$. To focus on deviations from SM values, let us define $f_1^L \equiv 1 + \epsilon_L$.

It is well known that $b \to s\gamma$ can impose a strong constraint on f_1^R and f_2^L to be less than 0.004 [10, 11]. These constraints can be viewed as the result of an m_b suppression for right-handed bottom quark couplings [11]. On the other hand, $b \to sl^+l^-$ can be sensitive to a left-handed bottom quark coupling like f_2^R, and it can impose a constraint of order 0.03 [11]. For ϵ_L, the LEP precision data imposes some constraint but only in correlation with similar neutral current anomalous ttZ couplings. Assuming no deviations from the SM ttZ vertex we would have that $\epsilon_L \leq 0.02$ [10]. To bear in mind, these constraints assume there are no other sources of new physics that could cancel the effects of these couplings on the data. Moreover, the dimension 5 couplings f_2^R and f_2^L may induce a bad high energy behavior in top quark production processes, hence, we will consider values at most of order 0.5 in order to satisfy the unitarity condition [12].

Studies of the dimension 5 couplings $f_2^{L,R}$ in connection with the single top quark production at hadron colliders have shown that a sensitivity of order 0.2 (0.05) might be achieved at the Tevatron (LHC) [13]. Information on the helicity of the W boson in $t \to bW$ can be obtained by measuring a forward-backward asymmetry (A_{FB}) based on the angle between the charged lepton and the b-jet of the observed decay process [14]. Preliminary studies show that if A_{FB} is measured with 20% accuracy at the Tevatron, it may be sensitive to values of order $f_2^{L,R} \sim 0.3$; similarly, if A_{FB} is measured with 1% accuracy at the LHC this may be translated to a sensitivity of order $f_2^L \sim 0.03$ and $f_2^R \sim 0.003$ [9].

We would like to point out that, since the observable A_{FB} is only proportional to the difference between f_+ and f_- [14], it is clear that it does not provide any more information than the separate measurements of (two of) the ratios f_0, f_- and f_+.

Let us summarize the status of the SM predictions for the observables of our study: the cross sections σ_t and σ_s, and the branching fractions f_0, f_+ and f_-. In Table I we show the leading order (LO) and the next-to-leading order (NLO) SM predictions for σ_t and σ_s at the Tevatron and at the LHC [4]. For the LO predictions the CTEQ6L1 parton distribution function (PDF) has been used [15]. For the NLO predictions the CTEQ6M PDF has been used [4]. In this letter we are taking the mass of the top quark as $m_t = 178\,\text{GeV}$ and the mass of the W boson as $m_W = 80.4\,\text{GeV}$.

Channel	Tevatron (t LO)	(t NLO)	LHC (t LO)	(t NLO)	LHC ($\bar{t}$ LO)	($\bar{t}$ NLO)
t-channel	0.827	0.924	146.0	150.0	84.9	88.5
s-channel	0.27	0.405	4.26	6.06	2.59	3.76

TABLE I: SM single top production cross section predictions in units of pb [4]. The mass of the top quark is taken as $m_t = 178\,\text{GeV}$.

Neglecting terms proportional to the bottom mass, the Born level values of the top quark width and its W-polarization ratios are $\Gamma_t = 1.65\,\text{GeV}$, $f_0 = 0.71$, $f_- = 0.29$ and $f_+ = 0$. In the SM, including terms proportional to m_b, order α_s^2 QCD, electroweak, and finite W width corrections produce a 10% decrease in the top's width ($\Gamma_t = 1.49$) and a small $\sim 1\%$ variation for decay ratios ($f_0 = 0.701$, $f_- = 0.297$ and $f_+ = 0.002$) [14].

In this work we will be interested in deviations from the SM values (up to the NLO) that come from the effects of the anomalous ϵ_L, f_1^R, f_2^L and f_2^R couplings, cf. Eq. (1), induced by

heavy new physics effects. In the following, we will write down the Born level contributions of these couplings on the observables f_0, f_+, f_-, σ_t and σ_s.

III.   SINGLE TOP PRODUCTION AND W HELICITY IN $t \to bW$ DECAY

The tree level $t \to bW$ decay width of the top quark with the general tbW vertex can be easily obtained with the helicity amplitude method, and it is given by [8]:

$$
\begin{aligned}
\Gamma_t &= \Gamma_0 + \Gamma_- + \Gamma_+ \\
&= \frac{g^2 m_t}{64\pi} \frac{(a_t^2 - 1)^2}{a_t^4} \left(a_t^2 L_0^2 + 2T_m^2 + 2T_p^2 \right) , \\
L_0^2 &\equiv 1 + x_0 = (f_1^L + f_2^R/a_t)^2 + (f_1^R + f_2^L/a_t)^2 , \\
T_m^2 &\equiv 1 + x_m = (f_1^L + a_t f_2^R)^2 , \\
T_p^2 &\equiv x_p = (f_1^R + a_t f_2^L)^2 , \\
a_t &\equiv \frac{m_t}{m_W} .
\end{aligned}
\tag{2}
$$

As the notation suggests, x_0, x_m and x_p are the effective terms that originate the contribution to f_0, f_- and f_+, respectively. Below, we will write down the explicit expressions for these decay ratios.

The t-channel total cross section at the parton level comes from two processes: $ub \to dt$ and $\bar{d}b \to \bar{u}t$. For the first one the expression is:

$$
\begin{aligned}
\sigma(ub \to dt) &= \frac{g^4}{64\pi s}(I_0 L_0^2 + I_m T_m^2 + I_p T_p^2 - I_i x_i + I_5 x_5) , \\
I_0 &= x_t(C_b - C_a) , \\
I_m &= C_a - x_t C_b , \\
I_p &= I_m + (1 + C_{tw})(x_w C_a - C_l) + 1 - x_t - x_w C_l , \\
I_i &= (\ln x_t + C_{tw} C_l)/(x_t - x_w) , \\
I_5 &= 1 - (1 + \ln x_t)/x_t - 2I_i/a_t^2 , \\
x_5 &= a_t^2 (f_2^{L2} + f_2^{R2}) , \\
x_i &= 2a_t(f_1^L f_2^R + f_2^L f_1^R) = \frac{a_t^2}{a_t^2 - 1}(x_m + x_p - x_0) - \frac{1 + a_t^2}{a_t^2} x_5 ,
\end{aligned}
\tag{3}
$$

where $s = (p_u + p_b)^2$ is the total energy squared of the colliding partons. We have defined the following terms:

$$
x_t = \frac{m_t^2}{s} , \quad x_w = \frac{m_w^2}{s} , \quad C_{tw} = 1 - x_t + x_w , \quad C_l = \ln \frac{C_{tw}}{x_w} ,
$$

$$C_a = \frac{1 - x_t}{x_w C_{tw}} \quad , \qquad C_b = \frac{C_a}{x_t - x_w} - \frac{C_l + \ln x_t}{(x_t - x_w)^2} \quad .$$

The formula for $\bar{d}b \to \bar{u}t$ can be obtained from Eq. (3) by interchanging the coupling coefficients $f_1^L \leftrightarrow f_1^R$ and $f_2^L \leftrightarrow f_2^R$ (or simply, $T_m^2 \leftrightarrow T_p^2$). For the anti-top production we have $\sigma(\bar{u}\bar{b} \to \bar{d}\bar{t}) = \sigma(\bar{d}b \to \bar{u}t)$ and $\sigma(d\bar{b} \to u\bar{t}) = \sigma(ub \to dt)$.

The s-channel total cross section at the parton level is:

$$\sigma(u\bar{d} \to t\bar{b}) = \frac{g^4}{128\pi s} \frac{(s - m_t^2)^2}{(s - m_t^2)^2 + m_w^2 \Gamma_w^2} (T_m^2 + T_p^2 - I_s),$$

$$I_s = (f_1^{L2} + f_1^{R2} - x_5/x_t)(1 - x_t)/3. \qquad (4)$$

Where $\Gamma_w = 2.1$ GeV is the W boson's width. The cross section formula for $u\bar{d} \to t\bar{b}$ is the same as above. To write Eq. (4) in terms of the variables x_0, x_m, x_p and x_5, we can use the relation: $f_1^{L2} + f_1^{R2} = 1 + x_m + x_p - x_5 - x_i$.

In summary, the contributions of the effective tbW couplings to the observables of interest are:

$$f_0 = \frac{a_t^2(1 + x_0)}{a_t^2(1 + x_0) + 2(1 + x_m + x_p)}, \qquad (5)$$

$$f_+ = \frac{2x_p}{a_t^2(1 + x_0) + 2(1 + x_m + x_p)}, \qquad (6)$$

$$f_- = \frac{2(1 + x_m)}{a_t^2(1 + x_0) + 2(1 + x_m + x_p)},$$

$$\Delta\sigma_t = a_0 x_0 + a_m x_m + a_p x_p + a_5 x_5, \qquad (7)$$

$$\Delta\sigma_s = b_0 x_0 + b_m x_m + b_p x_p + b_5 x_5, \qquad (8)$$

where $\Delta\sigma$ stands for the variation from the SM NLO prediction. The numerical values of the a_i and b_i coefficients are given in Table II for the Tevatron and the LHC. They have been obtained by integrating over the parton luminosities which are evaluated using the PDF CTEQ6L1 [15].

Eqs. (5)-(8) can be used to make a general analysis of the effective tbW vertex. We note that in case a new light resonance is found, like a scalar or vector boson, the s-channel process could be significantly enhanced and its production rate may not be dominated by a virtual W-boson s-channel diagram [16].

The above formulas (summarized in Eqs. (5-8)) also apply to models with extra heavy fermion (t'), such as the Little Higgs Models [17], that couples to the SM b quark and W

t-channel:	a_0	a_m	a_p	a_5
Tevatron	0.896	-0.069	-0.153	0.292
LHC (t)	165.2	-19.1	-34.2	71.7
LHC ($\bar{t}$)	105.8	-20.9	-12.5	44.5
s-channel:	b_0	b_m	b_p	b_5
Tevatron	-0.081	0.352	0.352	0.230
LHC (t)	-1.41	5.67	5.67	6.34
LHC ($\bar{t}$)	-0.836	3.43	3.43	3.38

TABLE II: The single top production cross section coefficients of Eqs. (7-8). In units of pb.

boson. The $t'bW$ coupling in general has the same form of our general tbW coupling, and the expressions for single-t' production cross sections are exactly the same as single-top except for the heavy mass $m_{t'}$. The size of the coefficients in the production cross sections decrease drastically with a greater mass $m_{t'}$. In Fig. 1 we show their dependence with respect to $m_{t'}$. For instance, at $m_{t'} = 500$ GeV the a_0 coefficient decreases one order of magnitude with respect to the value for $m_{t'} = 178$ GeV. Furthermore, in the t-channel single-t' process, the a_0 coefficient, corresponding to longitudinal W boson contribution, dominates its production cross section.

IV. MODELS OF EWSB

For the second part of this paper, we would like to illustrate how this approach can be used to make distinction among different models of EWSB beyond the SM. For simplicity, we assume that no right-handed bottom quark couplings are present, i.e. $f_1^R \simeq 0$, $f_2^L \simeq 0$. Thus, we only need two observables, like f_0 and σ_t, to make our analysis.

At this time it is convenient to notice that f_0 will not depend on $\epsilon_L (\equiv f_1^L - 1)$ if the other three couplings are zero. In our simplified scenario, if f_0 (and f_-) departs from the SM prediction then f_2^R cannot be zero. In fact, the sign of $\Delta f_- \equiv f_- - f_-^{SM}$ is fixed by the sign of f_2^R.

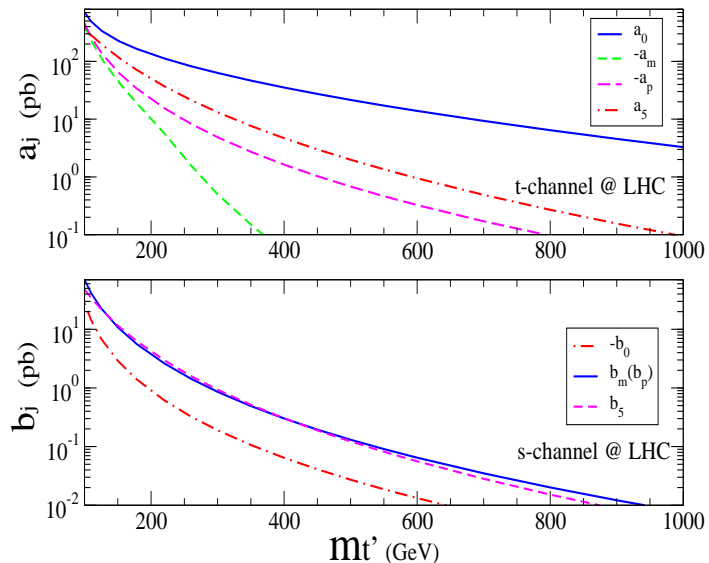We would like to consider two models in particular:

FIG. 1: The coefficients for the s and t channels of single t' production as given by Eqs. (7) and (8) at the LHC.

- The Minimal Supersymmetric Standard Model (MSSM) with $\tan\beta > 1$ studied in Ref. [18], and

- the Topcolor assisted Technicolor model (TC2) considered in Ref. [19].

Let us start with the case of the MSSM discussed in Ref. [18]. Concerning the W-polarization in $t \to bW$ decay, Electroweak-Supersymmetry (SUSY) and QCD-SUSY corrections are of order a few per-cent and tend to cancel each other. The overall effect is to increase the left-handed decay mode at the expense of reducing the longitudinal mode. Thus, for most of the SUSY parameter space the prediction is for a positive f_2^R. It is not true that f_2^R must be positive for all of the MSSM parameter space, but we can consider the positive sign of this coupling as an indication of some scenarios of MSSM [18].

As for the second model, the TC2 scalars that couple strongly with the top quark will modify the tbW vertex in such a way as to reduce f_- in favor of f_0 [19]. This means that in this case the sign of f_2^R must be negative.

From the above discussion we can see that these two models have a general tendency to predict opposite signs for the coupling f_2^R. The size and sign of the other coefficient ϵ_L may depend on the corresponding set of parameters of each model, let us assume the following

values as representative of each model:

$$\text{MSSM}: \ \epsilon_L \ = \ 0.01 \,, \quad f_2^R = 0.005 \,,$$

$$\text{TC2}: \ \epsilon_L \ = \ -0.01 \,, \quad f_2^R = -0.005 \,, \tag{9}$$

These numerical values were chosen such that the predictions for the observables are consistent with the results shown in Refs. [18, 19]. (In the TC2 model, the size of the allowed ϵ_L and f_2^R could be much larger [19].) Here, we ignore the q^2 dependence of the form factors. This is a reasonable approximation for the study of $t \to bW$. Furthermore, σ_t comes predominantly from the small region of the invariant mass of the $t\bar{b}$ pair, where the variation on q^2 can be ignored.

	MSSM	TC2
ϵ_L	0.01	-0.01
f_2^R	0.005	-0.005
$\Delta f_0 / f_0^{SM}$	-0.5%	0.5%
$\Delta f_- / f_-^{SM}$	1.2%	-1.2%
(Tevatron) $\Delta\sigma_t / \sigma_t^{SM}$	2.1%	-2.0%
(Tevatron) $\Delta\sigma_s / \sigma_s^{SM}$	3.2%	-3.1%
(LHC) $\Delta\sigma_t / \sigma_t^{SM}$	2.2%	-2.1%
(LHC) $\Delta\sigma_s / \sigma_s^{SM}$	3.4%	-3.3%
$\Delta\Gamma_t / \Gamma_t^{SM}$	3.5%	-3.4%

TABLE III: Different model predictions for f_0, f_-, σ_t, σ_s and Γ_t. Production of $\bar{t}$ is not included.

In Table III we show the predictions of the two models on the proposed observables. Here, we do not include possible new production channels for the s-channel single top events. For example, it can be produced from a W' resonance whose contribution to σ_s depends on the other parameters of the model. Nevertheless, the t-channel production rate σ_t is less sensitive to the other parameters because the heavy resonance state contribution is suppressed by its large mass. Therefore, we shall concentrate on the measurements of f_0 and σ_t in the following.

In Fig. 2 we show the sensitivity of the Tevatron and the LHC to the determination of the couplings ϵ_L and f_2^R for the above two model scenarios. We assume that f_0 (σ_t) can be
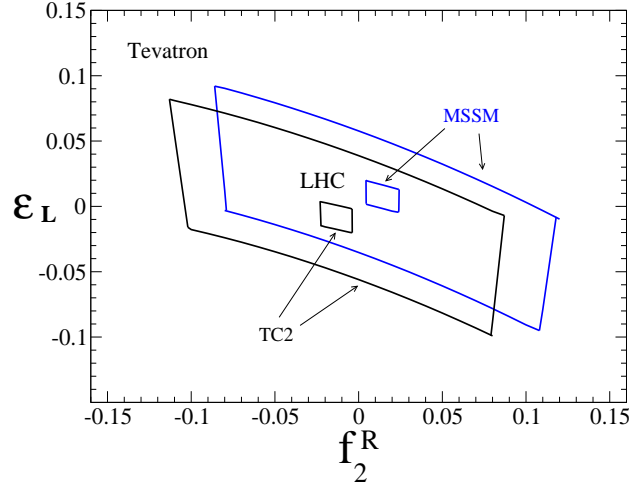
FIG. 2: Possible scenarios and the allowed f_2^R vs ϵ_L region as given by measurements at the Tevatron and the LHC.

measured to 10% (10%) accuracy at the Tevatron, and to 1% (2%) accuracy at the LHC [1]. As for the LHC potential to measure single top production, the CKM matrix element V_{tb} could be measured down to less than one percent error (statistical error only) at the ATLAS detector [20]. We conclude that the MSSM and TC2 could be distinguished from each other at the LHC, but not at the Tevatron.

We want to emphasize that in general all four observables of Eqs. (5)-(8) are needed to determine the four couplings of the tbW vertex and to make a complete analysis that could test the different models of EWSB.

[1] D. Chakraborty, J. Konigsberg, D. Rainwater, Annu. Rev. Part. Nucl. Sci. **53** (2003) 301; M. Beneke, et.al., *Top Quark Physics: 1999 CERN Workshop on the SM Physics (and more) at the LHC* (hep-ph/0003033).

[2] R. Schweinhorst, for the DØ and CDF collaborations, hep-ex/0411039.

[3] By the DØ collaboration, hep-ex/0404040 and references there in; by the CDF collaboration, hep-ex/0411070 and references therein.

[4] Z. Sullivan, *Phys. Rev.* D **70** (2004) 114012, and references therein; J. Campbell, R.K. Ellis and F. Tramontino, *Phys. Rev.* D **70** (2004) 094012.

[5] LEP Higgs working group, *Search for the SM Higgs Boson at LEP* hep-ex/0107029.

[6] H. Georgi, Annu. Rev. Nucl. Part. Sci. **43** (1993) 209, and references therein.

[7] F. Larios and C.-P. Yuan, *Phys. Rev.* D **55** (1997) 7218; O.J.P. Eboli, M.C. Gonzalez-Garcia and S.F. Novaes, *Phys. Lett.* B **415** (1997) 75.

[8] G.L. Kane, G.A. Ladinsky and C.-P. Yuan. *Phys. Rev.* D **45** (1992) 124.

[9] F. del Aguila and J.A. Aguilar-Saavedra, *Phys. Rev.* D **67** (2003) 014009.

[10] F. Larios, M.A. Pérez and C.-P. Yuan, *Phys. Lett.* B **457** (1999) 334, and references therein.

[11] G. Burdman, M.C. Gonzalez-Garcia and S.F. Novaes, *Phys. Rev.* D **61** (2000) 114016.

[12] G.J. Gounaris, F.M. Renard and C. Verzegnassi, *Phys. Rev.* D **52** (1995) 451.

[13] E. Boos, L. Dudko and T. Ohl, Eur. Phys. J. C**11** (1999) 473.

[14] H.S. Do, S. Groote, J.G. Korner and M.C. Mauser, *Phys. Rev.* D **67** (2003) 091501, and references therein.

[15] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky and W.K. Tung, JHEP **0207** (2002) 012.

[16] H.-J. He, L. Diaz-Cruz and C.-P. Yuan, *Phys. Lett.* B **530** (2002) 179.

[17] M. Perelstein, *Top Physics in Little Higgs Models*, talk presented at the Top Quark Symposium, April 7-8, 2005, Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor.

[18] J. Cao, R.J. Oakes, F. Wang and J.M. Yang, *Phys. Rev.* D **68** (2003) 054019.

[19] X. Wang, Q. Zhang and Q. Qiao, *Phys. Rev.* D **71** (2005) 014035.

[20] J. Parsons, *Top Quark Physics at the LHC I*, talk presented at the Top Quark Symposium, April 7-8, 2005, Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor.