Extreme walking behavior and SDE boundary conditions in a 331-TC model

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Abstract

The solution of the phenomenological problems of technicolor (TC) models may reside in the different dynamical behavior of the technifermions self-energy appearing in walking (or quasi-conformal) theories. Motivated by recent results where it is shown how the boundary conditions (bc) of the anharmonic oscillator representation of the Schwinger-Dyson gap equation (SDE) to $SU(N)$ are directly related with the mass anomalous dimensions, and different bc cause a change in the ultraviolet asymptotic behavior of the self-energies, in this work we verify that it is possible to have a hard technifermion self-energy in TC models originated through radiative corrections coming from the interactions mediated by the new massive neutral and charged gauge bosons, $Z'$ and $U^{\pm\pm}$ in the context of a 331-TC model.

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I. INTRODUCTION

The origin of fermion and gauge boson masses in the standard model (SM) of elementary particles is explained by their interaction with the Higgs boson. The 125 GeV new resonance discovered at the LHC [1, 2] has many of the characteristics expected for the Standard Model (SM) Higgs boson, however the data still cannot discard the possibility of this boson to be a composite one. If this particle is a composite or an elementary scalar boson is still an open question that probably may be answered by the future LHC data.

The case of a composite state generating dynamical symmetry breaking (DSB) instead of an elementary one is more akin to the phenomenon of spontaneous symmetry breaking that originated from the Ginzburg-Landau Lagrangian, which can be derived from the microscopic BCS theory of superconductivity describing the electron-hole interaction (or the composite state in our case). A similar mechanism happens in QCD where the chiral symmetry breaking is promoted by a non-trivial vacuum expectation value of a fermion bilinear operator and the Higgs role is played by the composite $\sigma$ meson. In particular, the TC idea was the earliest attempt of building models in this direction [3–5].

In some extensions of the standard model (SM), as in the so called 3-3-1 models [6–10] $SU(3)_L \otimes SU(3)_c \otimes U(1)_X$, new massive neutral and charged gauge bosons, $Z'$ and $V^\pm, U^{\pm\pm}$, are predicted. The 3-3-1 model is the minimal gauge group that at the leptonic level admits charged fermions and their antiparticles as members of the same multiplet, the extra predictions of these $GW = SU(2)_L \otimes U(1)_Y$ alternative models are leptoquark fermions with electric charges $-5/3$ and $4/3$ and bilepton gauge bosons with lepton number $L = \pm 2$. The quantization of electric charge is inevitable in the $G = 3 - m - 1$ (to $m=3,4$) models [11–18] with three non-repetitive fermion generations, breaking universality independently on the character of the neutral fermions.

In the Refs. [19, 20] it was suggested that the gauge symmetry breaking of a specific version of a 3-3-1 model [20] could be implemented dynamically, because at the scale of a few TeVs the $U(1)_X$ coupling constant becomes strong and the exotic quark $T$ (charge $5/3$) will form a $U(1)_X$ condensate breaking $SU(3)_L \otimes U(1)_X$ to the electroweak symmetry. This possibility was explored in the Refs. [20–23] assuming a model based on the gauge symmetry $SU(2)_{TC} \otimes SU(3)_L \otimes SU(3)_c \otimes U(1)_X$ (331-TC model), where the electroweak symmetry is broken dynamically by a technifermion condensate, that is characterized by the $SU(2)_{TC}$
Technicolor (TC) gauge group.

The early technicolor models \([3, 4, 24, 25]\) suffered from problems like flavor changing neutral currents (FCNC) and contributions to the electroweak corrections not compatible with the experimental data, as can be seen in the reviews of Refs.\([26–29]\). However, the TC dynamics may be quite different from the known strong interaction theory, i.e. QCD, this fact has led to the walking TC proposal \([30–38]\), which are theories where the incompatibility with the experimental data has been solved, making the new strong interaction almost conformal and changing appreciably its dynamical behavior.

It is possible to obtain an almost conformal TC theory when the fermions are in the fundamental representation, with the introduction of a large number of TC fermions \((n_{TF})\), leading to an almost zero \(\beta\) function and flat asymptotic coupling constant. The cost of such procedure may be a large \(S\) parameter \([39, 40]\) incompatible with the high precision electroweak measurement when it is assumed that technicolor is just QCD scaled up to a higher energy scale \([41]\). However, this problem can be solved by assuming that TC fermions are in other representations than the fundamental one \([42–44]\), and an effective Lagrangian analysis indicates that such models also imply in a light scalar Higgs boson \([44]\). This possibility was also investigated and confirmed through the use of an effective potential for composite operators \([45]\) and through a calculation involving the Bethe-Salpeter equation (BSE) for the scalar state \([46]\).

In Refs.\([45–48]\) we discussed the possibility of obtaining a light composite TC scalar boson, this result is a direct consequence of an extreme walking (or quasi-conformal) technicolor theories, where the asymptotic TC self-energy behavior is described by the so called irregular form. There are different ways to obtain of extreme walking (or quasi-conformal) behavior in technicolor theories, in the Ref.\([49]\) this behavior was obtained based on a 331-TC model. The present work was motivated by the results obtained in Ref.\([50]\), where it is discussed how the boundary conditions of the anharmonic oscillator representation of the Schwinger-Dyson gap equation (SDE) for \(SU(N)\) gauge theories are directly related with the mass anomalous dimensions, and the result of Ref.\([51]\) where it was verified that when TC is embedded into a larger theory including also QCD, the radiative corrections, coupling the different strongly interacting Dyson equations, change the ultraviolet behavior of the gap equation solution. Here we show that it is possible to have a hard technifermion self-energy in TC models originated through radiative corrections coming from the interactions mediated by the new
massive neutral and charged gauge bosons, $Z'$ and $U^{\pm\pm}$, in the context of the 331-TC model.

This article is organized as follows: In section II we present the TC Schwinger-Dyson equations (SDE) for exotic techniquarks, including $U(1)_X$ corrections such that exotic techniquarks are coupled to themselves via exchange of a $Z'$ boson. The inclusion of these corrections change the boundary conditions of the $Q' = (U', D')$ TC gap equations and the asymptotic behavior of the self-energy. In section III we extend this result to the usual techniquarks sector, $Q = (U, D)$, and we show that the inclusion of $U^{\pm\pm}$ corrections will change the boundary conditions of the $Q = (U, D)$ TC gap equations leading to a quasi-conformal behavior for all technicolor self-energies ($\Sigma_{Q'}(p)$ and $\Sigma_Q(p)$) resulting in a totally different model of dynamical gauge symmetry breaking. In Section V we draw our conclusions.

II. THE $U(1)_X$ CORRECTIONS TO THE $(U', D')$ TC GAP EQUATION

In the Ref.[49] we computed the dynamically generated masses of heavy exotic quarks $(T, S, D)$ and exotic techniquarks $Q' = (U', D')$, and reproduced the results obtained in Ref.[19] for heavy exotic quarks. The TC SDE including $U(1)_X$ corrections is depicted in Fig.(1), where the curly line correspond to technigluons and the wavy line to $Z'$ bosons.

In the sequence we will consider the TC SDE for exotic techniquarks (see Ref.[49]) including the $U(1)_X$ correction such that exotic techniquarks are coupled to themselves via exchange of a $Z'$ boson (Fig.(1b)). Our main point is to show that the inclusion of this type of correction change the boundary conditions of the TC gap equations as emphasized recently in Ref.[50], where it was shown how the asymptotic solution of the gap equation is modified by this new condition. Including the $U(1)_X$ correction depicted in Fig.(1) into the SDE, where the self-energy, coupling constant and respective Casimir operator are indicated by the index ($TC$), and the $Z'$ boson exchange is indicated by the index ($Z'$) we obtain

![Image of Fig. 1: The Schwinger-Dyson equation for TC including $U(1)_X$ corrections](image)
the angle approximation to transform the terms components of the exotic techniquarks (Q'). To obtain the last equation we also assumed TC

\( T_{C}(1 = U) \) equation are modified by the index following gap equation

\[ m \]

\[ G \]

represents the technigluons mass scale (|p|). To illustrate how the boundary conditions of the exotic techniquarks(Q') TC gap equation can be regularized in order to regularize the (IR) divergence in the gap equation.

\[ \Sigma_{Q'}(p^{2}) = \frac{3C_{TC} \cdot \alpha_{TC}}{4\pi} \left( \frac{1}{p^{2} + m_{G}^{2}} \int_{0}^{p^{2}} dk^{2} \frac{k^{2} \Sigma_{Q'}(k^{2})}{k^{2} + \Sigma_{Q'}(k^{2})} + \int_{p^{2}}^{\Lambda^{2}} dk^{2} \frac{\Sigma_{Q'}(k^{2})}{k^{2} + m_{G}^{2} k^{2} + \Sigma_{Q'}^{2}(k^{2})} \right) \]

\[ + \frac{3\alpha_{x}(Y_{L}Y_{R})}{4\pi} \left( \frac{1}{p^{2} + M_{Z'}^{2}} \int_{0}^{p^{2}} dk^{2} \frac{k^{2} \Sigma_{Q'}^{2}(k^{2})}{k^{2} + \Sigma_{Q'}^{2}(k^{2})} + \int_{p^{2}}^{\Lambda^{2}} dk^{2} \frac{\Sigma_{Q'}^{2}(k^{2})}{k^{2} + \Sigma_{Q'}^{2}(k^{2})} \frac{1}{k^{2} + M_{Z'}^{2}} \right) \] \( \text{(1)} \)

where \( M_{Z'} \) is the Z' boson mass, \( Y_{L,R} \) are \( U(1)_{X} \) hypercharges attributed to the chiral components of the exotic techniquarks (Q'). To obtain the last equation we also assumed the angle approximation to transform the terms \( \frac{1}{(p-k)^{2} + M_{Z'}^{2}} \) as

\[ \frac{1}{(p-k)^{2} + M_{Z'}^{2}} = \frac{\theta(p-k)}{p^{2} + M_{Z'}^{2}} + \frac{\theta(k-p)}{k^{2} + M_{Z'}^{2}} \] \( \text{(2)} \)

In order to illustrate how the boundary conditions of the exotic techniquarks(Q') TC gap equation are modified by the \( U(1)_{X} \) correction, we can assume a compact notation where \( (1 = TC) \) and \( (2 = U(1)_{X}) \) such that

\[ f_{1}(x) = \sigma_{1}(x) I_{1}^{a}(x) + \theta_{1} I_{1}^{b}(x) + \sigma_{2}(x) I_{2}^{a}(x) + \theta_{2} I_{2}^{b}(x) \] \( \text{(3)} \)

where we introduced the following set of new variables and auxiliary functions

\[ p^{2} = M_{Q'}^{2} x, \quad \Sigma_{i}(p^{2}) = M_{Q'}^{2} f_{i}(x), \quad \omega_{i} = \frac{m_{G}^{2}}{M_{Q'}^{2}} \]

\[ k^{2} = M_{Q'}^{2} y, \quad \Sigma_{i}(k^{2}) = M_{Q'}^{2} f_{i}(y), \quad \omega_{2} = \frac{M_{Z'}^{2}}{M_{Q'}^{2}} \]

\[ \sigma_{i}(x) = \frac{\theta_{i}}{x + \omega_{i}}, \quad \theta_{1} = \frac{3C_{TC} \cdot \alpha_{TC}}{4\pi}, \quad \theta_{2} = \frac{3\alpha_{x}(Y_{L}Y_{R})}{4\pi} \]

\[ I_{1}^{a}(x) = \int_{0}^{x} dy \frac{y f_{1}(y)}{y + f_{1}^{2}(y)} \quad g_{i}(x) = \frac{xf_{i}(x)}{x + f_{i}^{2}(x)} \]

\[ I_{1}^{b}(x) = \int_{x}^{\Lambda^{2}} dy \frac{y f_{1}(y)}{y + f_{1}^{2}(y)} \quad 1 \]

\[ I_{2}^{a}(x) = \int_{x}^{\Lambda^{2}} dy \frac{y f_{2}(y)}{y + f_{2}^{2}(y)} \quad 1 \]

\[ I_{2}^{b}(x) = \int_{x}^{\Lambda^{2}} dy \frac{y f_{2}(y)}{y + f_{2}^{2}(y)} \quad 1 \] \( \text{(4)} \)

as mentioned before the index \( i = 1 \)\((or 2)\) denote the \( TC \)\((or \ U(1)_{X}) \) contribution to the SDE, \( m_{G} \) represents the technigluons mass scale (\( m_{G} \sim O(\mu_{TC}) \)) which was introduced in order to regularize the (IR) divergence in the gap equation.
With Eq. (3) we can obtain the following relation between \( f_1(x) \) and \( f'_1(x) \) in the asymptotic region \( x = \frac{\Lambda^2}{M^2_{Z'}} \gg 1 \)

\[
f_1(x) = \frac{\sigma_1(x)}{\sigma'_1(x)} f'_1(x) + \theta_2 \frac{M^2_{Z'}}{\Lambda^2} I^a_2(x)
\]

(5)

Considering this relation and the definitions of variables and auxiliary functions presented in (4) it is possible to write

\[
\Sigma_1(p^2) + p^2 \Sigma'_1(p^2) \approx \frac{\kappa_X}{\Lambda^2} \int \frac{d^2 k^2 \Sigma_2(k^2)}{k^2 + \Sigma'_2(k^2)} ,
\]

(6)

from where we can read the ultraviolet (UV) boundary condition satisfied by the \( f_1(x) \) differential equation. Notice that the term due to the \( U(1)_X \) interaction on the right side of Eq. (6) looks like as a bare mass being added to the TC \( (Q') \) gap equation, which can be described by an effective four fermion interaction with an effective coupling

\[
\kappa_X = \frac{3\alpha_X(Y_L Y_R)}{4\pi} \approx O(1).
\]

(7)

It is opportune to remember that the effective four-fermion couplings, here indicated by the letter \( \kappa \), are the ones that once introduced into the SDE generate the same effect of the radiative corrections discussed in this work.

In Fig. (2) we show the results obtained for the dynamically generated masses due to the \( U(1)_X \) interaction for the heavy exotic quark \( (T) \) and exotic techniquarks \( Q = (U', D') \), obtained in the Ref. [49] and we compare that result with \( (M_F(TeV)) \) generated by the four fermion interaction described by Eq. (8)

\[
M_F = \frac{\kappa_X}{\Lambda^2} \int \frac{d^2 k^2 \Sigma_2(k^2)}{k^2 + \Sigma'_2(k^2)} ,
\]

(8)

where \( M_F = \Sigma_2(0) \approx \text{const.} \) and we have

\[
M_F(\kappa_X - 1) = \kappa_X \frac{M^3_F}{\Lambda^2} \ln \left( \frac{\Lambda^2}{M^2_F} \right) .
\]

(9)

In the above expression \( (\Lambda) \) is defined as a function of \( M_{Z'} \) mass according to table 2 in Ref. [49].
FIG. 2: Dynamically generated masses \( (M_{F}(TeV)) \) of exotic quarks \( (T) \) and techniquarks \( Q' = (U', D') \) due to the \( U(1)_X \) contribution \([19, 49]\) in comparison with the ones obtained from the Eq.\((9)\).

The integral equation described by Eq.\((3)\) can be transformed into a differential equation for \( f_1(x) \), as reproduced below

\[
f''_1(x) + \frac{2}{x + \omega_1} f'_1(x) - \sigma'_1(x) \frac{x f_1(x)}{(x + f^2_1(x))} = 0, \tag{10}
\]

therefore, the \( U(1)_X \) correction change the boundary conditions of the TC SDE equation for the exotic techniquarks \( Q' = (U', D') \). These SDE boundary conditions will also cause a change in the anomalous mass dimension \( (\gamma_m) \) as discussed in Ref.\([50]\), leading to \( \gamma_m \sim O(2) \) because \( \kappa_X \approx O(1) \).

III. THE \( U(1)_X \) CONTRIBUTIONS TO \((U, D)\) TC GAP EQUATION: \( U^{\pm\pm} \) INDUCED CORRECTIONS

In Refs.\([56–60]\) the author describes in a very detailed way the possibility of \( W^{\pm} \) boson coupling to right-handed fermions. These couplings are induced only at high energies, since the four fermion operators of the third fermion family will induce a 1PI vertex function of the \( W^{\pm} \) boson coupling to the right-handed fermions. In the context of the 331-TC model that we consider in this work, as shown in the previous section, the \( U(1)_X \) interaction of the
exotic technifermions \( Q' = (U', D') \) is strong enough to generate an effective four fermion interaction, so that at high energies the interactions mediated by bilepton bosons \( U^{\pm\pm} \), containing exotic technifermions, becomes approximately vectorlike at \( \mu_2 \approx \mu_{331} \approx O(\text{TeV}) \).

The coupling of right-handed techniquarks \( D_R \), with exotic ones \( U_R' \), mediated by bilepton bosons with the effective nontrivial 1PI vertex function of \( U^{++} \) is given by

\[
\mathcal{L}_{U^{++}}^{\text{eff}} \approx \frac{g_{331}^{331}}{\sqrt{2}} G^2 N_{TC} (Y_L Y_R) D_R^\eta \{ [U_R' \bar{U}^\prime_L]^{\lambda\eta} [D_L \bar{D}_R]^{\alpha\beta} \times [U_L' \bar{U}^\prime_L]^{\beta\theta} [\gamma^\mu P_L]^{\theta\delta} [D_L \bar{D}_L]^{\delta\lambda} \} \bar{U}^\prime_R \sigma_\mu U^{++}_\mu (p' - p).
\]

In the above expression the fields in brackets \([...]\) are contracted, and \((p', p)\) are the external moments. This expression is analogous to Eqs. (28) and (29) in Ref. [60]. Considering this coupling in Fig. (3) we show the \( U^{++} \) boson contribution to the techniquark \( D \) self-energy \( \Sigma_D(p^2) \) (where this figure is analogous to the Fig.4 described in Ref. [60]).

The contribution discussed above will be responsible for generating a correction to the usual techniquarks \( Q = (U, D) \) SDE, as depicted in Fig. (4), where the curly lines correspond to techniguons and the wavy lines to the \( U^{\pm\pm} \) correction, which can be identified as an bare mass being added to the TC \( (Q) \) gap equation.

Assuming the TC SDE including the \( U^{\pm\pm} \) contributions depicted in Fig. (4), we obtain...
FIG. 4: The Schwinger-Dyson equation (SDE) for techniquarks $Q = (U, D)$ including $U^{\pm \pm}$ bosons corrections

The following SDE satisfied by the techniquarks $Q = (U, D)$

$$
\Sigma_Q(p^2) = \frac{3C_W \alpha_{EC}}{4\pi} \left( \frac{1}{p^2 + m^2_G} \int \frac{d^2k}{(2\pi)^2} \frac{k^2 \Sigma_Q(k^2)}{k^2 + \Sigma_Q(k^2)} + \int \frac{d^2k}{(2\pi)^2} \frac{\Sigma_Q(k^2)}{k^2 + m^2_G} \right) + \frac{3\alpha_{331}^L \gamma_{U^{\pm \pm}}}{4\pi \sqrt{2}} \left( \frac{1}{p^2 + M_{U^{\pm \pm}}^2} \int \frac{d^2k}{(2\pi)^2} \frac{k^2 \Sigma_Q'(k^2)}{k^2 + \Sigma_Q'(k^2)} + \int \frac{d^2k}{(2\pi)^2} \frac{\Sigma_Q'(k^2)}{k^2 + \Sigma_Q'(k^2)} \right),
$$

(12)

in Eq. (12) the factor $(\alpha_{331}^L \gamma_{U^{\pm \pm}} / \sqrt{2})$ corresponds to the one obtained in Refs. [59][60], where $(\alpha_w(E) \gamma_{W^{\pm}} / \sqrt{2} \alpha_c)$, and we have assumed $\alpha_c = \frac{\pi}{3} \approx 1$. As performed in these references we can consider $\gamma_{U^{\pm \pm}} = (Y_L Y_R) \Gamma_{\pm \pm}(p', p)|_{p, p' \to \Lambda} \approx (Y_L Y_R)$. The integral equation described by Eq. (12) can be transformed into a differential equation $\Sigma_Q(p^2)$, and the (UV) boundary condition that should be satisfied by this differential equation is given by

$$
\Sigma_Q(p^2) + p^2 \Sigma_Q'(p^2) \approx \frac{\kappa_{\pm \pm}}{\Lambda^2} \int \frac{d^2k}{(2\pi)^2} \frac{k^2 \Sigma_Q(k^2)}{k^2 + \Sigma_Q(k^2)},
$$

(13)

The term described on the right side of Eq. (13) looks like as a bare mass being added to the $Q = (U, D)$ gap equation, which can be generated by an effective coupling $(\kappa_{\pm \pm})$

$$
\kappa_{\pm \pm} \approx \frac{3\alpha_L (Y_L Y_R)}{4\pi} \approx \frac{\alpha_L}{\sqrt{2} \alpha_X} \kappa_X,
$$

(14)

where we defined $\alpha_{331}^L = \alpha_L$. The ratio between the coupling constants $\frac{\alpha_X}{\alpha_L}$ can still be expressed in terms of the following relationship [6][61][62][63][64]

$$
\frac{\alpha_X}{\alpha_L} = \frac{\sin^2 \theta_W(\mu)}{1 - 4 \sin^2 \theta_W(\mu)},
$$

(15)

where $\theta_W$ is the electroweak mixing angle. In Ref. [50] we verified that the anomalous mass dimension can be read out directly from the UV boundary conditions, such that, assuming
the addition of an effective four fermion interaction, we have

\[ \gamma_m(t_\Lambda) = \frac{(\gamma_m - 2) + 2\kappa(1 + \gamma_m)}{1 + 2\kappa}. \]  

(16)

In the above equation \( \gamma_m \) is the mass anomalous dimension, \( \kappa \) is a four fermion effective coupling as commented earlier, \( t_\Lambda = \ln \frac{\Lambda}{\mu_{TC}} \), and \( \mu_{TC} \) is the characteristic TC scale. As we saw in Section II, \( \kappa_X \sim O(1) \), and we can represent the UV behavior of the anomalous mass dimension \( \gamma_m \) attributed to techniquarks \( Q \) assuming Eqs. (14), (15) and (16), which leads to \( \gamma_m \approx O(0.8 \sim 1.3) \) assuming \( \sin^2 \theta_W(M_Z) \approx 0.231 \) as a lower limit and considering the extrapolation of the perturbative calculation presented in [64], as an upper limit.

IV. CONCLUSIONS

The possibility of obtaining a light composite scalar \( (M_\phi \approx 125 GeV) \) along the approach discussed in Refs. [45–48], is a direct consequence of extreme walking (or quasi-conformal) technicolor theories, where the asymptotic self-energy behavior is described by a irregular form of the TC self-energy [45, 46]. Recently in Ref. [49] we proposed an scheme to obtain a quasi-conformal self-energy behavior based on a 331-TC model. Motivated by the result obtained in Ref. [50], where we discuss how the boundary conditions of the anharmonic oscillator representation of the \( SU(N) \) gauge theories SDE are directly related with the mass anomalous dimensions. In this work we show that it is possible to have a hard technifermion self-energy in TC models originated through radiative corrections coming from the interactions mediated by the new massive neutral and charged gauge bosons, \( Z' \) and \( U^{\pm\pm} \).

In section II we presented the TC SDE of exotic techniquarks, including \( U(1)_X \) radiative corrections, such that exotic techniquarks are coupled to themselves via exchange of a \( Z' \) boson. We verified that the inclusion of these corrections change the boundary conditions of the \( Q' = (U', D') \) TC gap equations, and we extended this result to the sector of usual techniquarks, verifying that the inclusion of \( U^{\pm\pm} \) radiative corrections change the boundary conditions of the \( Q = (U, D) \) TC gap equations leading to a walking (or quasi-conformal) behavior for \( \Sigma_Q(p^2) \).
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