Technicolor with Scalar Doublet After the Discovery of Higgs Boson

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Abstract

The SM-like Higgs boson with mass of 125 GeV discovered at the LHC is subject to a natural interpretation of electroweak symmetry breaking. In this note we consider implications of the LHC data about Higgs boson to technicolor (TC) from viewpoint of low-energy effective theory. We find TC model which includes both technicolor- and $SU(3)_{c}$-colored scalars below the scale of techni-fermion condensation is still consistent with direct and indirect experimental limits. In particular, the consistency with precision electroweak measurements is realized by the colored scalars, which give rise to a large negative contribution to $S$ parameter.
1 Introduction

Since the discovery of a standard model (SM)-like Higgs boson with mass of 125 GeV [1] reported by the ATLAS and CMS collaboration, extensive efforts have been devoted to explore the implication to electroweak symmetry breaking (EWSB) in the context of new physics. It is now believed that a large part of natural supersymmetry (SUSY) fails to achieve this due to the absence of SUSY signals at the Large hadron collider (LHC) with $\sqrt{s} = 8$ TeV.

In parallel to SUSY as a promising candidate of new physics providing EWSB, TC was also considered as another interesting one decades ago. TC-model differs from SUSY in the way that it provides EWSB through condensation of techni-fermions. Unlike in SUSY models where the electroweak mass parameters are tightly related to the SUSY-breaking scale due to EWSB, naturalness is not a concern in TC-model. However, it also suffers from its own problems, such as the large $S$ parameter in precision electroweak measurements and generations of SM fermions masses (for a review, see [2]).

In this paper, we consider a variant TC model based on previous works in [3, 4]. These authors introduce scalar doublet(s) to original TC [1], which is known as TC with scalar. Unlike the earliest ones of TC-models, the SM fermions obtain their mass similarly to SM in this TC model. The vacuum expectation value (vev) of Higgs is induced by the condensation of techni-fermions, through the Yukawa couplings of Higgs scalar to techni-fermions. In particular, we want to emphasize that this TC-model serves as a low-energy effective theory. Otherwise, the hierarchy problem appears as in SM. It can be embedded either into extended-TC or SUSY. The realization in the former case suggests that the TC model imitates the low-energy behavior of a set of extended-TC and the scalar is actually composite. See Ref.[5] for earlier discussions. The later case has been less addressed in the literature.

Specifically we study TC-model with minimal ingredients needed to reconcile with experimental limits, i.e, with one scalar doublet $\phi$ and two additional colored techni-scalars, There are two input mass scales $f$ and $f'$, respectively, referring to decay constant of techni-pions and vev of $\phi$, which are supposed to satisfy $f^2 + f'^2 = v^2 = (246 GeV)^2$ from consideration of EWSB. The coupling of neutral scalar of $\phi$ to SM fermions are the same as those of SM except a common factor $f'/v$. Therefore this factor determines the deviation of our model

\[^{1}\text{For recent works on other variants of TC model, see, e.g., [6].}\]
from SM. Using the LHC data about Higgs immediately leads to,

$$0 < \theta \lesssim 0.2, \quad \theta \equiv f/f'$$

(1.1)

The couplings of techni-pions to SM fermions are similar to those of charged Higgs boson in type I Higgs doublet model, except a common $\theta$ factor.

The physical states below $4\pi f$ are $\sigma$ scalar, techni-pions and colored techni-scalars. The key points in this model are (1) the small $\theta \sim 0.2$ in (1.1) is sufficient to provide a Higgs scalar of 125 GeV and techni-pion of $210 - 280$ GeV, and at the meantime guarantees that techni-pions evades both the direct and indirect experimental limits; (2) Besides the production of vev of scalar doublet, the colored techni-scalars receive their masses of order $\nu$ via their $\phi^4$ couplings to scalar doublet; (3) These colored techni-scalars provide a large negative contribution to $S$, which eliminates the large positive contribution arising from condensation, therefore makes our model consistent with precision electroweak measurements.

The paper is organized as follows. In section 2, we present our model in detail. Then we discuss the constraints arising from the direct searches on Higgs scalar, techni-pions and colored techni-scalars in subsection 3.1, leaving discussions on indirect experiments on techni-pions in subsection 3.2 and on colored techni-scalars in subsection 3.3. In the latter case, we address the masses of colored techni-scalars and effects on precision electroweak measurements due to these two scalars. We finally conclude in section 4.

2 The Model

The TC model with two complex colored scalars we are considering is as follows,

$$Y_L = \left( \begin{array}{c} p \\ m_L \end{array} \right) : (N_{TC}, 1, 2)_0$$

$$p_R : (N_{TC}, 1, 1)_{1/2}$$

$$m_R : (N_{TC}, 1, 1)_{-1/2}$$

$$\omega_t : (N_{TC}, 3, 1)_{-1/6}$$

$$\omega_b : (N_{TC}, 3, 1)_{-1/6}$$

(2.1)

with addition of a fundamental scalar $\phi : (1, 1, 2)_{1/2}$. The assignments of representations are under the notation of $SU(N_{TC}) \times SU(3)_c \times SU(2)_L \times U(1)_Y$. In comparison with the
simplest TC model, two additional colored- and weak- singlets $\omega_{t,b}$ are added.

The hidden TC and SM matters can communicate through the $\phi$ scalar, which is in the form, respectively,

$$\mathcal{L}(\phi, T) = h_+ \bar{Y}_L \phi p_R + h_- \bar{Y}_L \phi m_R + H.C$$

and

$$\mathcal{L}(\phi, f_{SM}) = h_l \bar{L} \phi_l R + h_U \bar{Q}_L \phi U_R + h_D \bar{Q}_L \phi D_R + H.C$$

where $Q_L$ and $L$ refer to the quark and lepton-doublets of SM, while $U_R$, $D_R$ and $l_R$ refer to the right-hand singlets of quark and lepton, respectively. $hs$ in (2.3) are the ordinary SM Yukawa couplings. There also exists strong communication between the quarks of third generation and techni-fermions of the TC sector through $\omega$ scalars.

$$\mathcal{L}(t_R/b_R, T) = \lambda_{\omega_t} \bar{t}_R \omega_t^\dagger + \lambda_{\omega_b} \bar{b}_R m_R \omega_b^\dagger + H.C$$

An advantage of adding $\omega$ scalars is that the four-fermions operators involving top and bottom quark induced by Yukawa interaction in (2.4) contribute to significant negative $S$, which cancels the large positive tree-level contribution after condensation. There is also a disadvantage. Carrying colors implies that $\omega$ scalars can be directly produced at hadron colliders. This will be discussed in the next section.

The self-couplings among the scalars can be determined from the symmetries in (2.1). Below the scale of $\Lambda_{TC} = 4\pi f$ we will work in effective field analysis, it is more convenient to express $\phi$ doublet and its conjugate in the form of unitary matrix $\Phi$ [4], which can be defined as,

$$\Phi = \frac{\sigma + f'}{\sqrt{2}} \Sigma', \quad \Sigma' = \exp(2i\Pi'/f')$$

Using $\Phi$, we can write the self-couplings as,

$$V(\phi, \omega) = \frac{\lambda_1}{8} [Tr(\Phi^\dagger \Phi)]^2 + \frac{\lambda_6}{8} [\omega_t^\dagger \omega_t]^2 + \frac{\lambda_7}{8} [\omega_b^\dagger \omega_b]^2$$

$$+ \frac{\lambda_2}{8} Tr(\Phi^\dagger \Phi) \omega_t^\dagger \omega_t + \frac{\lambda_3}{8} Tr(\Phi^\dagger \Phi) \omega_b^\dagger \omega_b + \frac{\lambda_4}{8} Tr(\Phi^\dagger \Phi) \omega_t^\dagger \omega_b + \frac{\lambda_5}{8} \omega_t^\dagger \omega_t \omega_b$$

We want to emphasize again that we only include minimal ingredients needed to reconcile with the experimental limits in our low-energy model. More $\omega$-like scalars are needed to guarantee the model of gauge anomaly free. For example, in Ref.[20], an extra $\omega$-scalar is added to keep it anomaly free with rearrangement of $U(1)$ hypercharges.

In dynamical models of EWSB, similarly to the magnitudes of Yukawa couplings of Higgs boson to SM fermions, we assume that the largest effect is in the Yukawa couplings of top-bottom doublet.
3 Experimental Limits

As well known we can use the effective chiral Lagrangian to describe the TC model below
the TC scale \( \Lambda_{TC} \). In this approach, the pseudoscalars that result from the chiral symmetry
breaking are the isotriplet of technipion \( \Sigma \). Guided by non-linear realization of \( \pi \) mesons in
QCD, \( \Sigma \) can also be similarly treaded as,

\[ \Sigma = \exp(2i\Pi/f) \]  (3.1)

which transforms as \( \Sigma \to L\Sigma R^\dagger \) under the chiral symmetries. It is then straightforward to
write the kinetic terms of our model,

\[ L = \frac{f^2}{4} Tr \left( D_\mu \Sigma^\dagger D^\mu \Sigma \right) + \frac{1}{2} Tr \left( D_\mu \Phi^\dagger D^\mu \Phi \right) \]  (3.2)

with the derivative \( D_\mu \Sigma = \partial_\mu \Sigma - igW_\mu^a \frac{\tau^a}{2} \Sigma + ig'B^\mu \Sigma \frac{\tau^3}{2} \). From (3.2) one observes that thechnipions in \( \Sigma \) in the linear combination \( \pi_a \sim f\Pi + f'\Pi' \) become the longitudinal components
of the EW gauge bosons, leaving its orthogonal combination \( \pi_p = (-f'\Pi + f\Pi')/\sqrt{f^2 + f'^2} \)
as the physical states of low energy region. Therefore, we obtain \( f^2 + f'^2 = v^2 \).

3.1 Direct Searches

Now we understand \( \sigma \) and \( \pi_p \) are the freedoms below \( \Lambda_{TC} \). The mass of \( \sigma \) can be directly
determined from (2.6) as in \[4\],

\[ m_\sigma^2 = \frac{3}{2} \tilde{\lambda} f'^2 \]  (3.3)

where

\[ \tilde{\lambda} = \lambda_1 + \frac{11}{24} \left[ 3h_\uparrow^4 + N_{TF}(h_\uparrow^4 + h_\downarrow^4) \right] \]  (3.4)

As for mass of \( \pi_p \), it follows from the effective potential \[4\].

\[ V_{eff}(\sigma) = c_1 4\pi f^3 Tr \left( \Phi \ H \Sigma^\dagger \right) + H.C \]  (3.5)

with the coefficient \( c_1 \sim O(1) \). Substituting \( \pi_p \) into (3.5) gives rise to\[4\]

\[ m_{\pi_p} = 2c_1 \sqrt{2} \frac{4\pi f}{f'} h v^2 = 8h \theta v^2, \quad h = (h_+ + h_-)/2 \]  (3.6)

\[ \text{Here } H = \begin{pmatrix} h_+ & 0 \\ 0 & h_- \end{pmatrix}. \text{ As manifested in (2.2), it combines with } \Phi \text{ to transform as } \Phi H \to L\Phi HR^\dagger. \]

\[ \text{In what follows, we set } c_1 = 1 \text{ for discussion.} \]
Direct search on $\sigma$

The couplings of $\sigma$ to SM fermions and EW gauge bosons are suppressed by a factor $f'/\upsilon$. Identifying $\sigma$ as the Higgs boson discovered at the LHC implies that the ratio $\mu_\gamma$ of signal strength of $h \rightarrow \gamma\gamma$ over its SM prediction, and $\mu_V$ of Higgs decaying into four-leptons via $WW^*$ and $ZZ^*$ both equal to

$$\mu_\gamma = \mu_{VV} = (f'/\upsilon)^2,$$

(3.7)

Global fit to the LHC data [7] suggests that (3.1) and

$$\tilde{\lambda} = 0.15 - 0.18, \quad h = 1.75\tilde{\lambda}. \quad (3.8)$$

The requirement $4\pi f > \upsilon$ from consistency further constrains $\theta$ being in the range $(0.08, 0.2)$. As for the decays of Higgs boson to $bb$ and $\tau\tau$, the uncertainty is still large at present status.

Direct search on $\pi_p$

The Yukawa couplings of charged technipion to SM fermions can be extracted from (2.3) [4],

$$i \left( \frac{f}{\upsilon} \right) \left[ \bar{D}_L V^+ \pi^-_p h_U U_R + \bar{U}_L \pi^+_p V h_D D_R + H.c \right] \quad (3.9)$$

where $V$ denotes the CKM matrix of SM. Eq.(3.9) implies that couplings of $\pi_p$ to SM fermions are similar to those of charged higgs boson in type I Higgs doublet model, except a suppression by $f/\upsilon \simeq f/f' = \theta$. From (3.6) and (3.8) $m_{\pi_p}$ corresponds to be in the range $(210.3, 334.3)$ (GeV). Searches on this range of mass for charged Higgs boson are mainly from the channel $H^+ \rightarrow t\bar{b}$. We find for the ratio of signal strength for $\pi_p \rightarrow t\bar{b}$ over SM background in terms of that for $H^+$,

$$\mu(\pi^+_p \rightarrow t\bar{b}) = \theta^2 \mu(H^+) (H^+ \rightarrow t\bar{b}) \quad (3.10)$$

Charged Higgs boson mass below 78.6 GeV has been excluded by direct searches at LEP [8] (for searches at the LHC, see, e.g., [10]). This bound on $m_{\pi_p}$ however can be significantly relaxed due to the $\theta^2$ suppression on event rate.

Direct search on $\omega_{t,b}$

As we will discuss in the next section, the fit to precision electroweak measurement typically suggests that,

$$\lambda_{\omega_t} \simeq 0.3 - 1.0, \quad m_{\omega_t} \simeq 580 - 1500 \, GeV,$n$$

$$\lambda_{\omega_b} \simeq 1.3 - 3.0, \quad m_{\omega_b} \simeq 100 - 250 \, GeV \quad (3.11)$$
Note that this spectra are consistent with precision measurements at $1\sigma$ level. Allowing consistency at less than $3\sigma$ level will further decrease the Yukawa coupling $\lambda_{\omega_i}$, which helps evading the direct search. The spectra of (3.11) can easily evade the direct detection at the $e^+e^-$ collider. The dominant channel for searching $\omega_{t,b}$ scalars is through $e^+e^- \rightarrow \omega_{t/b}\omega_{t/b}^\ast \rightarrow t\bar{t}/b\bar{b}$. The ratio of cross section of $\sigma(e^+e^- \rightarrow \omega_{t/b}\omega_{t/b}^\ast)$ over its SM background $\sigma_{SM}(e^+e^- \rightarrow t\bar{t}/b\bar{b})$ is very small for each of them. The reason is due to severe suppression by $\beta = \sqrt{1-4m_{\omega_i}^2/s}$ even if light $\omega$ scalars near 100 GeV can be produced. At a hadron collider such as LHC $\omega_{t/b}$ scalar is mainly produced from gluon fusion (GF), and its decay is dominated by $\omega_{t/b} \rightarrow t/b + p_R/m_R$. The SM background for this is $gg \rightarrow m$-jets (with either 2t-jets for $\omega_t$ or 2b-jets for $\omega_b$ included) plus missing energy. Their mass bounds can be estimated in terms of their analogies in supersymmetric models, i.e, stop and sbottom, $\mu_{\omega_{t/b}}^{GF}$

$$
\mu_{\omega_{t/b}}^{(GF)} = \frac{\sigma(gg \rightarrow \omega_{t/b}\omega_{t/b}^\ast \rightarrow b\bar{b} + E_T)Br(\omega_{t/b}\omega_{t/b}^\ast \rightarrow b\bar{b} + E_T)}{\sigma(gg \rightarrow b_1b_1^\ast \rightarrow b\bar{b} + E_T)Br(b_1b_1^\ast \rightarrow b\bar{b} + E_T)}\mu_{\tilde{t}_1}^{(GF)}(gg \rightarrow \tilde{t}_1\tilde{t}_1^\ast \rightarrow 2b - \text{jets} + \text{other jets} + E_T),
$$

where $\mu_{\omega_{t/b}}^{GF}$s refer to the ratio of signal strength over the SM prediction via production of gluon fusion. The small ratio between couplings $\lambda_{\omega_i}/h_{t_i}^{SM} \simeq 0.5$ indicates that mass bound on $m_{\omega_i}$ can be relaxed in comparison with that on $m_{\tilde{t}_1}$. The bound on $m_{\omega_b}$ is heavily dependent on the mass of techni-fermion $m_R$ [9], the large part of mass range in (3.11) can still survive in specific situation.

3.2 Indirect Searches

In what follows, we consider the indirect experimental limits on $\pi_p$ in the case of $\theta \sim 0.08 - 0.2$.

**Correction to $Br(Z \rightarrow bb)$**

The radiative correction to $Br(Z \rightarrow bb)$ coming from technipion is mostly through the exchange of technipion and top quark. There are three kinds of Feynman diagrams, the calculation of which can be similarly considered as for that of charged Higgs bosons in the minimal supersymmetric standard model in [11]. In addition, there are higher-order corrections due to $\omega_t$ scalar, which are smaller effects and will be neglected. We summarize the experimental and theoretical results in Table one. One observes that small $\theta$ factor severely suppresses the correction for technipion, and forbids it from exposition through the
measurement of $R_b$.

| $R_b$ | Exp value       | SM prediction | Exp-SM       | TC-correction |
|-------|-----------------|---------------|--------------|---------------|
|       | $0.21629 \pm 0.00066$ [12] | $0.21581$ | $(4.8 \pm 6.6) \times 10^{-4}$ | $-5.0 \times 10^{-4} \cdot \theta^2$ |

Table 1: The correction to $\text{Br}(Z \to b \bar{b})$ and its experimental limit.

**Correction to $B_s^0 - \bar{B}_s^0$**

The measurement of $B_s^0 - \bar{B}_s^0$ mixing is another experiment which can be useful to expose the technipion. Because $\pi^\pm_p$ gives rise to two additional one-loop diagrams to this process, which involve one-$\pi^\pm_p$-$W$ and two-$\pi^\pm_p$ exchange, respectively. Following the results in [4, 13] (for an earlier work, see [14]), the correction is derived to be,

$$\Delta M_s^{(\pi_p)} \simeq \Delta M_s^{SM} \left( -0.18 \cdot \theta^2 - 0.63 \cdot \theta^4 \right) \quad (3.13)$$

when $\theta$ closes to $\theta_{max}$. The updated analysis of $\Delta M_s^{SM}$ in SM is discussed in [16], whereas its latest experimental value is given in [12]. We collect these results in Table 2. Similar to the correction to $\text{Br}(Z \to b \bar{b})$, as a result of $\theta$ suppression technipion doesn’t produce obviously effects in this experiment.

| $\Delta M_s$ | Exp value       | SM prediction | (Exp-SM)       | TC-correction |
|--------------|-----------------|---------------|----------------|---------------|
| $17.719 \pm 0.036$ (stat) | $17.3 \pm 2.6$ | $0.42 \pm 2.6$ | $-3.11 \cdot \theta^2 - 10.90 \cdot \theta^4$ |

Table 2: Correction to $B_s^0 - \bar{B}_s^0$ mixing in our model and its experimental limit. Here $\Delta M_s$ is in unite of $\text{ps}^{-1}$.

**Correction to $b \to s \gamma$**

The partial width for $b \to s \gamma$ in our model is similar to that of type I two Higgs doublet model (see [15] for the calculation), with the replacement of $H^\pm$ by $\pi^\pm_p$ in the one-loop Feynman diagrams. However, our model differs from the type I two Higgs doublet model in the way that the couplings of $\pi_p$ to SM fermions are suppressed by $\theta$ factor. In Table 3 we show the experimental and theoretic results. In Fig 1, we plot $\delta \Gamma/\Gamma_{SM}$ as function of $\theta$. At present status, it is consistent with the experimental result at $3\sigma$ level in the range $\theta = 0.08 - 0.15$, or equivalently in the range of mass $210 - 287$ (GeV).

One may wonder the implications of direct search on the charged Higgs boson to technipion. For $\pi_p$ with mass of about 90 GeV which is the lower bound found at colliders, it corresponds to $\theta = 0.015$ in our model. It easily evades the experiments we discuss in this section such as $b \to s \gamma$. 

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3.55 ± 0.26 \textsuperscript{[17]} & 3.15 ± 0.23 \textsuperscript{[18]} & −0.3 − 1.1 & \text{Fig.1} \\

| Exp value | SM prediction | (Exp-SM)(\lesssim 2\sigma) | (TC-correction) |
|-----------|---------------|-----------------------------|-----------------|

Table 3: Correction to $B(b \to s\gamma)$ and its experimental limit. $B$ is in unite of $10^{-4}$.

Figure 1: Contour of $\delta \Gamma/\Gamma_{SM}$ for $b \to s\gamma$. At present status, it is consistent with the experimental result in the range of 0.08 − 0.16 at 3$\sigma$ level. The choice of $\theta > 0.08$ is required by $hf' < 4\pi f$ and $\nu < 4\pi f$ as explained above.

### 3.3 Precision Measurement

As well known a severe problem that plagues the technicolor model is the precision electroweak measurement since the report of Peskin and Takeuchi \textsuperscript{[19]}. Because the condensation of techni-fermions gives rise to a tree-level contribution to the oblique parameter

$$S_0 \simeq 0.1 \frac{N_{TF}}{2} N_{TC} \simeq 0.1 N_{TC}$$

$$T_0 \simeq 0.01 \left( \frac{\Lambda'}{1 \ TeV} \right)^4$$

for two flavors $N_{TF} = 2$. It is hard to make precise estimate of $\Lambda'$. As noted from (3.14), $S_0$ is too large ($N_{TC} = 4$). In our model, the introduction of colored $\omega$ scalars also produces significant contributions to $S$. What is of interest is these new parts always cancel out the tree-level part of $S$, and help evading the precision measurements when the masses of $\omega_{t,b}$ are of order $\sim \nu$.

Following the definition of $S$ and $T$ parameters, we derive the total contribution in our
model 6

\[ S = S_0 + \frac{2}{3\pi} (2\delta g_R^t - \delta g_R^b) \]

\[ T = T_0 + \delta g_R^t \frac{3m_t^2}{\pi^2 \alpha^2} \ln \left( \frac{\Lambda_{TC}}{m_t} \right) \]  (3.15)

where

\[ \delta g_R^t = -\frac{\lambda_{\omega t} v^2}{8m_{\omega t}^2}, \quad \delta g_R^b = \frac{\lambda_{\omega b} v^2}{8m_{\omega b}^2} \]  (3.16)

The experimental limits on \( S \) and \( T \) of (3.15) have been updated from global fit. Following the results in the second reference of [21],

\[ S = 0.07 \pm 0.10, \quad T = 0.05 \pm 0.12, \]  (3.17)

in Table 4 we show four benchmark points involving parameters of \( \omega \)-scalar mass and their Yukawa couplings.

As shown in Table 4, it is sufficient for \( m_{\omega t, b} \) of EW scale to cancel the tree-level contribution \( S_0 \). Actually, this requirement can be naturally realized in our model. To see this, note that the VEV of \( \Phi \) induced by the condensation gives rise to \( m_{\omega t, b} \) from potential \( V(\phi, \omega) \). In particular, these bounds on \( m_{\omega t, b} \) can be used to constrain the \( \phi^4 \) couplings of (2.6).

| \( \lambda_{\omega t} \) | \( \lambda_{\omega b} \) | \( m_{\omega t} \) | \( m_{\omega b} \) | \( \Lambda' \) |
|---|---|---|---|---|
| 0.3 | 1.3 | 583.4 | 100 | 800 |
| 0.5 | 3.0 | 972.4 | 229 | 800 |
| 0.3 | 1.3 | 476.3 | 100 | 1500 |
| 0.5 | 3.0 | 794 | 229 | 1500 |

Table 4: Benchmark points hinted by the precision measurements. Here mass is in unite of GeV. \( \Lambda' = 0.8 (1.5) \text{ TeV} \) corresponds to central value \( \delta g_R^t = -0.002 (-0.003) \), respectively, and \( \delta g_R^b = 1.3 \).

4 Conclusions

In this paper we consider the TC-model with one scalar doublet and two extra colored techni-scalars. After the condensation of techni-fermion at scale \( \Lambda = 4\pi f \sim 480 \text{ GeV} \) which

\footnote{To calculate \( S \) and \( T \) we follow the notation in [20]. In this reference, the four fermions interactions below \( \Lambda_{TC} \) induced by the \( \omega \) scalars are carefully considered. The effects on oblique parameters from these operators can be extracted in terms of the effective field theory analysis.}
is above the EW scale, the scalar doublet receives its vev \( f' \) through its coupling to techni-fermions, gives rises to a SM-like scalar \( \sigma \) discovered at the LHC when \( \theta = f/f' \lesssim 0.2 \). When \( m_\sigma = 125 \) GeV, experimental limits suggest that \( m_\pi^p \) in the range \( 210 - 280 \) GeV. Because of \( \theta \) suppression on Yukawa couplings of techni-pions to SM fermions, they can evade the present experimental limits from both direct and indirect searches.

On the other hand, the colored techni-scalars obtain their masses of order \( \mathcal{O}(0.1-1) \) TeV, through \( \phi^4 \) coupling with scalar doublet. They can provide a large negative contribution to \( S \), which eliminates the large positive contribution arising from condensation, therefore make our model consistent with precision electroweak measurements.

A detailed analysis on bounds of \( \omega \) scalars masses is needed in the further. It is also of interest to consider TC-models with two fundamental scalar doublets instead of one. Finally, it is most important to address the high energy completion of TC model considered here and in earlier works.

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