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Walking from 750 GeV to 950 GeV in the technipion zoo

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If the 750-GeV diphoton excess is identified with the color-singlet isosinglet technipion P^0 (750) in the one-family walking technicolor model, as in our previous paper, then there should exist another color-singlet technipion-isotriplet one, $P^{\pm,3}$, predicted at around 950 GeV independently of the dynamical details. The $P^{\pm,3}(950)$ are produced at the LHC via vector-boson and photon-fusion processes, predominantly decaying to $W\gamma$ and $\gamma\gamma$, respectively. Those walking technicolor signals can be explored at run 2 or 3, which would further open the door for a plethora of other (colored) technipions.

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The ATLAS and CMS groups [1,2] have reported a diphoton excess with a global significance of about 3 standard deviations at around 750 GeV. This would provide a clue for new physics beyond the standard model.

In a previous work [3] the authors gave an interpretation for the diphoton excess by identifying the 750-GeV resonance as a color-singlet isosinglet technipion P^0 of the one-family model [4], which was shown [5,6] to have this large of a mass in the walking technicolor model, with large anomalous dimension $\gamma_m = 1$ [7]. In this paper, we present another implication following the 750-GeV resonance: that is, the presence of the technipion with a mass of 950 GeV, which is color-singlet isotriplet (denoted as $P^{\pm,3}$), enrolled in the technipion "zoo" with 60 entries in total.

The one-family walking technicolor model is a scale-invariant (walking) version of the original one-family technicolor model [4], a naive-scale version of QCD. The theory possesses eight technifermion flavors, $F = (Q^c, L)$, which consist of six techniquarks $[Q^c = (U, D)^c]$, with QCD charge $(c = r, g, b)$ and two technileptons $[L = (N, E)]$, which are singlet under the QCD. The chiral symmetry in the theory is thus enlarged from the $SU(2)_L \times SU(2)_R$ in the standard model to the $SU(8)_L \times SU(8)_R$. The technifermions develop the chiral condensate $\langle \bar{F}F \rangle$ from the strong dynamics to break the chiral $SU(8)_L \times SU(8)_R$ symmetry down to the vectorial $SU(8)_V$. The 63 Nambu-Goldstone (NG) bosons then emerge; three are eaten by the W and Z bosons once the electroweak gauge is turned on, while the other 60 become pseudo-NG bosons due to the explicit breaking effects supplied outside the walking technicolor dynamics. Thus, the low-lying spectra consist of those 60 technipions, as well as the characteristic composite Higgs ("technidilaton," a pseudo-NG boson of the scale symmetry, predicted in the walking technicolor model [7,8]), identified as the 125-GeV LHC Higgs. (Several discussions on the lightness of the technidilaton and the consistency of its coupling property with the LHC Higgs have been given in recent works. See Refs. [9,10].)

The technipions are classified on the basis of the standard-model charges: the color-singlet technipions P^0 and P^i (with $i = 1, 2, 3$ being the isospin charges) are constructed from technifermions as $P^0 \sim \frac{i}{4\sqrt{3}}(\bar{Q}\gamma_5 Q - 3\bar{L}\gamma_5 L)$, $P^i \sim \frac{i}{4\sqrt{3}}(\bar{Q}\gamma_5\sigma^i Q - 3\bar{L}\gamma_5\sigma^i L)$, where σ^i stands for the Pauli matrices. As was discussed in Refs. [5,6] in the context of the walking technicolor model, they get their masses from a four-fermion interaction induced by an extended technicolor model which explicitly breaks the associated chiral symmetry (but keeps the standard-model symmetry),

$$\frac{1}{\Lambda_{\mathrm{ETC}}^2}(\bar{Q}Q\bar{L}L - \bar{Q}\gamma_5\sigma^i Q\bar{L}\gamma_5\sigma^i L). \qquad (1)$$

The masses are calculated by using the standard current algebra. Then one gets the formula [5,6]

$$m_{P^i}^2 = \frac{8}{5} m_{P^0}^2. \qquad (2)$$

It is remarkable to note that this formula is fixed without any detail of the walking dynamics and modeling of the extended technicolor model: the prefactor $(8/5)$ merely comes from the difference in the associated chiral charges for P^0 and $P^{\pm,3}$. As was shown in Ref. [3], the P^0 can be interpreted as the 750-GeV diphoton resonance, so we take $m_{P^0} = 750$ GeV in Eq. (2) to get the P^i mass:

$$m_{P^i} = \sqrt{\frac{8}{5}} m_P^0|_{P^0 \equiv P^0(750)} \simeq 950 \text{ GeV}. \qquad (3)$$

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Thus, the presence of the 750-GeV resonance simultaneously predicts the 950-GeV isotriplet technipion, $P^i \equiv P^i(950)$.

Besides the color-singlet technipions, the theory predicts the color-octet and color-triplet ones. The masses of the colored technipions originate from a different source: they are generated by the QCD interactions, just like the photon exchange contribution to the charged pion mass in QCD. The explicit breaking effect of all the technipions is actually amplified by the large anomalous dimension $\gamma_m \simeq 1$ characteristic of the walking technicolor model [5,6] to lift the mass up to $\mathcal{O}(\mathrm{TeV})$. The precise size of the mass is, however, subject to the nonperturbative calculation of the vector current correlator in the walking dynamics, in sharp contrast to the case of the color-singlet technipions, particularly the ratio m_{P^i}/m_{P^0} which is free from the dynamical details as mentioned above.

The coupling of $P^i(950)$ to the standard-model gauge bosons is only given by the Wess-Zumino-Witten term [11] for the non-Abelian anomaly of the underlying walking technicolor model since the three-NG-boson vertex is forbidden by the low-energy theorem of the spontaneously broken chiral symmetry in the nonanomalous part (see, e.g., Sec. 2.2. of Ref. [12]), which is in sharp contrast to the coupling of the (charged) non-NG boson-heavy Higgs boson in extended Higgs models. The Wess-Zumino-Witten construction for the chiral $SU(8)_L \times SU(8)_R$ symmetry reads

$$S_{\mathrm{WZW}} = -\frac{N_C}{12\pi^2 F_\pi}\int_{M^4} \mathrm{tr}[(3d\mathcal{V}d\mathcal{V} + d\mathcal{A}d\mathcal{A})\pi], \quad (4)$$

which breaks the intrinsic parity[1] [5], where N_C denotes the number of the technicolor model and F_π is the technipion decay constant, fixed by the electroweak scale $v_{\mathrm{EW}} = 246$ GeV as

$$F_\pi = v_{\mathrm{EW}}/\sqrt{N_D}|_{N_D=N_F/2=4} = 123\ \mathrm{GeV}, \quad (5)$$

for the one-family model with eight techniflavors, forming the four electroweak doublets ($N_D = N_F/8 = 4$). Equation (4) has been written in terms of the differential form. The $P^i(950)$ are parametrized in the π matrix, $\pi \ni P^i X_P^i$, with the corresponding $SU(8)$ generator,

$$X_P^i = \frac{1}{4\sqrt{3}}\left(\begin{array}{c|c} \sigma^i \otimes \mathbf{1}_{3\times3} & 0 \\ \hline 0 & -3\cdot\sigma^i \end{array}\right)_{\mathbf{8\times8}}. \quad (6)$$

The standard-model gauge boson fields $(W_\mu^\pm, Z_\mu, A_\mu)$ are embedded in the chiral-external gauge fields $\mathcal{V}_\mu$ and $\mathcal{A}_\mu$ as follows [5]:

$$\begin{aligned} \mathcal{V}_\mu &= eQ_{\mathrm{em}}A_\mu + \frac{e}{2sc}(I_3 - 2s^2 Q_{\mathrm{em}})Z_\mu \\ &\quad + \frac{e}{2\sqrt{2}s}(W_\mu^+ I^+ + W_\mu^- I^-), \\ \mathcal{A}_\mu &= -\frac{e}{2sc}I_3 Z_\mu - \frac{e}{2\sqrt{2}s}(W_\mu^+ I^+ + W_\mu^- I^-), \end{aligned} \quad (7)$$

where e is the electromagnetic coupling, s ($c^2 \equiv 1 - s^2$) denotes the weak mixing angle, and

$$\begin{aligned} Q_{\mathrm{em}} &= I_3 + Y, \\ I_3 &= \frac{1}{2}\left(\begin{array}{c|c} \sigma^3 \otimes \mathbf{1}_{3\times3} & 0 \\ \hline 0 & \sigma^3 \end{array}\right), \\ Y &= \frac{1}{6}\left(\begin{array}{c|c} \mathbf{1}_{2\times2} \otimes \mathbf{1}_{3\times3} & 0 \\ \hline 0 & -3\cdot\mathbf{1}_{2\times2} \end{array}\right), \\ I^\pm &= \frac{1}{2}\left(\begin{array}{c|c} \sigma^\pm \otimes \mathbf{1}_{3\times3} & 0 \\ \hline 0 & \sigma^\pm \end{array}\right), \end{aligned} \quad (8)$$

with $\sigma^\pm = (\sigma^1 \mp i\sigma^2)$. In evaluating Eq. (4) we have omitted the gluon field to which the $P^i(950)$ does not couple because of the isospin symmetry. From this, we extract the $P^i(950)$ couplings to find

$$\begin{aligned} \mathcal{L}_{P^3AA} &= -\frac{e^2 N_C}{4\sqrt{3}\pi^2 F_\pi} P^3 dAdA, \\ \mathcal{L}_{P^3ZZ} &= \frac{e^2(c^2 - s^2)N_C}{8\sqrt{3}\pi^2 c^2 F_\pi} P^3 dZdZ, \\ \mathcal{L}_{P^3AZ} &= -\frac{e^2(1-4s^2)N_C}{8\sqrt{3}\pi^2 sc F_\pi} P^3 dAdZ, \\ \mathcal{L}_{P^\pm AW} &= -\frac{e^2 N_C}{8\sqrt{3}\pi^2 s F_\pi} P^+ dAdW^- + \mathrm{H.c.}, \\ \mathcal{L}_{P^\pm ZW} &= \frac{e^2 N_C}{8\sqrt{3}\pi^2 c F_\pi} P^+ dZdW^- + \mathrm{H.c.}, \end{aligned} \quad (9)$$

where $P^\pm \equiv (P^1 \mp iP^2)/\sqrt{2}$ and $dV_1 dV_2 \equiv \epsilon^{\mu\nu\rho\sigma}\partial_\mu V_{1\nu}\partial_\rho V_{2\sigma}$ for arbitrary vector fields $V_{1\mu}$ and $V_{2\mu}$. Note the absence of the P^3 coupling to WW due to the one-family $SU(8)$ symmetry, such that $\mathrm{tr}[X_P^3\{I^+, I^-\}] = 0$, where the contribution from techniquarks is canceled by that from technileptons, as in the case of the $P^0(750)$ [3,5]. Thus, no coupling of $P^3(950)$ to WW, as well as $P^0(750)$, is the characteristic feature: if the 750-GeV resonance is confirmed in the future, not only in the diphoton channel but also in the WW channel, the present one-family model will definitely be ruled out.

From Eq. (9) we thus compute the partial decay rates of the $P^i(950)$ to get

[1]The intrinsic parity is defined to be even when a particle has parity $(-1)^{\mathrm{spin}}$, and it is odd otherwise.

$$\Gamma(P^3 \to \gamma\gamma) = \left(\frac{\alpha_{\rm em} N_C}{\sqrt{3}\pi F_\pi}\right)^2 \frac{m^3_{P(950)}}{16\pi},$$
$$\Gamma(P^3 \to ZZ) = \left(\frac{\alpha_{\rm em}(c^2 - s^2) N_C}{2\sqrt{3}\pi c^2 F_\pi}\right)^2 \frac{m^3_{P(950)}}{16\pi}\left(1 - \frac{4m_Z^2}{m^2_{P(950)}}\right)^{3/2},$$
$$\Gamma(P^3 \to Z\gamma) = \left(\frac{\alpha_{\rm em}(1 - 4s^2) N_C}{2\sqrt{3}\pi s c F_\pi}\right)^2 \frac{m^3_{P(950)}}{32\pi}\left(1 - \frac{m_Z^2}{m^2_{P(950)}}\right)^{3}, \quad (10)$$

and

$$\Gamma(P^\pm \to W^\pm\gamma) = \left(\frac{\alpha_{\rm em} N_C}{2\sqrt{3}\pi s F_\pi}\right)^2 \frac{m^3_{P(950)}}{32\pi}\left(1 - \frac{m_W^2}{m^2_{P(950)}}\right)^{3},$$
$$\Gamma(P^\pm \to W^\pm Z) = \left(\frac{\alpha_{\rm em} N_C}{2\sqrt{3}\pi c F_\pi}\right)^2 \frac{m^3_{P(950)}}{32\pi}\left(1 - \left(\frac{m_W + m_Z}{m_{P(950)}}\right)^2\right)^{3/2} \times \left(1 - \left(\frac{m_W - m_Z}{m_{P(950)}}\right)^2\right)^{3/2}, \quad (11)$$

where $\alpha_{\rm em} \equiv e^2/(4\pi)$. Note that the branching ratios are estimated independently of N_C and F_π to be

$$\mathrm{Br}[P^3 \to \gamma\gamma] \simeq 89.5\%,$$
$$\mathrm{Br}[P^3 \to ZZ] \simeq 10.2\%,$$
$$\mathrm{Br}[P^3 \to Z\gamma] \simeq 0.30\%, \quad (12)$$

and

$$\mathrm{Br}[P^\pm \to W^\pm\gamma] \simeq 77\%,$$
$$\mathrm{Br}[P^\pm \to W^\pm Z] \simeq 23\%. \quad (13)$$

The total widths are estimated by using the value of F_π in Eq. (5) and taking typical numbers for N_C, say, $N_C = 3$, 4:

	$N_C = 3$	$N_C = 4$
$\Gamma_{\rm tot}^{P^3(950)}$ (MeV)	23	42
$\Gamma_{\rm tot}^{P^\pm(950)}$ (MeV)	14	25

(14)

which shows that the $P^{\pm,3}(950)$ are quite narrow resonances.

Note that the $P^{\pm,3}(950)$ are basically NG bosons, so they do not couple to longitudinal modes of weak gauge bosons, which are essentially the NG bosons, and hence the coupling would be the forbidden three-NG-boson vertex as mentioned before, as far as the nonanomalous part with the intrinsic-parity even is concerned. The couplings to WZ and ZZ, corresponding to the transverse modes, then arise from the loop-induced anomalous term, the Wess-Zumino-Witten term with intrinsic-parity odd as in Eq. (9). [Note again that the $SU(8)$ symmetry forbids the coupling to WW.] Thus, all the $P^{\pm,3}(950)$ couplings are necessarily loop suppressed; hence, the total widths are very small as in Eq. (14). Thus, the $P^{\pm,3}(950)$ have small couplings to weak gauge bosons, leaving the small $P^{\pm,3}$ production cross sections to easily escape from the current LHC limits, as will be seen later.

Of interest is that the charged $P^\pm(950)$ mainly decay to $W^\pm\gamma$ rather than $W^\pm Z$ [see Eq. (13)]. This is simply due to the suppression by the weak mixing angle for the coupling to Z compared to that to the photon [see Eq. (9)]. This feature is in sharp contrast to other model isotriplet heavy Higgses which hardly decay to $W\gamma$ as addressed above. Hence the $P^\pm(950) \to W^\pm\gamma$ channel will give the characteristic signature at the LHC, a smoking gun of the one-family walking technicolor model, although the production cross section is somewhat small, as will be discussed below.

Now we discuss the $P^{\pm,3}(950)$ signatures at the LHC. First, we look into the neutral $P^3(950)$. Because of the large coupling to the diphoton as in Eq. (12), the $P^3(950)$ can dominantly be produced by the photon-photon fusion ($\gamma\gamma$F). Using the effective photon approximation [13] as in the literature [14], we may calculate the production cross section of $P^3(950)$ at $\sqrt{s} = 13$ TeV via the elastic photon-photon–fusion process to get

$$\sigma^{13\,\mathrm{TeV}}_{\gamma\gamma\mathrm{F}}(pp \to P^3(950))|_{\rm elastic} \simeq 0.018(0.034)\ \mathrm{fb}, \quad (15)$$

for $N_C = 3(4)$. Including the inelastic scattering contributions would largely enhance the cross section as discussed in several works listed in Refs. [15,16]. According to this literature, the enhancement factor will be $\mathcal{O}(20)$, or more, normalized to the elastic scattering process at the resonance mass of 750 GeV. Quoting the result in Ref. [16] and scaling the resonance mass (m_R) from 750 GeV up to 950 GeV, one finds $\sigma^{13\,\mathrm{TeV}}_{\gamma\gamma F}(m_R = 950\ \mathrm{GeV})/\sigma^{13\,\mathrm{TeV}}_{\gamma\gamma F}(m_R = 750\ \mathrm{GeV}) \sim 0.76$. Taking into account this factor, together with the enhancement factor as above, we may roughly estimate the production cross section,

$$\sigma^{13\,\mathrm{TeV}}_{\gamma\gamma\mathrm{F}}(pp \to P^3(950))|_{\rm elastic+inelastic} \sim 0.27(0.52)\ \mathrm{fb}. \quad (16)$$

Using the numbers listed in Eq. (12), we thus estimate the $P^3(950)$ signal strengths:

$\sigma^{13\,\mathrm{TeV}}_{\gamma\gamma\mathrm{F}}(P^3) \times \mathrm{Br}$ (fb)	$N_C = 3$	$N_C = 4$
$\gamma\gamma$	0.24	0.46
ZZ	0.028	0.052
$Z\gamma$	0.00091	0.0015

(17)

The most stringent signal is seen in the diphoton channel, which is compared with the ATLAS and CMS 13-TeV limits at around 950 GeV, $\sigma_{\gamma\gamma}^{\rm ATLAS13} \lesssim 1.6$ fb ($\mathcal{L} = 3.2$ fb^{-1}) and $\sigma_{\gamma\gamma}^{\rm CMS13} \lesssim 5$ fb ($\mathcal{L} = 2.6$ fb^{-1}), so it is far below the present bound, to be excluded, or detected in the future experiments with higher statistics.

We next turn to the charged $P^{\pm}(950)$ production at the LHC. Looking at Eq. (13) we find that the $P^{\pm}(950)$ couple to the diboson WZ, so they can be singly produced by vector-boson fusion (VBF). Applying the effective vector-boson approximation [17] with the parton distribution function CTEQ6L1 [18], we may estimate the 13-TeV production cross section of the $P^{\pm}(950)$ to get

$$\sigma_{\rm VBF}^{\rm 13\ TeV}(pp \to WZ \to P^{\pm} + jj) \simeq 0.18(0.31)\ \text{fb}, \quad (18)$$

for $N_C = 3(4)$, where j denotes quarks and antiquarks. Using the numbers displayed in Eq. (13), we thus calculate the signal strengths of the $P^{\pm}(950)$:

$\sigma_{\rm VBF}^{\rm 13\ TeV}(P^{\pm}) \times {\rm Br}$ [fb]	$N_C = 3$	$N_C = 4$
$W\gamma + jj$	0.14	0.24
$WZ + jj$	0.041	0.073

(19)

As for the WZ channel, the ATLAS Collaboration has placed the 95% C.L. upper limit at 8 TeV ($\mathcal{L} = 20.3$ fb^{-1}) on charged scalar resonances produced via the VBF, which is $\sigma_{\rm VBF}^{\rm 8\ TeV}(WZ) \lesssim 70$ fb at around 950 GeV [19]. On the other hand, the $P^{\pm}(950)$ predicts $\sigma_{\rm VBF}^{\rm 8\ TeV}(pp \to P^{\pm} \to WZ) \simeq 0.0088(0.016)$ for $N_C = 3(4)$, so it is far below the presently available upper bound.

As noted above, the $W\gamma$ cross section is much larger than the WZ cross section, in contrast to other charged heavy scalars like in models with the extended Higgs sector. This $W\gamma$ signal is the salient phenomenological feature of the $P^{\pm}(950)$, to be tested in future LHC experiments.

Actually, the $P^{\pm,3}(950)$ can also be produced through the decay of the technirho (denoted as ρ_Π), which might be responsible for the 8-TeV diboson excess at around 2 TeV [20]: the ρ_Π couplings to the $P^{\pm,3}$ can be read off from the third reference of Ref. [20]. As done in the 8-TeV analysis in the references, we may set the overall strength of the diboson coupling ($g_{\rho\pi\pi}$) to 4 so as to control the total width of the ρ_Π to be less than 100 GeV, which is fitted to the ATLAS diboson excess data [21]. As for the Drell-Yan coupling of the ρ_Π (F_ρ), however, it is now more severely constrained by the 13-TeV diboson data, most stringently on $WZ \to jj\nu\bar{\nu}$ [22], updated from the previous publication [20], to be $F_\rho \lesssim 350$ GeV. (The ρ_Π diboson cross section with the Drell-Yan coupling $F_\rho \lesssim 350$ GeV cannot account for the 8-TeV excess, which is due to the current tension between the 8-TeV and the 13-TeV results on the diboson data.) Taking this into account, we find that the branching ratio for $\rho_\Pi \to PP$ is about 3%. By scaling the result in Ref. [20], we thus estimate the $P^{\pm,3}(950)$ pair-production cross section at 13 TeV:

$$\sigma_{\rm DY}^{\rm 13\ TeV}(pp \to \rho_\Pi^3 \to P^+P^-) \simeq 0.30\ \text{fb},$$
$$\sigma_{\rm DY}^{\rm 13\ TeV}(pp \to \rho_\Pi^\pm \to P^\pm P^3) \simeq 0.59\ \text{fb}, \quad (20)$$

for $F_\rho = 350$ GeV and $g_{\rho\pi\pi} = 4$. In this production process the final-state topology will be like multiphoton plus jets through the dominant decay modes $P^3 \to \gamma\gamma$ and $P^\pm \to W\gamma$, in which two of the multiphotons are detected with an invariant mass around 950 GeV and all the final states can be fully reconstructed to be the 2-TeV resonance. This is an exotic topology, so it would be a clean signal to be tested at the future LHC experiments.

In conclusion, the LHC 750-GeV diphoton excess implies the presence of yet another resonance at 950 GeV, which is the color-singlet isotriplet-technipion, $P^{\pm,3}$, in the one-family walking technicolor model. The $P^{\pm,3}$ mass is completely fixed at 950 GeV, which is free from any detail of the walking dynamics, once the 750-GeV resonance is identified with the color-singlet isosinglet technipion $P^0(750)$. The $P^{\pm,3}(950)$ are singly produced at the LHC via vector-boson and photon-fusion processes, and doubly produced by the (2-TeV) technirho decay. Those technipions predominantly decay to $W\gamma$ [for the charged $P^{\pm}(950)$] and $\gamma\gamma$ [for the neutral $P^3(950)$]. In particular, the charged $P^{\pm}(950)$ signal is quite intrinsic for the $W\gamma$ channel, which yields a sizable cross section, leading to an intriguing topology such as dijet plus monophoton (along with forward jets). This is the rare signal for other charged heavy scalars as in models with the extended Higgs sector, so it will be characteristic only for the $P^{\pm}(950)$, to be accessible at run 2 or 3.

In addition to the color-singlet technipions, there are colored ones in the technipion "zoo" in the one-family walking technicolor model. As noted in the early stage of the present paper, colored technipion masses are predicted to be around TeV, though they are subject to details of the walking dynamics. The colored technipions would also show up in the LHC experiments, through the large signals in the dijet channel, or monojet and single photons, as was analyzed in the literature [5,6]. Thus, a number of technipions are standing by behind the 750-GeV one in the one-family walking technicolor model.

A more precise estimation of the walking signals in the technipion zoo and comparison with the standard-model background will be pursued in another publication.

In closing, in the present analysis we have so far been restricted to discussing the technipion couplings to the standard-model gauge bosons. Besides those, the technipions may actually be allowed to couple to the standard-model fermions, through extended technicolor interactions, though those couplings are formally generated at higher loops involving physics well outside of the walking technicolor dynamics. Among the standard-model fermions, the Yukawa couplings to top quark and bottom quark pairs would be the most influential in giving significant corrections to the branching fraction of the technipions, as explicitly discussed in Ref. [5]. The strength of such Yukawa couplings is actually highly dependent on the details of the extended-technicolor model building, such as the variants of strong extended technicolor model [23] having an anomalous dimension, $1 < \gamma_m < 2$, even larger than the walking technicolor model. Hence we have disregarded those Yukawa couplings in the present analysis, in order to estimate effects of the purely walking technicolor dynamics as a starting point of the future analyses. A detailed study on the phenomenologically allowed size of the Yukawa couplings and the related flavor physics predicted from the walking technicolor model will be done elsewhere.

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