Ref.TH.2868-CERN

MINIMAL COMPOSITE HIGGS SYSTEMS

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A B S T R A C T

Extending to technicolour models recent results on the chiral, large N_c limit of QCD, we argue that minimal composite Higgs systems must contain an η like Higgs particle, whose peculiar properties follow from current algebra and large N arguments only. By contrast, the usual scalar Higgs is a model-dependent entity without clear experimental signature.

Ref.TH.2868-CERN

28 May 1980

1. The presence of elementary Higgs fields in the standard Glashow-Weinberg-Salam (GWS) model is generally regarded as one of its less attractive features: it is, for instance, "unnatural" in the sense recently defined by 't Hooft⁽¹⁾.

A simple alternative to elementary Higgs scalars is to regard⁽²⁾ them as bound states of a new kind of "quarks" and "gluons", which interact strongly according to a QCD-like Lagrangian, $\mathcal{L}_{\text{QC'D}}$, in which the colour gauge symmetry $SU(N)$ ($N=N_c=3$) is replaced by a new one (techni-prime-hyper-meta-heavy-colour in the literature) taken to be, for simplicity, $SU(N')$. In order to get the right value of m_W (or of G_F), this technicolour (TC) interaction is assumed to become strong at a scale Λ' , some three orders of magnitude larger⁽⁺⁾ than $\Lambda = \Lambda_{\text{Colour}} \simeq 0.5 \text{ GeV}$.

The dynamical Higgs mechanism originates in TC schemes from gauging a spontaneously broken chiral symmetry of QC'D. It is important therefore to start our discussion from a consistent picture of chiral symmetry breaking in QCD-like theories. One such picture has recently emerged^(3,4) within the framework of the $1/N_c$ expansion of QCD: in particular the famous $U(1)$ problem⁽⁵⁾ can be brought under control, a very reasonable mass spectrum and interaction pattern for the nine low-lying pseudoscalars is obtained and a consistent θ -dependence of physical quantities is derived⁽⁶⁾.

The above results are neatly summarized by an effective Lagrangian⁽⁷⁻⁹⁾ containing the light degrees of freedom of QCD in the combined chiral, large N limit. There is, as usual, a great deal of arbitrariness in the choice of $\mathcal{L}_{\text{eff}}$; yet, the quantities we shall be concerned with follow just from current algebra and large N expansion arguments and will not depend on the actual choice made.

In this paper a minimal composite-Higgs model is thus constructed out of a single doublet of light techniquarks. After combining QCD, QC'D and electroweak interactions à la GWS, an almost conventional scheme results.

(+) According to grand-unification ideas, this occurs naturally if $N' > N = 3$, in which case the $1/N$ expansion arguments, we are going to make, should work better for QC'D than for QCD.

There is however an interesting novelty: whereas the properties of the usual scalar Higgs meson appear to be model dependent (to the extent that such a particle even disappears in the non linear version presented here), one predicts the existence of a composite η -Higgs particle (the U(1) particle of QC'D, denoted hereafter by η_H) whose peculiar properties can be reliably computed via current algebra and $1/N'$ expansion techniques. The most amazing property of η_H will turn out to be its narrow width (Γ/M of order 10^{-4} to be contrasted with $1/3$ to $1/2$ for a typical technicolour scalar Higgs).

2. We shall first recall the form of $\mathcal{L}_{\text{eff}}^{\text{QCD}}$ proposed in Refs.7 and 8 for the large N chiral limit of QCD. In its most economical version, where only physical light fields appear, it reads:

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{\text{QCD}} &= \mathcal{L}_{\text{inv}}^{\text{QCD}} + \mathcal{L}_{\text{anom.}}^{\text{QCD}} + \mathcal{L}_{\text{mass}}^{\text{QCD}} \\ \mathcal{L}_{\text{inv.}}^{\text{QCD}} &= \frac{1}{2} \text{Tr}(\partial_\mu V^\dagger \partial_\mu V) \quad ; \quad \mathcal{L}_{\text{anom.}}^{\text{QCD}} = -\frac{af_\pi^2}{2N} \left[\theta - \frac{i}{2} \text{Tr} \log \frac{V}{V^\dagger} \right]^2 \\ \mathcal{L}_{\text{mass}}^{\text{QCD}} &= \frac{f_\pi}{2} \text{Tr}(MV + M^\dagger V^\dagger)\end{aligned}\tag{1}$$

The mesonic field $V(x)$ is here an $f \times f$ matrix (f being the number of quark flavours) subject to the constraint $V^\dagger V = VV^\dagger = f_\pi^2 \mathbb{1}$. We then write :

$$V = f_\pi \exp(i f_\pi^{-1} \tau_i \pi^i) \quad ; \quad \text{Tr}(\tau_i \tau_j) = \delta_{ij} \quad , \quad i, j = 1, 2, \dots, f^2 \tag{2}$$

with $f_\pi \simeq 66$ MeV the pion decay constant and π_i the f^2 pseudoscalar fields. Since V_{ij} transforms like $\bar{\psi}_R \psi_L$ under (global) chiral $U(f) \times U(f)$ transformations:

$$V(x) \rightarrow A V(x) B^\dagger \quad ; \quad A, B \in U(f) \tag{3}$$

eq.(2) implies $\langle V_{ij} \rangle = f_\pi \delta_{ij}$ i.e. the spontaneous breaking of $U(f) \times U(f)$ down to $SU(f)_{\text{vector}}$. Furthermore, an explicit breaking term $\mathcal{L}_{\text{mass}}^{\text{QCD}}$ has been included to represent the effect of quark masses and the U(1) axial subgroup is also broken explicitly by $\mathcal{L}_{\text{anom.}}$. Such a term does also include⁽⁸⁾, through the parameter a , the effect of Kogut-Susskind (KS) poles so that, in the chiral limit ($\mathcal{L}_{\text{mass}} \rightarrow 0$), the model has (f^2-1) massless Goldstone bosons and one massive $SU(f)$ singlet particle with⁽⁴⁾:

$$m_{\text{singlet}}^2 = f a/N \quad (4)$$

Through anomalous Ward identities expanded in $1/N$, the parameter a can be related ^(3,4) to a quantity of the theory without quarks (pure Yang-Mills) i.e.

$$\int d^4x \, T \langle Q(x) Q(0) \rangle \Big|_{N \rightarrow \infty}^{\text{Y.M.}} = i a \frac{f_\pi^2}{N} \quad (5)$$

with $Q(x)$ the usual topological charge density. Since $Q(x)$ is a total divergence, $a \neq 0$ implies KS poles. To leading order in $1/N$ $a = k \Lambda^2$ with k (in principle) a calculable constant.

Fitting pseudoscalar masses with $\mathcal{L}_{\text{mass}}$ taken into account, one finds ⁽⁴⁾:

$$a \simeq 0.7 \div 0.75 \text{ GeV}^2 \quad (6)$$

Finally, in eq.(1), θ is the QCD vacuum angle ⁽¹⁰⁾ and M is a real-diagonal mass matrix:

$$M_{ij} = \mu_i^2 \delta_{ij} \quad (7)$$

3. We now consider a rescaled version of eq.(1) for a new strong interaction, QC'D, characterized by a scale Λ' with:

$$\Lambda' = \rho \Lambda \quad ; \quad \rho \gg 1 \quad (8)$$

Besides ρ , the other free parameter of QC'D in the chiral limit are N' and the number of techniflavours f' . The rest is fixed from rescaling and large N counting so that $\mathcal{L}_{\text{inv}}^{\text{QC'D}}$ is obtained from $\mathcal{L}_{\text{inv}}^{\text{QCD}}$ by the replacements:

$$f_\pi \rightarrow f'_\pi = \rho \sqrt{\frac{N'}{3}} f_\pi \quad ; \quad a \rightarrow a' = \rho^2 a \quad (9)$$

and by "priming" all fields and parameters ($V \rightarrow V'$, $\theta \rightarrow \theta'$ etc.).

At this stage, in the absence of $\mathcal{L}_{\text{mass}}$, we have two decoupled worlds with global invariance under:

$$G^{\text{Global}} = SU(f) \otimes SU(f) \otimes SU(f') \otimes SU(f') \quad (10)$$

which is spontaneously broken by f_{π} , $f'_{\pi} \neq 0$.

In order to construct a model containing a minimal number of light particles (in particular, no other massless particle in the chiral limit) we choose $f'=2$. Since our next step is the gauging of an $SU(2) \times U(1)$ subgroup of G^{Global} , we need to replace $\mathcal{L}_{\text{mass}}^{\text{QCD}} + \mathcal{L}_{\text{mass}}^{\text{QC'D}}$ by a term which preserves such group e.g.

$$\mathcal{L}_{\text{mass}}^{\text{QCD+QC'D}} \rightarrow \mathcal{L}_{\text{mass}} \equiv f_{\pi} f'_{\pi} \text{Tr} [\lambda \tilde{V}'^+ V + h.c.] \quad (11)$$

where V' is an f by f matrix made of $f/2$ two by two blocks equal to V' and λ is a real diagonal⁽⁺⁾ coupling matrix:

$$\lambda_{ij} = \lambda_i \delta_{ij} \quad (12)$$

$\mathcal{L}_{\text{mass}}$ does indeed preserve the GWS subgroup of G^{Global} given by two-by-two block diagonal matrices with the following matrices in each block:

$$SU(2)_L : A = A' \in SU(2) ; B = B' = 1 \quad (13)$$

$$U(1) : A = e^{\frac{i}{2}\sigma\beta}, A' = e^{\frac{i}{2}\sigma'\beta}$$

$$B = e^{\frac{i}{2}\tau_3\beta} e^{\frac{i}{2}\sigma\beta} ; B' = e^{\frac{i}{2}\tau_3\beta} e^{\frac{i}{2}\sigma'\beta}$$

Since we want $SU(2)_L \times U(1)$ to break down to $U(1)_Q$ of electric charge, we see immediately that σ, σ' are determined by the requirement that:

(+) It is easy to see, however, that the most general form of $\mathcal{L}_{\text{mass}}$ compatible with $SU(2) \times U(1)$ invariance allows for arbitrary Cabibbo angles and Kobayashi-Maskawa phases. However, for the purposes of this paper we can set to zero all these angles as well as θ and θ' .

$$\begin{aligned}\tau_3/\sqrt{2} + \sigma &= Q = \begin{pmatrix} 2/3 & 0 \\ 0 & -1/3 \end{pmatrix} \text{ i.e. } \sigma = 1/6 \\ \tau_3/\sqrt{2} + \sigma' &= Q' = \begin{pmatrix} Q_u' & 0 \\ 0 & Q_d' = Q_u' - 1 \end{pmatrix} \text{ i.e. } \sigma' = Q_u' - 1/2\end{aligned}\quad (14)$$

Gauging this GWS group we arrive at our final Lagrangian:

$$\begin{aligned}\mathcal{L}^{QCD+QC'D+GWS} &\equiv \mathcal{L} = \mathcal{L}_{inv.}^{QCD}(\partial_\mu V \rightarrow \partial_\mu V + ig_2 \tilde{A}_\mu V - ig_1 V B_\mu \tilde{\tau}_3/\sqrt{2}) \\ &+ \mathcal{L}_{inv.}^{QC'D}(\partial_\mu V' \rightarrow \partial_\mu V' + ig_2 A_\mu V' - ig_1 V' B_\mu \tau_3/\sqrt{2}) + \mathcal{L}_{mass} + \\ &- 1/4 F_{\mu\nu}^i F_{\mu\nu}^i - 1/4 G_{\mu\nu} G_{\mu\nu} + \mathcal{L}_{WEM\ anomaly} + \mathcal{L}_{leptons}^{GWS}\end{aligned}\quad (15)$$

Here g_1, g_2 are the two usual gauge couplings of $SU(2)_L \times U(1)$ and

$$\begin{aligned}A_\mu &= A_\mu^i \frac{\tau_i}{\sqrt{2}} \quad ; \quad F_{\mu\nu}^i = \partial_\mu A_\nu^i - \partial_\nu A_\mu^i + g_2 \epsilon^{ijk} A_\mu^j A_\nu^k \\ G_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu\end{aligned}\quad (16)$$

In eq.(15) $\tilde{A}_\mu$ and $\tilde{\tau}_3$ stand for obvious block diagonal fxf matrices.

Besides the mass term (11) we have also added electroweak anomalies and a leptonic term (see below). The latter is supposed to free the model from the dangerous anomalies of gauged axial currents. This is easily achieved with $l/2$ standard leptonic doublets if

$$l/2 = f/2 + (2Q_u' - 1)N' = f/2 + 2\sigma'N' \quad (17)$$

which is an integer if "technibaryons" (made out of N' techniquarks) have integer charge (e.g. $Q_u' = (N'-1)/N'$, $2\sigma'N' = (N'-2)$).

4) We now discuss the spectrum of the model defined by eq.(15). It is convenient to perform a "gauge transformation" on the vector fields A_μ^i by defining:

$$W_\mu = W_\mu^i \frac{\tau_i}{\sqrt{2}} = U^\dagger A_\mu U - \frac{i}{g_2} U^\dagger \partial_\mu U = -\frac{i}{g_2} U^\dagger D_\mu U \quad (18)$$

with

$$U = (U^+)^{-1} = 1 + i \tau_i X_i + \dots; \quad X_i = (f_\pi'^2 + \frac{f_2}{2} f_\pi^2)^{-1} \left[f_\pi' \pi_i' + f_\pi \sum_{k=1}^{\frac{N}{2}} \pi_i^{(k)} \right] \quad (19)$$

where $\pi_i^{(1)} = \pi_i$, $\pi_i^{(2)}$ is the analog of π_i for the 2nd generation of quarks etc.

We also introduce the usual combinations:

$$Z_\mu^0 = (g_1^2 + g_2^2)^{-1/2} [g_2 W_\mu^3 - g_1 B_\mu]; \quad A_\mu^{el} = (g_1^2 + g_2^2)^{-1/2} [g_1 W_\mu^3 + g_2 B_\mu] \quad (20)$$

One then finds that $W^\pm = 1/\sqrt{2}(W^1 \pm iW^2)$ and Z^0 fields acquire a mass term à la Higgs through the following piece of $\mathcal{L}$:

$$\mathcal{L}_{Higgs} = \frac{1}{8} g_2^2 F^2 \sum_{i=1}^2 (W_\mu^i)^2 + \frac{1}{8} (g_1^2 + g_2^2) F^2 (Z_\mu^0)^2; \quad F^2 = 2(f_\pi'^2 + \frac{f_2}{2} f_\pi^2) \quad (21)$$

giving⁽⁺⁾:

$$m_{W^\pm} = \frac{g_2}{2} F; \quad m_{Z^0} = \frac{m_W}{\cos \theta_W}; \quad \cos \theta_W = \frac{g_2}{\sqrt{g_1^2 + g_2^2}} \quad (22)$$

Since $8G_F/\sqrt{2} = g_2^2 m_W^{-2}$ we find:

$$F = \sqrt{2} (f_\pi'^2 + \frac{f_2}{2} f_\pi^2)^{1/2} = (G_F \sqrt{2})^{-1/2} = 246 \text{ GeV} \quad (23)$$

Consequently, from eq.(9):

$$f_\pi'/f_\pi = \rho \sqrt{N'/3} \simeq 2.6 \cdot 10^3; \quad \rho = 2.6 \cdot 10^3 \sqrt{3/N'} \quad (24)$$

At this point one can rewrite (21) in terms of the original fields and observe that exactly the X_i combinations of eq.(19) have been eaten up (having lost their kinetic term) by becoming the longitudinal components of $W^\pm$ and Z^0 .

(+) Notice that we are able to preserve the standard relation $m_W = m_Z \cos \theta_W$ even if we allow, from $\mathcal{L}_{mass}$, $m_u \neq m_d$. In the spirit of Ref.11, we can say that our technicolour condensate conserves isospin, whereas extended technicolour interactions (which we do not analyze here) may not do so.

We now turn to $\mathcal{L}_{\text{mass}}$. Because of its invariance under $SU(2) \times U(1)$ (broken spontaneously to $U(1)$), $\mathcal{L}_{\text{mass}}$ gives a mass matrix with three eigenvectors which are just the X_i combinations of eq.(19), eaten up in the Higgs phenomenon⁽⁺⁾. The rest of the spectrum is easy to describe even if not easy to determine analytically. It consists of

a) Flavourful pseudo-Goldstone bosons of QCD which are unaffected (i.e. unmixed) by QC'D (e.g. $\bar{u}s, \bar{u}c$ etc). They have masses given by

$$\mu_{\alpha\beta}^2 = (\lambda_\alpha + \lambda_\beta) f_\pi^2 \quad (25)$$

in agreement with standard formulae⁽⁸⁾ if we identify μ_α^2 of eq.(7) with $2\lambda_\alpha f_\pi^2$.

b) Flavourful pseudo-Goldstone bosons which are the surviving (i.e. not eaten up) mixtures of QCD and QC'D states. A typical example are the physical $\pi^\pm$ eigenstates (which are orthogonal to $X^\pm$ of eq.(19)) given by :

$$\pi_{ph}^\pm = \pi^\pm - \frac{f_\pi}{f_\pi'} \pi^{\pm'} + O\left(\left(\frac{f_\pi}{f_\pi'}\right)^2 \pi_\alpha^\pm\right) \quad (26)$$

We conclude that, in the above two sectors, physics is just conventional QCD once the $X^\pm$ states are absorbed.

c) There are, finally, flavourless pseudoscalars. Besides the eaten-up combination X_3 , we find the usual QCD flavourless pseudoscalars (with a tiny admixture of $\bar{u}'u'$ and $\bar{d}'d'$). One of them becomes, in the chiral limit ($\lambda_\alpha \rightarrow 0$), the $U(1)$ particle of QCD of mass given as in eq.(4). For a general mass (or coupling) matrix the situation is as discussed Refs.4,8 up to $O(f_\pi/f_\pi')$ corrections.

There is, however, a new state in this sector: it is (again up to a small mixing) the $U(1)$ particle of QC'D, i.e.

(+) $\mathcal{L}_{\text{mass}}$ is also invariant under a subgroup of $U_A(1) \times U_A'(1)$ and, as a consequence, one finds that only a linear combination of θ and θ' affects physics (we can set $\theta'=0$). However, unless something more is done for the techniquark mass terms, (essentially) the same CP violating interaction discussed in Ref.6 originates if $\theta \neq 0$.

$$\eta_H \equiv \frac{1}{\sqrt{2}} (\pi'_u + \pi'_d) + O\left(\left(\frac{f_\pi}{f_{H'}}\right)(\pi_u^* + \pi_d^*)\right) \quad (27)$$

In perfect analogy with Eq. (4) its (mass)² is:

$$m^2(\eta_H) = 2 a'/N' \quad (28)$$

We stress that this particle is a singlet of SU(2) x U(1) and that, as such, it does not enter directly in the GWS Higgs phenomenon.

Its existence, however, is necessary in the 1/N' expansion of QC'D or, equivalently, in any techniquark model. Furthermore, as shown in our last paragraph, its properties can be reliably computed from the effective Lagrangian approach and bear resemblance to those of either an η or a Higgs particle according to the process considered.

5. We now discuss the detailed properties of the η_H particle. Using eqs.(24) and (29) the mass of η_H is given by

$$m(\eta_H) = \sqrt{\frac{2a'}{N'}} = \rho \sqrt{\frac{2a}{N'}} = \frac{5.4}{N'} \text{ TeV} \quad (29)$$

There is no "light" (i.e. $m < m_W$) Higgs particle in this model. The analog of the σ particle of QCD (0^{++} broad $\pi\pi$ structure at about 700 MeV) would have a mass⁽¹⁾:

$$m(\sigma_H) \simeq 0.7 \rho \text{ GeV} \simeq \frac{3.2}{\sqrt{N'}} \text{ TeV} > m(\eta_H) \text{ for } N' \geq 4 \quad (30)$$

As in QCD, this particle would have a very large width, this time into W^+W^- and $2Z^0$. By going into a non linear " σ -model" we have sent $m(\sigma_H)$ to infinity⁽⁺⁾. One can easily check, however, that in a linear version with $m(\sigma_H) \sim 1 \text{ TeV}$ one gets $\Gamma(\sigma_H \rightarrow W^+W^-, 2Z^0) \simeq 0.3 \text{ TeV}$.

(+) In a recent investigation⁽¹²⁾ it has been shown that low energy phenomenology depends only weakly (i.e. logarithmically) on the mass of the scalar Higgs particle, hence "low energy" phenomena depend very little on $m(\sigma_H)$.

By contrast, η_H has a hard time decaying just like her QCD fellows η, η' . There is no first order decay of $\eta_H \rightarrow$ vector mesons but there is one via the electroweak anomaly (same as for $\pi^0, \eta^0 \rightarrow 2\gamma$). This turns out to be one of the main decay channels of η_H together with lepton pairs and $q\bar{q}$ pairs (i.e. jets).

The decay into pairs of vector mesons can be evaluated using the standard analysis of electroweak anomalies⁽¹³⁾. We found the following amplitudes:

$$\begin{pmatrix} \eta_H \rightarrow 2\gamma \\ \eta_H \rightarrow 2Z^0 \\ \eta_H \rightarrow Z^0\gamma \\ \eta_H \rightarrow W^+W^- \end{pmatrix} = I \begin{pmatrix} 3(1+4\sigma'^2) \\ 4[1+3(1+4\sigma'^2)\sin^2\theta - 3\sin^2\theta]/\sin^2 2\theta \\ 3[2(1+4\sigma'^2)\sin^2\theta - 1]/\sin 2\theta \\ (\sin^2\theta)^{-1} \end{pmatrix} \quad (31)$$

where σ' is defined in eq.(14) and:

$$I = -\frac{\alpha N'}{6\sqrt{2}\pi f_\pi'} \epsilon_{\mu\nu\rho\sigma} p_{1\mu} \epsilon_{1\nu} p_{2\rho} \epsilon_{2\sigma} ; \quad \sin^2\theta \equiv \sin^2\theta_W \simeq 0.23$$

With this value of $\sin^2\theta_W$ and taking for instance $\sigma' = 1/6 = \sigma$ one gets:

$$\begin{aligned} \Gamma(\eta_H \rightarrow W^+W^-) &= \frac{73}{N'} \text{ MeV} ; \quad \Gamma(\eta_H \rightarrow Z^0\gamma) = \frac{12}{N'} \text{ MeV} \\ \Gamma(\eta_H \rightarrow 2\gamma) &= \frac{21.5}{N'} \text{ MeV} ; \quad \Gamma(\eta_H \rightarrow 2Z^0) = \frac{15}{N'} \text{ MeV} \end{aligned} \quad (32)$$

provided that N' is small enough so that $m(\eta_H) \gg 2m(Z^0)$ (e.g. $N'=4,5$).

Notice the small width obtained. For $N'=4$, the total width into vector mesons is of order⁽⁺⁾ 30 MeV: we can say that η_H behaves rather like π^0, η, η' in this respect!

Before saying that we are dealing with a narrow object we have to search for other possibly large decay modes. We found the only appreciable ones to be those induced by the mass generating Higgs couplings to quarks and leptons.

(+) Even smaller widths are predicted into $W^+W^-\gamma$ etc.

For instance, if all⁽⁺⁾ the mass of leptons comes from coupling $\bar{\psi}_\ell \psi_\ell$ to V' , one inherits for η_H a coupling:

$$\mathcal{L}_{\eta_H \rightarrow \ell^+ \ell^-} = \frac{1}{\sqrt{2}} \sum_\ell \frac{m_\ell}{f_\pi'} \bar{\psi}_\ell \gamma_5 \psi_\ell \eta_H \quad (33)$$

We see here the η_H behaving like a bona fide Higgs particle!

From (33) we get a decay rate:

$$\Gamma(\eta_H \rightarrow \ell^+ \ell^-) = \frac{1}{16\pi} \left(\frac{m_\ell}{f_\pi'} \right)^2 m(\eta_H) \quad (34)$$

i.e. negligible (compared to eq.(32)) widths into light leptons and

$$\Gamma(\eta_H \rightarrow \tau^+ \tau^-) = 11.5/N', \text{ MeV} \quad (35)$$

For $q, \bar{q}$ jets the situation is analogous with an obvious extra factor of three for colour. For a b-quark of mass 5 GeV one gets :

$$\Gamma(\eta_H \rightarrow \bar{b} b \rightarrow \text{jets}) \simeq \frac{260}{N'} \text{ MeV} \quad (36)$$

We conclude that, if the sequence of quarks does stop at about 10 GeV, the η_H particle will have a total width of about 100 MeV mainly into $\bar{t}t, \bar{b}b$ jets, but also with appreciable branching ratios into $\tau^+ \tau^-$ or pairs of vector mesons.

All this may sound exciting since the η_H will have some clear experimental signature. Unfortunately, however, we have to conclude on a more pessimistic note for Higgs hunters.

Unlike what happens⁽¹⁵⁾ in TC models with $f' > 2$ (hence with technipions) our minimal model has a sort of desert between m_{W,Z^0} and 1 TeV. But even with this type of energies available, production of η_H is not easy (for reasons related to its small width).

(+) It is important that this is so to a high precision if one wants f_π to be the decay constant of $\pi \rightarrow \mu\nu$. In this case, as first noticed by Weinstein⁽¹⁴⁾, the decay proceeds via the small physical pion content of π' and the $\pi'\mu\nu$ coupling of magnitude $m_\mu/f_{\pi'}$.

The least impossible way to produce η_H appears to be that of Wilczek⁽¹⁶⁾ i.e. 2-gluon fusion in hadron hadron collisions ($\bar{p}p$ energy doubler at FERMILAB?) or heavy $q\bar{q}$ fusion (which is essentially the same). We have not made a detailed study of this possibility, but there seems to be little hope for a reasonably large production cross section.

One of us (GV) wishes to acknowledge fruitful discussions with D. Amati, R. Barbieri, J. Iliopoulos and P. Sikivie.

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