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THE TeV PICTURE

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In this talk we shall discuss a not-so-standard model of strong and electroweak interactions. We will discuss some direct consequences of this model and finally we will speculate on the outlook for the future.

Let's now briefly describe the parameters of the standard model so that we will know exactly what we shall be missing in the not-so standard model which follows. There are three sectors: gauge, fermion and Higgs.

(a) Gauge sector: we have the three gauge groups $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ and their respective gauge couplings g_3, g_2, g_1. $SU(3)_c$ is asymptotically free and thus g_3 gets strong at low energies and sets the scale of strong hadronic interactions. g_1 and g_2 are electroweak parameters which are directly related to the measured parameters α and $\sin^2\theta_W$ (discussed previously by Langacker and Marciano). Finally there are the gauge bosons—8 gluons, photon, $W^\pm$ and Z^0 where the last two, of course, have yet to be directly observed. Note that the $W^\pm$ and Z^0 masses are determined by parameters in the Higgs sector.

(b) Fermion sector: there are three generations of quarks and leptons (assuming the top quark exists). Their gauge couplings are determined by their standard charge assignments. However at least 9 masses and 4 mixing angles of this sector are given by 13 arbitrary parameters in the Higgs sector (namely Yukawa couplings).

Finally when I talk about these masses, I am referring to the so-called current algebra masses which are essentially local mass terms in the effective low energy standard model Lagrangian. This is to distinguish them from their dynamical masses obtained as a result of QCD which I shall refer to later.

(c) Higgs sector: we have the standard Higgs doublet $\phi = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$ with $Y = +1$. Its self interactions are described by the scalar

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potential $V(|\phi|) = -\mu^2|\phi|^2 + \lambda|\phi|^4$. We thus have two additional parameters making a total of 18—15 arbitrary constants in addition to the 3 gauge couplings—which successfully parametrize the low-energy physics.

The two Higgs couplings λ and μ determine: (1) the $W^\pm$ mass via the relations $G_F^{-\frac{1}{2}} \sim \langle\phi_o\rangle \sim \mu/\sqrt{\lambda}$ and $G_F/\sqrt{2} = g_2^2/8M_W^2$; (2) the neutral current parameter $\rho = M_W^2/M_Z^2 \cos^2\theta_W = 1$ + small corrections, and (3) the physical Higgs boson mass $\mu_h \sim \sqrt{\lambda}\, G_F^{-\frac{1}{2}}$. Hence we see that two Higgs parameters determine the above 3 measurable parameters. Consequently one of them, (2), is a natural relation having to do with symmetries which I shall discuss shortly. It is the soft violation of these symmetries which allows for the small corrections to ρ as discussed originally by Veltman [1] (see Marciano, these talks). Finally the quark and lepton masses are given in terms of arbitrary Yukawa couplings; i.e., $m_{q,\ell} \sim g_Y\langle\phi^o\rangle$. Since $\langle\phi^o\rangle \sim 250$ GeV as determined from G_F, then g_Y is of order 10^{-5} for the lightest generation of quarks and leptons.

We know that this effective Lagrangian for the standard model, accurately describes the low energy world as borne out by experiment, modulo a few particles which have yet to be discovered. What are the remaining open questions. There are marked regularities in the fermion mass matrix which have no explanation—the generation hierarchy, up-down symmetry breaking masses, Cabibbo and CP violating angles. All of these are determined in terms of small and arbitrary dimensionless parameters $g_Y \sim 10^{-5}$–10^{-1}. In addition there is no explanation for the huge gauge hierarchy associated with the small dimensionless ratio $G_F^{-\frac{1}{2}}/m_{p\ell} \sim 10^{-17}$. What we would like to do is to remove the Higgs sector from the theory and replace it by a more fundamental component. (By more fundamental, I mean that the 15 extra parameters in the Higgs sector are in principle determinable by a few parameters in the new sector).

For the moment, let us just remove the Higgs sector from the theory and imagine what the physics would be like before we replace it with any other component. We note that the leptons would be massless. However the quarks are still massive as a result of the strong QCD forces. They have their so-called constituent masses.

What about the W's and Z^o? Note that they are in fact massive with a mass $M_W = g_2 f\pi/2 = M_Z \cos\theta_W$. Let's consider this in more detail. Consider u and d quarks only for simplicity. We have a left-handed doublet and two right-handed singlets

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{matrix} u_R \\ d_R \end{matrix} \quad . \tag{1}$$

If we turn off the weak interactions, i.e., $g_1 = g_2 = 0$, the Lagrangian is invariant under a global chiral symmetry $SU(2)_L \otimes SU(2)_R$. However, as we all know, this symmetry is <u>not</u> a symmetry of the QCD vacuum. The condensates $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle \sim (3f_\pi)^3$ form and spontaneously break $SU(2)_L \otimes SU(2)_R$ down to the remaining symmetry $SU(2)_{Isospin}$. As a result of this spontaneous symmetry breaking, we obtain 3 massless Nambu-Goldstone bosons $\pi^\pm$, π^0.

Technically we say that the 3 axial vector currents create these massless states out of the vacuum with a characteristic decay constant $f_\pi = 93$ MeV; i.e., we have

$$\left\langle 0 \left| J^i_{\mu 5} \right| \pi^j \right\rangle \propto f_\pi \, \delta_{ij} \, q_\mu \tag{2}$$

Note that as a result of $SU(2)_{Isospin}$ all the pions have the same f_π. This result is very important as we shall soon see.

Now we turn on the weak interactions. The pions couple directly to the electroweak gauge bosons W^i_μ $(i = 1, 2, 3)$ and B_μ via the currents $J^i_{\mu L} = \frac{1}{2}(J^i_{\mu\,vector} - J^i_{\mu 5})$ and $Y_\mu = J^3_{\mu 5}$ + vectorial pieces. Hence the pions are eaten, leading directly to the gauge mass squared matrix

$$\frac{g_2^2\, f_\pi^2}{4} \left(\begin{array}{cc|cc} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 0 & 1 & -g_1/g_2 \\ 0 & 0 & -g_1/g_2 & g_1^2/g_2^2 \end{array} \right) \begin{matrix} W^1_\mu \\ W^2_\mu \\ W^3_\mu \\ B_\mu \end{matrix} \tag{3}$$

As a result we obtain

$$M_W = \frac{g_2 f_\pi}{2} \,, \qquad \tan\theta_W = g_1/g_2 \tag{4}$$

and the relation $M_W = M_Z \cos\theta_W$ follows directly from the symmetry $SU(2)_{isospin}$ which required all the f_π's to be equal.

The moral of our short monologue is twofold: (1) the non-Abelian gauge symmetry QCD has provided naturally light scalars whose scale ($f_\pi \sim \Lambda_{QCD}$) is determined by a logarithmically varying coupling constant, and (2) the relation $M_W = M_Z \cos\theta_W$ can be natural in such a scenario.

We are thus lead to consider the following not-so-standard model - preliminary version as discussed originally by Weinberg and Susskind [2]. It includes a gauge sector and fermion sector only.

(a) Gauge sector: we have the gauge group $G_T \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ containing the four parameters g_T, g_3, g_2 and g_1, respectively. The gauge group G_T where T stands for Technicolor (or Hypercolor) is assumed to be asymptotically free. Thus g_T becomes strong at a scale $\Lambda_T \gg \Lambda_{QCD}$ which sets the scale for all strong Technihadronic physics.

(b) Fermion sector: we assume the usual 3 generations of quarks and leptons. In addition we suppose that there is at least one left-handed $SU(2)_L$ doublet of Technifermions and 2 right-handed singlets with hypercharge assignments Y = 0, ±1 such that the theory is anomally free.

$$\begin{pmatrix} N \\ E \end{pmatrix} \qquad \begin{matrix} \bar{N} \\ \bar{E} \end{matrix} \qquad . \tag{5}$$
$$Y = 0 \qquad Y = \mp 1$$

If we turn off the weak interactions ($g_1 = g_2 = 0$), we have:

(a) $SU(2)_L \otimes SU(2)_R$ global symmetry in the Technifermion sector;

(b) when g_T becomes strong we assume that the following strong interaction condensates form

$$\langle \bar{N}N \rangle = \langle \bar{E}E \rangle \sim \left(3F_T\right)^3 \quad , \tag{6}$$

(c) hence $SU(2)_L \otimes SU(2)_R$ is spontaneously broken to $SU(2)_I$, and

(d) as a result, 3 Nambu-Goldstone bosons $\pi_T^\pm$, π_T^3 are formed, with a decay constant $F_T \sim \Lambda_T$. Finally, if we now turn on the weak interactions, we obtain

$$M_W = \frac{g_2 F_T}{2} = M_Z \cos\theta_W \tag{7}$$

which determines the Technicolor scale F_T to be ~250 GeV. In general if there are several Techni-doublets with their right-handed singlet partners we obtain

$$M_W = \frac{g_2 F_T}{2} \sqrt{N_{TD}} \qquad (8)$$

where N_{TD} is the number of Techni-doublets and thus we have

$$F_T \sim 250\ \mathrm{GeV}/\sqrt{N_{TD}} \quad . \qquad (9)$$

This is a preliminary version, however, since it is easy to see that quarks and leptons remain massless. There is no mechanism whereby they may flip their chirality. To remedy this difficulty, the following authors: Weinberg, Dimopoulos and Susskind, Eichten and Lane, have suggested unifying G_T with some symmetry of the ordinary generations; i.e., $SU(3)_c$ or generation symmetry, etc. What this means is that we put some Technifermions (Q) and ordinary fermions (q) together in a single representation of a larger group, referred to as Extended Technicolor (ETC) (or Sideways color). This group ETC must then break down at a scale V_{ETC} leaving only TC which then gets strong as before. If left- and right-handed couplings exist (not necessarily vectorial) then we can flip the chirality of an ordinary quark by letting it feel the spontaneously generated mass of the Technifermion. If V_{ETC} is much greater than F_T, then in the low energy world we may describe this ETC interaction by the following effective four-Fermi interaction

$$\frac{1}{V_{ETC}^2} \quad \bar{Q}^* \sigma_\mu \bar{q}\ Q^* \sigma^\mu q \qquad (10)$$

where Q and $\bar{Q}$ are left-handed Techniquarks and q and $\bar{q}$ are left-handed ordinary quarks. Upon Fierz transforming Eq. (10) we obtain

$$\frac{1}{V_{ETC}^2} \quad \bar{q}q\ \bar{Q}^* Q^* \qquad (11)$$

or an effective current quark mass

$$m_q = \frac{\langle \bar{Q}Q \rangle}{V_{ETC}^2} \quad . \qquad (12)$$

Note that all strong TC corrections are implicit in the condensate $\langle\bar{Q}Q\rangle$. In addition the scale of $\langle\bar{Q}Q\rangle$ is determined by the weak interactions is of order ~ 600 GeV (for $N_{TD} = 1$) or ~ 300 GeV (for $N_{TD} = 4$). Thus the scale V_{ETC} effectively determines the quark and lepton masses.

In general in order to give mass to all the quarks and leptons, one seems to require a complete family of Technifermions [4]. In the minimal scenario we have the following Technifermions

$$\begin{pmatrix} U \\ D \end{pmatrix} \quad \begin{matrix} \bar{U} \\ \bar{D} \end{matrix} \qquad \begin{pmatrix} N \\ E \end{pmatrix} \quad \begin{matrix} \bar{N} \\ \bar{E} \end{matrix} \quad . \tag{13}$$

In the limit $g_1 = g_2 = g_3 = 0$ there is an $SU(8)_L \otimes SU(8)_R$ global symmetry of the Techni-Lagrangian. When g_T gets strong, the condensates $\langle\bar{U}U\rangle = \langle\bar{D}D\rangle = \langle\bar{N}N\rangle = \langle\bar{E}E\rangle$ are assumed to form which spontaneously breaks $SU(8)_L \otimes SU(8)_R$ down to $SU(8)_{vector}$. As a result, 63 Nambu-Goldstone bosons are produced. Three of these are eaten by the W's and Z^0 when the weak interactions are turned on. The other 60 remain as physical pseudo-Nambu-Goldstone bosons. Many authors [4-6] have discussed the following properties of these very interesting states.

(a) Spectrum: they obtain their mass from interactions which are weak at the scale F_T. They are all very light on this scale and will thus be the leading signals for TC. In addition their mass may be calculated reliably using standard current algebra and Dashen's theorem. The results are listed in Table I. Note that the lightest states, the neutral axions a_T^0 and a_T^3 do not receive any mass from $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ forces. In evaluating their mass we have assumed that there is a Pati-Salam interaction which gives them a maximum mass of 2-3 GeV since lepto-quark gauge bosons are constrained by limits on the reaction $K_L \to \mu^+ e^-$ to be heavier than 310 TeV [6].

(b) Production: the production cross sections and decay rates may be found in the literature cited [4-6]. It suffices to remark here that the neutral states η_T^8 and a_T^0 may be produced singly in the reactions pp or $\bar{p}p$ going to η_T^8 + anything or a_T^0 + anything. For example in a 1 TeV on 1 TeV beam at the Tevatron one would expect about 440 η_T^8 events/10^7 sec assuming $\mathcal{L} = 10^{30}/\text{cm}^2\cdot\text{sec}$. The charged axions should be seen in the reaction $e^+e^- \to a_T^+ + a_T^-$, especially if one sits on the Z^0 (see Lane [5]). The dominant decay modes for all these states are via Yukawa couplings to the heaviest fermions allowable.

TABLE I

STATE	COLOR	CHARGE	MASS (GeV)	NAME
$\bar{U}U-\bar{D}D+\bar{N}N-\bar{E}E$	1	0	0	Technipions (eaten
$\bar{U}D+\bar{N}E$	1	−1	0	by gauge bosons)
$\bar{U}(\lambda^a/2)U+\bar{D}(\lambda^a/2)D$	8	0	$240\sqrt{4/N}$	Colored Technieta η_T^a
$\bar{U}(\lambda^a/2)U-\bar{D}(\lambda^a/2)D$	8	0	$240\sqrt{4/N}$	Colored Technipions
$\bar{U}(\lambda^a/2)D$	8	−1	$240\sqrt{4/N}$	π_T^{a3}, $\pi_T^{a\pm}$
$\bar{E}U$	3	5/3	$165\sqrt{4/N}$	
$(1/\sqrt{2})(\bar{E}D-\bar{N}U)$	3	2/3	$160\sqrt{4/N}$	Techni-
$\bar{N}D$	3	−1/3	$155\sqrt{4/N}$	leptoquarks
$(1/\sqrt{2})(\bar{E}D+\bar{N}U)$	3	2/3	$160\sqrt{4/N}$	
$\bar{U}U+\bar{D}D-3(\bar{N}N+\bar{E}E)$	1	0	2-3	Paraxion a_T^0
$\bar{U}U-\bar{D}D+\bar{E}E-\bar{N}N$	1	0	2-3	Axion a_T^3
$\bar{U}D-\bar{N}E$	1	−1	8-10	Charged Axion $a_T^{\pm}$

Generation hierarchy: Dimopoulos, Raby and Susskind [7] have discussed the possibility that a large group, e.g., SU(N), may sequentially spontaneously break itself down at different scales (so-called Tumbling). This could lead to the following possible explanation of the generation hierarchy. Assume that the ETC group is $SU(N+3)_{ETC}$ which sequentially breaks down to

$$SU(N+3)_{ETC} \xrightarrow{V_u} SU(N+2) \xrightarrow{V_c} SU(N+1) \xrightarrow{V_t} SU(N)_{TC} \qquad (14)$$

at a scale $V_u > V_c > V_t$, where $SU(N)_{TC}$ is the remaining TC group. We assume the fermions transform in fundamental representations of ETC as for example

$$\text{ETC} \updownarrow \begin{pmatrix} U \\ t \\ c \\ u \end{pmatrix} \underset{SU(2)_L}{\longleftrightarrow} \begin{pmatrix} D \\ b \\ s \\ d \end{pmatrix} \quad \begin{pmatrix} \bar{U} \\ \bar{t} \\ \bar{c} \\ \bar{u} \end{pmatrix} \quad \begin{pmatrix} \bar{D} \\ \bar{b} \\ \bar{s} \\ \bar{d} \end{pmatrix} \qquad (15)$$

where U, D, $\bar{U}$, $\bar{D}$ are Techniquarks. When $SU(N)_{TC}$ gets strong we expect the condensates $\langle\bar{U}U\rangle = \langle\bar{D}D\rangle$ to form. This then results in the following quark mass relations

$$m_t \sim \frac{\langle\bar{U}U\rangle}{V_t^2}$$

$$m_c \sim \frac{\langle\bar{U}U\rangle}{V_c^2} \qquad (16)$$

$$m_u \sim \frac{\langle\bar{U}U\rangle}{V_u^2}$$

or $m_t > m_c > m_u$ since $V_u > V_c > V_t$. We thus obtain a generation hierarchy as a direct result of a presumed gauge hierarchy. In addition we note that such a gauge hierarchy is necessary in order to suppress dangerous neutral current processes, which we discuss next.

Generation changing neutral currents: there are of course many unavoidable experimental consequences of a local generation symmetry. These have been discussed by several authors [8].

The $\Delta G = 2$ processes are the most dangerous. By using the relations of Eq. (16) to evaluate the scales, V_t, V_c, V_u one can predict the rates for $K_0 \to \bar{K}_0$ or $D_0 \to \bar{D}_0$ modulo Cabibbo-like mixing angles in the up or down quark sectors. One finds that any s-d mixing angle must be less than 10^{-2} in order to be consistent with the $K_L - K_S$ mass difference. Theoretically this can be arranged if the ETC group in the down quark sector is vectorial. We are then forced to have essentially the entire Cabibbo angle in the up quark sector. As a result the process $D_0 \to \bar{D}_0$ should be seen at a rate which is close to the present experimental limits. $\Delta G = 1$ processes such as $\mu N \to eN$ (where N is any nucleus) or $\mu \to e\bar{e}e$ should be seen soon if the μ-e mixing angle is of order one. The $\Delta G = 0$ process $K^+ \to \pi^+\mu^+e^-$ should be seen at a rate which is just below the experimenal upper bound, i.e., $\Gamma(K^+ \to \pi^+\mu^+e^-)/\Gamma(K^+ \to \pi^0\nu_\mu\mu^+) \leq 1.5 \times 10^{-7}$ [9]. The amplitude for the analogous process $K_L \to \mu^+e^-$ vanishes if ETC is vectorial in the down quark sector.

Finally we should note that, as discussed, ETC in the down quark is expected to be vectorial. As a consequence, the Yukawa couplings of pseudo-Nambu-Goldstone bosons to the down quark sector should be parity conserving and of course pseudoscalar. This should not be true in the up quark sector, however, sin-e ETC cannot be purely vectorial there. Thus the parity of the pseudos cannot be measured via their up quark decay modes.

To summarize, the TeV picture looks as follows:

$$
\begin{array}{ll}
 & a_T^{\pm},\ a_T^{3}\ a_T^{o} \\
 & W^{\pm},\ Z^{o} \\
100\ \text{GeV}\ - & \\
 & \text{Technileptoquarks} \\
 & \pi_T^{\pm a},\ \pi_T^{3a},\ \eta_T^{a} \\
 & \\
 & \sigma_T \\
1\ \text{TeV}\ - & \rho_T,\ W_T,\ \phi_T,\ \rho_T^{a} \\
 & \text{Technibaryons} \\
 & \text{-----------------}\ V_{t,b} \\
 & \\
10\ \text{TeV}\ - & \text{-----------------}\ V_{c,s} \\
 & \\
100\ \text{TeV}\ - & \text{-----------------}\ V_{u,d}
\end{array}
\qquad (17)
$$

Technicolor and GUTS: Frampton [10] has asked the question whether or not there can exist a grand unified Technicolor model. For example he considered, among others, the case $SU(N) \supset SU(n)_{TC} \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. He required the resulting theory to satisfy 4 criteria:

(1) SU(N) is anomally free;

(2) $SU(n)_{TC}$ is asymptotically free;

(3) g_T grows faster than g_3, and

(4) there are at least two complete generations of quarks and leptons.

He was not able to find a set of fermion representations which satisfied all these assumptions. Although this result is not at the level of a rigorous no-go theorem it nevertheless seems extremely plausible that there are no grand unified Technicolor theories.

Let's thus conclude by discussing a few of the alternatives to grand unification. (1) It is extremely possible that there is a grand proliferation of new scales and new groups as one goes up in energy. (2) Grand unification did not appear possible since there are too many elementary fermions [10]. This might suggest a composite structure of quarks and leptons at a TeV scale. (3) Elementary scalars are necessary, and even possible if we include supersymmetry to keep them naturally light down to a TeV scale, (see the discussions by Dimopoulos, Georgi and Srednicki, this conference). Finally there is always the fourth possibility: none of the above. It is clear, however, that the TeV picture is certain to provide answers to some very fundamental questions.

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