Decoupling Dynamical Electroweak Symmetry Breaking
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Abstract

The modern precision accelerator data has essentially ruled out the most obvious model of dynamical electroweak symmetry breaking, technicolour. The idea is though well motivated and it is important to construct models compatible with the precision data of this ilk to motivate experimental searches. We describe the top-see-saw and flavour universal symmetry breaking models that break electroweak symmetry dynamically yet have a decoupling limit for all new physics. Limits on the scale of such new physics may be placed using precision data and direct search results from the Tevatron.
1 Introduction

Electroweak symmetry (EWS) is a gauged chiral symmetry of the standard model (SM) fermions broken by a mechanism which at this stage remains elusive. Influenced by the breaking of electro-magnetism in superconductors through the dynamical formation of an electron pair condensate, and by the breaking of chiral symmetry in QCD through a quark condensate, it is natural to propose that electroweak symmetry may be broken by a dynamically driven fermion condensate. If the responsible dynamics were a gauge interaction then the logarithmic running of the gauge coupling would naturally provide a separation between the planck and electroweak scales, i.e. a solution to the hierarchy problem. The most obvious such extension to the standard model in this vein is technicolour [1] - essentially a repeat of QCD but with a strong interaction scale of order the weak scale. Such models though run into problems because in a broken gauge theory there is a violation of the decoupling theorem [2]. The sector responsible for the symmetry breaking gives large contributions to parameters in the low energy theory applicable at LEP and is, at least naively, incompatible. The most natural mechanism for the generation of the standard model fermion masses in this context is by a feed-down mechanism involving broken gauge interactions, extended technicolour (ETC) [3]. ETC also runs into grave trouble - in its case accommodating sufficient isospin breaking to generate the large top-bottom mass splitting without contradicting the precision data [4]. In this article we discuss recent model building that overcomes many of the failures of technicolour [5, 6].

Why, given the failures of the arch-type model, and the existence of other well motivated solutions of the hierarchy problem (supersymmetry and large extra dimensions), should one perservere with dynamical symmetry breaking models? Firstly I believe that the motivation that inspired technicolour remains even with its fall but, most importantly, I do not believe it is the place of theory to claim the exclusion of entire paradigms. In the current era of particle physics it is the theorist’s role to provide as wide a variety of viable models for experiment to eventually differentiate between.

The dynamical models I discuss below are intended to provide insight into how dynamical symmetry breaking might manifest in nature and hence inspire experimental searches. The biggest success of these most recent models is that they are compatible with the precision data because they have a decoupling limit in which low energy predictions are precisely those of the standard model.

I will begin in Section 1 by reviewing technicolour and the pitfalls that must be avoided. The first example of a dynamical EWS breaking model with a decoupling limit proposed was top condensation [7] which I review in section 2 - the model is though ruled out by the
small measured top mass. In section 3 I describe recent models that successfully implement a
decoupling limit in dynamical symmetry breaking models [5, 6]. Finally in section 4 I discuss
the experimental limits on the scale of the new physics proposed in these models both from
precision data and from direct searches at the Tevatron. Much of the work reported here
was carried out with Gustavo Burdman and Sekhar Chivukula in [3, 8, 9].

2 Technicolour and its failures

The simplest model of dynamical EWS breaking is technicolour [1]. We assume there is an
$SU(N_{TC})$ gauge group acting on say a single electroweak doublet of left handed “techni-
quarks”, $(U,D)_L$, and two electroweak singlet right handed techniquarks, $U_R$, $D_R$. The
techniquarks are massless so there is an $SU(2)_L \times SU(2)_R$ chiral symmetry. We assume the
asymptotically free SU($N$) group becomes strong at a scale $O$(1 TeV), generating techniquark
condensates, $\langle \bar{U}U \rangle$, $\langle \bar{D}D \rangle \neq 0$, which break the chiral symmetry to the vector subgroup. The
chiral EWS is broken. The Goldstones eaten by the W and Z are the Goldstones of chiral
symmetry breaking, the technipions. The weak scale $v$ is traded for the technipion decay
constant, $F_{\pi}$. Such a model would be characterized by the discovery of technihadrons at the
TeV or so scale.

This sort of model though gets in trouble with the precision electroweak data from LEP
and SLD [2]. In a broken gauge theory particles with masses violating the gauge symmetry do
not decouple. These effects enter through oblique corrections which can be parameterized by
the three parameters $S, T, U$ [2]. The $S$ parameter turns out to essentially count the number
of such massive particles. One can estimate the contribution to $S$ from massive, strongly
interacting fermions by scaling up normal QCD data to the appropriate scale [3]. The result
for technifermions is

$$\Delta S_{TC} \simeq N_{TC}N_D 0.1$$  \hspace{1cm} (1)

where $N_D$ is the number of doublets. The experimental limit on $S$ (assuming a heavy higgs)
is $-0.27 \pm 0.12$ [10]! Even a very minimal one doublet SU(2) technicolour theory appears
ruled out. Of course it is possible that there are other pieces of new physics contributing to
$S$ with negative sign or that the naive scaling of QCD data might be inappropiropriate to the
technicolour dynamics. In any case at most a relatively minimal technicolour sector seems
possible.

Breaking EWS is not the only job a technicolour model must accomplish. The SM
fermions must also be given their masses. The usual mechanism considered is extended
technicolour. At high scales the technicolour group is unified with the flavour symmetries
of the SM fermions. This larger symmetry is assumed to be broken down to technicolour leaving massive gauge bosons which can feed the technifermion condensate down to provide the SM fermion masses. One finds

\[ m_f \simeq \frac{g_{\text{ETC}}^2}{M_{\text{ETC}}^2} \langle \bar{T} T \rangle \simeq \frac{g_{\text{ETC}}^2}{M_{\text{ETC}}^2} 4\pi F^3_{\text{TC}} \quad (2) \]

The gauging of the SM flavour symmetries is though a dangerous game and one may expect to find flavour changing neutral currents in the theory mediated by single gauge boson exchange. To suppress such contributions to \( K^0 - \bar{K}^0 \) mixing requires \( M_{\text{ETC}} \geq 600 \text{ TeV} \). Such an ETC gauge boson can only generate a fermion mass of 0.5 MeV though which is well short of the second family quark masses. This is a long standing problem with ETC.

A second problem is the generation of the large top mass. A 175 GeV fermion mass would require a 1 TeV or so ETC gauge boson. The interactions of this light gauge boson must violate custodial isospin since the bottom quark is so much lighter than the top. Including such a isospin violating gauge boson in the loops of technifermions generating the W and Z masses gives contributions to \( \Delta \rho (\equiv \alpha T) \simeq 12\% \) [4] - two orders of magnitude above the experimental limit!

The lessons of technicolour appear to be that there are no extra electroweak doublets beyond the SM and that the SM fermion masses do not result from a simple feeddown mechanism.

### 3 Top condensation and its failure

Top condensation models [1] were a first attempt to avoid the excessive baggage of technicolour. Inspired by the large top mass it was suggested that the top may play a unique role in EWS breaking - perhaps the “top is the technifermion” and it is a \( \langle \bar{t} t \rangle \) condensate that breaks EWS. The simplest model is to introduce a four fermion interaction acting on the top

\[ \mathcal{L} = \frac{\kappa}{M^2} \bar{\psi}_L t_R \bar{t}_R \psi_L \quad (3) \]

where we might imagine some broken gauge theory was providing the origin of the interaction. At least at large N, the model can be solved and the behaviour of the condensate as a function of \( \kappa \) is shown in Fig 1. There is a critical coupling at which chiral symmetry breaking switches on. At large \( \kappa \) the condensate flattens out to of order the scale \( M \). If \( M \approx 1 \text{ TeV} \) then arranging \( \kappa \) so that the correct top mass/EWS breaking scale is realized is relatively easy. If \( M \gg 1 \text{ TeV} \) then one must fine tune \( \kappa \rightarrow \kappa_c \) to achieve such a low scale as \( v \). Below the scale \( M \) the effective theory contains a higgs boson which is a bound state of the top quark.
The higgs mass at tree level can be calculated from resumming top loops in the four top scattering amplitude and at large $N$ is given by $2m_t$. One may also estimate the relation between $m_t$ and $v$ through a loop diagram and here is where the theory runs into trouble. To generate $v \simeq 250$ GeV requires $m_t \simeq 600$ GeV (assuming $M \simeq 5$ TeV)!

It is possible to combine top condensation and technicolour \cite{11} to lessen the $\rho$ parameter problems that technicolour alone suffered. One allows EWS to be broken by technicolour whilst a direct top condensate supplies the top mass without a light ETC gauge boson. Such models have most of the troublesome baggage of technicolour remaining though.

4 Viable dynamical symmetry breaking models

We move now to discuss models that are compatible with all low energy data. The archtype was provide by Dobrescu and Hill in their top see-saw model \cite{5}. Their model provides a mechanism for reconciling $m_t$ with the idea that a top condensate provides the entirety of $v$. A similar idea was proposed in \cite{12}.

The trick is to use the left handed top as a “technifermion” but introduce a new field $\chi_R$ to be the right handed technifermion. $\chi_R$ has the same quantum numbers as the $t_R$ and is bound into a massive Dirac fermion with a partner $\chi_L$ which shares it’s quantum numbers ($m_\chi \simeq 3$ TeV). We now imagine an interaction of the form (3) that is strong and drives a $\langle \bar{t}_L \chi_R \rangle$ condensate that breaks EWS at the scale $v$. A mass of order $600$ GeV has been generated between $t_L$ and $\chi_R$. To generate the top mass we include a mass term between $\chi_L$ and $t_R$ - this is gauge invariant so we would have to explain why it wasn’t there if it wasn’t! The result of all these masses, if we choose the EWS singlet masses correctly, is a see-saw like mass spectrum with a massive eigenstate ($1$-$5$ TeV) and a light eigenstate, the top ($175$ GeV). It may seem a bit strange that $\chi_R$ which is part of a Dirac fermion with mass of several TeV can participate in dynamics that gives rise to a scale of $v$. For this to

Figure 1: The top condensate as a function of coupling in the four fermion interaction theory.
be possible we require that the scale $M$ in (3) be larger than $\chi$’s Dirac mass term so the dynamics is really above that scale. The fact that the scale $v$ emerges hints at a degree of fine tuning - in this sense it is best if $M$ is not too large.

The higgs in these models is a bound state of $t_L$ and $\chi_R$ and, at large $N$, as in the top condensate model, has a mass of twice the EWS breaking mass, ie 1.2 TeV. This mass is only the tree level mass and does not take into account the running of the quartic coupling between $M$ and the weak scale. This running is quite strong and for large values of $M$ will display the fixed point behaviour of the SM couplings. We expect for $M < 10$ TeV that the physical higgs mass will be between 400-600 GeV.

The appealing aspect of this model is that it has a decoupling limit. $\chi$ is an electroweak singlet and so its mass may be taken to infinity where it will decouple completely from the low energy theory leaving the SM as the effective field theory. To maintain the physical top mass the ratio of the mass between $\chi_L$ and $b_R$ to that of the $\chi_L - \chi_R$ mass must be kept constant in this limit. Of course taking the extreme limit of $M \to \infty$ introduces fine tuning as discussed above but if $M \simeq 3+\text{ TeV}$ the decoupling is almost complete and the fine tuning “barely” present [5].

Extending this type of model to include masses for all the SM fermions is relatively easy. One example is the flavour universal EWS breaking model [6]. The top mass is no longer a direct measure of $v$ in the see-saw model so there is in fact no reason to use it, or it alone, to break EWS. In the flavour universal model all the SM fermions participate equally in EWS breaking. We introduce two Dirac singlet fermions ($\chi$ and $\omega$) with masses of 3 TeV or so and the quantum numbers of the SM fermion’s right handed spinor for each SM fermion. A strong interaction is assumed to cause condensation between the left handed SM fermion and its $\chi_R$ field. A mass term is included between $\omega_L$ and the right handed SM fermion. The SM fermion mass then results from a mass mixing between the two massive singlets according to graphs such as

\[
\begin{array}{cccccc}
\text{e}_L & x_R & x_L & w_R & w_L & \text{e}_R \\
\times & \times & \times & \times & \times & \\
\frac{1}{\tilde{M}_{xx}} & \frac{1}{\tilde{M}_{xx}} & \\
\end{array}
\]

EWS breaking mass

The SM fermion masses are simply the result of mass terms, $\tilde{M}$, chosen in the singlet sector - the problem of flavour is defer to a higher scale. This mechanism introduced in [13] is essentially a way of introducing yukawa couplings into dynamical models. Since all
the SM fermions participate equally in EWS breaking the EWS breaking masses between the SM fermions and the singlet sector are reduced by a factor of $\sqrt{N_D/3}$ and the higgs mass is approximately 350-450 GeV (with running of the quartic coupling the mass could be as low as 300 GeV).

More complete models of both the top see-saw and the flavour universal EWS breaking model exist in the literature. The origins of the strong coupling are broken, strong, gauged flavour symmetries. For example to generate a top condensate one must have an interaction that acts solely on the top - one possibility is to gauge the SU(3) colour group of the top separately from that of the rest of the standard model [5]. At the 3 TeV or so scale this extended gauge symmetry is broken to the SM leaving a colour octet of massive strongly interacting gauge bosons. These top colour interactions are responsible for the top condensation. To distinguish between the top and bottom quarks these interactions must be chiral. The flavour universal models suggest the gauging (and then breaking) of the chiral family symmetry groups of the standard model or the full SU(12) flavour symmetry of the standard model left handed fermions [5]. One might worry that as in ETC FCNCs will be generated. In fact if we are careful to preserve the $SU(3)^5$ chiral flavour symmetry of the standard model, which is responsible for the SM’s GIM mechanism, then the GIM mechanism persists above the weak scale and these symmetries can be gauged at scales of only a few TeV [13]. Since this class of model requires different interactions for the left handed doublets from the right handed fermions such a scheme is very natural in this context.

5 Experimental limits

The dynamical symmetry breaking models described above have been engineered to have a decoupling limit and hence to avoid making an experimental prediction! However, the desire to avoid fine tuning requires that the scale of the new physics is actually not too far above the weak scale. It is therefore possible to place meaningful lower limits on the scale of the dynamics from precision EW data and direct search limits from the Tevatron.

The new physics in the models enters the precision data in two ways. Firstly there is mixing between the SM fermions and EWS singlets which will give rise to corrections to the SM Z-fermion couplings of the form

$$\delta g_f \simeq -\frac{e}{s_W c_W} Q_f s_\theta^2 m_{mix}^2 / m_\chi^2$$

where $m_{mix}$ is the mixing mass which we expect of order a few 100 GeV and $m_\chi$ is the Dirac mass of the singlet. Assuming flavour universal mixing and fitting to the data places a limit of 1.9, 2.6 TeV on $m_\chi$ for $m_{mix} = 100, 200$ GeV.
The flavour gauge bosons may also correct the vertices of the SM fermions they act on and provide corrections to the $\rho/T$ parameter through loops of top quarks. In [8] we have performed a global fit to the Z-pole data including these effects. The 95% confidence level limits on the mass scale of the new interactions in a variety of models when their coupling is the critical coupling from the NJL model are

\begin{align*}
\text{Top colour} & \quad M(\kappa_c) \geq 1.3 \text{ TeV} \\
\text{Left handed quark family symmetry} & \quad M(\kappa_c) \geq 2 \text{ TeV} \\
\text{Left handed SU(12) flavour symmetry} & \quad M(\kappa_c) \geq 2 \text{ TeV}
\end{align*}

These bounds assume a 100 GeV higgs mass but are in fact fairly insensitive to the higgs mass since the higgs mass enters only logarithmically in the precision variables whilst the mass scale in these corrections enter quadratically. The precision data currently favours a low standard model higgs mass $m_h \leq 260$ GeV (the bound rises to 400 GeV if the SLD forward backward asymmetry measurement is not included) whilst the models we have discussed have a higgs mass in the $300 - 600$ GeV range. The precision limit is though extremely sensitive to new physics - in particular positive contributions to the $\delta \rho/T$ parameter such as are provided by these flavour gauge bosons can restore heavier higgs masses to agreement with the precision data. For example the top coloron model with $M(\kappa_c)$ of order 2 TeV is compatible with a 400 GeV higgs.

Direct search limits on the flavour gauge bosons may be obtained from the Tevatron Run I data. Top colour gives enhanced top production, the larger flavour symmetry models enhance $q\bar{q}$ production and can make use of the bottom quark content of the proton to make single top events. Finally the SU(12) flavour model which involves the leptons gives contributions to Drell-Yan production. These limits are currently under study [9] and place bounds of 1-3 TeV on the flavour gauge bosons. Expectations for Run II’s limits are that they will be competitive with the precision data and probe scales of order 3+ TeV in these dynamical symmetry breaking models.

6 Conclusions

The idea that EWS is broken by a dynamically generated fermion condensate offers the possibility of a natural and low scale extension of the SM. Technicolour was the obvious first model to propose since it is simply a repeat of QCD. However, the precision data is incompatible with an extended symmetry breaking sector. Top condensation was proposed as a dynamical symmetry breaking model with a minimum of new physics and provides a natural explanation for a heavy top. In fact the top turns out to be too heavy in this
scheme. The top see-saw model resolves this problem by introducing singlet fermions and a see-saw mass mechanism that gives a lightest mass eignestate that can be interpreted as the top quark. The flavour universal symmetry breaking model extends the idea to include masses for the full set of SM fermions. These models have a decoupling limit since all the additional fields beyond the SM fields are EWS singlets. The dynamics is assumed to result from broken gauged flavour symmetries. Precision data and Tevatron direct searches put a lower limit of order a few TeV on these models. The Tevatron at Run II has discovery potential.

The models discussed though are not complete models in any sense. The origin of the SM fermion masses is deferred for example. That the dynamics is the result of gauge interactions broken close to their strong scale so they can nevertheless generate condensation themselves requires unproven gauge dynamics [14]. The hope is that the models provide examples of how dynamical symmetry breaking might be realized in nature and guidance for experimental searches. In the end experiment must surely be an essential guide to the true model of EWS breaking.

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