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Signals in the TeV Era and the Lattice

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In this work I give an overview of models with strong dynamics at or near the TeV scale and how these models can benefit from lattice input.

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1. Introduction

High energy particle physics stands at a threshold of discovery. The LHC has rocketed into production and the multiverse of models of physics beyond the standard model (SM) will soon be forced to confront data. Even the first inverse femtobarns of data have brought surprises: supersymmetry, the most widely agreed upon extension of the SM, was not waiting right around the corner. More exotic SM extensions which share the same gross collider features – light colored particles and large missing energy signatures – are also being rapidly excluded. New resonances, cousins of the W,Z or gluon are also nowhere to be seen. Finally, and perhaps most interestingly, the SM Higgs boson has been excluded for all masses except the narrow range $\sim 120-125\,\mathrm{GeV}$.

We are still in the earliest days of the LHC era, so it is premature to pronounce the SM or any of its extensions as dead at this point. However, these initial findings of the LHC are in complete agreement with models of dynamical electroweak symmetry breaking. In these models, generally known as 'technicolor' there is no fundamental Higgs boson. Electroweak symmetry is broken spontaneously as the result of some new strong dynamics at the TeV scale [1, 2]. Technicolor models have strikingly different collider signals from supersymmetry or supersymmetry look-alikes; there is no (SM-like) Higgs boson in the spectrum, and there are often no new colored particles. The new particles – bound states of new, technimatter – couple very weakly to quarks and leptons. Finally, while the lightest composite of technimatter, a technibaryon, may be stable and can provide a dark matter candidate [3, 4], technibaryons are not produced in all collisions so there is usually no large missing energy signal.

Technicolor is an old and elegant idea, but it is not without its weaknesses. The biggest weakness is that technicolor inherently involves strong coupling, and hence the quantities we can reliably calculate are extremely limited. One way to proceed is to use QCD as a guide and extrapolate masses and relations from the GeV scale up to the electroweak scale. While this is convenient, there is absolutely no reason *a priori* to expect that whatever new dynamics lurks at the weak scale should behave like QCD. Additionally, evidence from indirect probes of the weak scale strongly disfavors QCD-like strong dynamics – so we cannot draw any intuition from QCD for building viable technicolor models.

One tool that remains, and which has only recently begun to be used, is lattice calculations. This is a very exciting prospect and there is much to be learned. Using the lattice, we may be able to move beyond the uncontrolled approximations or assumptions imbedded in many 'traditional' technicolor calculations and begin to probe gauge dynamics outside of QCD [1]. This new domain for lattice simulations is exciting not only for the phenomenological questions it can answer but for the insight it can bring to gauge theories in general and for the advancements it may bring to other areas of lattice computation.

The setup of this note is the following: Given its pivotal role in the SM, I will first review the status of the Higgs boson search at the LHC. As results are rapidly flowing in from the LHC and the experimenters are quickly learning how to optimize various components of the detectors, it is difficult to speculate about what will or will not be possible at any given time, however I will give some overview of what Higgs results to expect by the end of LHC running in 2012. The remaining

[1] More precisely, non-supersymmetric gauge theories. Aided by the power of supersymmetry, non-perturbative results in supersymmetric QCD have been reliably explored for many years

sections are then devoted to technicolor models and how they can benefit from lattice input. I will give a rough overview of the classic signals of models of TeV-scale strong dynamics, then go through the obstacles technicolor models typically face. To avoid these obstacles we must consider strong dynamics scenarios that are quite different from QCD. To confidently build models in this area, lattice input is essential. To this end, I present a 'wish-list' of questions that the lattice may be able to provide answers or insight to. I will then finish with a conclusion. Other technicolor reviews covering similar topics can be found in Ref. [5, 6, 7, 8, 9, 10, 11].

2. Collider searches

2.1 Where are we now?

Initial LHC results first appeared in January 2011 and contained analysis performed on the 2010 data set of $\sim 30\,\mathrm{pb}^{-1}$. The next sizable chunk of results was released in the summer, with an astounding $1\,\mathrm{fb}^{-1}$ of data – a factor of 30 increase since the initial results. At years end, the data had quintupled yet again. By the end of 2012, when a shutdown for upgrading the center of mass energy is scheduled to occur the projections are for up to 15 fb^{-1} per experiment, at an energy of 8 TeV. Such an explosion of new data is certainly a once in a lifetime experience! Meanwhile, the Tevatron ended its 25 year run at the end of September 2011 with a total integrated luminosity in $p\bar{p}$ collisions of approximately $10\,\mathrm{fb}^{-1}$ per experiment.

2.2 Higgs

The search for the Higgs boson is central to the LHC program and it has been the focus of many early searches. The Higgs searches are an assemblage of many different channels, though three particular final states carry the majority of the sensitivity: $h \to W(\ell\nu)W(\ell\nu), h \to Z(\ell\ell)Z(\ell\ell), h \to Z(\ell\ell)Z(\nu\bar{\nu})$. One aspect these final states all have in common is that they only involve leptons. As such, they suffer from fewer standard model backgrounds and are less prone to mis-measurement. The WW channel is the most sensitive channel for Higgs masses $130\,\mathrm{GeV} \lesssim m_H \lesssim 180\,\mathrm{GeV}$, whle ZZ dominates for heavier Higgses. The fully leptonic ZZ channel is the cleaner of the ZZ modes, but suffers due to a low branching fraction. The low mass region, $m_H \lesssim 130\,\mathrm{GeV}$ is the most difficult mass range for the LHC; overwhelming backgrounds force experimenters to rely on rare decay modes, $h \to \gamma\gamma$, $h \to \tau^+\tau^-$ and $h \to ZZ^* \to 4\,\ell$.

However, with the first 5 fb^{-1} of LHC data, the Higgs has yet to be seen. Both ATLAS and CMS exclude a SM Higgs at the 95% CL for an impressive range of masses; masses $m_H < 120$ and $m_H > 130\,\mathrm{GeV}$ are no longer allowed. The exclusion limits as a function of mass are shown below in Fig. 1.

Aside from the imposing exclusion region, the next question is, what is happening between $120-130$ GeV? The wiggles in the observed limit are not significant in any single signal channel, however taken together, the observation is compatible with a tantalizing first glimpse of the Higgs. The deviations between the observed and expected (background only) hypothesis are most significant for the high-resolution channels such as $h \to \gamma\gamma, h \to ZZ^* \to 4\ell$, with little or no deviation seen in the WW^*, $\bar{b}b$, or $\tau^+\tau^-$ modes.

Is it a standard model Higgs boson? Time will tell. Many are already convinced, and they may be right, but this conviction comes more from faith than from the data itself. For now, I will

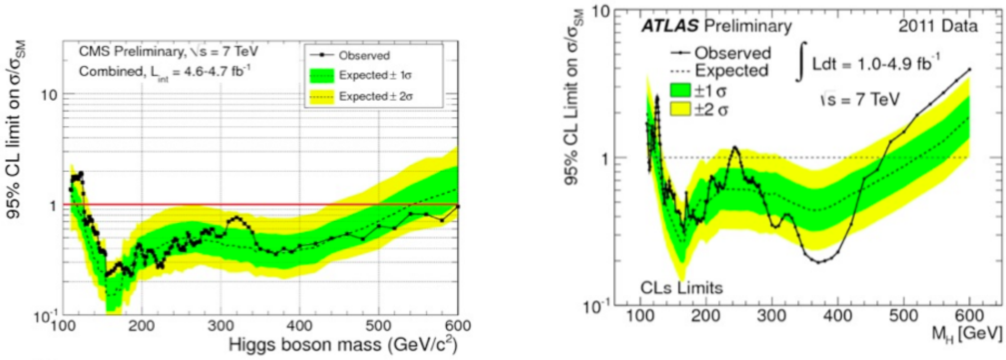

Figure 1: Results of the standard model Higgs search as of December 2011. A SM Higgs is excluded in all areas where the solid line (obs. limit) falls below 1. These results are combinations over several channels. For more results and complete, channel-by-channel breakdown, see [12, 13]

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keep an open mind. If nothing else, why should the Higgs boson lie in the last possible region to be explored? Thankfully, beliefs and suspicions will be irrelevant by the end of 2012, as we will have an answer.

3. Strong Dynamics in the LHC Era

With all of the attention the Higgs boson receives, it is important to remember that we do not actually need it! In order to combine the well-tested symmetry structure of the standard model with massive particles, we need electroweak symmetry to break down spontaneously – we need some new interaction which treats particles with electroweak charge differently than those that carry no (EW) charge. A single, fundamental Higgs residing in the familiar 'Mexican-hat' potential is one way to achieve this symmetry breakdown, but it is by no means the only way. For instance, nature has already provided us with two examples of mass generation via symmetry breaking, QCD (protons, neutrons, etc.) and superconductivity [14] (Meissner effect). In both of these cases, the symmetry is broken *dynamically*, rather than the result of a fundamental field. Why not apply the same idea to electroweak symmetry?

While it is challenging to write down a complete, viable model of dynamical electroweak symmetry, a simple toy model will serve to illustrate the mechanism, its pros, and cons. Let us introduce some new matter, called "technifermions". We charge these technifermions under electroweak interactions and under a new gauge interaction dubbed "technicolor" [1, 2].

$$\begin{aligned} T_{iL} &\sim (N_{TC}, 2)_0 \\ T_{iR} &\sim (N_{TC}, 1)_{\pm\frac{1}{2}}. \end{aligned} \tag{3.1}$$

Here N_{TC} indicates the new fermions lie in fundamental representations of the technicolor gauge group $SU(N_{TC})$, and i labels a generation index which we do not specify now; it runs from 1 to N_D where N_D is the number of $SU(2)_w$ technidoublets[2]. Both left-handed and right-handed

[2]Fundamentals of the technicolor group is just one option – other possibilities have been explored extensively, for example see Ref. [15, 16, 17] and references therein.

technifermions interact with technicolor, while the electroweak charge is chiral – only left-handed fermions feel $SU(2)_w$. The combination of chiral $SU(2)_w$ charge and common technicolor charge are the only model independent features of our setup. There are many equally good possibilities for the technicolor representation and the hypercharge assignment.

Because of the chiral $SU(2)_w$ charge, we cannot write down a mass term for the technifermions. However, let us imagine that technicolor becomes strongly coupled and confining at the electroweak scale – analogous to how QCD behaves at $\sim 1,$GeV, just rescaled to $\sim$ 100's of GeV. As we know from QCD, as a result of the confining interaction, a condensate will form

$$\langle \bar{T}_{iL} T_{iR} \rangle \neq 0, = 2\pi v^3 \tag{3.2}$$

This condensate is a vacuum expectation value (vev) for an operator which is not an electroweak singlet, so a nonzero value for this vev means electroweak symmetry is broken. We have added no scalars, just new matter and a new strong gauge interaction, and we get out electroweak symmetry breaking.

Continuing with our toy setup, let us study the symmetries. Momentarily ignoring the electroweak charges in Eq. (3.1), the system has a large symmetry: $SU(2N_D)_L \otimes SU(2N_D)_R \otimes U(1)_{TB}$[3]. The condensate is only invariant under common rotations on the left- and right-handed technifermions. The strong dynamics has caused chiral symmetry to break down:

$$SU(2N_D)_L \otimes SU(2N_D)_R \otimes U(1)_{TB} \rightarrow SU(2N_D)_V \otimes U(1)_{TB}. \tag{3.3}$$

For each broken global symmetry generator, we know there as a corresponding Nambu-Goldstone-Boson (NGB), thus technidynamics leaves our simple model with $(2N_D)^2 - 1$ NGBs. Restoring electroweak gauge interactions, three of these NGB are 'eaten' to become the longitudinal polarization modes of the $W^\pm/Z^0$ (the $SU(2)_w \otimes U(1)_Y$ symmetries clearly don't treat T_L and T_R the same, thus they are broken as a subset of the techni-chiral symmetry). Removing the eaten NGB, we are left with $(2N_D)^2 - 4$ massless "technipions".

What other composite states are there? We cannot rigorously answer this question using perturbative methods, however we can turn to QCD – the 4D strongly coupled theory we are most familiar with – for guidance. After the pions, the next lightest states in QCD are the spin-1 vector mesons, the $\rho(770)$, the $a_1(1080)$, and the $\omega(770)$. Rescaled to the electroweak scale, we expect spin-1 resonances at the TeV scale; a technirho (ρ_T), techni-a (a_T) and techni-omega (ω_T). Continuing the analogy with QCD, one expects the $\rho_T/a_T/\omega_T$ to interact strongly with the technipions, including the longitudinally modes of the W and Z, while interactions with SM fermions proceed through $\rho_T - W^\pm/Z^0$ mixing (or, analagously $a_T - W^\pm/Z^0$ or $\omega_T - \gamma$ mixing). This production-by-mixing is often referred to as 'vector-meson dominance' given its similarity to $e^+e^- \rightarrow \rho$ production in QCD. The color neutrality of the techniresonances and the weakness of the SM fermion-resonance interactions dictates the LHC phenomenology. To produce $\rho_T/a_T/\omega_T$, the collision must involve a quark and an antiquark. The low partonic luminosity for this type of collision at a pp collider combined with sub-electroweak strength couplings means technicolor rates haven't been probed with the first year of LHC data.

[3] As in QCD, the axial $U(1)$ symmetry is not present due to techni-instanton effects.

Given enough luminosity, techniparticles will certainly be created, but their observability also depends on how they decay. The preferred decay channel of the vector resonance ρ_T is into technipions. Depending on the size of the technicolor symmetry, there may be no uneaten technipions, in which case the ρ_T will decay to $W^\pm + Z$ (charged ρ_T) or to W^+W^- (neutral ρ_T). Of these modes, the best option for discovery is likely $\rho_T^\pm \to W^\pm Z \to 3\ell + \nu$. With three leptons and only one invisible particle, this mode is clean, has low background, and one can completely reconstruct the mother resonance. The results of a CMS search in this channel are shown below in Fig. 2. The bounds are roughly 500 GeV, depending on some model parameters. This bound can be contrasted with a 'sequential-SM' W', a heavy resonance assumed to have the same couplings as the SM.

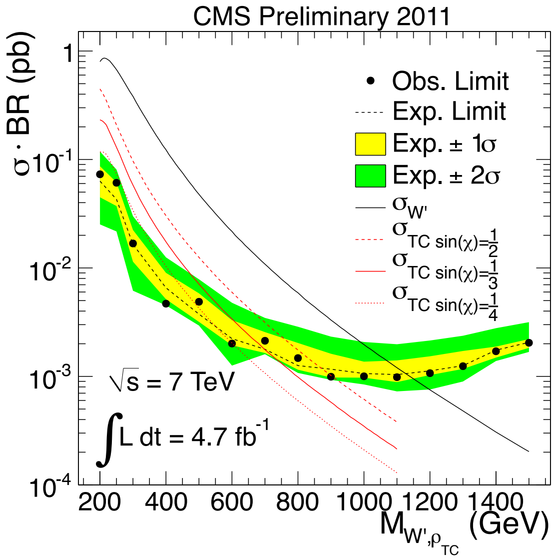

Figure 2: Limits on cross section times branching ratio for a technicolor ρ_T (dashed lines) and a sequential SM W', taken from Ref. [18]. The parameter $\sin\chi$ sets the strength of various SM-ρ_T couplings in the scenarios of Ref. [19, 20, 21, 22, 23, 24, 25].

The sequential W' is produced from $q\bar{q}$, like the ρ_T, but it has larger couplings (SM-sized) to fermions and gauge bosons and therefore a significantly larger production cross section. Current limits on sequential W' are roughly 1.2 TeV[4]. The isospin and parity partners of ρ_T, the a_T, ω_T cannot decay into WW/WZ, but they have clean signals of their own: $W+\gamma$ (for a_T) and $Z+\gamma$ (for ω_T). For details see Ref. [26, 27].

In addition to the vector-meson dominance production, techniparticles can also be produced via vector-boson fusion. In this process, incoming quarks radiate $W^\pm/Z^0$ which then 'fuse' to produce ρ_T/a_T. The fusion processes scale like $log(s/M_W)/s$, compared to $1/s$ for s-channel production, so they becomes more and more relevant for heavier techniresonances. Even if it is a subdominant production mode, one would still like to observe the fusion process because it is the most direct test of WW-scattering. However, the complicated final state and electroweak production cross section makes this a difficult process to observe (with or without new physics

[4] The bound on sequential Z' are equally strong. If W'/Z' decays to gauge bosons are forbidden, as is often assumed in sequential gauge boson searches, the limits are even stronger.

present). Sample diagrams showing the different techniparticle production mechanisms are shown below in Fig. 3.

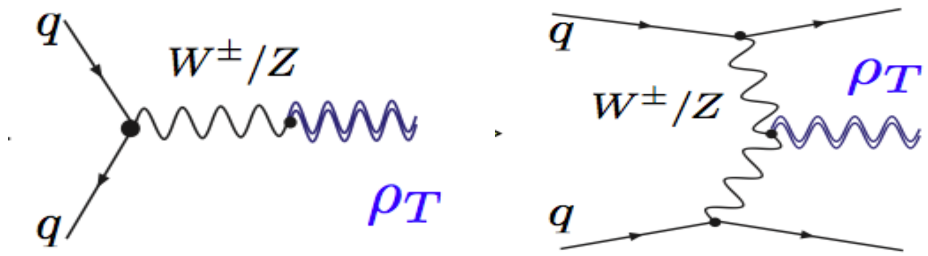

Figure 3: Sample techniparticle production mechanisms. The vector-meson dominance process is shown on the left and the vector boson fusion process is shown on the right. Notice that vector-meson dominance always involves a quark and an antiquark, while fusion processes can be initiated be either $q\bar{q}$ or qq.

The limiting factor in all techniparticle signals is the rate. Final states with many leptons may be viable, low-luminosity ($\lesssim 30\,\mathrm{fb}^{-1}$) discovery modes for resonances $\lesssim 1\,\mathrm{TeV}$, but for heavier resonances we must either pursue other modes and fight larger backgrounds, or wait for 100's of fb^{-1}. Phenomenological studies backing up these numbers can be found in Ref. [28, 29], and an example plot from that study illustrating the technirho peak over the background is shown below in Fig. 4. Notice the event counts are $\sim$ few events per bin even assuming $100\,\mathrm{fb}^{-1}$!

While we have seen how to break electroweak symmetry and thereby give longitudinal modes to $W^{\pm}/Z^0$, there is no state with the quantum numbers of the Higgs, a neutral scalar $J^{PC} = 0^{++}$, in the spectrum. In the usual 'Mexican hat' picture, the Higgs possesses very particular couplings to $W^{\pm}/Z^0$ bosons. In technicolor setups, such a special scalar mode is not present. One (or more) scalar bound states 0^{++} may exist in technicolor, but there is no reason they should be light or possess the same special couplings as the SM Higgs. At first this may seem to be a problem. While the physical Higgs boson is not eaten by the $W^{\pm}/Z^0$, it does remain connected to the eaten modes in WW scattering. In fact, WW scattering has been famously been used to set upper bounds on the Higgs mass [30, 31], and one often hears the statement that "if we don't find the Higgs then unitarity is violated". The origin of this statement is the fact that, if the diagrams involving the physical Higgs are removed from a calculation of WW scattering, the tree-level amplitude grows as E^2 and would seemingly be disastrous at energies of roughly $1 \sim$ TeV. However, there are other orders in perturbation theory. These higher order terms are even more poorly behaved, and grow to be as important as the tree-level diagrams as one approaches the TeV scale. If higher order diagrams are as important as tree-level terms, we have lost all calculational control and the theory is strongly coupled. This does *not* mean any violation of unitarity – QCD is perfectly unitarity and also strongly coupled – it just means we cannot do perturbation theory. In short, the correct statement is "we either see a light Higgs, or we have to see strong interactions".

3.1 Challenges for technicolor

The two largest hurdles for technicolor are electroweak observables and flavor physics – precise, low energy tests which indirectly bound physics at the TeV scale. As technicolor is strongly interacting, calculations of low-energy effects are approximate at best, and usually rely on naive

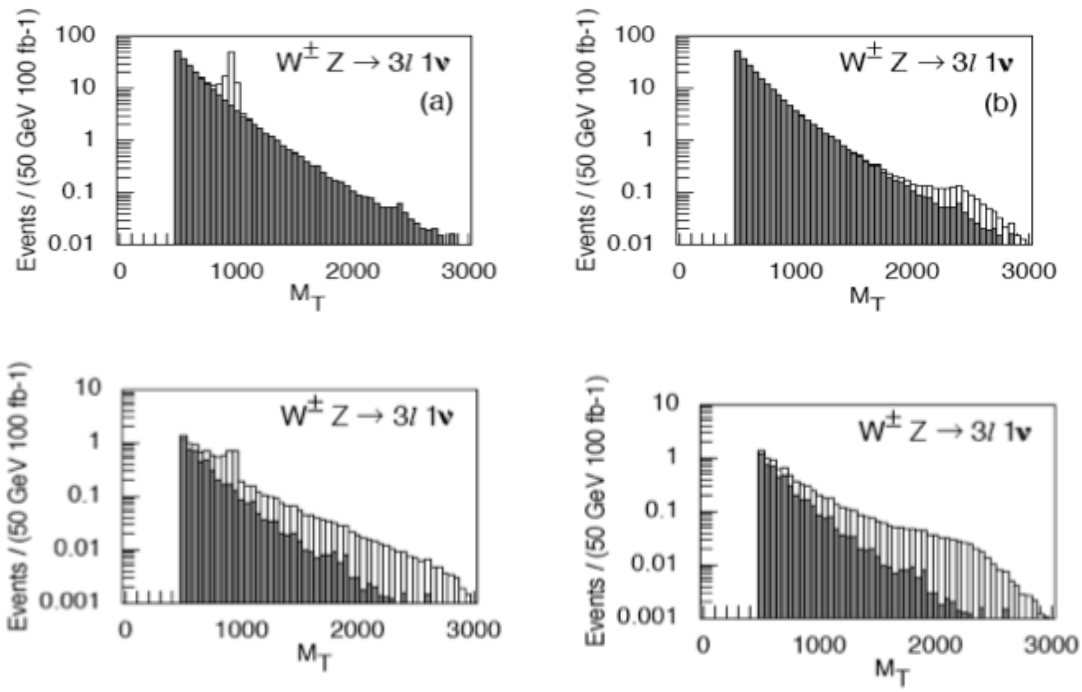

Figure 4: Technirho signals atop background from the phenomenology studies in Ref. [28, 29]. The top panel shows vector-meson-dominance production $pp \to \rho_T \to W^{\pm}Z$ for a 1 TeV resonance (left side) and a 2.5 TeV resonance (right side). The bottom panel shows the vector-boson fusion channel for the same mass ρ_T.

dimensional analysis or rescaling QCD for answers. While these methods are a good test and they do tell us some gross features about what is allowed and what is not, it is important to remember that the methods are only approximate and do not apply to all (even most) models of TeV-scale strong dynamics.

3.1.1 Precision Electroweak Observables

Under the assumption that the dominant effect from new physics (in the electroweak sector) lies in the masses and propagators of the electroweak gauge bosons, deviations from the standard model can be parameterized by three functions. The functions depend on the dimensionless variable Q^2/M_X^2, where Q^2 is the momentum flowing through the propagator and M_X^2 is a generic mass for the new physics particles. When $Q^2 \ll M_X^2$, the functions can be Taylor expanded; the coefficients of the first non-vanishing terms in this expansion are the familiar S, T, U parameters. Roughly speaking, T is a measure of the isospin-breaking new physics – this is usually not an issue for technicolor theories due to the presence of a custodial $SU(2N_D)$ symmetry present in Eq. (3.3). The U parameter can be thought of as a higher derivative of T and is therefore not a problem in technicolor theories either. The final parameter, S, roughly counts the new degrees of freedom with electroweak charge. There is no symmetry to forbid contributions to S, and for theories with a lot of new matter in the EW sector (like our simple N_D doublet model), we expect deviations from the SM value.

We cannot calculate how large the S parameter is in any arbitrary technicolor model, so we are forced to look at some special cases. The simplest special case is to just to assume the technicolor spectrum is the same as in QCD, modulo factors of N_{TC} or N_D. This was the approach used by Peskin and Takeuchi [32], and the result is a rather large S parameter, especially as the number of technicolors or techniflavors is large [32, 33]. The result of Ref. [32] is only strictly valid for a rescaled QCD, but how could a more general theory give a different result? In using rescaled version of the QCD spectrum to model technicolor, the result of [32] makes the assumption that the spectral functions involved in the determination of S are essentially saturated by single resonances. The hierarchy and strength of the resonances depends on the running behavior of the coupling constant – α_s for QCD or α_T for technicolor. The QCD coupling is quickly running, $\alpha_s(Q^2) \sim 1/\log(Q^2)$, hence the lowest resonances, where the coupling is still strong, dominate the spectrum. For technicolor the running could easily be different. If the coupling runs very slowly [34, 35], more resonances will play a role in the spectral functions and all intuition or arguments based on QCD are *not applicable* [36]. For this reason, combined with beneficial effects a slowly running technicolor coupling has on fermion mass generation which we will describe soon, so-called 'walking' technicolor theories [34, 37, 38] have become the modern paradigm for dynamical electroweak symmetry breaking

In perturbation theory one can achieve a slowly running coupling by dialing the amount of technimatter present. Writing out the first two coefficients of the α_T beta function:

$$\beta(\alpha_T) = -\frac{2\beta_0}{4\pi}\,\alpha_T^2 - \frac{2\,\beta_1}{(4\pi)^2}\,\alpha_T^3 + \cdots \tag{3.4}$$

$$\beta_0 = \frac{11\,N_{TC} - 2\,N_F}{3}, \quad \beta_1 = \frac{34}{3}N_{TC}^2 - \frac{10}{3}N_{TC}N_F - \frac{8}{3}N_F, \tag{3.5}$$

where N_{TC} is the number of (techni-) colors in a $SU(N)$ gauge theory, and N_F is the number of (Dirac) flavors. While this tactic is interesting, it does not tell us the complete story since we know technicolor must be strongly coupled in order to do the job of EWSB. Perturbative arguments cannot be trusted.

One way to go beyond perturbation theory (in α_T) is to make a large N_{TC} expansion. This is the expansion made in many extra-dimensional models of technicolor [39, 40, 41, 42, 43], where large-N_{TC} is replicated by taking a small 5D gauge coupling. Given that S essentially counts new EW degrees of freedom, taking large N_{TC}, meaning *more* technimatter, does not appear to be a fruitful direction, and the explicit calculations of S in many 5D setups back up this intuition; S is typically large, even though α_T is not running quickly[5]. Regardless of this result, 5D models are an invaluable tool for modern technicolor model-building, and we will return to them shortly.

To fully answer explore S we need better non-perturbative tools, such as the lattice.

3.1.2 Fermion masses and Flavor

We have seen that dynamical electroweak symmetry breaking is a natural, elegant way to generate masses for the EW gauge bosons, however $W^\pm/Z^0$ are not the only massive particles in the SM. We need to connect SM fermions to the techni-sector in a manner than is flexible enough to accommodate the huge hierarchy of fermion masses, can support the observed flavor structure

[5]Small S can be achieved, but requires tuning different sectors against each other [41, 44, 45]

(CKM-matrix), yet does not lead to any extra flavor-changing effects. This is a tall order, and there is no completely satisfactory model that achieves all of this. There are a couple of different ways to attach SM matter to technimatter, they have different pros and cons and different observable consequences at the LHC.

The older and more common mechanism of fermion mass-generation in technicolor theories is called Extended Technicolor (ETC) [46, 47]. In ETC, mass generation comes from dimension-6 operators joining a bilinear of SM fermions to a pair of technifermions,

$$\mathscr{O}_{mass} = \frac{(\bar{T}T)(\bar{f}f)}{M^2}. \quad (3.6)$$

After the technifermions condense, this operator becomes a conventional mass term. The UV dynamics behind Eq. (3.6) is assumed to be a new gauge interaction (the "extended technicolor" interaction) which can transform a SM fermion into a technifermion (and vice versa). Breaking the ETC group[6] at the scale $\sim M$ and integrating out the massive ETC gauge bosons, we get Eq. (3.6).

However, $\mathscr{O}_{mass}$ is not the only operator that gets generated. Dimension-6, purely SM operators

$$\mathscr{O}_{FCNC} = \frac{(\bar{f}_i f_j)(\bar{f}_k f_l)}{M^2}, \quad (3.7)$$

will also be generated (this can be proven from ETC representation theory, see Ref. [46].). Here, i, j, k, l label the fermion flavor, and there is no reason to assume these operators are flavor-diagonal in the same basis as the fermion mass terms. For a generic flavor assignment, the operators (3.7) will contribute to flavor changing processes. The most stringent bounds on BSM flavor changing contributions come from neutral meson systems; $K^0 - \bar{K}^0$ mixing provides the strongest bound, but $B^0_{s,d} - B^{\bar{0}}_{s,d}$ mixing are also important. To fit within the allowed uncertainty on magnitude of $K^0 - \bar{K}^0$ mixing and assuming anarchic flavor structure of Eq. (3.7), the new physics scale M is forced to the hundreds of TeV range. The phase in Kaon mixing, $Im(\varepsilon_K)$ is more constraining – for anarchic flavor structure, the suppression scale is forced even higher, to the thousands of TeV range [9]. As the scale suppressing the mass-generating operator in Eq. (3.6) is naively the same as the scale in Eq. (3.7), getting sufficiently heavy fermions seems impossible[7].

A more careful phrasing of the tension between scales shows the way to a solution. The operator in Eq. (3.6) is formed at a high scale, the ETC scale, but the operator only become a mass term once we reach the EW scale where TC becomes strongly interacting. Between the ETC and EW scales, renormalization group evolution occurs and is controlled by the anomalous dimension of the technifermion bilinear:

$$\langle \bar{T}_L T_R \rangle_{ETC} = \langle \bar{T}_L T_R \rangle_{EW} \times \int_{\Lambda_{ETC}}^{\Lambda_{EW}} \frac{d\mu}{\mu} \gamma_{\bar{T}T}(\mu) \quad (3.8)$$

If the anomalous dimension is small or falls off quickly with μ, the integral is O(few), and the bilinears (or condensates) at the two scales are comparable. However, if the anomalous dimension

[6] This breaking is presumably also by caused by strong dynamics, though that is unimportant for this discussion

[7] In so-called 'tumbling' models [48, 49] of ETC, different fermion generation masses are attributed to different scales. While this idea could ameliorate the tension between second/third generation fermion masses and flavor, no complete, viable models (which generate all the various scales dynamically) have been found.

is $O(1)$, the running has a large effect

$$\langle \bar{T}_L T_R \rangle_{ETC} \sim \langle \bar{T}_L T_R \rangle_{EW} \times \left(\frac{\Lambda_{ETC}}{\Lambda_{EW}} \right). \quad (3.9)$$

Applied to the problem at hand, such a large running effect would enhance the mass-generating term (as it has technimatter in it), while leaving the dangerous flavor operators untouched. Provided we can arrange fro $\gamma_{\bar{T}T} \sim 1$, we can push the ETC scale to very high values – safe enough to satisfy flavor constraints – while still generating viable quark mass. For this fix to work, we must argue why such large anomalous dimensions are feasible. Large anomalous dimensions $\gamma_{\bar{T}T} \sim 1$ have long been argued to be a consequence of conformal or near-conformal dynamics [34, 37, 38, 50, 35, 51, 52].

An alternative method for generating fermion masses is to consider *linear* mixing between SM fermions and technicomposites [53],

$$\mathscr{L} \supset -\lambda_L f_L \mathscr{O}_L - \lambda_R f_R \mathscr{O}_R + h.c. \quad (3.10)$$

The composite states (which one can think of as technibaryons) acquire a large mass from the strong dynamics $M_{\mathscr{O}} \sim \Lambda_{TC}$, which is partially passed on to the SM fermions via the mixing. The larger the mixing, controlled by dialing the dimension of $\mathscr{O}_L, \mathscr{O}_R$, the larger the SM fermion mass.

This approach to fermion masses is used extensively in extra-dimensional technicolor models. Inspired by the Ads-CFT correspondence [54, 55], extra dimensional models seek to describe conformal techni-dynamics by fields living in slice of AdS space. The slice is bounded by two 'branes' with different boundary conditions: a UV brane which preserves $SU(2)_w \otimes U(1)_Y$, and an IR brane which breaks EW symmetry [39, 40, 42, 41]. Within the AdS-CFT correspondence, interactions between fundamental fermions and composite operators such as Eq. (3.10) can be described by promoting SM fermions to 5D fermions propagating in the AdS space. Under this setup, the dimension of the CFT composite $\mathscr{O}_L, \mathscr{O}_R$ is controlled by the wave-function (or 'profile') of the fermions in the extra dimension – different profiles can be arranged for by giving different fermions different 5D masses (relative to the AdS curvature). By making the top quark (right-handed top, in particular) nearly composite, meaning its wave-function is peaked near the symmetry-breaking brane, the observed hierarchy of fermion masses can be recreated.

In order for this mass-generation mechanism to work, there must be spin-1/2 'technibaryons' in the spectrum (KK-exctiations of fermions in the 5D approaches). These states can be searched fro at the LHC – and since they are necessarily colored they may be easier to produce than the technimesons mentioned earlier – but there is much uncertainty in how the baryons of a non-QCD like theory interact with each other and with the other states in the spectrum. This is yet another area where lattice input would be extremely useful.

4. Strong dynamics lattice wishlist

In the last section I have argued that viable technicolor models – models free (or at least safer) from low energy constraints – necessarily are very different from rescaled QCD. Specifically, to be viable the technicolor coupling must be nearly conformal for some window in energy. The only tool we have to rigorously explore all corners of this type of theory is the lattice; Ads-CFT inspired, extra-dimensional analogs or Schwinger-Dyson methods [56, 57, 58, 59, 60] may work in some corners, but to apply those results elsewhere requires uncontrolled extrapolation. While it is our only tool, using the lattice to study near-conformal gauge theory is not an easy task. Conformal theory has no scales, while lattice calculations necessarily involve multiple scales, the lattice spacing, the volumes, the fermion masses, etc. Understanding all of the interplay between these scales and correctly subtracting out their effects is just one of the hurdles a lattice study of conformal dynamics must overcome[8].

The starting place for many explorations into the conformal regime has been $SU(3)$ gauge theory with a variable number N_F of flavors. At low $N_F \sim 3$ the theory is QCD and we know there is confinement, chiral symmetry breaking, etc. At $N_F \sim 16$ the theory is barely asymptotically free; the first term of the beta function is nearly zero and, for small coupling, can be balanced by the second term, leading to $\beta(\alpha_T^*) \cong 0$ for non-zero α_T^*, a so-called Banks-Zaks fixed point [68, 69]. For fewer flavors, the fixed point coupling gets stronger, and eventually α_T^* is large enough that two-loop perturbative analysis is inadequate. Continuing to decrease N_F, at some point the IR theory will no longer be conformal and will switch to more QCD-like behavior. While the general picture is robust, the exact location of where the theory enters and exits this conformal 'window' remain undetermined. Using the phase diagram of this theory as a playground, lattice studies such as Ref. [70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81] have tested different techniques and methods.

Once the phase diagram has been determined and the best computational and analysis techniques determined, there are several other questions the lattice can begin to answer. A few examples are:

- How does the anomalous dimension of the chiral condensate $\gamma_{\bar{T}T}$ behave as a function of N_F, N_c and representation? As shown in Sec. 3.1.2, this quantity is crucial in decoupling flavor effects from mass-generation dynamics.

- How does the S parameter behave as a function of the same parameters? Initial study of this quantity shows a decrease in the S/N_D (N_D is the number of EW doublets) as the number of flavors increases [82]. While still preliminary, this result directly shows the path to technicolor models with $S \lesssim 0.1$. This result is particularly striking since the precision electroweak constraints apply to the technicolor theory itself (generation of gauge boson masses) and not to any extensions (such as ETC).

- How stable are walking or conformal phases in the presence of perturbations, such as ETC-like interactions? Dynamics beyond technicolor is required in all theories of dynamical electroweak symmetry breaking, typically phrased in the form of four-fermion interactions. What effect do these other interactions have?

[8] While I have focused on technicolor models (no Higgs) as a scenario with TeV-scale strong dynamics, there is an entire class of models, called 'composite Higgs' models in which there is both new strong dynamics and a light Higgs in the spectrum [61, 62, 63, 64, 65, 66, 67]. In these models, the Higgs is a pseudo-NGB of some (EW-preserving) strong dynamics, assumed to take place at a scale $f > v_{EW}$. While the composite Higgs is a pure goldstone boson at tree-level, radiative effects (Yukawa interactions, gauge interactions, etc.) generate a potential, causing EWSB. While different from technicolor scenarios in many ways, composite Higgs models suffer from many of the same problems and often invoke conformal dynamics to work around these ills. Thus, composite Higgs models will also benefit from lattice explorations of conformal theories.

- When an internal symmetry from a compact group is approximately broken, the theory has a pNBG, but what about for the case of a dilations, a non-compact group? Since scale invariance is nearly a good symmetry in walking TC models, so is there a light 0^{++} 'dilaton'? Both sides have been argued (see, for example, Refs. [83, 84, 85]), but there is no consensus.

The answers to these issues, and more, can be picked up and used immediately by model builders and collider physicists.

5. Conclusion

Strong dynamics beyond the standard model is an exciting frontier, and one where lattice input can have a dramatic impact. While the focus of this review has been on strong dynamics that is intimately tied to electroweak symmetry breaking (technicolor), that is only one option. If a light SM-like Higgs is discovered by the end of the year, traditional technicolor may be history, but the next question will be whether the Higgs is fundamental or a bound state of some more-UV dynamics (a 'composite' Higgs). In order to understand and discriminate between different composite Higgs models, lattice input will be needed. Even if the Higgs is fundamental and stabilized by supersymmetry, then how is supersymmetry broken without re-introducing a hierarchy problem? Strong dynamics, yet again. In short, regardless of the outcome of the SM Higgs search, the understanding of gauge dynamics in non QCD-like theories that the lattice can provide is an invaluable tool to the advancement of model building and phenomenology.

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