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STRONG ELECTROWEAK SYMMETRY BREAKING

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Models of spontaneous breaking of electroweak symmetry by a strong interaction do not have fine tuning/hierarchy problem. They are conceptually elegant and use the only mechanism of spontaneous breaking of a gauge symmetry that is known to occur in nature. The simplest model, minimal technicolor with extended technicolor interactions, is appealing because one can calculate by scaling up from QCD. But it is ruled out on many counts: inappropriately low quark and lepton masses (or excessive FCNC), bad electroweak data fits, light scalar and vector states, etc. However, nature may not choose the minimal model and then we are stuck: except possibly through lattice simulations, we are unable to compute and test the models. In the LHC era it therefore makes sense to abandon specific models (of strong EW breaking) and concentrate on generic features that may indicate discovery. The Technicolor Straw Man is not a model but a parametrized search strategy inspired by a remarkable generic feature of walking technicolor, that technivector mesons are light, narrow and decay readily into electroweak vector mesons and photons. While walking technicolor is popular among practitioners, alternatives exist and the Straw Man may not lead to their discovery.

1 Introduction: Why Strong Electroweak Symmetry Breaking?

Theories of strong electroweak symmetry breaking (SESB) do not include fundamental scalar fields. Masses of vector and spinor fields are protected from divergent corrections automatically, those of vectors by gauge invariance and those of spinors by chiral symmetry. Hence, at least in principle, such theories elegantly and thriftily solve the fine tuning problem.

Moreover, they easily and naturally generate large hierarchies of scales. These theories are asymptotically free. If Λ_s denotes the scale at which the running coupling $\alpha(\mu)$ becomes large, inducing an electroweak symmetry breaking condensate, then roughly

$$\Lambda_s = M \exp\left(\frac{8\pi/b}{\alpha(M)}\right), \quad (1)$$

where b is the one loop coefficient of the beta function and M is, say, the Planck mass.

We don't know "why" nature would use one mechanism or another to break a symmetry spontaneously. But we do know it did choose non-perturbative condensates to break flavor symmetry, $SU(3) \times SU(3) \rightarrow SU(3)$, and, according to the BCS theory, electron condensates to break $U(1)_{\text{em}}$.

Disclaimer We can classify SESB according to whether or not the strong interaction produces a composite light scalar (*e.g.*, a pseudo goldstone boson) that acts as a higgs field. I had hoped to talk about the case where there are higgs-like light bound states, but to avoid duplication I agreed to talk about something I know less about, higgsless models, while Christophe Grojean's talk is on pseudo goldstone higgs particles. The two talks roughly parallel the entries on SESB in the 2009 Les Houches LHC report.¹

1.1 Why not

In addition to the inherent inability to calculate with them, a number of shortcomings have made theories of SESB unpopular. The simplest models of SESB, which we review below, have difficulty generating quark and lepton masses, run into trouble with constraints from FCNCs and electroweak precision data, have very light spin-0 particles and it is not apparent how, if at all, can be incorporated into a GUT.

Several frameworks, like extended-, walking-, conformal- and top-color assisted- technicolor, have been formulated to address these problems. The plan of the talk is as follows: first review the minimal technicolor model so we may better appreciate the "why not's" of SESB. Then review some of the frameworks that address these. In particular because of time and space limitations we shall focus on extended- and walking- technicolor (find more details in lectures by Ken Lane²). After evaluating these we will proceed to briefly discuss LHC discovery prospects.

2 Minimal Technicolor: A beautiful idea that does not work

Two flavor QCD is a theory that well approximates the world at low energies. It has an approximate chiral $SU(2)_L \times SU(2)_R$ symmetry that is broken spontaneously to the vector (diagonal sum) $SU(2)_V$ by a strong interaction condensate. In a bit more detail $q_{L(R)} = (u_{L(R)}, d_{L(R)})^T$ is an $SU(2)_{L(R)}$ doublet, and the strong interaction induces condensation:

$$\langle \bar{q}_L^i q_R^j \rangle = \Lambda_\chi^3 \delta^{ij} \quad (2)$$

We interpret the resulting pseudo-Goldstone bosons as pions (π^\pm, π^0), so the scale Λ_χ of the condensate must be related to their decay constant, f_π . One typically estimates $\Lambda_\chi \sim 4\pi f_\pi$, or, perhaps, $\Lambda_\chi^3 \sim 4\pi f_\pi^3$. Pions are not exact goldstone bosons. The quark masses $m_{u,d} \neq 0$ and electromagnetic couplings break the chiral symmetry explicitly resulting in non-vanishing pion masses.

Recall that in the standard model (SM) of electroweak interactions an $SU(2)_L \times U(1)_R$ subgroup of the chiral $SU(2)_L \times SU(2)_R$ is gauged.^a Even in the absence of a higgs field, the symmetry of the SM is spontaneously broken by the QCD condensate in (2). The would-be goldstone bosons are "eaten," that is, they become the longitudinal components of the W and Z . The W and Z masses obtained this way are too small, of the order of the pion decay constant. However, there is one successful relation. In $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ the group $SU(2)_V$ is

^aConsistent quantization of the gauge symmetry requires that the symmetry be exact. Hence the explicit masses of quarks, $m_{u,d}$, have to be put to zero.

explicitly broken by the gauging of $U(1)_R$. Hence, up to hypercharge corrections, this $SU(2)_V$ “custodial symmetry” guarantees

$$M_W = M_Z \cos \theta_W, \quad \text{that is,} \quad \rho = \frac{M_W^2}{\cos^2 \theta_W M_Z^2} = 1. \quad (3)$$

Minimal Technicolor³ is a copy of 2-flavor QCD with:

- “QCD” replaced by “TC,” “gluons” by “technigluons,” “quarks” by “techniquarks,” etc.
- The technistrong coupling constant taken so that the condensate is at the electroweak scale: $\Lambda_{\text{TC}} \sim 4\pi v = 4\pi(246 \text{ GeV})$.
- An $SU(2)_L \times U(1)_R$ subgroup of $SU(2)_L \times SU(2)_R$ gauged giving electroweak interactions.

While we cannot calculate much from first principles in this model, we can infer a lot from experiment: since it is a scaled up copy of QCD it suffices to measure QCD parameters and scale them by the appropriate factor. This is what was done, for example, in order to confront with electroweak data and conclude that minimal technicolor is all but ruled out.⁴

3 Masses, Goldstone Bosons, Extended Technicolor and the Problem with FCNC

The higgs field in the SM plays a dual role. On the one hand it breaks electroweak symmetry, giving the W and Z masses, and on the other its Yukawa interactions with quarks and leptons, $Y_U \bar{H} \bar{q}_L u_R + Y_D \bar{H} \bar{q}_L d_R + Y_E \bar{H} \bar{\ell}_L e_R$, produce their masses. In the minimal TC model techniquark condensates $\langle \bar{Q}_L Q_R \rangle$ break electroweak symmetry and give masses to the W and Z , but quarks and leptons remain massless. Couplings of techniquarks to quarks and leptons are needed to generate their masses.

Whatever new interaction is responsible for quark and lepton masses, they may solve another problem with TC models. In the minimal TC model above there are exactly three would-be goldstone bosons that are eaten by the W^\pm and Z^0 . It is exactly three because the pattern of symmetry breaking involved small groups, $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$. Many different patterns of symmetry breaking are possible and generically lead to more goldstone bosons. Three are still eaten by the W/Z but the rest, the “technipions,” remain in the spectrum. Their masses arise from electroweak interactions. Hence they are light and ruled out experimentally. The additional interactions that give rise to quark masses may perhaps render the technipions safely heavier.

In Extended TC (ETC)⁵ we assume there are additional interaction terms of the form^b

$$\frac{C}{M^2} \bar{Q} Q \bar{q}_L q_R \quad \text{and} \quad \frac{C}{M^2} \bar{Q} Q \bar{\ell}_L e_R. \quad (4)$$

These are operators of dimension 6 so they appear in the Lagrangian with two inverse powers of a mass-dimensional parameter, here denoted by M . The C are dimensionless constants that characterize the quark mass matrices (playing a role analogous to that of the Y_Q of the SM). We read off the quark and lepton masses:

$$m_{q,\ell} \sim \frac{C}{M^2} \langle \bar{Q} Q \rangle \sim \frac{C}{M^2} \Lambda_{\text{TC}}^3. \quad (5)$$

The operators in (4) are nothing but the effective description of an interaction that arises from the exchange of a heavy particle of mass $\sim M$. A complete ETC model should specify

^bThere are alternatives to ETC for mass generation, like partial compositeness.⁶ See the discussion of Minimal Composite Higgs⁷ in Grojean’s talk, this volume.

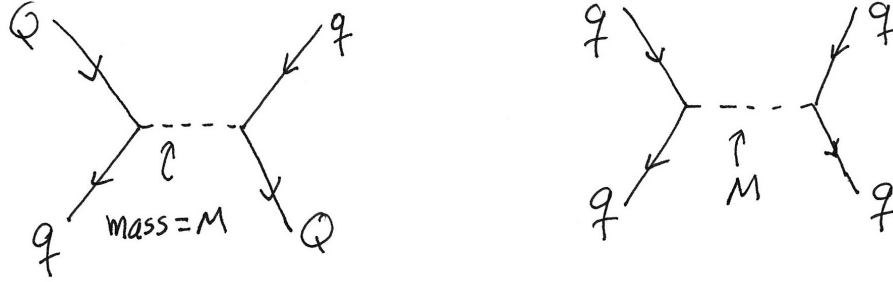


Figure 1: Feynman diagrams of some Extended Technicolor interactions. At energies well below M they give rise to four-fermion operators. The diagram on the left produces effective interactions like those in (4), responsible for quark and lepton masses. The diagram on the right induces troubling FCNCs.

the new interaction, but for our purposes it suffices to assume its existence. The first of the Feynman diagrams in Fig. 1 is an example of the exchange of a particle of mass M that gives rise to the effective interaction in (4). The second Feynman diagram in the figure shows exchange of the same heavy particle between quarks only, using the same basic vertices that were introduced in order to produce quark masses. The inescapable conclusion is that ETC interaction will generically produce four quark operators too, like

$$\frac{C'}{M^2} \bar{q}q\bar{q}q, \quad \text{and in particular } \Delta S = 1, \text{ FCNC terms like } \frac{C'}{M^2} \bar{s}d\bar{s}d. \quad (6)$$

A quick and dirty bound on C'/M^2 can be found by requiring it does not exceed the corresponding coefficient of the four quark operator in the SM.^c Now, in the SM this arises largely from a 1-loop diagram, a W -box with internal top quarks. So we must have

$$\frac{C'}{M^2} \lesssim \frac{1}{16\pi^2} G_F |V_{td}V_{ts}|^2 \quad \Rightarrow \quad M/\sqrt{|C'|} \gtrsim 10^4 \text{ TeV} \quad (7)$$

Herein lies the problem: using the bound (7) in (5) and assuming roughly that $C' \approx C$ the largest possible quark and lepton masses are in the MeV range. One can try to get around this problem by making C' very small compared to C , which requires creative model building. In particular, for a technipurist there ought not to exist any scalar fields: the particle exchanged in the ETC must be a heavy vector boson, presumably associated with some non-abelian symmetry (that does not commute with neither EW nor TC interactions). Then the relative size of C' and C is fixed by group theory and we expect $C' \sim C$.^d

The ETC will also give four-techniquark operators, $(C''/M^2)\bar{Q}Q\bar{Q}Q$. These generically break the global symmetries of the TC theory and therefore contribute to the mass of technipions. But the extremely high mass of the ETC scale renders the effect insufficient: roughly $f_\pi^2 m_\pi^2 \sim C'' \Lambda_{\text{TC}}^6 / M^2$, or $m_\pi \sim 4\pi \Lambda_{\text{TC}}^2 / M \lesssim 10 \text{ GeV}$.

4 Walking Technicolor: *A fairy tale (but a good one, and an interesting one)*

Here is what Walking⁸ TC (WTC) is supposed to do: dynamically replace Λ_{TC}^2/M for $\Lambda_{\text{TC}}^3/M^2$ in the ETC quark mass formula, so that $m_q \sim C\Lambda_{\text{TC}}^2/M$. Using the same assumptions as before this gives $m_q \lesssim 10 \text{ GeV}$. Therefore in walking technicolor one can account for the masses of quarks and leptons without running afoul of FCNC bounds. Except for the top quark.

^cThis ignores actual top quark mass dependence and differences in the Dirac structure of the four quark operators, but it is good enough for order-of-magnitude estimates

^dAn exception is if quarks and techniquarks belong in distinct representations of the ETC gauge group that are very different in size. But then it is difficult to maintain asymptotic freedom

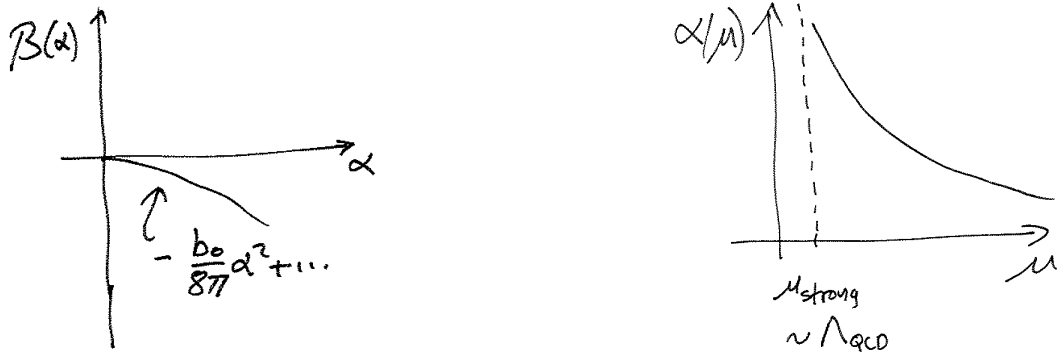


Figure 2: Sketch of the *beta*-function of QCD (left) and the corresponding running coupling constant $\alpha(\mu)$ (right).

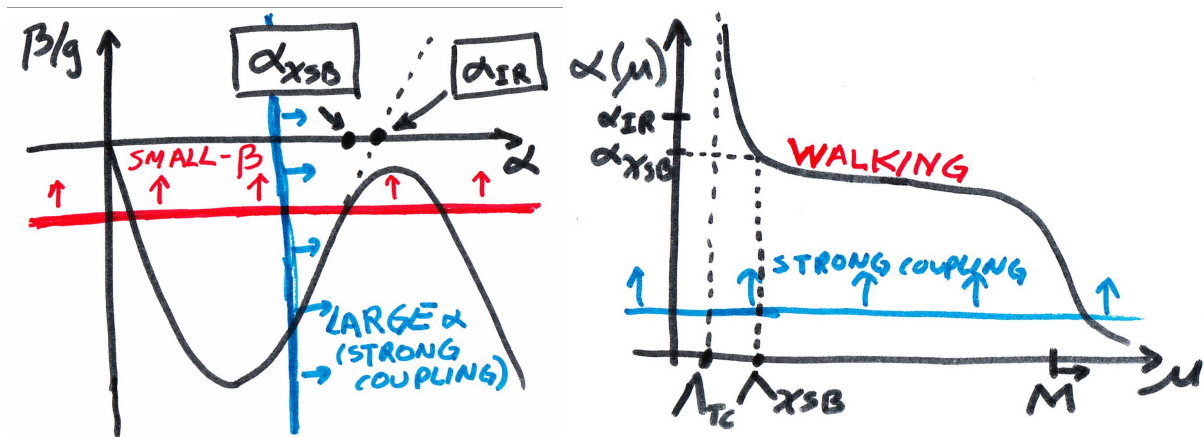


Figure 3: Sketch of the beta function of WTC (left) and the corresponding running coupling constant (right).

Being extraordinarily heavy it has to be dealt with separately (this is true also of many an SM extension). New interactions must be introduced, *e.g.*, topcolor assisted technicolor,⁹ but because of time and space limitations we do not consider them further here.

Before discussing how WTC works let us review a more familiar example. The left diagram in Fig. 2 is a sketch of the beta function of QCD. It is a negative, monotonically decreasing function of α . The sketch on the right hand of the figure shows the running coupling, that is, the solution to the RGE: $\mu\partial\alpha/\partial\mu = \beta(\alpha)$. It is best to think of this as starting from some $\alpha(\mu_0) \ll 1$ and integrating the RGE towards the region $\mu < \mu_0$. In physics lingo, fix the value of α to be perturbatively small in the UV and figure out what it flows to in the IR. The sketch shows that α gets increasingly large as it flows towards the IR and eventually at some scale $\mu = \mu_{\text{strong}} \sim \Lambda_{\text{QCD}}$ becomes strong.

Fig. 3 shows a hypothetical β -function (or, should I say, the β -function for a hypothetical theory?) and the corresponding solution to the RGE. Starting from $\alpha(\mu_0) \ll 1$ the movie script is as follows: α runs slowly because β is small (close to the origin of the left sketch in Fig. 3); eventually β is large and α runs fast to large values; as $\alpha \sim 1$ increases further β decreases to a small value, and the rate of change of α gets to be puny. At this stage of the movie we say that α is “walking” rather than “running.” Now, in fact, it looks like this would go on indefinitely: if we extrapolate the β -function it appears as if it would cross the abscissa at the point labeled “would-be IR fixed point, α_{IR} ” in the figure. But although α is barely changing, it reaches and then exceeds a critical coupling, $\alpha_{\chi\text{SB}}$ that triggers chiral symmetry breaking (χSB). Note that

by necessity $\alpha_{\chi\text{SB}} < \alpha_{\text{IR}}$. As a result of χSB techniquarks acquire mass, which in turn produces the sudden change in the β -function that, in the last frame of the movie, drives α arbitrarily large, much like the end state of QCD. Finally, as indicated in the sketch we assume the scale M of ETC is large, in the region before the coupling walks.^e

Now, here is how this helps. The effective ETC interaction of (4) is an RGE invariant, but both the coefficient C and the operator $\bar{Q}Q$ are rapidly varying functions of μ . The quark mass term in the Lagrangian can be written as

$$\mathcal{L}_{\text{mass}} = \frac{C(\mu)}{M^2} \langle \bar{Q}Q \rangle(\mu) \bar{q}q = \frac{C(M)}{M^2} \langle \bar{Q}Q \rangle(M) \bar{q}q = \frac{C(\Lambda_{\text{TC}})}{M^2} \langle \bar{Q}Q \rangle(\Lambda_{\text{TC}}) \bar{q}q. \quad (8)$$

The three forms of the equation are equivalent, by RGE invariance. $C(M)$ is readily computed by “matching” to the full ETC, and does not involve the scale Λ_{TC} at all. On the other hand $\langle \bar{Q}Q \rangle(\Lambda_{\text{TC}}) \sim \Lambda_{\text{TC}}^3$ from TC dynamics and does not involve the scale M at all. To compute the quark mass one needs either $C(\Lambda_{\text{TC}})$ or $\langle \bar{Q}Q \rangle(M)$ both of which involve implicit dependence on Λ_{TC}/M . Fortunately, the RGE tells us what this dependence is. The dominant effect is from the region where α is walking and large, producing a nearly constant and large anomalous dimension γ_* . Hence

$$C(\Lambda_{\text{TC}}) = \left(\frac{M}{\Lambda_{\text{TC}}} \right)^{\gamma_*} C(M). \quad (9)$$

Furthermore, it is argued that $\gamma_* \approx 1$.¹⁰ So we read off $m_q \sim C(M) \Lambda_{\text{TC}}^{3-\gamma_*} / M^{2-\gamma_*} \sim C(M) \Lambda^2 / M$ as advertised at the top of the section.

As a bonus, this mechanism raises the mass of technipions in non-minimal TC. Recall the ETC interaction $C''/M^2 (\bar{Q}Q)^2$ induces a technipion mass. In WTC this interaction will be enhanced, much like the quark masses. In fact, since this involves the square of $\bar{Q}Q$ we venture a guess that the anomalous dimension for C'' is now closer to $2\gamma_* \approx 2$. This means that $(\bar{Q}Q)^2$ is effectively a dimension 4 operator, *i.e.*, it is near marginal. If that is the case there is no sense in which the symmetry was even approximate and the technipions are heavy, roughly as heavy as other technimesons (like technirhos). This plays a central role in next section: $m_{\rho_T} < 2m_{\pi_T}$ implies narrow, and hence more easily detected, technirho.¹¹

Speculation And Conjecture WTC is speculation on the nature of the universe based on a conjecture, namely, that a class of quantum field theories behave as wanted. We don’t have any examples of such a theory. Yet, there is no no-go theorem. The conjecture may be affirmed or repudiated by studies of QFT on the Lattice. The speculation may be confirmed by the LHC. If that were the case the future of particle physics may be much like learning about strong interactions from experiment, all over again. The new technistrong interaction would necessarily behave very differently from QCD and possibly be less amenable than QCD to analytic studies.

EW Precision Tests Since the EW sector in TC models is strongly coupled there does not exist a reliable way to calculate radiative corrections (S and T parameters). The exception is minimal TC, since one can scale up from QCD measured quantities. Minimal TC is ruled out by EW precision data. So what? It is also ruled out by quark masses/FCNCs, light technipions, etc. To repeat from the previous paragraph, the WTC theory is surely very unlike QCD. Low energy data offers no guidance as to how to calculate EW corrections.

5 WTC at the LHC: the TCSM

If WTC is discovered then there will be a long period of learning from experiment about this new strongly coupled dynamics. The prerequisite is the discovery, and we shall focus on it for

^e There are other ways of achieving this effect. All that is needed really is that β be small when χSB occurs.⁸

now. In spite of lacking detailed understanding of the dynamics, there are rough requirements on it that may guide a search. This is the approach adopted by the TC working group of the Les Houches Report.¹ I will summarize here their work, but in passing will butcher it,^f so readers interested in details are advised to proceed directly to the source.

The idea is to focus on the least dynamics specific and most model independent features of WTC. Since we must have $SU(2)_W$ we can use it as the analogue of isospin to classify the spectrum: $\pi_T, \rho_T, a_T, f_T, \pi'_T, \dots$. We make the plausible assumption that the large symmetry breaking effect of $(\bar{Q}Q)^2$ makes π_T sufficiently heavy that the other low mass mesons cannot decay into technipions, $m_{\rho_T} < 2m_{\pi_T}$, $m_{\omega_T} < 3m_{\pi_T}$, etc. Hence there are many *narrow* states. This set-up is called “Low Scale TC” or, alternatively, the “TC Straw Man” (TCSM).

The Les Houches report presents studies of Drell-Yan production of technimesons in pp collisions at 10 TeV energy searched for in $\rho_T^\pm \rightarrow W^\pm Z^0$, $(\rho_T, a_T) \rightarrow W\gamma$, $\omega_T \rightarrow \gamma Z^0 \rightarrow \gamma \ell^+ \ell^-$ and $(\rho_T^0, a_T^0, \omega_T) \rightarrow \ell^+ \ell^-$. The last process would be forbidden if the electric charges of the up and down techniquarks coherently vanish, $Q_U + Q_D = 0$; for that study it is assumed that $Q_U + Q_D = 1$. If $Q_U + Q_D = 0$ the discovery channel for ω_T may well be $\omega_T \rightarrow \gamma Z^0$. The cases studied (assumed mass spectra) and gross results are presented in Table 1. $\text{Br}(W/Z \rightarrow (e, \mu)X)$ are included. $\sigma(e^+e^-)$ includes SM plus signal production integrated over approximately $M_{\rho_T, \omega_T} - 25$ GeV to $M_{a_T} + 25$ GeV; for orientation, the cross section in the SM alone is in parentheses. As you can see, many of these events will be produced in 1 fb^{-1} of data.

| Case | M_{ρ_T, ω_T} | M_{a_T} | M_{π_T} | $\sigma(W^\pm Z^0)$ | $\sigma(\gamma W^\pm)$ | $\sigma(\gamma Z^0)$ | $\sigma(e^+e^-)$ |
|------|------------------------|-----------|-------------|---------------------|------------------------|----------------------|------------------|
| 1a | 225 | 250 | 150 | 230 | 330 | 60 | 1655 (980) |
| 1b | 225 | 250 | 140 | 205 | 285 | 45 | 1485 (980) |
| 2a | 300 | 330 | 200 | 75 | 105 | 11 | 425 (290) |
| 2b | 300 | 330 | 180 | 45 | 85 | 7 | 380 (290) |
| 3a | 400 | 440 | 275 | 22 | 40 | 4 | 130 (90) |
| 3b | 400 | 440 | 250 | 14 | 35 | 3 | 120 (90) |

Table 1: Technihadron masses (in GeV) and approximate signal cross sections (in fb) for pp collisions at $\sqrt{s} = 10$ TeV taken from the 2009 Les Houches report (where details of parameters of the TCSM can be found).

6 Other Stuff and Final Remarks

The title I had been assigned when invited to give this talk was “Strong Dynamics and New Electroweak Models.” As I explained, to avoid overlap with other, earlier talks I decided to concentrate on “Strong EW Symmetry Breaking.” I would like to close with a few words about other possibilities (that do not overlap previous talks!).

In WTC the bilinear $\bar{Q}_L Q_R$ plays the role of H , the SM’s higgs doublet. As we saw, it’s scaling dimension is 2 and therefore the quark/lepton mass terms are irrelevant operators (dimension 5). *Conformal TC*¹² proposes that $H \sim \bar{Q}_L Q_R$ has dimension close to 1 while $H^2 \sim (\bar{Q}_L Q_R)^2$ has dimension close to 4. If this were the case both the quark/lepton mass terms (*e.g.*, $H\bar{q}d$) and the “higgs mass” H^2 would be marginal operators. It would follow that their dependence on cutoff is logarithmic and again there would be no hierarchy or fine tuning problem. Moreover, accommodating a top quark mass should be as simple as in the standard model. Unfortunately there is some evidence against this arrangement of anomalous dimensions.¹³

^fSo I will not give you the detailed parameters used, what the analysis strategy is for each mode, nor will I talk about signal and event selection or background estimation.

5D models give a means to study the idea that the masses of W and Z arise from internal structure. That is, if you believe duality applies here. Take for example a model with the W/Z localized on the IR brane, and let boundary conditions break gauge symmetry explicitly.¹⁴ The 5D/4D dictionary then gives a higgsless 4D dual with composite W/Z . Just like techniresonances in TC this model has 4D resonances, the duals of the Kaluza-Klein 5D modes. Even in this setup, the top mass remains a problem.

Strong EW symmetry breaking is very appealing. I believe news of its demise are premature, driven mostly by our frustration with our inability to calculate. What we do know is that it is not a scaled up version of QCD. These comments apply equally to all alternatives to TC. So the strategy for progress is to (i) search and discover, (ii) study in detail and (iii) build a model and learn about strong dynamics. In that order!

The TCSM is a good example of how to engage this strategy. It is not a model but a template for searching for WTC, making a number of assumptions (hopefully minimal and reasonable). Similar efforts that can cover alternative strong EW breaking scenarios are needed.

Can strong EW symmetry breaking be excluded? Or, at what point after not finding evidence do we give up on the idea? Lack of a definite answer by practitioners has often frustrated others, prompting some to facetiously ask¹⁵ “Can One Tell Technicolor from a Hole in the Ground?” I think the question is no different than for other models (when do we give up on SUSY?). This is not a productive avenue of thought, particularly if you believe that many discoveries await us in the dawn of LHC physics. As of this writing the CMS and ATLAS experimental collaborations posted integrated luminosities of about 700 nb^{-1} each. That’s 1400 down, 998,600 to go. Looking forward to it!

Acknowledgments

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