QCD BEYOND THE STANDARD MODEL*

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The importance of QCD-like theories in Beyond the Standard Model physics is briefly reviewed.

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1. Introduction

In spite of the modern focus on the Standard Model as an effective field theory, it is worth remembering that QCD is a "perfect" field theory in that it is self-consistent (as opposed to QED, which suffers from Landau poles). Thus it is natural to look at QCD-like theories in attempts to construct "beyond the Standard Model" (BSM) theories. Of course, one also hopes to resolve a collection of theoretical issues that exist with the current Standard Model. Thus interest in general properties of QCD-like theories has risen sharply along with the need to understand nonperturbative field theory.

2. Mass hierarchy

Quark and lepton masses array themselves over eleven or twelve orders of magnitude. How are we to understand this? In terms of naturalness, it is certainly not satisfactory to regard the mass scale hierarchy as due to happenstance with Yukawa couplings.

An attractive alternative is that large ratios of scales can be generated dynamically. It was with this goal in mind that Appelquist and Pisarski suggested examining the properties of QCD (or QED) in three dimensions [1]. The theory is superrenormalisable, which is a fancy way of saying that the coupling carries (positive mass) units. Setting fermion masses to zero implies that the coupling sets the scale unless spontaneous chiral symmetry breaking occurs. In this case it is possible that the generated scale is

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much different from that of the coupling. And in fact, studies of QED3 reveal that this is precisely what happens [2]. One finds that the generated mass is strongly dependent on the number of fermion flavours. One flavour yields $m_{\rm gen}(N_f = 1) \approx e^2$ while $m_{\rm gen}(N_f = 2) \approx e^2/10$, and $m_{\rm gen}(N_f = 3) \approx 10^{-8}e^2$. Thus it is possible to leverage the nonperturbative properties of strongly interacting field theory to generate enormous mass ratios with $\mathcal{O}(1)$ changes in model parameters.

Obtaining precise values for the dynamical fermion mass is difficult. Lattice gauge computations are problematic since the dynamical symmetry breaking effectively vanishes once the dynamical mass drops below the infrared cut-off (which is typically 50 MeV in QCD computations). Alternatively, Schwinger–Dyson calculations are bedeviled by truncation and gauge-dependence [2].

3. Electroweak symmetry breaking

It is widely held that the Higgs sector of the Standard Model is simply an effective description of more complex dynamics [3]. And ideally, the new dynamics, for example, does away with the fine tuning problem associated with the Higgs mass. Not long after the advent of QCD, Weinberg suggested that a version of QCD, scaled up to the TeV range, could provide this dynamics [4]. Weinberg dubbed this model "hypercolor" and suggested that dynamical chiral symmetry breaking would generate hyper-Goldstone bosons that are eaten by the W and Z, providing the mechanism for generating a viable electroweak (EW) force.

Hypercolor has problems: there are other light hyper-Goldstone bosons and there is no mechanism to generate the fermion masses. A way forward was postulated by Dimopoulos and Susskind, who introduced extra gauge interactions to raise the fermion and hyper-Goldstone boson masses [5]. The theory, renamed "extended technicolor" (ETC), is broken at the ETC scale giving rise to effective four-fermion operators at the EW scale [6]. Calling Q a techniquark and q a quark, these operators are of the form $(\bar{Q}Q)(\bar{Q}Q)/\Lambda^2_{\rm ETC}$, $(\bar{Q}Q)(\bar{q}q)/\Lambda^2_{\rm ETC}$, and $(\bar{q}q)(\bar{q}q)/\Lambda^2_{\rm ETC}$. Spontaneous symmetry breaking allows one to replace $(\bar{Q}Q)$ with $\langle\bar{Q}Q\rangle$. Thus the first operator raises ETC Goldstone boson masses and the second generates fermion masses. Unfortunately, the third generates flavour changing neutral currents, which are strongly suppressed in nature, implying that $\Lambda_{\rm ETC} \sim 1$ TeV. This in turn implies that fermion masses are smaller than desired.

A possible finesse was suggested by Holdom [7]: if the technicolor coupling ran sufficiently slowly it would enhance condensates while keeping the technipion decay constant stable (it is the latter that sets the EW scale, while the former sets the technihadron mass scale). Exploring the properties of "walking technicolor" is thus a high priority for model builders.

Couplings run slowly near fixed points and it is thus natural to examine the beta function of QCD-like theories. In particular, one seeks the conformal window, which is the range of N_f for which the theory is asymptotically free and has no infrared fixed point. The theory walks just below the conformal window. For example, to two-loop order and for three colours, the conformal window is $N_f \in (7.75, 16.5)$ [8]. Recent lattice computations imply that there is an IR fixed point for $N_c = 3$, $N_f = 12$, but no IR fixed point for $N_c = 3$, $N_f = 8$ [9].

Other constraints on model building exist. For example, one can parameterise extensions to the Standard Model in terms of "Peskin–Takeuchi parameters", S, T, and U. Nature tells us that S and T are very small, and ETC models need to obey this constraint [10]. For example, the expression for S is roughly given by

$$g^{\mu\nu} S \sim \frac{d}{dq^2} \left[\langle V^\mu(q) V^\nu(0) \rangle - \langle A^\mu(q) A^\nu(0) \rangle \right]_{q^2=0} ,$$

where the matrix elements are vector–vector and axial–axial correlators in the new theory. These correlators thus represent techni-ρ and techni-a_1 spectral densities, which leads to the remarkable conclusion that the prosaic ρ and a_1 particles could tell us something deep about BSM physics.

4. Dark matter

The advent of the Concordance Model of cosmology has led to several interesting theoretical issues. For example, why is the density of dark matter about five times that of baryonic matter? If dark matter consists of WIMPS, its interactions with the Standard Model must be weak. How, then, is the WIMP mass generated? Perhaps strong Yang–Mills theories can help here as well?

Many years ago Nussinov suggested that a natural way to generate a dark matter abundance of the same order as the baryon abundance is to invoke the same Standard Model mechanism that generates baryon matter asymmetry in the technibaryon sector [11]. Thus the same nonperturbative physics that results in the predominance of matter will give rise to dark matter. Again, nonperturbative field theory may provide the way forward in a difficult problem.

Technibaryons that are charge and electroweak neutral would also provide a natural explanation for the second problem since they would have suppressed Standard Model couplings [12]. Alternatively, it has been proposed that dark matter is "quirky", namely scalar baryonic bound states of a new nonAbelian force that becomes strong below the electroweak scale [13]. The baryon is made of chiral quarks that transform under the new force and in chiral representations of the electroweak group. Interestingly, the authors of the latter paper note that the decay of quirky glueballs to photons can disrupt the successes of nucleosynthesis. Thus understanding glueball decays takes on cosmological significance.

5. Conclusions

BESIII and RHIC continue their labours; the LHC has started collecting data; JLab at 12 GeV is set to start in 2014; PANDA in 2016; and perhaps a super B factory or two some time after that. Thus it appears that many hadrons, old and new, will be created in labs around the world. In the meantime, theoretical understanding and technique continue to improve, aided greatly by massive investment in computational resources. Furthermore, it seems very possible that a high energy version of QCD is what is required to bring the Standard Model into a state of "naturalness".

At the start of the LHC era we have heard many times how the "God Particle" creates mass for all other particles. But it is worth remembering that quarks contribute only $1/2\%$ of the mass of baryons, and hence almost all the mass of all the matter we understand (*i.e.*, not dark energy or dark matter) is generated by gluons. I therefore propose that the true location of divinity in the Standard Model should be shifted from the electroweak sector to the strong sector. As we have seen, many people are working on effecting this shift for the entire Standard Model.

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REFERENCES

[1] T. Appelquist, R. Pisarski, *Phys. Rev.* **D23**, 2308 (1981).

[2] T. Appelquist *et al.*, *Phys. Rev.* **D33**, 3704 (1986); T. Appelquist *et al.*, *Phys. Rev. Lett.* **60**, 2575 (1988); M. Pennington, D. Walsh, *Phys. Lett.* **B253**, 246 (1991); P. Maris, *Phys. Rev.* **D54**, 4049, (1996); S.J. Hands, J.B. Kogut, L. Scorzato, C.G. Strouthos, *Phys. Rev.* **B70**, 104501 (2004).

[3] For a nice review of modern efforts in this area see G.T. Fleming, *PoS* **LAT2008**, 021 (2008) [arXiv:0812.2035 [hep-lat]].

[4] S. Weinberg, *Phys. Rev.* **D13**, 974 (1976).

[5] S. Dimopoulos, L. Susskind, *Nucl. Phys.* **B155**, 237 (1979).

[6] It is worth remembering something Dimopolous and Susskind said, "... we must warn the reader that we will deal with complicated systems of interacting gauge sectors, some of which are strongly interacting. Thus we can only guess the patterns of spontaneous symmetry breaking which occur".

[7] B. Holdom, *Phys. Rev.* **D24**, 1441 (1981).

[8] T. Banks, A. Zaks, *Nucl. Phys.* **B196**, 189 (1982).

[9] T. Appelquist, G. Fleming, E. Neil, *Phys. Rev. Lett.* **100**, 171607 (2008).

[10] M. Peskin, T. Takeuchi, *Phys. Rev. Lett.* **65**, 964 (1990); B. Holdom, J. Terning, *Phys. Lett.* **B247**, 88 (1990).

[11] S. Nussinov, *Phys. Lett.* **B165**, 55 (1985).

[12] S. Gudnason, C. Kouvaris, F. Sannino, *Phys. Rev.* **D74**, 095008 (2006).

[13] G.D. Kribs, T.S. Roy, J. Terning, K.M. Zurek, `arXiv:0909.2034 [hep-ph]`.