PROCEEDINGS OF SCIENCE

Lattice calculations for Physics Beyond the Standard Model

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I review some recent theories of Physics Beyond the Standard Model whose development could benefit from lattice simulations.

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1. Introduction

While much beyond the standard model physics theory is perturbative in nature, it is likely that nonperturbative strongly coupled physics plays a role. In this talk I review some recent developments which could benefit from what I believe will be feasible lattice simulations. First I will review some recent and old ideas about replacing the Higgs with a strongly coupled sector. Second I will review the “Split Supersymmetry” idea and discuss the motivation for using the lattice to obtain the spectrum of “R-hadrons”– hadrons containing a long lived gluino.

2. Why Go Beyond the Standard Model?

We have rather overwhelming evidence that the Standard Model is incomplete, and must be incorporated into a more comprehensive theory. This evidence is both theoretical and experimental. On the theoretical side, we have the triviality of the Higgs self coupling and of the U(1) coupling, which prevent us from using the theory above some finite energy scale. On the experimental side we have a evidence for a variety of phenomena which require physics beyond the Standard Model, including gravity, inflation, the cosmological matter-antimatter asymmetry, neutrino oscillations, dark matter and the acceleration of the universe. Although the evidence is unambiguous and overwhelming, there is no single leading theoretical extension of the standard model which can explain all or even most of the evidence in a compelling way.

In addition to the rigorous arguments and compelling experiments, we also have some less rigorous and more indirect theoretical and experimental hints that new particle might be directly coupled to the Standard Model at or not far above the weak scale, which is a primary motivation for the TeVatron and LHC colliders and the proposed ILC. In the Standard Model, the weak scale is set by a single relevant parameter, the Higgs mass squared, which is quadratically sensitive to high scales. If this parameter is in fact something that could be calculated from a more fundamental theory, the calculation would have to involve a tremendously finely tuned cancellation between quantum contributions from vastly different scales. Such cancellations violate a proposed principle called "naturalness". Naturalness has not yet been tested experimentally and personally I am on the fence about it. However this is a very exciting time for physics beyond the Standard Model as the LHC will begin to probe this principle and either provide evidence for a natural model or rule out most of them.

Interpreting LHC results is likely to be quite confusing for some time. Despite many years of intense effort, there is no “natural” model of physics beyond the standard model to compare data against which is also robust, economical, compelling and elegant.

Instead we have to settle for some rather complicated looking models which are generally rather contrived looking, have many free parameters and are at least modestly finely tuned. Still, such models have taught us a great deal about the possibilities of field theory and about possible experimental signatures of new physics.

3. Must the Higgs be elementary?

There is a long history of models that replace the elementary Higgs scalar with a fermion condensate or composite scalar. Part of the attraction is to be able to calculate electroweak symmetry

Figure 1: The evidence for Physics Beyond the Standard Model is quite overwhelming, but it is difficult to interpret.

breaking, at least in principle, rather than merely parameterize it as in the Standard Model. Models without elementary scalars also address the naturalness issue since corrections to the Higgs mass squared parameter are softened and no longer as UV sensitive. A recent popular catagory of such models are the "little Higgs" models where the Higgs is a pseudo-Nambu-Goldstone Boson, somewhat analgous to the pion. This set of ideas has come in and out of fashion over the past 30 years. Models which have no Higgs boson, such as technicolor are sometimes reported to be ruled out by precision electroweak corrections or flavor changing neutral currents. However such conclusions are very premature.

The models which are not ruled out involve new dynamics which is not QCD-like, and is strongly coupled over a large energy range. An advantage of strong coupling is that if elementary scalars are to be done away with and replaced with composite operators, then the perturbative dimensions of the operators needed to give masses to quarks and leptons are too big. So models such as "walking technicolor " which have strong, nearly conformal dynamics over a large energy range can reduce the scaling dimension and allow such operators to be more important in the in-

Figure 2: Ideal Model: Robust, Compelling and Elegant

Figure 3: Typical Model of Physics Beyond the Standard Model. Despite the shortcomings, trying to operate the model can be a useful exercise for theorists and experimentalists.

frared. An especially attractive way to get large enough masses for quarks and leptons without large flavor changing neutral currents is to have the quarks and leptons mix with composite operators of strongly coupled particles. These ideas have received several theoretical boosts. In the 90's there was the discovery of of large classes of supersymmetric gauge theories which exhibit such behavior. More recently there was the realization that through the AdS/CFT correspondance (8), in the large N and large 'tHooft coupling limit such models couId be considered as dual to weakly coupled 5D warped Randall-Sundrum-type models (9-12), allowing for calculation of, e.g., the much feared precision electroweak corrections (13-19). Such calculations have provided rather encouraging evidence in favor of the experimental viability of such models.

There are many recent reviews of these ideas, e.g. refs. (1-5), so I will leave the review of the little Higgs models, strongly coupled models, and Higgless theories out of this writeup.

A central issue is whether nonsupersymmetric theories with no elementary scalars can exhibit a strongly coupled conformal or nearly conformal phase. We do have the evidence of the Bank-Zaks fixed point (6), but this is fairly weakly coupled without large enough anomalous dimensions to be useful for model building. The lattice QCD community could shed some light, by by varying the number of colors and flavors of QCD. It would be interesting to know whether and at what point increasing the number of flavors pushes QCD into such a phase. Obtaining a viable model of fermion mass requires that in this phase come composite operators with anomalous dimensions of order 1, so if such a phase exists, it would be great to measure anomalous dimensions.

If such theories are indeed the route nature chooses then lattice simulations will be crucial to understand electroweak symmetry breaking and LHC results.

4. Top Down Approach to Physics Beyond the Standard Model and the long lived gluino

Model building seems messy and arbitrary to many, and it has long been hoped that an alternative route to physics beyond the standard mode will be found. The dream goes back to Einstein, who is quoted

> NATURE IS CONSTITUTED SO THAT IT IS POSSIBLE TO LAY DOWN SUCH STRONG DETERMINED LAWS THAT WITHIN THESE LAWS ONLY RATIONALLY COMPLETELY DETERMINED CONSTANTS OCCUR, NOT CONSTANTS THEREFORE THAT COULD BE CHANGED WITHOUT COMPLETELY DESTROYING THE THEORY.

For over 20 years, most of the people chasing this dream have focussed on string theory, as it is formulated as a parameter free theory which allows for coexistence of gravity and quantum mechanics. String theory is extremely rich, requiring for self consistency many things which have not yet been observed such as new forces, supersymmetry, new dimensions, and a variety of extended objects called branes. There are therefore a variety of conceivable experimental tests of the theory, none of which have yet found any hint. However although the theory may be parameter free, any given metastable configuration within the theory, such as might describe our universe, is not. There seem to be too many such configurations (10^{500}? to check them all. A recent popular approach to attempting to get predictions is to look for statistical correlations between other observables and the possibility of our existence—the anthropic landscape. While such statistical studies seem unlikely to yield a compelling prediction, the landscape does open the door to considering the possibility that effective theories with 'unnatural' parameters could plausibly describe the physics we observe. Such theories yield interesting experimental predictions which are different from those of natural theories. That makes them worth considering.

One popular unnatural model is called 'Split SUSY' (20). The idea is to consider the minimal supersymmetric extension of the Standard Model in the finely tuned limit where the all the scalar superpartners, but not the Higgs or the fermion superpartners, are very heavy. In this limit supersymmetry is much harder to find, however it can still provide a dark matter candidate and give coupling constant unification. The gluino can only decay through virtual squark exchange and so is long lived. The gluino may even escape the LHC detectors before it decays (21). Testing this idea requires simulating gluino hadronization. So far the experimentalists and phenomenologists are mostly relying on old fashioned bag models to compute the spectrum of "R- hadrons" carrying a gluino (22,23). The charge of the lightest R-hadron plays a particularly important role in the phenomenology. It would be great to have a first principles calculation of the R-hadron spectrum. Since preliminary lattice studies were done several years ago (24) it seems to me that this must be feasible now.

5. Summary

While currently the QCD lattice community has focussed on getting predictions out of the Standard model for properties of mesons and baryons, these efforts are coming to fruition, and an end can be foreseen. At the same time particle physics is about to enter a new energy regime where new phenomena are expected. Understanding these phenomena is likely to involve nonperturbative calculations. In this talk I focussed on a couple of areas whose development can benefit from lattice simulations. In the future lattice calculations at non QCD values of N_c and N_f, or with new strongly coupled particles which are not in the fundamental representation, could play an essential role in the development of the new theory and its connection to experiment.

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