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Research Statement

My work focuses on the non-perturbative behavior of systems described by quantum field theory (QFT). In the last few years there have been dramatic advances in studies of non-supersymmetric QFTs, driven by an improved understanding of the structure of path integrals via resurgence theory, and new approaches for handling confining gauge theories. I study the non-perturbative physics of QFTs by exploiting these new techniques, and developing new ones. The QFT landscape mostly consists of non-supersymmetric QFTs, so the development of new methods to study them is very exciting both for practical and theoretical reasons. As an organizing focus, I generally work on the properties of phenomenologically-relevant theories. Consequently, I explore a wide variety of topics, ranging from studies of the formal structure of QFTs to phenomenological applications of QFT in particle physics, nuclear physics, and astrophysics. Here I give an overview of three major areas of my current research program, which are aimed at better understanding confining gauge theories.

DYNAMICS OF CONFINING GAUGE THEORIES

It is difficult to overstate the importance of quark confinement and spontaneous chiral symmetry breaking (χ-SB) in QCD for our understanding of particle and nuclear physics. However, the microscopic workings of these phenomena are still not well understood. The essential problem is that the physics that drives these features is non-perturbative and strongly coupled, and for now we do not understand non-supersymmetric QFTs well enough to explore their properties directly at strong coupling. My work has exploited various simplifying limits of confining QFTs where their interesting non-perturbative properties can be studied analytically.

A. Gauge theory at finite N

One approach to push confinement into a calculable regime involves taking 4D $SU(N)$ gauge theories with N fixed, say to the physical value $N = 3$, and compactifying them on a circle, $\mathbb{R}^4 \to \mathbb{R}^3 \times S^1_L$. The idea is to make the circle size L small enough that the theory becomes weakly coupled. The difficult trick is to find a compactification which has no phase transitions as a function of L, so that the non-perturbative features of the large L theory survive into the weakly-coupled domain. Fortunately, a few years ago M. Ünsal and collaborators found ways to do this. Once smoothness is ensured, the low-energy physics — in particular, the microscopic dynamics behind quark confinement — becomes analytically calculable in the small-L regime.

But this approach has had a large problem. If a confining 4D gauge theory has massless fundamental fermions — as in QCD in the chiral limit — then at large L we usually expect to see χ-SB, and a resulting collection of gapless pions. But the known small-L compactifications did not exhibit continuous χ-SB. This was unfortunate for two reasons. First, χ-SB is one of the most interesting features of QCD, but one could not use the adiabatic-compactification approach to study its microscopic dynamics. Second, the smoothness assumption underlying the whole adiabatic compactification approach was not correct in the chiral limit: the large L and small L regimes were separated by a χ-SB phase transition.

My recent work [1], which leveraged advances developed in my work on 2D sigma models [2], solved these problems. The trick involves using certain special fermion boundary conditions to produce a smooth small-L limit. The modification is designed to be irrelevant at large L, but becomes important at small L. The resulting small-L limit of the theory indeed exhibits χ-SB. As expected, the low-energy physics is described by the chiral Lagrangian, with the novelty that at small L we can explicitly see how this arises directly from the microscopic physics! The non-perturbative dynamics that drive χ-SB turn out to be quite novel, involving condensation of monopole operators, color-flavor transmutation, and fractionalization of fermion zero modes. Our work means that there is now a way to systematically study the microscopic dynamics of *both* confinement and chiral symmetry breaking, and should yield many new insights.

I have already found two useful spin-offs of these ideas [3]. First, the perspective on fermion boundary conditions developed in [1] inspired us to develop a method to exponentially reduce the finite-space-time volume artifacts in lattice Monte Carlo calculations. This should yield large computational efficiency improvements in lattice QCD. Another spin-off has been the construction of new order parameters for QCD-like theories which are useful to map out their phase structure as a function of e.g. the number of fundamental fermion flavors.

B. Gauge theory at large N

Another major direction in my work has been aimed at the exploration of new emergent symmetries in the large N limit. It has long been understood that confining theories simplify dramatically in the limit where the number of colors N becomes large. In particular, these theories become free when formulated in terms of their physical degrees of freedom, the mesons and glueballs. At the same time, the large N limit gives important insights into the behavior of QCD in our $N = 3$ world, because for many observables the $1/N$ corrections turn out to be small at $N = 3$. But a quantitative understanding of large N QCD has remained far out of reach. An extremely valuable step forward would be to identify any symmetries which emerge at large N and help organize the confined-phase spectrum and interactions. The goal of my research program has been to show that such symmetries indeed exist, and to characterize their properties. Understanding these symmetries is likely to lead to many insights into the behavior of strongly-interacting gauge theories.

To make progress on this program I have used two techniques. One approach is to study the large N limit of the adiabatic small-circle $\mathbb{R} \times S^1_L$ compactifications described above. The other is to compactify a 4D theory on a curved manifold, for instance $S^3_R \times \mathbb{R}$, and make the sphere radius small to push the theory toward weak coupling. Both of these approaches have been fruitful, and have yielded persuasive evidence for the presence and importance of emergent large N symmetries.

In one of my recent papers [4], we presented the first study of the large N limit of the small-L regime of confining theories on $\mathbb{R}^3 \times S^1_L$. The theories we explored included pure $\mathcal{N} = 1$ super-Yang-Mills theory and its supersymmetry-breaking deformations into the universality classes of pure Yang-Mills theory and QCD. At finite N and all L, it is known that these theories confine, have a finite string tension, and have a finite mass gap when there are no exactly massless fundamental quarks. The naive widely-held expectation would be that all of these features would also be present at large N. And, indeed, we found that confining string tensions remain finite at large N. But studying the mass gap delivered a major surprise: it turns out that the mass gap *vanish* at large N in all the theories we studied, even when there is no continuous χ-SB! Moreover, one might have expected a small-L theory on $\mathbb{R}^3 \times S^1_L$ to look like a 3D theory at long distances, but this is not what happens at large N. Instead, at large N the long-distance small-L dynamics turns out to be described by an interesting scale-invariant *four-dimensional* theory, including at least one gapless four-dimensional scalar field! The fourth dimension and the scale invariance of the resulting long-distance theory emerge in a highly non-trivial way from a dual description of the non-perturbative dynamics.

The emergence of extra spacetime dimensions in large N dual descriptions of gauge theories is of course a famous feature of gauge/string duality. It is very exciting to see a new realization of this sort of phenomenon in an explicitly calculable field-theoretic setting. At the same time, there are very few known ways to get emergent gapless 4D scalar fields out of interacting QFTs. Our results give a new way to do this, which is both theoretically fascinating as well as phenomenologically tantalizing. After all, the lightness of the Higgs field in the Standard Model remains an enduring mystery. Perhaps generalizations of our constructions could be useful in BSM model building. Consequently, the most pressing challenge is probably to understand how large N mass gaps behave as we pass from small L to large L. We are now exploring the large-N symmetries of the small-L description, with a view to building tools that would let us comment on the large L extrapolation of our results toward $\mathbb{R}^4$.

My work on the other approach to large N physics, involving studying the theory on $S^3 \times \mathbb{R}$, was triggered by discovering the symmetry implications of the old idea of large N volume independence[5, 6]. This story is simplest in adjoint QCD, a non-supersymmetric confining gauge theory which has N_f adjoint quarks, and has useful quantitative connections to QCD explored in some of my earlier work[7]. The fact that adjoint QCD enjoys large N volume independence has a surprising consequence: despite being manifestly non-supersymmetric, the theory must have a novel emergent fermionic symmetry in the large N limit. Such emergent fermionic symmetries are not forbidden by Coleman-Mandula-type no-go theorems precisely because the large N limit is free. Historical experience with supersymmetry suggests that fermionic symmetries should have very useful consequences for the spectrum and properties of a theory. And indeed, working on $S^3_R \times \mathbb{R}$, we explicitly showed that adjoint QCD exhibits a remarkably intricate and powerful pattern of correlations between the spectra of bosonic and fermionic states at large N[6], despite the manifest lack of any sort of standard supersymmetry.

The features of adjoint QCD which we uncovered closely resemble some spectral properties of non-supersymmetric string theory[8]. In string theory, these properties are a consequence of the existence of 2D conformal field theory (CFT) descriptions of strings, and follow from the modular symmetry of the worldsheet theories. Since large N confining theories are supposed to be string theories in disguise, we searched for 2D CFT descriptions of 4D large N gauge theories. It turns out that there is surprisingly simple relation between the spectra of some special 2D CFTs and a broad class of large N confining gauge theories (including pure Yang-Mills theory) in a calculable part of their phase diagram[9]. Since 2D CFTs have rich infinite-dimensional spectrum-generating symmetries, this gives a concrete path toward understanding the emergent symmetries of large N confining gauge theories, as well of some of their interesting consequences[10].

The exploration of large N emergent symmetries of QFTs is just beginning, but the results we have already found make me very excited about this part of my research program. I believe that these studies are likely to yield many new insights into the behavior of gauge theory over the next several years, with applications in several parts of theoretical physics.

C. Relations between perturbative and non-perturbative phenomena

Another major direction in my work is focused on obtaining a deeper non-perturbative understanding of QFTs using resurgence theory. The idea of resurgence theory is that perturbative and non-perturbative contributions to observables are intimately related, and must be treated in a unified way for consistency. This perspective is currently driving a revolution in semi-classical methods, with applications across theoretical physics, from hydrodynamics, to quantum mechanics, condensed matter physics, quantum field theory, and string theory, as well as applications in mathematics. The reason for this is that, in almost all interesting problems in physics, perturbative series diverge, and to make sense of the resulting apparent ambiguities one needs resurgence theory. For example, renormalized perturbative expansions of QCD observables diverge at large order, and lead to apparent resummation ambiguities. The most important ambiguities are known as renormalons, and have long been suspected to be related to confinement and the appearance of the mass gap in QCD. Resurgence theory has revealed that resummation ambiguities very generally contain quantitative information about the non-perturbative contributions to observables, and produced practical techniques to get unambiguous descriptions the physics[11].

The program of applying resurgence theory to QFT has already produced a variety of enlightening results. For example, resurgence theory has produced a new way to detect, classify and treat non-perturbative saddle-points in path integrals [2, 12, 13], going far beyond traditional instanton methods. Indeed, it turns out that the non-topological saddle points, resurgence theory, and closely related ideas like analytic continuation of path integrals, all play vital roles in the consistency of the semi-classical expansion. From these studies, we have found explicit evidence for a connection (which was conjectured by 't Hooft long ago) between the mechanism of cancellations of ambiguities of high-order perturbation theory and the appearance of the mass gap in QCD-like theories. In this way, understanding the non-perturbative structure of path integrals gives insights into the physics of confinement. Many challenges remain, and I look forward to continuing to explore the conceptual and phenomenological implications of resurgence theory in the future.

OUTLOOK

This survey of three major parts of my research program gives a picture of some of the topics I am likely to explore over the next several years. My research program has lots of room for exciting projects for students, and I look forward to helping build a dynamic QFT research group. I am confident that as we develop a deeper non-perturbative understanding of QFT, there will be an ever-increasing range of exciting phenomena which we can profitably study. Indeed, I am always looking for interesting systems, both in high energy physics as well as in other areas, where the non-perturbative aspects of quantum field theory are important and can be analyzed. For instance, I am now exploring the implications of an effective field theory of exotic quantum liquids, originally developed in [14], for the behavior of dense quark matter relevant to neutron stars.

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