David Schaich — Research

My research uses high-performance computing to gain insight into strongly interacting quantum field theories both within and beyond the standard model of particle physics. I employ lattice gauge theory, a non-perturbative framework that enables first-principles investigations of strongly coupled systems. Making use of lattice regularization as a broadly applicable tool allows me to address a wide range of theoretical and phenomenological issues.

The focus of my recent research has been **supersymmetric lattice field theories**, in particular $\mathcal{N} = 4$ supersymmetric Yang–Mills (SYM) in four space-time dimensions. Lattice discretization provides a unique means to investigate such theories away from the regime of weak coupling and for arbitrary numbers of colors N. However, these lattice systems only recover manifest super-Poincaré invariance in the continuum limit where the spacing between lattice sites $a \to 0$, corresponding to the removal of the UV cutoff a^{-1}. This presents a serious challenge to lattice supersymmetry, only overcome during the past decade for certain theories including $\mathcal{N} = 4$ SYM.

I have taken advantage of this recent progress to initiate large-scale numerical analyses of $\mathcal{N} = 4$ SYM, through which many important quantities can be investigated. As an example, Fig. 1 shows preliminary lattice results for the Coulomb coefficient $C(\lambda)$ in the $\mathcal{N} = 4$ SYM static potential $V(r) = A + C/r$, as a function of the 't Hooft coupling λ. In certain regimes there are analytic predictions for this quantity: from perturbation theory at small λ and from AdS/CFT duality at strong coupling $1 \ll \lambda \ll N$ in the large-N limit. My work can provide new insight into the non-perturbative dynamics beyond these regimes, including the approach to the strong-coupling limit. To further promote the advancement of the entire subfield of lattice supersymmetry, I publicly release the high-performance parallel software that I develop to carry out these studies.

The next major goal of my research on $\mathcal{N} = 4$ SYM is to complete similar calculations for the anomalous dimensions of conformal operators, beginning with the well-known Konishi operator. In the longer term I will use lattice techniques to study theories with less supersymmetry, ultimately addressing minimal ($\mathcal{N} = 1$) supersymmetric extensions of the standard model. Such systems rely on spontaneous supersymmetry breaking that must be non-perturbative in nature, making lattice regularization an important tool to apply.

This line of research is ambitious since the absence of maximal $\mathcal{N} = 4$ supersymmetry and the presence of matter fields (quarks and squarks) imply that challenging fine-tuning is required to reach the supersymmetric continuum limit. I will therefore proceed systematically, with an initial focus on two- and three-dimensional supersymmetric QCD where this problem is avoidable. Investigations of lower-dimensional systems are important in their own right, as they allow non-perturbative tests of AdS/CFT duality and potential insight into quantum gravity. The smaller scale of these studies also makes them excellent student projects, more easily customizable to the background and goals of the student.

Lower-dimensional supersymmetric systems have already proven to be a valuable testbed for exploring the fermion sign problem that can obstruct importance-sampling Monte Carlo calculations. Canonical reformulations of these theories provide a means to control the sign problem and thereby obtain more reliable predictions. I have initiated a project to adapt this approach to **finite-density lattice QCD**, where the sign problem complicates investigations of the physics of neutron stars and relativistic heavy-ion collisions. I am currently working to develop novel algorithms, including multilevel Monte Carlo methods for fermions, that promise to reduce the impact of the sign problem for finite-density QCD.

Finally, I also research potential non-supersymmetric new strong dynamics beyond the standard model. One example is composite dark matter, a compelling possibility in which extremely weak interactions between the dark sector and the visible universe proceed through non-perturbative form factors such as the electromagnetic polarizability. I worked on recent lattice computations of these form factors, predicting the composite dark matter direct-detection cross section for future experimental searches. I am exploring additional lattice measurements that would be required to analyze the production and decay of composite dark matter in collider experiments, as well as the spectrum of gravitational waves it may produce in the early universe.

In the context of composite Higgs models I lead projects to calculate the electroweak S parameter for SU(3) gauge theories with different numbers of light fermions, $N_f = 2$, 6 and 8. The S parameter is a low-energy constant of the electroweak effective lagrangian that tightly constrains new strong dynamics. Naively rescaling QCD leads to a value $S \approx 0.43$ far larger than the experimental result $S = 0.03(10)$. As illustrated in Fig. 2, I found that S decreases significantly as N_f increases, which strengthens the phenomenological viability of strongly coupled electroweak symmetry breaking. Such a reduction in the S parameter is expected to result from near-conformal strong dynamics, which forbids reliance on rescaled QCD and makes lattice gauge theory an indispensable tool. Much of my research in the recent past explores the most effective methods to study **near-conformal lattice systems**, developing improved techniques based on finite-size scaling, the Yang–Mills gradient flow, and the Dirac operator eigenmode spectrum.

My next goal for research into non-supersymmetric new strong dynamics is to incorporate the paradigm of partial compositeness, which addresses phenomenological constraints from both electroweak and flavor physics. Partial compositeness involves the known quarks and leptons coupling linearly to appropriate fermionic operators in the strong sector, and relies sensitively on the anomalous dimensions of those operators. Lattice gauge theory is the most reliable method to compute these anomalous dimensions, through standard techniques of non-perturbative renormalization. I have initiated a project to carry out this computation for near-conformal SU(3) gauge theories with $N_f = 8$ and 12.

All of the research discussed above, from lattice supersymmetry to finite-density QCD and partial compositeness, shares the goal of gaining insight into strongly interacting quantum field theories through high-performance computing. The wide range of important open questions to be addressed by these investigations provides diverse opportunities for student involvement and multidisciplinary collaboration.

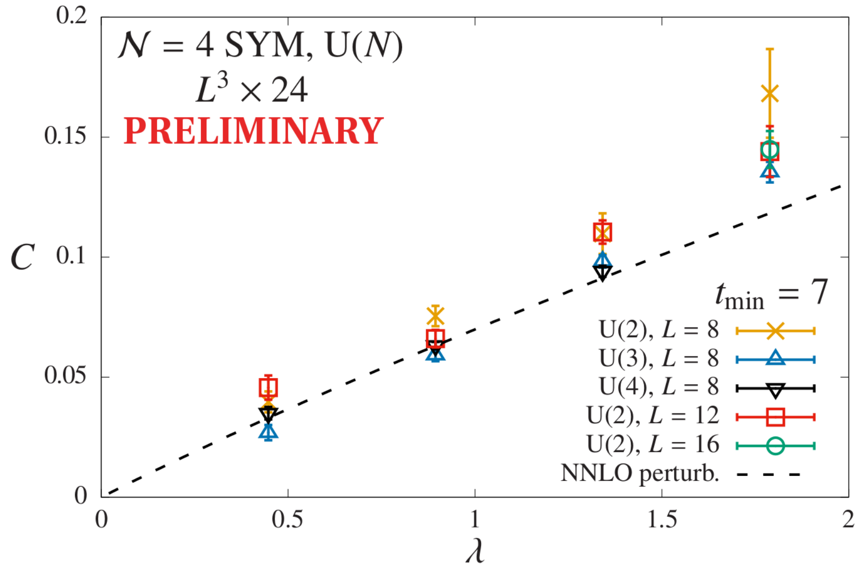

Figure 1: Static potential Coulomb coefficient vs. 't Hooft coupling from lattice $\mathcal{N} = 4$ SYM, compared to NNLO perturbation theory. The consistency with perturbative predictions for these relatively weak couplings provides a check of the lattice calculation and a foundation from which stronger couplings are being explored.

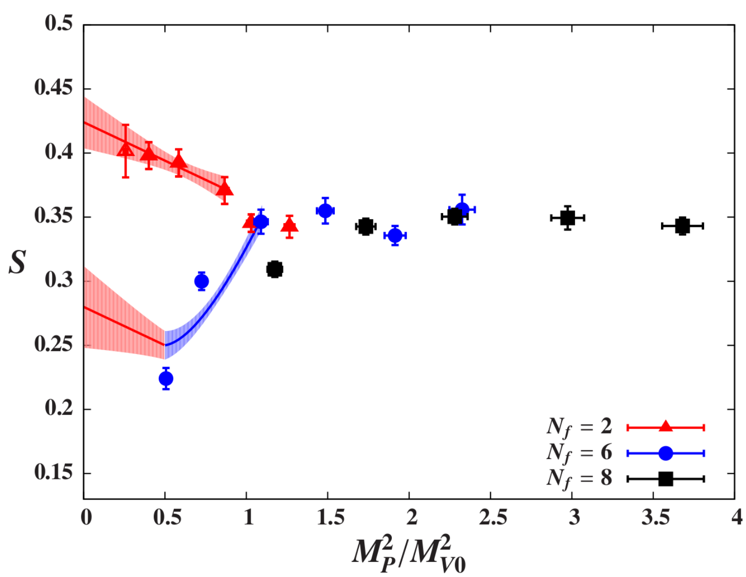

Figure 2: The electroweak S parameter from lattice studies of SU(3) gauge theories with $N_f = 2$, 6 and 8 light fermions. The two-flavor calculation reproduces rescaled QCD in the physical $M_P^2 \to 0$ limit. Larger N_f leads to significant reductions (better agreement with experiment) potentially related to near-conformal strong dynamics.