Research Summary and Goals

Urs M. Heller

My research is focused on Theoretical High Energy and Nuclear Physics, with a concentration on the field commonly referred to as *Lattice Field Theory*. This is an area that I will continue to pursue in the future. Many of the phenomena caused by the fundamental interactions of particle physics, such as confinement and chiral symmetry breaking in Quantum Chromodynamics (QCD), are intrinsically non-perturbative. Formulating quantum field theories on a space-time lattice provides a non-perturbative regularization and opens the way for the application of non-perturbative analytic and powerful numerical methods to study these phenomena.

Lattice gauge theory, by way of large scale numerical simulations, provides the only comprehensive method to extract, with controlled systematic errors, first-principles predictions from QCD for a wide range of important particle phenomena. Progress in lattice QCD simulations has not only come from the efficient use of ever faster and more powerful (super-)computers. It also comes from improvements in the simulation algorithms and from improvements in the way the continuum QCD equations are transcribed to the lattice. This consists in the construction of improved lattice actions that lead to diminished "lattice artifacts" or discretization errors, *i.e.* which approach the continuum limit, $a \to 0$, faster and with less deviations at finite lattice spacing a, allowing for more reliable continuum extrapolations. I have been at the forefront of these developments and their validation. Use of improved actions promises substantial gain in the accuracy of lattice QCD predictions for continuum physics.

I have done extensive work on numerical simulations of lattice field theories using the Monte Carlo method, techniques based on stochastic quantization — the Langevin formalism — and the microcanonical description of lattice field theories, and I've been involved in the development and testing of some of the algorithms used in numerical simulations today. I have worked alone, in small collaborations, and in the larger "High Energy Monte Carlo Grand Challenge" (HEMCGC) collaboration, and currently the "MIMD Lattice Calculation" (MILC) collaboration. Such larger collaborations are needed to obtain the necessary computer resources and man power for the large scale simulations of QCD, especially simulations with dynamical fermions.

I am participating actively in the MILC collaborations wide variety of QCD simulation projects, dealing both with zero temperature and finite temperature properties. Currently, a first-principles computation of properties of the B-meson, such as its decay constant, f_B, its "B-parameter", B_B, and various form-factors, are one of the MILC collaborations main research goals. f_B is a theoretical input needed for the extraction of matrix elements of the CKM-matrix from current and future experiments. B_B is needed to understand mixing of B_0 with $\bar{B}_0$, which leads to insights into the mechanism of CP-violation. Finally, the computation of form factors will increase our understanding of QCD by comparison with various model computations and give new venues for extracting CKM-matrix elements from experiments.

The second main project of the MILC collaboration is a study of three-flavor dynamical

QCD, with two light flavors, which will be extrapolated to the average of up and down quark mass, and one heavier flavor fixed at the strange quark mass. The simulations are done with an improved gauge and staggered fermion action. Zero temperature simulations are, and will be performed at three different lattice spacings and with several values for the light quark mass to allow for chiral and continuums extrapolations. The library of gauge field configurations generated will be used to compute light hadron spectroscopy, including so-called hybrid mesons and glueballs that are distinct predictions of QCD going beyond the naive quark model, the heavy quark potential, light quark masses, as well as the B-physics projects mentioned above. I have very recently started companion finite temperature simulations. The first goal is the determination of the phase diagram. In particular, we are aiming to determine the order of the finite temperature phase transition at physical light and strange quark masses. At a later stage we aim at determining the equation of state of the high temperature quark gluon plasma.

Another focus of my research has been the study of the properties of the high temperature quark-gluon plasma phase, relevant to heavy ion collision experiments as planned, for example, for RHIC. To cut down on computational cost, a lot of my work has concentrated on pure gauge SU(2) studies. We have established so-called spatial confinement at high temperature, characterized by a QCD coupling constant that runs with temperature according to the renormalization group β-function. We have also recently computed electric and magnetic gluon screening masses at high temperature. As anticipated, they too are characterized by a running coupling constant. However, the electric screening mass was found to be considerably larger than expected from resummed perturbation theory.

Recently, I have become interested in topological aspects of lattice gauge theory, in particular as seen by lattice fermions. On smooth continuums gauge field backgrounds we have the Atiyah–Singer index theorem, which relates the number of left handed minus the number of right handed zero modes of the Dirac operator to the topological charge of the gauge field background. We showed, how this result carries over for smooth gauge fields, in somewhat modified form, to Wilson fermions on the lattice. Postulating the connection between index and topological charge for non–smooth configurations as they occur in a Monte Carlo simulation, we obtained a method to measure the topological charge and the topological susceptibility. We found results in agreement with other approaches to lattice topology.

Chirality plays a major role in particle physics. QCD has a chiral symmetry that is spontaneously broken at low temperature but restored at high temperature. The weak interactions only couple to the left handed components of quarks and leptons. For a long time it was thought to be impossible to put the fermions on a lattice without explicitly breaking chiral symmetry, which is then only restored in the continuum limit, while the weak interations simply could not be regularized using a lattice. Recently, Neuberger succeeded in constructing a lattice discretization for massless fermions that retains all the chiral properties of continuum fermions on the lattice *exactly*. These fermions go under the name of "overlap fermions". With former colleagues at SCRI I have developed a numerical algorithm that makes the use of overlap fermions feasible, albeit still very costly, in numerical simulations. With this, we have verified numerically some of the beautiful properties of overlap fermions. In particular we have found the correct number of exact zero modes in background gauge fields with non-trivial topology. We have studied chiral symmetry breaking in quenched

QCD and have verified universal predictions for the low lying spectrum of the overlap Dirac operator as summarized by random matrix theory for the first time in topologically non-trivial sectors. At present I am studying the generation of the mass of the eta-prime meson and its relation to gauge field topology in quenched QCD. However, major improvements in the numerical techniques for simulations with overlap fermions are needed before they become practical in QCD simulations, in particular with dynamical fermions. I am actively working on possible algorithmic improvements.

But my research activity goes beyond the study of lattice QCD. One of my main achievements, with H. Neuberger and a few other collaborators, was the establishment and determination of an upper bound on the Higgs mass, within the Standard Model of elementary particle physics. This bound follows from the so-called triviality of the scalar sector of the Standard Model. We found that either the Higgs particle will be detected with a mass, $M_H \leq 710 \pm 60\ GeV$, or other phenomena that go beyond the Standard Model, will be discovered in that energy range. Our investigations also exclude a strongly interacting Higgs sector.

Other research accomplishments, that I participated in, include:

- a detailed scaling study of the string tension in quenched QCD;
- a calculation of the equation of state of QCD with two flavors of dynamical staggered quarks;
- the first study of the heavy quark potential in the presence of two flavors of dynamical quarks;
- studies of mass and decay constant of the B-meson with the heavy quark treated in the NRQCD approximation and with the effect of two light sea quarks included;
- the first lattice study of mass and decay constant of the a_1 meson;
- computation of the strong interaction coupling constant, $\alpha_s(q)$, in a theory with two dynamical quark flavors;
- studies of the deconfinement transition in pure SU(2) gauge theory, and in QCD with two flavors of dynamical quarks;
- the first non-perturbative studies of the U(1)-Higgs model in an external electromagnetic field: we found evidence for (1) expulsion of weak external fields — the Meissner effect —, (2) penetration in the form of vortices for larger fields, (3) restoration of the symmetry for sufficiently strong fields, all as expected from the analogy with the Ginzburg-Landau model;
- some of the first studies of symmetry restoration in the SU(2)-Higgs model at finite temperature;
- some of the first Monte Carlo renormalization group studies to determine the β-function of lattice gauge theory non-perturbatively;
- construction of the quenched Eguchi–Kawai model of large N lattice gauge theory.