HIGH ENERGY PHYSICS ON BLUE WATERS

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EXECUTIVE SUMMARY

The goal of this project is to carry out groundbreaking studies of the standard model of high-energy physics. The calculations we have in progress address basic questions in high-energy physics and are directly supportive of the very large, worldwide experimental studies in this field. This project is a joint effort of the Fermilab Lattice, MILC, and RBC Collaborations, which among them contain almost all of the high-energy physicists in the United States working on the numerical study of the standard model. The advent of petascale computers such as Blue Waters has had a transformational impact on our field. Members of our three groups have played a leading role in this transformation through the development of algorithms and community codes, and by carrying out petascale simulations. We are using Blue Waters to build upon these advances in order to make major progress in understanding the fundamental laws of physics.

RESEARCH CHALLENGE

The standard model of high-energy physics encompasses our current knowledge of the fundamental interactions of nature. It consists of two quantum field theories: the Weinberg–Salam theory of electromagnetic and weak interactions, and quantum chromodynamics (QCD), which is the theory of the strong interactions. The standard model has been enormously successful in explaining a wealth of data over the past forty years; however, high-energy physicists believe that a more general theory will be needed to explain physics at the shortest distances or highest energies. The research in which we are engaged aims at obtaining a deeper understanding of the standard model and at searching for physical phenomena that go beyond it.

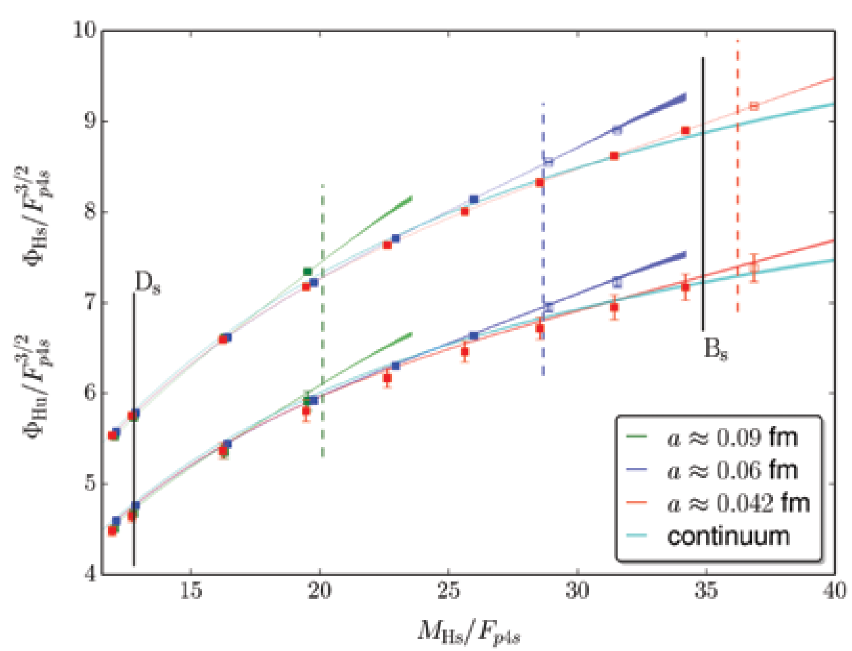

Figure 1: Lattice data (squares) with a chiral-continuum-HQET fitting function. The solid curves are fit results for single lattice spacings and for the continuum limit. The quantity plotted on the x-axis is proportional to the strange quark mass, and those on the y-axis are proportional to the leptonic decay constants for the B and Bs mesons.

METHODS & CODES

QCD is formulated in the four-dimensional space–time continuum; however, in order to carry out numerical calculations, one must reformulate it on a lattice or grid. To obtain physical results, one carries out calculations for a range of small lattice spacings and then performs extrapolations to the zero lattice spacing (continuum) limit. This continuum extrapolation is one of the major sources of errors in lattice QCD calculations. Another important source of systematic errors arises because the calculations must take place in a finite box, whose physical size must be much larger than the largest lengths in the problem. Keeping both the continuum extrapolation and finite size effects under control requires working on very large lattices. The power of petascale computers is critical for enabling us to do this.

A number of different formulations of quarks, an elementary particle of matter in QCD, on the lattice are currently being used in numerical studies of QCD, all of which are expected to yield the same results in the continuum limit. We are using the two formulations most widely employed in the study of high-energy physics: domain wall fermions (DWF) and highly improved staggered quarks (HISQ). The DWF and HISQ actions each has important advantages for different aspects of our work. DWFs have nearly exact chiral symmetry at finite lattice spacings. This high degree of chiral symmetry is required for key studies of kaon decays that lead to precise tests of the standard model. On the other hand, staggered quarks are essential for studies of the decays and mixings of particles with heavy quarks for which chiral symmetry plays a less important role. However, the large lattice volumes, made accessible by the lower computational cost of staggered fermions, are necessary for accurate control of finite lattice spacing errors. The HISQ calculations are aimed at precise determination of some of the least well-known parameters of the standard model, and at making further precise tests of it.

Lattice QCD calculations proceed in two steps. In the first, one uses importance-sampling techniques to generate gauge configurations, which are representative samples from the Feynman path integrals that define QCD. These configurations are saved, and in the second step they are used to calculate a wide variety of physical quantities. Generating gauge configurations is the rate-limiting step and requires the most capable supercomputers available.

RESULTS & IMPACT

During the first year of our PRAC grant, we have used our allocation to generate DWF and HISQ gauge configurations that are among the most challenging produced to date. The initial applications of the DWF configurations will be to study two processes that are highly suppressed in the standard model and therefore favored as places where physics beyond the standard model may emerge. The first of these is the direct violation of CP (charge conjugation parity) symmetry in the decay of neutral kaons. The second is the determination of the mass difference between the two neutral kaon-decay eigenstates, which is the smallest particle mass difference ever measured.

The first application of the HISQ gauge configurations generated under this allocation has been to enhance the determination of quark masses and leptonic decay constants of unprecedented precision.

One particularly striking result is the determination of the leptonic decay constant of the B meson to a precision of 0.4%, a factor-of-five reduction of uncertainty from the world average. This calculation is illustrated in Fig. 1. A preliminary report on this work was published in [1]. Near-final results were presented at the Lattice 2017 conference, and a journal article is in progress.

WHY BLUE WATERS

Work on lattice QCD calculations has made major progress in the last few years, with a limited number of calculations reaching precision of a fraction of a percent, and techniques in place to determine many more quantities to this level of accuracy. Such precision is needed to test the standard model and to obtain a quantitative understanding of physical phenomena controlled by the strong interactions. This progress has been enabled by the advent of petascale computers, such as Blue Waters, and could not have been made without them.

PUBLICATIONS AND DATA SETS

Komijani, J., et. al, Decay constants fB and fBs and quark masses mb and mc from HISQ simulations. in *Proceedings of the 34th International Symposium on Lattice Field Theory* (Lattice, Southampton, UK, July 24–30, 2016).