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, the MIMD Lattice Computation Collaboration, and RBC Collaborations, which among them contain almost all 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 leading roles 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 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), the theory of the strong interactions. The standard model has been enormously successful in explaining a wealth of data over the past 40 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 to obtain a deeper understanding of the standard model and to search for physical phenomena that go beyond it.

METHODS & CODES

QCD is formulated in the four-dimensional spacetime 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 so.

Numerical studies of QCD current use a number of different formulations of quarks on the lattice, 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. Domain wall fermions 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.

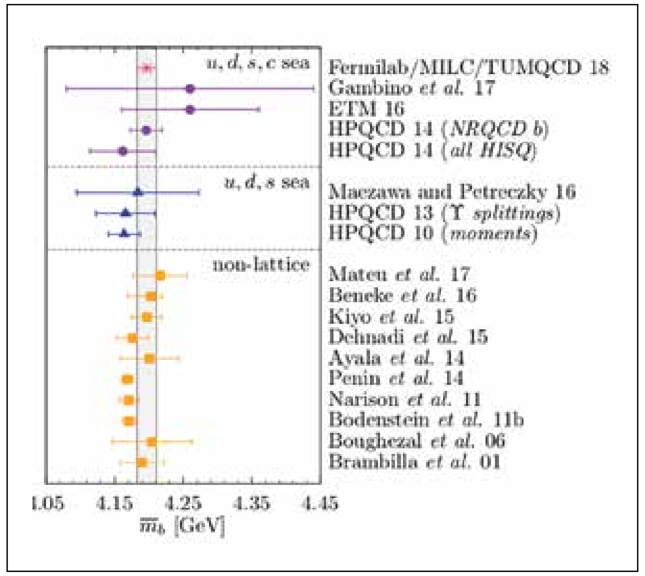

Figure 1: Comparison of our result (magenta burst) for the mass of the bottom quark in the MS-bar renormalization scheme to results from other calculations and from nonlattice methods.

RESULTS & IMPACT

We have used our allocation under this grant to generate DWF and HISQ gauge configurations that are among the most challenging produced to date. The initial applications of the DWF configurations are in the study of three processes that are highly suppressed in the standard model and, therefore, favored as places where physics beyond the standard model may emerge: 1) the calculation of the long-distance contributions to the indirect violation of Conjugation Parity symmetry in the decay of neutral kaons; 2) the calculation of the long-distance contributions to the rare kaon decay of the charged kaon into a pion and a neutrino–antineutrino pair; and 3) the determination of the mass difference between the two neutral kaon-decay eigenstates, which is the smallest particle mass difference ever measured. The first calculation of this final quantity with physical quark masses is now underway using the ensemble to which our Blue Waters calculation is contributing [1].

The HISQ gauge configurations generated under this allocation have been used in the determinations of quark masses [2] and leptonic decay constants [3] of unprecedented precision. In particular, our results for the charm quark mass matches the precision of the most accurate previous calculations, and those for the other quark masses and their ratios are the most precise to date. Similarly, our results for the decay constants of D and B mesons are the most precise to date. Some comparisons with previous calculations are shown in Figs. 1 and 2.

WHY BLUE WATERS

Lattice QCD calculations have 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.

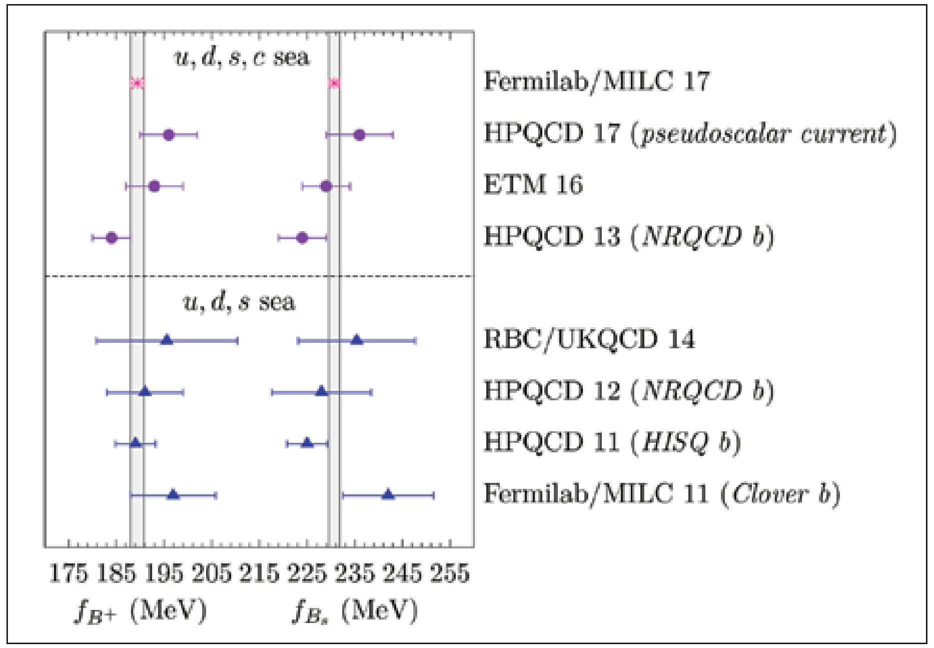

Figure 2: Comparison of our results (magenta bursts) for the leptonic decay constants of the B+ and Bs mesons with those from earlier calculations. These quantities play an important role in testing the standard model, and when coupled with experimental results yield some of the basic parameters of the standard model.