THE ANOMALOUS MAGNETIC MOMENT OF THE MUON: AN IMPROVED *AB INITIO* CALCULATION OF THE HADRONIC VACUUM POLARIZATION CONTRIBUTION

Allocation: Illinois/225 Knh
PI: Aida X. El–Khadra[1]
Co-PIs: Zech Gelzer[1], Ruth Van de Water[2]
Collaborators: Shaun Lahert[1], Carleton DeTar[3], Steve Gottlieb[4], Andreas Kronfeld[2], Doug Toussaint[5]

[1]University of Illinois at Urbana–Champaign
[2]Fermi National Accelerator Laboratory
[3]University of Utah
[4]Indiana University
[5]University of Arizona

EXECUTIVE SUMMARY

A central goal of high-energy physics is to search for new particles and forces beyond the Standard Model of particle physics. The muon anomalous magnetic moment is sensitive to contributions from new particles and is also one of the most precisely measured quantities in particle physics, with an experimental uncertainty of 0.54 parts per million. At present, the measurement disagrees with Standard Model theory expectations by more than three standard deviations.

The Fermilab Muon g-2 Experiment will ultimately reduce the experimental error by a factor of four; first results are expected in the fall of 2019. To identify definitively whether any deviation observed is due to new particles or forces, the theory error must be reduced to a commensurate level. An ongoing project by this collaboration uses numerical lattice quantum chromodynamics (QCD) to target the hadronic vacuum polarization contribution, which is the largest source of theory error. This Blue Waters project targets one of the largest sources of error in the current calculation—the statistical errors at large Euclidean times—and complements the ongoing project by calculating additional correlation functions to quantify contributions from two-pion states, which become important at large Euclidean times. While the ensemble to be used in this project is relatively small, the large number of propagator inversions needed to compute the additional correlation functions requires a petascale machine such as Blue Waters.

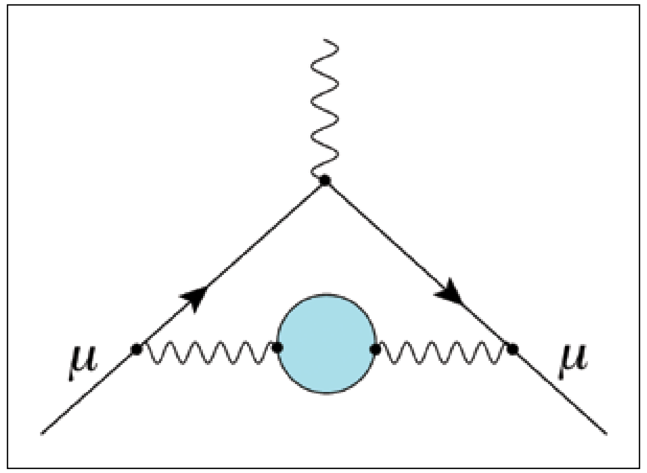

Figure 1: Hadronic vacuum polarization contribution to the muon's anomalous magnetic moment.

RESEARCH CHALLENGE

The muon anomalous magnetic moment (g-2) enables a very precise test of the Standard Model of particle physics and a probe of new particles and forces beyond. In the Standard Model, the anomaly arises owing to quantum–mechanical loop contributions. Virtual contributions from new particles could therefore lead to an observable deviation between measurements and the expected Standard Model value for the muon g-2, given sufficiently precise theory and experiment. The most recent measurement of the muon g-2 has a precision of 0.54 parts per million [1] and disagrees with Standard Model theory expectations by more than three standard deviations. The Muon g–2 Experiment at Fermilab (with team members from the University of Illinois at Urbana–Champaign) began running in 2019, and expects to reduce the experimental error by a factor of four [2]. To leverage the anticipated reduction in experimental errors and determine unambiguously whether or not the present disagreement is due to effects from new particles or forces, the theoretical errors on the Standard Model prediction must be brought to a commensurate precision on the experimental timescale.

The dominant source of uncertainty in the Standard Model prediction of the muon g-2 is from the hadronic vacuum polarization contribution owing to virtual quarks and gluons [3] (see Fig. 1), which is the target of this work. Numerical lattice–QCD simulations provide the only method for calculating the nonperturbative hadronic contributions to the muon g-2 with controlled uncertainties that are systematically improvable.

The basic quantity from which the hadronic vacuum polarization correction is calculated is a two-point function with vector-current operators at the source and sink [4]. The hadronic vacuum polarization is obtained from integrals of this correlation function over Euclidean time. However, at large Euclidean time the vector-current correlation function receives contributions from two-pion states that cannot be resolved from a statistical analysis of the vector-current correlation function alone, because its statistical errors increase rapidly with the Euclidean time. In the joint project described above, these contributions are currently estimated phenomenologically from a scalar quantum electrodynamics calculation.

The goal of the project is a direct calculation of the two-pion contribution from correlation functions of two-pion operators, which will provide us with a better description of the contributions to the hadronic vacuum polarization from the large Euclidean time region. This requires the computation of two-, three-, and four-point functions, as illustrated in Fig. 2, including local and smeared source and sink operators, a range of momenta and source sink combinations, and up to three combinations of pion species, resulting in a large number of correlation functions.

METHODS & CODES

This project was carried out using the MIMD lattice computation (MILC) collaboration code [5], which has been in production use on a wide variety of massively parallel computers for over 20 years, with continual improvements to address the community's evolving science goals and to accommodate changing hardware. The MILC code, which currently consists of about 300,000 lines, makes extensive use of the libraries of the U.S. Lattice–QCD collaboration's QCD applications programming interface for CPUs ([6] and the QUDA framework for lattice-QCD on GPUs [7,8]). It was part of the Blue Waters acceptance test and one of the applications launched at its dedication and has been running on Blue Waters for over five years with significant improvement in performance over this period. Porting the MILC code to Blue Waters' XE nodes was straightforward, and with the integration of the QUDA libraries, the MILC code also runs efficiently on the XK nodes.

RESULTS & IMPACT

The computations for this project are ongoing. The research team has already generated all of the needed two-point functions and is currently computing the three- and four-point functions, for which the team is reusing the propagators that were generated for the two-point functions. After the computations are finished, the researchers will perform a statistical analysis to determine contributions of the two-pion states to the hadronic vacuum polarization. This work is the first computation of its kind with staggered fermions. If successful, it will open up a new set of observables to be studied on the large library of ensembles with "highly improved staggered fermions" that has been generated by the MILC collaboration.

WHY BLUE WATERS

This project requires the computation of a large (approximately 100) number of propagators on each available configuration in order to obtain the desired correlation functions. While the small ensemble the research team used in this project allowed them to compute each propagator on only three or four nodes, performing all the propagator inversions needed on each of the 10,000 configurations in the ensemble required a petascale resource such as Blue Waters.

Another essential aspect is that the code used in this project had already been adapted and optimized to Blue Waters (with the help of Blue Waters' staff) in the course of prior projects funded under PRAC allocations.

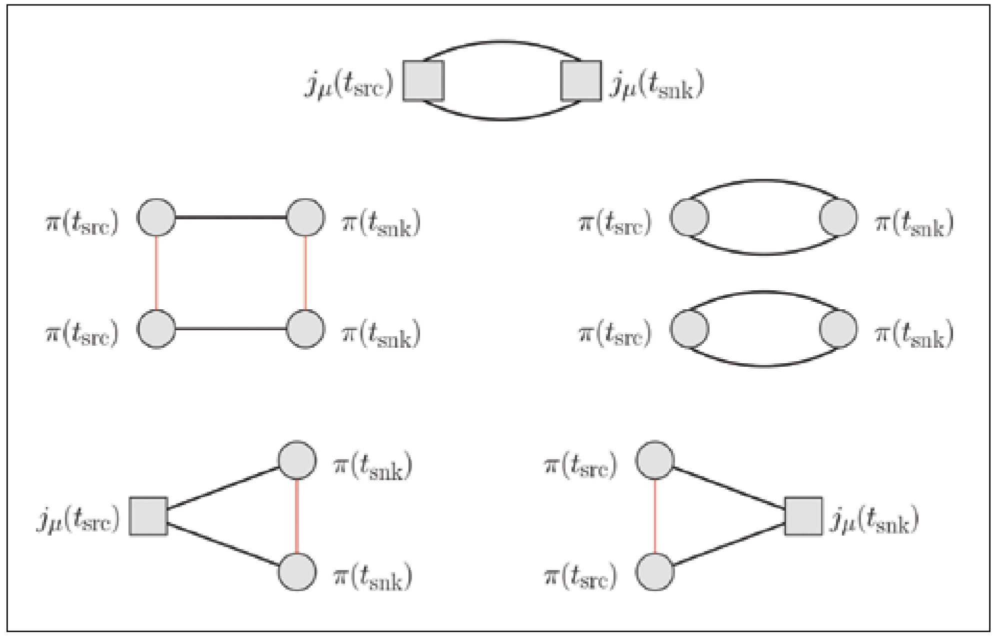

Figure 2: A representative subset of the correlation functions to be computed in this work. A single square at the source or sink indicates a fermion bilinear vector-current operator, while two circles with (without) a red line represent connected (disconnected) two-pion operators. The temporal locations are abbreviated as t_{src} and t_{snk} and the black lines indicate propagation in time.