2023 INCITE Proposal Submission
Proposal

Title: Advances in Quark and Lepton Flavor Physics with Lattice QCD
Principal Investigator: Andreas Kronfeld
Organization: Fermilab
Date/Time Generated: 6/17/2022 7:05:24 PM

Section 1: PI and Co-PI Information

Question #1

Principal Investigator: *The PI is responsible for the project and managing any resources awarded to the project. If your project has multiple investigators, list the PI in this section and add any Co-PIs in the following section.*

Principal Investigator

First Name

Andreas

Last Name

Kronfeld

Organization

Fermilab

Email

ask@fnal.gov

Work Phone

+1-630-840-3753

Address Line 1

Fermilab -- MS 106

Address Line 2

PO Box 500

City

Batavia

State

IL

Zip Code

60565

Question #2

Co-PI (s)

First Name

Thomas

Last Name

Blum

Organization

University of Connecticut

Email

thomas.blum@uconn.edu

First Name

Peter

Last Name

Boyle

Organization

Brookhaven National Laboratory

Email

pboyle@bnl.gov

First Name

Norman

Last Name

Christ

Organization

Columbia University

Email

nhc@phys.columbia.edu

First Name

Carleton

Last Name

DeTar

Organization

University of Utah

Email

detar@physics.utah.edu

First Name

Aida

Last Name

Khadra

Organization

University of Illinois at Urbana-Champaign

Email

axk@illinois.edu

First Name

Steven

Last Name

Gottlieb

Organization

Indiana University

Email

sg@iu.edu

First Name

William

Last Name

Jay

Organization

Massachusetts Institute of Technology

Email

willjay@mit.edu

First Name

Luchang

Last Name

Jin

Organization

University of Connecticut

Email

luchang.jin@uconn.edu

First Name

Chulwoo

Last Name

Jung

Organization

Brookhaven National Laboratory

Email

chulwoo@bnl.gov

First Name

Christoph

Last Name

Lehner

Organization

Universität Regensburg

Email

christoph.lehner@ur.de

First Name

Andrew

Last Name

Lytle

Organization

University of Illinois at Urbana-Champaign

Email

atlytle@illinois.edu

First Name

Robert

Last Name

Mawhinney

Organization

Columbia University

Email

rdm10@columbia.edu

First Name

Ruth

Last Name

Van de Water

Organization

Fermilab

Email

ruthv@fnal.gov

Question #3

__Institutional Contact:__ For the PI's institution on the proposal, identify the agent who has the authority to review, negotiate, and sign the user agreement on behalf of that institution. The person who can commit an organization may be someone in the contracts or procurement department, legal, or if a university, the department head or Sponsored Research Office or Grants Department.

Institutional Contact

Institutional Contact Name

Andrew Hime

Institutional Contact Phone

+1-630-840-4566

Institutional Contact Email

ahime@fnal.gov

Section 2: Project Information

Question #1

Select the category that best describes your project.

Research Category

Physics: Particle Physics

Question #2

Please provide a project summary in two sentences that can be used to describe the impact of your project to the public (50 words maximum)

Project Summary

Starting from the Standard Model of elementary particles, this project performs high-precision numerical calculations, so that the results can be compared with results of high-precision experiments. Any discrepancies between theory and experiment will provide clues for as-yet undiscovered physical processes at work.

Section 3: Early Career Track

Question #1

Early Career

Starting in the INCITE 2022 year, INCITE is committing 10% of allocatable time to an [Early Career Track](#) in INCITE. The goal of the early career track is to encourage the next generation of high-performance computing researchers. Researchers within 10 years from earning their PhD (after December 31st 2012) may choose to apply. Projects will go through the regular INCITE Computational Readiness and Peer Review process, but the INCITE Management Committee will consider meritorious projects in the Early Career Track separately.

***Who Can Apply**: Researchers less than 10 years out from their PhD that need LCF-level capabilities to advance their overall research plan and who have not been a previous INCITE PI.*

How to Apply:

In the regular application process, there will be a check-box to self-identify as early career.

- *The required CV should make eligibility clear.*
- *If awarded, how will this allocation fit into your overall research plan for the next 5 years?*

Projects will go through the regular INCITE review process. The INCITE Program is targeting at least 10% of allocatable time. When selecting the INCITE Career Track, PIs are not restricted to just competing in that track.

- *What is the Early Career Track?*
  - *The INCITE Program created the Early Career Track to encourage researchers establishing their research careers. INCITE will award at least 10% of allocatable time to meritorious projects.*
- *Will this increase my chances of receiving an award?*
  - *Potentially, this could increase chances of an award. Projects must still be deemed scientifically meritorious through the review process INCITE uses each year.*
- *What do I need to do to be considered on the Early Career Track?*
  - *In the application process, select 'Yes' at 'If you are within 10 years of your PhD, would you like to be considered in the Early Career Track?' You will need to write a paragraph about how the INCITE proposal fits into your 5-year research and career goals.*
- *What review criteria will be used for the Early Career Track?*
  - *The same criteria for computational readiness and scientific merit will be applied to projects in the Early Career Track as will be applied to projects in the traditional track. The different will be manifest in awards decisions by the INCITE management committee.*

Early Career Track

If you are within 10 years of your PhD, would you like to be considered in the Early Career Track? Choosing this does not reduce your chances of receiving an award.

No

If ‘yes’, what year was your PhD? If 'no' enter N/A

N/A

If ‘yes’, how will this allocation fit into your overall research plan for the next 5 years? If 'no' enter N/A.

N/A

Section 4: INCITE Allocation Request & Other Project Funding/Computing Resources

Question #1

OLCF Summit (IBM / AC922) Resource Request - 2023

Node Hours

1,000,000

Storage (TB)

58

Off-Line Storage (TB)

75

Question #2

OLCF Frontier (Cray Shasta) Resource Request – 2023

Node Hours

2,200,000 Frontier node-hours

Storage (TB)

500

Off-Line Storage (TB)

4,500

Question #3

OLCF Frontier (Cray Shasta) Resource Request – 2024

Node Hours

2,200,000 Frontier node-hours

Storage (TB)

500

Off-Line Storage (TB)

6,500

Question #4

OLCF Frontier (Cray Shasta) Resource Request – 2025

Node Hours

2,200,000 Frontier node-hours

Storage (TB)

600

Off-Line Storage (TB)

9,500

Question #5

ALCF Theta (Cray XC40) Resource Request - 2023

Question #6

ALCF Polaris Resource Request - 2023

Question #7

ALCF Polaris Resource Request - 2024

Question #8

ALCF Polaris Resource Request - 2025

Question #9

ALCF Aurora (Intel X^e) Resource Request – 2023

Node Hours

1,000,000 Aurora node-hours

Storage (TB)

300

Off-Line Storage (TB)

0

Question #10

ALCF Aurora (Intel X^e) Resource Request – 2024

Node Hours

2,300,000 Aurora node-hours

Storage (TB)

400

Off-Line Storage (TB)

6,500

Question #11

ALCF Aurora (Intel X^e) Resource Request – 2025

Node Hours

2,300,000 Aurora node-hours

Storage (TB)

650

Off-Line Storage (TB)

9,500

Question #12

List any funding this project receives from other funding agencies.

Funding Sources

Funding Source

DOE national laboratories

Grant Number

DE-AC02-07CH11359 (FNAL), DE-SC0012704 (BNL)

Funding Source

DOE university program

Grant Number

DE-SC0011941 (Columbia), DE-SC0010339 (UConn), DE-SC0015655 (UIUC), DE-SC0010120 (Indiana), DE-SC0011090 and DE-SC0021006 (MIT)

Funding Source

NSF university program

Grant Number

PHY20-13064 (Utah)

Funding Source

STFC (U.K.)

Grant Number

ST/T000600/1

Funding Source

DOE Early Career Program

Grant Number

DE-SC0021147 (Jin/UConn)

Question #13

List any other high-performance computing allocations being received in support of this project.

Other High Performance Computing Resource Allocations

Resource

Summit

Allocation Agency

ALCC

Allocation

1,000,000 node-hr

Allocation Year

2022-2023

Resource

Perlmutter

Allocation Agency

ALCC

Allocation

100,000 GPU-hr

Allocation Year

2022-2023

Resource

Polaris

Allocation Agency

ALCC

Allocation

100,000 node-hr

Allocation Year

2022-2023

Resource

Frontera

Allocation Agency

LRAC

Allocation

4,200,000 node-hr

Allocation Year

2022

Resource

Stampede2 (KNL 68 core/node)

Allocation Agency

XSEDE

Allocation

750,000

Allocation Year

2022

Resource

Delta

Allocation Agency

XSEDE

Allocation

400,000 GPU-hr

Allocation Year

2022

Resource

Perlmutter

Allocation Agency

ERCAP

Allocation

48,400 GPU-hr

Allocation Year

2022

Resource

Cori KNL (68 core/node)

Allocation Agency

ERCAP

Allocation

525,000 node-hr

Allocation Year

525,000

Resource

JUWELS Booster

Allocation Agency

GSC (Germany)

Allocation

200,000 node-hr

Allocation Year

2022

Resource

LQ1, BNL KNL, JLab KNL

Allocation Agency

USQCD

Allocation

42,000,000 core-hr

Allocation Year

2022-2023

Resource

BNL GPU IC

Allocation Agency

USQCD

Allocation

348,000 K80 GPU-hr

Allocation Year

2022-2023

Resource

DiRAC Tursa

Allocation Agency

EPCC (Edinburgh, U.K.)

Allocation

600,000 + 725,000 + 725,000 node hours

Allocation Year

2023 + 2024 + 2025

Section 5: Project Narrative and Supplemental Materials

Question #1

Using the templates provided here, please follow the INCITE Proposal Preparation Instructions to prepare your proposal. Elements needed include (1) Project Executive Summary, (2) Project Narrative, (3) Personnel Justification and Management Plan, (4) Milestone Table, (5) Publications Resulting from prior INCITE Awards (if appropriate), and (6) Biographical Sketches for the PI and all co-PI's. Concatenate all materials into a single PDF file. Prior to submission, it is strongly recommended that proposers review their proposals to ensure they comply with the proposal preparation instructions.

Concatenate all materials below into a single PDF file.

1. **Project Executive Summary (One Page Max)**
2. **Project Narrative (15 Pages Max)**
3. **Personnel Justification and Management Plan (1 Page Max)**
4. **Milestone Table**
5. **Publications resulting from prior INCITE Awards (if appropriate)**
6. **Biographical Sketches for the PI and all co-PI's.**

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The attachment is on the following page.

PROJECT EXECUTIVE SUMMARY

Title: Advances in Quark and Lepton Flavor Physics with Lattice QCD

PI: Andreas Kronfeld
Co-PIs: Thomas Blum, Peter Boyle, Norman Christ, Carleton DeTar, Aida El-Khadra, Steven Gottlieb, William Jay, Luchang Jin, Chulwoo Jung, Christoph Lehner, Andrew Lytle, Robert Mawhinney, Ruth Van de Water

Applying Institution/Organization: Fermi National Accelerator Laboratory

Number of Processor Hours Requested 2023: 1,000,000 Summit node-hr
2,200,000 Frontier node-hr; 1,000,000 Aurora node-hr
2024: 2,200,000 Frontier node-hr; 2,300,000 Aurora node-hr
2025: 2,200,000 Frontier node-hr; 2,300,000 Aurora node-hr

Amount of Storage Requested 2023: 558 TB disk, 4,575 TB tape (OLCF); 300 TB disk (ALCF)
2024: 500 TB disk, 6,500 TB tape (OLCF); 400 TB disk, 6,500 TB tape (ALCF)
2025: 600 TB disk, 9,500 TB tape (OLCF); 650 TB disk, 9,500 TB tape (ALCF)

Executive Summary:

We request a three-year project on three leadership-class computers at the Oak Ridge Leadership Facility (OLCF) and the Argonne Leadership Facility (ALCF), in order to address fundamental questions in elementary particle physics. The proposed calculations directly support extensive experimental efforts in this field ($\approx$ \$700M anually). We will use numerical simulations of the lattice gauge theory formulation of quantum chromodynamics (lattice QCD). In some cases, we also incorporate corrections from electromagnetism and the small difference in the up- and down-quark masses, because the precision of corresponding experiments requires these effects. The calculations are well aligned with the U.S. strategic plan, spelled out several years ago in the report of the Particle Physics Project Prioritization Panel. Because of these important, ambitious goals the highest-capability supercomputers—Summit (OLCF), Frontier (OLCF), and Aurora (ALCF)—are necessary to make an impact.

QCD is the component of the Standard Model of particle physics from which hadrons and atomic nuclei emerge. The only known systematically improvable way to treat the long-distance, strongly-coupled dynamics of QCD is a Markov chain Monte Carlo (MCMC) method, generating a sequence of lattice gauge-field configurations with importance sampling. The dependence of the lattice data on physical parameters, namely the quark masses, and the lattice spacing, is controlled with effective field theories. In this sense, the proposed work delivers *ab initio* results of the Standard Model. Here we propose some new MCMC runs, but most of the proposed compute time leverages earlier ensembles of lattice gauge-field configurations.

The PI, co-PIs, and team members together have decades of experience in large-scale high-performance computing campaigns dedicated to the lattice-QCD calculations of relevance to the DOE Office of Science, Office of High-Energy Physics. In many cases, participants in this proposal have produced the most comprehensive lattice-QCD calculations leading up to the work proposed here.

The software is based on the well-established USQCD software stack, developed steadily over the past two decades. For the past several years, this software has successfully run all the proposed calculations on Summit. Many team members are actively engaged in the Exascale Computing Project, so the code bases are undergoing continued improvement with tests on Summit, early hardware prototypes for Aurora and Frontier, and early access to Aurora and Frontier themselves.

PROJECT NARRATIVE

We request a three-year project on three leadership-class computers in order to address fundamental questions in elementary particle physics (also known as high-energy physics). The computers are Summit and Frontier at the Oak Ridge Leadership Computing Facility (OLCF) and Aurora at the Argonne Leadership Computing Facility (ALCF). The proposed calculations directly support many large, world-wide experimental efforts, particularly those searching for evidence of physics beyond the Standard Model via precision measurements of quark and lepton properties. Because these experiments deliver such precise results, it is essential that the theoretical predictions of the Standard Model be commensurately precise.

This proposal is from a large subset of the U.S. lattice-QCD community working on elementary particle physics, together with team members from Germany, the United Kingdom and Spain. The PI and six co-PIs belong to the Fermilab Lattice/MILC collaboration, and the remaining seven co-PIs belong to the RBC/UKQCD collaboration. We have joined forces for two reasons. First, much of the scientific motivation of our work is in common. Moreover, we stress that the stakes require more than one result (for each quantity), with different choices of fermion formulation, lattice sizes, and analysis choices.

This proposal is a direct successor to a 2022 INCITE project (PI: Andreas Kronfeld) that is running on Summit now, a 2021 INCITE project (PI: Kronfeld) that ran on Summit, and a portion of a 2020 proposal from USQCD (PI: Kronfeld) that also ran on Summit. With this and earlier support, the proponents have delivered many, if not most, of the world's best calculations in quark and lepton flavor physics. Some highlights include determinations of the quark masses (fundamental parameters of nature, now at the sub-percent level), matrix elements of B-, D-, and K-meson mixing and decay, and the hadronic contributions to the magnetic moment of the muon. With the advent of the exascale machines Aurora and Frontier, we are ready to take the next step. Via many team members' involvement in the Exascale Computing Project we will be among the most ready users of these new resources.

The proposed scientific objectives are carefully chosen not only to require the resources of the Summit, Aurora, and Frontier supercomputers, but also to have the greatest impact on the current experimental program in particle physics. Everything we propose is in harmony with the plan set out a few years ago in the report of the Particle Physics Project Prioritization Panel. The calculations proposed here leverage enormous investments in experimental physics ($\approx$ \$700M annually). Indeed, the proposed calculations allow the corresponding experimental measurements to be interpreted with the precision they demand. With Frontier and Aurora available imminently, we expect to satisfy several long-awaited needs of the particle-physics community, as outlined in three recent contributions to the APS Division of Particles and Fields Community Study (aka Snowmass) [1–3].

1 SIGNIFICANCE OF RESEARCH

We propose to focus on three main topics. The first is the anomalous magnetic moment of the muon, which is especially important and timely as an experiment underway at Fermilab announced its first measurement [4] on April 7, 2021 to world-wide media coverage. The second is a program of B- and D-meson physics, which supports the BES III, Belle 2 and LHCb experiments. Last, we study CP-violation in the kaon system, which leverages legacy experiments at Fermilab and CERN. In every case, the particle physics community expects lattice-QCD calculations to be performed to get the most out of the experimental program.

Two different formulations of lattice fermions are proposed for various calculations. We use the highly-improved staggered quark (HISQ) action for muon $g - 2$ and for B and D physics; we use domain wall fermions (DWF) for muon $g - 2$ and for K physics.

1.1 Hadronic-vacuum-polarization contribution to the anomalous magnetic moment of the muon

The anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$, which is currently measured in experiment to the remarkable precision 0.35 ppm [4,5], provides one of the most sensitive probes of physics beyond the Standard Model (SM) available today. For many years, the muon anomaly has hinted at the presence of new physics via a 3σ tension between its value measured in BNL Experiment E821 [5] and the SM expectation. Last year's highly anticipated result from the Muon $g - 2$ Experiment [4] at Fermilab—which garnered media attention worldwide—pushed the tension to 4.2σ. Because this difference is not large enough to claim discovery of new physics, the Fermilab experiment continues to collect and analyze data with the goal of reducing the measurement error by a factor of four within three years. Yet further improvements to the measured a_μ are expected from a planned experiment at J-PARC (in Japan).

By far, the dominant sources of uncertainty in the SM muon anomaly are from nonperturbative QCD effects that are well-suited to lattice QCD. In fact, lattice QCD is the *only* method for calculating a_μ using only the SM theory; other data-driven methods (such as the so-called R-ratio) assume no new physics in the measurements used. In this proposal, we build upon two multi-year projects to calculate the hadronic vacuum polarization (HVP) contributions to a_μ with lattice QCD—one by the Fermilab Lattice, HPQCD, and MILC Collaborations (FHM), and the other by the RBC/UKQCD Collaboration. (Elsewhere, RBC/UKQCD is also computing the hadronic contribution from light-by-light scattering.) These theoretical efforts are urgently needed to obtain a_μ with precision commensurate with current and planned experiments.

Figure 1 compares the current status of the HVP contribution to the muon anomaly in the SM with experiment. A recent lattice-QCD result from the BMW collaboration with 0.8% precision [6] is close to the the experimental average, but disagrees by more than 3σ with the R-ratio results. *If confirmed*, this clash between the R-ratio and direct QCD calculations would echo through many corners of particle physics. Conversely, agreement between the R-ratio and lattice-QCD HVP determinations is prerequisite for claiming discovery of new physics in the muon anomalous magnetic moment.

Given these high stakes, it is of utmost importance to obtain the HVP from several lattice-QCD calculations employing different methods with different systematics. As yet, the ongoing FHM and RBC/UKQCD efforts, which are fully independent, have produced HVP results with $\approx 2\%$ precision [9, 12]. With help from the computations proposed here, we will address two important systematics in the BMW result by employ-

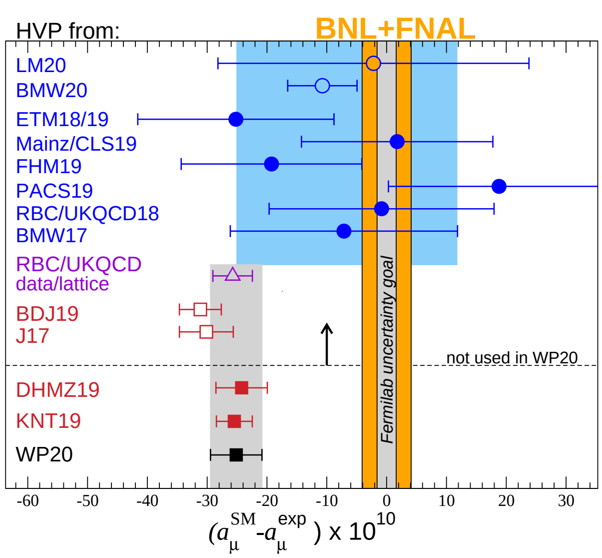

Figure 1. Comparison of theoretical predictions of a_μ with experiment [4] (orange band). Each data point represents a different evaluation of the leading order HVP, to which the remaining SM contributions, as given in Ref. [7], have been added. Blue circles indicate lattice-QCD calculations [6, 8–15]. Squares show results derived from the R-ratio [16–19], and the purple triangle gives a hybrid of the two [9]. The points below the dashed line are included in the consensus SM prediction [7], which is represented by the black square and gray band. Adapted from Ref. [7].

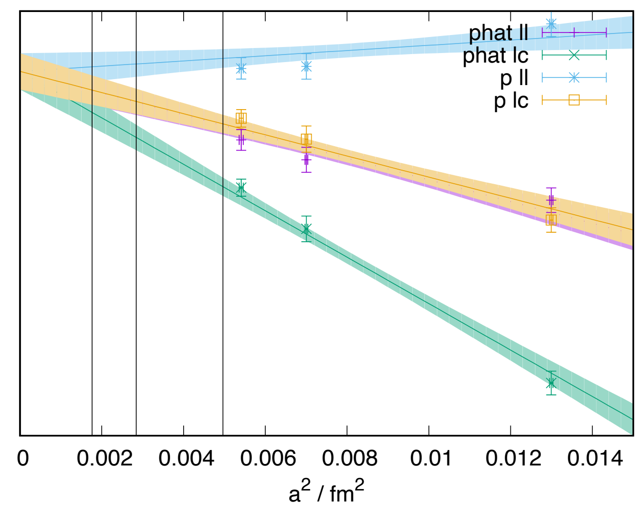

Figure 2. Preliminary result of the continuum extrapolation of the isospin-symmetric light-quark standard window quantity [9] with the three DWF+Iwasaki gauge ensembles at physical pion mass and the proposed new lattice spacings indicated as vertical black lines. The four different extrapolations correspond to different choices for momentum discretization (p/phat) and vector currents (ll: local-local, lc: local-conserved). The statistical uncertainties of the continuum extrapolation are currently 0.3%. The goal of this proposal is to reduce the remaining systematic uncertainties below this level.

ing finer lattice spacings than ever before and by directly calculating the long-distance contributions to the HVP from two-pion intermediate states. Our aim is to achieve total errors on the HVP contribution below 0.5%, which would surpass the (current) R-ratio and BMW results in Fig. 1 and match the end precision of the experiment.

1.1.1 Significance of the proposed HISQ HVP calculation

The proposed HVP calculation using HISQ ensembles builds on work by the Fermilab Lattice, HPQCD, and MILC collaborations [12, 20]. The most recent result [12], shown in Fig. 1 as "FHM19", is founded on a calculation of the light-quark connected contribution, a_μ^{ll}(conn). Because it accounts for roughly 90% of the total leading-order HVP, calculating a_μ^{ll}(conn) with sub-percent precision is crucial. The dominant sources of error on a_μ^{ll}(conn), which are statistics and the continuum extrapolation, are key targets of this proposal. To reduce the statistical errors, we propose enlarging the data sample at a lattice spacing of 0.03 fm with the unphysical sea-quark mass ratio $m_l/m_s = 1/5$. To improve the continuum extrapolation, we propose extending our work to 0.042 fm with all physical quark masses. With other resources, graduate student, Shaun Lahert, and several co-PIs are studying the two-pion long-distance tail [21]. Other significant sources of uncertainty, due to the lattice scale and the subleading disconnected and isospin breaking corrections, must also be reduced in order to reach our precision goal. Each of these are being tackled in separate projects, which are part of our overall program. The subleading corrections are deployed to non-leadership-class resources. Similarly, computations on ensembles at coarser lattice spacings, which are needed for the continuum extrapolation of a_μ^{ll}(conn), are being completed on less capable resources. Thus, this proposal focuses on computations on the most challenging ensembles, with very small lattice spacings, 0.06 fm and 0.042 fm, which will address our dual goals of improving the continuum extrapolation and reducing the overall statistical errors needed to achieve our target precision.

1.1.2 Significance of the proposed DWF HVP calculation

The proposed continuation of the HVP calculation on DWF ensembles builds on the success of the improved bounding method [22, 23], introduced by some of the co-PIs, to reduce the dominant statistical uncertainty to a level similar to the uncertainties of the R-ratio calculations. This method also produces as a byproduct detailed information about the two-pion elastic scattering which in turn can be used to reduce uncertainties of the infinite-volume extrapolation. Based on these improvements, the next dominant uncertainty is the continuum extrapolation, which is directly addressed in this proposal.

In Fig. 2 we show the current status of our continuum extrapolation for critical isospin-symmetric light-quark standard window quantity [9]. We note that we have achieved 0.3% statistical uncertainty in the continuum extrapolation, which we plan to slightly further reduce by additional measurements on the existing $96^3 \times 192$, $a = 0.071$ fm ensemble. Next, we need to address the remaining systematic uncertainties of the continuum extrapolation. It is well-known that a simple a^2 extrapolation will fail at sufficiently high precision and that the effect of higher-order terms in $a^m \ln(a)^n$ need to be considered as well. To satisfy the ambitious precision goal explained above, we therefore propose to generate three new ensembles with open boundary conditions in time, dynamical charm quarks, and physical pion mass with lattice spacing $a = 0.071$ fm, 0.053 fm, and 0.042 fm. The proposed new ensembles are indicated as black vertical lines in Fig. 2. The goal of our proposal is to move to sufficiently fine lattice spacings that the impact of these higher-order terms is well below our statistical uncertainty. As indicated in Fig. 2, at the proposed finest lattice spacing, the remnant size of the extrapolation may be of the size of the statistical uncertainties such that it is expected that the remaining systematic uncertainties will be negligible compared to the statistical error. At the end of this three-year proposal, we estimate our final uncertainties for the total HVP to be around 2×10^{-10} (or approximately 0.3%) which is comparable to the target uncertainty of the Fermilab E989 experiment. If fully funded, we therefore expect to provide the needed precision for the Fermilab experiment at a time-scale commensurate with the planned completion of the experimental program.

1.2 Heavy-quark physics: Semileptonic B- and D-meson decays

For the past decade, lattice QCD flavor-physics calculations have made critical contributions to determinations of CKM matrix elements (fundamental parameters of the SM for transitions between quark flavors) and to searches for beyond-the-SM effects in flavor physics. In the work proposed here, we will study semileptonic decays of B and D mesons. Earlier results for the leptonic B, B_s, D, and D_s decay constants [24, 25] (with crucial support from INCITE) have sub-percent errors and are 3–10 times more precise than any previous lattice-QCD calculation, providing a template for the more complicated semileptonic-decay processes. Semileptonic decays of these mesons, such as $B \to D^*\ell\nu$ and $B \to \pi\ell\nu$, permit a more precise determination of the CKM matrix elements than leptonic decays. The Belle II and LHCb experiments will soon supply much more accurate experimental measurements of these processes, which demands timely, commensurate SM precision improvements. To compute semileptonic form factors at *nonzero* recoil momenta, which are needed for $|V_{ub}|$, $|V_{cb}|$, $|V_{cd}|$, and $|V_{cs}|$ determinations and for rare decay phenomenology, with precision comparable to decay constants [24, 25], smaller lattice spacings are necessary.

Taken together, these results form the basis for stringent tests of the unitarity of the CKM matrix. In addition, rare semileptonic B-meson decays (such as $B \to \pi\ell^+\ell^-$, $B \to K\ell^+\ell^-$) are promising channels for new-physics searches because their rates are suppressed in the SM. They share the same lattice-QCD calcuations with $\ell\nu$ in the final state. SM expectations for these processes are based on our earlier lattice-QCD results [26–28] and differ in several places from experimental measurements at the 2σ level. The tensions addressed by this proposal are [29]

- The approximately 3σ discrepancy between inclusive and exclusive determinations of the CKM matrix elements $|V_{cb}|$ (3.3σ from $B \to D^*\ell\nu$ and 2.0σ from $B \to D\ell\nu$) and $|V_{ub}|$ (2.8σ from $B \to \pi\ell\nu$).
- The combined 3.1σ discrepancy between $R(D)$ and $R(D^*)$, the ratios of the branching fraction for $B \to D\tau\nu$ vs. $B \to D\mu\nu$ and $B \to D^*\tau\nu$ vs. $B \to D^*\mu\nu$.
- A 2.6σ tension in the low-q^2 region for the measured ratio R_K of branching fractions for the decays $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$.
- The approximately 2σ discrepancy between the observed differential decay rate for the flavor-changing neutral current process $B \to K\mu^+\mu^-$ and theoretical predictions.

Recent years have established lattice QCD as an essential tool in quark-flavor physics. In particular, together with collaborators in the Fermilab Lattice and MILC collaborations, some of us have produced the most precise results to date for quark masses and many hadronic matrix elements relevant for weak kaon, D- and B-meson processes, with significant reductions in the uncertainties compared with earlier results. For example, our 2014–2017 results for the leptonic B, B_s, D, and D_s decay constants [24, 25] have sub-percent errors and are 3–10 times more precise than any previous lattice-QCD calculation. In this proposal, we focus on the form factors of semileptonic decays, which are not mere constants but functions of the decay kinematics. Our published calculations of semileptonic B-meson form factors at both zero and nonzero recoil, when combined with experimental measurements of the corresponding decay rates, yield the best constraints on the CKM matrix of the SM [26, 30–34], as well as models of new physics [27, 35, 36].

With the start of the Belle II experiment in Spring 2019, data sets that are 50–100 times larger than those taken by the BaBar and Belle experiments [37] pose a new challenge to lattice QCD. For example, Belle II measurements of the semileptonic $B \to \pi\ell\nu$ differential distributions could yield a determination of $|V_{ub}|$ at close to 1% uncertainty [38], provided that there are commensurate improvements in the accuracy of the corresponding lattice QCD form factors. Similarly, it is expected that the LHC luminosity and detector upgrades will yield improved measurements at LHCb [39] with, again, significant reductions in the experimental uncertainties. These anticipated experimental improvements require similarly-precise lattice-QCD calculations, as detailed in Sec. 2.2 of this proposal.

1.3 Indirect CP violation in kaon decay

Another topic in quark-flavor physics addresses the violation of CP symmetry (the combined symmetry of particle-antiparticle reversal and spatial inversion). Violation of CP symmetry is predicted by the SM, but the SM mechanism appears unable to explain the excess of baryons over anti-baryons found in the Universe, suggesting that CP-violating phenomena present a promising direction to search for effects not predicted by the Standard Model. The effects of CP violation were first seen in the neutral kaon system and at present are consistent with the predictions of the Standard Model. In the case of indirect CP violation (CP violation caused by the mixing of the neutral kaon with its anti-particle), they are described by the parameter $|\varepsilon_K| = (2.228 \pm 0.011) \times 10^{-3}$, whose small size makes this quantity particularly sensitive to new physics. Of equal importance is the K_L-K_S mass difference, $\Delta M_K = 3.483(6) \times 10^{-12}$ MeV, whose extremely small size makes it sensitive to new physics at energy scales as high as 10^4 TeV.

Reference [40] estimates the Standard Model prediction for ε_K to be $|\varepsilon_K| = 2.161(65)(76)(153)\times10^{-3}$, where the first error is short-distance, the second long-distance, and the third parametric. The parametric error is dominated by the uncertainty in $|V_{cb}|$, which enters the expression for ε_K raised to the fourth power. The Belle II experiment and calculations presented elsewhere in this proposal aim to reduce the error on $|V_{cb}|$ by more than a factor of two [41], reducing the parametric error to a few percent and making the long-distance error dominant. The standard model perturbative prediction for ΔM_K has an uncertainty of at least 40% [42]. Over the last decade we have developed methods to compute both the long-distance contribution to ε_K [43] and ΔM_K [44, 45]. As described below we propose to use Summit, Aurora and Frontier to determine both quantities to 10% accuracy.

2 RESEARCH OBJECTIVES AND MILESTONES

2.1 Hadronic-vacuum-polarization contribution to the anomalous magnetic moment of the muon

Because of the high stakes of the muon $g - 2$, calculations employing independent and complementary methods are crucial, so, as discussed above, this proposal includes two complementary HVP projects. The surprising lattice-QCD result from BMW [6], which claims sub-percent precision but is in tension with the

R-ratio, makes the need even more urgent. The common objective of both proposed HVP projects is to go beyond BMW and match the target precision of the Fermilab experiment. It is thus necessary to reduce the dominant sources of error in the dominant contribution (90%) to HVP, namely the connected light-quark contribution, $a_\mu^{ll}(\mathrm{conn})$. Using the HISQ action, we will extend our 2019 calculation Ref. [12] of $a_\mu^{ll}(\mathrm{conn})$ to a new lattice spacing of 0.042 fm, our smallest yet. Most of the needed gauge configurations are already in place. We expect the new calculation will be essential for a sub-percent-precision determination of $a_\mu^{ll}(\mathrm{conn})$. Using the DWF formulation, we will increase the statistics for the HVP calculation on our finest existing ensemble, thereby reducing the overall error to below 0.3%. In addition, we will generate three additional ensembles at finer lattic spacings up to $a^{-1} = 4.7$ GeV, which we expect to push remaining systematic uncertainties related to the continuum extrapolation to below 0.3% as well.

2.1.1 Details on the HISQ HVP milestones

The Fermilab-HPQCD-MILC result for the HVP contribution to $g - 2$ [12], shown in Fig. 1 as "FHM19", is based on the most recent calculation of the light-quark connected contribution, $a_\mu^{ll}(\mathrm{conn})$. The work employs HISQ ensembles with physical pion masses at four different lattice spacings, namely 0.15 fm, 0.12 fm, 0.09 fm, and 0.06 fm. The dominant source of error in $a_\mu^{ll}(\mathrm{conn})$ is statistics, especially in the long-distance tail of the Euclidean-time correlation function, where contributions from $\pi\pi$ states dominate. The next dominant error comes from the continuum extrapolation. As we have seen in Ref. [12], the finest lattice spacings anchor the continuum extrapolation. Thus, we have been enlarging the statistics at 0.09 fm and 0.06 fm with our 2022 INCITE award and other resources. The power of Frontier and Aurora allows us, for the first time, to add the 0.042 fm ensemble to our calculations. We propose here to analyze a few hundred gauge configurations from this ensemble using the low-mode-improvement (LMI) method [46]. We selected this method after an extensive Summit evaluation of alternatives.

We have already generated 1000 gauge configurations in the 0.042 fm ensemble with other resources. As this project progresses, we anticipate needing to enlarge this ensemble. Thus we include a request for time to double the size of this ensemble. The enlarged resource will be made available to other researchers.

The large eigenvector sets generated with this method will be reused in other projects, particularly for a dedicated computation of the two-pion contributions [21].

2.1.2 Details on the DWF HVP milestones

The uncertainties of the RBC/UKQCD 2018 results for the HVP contribution to $g_\mu - 2$, shown in Fig. 1 as RBC/UKQCD18, are dominated by statistical noise in the light-quark-connected contribution. In Ref. [23], we have shown how to address this problem such that a calculation at the few per-mille level precision is feasible once we address other currently sub-leading systematics. The most difficult challenge is addressed in this proposal: we propose to generate three additional finer ensembles at $a = 0.071$ fm, 0.053 fm, and 0.042 fm with dynamical charm quarks and open boundary conditions in time at physical pion mass. We then measure the ensemble parameters and the HVP contribution. To this end, we build on our successful strategy for physical pion masses [9], combining a full low-mode average using local coherence of the Dirac eigenvectors [47] and a small number of high-mode solves to achieve a full volume average, maximizing the statistical yield per measured lattice configuration. The new $a = 0.071$ fm runs and 0.053 fm runs will be performed on Frontier and the 0.042 fm runs will be performed on Aurora. We propose to measure on 28, 28, and 31 configurations, respectively, see Table 2. In addition, we propose to increase the statistics of our existing $a = 0.071$ fm data set from 30 configurations to 40 configurations on Summit. As in previous years, we employ a master-field statistical error analysis.

These new ensembles rely on three innovations that are under active development in our Exascale Com-

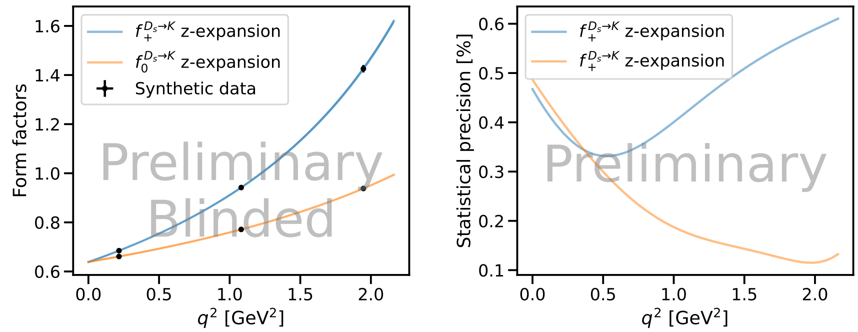

Figure 3. (Left) Preliminary blinded results for the form factors $f_+^{D_s\to K}(q^2)$ and $f_0^{D_s\to K}(q^2)$ at the physical point and in the continuum limit. (Right) Sub-percent precision is obtained throughout the full kinematic range of the decay. To reach percent-level precision for B-meson decays, we are requesting an INCITE allocation to extend our calculations to finer lattice spacings.

puting Project in preparation for said resources: (i) the domain decomposed HMC (DDHMC) algorithm to mitigate limited inter-node communications; (ii) the Riemannian Manifold HMC (RMHMC) algorithm with open boundary conditions to overcome critical slowing down; (iii) quark-flavor reweighting to upgrade our existing 2+1 flavor ensembles to 2+1+1, allowing all results to lie on a single scaling trajectory. These new methods are being actively developed (see Section 3.4). Also broken out as a separate milestone is the standard measurements required by the extended and new ensembles. These measurements provide more accurate values of the lattice scale and choice of physical quark masses needed to meet our HVP goals.

2.2 Heavy-quark physics: Semileptonic B- and D-meson decays

In 2019, we began a multiyear lattice QCD effort to calculate the decay form factors for semileptonic D-, D_s-, B-, and B_s-meson transitions [48]. Our calculations furnish three Lorentz-invariant form factors: scalar, vector, and tensor. The scalar and vector enter the calculations of the tree-level weak decays $B \to \pi\ell\nu_\ell$ and $B_s \to K\ell\nu_\ell$, $B_{(s)} \to D_{(s)}\ell\nu_\ell$, $D \to \pi\ell\nu_\ell$ and $D_s \to K\ell\nu_\ell$, and $D \to K\ell\nu_\ell$, and enable determinations of the CKM elements $|V_{ub}|$, $|V_{cb}|$, $|V_{cd}|$, and $|V_{cs}|$, respectively. The tensor contributes to flavor-changing-neutral current decays such as $B \to \pi\ell\ell$ and $B \to K\ell\ell$. Such processes are allowed only at second order in the Standard Model weak interaction, so they are suppressed and could expose new physics. Our uncertainties in the form factors for B-meson decays will be at the 1% level and the sub-percent level for D-meson decays. These calculations will therefore enable determinations of unprecedented precision of the CKM elements listed above from experimental measurements of the corresponding differential decay rates and provide crucial support for ongoing searches for new physics in rare flavor-changing neutral-current decays.

Our precision goals for this project are guided by our recent high-precision work on the K-, D-, and B-meson decay constants [24, 25], and the methods employed in earlier studies of semileptonic decays [26, 27, 30–36]. The key new elements in this improvement are i) a large set of gauge-field configurations at lattice spacings ranging from 0.03–0.15 fm with physical-mass up, down, strange, and charm sea quarks; ii) a highly improved fermion action for all quarks. Very fine lattices, such as are proposed here, are needed in order to simulate at the physical b quark mass. Physical-mass quarks greatly reduced the systematic error associated with the chiral-continuum extrapolation. The multiyear effort is progressing from coarser to finer lattices and from clusters to the most capable Leadership-Class Facilities.

Table 1 summarizes the gauge-field ensembles in our multi-LCF campaign. Our three-year request is for the

Table 1. List of HISQ gauge-configuration ensembles for the multiyear campaign for measuring semileptonic decays of B, D, etc., mesons with HISQ fermions. The columns show the approximate lattice spacing in fm, the ratio of the simulation light sea-quark masses to the physical strange sea-quark mass, the lattice dimension, the allocated or proposed resource for the calculation, and the project status. Not shown are ensembles that were completed on local clusters at larger lattice spacing. The ensembles highlighted in blue were completed last year using our INCITE allocation or started, as indicated. We are requesting an INCITE allocation for the ensembles highlighted in red.

$\approx a$ (fm)	m_l/m_s	$N_s^3 \times N_t$	Resource	Status
0.09	1/27	$64^3 \times 96$	NERSC Cori, ALCF Theta	completed
0.06	1/10	$64^3 \times 144$	NERSC Cori, OLCF Summit	completed
0.06	1/27	$96^3 \times 192$	TACC Frontera	completed
0.042	1/5	$64^3 \times 192$	OLCF Summit	completed
0.042	1/27	$144^3 \times 288$	OLCF Frontier, ALCF Aurora	planned 2023-5
0.03	1/5	$96^3 \times 288$	OLCF Summit	started 2022
0.03	1/5	$96^3 \times 288$	OLCF Summit	planned 2023

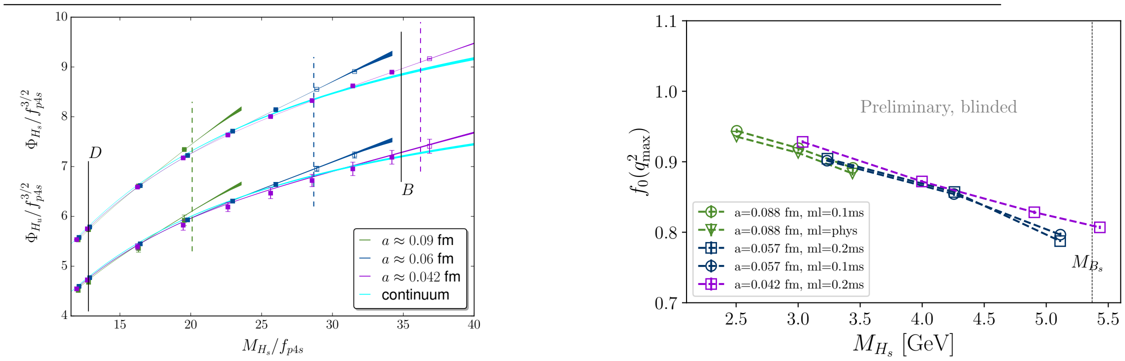

Figure 4. (Left) Extrapolation of heavy meson decay constant data from Ref. [25]. The current work adapts this method to semileptonic form factors over a range of momentum. (Right) Raw data (prior to fitting) for the scalar form factor for the decay $H_s \to K$ at maximum momentum transfer ($q^2_{\rm max}$) as a function of the heavy-strange H_s meson mass up to just above the B_s meson mass M_{B_s} for three lattice spacings and various sea-quark mass ratios. The statistical accuracy is excellent and will improve as we complete our data sample. Reaching the B_s mass requires our finest lattices (0.042 fm and 0.03 fm), and controlling the light-quark mass dependence requirea the analysis (proposed here) of the 0.042 fm ensemble with *all-physical* quark masses.

analysis at the smallest lattice spacing in our campaign with all physical quark masses, namely $a \approx 0.042$ fm and a volume of $144^3 \times 288$. At this spacing we reach the physical mass of the b-quark with controlled discretization errors. We are also requesting Summit time to complete the analysis of our large ensemble at 0.03 fm with light-quark to strange-quark mass ratio 1/5 and a volume of $96^3 \times 288$. Both ensembles will play a crucial role in anchoring and controlling the interpolation of the heavy quark to the mass of the b quark. To reach our precision goals, we will need results from all of the listed ensembles.

With last year's INCITE allocation, we completed our first ensemble at $a \approx 0.042$ fm with quark mass ratio $m_l/m_s = 1/5$. Our statistical analysis of this ensemble is ongoing, but we already have preliminary results for the semileptonic decays of B and B_s mesons to D, D_s, K, and π mesons. Figure 4 (right) shows the good precision we achieve for the $B_s \to K$ decay, with statistical uncertainties of sub-1% at $a \approx 0.042$ fm.

Our results are blinded until the analysis is complete. Our errors will improve further once results are available from the rest of the ensembles listed in Table 1. This expectation is informed by our experience with leptonic decays, illustrated in the left panel of Fig. 4, where the error in the final continuum result decreased by a factor of 2 to 3 when we went from a partial set of ensembles in 2014 to the full set in 2017 [24, 25]. Overall we expect to deliver B-meson semileptonic form factors with percent-level errors for recoil energies below 1 GeV. Still higher recoil energies are also of phenomenological importance for rare B-meson decays. In this energy range, we expect 2–3 times larger errors, since an extrapolation from low recoil is needed [27, 32, 35, 36].

2.3 Indirect CP violation in kaon decay

The mass matrix describing the mixing of the K^0 and $\overline{K}^0$ mesons results from a second-order weak process that involves energy scales from the pion mass up to the mass of the top quark. It becomes accessible to a lattice QCD calculation [43, 44] by working with the conventional four-Fermi effective weak Hamiltonian [49] to second order. Given the importance of the GIM mechanism and the difficulty of employing perturbative QCD below the charm quark mass [42], the calculation must be performed with four active quark flavors.

In contrast with the calculation of ΔM_K, the imaginary part of $M_{0\overline{0}}$ which determines ε_K receives its largest contributions from energies on the order of the top mass and is thus short-distance dominated. This implies that the long-distance contribution which we propose to calculate here is an $\approx$ 5% effect and contains a logarithmically divergent piece when computed in the second order effective theory which requires non-perturbative renormalization of a bilocal operator. A complete exploratory calculation with unphysical quark masses including all five types of diagram and the required non-perturbative renormalization of both the local and bilocal operators has been performed [43].

Our physical computation of these quantities began with the simpler ΔM_K which was calculated on Mira using 152, $64^3 \times 128$ configurations [45], achieving a 10% statistical error. The final step in this calculation was a comparison of two unphysical results using $24^3 \times 64$, $1/a = 1.73$ GeV and $32^3 \times 64$, $1/a = 2.38$ GeV ensembles to provide an estimate of the finite lattice spacing errors. To our surprise we discovered large $\approx$ 40% scaling violations that required further study [45]. Individual matrix elements of the operator $(Q_1 - Q_2)$, which appears squared in ΔM_K, showed $\approx$ 20% scaling errors. This discovery has been the subject of our current Summit calculations.

Here we propose to exploit the large increase in capability offered by Frontier and Aurora to work at the smaller lattice spacings of 0.071 and 0.053 fm. Since our previous calculation was performed at $a = 0.086$ fm, these 40% errors should be reduced to 15% and 10% (or smaller if the earlier 40% error included a substantial a^4 contribution). The proposed 3-year calculation should provide 10% statistical errors and allow a continuum extrapolation.

3 COMPUTATIONAL READINESS

3.1 Use of Resources Requested

We describe here the resource usage and explain the request for each of the Section 4 milestones. The resource estimates are based on timings of the same- or similar-sized calculations on Crusher, Summit, and Perlmutter. Timings for Frontier are firm estimates based on Crusher benchmarks. Timings for Aurora are our best estimates based on our experience with early hardware. Via ECP, we will have access to Aurora components as they are made available, allowing time to provide more accurate estimates in mid 2023.

Table 2. Computational objectives for each machine given as the number of time units evolved or configurations measured. Here HVP refers to the isospin symmetric, connected HVP contribution to $g_\mu - 2$ while Kaon-mixing refers to the calculation of ΔM_K and the LD contribution to ε_K. The 2023 calculations proposed on Summit are not shown.

Ensemble	MD time units		Eigenvectors		HVP		Kaon-mixing	
	Frontier	Aurora	Frontier	Aurora	Frontier	Aurora	Frontier	Aurora
$96^3 \times 384$	1260	1200	48	62	28	0	48	62
$128^3 \times 512$	860	1720	28	86	28	0	0	87
$160^3 \times 640$	0	920	0	31	0	31	0	0

Milestone 1 This milestone improves the continuum extrapolation of HVP with HISQ. The power of Frontier and Aurora makes it feasible to mount a campaign at our smallest lattice spacing thus far, namely 0.042 fm. We expect it to be crucial in reducing the uncertainty in the extrapolation to zero lattice spacing and thus key to achieving subpercent accuracy. We have set a goal of analyzing 1100 configurations at that spacing using the low-mode-improved (LMI) method on Frontier, which we have planned in the Milestone table. We will implement the method with the Hadrons plus Grid code, which has been adapted for HISQ fermions and is currently in production on Summit on a smaller 0.06 fm $96^3 \times 192$ ensemble. We will calculate 2000 low-mode eigenvectors per gauge configuration of the Dirac operator and 100s of deflated solutions of the Dirac equation to capture the high-mode contributions. The eigenvector files for this project are approximately 40 TB in size; hence the 200 TB scratch storage request. They will be stored on tape for use in other projects. We estimate this project can be run on 768 Frontier nodes. We obtain the cost by scaling from the cost of the smaller 0.06 fm $96^3 \times 192$ problem. We estimate we will need LMI measurements on a few hundred gauge configurations, which will require continuing this calculation in years 2 and 3.

Milestone 2. This milestone addresses the HVP continuum limit with chiral quarks. It depends on results of Milestone 3. We will make use of the locally-coherent (multi-grid) Lanczos algorithm [47], which for the existing $a = 0.071$ fm ensemble reduces the memory footprint by a factor of 30 compared with the regular fine-grid Lanczos. A similar reduction in memory footprint is expected for the new $a = 0.071$ fm ensemble with open boundary conditions and dynamical charm quarks. For the new proposed $a = 0.053$ fm and $a = 0.042$ fm ensembles, a larger compression factor is expected since local coherence allows for the fine-grid basis blocks to remain of approximately constant size in physical units. We will generate on all ensembles 5000 coarse-grid eigenvectors, which has been observed to be optimal with the existing $a = 0.071$ fm and $L = 6.8$ fm ensemble at physical pion mass. Since the physical extent of the new ensembles will remain the same, we expect this choice to be optimal also for the new ensembles. As in previous years, we will perform a full-volume average of the HVP correlation functions over the low-mode space. A subsequent all-to-all contraction uses 800 randomly-positioned point-sources for high-mode solves. Preliminary results indicate we will again reach the gauge-noise level allowing us to reach our target precision for the local-local vector current correlator. Without these eigenvectors, we would need 100 times as many solves. The eigenvectors for the new ensemble require up to 30 TB of storage per configuration for the new $a = 0.071$ fm ensemble, 80 TB of storage per configuration for the $a = 0.053$ fm ensemble, and 150 TB of storage for the $a = 0.042$ fm ensemble. These eigenvectors can be re-used for other projects and have a high cost of re-generation. We therefore also request archival storage space for these eigenvectors and 10% of the corresponding incremental yearly archival storage as disk space.

We propose to measure on 28 configurations (8 in Year 1, 10 in Years 2 and 3) of both the $a = 0.071$ fm and $a = 0.053$ fm ensembles on Frontier and 31 (5 in Year 1 and 13 in Years 2 and 3) configurations of the $a = 0.042$ fm ensemble on Aurora. We find that the corresponding problem sizes are well matched to the respective machines. The cost estimate is based on current Summit running and timings obtained on Crusher and appropriately scaled for the new machines. We will also explore further cost reduction based on block Lanczos method [50].

Milestone 3. To support the DWF HVP objectives in milestone 2 and the kaon mixing calculations in milestone 6, we propose to generate a sequence of three new 2+1+1 ensembles listed in Tab. 2 and the corresponding low Dirac eigenmodes needed for deflation and all-to-all propagators. The proposed MD time units/eigenvector counts as well as the measurement counts for milestones 2, 3 and 6 are also shown. These ensembles exploit the large capability increase provided by Frontier and Aurora to dramatically enhance the future predictive power of lattice QCD calculations with chiral quarks. These three new configurations will eventually supplant in importance the $48^3{\times}96$, $64^3{\times}128$ and $96^3{\times}192$ 3-flavor physical-mass ensembles [51, 52] whose creation began more than a decade ago. The new ensembles use open boundary conditions [53] to reduce the autocorrelation of topological charge and a time-to-space aspect ratio of four to allow the unphysical effects of open boundaries to be avoided. As has been our experience with the recent 3-flavor, $a = 0.071$ fm, $96^3 \times 192$ calculations performed on Summit, we expect the small lattice spacing and average over the large $(6.7\text{ fm})^3$ volumes will yield parts-per-mille statistical errors for the quantities of interest even with a few tens of configurations.

This milestone also includes basic measurements of f_π, f_K, f_D, f_{D_s}, M_π, M_K, M_D, M_Ω and B_K. These will provide accurate characterization the new ensembles needed for the HVP milestone 2. and in addition new flavor-physics predictions. For example, when these new results for f_π and f_K are combined with the planned IVR calculation of E&M corrections [54], a part-per-mille first-row unitarity test should be possible.

Milestone 4 and 5. Two tasks comprise the all-HISQ B-meson form-factor project. We use the ensembles with our smallest lattice spacings, namely, 0.03 fm ($96^3 \times 192$, $m_l/m_s = 0.2$) and 0.042 fm (physical quark masses) $144^2 \times 288$. At these lattice spacings, the B-meson mass is reached without large discretization errors. We estimate we will need measurements on at least 1000 configurations in each of these ensembles. This year's INCITE allocation on Summit has brought the number of analyzed 0.03 fm configurations to 200. We are requesting a Summit and Polaris allocation in years 1 and 2 to finish this ensemble. The larger $144^3 \times 288$ configurations require the power of Frontier and Aurora. We propose to analyze 1000 on each of Frontier and Aurora in three years. Our cost estimate is based on Crusher timings of the production code.

Milestone 6. The values for the smaller lattice spacing available for the new ensemble generated in milestone 3. provide essential support for the calculation of ΔM_K and the LD part of ε_K since 40% scaling violations were seen for larger lattice spacing. The proposed sample size shown in Tab. 2 should be sufficient to achieve the 10% statistical errors obtained in our earlier calculation on Mira [45]. The smaller lattice spacings show allow a continuum extrapolation from ensembles with safer, 15% and 10% a^2 errors.

Milestone 7. To reduce the statistical uncertainty of the continuum extrapolation shown in Fig. 2, we will measure the HVP on 10 additional configurations of the existing $a = 0.071$ fm ensemble in the first allocation year on Summit. To this end we will also generate the needed configurations and eigenvectors as done in previous years. We continue to measure 20 MD units apart, where we can show negligible auto-correlations. For this reason we generate 200 additional configurations. The timing was measured in current production runs of the same tasks on Summit.

Milestone 8. To avoid strong autocorrelations in the HISQ $g-2$ project, especially for the LMI method, we need to make sure the gauge configurations we choose are widely separated in Monte-Carlo time. Thus we propose to extend the 0.042 fm physical-quark-mass $144^3 \times 288$ ensemble by 1000 more gauge configurations. This extension will be performed in year 3. It should run on 64 Frontier nodes.

3.2 Computational Approach

3.2.1 Codes, libraries, and scripts

This project uses three lattice QCD codes, the Columbia Physics System (CPS) and Grid Python Toolkit (GPT) codes for domain-wall fermions (DWF) and the MILC code for highly-improved staggered quarks (HISQ). All are supported by the QUDA and Grid libraries, which are optimized specifically for GPUs. The QUDA library was created for lattice QCD by NVIDIA scientist Kate Clark *e*t al. It contains a large set of utilities that are accessed by higher-level code. It uses a wide variety of optimization strategies, including autotuning to optimize block sizes and layouts on diverse architectures, hierarchical multi-precision calculation, data compression, and reduced-precision communication. The QUDA solvers make use of highly optimized BLAS. The Grid framework [55] authored by Peter Boyle *et al.* is designed to run optimally on a variety of GPU architectures including Summit's NVIDIA V100s, Aurora's Intel GPUs, and Frontier's AMD GPUs. It also provides utilities that can be accessed by higher-level code. All of our codes use OpenMP for threaded operation on the host CPUs and MPI for inter-GPU communication. In some cases we replace intra-node communication with direct use of NVLink or SHMEM.

Most members of our team participate in the Lattice QCD Application Development component of the Exascale Computing Project, which has the explicit purpose of readying our codes for high performance on Frontier and Aurora. Team members are using ECP or COE development machines (OLCF Tulip, Spock, Crusher, AMD Dev Cloud, and ALCF/JLSE Iris, Arcticus, and Florentia). This development effort included porting the QUDA and Grid frameworks to AMD GPUs via HIP and Intel GPUs via SyCL and developing new, highly efficient algorithms. The HIP port is fully functional and has been running successfully on OLCF Crusher and Borg. The SyCL port is nearing completion.

The Grid framework is written in C++ and accesses NVIDIA GPUs (Cuda), Intel GPUs (SyCL) and AMD GPUs (HIP). Grid has been run successfully on the development machines for Frontier and Aurora, delivering performance commensurate with available memory bandwidth. For propagator calculation Grid can make use of partitioned MPI communicators to reduce communication load, while for gauge configuration generation parallel performance is key.

3.2.2 Workflow

In all of these calculations, physical results are based on the calculation of a vast set of correlators that describe the propagation across the space-time lattice and the interaction of hadrons (mesons) consisting of quarks and antiquarks. Propagators for the hadrons are, in turn, composed of the propagators for their constituent quarks and antiquarks. These latter propagators are obtained by solving the Dirac equation, which, on a lattice, is represented as a large, uniformly sparse linear system. Solving the Dirac equation and tying together the quarks and antiquarks to make the hadrons represent nearly the entire cost of our calculations. As we reduce the lattice spacing to approach the physical space-time continuum, the condition number of the linear system grows rapidly, requiring special strategies to mitigate the rapidly rising cost. Considerable effort has been devoted to optimizing our QUDA and Grid linear solvers.

In most of our work, we use a variety of variance-reduction methods, among them, the truncated solver method (TSM) pioneered in Ref. [56]. Combined with deflation, this method has been called "all-mode-averaging" (AMA) [57]. The "all-to-all" method (A2A) [58] provides a further dramatic boost in the statistical sampling of a hadron propagator. This method makes it possible to average over hadron propagators

Table 3. Weak-scaling Summit performance of the MILC/QUDA/HISQ double-precision multimass solver with a local volume of 32^4 per GPU and of the CPS/QUDA/DWF with a local volume of $12^3 \times 16$ per GPU. The latter calculation was done in half-precision with correction steps to give double-precision accuracy. (The HISQ formulation has intrinsically lower arithmetic intensity than DWF.)

Code	Nodes→	16	32	64	128	256	512	1024
MILC/QUDA/HISQ	(GF/s-node)	432	426	306	300	282	258	228
CPS/QUDA/DWF	(GF/s-node)	—	—	1990	—	—	1590	1550

that start from all lattice sites and end on all sites. Finally, the low-mode-improved (LMI) [46] method uses stochastic sampling as in AMA, but replaces the low-mode sample with the exact low-mode contribution.

The project workflow consists of copying gauge-configuration files and, in some cases, eigenvector files from remote archives, carrying out the calculations with them, and copying the resulting hadron correlator files to remote workstations for analysis. There are typically hundreds of thousands of such correlator files. No significant post-processing is required on the LCF machines. Some of our projects use deflation with thousands of eigenvectors, which requires several tens of TB of temporary disk storage, as we have noted in the Milestone section. We use SSDs for temporary intermediate storage.

Disk storage is required for the gauge-configuration, eigenvector files, and “meson fields,” as well as the resulting hadron-correlator data. External I/O transfers of large files are done through Globus Online.

Almost all of these calculations are “ensemble” type in that they involve many thousands of similar, independent calculations. Thus, bundling of calculations with multiple gauge configurations is possible and is supported by our workflow scripts. A significant exception is gluon-configuration generation. They are serial jobs that extend a Markov chain. Since time to completion is important, they are run as a single sequence of jobs. For example, we plan to run on up to 512 nodes on a $128^3 \times 512$ volume. Here the good interconnect performance of Crusher is key, while algorithmic development is well underway to target Aurora.

3.3 Parallel Performance

The MILC and CPS code have been in production for decades on NSF and DOE LCFs, including on Summit, and they are being constantly improved. GPT has been used in last year’s INCITE proposal on Summit and on leadership-class machines in the US and Europe. CPS, GPT and the Hadrons library use Grid for the Dirac operators on Frontier and Aurora, and so the performance will be the same as Grid.

For MILC, the multimass CG solver accounts for 60–80% of the cost of our calculation and is a key performance indicator. We have found on Crusher that the QUDA/HIP multimass solver delivers 4.6 TF/s per node in a 64-node calculation. Weak scaling results in Table 3 are from Summit in early 2018. Since then, there have been considerable improvements in system software, our codes, and run parameters.

Good halo exchange communication bandwidth is critical to scaling with powerful multi-GPU nodes and current algorithms. We find excellent performance with the Cray Slingshot 11 network on Crusher, and anticipate similar interconnect efficiency on the Frontier and Aurora systems. See Figure 5.

In Figure 6 we display the performance per node versus number of nodes for Grid in Crusher, Perlmutter phase 1 and Summit. We can see that Crusher presents a nearly six-fold gain over Summit in per node performance principally due to the substantially better communication performance. Crusher also affords a three-fold gain relative to Perlmutter phase 1, and should be similar to the phase-2 upgrade of Perlmutter.

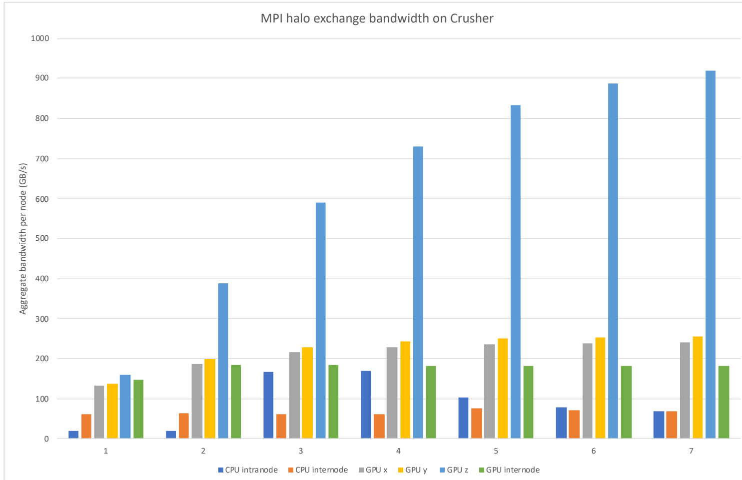

Figure 5. We display the Grid Halo exchange bandwidth delivered on Crusher both from CPU memory to CPU memory and from GPU memory to GPU memory. Two nodes were used and 16 MPI ranks mapping one to each Graphics Compute Device. Careful layout (map_gpu:0,1,2,3,7,6,5,4) enables the 2^4 Cartesian communicator to match the topology of the infinity link network on the node well. Both directions (send + receive) are driven concurrently and near wirespeed progress (green) is achieved, in aggregate 183GB/s out of a possible 200GB/s (= 4 HFIs x 200 Gbit/s x bidirectional / 8 bits-per-byte). The performance over the intranode infinity link bus is even higher with the bandwidth varying with direction depending on the asymmetrical speeds of different links.

Crusher therefore represents an excellent resource to perform these calculations with sustained 6 TF/s per node even with full communication loading. Perfect weak scaling is seen up to 64 nodes and we expect the communication pattern should replicate with continued weak scaling up to our target problem size at 512 nodes as each individual node had the matching communication pattern in our test and Slingshot is strongly advertised to address switching issues.

Based on the Frontier benchmarking, for our cost projections on Frontier we take our expected ratio between Summit and Frontier as a 6-fold performance increase, and scale our measured cost on Summit by this factor.

We have been active in the DOE-Intel Pathforward program, but NDA terms prevent a discussion of details and performance. GPU hardware at Argonne's JLSE delivering performance in line with that expected for the memory bandwidth. The detailed performance is subject to NDA, but we expect that satisfactory efficiency should also be achieved with the eventual Aurora system.

From public information, Aurora will provide a very substantial uplift in floating point and memory system performance per node, with public information reporting indicating over 130TF/s double precision peak performance [59] per node. For Grid profiling tools report we obtain up to 40% of floating point pipeline usage on A100 GPUs [60], and we hope to obtain a good efficiency on Aurora also. Our performance estimates should include a further doubling of single precision throughput relative to double precision in memory limited code. Conservatively, we take in our projections 10% of the double precision quoted peak performance, and twice this for single precision. We anticipate more than this looking only at single GPU performance, but as with Frontier and Perlmutter, Figure 6, there is likely some loss of performance even scaling within one node. We are not able to estimate this at this time, and conservatively estimate only 10% of peak in double precision. This suggests that at least 27 TF/s single node performance should be achieved.

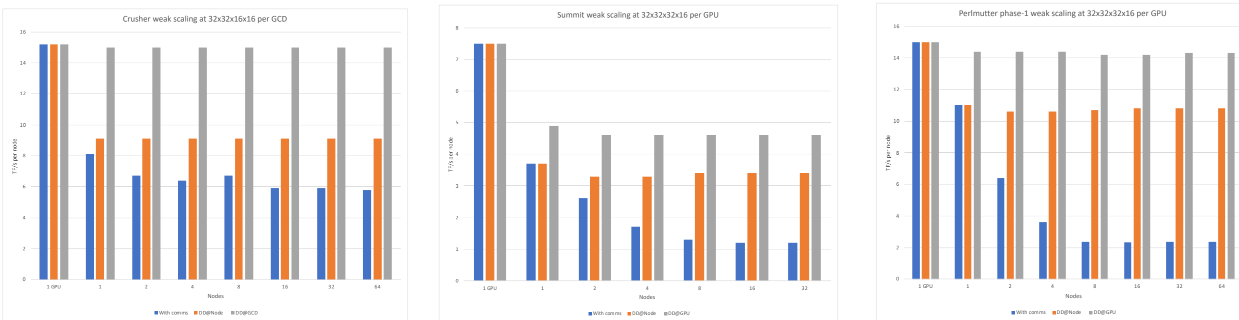

Figure 6. Performance (TF/s per node) versus number of nodes for Grid on Crusher, Perlmutter phase 1 and Summit (utilizing only four of the six GPUs due to power-of-two constraints) on the target local volume we expect to use on a $128^3 \times 512$ evolution on 512 nodes on Crusher in this proposal. We show in blue the fully communicating DWF Dirac operator. We also domain decomposed operators which drop communications at the node boundary (orange) and GPU boundary (gray). These are relevant to planned algorithmic development in the Rational DDHMC algorithm. For DWF, Crusher presents a nearly six-fold gain over Summit in per node performance for the fully communicating Dirac operator (blue) increasing from 1.2 TF/s on Summit to 6 TF/s on Crusher. For HISQ, the corresponding increase is from 2 TF/s to 4.6 TF/s per node. We are developing domain decomposition as an approach under SciDAC-5, and targeted principally for Aurora. Systems like Summit, Perlmutter phase-1, and Aurora are likely to benefit greatly from an algorithm that allows the reduction of communication, here showing up to 15 TF/s per node. As the performance per node is shown, perfect scaling is a flat behavior. One might reasonably extrapolate that a DDHMC algorithm could obtain well over 100PF/s on the entire Frontier system and several times this on the full Aurora system.

This is enough to place a great strain on the interconnect, which we plan to address with on-going DDHMC algorithmic development discussed in the next section for gauge evolution.

3.4 Developmental Work

Our active participation in the ECP assures that our major codes CPS, GPT, and MILC, and the essential packages QUDA and Grid, are intensively enhanced for portability and performance. New test hardware resembling Aurora and Frontier allows increasingly relevant code optimization.

To fully exploit Aurora and Frontier for the proposed generation of gauge ensembles with chiral quarks, important algorithmic developments are required, which have been the target of independent research and ECP programs for four years, and several projects will be soon supported by SciDAC-5. An important example is the development of a multigrid solver for the HISQ [61] and DWF [62–64] formulations.

The time-to-solution for gauge-field evolution requires many-node jobs with small local volumes, placing severe demands on the inter-node communication. Under SciDAC-5 we will develop a domain decomposed approach to 2+1 flavor gauge ensemble generation [65]. The approach has been restructured to exploit the high single-node performance of Exascale hardware. It should greatly reduce inter-node communications and deliver near single-node performance for 4096-node evolution jobs on Aurora.

The $1/a^2$ scaling of the HMC algorithm autocorrelation length [53] and freezing of global topology are serious barriers to the smaller lattice spacings needed for HVP and calculations involving charm and bottom quarks. The use of open boundary conditions and the RMHMC algorithm [66] being developed under ECP and being extended under SciDAC-5 promise to largely eliminate these problems.

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PERSONNEL JUSTIFICATION AND MANAGEMENT PLAN

The management structure is as follows. Andreas Kronfeld is PI and spokesperson, Norman Christ is co-PI and lead for the RBC/UKQCD team, and Aida El Khadra is co-PI and lead for the Fermilab/MILC team. Co-PIs Thomas Blum, Peter Boyle, Luchang Jin, Chulwoo Jung, Christoph Lehner, and Robert Mawhinney play key roles in the RBC/UKQCD team. Co-PIs Carleton DeTar, Steve Gottlieb, William Jay, Andrew Lytle, and Ruth van de Water play key roles in the Fermilab/MILC team. Below, the responsibilities of these and further participants are tied to milestones for the two subgroups separately.

The team for *flavor physics with the HISQ action* is a subset of the Fermilab Lattice and MILC Collaborations with many years of experience carrying out large-scale lattice QCD calculations on supercomputers at DOE and NSF supercomputer centers. These two collaborations have been working together for over 20 years to study weak decays of strongly interacting particles. Results of their calculations of quark masses, decay constants, semileptonic form factors, and neutral-meson mixing rank with those of the highest precision available. In the list below, years of experience with lattice-QCD calculations are given for each team member. Responsibilities are also given.

- Carleton DeTar (co-PI), Professor of Physics, University of Utah: 41 years; Principal architect of the MILC code to be used in this project. Coordinator of the LatticeQCD software team within the Exascale Computing Project. Responsibilities: Code improvements and optimization; data management and analysis.
- Aida El-Khadra (co-PI), Professor of Physics, University of Illinois: 35 years. Leader of recent collaboration calculations of neutral B^0, B_s, and D^0 mixing matrix elements; co-chair of the Muon $g-2$ Theory Initiative and chief editor of the recent major white paper on the $g-2$ calculations and measurements [T. Aoyama *et al.* Phys. Rept. **887**, 1-166 (2020)]; frequent speaker at flavor-physics conferences; expert in lattice perturbation theory; supervisor of successful Ph.D. students. Responsibilities: Scientific campaign planning, current renormalization, data analysis.
- Elvira Gámiz, Professor of Physics, University of Granada (Spain): 18 years. Leader in successful calculations of $K \to \pi\ell\nu$ form factors; key participant in recent calculations of neutral-meson mixing matrix elements; expert in flavor-physics phenomenology and in lattice perturbation theory. Responsibilities: Scientific campaign planning, data analysis.
- Steven Gottlieb (co-PI), Distinguished Professor Emeritus, Provost Professor Emeritus of Physics, Indiana University: 40 years. Principal coordinator of optimized collaboration code on the latest and upcoming chipsets; key participant in studies of semileptonic form-factor calculations; co-PI Intel Parallel Computing Center at Indiana University; member of FLAG heavy-quark semileptonic working group. Responsibilities: Code improvements, optimization, production running, data analysis.
- William Jay (co-PI), Postdoctoral Research Associate, MIT: 6 years. While at Fermilab, he has carried out an initial analysis of results from the form-factor project proposed here. Responsibilities: Continued analysis of B-meson form factor results.
- Andreas Kronfeld (PI), Distinguished Scientist, Fermilab: 37 years. Co-leader of closely related calculations of leptonic decay constants and quark masses; expert in heavy-quark physics and in lattice perturbation theory; strong ties with phenomenology and experiment. Responsibilities: Project management, current renormalization, heavy-quark effective theory.
- Shaun Lahert, Ph.D. student, University of Illinois. Experience with production running on GPU platforms, analysis of of muon $g-2$ HVP results. Responsibilities: Developing scripts for two-pion contributions to $g-2$ HVP; data analysis.
- Jack Laiho, Associate Professor of Physics, Syracuse University: 16 years. Leader of major collaboration calculations of $B \to D^*\ell\nu$ calculations; expert in heavy-meson chiral perturbation theory; co-coordinator of scripting tools for running on several disparate systems. Responsibilities: Scientific

campaign planning, data analysis, chiral perturbation theory.

- Michael Lynch, Ph.D. student, University of Illinois. Experience testing and running on various platforms, including Summit. Responsibilities: Developing interface of the Hadrons package to the MILC code.
- Andrew Lytle (co-PI), Postdoctoral Research Associate, University of Illinois: 13 years. Strong experience with calculations of heavy-quark decays. Responsibilities: Development of run plans, production running, data analysis.
- Ethan Neil, Associate Professor of Physics, University of Colorado, and Riken, Brookhaven National Laboratory: 15 years. Expert in lattice simulations of models of new physics. Expert in workflow and automation for lattice gauge theory. Responsibilities: Production running, data analysis.
- Curtis Peterson, Ph.D. student, University of Colorado. Responsibilities: Analysis of isospin-breaking effects in the muon $g-2$ HVP.
- James Simone, Senior Scientist, Fermilab Computing Division: 33 years. Expert in GPU coding, algorithms for lattice QCD, and analysis of lattice-QCD data. Responsibilities: Developing and implementing improvements to QUDA, computing renormalization factors.
- Ruth Van de Water (co-PI), Scientist, Fermilab: 19 years. Leader of HISQ $g-2$ HVP calculations and earlier calculations of the $B \to \pi\ell\nu$, $B \to K\ell\ell$ form factors; frequent speaker at flavor-physics conferences; member of FLAG advisory board. Responsibilities: Data analysis, chiral perturbation theory.
- Alejandro Vaquero, Postdoctoral Research Associate, University of Utah: 14 years. Contributor to the QUDA library. Experienced with calculations of $B \to D^*\ell\nu$ semileptonic decays. Responsibilities: Code development, data analysis.

The team for *flavor physics with domain-wall fermions* is a subset of the RIKEN Brookhaven Columbia (RBC) and UKQCD collaborations. These two groups have been working together for the past 15 years, developing methods that allow lattice fermions with accurate chiral symmetry to be used in realistic, large-scale lattice QCD calculations. These two groups have extensive experience in creating large gauge ensembles with dynamical chiral quarks and in the use of these ensembles for a wide range of physics studies, including all of the physics topics addressed in this proposal.

- Tom Blum (Co-PI), Professor, University of Connecticut: 26 years. Innovative expert on lattice QCD. Pioneer of the use of lattice QCD to calculate the hadronic vacuum polarization (HVP) and light-by-light scattering (HLbL) contributions to the anomalous moment of the muon; PI of a series of five large-scale ALCC $g_\mu - 2$ proposals; member of FLAG.
- Peter Boyle (Co-PI), Physicist, Brookhaven National Laboratory, and Professor, University of Edinburgh: 22 years. Expert on lattice QCD studies of heavy quarks, chiral fermions, non-perturbative renormalization, numerical algorithms, large-scale software engineering, hardware design and optimization. The creator of the BAGEL and GRID software packages; led the design of the level-1 prefetch cache in the IBM BlueGene/Q computer.
- Norman Christ (Co-PI), Professor of Physics, Columbia University: 42 years. Expert on the properties and use of lattice chiral fermions, an inventor of lattice methods for computing second-order-weak long-distance effects, such as ΔM_K. Experienced in computer hardware design and optimization for lattice QCD as well as the management of large-scale hardware and computational projects.
- Felix Erben, Postdoctoral Fellow, University of Edinburgh: 4 years. Expert on using distillation lattice methods to study heavy quark physics. Major contributor to the UKQCD heavy quark physics program being extended here.
- Jonathan Flynn, Professor University of Southampton: 34 years. Expert in perturbative QCD, heavy quark phenomenology and the application of lattice QCD to heavy quark physics.

- Yikai Huo, Ph.D. student, Columbia University. Joining the effort on the long-distance second-order weak calculation of ΔM_K and ε_K proposed here.
- Taku Izubuchi, Physicist, BNL: 23 years. Expert in lattice QCD, a pioneer in applying lattice methods to new problems, inventor of many highly successful lattice algorithms, many of which are used in the calculations proposed here.
- Luchang Jin (Co-PI), Assistant Professor, University of Connecticut: 7 years. Inventor of new approaches to lattice QCD calculation. A major contributor to the forefront calculation of $g_\mu - 2$ HVP and HLbL including the calculation proposed here.
- Chulwoo Jung (Co-PI), Physicist, BNL: 23 years. Expert on a wide range of lattice QCD algorithms from complex strategies to make the generation of gauge ensembles more efficient to the techniques for accelerating sparse matrix inversion, including machine-specific challenges such as communication avoidance.
- Andreas Jüttner, Principal Research Fellow, University of Southampton: 17 years. Expert on heavy quark phenomenology and lattice studies. Important contributor to the UKQCD program in charm physics which is critical for both the second-order weak charm-dominated amplitudes whose study is proposed here and the direct calculation of the properties charm decays that are enabled by this proposal. Member of FLAG.
- Christoph Lehner (Co-PI), Professor, Universität Regensburg: 11 years. Broad experience in both perturbative and lattice QCD. A leader of the RBC/UKQCD calculation of the HVP contribution to $g_\mu - 2$ whose extension is proposed here; co-chair of the Muon $g - 2$ Theory Initiative and chief editor of the recent major white paper on the $g - 2$ calculations and measurements [T. Aoyama *et al.* Phys. Rept. **887**, 1-166 (2020)]
- Meifeng Lin, Computer Scientist, BNL: 18 years. Expert in both lattice QCD and HPC software, including the effective use of GPUs and the porting of Grid to GPUs.
- Michael Marshall, Ph.D. student, University of Edinburgh. Carrying out charm and bottom semileptonic decay analyses with domain wall fermions.
- Robert Mawhinney (Co-PI), Professor of Physics, Columbia University: 34 years. Expert on lattice QCD, chiral fermions and numerical methods. The leader of RBC and RBC/UKQCD generation of gauge ensembles for twenty two years. Member of FLAG.
- Shigemi Ohta, Physicist, KEK, Tsukuba and Sokendai: 36 years. Expert on lattice QCD and numerical methods, specializing in the physics of the nucleon.
- Antonin Portelli, Chancellor's Fellow, University of Edinburgh: 9 years. Broad experience in lattice QCD. Expert on the inclusion of electromagnetism in lattice QCD calcultions. Leader of the RBC/UKQCD calculation of the rare kaon decay $K \to \pi\ell^+\ell^-$.
- Christopher Sachrajda, Professor Emeritus, University of Southampton: 42 years. Broad expert in particle physics and QCD and an innovator in lattice QCD. Expert on heavy quark physics and the lattice calculation of second-order-weak long-distance effects proposed here.
- Amarjit Soni, Physicist, BNL: 42 years. Expert on particle physics phenomenology including the implications being studied here of beyond the standard model theories. Pioneer in lattice QCD calculations of both kaon and heavy quark physics.
- J. Tobias Tsang, Postdoctoral Fellow, CP3-Origins and IMADA, University of Southern Denmark: 4 years. Expert on using lattice methods to study heavy quark physics. Major contributor to the UKQCD heavy quark physics program being extended here.
- Bigeng Wang, Postdoctoral Fellow, University of Kentucky: 5 years. Currently completing analysis of ΔM_K calculations on Mira. Experienced with both ΔM_K and ε_K BG/Q code and critical participant in the development of the corresponding code for Summit.

Year 1 – 2023		
Milestone	**Details**	**Dates**
1a. Connected HVP at 0.042 fm with HISQ using the LMI method.	**Resource:** Frontier **Node-hours:** 600,000 **File system storage (TB and dates):** 200 TB through December 2023 **Archival storage (TB and dates):** 2,000 TB through December 2023 **Software Application:** Hadrons code with Grid **Tasks:** Calculation on 200 $144^3 \times 288$ configurations **Dependencies:** None	01/23 – 12/23
2a. HVP continuum limit with chiral quarks	**Resource:** Frontier **Node-hours:** 104,000 **Resource:** Aurora **Node-hours:** 28,000 **File system storage (TB and dates):** none (provided by 3a.) **Archival storage (TB and dates):** none (provided by 3a.) **Software Application:** GPT with Grid **Tasks:** Calculate the connected HVP contribution to $g_\mu - 2$ on 8 0.071 fm, 8 0.053 fm and 5 0.042 fm configurations. **Dependencies:** Completion of the gauge configurations and eigenvectors in Milestone 3a	03/23 – 12/23
3a. Chiral fermion configurations, eigenvectors and basic measurements	**Resource:** Frontier **Node-hours:** 931,000 **Resource:** Aurora **Node-hours:** 409,000 **File system storage (TB and dates):** 250 TB, Jan-Dec 2023. **Archival storage (TB and dates):** 2500 TB Jan-Dec 2023. **Software Application:** Grid, GPT, and CPS **Tasks:** Generate 900 MD time units, compute low eigenmodes on 36 configurations and measure basic quantities on 8 configurations for a=0.071 fm, while for a=0.053 fm and 0.042 fm the corresponding numbers are 460, 8, 8 and 400, 5, 5. **Dependencies:** None	01/23 – 12/23
4a. B meson form factors at 0.042 fm and physical mass	**Resource:** Frontier **Node-hours:** 500,000 **File system storage (TB and dates):** 50 TB through December 2023 **Archival storage (TB and dates):** none **Software Application:** MILC code with QUDA/HIP **Tasks:** Calculation on 200 $144^3 \times 288$ configurations **Dependencies:** None	01/23 – 12/23
4b. B meson form factors at 0.042 fm and physical mass	**Resource:** Aurora **Node-hours:** 500,000 **File system storage (TB and dates):** 100 TB through December 2023 **Archival storage (TB and dates):** none **Software Application:** MILC code with QUDA/SYCL **Tasks:** Calculation on 200 $144^3 \times 288$ configurations **Dependencies:** None	03/23 – 12/23

Year 1 – 2023		
Milestone	**Details**	**Dates**
5. B meson form factors at 0.03 fm and $m_l = 0.2 m_s$.	**Resource:** Summit **Node-hours:** 500,000 **File system storage (TB and dates):** 50 TB through December 2023 **Archival storage (TB and dates):** none **Software Application:** MILC code with QUDA/CUDA **Tasks:** Calculation on 600 $96^3 \times 288$ configurations **Dependencies:** None	01/23 – 12/23
6a. Calculate ΔM_K and the LD part of ε_K	**Resource:** Frontier **Node-hours:** 65,000 **Resource:** Aurora **Node-hours:** 63,000 **File system storage (TB and dates):** none (provided by 3a.) **Archival storage (TB and dates):** none (provided by 3a.) **Software Application:** Grid **Tasks:** Calculate ΔM_K and the long-distance contribution to ε_K on 34 a = 0.071 fm and 3 a = 0.053 fm configurations **Dependencies:** Configurations and low eigenmodes from milestone 3a	06/23 – 12/23
7a. 2+1 flavor, HVP results	**Resource:** Summit **Node-hours:** 80,000 **File system storage (TB and dates):** none (provided by 7b.) **Archival storage (TB and dates):** none (provided by 7b.) **Software Application:** GPT with Grid **Tasks:** Extend earlier a=0.071, 2+1 flavor HVP calculation obtaining results from 10 additional configurations. **Dependencies:** Configurations and low eigenmodes from milestone 7b.	04/23 – 09/23
7b. a = 0.071, 2+1 flavor, chiral fermion configurations, eigenvectors and basic measurements	**Resource:** Summit **Node-hours:** 340,000 **File system storage (TB and dates):** 8 TB Jan 2023 - Dec 2023 **Archival storage (TB and dates):** 75 TB Jan 2023 - Dec 2025 **Software Application:** Grid, GPT and CPS **Tasks:** Extend earlier a=0.071, 2+1 flavor, calculation generating 200 configurations and obtaining low eigenmodes and basic measurements for 10 configurations. **Dependencies:** None	01/23 – 06/23
7c. ΔM_K and LD ε_K results from 10 configurations	**Resource:** Summit **Node-hours:** 80,000 **File system storage (TB and dates):** none (provided by 7b.) **Archival storage (TB and dates):** none (provided by 7b.) **Software Application:** Grid and Hadrons **Tasks:** Tune the kaon-mixing calculation at scale and obtaining results from 10 $96^3 \times 192$, 2+1 flavor configurations. **Dependencies:** Configurations and low eigenmodes from milestone 7b.	04/23 – 09/23

Year 2 – 2024		
Milestone	**Details**	**Dates**
1b. Connected HVP at 0.042 fm with HISQ using LMI method.	**Resource:** Frontier **Node-hours:** 600,000 **File system storage (TB and dates):** 200 TB through December 2024 **Archival storage (TB and dates):** 2,000 TB through December 2024 **Software Application:** Hadrons code with Grid **Tasks:** Calculation on 200 $144^3 \times 288$ configurations **Dependencies:** None	01/24 – 12/24
1c. Connected HVP at 0.042 fm with HISQ using LMI method.	**Resource:** Aurora **Node-hours:** 650,000 **File system storage (TB and dates):** 200 TB through December 2024 **Archival storage (TB and dates):** 2,000 TB through December 2024 **Software Application:** Hadrons code with Grid **Tasks:** Calculation on 220 $144^3 \times 288$ configurations **Dependencies:** None	01/24 – 12/24
2b. HVP continuum limit with chiral quarks	**Resource:** Frontier **Node-hours:** 130,000 **Resource:** Aurora **Node-hours:** 72,000 **File system storage (TB and dates):** none (provided by 3b.) **Archival storage (TB and dates):** none (provided by 3b.) **Software Application:** GPT with Grid **Tasks:** Calculate the connected HVP contribution to $g_\mu - 2$ on 10 0.071 fm, 10 0.053 fm and 13 0.042 fm configurations. **Dependencies:** Completion of the gauge configurations and eigenvectors in Milestone 3b	03/24 – 12/24
3b. Chiral fermion configurations, eigenvectors and basic measurements	**Resource:** Frontier **Node-hours:** 810,000 **Resource:** Aurora **Node-hours:** 809,000 **File system storage (TB and dates):** 650 TB, Jan-Dec 2024 **Archival storage (TB and dates):** 9000 TB, Jan-Dec 2024 **Software Application:** Grid, GPT, and CPS **Tasks:** Generate 780 MD time units, compute low eigenmodes on 37 configurations and measure basic quantities on 10 configurations for a=0.071 fm, while for a=0.053 fm and 0.042 fm the corresponding numbers are 1060, 39, 10 and 260, 13, 13. **Dependencies:** None	01/24 – 09/24
4c. *B* meson form factors at 0.042 fm and physical mass	**Resource:** Frontier **Node-hours:** 500,000 **File system storage (TB and dates):** 50 TB through December 2024 **Archival storage (TB and dates):** none **Software Application:** MILC code with QUDA/HIP **Tasks:** Calculation on 200 $144^3 \times 288$ configurations **Dependencies:** None	01/24 – 12/24

Year 2 – 2024		
Milestone	**Details**	**Dates**
4d. B meson form factors at 0.042 fm and physical mass	**Resource:** Aurora **Node-hours:** 500,000 **File system storage (TB and dates):** 100 TB through December 2024 **Archival storage (TB and dates):** none **Software Application:** MILC code with QUDA/SYCL **Tasks:** Calculation on 200 $144^3 \times 288$ configurations **Dependencies:** None	01/24 – 12/24
6b. Calculate ΔM_K and the LD part of ε_K	**Resource:** Frontier **Node-hours:** 160,000 **Resource:** Aurora **Node-hours:** 269,000 **File system storage (TB and dates):** none (provided by 3b.) **Archival storage (TB and dates):** none (provided by 3b.) **Software Application:** Grid **Tasks:** Calculate ΔM_K and the long-distance contribution to ε_K on 38 a = 0.071 fm and 42 a = 0.053 fm configurations **Dependencies:** Configurations and low eigenmodes from milestone 3a	06/24 – 12/24

Year 3 – 2025		
Milestone	**Details**	**Dates**
1d. Connected HVP at 0.042 fm with HISQ using LMI method.	**Resource:** Frontier **Node-hours:** 800,000 **File system storage (TB and dates):** 200 TB through December 2025 **Archival storage (TB and dates):** 2,000 TB through December 2025 **Software Application:** Hadrons code with Grid **Tasks:** Calculation on 300 $144^3 \times 288$ configurations **Dependencies:** None	01/25 – 12/25
1e. Connected HVP at 0.042 fm with HISQ using LMI method.	**Resource:** Aurora **Node-hours:** 650,000 **File system storage (TB and dates):** 200 TB through December 2025 **Archival storage (TB and dates):** 2,000 TB through December 2025 **Software Application:** Hadrons code with Grid **Tasks:** Calculation on 220 $144^3 \times 288$ configurations **Dependencies:** None	01/25 – 12/25

Year 3 – 2025		
Milestone	**Details**	**Dates**
2c. HVP continuum limit with chiral quarks	**Resource:** Frontier **Node-hours:** 130,000 **Resource:** Aurora **Node-hours:** 72,000 **File system storage (TB and dates):** none (provided by 3c.) **Archival storage (TB and dates):** none (provided by 3c.) **Software Application:** GPT with Grid **Tasks:** Calculate the connected HVP contribution to $g_\mu - 2$ on 10 0.071 fm, 10 0.053 fm and 13 0.042 fm configurations. **Dependencies:** Completion of the gauge configurations and eigenvectors in Milestone 3b	03/25 – 12/25
3c. Chiral fermion configurations, eigenvectors and basic measurements	**Resource:** Frontier **Node-hours:** 810,000 **Resource:** Aurora **Node-hours:** 809,000 **File system storage (TB and dates):** 650 TB, Jan-Dec 2025 **Archival storage (TB and dates):** 15000 TB, Jan-Dec 2025 **Software Application:** Grid, GPT, and CPS **Tasks:** Generate 780 MD time units, compute low eigenmodes on 37 configurations and measure basic quantities on 10 configurations for a=0.071 fm, while for a=0.053 fm and 0.042 fm the corresponding numbers are 1060, 39, 10 and 260, 13, 13. **Dependencies:** None	01/25 – 09/25
4e. B meson form factors at 0.042 fm and physical mass	**Resource:** Aurora **Node-hours:** 500,000 **File system storage (TB and dates):** 100 TB through December 2025 **Archival storage (TB and dates):** none **Software Application:** MILC code with QUDA/SYCL **Tasks:** Calculation on 200 $144^3 \times 288$ configurations **Dependencies:** None	01/25 – 12/25
6c. Calculate ΔM_K and the LD part of ε_K	**Resource:** Frontier **Node-hours:** 160,000 **Resource:** Aurora **Node-hours:** 269,000 **File system storage (TB and dates):** none (provided by 3c.) **Archival storage (TB and dates):** none (provided by 3c.) **Software Application:** Grid **Tasks:** Calculate ΔM_K and the long-distance contribution to ε_K on 38 a = 0.071 fm and 42 a = 0.053 fm configurations **Dependencies:** Configurations and low eigenmodes from milestone 3a	06/25 – 12/25
8. Extend HISQ 0.042 fm physical-mass ensemble.	**Resource:** Frontier **Node-hours:** 300,000 **File system storage (TB and dates):** 100 TB through December 2025 **Archival storage (TB and dates):** none **Software Application:** Hadrons code with Grid **Tasks:** Generate 1000 new $144^3 \times 288$ configurations **Dependencies:** None	01/25 – 12/25

PUBLICATIONS RESULTING FROM INCITE AWARDS

[1] **Fermilab Lattice, MILC** Collaboration, W. I. Jay, A. Lytle, C. DeTar, A. El-Khadra, E. Gamiz, Z. Gelzer, S. Gottlieb, A. Kronfeld, J. Simone and A. Vaquero, *B- and D-meson semileptonic decays with highly improved staggered quarks*, *PoS* **LATTICE2021** (2021) 109 [2111.05184].

[2] **Fermilab Lattice, HPQCD, MILC** Collaboration, A. Bazavov *et. al.*, *Progress report on computing the disconnected QCD and the QCD plus QED hadronic contributions to the muon's anomalous magnetic moment*, *PoS* **LATTICE2021** (2021) 039 [2112.11339].

[3] **Fermilab Lattice, HPQCD, MILC** Collaboration, S. Lahert, C. DeTar, A. El-Khadra, E. Gámiz, S. Gottlieb, A. Kronfeld, E. Neil, C. T. Peterson and R. Van de Water, *Hadronic vacuum polarization of the muon on 2+1+1-flavor HISQ ensembles: an update*, *PoS* **LATTICE2021** (2021) 526 [2112.11647].

[4] **Fermilab Lattice, MILC** Collaboration, A. Bazavov *et. al.*, *Semileptonic form factors for $B \to D^* \ell \nu$ at nonzero recoil from 2 + 1-flavor lattice QCD*, *Eur. Phys. J. C* **82** (2022) [2105.14019].

[5] **HPQCD** Collaboration, D. Hatton, C. T. H. Davies, B. Galloway, J. Koponen, G. P. Lepage and A. T. Lytle, *Charmonium properties from lattice QCD+QED : Hyperfine splitting, J/ψ leptonic width, charm quark mass, and a_μ^c*, *Phys. Rev. D* **102** (2020), no. 5 054511 [2005.01845].

[6] **Fermilab Lattice, HPQCD, MILC** Collaboration, C. T. H. Davies *et. al.*, *Hadronic-vacuum-polarization contribution to the muon's anomalous magnetic moment from four-flavor lattice QCD*, *Phys. Rev. D* **101** (2020), no. 3 034512 [1902.04223].

[7] **Fermilab Lattice, MILC** Collaboration, Z. Gelzer *et. al.*, *B-meson semileptonic form factors on (2+1+1)-flavor HISQ ensembles*, *PoS* **LATTICE2019** (2019) 236 [1912.13358].

[8] **Fermilab Lattice, MILC** Collaboration, A. V. Avilés-Casco, C. DeTar, A. X. El-Khadra, A. S. Kronfeld, J. Laiho and R. S. Van de Water, *The $B \to D^* \ell \nu$ semileptonic decay at nonzero recoil and its implications for $|V_{cb}|$ and $R(D^*)$*, *PoS* **LATTICE2019** (2019) 049 [1912.05886].

[9] **Fermilab Lattice, HPQCD, MILC** Collaboration, C. E. DeTar *et. al.*, *The hadronic vacuum polarization of the muon from four-flavor lattice QCD*, *PoS* **LATTICE2019** (2019) 070 [1912.04382].

[10] **Fermilab Lattice, MILC** Collaboration, R. Li *et. al.*, *D meson semileptonic decay form factors at $q^2 = 0$*, *PoS* **LATTICE2018** (2019) 269 [1901.08989].

[11] **Fermilab Lattice, MILC** Collaboration, A. Bazavov *et. al.*, *$B_s \to K \ell \nu$ decay from lattice QCD*, *Phys. Rev. D* **100** (2019), no. 3 034501 [1901.02561].

[12] **Fermilab Lattice, MILC** Collaboration, A. V. Avilés-Casco, C. DeTar, A. X. El-Khadra, A. S. Kronfeld, J. Laiho and R. S. Van de Water, *$B \to D^* \ell \nu$ at non-zero recoil*, *PoS* **LATTICE2018** (2019) 282 [1901.00216].

[13] **MILC** Collaboration, S. Basak *et. al.*, *Lattice computation of the electromagnetic contributions to kaon and pion masses*, *Phys. Rev.* **D99** (2019) 034503 [1807.05556].

[14] C. DeTar, S. Gottlieb, R. Li and D. Toussaint, *MILC code performance on high end CPU and GPU supercomputer clusters*, *EPJ Web Conf.* **175** (2018) 02009 [1712.00143].

[15] **Fermilab Lattice, MILC, TUMQCD** Collaboration, A. Bazavov *et. al.*, *Up-, down-, strange-, charm-, and bottom-quark masses from four-flavor lattice QCD*, *Phys. Rev.* **D98** (2018) 054517 [1802.04248].

[16] **Fermilab Lattice, MILC** Collaboration, A. Bazavov *et. al.*, *B- and D-meson leptonic decay constants from four-flavor lattice QCD*, *Phys. Rev.* **D98** (2018) 074512 [1712.09262].

[17] **Fermilab Lattice, MILC** Collaboration, Y. Liu *et. al.*, *$B_s \to K\ell\nu$ form factors with 2+1 flavors*, *EPJ Web Conf.* **175** (2018) 13008 [1711.08085].

[18] **Fermilab Lattice, HPQCD, MILC** Collaboration, B. Chakraborty *et. al.*, *Strong-isospin-breaking correction to the muon anomalous magnetic moment from lattice QCD at the physical point*, *Phys. Rev. Lett.* **120** (2018) 152001 [1710.11212].

[19] **Fermilab Lattice, MILC** Collaboration, A. Vaquero Avilés-Casco, C. DeTar, D. Du, A. El-Khadra, A. S. Kronfeld, J. Laiho and R. S. Van de Water, *$\overline{B} \to D^*\ell\overline{\nu}$ at non-zero recoil*, *EPJ Web Conf.* **175** (2018) 13003 [1710.09817].

[20] **Fermilab Lattice, MILC** Collaboration, Z. Gelzer *et. al.*, *Semileptonic B-meson decays to light pseudoscalar mesons on the HISQ ensembles*, *EPJ Web Conf.* **175** (2018) 13024 [1710.09442].

[21] **Fermilab Lattice, MILC** Collaboration, A. Bazavov *et. al.*, *Short-distance matrix elements for D^0-meson mixing for $N_f = 2 + 1$ lattice QCD*, *Phys. Rev.* **D97** (2018) 034513 [1706.04622].

[22] **Fermilab Lattice, MILC** Collaboration, C. C. Chang, C. M. Bouchard, A. X. El-Khadra, E. Freeland, E. Gámiz, A. S. Kronfeld, J. W. Laiho, E. T. Neil, J. N. Simone and R. S. Van de Water, *D-meson mixing in 2+1-flavor lattice QCD*, *PoS* **LATTICE2016** (2017) 307 [1701.05916].

[23] **Fermilab Lattice, MILC** Collaboration, T. Primer *et. al.*, *D meson semileptonic form factors with HISQ valence and sea quarks*, *PoS* **LATTICE2016** (2017) 305.

[24] **Fermilab Lattice, MILC, TUMQCD** Collaboration, J. Komijani *et. al.*, *Decay constants f_B and f_{B_s} and quark masses m_b and m_c from HISQ simulations*, *PoS* **LATTICE2016** (2016) 294 [1611.07411].

[25] **MILC** Collaboration, S. Basak *et. al.*, *Electromagnetic effects on the light pseudoscalar mesons and determination of m_u/m_d*, *PoS* **LATTICE2015** (2016) 259 [1606.01228].

[26] **Fermilab Lattice, MILC** Collaboration, A. Bazavov *et. al.*, *$B^0_{(s)}$-mixing matrix elements from lattice QCD for the Standard Model and beyond*, *Phys. Rev.* **D93** (2016) 113016 [1602.03560].

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[29] P. Boyle, G. Cossu, G. Filaci, C. Lehner, A. Portelli and A. Yamaguchi, *Grid: OneCode and FourAPIs*, *PoS* **LATTICE2021** (2022) 035 [2203.06777].

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[31] X. Feng, T. Izubuchi, L. Jin and M. Golterman, *Pion electric polarizabilities from lattice QCD*, *PoS* **LATTICE2021** (2022) 362 [2201.01396].

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[33] X. Feng, L. Jin and M. J. Riberdy, *Lattice QCD Calculation of the Pion Mass Splitting*, *Phys. Rev. Lett.* **128** (2022), no. 5 052003 [2108.05311].

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[35] A. Z. N. Yong *et. al.*, *Near-Physical Point Lattice Calculation of Isospin-Breaking Corrections to* $K_{\ell 2}/\pi_{\ell 2}$, *PoS* **LATTICE2021** (2022) 110 [2112.11823].

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[37] P. Boyle, L. Del Debbio, F. Erben, A. Jüttner, T. Kaneko, M. Marshall, A. Portelli, J. T. Tsang and O. Witzel, *BSM* B–$\bar{B}$ *mixing on JLQCD and RBC/UKQCD* $N_f = 2+1$ *DWF ensembles*, *PoS* **LATTICE2021** (2022) 224 [2111.11287].

[38] **RBC, UKQCD** Collaboration, T. Blum *et. al.*, *Lattice determination of* $I = 0$ *and* 2 $\pi\pi$ *scattering phase shifts with a physical pion mass*, *Phys. Rev. D* **104** (2021), no. 11 114506 [2103.15131].

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[53] X. Feng, L.-C. Jin, X.-Y. Tuo and S.-C. Xia, *Light-Neutrino Exchange and Long-Distance Contributions to $0\nu2\beta$ Decays: An Exploratory Study on $\pi\pi \to ee$*, *Phys. Rev. Lett.* **122** (2019), no. 2 022001 [1809.10511].

[54] L. Jin, T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, C. Jung and C. Lehner, *The connected and leading disconnected diagrams of the hadronic light-by-light contribution to muon $g-2$*, *PoS* **LATTICE2016** (2016) 181 [1611.08685].

[55] T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung and C. Lehner, *Connected and leading disconnected hadronic light-by-light contribution to the muon anomalous magnetic moment with a physical pion mass*, *Phys. Rev. Lett.* **118** (2017), no. 2 022005 [1610.04603].

Curriculum Vitae
Andreas S. Kronfeld

Contact Information

Theory Division
Fermilab
Batavia, IL 60510
phone: (630) 840 3753
fax: (630) 840 5435
email: ask@fnal.gov

Professional Preparation

PhD 1985, Cornell University
BA 1980, University of Pennsylvania

Appointments

2020–present, Distinguished Scientist, Fermi National Accelerator Laboratory
1999–2020, Senior Scientist, Fermi National Accelerator Laboratory
1993–1999, Scientist I, Fermi National Accelerator Laboratory
1989–1993, Associate Scientist, Fermi National Accelerator Laboratory
1988–1989, Research Associate, Fermi National Accelerator Laboratory
1985–1988, Gastwissenschaftler (postdoctoral), Deutsches Elektronen Synchrotron (DESY)

Five Publications Most Relevant to This Proposal

1. "Hadronic-vacuum-polarization contribution to the muon's anomalous magnetic moment from four-flavor lattice QCD," C.T.H. Davies *et al.*; *Phys. Rev. D* **101**, 034512 (2020) [arXiv:1902.04223]
2. "Up-, down-, strange-, charm-, and bottom-quark masses from four-flavor lattice QCD," A. Bazavov *et al.*; *Phys. Rev. D* **98**, 054517 (2018) [arXiv:1802.04248]
3. "*B*- and *D*-meson leptonic decay constants from four-flavor lattice QCD," A. Bazavov *et al.*; *Phys. Rev. D* **98**, 074512 (2018) [arXiv:1712.09262]
4. "Phenomenology of semileptonic *B*-meson decays with form factors from lattice QCD," Daping Du, A.X. El-Khadra, Steven Gottlieb, A.S. Kronfeld, J. Laiho, E. Lunghi, R.S. Van de Water, and Ran Zhou; *Phys. Rev. D* **93**, 034005 (2016) [arXiv:1510.02349]
5. "Massive fermions in lattice gauge theory," Aida X. El-Khadra, Andreas S. Kronfeld, and Paul B. Mackenzie; *Phys. Rev. D* **55**, 3933 (1997) [arXiv:hep-lat/9604004]

Research Interests and Expertise

My research focuses on applications of numerical lattice quantum chromodynamics, especially calculations needed to interpret high-energy physics experiments. Papers from my collaboration are known for the thoroughness of the estimates of systematic uncertainties based on rigorous analysis. In addition to numerical computations, my work includes research into the theory and algorithms in lattice QCD.

Synergistic Activities

1. Spokesperson and Executive Committee Chair, USQCD Collaboration, April 2018–present
2. Principal Investigator, Exascale Computing Project for Lattice QCD, June 2018–present
3. Board member, Neutrino Scattering Theory-Experiment Collaboration (NuSTEC), January 2017–present
4. Scientific Program Committee, USQCD Collaboration, 2004—2009 (Chair, October 2006–December 2008)
5. Consultant/referee for computational physics at DOE (U.S), NSF (U.S.), Cy-Tera (Cyprus), DFG (Germany), FWF (Austria), INFN (Italy), NSERC (Canada), RSNZ (New Zealand), SFI (Ireland), the Royal Society (UK), SNF (Switzerland), STFC (UK)

Honors and Awards

2014, Hans Fischer Senior Fellowship Prize, Technische Universität München
2013, Fellow, American Association for the Advancement of Science
2002, Fellow, American Physical Society

Collaborators

J.A. Bailey, Seoul National University (South Korea)
A. Bazavov, Michigan State University
C. Bernard, Washington University, St. Louis
C.M. Bouchard, University of Glasgow (U.K.)
N. Brambilla, Technische Universität München (Germany)
N. Brown, Washington University, St. Louis
B. Chakraborty, University of Cambridge (U.K.)
C.C. Chang, Lawrence Berkeley National Laboratory
C.T.H. Davies, University of Glasgow (U.K.)
C. DeTar, University of Utah
Daping Du, Globality, Inc.
A.X. El-Khadra, University of Illinois, Urbana-Champaign
E.D. Freeland, School of the Art Institute of Chicago
E. Gámiz, Universidad de Granada (Spain)
Steven Gottlieb, Indiana University
D. Hatton, University of Glasgow (U.K.)
U.M. Heller, American Physical Society
Y.-C. Jang, Brookhaven National Laboratory
J. Komijani, University of Glasgow (U.K.)
J. Koponen, INFN, Sezione di Roma Tor Vergata (Italy)
J. Laiho, Syracuse University
S.-h. Lee, University of Utah
W. Lee, Seoul National University (South Korea)
G.P. Lepage, Cornell University
Yin Lin, University of Chicago
Yuzhi Liu, Indiana University
P.B. Mackenzie, Fermi National Accelerator Laboratory
C. McNeile, University of Plymouth (U.K.)
Y. Meurice, University of Iowa
A. Meyer, Brookhaven National Laboratory
D. Mohler, Universität Mainz (Germany)
E.T. Neil, University of Colorado
M.B. Oktay, University of Utah
T. Primer, University of Arizona
J.N. Simone, Fermi National Accelerator Laboratory
A. Strelchenko, Fermi National Accelerator Laboratory
R.L. Sugar, University of California, Santa Barbara
D. Toussaint, University of Arizona
A. Vairo, Technische Universität München (Germany)
R.S. Van de Water, Fermi National Accelerator Laboratory
A. Vaquero Avilés-Casco, University of Utah
Ran Zhou, Xilinx, Inc.

Curriculum Vitae
Thomas Charles Blum

Contact Information

Physics Department phone: (860) 486 6416
University of Connecticut
Storrs, CT 06269-3046 email: thomas.blum@uconn.edu

Professional Preparation

Ph.D. Theoretical Physics, University of Arizona, 1995, (advisor, Doug Toussaint)
M.S. Aeronautical and Astronautical Engineering, University of Washington, 1986
B.S. Aeronautical and Astronautical Engineering, University of Washington, 1985

Appointments

2018–2021, Fermilab Distinguished Scholar
2015–present, Associate Department Head, Undergraduate Affairs
2004–present, Professor of Physics, UConn
2008–present, Visiting Scientist, RIKEN BNL Research Center
2003, Associate Physicist, Brookhaven National Lab
1998–2003, RIKEN Fellow, RBRC, Brookhaven National Lab
1995–1998, Postdoctoral Fellow, HET group, Brookhaven National Lab

Five Publications Most Relevant to This Proposal

1. C. Aubin, T. Blum, M. Golterman and S. Peris, *The muon anomalous magnetic moment with staggered fermions: is the lattice spacing small enough?*, [arXiv:2204.12256 [hep-lat]].

2. T. Aoyama, N. Asmussen, M. Benayoun, J. Bijnens, T. Blum, M. Bruno, I. Caprini, C. M. Carloni Calame, M. Cè and G. Colangelo, *et al. The anomalous magnetic moment of the muon in the Standard Model*, Phys. Rept. **887**, 1-166 (2020) doi:10.1016/j.physrep.2020.07.006 [arXiv:2006.04822 [hep-ph]].

3. T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung and C. Lehner, *Hadronic Light-by-Light Scattering Contribution to the Muon Anomalous Magnetic Moment from Lattice QCD*, Phys. Rev. Lett. **124**, no.13, 132002 (2020) doi:10.1103/PhysRevLett.124.132002 [arXiv:1911.08123 [hep-lat]].

4. C. Aubin, T. Blum, C. Tu, M. Golterman, C. Jung and S. Peris, *Light quark vacuum polarization at the physical point and contribution to the muon* $g-2$, Phys. Rev. D **101**, no.1, 014503 (2020) doi:10.1103/PhysRevD.101.014503 [arXiv:1905.09307 [hep-lat]].

5. T. Blum *et al.* [RBC and UKQCD], *Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment*, Phys. Rev. Lett. **121**, no.2, 022003 (2018) doi:10.1103/PhysRevLett.121.022003 [arXiv:1801.07224 [hep-lat]].

Honors and Awards

Faculty Excellence in Research and Creativity Sciences Award (2022)
Fermilab Distinguished Scholar (2018-2021)
Fellow, American Physical Society (2015)
Phi Kappa Phi National Honor Society (2012)
Ken Wilson Lattice Award (2012)
Outstanding Junior Investigator, US Department of Energy, HEP, 2004-2008

Synergistic Activities

National Committees

USQCD deputy spokesperson and deputy chair of the Executive Committee, 2021–
Snowmass 2021–2022, Rare processes and Precision Measurements topical group convener for Fundamental Physics in Small Experiments
USQCD Executive Committee, 2020–
USQCD Program Committee, 2005–2010, 2015–2019
NSF XSEDE Resource Allocation Committee, 2012–2013
Flavianet Lattice Averaging Group (FLAG), 2012–
NSF TERAGRID Resource Allocation Committee, 2010–2011

Conference Organization

Co-organizer (Chair), SchwingerFest 2022: muon g-2, Bhaumik Institute for Theoretical Physics, UCLA, June 14-17, 2022
Co-organizer, Workshop on Dipole Moments (Snowmass 2021), virtual, September 15-17, 2020
Co-organizer, SchwingerFest 2018, Bhaumik Institute, UCLA, December 3-5, 2018
Co-organizer, Muon g-2 Theory Initiative Hadronic Light-by-Light Working Group Workshop, University of Connecticut (March 2018)
Local Organizing Committee, XXXIIth International Symposium on Lattice Field Theory (Lattice 2014), New York (June 2014)
Organizer, Hadronic contributions to the muon anomalous magnetic moment Workshop, MITP, Waldthausen Castle, Mainz Germany, April 1-5, 2014
Organizer, Galileo Galilei Institute Workshop, New Frontiers in Lattice Gauge Theory, Galileo Galilei Institute, Florence, Italy, August 27–September 28, 2012
Program Committee, XXIVth International Symposium on Lattice Field Theory (Lattice 2006), Tucson (July 2006)
International Advisory Committee, XXIst International Symposium on Lattice Field Theory, Tsukuba (2003)

Collaborators

RBC and UKQCD Collaborations, including, R. Mawhinney (Columbia), C. Sachrajda (Southampton), A. Soni; C. Aubin (Fordham), M. Golterman (SFSU), H. Meyer (Mainz), S. Peris (Barcelona), S. Syritsin (SU Stony Brook), H. Wittig (Mainz)

Curriculum Vitae
Peter Boyle

Contact Information

High Energy Theory Group phone: (631) 344-8194
Brookhaven National Laboratory
Upton, NY 11973 email: pboyle@bnl.gov

Professional Preparation

Institution	Location	Major	Degree	Year
University of Glasgow	Glasgow, UK	Mathematics and Physics	BSc combined honours	1994
University of Edinburgh	Edinburgh, UK	Theoretical Physics	PhD	1997
University of Glasgow	Glasgow, UK	Lattice QCD	PPARC Personal fellowship	1997-2000
University of Edinburgh	Edinburgh, UK	Lattice QCD	Postdoctoral researcher	2000-2004
Columbia University	New York		Visiting Scholar	2001-2004

Appointments

Oct 2019 - Present	BNL Senior Scientist (dual appointment 92%)
Oct 2019 - Present	University of Edinburgh, UK. (dual appointment 8% until Oct 2023)
Sept 2014 - Oct 2019	University of Edinburgh, Professor
Sept 2010 - Sept 2014	University of Edinburgh, Reader
April 2005 - Sept 2010	University of Edinburgh, Lecturer
April 2005 - Sept 2010	RCUK Fellow

Five Publications Most Relevant to This Proposal

1. *Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment*, T. Blum, P.A. Boyle, V. Gülpers, T. Izubuchi, L. Jin, C. Jung, A. Jüttner, C. Lehner, A. Portelli, and J.T. Tsang, arXiv:1801.07224, accepted by PRL as Editors' suggestion. Phys. Rev. Lett. 121 (2018) 022003
2. *Domain wall QCD with physical quark masses*, T. Blum, P.A. Boyle, N.H. Christ, J. Frison, N. Garron, R.J. Hudspith, T. Izubuchi, T. Janowski, C. Jung, A. Jüttner, C. Kelly, R.D. Kenway, C. Lehner, M. Marinkovic, R.D. Mawhinney, G. McGlynn, D.J. Murphy, S. Ohta, A. Portelli, C.T. Sachrajda, A. Soni Phys. Rev. D93, 074505 2016, (arXiv:1411.7017 [hep-lat]).
3. *The decay constants f_{D_s} and f_D in the continuum limit of $N_f = 2 + 1$ domain wall lattice QCD*, Peter A. Boyle, Luigi Del Debbio, Andreas Jüttner, Ava Khamseh, Francesco Sanfilippo, Justus Tobias Tsang.
4. *$SU(3)$ breaking ratios for D_s and B_s mesons*, Peter A. Boyle, Luigi Del Debbio, Nicolas Garron, Andreas Jüttner, Amarjit Soni, Justus Tobias Tsang, Oliver Witzel, arXiv:1812.08791.
5. Ruud A. Haring, Martin Ohmacht, Thomas W. Fox, Michael K. Gschwind, Peter A. Boyle, Norman H. Christ, Changhoan Kim, David L. Satterfield, Krishnan Sugavanam, Paul W. Coteus, Philip Heidelberger, Matthias A. Blumrich, Robert W. Wisniewski, Alan Gara, George L. Chiu, *The IBM Blue Gene/Q Compute Chip*, IEEE Micro, Vol 32, 48, 2012.

Research Interests and Expertise

My research interests are the study of high energy particle physics in all its aspects. I have made use of lattice QCD and computer simulation as a theoretical tool to aid experimental discovery not described by present theories. I have in particular focused on those aspects of the low-energy hadronic sector that enter as critical elements of constraints on new high energy physics from experiments, such as the muon $g-2$ experiment at Fermilab and at the LHC.

Synergistic Activities

1. Snowmass Computational Frontier, Theoretical calculations and simulation topical group convener
2. Led design of Level 1 prefetch engine of IBM BlueGene/Q compute chip (2008-2012)
3. Led Alan Turing Institute Intel codesign project (2016-2019)
4. Lead development of the Grid LQCD software library

Honors and Awards

2004 Gordon Bell prize finalist (Supercomputing 2004)
2012 Ken Wilson Lattice Award (Lattice 2012)
2012 Gauss Award (International Supercomputing Conference 2012)
2013 Gordon Bell prize finalist (Supercomputing 2013)
2016 Visiting Scientist Brookhaven National Laboratory
2016 Royal Society Wolfson Research Merit Award
2016–2019 Alan Turing Institute Faculty Fellow

Collaborators

T. Blum (UConn), N. Christ (Columbia), L. del Debbio (Edinburgh), N. Garron (Liverpool). S. Hashimoto (KEK), T. Izubichi (BNL), L. Jin (UConn), A. Jüttner (Southampton), C. Kelly (Columbia), C. Lehner (Regensburg), R. Mawhinney (Columbia), A. Portelli (Edinburgh), C. Sachrajda (Southampton), A. Soni (BNL). T. Tsang (Odense), T. Wettig (Regensburg).

Curriculum Vitae
Norman H. Christ

Contact Information

Department of Physics
Columbia University
538 W120th St., NY, NY 10533

phone: (212) 854 3307
fax: (212) 932 3169
email: nhc@phys.columbia.edu

Professional Preparation

Ph.D. Physics, Columbia University, 1966 (Advisor, T.D. Lee)
B.A. Physics, Columbia University, 1965 (Salutatorian, Summa Cum Laude)

Appointments

1999-present, Gildor Professor of Computational Physics, Columbia University
1994-1999, Chair, Department of Physics, Columbia University
1974-1999, Professor of Physics, Columbia University
1969-1974, Associate Professor of Physics, Columbia University
1966-1969, Assistant Professor of Physics, Columbia University
1967-1969, Instructor, Princeton University

Five Publications Most Relevant to This Proposal

1. Ruud A Haring, Martin Ohmacht, Thomas W Fox, Michael K Gschwind, Peter A Boyle, Norman H Christ, Changhoan Kim, David L Satterfield, Krishnan Sugavanam, Paul W Coteus, Philip Heidelberger, Matthias A Blumrich, Robert W Wisniewski, Alan Gara, George L Chiu, *The IBM Blue Gene/Q Compute Chip*, IEEE Micro, Vol 32, 48, 2012.
2. Z. Bai, N.H. Christ, T. Izubuchi, C.T. Sachrajda, and A. Soni and J. Yu $K_L - K_S$ *Mass Difference from Lattice QCD*, Phys. Rev. Lett., 113, 112003, 2014 (arXiv:1406.0916 [hep-lat]).
3. T. Blum, N.H. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung, and C. Lehner, *The hadronic light-by-light scattering contribution to the muon anomalous magnetic moment from lattice QCD* Phys. Rev. Lett. 124, 132002, 2020 (arXiv:1911.08123 [hep-lat]).
4. R. Abbott, T Blum, P.A. Boyle, M. Bruno, N.H. Christ, D. Hoying, C. Jung, C. Kelly, C. Lehner, R.D. Mawhinney, D.J. Murphy, C.T. Sachrajda, A. Soni, M. Tomii, T. Wang *Direct CP violation and the* $\Delta I = 1/2$ *rule in* $K \to \pi\pi$ *decay from the Standard Model* Phys. Rev. D102 054509 2020, (arXiv:2004.09440 [hep-lat]).
5. T. Blum, P.A. Boyle, M. Bruno, N.H. Christ, D. Hoying, C. Kelly, C. Lehner, R.D. Mawhinney, A.S. Meyer, D.J. Murphy, C.T. Sachrajda, A. Soni, T. Wang *Lattice determination of* $I = 0$ *and 2* $\pi\pi$ *scattering phase shifts with a physical pion mass* Phys. Rev. D104 114506 2021, (arXiv:2103.15131 [hep-lat]).

Research Interests and Expertise

My research develops and uses high performance computing to address fundamental questions in particle physics. A recent focus is on first-principles calculation of the K meson decay matrix elements, in particular those showing violation of CP (charge conjugation and parity) and the long-distance effects in second order weak kaon decays and mixing. A significant component of my research has involved the design and construction of massively parallel, high performance systems that can be used for these calculations. These include the QCDSP and QCDOC computers, the IBM Blue Gene/Q machine and future Intel computers.

Synergistic Activities
Member Executive Committee, USQCD Collaboration, 1999 - present
Leader of QCDOC and QCDSP computer projects
IBM contractor, participating in design of BG/Q processor
Contractor and Privileged Visitor, Intel Corporation, 2016 - present
Member International Advisory Committee, Lattice Field Theory Symposia:

- Lattice 2016, Southampton, UK
- Lattice 2015, Kobe, Japan
- Lattice 2013, Mainz, Germany
- Lattice 2012, Cairns, Australia
- Lattice 2011, Lake Tahoe, USA
- Lattice 2010, Sardinia, Italy
- Lattice 2009, Beijing, China
- Lattice 2008, William and Mary, USA
- Lattice 2007, Regensburg, Germany
- Lattice 2004, Fermilab, USA
- Lattice 2000, Bangalore, India
- Lattice 1996, Saint Louis, USA
- Lattice 1995, Melbourne, Australia

Co-Chair Lattice Field Theory Symposium, Latttice 2014, New York, USA

Honors and Awards
1967 Sloan Fellowship
1981 Fellow, American Physical Society
1998 Gordon Bell prize for QCDSP cost/performance
2012 Kenneth Wilson Lattice Award

Collaborators and co-authors within the last 5 years, not including current Ph.D. students, Intel or IBM engineers

Blum, T., Connecticut	Boyle, P. A., BNL	Cossu, G.
Bruno, M., CERN	Feng, X., Peking	Flynn, J. M., Soton
Garron, N., Plymouth	Hayakawa, M., Nagoya	Hoying, D. Mich. State
Izubuchi, T., BNL	Jin, L., Connecticut	Jung, C., BNL
Juttner, A., Soton	Lehner, C., BNL	Meyer, A., UC Berkeley
Portelli, A. Edinburgh	Sachrajda, C. T., Soton	Sanfilippo, F., Rome3
Soni, A., BNL	Wang, B., Kentucky	

Curriculum Vitae
Carleton DeTar

Contact Information

Department of Physics and Astronomy
University of Utah
115 S 1400 E Rm 201
Salt Lake City, UT 84112
phone: (801) 581-7537
cell: (801) 244-4912
email: detar@physics.utah.edu

Professional Preparation

Ph.D. Physics, 1970, University of California, Berkeley
A.B. Chemistry and Physics, 1966, Harvard College

Appointments

1986–present, Department of Physics and Astronomy, University of Utah, Professor
2013–2016, Department of Physics and Astronomy, University of Utah, Chair
1998–2005, Department of Physics, University of Utah, Associate Chair
1983–1989, Department of Physics, University of Utah, Associate Chair
1978–1985, Department of Physics, University of Utah, Associate Professor
1972–1978, Department of Physics, Massachusetts Institute of Technology, Assistant Professor
1970–1972, Center for Theoretical Physics, Massachusetts Institute of Technology, Postdoctoral Research Associate

Five Publications Most Relevant to This Proposal

1. "The anomalous magnetic moment of the muon in the Standard Model," (with the Muon g-2 Theory Initiative, Phys. Rept. **887** (2020) [arXiv:2006.04822]
2. "Hadronic-vacuum-polarization contribution to the muon's anomalous magnetic moment from four-flavor lattice QCD," (with the Fermilab Lattice and HPQCD and MILC Collaborations), Phys.Rev. D **101**, 034512 (2020) [arXiv:1902.04223].
3. "Strong-isospin-breaking correction to the muon anomalous magnetic moment from lattice QCD at the physical point," (with the Fermilab Lattice, HPQCD, and MILC collaborations), Phys. Rev. Lett. **120**, 152001 (2018).
4. "Performance Portability Strategies for Grid C++ Expression Templates", (with Peter A. Boyle, M. A. Clark, Meifeng Lin, Verinder Rana, and Alejandro Vaquero Avilés-Casco), EPJ Web Conf. **175**, 09006 (2018) [arXiv:1710.09409].
5. "*B*- and *D*-meson leptonic decay constants from four-flavor lattice QCD," (with the Fermilab Lattice and MILC Collaborations), Phys. Rev. D **98**, 074512 [arXiv:1712.09262].

Research Interests and Expertise

I am interested in using methods of lattice QCD to guide and assist in high-precision experimental searches for fundamental interactions beyond the standard model and for constraining models of such interactions.

Synergistic Activities

1. Steering Committee, LatticeQCD AD, DOE Exascale Computing Project, 2017–present.
2. USQCD Executive Committee, 2016–present
3. Heavy Ion Session Convenor, ICHEP 2016
4. DOE SciDAC Software Coordinating Committee 2002–2017
5. International Advisory Committee, International Symposium on Lattice Field Theory: Lattice 2014
6. Local Organizing Committee, International Symposium on Lattice Field Theory: Lattice 2006
7. Local Organizing Committee, International Symposium on Lattice Field Theory: Lattice 1998

Collaborators

A. Bazavov, Michigan State University
C. Bernard, Washington University, St. Louis
C.M. Bouchard, University of Glasgow (U.K.)
N. Brambilla, Technische Universität München (Germany)
R. Brower, Boston University
B. Chakraborty, University of Cambridge (U.K.)
C.C. Chang, Lawrence Berkeley National Laboratory
C.T.H. Davies, University of Glasgow (U.K.)
C. DeTar, University of Utah
Daping Du, Globality, Inc.
Robert Edwards, Jefferson Laboratory
A.X. El-Khadra, University of Illinois, Urbana-Champaign
E. Gámiz, Universidad de Granada (Spain)
Steven Gottlieb, Indiana University
Rajan Gupta, Los Alamos National Laboratory
D. Hatton, University of Glasgow (U.K.)
U.M. Heller, American Physical Society
Y.-C. Jang, Brookhaven National Laboratory
W. Jay, Massachusetts Institute of Technology
Chulwoo Jung, Brookhaven National Laboratory
F. Karsch, University of Bielefeld
J. Komijani, University of Glasgow (U.K.)
J. Koponen, Universität Mainz
A.S. Kronfeld, Fermi National Accelerator Laboratory
J. Laiho, Syracuse University
A. Lytle, University of Illinois
W. Lee, Seoul National University (South Korea)
G.P. Lepage, Cornell University
P.B. Mackenzie, Fermi National Accelerator Laboratory
R.D. Mawhinney, Columbia University
C. McNeile, University of Plymouth (U.K.)
C. Monahan, William & Mary University
S. Mukerhjee, Brookhaven National Laboratory
James Osborn, Argonne National Laboratory
J.N. Simone, Fermi National Accelerator Laboratory
RAlexei Strelchenko, Fermi National Accelerator Laboratory
Robert Sugar, Univ. of Calif., Santa Barbara
Douglas Toussaint, Univ. of Arizona
Ruth Van de Water, Fermilab
A. Vaquero, University of Utah Ran Zhou, Xilinx, Inc.

Curriculum Vitae
Aida X. El-Khadra

Contact Information
Department of Physics phone: (217) 333-5026
University of Illinois at Urbana-Champaign email: axk@illinois.edu
1110 W. Green St.
Urbana, IL 61801

Professional Preparation
Ph.D. Physics, 1989, University of California, Los Angeles
MS (Diplom), Physics, 1986, Freie Universität Berlin, Germany

Appointments
2008–present, Professor, University of Illinois at Urbana-Chanpaign
2001–2008, Associate Professor, University of Illinois at Urbana-Champaign
1995–2001, Assistant Professor, University of Illinois at Urbana-Champaign
1993–1995, Postdoctoral Research Associate, Ohio State University
1990–1993, Postdoctoral Research Associate, Fermilab
1989–1990, Postdoctoral Research Associate, Brookhaven National Laboratory

Five Publications Most Relevant to This Proposal

1. G. Colangelo, M. Davier, A. X. El-Khadra, M. Hoferichter, C. Lehner, L. Lellouch, T. Mibe, B. L. Roberts, T. Teubner and H. Wittig, *et al.* "Prospects for precise predictions of a_μ in the Standard Model," Contribution to 2022 Snowmass Summer Study. [arXiv:2203.15810 [hep-ph]].
2. S. Lahert, C. DeTar, A. El-Khadra, E. Gámiz, S. Gottlieb, A. Kronfeld, E. Neil, C. Peterson, R. Van de Water [Fermilab Lattice, HPQCD and MILC], "Hadronic vacuum polarization of the muon on 2+1+1-flavor HISQ ensembles: an update," Proceedings of the 38th International Symposium on Lattice Field Theory (Lattice 2021). [arXiv:2112.11647 [hep-lat]].
3. W. I. Jay *et al.* [Fermilab Lattice and MILC], "B- and D-meson semileptonic decays with highly improved staggered quarks," Proceedings of the 38th International Symposium on Lattice Field Theory (Lattice 2021). [arXiv:2111.05184 [hep-lat]].
4. T. Aoyama, *et al.* "The anomalous magnetic moment of the muon in the Standard Model," Phys. Rept. **887**, 1-166 (2020) doi:10.1016/j.physrep.2020.07.006.
5. C. T. H. Davies *et al.*, "Hadronic-vacuum-polarization contribution to the muon's anomalous magnetic moment from four-flavor lattice QCD," Phys. Rev. D **101**, no.3, 034512 (2020).

Research Interests and Expertise

My research program is focused on lattice QCD calculations that support high energy experiments at the intensity frontier, where new physics searches proceed by comparing precision measurements with Standard Model theory. The goal of this effort is to bring the errors associated with hadronic effects under quantitative control in order to make full use of the experimental measurements and to obtain precision tests of the Standard Model and constrain (or discover) possible effects of new physics. I have extensive experience in flavor physics phenomenology, designing data analysis projects, and lattice perturbation theory calculations of the needed renormalization factors.

Synergistic Activities (select)

1. Convener, Theory Frontier, Particle Physics Decadal Community Planning Process (Snowmass 2021), organized by the APS Division of Particles and Fields.
2. Chair, Steering Committee of the Muon g-2 Theory Initiative, 2017–present.
3. Particle Data Group, Review of *Semileptonic b-Hadron Decays, Determination of V_{cb}, V_{ub}*, 2021–present.

4. USQCD Committee on Diversity, Equity, and Inclusion, 2020–present.
5. Conference and Workshop Organization (ten in the last 4 years). Recent example:
   Fourth Plenary Workshop of the Muon g-2 Theory Initiative (virtual), KEK, 28 Jun - 2 Jul 2021.

Honors and Awards

2022	Simons Foundation Fellowship
2021	Fellow, American Association for the Advancement of Science
2016	Distinguished Scholar, Fermilab
2011	Fellow, American Physical Society
2002	Frontier Fellow, Fermilab
1999	Collins Award for Innovative Teaching, College of Engineering, University of Illinois at Urbana-Champaign
1998	Xerox Award for Faculty Research, College of Engineering, University of Illinois at Urbana-Champaign
1997	Fellow, Alfred P. Sloan Foundation
1996	Outstanding Junior Investigator Award, US Department of Energy, Office of High Energy Physics

Collaborators

J. Bailey (Seoul National University, South Korea); A. Bazavov (Michigan State University); C. Bernard (Washington University, St. Louis); T. Blum (RIKEN-BNL, Connecticut U.); P. Boyle (BNL); M. Bruno (CERN, Switzerland); C. Bouchard (University of Glasgow, U.K.); N. Brambilla (Technische Universität München, Germany); N. Brown (Washington University, St. Louis); M. Cè (CERN, Switzerland); B. Chakraborty (University of Cambridge, U.K.); C. Chang (Lawrence Berkeley National Laboratory); G. Colangelo ((ITP, Universität Bern, Switzerland); M. Davier (LAL, Orsay, France); C. Davies (University of Glasgow, U.K.); M. Della Morte (Southern Denmark U., Denmark); C. DeTar (University of Utah); D. Du (LinkedIn); S. Eidelman (Novosibirsk, Russia); J. Foley (Indiana U.); E. Freeland (School of the Art Institute of Chicago); Z. Gelzer (University of Illinois at Urbana-Champaign); E. Gámiz (Universidad de Granada, Spain); D. Giusti (Regensburg University, Germany); S. Gottlieb (Indiana University); V. Gülpers (University of Edinburgh, UK); M. Hansen (University of Edinburgh, U.K.); S. Hashimoto (KEK, Japan); D. Hatton (University of Glasgow, U.K.); U. Heller (American Physical Society); G. Herdoíza (Universidad Autónoma de Madrid, Spain); M. Hoferichter (ITP, Universität Bern, Switzerland); T. Izubuchi (BNL and RBRC); J. Kim (Samsung Electronics); J. Komijani (University of Glasgow, U.K.); J. Koponen (KEK, Japan); A. Kronfeld (Fermi National Accelerator Laboratory); J. Laiho (Syracuse University); C. Lehner (BNL and Regensburg University, Germany); L. Lellouch (Marseille U., France); G. Lepage (Cornell University); L. Levkova (Nauto, Inc.); Z. Ligeti (Lawrence Berkeley National Laboratory); Y. Liu (Google); A. Lytle (University of Illinois at Urbana-Champaign); P. Mackenzie (Fermi National Accelerator Laboratory); M. Marinković (ETH Zürich, Switzerland); C. McNeile (University of Plymouth, U.K.); Y. Meurice (University of Iowa); A. S. Meyer (UC Berkeley); T. Mibe (KEK); K. Miura (Mainz Univ., Germany); E. Neil (University of Colorado); A. Nyffeler (Mainz U., Germany); T. Primer (University of Arizona); A. Portelli (University of Edinburgh, UK); L. Roberts (Boston University); S. Qiu (Brandeis University); S. Sharpe (U. of Washington); J. Simone (Fermi National Accelerator Laboratory); S. Simula (INFN, Rome, Italy); R. Sugar (University of California, Santa Barbara); T. Teubner (Liverpool University, U.K.); D. Toussaint (University of Arizona); A. Vairo (Technische Universität München, Germany); R. Van de Water (Fermi National Accelerator Laboratory); A. Vaquero Avilés-Casco (University of Utah); A. Veernala (Fermi National Accelerator Laboratory); G. von Hippel (Mainz Univ., Germany); S. Yamamoto (University of Utah); H. Wittig (Mainz Univ., Germany); O. Witzel (Siegen Univ., Germany); R. Zhou (Xilinx, Inc.).

Curriculum Vitae
Steven Gottlieb

Contact Information

Department of Physics phone: (812) 855-0243
Indiana University
727 E Third St email: sg@iu.edu
Bloomington, IN 47405

Professional Preparation

Ph.D. Physics, Princeton University 1978
M.A. Physics, Princeton University 1975
A.B. Mathematics and Physics, Cornell University 1973

Appointments

2017–present, Distinguished Professor Emeritus, Indiana University
2017–present, Provost Professor Emeritus of Physics, Indiana University
2009–2017, Distinguished Professor, Indiana University
1992–2008, Professor of Physics, Indiana University
1988–1992, Associate Professor of Physics, Indiana University
1985–1988, Assistant Professor of Physics, Indiana University
1982–1985, Assistant Research Physicist, University of California San Diego
1980–1982, Research Associate, Fermi National Accelerator Laboratory
1978–1980, Postdoctoral Appointee, Argonne National Laboratory

Five Publications Most Relevant to This Proposal

1. "Up-, down-, strange-, charm-, and bottom-quark masses from four-flavor lattice QCD," (with the Fermilab Lattice and MILC and TUMQCD Collaborations), Phys. Rev. D **98**, 054517 (2018) [arXiv:1802.04248].
2. "*B*- and *D*-meson leptonic decay constants from four-flavor lattice QCD," (with the Fermilab Lattice and MILC Collaborations), Phys. Rev. D **98**, 074512 [arXiv:1712.09262].
3. "$B^0_{(s)}$-mixing matrix elements from lattice QCD for the Standard Model and beyond," (with the Fermilab Lattice and MILC Collaborations), Phys. Rev. D **93**,113016 (2016).
4. "$B \to D\ell\nu$ form factors at nonzero recoil and $|V_{cb}|$ from 2+1-flavor lattice QCD," (with the Fermilab Lattice and MILC Collaborations), Phys. Rev. D **92**, 034506 (2015)
5. "Full nonperturbative QCD simulations with 2+1 flavors of improved staggered quarks," (with the MILC Collaboration) Rev. Mod. Phys. **82**, 1349 (2010).

Research Interests and Expertise Lattice QCD as a tool to understand nonperturbative field theory, in particular, using lattice QCD to make Standard Model predictions of phenomena in which we might expect to find evidence of new physics or to determine with precision the parameters of the Standard Model. High performance computing and performance portability.

Synergistic Activities

1. OLCF User Group Executive Board, 2021–
2. Co-convener of Computational Frontier, American Physical Society (APS) Division of Particles and Fields, Snowmass Community Planning Process, 2013 & 2021
3. APS Aneesur Rahman Prize for Computational Physics Selection Committee, 2021
4. Associate Editor in Chief, *Computing in Science & Engineering*, 2007–
5. American Physical Society, Division of Computational Physics, Divisional Councillor, 2012–2015
6. International Advisory Committee, *Lattice '22, '20, '04, '03, '95, '94, '91*

7. Local Organizing Committee, *Lattice '18*
8. arXiv Advisory Board Member, 2004–2015

Collaborators

J.A. Bailey, Seoul National University (South Korea)
A. Bazavov, Michigan State University
C. Bernard, Washington University, St. Louis
C.M. Bouchard, University of Glasgow (U.K.)
N. Brambilla, Technische Universität München (Germany)
N. Brown, Washington University, St. Louis
B. Chakraborty, University of Cambridge (U.K.)
C.C. Chang, Lawrence Berkeley National Laboratory
C.T.H. Davies, University of Glasgow (U.K.)
C. DeTar, University of Utah
Daping Du, Globality, Inc.
Robert Edwards, Jefferson Laboratory
A.X. El-Khadra, University of Illinois, Urbana-Champaign
E.D. Freeland, School of the Art Institute of Chicago
E. Gámiz, Universidad de Granada (Spain)
Rajan Gupta, Los Alamos National Laboratory
D. Hatton, University of Glasgow (U.K.)
U.M. Heller, American Physical Society
Y.-C. Jang, Brookhaven National Laboratory
Chulwoo Jung, Brookhaven National Laboratory
J. Komijani, University of Glasgow (U.K.)
J. Koponen, INFN, Sezione di Roma Tor Vergata (Italy)
A.S. Kronfeld, Fermi National Accelerator Laboratory
J. Laiho, Syracuse University
W. Lee, Seoul National University (South Korea)
G.P. Lepage, Cornell University
L. Levkova, Nauto, Inc.
Yuzhi Liu, Google
P.B. Mackenzie, Fermi National Accelerator Laboratory
R.D. Mawhinney, Columbia University
C. McNeile, University of Plymouth (U.K.)
Y. Meurice, University of Iowa
C. Monahan, University of Washington
D. Mohler, Universität Mainz (Germany)
E.T. Neil, University of Colorado
J. Osborn, Argonne National Laboratory
J.N. Simone, Fermi National Accelerator Laboratory
R.L. Sugar, University of California, Santa Barbara
D. Toussaint, University of Arizona
A. Vairo, Technische Universität München (Germany)
R.S. Van de Water, Fermi National Accelerator Laboratory
A. Vaquero Avilés-Casco, University of Utah
Ran Zhou, Xilinx, Inc.

Curriculum Vitae
William Jay

Contact Information

Center for Theoretical Physics
Massachusetts Institute of Technology
Cambridge, MA 02139
phone: 574-355-9997
email: willjay@mit.edu

Professional Preparation

PhD in Physics, University of Colorado Boulder, 2018
MASt in Applied Mathematics and Theoretical Physics, University of Cambridge, 2013
BA in Physics, Ball State University, 2012

Appointments

2021 – present, Research Associate, Massachusetts Institute of Technology
2018 – 2021, Research Associate, Fermi National Accelerator Laboratory

Five Publications Most Relevant to This Proposal

1. "Bayesian model averaging for analysis of lattice field theory results," W.I. Jay and E.T. Neil; *Phys. Rev. D* **103**, 114502 (2021) [arXiv:2008.01069]
2. "Radiative Contribution to the Composite-Higgs Potential in a Two-Representation Lattice Model," V. Ayyar *et al.*; *Phys. Rev. D* **99**, 094504 (2019) [arXiv:1903.02535]
3. "Partial compositeness and baryon matrix elements on the lattice," V. Ayyar *et al.*; *Phys. Rev. D* **99**, 094502 (2019) [arXiv:1812.02727]
4. "Baryon spectrum of SU(4) composite Higgs theory with two distinct fermion representations," V. Ayyar *et al.*; *Phys. Rev. D* **97**, 114505 (2018) [arXiv:1801.05809]
5. "Spectroscopy of SU(4) composite Higgs theory with two distinct fermion representations," V. Ayyar *et al.*; *Phys. Rev. D* **97** 074505 (2018) [arXiv:1710.00806]

Research Interests and Expertise

My reserach focuses on studying strongly coupled quantum field theories using numerical lattice gauge theroy. As a graduate student, I studied composite Higgs models of physics beyond the Standard Model. As a postdoc, I have focused on high-precision calculation of QCD to constrain possible new physics scenarios. I have particular expertise in analyzing statistical and systematic uncertainties in lattice gauge theory calculations.

Synergistic Activities

1. Referee for *Physical Review Letters* and *Physical Review D*, 2018 – present
2. Invited talk, Snowmass Virtual Workshop, Theory meets experiment on $|V_{ub}|$ and $|V_{cb}|$: *Inclusive semileptonic decays from lattice QCD*, 2020
3. Invited seminar, Fermilab, Neutrino Seminar: *Lattice QCD for Neutrinos*, 2020
4. Invited talk, Snowmass Rare Processes and Precision Frontier Townhall Meeting: *Lattice-QCD studies of inclusive B-meson decays*, 2020
5. Contributed talk, Snowmass Mini-Workshop on Neutrino Theory: *Event Generators for Accelerator-Based Neutrino Experiments*, 2020
6. Invited seminar, Jefferson Lab, Theory Seminar: *Bayesian Model Averaging*, 2020
7. Invited colloquium, Virtual Lattice Colloquium Series, Massachusetts Institute of Technology: *Precision Flavor Physics and Lattice QCD*, 2020

Honors and Awards

2012, Provost's Prize Winner, Ball State University
2011, Barry M. Goldwater Scholarship

Collaborators

V. Ayyar, Lawrence Berkeley National Lab
T. DeGrand, University of Colorado Boulder
M. Golterman, San Francisco State University
D.C. Hackett, Massachusetts Institute of Technology
J. Isaacson, Fermi National Accelerator Laboratory
A. Lovato, Argonne National Laboratory
P.A.N. Machado, Fermi National Accelerator Laboratory
E.T. Neil, University of Colorado Boulder
N. Rocco, Fermi National Accelerator Laboratory
Y. Shamir, Tel Aviv University (Israel)
B. Svetitsky, Tel Aviv University (Israel)

Curriculum Vitae
Luchang Jin

Contact Information

Physics Department phone: (860) 486 5368
University of Connecticut
196 Auditorium Road email: luchang.jin@uconn.edu
Storrs, CT 06269-3046

Professional Preparation

Ph.D. 2016, Columbia University (Advisor, Norman Christ)
B.S. 2011, Peking University

Appointments

2017–present, Assistant Professor of Physics, University of Connecticut
2016–2017, Research Associate, Brookhaven National Lab

Five Publications Most Relevant to This Proposal

1. T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung and C. Lehner, "Hadronic Light-by-Light Scattering Contribution to the Muon Anomalous Magnetic Moment from Lattice QCD," Phys. Rev. Lett. **124** no.13, 132002 (2020)
2. T. Blum, P.A. Boyle, V. Gulpers, T. Izubuchi, L. Jin, C. Jung, A. Juttner, C. Lehner, A. Portelli, J.T. Tsang, "Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment," Phys. Rev. Lett. **121**, no. 2, 022003 (2018)
3. T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung and C. Lehner, "Using infinite volume, continuum QED and lattice QCD for the hadronic light-by-light contribution to the muon anomalous magnetic moment," Phys. Rev. D **96**, no. 3, 034515 (2017)
4. T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung, C. Lehner, "Connected and Leading Disconnected Hadronic Light-by-Light Contribution to the Muon Anomalous Magnetic Moment with a Physical Pion Mass," Phys. Rev. Lett. **118**, no. 2, 022005 (2017)
5. T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Lehner, "Lattice Calculation of Hadronic Light-by-Light Contribution to the Muon Anomalous Magnetic Moment," Phys. Rev. D **93**, no. 1, 014503 (2016)

Research Interests and Expertise

My research uses the lattice method to calculate the non-perturbative QCD physics from the first principle. In particular, I am experienced in treating the QED interactions in lattice QCD calculations. One particular successful application was the lattice QCD calculation of the hadronic light-by-light contribution to muon $g-2$.

Synergistic Activities

1. Chair of the Local Organizing Committee "Muon $g-2$ Theory Initiative Hadronic Light-by-Light Working Group Workshop" University of Connecticut, March 12–14, 2018
2. Invited plenary talk at Brookhaven Forum 2019: Particle Physics and Cosmology in the 2020's, 09/2019
3. Invited plenary talk at The 37th Annual International Symposium on Lattice Field Theory (LATTICE 2019), 06/2019
4. Invited plenary talk at The 36th Annual International Symposium on Lattice Field Theory (LATTICE 2018), 07/2018
5. Invited lectures at "Summer School on Frontiers in Lattice QCD at Peking University" 2019

Honors and Awards

2019, Kenneth G. Wilson Award for Excellence in Lattice Field Theory.
2016, Intel Fellowship for exceptional research achievements by a PhD student.
2016, Champion of Battlecode—MIT AI programming competition (teamed with Greg McGlynn).

Collaborators

Thomas Blum (University of Connecticut)
Mattia Bruno (Brookhaven National Lab)
Jiunn-Wei Chen (National Taiwan University)
Norman Christ (Columbia University)
Xu Feng (Peking University)
Masashi Hayakawa (Nagoya University)
Daniel Hoying (UConn student)
Tomomi Ishikawa (Tsung-Dao Lee Institute)
Taku Izubuchi (Brookhaven National Lab)
Xiang-Dong Ji (Tsung-Dao Lee Institute)
Andreas Juettner (University of Southampton)
Chulwoo Jung (Brookhaven National Lab)
Christos Kallidonis (Stony Brook University)
Nikhil Karthik (Brookhaven National Lab)
Christoph Lehner (Brookhaven National Lab)
Huey-Wen Lin (Michigan State University)
Yu-Sheng Liu (Tsung-Dao Lee Institute)
Kim Maltman (York University)
Marina Marinkovic (CERN)
Swagato Mukherjee (Brookhaven National Lab)
Peter Petreczky (Brookhaven National Lab)
Antonin Portelli (University of Edinburgh)
Chris Sachrajda (Southampton)
Andreas Schaefer (University of Regensburg)
Matthew Spraggs (University of Southampton)
Iain Stewart (Massachusetts Institute of Technology)
Peng Sun (Michigan State University)
Sergey N. Syritsyn (Stony Brook University)
Cheng Tu (UConn student)
Xin-Yu Tuo (Peking University)
Shi-Cheng Xia (Peking University)
Yi-Bo Yang (Chinese Academy of Sciences)
Feng Yuan (Lawrence Berkeley National Laboratory)
Jian-Hui Zhang (University of Regensburg),
Rui Zhang (Michigan State University)
Yong Zhao (Argonne National Laboratory)

Curriculum Vitae
Chulwoo Jung

Contact Information

High Energy Theory Group phone: (631) 344-5254
Brookhaven National Laboratory
Upton, NY 11973 email: chulwoo@bnl.gov

Professional Preparation

Ph.D. Physics, Columbia University, Feb. 1998 (Thesis Advisor: Robert D. Mawhinney)
M.Phil. Physics, Columbia University, 1995
B.S. Physics, Korea Advanced Institute of Science and Technology, Daejon, Republic of Korea, 1992

Appointments

October 2007–present, Physicist, Brookhaven National Laboratory,
October 2004–September 2007, Associate Physicist, Brookhaven National Laboratory,
September 2002–September 2004, Assistant Physicist, Brookhaven National Laboratory,
September 2001–August 2002, Associate Research Scientist, Columbia University.
September 1999–August 2001, Research Associate, University of Maryland.

Five Publications Most Relevant to This Proposal

1. Hadronic Light-by-Light Scattering Contribution to the Muon Anomalous Magnetic Moment from Lattice QCD, T. Blum *et al.*, Phys. Rev. Lett. **124**, no.13, 132002 (2020) doi:10.1103/PhysRevLett.124.132002 [arXiv:1911.08123 [hep-lat]].

2. Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment, T. Blum *et al.* [RBC and UKQCD Collaborations], Phys. Rev. Lett. **121**, no. 2, 022003 (2018) [arXiv:1801.07224 [hep-lat]].

3. Using infinite volume, continuum QED and lattice QCD for the hadronic light-by-light contribution to the muon anomalous magnetic moment, T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung and C. Lehner, Phys. Rev. D **96**, no. 3, 034515 (2017) [arXiv:1705.01067 [hep-lat]].

4. Connected and leading disconnected hadronic light-by-light contribution to the muon anomalous magnetic moment with physical pion mass, T. Blum, *et al.*, Phys. Rev. Lett. **118**, no. 2, 022005 (2017) [arXiv:1610.04603 [hep-lat]].

5. Domain wall QCD with physical quark masses, T. Blum *et al.* [RBC and UKQCD Collaborations], Phys. Rev. D **93**, no. 7, 074505 (2016) [arXiv:1411.7017 [hep-lat]].

Research Interests and Expertise Numerical studies of QCD
Properties of hadrons - structure functions, hadron interaction
Low energy properties of QCD, Weak matrix elements.
Special purpose computers for lattice field theory -
Design, testing and optimizing applications.

Honors and Awards

2012: Ken Wilson Lattice Award
1998: First prize, Gordon Bell prize (performance per dollar category),
IEEE Computer society (as a member of QCDSP group)

Collaborators and co-authors within the last 5 years, not including current Ph.D. students

Blum, T., Connecticut	Boyle, P. A., BNL	Bruno, M., CERN
Christ, N.H., Columbia	Izubuchi, T., BNL	Jang, Y.-C., Columbia
Jin, L., Connecticut	Kelly, C., BNL,	Lee, W., SNU
Lehner, C., BNL	Mawhinney, R. D., Columbia	Soni, A., BNL

Curriculum Vitae
Christoph Lehner

Contact Information

Physics Department phone: +49 (941) 943 2001
University of Regensburg
Universitätsstr. 31 email: christoph.lehner@ur.de
93053 Regensburg, Germany

Professional Preparation

Ph.D. in Theoretical Physics, University of Regensburg, Germany, Summa Cum Laude, 2010
Diploma in Physics, University of Regensburg, Germany, With Highest Honors, 2007

Appointments

2019–present, Professor, University of Regensburg
2017–2022, Physicist, High Energy Theory Group, BNL
2015–2017, Associate Physicist, High Energy Theory Group, BNL
2013–2015, Assistant Physicist, High Energy Theory Group, BNL
2010–2013, RIKEN FPR fellow, RIKEN BNL Research Center

Five Publications Most Relevant to This Proposal

1. Hadronic Light-by-Light Scattering Contribution to the Muon Anomalous Magnetic Moment from Lattice QCD, T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung and C. Lehner, Phys.Rev.Lett. 124 (2020), 13, 132002, PRL Editors' suggestion.
2. Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment, T. Blum, P.A. Boyle, V. Gülpers, T. Izubuchi, L. Jin, C. Jung, A. Jüttner, C. Lehner, A. Portelli, and J.T. Tsang, Phys.Rev.Lett. 121 (2018) 2, 022003 , PRL Editors' suggestion.
3. Using infinite volume, continuum QED and lattice QCD for the hadronic light-by-light contribution to the muon anomalous magnetic moment, T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung, and C. Lehner, Phys. Rev. D96 (2017), 034515.
4. Lattice Calculation of Hadronic Light-by-Light Contribution to the Muon Anomalous Magnetic Moment, T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, and C. Jung, and C. Lehner, Phys.Rev.Lett. 118 (2017), 022005.
5. Calculation of the hadronic vacuum polarization disconnected contribution to the muon anomalous magnetic moment, T. Blum, P.A. Boyle, T. Izubuchi, L. Jin, A. Jüttner, C. Lehner *et al.* (2015) Phys.Rev.Lett. 116 (2016), 232002.

Research Interests and Expertise

I am interested in precision tests of the standard model. Since a few years, I have focused on precise calculations of hadronic contributions to the muon anomalous magnetic moment in anticipation of the upcoming Fermilab E989 experiment and its expected fourfold increase in experimental precision. The proposed research aims to clarify the current 3.7σ tension. I have been awarded a 2016 DOE Early Career award for these investigations.

Synergistic Activities

1. Local Organizing Committee, workshop on hadronic light-by-light contributions for the muon $g-2$, UConn, March 12-14, 2018
2. Local Organizing Committee, workshop on hadronic contributions for the muon $g-2$, FNAL, June 3–6, 2017
3. Local Organizing Committee, XXXIIth International Symposium on Lattice Field Theory (Lattice 2014), New York (June 2014)

4. Organizer of workshop “Lattice meets experiment 2013,” BNL, Dec. 5-6, 2013
5. Co-chair of steering committee of the “Theory Initiative for the muon $g-2$ (TGM2)”.

Collaborators (*past 5 years including name and current institution*)

Y. Aoki, Nagoya
T. Blum, UConn
M. Bruno, BNL
P.A. Boyle, University of Edinburgh
M.A. Clark, NVIDIA
G. Cossu, University of Edinburgh
J. Flynn, University of Southampton
P. Fritzsch, Humboldt University Berlin
N. Garron, University of Liverpool
V. Gülpers, University of Southampton
M. Hayakawa, Nagoya
R.J. Hudspith, York
T. Izubuchi, BNL
T. Ishikawa, RIKEN
L. Jin, UConn
C. Jung, BNL & Columbia
A. Jüttner, University of Southampton
E. Lunghi, Indiana
M. Marinkovic, CERN
C. Kelly, Columbia
P. Korcyl, Regensburg
Y. Kuramashi, Tsukuba
R. Lewis, York
A.T. Lytle, University of Glasgow
K. Maltman, York
H. Ohki, Nara
A. Portelli, University of Edinburgh
C. Sachrajda, University of Southampton
E. Shintani, Kobe
A. Soni, BNL
M. Spraggs, University of Edinburgh
J.T. Tsang, University of Edinburgh
R.S. Van De Water, Fermilab
O. Witzel, Boulder

Curriculum Vitae
Andrew Lytle

Contact Information

Department of Physics
University of Illinois at Urbana-Champaign email: atlytle@illinois.edu
1110 W. Green St.
Urbana, IL 61801

Professional Preparation

Ph.D. Physics, 2010, University of Washington, Seattle
M.S. Physics, 2005, University of Washington, Seattle

Appointments

2020–present, Research Associate, University of Illinois at Urbana-Chanpaign
2018–2020, Research Associate, INFN Roma Tor Vergata
2014–2017, Research Associate, University of Glasgow
2013–2014, Visiting Scientist, Tata Institute of Fundamental Research
2010–2012, Research Fellow, University of Southampton

Five Publications Most Relevant to This Proposal

1. "$B_c \to J/\psi$ Form Factors for the full q^2 range from Lattice QCD," Phys. Rev. D **102**, 094518 (2020)
2. "$R(J/\psi)$ and $B_c^- \to J/\psi \ell^- \bar{\nu}_\ell$ Lepton Flavor Universality Violating Observables from Lattice QCD," Phys. Rev. Lett. **125**, 222003 (2020)
3. "Renormalising vector currents in lattice QCD using momentum-subtraction schemes," Phys. Rev. D **100**, 114513 (2019)
4. "$B_s \to D_s \ell \nu$ Form Factors for the full q^2 range from Lattice QCD with non-perturbatively normalized currents," Phys. Rev. D **101**, 074513 (2020)
5. "Lattice QCD form factors for $B_s \to D_s^* l \nu$ at zero recoil with non-perturbative current renormalisation," Phys. Rev. D **99**, 114512 (2019)

Research Interests and Expertise My research focuses on applications of nonperturbative lattice field theory, especially lattice QCD, to address core areas of high energy physics and particle physics phenomenology. This work bears on several outstanding 'big question' issues in the field today, including the origin of matter/antimatter asymmetry, the origin of mass, and the search for new physics beyond the Standard Model (SM). Essential to this program is developing the methods for high-precision (percent-level) determination of SM processes also being studied experimentally, in order to extract fundamental parameters and constrain the SM.

Synergistic Activities

1. **Invited talks**: Over twenty seminar, workshop, and conference talks since 2017, including plenary talks at Lattice 2019 (Beijing 16-22 June 2019) and Workshop on Charm Physics (CHARM 2020, postponed until 31 May - 4 June 2021).
2. **Journal Reviews:** 2017–present, Journal referee for Physical Review D, Physical Review Letters, and European Physical Journal C.

Honors and Awards

INFN Fellini Fellowship, INFN Marie Sklodowska-Curie COFUND Fellowship Programme (2020, declined) • Ken Wilson Lattice Award (2012) • Baumgartner Fellowship, University of Washington (2004) • Van Allen Award, University of Iowa (2004) • Presidential Fellowship, University of Iowa (2000)

Collaborators M. Abramczyk (Connecticut U.); P. Boyle (Brookhaven); T. Blum (Connecticut U.); M. Brida (INFN Milan); I. Campos (Cantabrian Inst. of Physics); B. Colquhoun (KEK, Tsukuba); S. Datta

(TIFR, Mumbai); C. Davies (University of Glasgow); C. DeTar (University of Utah); G. Divitiis (INFN Rome Tor Vergata); E. Gámiz (Universidad de Granada); N. Garron (Liverpool U.); S. Gottlieb (Indiana U.); S. Gupta (TIFR, Mumbai); J. Harrison (University of Glasgow); D. Hatton (University of Glasgow); R. Hudspith (York U., Canada); T. Izubuchi (Brookhaven); C. Jung (Brookhaven); A. El-Khadra (University of Illinois); J. Komijani (University of Glasgow) J. Koponen (Helmholtz Institute, Mainz); A. Kronfeld (Fermilab); C. Lehner (Brookhaven); G. Lepage (Cornell University); M. Lin (Brookhaven); E. McLean (University of Glasgow); C. McNeile (Plymouth U.); M. Papinutto (Rome La Sapienza); J. Simone (Fermilab); C. Sturm (U. Wurzburg); A. Vaquero (University of Utah); A. Vladikas (INFN Rome Tor Vergata); A. Zimmermane-Santos (Sao Paulo U.)

Curriculum Vitae
Robert Mawhinney

Contact Information

Department of Physics
Columbia University
538 W120th St., NY, NY 10027
phone: (212) 854 3350
fax: (212) 932 3169
email: rdm10@columbia.edu

Professional Preparation

Ph.D. in Physics, 1987, Harvard University
M.A. in Physics, 1982, Harvard University
B.S. in Physics, 1980, University of South Florida

Appointments

2020–present, Dean of Science, Faculty of Arts and Sciences, Columbia University
2017–2020, Chair, Department of Physics, Columbia University
2007–present, Professor, Department of Physics, Columbia University
1997–2007, Associate Professor, Department of Physics, Columbia University
1992–1997, Assistant Professor, Department of Physics, Columbia University
1990–1992, Postdoctoral Research Associate, Department of Physics, Columbia University
1987–1990, Postdoctoral Research Associate, Department of Physics, University of Pittsburgh

Five Publications Most Relevant to This Proposal

1. T. Blum *et al.* [RBC and UKQCD], "Domain wall QCD with physical quark masses," Phys. Rev. D **93**, no.7, 074505 (2016) doi:10.1103/PhysRevD.93.074505 [arXiv:1411.7017 [hep-lat]].
2. C. Jung, C. Kelly, R. D. Mawhinney and D. J. Murphy, "Domain Wall Fermion QCD with the Exact One Flavor Algorithm," Phys. Rev. D **97**, no.5, 054503 (2018) doi:10.1103/PhysRevD.97.054503 [arXiv:1706.05843 [hep-lat]].
3. R. Abbott *et al.* [RBC and UKQCD], "Direct CP violation and the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decay from the standard model," Phys. Rev. D **102**, no.5, 054509 (2020) doi:10.1103/PhysRevD.102.054509 [arXiv:2004.09440 [hep-lat]].
4. T. Blum *et al.* [RBC and UKQCD], "Lattice determination of I=0 and 2 $\pi\pi$ scattering phase shifts with a physical pion mass," Phys. Rev. D **104**, no.11, 114506 (2021) doi:10.1103/PhysRevD.104.114506 [arXiv:2103.15131 [hep-lat]].
5. J. Tu, M. A. Clark, C. Jung and R. Mawhinney, "Solving DWF Dirac Equation Using Multi-splitting Preconditioned Conjugate Gradient with Tensor Cores on NVIDIA GPUs," doi:10.1145/3468267.3470613 [arXiv:2104.05615 [hep-lat]].

Research Interests and Expertise

My research focuses on numerical lattice quantum chromodynamics (LQCD), including calculations needed to interpret high-energy physics experiments, the development of software and hardware for these calculations and the improvement of the algorithms used therein. I have also had a particular focus on the algorithms and methods used to generate gauge field configurations in LQCD and, with a student, recently used the Exact One Flavor Algorithm for Domain Wall Fermions to speed up the generation of ensembles that the RBC-UKQCD Collaboration used our recent calculation of direct CP violation by a facter of 5-6.

Synergistic Activities

1. USQCD Co-Site Manager for BNL, 2011–2020
2. NSF XSEDE Resource Allocation Committee, 2011–present
3. Flavianet Lattice Averaging Group (FLAG), 2015–2018
4. Scientific Program Committee, USQCD Collaboration, 2004—2009

5. Co-chair, XXXIIth International Symposium on Lattice Field Theory (Lattice 2014), New York (June 2014)

Honors and Awards

2013, Fellow, American Physical Society

Collaborators

T. Blum (UConn), P. Boyke (BNL), N. Christ (Columbia), L. del Debbio (Edinburgh), N. Garron (Liverpool). S. Hashimoto (KEK), T. Izubichi (BNL), L. Jin (UConn), A. Jüttner (Southampton), C. Kelly (BNL), C. Lehner (Regensburg), A. Portelli (Edinburgh), C. Sachrajda (Southampton), A. Soni (BNL). T. Tsang (Odense), T. Wettig (Regensburg).

Curriculum Vitae
Ruth S. Van de Water

Contact Information

Theory Division
Fermilab
Batavia, IL 60510

phone: (630) 840 6383
fax: (630) 840 5435
email: ruthv@fnal.gov

Professional Preparation

PhD 2005, University of Washington
BS 2000, College of William and Mary

Appointments

2015– present, Scientist, Fermi National Accelerator Laboratory
2018–2020, Visiting Associate Professor, North Central College
2012–2015, Associate Scientist, Fermi National Accelerator Laboratory
2011–2012, Assistant Physicist, Brookhaven National Laboratory
2008-2011, Goldhaber Distinguished Fellow, Brookhaven National Laboratory
2005–2008, Postdoctoral Research Associate, Fermi National Accelerator Laboratory

Five Publications Most Relevant to This Proposal

1. "The anomalous magnetic moment of the muon in the Standard Model," T. Aoyama *et al.* [Muon g-2 Theory Initiative], *Phys. Rept.* **887**, 1-166 (2020) [arXiv:2006.04822]
2. "Hadronic-vacuum-polarization contribution to the muon's anomalous magnetic moment from four-flavor lattice QCD," C.T.H. Davies *et al.* [Fermilab Lattice, HPQCD and MILC Collaborations], *Phys. Rev. D* **101**, 034512 (2020) [arXiv:1902.04223]
3. "Higher-Order Hadronic-Vacuum-Polarization Contribution to the Muon $g-2$ from Lattice QCD," B. Chakraborty, C. T. H. Davies, J. Koponen, G. P. Lepage and R. S. Van de Water, *Phys. Rev. D* **98**, 094503 (2018) [arXiv:1806.08190]
4. "Strong-Isospin-Breaking Correction to the Muon Anomalous Magnetic Moment from Lattice QCD at the Physical Point," B. Chakraborty *et al.* [Fermilab Lattice, HPQCD and MILC Collaborations], *Phys. Rev. Lett.* **120**, 152001 (2018) [arXiv:1710.11212]
5. "The hadronic vacuum polarization contribution to a_μ from full lattice QCD," B. Chakraborty, C. T. H. Davies, P. G. de Oliviera, J. Koponen, G. P. Lepage and R. S. Van de Water; *Phys. Rev. D* **96**, 034516 (2017) [arXiv:1601.03071]

Research Interests and Expertise

High-precision numerical lattice-QCD calculations needed to interpret current and future experimental measurements as tests of the Standard Model and searches for new physics, with a focus on quark and lepton flavor physics.

Synergistic Activities

1. APS Division of Particles and Fields Ethics Advisory Committee, 2020–present (*chair since May 2021*)
2. Muon $g-2$ Theory Initiative, 2017–present
3. Advisory Board of Flavor Lattice Averaging Group, 2017–present
4. Author of Particle Data Group Review of Particle Physics, 2015–present
5. Organizer of First Workshop of Muon $g-2$ Theory Initiative, 2017
6. Scientific Program Committe, USQCD Collaboration, 2013–2015,
7. Convener of Lattice Field Theory Working Group , APS Division of Particles and Fields Community Planning Exercise, 2013

Honors and Awards

2019, Fermilab Exceptional Performance Recognition Award
2011, Finalist, NY Academy of Sciences Blavatnik Award for Young Scientists
2008, Goldhaber Distinguished Fellowship
2007, Finalist, MIT Pappalardo Fellowships in Physics

Recent collaborators

A. Bazavov, Michigan State University
C. Bernard, Washington University, St. Louis
N. Brambilla, Technische Universität München (Germany)
G. Colangelo, Universität Bern (Switzerland)
C.T.H. Davies, University of Glasgow (U.K.)
C. DeTar, University of Utah
A.X. El-Khadra, University of Illinois, Urbana-Champaign
E. Gámiz, Universidad de Granada (Spain)
M. Golterman, San Fransisco State University, Steven Gottlieb, Indiana University
U.M. Heller, American Physical Society
P. Hernandez, Universidad de Valencia (Spain)
W. Jay, Fermi National Accelerator Laboratory
J. Komijani, University of Glasgow (U.K.)
A.S. Kronfeld, Fermi National Accelerator Laboratory
S. Lahert, University of Illinois, Urbana-Champaign
J. Laiho, Syracuse University
G.P. Lepage, Cornell University
A. Lytle, University of Illinois, Urbana-Champaign
P.B. Mackenzie, Fermi National Accelerator Laboratory
C. McNeile, University of Plymouth (U.K.)
E.T. Neil, University of Colorado
J. Rosner, University of Chicago
J. Simone, Fermi National Accelerator Laboratory
S. Stone, Syracuse University
R. Sugar, University of California, Santa Barbara
D. Toussaint, University of Arizona
A. Vairo, Technische Universität München (Germany)
A. Vaquero, University of Utah

Section 6: Software Applications and Packages

Question #1

Please list any software packages used by the project, and indicate if they are on open source or export controlled.

Application Packages

Package Name

CPS (Columbia Physics System)

Indicate whether Open Source or Export Controlled.

Open Source

Package Name

MILC (MIMD Lattice Computations)

Indicate whether Open Source or Export Controlled.

Open Source

Package Name

QUDA/CUDA

Indicate whether Open Source or Export Controlled.

Open Source

Package Name

Grid

Indicate whether Open Source or Export Controlled.

Open Source

Package Name

USQCD Supporting libraries

Indicate whether Open Source or Export Controlled.

Open Source

Package Name

AMD HIP

Indicate whether Open Source or Export Controlled.

Open Source

Section 7: Wrap-Up Questions

Question #1

National Security Decision Directive (NSDD) 189 defines Fundamental Research as "basic and applied research in science and engineering, the results of which ordinarily are published and shared broadly within the scientific community, as distinguished from proprietary research and from industrial development, design, production, and product utilization, the results of which ordinarily are restricted for proprietary or national security reasons." Publicly Available Information is defined as information obtainable free of charge (other than minor shipping or copying fees) and without restriction, which is available via the internet, journal publications, textbooks, articles, newspapers, magazines, etc.

The INCITE program distinguishes between the generation of proprietary information (deemed a proprietary project) and the use of proprietary information as input. In the latter, the project may be considered as Fundamental Research or nonproprietary under the terms of the nonproprietary user agreement. Proprietary information, including computer codes and data, brought into the LCF for use by the project - but not for generation of new intellectual property, etc., using the facility resources - may be protected under a nonproprietary user agreement.

Proprietary Information

Are the proposed project and its intended outcome considered Fundamental Research or Publicly Available Information?

Yes

Will the proposed project use proprietary information, intellectual property, or licensing?

No

Will the proposed project generate proprietary information, intellectual property, or licensing as the result of the work being proposed?

If the response is Yes, please contact the INCITE manager, INCITE@doeleadershipcomputing.org, prior to submittal to discuss the INCITE policy on proprietary work.

No

Question #2

The following questions are provided to determine whether research associated with an INCITE proposal may be export controlled. Responding to these questions can facilitate - but not substitute for - any export control review required for this proposal.

PIs are responsible for knowing whether their project uses or generates sensitive or restricted information. Department of Energy systems contain only data related to scientific research and do not contain personally identifiable information. Therefore, you should answer "Yes" if your project uses or generates data that fall under the Privacy Act of 1974 U.S.C. 552a. Use of high-performance computing resources to store, manipulate, or remotely access any national security information is prohibited. This includes, but is not limited to, classified information, unclassified controlled nuclear information (UCNI); naval nuclear propulsion information (NNPI); and the design or development of nuclear, biological, or chemical weapons or of any weapons of mass destruction. For more information contact the Office of Domestic and International Energy Policy, Department of Energy, Washington DC 20585, 202-586-9211.

Export Control

Does this project use or generate sensitive or restricted information?

No

Does the proposed project involve any of the following areas?

i. Military, space craft, satellites, missiles, and associated hardware, software or technical data

ii. Nuclear reactors and components, nuclear material enrichment equipment, components (Trigger List) and associated hardware, software or technical data

iii. Encryption above 128 bit software (source and object code)

iv. Weapons of mass destruction or their precursors (nuclear, chemical and biological)

No

Does the proposed project involve International Traffic in Arms Regulations (ITAR)?

No

Question #3

The following questions deal with health data. PIs are responsible for knowing if their project uses any health data and if that data is protected. Note that certain health data may fall both within these questions as well as be considered sensitive as per question #2. Questions regarding these answers to these questions should be directed to the centers or program manager prior to submission.

Health Data

Will this project use health data?

No

Will this project use human health data?

No

Will this project use Protected Health Information (PHI)?

No

Question #4

The PI and designated Project Manager agree to the following:

Monitor Agreement

I certify that the information provided herein contains no proprietary or export control material and is correct to the best of my knowledge.

Yes

I agree to provide periodic updates of research accomplishments and to acknowledge INCITE and the LCF in publications resulting from an INCITE award.

Yes

I agree to monitor the usage associated with an INCITE award to ensure that usage

is only for the project being described herein and that all U. S. Export Controls are complied with.

Yes

I understand that the INCITE program reserves the right to periodically redistribute allocations from underutilized projects.

Yes

Section 8: Outreach and Suggested Reviewers

Question #1

By what sources (colleagues, web sites, email notices, other) have you heard about the INCITE program? This information will help refine our outreach efforts.

Outreach

By what sources (colleagues, web sites, email notices, other) have you heard about the INCITE program? This information will help refine our outreach efforts.

As a current INCITE PI, I received several email reminders (thanks) and had visited the web pages before that.

Question #2

Suggested Reviewers

Section 9: Testbed Resources

Question #1

The ALCF and OLCF have test bed resources for new technologies, details below. If you would like access to these resources to support the work in this proposal, please provide the information below. (1 Page Limit)

The OLCF Quantum Computing User Program is designed to enable research by providing a broad spectrum of user access to the best available quantum computing systems, evaluate technology by monitoring the breadth and performance of early quantum computing applications, and Engage the *quantum computing community and support the growth of the quantum information science ecosystems. More information can be found here: https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/quantum-computing-user-support-documentation.*

The ALCF AI Testbed provides access to next-generation of AI-accelerator machines to enable evaluation of both hardware and workflows. Current hardware available includes Cerebras C-2, Graphcore MK1, Groq, Habana Gaudi, and SambaNova Dataflow. New hardware is regularly acquired as it becomes available. Up to date information can be found here: https://www.alcf.anl.gov/alcf-ai-testbed.

Describe the experiments you would be interested in performing, resources required, and their relationship to the current proposal. Please note, these are smaller experimental resources and a large amount of resources are not available. Instead, these resources are to explore the possibilities for these technologies might innovate future work. This request does not contribute to the 15-page proposal limit.

qtest.pdf
The attachment is on the following page.

not with this proposal
(response was required)