HEP-QIS QuantISED Awards FY2019

PI	Proposal Title	Institution	Institution Address	9-Digit Zip Code
Univeristy Awards				
Formaggio, Joseph	Quantum Devices for Neutrino and Rare Particle Detection	Massachusetts Institute of Technology	Cambridge, MA	02139-4307
Wu, Sau	Application of Quantum Machine Learning to High Energy Physics Analysis at LHC using IBM Quantum Computer Simulators and IBM Quantum Computer Hardware	Board of Regents of the University of Wisconsin System, operating as University of Wisconsin-Madison	Madison, WI	53715-1218
Lawrence, Albion	Structure and Dynamics of Entanglement in Large Quantum Systems	Brandeis University	Waltham, MA	02453-2728
Balasubramanian, Vijay	Distributed Quantum Information: Theory and Applications	The Trustees of the University of Pennsylvania	Philadelphia, PA	19104-6205
Hartman, Thomas	Theory and Simulations of Emergent Geometry in Quantum Gravity	Cornell University	Ithaca, NY	14850-2820
Smith, Graeme	Measures of Holographic Correlation: Discovery, Interpretation, Application	The Regents of the University of Colorado d/b/a University of Colorado	Boulder, CO	80303-1058
National Lab Awards				
Nomerotski, Andrei	Quantum Astrometry	Brookhaven National Laboratory (BNL)	Upton, NY	11973-5000
Barry, Peter	Quantum Sensors for Wide Band Axion Dark Matter Detection	Argonne National Laboratory (ANL)	Lemont, IL	60439-4803
Nanni, Emilio	Transduction for New Regimes in Quantum Sensing	SLAC National Accelerator Laboratory	Menlo Park, CA	94025-7015
Orrell, John	Phonon coupling to superconducting quasiparticle-sensitive sensors and qubits	Pacific Northwest National Laboratory (PNNL)	Richland, WA	99354-1793
Cancelo, Gustavo	Research Technology for QIST	Fermi National Accelerator Laboratory (FNAL)	Batavia, IL	60510-5011
Osborn, James	Discovering new microscopic descriptions of lattice field theories with bosons	Argonne National Laboratory (ANL)	Lemont, IL	60439-4803
Lyon, Adam	Large Scale Simulations of Quantum Systems on HPC with Analytics for HEP Algorithms	Fermi National Accelerator Laboratory (FNAL)	Batavia, IL	60510-5011
Yoo, Shinjae	Quantum Convolutional Neural Networks for High Energy Physics Data Analysis	Brookhaven National Laboratory (BNL)	Upton, NY	11973-5000
Spier Moreira Alves, Daniele	Renormalization of Entanglement in Quantum Field Theories	Los Alamos National Laboratory (LANL)	Los Alamos, NM	87545-1362
Pooser, Raphael	Challenges and Opportunities in Noise-Aware Implementations of Quantum Field Theories on Near-Term Quantum Computing Hardware	Oak Ridge National Laboratory (ORNL)	Oak Ridge, TN	37831-6231
National Lab Exemplar Awards				
Brown, David	Search for Beyond the Standard Model Physics by Measuring the Fine Structure Constant	Lawrence Berkeley National Laboratory (LBNL)	Berkeley, CA	94720-8099
Plunkett, Robert	Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)	Fermi National Accelerator Laboratory (FNAL)	Batavia, IL	60510-5011
National Lab Collaborative Awards				
Sonnenschein, Andrew	Quantum Sensors for Wide Band Axion Dark Matter Detection	Fermi National Accelerator Laboratory (FNAL)	Batavia, IL	60510-5011
Alexeev , Yuri	Large Scale Simulations of Quantum Systems on HPC with Analytics for HEP Algorithms	Argonne National Laboratory (ANL)	Lemont, IL	60439-4803
Chang, Clarence	Quantum Devices for Neutrino and Rare Particle Detection	Argonne National Laboratory (ANL)	Lemont, IL	60439-4803

Theory and Simulations of Emergent Geometry in Quantum Gravity

Thomas Hartman, Paul Ginsparg, and Peter McMahon

Cornell University

The standard approach to quantum field theory, based on particles interacting weakly, has significant limitations in quantum gravity, and in field-theoretic systems with strong interactions. A promising alternative is to approach quantum field theory, at a fundamental level, through the lens of quantum information. Quantum field theory and quantum gravity must describe how quantum information is encoded in a continuous system, and how it evolves dynamically, subject to the constraints of symmetries, gauge invariance, and locality. We will use this approach to develop new, non-perturbative techniques in field theory and quantum gravity, in order to answer fundamental questions about the nature of quantum fields, emergent geometry, black holes, highly entangled quantum systems, and cosmology in the early universe. We will also develop techniques toward simulating quantum gravity on a quantum computer, to illustrate and test the concept of emergent spacetime geometry.

Challenges and Opportunities in Noise-Aware Implementations of Quantum Field Theories on Near-Term Quantum Computing Hardware

Raphael Pooser,[1] Patrick Dreher,[2] Lex Kemper[2]

Today the high energy physics community has access to the first generation of Noisy Intermediate Scale Quantum (NISQ) quantum computing (QC) hardware platforms. This now gives physicists a first opportunity to reformulate existing the quantum field theory algorithms designed for digital computers onto quantum computing hardware platforms. This new capability allows the high energy physics community an “on-ramp” into quantum computing for getting “quantum ready” to explore problems that up to this point have been inaccessible using even the most powerful digital high performance computers. At the present time there are multiple HEP efforts underway to begin the re-formulation of digital based HEP algorithms into a form suitable for quantum computers. However, these NISQ machines can only maintain a coherent quantum state for short periods of time. These times are usually expressed in standard metrics of T1 (relaxation time) and T2 (dephasing time) with typical values for T1 being on the order of approximately 50−100μ sec and T2 being 20−50μ sec. In addition, NISQ devices are highly error-prone, making it difficult to leverage them for large-scale HEP applications. This project is focused on addressing these issues using today’s quantum computers as a testbed with HEP-focused codes, particularly in lattice-QCD, as the test algorithms. We rely on Qiskit and OpenPulse from IBM to build our algorithm and characterization tools.

Through a careful analysis of the behavior of noisy qubits, the we explore the possibility to identify and characterize a rudimentary noise-aware quantum computing capability. Using information gathered from this research project it may be possible to develop a library of noise aware qubit primitives that users can access. With the availability of this type of information, a researcher will be better informed about the competition between decoherence and circuit depth when choosing gates, gate order, and the topology and placement of codes on these machines when building QC circuits for HEP calculations.

At the present time lattice QCD is the best computational method available that describes the physics of the strong interactions. Despite the many successes of lattice QCD using digital computers, many intellectual areas of HEP lattice QCD remain inaccessible. There are numerous challenging HEP problems ranging from confinement and deconfinement, chiral symmetry breaking and its restoration at finite baryon density, color superconductivity, the real-time evolution of heavy-ion collisions and other strongly coupled quantum systems, which are impossible to numerically simulate with classical simulation methods. These difficulties arise from the very severe sign problems which prevent the importance sampling method underlying classical and quantum Monte Carlo using digital computers. Quantum computing can solve these issues, as it is not subject to the sign problem, but the noise and decoherence issues outlined above must be overcome before we achieve a commensurate benefit. We focus on reformulating the QCD Hamiltonian using the Link model and Rishons, which result in a finite-dimensional Hilbert space amenable to circuit implementations. By joining this reformulation with noise-aware compiling, error mitigation, and other benchmarking techniques, we hope to demonstrate prototypical lattice QCD on NISQ devices.

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[1] Oak Ridge National Laboratory

[2] North Carolina State University

Quantum Sensors for Wide Band Axion Dark Matter Detection

Peter S Barry,[1] Andrew Sonnenschein, Clarence Chang,[1] Jiansong Gao,[3] Steve Kuhlmann,[1] Noah Kurinsky,[2] Joel Ullom[3]

This pilot program will take advantage of quantum readout techniques to develop ultra-sensitive THz single-photon counting kinetic inductance detector (KIDs) for future generation wide-band axion dark matter experiments. The signals in broadband axion search experiments will be small, expected to be at levels as low as 1 photon per day. The axion-to-photon coupling in this mass range necessitates high-efficiency observations at frequencies in the range 1-20 THz with detectors capable of resolving individual THz photons.

The ultimate performance of the KID has yet to be fully realized. We will focus on two areas that we have identified that, with improvement, would result in the substantial advances in sensitivity required to enable this new class of axion searches. Through a combination of innovative application of quantum readout techniques, such as quantum-limited amplifiers, along with application of new lower-Tc superconducting materials, we expect to make the important progress toward realizing single-photon counting KIDs at THz frequencies.

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[1] Argonne National Laboratory
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[3] National Institute for Standards and Technology

Design of RF Readout and Controls for mid to large quantum information systems.

Principal Investigator: **Dr. Gustavo Cancelo (Fermi National Accelerator Laboratory)**.

Abstract

The objective of this project is to develop a Readout and Control system for quantum bits (qubit). The system will be designed towards achieving “fault tolerance” for a medium to large size Quantum Information System (QIS). Readout and Control fault tolerance is defined as the ability to perform quantum error correction (QEC) significantly above the “break-even point” for a sustained period of time. That means, the error detection and correction rates must be larger than the error generation rate during the lifetime of a quantum algorithm. In order to build logic quantum gates, we need fault tolerant logic qubits. Fault tolerance of a logic qubit is a daunting task yet to be demonstrated at a large scale. Logic qubits are made of physical qubits that if left alone change their quantum state, generating errors in the computations. The errors are due to the unavoidable interaction of qubits with the environment. A qubit state will evolve due to decoherence and dephasing. To overcome errors during the life of a computational program error correction methods are required. QEC methods require many physical qubits to build a single logical qubit. The Readout and Control is the electronics system by which a QIS interacts with the non-quantum world. The readout system is in charge of initializing a QIS, supervising its evolution through measurements and steering or correcting its course in real time.

The project will develop and deliver hardware, firmware and software to Readout and Control a multi-qubit system. The system will integrate all the functionality needed to perform or at least set the course towards a fault tolerant logical qubit. The Readout system will be able to query about qubit states using readout excitations and quantum non-demolition techniques. The system will be able to control qubit errors in real time applying low latency commands.

The Readout and Control system will be tested with qubits from our collaborators and at Fermilab. Other project deliverables will be an optimum scalable architecture for a large QIS and a library of firmware and software that can be ported to the proposed hardware. All the data deliverables will be made available.

Renormalization of Entanglement in Quantum Field Theories

Daniele S. M. Alves[1], M. Burak Sahinoglu[2], Varun Vaidya[3], Boram Yoon[4]

Our modern understanding of Standard Model (SM) phenomena (and its extensions) is formulated in terms of Effective Field Theories (EFTs), which describe the dynamics of a system below a given energy cutoff by keeping only the relevant, low frequency degrees of freedom. The short distance (or high frequency) modes are “integrated out” in the path integral of the effective action, their effects amounting to a renormalization of the couplings between low frequency modes and the addition of irrelevant operators suppressed by the energy cutoff.

While EFTs, combined with the Wilsonian Renormalization Group (RG), have led to tremendous conceptual and computational progress in High Energy Physics (HEP), they have obscured the role of entanglement between short (UV) and long (IR) distance modes in interacting theories. Renormalization schemes that keep track of entanglement across different scales along the RG flow have not been broadly explored in the context of EFTs, and might lead to new conceptual insights into the properties of Quantum Field Theories (QFTs).

In condensed matter physics, in particular, the method of Entanglement Renormalization (a.k.a. Multiscale Entanglement Renormalization Ansatz, or MERA) has been developed to describe emergent, collective behavior of quantum many-body physics [Vidal, 2007]. In this method, formulated with Tensor Networks, short-range entanglement is removed at each coarse-graining step, enabling a proper RG flow. Generalizations of MERA to continuum field theories so far have had some shortcomings: (i) they have not been formulated explicitly in position space, obscuring the property of (quasi-) locality of entanglement, and (ii) they have not been successfully implemented in any nontrivial, i.e., interacting, QFTs.

In order to address these issues, we have proposed a reformulation of continuous MERA (cMERA) on a multiresolution expansion basis (i.e., wavelets) for the quantum fields. In this formulation (i) separation of scales is automatically built-in; (iii) the degrees of freedom have compact support in position space, and therefore locality is kept explicit; (iii) the degrees of freedom and scales are automatically discretized, and therefore numerical methods developed for Tensor Networks on the lattice can be adapted to QFTs, enabling numerical simulation of interacting theories, in particular in strongly-coupled regimes.

In this meeting we will present our partial results: (i) using this new wavelet-cMERA formulation, we will show how to fully capture entanglement in free field theories, as well as its evolution with scale; (ii) we will show progress in applying this method to simple interacting theories, and discuss how correlation functions can be (numerically) computed much more efficiently with this method.

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[3] Massachusetts Institute of Technology – MIT Center for Theoretical Physics
[4] Los Alamos National Laboratory – Computer, Computational, and Statistical Sciences Division

Quantum Devices For Neutrino And Rare Particle Detection

J. A. Formaggio,[1] S. Gustavsson,[1] W. Oliver[1], S. Hertel[2], K. Palladino[3]

Much progress has been made over the past decade to extend the sensitivity of cryogenic detectors. In many cases, the technology and techniques employed in rare particle searches mirrors those already employed by quantum engineers in the development of quantum devices and computers. The two communities share similar challenges: scaling, increased signal sensitivity, and strict manufacturing tolerances for operations at low temperatures. We are advancing the technology of low-noise, frequency-based multiplexing for both qubit sensing and low energy particle detection. Specifically, we plan to design, integrate, and test multiplexed microwave resonators and quantum amplifiers, as applied to the specific particle physics challenge of reading out superconducting transition edge sensors. One unique aspect of our approach is to utilize extremely low readout power in combination with travelling wave paremeteric amplifiers. This technique allows for a greater dynamic range, reducing the effects of non-linear inter-modulation and cross-talk between adjacent frequency channels. The low photon readout power also allows greater compatibility with the needs prevalent for quantum bit readout.

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[3] University of Wisconsin at Madison, Madison WI USA

Quantum Convolutional Neural Networks for High Energy Physics Data Analysis

Shinjae Yoo[1], Chao Zhang[1], Tzu-Chieh Wei[2]

High Energy Physics (HEP) communities have a long history of working with large data and applying advanced statistical techniques to analyze experimental data from all three frontiers: energy, intensity, and cosmic. With ever-increasing data volumes, the HEP community needs a significant computational breakthrough to continue on this trajectory, and Quantum Information Science (QIS) could be a viable solution. In the past few decades, the scale of HEP experiments and the size of the data they produce have grown significantly. In 2017 the CERN Large Hadron Collider (LHC) data archive surpassed 200 Peta Bytes (PBs). Meanwhile, future experiments, such as the High Luminosity LHC (HL-LHC), Deep Underground Neutrino Experiment (DUNE), Belle II, and Large Synoptic Survey Telescope (LSST), will see orders of magnitude of increase of data volume, moving well into the 10's of exabyte range. Next to the physics challenges, these data volumes present tremendous data and computing challenges in the simulation, event reconstruction, and data analysis of upcoming HEP experiments. As sensing and simulation technologies improve and data volumes increase by orders of magnitudes, the need for scalable data analytics solutions will only increase. Quantum computing and algorithms hold the potential of significant analysis speed improvements, by leveraging the so-called quantum advantage. Quantum advantage is the potential to solve problems faster. In computational complexity-theoretic terms, this generally means providing a superpolynomial speedup over the best known or possible classical algorithm.

Objectives: In this effort, we propose to utilize and develop Quantum-Accelerated Convolutional Neural Networks to exploit 1) quantum advantage for potential speed-up and 2) data sparsity on challenging data-intensive HEP applications. The developed techniques will be assessed on practical problems in the DUNE experiment, such as event classification and trajectory fitting. The resulting quantum algorithms would, however, benefit many more HEP communities.

Technical Approach: To fulfill both data sparsity and representation learning needs, we propose novel sparse data Quantum Convolutional Neural Networks (QCNNs), which is a generalized form of traditional CNNs that supports convolution operation on the sparse data. Therefore, our proposed QCNNs would be an ideal algorithm to be accelerated within quantum computers, making it the strong candidate algorithm for addressing HEP data analytics challenges. Another core contribution of this proposed activity is incorporating the data sparsity in quantum random access memory (qRAM) and leveraging it on the proposed QCNNs. So, we can 1) alleviate the quantum computer data loading bottleneck, 2) improve qRAM space, and 3) enhance state preparation. We plan to employ a quantum key value map (qKVM) and augmented qRAM to handle this sparse data challenge. We also plan to present the systematic study of recent linear solver approaches on quantum computers, including quantum gradient solver and parallel quantum swap test, so that we can ensure that our developed algorithms leverage the best in practice for our convolutional neural network algorithm development.

Impact: Based on our proposed team's collective expertise, DUNE has been selected as a proxy for broader HEP problems. The case problems described in DUNE will afford a good representation of typical problems encountered in HEP experiments at different HEP frontiers and beyond.

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[1] Brookhaven National Laboratory

[2] Stony Brook University, unpaid collaborator

Large Scale Simulation of Quantum Systems with Analytics for HEP Algorithms

Adam L. Lyon[1], Yuri Alexeev[2], Matthew Otten[2], James Kowalkowski[1], Panagiotis Spentzouris[1]

The large scale-simulation of quantum computers has elements in common with simulations in high-energy physics (HEP): Both need to sweep over many variables. Both are similar in how they organize the input configurations and output results. And in both cases, the simulation must be analyzed and consolidated into results that then go into summaries for publications and presentations. In this pilot project, we will explore and provide tools from experience in HEP to produce and analyze simulations using high-performance computers at the Argonne Leadership Computing Facility (ALCF). In particular, we will simulate in detail the operation of very long coherence time Superconducting RF Cavity (SRF) qudit (*e.g.* multi-level) devices and determine their impact on optimization of algorithms relevant to HEP. This project will further several trajectories of current ongoing research: 1) the construction of SRF cavities for 3D qudits (a unique capability of Fermilab), 2) quantum algorithms useful for HEP applications, and 3) development of highly parallel quantum device and system simulation codes requiring the resources of High Performance Computing, a capability available at the ALCF.

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Matter Wave Atomic Gradiometer Interferometric Sensor

Rob Plunkett,[1] Jason Hogan,[2] Timothy Kovachy,[3]

Swapan Chattopadhyay,[4] Surjeet Rajendran,[5] Jonathan Coleman[6]

MAGIS-100 is an experiment to utilize the sensitivity provided by using atomic techniques from the clock and interferometry communities, implemented on a 100 m vertical scale at Fermilab. This University-National Laboratory consortium will enable record-breaking quantum science, world-leading searches for ultra-light dark matter, and path-breaking demonstration of technology needed for gravitational wave detectors sensitive to frequencies in the area of .3 - 3 Hz.

MAGIS-100 will precisely manipulate atomic systems to demonstrate the principles of quantum mechanics on unprecedented macroscopic time (many seconds) and length (10 meter superposition) scales, due to free-fall in a 100 meter vertical vacuum tube. The sensor design takes advantage of features used by the best Strontium atomic clocks in the world and combines them with established techniques for building inertial sensors based on atom interferometry. The scheme will be physically implemented using three atom interferometers (quantum sensors) installed vertically in the 100-meter existing MINOS access shaft at Fermilab. The quantum sensor information, stored as a phase in each sensor, can be compared across this long 100-meter baseline.

Examples of expected basic physics include time varying signals that could be caused by ultra-light dark matter candidates several orders of magnitude beyond current bounds. Additionally, the detector is sensitive to new fundamental forces and interactions. MAGIS-100 will also serve as an intermediate testbed for full scale terrestrial (kilometers-scale) and space-based detectors, bridging the gap between these and existing research-oriented atom interferometers that are at the 10-meter scale, whose technical feasibility has already been demonstrated.

MAGIS-100 is a collaboration between Fermilab and seven academic institutions: Stanford University, Northwestern University, Johns Hopkins University, Northern Illinois University, University of Liverpool, Cambridge University, and Oxford University. Funding has been received from both the DOE QuantiSED program and the Gordon and Betty Moore Foundation. The experiment is being constructed over a period of three years, with first results of fundamental quantum science appearing in the third year (FY22).

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[1] Fermi National Accelerator Laboratory (Fermilab)
[2] Stanford University
[3] Northwestern University
[4] Northern Illinois University
[5] Johns Hopkins University
[6] University of Liverpool, UK

Transduction for New Regimes in Quantum Sensing

Emilio Nanni,[1] Paul Welander,[1] Tony Heinz[1,2] and Amir Safavi-Naeini[2]

Quantum transduction is the coherent manipulation of quantum states at the boundaries of quantum systems, and it lies at the heart of engineering these “systems” into networks, sensors or computers. Coherent transduction of quantum states between two different frequencies is an essential component of many emerging quantum information science (QIS) applications, as it provides an effective way for linking the classical and quantum world, and for macroscopic transport of quantum information.

For applications that link microwave qubits with optical networks, transducer performance will be determined by the achievable data rates and fidelity in transferring quantum information between these two extreme wavelengths. Unfortunately, direct transduction between these frequencies is inherently dissipative, leading to thermal losses which limit the performance of microwave circuits operating at millikelvin (mK) temperatures. We propose to utilize the mm-wave regime as an intermediate state in a two-step transduction scheme that can provide significant improvements. Our “quantum bus” would perform the microwave to mm-wave transduction with a superconducting resonator at mK temperatures before transporting the photon and its quantum information to higher temperatures. Converting to mm-wave frequencies can be achieved with much lower dissipation, and even at these intermediate photon energies coherence can be maintained at elevated temperatures.

In addition, a significant portion of the candidate dark matter spectrum spanning the µeV-eV range lacks techniques for processing or transducing quantum states, thereby greatly limiting the possible reach of quantum sensors. Indeed, transduction from the mm-wave regime would also greatly benefit dark matter searches. The frequency range for axions above ~10 GHz (~40 µeV) is beyond the reach of current experiments. Development of resonant structures that may couple to the axion field at mm-wave frequencies is actively being pursued by a number of groups. Transduction from mm-wave to either microwave or optical frequencies will permit quantum-limited photon counting with well-developed devices.

We aim to demonstrate a quantum transducer, whereby quantum information is coherently exchanged between a superconducting qubit at microwave frequencies and a resonant high-Q device at mm-wave frequencies. We will present an experimental approach to fabricate mm-wave superconducting resonators [1,2] that could be combined with transmon qubits and used in future microwave-mm-wave converters that distribute entanglement at a high rate in low-loss quantum networks. We propose a method that facilitates a long-range spread of quantum information via direct coupling of such a device into the W-band (75-110 GHz) waveguide.

[1] Stokowski, Hubert, et al. "Towards Millimeter-Wave Based Quantum Networks." *2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*. IEEE, 2019.

[2] K. Multani, H. Stokowski, J. Witmer, W. Jiang, R. Patel, N. Lee, M. Pechal, E. Snively, P. Welander, E. A. Nanni, A. Safavi-Naeini, “Towards the development of a microwave to millimeter-wave quantum frequency converter.” *APS March Meeting* 2020

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[1] SLAC National Accelerator Laboratory, Stanford University

[2] Department of Applied Physics, Stanford University

Quantum Astrometry

PI: Andrei Nomerotski[1], Co-I: Eden Figueroa[1,2] , Co-I: Paul Stankus[1]

Observations using interferometers provide sensitivity to features of images on angular scales much smaller than any single telescope, on the order of Delta theta ~ lambda/b where b is the interferometric baseline. Present-day optical interferometers are essentially classical, interfering single photons with themselves. However, there is a new wave of interest in interferometry using multiple photons, whose mechanisms are inherently quantum mechanical, which offer the prospects increased baselines and finer resolutions among other advantages. We will develop and implement recent ideas for quantum-assisted interferometry using the resource of entangled pairs, and specifically a two-photon amplitude technique aimed at improved precision in dynamic astrometry.

It was pointed out by Gottesman, Jennewein and Croke [1] in 2012 that optical interferometer baselines could be extended, without an optical connecting path, if a supply of entangled Bell states between the two stations could be provided. If these states could then be interfered locally at each station with an astronomical photon that has impinged on both stations, the outcomes at the two stations would be correlated in a way that is sensitive to the phase difference in the two paths of the photon, thus reproducing the action of an interferometer. Equivalently, this can be seen as using a Bell state measurement at one station to teleport the state of that station's astronomical photon to the other station, and interfering it with its counterpart there.

In the Quantum Astrometry project we will study QIS techniques of two-photon interferometry which, in principle, could enable practically arbitrarily large synthesized apertures, opening completely new windows into astrophysical phenomena. We will experiment with several practical implementations of the technique to demonstrate how this can be deployed for cosmological and astronomical measurements derived from precise astrometry of stars and galaxies.

[1] Gottesman, Jennewein and Croke, "Longer-Baseline Telescopes Using Quantum Repeaters", Phys. Rev. Lett. 109, 070503 (2012).

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[1] Brookhaven National Laboratory

[2] Stony Brook University

Discovering new microscopic descriptions of lattice field theories with bosons

James C. Osborn[1], Xiao-Yong Jin[1]

Quantum field theories lie at the heart of our fundamental understanding of nature. In particular, they provide a description of the strong nuclear force, Quantum Chromodynamics (QCD), which binds the fundamental quarks to make atomic nuclei. However, performing precise calculations of QCD is extremely challenging, in many cases requiring exascale resources. For certain challenging problems, even exascale resources are not sufficient and entirely new methods to calculate results are needed. One possible solution in the future will be to simulate field theories on quantum computers.

Field theories with bosons present a special challenge for quantum computing due to the infinite Hilbert space that must be truncated to fit within a finite number of qubits. Here we propose to search for new microscopic descriptions of lattice field theories with bosonic degrees of freedom. The new microscopic models would be designed to reproduce the important long-range properties of the target theory to high accuracy, but would try to do so from a short-range interaction that has the fewest degrees of freedom possible per lattice site.

These new lattice descriptions should then be easier to simulate on quantum computing hardware. They could also help reveal new relationships between seemingly different forms of field theories and expose potentially hidden symmetries.

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[1] Computational Science Division, Argonne National Laboratory

Phonon Coupling to Superconducting Quasiparticle-Sensitive Sensors and Qubits

Raymond Bunker,[1] Alexander Melville,[2] William Oliver,[3] John Orrell (PI),[1] Kyle Serniak,[2] David Toback[4]

There are several physical analogues between the detectors used by the Super Cryogenic Dark Matter Search (SuperCDMS) and superconducting qubits. Both types of devices utilize a crystalline substrate (e.g. silicon), upon which superconducting thin films are patterned. The dark matter detectors use aluminum films to absorb phonon energy (crystal lattice vibrations) resulting from particle interactions in the substrate. Superconducting qubits rely on aluminum films to act as a superconducting circuit. In both cases, superconducting thin films absorb energy from the substrate through the process of quasiparticle production—the breaking of Cooper pairs of electrons into single, energetic electrons. Sensitivity to quasiparticle production in the superconducting films plays a crucial role in the functionality of the device. In particular, the efficiency with which phonons in the substrates couple to quasiparticle production in the superconducting material is a key performance driver. In the case of dark matter detectors, a very efficient coupling is desirable in order to achieve a high degree of sensitivity to energy deposited from dark matter interactions. Whereas in the case of superconducting qubits, an inefficient coupling is desirable in order to better isolate the qubit from environmental energy disturbances, which will generally shorten the qubit coherence lifetime and thus degrade performance. Thus, in both cases, understanding the coupling of phonon energy modes into the superconducting thin films is paramount to understanding and enhancing device performance. We seek to understand the range of mechanisms that influence the phonon energy transfer into quasiparticles in superconducting sensors and circuits.

Our project utilizes expertise in fabrication and operation of superconducting qubits at MIT Lincoln Laboratory and MIT. The knowledge and experience in understanding phonon energy transport and coupling to a sensor system is provided by the SuperCDMS experiment collaborators at PNNL and Texas A&M University. The objective is to design, fabricate, test, and evaluate the performance of a range of superconducting qubit devices, thereby exploring the impact of superconducting material choice (beyond just aluminum) and device design. Each device will include an energy injection mechanism to deliberately excite phonons in the substrate and thus enable us to systematically measure the relative sensitivity of different device designs to quasiparticle production. We will also model the underlying phonon energy transport using a crystal physics Monte Carlo simulation package (G4CMP) developed by the SuperCDMS collaboration. Simulations of the underlying phonon energy transport will inform development of models describing the most important design features to either enhance or isolate the superconducting sensor or circuit from the phonon energy present in the device substrate. The work will benefit both future searches for dark matter and the development of quantum computing qubits. For the former, methods to enhance the sensitivity of the sensor to phonon energy will increase the sensitivity to dark matter interactions in the detector. In the latter case, isolation of the superconducting qubits from energy sources in the environment (the chip substrate) will improve performance—notably the qubit coherence lifetime—promoting advancement in quantum computing methods.

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[1] Pacific Northwest National Laboratory
[2] MIT Lincoln Laboratory
[3] Massachusetts Institute of Technology
[4] Texas A&M University

ABSTRACT: Application of Quantum Machine Learning to High Energy Physics Analysis at Large Hadron Collider (LHC) using IBM Quantum Computer Simulators and IBM Quantum Computer Hardware

Sau Lan Wu, Physics Department, University of Wisconsin-Madison (Principle Investigator)
Miron Livny, Computer Sciences Department, University of Wisconsin-Madison (Co-Investigator)
Federico Carminati and Alberto Di Meglio, CERN openlab, IT Department, CERN (Co-Investigators)
Panagiotis Barkoutsos, Ivano Tavernelli and Stefan Woerner, IBM Research Zurich (Co-Investigators)
Joseph Lykken and Panagiotis Spentzouris, Quantum Institute, Fermilab (Co-Investigators)
Shinjae Yoo, Computational Science Initiative, Brookhaven National Lab (Co-Investigators)

(1) Our Goal: The ambitious HL-LHC program will require enormous computing resources in the next two decades. New technologies are being sought after to replace the present computing infrastructure. A burning question is whether quantum computer can solve the ever growing demand of computing resources in High Energy Physics (HEP) in general and physics at LHC in particular. **Our goal** here is to explore and to demonstrate that Quantum Computing can be the new paradigm (Proof of Principle).

The experimental programs of PI Wu at the LHC revolve around one major objective: discovery of new physics. This requires the identification of rare signals in immense backgrounds. Using machine learning algorithms greatly enhance our ability to achieve this objective. Our group in the ATLAS/LHC is one of the groups which have pioneered the use of machine learning in **high profile** physics analyses. We have used machine learning algorithm on the measurement of Higgs coupling to top quark pairs (ttH). The impact of this ttH channel resulted in the CERN press release on June 4, 2018. However, with a rapidly increasing volume of data in the future HL-LHC program, applying quantum machine learning method may well be a new direction to go. Specifically, **our goals** are: **(i)** To Perform Research and Development of Quantum Machine Learning and Data Analysis Techniques, with Qubit Platform, using IBM Quantum Simulators and IBM Quantum Computer Hardware to Enhance Efficiency and Analysis Methods for HEP at LHC;
(ii) To Enhance the Software Development of Quantum Machine Learning for HEP at the LHC to provide Scalable Quantum Codes and Tools for Future HEP Analysis.

(2) Our Interdisciplinary Collaboration and Work in Progress: We form a team of HEP physicists and computer scientists from Wisconsin, CERN openlab of CERN IT Department, IBM Research Zurich, Fermilab Quantum Institute, and Computational Science Initiative of BNL. We have made promising progress in LHC physics channel ttH (Higgs coupling to top quark pairs) with IBM quantum machine learning algorithms in simulation and in hardware. In this past one year, Wu's team has given ten presentations in conferences and workshops including EPS-HEP 2019 and LP 2019. We are extending this experience to four LHC flagship physics channels: ttH, Higgs to two muons (Higgs coupling to second generation fermions), double Higgs production (Higgs self-coupling), and to search for Dark Matter (Mono-Higgs) at LHC. We use AUC as benchmark of performance for the ttH channel where AUC is the Area Under the ROC curves in the plane of background rejection versus signal efficiency. Employing the QSVM Variational quantum machine learning algorithm with 5 qubits on the IBM Quantum Computer Hardware ("IBM Boeblingen"), we obtain excellent result of AUC=0.759 compared with AUC=0.837 from the corresponding quantum simulation.

(3) Impact on HEP: Our Program on Higgs Physics and Dark Matter Searches at LHC using quantum machine learning in the future corroborates the U.S. particle physics community's visions documented by 2014 Particle Physics Project Prioritization Panel (P5). We are aligned with 2 out of the 5 science drivers: (1) Using the Higgs boson as a new tool for discovery, (2) Identify the new physics of Dark Matter.

(4) Impact on QIST: **Our Goal** is to pioneer the use of **qubit platform** to solve the challenges in deploying quantum machine learning in HEP using IBM Quantum Simulator and IBM Quantum Computer Hardware. We plan to overcome challenges to encode the classical LHC datasets with many variables per event into limited number of qubits by entangling qubits, to develop a variational quantum circuit to extend our analysis to larger numbers of events, and to enhance quantum machine learning algorithms for HEP. We will work on quantum error mitigation in the context of quantum machine learning algorithms.

Structure and dynamics of entanglement in large quantum systems

PI: Albion Lawrence,[1] Co-I Matthew Headrick[1]

This project is to study the structure of quantum entanglement in states of large, complex quantum systems. The primary goal for the investigators is to better understand the emergence of classical gravitational physics from non-gravitational quantum theories, a phenomenon known as holographic duality. However, much of our focus will be on general quantum systems, and we expect these results to be important for improving our conceptual and quantitative understandings of the structure of complex quantum systems that will have an impact on large-scale quantum computation and on quantum materials science.

This proposal contains two parts. In the first, the project team is studying the detailed entanglement structure between multiple subsystems of a quantum system, uncovering the nature of what is called *multipartite* entanglement. The team will progress from random states in large Hilbert spaces to states containing more and features expected of those which have gravitational duals. One concrete question, motivated by recent work from studying holographic duality, is whether entanglement between subsystems is at least approximately characterized by entanglement between individual pairs of degrees of freedom

In the second part, the team is studying entanglement between degrees of freedom in quantum mechanical models with a large number of components, and a nontrivial gauge group whose size scales with these components, with a focus on theories of $N\ x\ N$ matrices at large N. In these models the gauge symmetry presents subtleties in formulating the partitioning between degrees of freedom as well as their entanglement. Such questions are thought to be key to uncovering the emergence of local physics in the gravitational dual of such theories. A specific question relating to the first part of this project is the multipartite entanglement structure in the ground state of such theories.

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Measures of Holographic Correlation: Discovery, Interpretation, and Application

Graeme Smith[1] and Oliver DeWolfe[2]

Our goal is to learn new ways to think about and quantify multiparty holographic entanglement, and how it is distinguished from generic multiparty entanglement. The project is divided into three interconnected thrusts. In the first thrust, we use linear programming to find new measures of holographic correlations and entanglement. Monotonicity under local processing plays a key role. In the second thrust, we seek interpretations of our newly discovered correlation measures in terms of bulk geometry, taking advantage of tensor-network models of AdS/CFT and the Ryu-Takayanagi formula. Here our aim is to use our axiomatic approach to quantifying quantum correlations to develop increasingly accurate and informative quantum-information-based models of AdS/CFT. The third thrust applies our geometric understanding of holographic states to answer questions in quantum information theory proper. Here we expect that holographic states will provide a set of examples for which (in general intractable) information theoretic questions can be answered. We are particularly interested in understanding operationally relevant entropic measures such as distillable entanglement.

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Distributed Quantum Information: Theory and Applications

Vijay Balasubramanian[1]

Objectives: Quantum entanglement can share and communicate information between multiple individuals. Computationally, this shared information is a resource that can be used to implement useful algorithms. In the quantum theory of gravity, the same shared information appears to underpin the connectedness of regions of spacetime. Most recent developments have focused on quantum information as being essentially bipartite (i.e. shared between two parties) and spatially organized (i.e. shared between spatially separated parties). However, in many of the most interesting situations, ranging from quantum cryptography to the possible existence of gravitational "wormholes" between regions of spacetime, quantum information can be inherently distributed over many parties and not even spatially organized. The nature and structure of information in such situations is poorly understood. The goal of my project is to develop the foundational theory necessary for understanding and manipulating information distributed across many parties and non-spatially.

Description: I will deploy classic methods and invent new tools in the fields of information theory, computer science, geometry, quantum field theory, and string theory – all subjects in which I am expert. Briefly, the project will elucidate the theory and applications of five kinds of information:

1. Quantum information shared between many parties
2. Quantum information spread across scales
3. Quantum information that is organized non-spatially (e.g. within matrices)
4. Quantum information shared across time
5. Quantum information as a probe of hidden physics

All these kinds of information have applications in both fundamental physics and quantum computation. In each of these cases my project will develop fundamental theory and methods to quantify and characterize each kind of information. I will apply the results to concrete systems that range from Chern-Simons models (which appear in the theory of quantum computation) to gauge field theories with hidden sectors (which appear in string theoretic models of matter, dark matter, and forces in our world).

Impact: My project aims to make foundational advances in both Quantum Information Science (QIS) and High Energy Physics (HEP). In QIS, the project will seek to produce: (a) a definition of entanglement across time, (b) ways of characterizing entanglement between internal, interacting, non-spatial degrees of freedom such as those appearing in many unified models of the forces of nature, and (c) progress in characterizing the possible patterns of entanglement between many parties that can be naturally induced by the dynamics of physical theories. In HEP the project will study: (a) a generalization to time of the understanding in string theory that smooth space with a negative cosmological constant arises from coherent patterns of entanglement, (b) an exploration of the question of whether flat space can be seen as emergent from entanglement, (c) entanglement between high and low energies as a way of probing the fundamental theory of nature, (d) tests of the conjecture that quantum entanglement produces spacetime wormholes.

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