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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.

Towards Directional Detection of WIMP Dark Matter using Spectroscopy of Quantum Defects in Diamond

Ronald Walsworth, Harvard-Smithsonian Center for Astrophysics, University of Maryland (Principal Investigator)

David Phillips, Harvard-Smithsonian Center for Astrophysics (Senior Investigator)
Alexander Sushkov, Boston University (Senior Investigator)

The next generation of dark matter experiments searching for weakly interacting massive particles (WIMPs) are expected to encounter a confounding background from coherent neutrino-nucleus scattering — a limit called the neutrino floor. We propose a proof-of-principle laboratory-scale demonstration of a new approach to discriminate WIMPs from the neutrino floor by using optical measurements of quantum defects in diamond that act as local sensors of strain within the diamond. When a WIMP scatters in diamond, the induced nuclear recoil is expected to create a tell-tale damage cluster, with an orientation to the damage track that correlates well with the direction of the recoil and hence the incoming WIMP. This damage cluster induces strain in the diamond, shifting the energy levels of nearby quantum defects — nitrogen vacancy (NV) color centers. The level shifts can be measured optically, making it potentially possible to map the strain environment around the defect in a solid sample, and thereby identify the incoming WIMP direction with high efficiency. The angular distributions of WIMP- and neutrino-sources are expected to differ substantially, potentially allowing effective WIMP signal discrimination from the neutrino floor background.

In our two-year pilot project supported by the DOE QuantISED program, we are addressing key enabling technical challenges (questions): (i) can NV optical measurements characterize damage tracks analogous to those expected to be induced by WIMPs; and (ii) can diamond samples be fabricated with sufficient strain uniformity to allow efficient damage track identification? We are also investigating complementary approaches such as tracks of NVs induced by a WIMP or neutrino; and x-ray nanotomography in collaboration with DOE scientists. Encouraging results would set the stage for later studies of the effect of realistic backgrounds; and then possible scale up of this new experimental modality to high densities of quantum defects and large total volumes of diamond, which will be required for practical directional detection of WIMP dark matter.

The proposed project is aligned with the U.S. particle physics community’s current vision for the future as embodied in the 2014 report from the Particle Physics Project Prioritization Panel (P5), which advocated path-finding R&D to "develop techniques that can indicate the direction of incoming dark matter particles". The project will also advance the state-of-the-art in quantum information science (QIS) by furthering knowledge of the strain environment that limits the performance of quantum defects in diamond — one of the most promising and broadly applicable QIS sensing platforms for both the physical and life sciences.

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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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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The Dark Matter Radio-: A Quantum-Enhanced Dark Matter Search

PI: Kent Irwin (Stanford, SLAC), Co-PI: Peter Graham (Stanford)

Advances in quantum sensors have opened a pathway to identify the new physics of dark matter. The nature of dark matter is one of the most important fundamental questions in modern physics. It has been highlighted in the P5 report as a science driver for the U.S HEP program. Quantum sensors are poised to accelerate dark-matter science by measuring the coupling of dark matter to the standard model better than the standard quantum limit (SQL), greatly increasing science reach. The Dark-Matter Radio (DM Radio) is a quantum sensor platform designed from the beginning to be a near-optimal experiment that takes advantage of quantum sensors to search for both axions and hidden photons. Quantum acceleration is required to maximize axion science in the frequency range below 1 MHz (the DMRadio-Quantum regime). In contrast, in the classical regime above 5 MHz, it is feasible to probe all the way down to the QCD axion band using large magnets and commercially available dc SQUID amplifiers. We will describe work on developing a pathfinder for a future DMRadio-Quantum axion search, and a testbed for quantum sensors in this frequency range.

The DM Radio Pathfinder probes new parameter space for hidden-photon dark matter between 500 peV and 50 neV. We have shown that the DM Radio single-pole resonant design nearly saturates the SQL on the sensitivity of searches for dark matter [See Chaudhuri, Irwin, Graham, and Mardon, J. arXiv:1803.01627 (2018)]. The DM Radio Pilot is thus a useful testbed for quantum sensors designed to perform better than the SQL. The DM Radio Pathfinder is operational and setting initial science limits. The components of the DM Radio Pathfinder are shown in Fig. 1. The DM Radio Pathfinder is also being used to elucidate the resonator physics and data analysis procedures needed to successfully utilize a quantum sensor, and to characterize materials for a DMRadio-Quantum axion search.

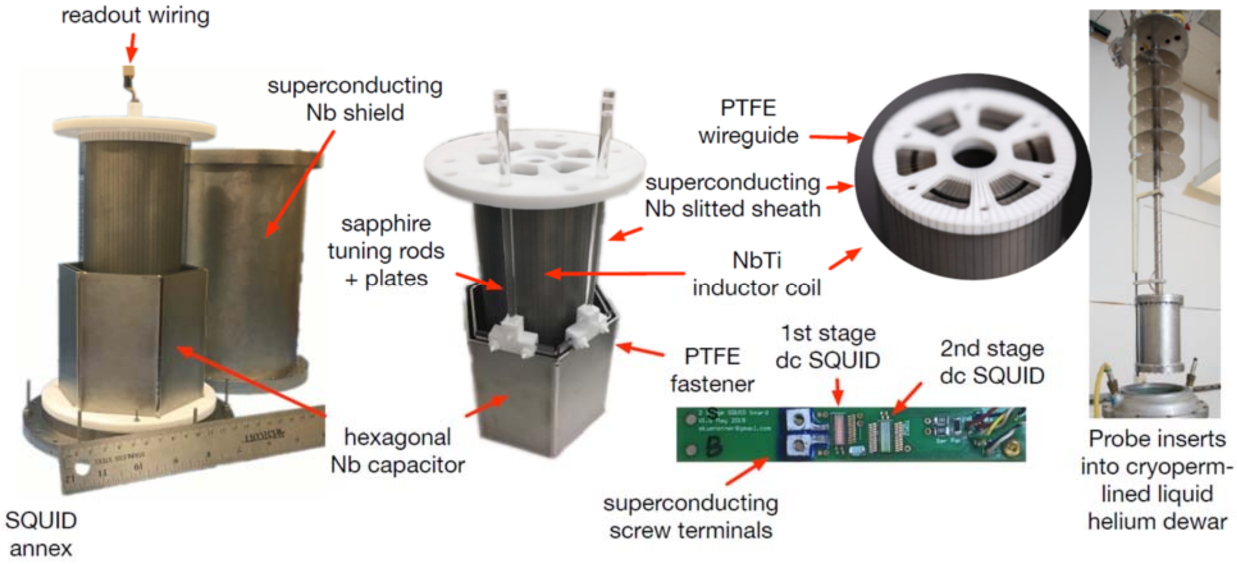

Fig. 1. The DM Radio Pathfinder detector, including the two insertable sapphire plates which are now being used to tune the resonator. The dc SQUID is mounted in a superconducting shield "annex" located at the bottom of the shield. Superconducting input connections (Nb wirebonds and Nb screw terminals) connect the dc SQUID to the slitted sheath. The cryogenic dip probe supports the detector in a bath of liquid helium. The helium dewar contains additional Cryoperm magnetic shielding to reduce interference.

Quantum Sensors for Light-field Dark Matter Searches

PI: Kent Irwin (Stanford, SLAC), Co-PIs: Peter Graham (Stanford), Alexander Sushkov (Boston University), Dmitry Budker (Mainz, Berkeley), Derek Kimball (Cal State East Bay)

Non-classical techniques that exploit quantum correlations can enable searches for ultralight dark-matter waves. Measurements below the Standard Quantum Limit (SQL) are more efficient and sensitive, opening opportunities to reveal new fundamental physics. We are developing quantum sensors for the detection of ultralight dark-matter waves, including the QCD axion. The detection of the QCD axion would both solve the Strong CP problem and identify the nature of the dark matter in our galaxy. These quantum sensors, which are based on photon upconverters, greatly accelerate searches for QCD axions below 1 micro eV. The DM Radio and CASPEr axion haloscopes search for the flux of dark matter caused by the motion of Earth through the galactic dark matter halo. They are sensitive to the axion's couplings to electromagnetism (DM Radio), gluons (CASPEr-Electric), or nuclear spin (CASPEr-Wind). DM Radio uses resonant electromagnetic modes, while the CASPEr experiments search for the influence of the axion field on highly coherent samples of nuclear spins. The RF Quantum Upconverter (RQU) will enhance both DM Radio and CASPEr, enabling the QCD axion band to be fully probed over about 60% of its allowed mass range, including all masses below 1 micro eV (down to the Planck-scale cutoff below 1 picoeV).

Radio-frequency quantum upconverters (RQUs) controllably couple a low-frequency signal (e.g. at the dark-matter Compton frequency) to a superconducting resonator, upconverting the signal to microwave frequencies, where it is processed with coherent superconducting quantum techniques. The RQU is a flexible platform for quantum mechanical readout and state preparation techniques, including sideband cooling, two-mode squeezing, and backaction evasion (BAE). Figure 1 shows RQU devices fabricated at SLAC/Stanford using a Nb ground plane and Nb trilayer Josephson junctions. Fig. 1(d) shows a single-junction design, and Fig. 1(f) shows a more advanced design with three Josephson junctions.

In a BAE measurement, the upconverter acts as a phase-sensitive amplifier, selectively amplifying a single quadrature of the signal with reduced quantum backaction noise. The other quadrature is not amplified and is subject to enhanced backaction noise. Overall, substantial sensitivity gains are possible in the single quadrature. As the first milestone to backaction evasion, we have demonstrated phase-sensitive gain with 29.6 dB of quadrature gain contrast. This result is shown in figure 1(g) and is a significant step towards the implementation of a full backaction-evasion protocol.

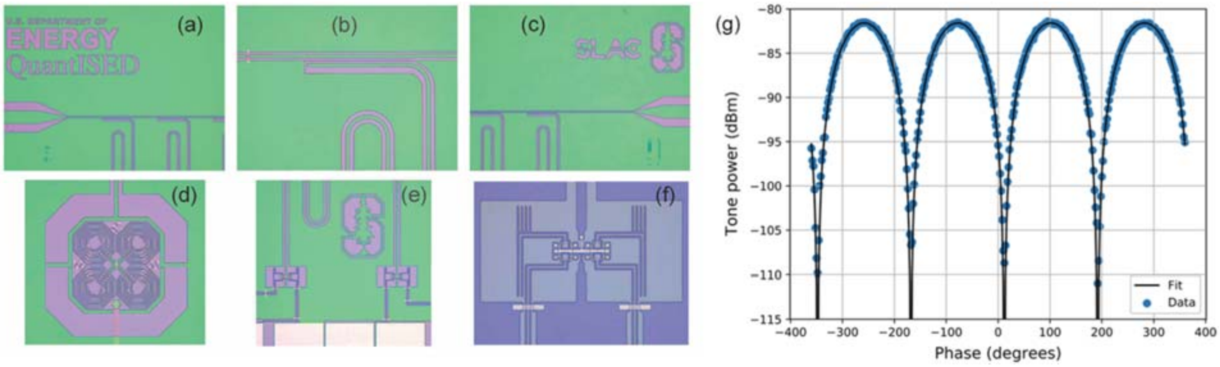

Fig. 1. RQU devices. (a) Microwave port where the 6 GHz carrier is launched onto a coplanar waveguide. (b) A quarter-wave resonator capacitively coupled to the coplanar waveguide. (c) Launch for microwave output port (d) single-junction RQU (e) Two three-junction RQUs multiplexed on the same feedline with different resonant frequencies. (f) Close in view of three-junction RQU. (g) Data showing phase sensitive gain. Output tone power is plotted for fixed input 50 kHz signal at fixed phase. The phase offset between a 50kHz input signal and the 50kHz AM carrier envelope is swept through 720 degrees. The maximum observed contrast between the gain for the X and Y quadratures was 29.6dB.

The Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology

Raphael Bousso[1], (Principal Investigator)
Ehud Altman[1], Ning Bao[1], Patrick Hayden[2], Christopher Monroe[3], Yasunori Nomura[1], Xiao-Liang Qi[2], Monika Schleier-Smith[2], Brian Swingle[3], Norman Yao[1], Michael Zaletel[1]

Research in quantum gravity has been accelerating thanks to powerful tools and insights from quantum information theory. At the same time, developments in quantum gravity are feeding back into quantum information science, leading to a rich interplay between these two fields. This collaboration aims to identify and develop nascent connections in key areas, including the black hole information problem and quantum information scrambling; the emergence of spacetime from entanglement via quantum error correcting codes; low energy applications and information theoretic interpretations of energy conditions originally derived in a quantum-gravitational context; and the dynamics of wormholes and its relation to quantum teleportation. A key feature of our collaboration is a focus on near term quantum devices: what are the quantum technologies that might arise from quantum gravity? Which puzzles about quantum gravity might be addressed with such quantum devices? A central organizing principle is the use of tensor networks, which were originally developed for understanding the structure of low-energy quantum states in nonrelativistic many-body systems. Quantum gravity research has shown that tensor networks can be used to model the emergence of spacetime geometry from an underlying quantum theory. At the same time, the appropriation of tensor networks for the study of quantum gravity and black holes has inspired novel applications elsewhere. Tensor networks can be calculational tools, useful not only for describing ground states, but also for elucidating the dynamics of quantum information in strongly coupled systems. As such, our collaborations is comprised of several distinct components. First, we have three distinct quantum device platforms, each with its unique advantages in probing quantum physics as inspired by holography and quantum gravity. Second, we have a team of high energy and quantum information theorists that are well-versed in (and in some cases, discovered) the emerging connections between quantum information and quantum gravity. Finally, we also have several experts in condensed matter/AMO physics to help translate these questions into a form that can be implemented by the experimental component of the collaboration. Examples of specific current projects include the study of scrambling, probing quantum energy conditions, studying the dynamics of quantum chaos, and benchmarking quantum error correcting codes inspired by holography.

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Nanowire Detection of Photons from the Dark Side

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Masha Baryakhtar,[4] Robert Lasenby,[6] Junwu Huang,[3] Marco Colangelo [1]

In this project, we design a dark photon dark matter detector that will be able to search for mass ranging from 10 meV to 10 eV. Existing searches for dark matter have so far covered only a small fraction of the 90 orders of magnitude of potential mass-parameter space in which it could exist. In recent years, the development of fast and low-dark-count single-photon detectors for photonic quantum information applications promise a radical improvement in our capacity to search for dark matter. The advent of superconducting nanowire detectors, which have fewer than 1 dark counts per day and have demonstrated sensitivity from the mid-infrared to the ultraviolet wavelength band, provides an opportunity to search for bosonic dark matter in the neighborhood of 1 eV. These detectors are simple to fabricate and operate, and can be combined with gas cells, dielectric stacks, or combinations of these structures in cryogenic targets, optimized for dark matter absorption. Furthermore, superconducting nanowires can be used as both target and sensor for direct detection of sub-GeV dark matter [1].

In this work, we combine resonator systems and quantum large-area single-photon detector, to establish a novel paradigm to look for dark matter with rest mass energies in the range of meV to 10 eV. Bosonic dark matter waves will coherently interact with both gaseous and solid materials to create a quantum superposition of excited states, which will efficiently convert the individual dark matter absorption quanta into single photons Inherently resonant systems at these energies—narrow molecular absorption transitions [2] and periodically layered dielectric stacks [3] —bring with them a range of advantages: selectivity, control, and natural background reduction. We report our measurements to measure the background/dark count rate of the nanowire intrinsically (not coupled to dark matter resonator). Our latest measurements indicate 3 counts with total integrated time 84 h 17 min. This count rate is roughly consistent with potential counts from background natural radioactivity and cosmic-ray muons. In the short term, we are developing new detector designs to confirm this hypothesis. However, even with our recently measured performance, future experiments using SNSPDs should enable probing new territory in the detection landscape, establishing the complementarity of this approach to other existing proposals.

[1] Y. Hochberg, I. Charaev, S.-W. Nam, V. Verma, M. Colangelo, K. K. Berggren, Phys. Rev. Lett. 123, 151802, 2019.

[2] A. Arvanitaki, S.Dimopoulos, and K. V. Tilburg, Phys. Rev. X8, 041001, 2018.

[3] M. Baryakhtar, J. Huang, and Robert Lasenby, Phys. Rev. D 98, 035006, 2018.

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Algebraic approach towards quantum information in quantum field theory and holography

PI: Daniel Harlow

Co-PIs: Aram Harrow and Hong Liu

Massachusetts Institute of Technology

This is a proposal for a two-year research grant from the DOE Office of Science to study connections between algebraic quantum field theory, holographic quantum codes, and approximate Markov states. These subjects have all been of much recent interest: the algebraic approach to quantum field theory has recently been used to prove remarkable general results such as the quantum null energy condition, and holographic quantum codes have given us a new perspective on classic problems in quantum gravity. In both cases the technical tools which lead to the new results can be understood as using the special properties of ``quantum Markov states''; states which saturate strong subadditivity. These states are also very interesting in quantum computing, with applications to quantum error-correction, efficient preparation of Gibbs states on quantum computers, efficient compression with side information, and many other areas.

Our proposal is to do a combined study of these three issues, seeking to systematically understand the connections between them. We are optimistic that this will lead to many new insights about quantum field theory, quantum gravity, and quantum information.

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.

Quantum Information in a strongly interacting quantum simulator: from gauge/string theory duality to analogue black holes

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The AdS/CFT correspondence implies that, in the strongly interacting regime where quantum effects are large, systems encode and transmit information in a very different way than they do at weak coupling. In particular, from the quantum mechanics of a field theory emerges a higher dimensional space time with non-trivial metric and gravity. Important as they are for the theory of quantum information, wider applicability of these ideas to Quantum Information Science (QIS) requires controllable experimental systems where similar ideas apply. Inspired by this far reaching ideas, we consider an experimental setup where an atomic quantum gas in an optical lattice is driven into a strongly coupled quantum critical regime. The system can be described by the Bose-Hubbard model and the critical region of interest by the O(2) three dimensional Wilson-Fisher fixed point. Theoretically this system is studied with a combination of techniques valid in various regimes, including, mean-field theory, 4-e expansion, conformal bootstrap, numerical simulations and qualitative ideas from AdS/CFT. Experimentally a 2D quantum gas is formed by evaporative-cooled cesium atoms trapped in an oblate optical potential to ensure a large surface area (> 400μm) occupying > 50x50 lattice sites. Recently we already performed interaction quench in a 2D quantum gas from repulsive to attractive interactions and studied its collapse dynamics observing the formation of localized excitation known as Townes solitons, a remarkable scale-invariant stationary state in two dimensions.

The main objective is to create and study the time evolution of entanglement between separated regions of space. As a result, we will get a new understanding into the encoding and transmission of quantum information in this and possible other strongly interacting systems.

Various techniques of measuring entanglement will be tried following ideas in the literature. Our immediate goals are to (1) use existing and newly developed theoretical tools to study the creation and evolution of entanglement in strongly coupled systems, and design experimental tests that can be carried out in the systems to which we already have experimental access, (2) develop new experimental techniques for synthesizing highly controllable strongly coupled quantum gases, and (3) perform the experimental tests and compare the results with the theory

Further goals include the manipulation of the local sound speed to create far from equilibrium states such as shock-waves and sonic black holes that should create large amounts of entanglement and lead to new quantum phenomena in strongly coupled systems. Further we plan to study circuit complexity in these quantum systems.

Interplay of quantum information, thermodynamics, and gravity in the early Universe

Nishant Agarwal,[1] Adolfo del Campo,[2,3] Archana Kamal,[1] and Sarah Shandera[4]

The early Universe is a rich testbed of quantum gravity and out-of-equilibrium quantum physics in general. The goal of this proposal is to explore fundamental questions in both domains: quantum origins of the early Universe and strongly-interacting quantum matter. Specifically, our proposal is divided into the following four goals.

Goal 1: Develop a quantum framework for the early Universe. We are using open quantum system techniques to study the dynamics of observable modes in the Universe; in particular we focus on the non-Markovian vs. Markovian evolution of system modes, quantum correlations, and signatures in late-time observables. We find non-Markovian dynamics in inflation and interacting quantum field theories and are currently investigating Markovian dynamics, renormalization in open systems, late-time resummations, and implications for inflationary correlators.

Goal 2: Explore resource theory techniques for initial conditions. We are using tools from quantum resource theory and thermodynamics to explore why it appears imperative to postulate a low entropy initial state of the Universe. We have studied low-entropy configurations in few-qubit systems and plan to extend our results to understand implications for gravity.

Goal 3: Investigate open system dynamics in strongly-coupled systems. We are investigating open quantum system dynamics in strongly-coupled qubit and oscillator systems; in particular we focus on detailed studies of entanglement dynamics, backaction cooling in the strong-coupling regime, the quantum-to-classical transition in open systems, and experimental realizations. We have obtained entanglement timescales in open systems, shown how to cool quantum systems in the strong-coupling regime, and demonstrated how dynamical switching effects can be used to study quantum-to-classical transitions.

Goal 4: Establish thermodynamics for chaotic quantum systems. We plan to understand the thermodynamics of chaotic quantum systems, with emphasis on the dynamics of information scrambling, and implications for black hole solutions in AdS/CFT and quantum gravity. We have studied the evolution of continuously monitored quantum systems, obtained bounds on timescales of correlators in isolated many-body systems, and studied the limits that quantum theory imposes on thermodynamics.

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Quantum Computing for Neutrino-nucleus Dynamics

Joseph Carlson[1], Rajan Gupta[1], Andy C.N. Li[2], Gabriel Perdue[2], Alessandro Roggero[3]

Uncertainties in neutrino-nucleus cross section are expected to be a dominant systematic in future accelerator neutrino experiments. The cross sections are determined by the linear response of the nucleus to the weak interaction with the neutrino. To understand the final states observed in the detector one has to model the initial state (dominated by energy and distance scales of the order of the separation between nucleons in the nucleus) and the struck state and then evolve it quantum mechanically and calculate the response functions that encode information about the final states observed in the detectors. We show progress towards the calculation of these response functions. We will present an analysis of required resources and expected scaling for scattering cross section calculations. We also examine simple small-scale neutrino-nucleus models on modern quantum hardware using variational methods to obtain the ground state and then implement the relevant time evolution. In order to tame the errors in present-day NISQ devices we explore the use of different error-mitigation techniques to increase the fidelity of the calculations. Details of the calculations and methodology are given in Ref. [1].

[1] "Quantum Computing for Neutrino-nucleus Scattering"
Alessandro Roggero, Andy C.-Y. Li, Joseph Carlson, Rajan Gupta, Gabriel Perdue,
arXiv:1911:06368.

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Quantum-Enhanced Metrology with Trapped Ions for Fundamental Physics

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John Bollinger[2], Gabe Lynch[1]

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Trapped atomic ions have exceptional properties as quantum sensors to answer questions in fundamental physics [1]. They offer long coherence times, precise control of their internal and external quantum states and the ability to produce interesting entangled states with high fidelity. Because of these properties they have been used in the most accurate atomic clocks [2] and the highest-fidelity quantum gates [3] to date. Measurements with these systems provide the most stringent constraints on the drift of fundamental constants [4], the parameters of ultralight dark matter models and violations of relativity [5], to name a few. Further improvements in all these applications can be made by developing new quantum techniques to enhance measurement sensitivity. We have recently demonstrated such techniques in multiple experiments using trapped-ion optical clocks and many-ion ensembles in a Penning Trap [6]. We will describe this recent progress and our current efforts to extend these techniques to further tests of fundamental physics. Additionally, we have developed a large-scale simulation capability for quantum condensate dark matter based on an extreme-scale spectral method that is designed for exascale compute platforms.

[1] M. S. Safronova et al., Rev. Mod. Phys. 90, 025008 (2018)
[2] S. M. Brewer et al., Phys. Rev. Lett. 123, 033201 (2019)
[3] J. P. Gaebler et al., Phys. Rev. Lett. 117, 060505 (2016)
[4] T. Rosenband et al., Science 319, 1808 (2008)
[5] C. Sanner et al., Nature 567, 204 (2019)
[6] K. A. Gilmore et al., Phys. Rev. Lett. 118, 263602 (2017)

Skipper-CCD: new single photon sensor for quantum imaging

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Quantum imaging addresses the possibility of beating the limits of classical imaging by exploiting the peculiar properties of quantum optical states, such as entanglement. Skipper-CCD present new opportunities in the field of quantum imaging. Here, we will report progress on three thrusts. First the imaging on entangled photons produced in spontaneous parametric down conversion with skipper-CCD. Second, the design a new faster skipper-CCD optimized for quantum imaging applications. Finally, we will discuss the potential use of non-linear optics for the search of entangle dark photons.

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Entanglement in String Theory and the Emergence of Geometry

Veronika Hubeny,[1] Mukund Rangamani,[2]

This project seeks to enlarge our understanding of nature by using newly-found connections with quantum information and quantum gravity. Hitherto, the best-understood context utilizes the gauge/gravity duality in a regime where the quantum effects of the gravitational theory are strongly suppressed: we have some (still rather limited) understanding how classical spacetime encodes certain quantities used in quantum information theory such as entanglement entropy. Over the last decade, we have come to regard such connections not as mere curiosities or coincidences but as profound and tantalizing hints into the fundamental nature of spacetime. However, to answer the long-standing questions of quantum gravity, we need to understand much more than just this near-classical spacetime regime: we need to explicate these connections in the quantum regime as well.

The overall aim of the project was to initiate a long-term research program which primarily transcends current investigations in the subject, and provides a platform for formulating the correspondence between entanglement and geometry directly at the level of the full string theory Hilbert space. Some of the directions the Investigators propose to explore are to understand how entanglement structures get repackaged across dualities (be they field theory dualities or more general open-closed string dualities), and to develop tools inspired by operator algebras to understand the emergence of locality in string theory. These investigations will draw from developments in general relativity, quantum field theory, string theory, and quantum information and will provide a concrete framework to further the connections between entanglement and geometry.

To this end, we explore two related questions. First, we wish to gain a deeper understanding of how spatially organized entanglement in quantum field theory maps under the holographic duality to the string theoretic dual. Second, we wish to ascertain if there is an intrinsic notion of entanglement directly within a quantum gravitational theory such as string theory. Aside from work in progress, the research accomplishments to date include:

- *Topological string entanglement*, Veronika E. Hubeny, Roji Pius, Mukund Rangamani, JHEP 1910 (2019) 239, [arXiv:1905.09890]
- *The holographic entropy arrangement*, Veronika E. Hubeny, Mukund Rangamani, Massimiliano Rota, Fortsch.Phys. 67 (2019) no.4, 1900011, [arXiv:1812.08133]

The themes of the research program focus on the foundational questions in high energy and quantum information areas. As such they lie within the remit of the HEP mission and P5 science drivers and they seek to forge new pathways to interdisciplinary progress in both fields.

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QIS for Applied Quantum Field Theories

Marcela Carena (PI)[1], John Preskill(Co-PI)[2], David B. Kaplan (Co-PI)[3], Martin Savage (Co-PI)[3]

Silas Beane[3], Alex Buser[2], Anthoney Ciavarella[3], Stephan Casper[3], Roni Harnik[1], Ciaran Hughes[1], Natalie Klco[3], Andreas Kronfeld[1], Henry Lamm[1], Junyu Liu[2], Alexandru Macridin[1], Ashley Milsted[2], James Simone[1], Jesse Stryker[3], Michael Wagman[1].

Quantum Information Science (QIS) is undergoing rapid development and the High Energy Physics (HEP) research program can both significantly benefit from, and contribute to, advances in this area. The ability to control quantum systems, including single-particle, many-particle, and macroscopic systems, is becoming feasible in laboratories around the world. This opens new opportunities to leverage the power of quantum computers and quantum devices to perform fully-controlled, simulations of Quantum Field Theory (QFT) and systems that are important to HEP.

The aim of the project is to explore the connections between QIS and QFT in high energy physics. We investigate the broad topic of Quantum simulation of QFT's in all its aspects. Specific topics of interest include simulation-suitable formulations of gauge theories [1] and the enforcement of Gauss' law [2], field digitization [3,4], initial state preparation [5], identifying HEP-related observables in simulations [6], error correction [7], and entanglement and symmetries [8]. We are exploring strategies for simulation of scattering in simple QFTs, and dynamics of domain walls and their interaction with particles, which may be relevant for phase transitions in the early Universe.

Going forward, we plan to further enhance the QIS Theory Consortium, integrating related ongoing QuantISED efforts. Uniting analysis techniques in HEP with cutting-edge advances in QIS, we will consider quantum algorithms for LHC data analysis. We will explore and support Fermilab-based quantum sensor searches for new physics. In the area of quantum simulation, near and medium term algorithms will be further developed. These will be used for simulations of HEP-related systems on available quantum devices, including collaborative efforts with Rigetti, and launching a new co-development effort on Superconducting Radio Frequency (SRF) devices at Fermilab. We aim at unleashing the QIS potential and identify quantum advantages for new directions in HEP.

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[1] N. Klco, J. R. Stryker, and M. J. Savage, "SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers," arXiv:1908.06935 [quant-ph].

[2] J. R. Stryker, "Oracles for Gauss's law on digital quantum computers," Phys. Rev. A99 (2019) no. 4, 042301,arXiv:1812.01617 [quant-ph].

[3] D. C. Hackett, K. Howe, C. Hughes, W. Jay, E. T. Neil, and J. N. Simone, "Digitizing Gauge Fields: Lattice Monte Carlo Results for Future Quantum Computers," Phys. Rev. A99 (2019) no. 6, 062341, arXiv:1811.03629 [quant-ph].

[4] N. Klco and M. J. Savage, "Digitization of scalar fields for quantum computing," Phys. Rev. A99 (2019) no. 5, 052335, arXiv:1808.10378 [quant-ph]. A. Macridin, P. Spentzouris, J. Amundson, and R. Harnik, "Electron-Phonon Systems on a Universal Quantum Computer," Phys. Rev. Lett. 121 (2018) no. 11, 110504, arXiv:1802.07347 [quant-ph].

[5] N. Klco and M. J. Savage, "Minimally-Entangled State Preparation of Localized Wavefunctions on Quantum Computers,"arXiv:1904.10440 [quant-ph].

[6] H. Lamm, S. Lawrence, and Y. Yamauchi, "Parton Physics on a Quantum Computer," arXiv:1908.10439 [hep-lat].

[7] P. Faist, S. Nezami, V. V. Albert, G. Salton, F. Pastawski, P. Hayden, and J. Preskill, "Continuous symmetries and approximate quantum error correction," arXiv:1902.07714 [quant-ph].

[8] S. R. Beane, D. B. Kaplan, N. Klco, and M. J. Savage, "Entanglement Suppression and Emergent Symmetries of Strong Interactions," Phys. Rev. Lett. 122 (2019) no. 10, 102001, arXiv:1812.03138 [nucl-th].

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Quantum Communication Channels for Fundamental Physics

Maria Spiropulu (PI)[1], Daniel Jafferis [2] , Cristian Pena [3] , Si Xie [1], Neil Sinclair [1,2] , Panagiotis Spentzouris [3]
Joseph Lykken[3] Nikolai Lauk [1], Raju Valivarthi [1]

The main theory goal of this project is to find teleportation circuits that realize causal propagation of the quantum information through an emergent traversable wormhole. The general framework is that the collective description of highly entangled chaotic quantum systems, analogous to the hydrodynamic description of atomic motion in a fluid, involves dynamical spacetime in an extra dimension. Moreover, the correspondence is conjectured to be an exact duality, so that if one knew how to include all quantum gravitational effects, the gravity side would precisely reproduce the behavior of the quantum system. Realizing wormhole teleportation would have several important implications. First, it would exhibit clear signatures of the gravitational physics that expected to describe highly entangled states. The teleportation protocol is crucial as it allows a causal probe of the ER=EPR wormhole dual to entanglement. Second, quantum circuits that realize teleportation through a wormhole are expected to have interesting quantum error protection properties. I addition wormhole teleportation serves as a useful benchmark of quantum circuit platforms, as they give sensitive tests of the fidelity of the circuit.

The experimental goal of the project involves the photon-based quantum teleportation experiment, namely the Fermilab Quantum Network (FQNET) and associated testbeds at Caltech in collaboration with JPL advanced photonics systems. The experimental platform offers a robust test bed for the study of quantum entanglement distribution using simple at start, and more complex eventually, protocols. Here we describe the topic of photon-based quantum teleportation on the Fermilab Quantum Network (FQNET) and the Caltech Quantum Network (CQNET). The system of these quantum teleportation experiments at Fermilab and Caltech offer a robust test bed for the study of quantum entanglement distribution using simple at start, and more complex eventually, protocols.

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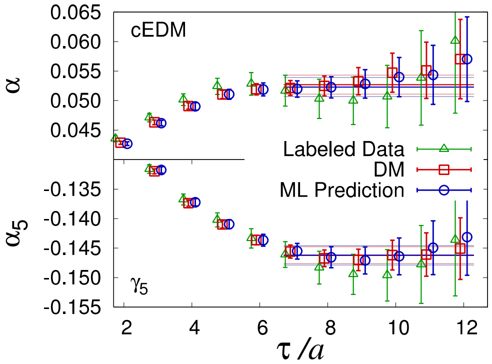
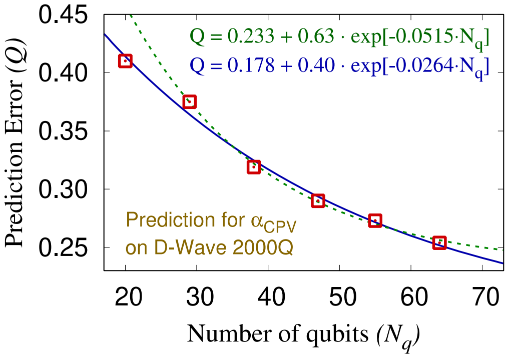
Quantum Machine Learning for Lattice QCD

Boram Yoon and Nga Nguyen (Los Alamos National Laboratory)



We established a machine learning (ML) approach for enhancing lattice quantum chromodynamics (QCD) calculations. By exploiting the correlation between the lattice QCD observables, ML-based prediction was able to replace computationally expensive direct calculations of some observables and reduce computational cost by 7% - 38%, depending on the observables. The approach includes bias correction and error estimation for the inexact ML predictions, which is essential for a scientific ML. The algorithm and applications are published in [1, 2]. Figure on the right-hand side shows the [red squares] direct measured (DM) CP-symmetry violating (CPV) phase α induced from the quark chromo-electric dipole moment (CEDM) interactions and [blue circles] its machine learning prediction (ML Prediction) only from the calculation without CEDM.



We also developed a ML regression algorithm that utilizes a learned dictionary optimized for sparse inference on a D-Wave quantum annealer. The regression algorithm encodes the high-order correlations between the dependent (output) and independent (input) variables into a dictionary optimized for sparse reconstruction. Here, we employ the quantum annealing to explore the complex energy landscape and solve the highly non-convex sparse coding optimization problem. The algorithm is demonstrated with a proof-of-principle study performed on the lattice QCD observables using D-Wave 2000Q and showed promising prediction performance. The results are published in [3]. Figure on the left-hand side shows the prediction error of the proposed regression algorithm on the D-Wave for the CEDM CPV phase α as a function of the number of qubits. Current prediction performance is limited by the maximum number of fully connected logical qubits that can be embedded on the quantum annealer, which is 64 for D-Wave 2000Q.

[1] Boram Yoon, Tanmoy Bhattacharya, Rajan Gupta, *"Machine Learning Estimators for Lattice QCD Observables"*, Phys. Rev. D 100, 014504 (2019)

[2] Rui Zhang, Zhouyou Fan, Ruizi Li, Huey-Wen Lin, Boram Yoon, *"Machine-Learning Prediction for Quasi-PDF Matrix Elements"*, arXiv:1909.10990 (2019)

[3] Nga T. T. Nguyen, Garrett T. Kenyon, Boram Yoon, *"A regression algorithm for accelerated lattice QCD that exploits sparse inference on the D-Wave quantum annealer"*, arXiv:1911.06267 (2019)

Quantum Machine Learning and Quantum Computation Framework in HEP

Maria Spiropulu (PI)[1], Seth Lloyd [2] , Daniel Lidar[3] , Panagiotis Spentzouris [4] Jean-Roch Vlimant [1], Javier Duarte [4,5], Joshua Job [6]

The QMLQCF program enhances and promotes the collaboration between the QIS and HEP by extending and improving the Higgs QML work preceding this project, and further demonstrating usability of quantum machine learning and quantum annealing in HEP problems, like charge particle tracking. The program opens opportunities for further investigation of research of QIS/HEP and solutions for the HL-LHC and other HEP challenges. From the QIS perspective using quantum annealing as well as using quantum enhanced feature spaces for kernel methods (e.g. on the Higgs background/signal classification problem) are instances of problems where the existence of a quantum speed-up is an open question. For both of these, fault-tolerant quantum computation is not required. Moreover, they represent a class of methods which can be implemented and are suitable for noisy intermediate-scale quantum (NISQ) hardware. Given that we are now seeing access to less restricted NISQ hardware, studying these problems empirically allows us to explore their limits and their theory. Working on these methods with respect to actual HEP problems orients us towards the kind of hardware that will be required to run real world problems. From the HEP perspective, as it is believed that we are moving towards a regime where Moore's law shall no longer hold true, we do not expect a drastic increase in classical computing power over time. Given the LHC upgrades to high luminosity, the computational needs grow immensely for most intensive problems. Hence, there is a need for faster hardware-specific implementations in HEP, for example, using FPGAs, GPUs or classical annealers. Near-term quantum hardware provide another such approach, where a potential quantum speedup or powerful co-processing can be exploited for advancing HEP. Specifically, this work may lead to the development of new low latency triggers using quantum algorithms. It can also allow for more rapid development and deployment of FPGA algorithms (by speeding up time needed to route the firmware) and better neural network optimization and compression algorithms. Additionally our QMLQCF research program is designed to answer hard and unsolved questions: Why do deep classical neural networks learn and generalize well? Can quantum networks outdo classical networks for analyzing certain types of data? Can we develop quantum inspired algorithms for performing inference and learning more effectively? If quantum networks can indeed outperform classical networks for machine learning tasks, this will have a transformative effect on quantum information processing: a wide set of novel applications for

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quantum computation will be opened up, with large potential benefits for society in terms of data handling and analysis. Finally within this program we study machine learning methods towards optimization of quantum circuits that realize teleportation protocols developed in the QCCFP QuantiSED Consortium and explore connections of renormalization-gorup flow with theories of learning.

Quantum simulations: from spin models to gauge-gravity correspondence

Vladan Vuletic,[1] Mikhail D. Lukin[2]

We use programmable quantum simulator, consisting from arrays of individually trapped atoms excited into Rydberg states, to gain critical insights into outstanding problems at the interface of many-body quantum physics and high energy physics (HEP). Over the past year, in the pilot project supported jointly by DOE and DoD, we used this new platform for the realization and study of quantum phase transitions and quantum dynamics in one-dimensional spin models. In this system we observed transitions into ordered states that break various symmetries, verified high-fidelity preparation of ordered states, and investigated quantum critical dynamics in large arrays of atoms. Our studies in the pilot phase focused on quantum dimer models and chiral clock models associated with transitions into states with various broken symmetries. To study these phases, we measured the growth of spatial correlations while crossing various quantum phase transitions. For the Ising-type phase transition, we experimentally verified the quantum Kibble-Zurek mechanism (QKZM), explored scaling universality, and observed corrections beyond QKZM predictions. This approach was then used to measure the critical exponents associated with chiral clock models, providing new insights into exotic systems that have not been understood previously, and opening the door for precision studies of critical phenomena and simulations of lattice gauge theories (LGT). In addition to using dynamics to probe quantum criticality, we discovered novel many-body dynamics involving persistent oscillations of an order parameter after a sudden quantum quench. These surprising oscillations have stimulated a great deal of new theoretical work into these “many-body scars”, which challenge the standard notions of thermalization in closed quantum systems. Specifically, we showed that this dynamics can be understood as resulting from special initial states that feature very slow entanglement growth that can be described in terms of Matrix Produce States (MPS) with low bond dimension. Recent technical upgrades, allowed us to implement high fidelity quantum operations and to generate large scale quantum entanglement using this system. By adding light shifts to specific atoms using off-resonant laser beams generated by an AOD, we demonstrated that it is possible to engineer the many-body energy spectrum. Combining these techniques with the use of the optimal control protocol to vary the control parameters, we realized the generation of N-partite entangled Greenberger- Horne-Zeilinger (GHZ) states in system sizes up to N = 20, the largest GHZ state produced to date. Our optimized pulse sequence is equivalent to an N-qubit quantum circuit with depth p such that Np ~400 with total probability of error < 0:5. In addition, we used our setup to realize high-fidelity multi-qubit gate operations for qubits encoded within the atomic hyperfine states. We also used novel approach to trapping to realize two-dimensional arrays containing more than 200 individually addressable atoms. These advances open the door for large scale quantum simulations of LGTs in one and two spatial dimensions and for realizing many-body analog of traversable wormhole teleportation.

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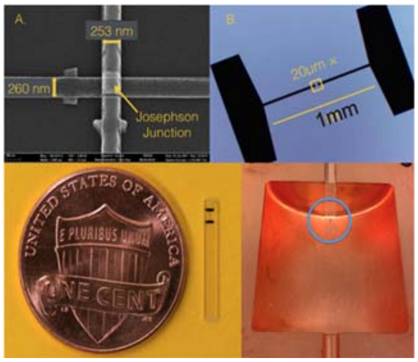
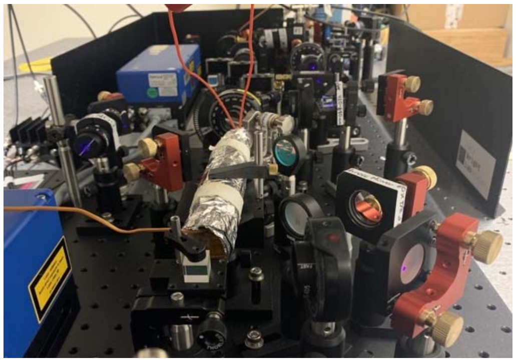
Quantum Metrology for Axion Dark Matter Detection

Aaron S. Chou (Fermilab), Konrad Lehnert (U.Colorado/JILA/NIST), Reina Maruyama (Yale),
David Schuster (U.Chicago)

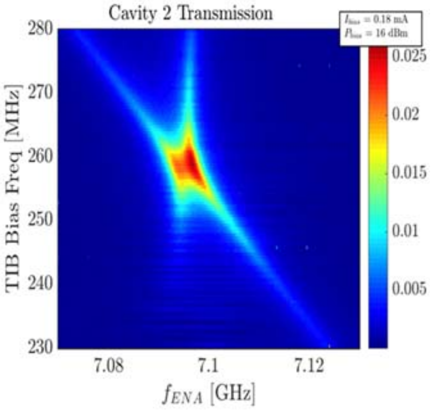
This consortium seeks to develop quantum-enhanced techniques to enable the detection of dark matter waves composed of QCD axions – new particles hypothesized to solve the strong-CP problem, i.e. the 70-year mystery of the vanishing neutron electric dipole moment. While current axion experiments are already operating near the standard quantum limit (SQL) noise of phase-preserving amplifiers, new microwave single-photon sensing technologies being developed will avoid the quantum zero-point noise by measuring only the signal wave's amplitude while ignoring the conjugate phase observable. For example, qubits (superconducting transmons or Rydberg atoms) can be used to perform quantum nondemolition measurements by nondestructively sensing the electric field of individual signal photons generated by the axion dark matter. This sensor can output yes/no (1 or 0) answers for whether it sees a signal, and has demonstrated readout noise levels far below the SQL. Also being developed is a high fidelity transport mechanism to shuttle probe photon states between field-free regions where the quantum sensors reside and the region with high magnetic field required to enable the dark matter interaction. Together these innovative technologies will enable future experiments to reach sensitivity to the long sought-after QCD axion and probe new physics from atomic to cosmological scales.



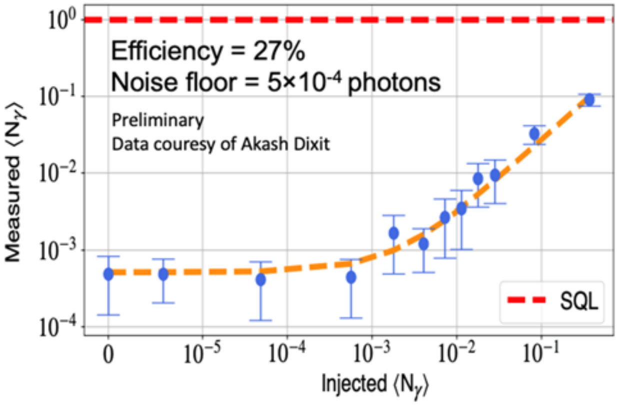
A superconducting qubit exhibits a quantized frequency shift in the presence of background cavity photons.



Cold Rydberg atoms can also be used to sense single photons by either frequency shift or by direct absorption.



An upconverting superconducting parametric mixer is used to transport photon states between two cavities.



Repeated quantum nondemolition measurements with a transmon qubit reduces the readout noise down to the residual thermal tail population, far below the SQL.

Quantum Enhanced Detection of Dark Matter and Neutrinos

A.B. Balantekin (PI),[1] Susan Coppersmith (Co-I),[2] Kim Palladino (Co-I),[1] Mark Saffman (Co-I),[1] Calvin Johnson (Co-I),[2] Peter Love (Co-I),[3] and Raphael Pooser (Co-I)[4]

Quantum simulation has the potential to enhance greatly the capabilities of dark matter experiments because it could enable the determination of the detailed many-body wavefunctions of the relevant targets with much more precision than is possible with current classical computations. In this project, an interdisciplinary team of theoretical and experimental physicists, computational physicists, as well as quantum computational scientists exploits the power of quantum computation to understand the response of various possible dark matter detectors via improved understanding of the interactions between dark matter particles and noble gas targets. Recent work based on effective field theories has demonstrated that symmetry constraints on the interactions between dark matter and detectors allow more than two interaction channels previously considered, and it is of great importance to understand the response of different targets to all possible effective operators governing these interactions.

A major component of the research plan is to understand and mitigate the behavior of the neutral atom array so that high accuracy and precision calculations can be performed. In other contexts it has been shown that correction and mitigation schemes that are tailored to the physics of the system have the potential to greatly enhance the ability to overcome errors and decoherence. The performance of the neutral atom array hardware has been substantially improved during the first year of this project [1].

Neutrino-neutrino interactions can have a substantial effect on neutrino flavor evolution in supernovae and subsequent detection at DUNE. We have investigated the quantum characterization of relevant many-body models, studying the time-dependence of entanglement entropy in a dynamical model of neutrino flavor evolution under the effects of neutrino-neutrino interactions, and focusing on the question of whether concepts from the field of quantum information can provide useful insight into the physics of supernova detection [2].

In addition to computing detector response to dark matter particles; one has to know the uncertainty in that response, when one is trying to compute an upper limit from an experiment consistent with zero signal. In a preliminary analysis we quantified and propagated the uncertainty in a high-quality phenomenological interaction for a selected dark matter target [3].

[1] T. M. Graham, M. Kwon, B. Grinkemeyer, Z. Marra, X. Jiang, M. T. Lichtman, Y. Sun, M. Ebert, and M. Saffman, Phys. Rev. Lett. (in press), arXiv: 1908.06103.

[2] M.J. Cervia, A.V. Patwardhan, A.B. Balantekin, S.N. Coppersmith, and C.W. Johnson, Phys. Rev. D **100** (2019), 083001.

[3] J.M.R. Fox and C.W. Johnson, arXiv: 1911.05208.

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NECQST: Novel Electronics for Cryogenic Quantum Sensors Technology

D. Braga, FNAL; J. D. Cressler, GeorgiaTech; M. Shaw, JPL; M. Spiropulu, Caltech

Superconducting nanowire single photon detectors (SNSPDs) are the highest performing detectors available for time-correlated single photon counting from the deep UV to the mid-infrared. SNSPDs have been widely adopted within the quantum information science (QIS) community to enable, among others, fundamental tests of quantum physics, long-distance quantum communication, and quantum computing with trapped ions.

By leveraging recent advances in cryogenic transistor technology and the expertise in high-speed detector readout circuits available in the high-energy physics community, there is significant potential to improve the timing jitter, maximum count rate, and scalability of SNSPDs to enable significant new advances in QIS technology.

NECQST is a two-year technology development effort that focuses on the development of low-noise cryogenic amplifiers specifically designed for use with SNSPDs, based on state-of-the-art, commercially available SiGe heterojunction bipolar transistors (HBTs), operating at 4 Kelvin. When cooled, SiGe HBTs naturally exhibit improved frequency response, current gain, noise, bandwidth, and output conductance. They exist in a BiCMOS implementation (SiGe HBT + Si CMOS), which are fabricated on large wafers at high yield and low cost using conventional silicon processing techniques and silicon economy-of-scale.

A prototype readout channel has been recently submitted for fabrication, and will be integrated with state-of-the-art SNSPDs to benchmark its performance. Meanwhile, CMOS devices will be characterized to evaluate the feasibility of highly integrated DSP backend in this technology process.

Improving the timing jitter, maximum count rate, and pixel count of SNSPDs by developing improved cryogenic readout circuits, will ultimately enable transformative new capabilities in ultra-high-rate quantum communication, such as the transfer of quantum information between remote quantum information processing systems, the secure transfer of classical data over fiber at multi-Gbps speeds, and free-space communication with space-based quantum assets. Such performance advances will directly benefit the Caltech Intelligent Quantum Networks & Technologies (INQNET) program, and specifically the Fermilab Quantum Network program (FQNET) which aims to demonstrate high-rate quantum communication at Fermilab.

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 parameteric 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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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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The HEP.QPR Project: Quantum Pattern Recognition for Charged Particle Tracking

PI: Heather Gray[1,2], Paolo Calafiura[2], Wim Lavrijsen[2], Lucy Linder[3], Eric Rohm[2], Illya Shapoval[2], Alex Smith[1], Amitabh Yadav[2]

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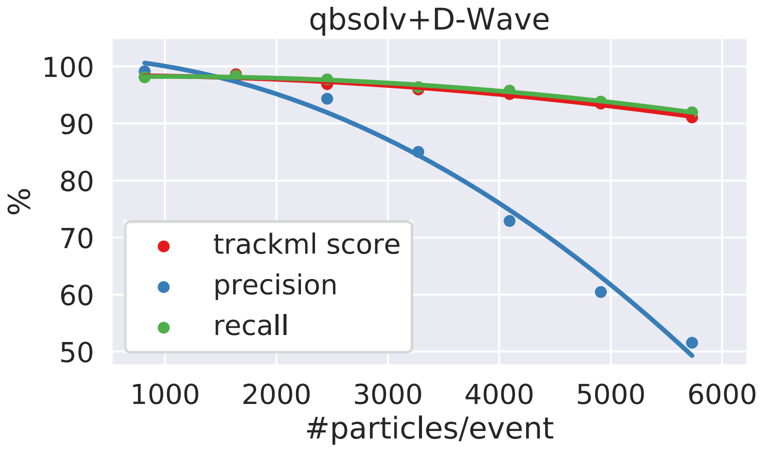
The upgrade to the Large Hadron Collider (LHC), the high-luminosity LHC (HL-LHC) is expected to result in a large increase in data rates and complexity compared to the LHC. This will make the reconstruction of the events to perform physics analysis extremely challenging. The reconstruction of charged particles is one of the most computationally challenging tasks within event reconstruction.

In the HEP.QPR project, we are studying the application of quantum computers and quantum algorithms to charged particle tracking. We have studied the potential of the Quantum Associative Memory (QuAM) algorithm, which could provide an exponential increase in storage capacity compared to classical Associative Memory used in the context of LHC data triggering. We presented a prototype implementation of the QuAM protocol on IBM 5Q[1].

We have expressed the LHC track finding problem as a Quadratic Unconstrained Binary Optimization (QUBO), that can be solved using a D-Wave Quantum Annealer[2]. We generated QUBOs that encode the pattern recognition problem at the LHC using the TrackML dataset and solved them using D-Wave qbsolv and its Leap Cloud Service. We achieved a performance exceeding 99% purity, efficiency, and TrackML score at low track densities. We have performed initial tests of the algorithm at the challenging track multiplicities expected at the HL-LHC.

We are currently studying the applicability of the Quantum Approximate Optimization Algorithm (QAOA) and Quantum Hough Transform (QHT) to pattern recognition problems.



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[2] Frederic Bapst, Wahid Bhimji, Paolo Calafiura, Heather Gray, Wim Lavrijsen, Lucy Linder, **A pattern recognition algorithm for quantum annealers**, February 2019, accepted for publication in Computing and Software for Big Science

Quantum Algorithms for Collider Physics

Prof. Jesse Thaler and Prof. Aram Harrow
Massachusetts Institute of Technology

The goal of our research is to unite powerful analysis techniques in high energy physics with cutting-edge advances in quantum computation. Broadly speaking, Thaler's research is aimed at discovering new physics at the Large Hadron Collider (LHC) and Harrow's research is aimed at unlocking the capabilities of quantum computers. Through this innovative work at the interface of high energy physics and quantum information science, we aim to maximize the discovery potential of the LHC and future colliders by demonstrating how quantum algorithms can expose important features in collision events that would otherwise be intractable with classical methods.

To search for new physics at colliders like the LHC, one relies on a series of algorithms to enhance signals of interest and mitigate backgrounds. Many of these algorithms are related to identifying and classifying jets—collimated sprays of particles that are copiously produced in high-energy collision events. Almost every LHC collision involves jets in some way, but classical computation constrains the kinds of algorithms that can be currently used to identify and classify jets. Quantum algorithms could fundamentally change the way that collider data is analyzed, either by speeding up existing classical algorithms or by enabling quantum representations of the collision debris.

We are currently pursuing two directions where quantum computation could have a direct impact on collider physics. The first direction is to use quantum clustering algorithms to identify jets. Jet clustering can be viewed as a kind of optimization problem, though most classical algorithms in use at the LHC only find approximate solutions. In Ref. [1], we show how a famous jet optimization problem—whose naïve classical runtime is $O(N^3)$ for N particles—can be implemented in $O(N^2)$ using a variant of Grover search. The second direction is to use quantum machine learning algorithms to analyze jets. The detailed pattern of particles within a jet (i.e. its substructure) contains valuable information about its origin, and classical machine learning algorithms have seen numerous applications in jet classification. In upcoming work [2], we develop a quantum annealing strategy to find sparse solutions to otherwise intractable regularized regression problems in jet physics. In the course of thinking about the quantum implementation of this algorithm, we discovered a way to improve the classical runtime of a well-known jet classifier from $O(N^3)$ to $O(N)$, with immediate applicability to the LHC [3].

By exploiting the capabilities of quantum computation, this research confronts the challenge of data analysis in collider physics. Moreover, it has inspired us to think about even more ambitious data analysis strategies that push the limits of classical computation [4]. We hope that the work described above will pave the way for future applications of quantum machine learning beyond high energy physics, in particular clustering and regression problems in other application domains.

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Quantum Sensors HEP-QIS Consortium

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The Quantum Sensors Consortium applies QIS technology to improve sensors and detection techniques for low mass particle dark matter (DM). At the same time, some of the DM sensor development is applied to investigating noise sources in superconducting qubits. The same device physics underlying DM detection in the athermal phonon channel governs the mechanisms that degrade qubit performance.

Elucidating the nature of DM is one or the most compelling problems of high energy physics. Interest in searching for particles of much lower mass than atomic nuclei and even electrons has been fueled by recent theoretical developments. Some promising theoretical directions, such as Asymmetric Dark Matter and Hidden Valleys, which predict low mass DM particles, were spearheaded by one of the PIs on this consortium. The search for low mass DM particles is mainly limited by our ability to detect very small signals with high fidelity and little or no background, and developments enabling lower noise detectors are a very promising avenue. While ultra low noise sensing of single quanta is a problem common to QIS and low mass DM detection, the detailed requirements are different. To fully take advantage of QIS technology, a multidisciplinary team has been assembled, bringing together expertise particle physics experiment and theory, materials science, and QIS.

We are instrumenting two different dark matter detection candidate target samples with a variety of sensors, with a sensitivity goal to reach unexplored parameter space. This concrete goal drives the sensor and readout development, and provides a basis for sensor comparisons. The sensor technologies are TES- (transition edge sensors) and KID- (kinetic inductance detectors) -based athermal phonon detectors, SNSPDs (superconducting nanowire athermal phonon detectors), and superfluid He quantum evaporation (both atoms and electron surface states). The initial target materials are superfluid He and GaAs crystals at cryogenic temperature. These materials are complementary in their predicted sensitivity to dark matter particle interactions, yet they can be instrumented with the same type of sensors. We explore system aspects and readout of sensors on these platforms, which are critical elements for deployment of new technologies. GaAs also produces IR scintillation light that we would like to detect with high quantum efficiency and single photon sensitivity. At the same time, we are re-purposing athermal phonon detectors to investigate phonon and quasiparticle sources (as unwanted backgrounds) in qubit device structures.

We are additionally exploring new potential target materials and have already theoretically discovered three ultra low bandgap materials. Through a significant theoretical effort we are singling out materials with enhanced coupling to DM, for example by coherent effects, and understanding how to maximize coupling of signals to different sensor types. We are also investigating the use of decoherence in ensembles of quantum states as a tool for DM detection, initially through calculation of possible sensitivity to DM models.

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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Foundations of Quantum Computing for Gauge Theories and Quantum Gravity

Yannick Meurice, University of Iowa (Principal Investigator); Alexei Bazavov, Michigan State University (Co-Investigator); David Berenstein, UCSB (Co-Investigator); Richard Brower, BU (Co-Investigator); Simon Catterall, Syracuse University (Co-Investigator) ; Xi Dong, UCSB (Co-Investigator); Stephen Jordan, U. Maryland/Microsoft (Co-Investigator); Seth Lloyd, MIT (Co-Investigator); Michael McGuigan, BNL (Co-Investigator)

Quantum computers are expected to exceed the capacity of classical computers and to revolutionize several aspects of computation especially for the simulation of quantum systems. We develop new methods for using quantum computers or quantum simulation experiments to study aspects of the evolution of strongly interacting particles in collisions, the quantum behavior of gravitational systems and the emergence of space-time which are beyond the reach of classical computing.

Our work is focused on the design of the building blocks of universal quantum computing relevant for these problems and the development algorithms which scale reasonably with the size of the system. Following on our recent work on Abelian models in 1+1 dimensions, we are progressing towards models with non-Abelian symmetries in higher dimensions. The scientists involved come from different communities (strong interactions, quantum gravity and quantum information) and are working together to achieve these goals. This will contribute to our understanding of fundamental interactions and improve our ability to deal with complex computational problems. It will have long-term beneficial effects for the society. The project involves analytical methods (design of quantum algorithms, estimations of scaling with size) and computational methods (lattice gauge theory tensor calculations, quantum links, determinantal Monte Carlo and numerical studies of quantum chaos).

After one year of active collaboration, new directions of research have emerged: 1) quantum simulation experiments involving cold atoms in optical lattices, Rydberg atoms and trapped ions (in collaboration with experimentalists currently at U. Maryland, Harvard and other locations in the future); 2) random tensor networks; and 3) benchmarking of existing quantum computing devices (IBM Q and Rigetti). This effort will be conducted in coordination with DOE National Laboratories.

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.

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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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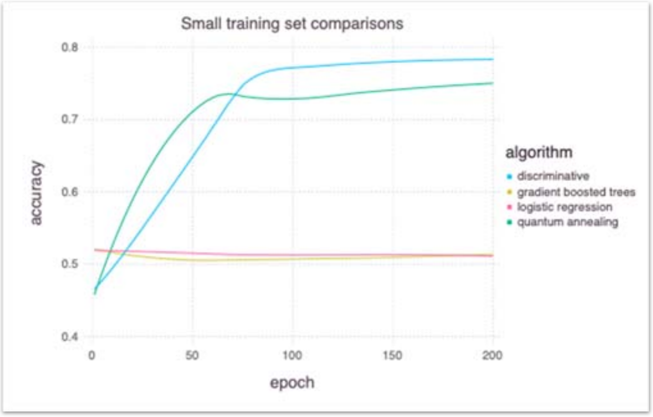
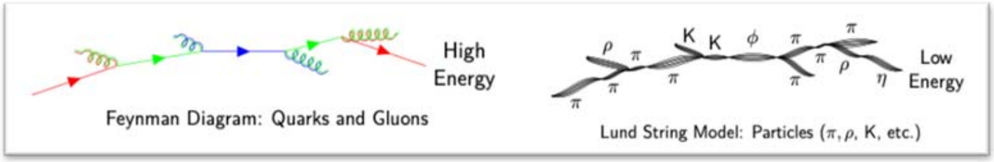
HEP Machine Learning (ML) and Optimization Go Quantum

PI: G. Perdue (FNAL), Co-PI: T. Humble (ORNL)

Senior Personnel: FNAL: J. Kowalkowski, S. Mrenna, B. Nord; ORNL: A. McCaskey

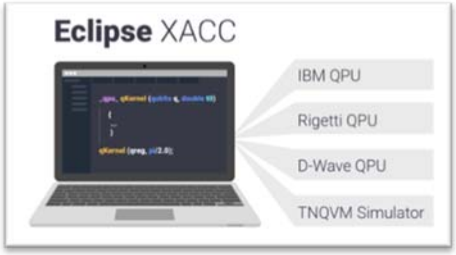
We are exploring machine learning and optimization problems from HEP that may be formulated on modern quantum computing hardware. We partnered with Lockheed-Martin to study Restricted Boltzmann Machines for galaxy morphology classification with a D-Wave quantum annealer, resulting in https://arxiv.org/abs/1911.06259. We found evidence that quantum annealing offers some classification accuracy advantages for small datasets (see figure). We are continuing our partnership with Lockheed to study variational circuits for classification tasks on gate-based machines. We are also working with scientists at Google to study quantum support vector machines for gravitational lens identification using their Sycamore chip. This work involves extensive noise modeling, device characterization, and performance simulation because the results are more sensitive to the computed state distributions than most variational algorithm work currently underway in the community.





Our optimization problem is to study the phenomenon of color reconnections (CRs) in high energy collisions using quantum algorithms. In the CR model, the gluons produced in a high energy collision are not bound by their local color partners but can change their partners to decrease the effective string energy. This optimization problem can be cast as an Ising model. We have developed a library of functions, models, and tools to facilitate our work. We can produce Hamiltonians that include cost and connectivity constraints for both node-based and edge-based models. We automatically configure state-of-the-art linear and quadratic programming solvers for comparison studies. Results are available from IBM's Qiskit simulators, D-Wave's 2000Q, and AMPL/CPLEX through the NEOS server. We expect to have results from the IBMQ machines for QAOA, with algorithm upgrades using ANL's multi-start optimizer.

The ML and the optimization components are implemented as classical/quantum hybrid applications. We have developed these QML methods for multiple quantum computing platforms. We use the XACC software framework to access and integrate conventional workflows with quantum information processing. We have developed realizations of this work for quantum annealing and circuit model platforms to demonstrate the potential of QML for HEP using ORNL's XACC (https://ornl-qci.github.io/xacc/) quantum programming framework. The structure also provides a setting for Fermilab HEPCloud (http://hepcloud.fnal.gov) integration. We will develop realizations of the above-described applications using mixed-language programs, targeting D-Wave and Google's quantum hardware, with C++ and Python to classical processing, while offloading of optimization to quantum hardware.



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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Towards practical quantum simulation for High Energy Physics.

Peter J. Love, Tufts University (Principal Investigator)
Gary R. Goldstein, Tufts University (Co-Investigator)

Over the last decade quantum algorithms for quantum simulation of electronic structure have become accepted as the most promising early application of quantum computing. They form a major focus of both Google and IBMs commercial efforts to construct a medium-scale quantum computer. The refinement of these algorithms has involved the development of numerous new quantum algorithmic techniques and small-scale experimental demonstrations in various quantum computing hardware platforms.

Quantum algorithms for HEP problems, including algorithms for the simulation of quantum field theory, remain in a more nascent state. However, several important results have recently been established. However, the algorithms proposed to date require many more qubits than are likely to be available in the next five to ten years.

We will therefore use the results and techniques developed for quantum chemistry over the course of the last decade to improve the practicality of simulation algorithms for quantum field theories with application to specific HEP questions. Here we give two specific examples. Firstly: how to evaluate the Fock space wave functions of hadrons for increasingly numerous gluons, approaching the quark-gluon condensate (QGC). Secondly, how to simulate various high-energy production processes that reveal the polarization of the gluons and quarks within the colliding protons at LHC.

Improved quantum algorithms for HEP problems align the HEP-QIS goals with synergistic work on quantum simulation in the QI community. Much of that work is aimed at the near-term simulation of chemistry and condensed matter problems. Near term means the ~ 20 qubit quantum computers available now, and scaling up over the next five years to use ~50-100 qubit quantum computers. The goal of the community in that timescale is to challenge and then exceed the capabilities of classical computers and algorithms for some chemical or condensed matter problem. Our objective is to use these lessons of the last ten years to improve quantum algorithms for HEP and define demonstration experiments that can be performed on the 20-100 qubit quantum computers that will appear over the next five years.

Quantum Simulation of Quantum Field Theories

T. Bhattacharya,[1] A. Buser,[2] S. Chandrasekharan,[3] R. Gupta,[1] H. Singh,[1] R. Somma[1]

The efficient simulation of quantum field theories (QFT) is one of the main challenges in high energy physics. When perturbation theory fails, the only first-principles method that is implementable on a classical computer involves taking the limit of a discretized path integral evaluated by importance sampling. Often, however, the relevant measure is not positive in any known set of classical variables, and the integral becomes exponentially hard to compute. Hence novel paradigms are highly desirable. We explore possible gains in using quantum computers to solve QFTs. Our goal is both to formulate the problem in the language of a finite quantum computer and to develop efficient quantum algorithms for computing the quantities of interest. We will focus on expectation values and correlations in thermal equilibrium as well as time-dependent properties such as scattering amplitudes and response functions.

We shall begin by understanding how to map any desired continuum field theory onto a discrete space-time lattice with a small Hilbert space at each lattice site. If we can discretize the problem preserving its symmetries, then renormalization group flow can help in the construction of the continuum field theory. As an example in this direction, we explored whether the physics of the O(3) sigma model is obtained from various O(3)-symmetric Hamiltonian in a system with two qubits per site. We explored the Wilson-Fisher fixed point in 2+1 dimensions, the Gaussian fixed point in 3+1 [1], and the asymptotic freedom of the O(3) sigma model in 1+1, using such a qubit Hamiltonian. We have developed and studied the fidelity of a low-depth qubit implementation for the adiabatic ground-state preparation for these. We have also explored a Z_2 lattice gauge theory in 1+1 dimensions and showed that it is yet another qubit regularization of a continuum gauge theory with confinement and chiral symmetry breaking [2].

Simultaneously, we are developing algorithms for simulating field theories on a quantum computer using a coupled system of naively discretized quantum oscillators as a realization of the free scalar field theory and constructing a quantum algorithm to prepare the vacuum state of this Hamiltonian. The main feature of our algorithm is that the time taken to prepare this state scales almost linearly in the number of space discretization points. This is an improvement over known quantum algorithms, where the time scales quadratically or worse. The core of our algorithm is a new factorization of the discrete Fourier transform that relates the field variables to the canonically conjugate momenta, and is inspired by the well-known quantum Fourier transform. We also make use of a recent procedure to prepare quantum states with Gaussian amplitudes [3], which was successfully implemented to simulate a simple QFT associated with a quantum harmonic oscillator. We also plan to study this free scalar field theory to find new algorithms for time dependent problems like scatterring amplitudes.

[1] H. Singh and S. Chandrasekharan, “A qubit regularization of the O(3) sigma model”, Phys. Rev. D 100, 054505 (2019). [2] J. Frank, E.Huffman and S.Chandrasekharan, “Emergence of Gauss’ Law in a Z2 Lattice Gauge Theory”, arXiv:1904.05414. [3] R.D. Somma, “Quantum simulations of one-dimensional quantum systems”, Quant. Inf. Comp. 16, 1125–1168 (2016).

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[2] Caltech
[3] Duke University

Quantum error correction and spacetime geometry

John Preskill (Caltech), Patrick Hayden (Stanford U)

Quantum error correction and the holographic principle are two of the most far-reaching ideas in contemporary physics. Quantum error correction is the basis of our belief that scalable quantum computers can be built and operated in the foreseeable future. The AdS/CFT holographic correspondence is currently our best tool for understanding nonperturbative quantum gravity. Remarkably, recent advances indicate that these two deep ideas are closely related. Specifically, AdS/CFT posits a dictionary in which the observables of a bulk spacetime are mapped to the observables of a quantum field theory living at the boundary of the spacetime, and this dictionary can be interpreted as the encoding map of a quantum error-correcting code.

In this project we are developing this connection further, in multiple directions, by advancing the theory of quantum error correction and by clarifying how this theory can be used to build more general and powerful approaches for probing spacetime physics. In particular, we will extend the formalism of operator algebra quantum error correction with the goal of clarifying how emergent gauge symmetry arises in the bulk spacetime, and develop the theory of approximate error correction with the goal of quantifying the robustness of bulk quantum geometry with respect to errors in the boundary theory. We anticipate that our work will illuminate how quantum information is encoded and processed by black holes, and the role of quantum entanglement in the very early history of the universe.

Currently we are studying the implications of computational pseudorandomness for the AdS/CFT correspondence. Under the plausible assumption that the Hawking radiation emitted by a partially evaporated black hole is pseudorandom (cannot be distinguished from a perfectly thermal state using reasonable computational resources), we have shown that quantum codes exist, potentially describing the interior of the black hole, such that the interior is almost completely inaccessible to computationally bounded observers who interact with the radiation.

In addition, we have applied the recently developed theory of universal subspace quantum error correction to the reconstruction of black hole microstates in AdS/CFT duality. This work explains how the approximate error-correcting code underlying the bulk-to-boundary dictionary becomes exact in the semiclassical limit.

Entanglement in Gravity and Quantum Field Theory

Robert G. Leigh, Ph.D., University of Illinois (Principal Investigator)
Thomas Faulkner, Ph.D., University of Illinois (Co-Investigator)
The Board of Trustees of the University of Illinois

It is becoming increasingly clear that ideas from quantum information theory, particularly the notion of quantum entanglement, play a fundamental role in some of the deepest aspects of our modern theories of quantum fields and gravity. The aim of this research is to explore the role that quantum entanglement plays in quantum field theories and in the nature of space-time and gravity. Building on a variety of new results obtained in these regards at the University of Illinois, we plan to explore the constraints on the dynamical content of quantum field theories that follow from their entanglement properties. Topological field theories are important examples of particularly simple quantum field theories whose patterns of entanglement make connections between high energy physics, condensed matter physics and mathematics. These theories are directly relevant to low energy properties of certain materials. The study of such theories will allow us to investigate ideas that are relevant to quantum information research, such as new notions of entanglement between multiple parties and the quantum properties of interfaces between different phases of such materials. In addition, we will employ new results in mathematics which strengthen monotonicity constraints on relative entropy to study their ramifications in quantum field theories, and we will use quantum information methods to study the emergence of quantum gravity and string theory in holographic quantum field theories. The project investigators are in an ideal position to make important contributions to these exciting areas, contributing both to the evolution of the application of quantum information concepts in high energy physics and to the further development of general quantum informational ideas.

Particle Track Pattern Recognition via Content-Addressable Memory and Adiabatic Quantum Optimization

Lauren Ice[1], Gregory Quiroz[1], Travis Humble[2], Andrea Delgado[2,3]

This project evaluates employing content-addressable memory (CAM) recall in combination with adiabatic quantum optimization (AQO) to improve particle track pattern recognition in high energy physics (HEP) experiments. To simplify track reconstruction, a challenging and necessary part of many HEP experiments, pattern recognition algorithms are commonly employed to prune data of random noise and to help discriminate signals that potentially correspond to particle tracks of interest from background events. Pattern recognition algorithms quickly identify potential track candidates by comparing the pattern of detector signals to a library of patterns known to be from events of interest. The time to search the library can be decreased by organizing the library patterns into a tree structure however, the speed and effectiveness of the tree search algorithm is sensitive to the amount of random detector noise, background processes, and the spatial resolution of the detector. For this project, the quantum CAM (QCAM) approach will be compared to the tree search method for potential improvements in pattern recognition quality and flexibility.

CAM represents an associative memory structure in which key-value data is recalled based on its value as opposed to its key. Incorporating AQO, an approach designed to exploit quantum phenomena to find the global minimum of an objective function, CAM recall is cast as a problem of finding the energetic minimum of an Ising model constructed from a database of known key-value pairs. The track recognition problem will be cast as a CAM recall problem and study the performance of AQO via the D-Wave Systems, Inc. 2000Q quantum processing unit (QPU), the newest generation 2048 quantum bit QPU.

Here we present our results for binary (signal/background) event classification and full key recovery for patterns produced using a flexible detector simulation, developed to characterize QCAM as a function of detector complexity, the number of patterns in the library, level of stochastic noise, and detector efficiency. We will also discuss our ongoing work on applying QCAM to data collected from the OLYMPUS experiment, an experiment designed to measure the two-photon exchange contribution to lepton-proton elastic scattering. For the OLYMPUS dataset, a hybrid classical-QCAM approach is used to reduce the size of each pattern, as well as the number of patterns in the library, down to sizes that can be evaluated using the D-Wave Systems QPU.

Ultimately, observed improvements provided by QCAM will give insight into the potential advantages of future track reconstruction algorithms that incorporate quantum hardware. QCAM performance will be evaluated and optimized with respect to recall accuracy, while exploring bounds on recall capacity. Ultimately, QCAM will be compared to the tree search method by examining the quality of track reconstruction and computational speed.

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Search for Bosonic Dark Matter Using Magnetic Tunnel Junction Arrays

M. Demarteau[1], V. Mitrovic[2]

The existence of dark matter, which constitutes the vast majority of the matter content of the universe, has been established by a variety of astrophysical observations. A multitude of particles have been introduced as possible dark matter candidates, but as of today, none of them have been detected and the nature of dark matter remains unknown. The expected signal of a dark matter detection is expected to be very faint. The axion particle, emerging from a solution to the strong-CP problem, is a well-motivated dark matter candidate, whose couplings to standard model particles are suppressed. Because no laboratory evidence for dark matter has emerged thus far, despite tremendous efforts, it is proposed to develop new detection strategies with increased sensitivity that are orthogonal to those already being tested. Three thrusts are being developed. Since signal recognition and reconstruction is a challenging but necessary part in the search for dark matter, especially in the case of faint signals over background, robust algorithms are needed using quantum machine learning (QML) methods to improve the event classification and simulation. The results from these studies will inspire the development of new techniques in the search of dark matter. The second thrust is a search for dark matter based on novel magnetic tunnel junctions. This is the main thrust of the research proposal. These studies will be supported by a complementary program using a quantum simulator to calculate the detector response to dark matter particles and neutrinos. In the key research area, magnetic tunnel junctions have been characterized at low temperature and their design for high frequency has being optimized. The magnetic field sensitivity at low temperatures is being measured. Magnetic tunnel junctions are being fabricated with the new design and the readout system is being developed. Sensitivity in the mass versus axion coupling has been mapped out for different sensitivity scenarios. Our next step is to start implementing the readout and characterizing the experimental setup.

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[1] Oak Ridge National Laboratory

[2] Brown University

Project Alpha

David Brown,[1] Holger Mueller[2]

Project Alpha will reduce the experimental error on the measured value of the fine structure constant α by roughly 1 order of magnitude, by improving the techniques and apparatus used to make the current most precise measurement, $\alpha = 1/137.035\,999\,046\,(27)$ (Parker et al. 2018). The current measured value differs by 2.5 σ from the value obtained from measurements of g_e-2, mirroring the well-known 3.7 σ difference observed in the current g_μ -2 measurement (E821 (2006)). Analogous to the remeasurement of g_μ -2 by E989 at Fermilab (Holzbauer 2017), and proposed g-2/EDM at J-Parc, the higher-precision measurement of α by project Alpha could reveal signs of new physics. Project Alpha will also advance the methods of quantum metrology and atomic interferometry, key techniques for discoveries in beyond-standard model physics (Chattopadhyay, Falcone, and Walsworth 2016; Binkley 2017; High Energy Physics Advisory Panel 2018).

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[1] Lawrence Berkeley National Laboratory

[2] University of California, Berkeley

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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Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit Coherence Times and Dark Sector Searches

Lead PI: Dr. Alexander Romanenko (Fermilab)
Co-PI: Prof. Robert McDermott (Univ. of Wisconsin-Madison)
Co-PI: Dr. David Pappas (NIST/Univ. of Colorado-Boulder)

3D superconducting cavities are key elements of the superconducting quantum computing architectures. They can both serve as qubits in alternative logical state encodings such as “cat” states, or as a means to manipulate the transmon quantum states, or as a quantum memory. The project combines complementary strengths of collaborating institutions – unique HEP SRF cavity technology and science (Fermilab) and QIS expertise (Univ. of Wisconsin-Madison and NIST) – for a potential thousand-fold increase in the coherence of the 3D superconducting qubits and memory. The same devices can be used as an enabling platform for the next generation of dark photon searches and exploring the proposed microwave communication concept, which is the secondary direction of the proposal.

Fermilab is the world leader in science and technology of superconducting radio frequency (SRF) cavities for accelerators and holds the capabilities to manufacture and surface-engineer niobium SRF cavities of record intrinsic quality factors $Q > 2 \times 10^{11}$ at $T \sim 1.4$ K. In addition, Fermilab possesses broad expertise in successful large-scale integration of high Q cavities. The most recent example is manufacturing ~20 cryomodules for LCLS-II at SLAC each containing eight 9-cell 1.3 GHz cavities with $Q > 2.7 \times 10^{10}$ operating at 2 K. Fermilab has also established a brand new ultralow temperature (down to < 10 mK) and quantum measurements SRF lab with two dilution refrigerators, magnetic shielding, and state-of the-art electronics for the full SRF cavity and qubit characterization.

Over the course of the 1st year of this work we demonstrated the SRF cavities in the full quantum regime with $Q \sim 2 \times 10^{10}$ corresponding to photon lifetimes up to **2 seconds,** which is beyond the QIS state-of-the-art by a margin of about 200x. This confirmed the transformative potential of this project and now enables to explore a multitude of scientific directions, substantially advancing the entanglement, macroscopic, and coherence frontiers of QIS. First measurements of the integrated SRF cavity with UWisc-Madison made transmon, utilizing the quantum-limited amplifiers from NIST/UColorado have been successfully performed as well.

Furthermore, both SRF cavities themselves and cavity-transmon coupled systems represent the ultra-high sensitivity quantum sensors which enable a multitude of the proposed fundamental physics experiments, including searches for dark photons, axions, and predicted (but not observed yet) ultra-small photon-photon vacuum-mediated interactions. Confirming this potential, the dark photon search platform has been successfully constructed and tested down to 1.4 K with the first scientific results to be reported at the upcoming APS meeting.

Quantum Information Science in High Energy Physics at the Large Hadron Collider and at Fermi National Accelerator Laboratory

O.K. Baker, Principle Investigator[1]

We pursue scientific research at the interface of High Energy Physics and Quantum Information Science. This includes studies of thermal radiation and quantum entanglement in high-energy collisions at the Large Hadron Collider (LHC), with special emphasis on entanglement entropy and the Higgs boson. This project has also been extended to include quantum entanglement and charged current weak interactions using Fermilab results. And most recently, we have begun tests of the temporal entanglement using LHC data.

Collider experiments such as proton-proton collisions at the LHC yield hadrons that exhibit an exponential behavior at low transverse momenta. This surprising behavior is seen in data from both the ATLAS and CMS collaborations. We attribute this phenomenon to quantum entanglement between the regions in the nucleon wave function. The exponential component to the transverse momentum distribution is a result of thermal radiation that is akin to Hawking or Unruh radiation that should exist at the event horizon of astrophysical black holes and neutron stars. The Principal Investigator, in collaboration with a theoretical physicist at Stony Brook University and Brookhaven National Laboratory, and with Yale University students, has shown evidence for this thermal radiation in several production and decay processes in the ATLAS and CMS data, and its connection to entanglement entropy (O.K. Baker and D.E Kharzeev, Phys. Rev. D 98, 054007 (2018)), including even the Higgs boson sector. Interestingly, this thermal behavior is also seen in momentum distributions of charged current weak interactions according to our studies. These findings suggest a deep connection between quantum entanglement (entanglement entropy) and thermalization in both hadron collisions at the energy frontier and neutrino scattering at the intensity frontier.

We have confirmed the proposed relation between the effective temperature and the hard-scattering scale at lower energies using the most recent LHC data for the following systems: Higgs bosons, top quarks, and charged hadrons. Additionally, we have results for hadron production in neutrino scattering from nuclei using Fermilab weak interaction data. This study is carried out using data from the MINERvA collaboration. In those cases where entanglement is expected, there is an exponential component to the momentum distribution, while this component is absent in those processes where no entanglement is expected. This research thus tests the hypothesis about a link between quantum entanglement and thermalization in strong and weak interactions.

Finally, ongoing studies in this broad area of research include testing the Leggett Garg Inequality in the context of temporal entanglement using diffractive physics results from the LHC. In this initial study, analysis is performed of diffractive scattering event measurements made of the proton status - whether intact or not - at different times and for different probabilities. This analysis makes use of both ATLAS and CMS data.

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[1] Yale University

Probing information scrambling via quantum teleportation

PI: Norman Y. Yao (LBNL & UC Berkeley)

The black-hole information paradox represents one of the central open questions at the interface of modern high energy physics and quantum information science. While general relativity predicts that the information is lost forever, the evolution according to quantum mechanics is unitary, hence reversible, suggesting that there may in principle be a way to recover the information. The classic thought experiments for the black hole information paradox is the following: suppose that Alice throws a secret quantum state into a black hole -- is it then possible for an outside observer, Bob, to reconstruct it by collecting the Hawking radiation emitted at a later time. Over two decades ago, seminal work by Page demonstrated that if the dynamics of the black hole could be approximated as a random unitary, then Bob would need to wait at least half the lifetime of the black hole. Recently, Hayden and Preskill added an interesting twist to this classic setup by considering a black hole, which is entangled with a quantum memory that Bob possesses. There, it was shown that the decoding of Alice's quantum state could be performed with an exponential speedup.

However, there is a subtlety in this argument. While it was shown that such a decoding is information-theoretically possible (i.e. that there exists a unitary operator which reconstructs the state by acting only on the Hawking radiation and quantum memory), it remains unclear if such a unitary is actually physically implementable and what form the quantum circuit might take.

In our work, building upon recent work by Yoshida and Kitaev, we have proposed a novel probabilistic decoding protocol for reconstructing a quantum state from the Hawking radiation in the Hayden-Preskill black hole thought experiment [Phys. Rev. X 9, 011006 (2019)]. The protocol attempts to teleports a quantum state thrown into a black hole to an outside observer by projecting pairs of outgoing Hawking radiation from two sides of an entangled black hole into EPR pairs. The chaotic dynamics of the black-hole is simulated by performing unitary operations to implement an effective "scrambling" operation. Experimental realizations of our protocol have been realized in a trapped ion quantum computer [Nature 567, 61-65 (2019)] and a superconducting qutrit system [forthcoming experiments in I. Siddiqi group]. One of the main focal points in both of these experiments is to demonstrate that our protocol can effectively distinguish between chaotic scrambling dynamics and decoherence. Looking forward, the advent of quantum information processors with high dimensional local Hilbert spaces open the door to studying new modalities of scrambling in continuous variable systems [Phys. Rev. A 99, 062334 (2019)].

FPGA-BASED QUANTUM CONTROL FOR HEP SIMULATIONS WITH QUTRITS

Irfan Siddiqi, Gang Huang, and Lawrence Doolittle[1]

Our objective is to develop broadly applicable, portable tool set within the framework of superconducting circuit-based quantum information systems that (i) leverages specialized technical expertise developed for accelerator controls and (ii) is optimized for executing quantum simulation experiments focused on HEP phenomena requiring the use of binary and ternary quantum logic. We propose to develop optically interconnected field programmable gate array (FPGA) modules for extensible control systems suitable for operating multiple quantum circuits with low latency and timing imprecision. Using this hardware, we will implement logical gate operations in qubit/qutrit logic and employ fast feedback routines to minimize fidelity losses.

We will use a high-bandwidth FPGA quantum control module to characterize the performance of qubit/qutrit devices, and implement novel computation and sensing protocols tailored for future HEP applications. We will realize optically interconnected FPGA modules with 14-bit resolution, < 3 ps timing jitter, single FGPA latency < 300 ns, and interconnect delays < 1 μs.

During the first year of the project, we developed and realized two qubit control modules (QubiC). The QubiC hardware is based on Xilinx Virtex 7 FPGA boards and COTS AD/DA conversion boards and customized analog front-end boards. The module contains 8 channels 16-bit DACs and 8 channels ADCs running at 1GSPS. Each QubiC module is capable of driving 3 qubits together with the readout. We also developed associated firmware and engineering software demonstrating single qubit initiation and gate characterization. These efforts included spectroscopy, relaxation, and dephasing measurements, as well single qubit randomized benchmarking. We also demonstrated basic two-qubits CR gate and CNOT gate. Two qubits gate optimization and optical inter-chassis communication are also under development.

We also explored quantum ternary logic. The team demonstrated genuine scrambling between two qutrits (three-level systems) in a transmon-based digital quantum processor. Owing to the fast repetition rates of experiments with superconducting circuits, we were able to do full-process tomography of the scrambling unitary, monitoring exactly how initially localized operators spread when they are being scrambled. This is the crucial building block of a five-qutrit quantum circuit, which verified the spread of quantum information through scrambling. The same circuit has an in the black hole information paradox where information, initially scrambled in a black hole, is recovered through a teleportation protocol. We demonstrated clear quantum advantage.

In the coming year, we will continue to develop and publish a design repository of the complete system (hardware, firmware and software) used to drive, read out, and rapidly reset multi-qudit processors. Our work will also pave the way for the future development of dedicated Application Specific Integrated Circuit (ASIC) devices, possibly operating in a cryogenic environment.

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[1] PI and CO PI's Location: Lawrence Berkeley National Laboratory (LBNL)

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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[1] JILA, CU Boulder, and CTQM

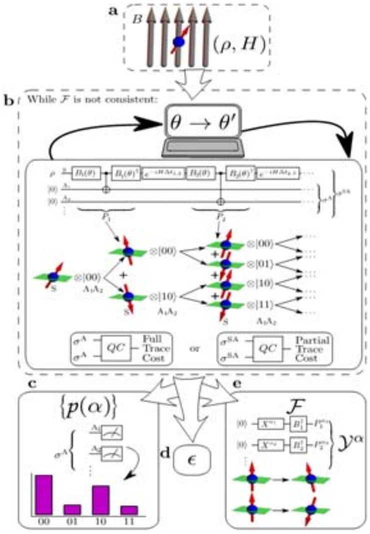
[2] CU Boulder and CTQM

Quantum Foundations on Quantum Computers

Andrew Sornborger,[1] Andreas Albrecht,[2] Andrew Arrasmith,[1,2] Lukasz Cincio,[1] Wojciech Zurek,[1] Patrick Coles[1]

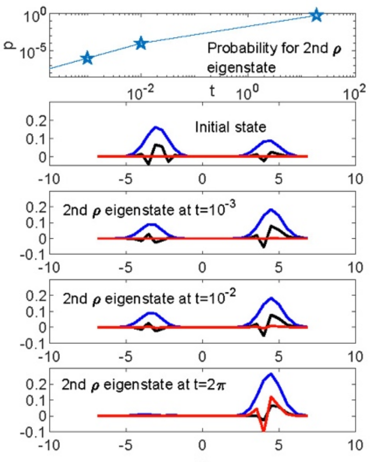
Quantum physics underlies all modern physics research and is crucial for investigations at the frontiers of High Energy Physics (HEP). Today, we have an important new tool at our disposal. Quantum computers (QCs) offer an apparatus with which one can explore the fundamental workings of quantum physics. This availability of an advanced quantum laboratory ``in the Cloud'' is already leading to advances, some of which have been produced by our collaboration. Our project uses quantum computers, as well as classical simulations, to study the emergence of classical from quantum. These studies explore the connection between the emergence of classicality and the locality and entropy increase which have foundational roles in particle physics and cosmology.

The consistent histories (CH) formalism is a powerful tool for exploring the emergence of classical from quantum. Our collaboration has produced a scalable, variational hybrid quantum-classical algorithm (VHQCA) for the CH formalism, which achieves an exponential speedup over classical methods both in terms of system size and the number of times considered. It will allow exploration beyond toy models, such as the quantum-to-classical transition in mesoscopic quantum systems.



Arrasmith, et al., Nature

Our VHQCA allows the CH formalism to become a practical tool, and we are currently using it on quantum computers to study the relationship between locality and the arrow of time and the emergence of classicality in mesoscopic systems.



Copycat state formation

Recently, we have discovered a novel phenomenon (the formation of “copycat states”) that occurs at the start of certain decoherence processes. We are studying the evolution of these states with VHQCAs that we have developed for near-term quantum simulations (using the Variational Fast Forwarding VHQCA).

With the impending arrival of the first useful noisy quantum computers, the field of VHQCAs, which make the most of short quantum circuits combined with classical optimizers, has been taking off. VHQCAs have now been demonstrated for myriad tasks ranging from finding the ground states of quantum systems to quantum factoring. Using VHQCA methodology, our new algorithms are enabling quantum computers to make significant explorations of deep questions crucial for understanding the foundations of particle physics and cosmology. LA-UR-19-31916

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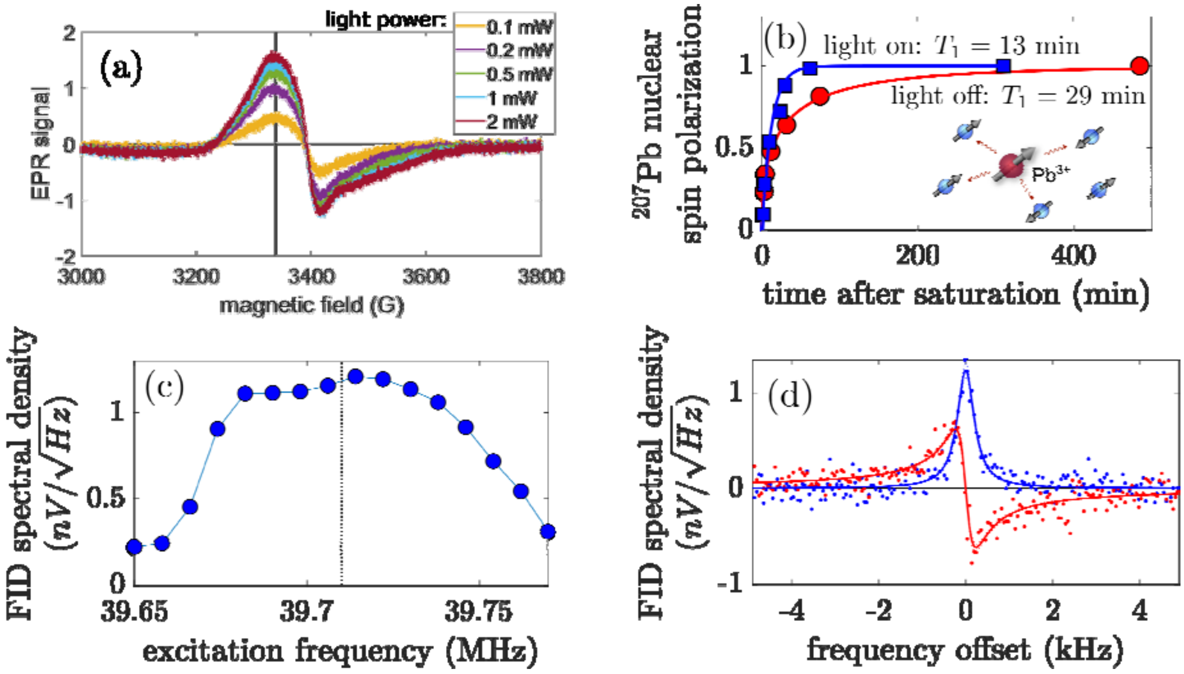
[1] Los Alamos National Laboratory

[2] University of California, Davis

Quantum system engineering for a next-generation search for axion dark matter

Alexander Sushkov,[1] Dmitry Budker,[2] Peter Graham,[3] Surjeet Rajendran,[4] Derek Jackson Kimball,[5] Kent Irwin[6]

Advances in quantum science and engineering enable new directions in the search for physics beyond the Standard Model. This project focuses on developing the quantum technology necessary to pursue one such promising direction: the search for ultra-light dark matter, using ensembles of ^{207}Pb nuclear spin qubits in ferroelectric PMN-PT crystals as quantum sensors of new physics. We have demonstrated several ways of optimizing control over macroscopic ensembles of spin qubits, relevant for such a search. Illuminating PMN-PT with 405 nm light creates transient paramagnetic centers, detected with EPR spectroscopy (a). These paramagnetic centers allow us to control the nuclear spin population relaxation time T_1 (b). ^{207}Pb nuclear magnetic resonance measurements indicate a broad inhomogeneous excitation linewidth (c). Nevertheless, when the ^{207}Pb nuclear spin driving pulse length is matched to the axion coherence time, we observe a much narrower resonance line, corresponding to the free induction decay time of ≈ 2 ms (d). These results open promising directions towards realizing the full potential science reach of magnetic resonance-based searches for ultralight axion dark matter.



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[1] Boston University

[2] UC Berkeley & Helmholtz-Institut Mainz

[3] Stanford University

[4] Johns Hopkins University

[5] California State University, East Bay

[6] Stanford University and SLAC

Quantum Algorithms for Parton Showers

PI: Christian Bauer (LBNL)

A central HEP question is whether nature at the highest available energies is still described well by the standard model (SM) of particle physics, or if physics beyond the SM (BSM) is required. Connecting experiments to theory requires detailed calculations that are directly comparable to the measurements. In almost all cases, these calculations can only be performed in certain limits of the theory, giving rise to theoretical uncertainties. As measurement precision increases, these uncertainties start to dominate. In particular, for events with high multiplicity of final state particles, the known theoretical algorithms severely limit the accuracy with which predictions can be made. In many cases these limitations are not fundamental, but due to calculation complexity growing exponentially with the number of final state particles. Given that quantum algorithms have been shown to provide exponential speedup over classical calculations in many cases, a focus our research has been to study how quantum algorithms can be used to simulate high multiplicity events without exponential growth.

We have shown in simplified models that effects intractable using known classical algorithms can be simulated on quantum computers with only polynomial scaling with particle multiplicity, rather than exponential. The particular simplified model consisted of two types of fermions interacting with bosons, including a “flavor mixing” coupling between them. This flavor mixing gives rise to numerically important interference effects, and the number of amplitudes that can interfere grows exponentially with the number of final state fermions. Standard parton shower algorithms would simply miss these interference effects, while classical algorithms that include them scale exponentially with the number of final states. Our quantum algorithm that explicitly includes all interference effects, yet scales only polynomial in the number of final state fermions. A comparison of the complexity of the quantum and classical algorithms revealed that the quantum algorithm outperforms the classical one for more than 10 fermions in the final state. While currently available quantum hardware is not yet able to run the full parton shower, we were able to run a simplified version to show that the quantum algorithm can clearly pick up the interference effects.

The goal going forward is to simulate the dynamics of an effective field theory that can describe long distance radiation of particles in high energy collisions, such as the LHC. We are developing a code library that allows for the simulation of such field theories in very simple setups. We are studying one of the important steps in the Jordan, Lee and Preskill algorithm, namely the adiabatic evolution required in the state preparation of the interacting field theory, and are determining the best strategies to perform these steps on NISQ-era devices. Given that reduction of operation errors is critical to quantum computation in the NISQ era, we have also started work on readout and gate error reduction.

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

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(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.

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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