High Energy Physics
Quantum Information Science Awards Abstracts
Foundational QIS- Theory and Simulations

Quantum Simulation of Quantum Field Theories
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Quantum Information Science for Applied Quantum Field Theory
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Co-PIs: J. Amundson, R. Harnik, A. Kronfeld, A. Macridin, P. Spenzouris, Fermilab,
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Dipolar molecule emulator of lattice gauge theories
PI: Bryce Gadway, University of Illinois Urbana-Champaign
Co-PIs: J. Shen, D. Luo, M. Highman, B. Clark, B. DeMarco, A. X. El-Khadra, University of Illinois at Urbana-Champaign

Foundations of Quantum Computing for Gauge Theories and Quantum Gravity
PI: Yannick Meurice, University of Iowa
Co-PIs: M. McGuigan (BNL), R. Brower (BU), S. Lloyd (MIT), (MSU) A. Bazavov (MSU), S. Catterall, (Syracuse), S. Jordan (Maryland), D. Berenstein and X. Dong (UCSB)

Variational Consistent Histories: A Hybrid Quantum-Classical Algorithm for Quantum Foundations
DOE HEP QuantISED Grant: Disentangling Quantum Entanglement:
PI: Andrew Sornborger, LANL
Co-PI: Andreas Albrecht (UC Davis)

Quantum Simulation of Quantum Field Theories

Tanmoy Bhattacharya (LANL), Shailesh Chandrasekharan (Duke University), Rajan Gupta (LANL), Hersh Singh (Duke University), Rolando Somma (LANL)

The efficient simulation of quantum field theories is one of the main challenges in high energy physics. The only first-principles method when perturbation theory fails involves taking the limit of a discretized path integral evaluated by importance sampling. Often, however, the relevant measure is not positive when the paths are expressed in any known set of classical variables, and the integral becomes exponentially hard to compute. Hence novel computational paradigms are highly desirable. Here, we explore possible gains in using quantum computers to solve quantum field theories. In this, our goal is both to formulate the problem in a language expressible on a finite quantum computer and to develop efficient quantum algorithms for computing the quantities of interest. In particular, we will focus on expectation values of physical observables and correlations in thermal equilibrium as well as on time-dependent properties of QFTs 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 finite Hilbert space at each lattice site. The idea is that if we can discretize the problem preserving its symmetries, then renormalization group flow can help in the construction of the continuum field theory. As the first example in this direction, we explore if the physics of the O(3) sigma model can be obtained from an O(3)-symmetric two-qubit Hamiltonian on each lattice site. As a first project, we shall explore if we can reproduce the physics of the Wilson-Fisher fixed point in 2+1-dimensions using such a qubit Hamiltonian. As a second project, we explore if we can obtain the asymptotic freedom of the O(3) sigma model in 1+1-dimensions via the qubit system. We will also explore how the approach to the continuum limit depends on the number of qubits used per site.

Simultaneously, we shall develop algorithms for simulating these systems on a quantum computer. Our current work in this direction uses a coupled system of naïvely discretized quantum oscillators as a discrete realization of the free scalar field theory and constructs 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 N of space discretization points. This is an improvement over other known quantum algorithms, where the time scales quadratically or worse with N. 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 developed by one of us [1], 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 scattering amplitudes.

[1] R.D. Somma, "Quantum simulations of one-dimensional quantum systems", *Quant. Inf. Comp.* **16** 1125–1168 (2016).

Quantum Information Science for Applied Quantum Field Theory

John Preskill, CalTech
J. Amundson, M. Carena (PI), R. Harnik, A. Kronfeld, A. Macridin, P. Spenzouris, Fermilab,
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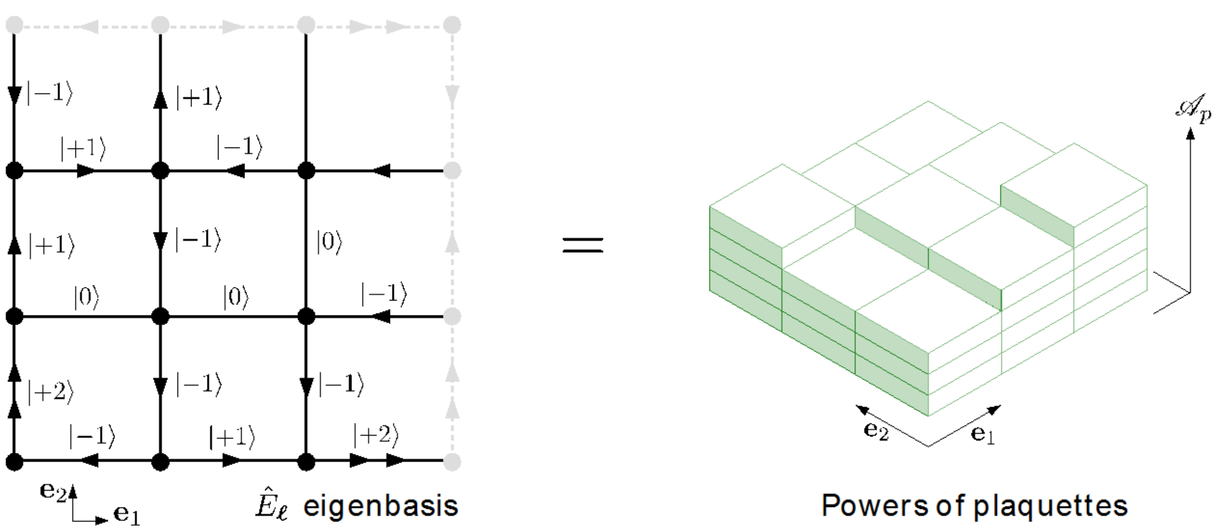
Quantum computer seems to be the right abstract model for capturing all information processing that Nature allows, including that being performed by the most fundamental processes. The aim of this project is to explore and further develop connections between quantum information science (QIS) and quantum field theories (QFTs) in high energy physics. QFTs provide the foundation of high energy physics, from QED and low energy effective field theories of the strong and weak interactions, to the gauge theories of the Standard Model (SM) of particle physics, and to possible extensions beyond the SM. Applied QFT, i.e., QFT-based calculation, is a critical part of the analysis and interpretation of high energy physics experiments.

QFT and its applications present us with a variety of challenges, both computational and conceptual. In our work we identify several specific QFT challenges that may be fruitfully attacked with the tools of QIS. We are exploring new approaches to simulations of the Standard Model of particle physics. In particular, we are investigating approaches to reducing error in quantum simulation of QFTs utilizing the techniques of effective field theories. We also employ QIS techniques to develop new tools for high energy physics experiments, such as simulation of models for hadronization at the LHC, as well as new approaches to Feynman integral reduction. In addition, we explore ways in which the tools and language of QIS can shed new light on models for physics beyond the SM. Our work will help harness the power of quantum information science into applications that will advance the field of high energy physics.



Foundations of Quantum Computing for Gauge Theories and Quantum Gravity

BNL (M. McGuigan), BU (R. Brower), MIT (S. Lloyd), MSU (A. Bazavov), Syracuse (S. Catterall), U. of Iowa (Y. Meurice, PI), U. Md. (S. Jordan), UCSB (D. Berenstein and X. Dong)

Goals. Developing the fundamental building blocks of quantum computing for problems in High Energy Physics that are beyond classical computing. This includes real time evolution and calculations with sign problems encountered in lattice gauge theory and holographic approaches to strongly coupled systems. The long-term goals are to provide scalable quantum codes to describe the evolution of hadrons in collider experiments (jet physics), the early universe and the exploration of new models in quantum gravity and conformal field theory (CFT).

Work in progress. The ongoing research combines overlapping expertise in quantum computing, gauge-gravity duality and lattice gauge theory. This includes:

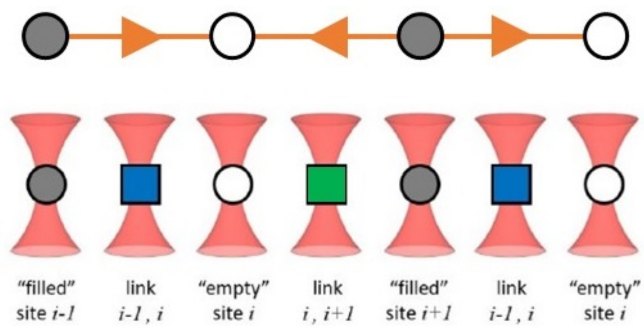
- Preparation of vacuum states of lattice field theories on universal quantum computers using the "jagged adiabatic path" method. MERA-based variational algorithms for simulating CFTs. Trapped ion implementations.
- Toolkit to translate tensor networks or quantum links formulations of lattice models into circuits implementable on quantum computers with polynomial time scaling.
- Benchmarks for real time scattering allowing comparison among quantum computers. Use of clock-shift, position, and harmonic oscillator basis for discrete quantum mechanics.
- Tensor network calculations for the non-abelian Higgs model and Euclidean de Sitter gravity. Discrete formulation of quantum algorithms in tessellations of AdS Space. Use of Rényi entropies of subregions (arXiv:1811.04081) to distinguish microcanonical from canonical features in theories holographically dual to gravity. Applications for evolution after quantum quenches.

Connection with quantum simulation experiments. Some of the procedures proposed can also be implemented using cold neutral atoms in optical lattices or trapped ions. Experimental implementations of variational procedures are being considered in collaboration with Guido Pagano from Chris Monroe's ion trap group. Our recent experimental proposal (PRL 121 22320) for the Abelian Higgs model could be implemented in cold atom facilities. This is an unexplored direction for high-energy physics models and there is a niche that could be filled in our National Laboratories.

Dipolar molecule emulator of lattice gauge theories

J. Shen, D. Luo, M. Highman, B. Clark, B. DeMarco, A. X. El-Khadra, B. Gadway
University of Illinois at Urbana-Champaign

The quantum many-body problem is a great unsolved, cross-cutting challenge in physics that is of fundamental importance. Our understanding of phenomena related to dense quark matter, in particular, is challenged by this practical intractability of classical simulations. Because of the sheer cost and challenge of performing experiments that probe the length and energy scales relevant to such physics, there are practical motivations for finding theoretical methods to address the many-body problem. One promising approach, first proposed by Richard Feynman in the 1980s [1], is based on the use of a programmable and controllable analog quantum system to emulate the physics of a many-body problem of interest. This idea has been greatly extended over the interceding decades. We now, for instance, have formalized protocols for how computers based on quantum logic and bits (*i.e.*, qubits) could improve performance for many computational tasks, including simulations of particle physics problems [2,3]. While there are currently worldwide efforts to develop mid- to large-scale quantum computers, we are still likely many years away from such devices outperforming classical supercomputers. Even though digital quantum computers are still at a stage too premature for such tasks, an approach more directly along the lines envisioned by Feynman based on analog quantum simulators has advanced rapidly over the past two decades and can now treat many-body problems on par with or beyond the capabilities of modern supercomputers [4]. There has already been a great deal of theoretical work in considering analog quantum simulation approaches to problems with HEP relevance [5,6].



We describe how ultracold polar molecules—reproducible, controllable, scalable, and highly coherent quantum particles—can be used for the analog emulation of dynamical phenomena central to our understanding of particle physics, such as string-breaking and confinement. Specifically, we discuss how Abelian quantum link models in (1+1)d can be constructed based on arrays of polar molecules that are fixed in space but support direct dipolar exchange interactions between different rotational states. We describe how Gauss' law is imposed in such a system, through control of the internal state-dependent energy landscape of the molecules. We also discuss the possibilities for extending to higher-dimensional and non-Abelian quantum link models, by harnessing the naturally large internal state space of polar molecules and their ability to be trapped in tunable geometries.

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[5] U.-J. Wiese. Ultracold quantum gases and lattice systems: Quantum simulation of lattice gauge theories. *Annalen der Physik* **525**, 777 (2013).
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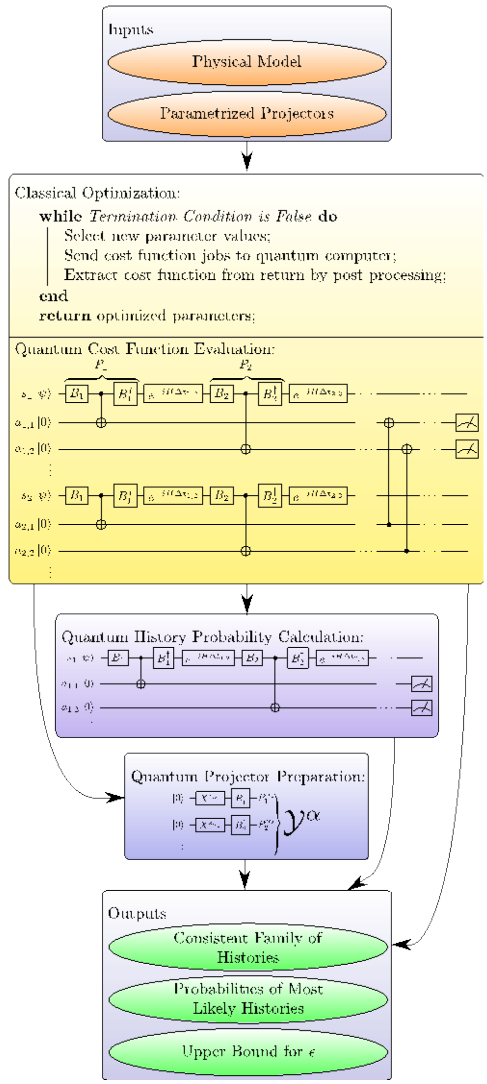
[7] A. V. Gorshkov, S. R. Manmana, G. Chen, E. Demler, M. D. Lukin, and A. M. Rey. Quantum magnetism with polar alkali-metal dimers. *Phys. Rev. A* **84**, 033619 (2011).

Title: Variational Consistent Histories: A Hybrid Quantum-Classical Algorithm for Quantum Foundations

DOE HEP QuantISED Grant: Disentangling Quantum Entanglement:
PI – Sornborger (LANL), Co-PI Albrecht (UC Davis)



The foundations of quantum mechanics have been debated for much of the past century. Of crucial importance to the understanding of the world we experience is the quantum-to-classical transition, i.e., the emergence of classical behavior from quantum laws. The Consistent Histories (CH) formalism was introduced by Gell-Mann, Hartle, Griffiths, and Omnès to address some of these fundamental issues. The inventors considered CH to be "the Copenhagen interpretation done right", as it resolves some of the paradoxes of quantum mechanics by enforcing strict rules for logical reasoning with quantum systems.

In this formalism, the Copenhagen interpretation's focus on measurements as the origin of probabilities is replaced by probabilities for sequences of events (histories) to occur. Hence, by avoiding measurements it avoids the measurement problem. The sets of histories whose probabilities are additive (as the histories do not interfere with each other) are considered to be consistent and are thus the only ones able to be reasoned about in terms of classical probability and logic. Regardless of one's opinion of the philosophical interpretation (on which we are agnostic), this computational framework has proven useful in applications such as investigating whether or not quantum cosmological theories are singular, understanding quantum jumps, and evaluating the arrival time for photons at a detector.

One of the main reasons that this framework has not received more attention and been more widely applied is that carrying out the calculations for non-trivial cases can be difficult. While numerical approaches have been attempted, they require exponentially more resources as either the number of times considered or the system size grow. This makes these approaches unusable for any but the simplest cases.

Here we present a scalable, variational hybrid quantum-classical algorithm (VHQCA) for the CH formalism, which achieves an exponential speedup over classical methods both in terms of the 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. We expect this to revitalize interest in the CH approach to quantum mechanics, by increasing its practical utility.

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. The VHQCA framework potentially brings the practical applications of quantum computers years closer to fruition. Hence, practical implementations of our algorithm will be feasible on near-term quantum devices.