Quantum Simulation of Quantum Field Theories for High Energy Physics

Zohreh Davoudi[1], Stephen Jordan[2], Yannick Meurice[3], Christopher Monroe[4], James Osborn[5], and John Preskill[6]

[1]Department of Physics and Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA, and RIKEN Center for Accelerator-based Sciences, Wako 351-0198, Japan
[2]Microsoft Quantum, Redmond, Washington 98052, USA
[3]Department of Physics and Astronomy, University of Iowa, IA 52242, USA
[4]Joint Quantum Institute, Center for Quantum Information and Computer Science, and Departments of Physics and Electrical and Computer Engineering, University of Maryland, College Park, MD 20742, USA
[5]Computational Science Division, Argonne National Laboratory, IL 60439, USA
[6] Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA

October 17, 2020

Abstract

This Letter of Interest outlines the motivation for, progress in, and outlook of quantum simulations of quantum field theories that are relevant to Nature. We argue that while the big physics payoff may still be far away, today's research can hasten the arrival of a new era in which quantum simulation fuels progress in fundamental physics. Even in the near term, studies of dynamics in strongly-coupled quantum field theories can provide revealing insights, and will pave the way to large-scale simulations of elementary particles and interactions, with potential impact on theoretical and experimental research in high-energy physics in the coming decades.

■ (CompF6) Quantum Computing
■ (TF10) Quantum Information Science
■ (TF05) Lattice Gauge Theory
■ (CompF2) Theoretical Calculations and Simulation

Contact Information:
Zohreh Davoudi
Email: davoudi@umd.edu

Why quantum simulation? The Standard Model of Particle Physics is comprised of gauge field theories which accurately describe the electroweak and strong interactions observed in nature. An ambitious numerical program called lattice gauge theory (LGT) was established over four decades ago to pursue quantum field theory (QFT) simulations in regimes where perturbation theory is inadequate. The program flourished to become a successful and reliable approach to evaluating certain properties of strongly-interacting hadrons and their unstable excitations, including scattering and transition amplitudes in the few-body sector, directly impacting the experimental programs in high-energy and nuclear physics. However, despite continuing growth in computing resources, present computational techniques that rely on Monte Carlo sampling of quantum fields are on a slow track toward achieving accurate descriptions of real-time phenomena governed by QFTs. Thus we have only a limited understanding of fundamental phenomena such as thermalization, fragmentation, and hadronization, or more generally the evolution of matter after being exposed to extreme conditions such as high-energy collisions, supernovae explosions, and neutron-star mergers. Even for matter in equilibrium, we have been unable to characterize accurately various phases and phase transitions as a function of thermodynamic quantities such as temperature and chemical potential, due to inherent sign and signal-to-noise problems in computations which demand computing resources scaling exponentially with the number of degrees of freedom. Motivated by Feynman's vision to employ quantum simulators to simulate Nature, and by the locality and causality of QFTs that comprise the Standard Model, we foresee that such classically intractable problems can be addressed successfully with quantum simulators. A coordinated quantum simulation program in high energy physics (HEP) over the next decade, therefore, promises to lay the cornerstones of an enhanced LGT program based on new paradigms in quantum computing and simulation.

Quantum simulators: analog, digital, or both? A range of quantum-simulation platforms, including trapped ions, neutral atoms in optical lattices, superconducting circuits, cavity QED, and Rydberg atoms, have been developed and made available for scientific benchmarking in recent years. Quantum hardware technology development is expected to be expedited over the next decade, boosted by the newly-established National Quantum Initiative centers in the U.S. and other investments worldwide. These systems can work in either digital or analog mode, or both, and each has its own capabilities and limitations, depending on its native degrees of freedom and interactions, coupling to the environment, and degree of controllability. In the near term, analog and digital quantum simulation of QFTs will advance via a vibrant process of co-design guiding the development of both algorithms and hardware. For example, in near-term simulations which are hampered by imperfect control and noisy quantum gates, it may prove beneficial to design and commission platforms which use higher-dimensional systems rather than qubits, and/or exhibit intrinsic multi-body interactions that are well suited for simulating gauge-theory dynamics. While fully error-corrected circuit implementations may still be a ways off, ever-improving noise mitigation protocols can push the scope of upcoming simulations. Over the next decade, coordinated theory-experiment collaborations will focus on such ideas.

Where do we stand today? Despite a proliferation of ideas, proposals, algorithms, and implementations of quantum simulations of QFTs over the past decade, much progress will be needed to achieve practical, reliable, and large-scale realizations. To study scattering in QFTs, subroutines are being developed to prepare initial states, simulate time evolution, and measure final-state observables; an important challenge is to assess and improve the quantum resource requirements for these tasks. Low-dimensional Abelian and non-Abelian gauge theories have been analyzed in various digitization frameworks, and both digital and analog quantum-simulation protocols have been developed on various simulation hardware. Realizations of a one-dimensional Abelian LGT, i.e., the Schwinger model, on trapped-ion and superconducting circuits have become a reality in the past five years, and a non-Abelian realization now exists for small systems in 2+1 dimensions. Detailed quantum resource requirements for near-term and far-term simulations of the Schwinger model have been formulated; meanwhile simulation algorithms have also been developed based on light-front quantization of fields, and using single-particle bases in systems with low particle number.

What next? The field is evolving fast, progressing from low-dimensional to high-dimensional theories, and from simple models towards complex theories that comprise the Standard Model. New tools are needed to evaluate and converge on the best methods for simulating Hamiltonian QFTs efficiently and accurately. The effect of truncation of the bosonic modes, e.g., gauge bosons in gauge theories, should be quantified; furthermore a practical renormalization program is needed to establish the scale independence of observables, accounting for boson-mode truncations and the ultraviolet scale-dependence of bare parameters. In addition, state preparation of both pure and thermal states in strongly-interacting QFTs, as well as state tomography, should be studied in depth. Hybrid classical/quantum protocols to facilitate various stages of simulations are being explored and may offer an earlier quantum advantage. The accessibility of Exascale classical computing resources, and the vast knowledge and experience of lattice gauge theorists at using these resources effectively, justify such a hybrid approach, especially in the near term.

Quantum sub-processors to enhance classical computations? In addition to the natural path to QFT simulations on quantum hardware based on the Hamiltonian framework, one can envision a parallel path that combines classical and quantum processors to accelerate different components of a conventional LGT program. In the upcoming years, ideas will be sought and tested to enhance importance sampling of quantum configurations, especially when sign or signal-to-noise problems are encountered, or when a critical slowing down is encountered toward the continuum limit. Quantum platforms might speed up inversion of poorly-conditioned large matrices, enhance semidefinite programming for construction of optimal field interpolating operators, or incorporate more economically the factorial growth of the number of contributions in nuclear correlation functions.

Where may quantum advantage lie? It is conceivable that quantum advantage will be achieved in studies of highly-entangled states for which state-of-the-art classical tensor network methods fail. Such states might arise in highly energetic collisions with complex multi-particle products, in processes where multiple scattering events occur, or in the far-from-equilibrium dynamics of strongly-interacting systems after a quench. From a practical standpoint, establishing quantum advantage in quantum simulation of QFTs and effective field theories of hadronic and nuclear physics will have a far-reaching impact, eventually encompassing: predictions for QCD backgrounds in collider experiments, constraints on the equation of state for nuclear matter, properties of quark-gluon plasma and other phases of matter relevant to cosmology, electroweak response of nuclear isotopes for intensity-frontier experiments, simulation of nuclear reactions for astrophysical modeling, exploration of strongly-coupled theories beyond the Standard Model, and steps toward simulation of quantum gravity based on holographic duality. We don't know yet how each of these problems will be addressed with quantum-simulation technology, but research over the next decade will illuminate the path forward.