Advancing High-energy Physics with Quantum Computing Research

Travis Humble, Andrea Delgado, Kübra Yeter-Aydeniz, Raphael Pooser,
Ryan Bennink, Vicente Leyton-Ortega, Eugene Dumitrescu, Titus Morris,
Zak Webb, Kathleen Hamilton, Cameron Reid, Alex McCaskey,
Prasanna Date, Yan Wang, Nick Peters, Kate Evans, Marcel Demarteau
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Quantum computing enables new paradigms for high-energy physics research through the development of computational tools for modeling and simulation, detection and classification, data analysis and forecasting of experimental phenomena. The emerging hardware, software, and applications of quantum computing are exciting opportunities, but it remains unclear how these techniques may integrate into the HEP community. We present the need for *integrated quantum computing research* to advance HEP discovery science. We describe specific opportunities for the focused development of algorithms, applications, software, hardware, and infrastructure to support both practical and theoretical applications of quantum computing to HEP problems within the next 10 years.

At Oak Ridge National Laboratory, we have previously led the development of quantum computing for domain-specific applications in chemistry, materials science, nuclear physics and, more recently, high-energy physics. We have a broad appreciation for the challenges and opportunities that quantum computing platforms offer to domain-specific science. Chief among these are unequaled expectations for algorithmic and computational scaling, accuracy, time-to-solution, and implementation complexity. But these promises come with hefty challenges including the necessity of exceeding conventional state-of-the-art methods, validating the maturity of quantum technological solutions, and redefining workflows that have trained generations of scientists to be productive and impactful.

Collaborations between high-energy physicists and quantum computer scientists are critical for progress since advancing HEP science using quantum computing cannot be accomplished by either community in isolation. A shared research agenda must learn to tailor quantum computing to the application-specific contexts offered by HEP experiments, including the forthcoming era of the high-luminosity Large Hadron Collider (LHC). We expect fast-paced changes in the field of quantum computing over the next 10 years to be an opportunity to prioritize both technology and application development. High-energy physics priorities must compete with alternatives from other disciplines, and early engagements with quantum computer scientists will lay the groundwork for the impact and schedule of quantum computing technology.

We identify two topical areas where cross-disciplinary, integrated research is fundamental to the advance of quantum computing for HEP discovery science over the next decade. Alongside workforce development and facility infrastructure, these research priorities will accelerate the next decade of high-energy physics through collaborative research and development of 1) applications and algorithms and 2) quantum computing codesign.

Priority: Collaborative Algorithmic and Applications Research

Quantum algorithms underpin many of the expected performance advantages offered by quantum computing, and specialization of quantum algorithms to HEP applications is an important collaborative research focus. Studying scattering amplitudes, transition rates, and other physical quantities in HEP systems becomes computationally intractable as the number of particles increases. Tailoring simulations of quantum field theories using fault-tolerant quantum computing models is a natural point of collaboration. For example, controlled approximations of the evolution process with fault-tolerant quantum computers can support the study of real-time dynamics for many-body HEP systems. This research will target the roadmap for fault-tolerant computers, set goals toward a 10-year horizon, and aligned with known HEP research priorities. These approaches also provide baselines by which to compare conventional methods for simulating specific field theories through their complexity analysis. Concurrently, algorithms that mitigate the limits of noisy quantum computers are important opportunities to leapfrog advances. For example, simulations of quantum many-body systems may be calculated with noisy hardware using a variety of short-depth algorithms, such as imaginary time evolution and Lanczos methods. However, developing these techniques to be competitive, or integrate, with conventional HEP approaches represents a clear challenge to the quantum computing community. Hybrid methods that accelerate existing approaches with quantum algorithms seems promising as do quantum machine learning methods for augmenting simulations of quantum field theories.

Priority: Collaborative Quantum Computing Codesign

The development of quantum computing hardware to enable algorithms and applications is a necessary part of the HEP research agenda. Co-design is a feedback process, by which users and developers communicate goals and requirements to advance quantum computer development. Only the HEP community can advocate for scientific goals that drive the development of quantum computing to support the high-luminosity regime of the LHC and the frontier experiments in neutrino physics. For example, tailoring analog quantum simulators using available technologies, such as ion traps and photonics, to deliver custom hardware for studying quantum field theories requires input from the HEP community to specialize the hardware and software that address these applications.

The best scientific results come from enabling the largest group of scientists to test and evaluate these applications. This is accomplished by lowering the adoption barrier for quantum computing systems, which will require efforts to standardize interfaces with quantum computing systems for HEP applications. The international HEP community will demand testing and evaluation of quantum computing with transparent and reproducible approaches to ensure the highest quality results. Communal efforts must emphasize verification and validation of quantum computing for HEP specific applications through consensus on well-defined metrics and benchmarks.

These research priorities will enable the HEP community to track the progress of quantum computing over the next decade, identify near-term opportunities for early access research, and establish the long-term research agenda required for quantum computing to advance HEP discovery science.