Snowmass2021 - Letter of Interest

Simulations for HEP with SQMS Quantum Hardware

Thematic Areas:

■ (TF10) QIS Theory
■ (CompF06) Quantum Computing

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Abstract: The Superconducting Quantum Materials and Systems (SQMS) Center, a Fermilab lead NQI center, will develop and deploy a beyond state of the art quantum computers. These systems will exhibit long coherent times, and a high degree of connectivity. We are interested in exploring the utility of these devices to address computational challenges in HEP, such as the simulation of strongly coupled quantum field theories. A progression of toy models and simulations can begin to chart a course towards simulating QCD-like systems.

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The SQMS Center will accelerate the basic science of coherence for superconducting quantum systems, including for high Q SRF cavities and Josephson qubit devices. A important goal of the Center is to integrate these insights into intermediate-scale prototypes for quantum information processing (QIP) systems. These will be based on two leading architectures for QIP [1]: (1) multi-level bosonic encodings in high quality, three-dimensional microwave resonators (e.g. SRF cavities); and (2) Josephson qubit-based processors (e.g. transmon-transmon circuits). We are here expressing our interest to identify the utility of these beyond-state-of-the-art quantum systems to address computational questions relevant for high energy physics and to engage the HEP and QIS communities in doing so. Long coherence time is expected to allow for greater algorithm depth. At the same time, the high degree of connectivity of SRF-approaches may allow for a broad plethora of "primitive gates" and more efficient quantum algorithms. Dedicated gate sets may be optimized for specific simulation tasks.

The inability to simulate nonperturbative quantum field theories (QFTs) in real time underlies many outstanding problems in high energy physics and cosmology. Of particular interest are gauge theories of the Standard Model: quantum electrodynamics (QED), weak interactions, and especially quantum chromodynamics (QCD), which is strongly coupled. Of relevance to the Large Hadron Collider are Parton distribution functions (PDFs), which quantify the probability of a proton containing quark and gluons of certain momentum, and hadronization, the fragmentation of QCD strings and the process by which quarks and gluons turn into hadrons. These are the only parts of the collision simulation chain that are treated with ad-hoc models rather than first principle calculations, and both can benefit from first principle based simulation, even in toy models. Initial work has been done for PDFs [2] and QED strings in one dimension [3,4]. SQMS hardware capabilities will allow one to begin to realize models of this and extend them to non-abelian strings. Informing these processes with quantum simulation in toy examples can be one of the first large scale impacts of quantum computing on high energy physics. Moreover, simulations of a QCD-like gluon plasma and its bulk properties including viscosity or conductivity can shed light on the conditions in the early Universe. Scalar field theories analysis may similarly be relevant in cosmology.

A challenge for any of these simulations is the high resource requirements, including large sets of highly connected qubits and high depth circuits, as recognized by many groups [2-12]. SQMS's SRF-based QPUs, with high coherence time and all-to-all connectivity, will be an ideal candidate for advancing these simulations. A progression of calculations can be used to benchmark simulations on the SRF-based QPUs. The progression can rely on a ladder of gauge theories, starting with simple toy theories of QED such as Z2 and leading to QCD and QCD-like theories such as S(1080)[5]. Within each theory, a ladder of increasingly complex calculations may be benchmarked, starting from the theories' "native gates" to single trotter time steps, to string dynamics simulations on a lattice.

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