QIS FOR APPLIED QUANTUM FIELD THEORY

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Precision predictions in HEP and non-equilibrium dynamics in the early universe require quantum computational technologies. Future quantum devices offer the possibility of performing these, complementing lattice quantum chromodynamics (QCD) studies on classical computers.

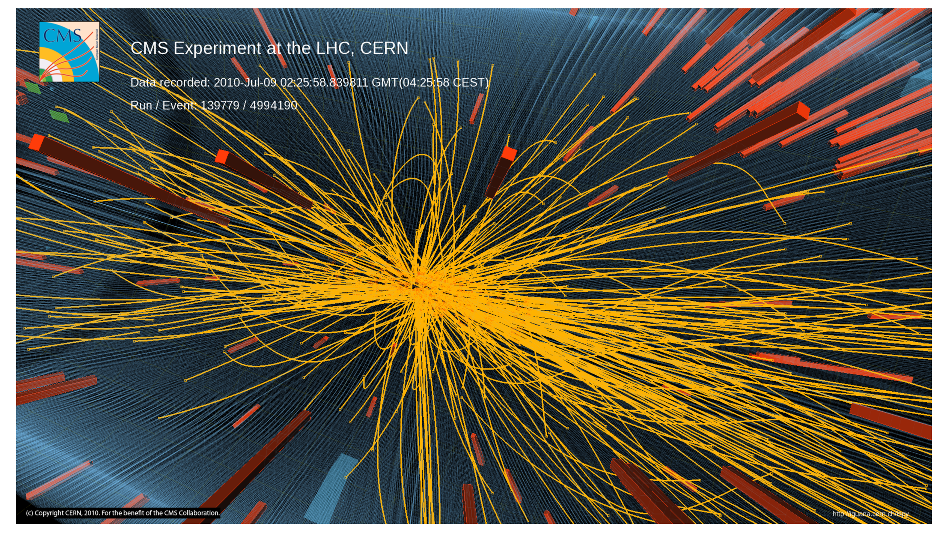

Figure 1: Event in the CMS Experiment detector from 7 TeV collisions. (Image credit: CMS)

We are investigating many aspects of the quantum simulation of quantum field theories. Specific topics include simulation-suitable formulations of gauge theories, state preparation, time evolution, extracting HEP-related observables from simulations, quantum error correction (QEC), and entanglement. We are exploring strategies for simulation of scattering in QFTs, and dynamics of the early Universe.

Formulations of Quantum Field Theories

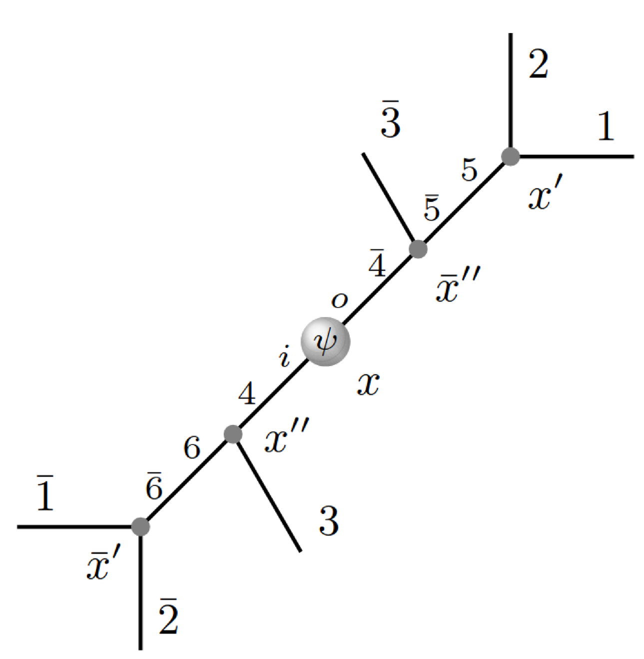

Figure 2: A loop-string-hadron (LSH) formulation for SU(2) Hamiltonian lattice gauge theory (1)

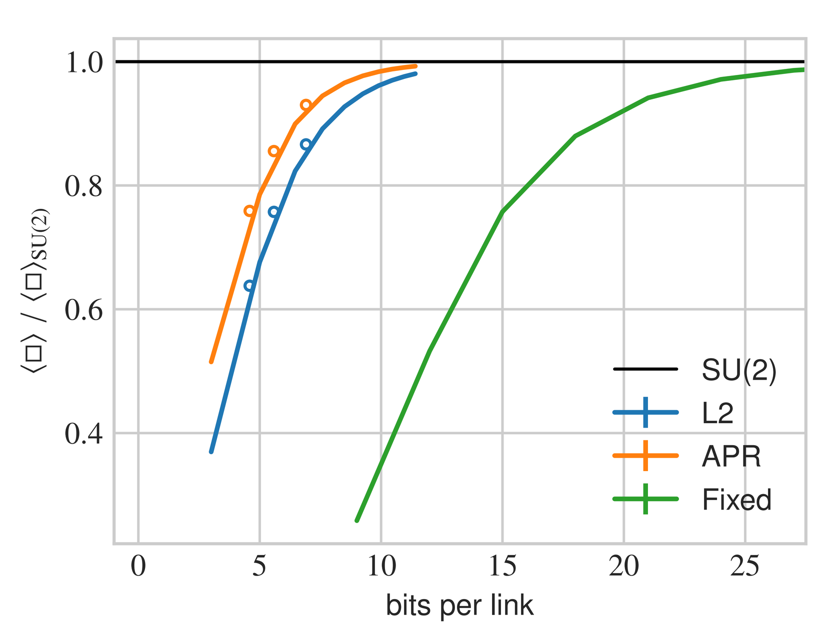

Figure 3: The expectation value of an SU(2) Wilson loop normalized to its true value as a function of qubits per site for several digitization schemes. A 10% error is attainable for as little as 7 qubits (2)

Efficient choices of basis, truncation, and quantum gate implementation are critical, particularly in the NISQ era. Our team has developed several promising options for simulating both gauge (*1–3*) and scalar theories (*4*, *5*). As these options mature, resource cost estimates and comparisons can be made.

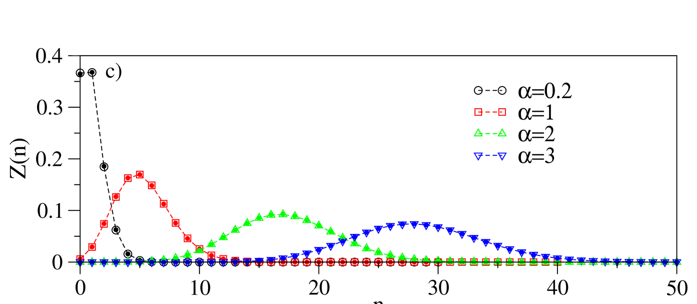

Figure 4: The phonon number distribution in the polaron state for different values of the coupling strength (4).

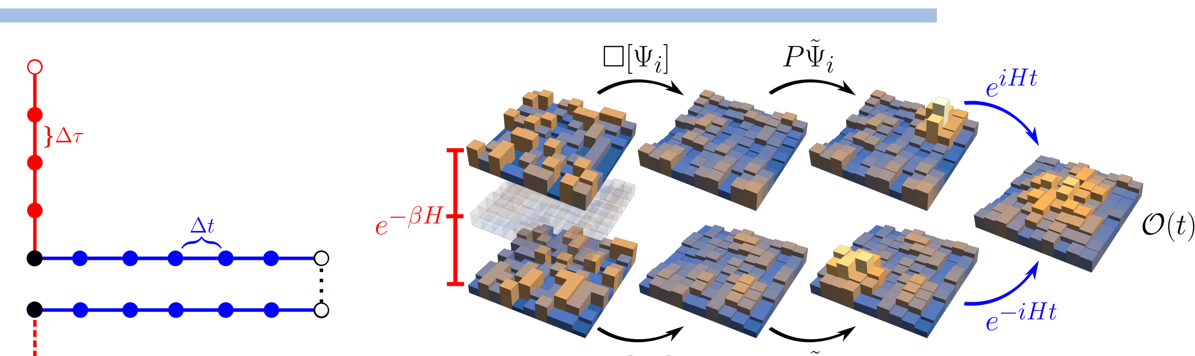

Figure 5: (left) Schwinger-Keldysh contour as real- (●) and imaginary-time (●) path integrals. At (●) two path integrals are matched, at (○) one inserts $\mathcal{O}$ (right) how smearing, $\Box[\Psi] = \tilde{\Psi}$, and sources P allow general state preparation (6)

State Preparation

Leveraging renormalization group and lattice QCD ideas, new state preparation protocols for strongly-coupled states have been found with fewer resources (*6–8*). Work is ongoing with Rigetti to initialize a scalar theory ground state.

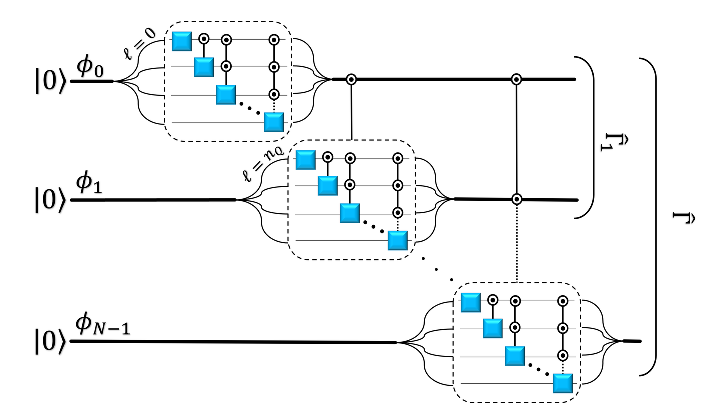

Figure 6: Quantum circuit for preparing an arbitrary real wavefunction for a scalar field (7)

Simulating Time Evolution of QFTs

We are continuing to develop algorithms for time evolution of QFTs. Simulations of a truncated, low-dimensional non-Abelian gauge theory were performed with IBM (*3*).

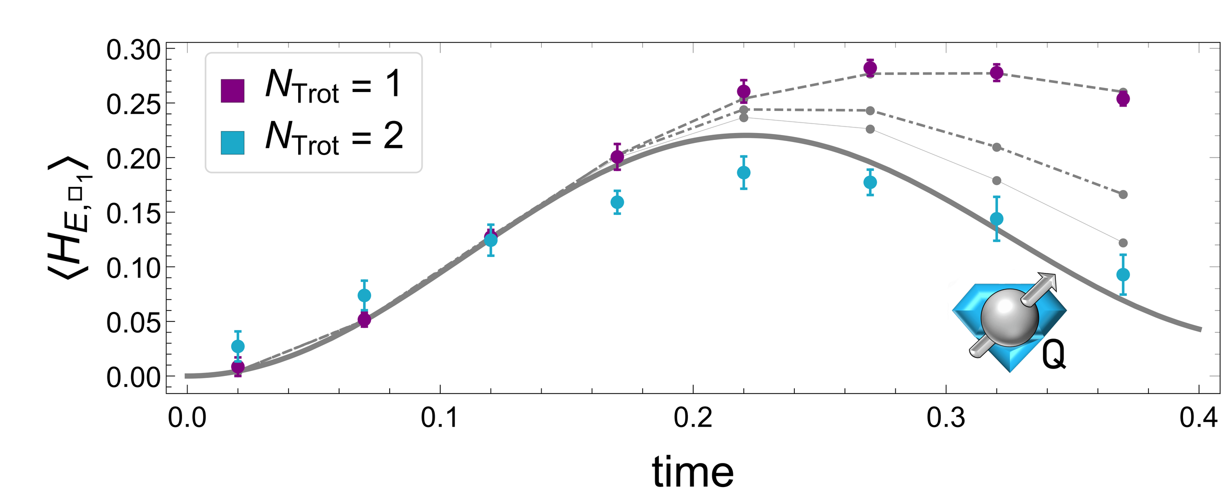

Figure 7: Expectation value of the electric energy contribution of the first plaquette in a two-plaquette non-Abelian lattice field theory using IBM's `Tokyo` *(3)*

Quantum Error Correction

Error correction is required for precision predictions from QFT. Studies have started of the interplay of QEC and continuous symmetries that arise in QFT (*9*).

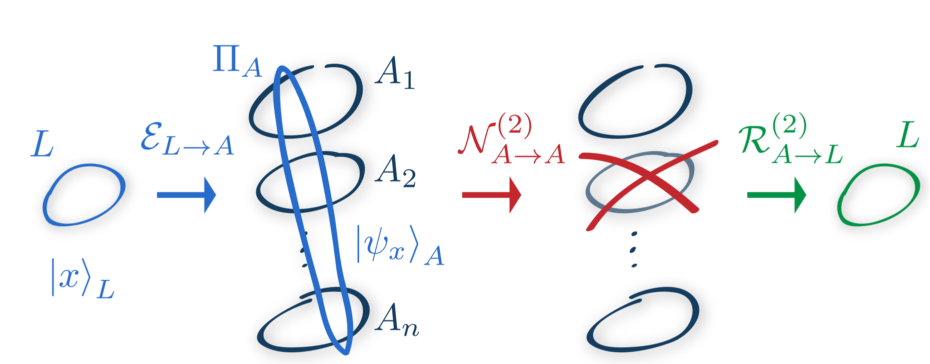

Figure 8: A code $\mathcal{E}_{L\to A}$ maps a logical state $|x\rangle$ to a physical state $|\psi_x\rangle_A$ composed of several subsystems $A = A_1 \otimes \cdots A_n$. While a subsystem can be erased, $\mathcal{N}^i_{A\to A'}$, a good error-correcting code recovers the original logical state $|x\rangle$ by applying $\mathcal{R}^i_{A\to L}$ (9)

Entanglement and QCD

QIS-inspired insight has lead to the discovery of new properties related to entanglement in nonperturbative QCD (*10*, *11*)

Observables for Colliders

We have shown how to compute parton distribution functions (*12*) and how many properties can be obtained with few measurements (*13*). These will be extended to fragmentation functions and viscosity.

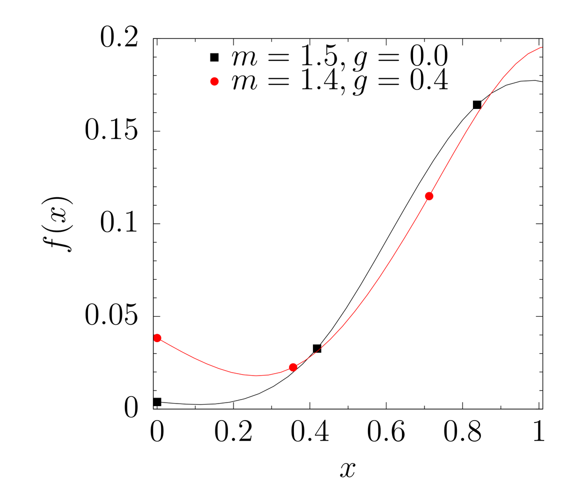

Figure 9: PDF of a 1+1d fermionic theory obtained from a quantum simulator (12)

Outlook: Simulating Cosmology

Our methods can be extended to early universe processes like: QFTs in curved spacetimes, bubble collisions, and CP-violating transmissions of fermions off bubbles.

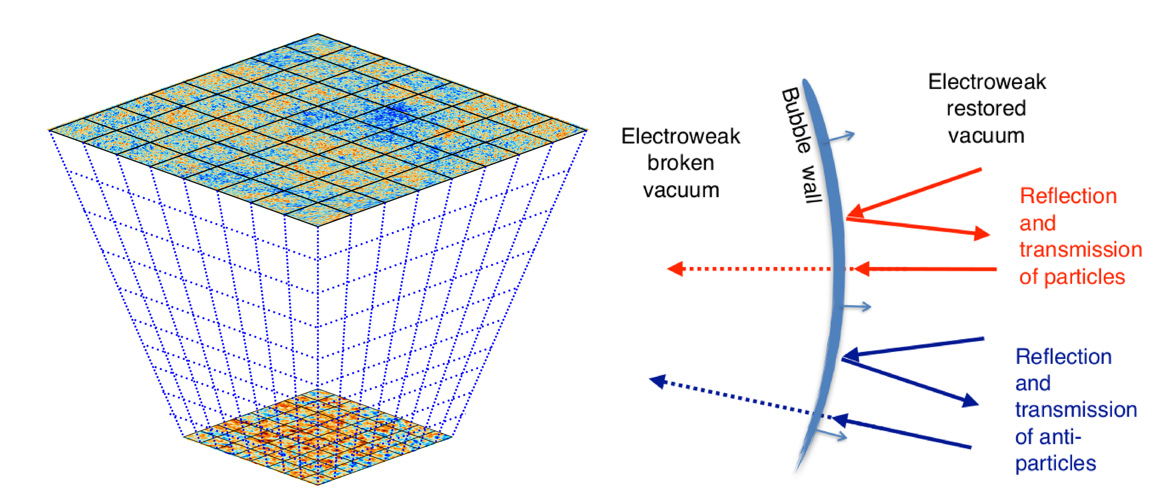

Figure 10: We are developing formalism for (left) QFTs in expanding backgrounds and (right) baryogenesis in the expanding universe.

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