Efficient simulation of high-energy particle collisions using long-range entanglement

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Abstract

Roland Farrell, winner of the Entanglement Prize 2026 of the QuantumLeaks Foundation, refers to the thesis 'The hypothesized instantaneous collapse of an entangled quantum state may imply a fundamental breakdown of spatial separation'.

Long-range entanglement challenges our classical intuition about spatial separation and raises fundamental questions about the nature of quantum correlations. The long-range entanglement inherent in particles with nonzero momentum is also present in W states, enabling the approximate preparation of scattering wavepackets at constant quantum-circuit depth through measurements and classical feedforward.

Heisenberg's uncertainty principle says that a particle with definite momentum must be spread over space [1]. As a consequence, a particle with momentum contains correlations between distant spatial regions. This was formalized by Gioia and Wang [2] who showed that any state with nontrivial lattice momentum must have long-range entanglement. Recent work [3] showed that this long-range entanglement is the same as in the W state [4], an important resource state in quantum information. These observations have important implications for simulating high-energy particle collisions using a quantum computer. The first step of such a simulation is to apply a quantum circuit that prepares the wavefunction of two particles traveling toward each other with large momentum and energy. This wavefunction has long-range entanglement because the incoming particles are sharply peaked in momentum. As a result, a local unitary circuit that prepares this state must have a depth that scales at least as $V^{1/d}$ where V is the volume over which the particle is spread and d is the dimension.

Surprisingly, there is a shortcut that reduces the depth of the wavepacket-preparation circuit to a constant independent of the wavepacket's spatial volume. The trick is to distribute long-range entanglement using mid-circuit measurements and classically conditioned operations. These conditional operations are decided by a classical computer. The protocol builds off the work of Piroli, Styliaris and Cirac [5] who showed how to approximately prepare the W state in constant circuit depth. The present work [3] improved upon this by extending to a class of generalized W states and removing the need for ancillary qubits. The approximate W states one obtains have sufficient quality to be used in quantum simulations of collisions. This hybrid method illustrates how quantum and classical computers can work together to simulate nature more efficiently.

These observations motivate the following questions: In nature, how are quantum correlations and entanglement built between spatially separated regions of space? Is it all done coherently (like a quantum circuit), or are there decoherent mechanisms that involve measurements and partial wave function collapse followed by classical logic that changes future processes?

References

[1] W. Heisenberg, *Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik*, Z. Physik **43**, 172–198 (1927)

[2] L. Gioia and Chong Wang, *Nonzero Momentum Requires Long-Range Entanglement*, Phys. Rev. X 12, 031007 (2022)

[3] R. Farrell *et al.*, *Digital quantum simulations of scattering in quantum field theories using W states*, Nature Physics (2026)

[4] Dür *et al.*, *Three qubits can be entangled in two inequivalent ways* Phys. Rev. A **62**, 062314 (2000)

[5] L. Piroli *et al.*, *Approximating many-body quantum states with quantum circuits and measurements*, Phys. Rev. Lett. **133**, 230401 (2024)