Letter of Interest: Quantum Algorithms for Parton Showers

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1 Introduction

A central HEP question is whether nature at the highest available energies is still described well by the standard model (SM) of particle physics, or if physics beyond the SM (BSM) is required. Connecting experiments to theory requires detailed calculations that are directly comparable to the measurements. In almost all cases, these calculations can only be performed in certain limits of the theory, giving rise to theoretical uncertainties. As measurement precision increases, these uncertainties start to dominate. In particular, for events with a high multiplicity of final state particles, the known theoretical algorithms severely limit the accuracy with which predictions can be made. In many cases these limitations are not fundamental, but due to calculation complexity growing exponentially with the number of final state particles. In particular, theoretical formulations of amplitude based showers exist, but are exponentially difficult to implement with known classical algorithms. Given that quantum algorithms have been shown to provide exponential speedup over classical calculations in many cases (e.g. [Gro96, Sho97]), it is very interesting and important to study how quantum algorithms can be used to simulate high multiplicity events without exponential growth.

2 Existing Work

It has been shown in simplified models that effects intractable using known classical algorithms can be simulated on quantum computers with only polynomial scaling with particle multiplicity, rather than exponential [BNPDJ19] (Fig. 2). The particular simplified model consisted of two types of fermions interacting with bosons, including a "flavor mixing" coupling between them. This flavor mixing gives rise to numerically important interference effects, and the number of amplitudes that can interfere grows exponentially with the number of final state fermions. Standard parton shower algorithms would simply miss these interference effects, while classical algorithms that include them scale exponentially with the number of final states. Our quantum algorithm explicitly includes all interference effects, yet scales only polynomially in the number of final state fermions. A comparison of the complexity of the quantum and classical algorithms revealed that the quantum algorithm outperforms the classical one for more than 10 fermions in the final state. While currently available quantum hardware is not yet able to run the full parton shower, we were able to run a simplified version to show that the quantum algorithm can clearly pick up the interference effects.

3 Future Work

In the planned white paper we will address ideas how to extend these ideas to more realistic examples. In particular, we will discuss how to extend the simplified model discussed above to make it more realistic and describe effects that are closer to quantum interference effects in the Standard Model of Particle Physics. We will also discuss ideas for constructing quantum algorithms that can include subleading color effects that are currently neglected in all parton shower implementations of parton shower algorithms.

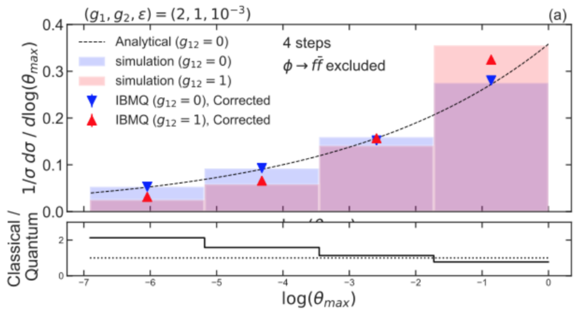

Figure 1: The normalized differential cross section for $\log \theta_{\max}$, for the simplified model from [BNPDJ19]. Interference effects were turned on ($g_{12} = 1$) and off ($g_{12} = 0$), leading to a clear effect in the quantum algorithm, both in simulation and on the IBM quantum hardware.

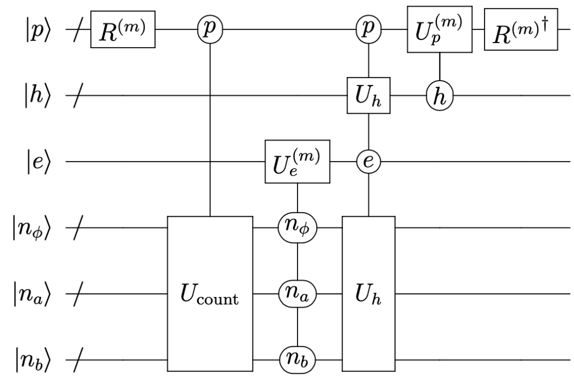

Figure 2: The quantum circuit that needs to be repeated for each timestep. The most computationally expensive step is the one involving U_h, which requires $n_f^2 \ln n_f$ gates, where n_f is the number of final fermions.

References

[BNPDJ19] C. W. Bauer, B. Nachman, D. Provasoli and W. A. De Jong, *A quantum algorithm for high energy physics simulations*, (2019), 1904.03196.

[Gro96] L. K. Grover, *A Fast Quantum Mechanical Algorithm for Database Search*, pages 212–219 (1996), quant-ph/9605043.

[Sho97] P. W. Shor, *Polynomial time algorithms for prime factorization and discrete logarithms on a quantum computer*, SIAM J. Sci. Statist. Comput. **26**, 1484 (1997), quant-ph/9508027.