Letter of Interest: Error correction for NISQ quantum algorithms

C. W. Bauer, B. De Jong, A. He, B. Nachman, M. Urbanek

to be submitted to the Computational Frontier (COMPF07) and Theory Frontier (TF10)

1 Introduction

While quantum computers hold great potential for many applications in HEP, the Noisy Intermediate-Scale Quantum (NISQ) [Pre18] computers of the near-term future come with a series of practical challenges. In particular, the quantum gates that are used in these computers are noisy and the readout is also noisy. Both sources of noise must be mitigated in order to for the output of NISQ devices to be useful for HEP. Therefore, the HEP quantum computing community should allocate resources to study, improve, and integrate these methods.

2 Readout Errors

Readout errors occur when a quantum state is readout to be different than the actual state. These errors arise from two sources: (1) measurement times are not short compared with decoherence times and thus a qubit in the $|1\rangle$ state can decay to the $|0\rangle$ state during a measurement, and (2) probability distributions of measured physical quantities that correspond to the $|0\rangle$ and $|1\rangle$ states have overlapping support and there is a small probability of measuring the opposite value.

Generally, readout errors are familiar to HEP experimentalists because our detectors introduce non-trivial resolution effects. In particular, unfolding a binned differential cross section with N bins is completely analogous to performing readout error corrections on a quantum computer with $\log_2(N)$ qubits. This connection was made explicit in Ref. [UNdJB19] (see also Fig. 1) and already applied in Ref. [BNPDJ19, UNdJ19], where traditional high energy physics unfolding strategies were applied to readout error corrections on quantum computers. In the future, a detailed comparison of unfolding methods applied to typical distributions in quantum computing may further improve the performance. It may also be that future methods developed specifically for quantum computers could be useful for HEP.

One of the biggest challenges with readout error corrections is that they always involve constructing a $2^n \times 2^n$ response matrix, where n is the number of qubits. A variety of approximations have been proposed to construct this matrix with sub-exponential resources, but it is still an active area of research.

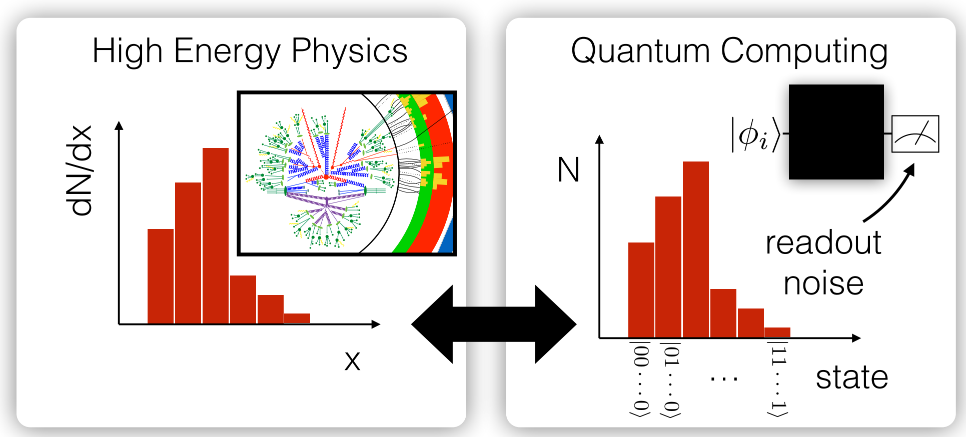

Figure 1: A schematic diagram illustrating the connection between readout errors and unfolding. Figure from Ref. [UNdJB19].

3 Gate Errors

Gate errors do not have a direct analog in experimental HEP, but are nonetheless very important for near term quantum computing. A variety of methods have been proposed and vary in their dependence on the particular circuit, the knowledge of the noise profile, and the types of noise affecting the circuit. Furthermore, existing methods can be very resource intensive (in terms of required gates and/or quantum computer runs).

One common method for gate error mitigation is to increase the noise of a circuit in a controlled way and then extrapolate to zero error ('zero noise extrapolation'). An observable can be measured for multiple value of the error inflation and then a parametric function can be used for the extrapolation. This method is effective at removing the important depolarizing noise, but can require significant resources to amplify noise. Recently, Ref. [AHB20] proposed an approach that trades gate depth for quantum computer runs by introducing randomness into the noise amplification. New methods like this could be empowering for near term projects using quantum computers. Alternatives to zero noise extrapolation have also been proposed and this is an active area of research. For example, there have been multiple proposals to learn the noise profile of a circuit by considering a similar circuit that can be efficiently simulated (e.g. one made of only Clifford gates) [CACC20, SQC+20]. Variations on this idea, as well as combinations with traditional zero noise extrapolation may provide the best approach to noise mitigation for NISQ devices and near-term HEP applications.

References

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