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Data Analysis in High-Energy Physics with Quantum Computers

Thematic Areas:

■ (CompF6) Computational Frontier: Quantum Computing

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Abstract: The physics reach of future high energy physics (HEP) experiments will be limited by how well computational resources are utilized. Currently, the HEP community takes and classifies an incredible amount of data for processing with extreme precision, requiring enormous computing power. Therefore, innovative computing technologies are vital to the HEP community for continuing the search to understand our universe's fundamental behavior. In particular, quantum computing holds the promise of substantially speeding up computationally challenging tasks such as processing the large-scale data available from HEP experiments. However, to take full advantage of these potential speed-ups, we must improve our understanding of quantum computers, how quantum algorithms can be used within the HEP context, and when they can outperform their classical counterparts. In this letter of interest, we explore some of the efforts related to exploring quantum computing for data analysis in HEP.

1 Introduction

Over recent decades, the high energy physics (HEP) community has acted as a driving force behind developments in many computing areas. The required computing power for the planned projects often outstrips what is likely to be available at the time of project realization. The amount of data currently generated by particle physics experiments presents a challenge to conventional information technologies. Therefore, innovative computing technologies are vital to the HEP community for continuing the search to understand the fundamental behavior of our universe.

Quantum computing holds the promise of substantially speeding up computationally challenging tasks such as processing the large-scale data available from HEP experiments. Therefore, it is essential to identify and explore which aspects of the data analysis workflow can benefit from quantum computing methods. In this letter of interest, we focus on collider experiments, where data processing includes the reconstruction of physics objects (such as tracks and jets), which are then used to select and classify events of interest.

2 Applications

Quantum computers are useful tools to solve optimization problems. This feature might be useful when the number of solutions is vast. Optimization algorithms often occur in HEP data analysis, such as fitting waveforms from particle detectors to pattern matching algorithms for track reconstruction. Therefore, HEP datasets constitute a natural test for quantum computing capabilities. However, to take full advantage of such capabilities, we must identify new computing models that can help us exploit the quantum nature of the universe. Besides, we should take advantage of the intersection between different fields, such as quantum computing and artificial intelligence, to develop a suite of new (or improved) methods for the analysis of HEP data. Some of the following problems are possible areas for application of quantum techniques:

- **Object/Event reconstruction:** Most of the efforts falling under this category are focused on the problem of track reconstruction, often cast as a pattern matching problem. Track reconstruction is a computationally expensive task in HEP experiments, but also an essential part in the reconstruction of higher level objects. The expectation is that current algorithms will fall short in terms of performance for future collider experiments. Track reconstruction also presents a good way to measure whether quantum computing devices will be able to process large datasets. Examples of these efforts include Ref. [1, 2, 3, 4]. In terms of higher-level physics objects, quantum-assisted algorithms have also been proposed as an alternative for jet clustering [5] and secondary vertex reconstruction [4], with the potential of speeding up the clustering task without compromising physics performance.
- **Event Selection/Classification:** Classification of events as coming from either the sought-after process (signal) or background is one of the main HEP tasks. The authors of Ref. [6] propose the use of quantum computing, in particular, quantum annealing, to classify events between a Higgs decaying to a pair of photons and the background events with two uncorrelated photons.
- **Quantum machine learning:** Machine learning has been playing a significant role in the physical sciences. With the advent of noisy intermediate-scale quantum (NISQ) computing devices, more quantum algorithms are being developed with the aim of exploring the capacity of the hardware for machine learning applications. The authors of Ref. [7] present an overview of how quantum machine learning is used in HEP.

3 Conclusion

While quantum computing's current impact in HEP data analysis is limited, and the future of hardware is uncertain, there is hope that future advances on both quantum devices and quantum algorithms will help alleviate the anticipated computational limitations in HEP. Also, while the question of whether there will ever be a quantum advantage, and the future of hardware is uncertain, it is still crucial to start identifying algorithms and applications suitable for the NISQ era of quantum computing. This way, we can also provide input about the HEP community's needs in terms of desirable features in the quantum computing devices. In the planned white paper, we shall try to identify promising opportunities for further quantum computing applications in HEP, with specific emphasis on reconstruction and data analysis.

References

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