Quantum Pattern Recognition for Tracking in High Energy Physics

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We present plans the design and implementation of quantum pattern recognition algorithms for high-energy physics charged-particle tracking at the High-Luminosity LHC.

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The High-Luminosity LHC (HL-LHC) [1] is expected to deliver 5 to 7 times the nominal instantaneous luminosity of the LHC. While this upgrade has its many advantages, e.g. a larger proton-proton dataset permitting more precise measurements, numerous hardware- and software-based innovations will be necessary to withstand the immense number of per-event particle multiplicities as a result of many simultaneous proton-proton collisions. Given the finite computing resources available, processing the full dataset therefore poses a serious challenge for existing event reconstruction methods. However, the field of quantum information science and computation have been rapidly evolving in recent years, and show potential for unparalleled computing capabilities over classical machines for special classes of problems [2]. It is pivotal (and natural) that high energy physics (HEP) experimentalists and theorists get in on the ground floor to begin exploring the potential of quantum computation, specifically.

The application of quantum technologies to HEP applications is a new and challenging paradigm. Fortunately, quantum computers are being made more available in labs and in the cloud [3–5], permitting prototyping in academia and industry. On the other hand, current quantum computers have only a limited number of qubits and suffer from destructive effects, namely quantum noise, or decoherence [6] – processes that corrupt the desired evolution of the system and therefore result in a loss of information. As a result, reliable computation on quantum devices is difficult due to low-fidelity unitary transformations (gates) acting on the qubits; the lack of a fully-connected system of qubits could require additional gates, adding in quadrature to the overall noise of the computation. Furthermore, unlike their classical counterparts, current quantum computing technologies cannot correct with high fidelity the errors that occur in gate operations, and robust error-correcting (fault-tolerant) codes for quantum computers [7] are likely still years away.[1]

This Letter of Interest proposes to explore the potential of quantum computation to improve the speed at which proton-proton collisions can be reconstructed; in particular, quantum pattern recognition for charged-particle track reconstruction. Initial algorithm implementations of track reconstruction rely on the fact that the whole calculation is performed by running small computational pieces repeatedly. Each piece is thus represented by a fixed set of quantum gates. However, this scheme generally leads to a situation where a same set of single- and two-qubit gates is applied over and over again, hence being prone to errors that occur during unitary gate operations. An idea is to identify such repeated gates commonly used in HEP applications to establish a path towards dedicated circuit design and hardware implementation for HEP applications with as few gates as possible. This would improve performance by minimizing the impact from noisy circuits.

The proposed research consists of two-step processes: 1) identification and implementation of available quantum gates for use in track reconstruction; and 2) optimization of the gates for dedicated circuit designs.

For track reconstruction, an example of a potential approach using variational circuits is the Variational Quantum Eigensolver (VQE) [12]. The VQE tries to find the lowest-cost state by applying different tunable parameters to individual qubits. The optimization of dedicated circuit gates is based on decomposing the quantum gates into single- and multi-qubit gates for merging. The mapping of merged gates to qubit layouts in existing hardware architecture is performed by following an earlier study, e.g. [13].

Another method considered follows more closely classical track reconstruction: the Hough Transform [14, 15]. The classical Hough Transform is a method of finding groups of collinear points in the coordinate space, by a mathematically

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[1] Though quantum error-correcting codes (QECC) is an active area of RD; see, for example, [8–11]

equivalent problem of finding concurrent curves in the parameter space. Each input valve maps to a curve in the parameter space and the accumulated values in this binned parameter space helps in finding the interesting patterns by detecting local maxima. Due to it's simple formulation and robustness against track overlaps and noise, it is an excellent candidate for as a Noisy Intermediate Scale Quantum (NISQ) [16] algorithm. Detecting arbitrary shapes in a dataset requires constructing a very large accumulator space for all parameters of interest. A quantum algorithm for performing the Hough Transform can potentially provide exponential improvements in memory by representing values in the accumulator space in a superposition quantum state. One of methods currently being developed uses Grover-Long Algorithm [17], a variant of Grover search algorithm [18], that provides quadratic speed up in searching the accumulator space for local maxima. By having close estimates of the ratio of the number of solutions M and the searched space N, this algorithm renders success probability close to 100%. However, the current algorithm presents strict constraints on the data that can be encoded in superposition. A potential improvement in quantum Hough Transform would be to explore ways to efficiently encoding hit values obtained from the collision events directly as superposition of quantum states while using Quantum Phase Estimation [19] to search for local maxima.

For gate optimization, several different approaches will be investigated, using available tools such as Qiskit's [20] transpiler passes and CQC t|ket⟩ [21]. The first possibility is to decompose a circuit to a set of basis gates (e.g, `U1`, `U2`, `U3` and `CNOT`) supported by a given hardware. The circuits used for track reconstruction can be also decomposed into a set of basis gates with rotation angles as parameters. After decomposition, all the `CNOT` gates are extracted and mapped onto connected qubits in the target chip as much as possible. This is necessary to minimize the use of `SWAP` gate, which requires several `CNOT` gates to implement and is hence expensive for quantum computation. A method based on the minimization of cost functions will be considered; one cost function for the circuit depth, and the other for the size of input states. The cost function for the depth is defined such that the amount of `SWAP` gates can be minimized after mapping the `CNOT` gates. The cost function needs to take into account actual connections on hardware chips, two-qubit error rates, mapping of `SWAP` gates, etc., and its definition is subject to optimization. The cost function for the input size controls the number of qubits used and will need to be minimized together with the circuit depth because more qubits could result in a shallow circuit but need more `SWAP` gates.

The expected outcome from the proposed research is an algorithm to optimize quantum gates for early HEP applications and a design for possible hardware implementation. As the optimization method, we propose to decompose the circuit for tracking into basis gates and merging them, including parameterized circuits. With this approach, we will obtain an algorithm to optimize quantum gates for shallow circuits, being compatible with the present and near-term NISQ devices.

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