Simulations for the Development of Quantum Computational Devices for HEP

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Quantum devices for HEP

Qubits

Rigetti QPU

Qudits

SQMS 3D Cavity

Sensors

Search for Dark Matter
Qubits?

- Qubits are two level devices $|0\rangle$ and $|1\rangle$
  2D Superconducting cavities, Ion Traps, ...

- Qudits are multilevel devices
e.g. ququart (4 levels) is equivalent to 2 qubits
  $|0\rangle \sim |00\rangle$, $|1\rangle \sim |01\rangle$, $|2\rangle \sim |10\rangle$, $|3\rangle \sim |11\rangle$

Strong interest in HEP algorithms on multilevel, multimode Qudit devices
Where can simulations fit in?

Co-design cycle

Classical simulations with fast turn-around time are important for device and algorithm design.
Open Quantum System Simulations

Includes device’s interaction with environment (noise & decoherence)

Evolves density matrix with *Lindblad master equation*

\[
\frac{d\rho(t)}{dt} = \sum_i \gamma_i L(C_i)[\rho(t)]
\]

- Real world behavior of device
- Gate design
- Optimal control

**QuaC**: A scalable, general-purpose quantum systems solver

**Quandary** - Optimal control for open and closed quantum systems

**QuTiP**: Quantum Toolbox in Python

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Example: Quantum memory – Qubit vs. Qudit

- Used QuaC to simulate and compare systems with
  - Multiple qubits
  - A multilevel qudit device

Example – Optimal Control

- Used Juqbox to determine optimal pulses for a QAOA in for a 8 level system

Özgüler and Venturelli,
Simulation for code validation
Desired Simulation Functionality

- Supports sufficient size parameters (# qubits, # qudit levels, modes)
- Performant: Quick turnaround time. High performance libraries HPC, GPU, TPU
- Friendly interface – use the system as you would a real device
- Interfaces with community standard gate circuit-building tools (e.g. IBM Qiskit)
  - Accepts standard instruction formats like QASM
- Can be driven from pulse descriptions and sequences
- Include a library of Hamiltonians and device profiles to get started quickly
- Usable from cloud services and HEP batch systems (HEPCloud)

- Many toolkits to drive Qubits (IBM Qiskit, Google CIRQ). Are they expressive enough to drive Qudits?
Summary

• Simulations can play a critical role in development of quantum computational devices

• Tools with desired functionality would be especially useful, enabling,
  – Development, Testing, Validation and Debugging
  – Design of algorithms and system building blocks (e.g. multi-level gates)
  – ... *Without tying up the in-high-demand hardware*

• Simulation of control systems will be fruitful – serve as a mock system

• Leverage HEP’s long experience with simulations