Quantum Computing for Neutrino-Nucleus Scattering

Towards Early Fault-Tolerant Implementations of Nuclear EFTs

Marina Maneyro

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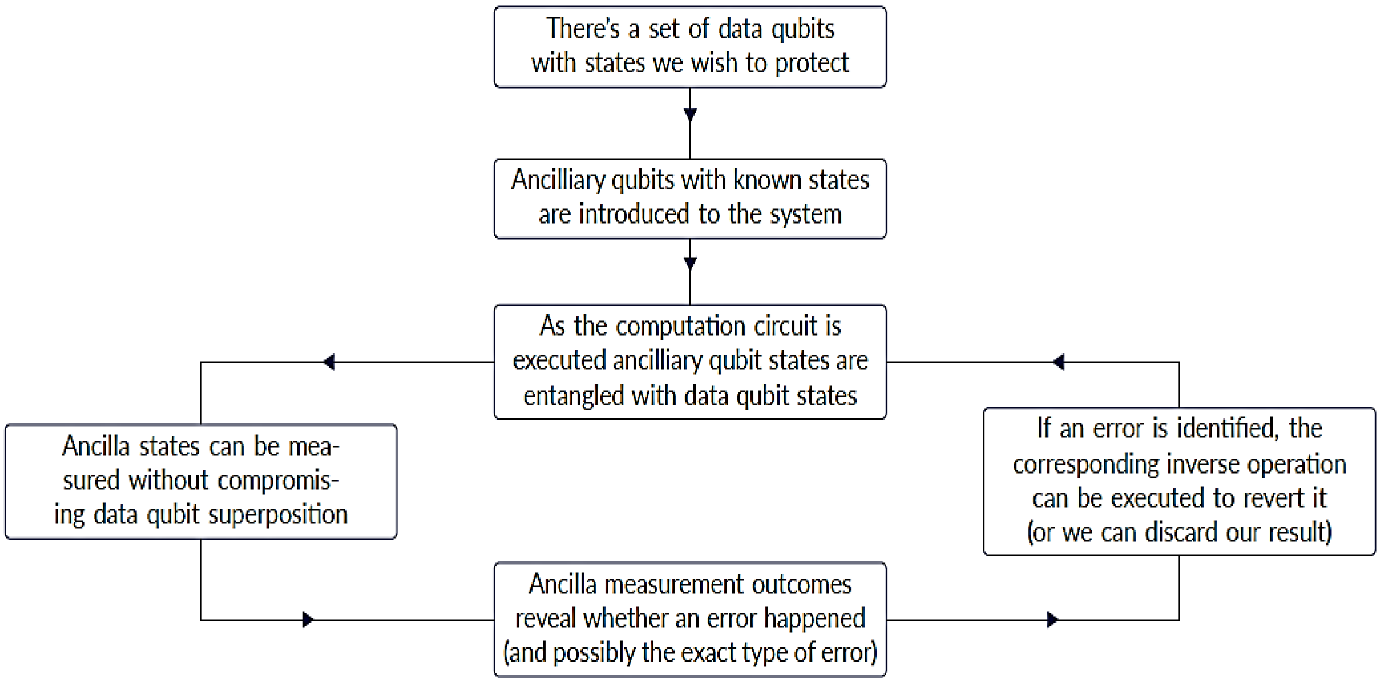
Quantum Computing

- Avenue to overcoming computational limitations in Particle Physics
- Noisy Intermediate-Scale Quantum era: limited system sizes, very prone to errors
- On the path towards Fault-Tolerant Quantum Computing: lower error rates, prevention of cascading errors

What HEP applications can we look forward to in the early Fault-Tolerant era?

Error Correction

Need to address depolarization, dephasing, gate errors



Neutrino Physics

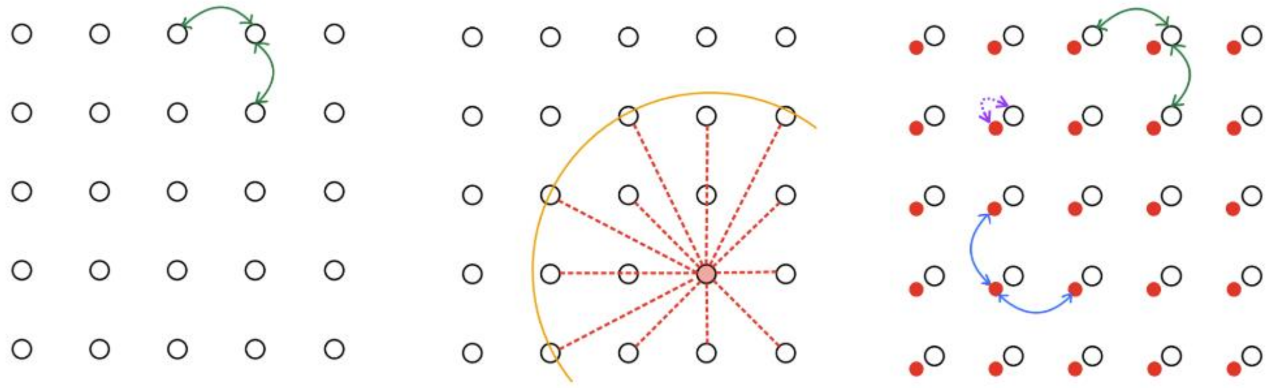
- We’re addressing challenges in Neutrino simulations, motivated by :
  - reliance on Event Generators for relating experimentally observed final states and underlying kinematics
  - increased simulation precision required as upcoming large experiments begin operation (Hyper-Kamiokande, DUNE, JUNO)

Neutrino Event Generation

- Simulations need to span wide energy ranges (perturbative, non-perturbative, regions described by different models)
- To increase interaction likelihood, neutrino experiments utilize nuclei, introducing the need to model nuclear physics effects
- Several complex mechanisms at play, e.g. hadronization
- Underlying theoretical models have several limitations, requiring MC builders to construct empirical models and make important approximations
- Sparse data for MC validation and tuning, leading to outputs with large flux uncertainties, often in conflict with each other

Neutrino-Nucleus Interaction

- Nucleon interactions and dynamics can be represented approximately using Nuclear EFTs
  - *Pionless*: Strong interactions mediated by pion exchanges are not included explicitly. Short range interactions
  - *One-Pion-Exchange:* Long range interactions, truncated as rapidly decaying
  - *Dynamical-Pion*: Explicit inclusion of bosonic pion field



Pionless EFT One-Pion-Exchange EFT Dynamical-Pion EFT

arXiv:2312.05344

Pionless EFT on the Lattice

Kinetic hopping term

$$H = 2DtA - t\sum_{f=1}^{N_f}\sum_{\langle i,j\rangle}^{M}\left[c^{\dagger}_{i,f}c_{j,f} + c^{\dagger}_{i,f}c_{j,f}\right]$$

$$+\frac{1}{2}C_0\sum_{f\neq f'}^{N_f}\sum_{i=1}^{M}n_{i,f}n_{i,f'}$$

Two–nucleon interaction

$$+\frac{D_0}{6}\sum_{f\neq f'\neq f''}^{N_f}\sum_{i=1}^{M}n_{i,f}n_{i,f'}n_{i,f''}\ ,$$

Three–nucleon interaction

Quantum Simulation

- *Fermionic encoding:* mapping fermionic creation-annihilation operators into qubit operators
- *State preparation:* The choice of initial state will affect the performance and runtime of many algorithms. We need to implement efficient procedures to construct, for example, energy ground states
- *Time evolution* in accordance with our theory
- *Obtaining observables*

Algorithmic choices in all steps of the simulation are key to achieving quantum advantage

Our goal is to produce a complete approach to the implementation of Nuclear EFTs in early Fault Tolerant Quantum Computers, with a focus on understanding the costs (gate counts and qubit counts) required to obtain useful and accurate results, as well as scalability

Current work

- Application of initial state preparation techniques suited for the early Fault Tolerant era, for pionless EFT
  - Initial guess using Hartree-Fock method to get good overlap with ground state
  - LT algorithm (Lin and Tong, 2022): strategic sampling to construct Cumulative Distribution Function for Hamiltonian spectra
- Estimating costs for state preparation procedure for example nuclei
- Evaluation of theory implementation choices (e.g. first-quantized vs second-quantized approaches)

Future perspectives

- Gauging time-evolution costs and precision trade-offs
- Considering strategies for obtaining observable measurements, weighing algorithmic constraints and physical interest
- Application of implemented algorithms to more sophisticated Nuclear EFTs