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Quantum data learning of phase transitions

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Abstract

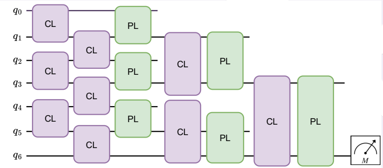
Quantum data learning (QDL) provides a framework for extracting physical insights directly from quantum states. In this presentation we develop QDL techniques for detecting the phase transition in the 2+1-dimensional toric-code loop-gas model in a magnetic field. Our unsupervised QDL approach recovers the phase structure and locates the phase transition with a small offset as expected in finite volumes; both supervised and unsupervised QDL methods outperform classical alternatives. These findings establish QDL as an effective framework for characterizing topological quantum matter, studying finite volume effects, and probing phase diagrams. (arXiv:2511.16851 [quant-ph])

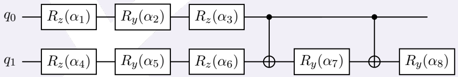
Outline

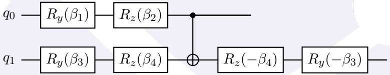
Introduction
Quantum Data Learning

- QDL is a type of Quantum Machine Learning
- It is a quantum circuit
  - that takes a quantum state as input
  - that ends with a measurement
  - whose parameters are trained
- Training is a classical choice of parameters
- We use a QCNN that alternates
  - Convolutional Layers (two-qubit gates)
  - Pooling layers (single-qubit rotations + controlled not + discard)

  followed by single-qubit rotation and measurement.
- $y_{\text{out}}^{\phi} = \operatorname{Tr} Z_{\text{out}}\, U_{\text{QCNN}}(\phi)\, \rho\, U_{\text{QCNN}}(\phi).$







Introduction
Toric Code Model

- The qubits live on links on a 2-dimensional square lattice.

$$H_{\mathrm{TCM}} = -\sum_{\mathrm{site}} \prod_{\mathrm{link} \ni \mathrm{site}} \sigma^x_{\mathrm{link}} - \sum_{\mathrm{plaq}} \prod_{\mathrm{link} \in \mathrm{plaq}} \sigma^z_{\mathrm{link}}$$

- Open boundary conditions stop degenerate superposition of Wilson line states.
- OBC produces anyons, but maintains long-range topological order.
- We study the ferromagnetic perturbation that produces aligned spins.

$$H(x) = (1-x) H_{\mathrm{TCM}} - x \sum_{\mathrm{link}} \sigma^z_{\mathrm{link}}$$

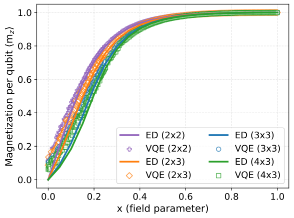
- The infinite system has a phase transition at $x_c \approx 0.25$.
- Order parameter: Magnetization $m_z = \langle \sigma^z_{\mathrm{link}} \rangle_{\mathrm{average}}$.

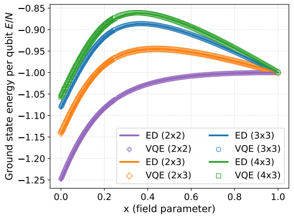
Introduction
Ground State Preparation

- Use Variational Quantum Eigensolver technique
- Use the ansatz

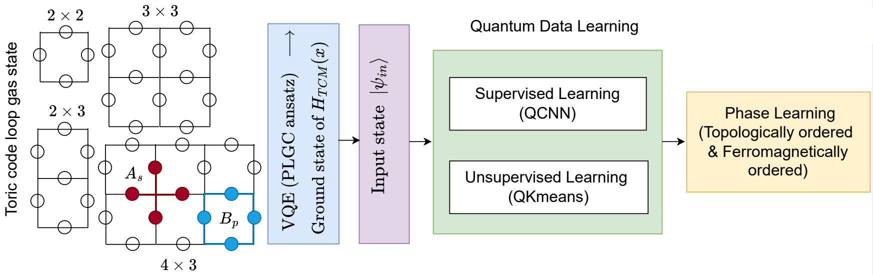
$$|\psi(\theta)\rangle = \prod_p \left[\cos\frac{\theta_p}{2} + \sin\frac{\theta_p}{2}\prod_{i\in p}\sigma_i^x\right]\bigotimes_i |0\rangle$$

  that creates a superposition of loops.
- Use classical minimization of measured energy.





Introduction
Overall strategy



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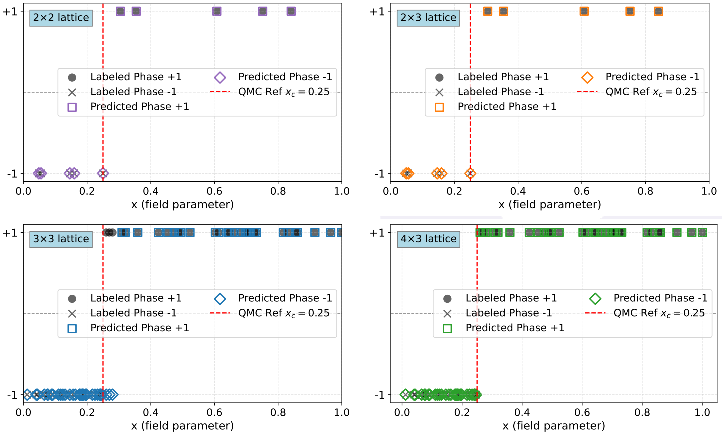
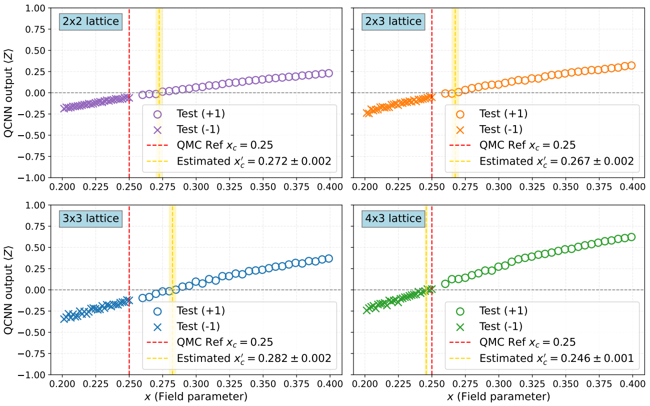
Supervised Learning
Classification

Define $x = 0.25$ as the phase boundary and train.



Supervised Learning
Determining phase boundary

Train only on samples $x \notin [0.2, 0.4]$.



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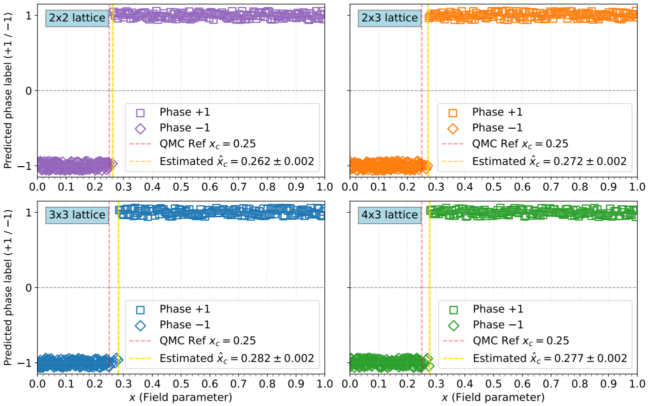
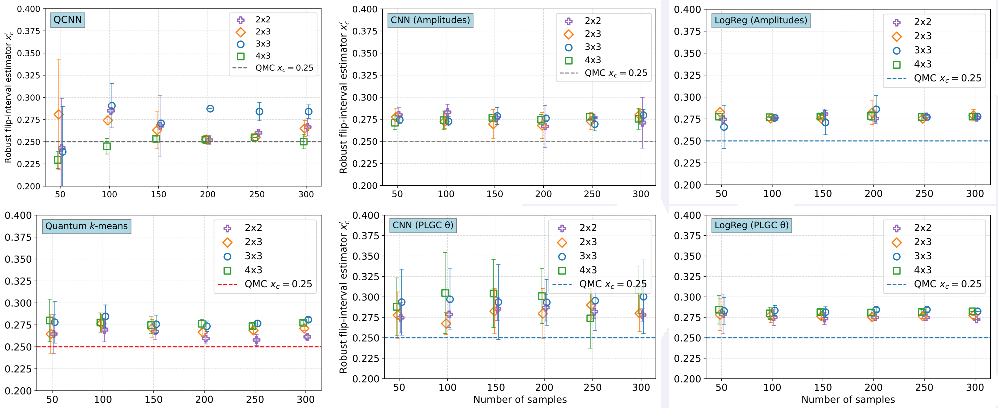
Unsupervised Learning
Results

k-means clustering into two sets based on Hilbert-Schmidt metric: $\sqrt{2(1-F)}$.



Conclusions
Comparison between quantum and classical results



Further studies needed to understand finite size effects.