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Unsupervised Quantum Circuit Learning in High Energy Physics

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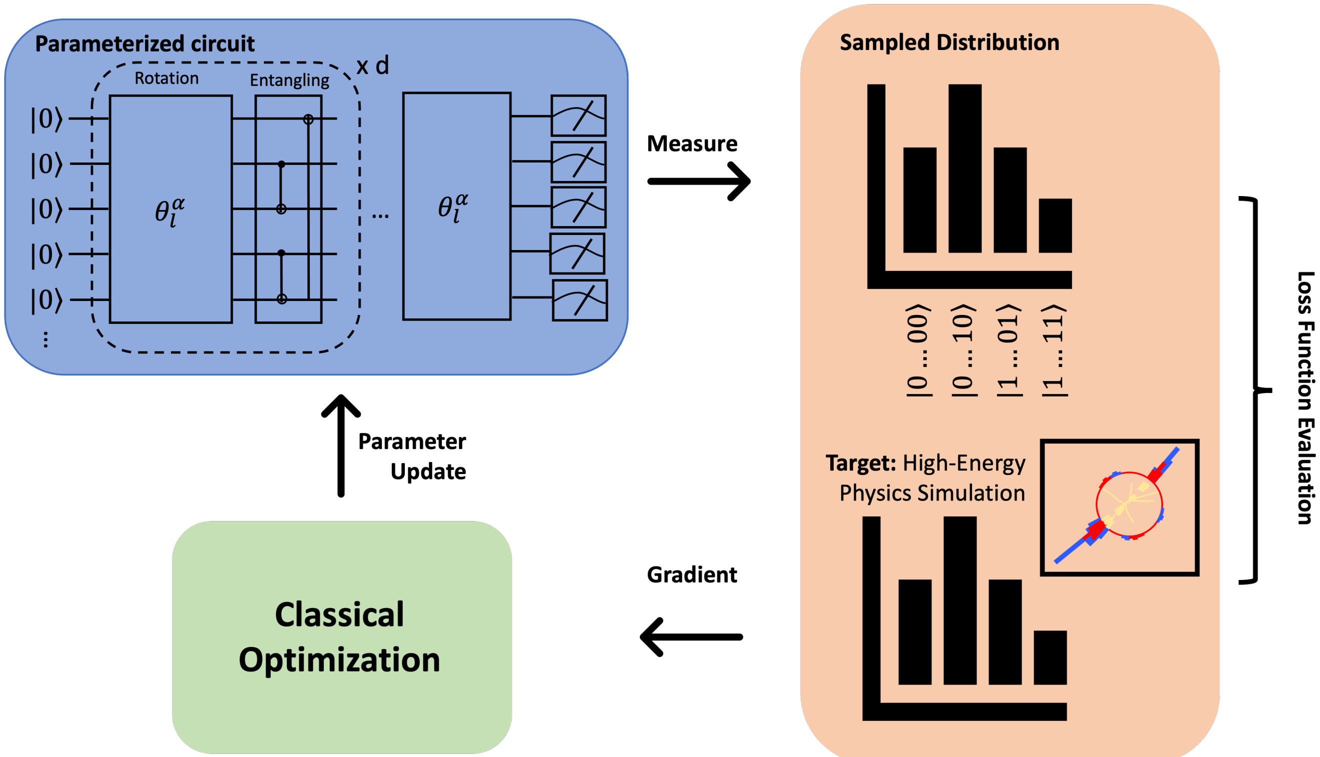
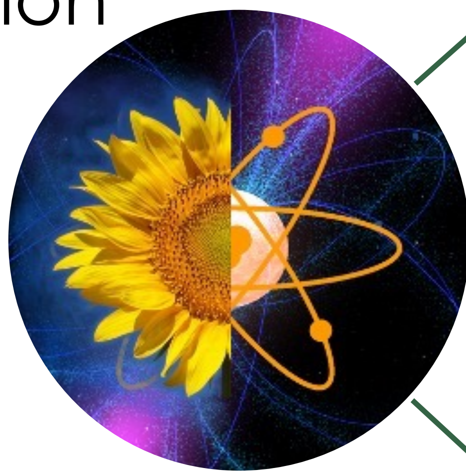
The topic of this talk…



- We use non-adversarial, gradient-based training of quantum circuit Born machines (QCBM) to generate joint distributions over 2 and 3 variables.
- The goal is to provide a quantum alternative to traditional MC methods for detector response simulation in HEP.

The Second Quantum Revolution

Quantum Information Science



Networks

- Quantum internet
- Communications, networks

Sensors

- Dark matter detection

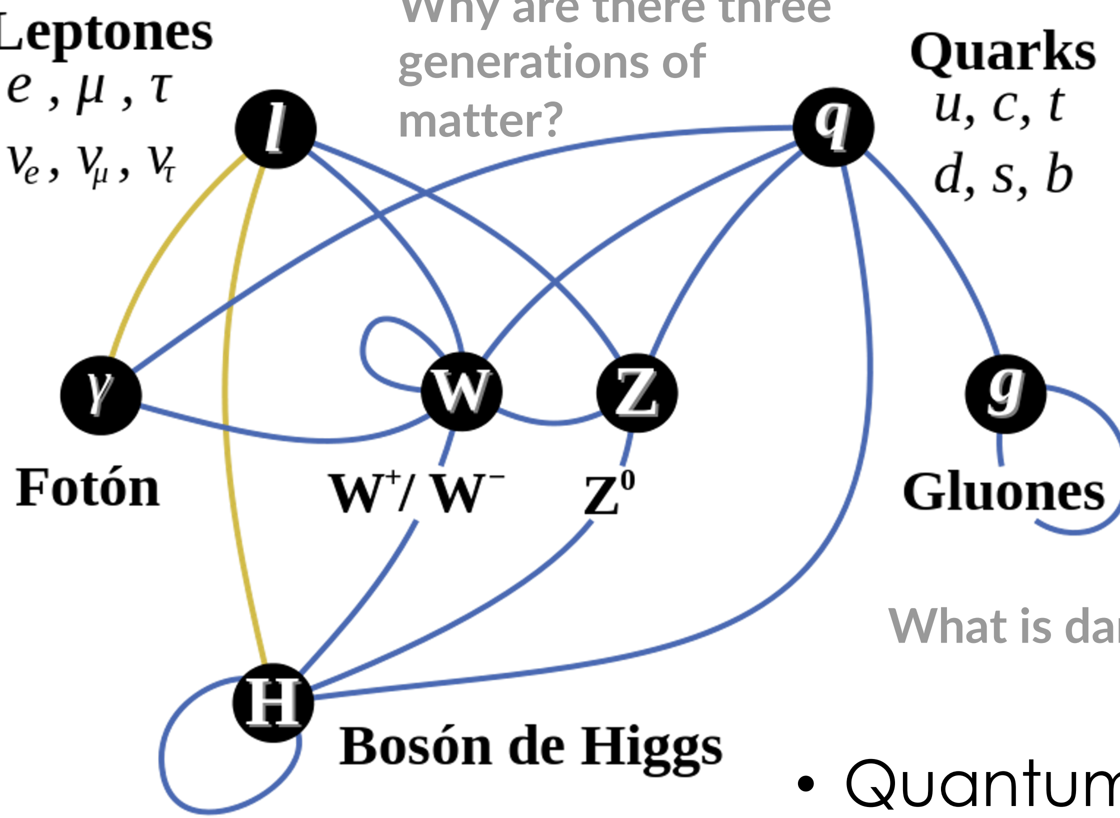
Computing

- Annealing vs gate based models
- Quantum annealers, superconducting qubits, ion traps, etc.

Quantum Computing Applications in High-Energy Physics

Why are there three generations of matter?

Why do neutrinos have mass?



Is there a particle associated with gravity?

What is dark matter?

Why does the Higgs boson has a mass of 125 GeV?

- Quantum gravity, entanglement.
- Simulation of field theories.
- **Data analysis**

Snowmass Workshop on QC for HEP:
https://indico.phy.ornl.gov/event/144/

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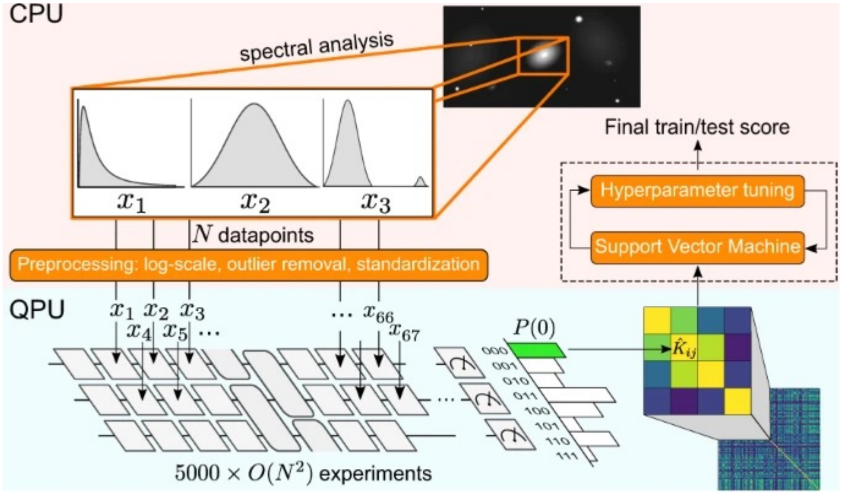
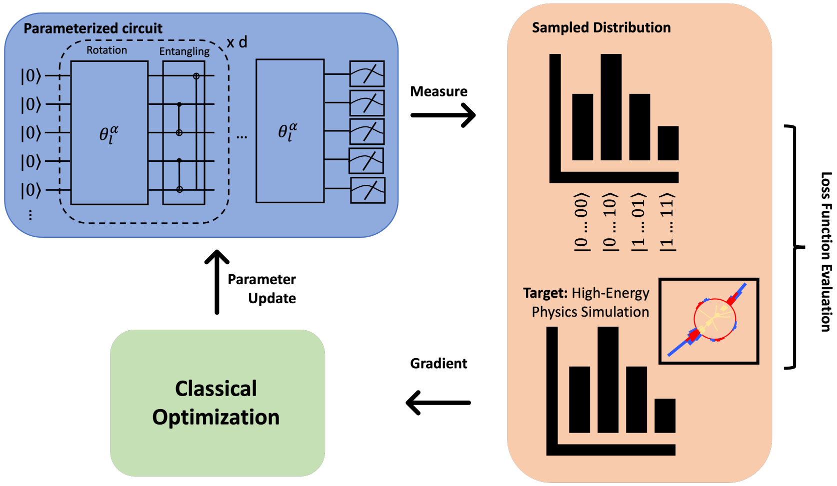
The many faces of Quantum Machine Learning

Data Type / **Algorithm Type**

Algorithm Type \ Data Type	Classical	Quantum
Classical	Quantum-inspired algorithms on classical data	Classical algorithms applied to quantum data
Quantum	Quantum algorithms applied to classical data	Quantum algorithms applied to quantum data

Promising QML Applications in HEP





Supervised Learning

- Classification based on kernel methods

Unsupervised Learning

- Generative modeling tasks

Peters, E., Caldeira, J., Ho, A. *et al.* **Machine learning of high dimensional data on a noisy quantum processor**. *npj Quantum Inf* **7**, 161 (2021).

This work in progress, A. Delgado, K. E. Hamilton

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Simulation in the 21st century

- The HEP community relies heavily on accurate simulation of the physics processes under study, as well as the interaction with the detector.
- Existing frameworks based on MC techniques provide a remarkable agreement between data and simulation.
  - They are also very demanding in terms of computational resources.
- Several alternatives have been explored
  - Including fast simulation, ML-assisted techniques, quantum computing!

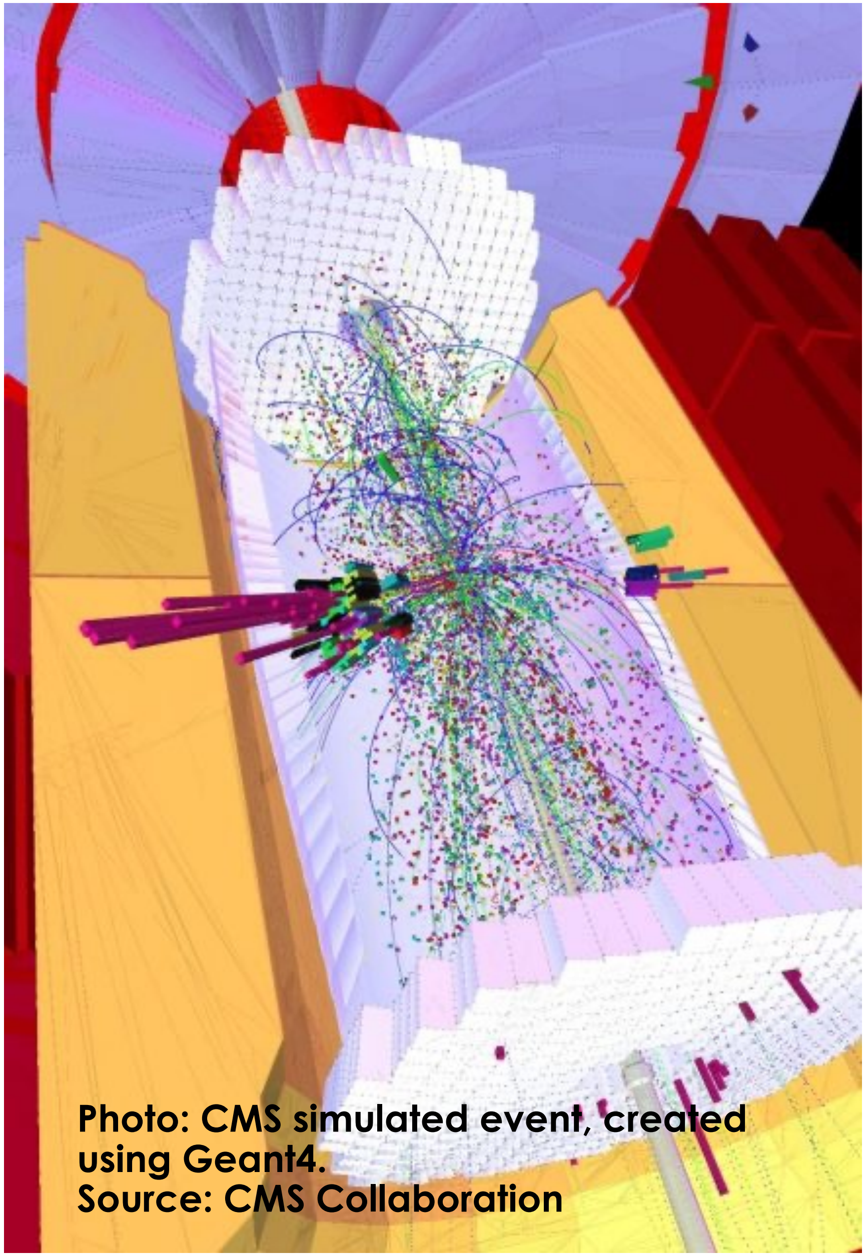

Photo: CMS simulated event, created using Geant4.
Source: CMS Collaboration

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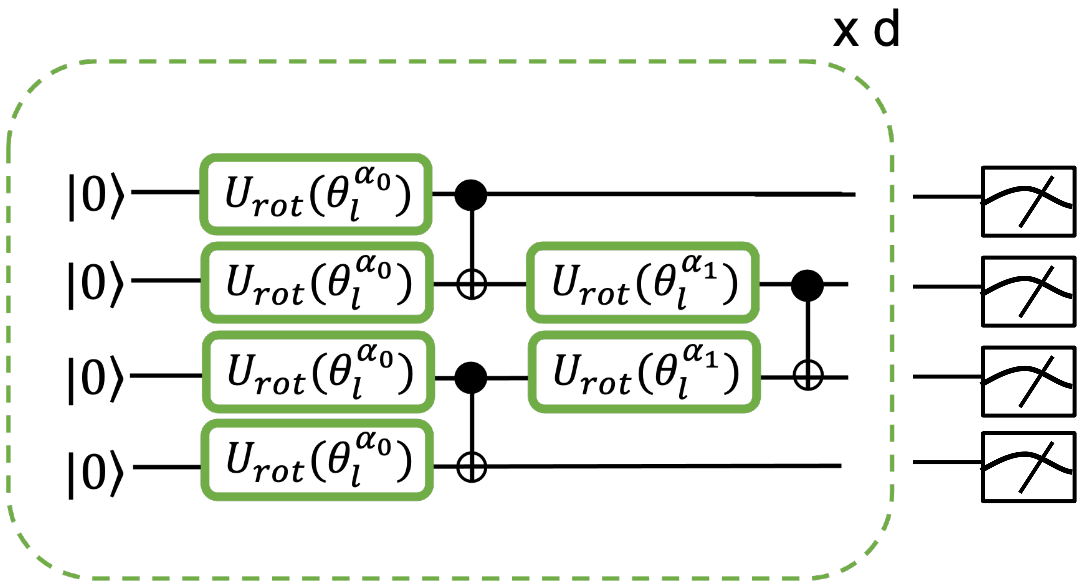
Unsupervised Quantum Circuit Learning

We use non-adversarial, gradient-based training of quantum circuit Born machines (QCBM) to generate joint distributions over 2 and 3 variables.

- QCBMs are parameterized quantum circuits used with the objective of preparing a target distribution with high-fidelity.
- A quantum state is prepared by a parameterized ansatz which takes the initial qubit register from the all-zero state to a final state.
- QCBMs are constructed by alternating layers of rotation gates with layers of two-qubit entangling operations



Unsupervised Quantum Circuit Learning

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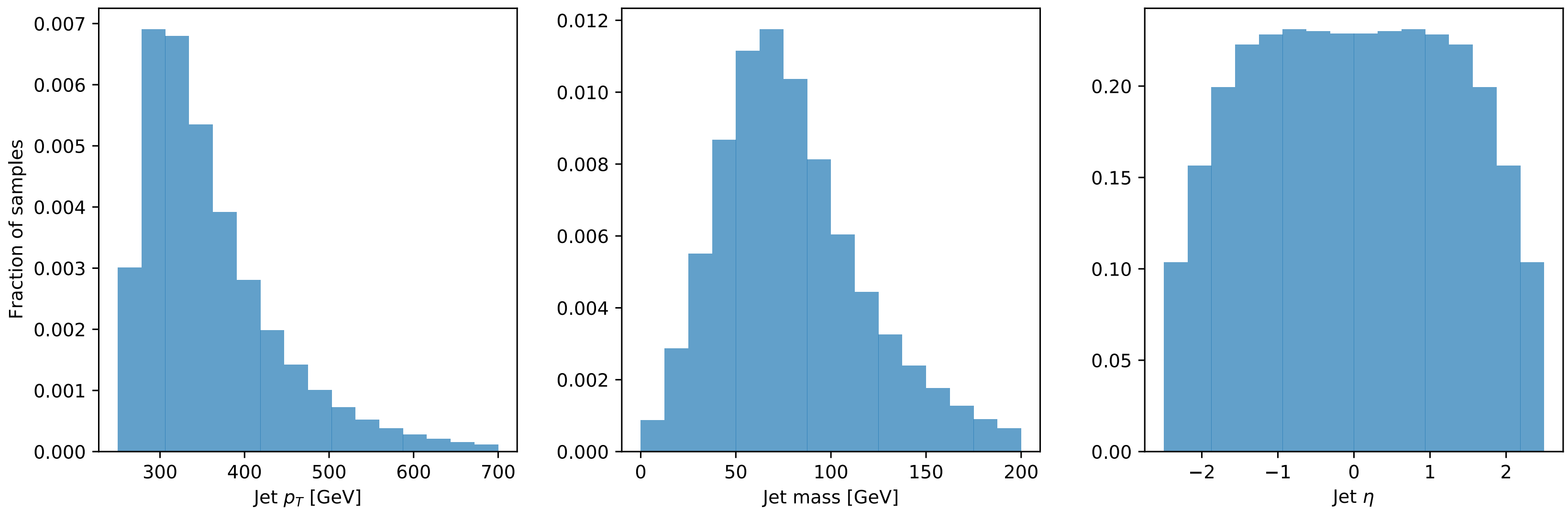
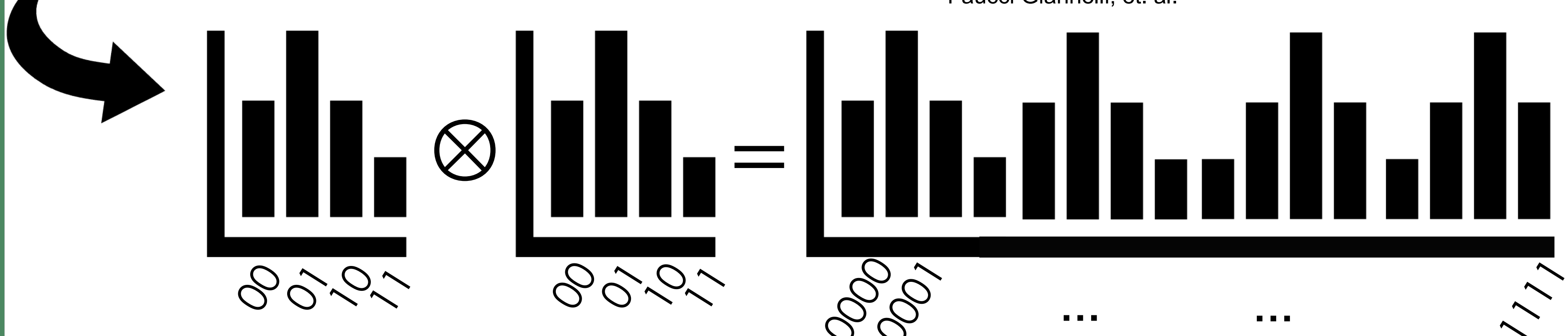


DijetGAN: A Generative-Adversarial Network Approach for the Simulation of QCD Dijet Events at the LHC (**https://arxiv.org/abs/1903.02433**) **–** R. Di Sipio, M. Faucci Giannelli, et. al.



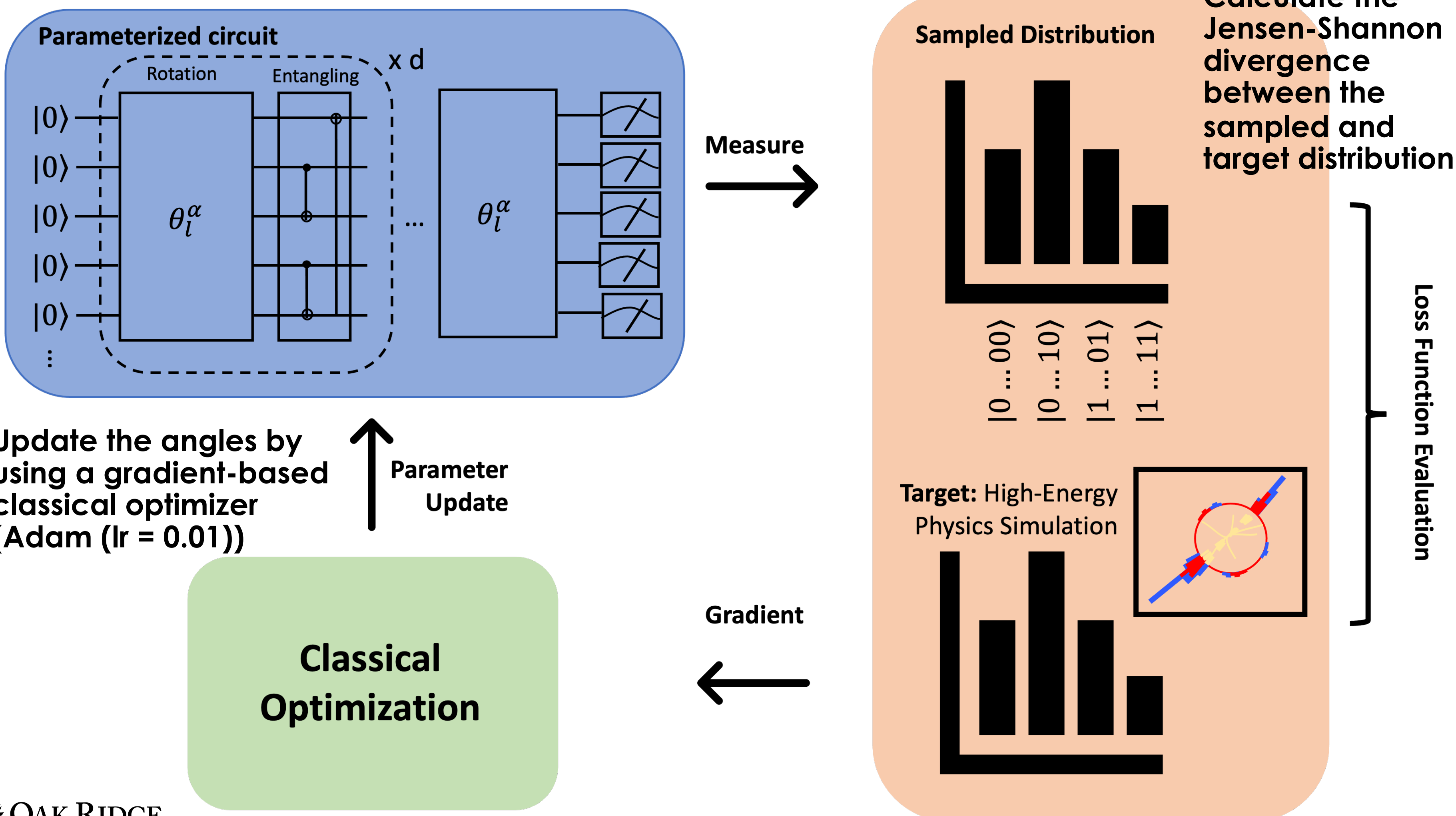
Unsupervised Quantum Circuit Learning

The training consists of a hybrid workflow:

Initialize ansatz parameters (angles of rotation gates)

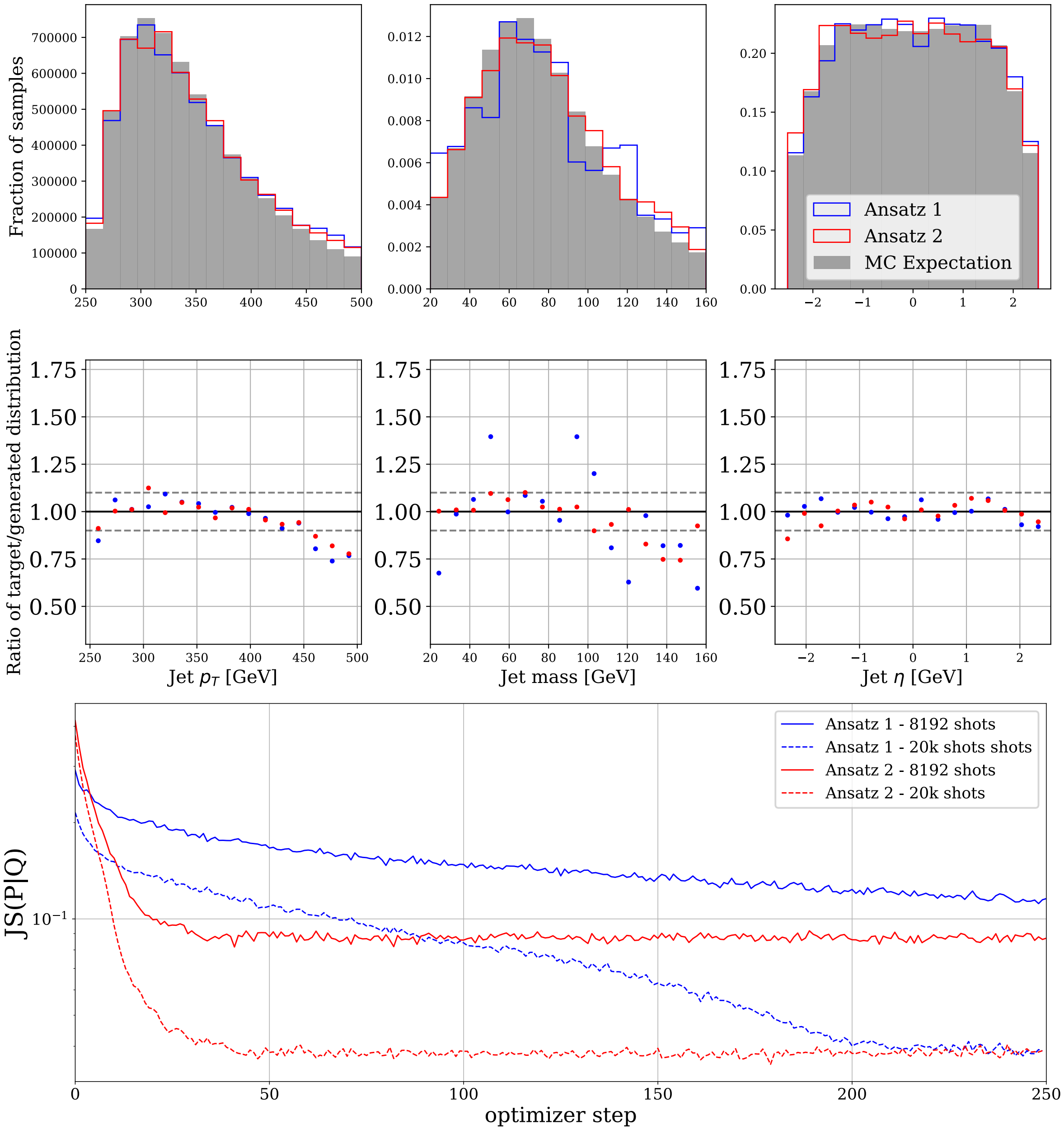
Run the quantum circuit with m shots

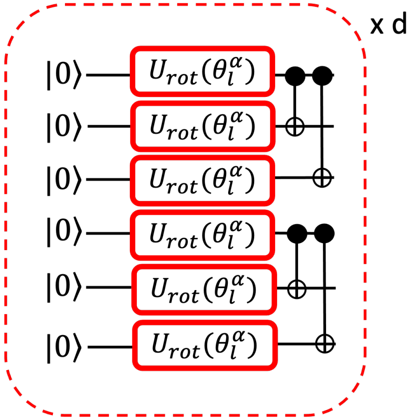
Calculate the Jensen-Shannon divergence between the sampled and target distribution

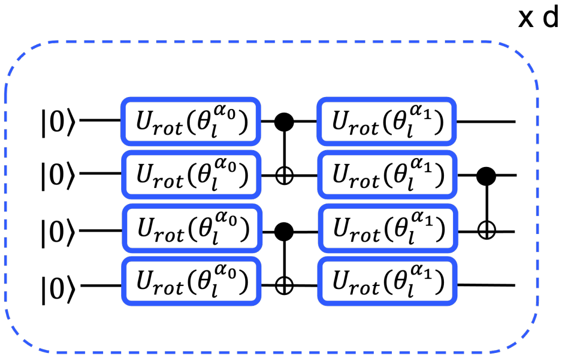


Update the angles by using a gradient-based classical optimizer (Adam (lr = 0.01))

Results for 3D Joint Distributions







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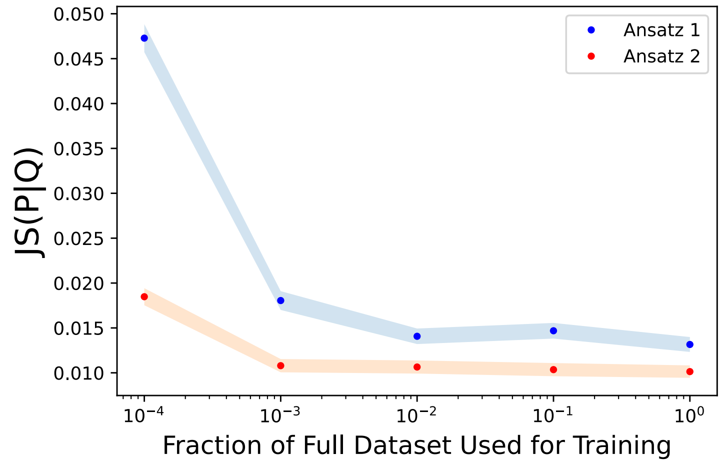
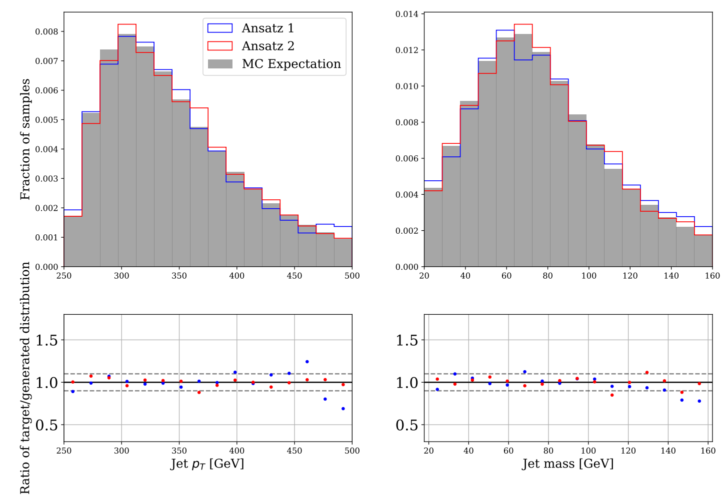
Summary

- This work is the first demonstration of a large-scale generative model that was successfully trained and deployed in hardware!
- There are still many things we don't fully understand.
- As an HEP application, it is a promising alternative to MC-based methods.





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Thank you!