

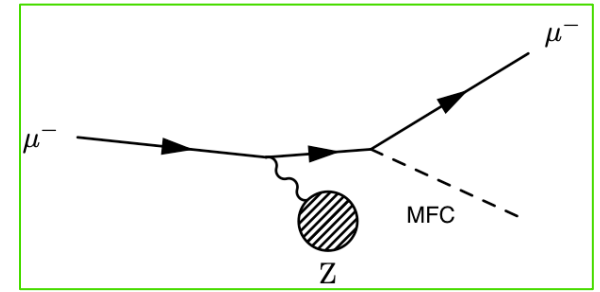
Conditional Born machine for Monte Carlo events generation

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Muonic Force Carriers

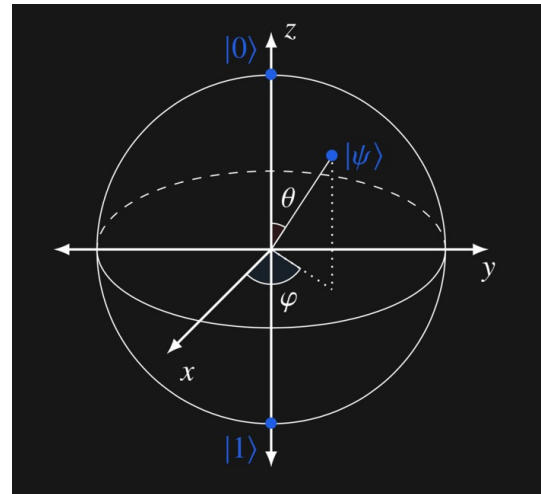
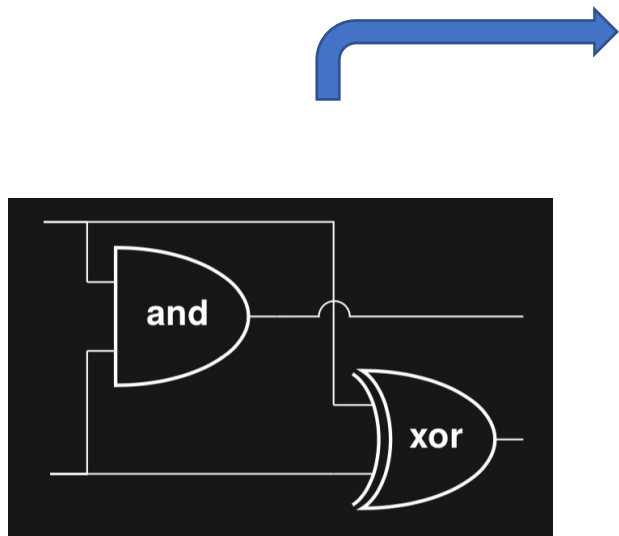


- MFCs appear in different theoretical hypothesis, as a constituent of **dark matter** and could explain the **anomalous magnetic dipole** moment of the muon or the anomaly in the measurement of the **proton radius**.
- 2 use cases: a) muon fixed-target collision (**FASER**).
b) muon interactions in the **ATLAS⁵** calorimeter.
- We are interested to generates following features for the outgoing muon and MFC: **energy** (E), **transversal momentum** (pt) and **pseudorapidity** (η).

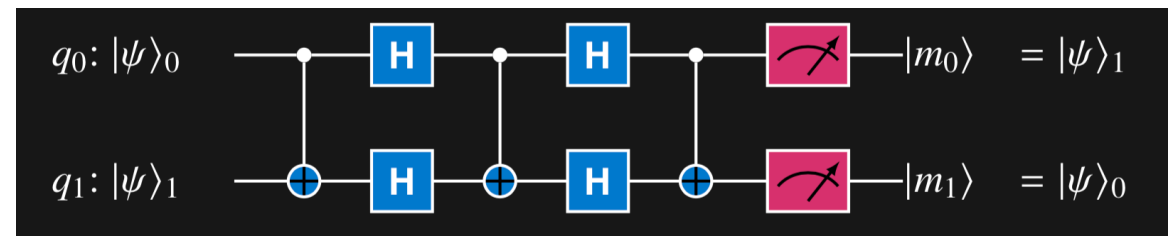
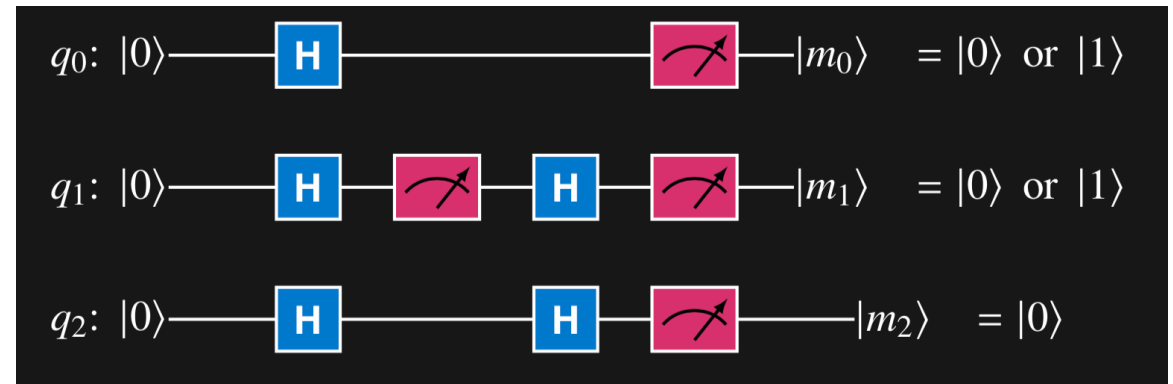
[5] Galon, I, Kajamovitz, E et al. "Searching for muonic forces with the ATLAS detector". In: *Phys. Rev. D* 101, 011701 (2020)

Quantum computing uses essential ideas from quantum mechanics

Gates / operations

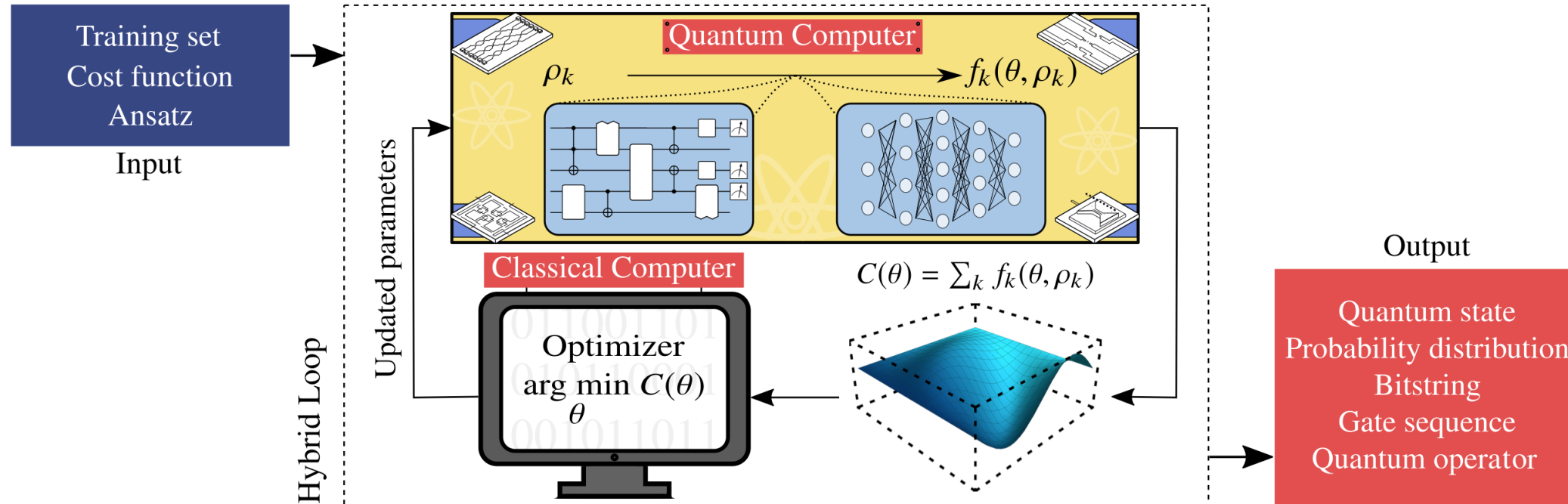


- Classical logical circuits use operations like and, or, not, nand, and xor. We also call these gates.
- Quantum circuits use reversible gates that change the quantum states of one, two , or more qubits.



Quantum machine learning models

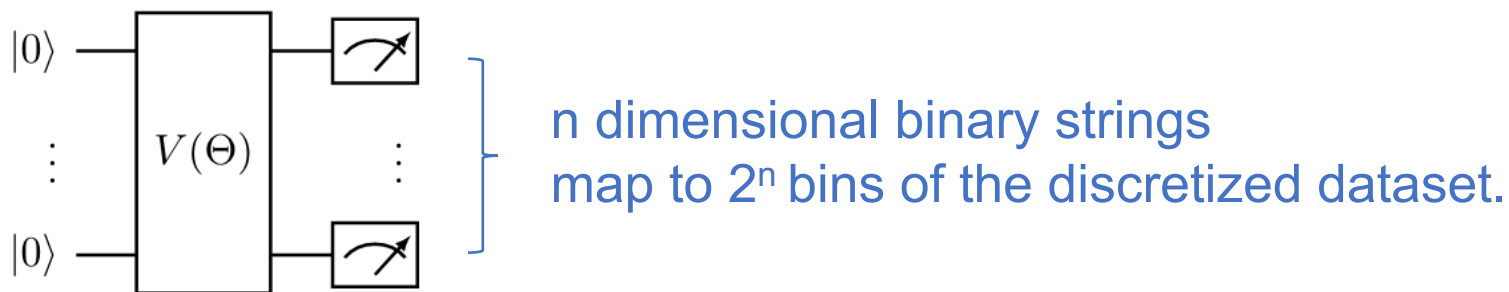
Quantum circuits as **heuristic** machine learning models.



Cerezo et al., *Nat Rev Phys* **3**, 625–644 (2021)

Quantum Circuit Born machine (QCBM)

1. **Sample** from a variational pure state $|\psi(\theta)\rangle$ by projective measurement with probability given by the **Born rule**: $p_{\theta}(x) = |\langle x|\psi(\theta)\rangle|^2$.



2. **Training** (Hybrid loop):

- KL divergence Delgado and Hamilton, arXiv:2203.03578 (2022).
- Adversarial (QGAN) Zoufal, et al., *npj Quantum Inf* **5**, 103 (2019).
- In the phase space. Kyriienko, et al., arXiv: 2202.08253 (2022).
- Maximum Mean Discrepancy

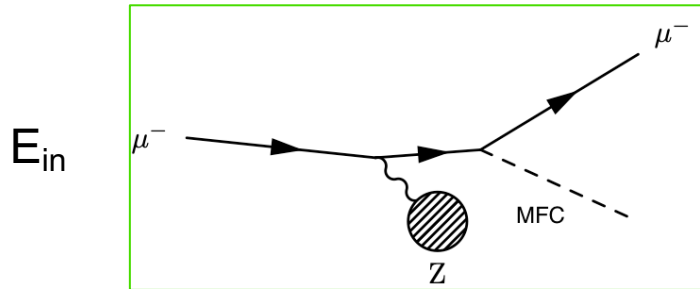
$$\text{MMD}(P, Q) = \mathbb{E}_{\substack{X \sim P \\ Y \sim P}}[K(X, Y)] + \mathbb{E}_{\substack{X \sim Q \\ Y \sim Q}}[K(X, Y)] - 2\mathbb{E}_{\substack{X \sim P \\ Y \sim Q}}[K(X, Y)]$$

3. **Why the Maximum Mean Discrepancy MMD ?**

- Resource efficient for NISQ devices.
- Stable.
- However, empirically less performant than adversarial.

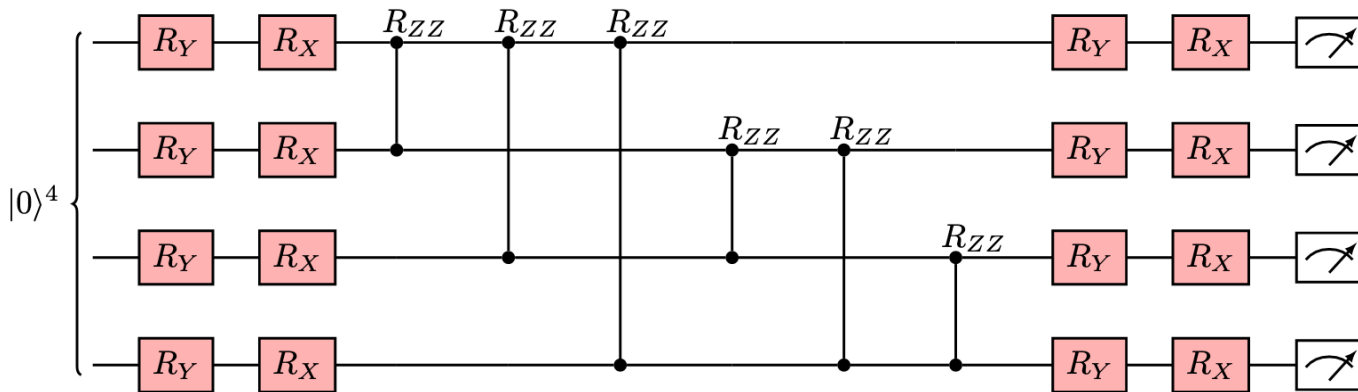
Generation of 1-D Monte Carlo samples

MC sampling: time consuming

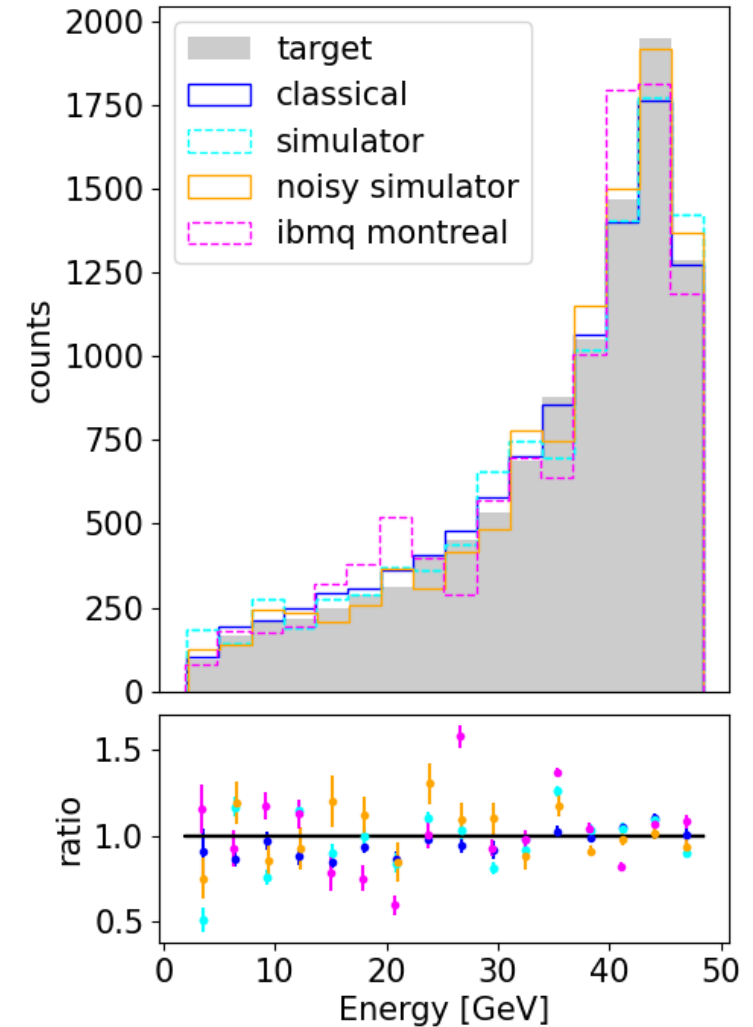


- Energy E
- Transversal momentum p_t
- Pseudorapidity η

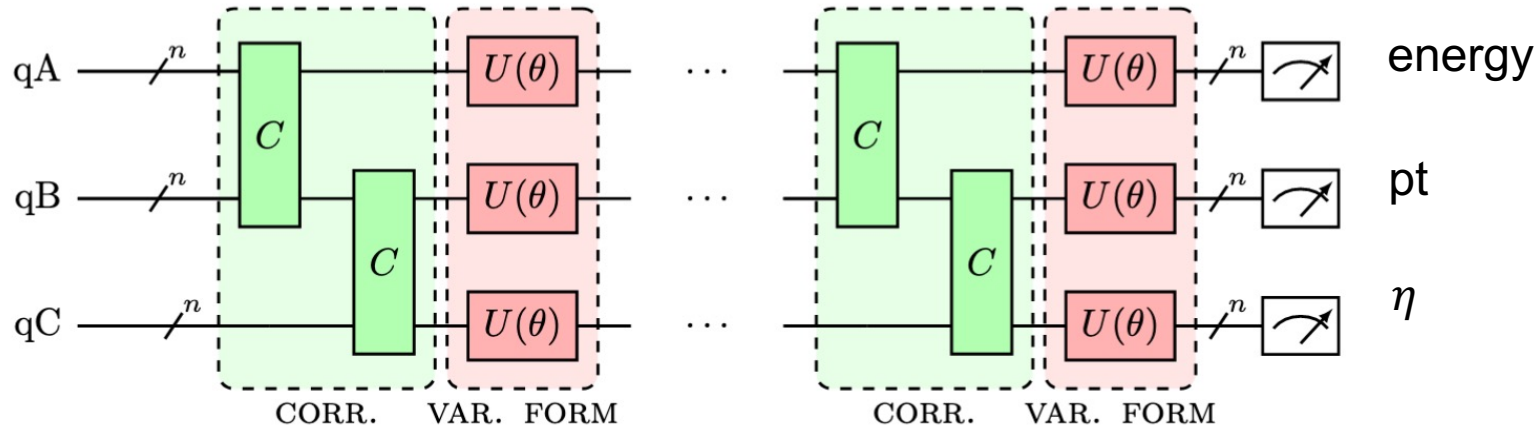
QCBM: hardware efficient ansatz (22 parameters)



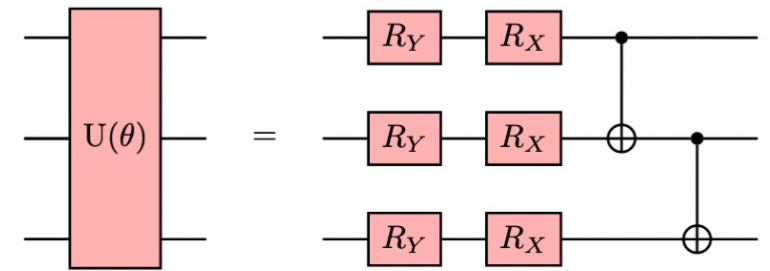
Kiss, Grossi, et al., *Phys. Rev. A* **106**, 022612 (2022)



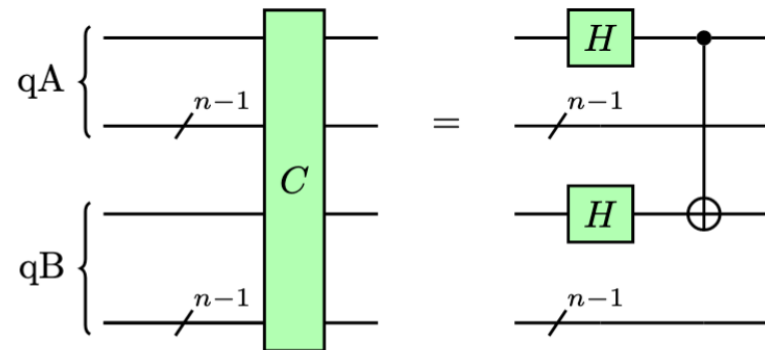
Multivariate probability distribution



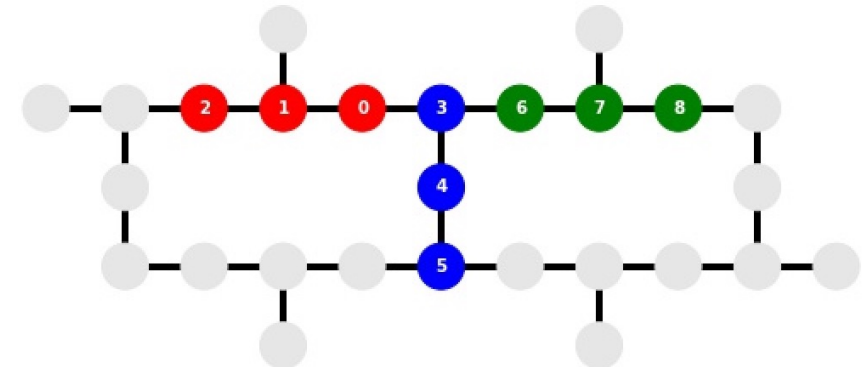
Local: learns the individual PDFs, time evolution of an Ising type Hamiltonian, conjectured to be difficult to simulate classically.



C: creates a correlated state between the first qubit in each register.

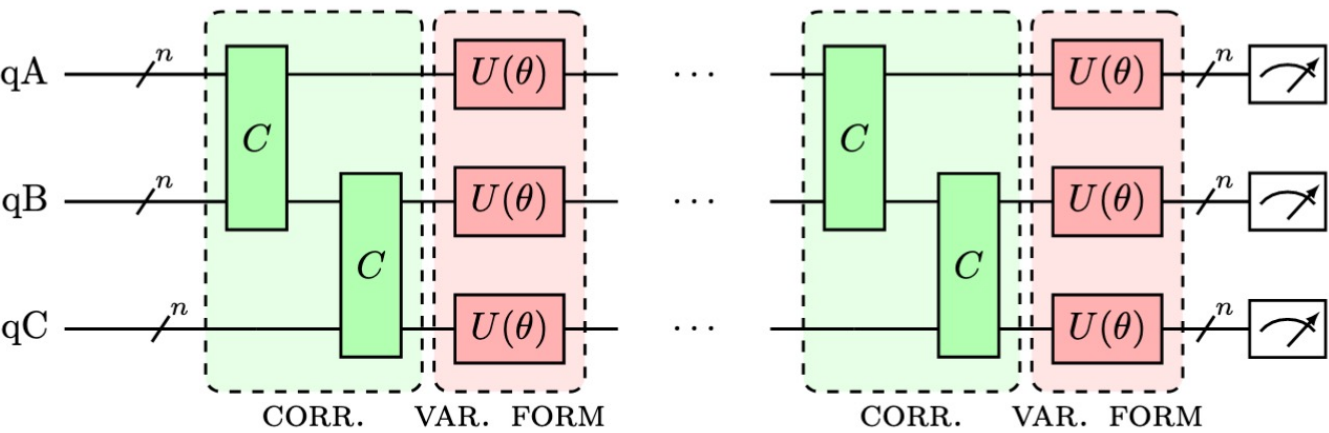


Can be mapped without swap gates on ibmq_mumbai



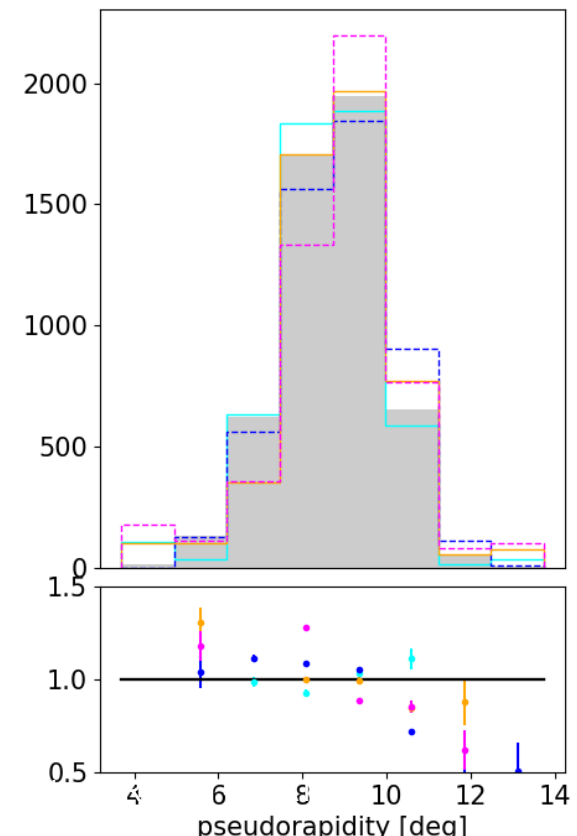
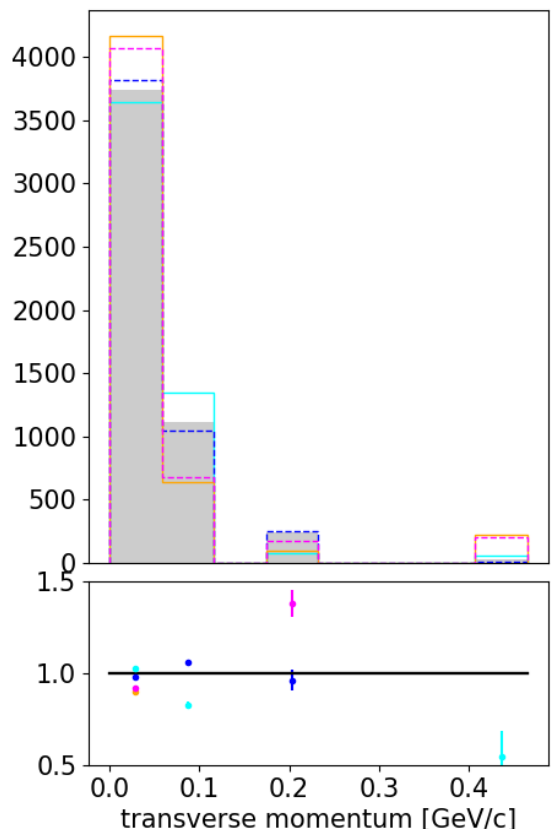
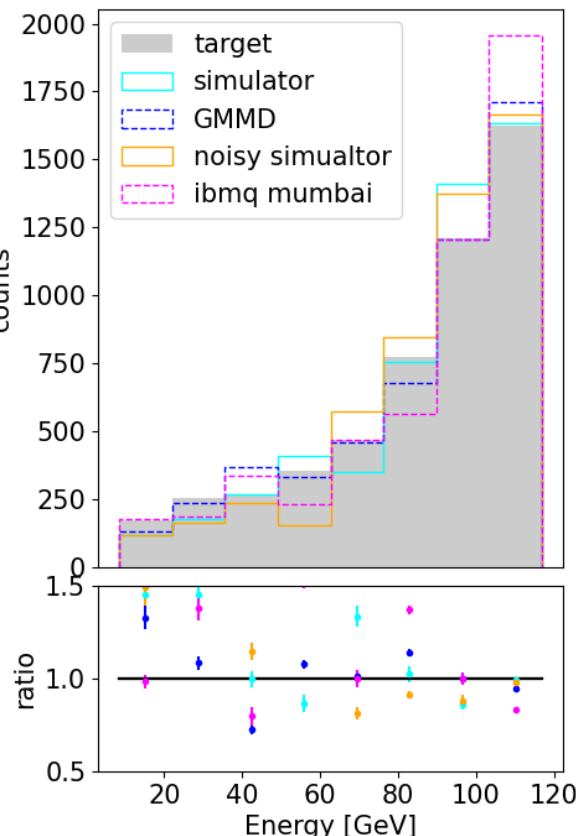
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Multivariate probability distribution



Simulation	Noisy simulation	IBMQ Mumbai	Classical
0.12	0.06	0.06	0.01

Mean difference between the correlations in the MC and generated samples



Mean difference between the correlations in the MC and generated samples

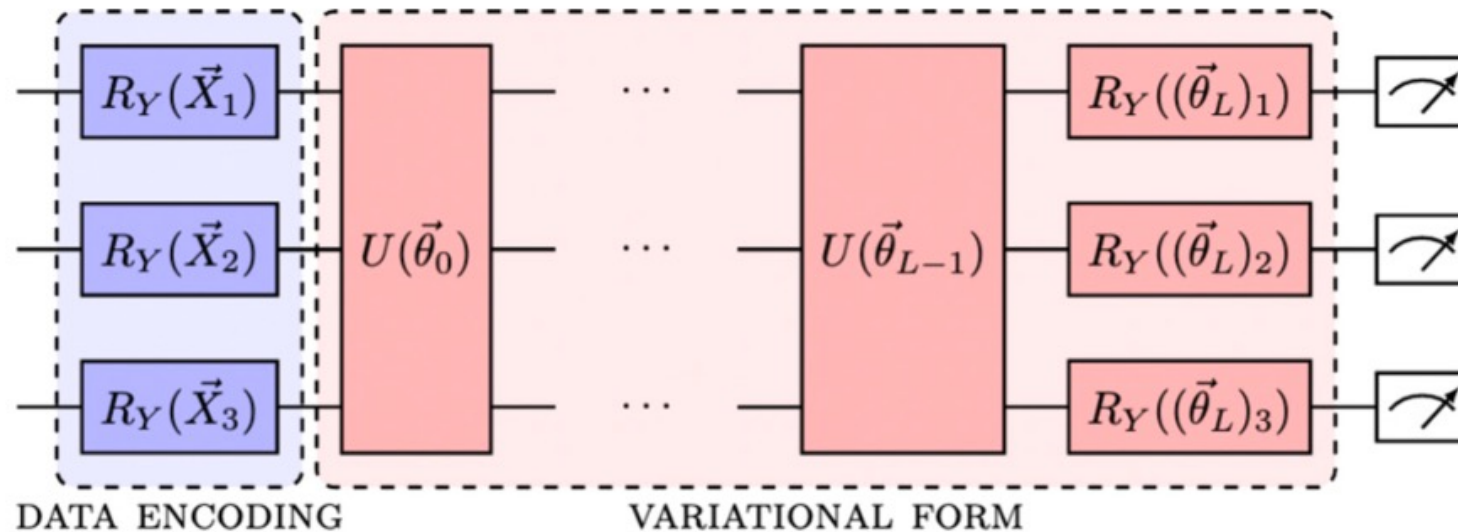
Conditional probability distribution

Data encoding: via data-parametrized rotations

Input: binning energy E (scaled between $[0,1]$ and preprocessed with $\arcsin()$)

Interpolation: train only on certain energy bins and the model should learn to predict in between.

green: fixed gates
blue: data encoding gates
red: trainable gates

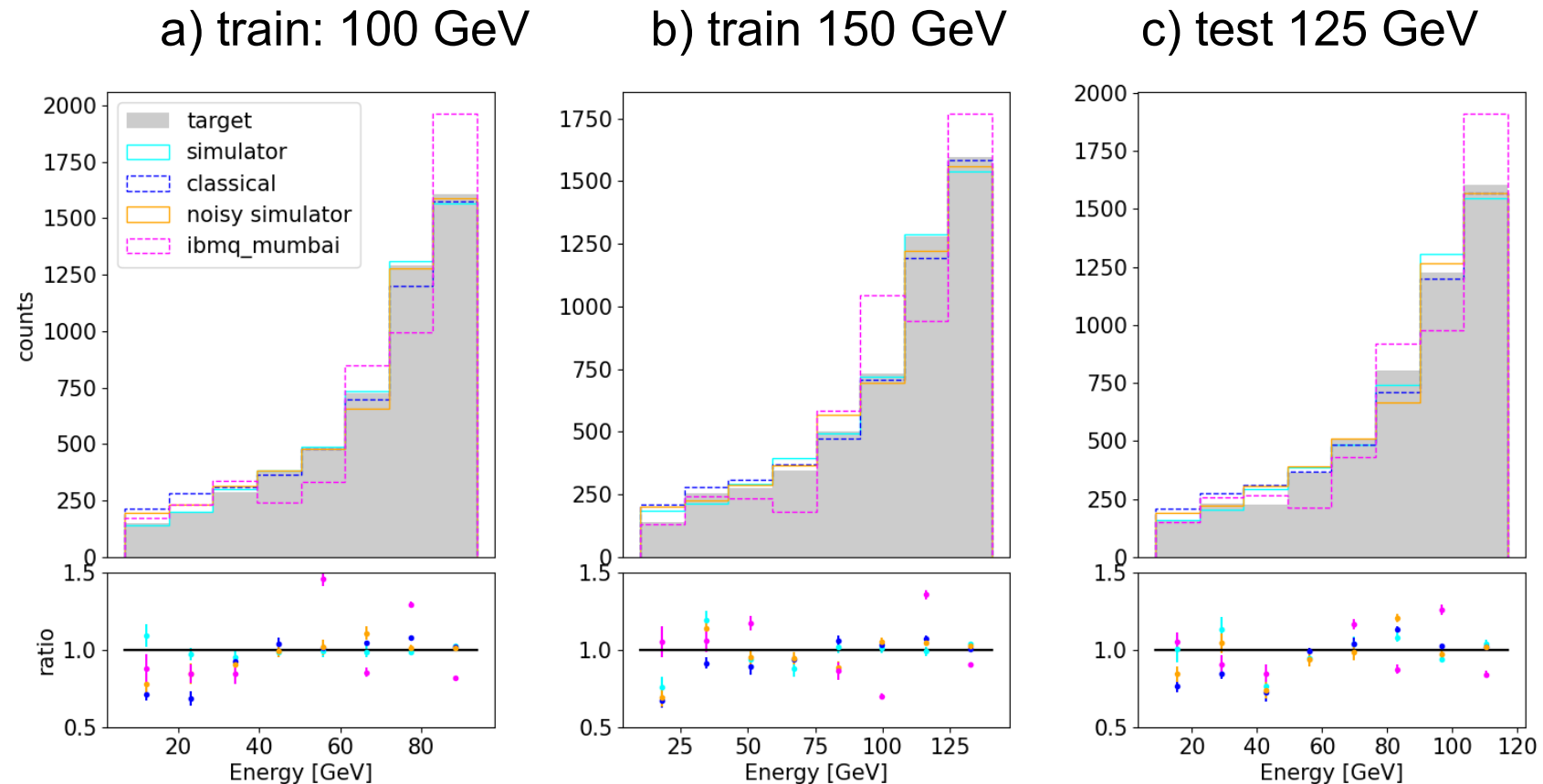


We want to modelize $p(\mathbf{y}|\mathbf{x})$ where \mathbf{x} is the incoming energy E_{in} .

Conditional probability distribution

Goal: Interpolation

1. Data re-uploading does not improve the sampling.
2. Training on hardware is important to assimilate the noise.



Conclusion:

1. Test of a quantum circuit Born machine to generate MFC events.
2. The Born machine is currently able to handle multivariate and conditional distributions.
3. Training on quantum hardware is important in order to assimilate the noise.
4. Futur work is devoted to scale the QCBM, in terms of number of qubits and register, and also extension to more difficult cases.

Thank you

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