Universidade do Minho

LIP — LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Quantum computing and quantum machine learning at High Energy Physics

Final Workshop

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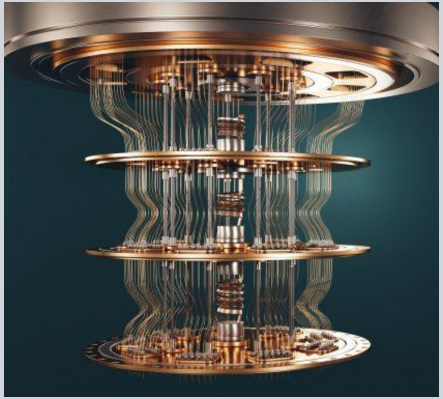
09/07/2022

01

Quantum Machine Learning In HEP



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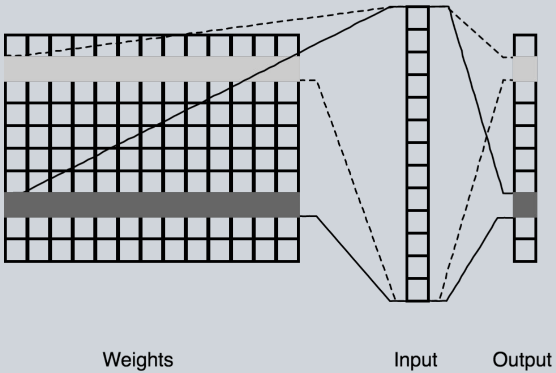
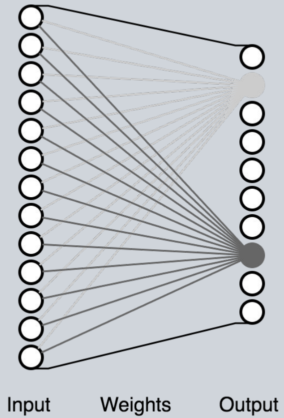
1. Motivation

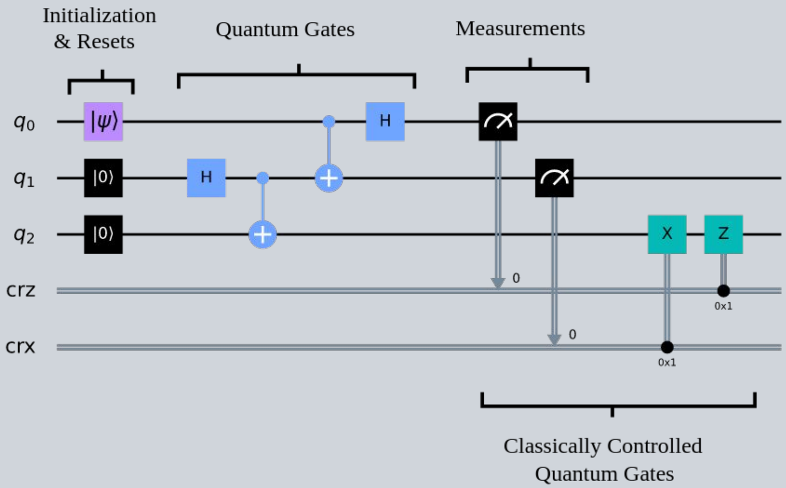
- It’s a new technology
- Few papers published, especially in HEP

1. Quantum Machine Learning

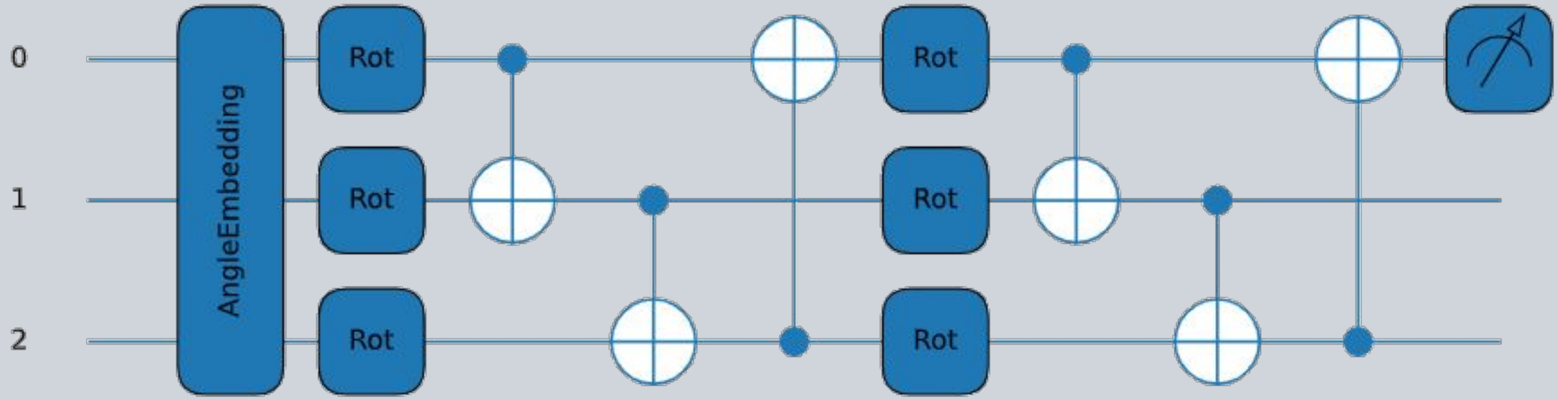
How do we move from classical ML to Quantum ML?







1.1 Variational Quantum Circuit



1.1 Variational Quantum Circuit

A VQC Pipeline in a Nutshell:

- **Data Embedding**
  Converting the classical information, a numerical vector, to the quantum space with a preparation of a fixed initial quantum state.

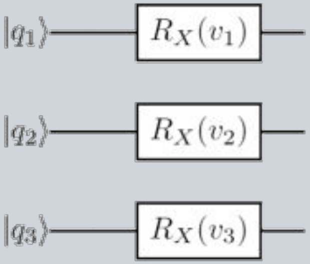
$$X = (x_1, x_2, \ldots, x_N)$$

$$\downarrow$$

$$\psi_X$$

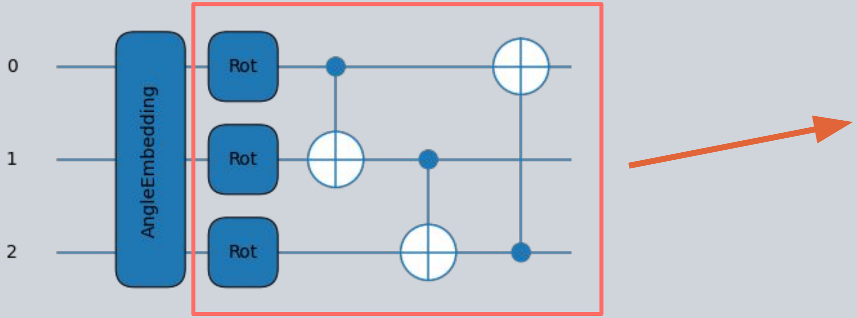
One of the ways of doing this is using **Angle Embedding**

$$|0\rangle^{\otimes N} \longrightarrow \psi_X$$



1.1 Variational Quantum Circuit

- **Quantum Circuit**
  A linear transformation U(**w**), parameterized by a set of learnable parameters **w**, is applied to the initial quantum state.

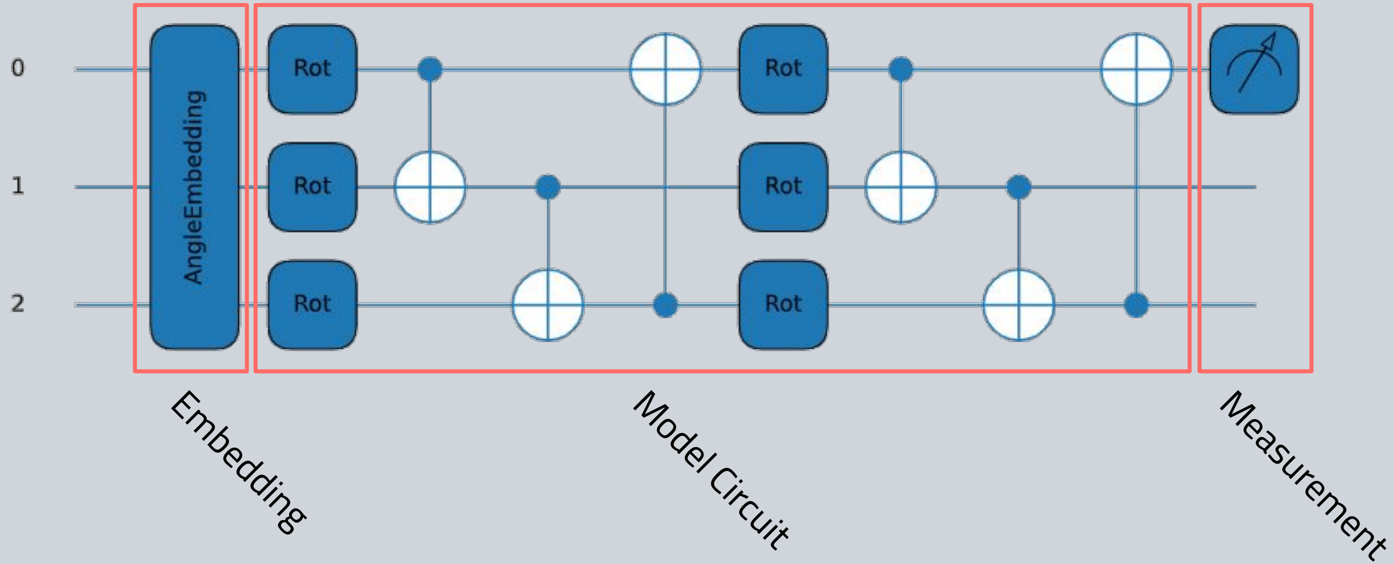


$$|\psi'_X\rangle = U(\theta)\,|\psi_X\rangle$$

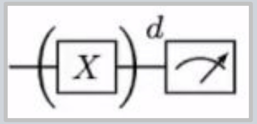
1.1 Variational Quantum Circuit

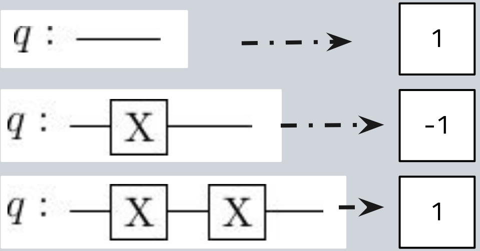
- **Measurement**
  A measurement of the expectation value of the Pauli Z operator is performed in one of the qubits of the final state.

1.1 Variational Quantum Classifier

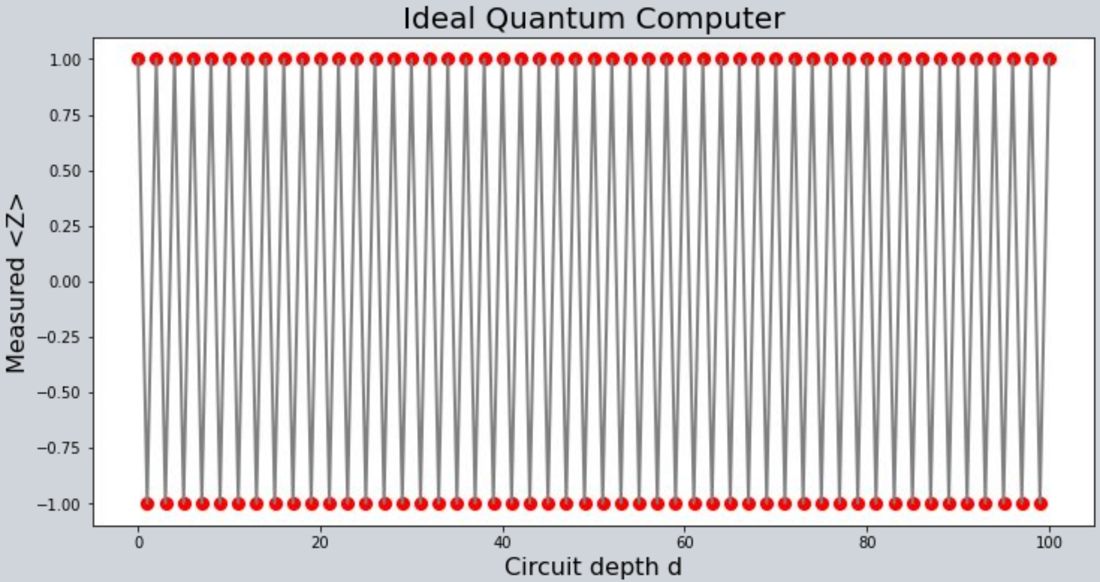


1.3 Quantum Noise in NISQ Era





$$< Z >= (-1)^d$$



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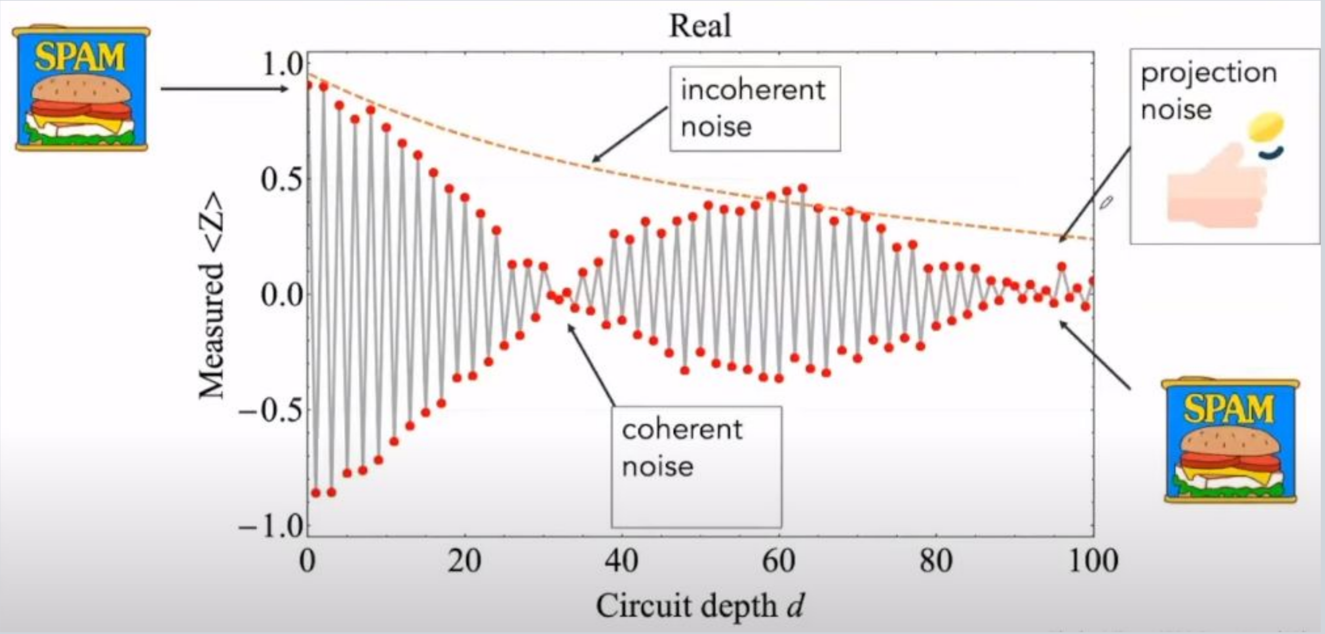
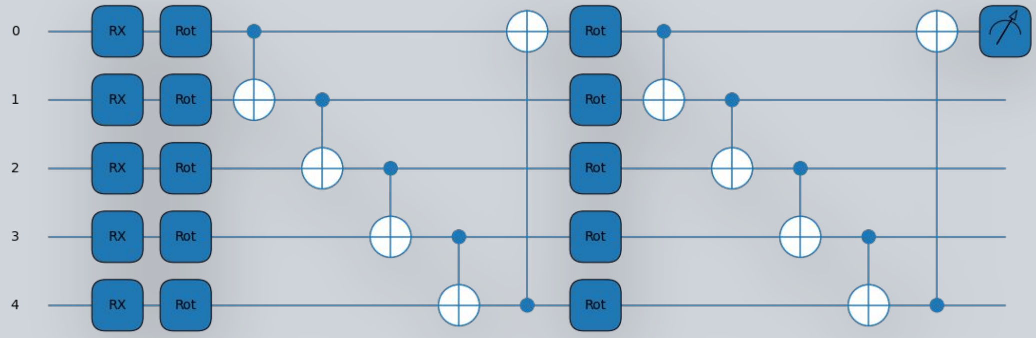
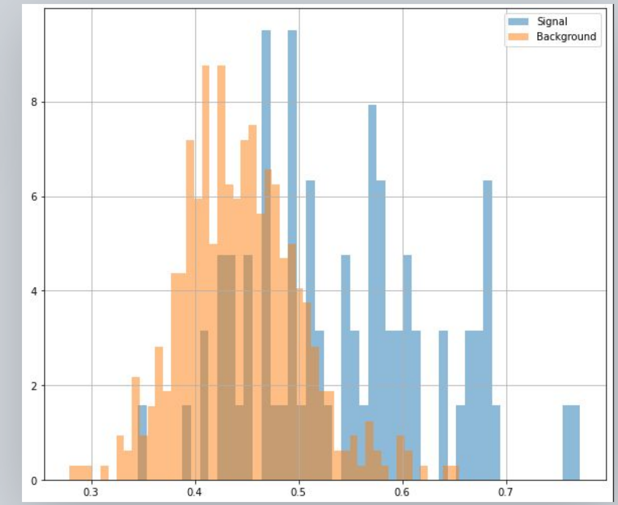


By Zlatko Minev, Qiskit Summer School 2022

1.4 How does it perform in HEP?





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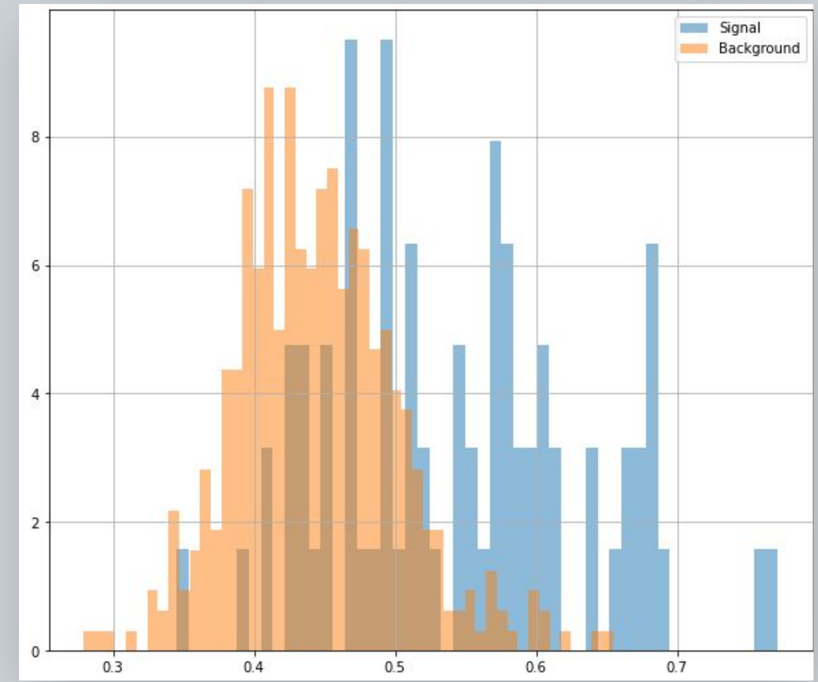

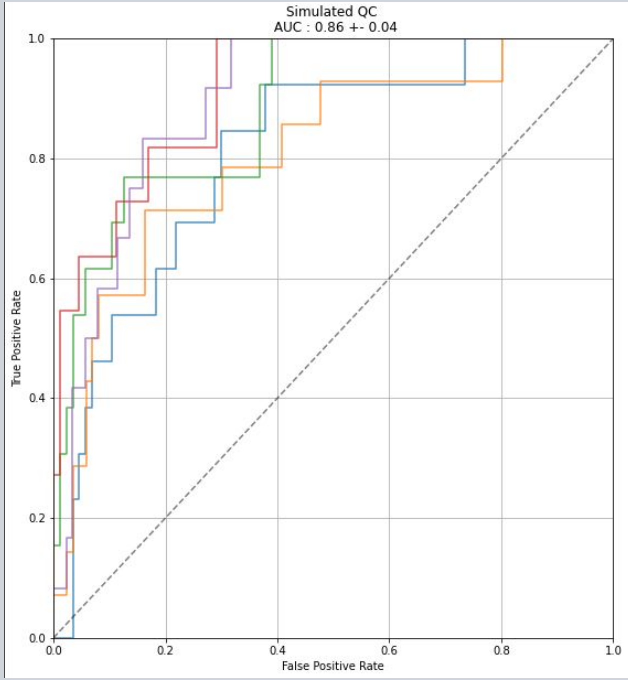

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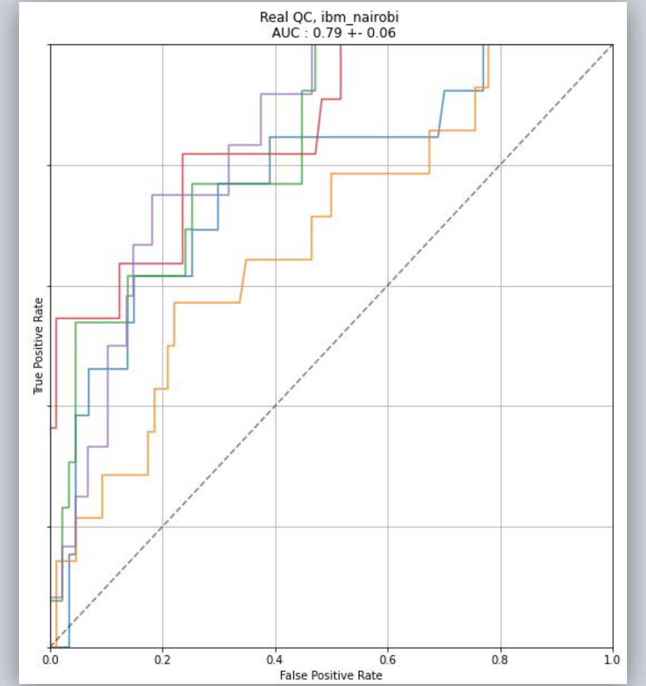

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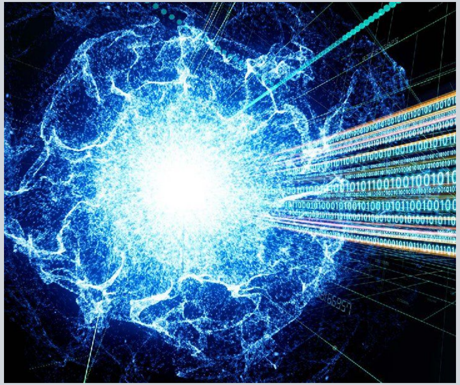
Quantum Phase Estimation



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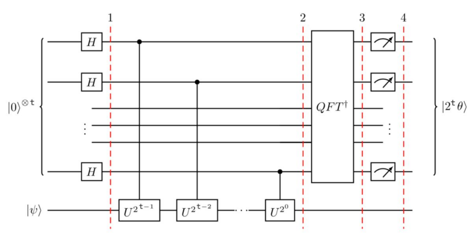
QPE algorithm

1. Initialization - An eigenstate of the target Hamiltonian is prepared and Hadamard gates are applied.
2. Phase Kickback - The k[th] qubit of the counting register is used as the control for a controlled U^{2^k} gate acting on the state register. Mathematically,

$$|count\rangle_n = \frac{1}{2^{\frac{n}{2}}} \sum_{k=0}^{2^n-1} e^{2\pi i\theta k} |k\rangle \oplus |\psi\rangle \,.$$

3. Inverse Fourier transform - permits to obtain the fractional digits of the phase through a measurement in the computational basis, so that readout gives access to the phase $\Theta(\tau)$.
4. Post-processing - Repeating the procedure for several values of the time parameter τ, the energy eigenvalue ε is obtained from

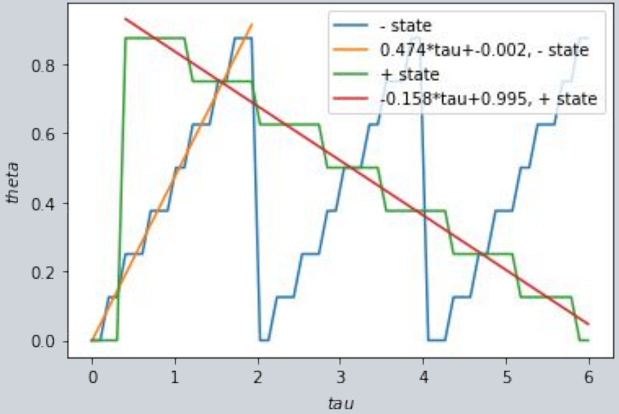
$$\varepsilon = -2\pi \frac{\Delta\theta}{\Delta\tau}.$$



Particular Problem - Ferromagnetism in a two spin-1/2 system

$$H = -J S_1 \cdot S_2$$

$$H = -J\frac{\hbar^2}{4}(\sigma_x^{(1)}\sigma_x^{(2)} + \sigma_y^{(1)}\sigma_y^{(2)} + \sigma_z^{(1)}\sigma_z^{(2)})$$

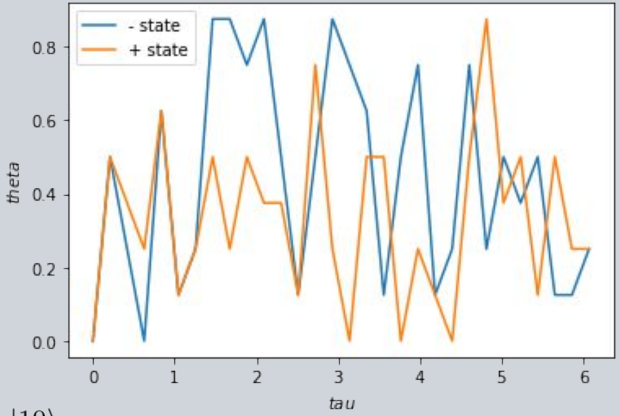


Simulation results

$E_+ = 0.993$
$E_- = -2.978$

$$|+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

$$|-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$



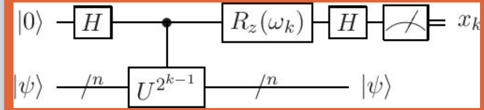
Quantum computer results
Basic algorithm

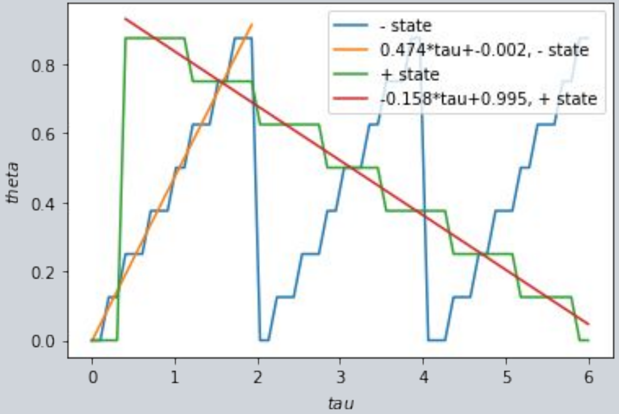
Analytical results:

$E_+ = 1$
$E_- = -3$

Iterative QPE algorithm

The iterative algorithm implements quantum phase estimation with only a counting qubit, hence the accuracy of the algorithm is restricted by the number of iterations rather than the number of counting qubits.
The iterative algorithm constructs θ bit by bit and, consequently, it's necessary to apply a rotation by an angle that depends on the previous measures.





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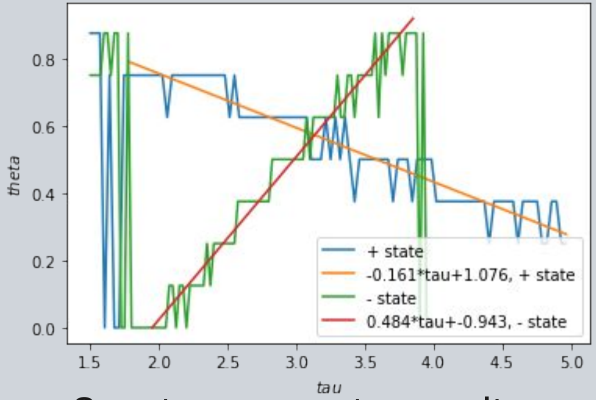

Quantum computer results iterative algorithm

$E_+ = 1.012$

$E_- = -3.041$

Analytical results:

$E_+ = 1$

$E_- = -3$

$$|+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

$$|-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

Future and ongoing work

- Error mitigation
- More spins
- Other algorithms - variational quantum eigensolver
- Other ways to map the hamiltonian

Thanks!

Any questions?

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Backup Slides

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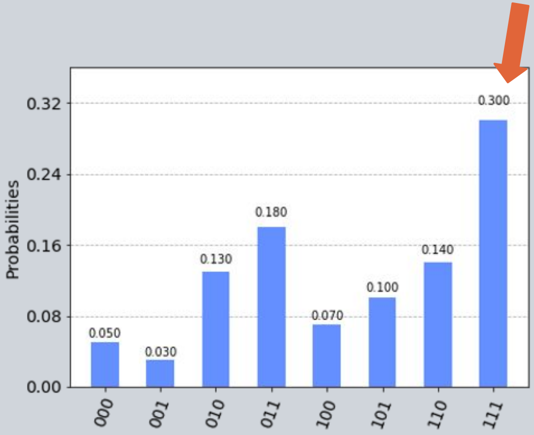
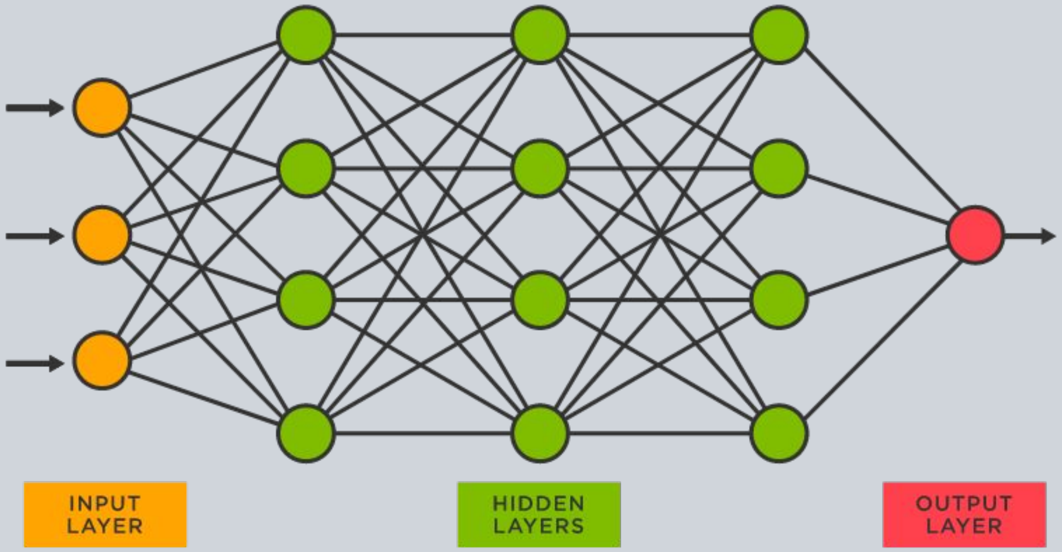
Histogram readout

The algorithm returns a histogram of probabilities, consequently, it's possible to simply consider the most probable phase or use circular statics to find the "mean phase".

The results presented in this presentation are obtained using the most probable phase. When used circular statistics the results don't improve.

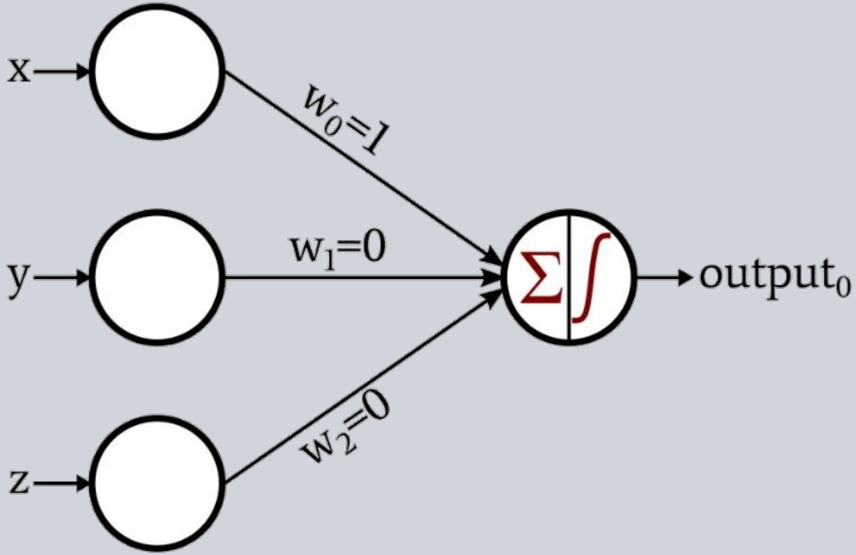


0. Classical Machine Learning



A Neural Network

0. Classical Machine Learning



$$y = f\left(\sum_{i=0}^{N}(\boldsymbol{w_i} \cdot \boldsymbol{x_i}) + b\right)$$