Intro to QC

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Disclaimer

Twofold goal for today: **what** and **why**

1. What: introduceQuantum Computing & Quantum Machine Learning
2. Why: kickstart a community to look for useful applications of QML for Nikhef's community within **Nikhef ML/AI**

There is 🌟not one single🌟 question too naive/too silly to ask

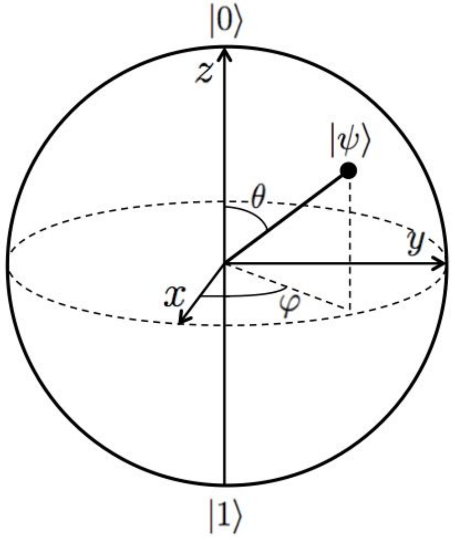
Please **ask away!**

The schedule for today

14:00 → 14:20	**Introduction to Quantum Computing** **Speaker**: Miriam Lucio Martinez	20m
14:20 → 14:40	**Building A Dutch Quantum Computer** **Speaker**: Ariana Torres (SURF)	20m
14:40 → 15:00	**Variational Algorithms** **Speakers**: George Scriven, Xenofon Chiotopoulos	20m
15:00 → 15:20	**A Hitchhikers Guide to (practical) Quantum Computing for HEP** **Speaker**: Vince Croft HitchhikersMini.pdf	20m

Quantum Computing in a nutshell

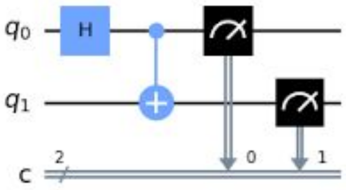
- Instead of **bits** we use **qubits**, the fundamental units of quantum information
  - Not 0 **or** 1, but a two-state quantum system → coherent superposition of both
  - They can be **measured** → probabilistic results
- There are **quantum logic gates** that operate on these qubits
  - Unitary transformations
  - Quantum gates can be **single** or **multiple**



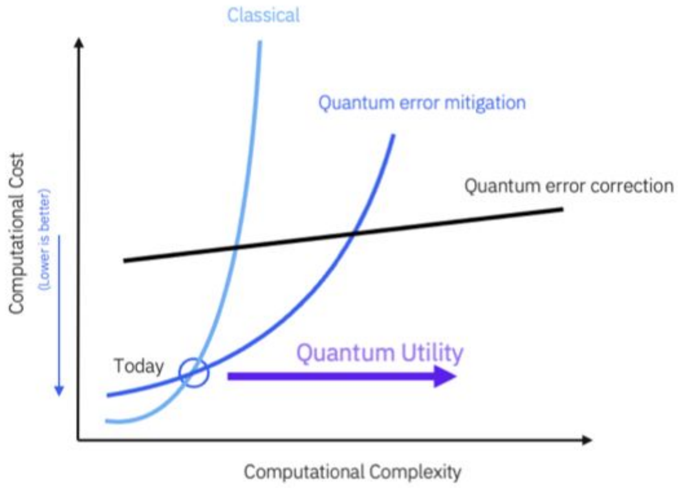
$$|0\rangle = \binom{1}{0},\ |1\rangle = \binom{0}{1}$$
$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

Quantum Computing in a nutshell

A sequence of gates acting on a register of qubits is called a **quantum circuit**



Some computational problems can profit from **Quantum Computing** using the principles of **superposition** and **interference**.



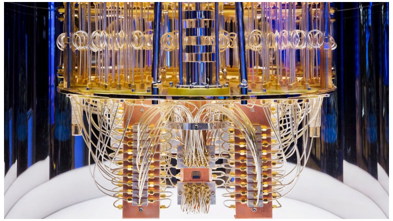
https://quantumalgorithmzoo.org/

Quantum Computing - Hardware

Several technologies are being explored as physical qubits:

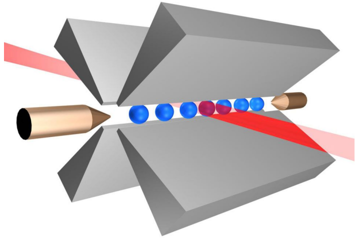
Superconducting

Superconducting electric circuits at 10mK behave as quantum systems with discrete energy levels



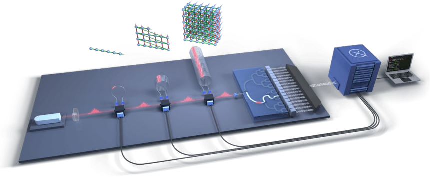
Trapped ions

Charged atoms constrained in electromagnetic traps and manipulated with laser



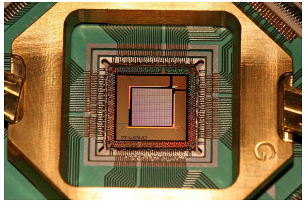
Optical

Linear optics devices using photons as information carriers



Annealing

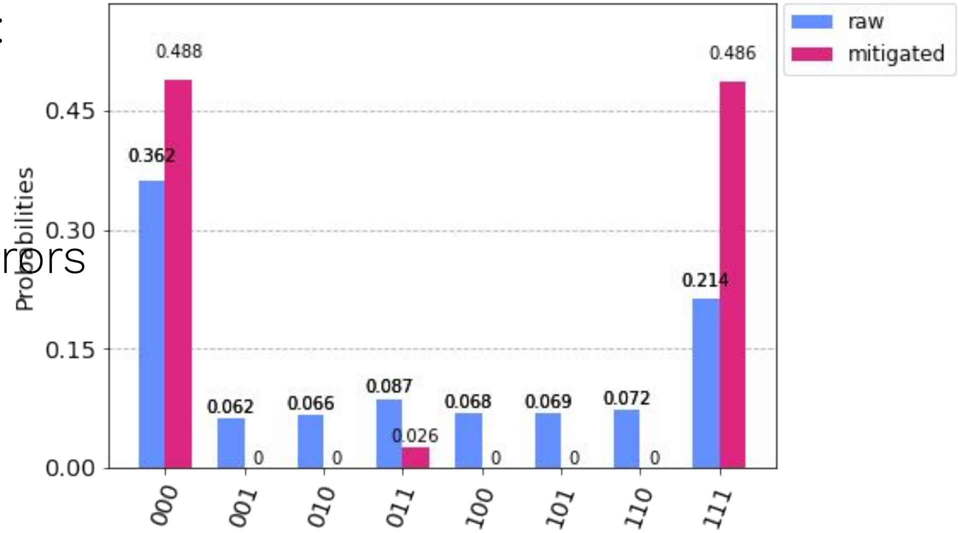
Ising-chain qubits interacting with a customizable Hamiltonian



Quantum Computing - Noise

All the previous technologies are far from being perfect. Current qubits are **noisy**:

- Measurement errors
- 1-qubit and 2-qubit gates fidelities
- T1 and T2 decoherence time
- Calibration errors



→ *Noise Error Mitigation*

Porting to hardware

IBM Quantum

ibm_perth

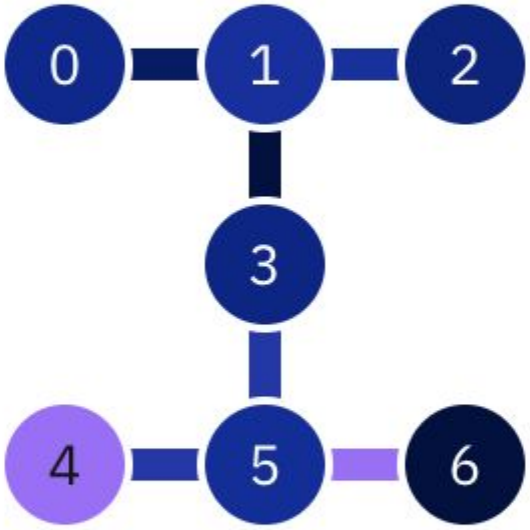
OpenQASM 3

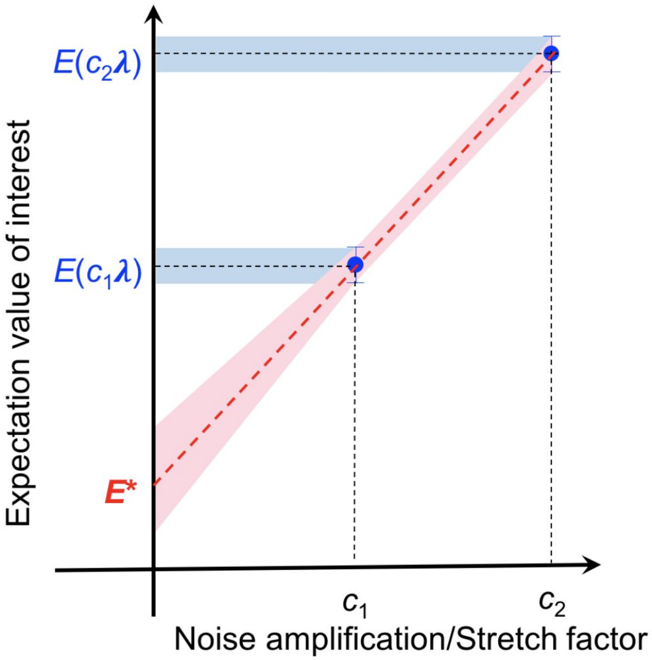
Details

7 Qubits	Status:	Online	Median CNOT error: 8.593e-3
32 QV	Total pending jobs:	1028 jobs	Median SX error: 3.052e-4
2.9K CLOPS	Processor type ⓘ:	Falcon r5.11H	Median readout error: 2.510e-2
	Version:	1.2.8	Median T1: 110.66 us
	Basis gates:	CX, ID, RZ, SX, X	Median T2: 105.71 us
	Your usage:	0 jobs	Instances with access: 1 Instances ↓

Porting to hardware

IBM **Quantum**

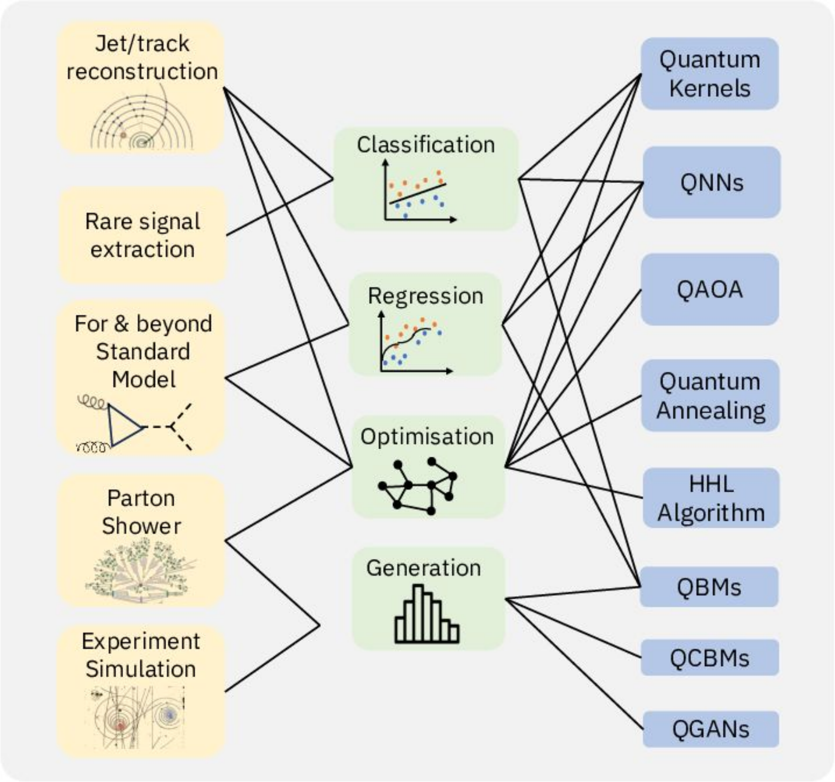




The world (python) is your quantum oyster

HEP use-cases

- Summary of the QC4HEP WG
- Focused mostly in projects concerning experimental particle physics at LHC
- For the majority of them: events are quantum in nature, but measurements are classical
- See colloquium that Vince gave a few weeks ag
  - https://indico.nikhef.nl/event/5852/



QC for Track Reconstruction

- QC has very interesting prospects of improvements in algorithm **complexity/timing**
- This talk: two track reconstruction algorithms
- Define **Ising-like** $H^{\text{TrackReco}}$(hits):

$$H = -\frac{1}{2}\sum_{ij}\omega_{ij}\sigma_z^i\sigma_z^j - \sum_i \omega_i \sigma_z^i$$

→ $\mathbf{H_{min}^{TrackReco}}$ == solution with the correct reconstructed tracks

HHL for Track Reconstruction [arXiv:2308.00619]

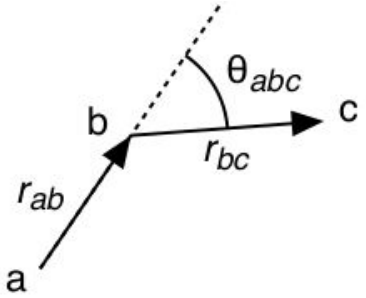
Differentiable Hamiltonian:

$$\nabla \mathcal{H} = 0 \Rightarrow A\mathbf{S} = \mathbf{b}$$

HHL: QC algorithm to solve the **system of linear equations**

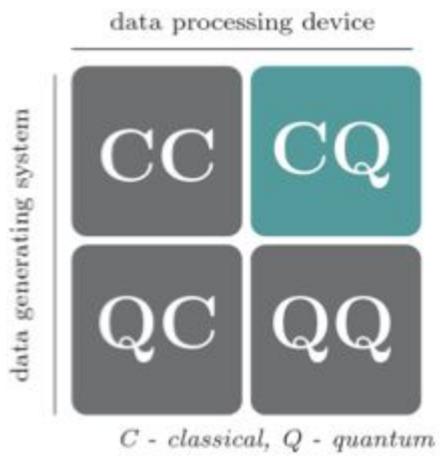
Segment [S_{ab}]: combination of hit *a* and hit *b*
→ in consecutive layers - for now

Hamiltonian accounts for **all** possible segments



Quantum Machine Learning

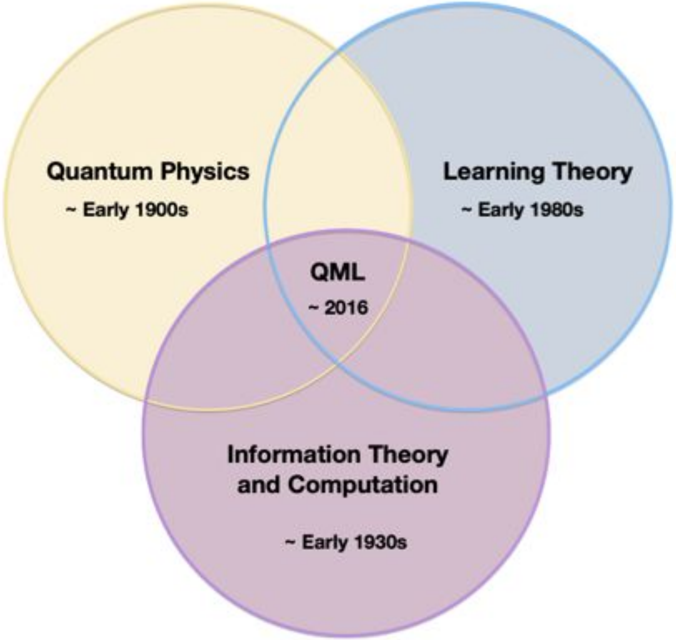
- The interface of **Quantum Computing** and **Machine Learning**
- Not a 1-1 correspondence with classical ML
- Potential for **large speedups** wrt classical
- However: watch out for barren plateaus
  - [talk by E. Combarro]



Imagine algorithms are cookies

Types of QML

- **Supervised ML:** Quantum Classifiers
- **Unsupervised ML**: Quantum Generative Models

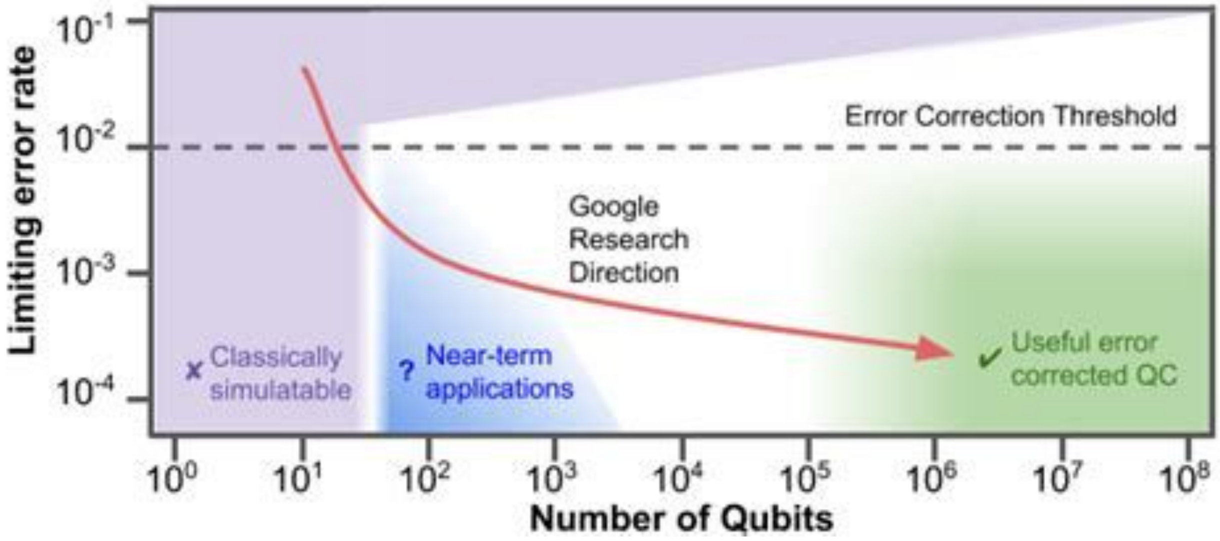


A bit of advertisement

Thanks for your attention!

QC and the NISQ era [arXiv:1801.00862]

NISQ: Noise Intermediate-Scale Quantum



HHL for Track Reconstruction [arXiv:2308.00619]

$$\mathcal{H}(\mathbf{S}) = -\frac{1}{2}\left[\sum_{abc} f(\theta_{abc}, \varepsilon) S_{ab} S_{bc} + \gamma \sum_{ab} S_{ab}^2 + \delta \sum_{ab} (1 - 2S_{ab})^2\right]$$

angular term (a) (b)

$$f(\theta_{abc}, \varepsilon) = \begin{cases} 1 & \text{if } \cos\theta_{abc} \geq 1 - \varepsilon \\ 0 & \text{otherwise} \end{cases}$$

- **(a) regularization term**: makes the spectrum of A positive
- **(b) gap term**: ensures gap in the solution spectrum

Validation with a classical linear solver

LHCb MC event $B_s \rightarrow \phi\phi$
1 collision event
Half of the VELO

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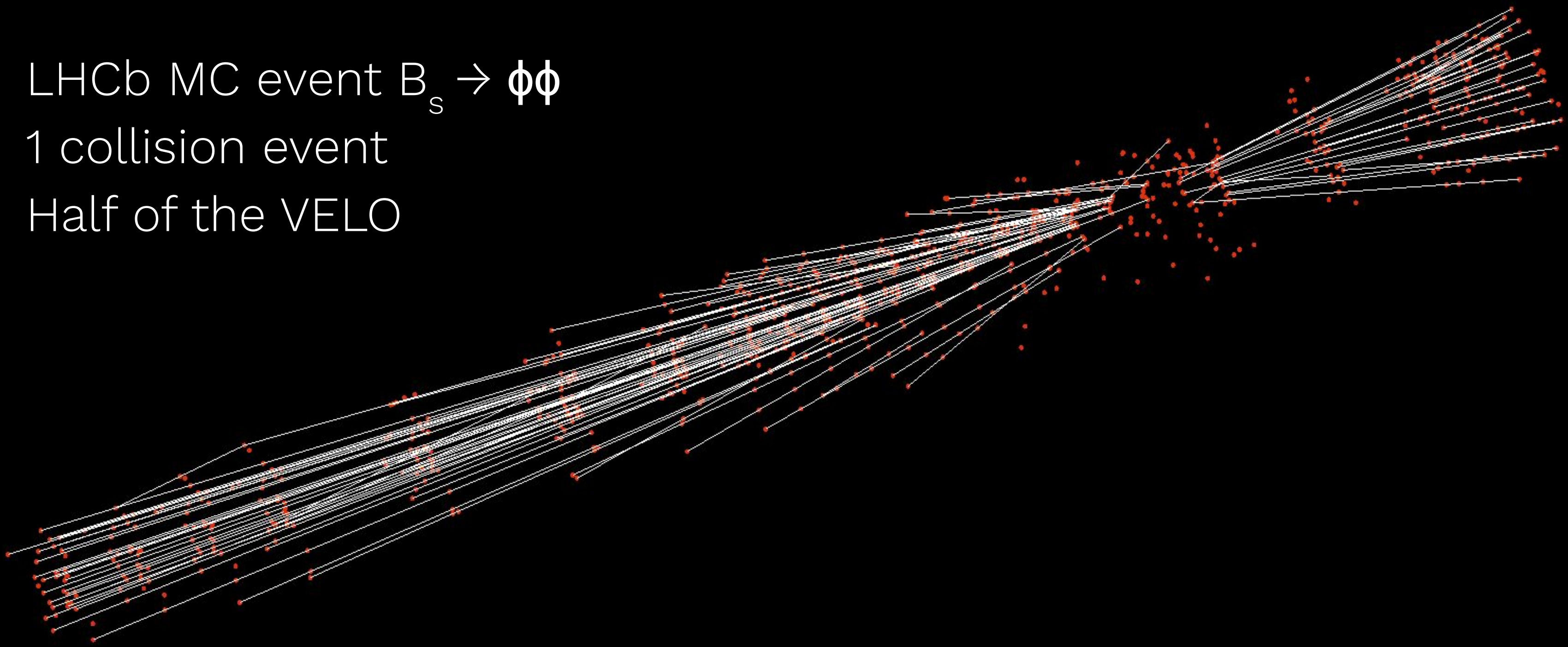

Tracking performances with classical solver

- Very good performance **with LHCb MC**, but **high** circuit depth.

Tracking performance on LHCb simulated events