Quantum Computing & High Energy Physics

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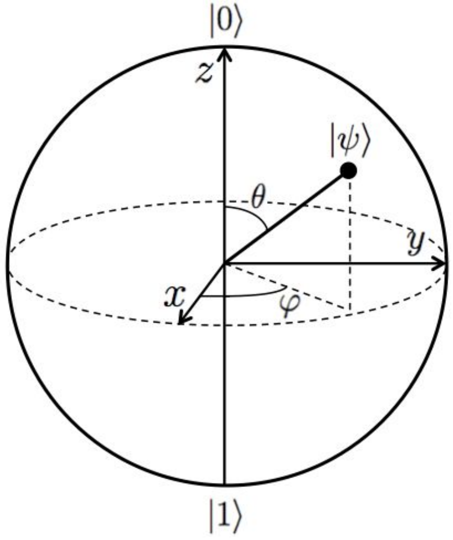
Quantum Computing in a nutshell

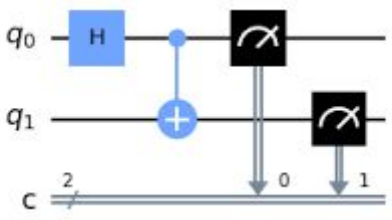
- Instead of **bits** we use qubits, the fundamental units of quantum information
  - Not 0 **or** 1, but a two-state quantum system → coherent superposition of both
  - They can be **measured** → probabilistic results
- There are quantum logic gates that operate on these qubits
  - Unitary transformations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

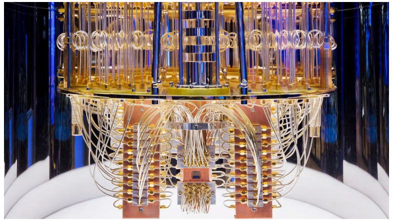
Quantum Computing - Hardware

Several technologies are being explored as physical qubits:

Superconducting

IBM Google

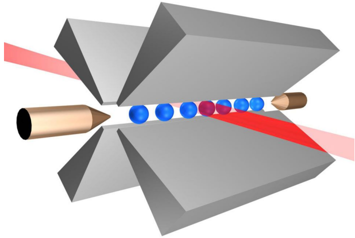
Superconducting electric circuits at 10mK behave as quantum systems with discrete energy levels



Trapped ions

IONQ QUANTINUUM

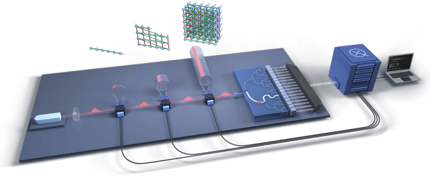
Charged atoms constrained in electromagnetic traps and manipulated with laser



Optical

XANADU

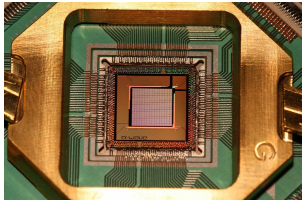
Linear optics devices using photons as information carriers



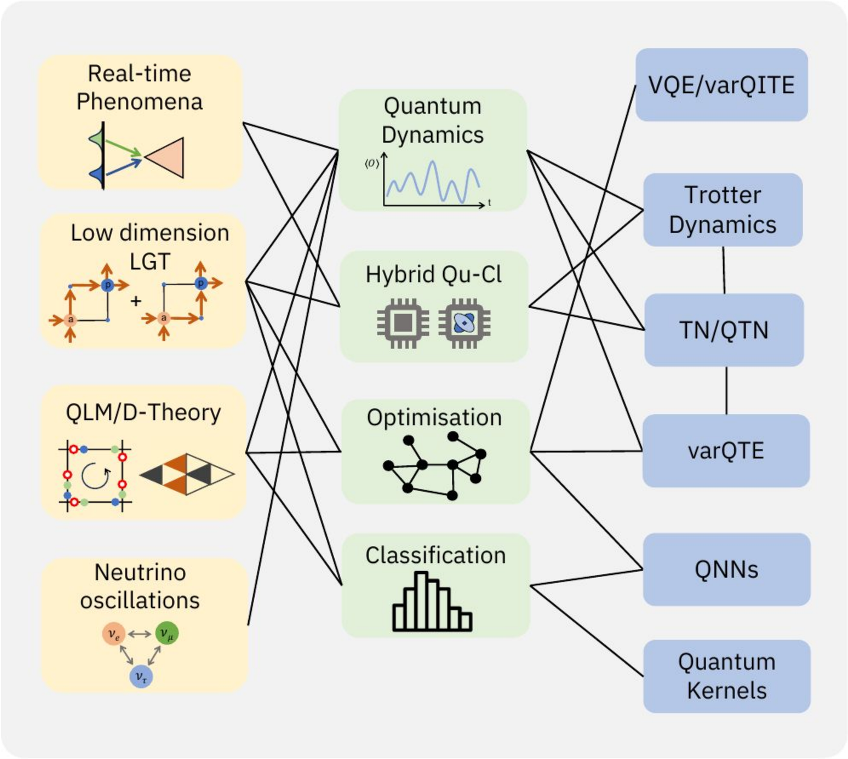
Annealing

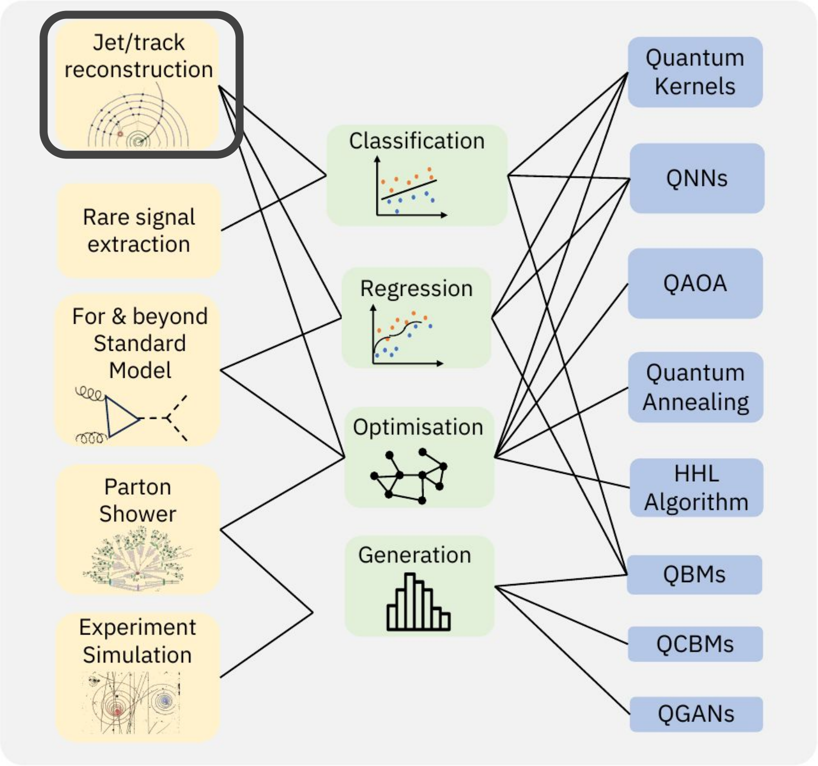
D-Wave The Quantum Computing Company™ QILIMANJARO QUANTUM · TECH

Ising-chain qubits interacting with a customizable Hamiltonian



HEP: Theory and experiment

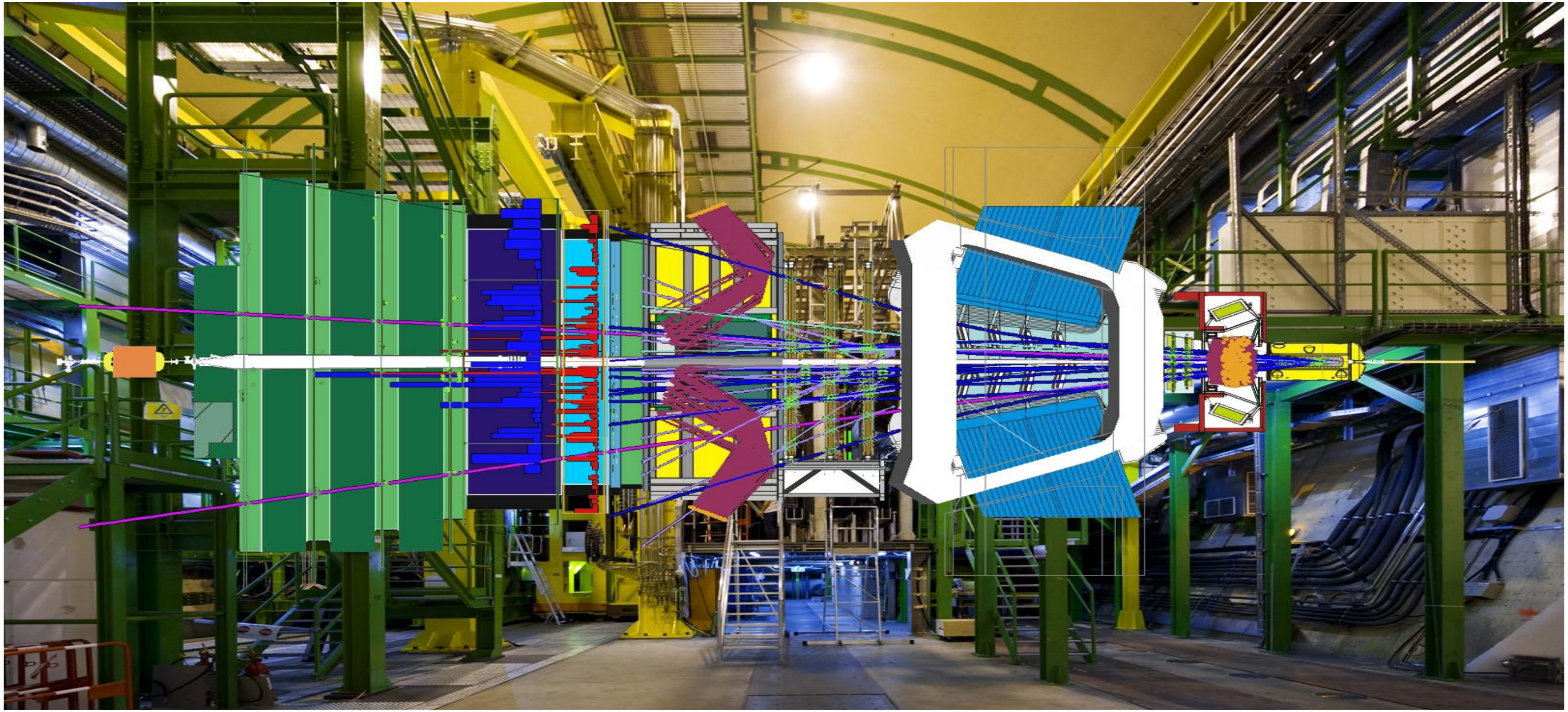




[Summary of the QC4HEP WG]

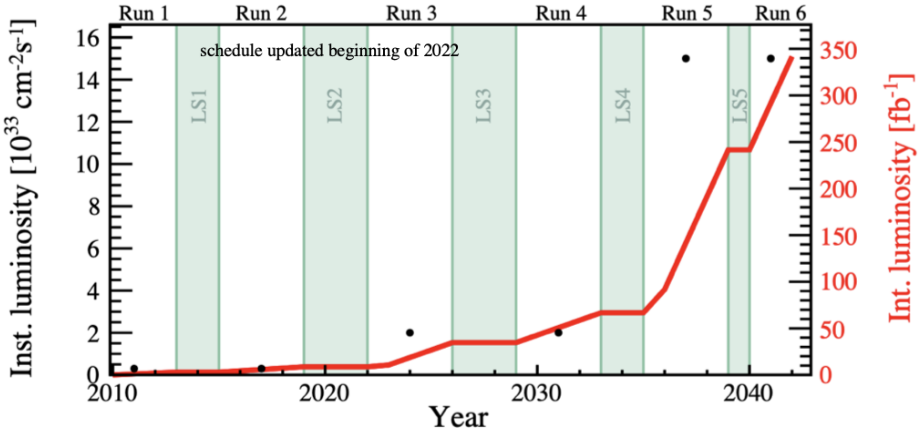
How does an LHCb event look like?

Reconstruct events 40 Million times per second.

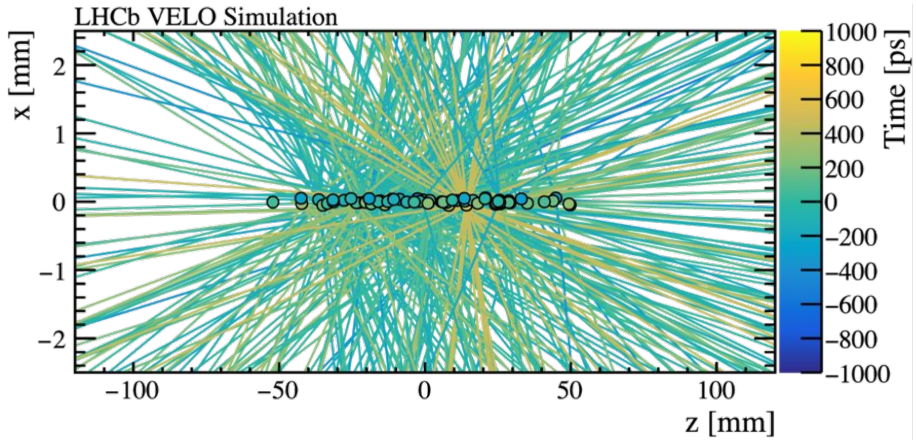


Motivation for QC

- New algorithms and architectures needed to deal with the increased luminosity & limited bandwidth @ **HL-LHC**



ECFA



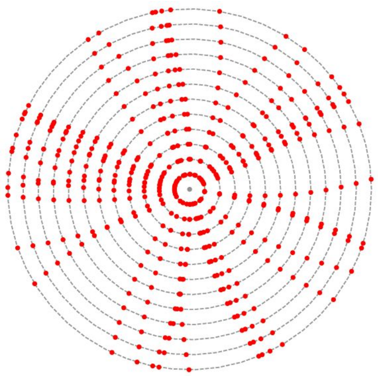
Courtesy of Robbert Geertsema

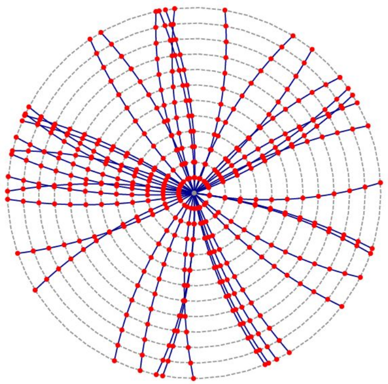
Track Reconstruction

- **Local tracking methods**: steps are performed sequentially. Some studies exist on QC for local tracking methods [arXiv:2104.11583]
- **Global tracking methods**: all hits are processed by the algorithm in the same way. Global algorithms are **clustering** algorithms. E.g.: QAOA, quantum annealing, Hopfield Networks, Hough transform

→ LHCb's current method of search by triplet

→ Focus of this talk: *global* algorithms





QC for Track Reconstruction

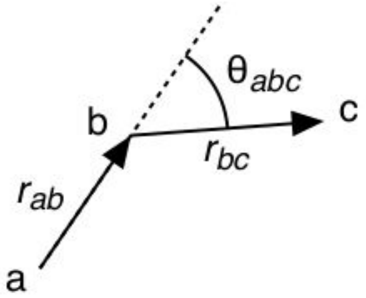
Ising-like Hamiltonian:

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

Tracks, modelled by a collection of **segments**

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

Hamiltonian accounts for all possible segments



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**

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

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

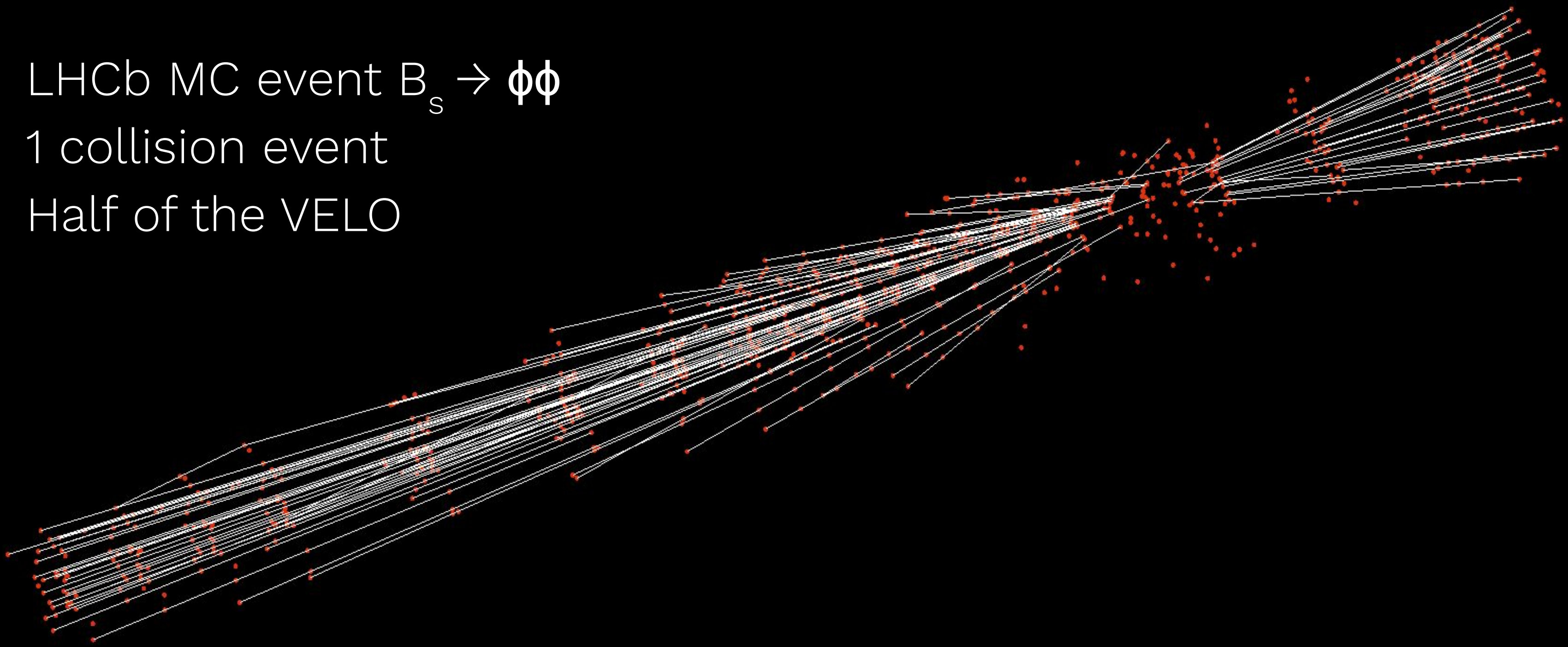
- **(a) regularization term**: makes the spectrum of A positive
- **(b) gap term**: ensures gap in the solution spectrum

Validation with a classical linear solver

LHCb MC event $B_s \rightarrow \phi\phi$

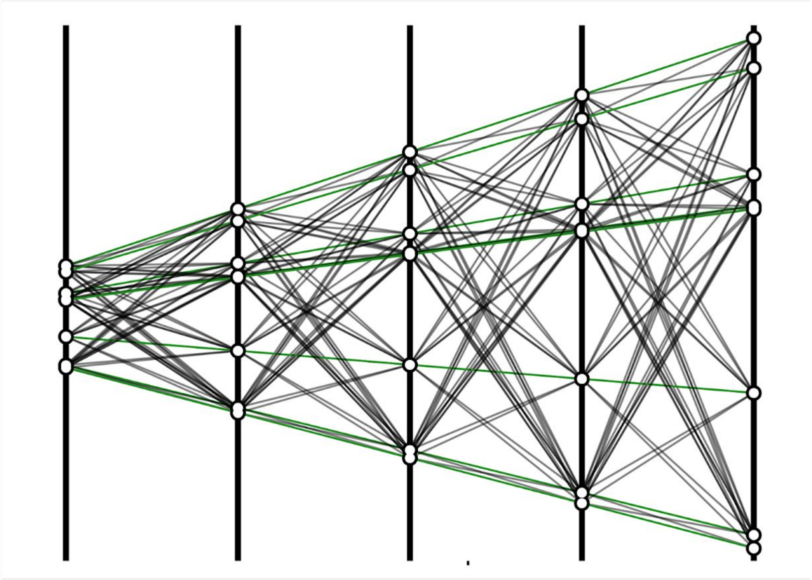
1 collision event

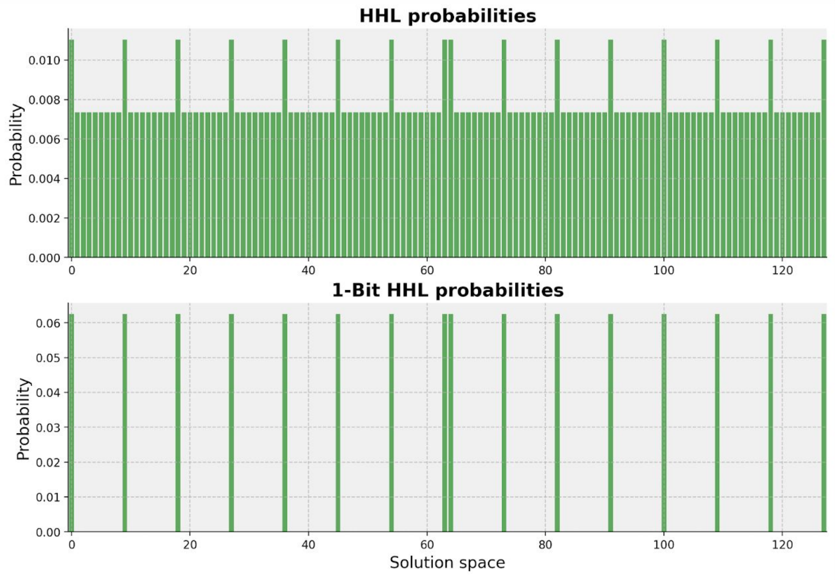
Half of the VELO



Performance results

- Very good performance (around 90%) **with LHCb MC**.
- Current work has significantly reduced the **circuit depth** [arXiv:2511.11458].





QAOA for Track Reconstruction

Quantum Approximate Optimization Algorithm [arXiv:1411.4028, tutorial]

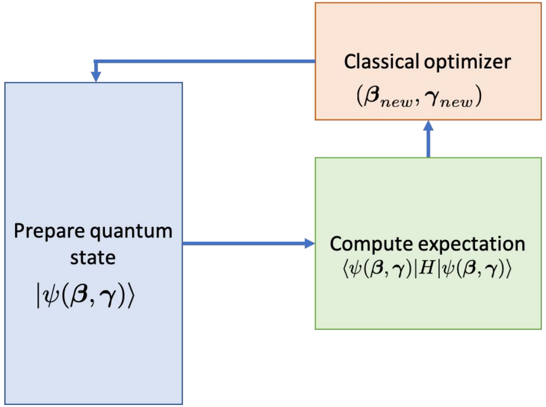
- A variational algorithm ideal to solve combinatorial optimization problems, e.g. Max-Cut problem
  - *'Finding an optimal object out of a finite set of objects'*

$$|\psi(\beta,\gamma)\rangle = U(\beta)U(\gamma)...U(\beta)U(\gamma)\,|\psi_0\rangle$$

$$U(\beta) = e^{-i\beta H_B},\ U(\gamma) = e^{-i\gamma H_P}$$

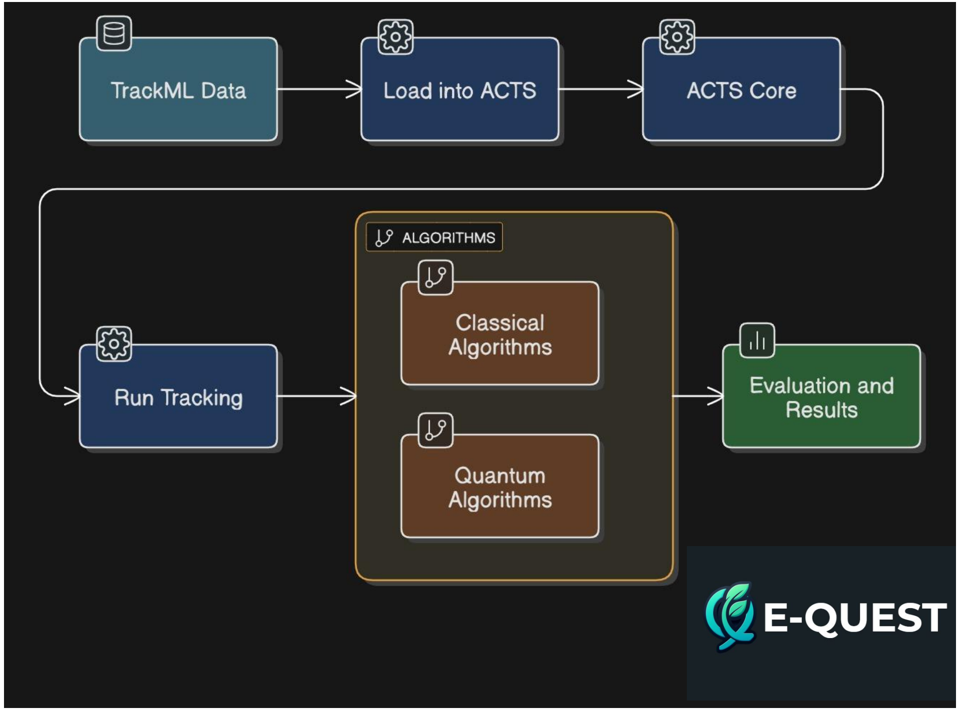
Goal: find optimal parameters $(\square_{opt}, \gamma_{opt})$ such that the quantum state encodes the solution to the problem

- Successful implementation and validation for small simulations
- Scalability poses an issue, affecting especially the simulator



Sustainability & Quantum

- Using ACTS as framework
- Hardware-dependent and/or computational complexity dependent
- Work done by K. Singh, check out talk by A. Oyanguren on CTD



Ongoing/future work

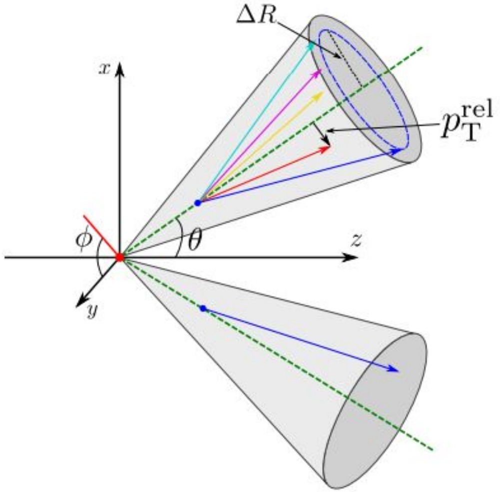
- Try simulation using Rydberg atoms
- Distributed QAOA
- Try a different algorithm, e.g. Pauli Correlation Encoding
- Further applications of QAOA for HEP with better scalability and/or different use-cases

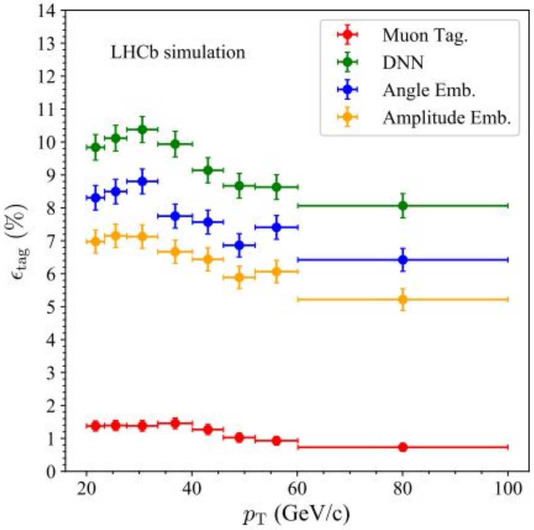
Moltes gràcies!

QML for b-jet flavour tagging

b-jet flavour tagging [JHEP 08 (2022) 014]

- Identify if a jet contains a hadron formed by a **b** or **anti-b** quark at the moment of production
  - (Q)ML algorithm that uses variables from the particles of the jets to do so
- Deep Neural Network vs 16-qubit **Variational Quantum Classifier**

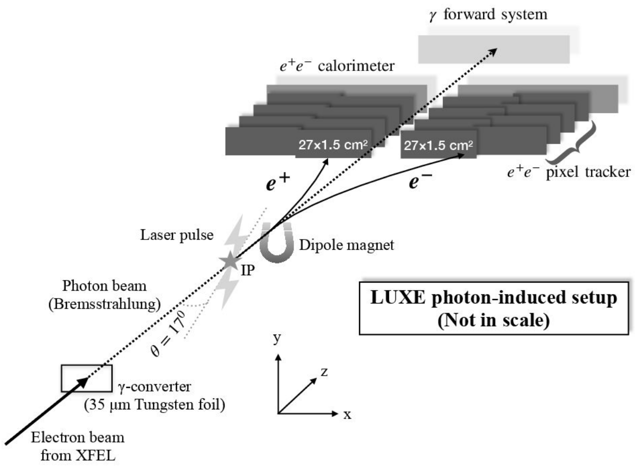




Related work [arXiv:2210.13021]

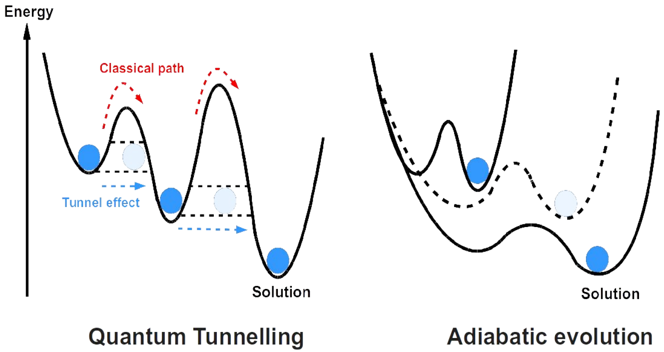
- **LUXE** experiment @ **DESY** to study QED in the strong-field regime
- Tracking of positrons traversing 4 layers of tracking detectors
- Classical methods:
  - Combinatorial Kalman Filter using triplets of hits
  - GNN where each hit is a node

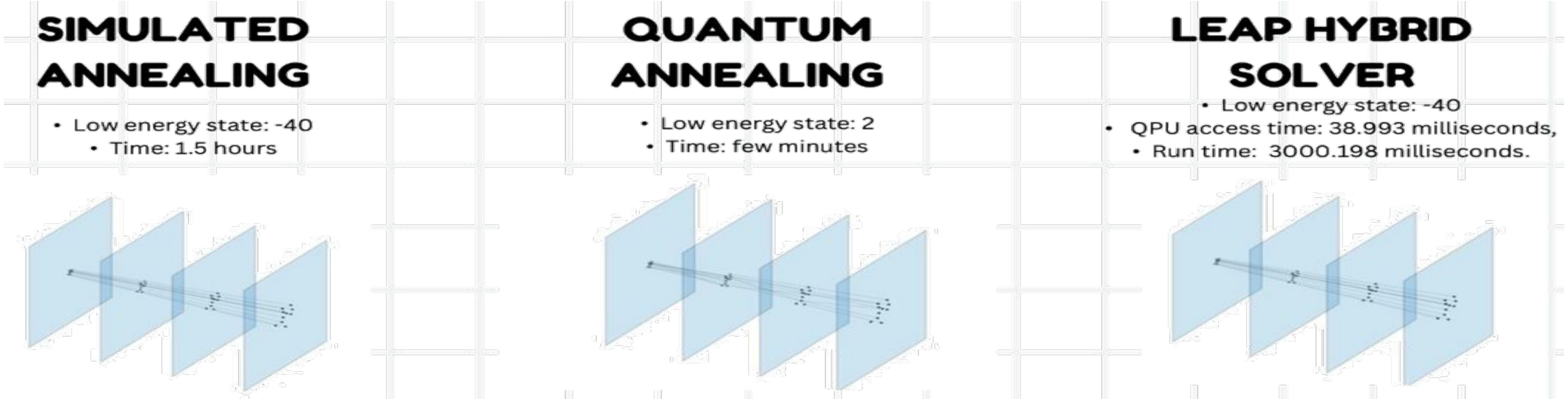
$$O = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i \quad T_i, T_j \in \{0, 1\}$$



Quantum Annealers

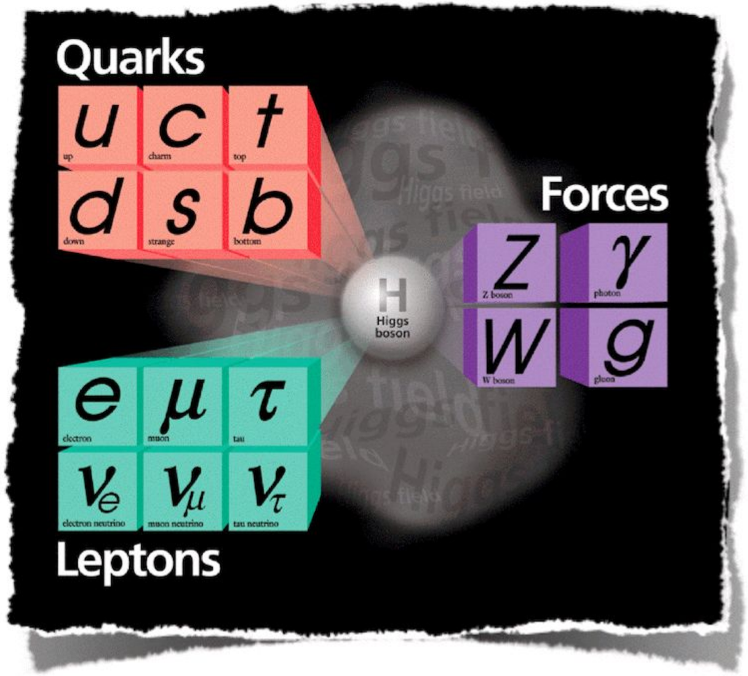
- Different hardware, not gate-based
- Optimal for minimizing Ising-like Hamiltonians





The Standard Model of Particle Physics

A **successful** theory that describes the interactions among particles …



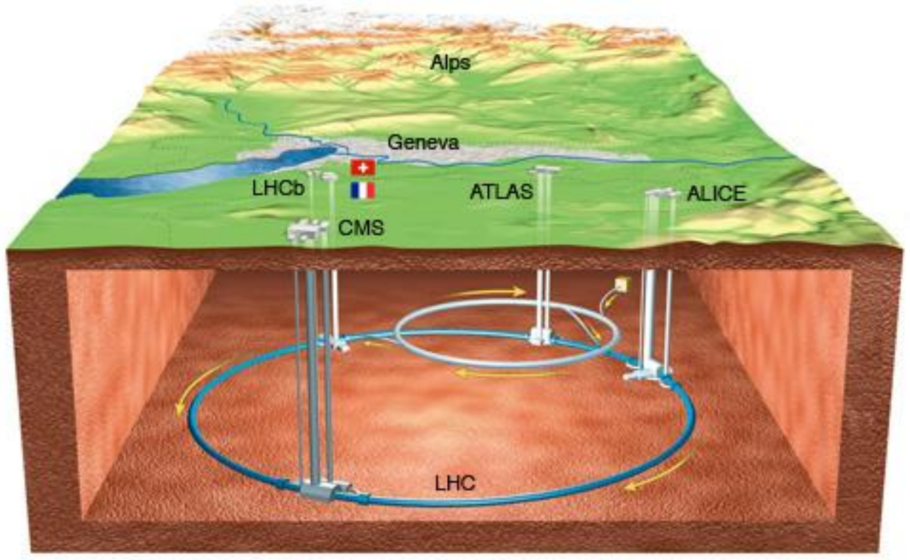
… **but** fails to explain several phenomena observed in the Universe:

- Neutrinos masses
- Origin of Dark Matter & Dark Energy
- etc

⇒ need of Beyond the Standard Model physics!!

The LHCb detector

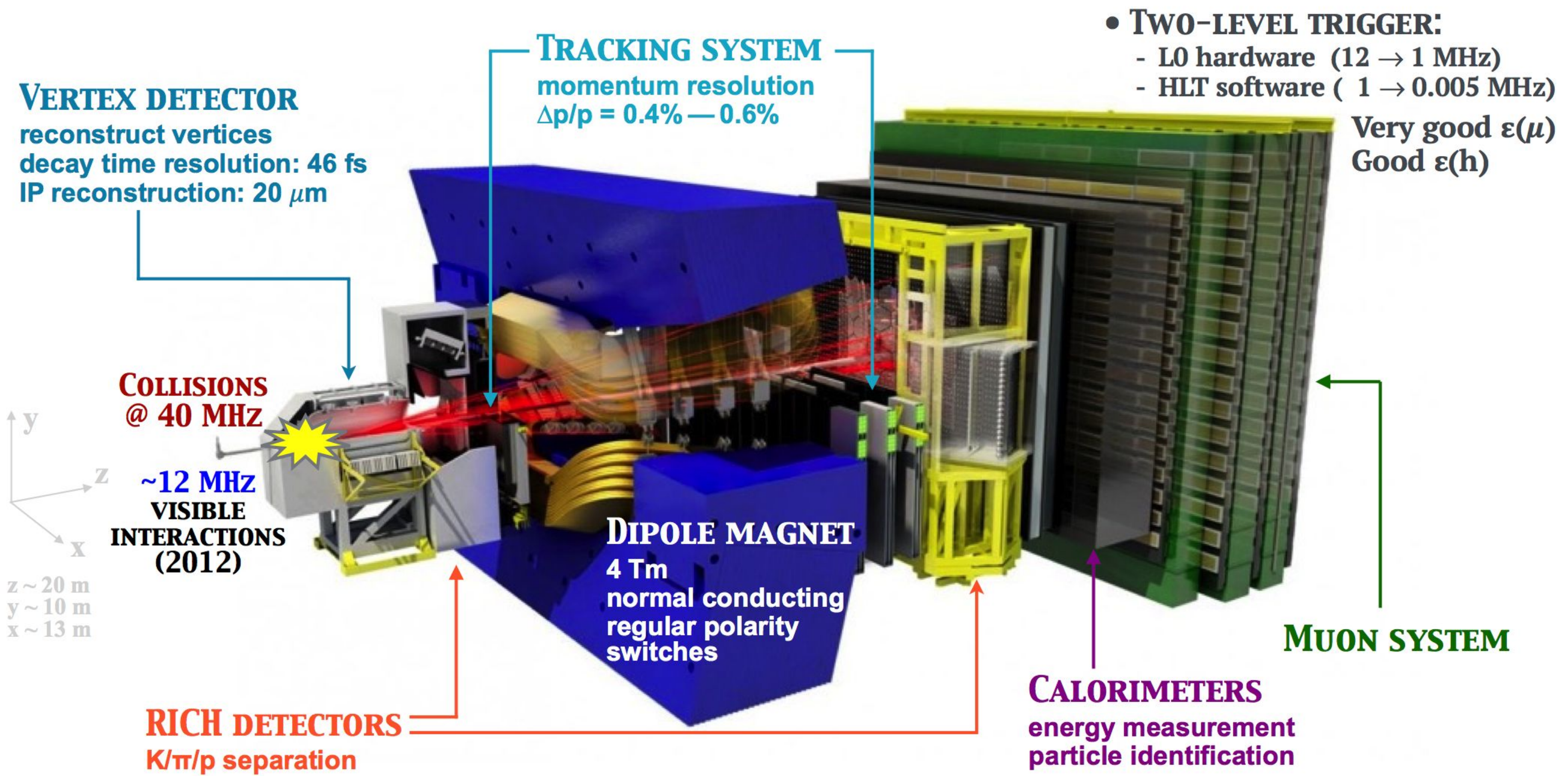
One of the 4 main experiments @ **L**arge **H**adron **C**ollider at CERN



- Initially designed for the study of the **b,c-quarks**
- Now evolved into a general purpose spectrometer in the forward region

The LHCb detector

Single forward-arm spectrometer

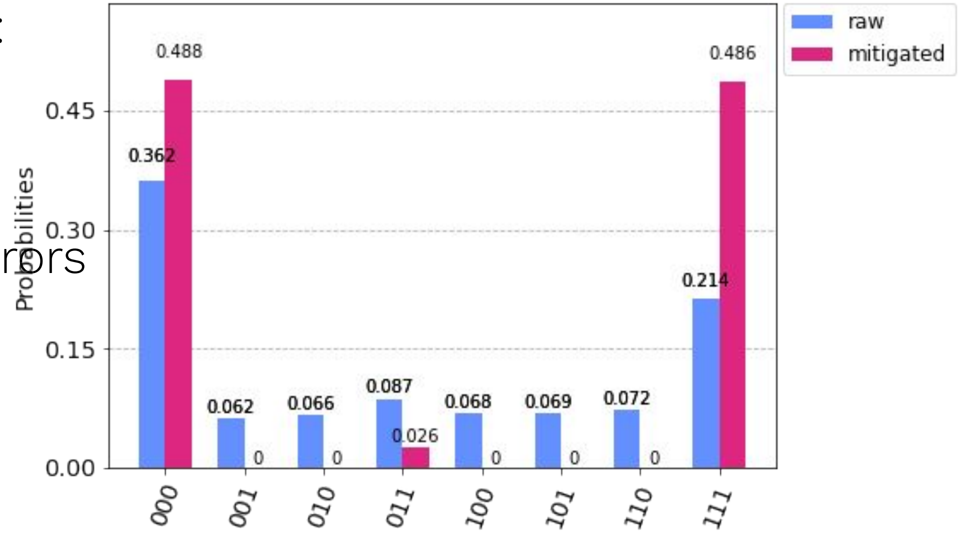


Quantum Computing - Noise

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

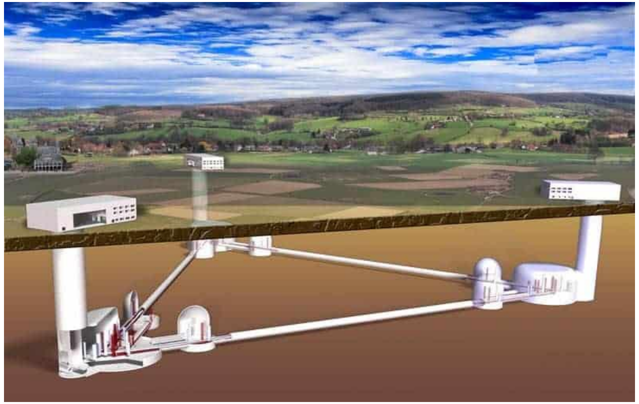
→ *Noise Error Mitigation*



QC & Gravitational Waves

Next generation of GW detectors: increased **bandwidth** and **sensitivity.**
→ new techniques are needed on top classical template matching

Grover search: for template matching.
Theoretical studies ongoing on the feasibility of this for GW detection.



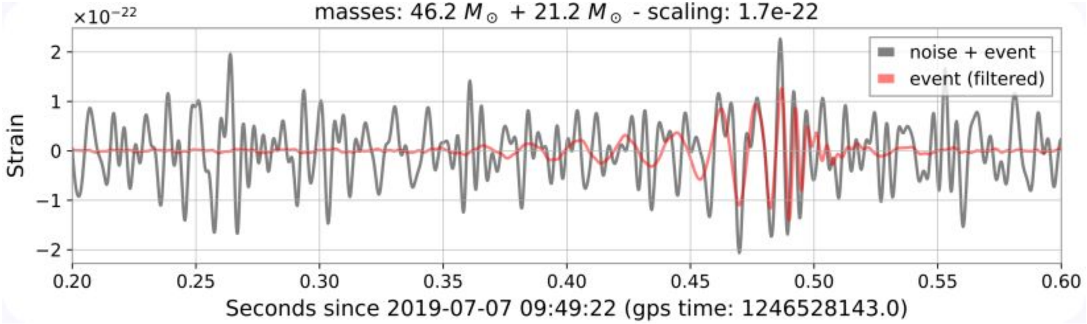
Solving Einstein Field Equations:

- The GW signals need to be calculated by solving the set of non-linear equations of the EFE.
- A proof of principle using the algorithms proposed by [2011.10395] to solve a simplified model has been implemented.

QC & Gravitational Waves

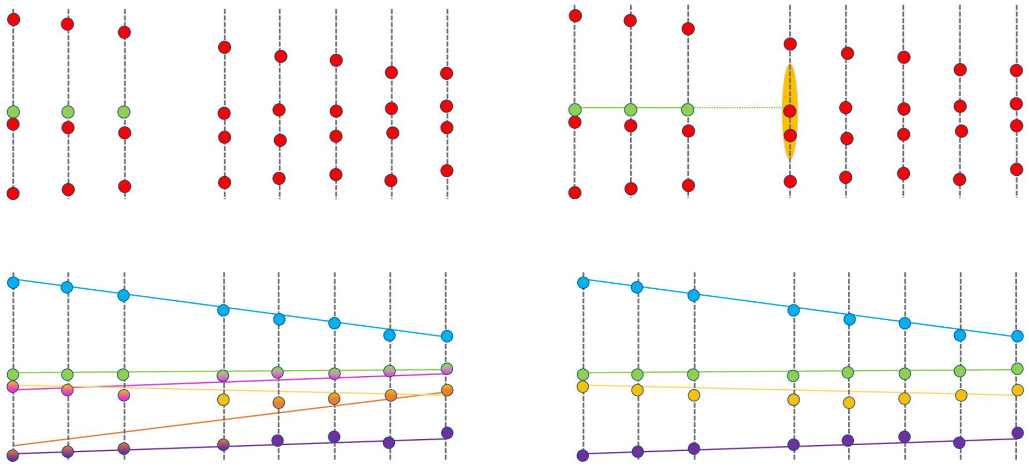
Quantum-enhanced Feature Spaces:

- Data is too noisy and large to be used directly by a QML algorithm.
- The number of events is too small for proper training.
- Real noise samples and a simulated event signal are used asc a *signal database* → a set of time-series features is extracted to create the training dataset.
- **Detection:** kernel method. **Characterisation:** support vector machine.



Local tracking methods [arXiv:2104.11583]

1. Seeding
2. Track building
3. Cleaning
4. Selection



Tracking stages	Input size	Output size	Classical complexity	Quantum complexity
Seeding	$O(n)$	k_{seed}	$O(n^c)$ (Theorem 2)	$\tilde{O}\left(\sqrt{k_{\text{seed}} \cdot n^c}\right)$ (Theorem 3)
Track Building	$k_{\text{seed}} + O(n)$	k_{cand}	$O(k_{\text{seed}} \cdot n)$ (Theorem 4)	$\tilde{O}\left(k_{\text{seed}} \cdot \sqrt{n}\right)$ (Theorem 5)
Cleaning (original)	k_{cand}	$O(k_{\text{cand}})$	$O(k_{\text{cand}}^2)$ (Theorem 6)	–
Cleaning (improved)	k_{cand}	$O(k_{\text{cand}})$	$\tilde{O}(k_{\text{cand}})$ (Theorem 7)	–
Selection	$O(k_{\text{cand}})$	$O(k_{\text{cand}})$	$O(k_{\text{cand}})$ (Theorem 8)	–
Full Reconstruction	n	$O(n^c)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{c+0.5}\right)$ (Theorems 3, 5, 7, 8)
Full Reconstruction with $O(n)$ reconstructed tracks	n	$O(n)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{(c+3)/2}\right)$ (Theorem 9)

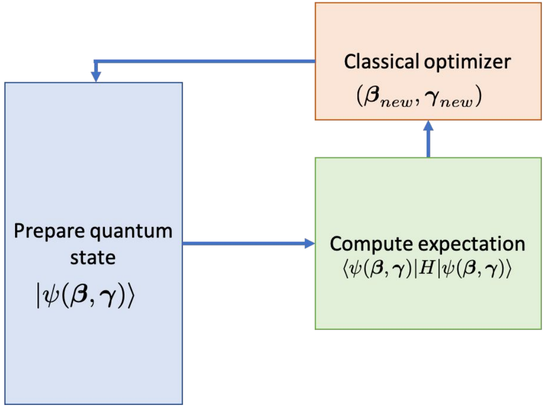
n: number of particles, c: number of hits, k_{seed}: total number of generated seeds, k_{cand}: number of track candidates

QAOA for Track Reconstruction

- Quantum Approximate Optimization Algorithm [arXiv:1411.4028, tutorial]
- A **variational** algorithm ideal to solve combinatorial optimization problems, e.g. Max-Cut problem
  - *'Finding an optimal object out of a finite set of objects'*

$$|\psi(\beta,\gamma)\rangle = U(\beta)U(\gamma)...U(\beta)U(\gamma)\,|\psi_0\rangle$$

$$U(\beta) = e^{-i\beta H_B},\ U(\gamma) = e^{-i\gamma H_P}$$



- H_B: mixing Hamiltonian, H_P: **problem** Hamiltonian
- **Goal:** find optimal parameters **(□$_{opt}$,γ_{opt})** such that the quantum state encodes the solution to the problem

QAOA implementation

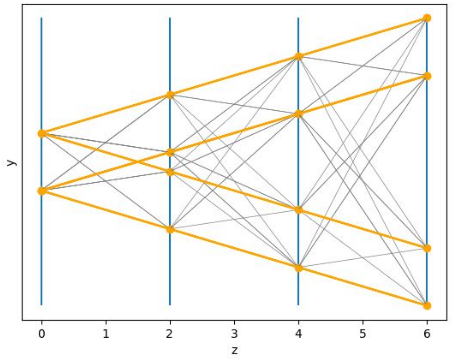
$$\mathcal{H} = -\frac{1}{2}\left[\left(\sum_{a,b,c}\frac{\cos^\lambda(\theta_{abc})}{r_{ab}+r_{bc}}s_{ab}s_{bc}\right) - \alpha\left(\sum_{b\neq c}s_{ab}s_{ac} + \sum_{a\neq c}s_{ab}s_{cb}\right) - \beta\left(\sum_{a,b}s_{ab} - N\right)^2\right]$$

(1) (2) (3)

(1) main term: favours aligned, short segments
(2) 1st penalty term: forbids segments that share head/tail from belonging to the same track
(3) 2nd penalty term: keeps the number of active segments equal to #hits

Results from simulation

- **Successful** implementation and validation for small simulations
- Scalability poses an issue, affecting especially the simulator
  - triplets instead of doublets → worse scalability

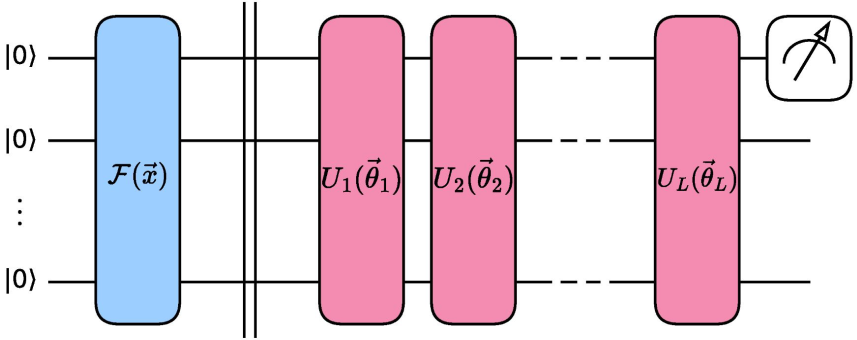


# tracks	# layers	#qubits (segments)	Circuit depth
2	**3**	**8**	**103**
2	**4**	**12**	**223**
3	**3**	**18**	**497**
3	4	27	1105
4	3	32	1553
4	4	48	3473
5	3	50	3775
5	4	75	8463

Entropy studies

Study of the Entropy production within a Variational Quantum Circuit during its training phase:

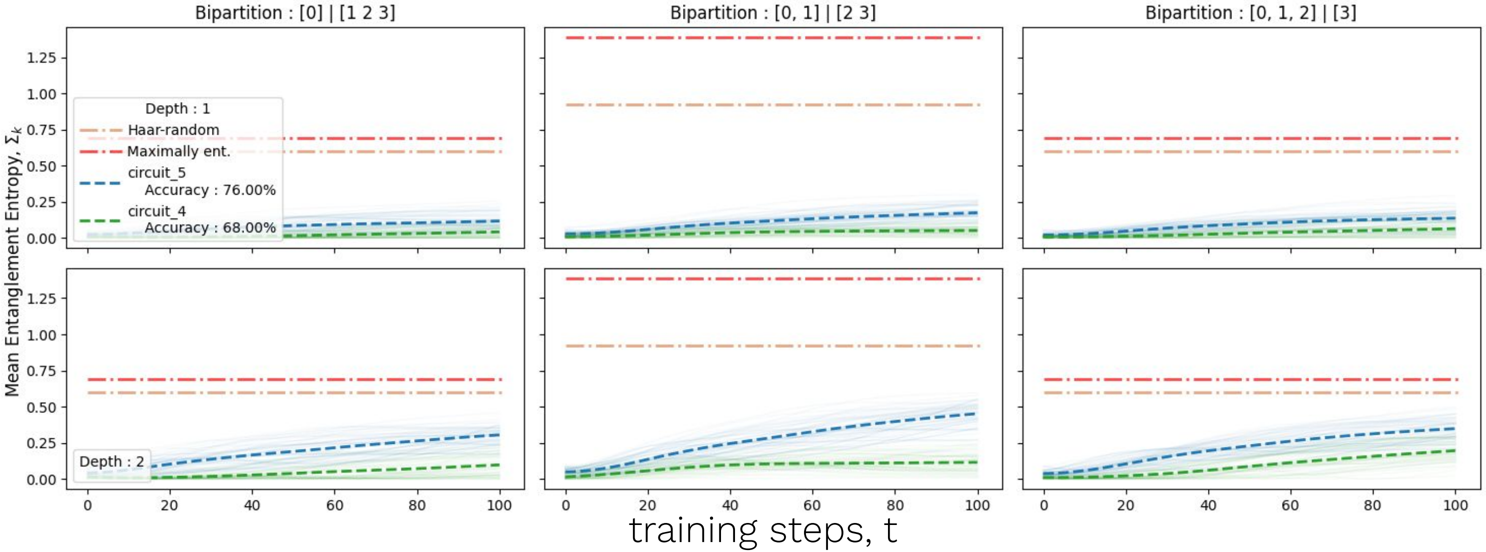
Goal: Use the information of the entropy values to enhance the training performance for the task of jet-tagging (b vs c)



Values of Entropy were inspected

- For each training step “t”
    - At each “depth” of the circuit:
        - depth 0 : $\mathcal{F}(\vec{x})\left|0^{\otimes N}\right\rangle$
        - depth 1 : $U_1(\vec{\theta}_1)\mathcal{F}(\vec{x})\left|0^{\otimes N}\right\rangle$
        - depth L : $U_L(\vec{\theta}_L)...U_1(\vec{\theta}_1)\mathcal{F}(\vec{x})\left|0^{\otimes N}\right\rangle$ (output state)

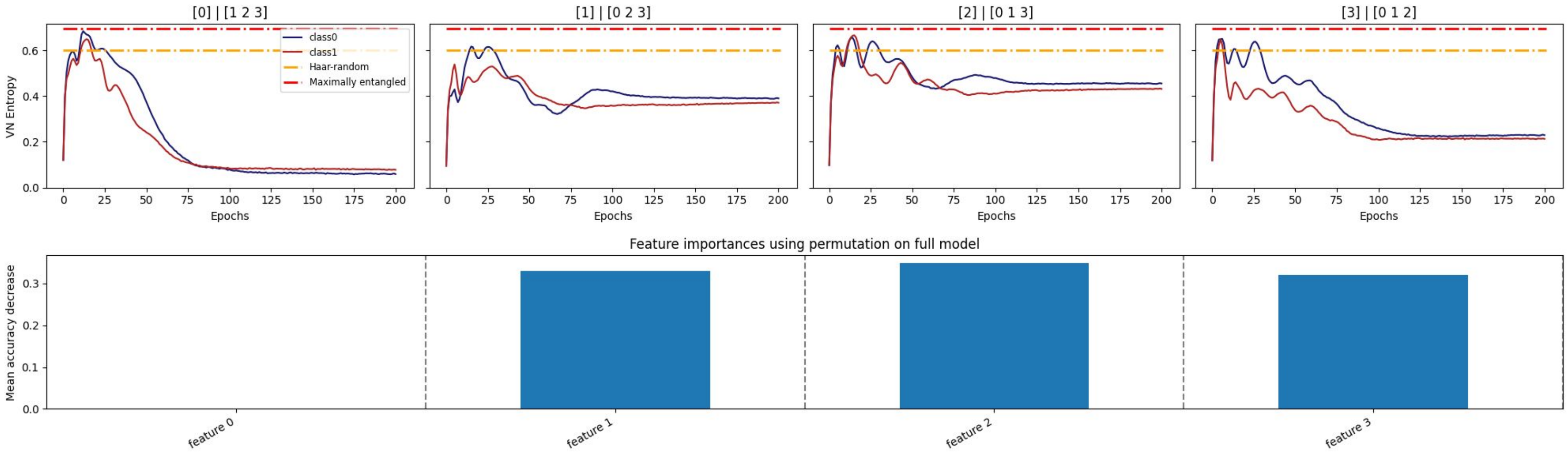
Study of the Entropy production within a Variational Quantum Circuit



- different circuits
- different datasets (b vs c jet-tagging and IRIS)
- different parameters initializations (Gaussian vs Uniform)
- different loss functions

Study of the Entropy production within a Variational Quantum Circuit

Feature importance from Entropy values



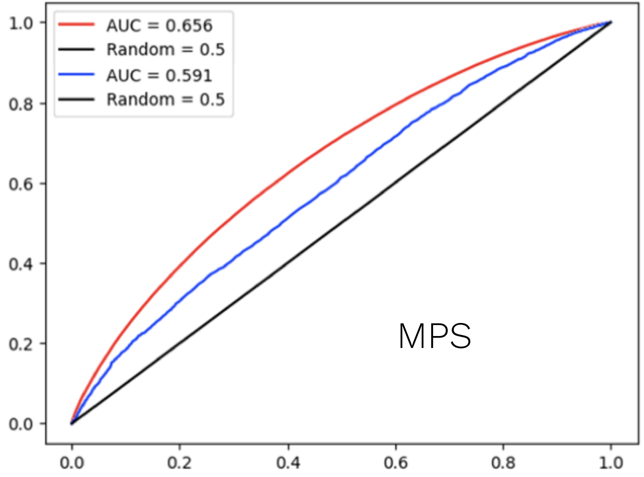
More results coming soon!

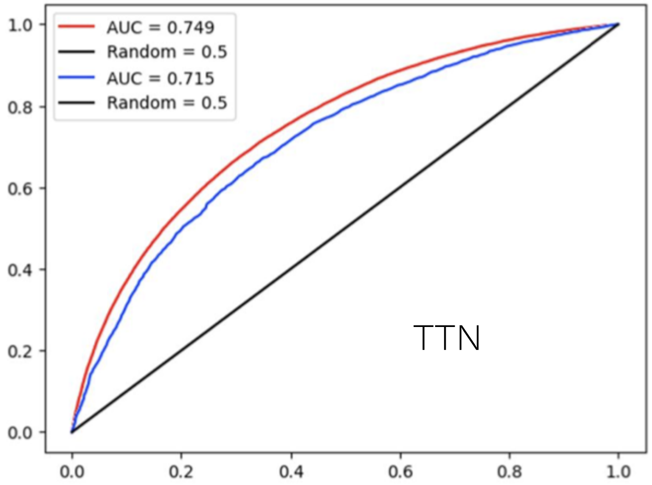
Optimization for hardware

IBM **Quantum**

- Ported from quantum simulations to *real* quantum computers ✅
- Tested and optimised several architectures ✅
  - Different advantages in terms of robustness against ***noise*** from hardware imperfections
- Currently trying *noise error mitigation* techniques 🚧

quantum simulator
quantum hardware





IBM: Qiskit, Xanadu: Pennylane

Tracking problem -> Ising-like Hamiltonian -> minimize Hamiltonian -> happiness

- HHL (Davide)
- QAOA (simulated annealing)
    - Toy simulation [Z, ZZ]
        - Approximated simulators –
        - Pennylane [GPUs] - ongoing
        - Circuit depth: pytket, qiskit transpiler - to be tried
        - Classical counterpart, energy spectrum <H> (local minima, hyperparameters?) - to be tried
        - Circuit cutting/ sub-QUBO: pre-processing, clustering geometrically, KDE - to be tried
    - MC simulation
        - Realistic effects: add curvature, material effects [Bette-Bloch]
    - Performance numbers, timing estimates
    - Comparison with classical algorithm
- Quantum annealing (DWave) - Xenofon
    - Try on hardware
    - Realistic tracks

Related work [arXiv:2210.13021]

Variational Quantum Eigensolver: hybrid quantum-classical algorithm