Progress towards scalable quantum computing for HEP

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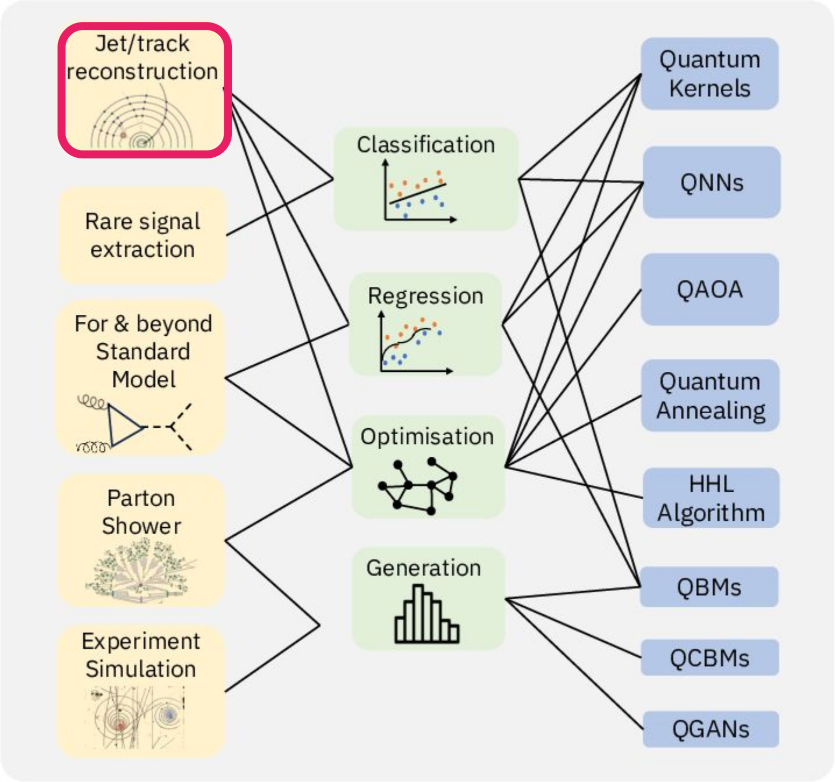
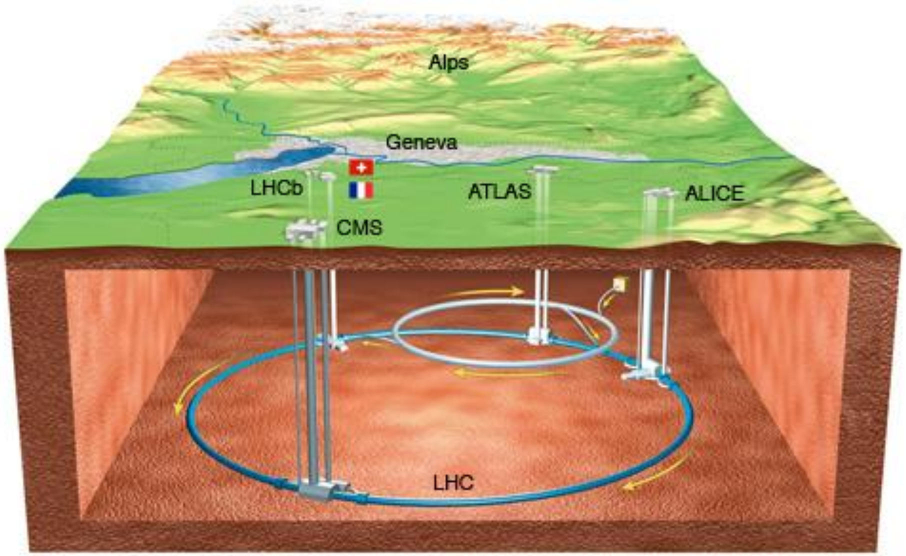
HEP use-cases

- Summary of the QC4HEP WG
- Focused mostly in projects concerning experimental particle physics at LHC and LHCb
- (LHC) Events are **quantum** in nature, but measurements are **classical**



The LHCb detector

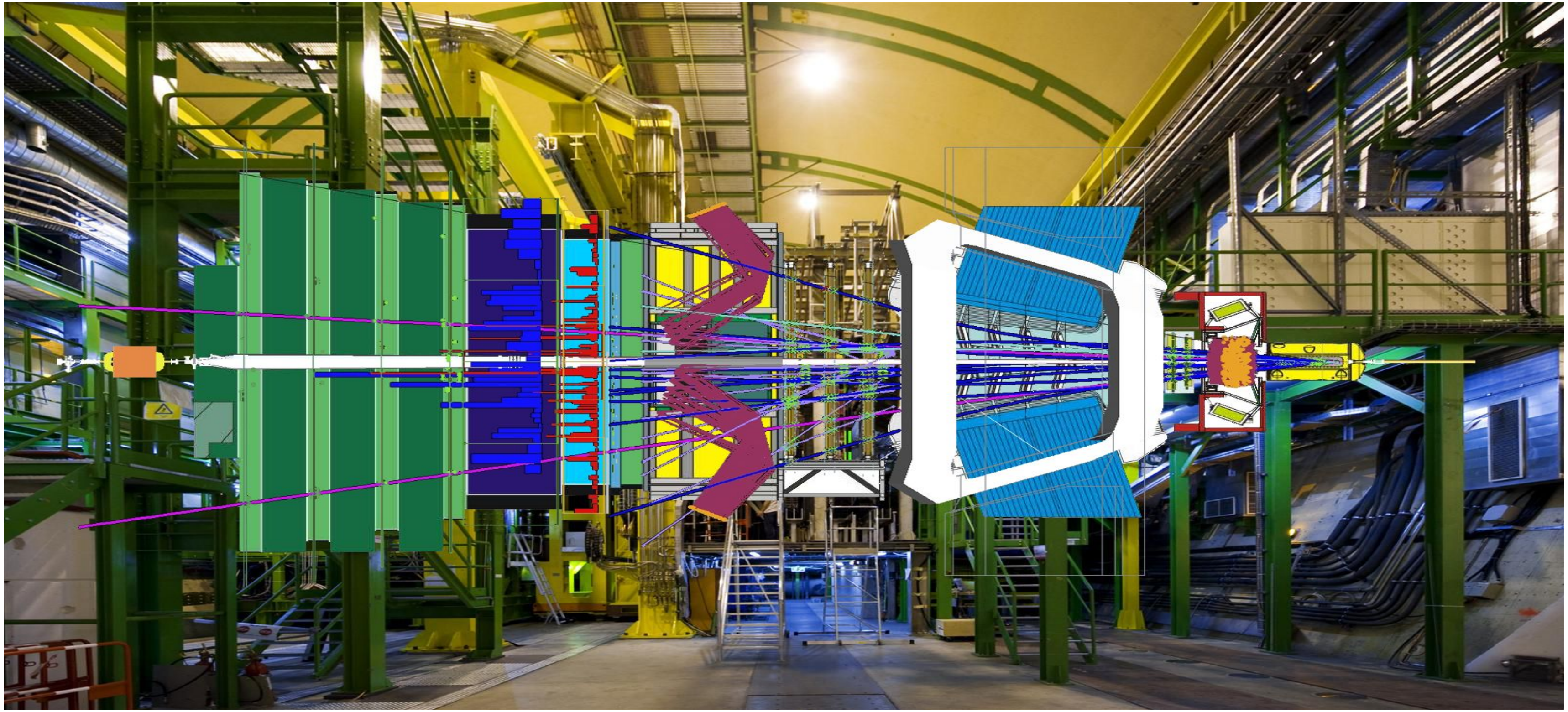
One of the 4 main experiments @ **L**arge **H**adron **C**ollider at CERN



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

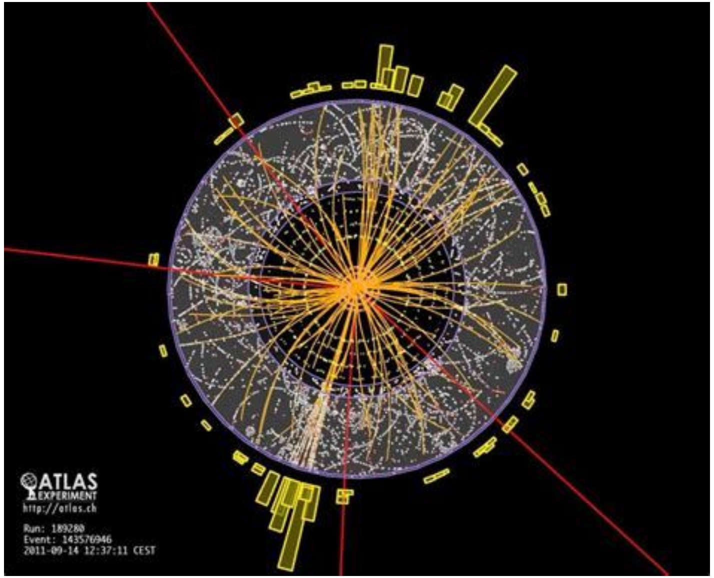
How does an event look like?

Reconstruct events **40 Million times per second**.



Track reconstruction

- Recover the original trajectories from signals left by charged particles
  - signals → 3D points or hits
  - need efficient distinction between the combinations of hits that are of interest and those that aren't
- Typical event: large number of tracks, modelled by a collection of segments

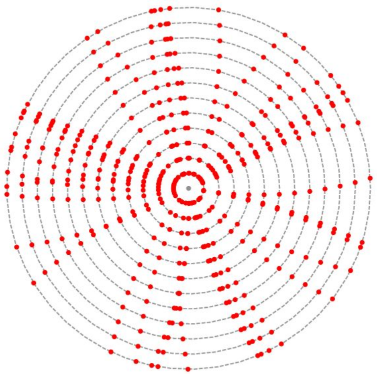


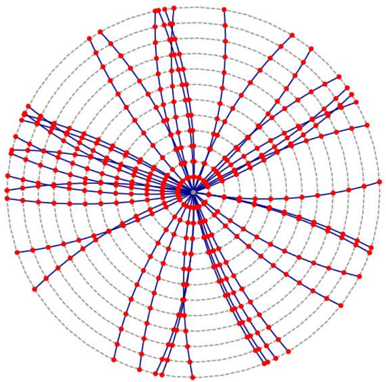
Track Reconstruction

- **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

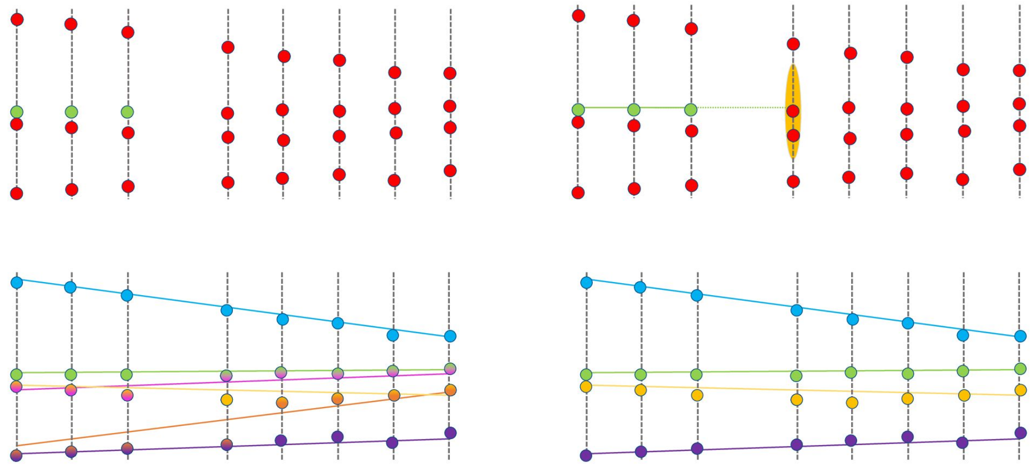
→ Focus of this talk: *global* algorithms





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)	$\tilde{O}(\sqrt{k_{\text{seed}} \cdot n^c})$ (Theorem 3)
Track Building	$k_{\text{seed}} + O(n)$	k_{cand}	$O(k_{\text{seed}} \cdot n)$ (Theorem 4)	$\tilde{O}(k_{\text{seed}} \cdot \sqrt{n})$ (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	$O(n^c)$	$O(n^{c+1})$ (Theorems 2, 4, 7, 8)	$\tilde{O}(n^{c+0.5})$ (Theorems 3, 5, 7, 8)
Full Reconstruction with $O(n)$ reconstructed tracks	n	$O(n)$	$O(n^{c+1})$ (Theorems 2, 4, 7, 8)	$\tilde{O}(n^{(c+3)/2})$ (Theorem 9)

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

QC for Track Reconstruction

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

QC for Track Reconstruction

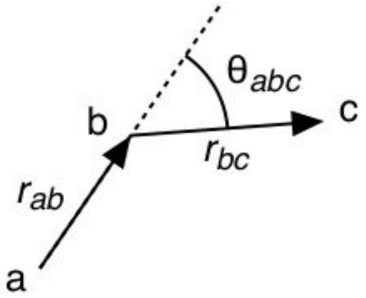
Ising-like Hamiltonian:

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

Segment [S_{ab}]: combination of hit *a* and hit *b*

→ in consecutive layers - for now

Hamiltonian accounts for **all** possible segments

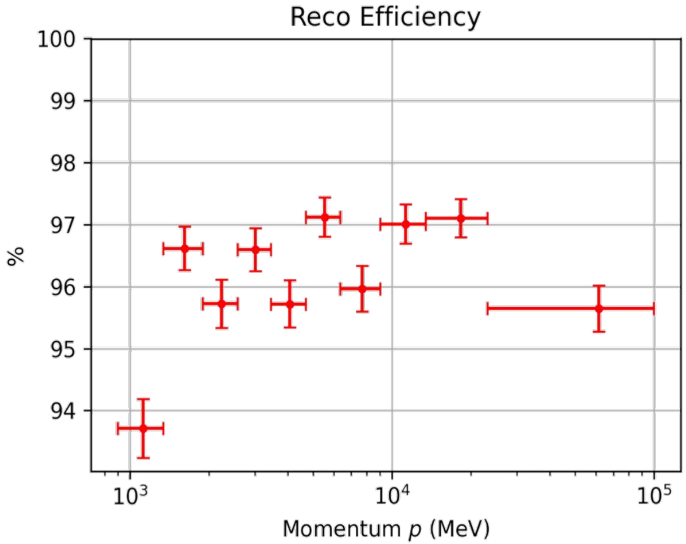


(Some) related results

[*JINST* 18 (2023) 11, P11028]

[HHL algorithm]

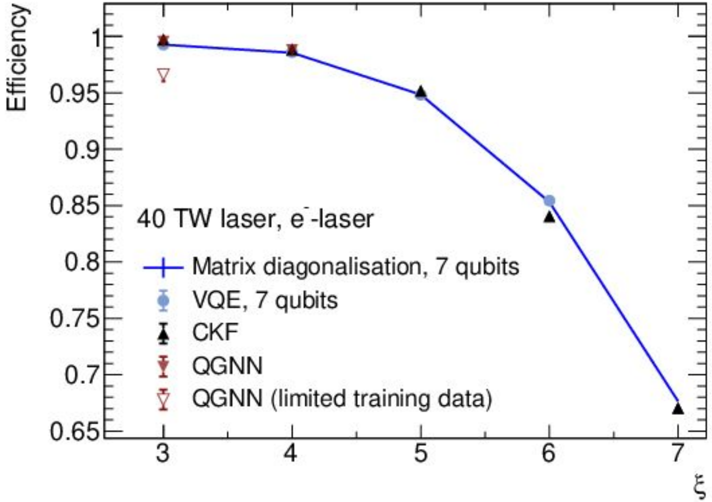
$$\nabla \mathcal{H} = 0 \Rightarrow A\mathbf{S} = \mathbf{b}$$



[*Comput.Softw.Big Sci.* 7 (2023) 1, 14]

[Variational Quantum Eigensolver]

LUXE



QAOA implementation

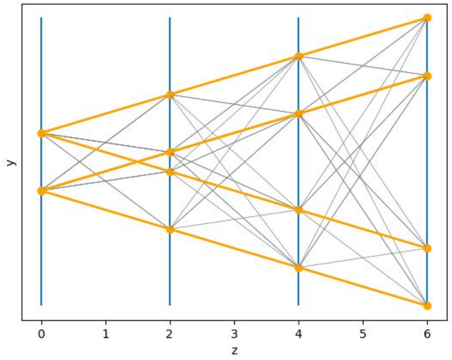
$$\mathcal{H} = -\frac{1}{2}\left[\left(\sum_{a,b,c}\frac{\cos^{\lambda}(\theta_{abc})}{r_{ab}+r_{bc}}s_{ab}s_{bc}\right) - \alpha\left(\sum_{b\neq c}s_{ab}s_{ac} + \sum_{a\neq c}s_{ab}s_{cb}\right) - \beta\left(\sum_{a,b}s_{ab} - N\right)^{2}\right]$$

(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

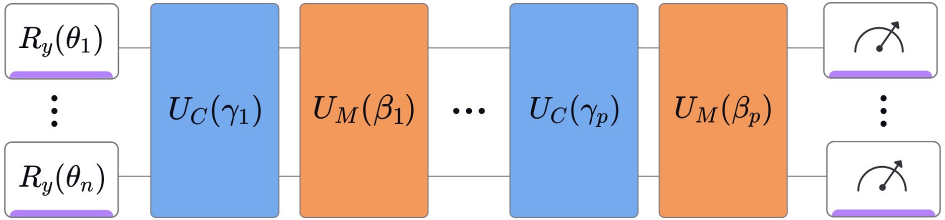
- **Successful** implementation and validation for small simulations
- Scalability poses an issue, affecting especially the simulator
    - triplets instead of doublets → worse scalability



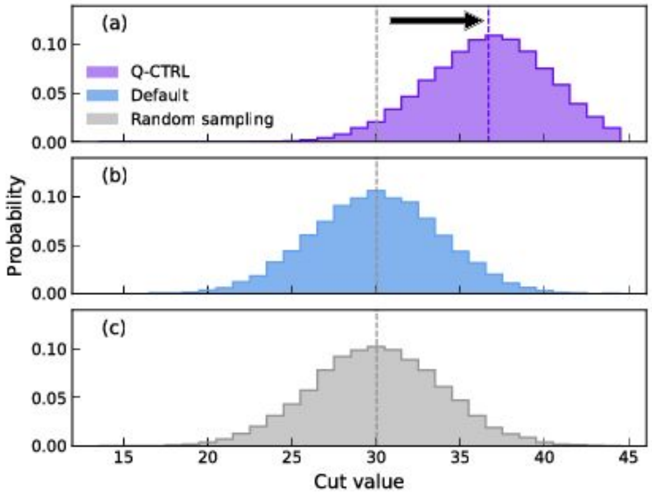
# tracks	# layers	#qubits (segments)	Circuit depth
2	**3**	**8**	**103**
2	**4**	**12**	**223**
3	**3**	**18**	**497**
3	4	27	1105
4	3	32	1553
4	4	48	3473
5	3	50	3775
5	4	75	8463

Modified QAOA (with P. Pariente, V. Chobanova, IFIC-UdC)

Using results from Q-CTRL and IBM [arXiv:2406.01743v1]

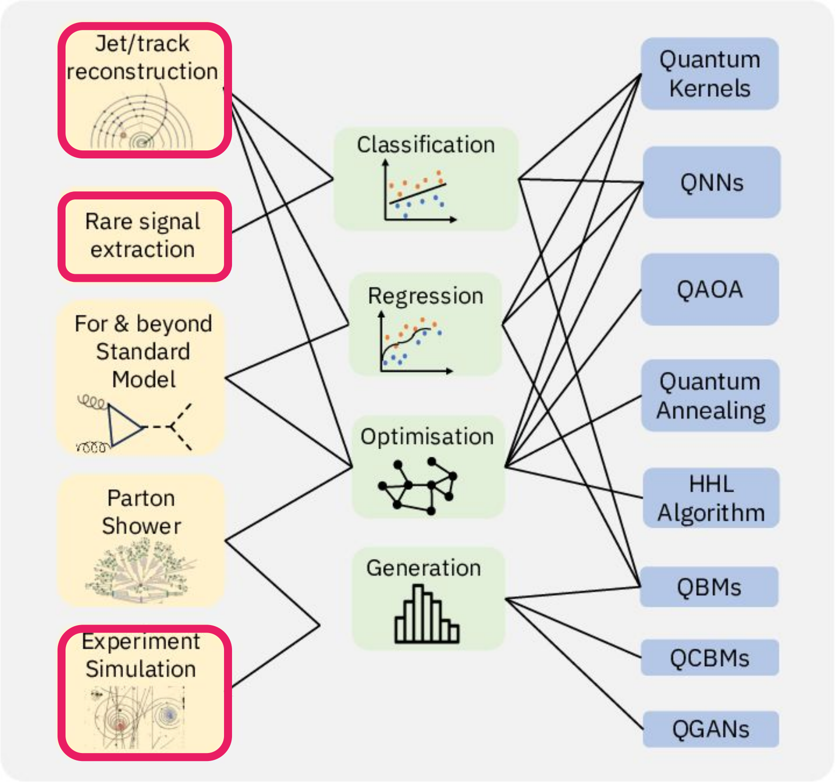


→ pdf of finding the correct solution seems to decrease



Ongoing/future work

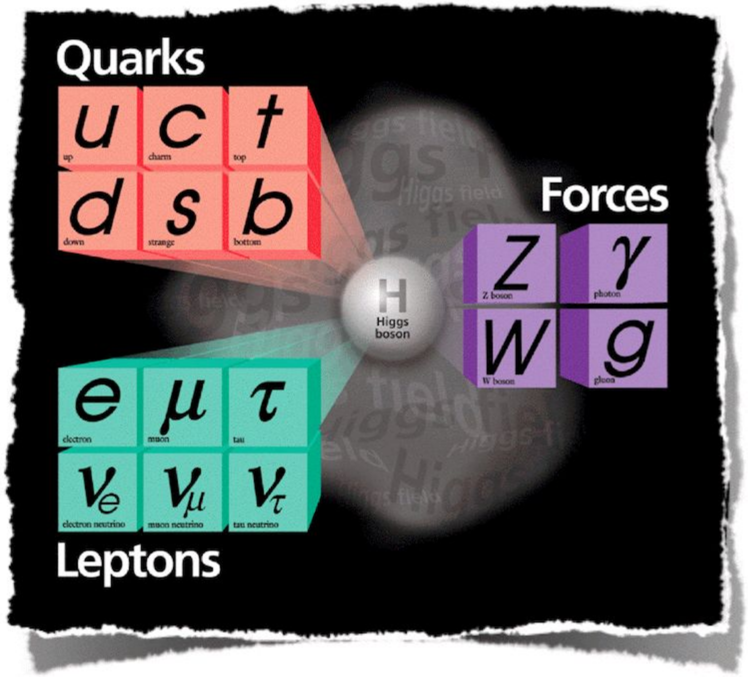
- Sustainability & Quantum: project with **GSoC & IFIC-UV**
    - Using ACTS as framework
    - Comparison in terms of computational complexity Quantum and Classical
- Try simulation using **Rydberg atoms, encoding**
- **Distributed** QAOA (OakRidge)
- Further applications of QAOA for HEP with better scalability and/or different use-cases



Thanks for your attention!

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!!

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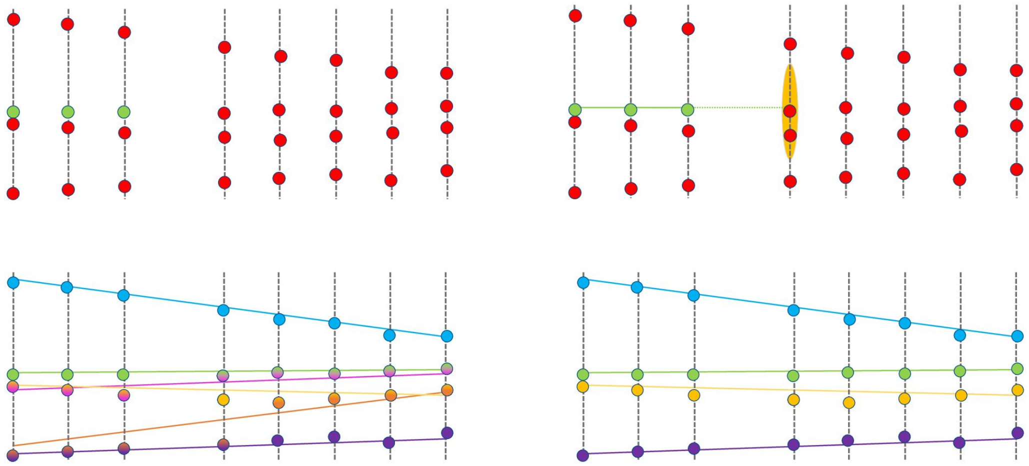
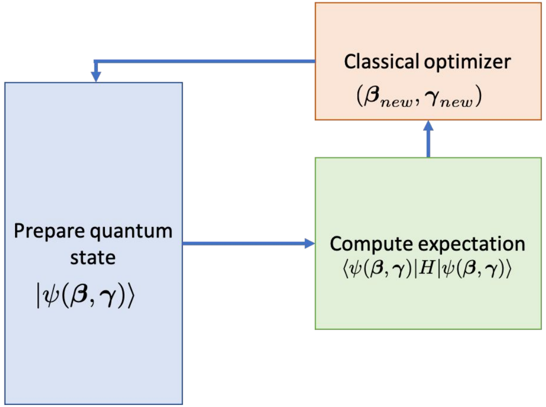


QAOA for Track Reconstruction

- 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 **$(\square_{opt},\gamma_{opt})$** such that the quantum state encodes the solution to the problem

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Modified QAOA (with P. Pariente, V. Chobanova, IFIC-UdC)

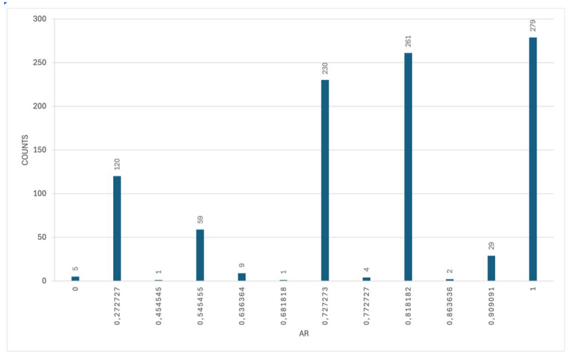
Approximation Ratio

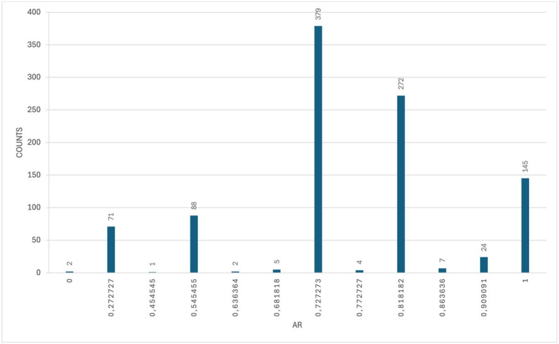
$$AR(\vec{x}) = \frac{C(\vec{x}) - C_{max}}{C_{min} - C_{max}}$$

Success Probability

$$SP = \frac{\text{Nr. Optimal solutions}}{\text{Nr. shots}}$$

- ★ Higher depth → higher clustering around AR > 0.7 for standard and modified QAOA
- ★ Modified QAOA has less occurrences with low AR, but also less at the exact solution

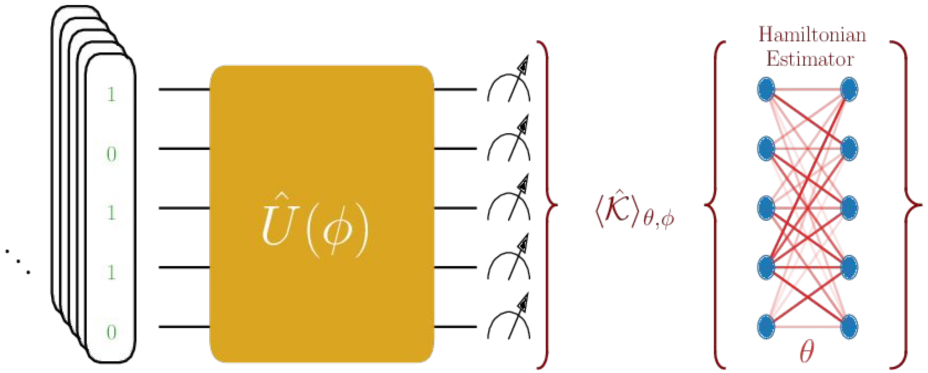




Another possible idea

‘Quantum-probabilistic Hamiltonian learning for generative modelling & anomaly detection’ [arXiv:2211.003803v2]

- Using LHC data & following a Quantum Hamiltonian-Based Models (QHBM) approach
- Generative modelling
- Anomaly detection



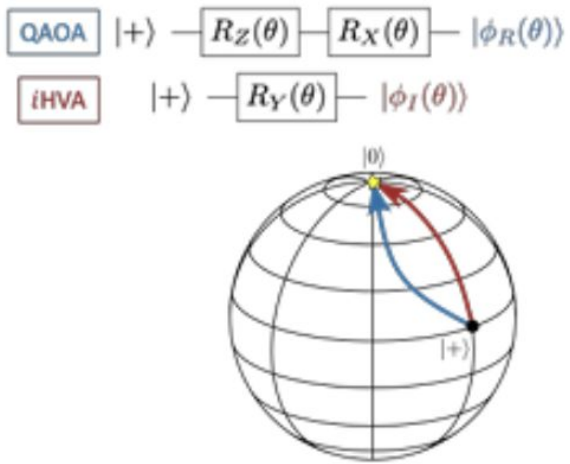
Recent progress QC4HEP-ex

iHVA (C. Tüysüz et al., DESY)

- QITE-inspired
- Avoid Barren Plateaus from QAOA
- Not unique set of gates possible
- Geodesics for parametrized quantum circuits also considered by people at IFIC

[arXiv:2408.09083, Presentation at QC4HEP]

Target Hamiltonian: $-Z$



The iHVA follows the geodesic.
This leads to faster convergence.