Designing VQE ansatz circuits for track reconstruction at LUXE

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LUXE

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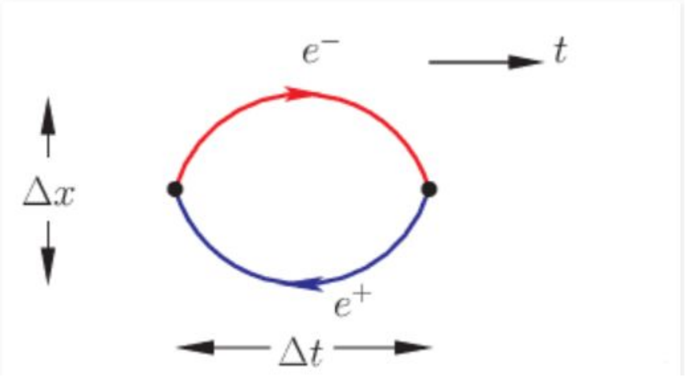
HELMHOLTZ

LUXE - Laser und XFEL Experiment I

Goals and theoretical background

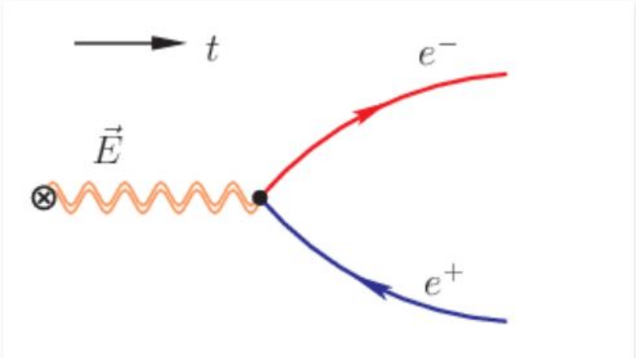
- Investigate transition into the non-perturbative regime of QED
- Search for new BSM particles coupled to photons
- Perturbative regime of QED very well known and tested
- Investigating phenomena starting above the *Schwinger Limit* ~ 10^{18} V/m

$$\Delta t \sim \frac{h}{2m_e c^2} \simeq 10^{-21}\,\mathrm{s}, \quad \Delta x \sim \frac{h}{2m_e c} \simeq 10^{-12}\,\mathrm{m}.$$

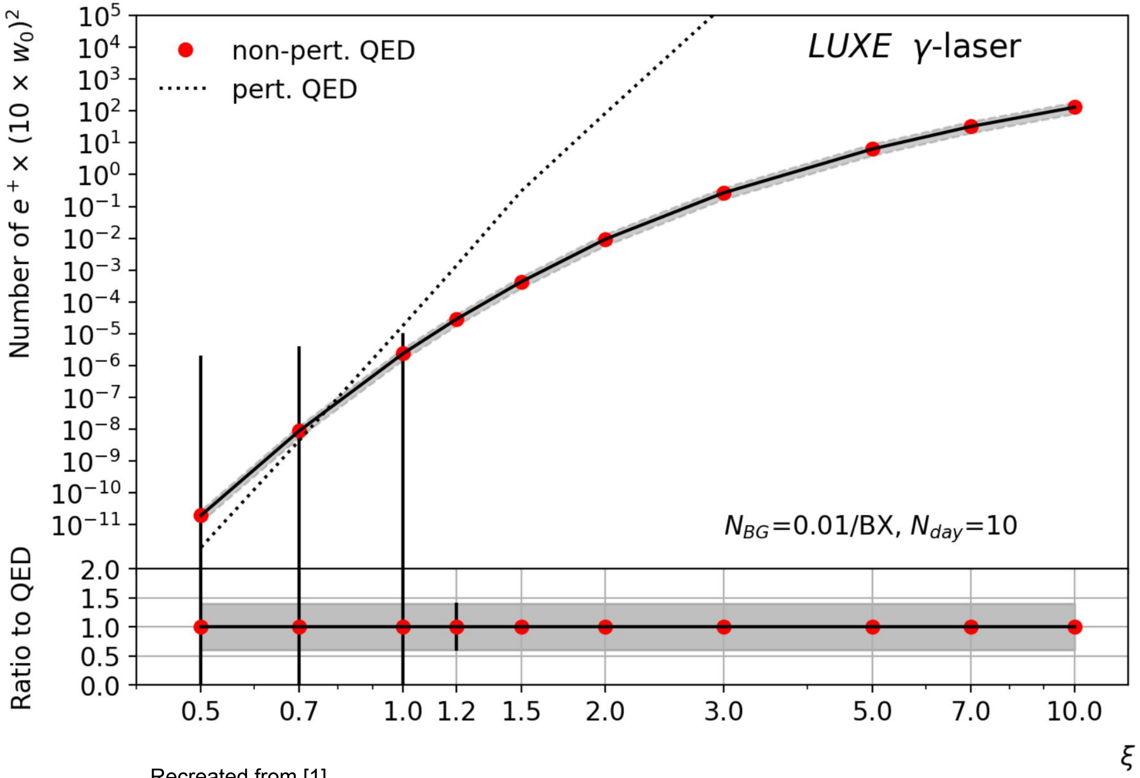


[2]

$$\mathscr{E}_{\mathrm{cr}} \triangleq \frac{2m_e c^3}{e\hbar} \simeq 10^{18}\,\mathrm{V/m}.$$



[2]



Recreated from [1]

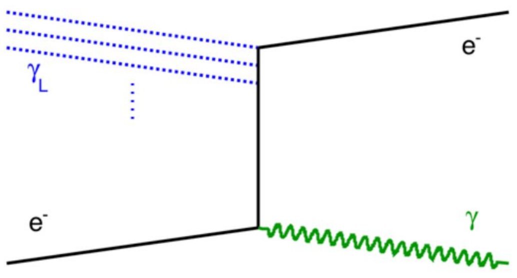
$$\xi = \frac{m_e}{\omega_L}\frac{\mathscr{E}_{\mathrm{L}}}{\mathscr{E}_{\mathrm{cr}}}$$

LUXE - Laser und XFEL Experiment II

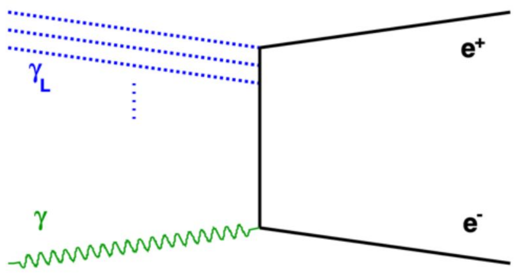
LUXE CDR: https://arxiv.org/abs/2102.02032

Goals and theoretical background

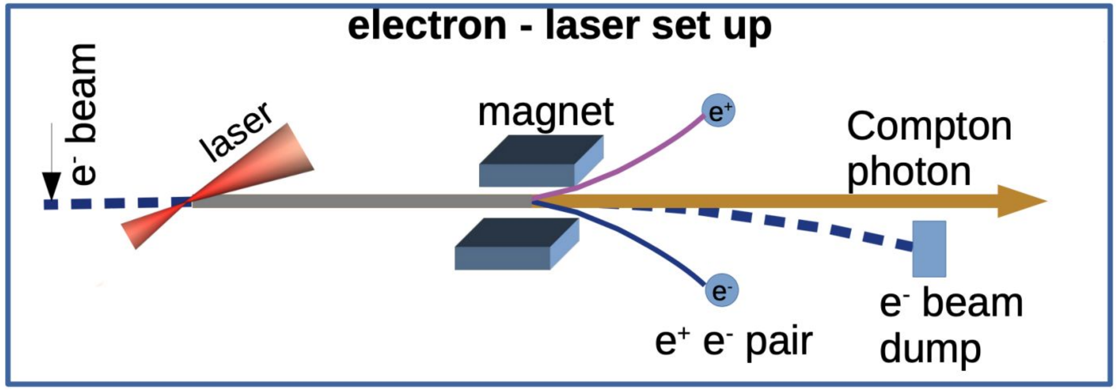
- 16.5 GeV e^- - beam from XFEL or a converted gamma beam crossed with a powerful laser (up to 350 TW) respectively
- Measuring Compton process in electron-laser interactions
- Measuring positron rate in electron- and photon-laser interactions

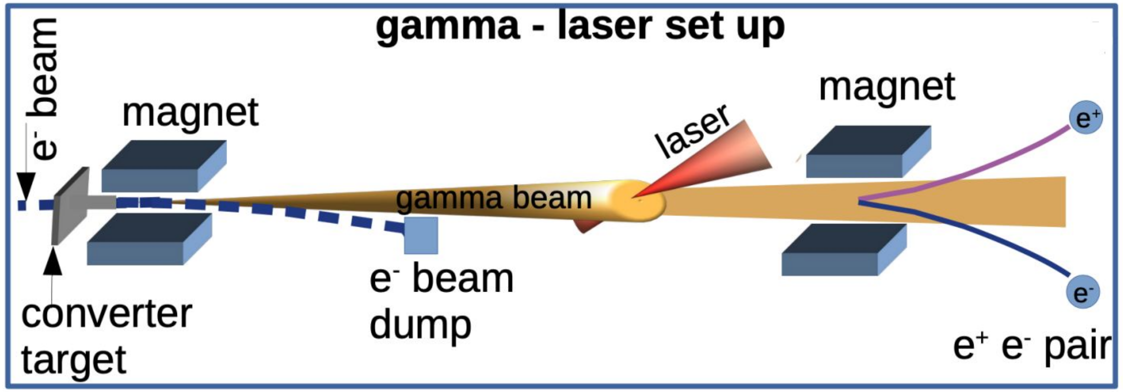


non-linear Compton scattering



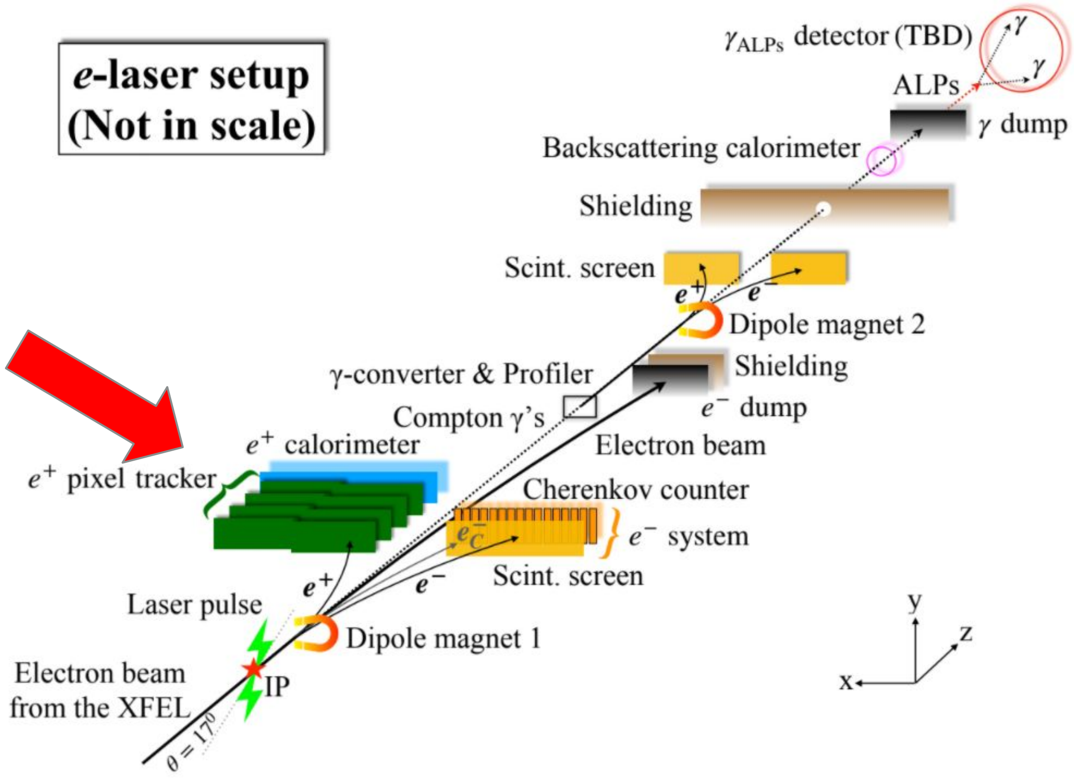
Breit-Wheeler pair production





LUXE positron tracking system I

Silicon pixel tracker



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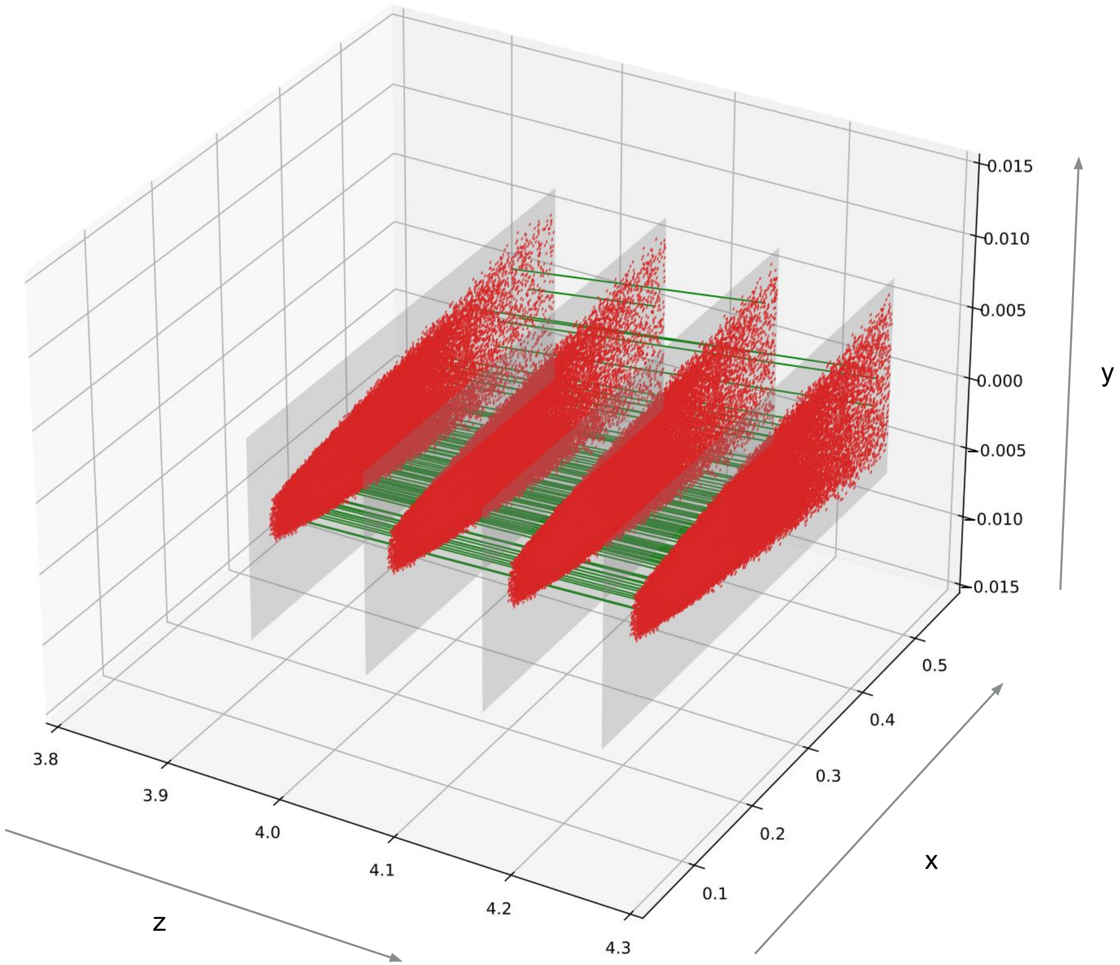
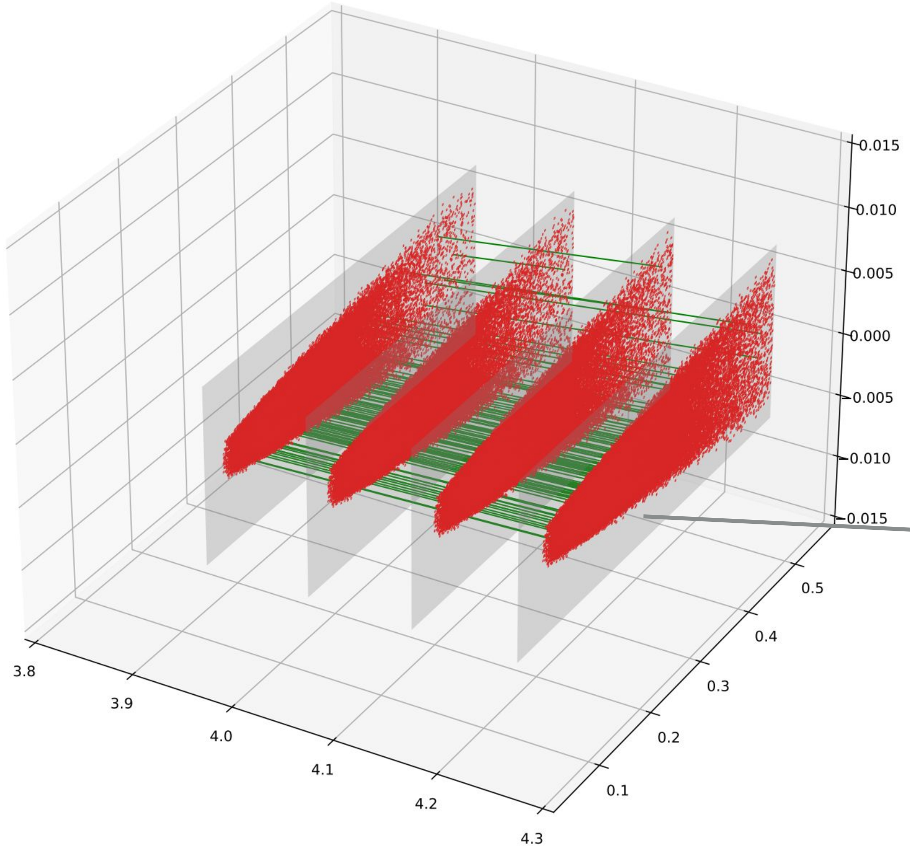


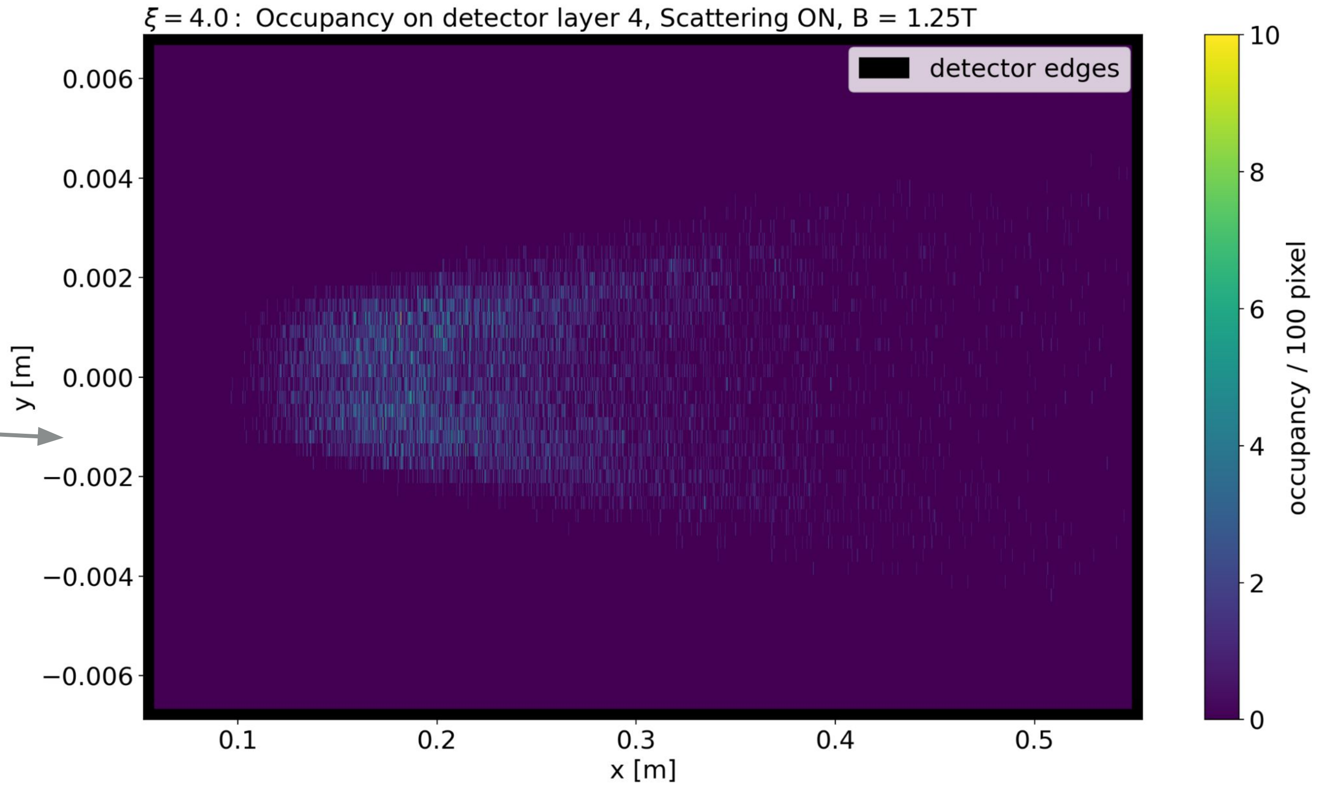
- Based on ALPIDE silicon pixel sensor, 27 x 29 μm² pixels on 30 x 15 mm² chips, 9 chips on each stave
- Simplified simulation to study track reconstruction

LUXE positron tracking system II

Detector occupancy

- 10^{-3} - 10^{6} positrons / BX expected
- low occupancy required to reconstruct tracks





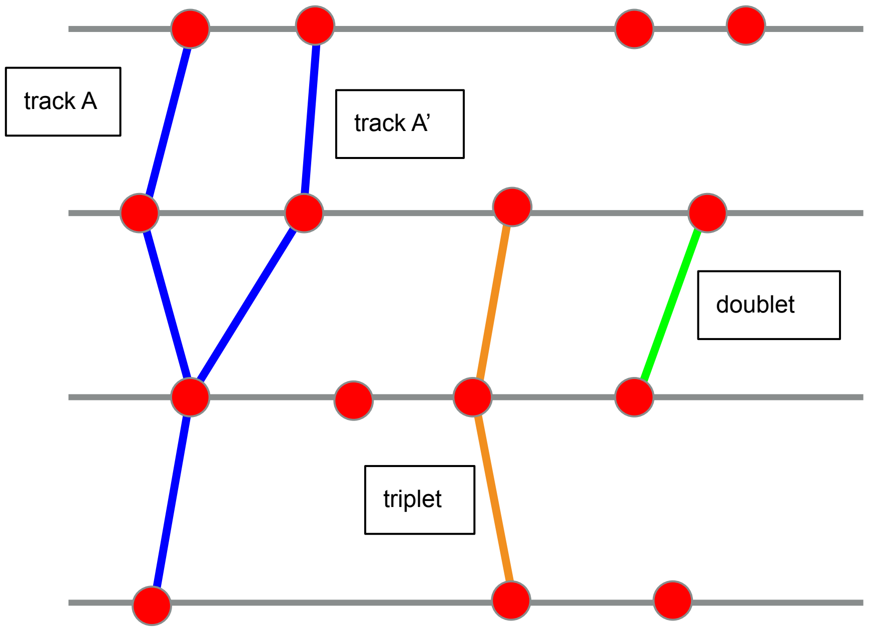
Track reconstruction technique

Forming tracks by connecting hits of consecutive layers

- Doublets → triplets → track
- Triplets as (part of) track candidates
- Binary value assigned to track candidates:
  1 → keep
  0 → discard
  result is a sequence, e.g 01100101001….

- Problem: 100 particles lead to 10^8 triplets

- Apply angle- and position-based preselection before :
  800 particles → 5k doublets → 2700 triplets



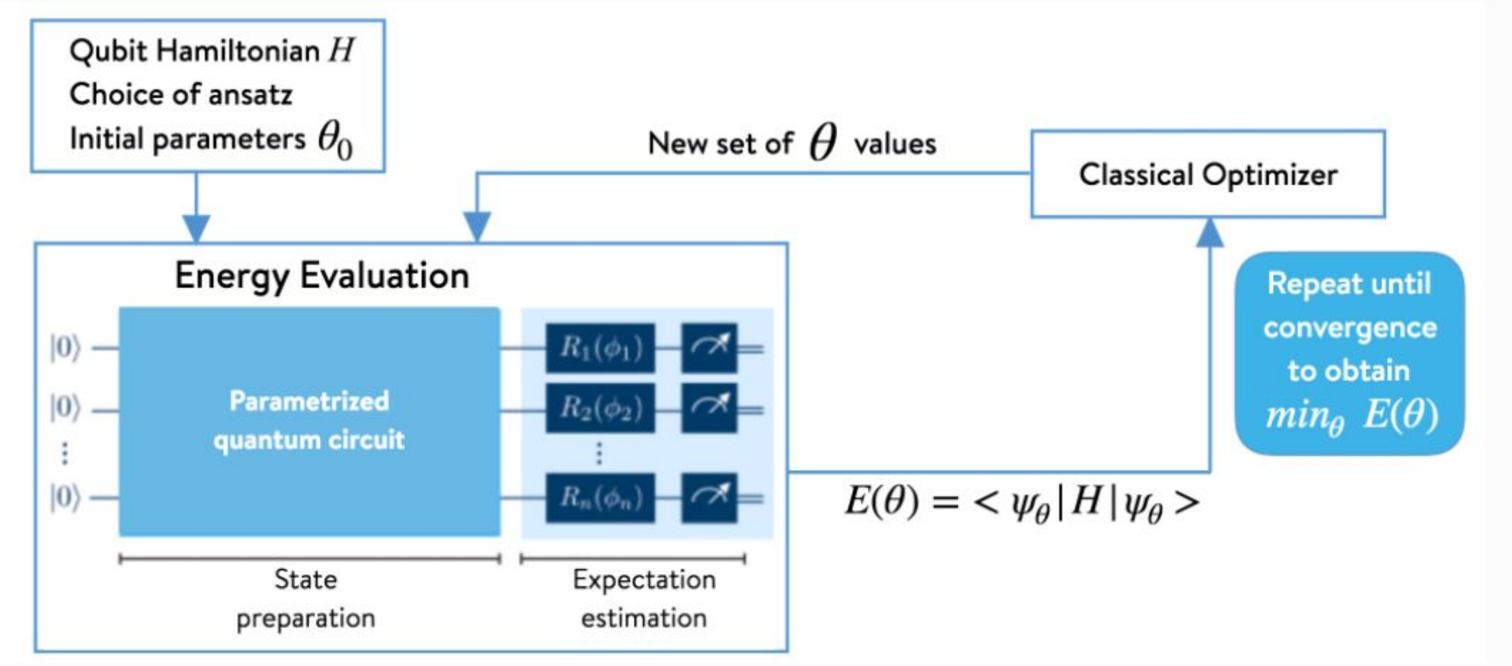
Variational Quantum Eigensolver (VQE)

Overview

- The variational method: Optimizing an upper bound for the lowest possible expectation value with respect to the trial wave function
- Find a parametrization of ψ such that the expectation value of the Hamiltonian is minimized
  → find approximation to the eigenvector ψ of Ĥ to the lowest eigenvalue
- Define an “ansatz” - wavefunction, implemented as a series of quantum gates

$$E_0 \leqslant \frac{\langle\psi|\,\hat{H}\,|\psi\rangle}{\langle\psi|\psi\rangle}$$

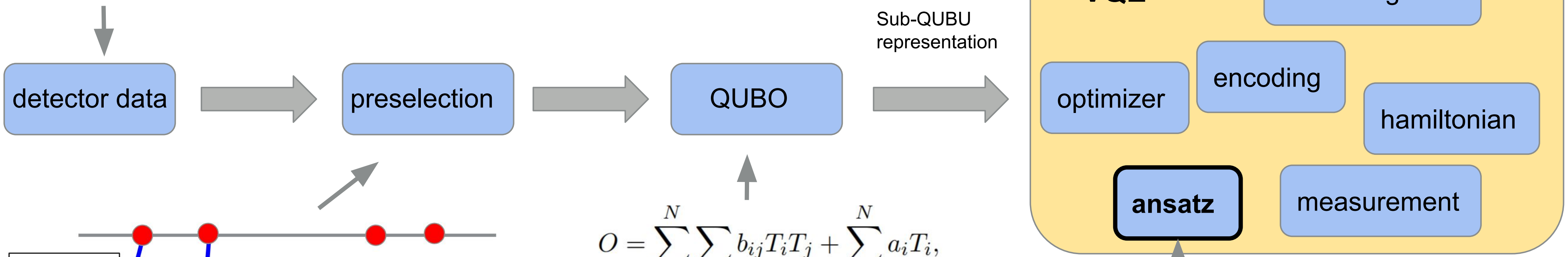
$$E_{\mathrm{VQE}} = \min_{\theta} \langle \mathbf{0}|\, U^{\dagger}(\theta)\hat{H}U(\theta)\,|\mathbf{0}\rangle$$

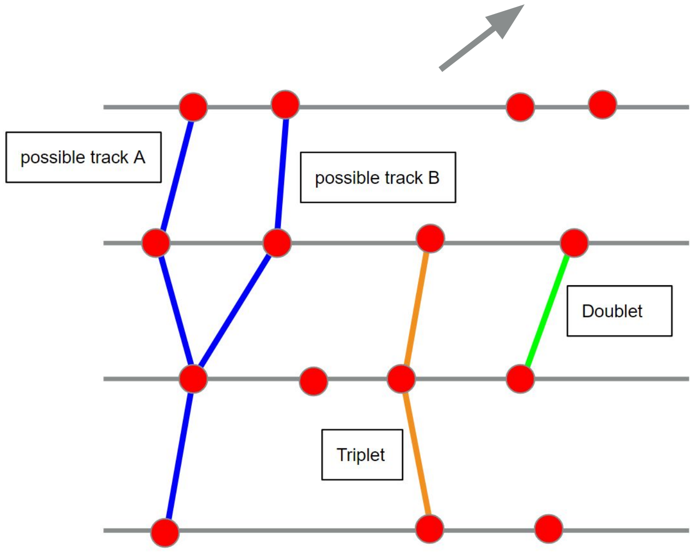


Track reconstruction workflow

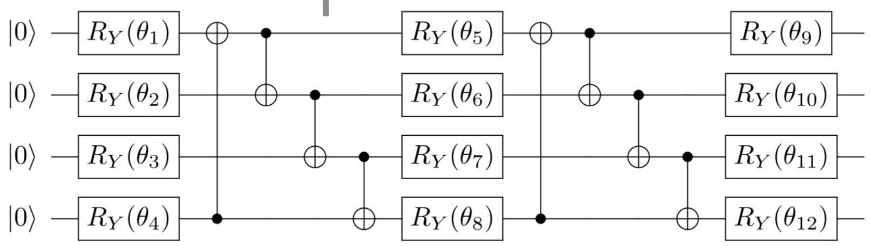
From data to track candidates

```
hit ID,x,y,z,layer ID,particle ID,particle energy
170,0.08803972966412998,-0.0008457822918929373,3.9560125,Plane 0,176,9993.59361866612
1453,0.09536578421939426,0.0002245677005404418,3.9560125,Plane 0,1490,9384.04494709521
1503,0.09305266093825634,-0.00032197814996196065,3.9560125,Plane 0,1541,9556.05485089185
1932,0.09616302090548992,0.0005395204647154564,3.9560125,Plane 0,1974,9264.120974413067
2135,0.0926626692659236,0.0007192040444779721,3.9560125,Plane 0,2184,9728.57071635576
2584,0.09392905408334201,0.00042446342315809453,3.9560125,Plane 0,2644,9461.153921583247
2660,0.0927978643386296,-0.002025577178921603,3.9560125,Plane 0,2721,9585.634111562935
```





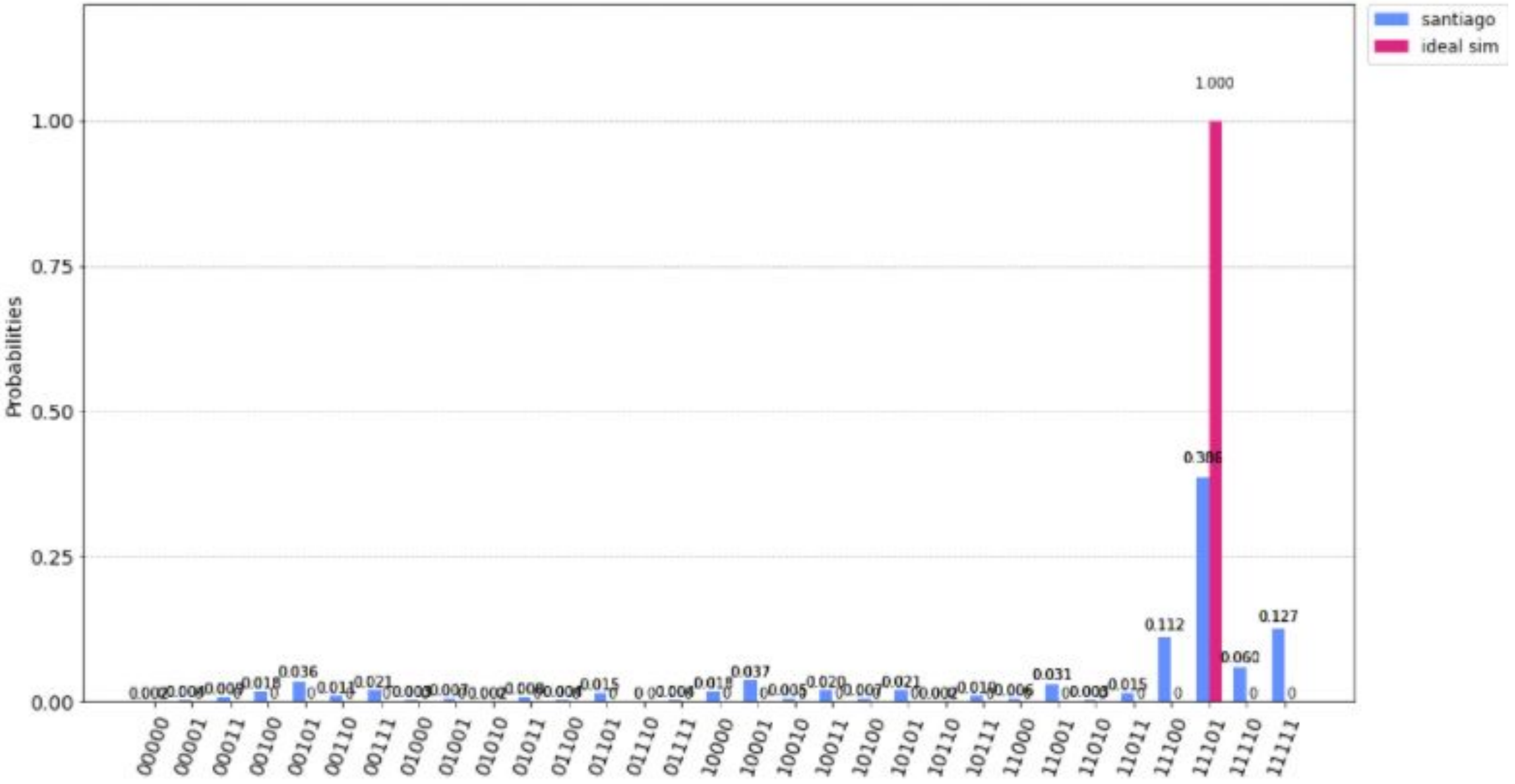
$$O = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i,$$



Designing a quantum circuit I

Noise and errors

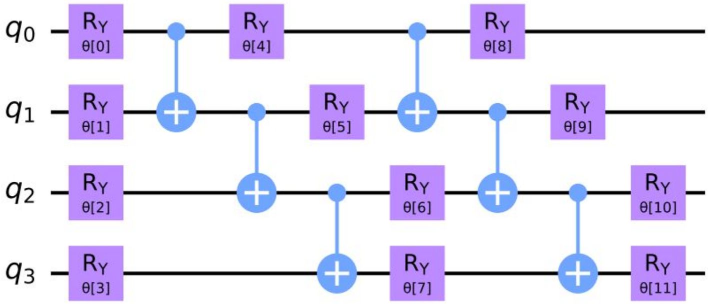
- Circuit depth, number of gates, particular the number of entanglements have a high influence on the outcome of a measurement on a real quantum device
- Optimization of these parameters crucial, especially in the NISQ era



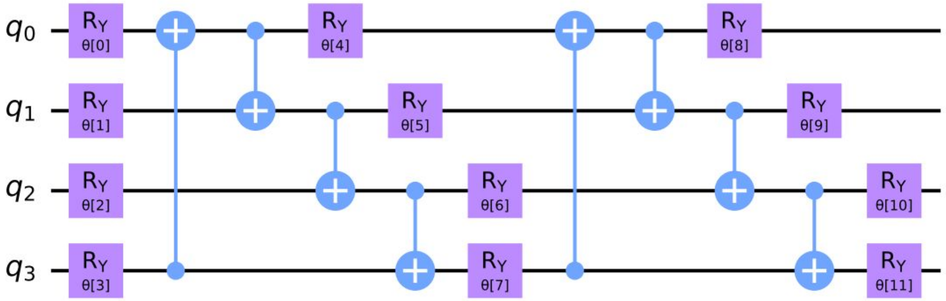
Designing a Quantum Circuit II

Two Local configurations as benchmarks

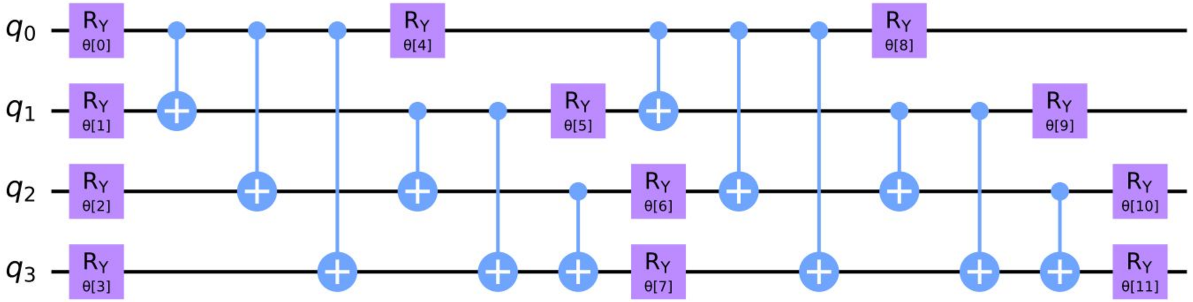
- Direct entanglements **only** possible if qubits on devices are connected, otherwise, one has to propagate values through the circuit
- Error rates of qubits and gates vary



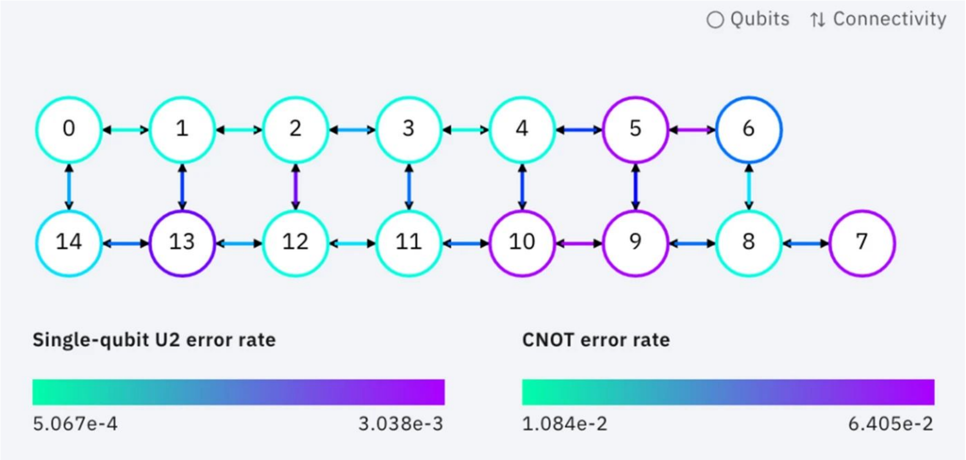
linear entanglement



circular entanglement



full entanglement



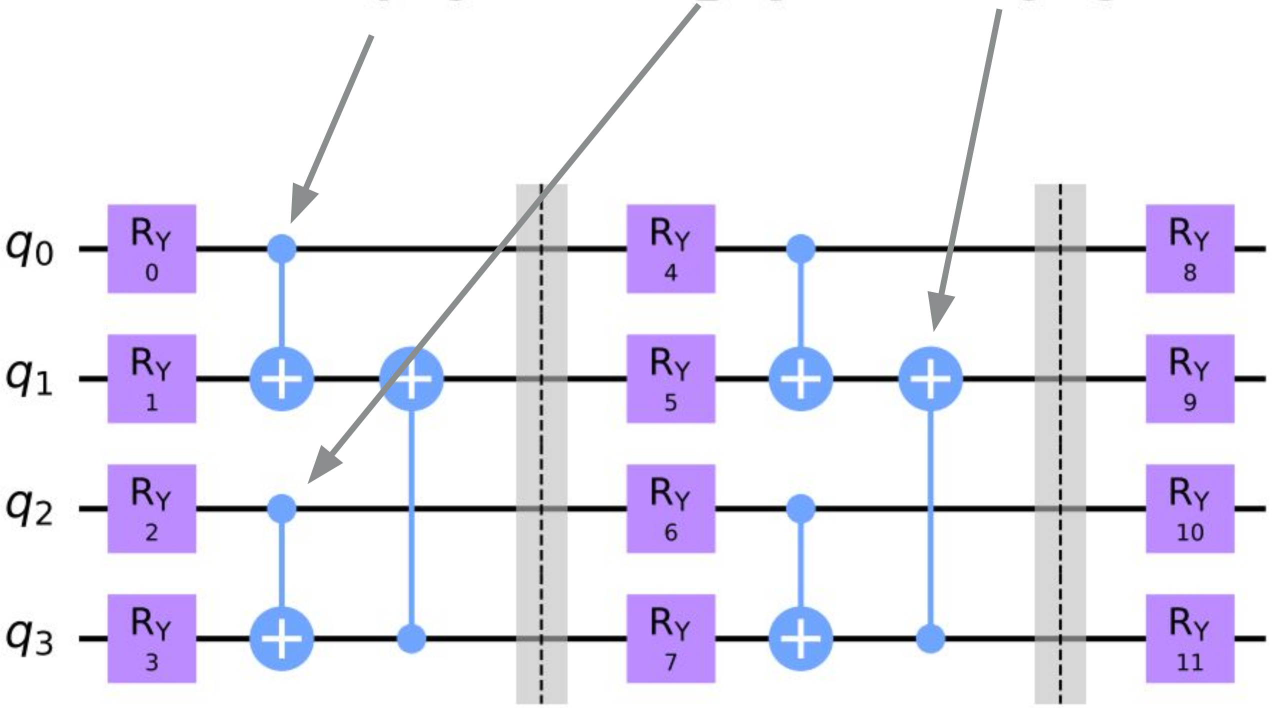
[5]

Designing a Quantum Circuit III

Dynamically created hamiltonian-aware ansatz

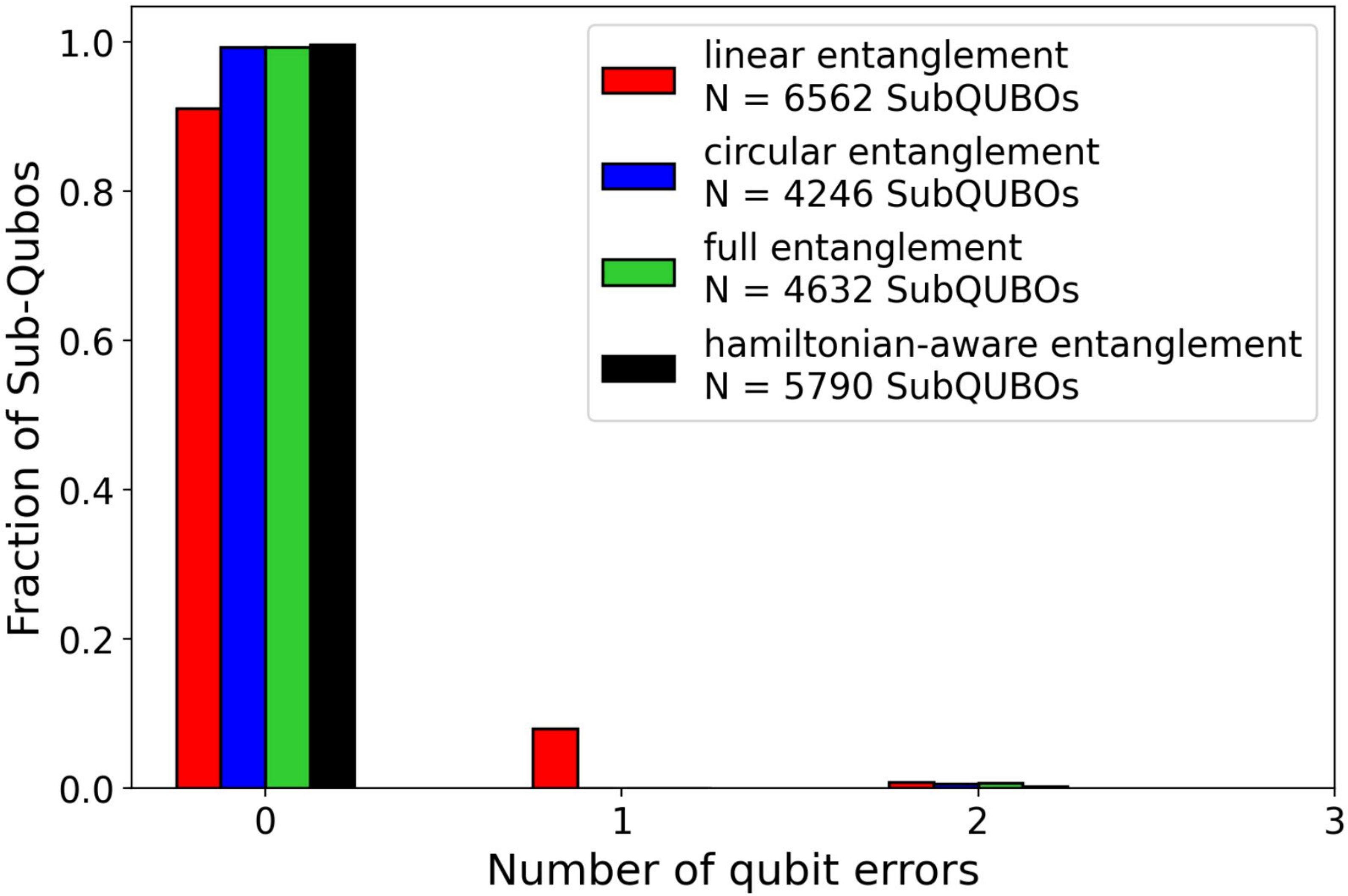
- Structure of the ansatz resembles structure of the hamiltonian
- CX - gates have a high error probability → use as few controlled CX - gates as possible

$$\hat{H} = 0.5x_0 - 0.3x_1 + 0.1x_2 - 0.3x_3 - 1.1x_0x_1 + 1.2x_2x_3 - 1.3x_3x_1$$



Performance on ideal simulation

Solving success and time performance



Solving time / SubQUBO:

- Linear: 2.17 ± 0.31s
- Circular: 3.62 ± 0.14s
- Full: 4.79 ± 0.54s
- custom: 3.35 ± 0.33s

Conclusion / Outlook

Summary / What’s next?

- Custom approach delivers slightly better results and is also faster in terms of SubQUBOs
- Significant decrease in CX-gates will lead to less noisy results on real hardware
- Investigating impact of global optimization algorithm on SubQUBO hamiltonian
- Next Step: Move from ideal to noisy simulation

Thank you very much!

Any questions?

Sources

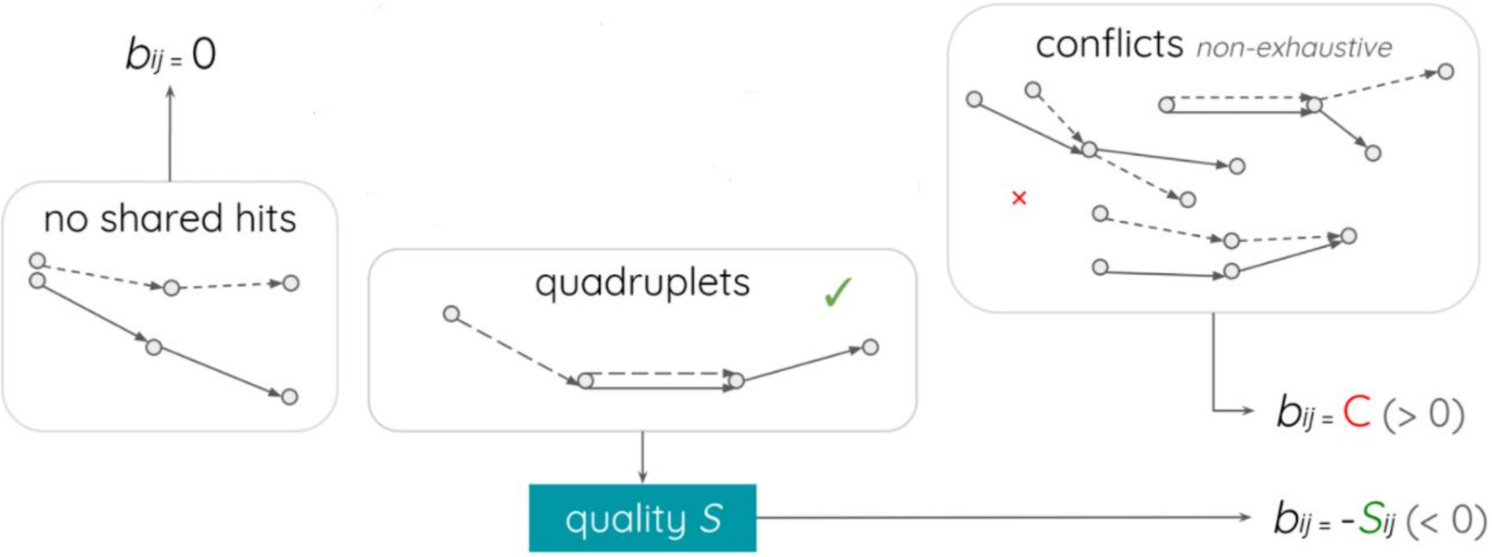
[1]https://arxiv.org/abs/2102.02032 on *23.2.2022*
[2]http://naturalunits.blogspot.com/2015/04/the-super-critical-charge.html on *23.2.2022*
[3]http://openqemist.1qbit.com/docs/vqe_microsoft_qsharp.html
[4]https://arxiv:1902.08324v1 *13.3.2022*
[5]https://www.nature.com/articles/s41598-022-05971-9
https://arxiv.org/pdf/2202.06874.pdf, *13.3.2022*
https://acts.readthedocs.io/en/latest/ *10.3.2022*
https://arxiv.org/pdf/2111.05176.pdf *13.3.2022*
qiskit.org *23.2.2022*

Appendix I

QUBO

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

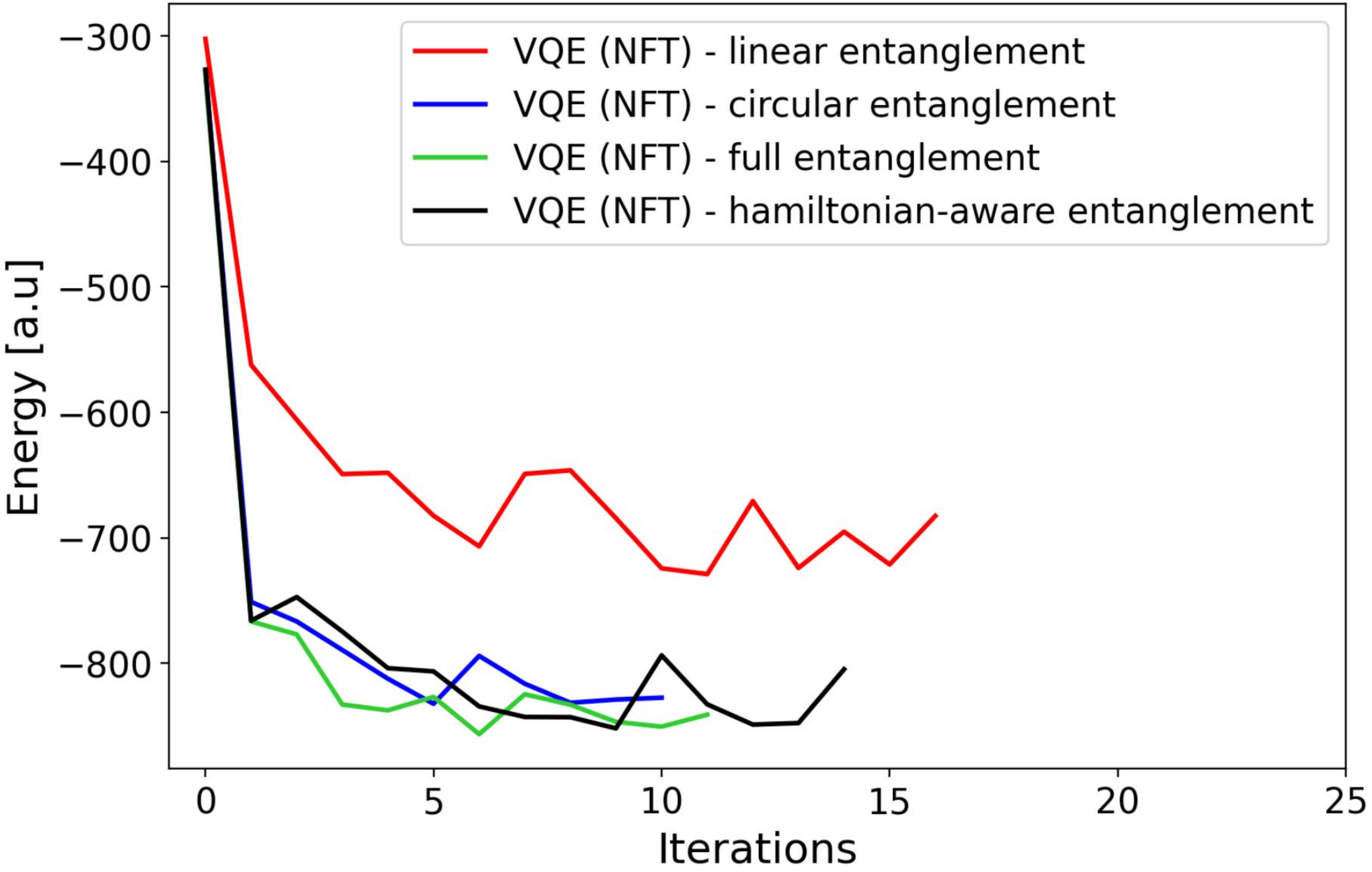
- Quadratic Unconstrained Binary Optimization (QUBO)
- Interactions of triplets are described via b_{ij}, the quality of a triplet as a_i
- Minimizing the objective results in a series of 1's and 0's, which represents the kept and discarded triplets respectively



A pattern recognition algorithm for quantum annealers[4]

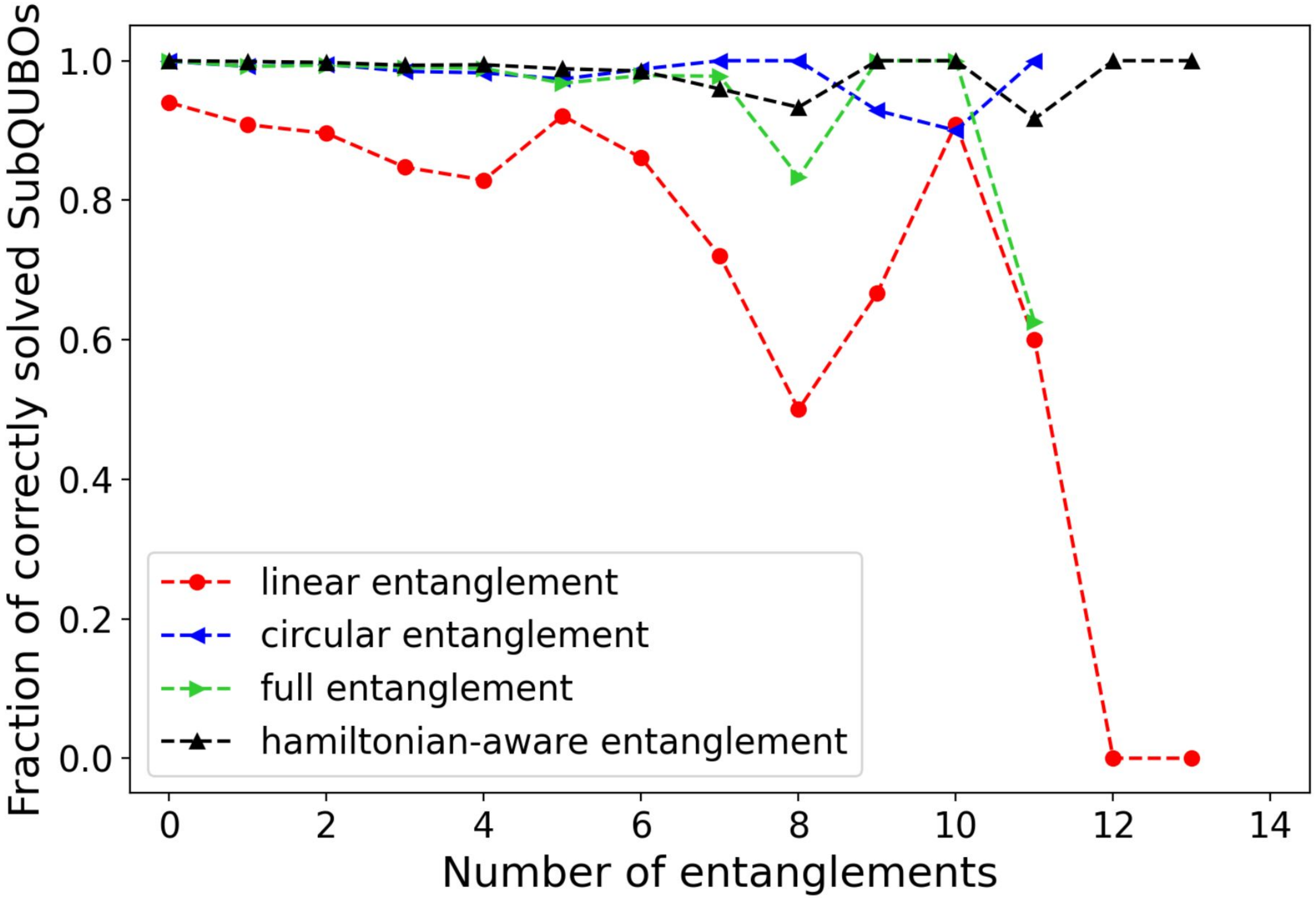
Appendix 2

Walking through the energy landscape



Appendix 3

Configuration vs. entanglements / per circuit



Appendix 3

Configuration vs. entanglements / per circuit