Benchmarking Variational Quantum Algorithms for the LUXE experiment

Arianna Crippa[1], Lena Funcke[2], Tobias Hartung[3], Beate Heinemann[1,4], Karl Jansen[1,6], **Annabel Kropf [1,4]**, Stefan Kühn[5], Federico Meloni[1], David Spataro[1,4], Cenk Tüysüz[1,6] , Yee Chinn Yap[1]

[1]Deutsches Elektron-Synchrotron DESY
[2]Massachusetts Institute of Technology, MIT
[3]University of Bath
[4]Albert-Ludwigs-Universität Freiburg
[5]CaSToRC, The Cyprus Institute
[6]Humboldt-Universität zu Berlin

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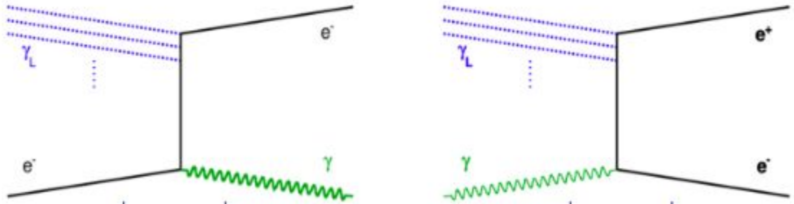
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES LUXE

LUXE

Laser und XFEL Experiment



e-laser mode: Non-linear Compton scattering

γ-laser mode: Non-linear Breit-Wheeler pair creation

Goal: Investigate the transition into the non-perturbative (strong-field) regime of QED

→ Precision measurement of photon-photon, photon-electron interactions

How: Use high intensity laser (40-350 TW) and the european XFEL's electron beam (16.5 GeV)

Crucial: Measure number of positrons as a function of the laser intensity parameter $\xi = \sqrt{4\pi\alpha}\left(\frac{\varepsilon_L}{\omega_L m_e}\right) = \frac{m_e \varepsilon_L}{\omega_L \varepsilon_{cr}}$

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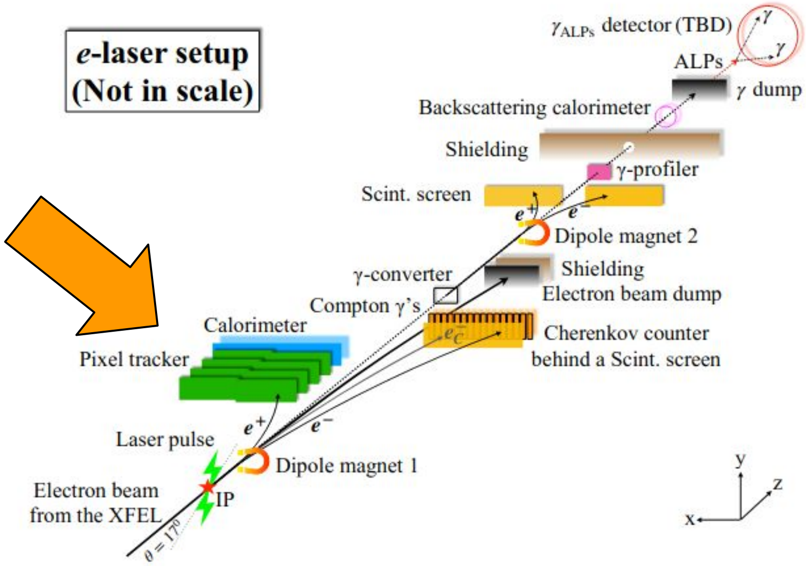
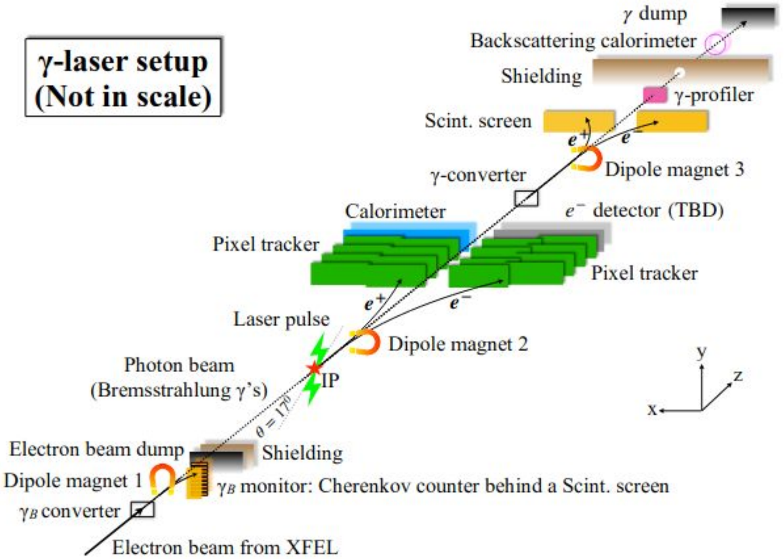
DESY.

LUXE setup





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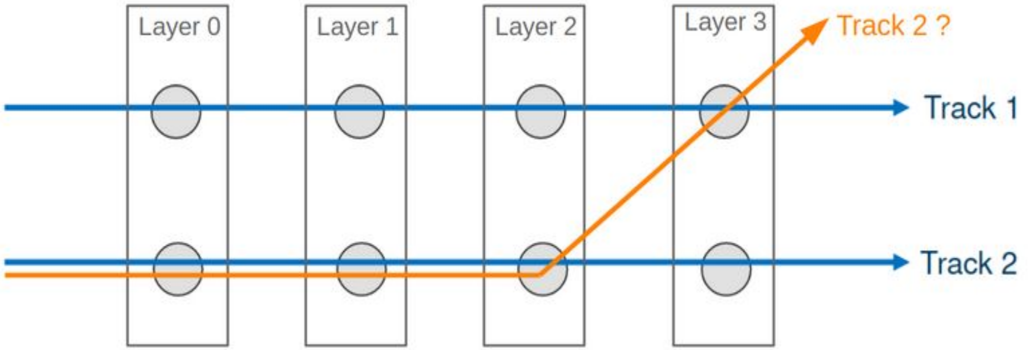
LUXE CDR: arXiv:2102.02032

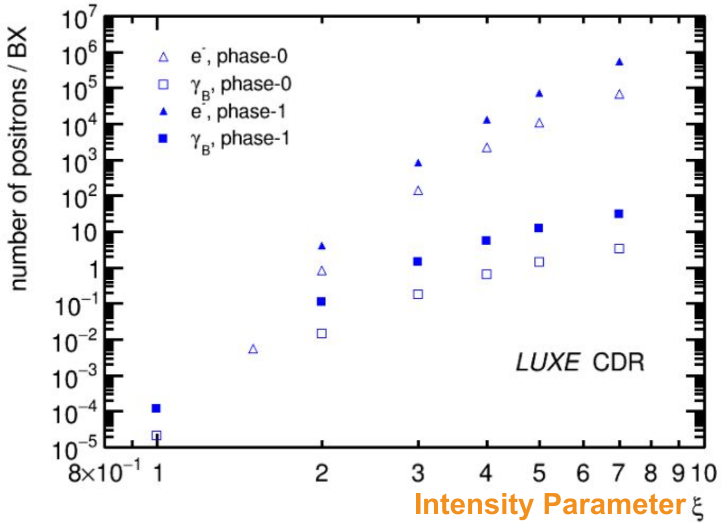
DESY.

Track Reconstruction

Positrons impinge on 4-layered binary hit/no-hit silicon detector (ALPID chip, 5 x 10^5 pixel of size 27 x 29 mm^2)

Challenge: Find tracks from a set of hits is computationally demanding





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DESY.

Track Reconstruction

Novel approach: Particle track reconstruction using quantum computers

A Pattern Recognition Algorithm for Quantum Annealers

Frédéric Bapst, Wahid Bhimji, Paolo Calafiura, Heather Gray, Wim Lavrijsen, Lucy Linder & Alex Smith

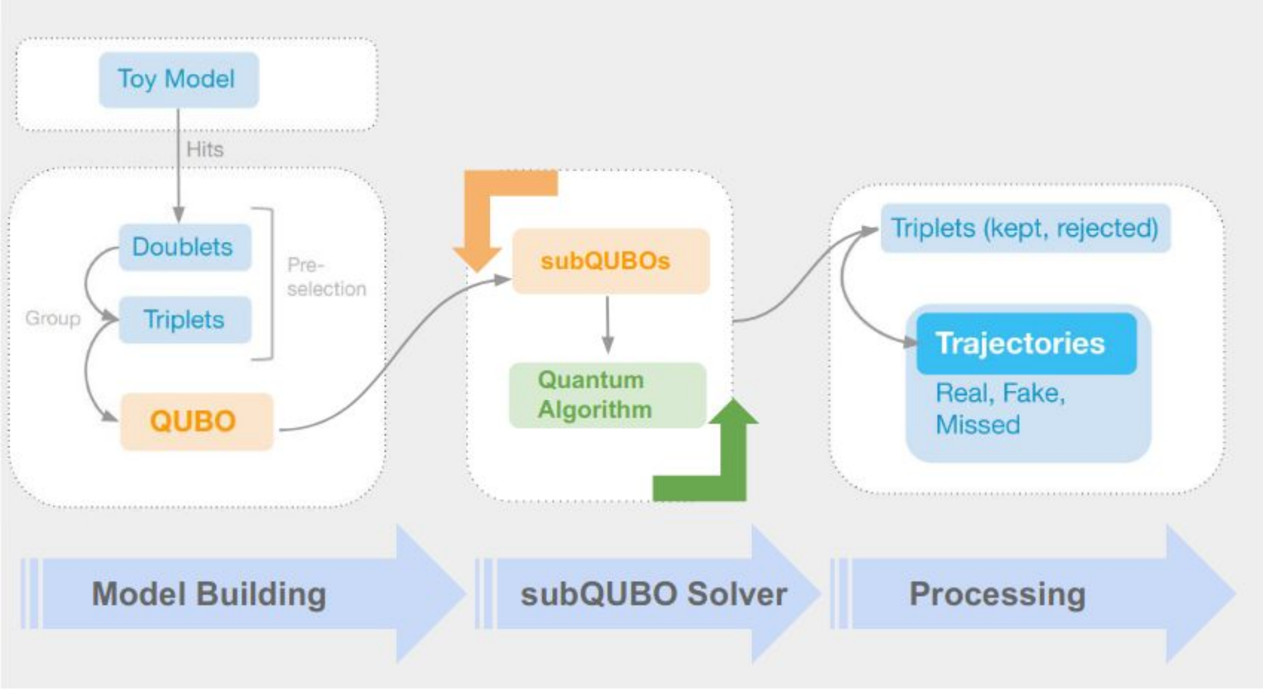
Computing and Software for Big Science **4**, Article number: 1 (2020) | Cite this article

+ Classical benchmark!

The goal is to benchmark both on basis of:

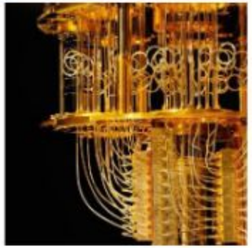
1. Generated signal interactions at the IP (T. G. Blackburn, A. J. MacLeod, B. King, arXiv:2103.06673),
2. Custom detector model where complexity can be controlled.

Quantum Algorithm Overview



Devices used:
IBM Q
1-7 real qubit systems available + qc simulators

IBM Quantum Experience:
(https://quantum-computing.ibm.com/)



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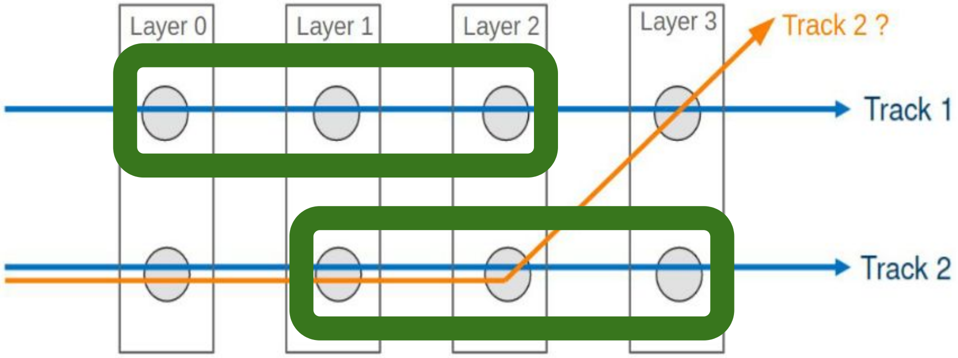
DESY.

Classical to Quantum

Tracking Formulation for a Quantum Computer

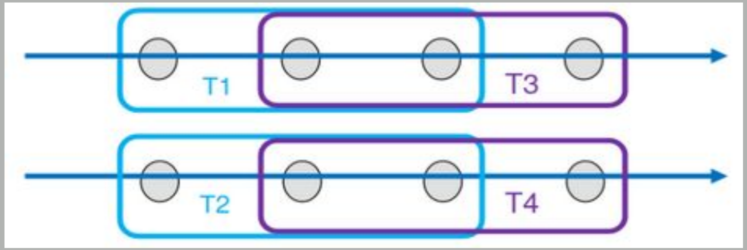
Task: Find formulation of the track reconstruction so that if simulated on a quantum computer, the ground state relates to correct tracks

Step 1:
Form sets of triplets
(three consecutive hits)

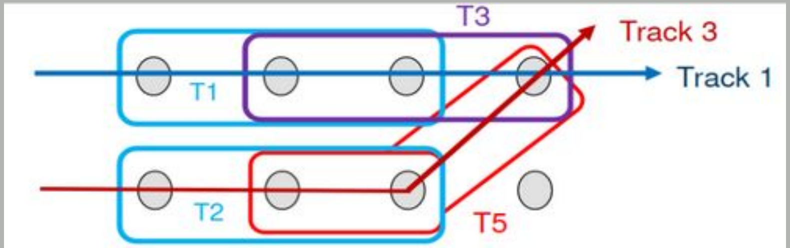


QUBO

Quadratic Unconstrained Binary Optimization



Well-aligned triplets



Conflict between triplets T3 and T5

Step 2: Maximize number of triplets that form well-aligned tracks and minimize triplets that contribute a conflict

- Express problem as a QUBO
- Minimizing the QUBO returns the best set of track candidates

QUBO

Quadratic Unconstrained Binary Optimization

In the QUBO formulation, triplets T_i are assigned a binary value, one if chosen and zero if discarded.

$$O(a,b,T) = \sum_{i=1}^{N} a_i T_i + \sum_{i}^{N} \sum_{j<i}^{N} b_{ij} T_i T_j \qquad T_i, T_j \in \{0,1\}$$

quality of triplet with quality parameter a_i

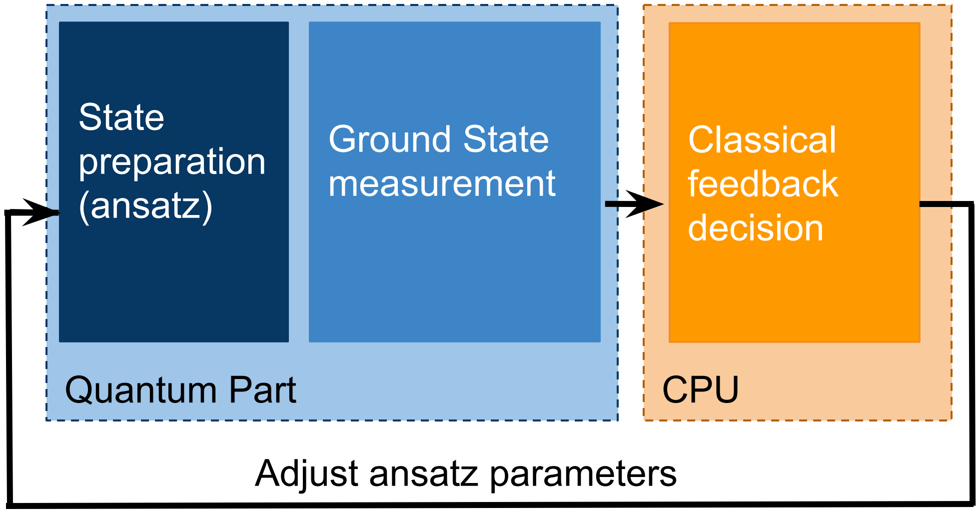
Compatibility between two triplets

$$b_{ij} = \begin{cases} -S(Ti,Tj), & \text{if } (T_i,T_j) \text{ form a quadruplet,} \\ \zeta & \text{if } (T_i,T_j) \text{ are in conflict,} \\ 0 & \text{otherwise.} \end{cases}$$

VQE/QAOA

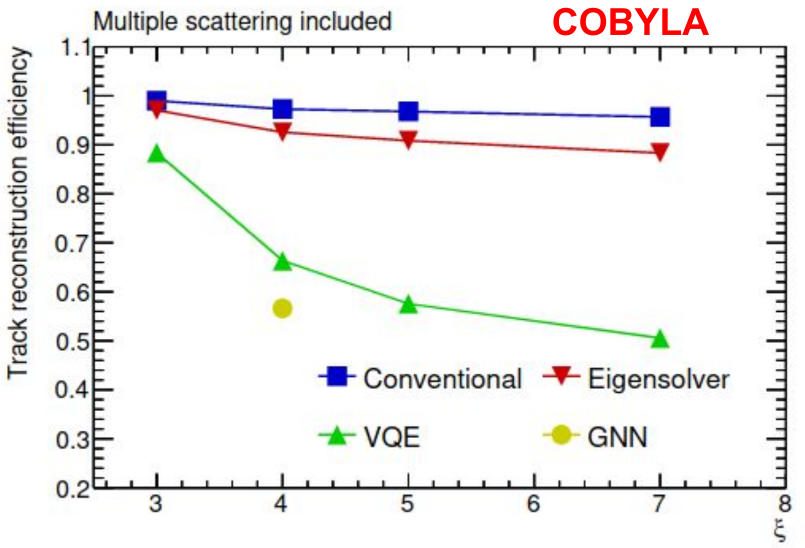
Step 3: Minimize the QUBO

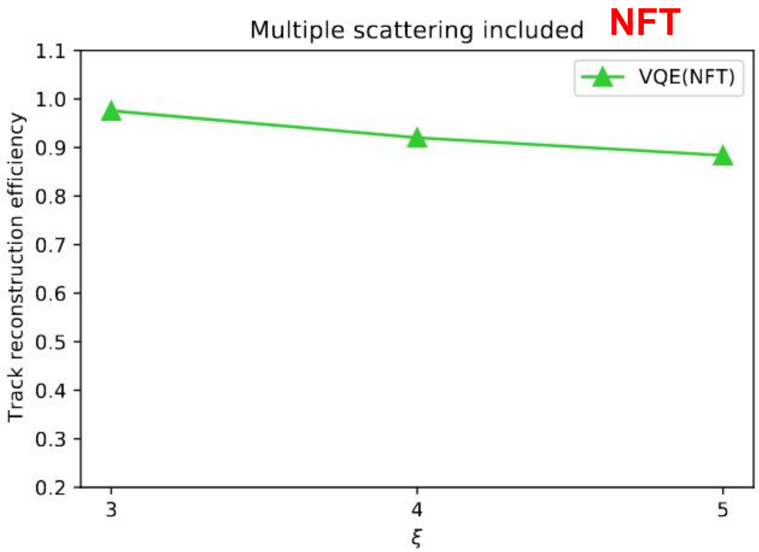
Variational-Quantum-Eigensolver (VQE): quantum/classical hybrid algorithm used to find eigenvalues of a matrix
Hybrid: Quantum subroutine run inside of a classical optimization loop
The **Quantum Approximate Optimization Algorithm (QAOA)** can be viewed as a special case of VQE



Efficiency with NFT

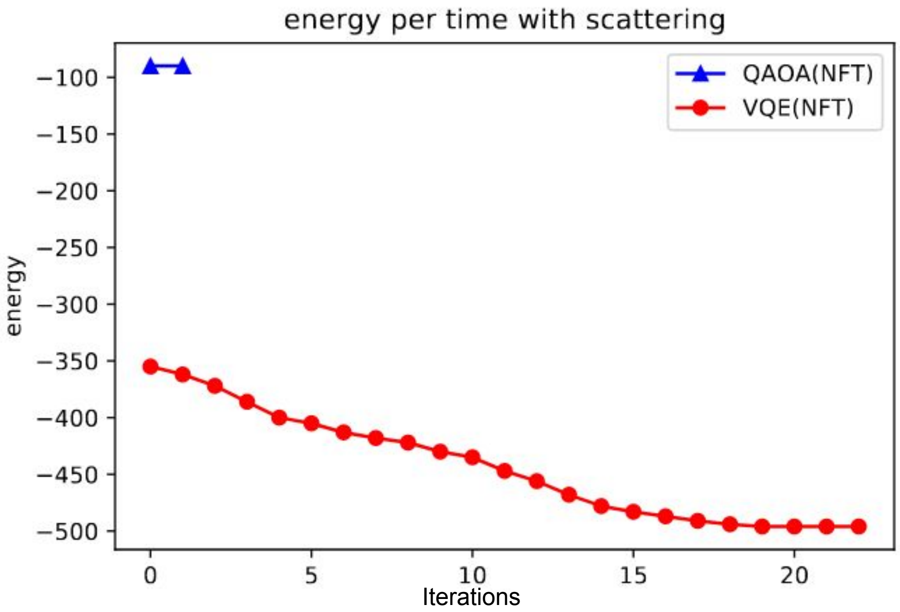
VQE highly depends on optimizer. Here, TwoLocal is used as ansatz





QAOA

- QAOA's efficiency depends on the number of repeats
- VQE approaches the Minimum faster than QAOA
- *more repeats coming *



Summary

Goal: Study the limits for a quantum algorithm on **noisy device** to tackle particle track reconstruction for the LUXE experiment (positron tracker)

- Start simple: Toy Experiment, classical pre-selection
- Formulation as QUBO,
- Use quantum algorithm to find ground state
- Benchmark against classical tracking reconstruction software

VQE(NFT) depends on optimizer and ansatz. Preliminary efficiencies > 88% reached
QAOA depends on circuit depth. QAOA is not yet comparable to VQE.

Thank you

QAOA

Solving the subQubo

-QAOA can be viewed as a special case of VQE.

- Hamiltonian contains only Z terms, we do not need to change the basis for measurements.

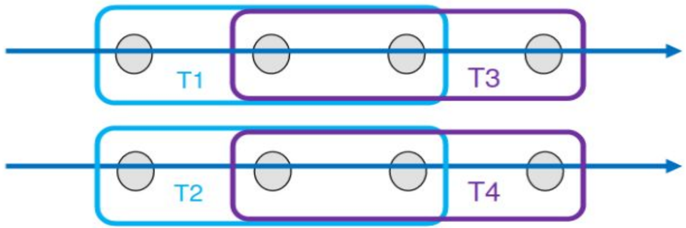
Differences to VQE:

- The form of the ansatz is limited
- Restricted to Ising Hamiltonians
- In QAOA our goal is to find the solution to the problem. To do that we don't need to find the ground state.

QUBOs

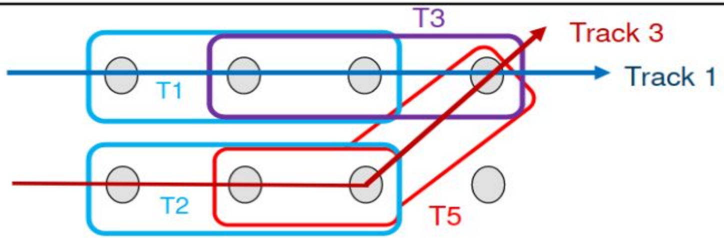
$$O(a,b,T) = \sum_{i=1}^{N} a_i T_i + \sum_{i}^{N} \sum_{j<i}^{N} b_{ij} T_i T_j \quad T \in \{0,1\}$$

$$b_{ij} = \begin{cases} -S(Ti,Tj), & \text{if } (T_i,T_j) \text{ form a quadruplet,} \\ \zeta & \text{if } (T_i,T_j) \text{ are in conflict,} \\ 0 & \text{otherwise.} \end{cases}$$



[T1, T2, T3,T4]→combinations:

T1T2	T1T3	T1T4	T2T3	T2T4	T3T4
+0	-S	+0	+0	-S	+0



[T1, T2, T3,**T5**] → combinations:

T1T2	T1T3	T1**T5**	T2T3	T2**T5**	T3**T5**
+0	-S	+0	+0	-S	conflict

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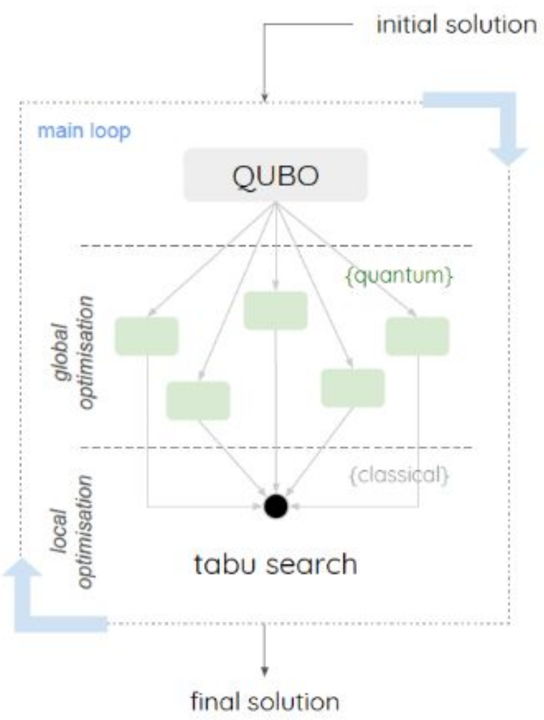
SubQubos

Problem: Devices restricted to small number of qubits

- Big QUBOS cannot be simulates
- Break QUBO into subsets → subQUBOS!
- Iterated vector converges to solution vector

TODO:
Small overview of subQUBO algorithms tested



Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Name Surname
Department
E-mail
Phone