Track reconstruction at LUXE using quantum algorithms

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

LUXE

CTD 2022, Princeton University

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

HELMHOLTZ

LUXE - Laser und XFEL Experiment

A new experiment

Proposed new experiment at DESY, Hamburg and European XFEL

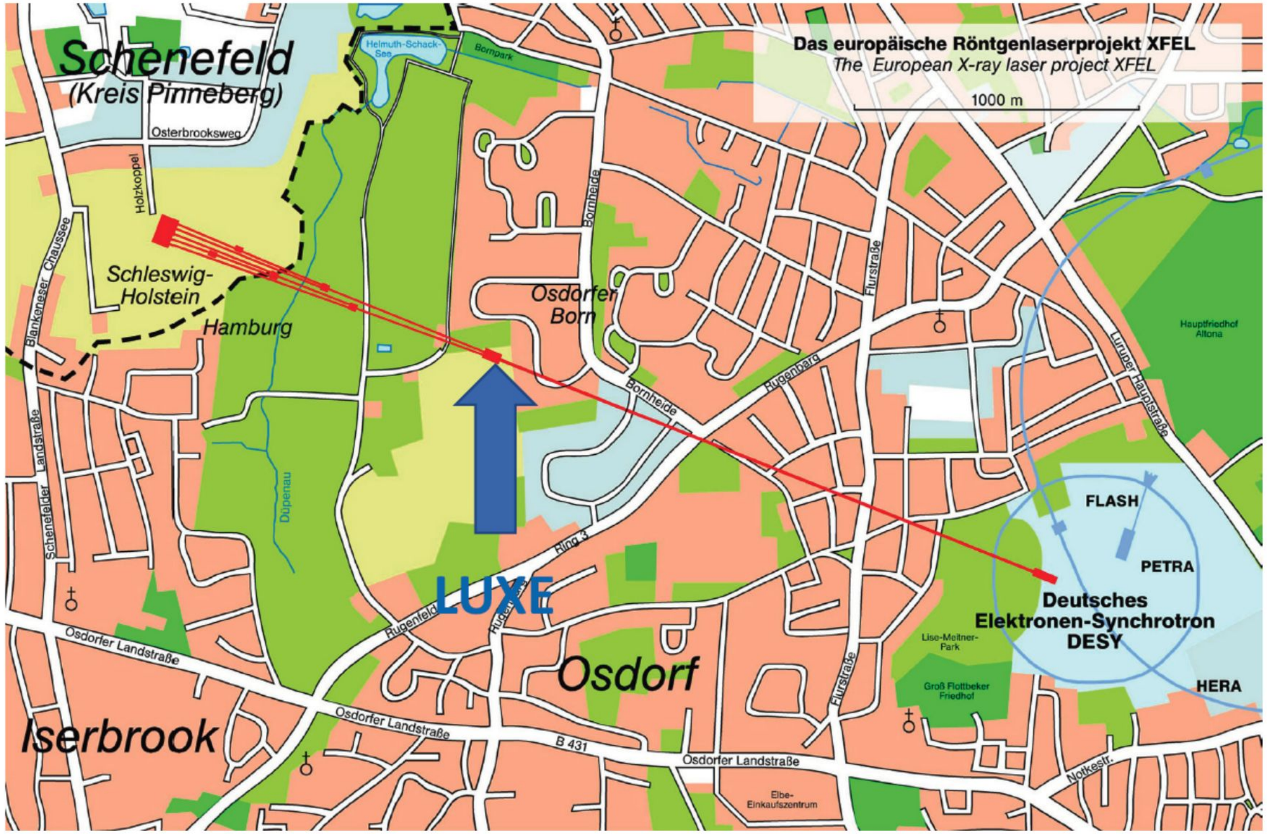
- collision of e^- - beam and a high-power laser
- study non-perturbative QED for the first time!

More information available at:

- https://luxe.desy.de
- CDR arXiv: 2102.02032

Previous results at:

- arXiv: 2202.06874



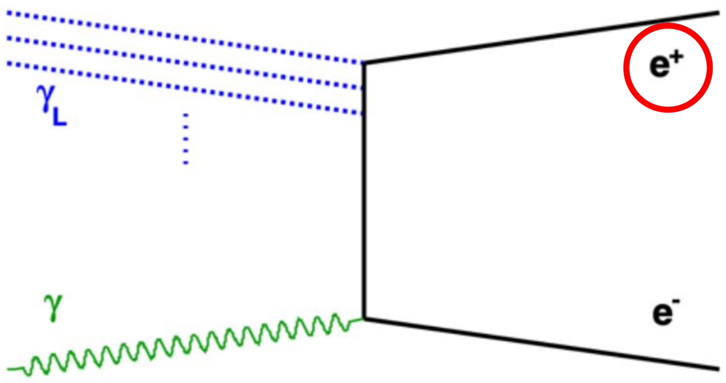
Source: LUXE CDR

LUXE - Laser und XFEL Experiment

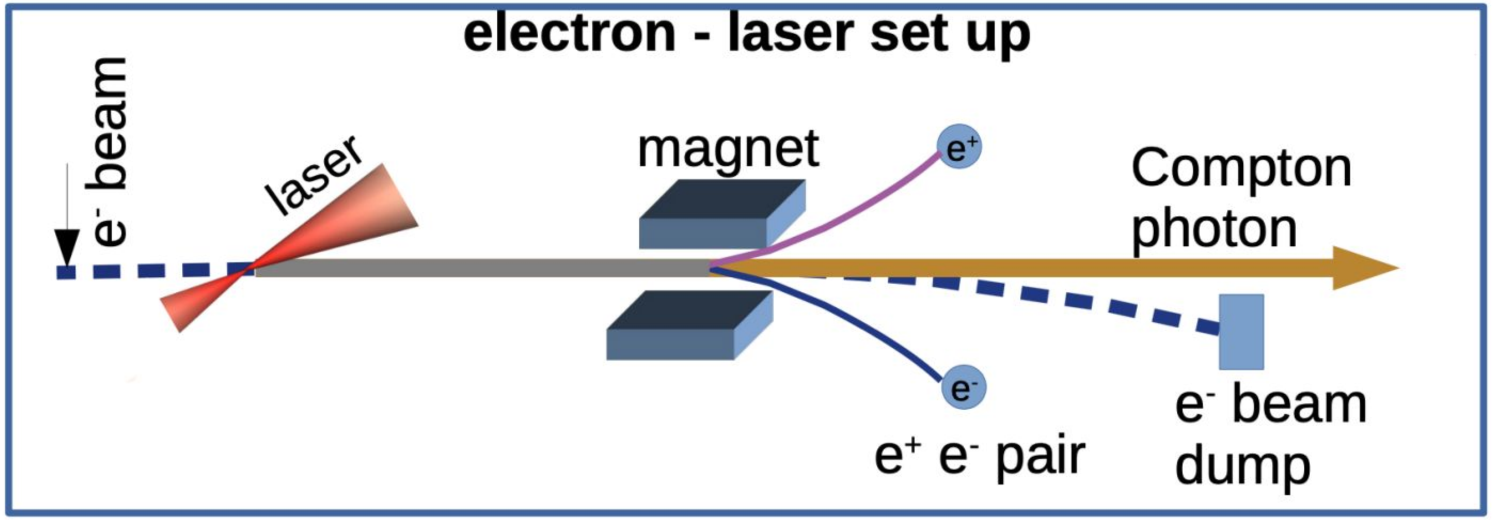
Setup and observable processes

XFEL 16.5 GeV electron beam or a bremsstrahlung photon beam crossed with a powerful laser (phase 0 = 40TW, phase 1 = 350TW):

- non-linear Compton scattering
- Breit-Wheeler pair production



Source: LUXE CDR

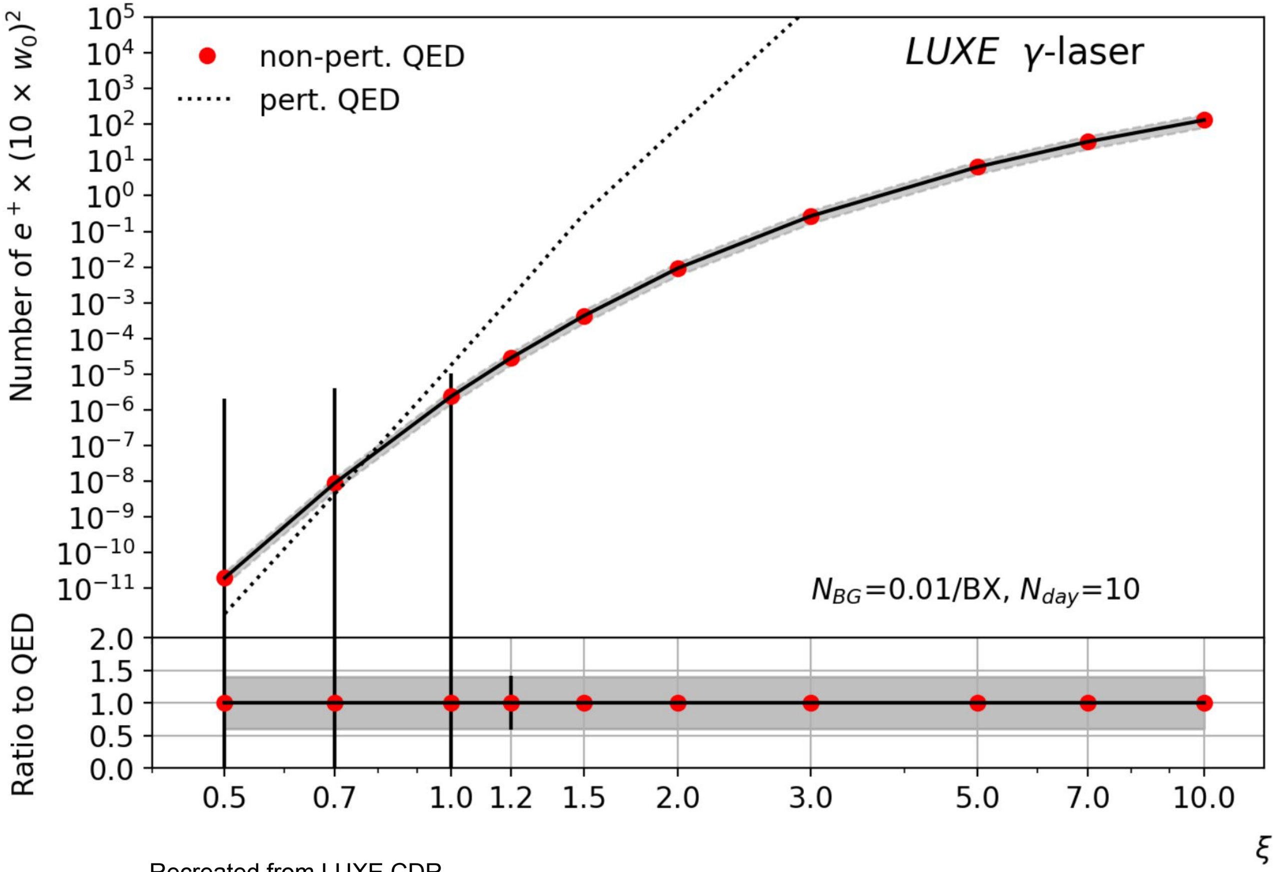


Source: LUXE CDR

LUXE - Laser und XFEL Experiment

Transition into non-perturbative QED

Investigate transition far into the non-perturbative regime of QED by scanning the classical non-linearity parameter ξ.



Recreated from LUXE CDR

Schwinger - Limit

$$\mathcal{E}_{cr} = \frac{m_e^2 c^3}{q_e \hbar} \simeq 1.32 \times 10^{18}\,\mathrm{V/m}$$

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

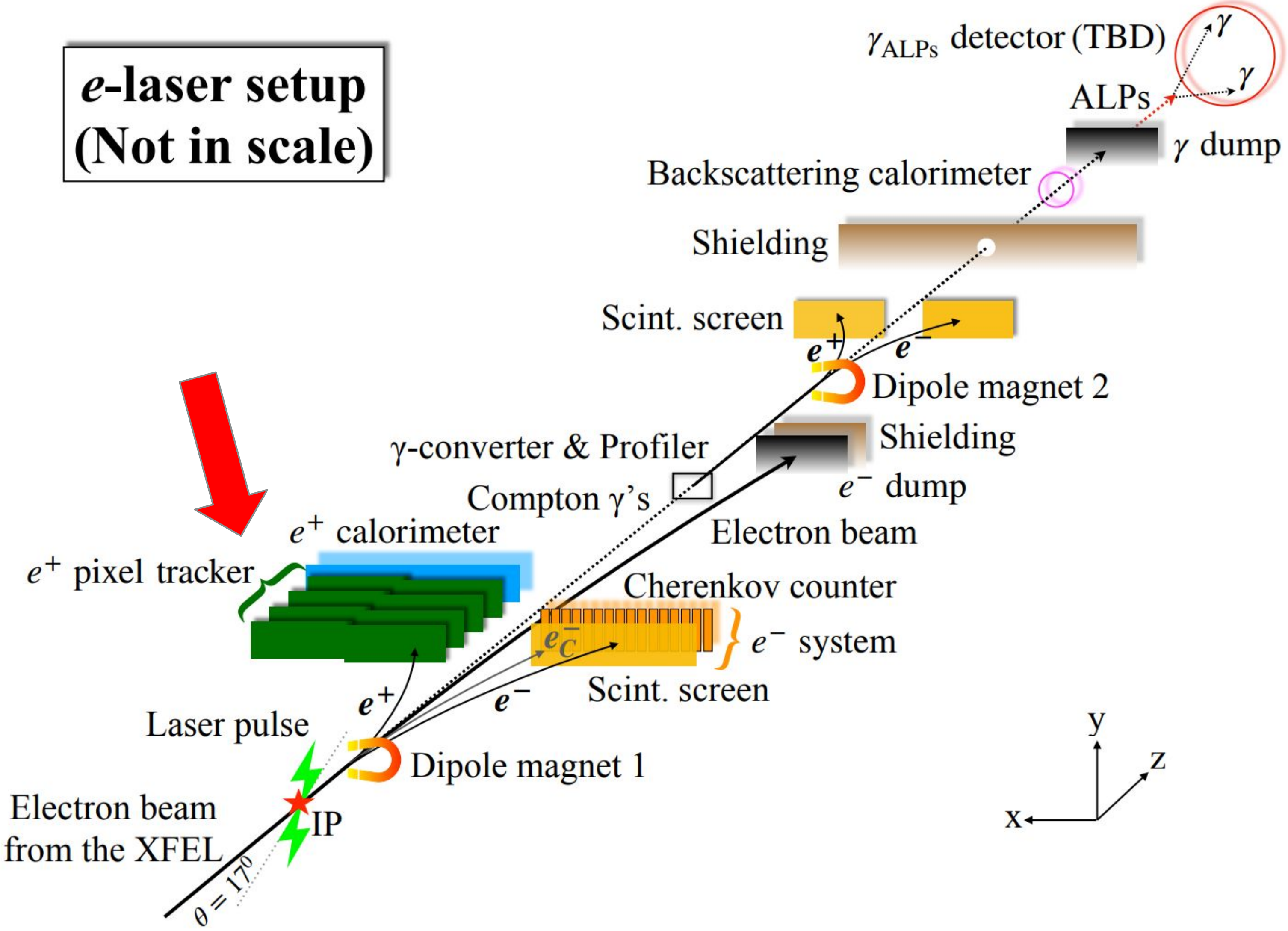
Instantaneous laser field strength

LUXE positron tracking system

Silicon pixel tracker

Positron tracking system based on ALPIDE silicon pixel sensor. It consists of:

- 9 chips on each stave
- 30 x 15 mm² chips
- 27 x 29 µm² pixels



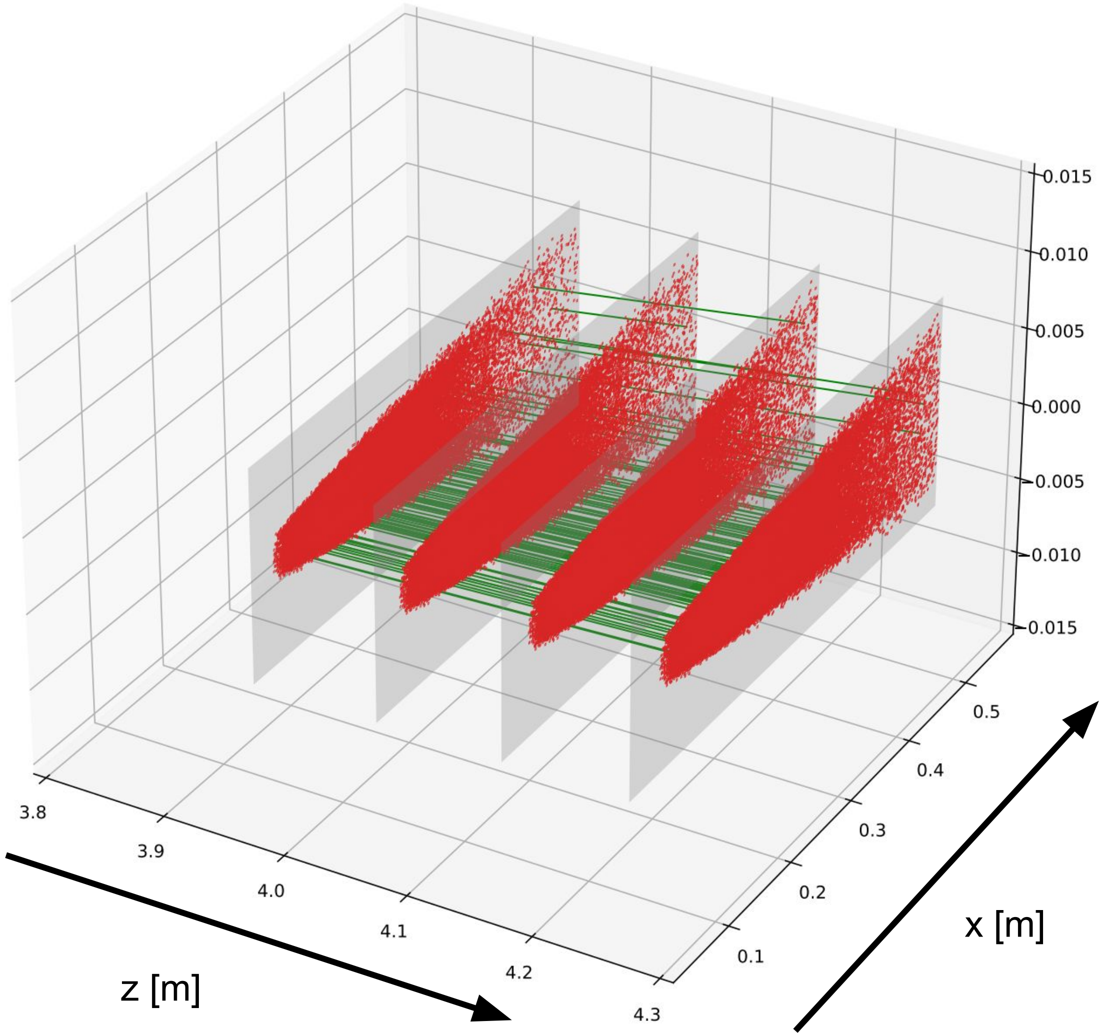
Source: LUXE CDR

Simplified Simulation

Tunable parameters and detector geometry

Simplified Simulation as a starting point to understand the performance of our quantum algorithms

- simplified detector setup
- tunable parameters, e.g. scattering ON/OFF
- simulated events from *ptarmigan*[1] as input



[1]Ponderomotive trajectories and radiation emission arXiv: 2108.10883

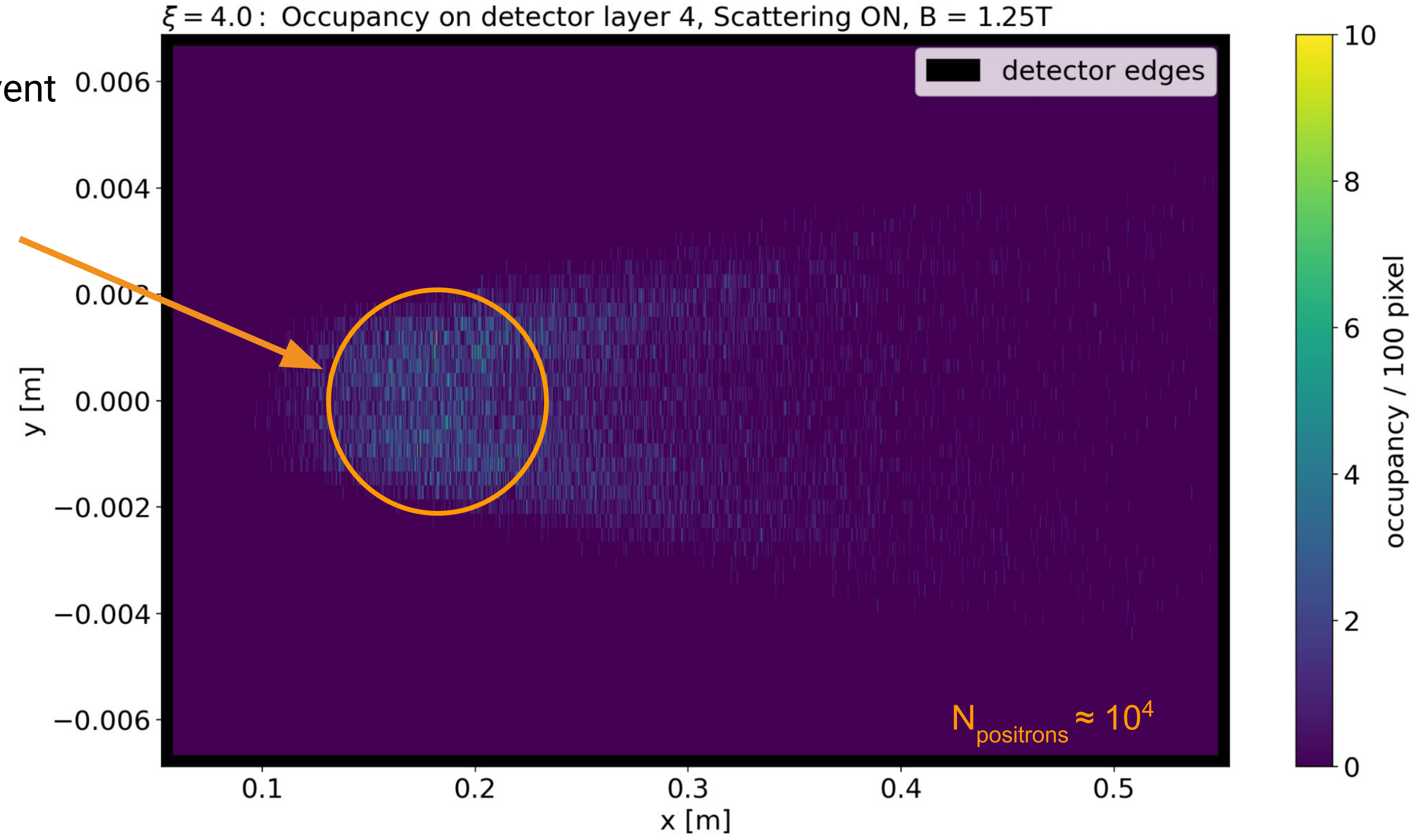
Detector occupancy

Hit density

Expecting 10^{-3} - 10^{6} positrons / event

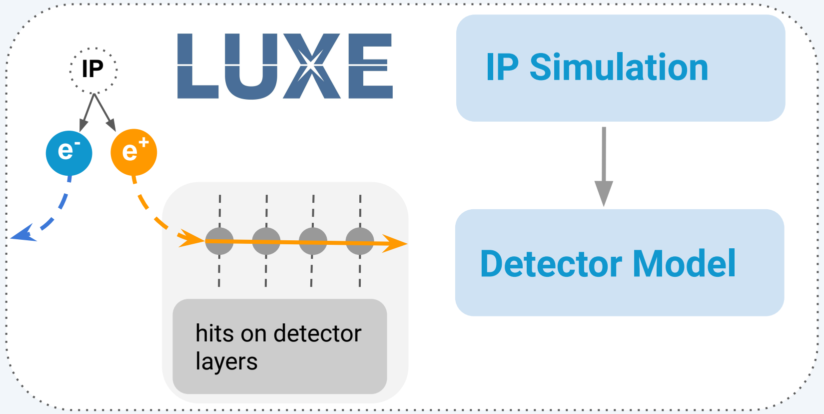
Region with increased occupancy

Performance of quantum algorithms in this region?



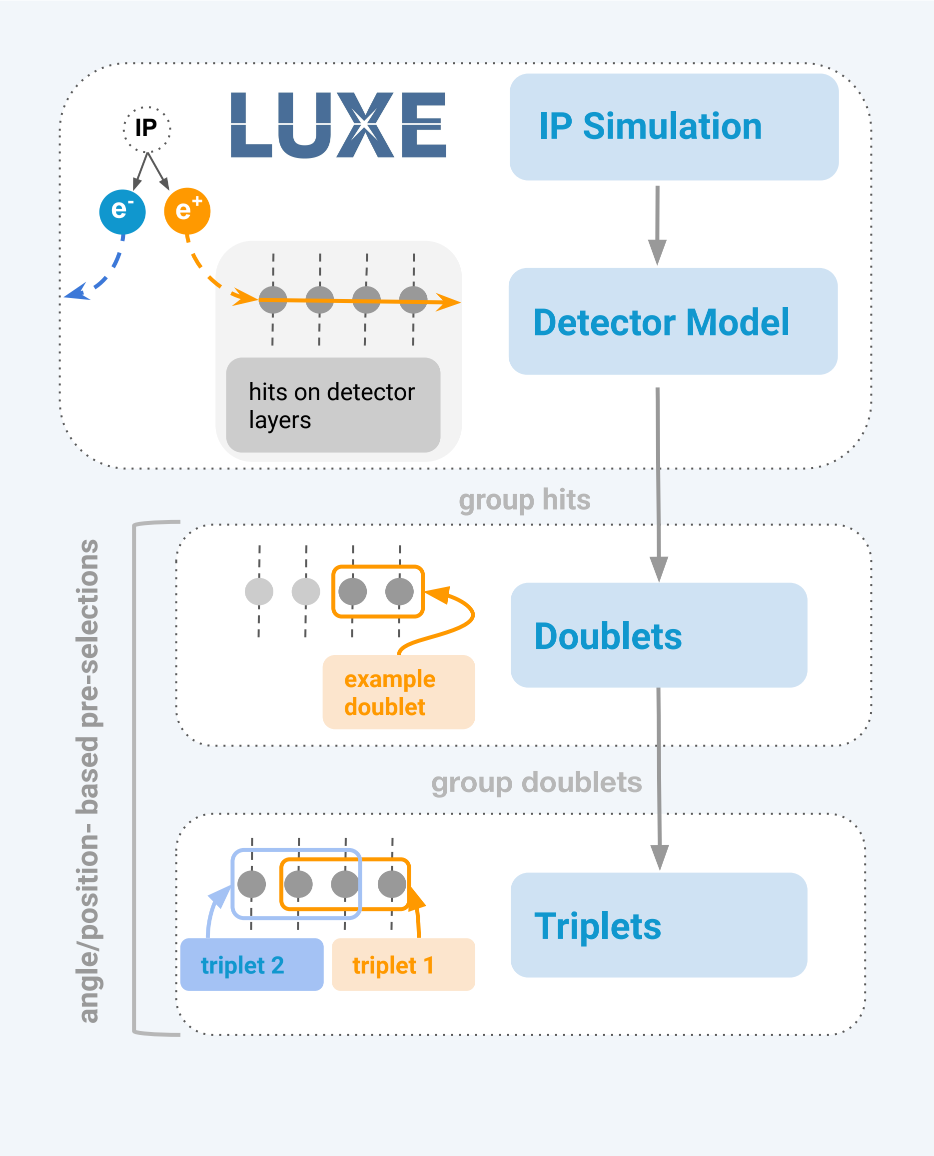
Track reconstruction

Comparing different approaches



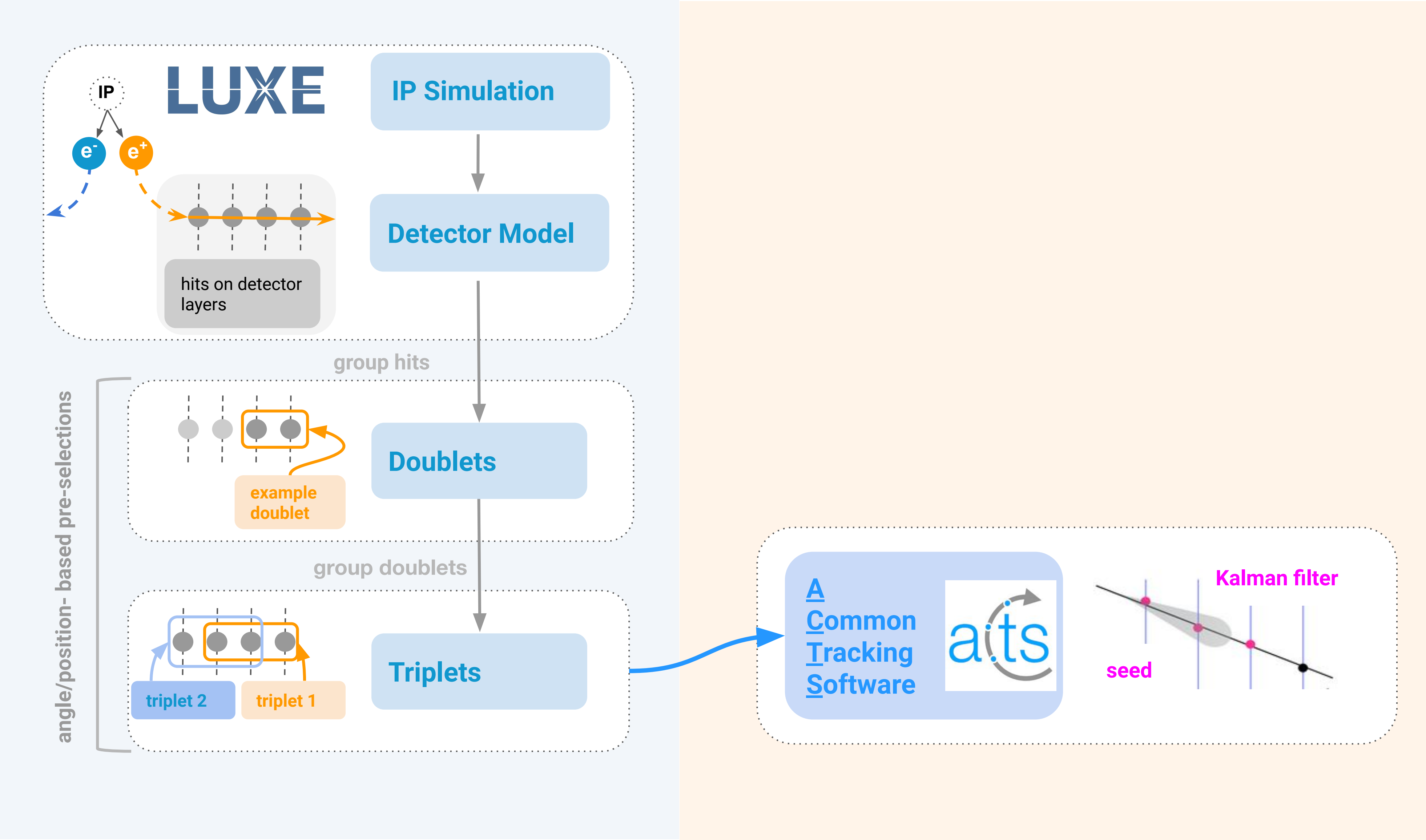
Track reconstruction

Comparing different approaches



Track reconstruction

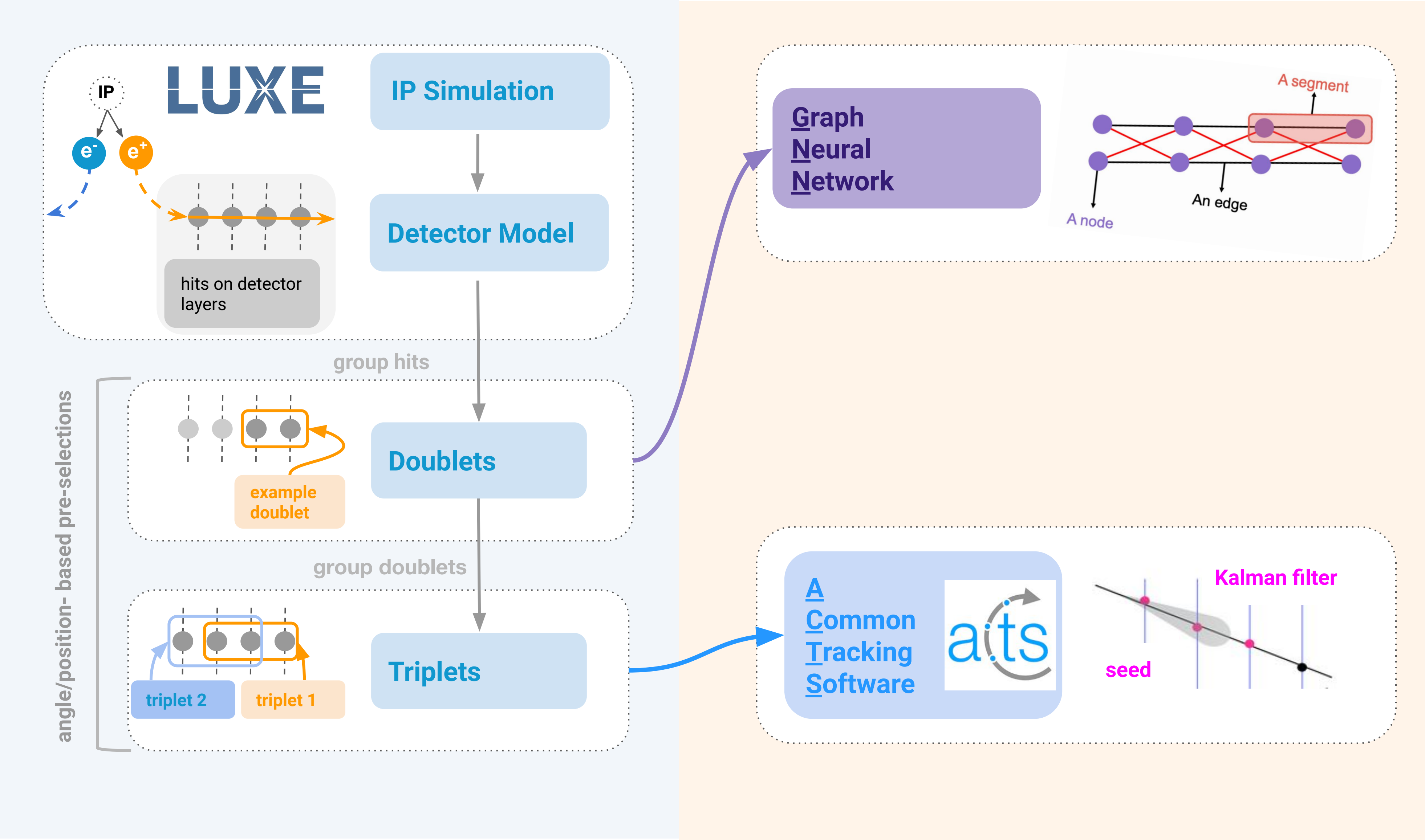
Comparing different approaches



arXiv: 2106.13593

Track reconstruction

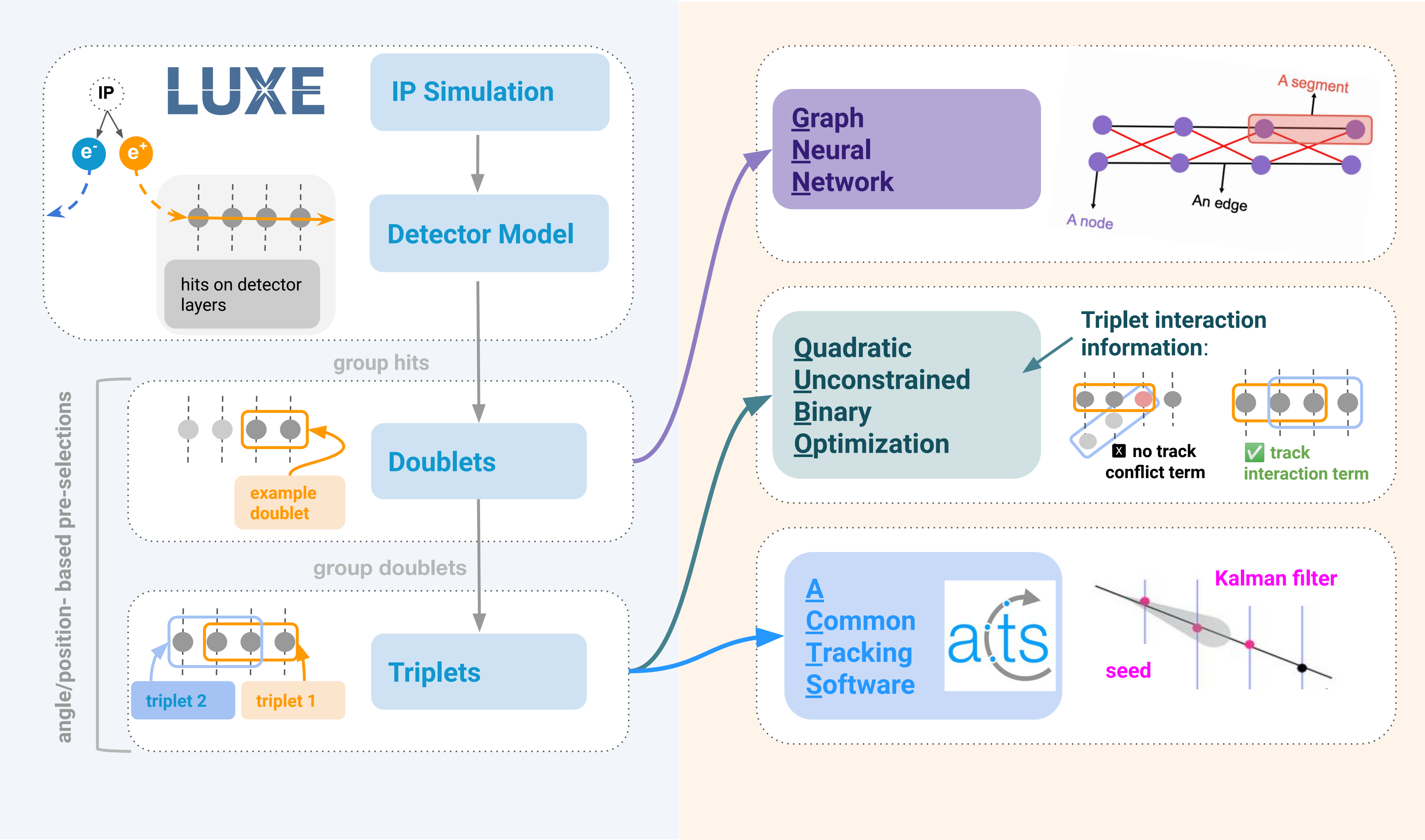
Comparing different approaches



Hep.TrkX: arXiv: 1810.06111
Exa.TrkX: arXiv: 2103.06995
Q.TrkX: arXiv: 2109.12636

Track reconstruction

Comparing different approaches



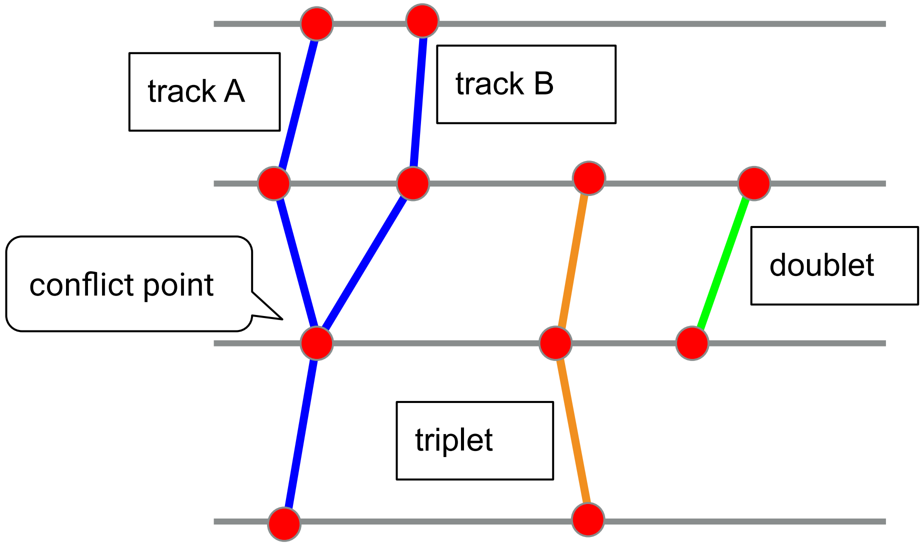
arXiv: 1902.08324

QUBO

Quadratic Unconstrained Binary Optimization

Problem formulation as in:

“A Pattern Recognition Algorithm for Quantum Annealers”*



Minimizing objective → finding the ground state of the Hamiltonian

“connection term” “quality term”

QUBO

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

$$b_{ij} = \begin{cases} 0, & \text{if no shared hit} \\ +1, & \text{if in conflict} \\ -S(T_i, T_j) & \text{if forming a track} \end{cases}$$

↓ map

Ising Hamiltonian

$$\mathcal{H} = -\sum_{n=1}^{N} \sum_{m<n} \bar{b}_{nm} \sigma_n^x \sigma_m^x - \sum_{n=1}^{N} \bar{a}_n \sigma_n^x$$

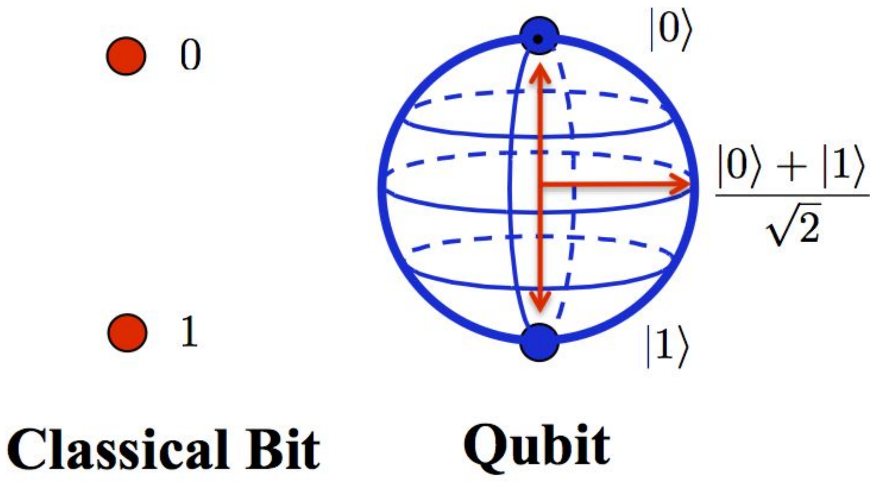
*Bapst, F., Bhimji, W., Calafiura, P. et *al*. A Pattern Recognition Algorithm for Quantum Annealers arXiv:1902.08324

Quantum Computing

A minimal introduction

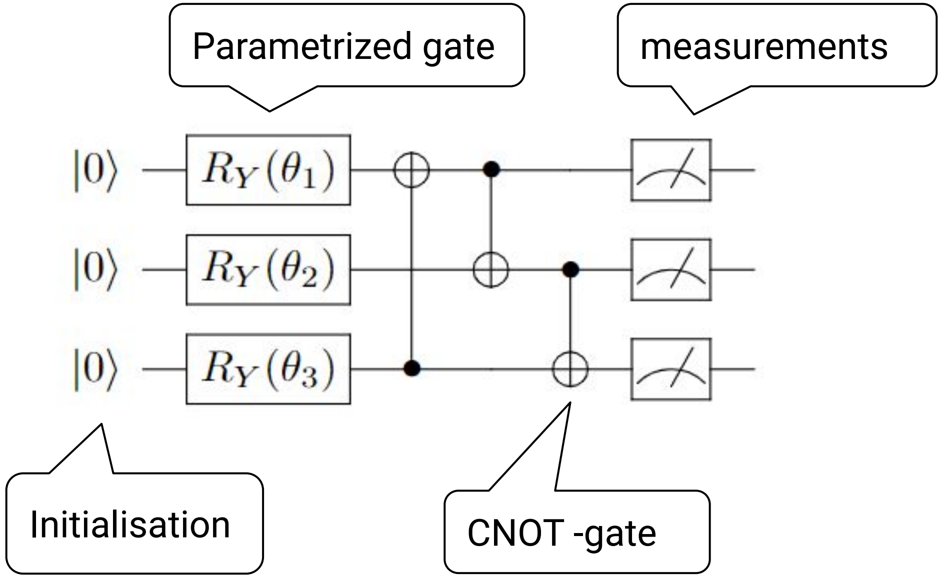
Qubits as two-level quantum system

Gates as unitary operators acting on qubits



Source: deepai.org

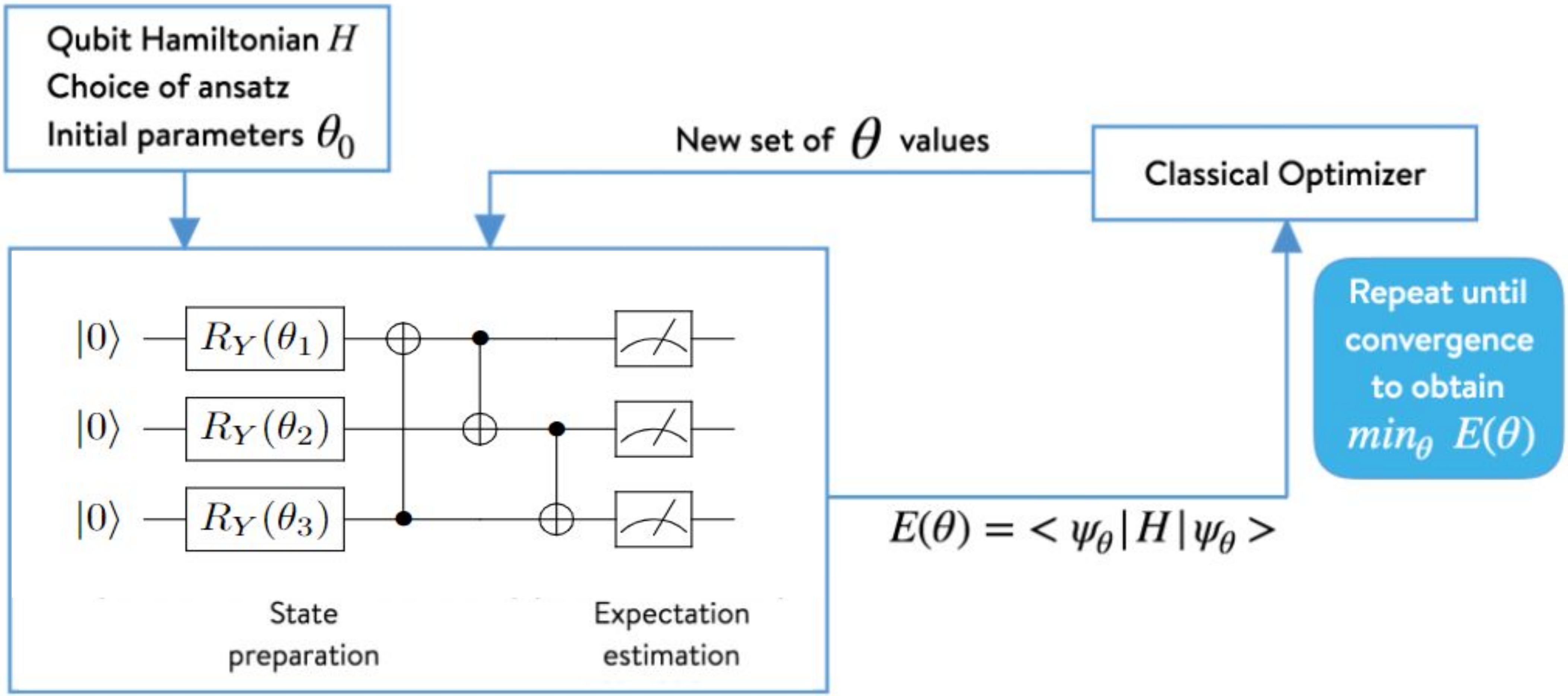
Quantum circuits consist of an initialisation, gates and a measurement



CNOT →
$|00\rangle \rightarrow |00\rangle$
$|01\rangle \rightarrow |01\rangle$
$|10\rangle \rightarrow |11\rangle$
$|11\rangle \rightarrow |01\rangle$

VQE - Variational Quantum Eigensolver

Hybrid quantum - classical algorithm



Source: edited from http://openqemist.1qbit.com/

Ansatz circuit

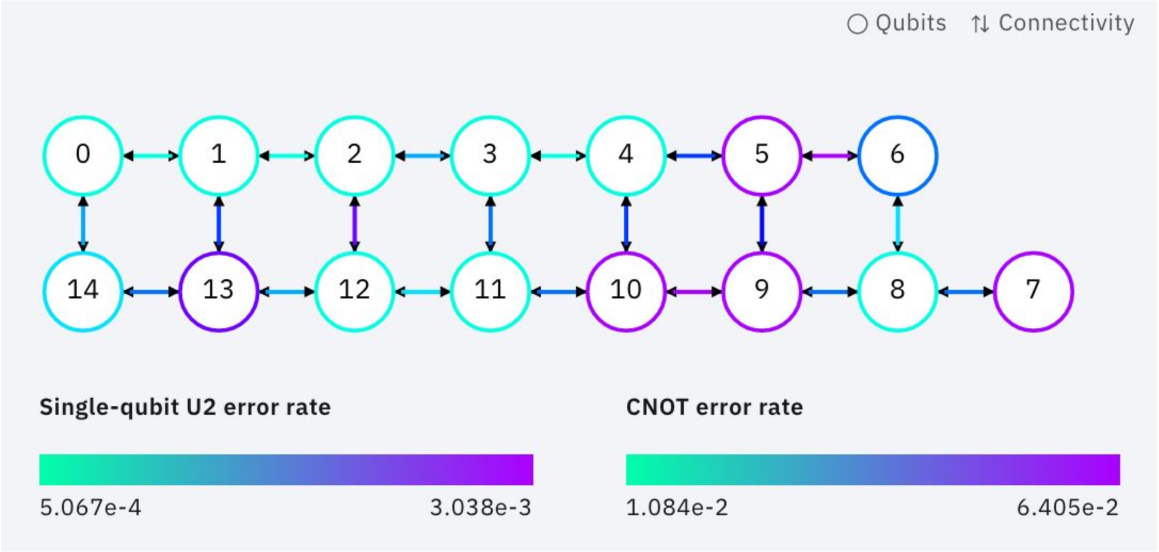
Hardware efficient ansatz

Expressivity of the quantum circuit

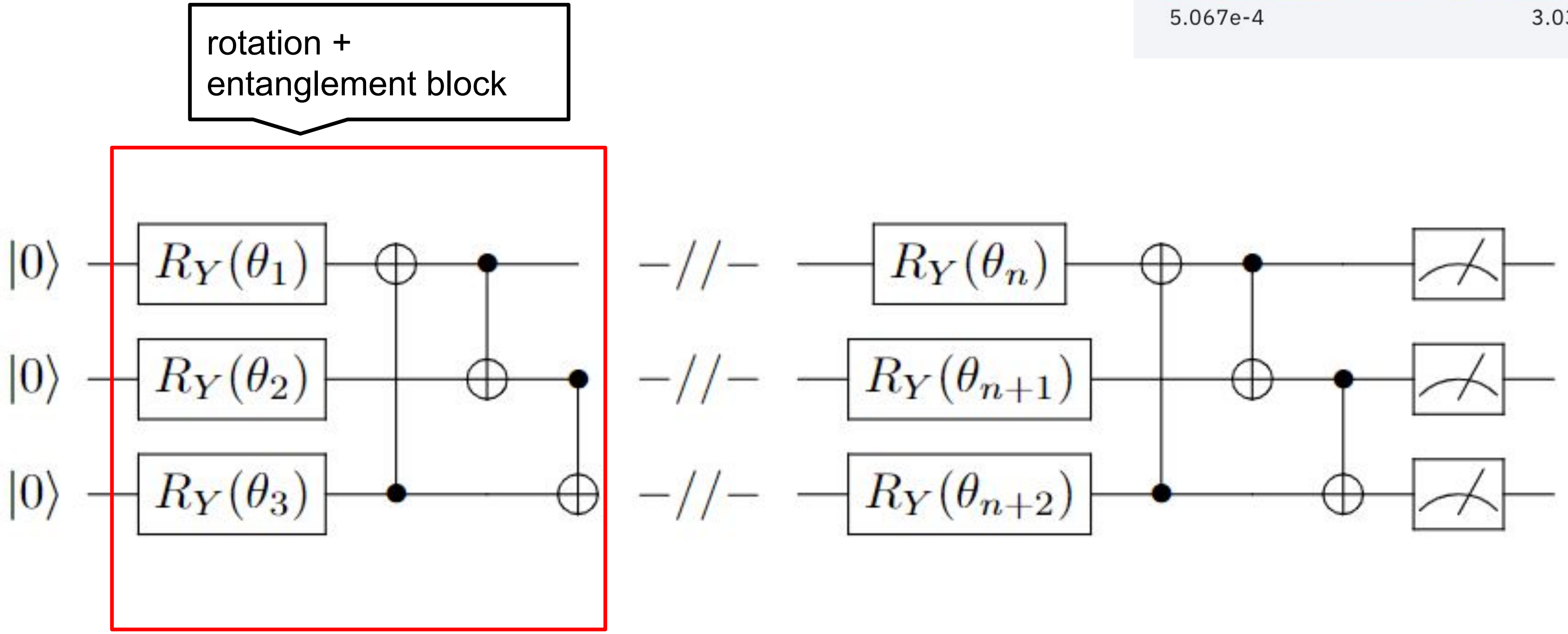
Quantum devices are noisy

Circuits need mapping to a real device

Using IBM Qiskit with an ideal simulation for now

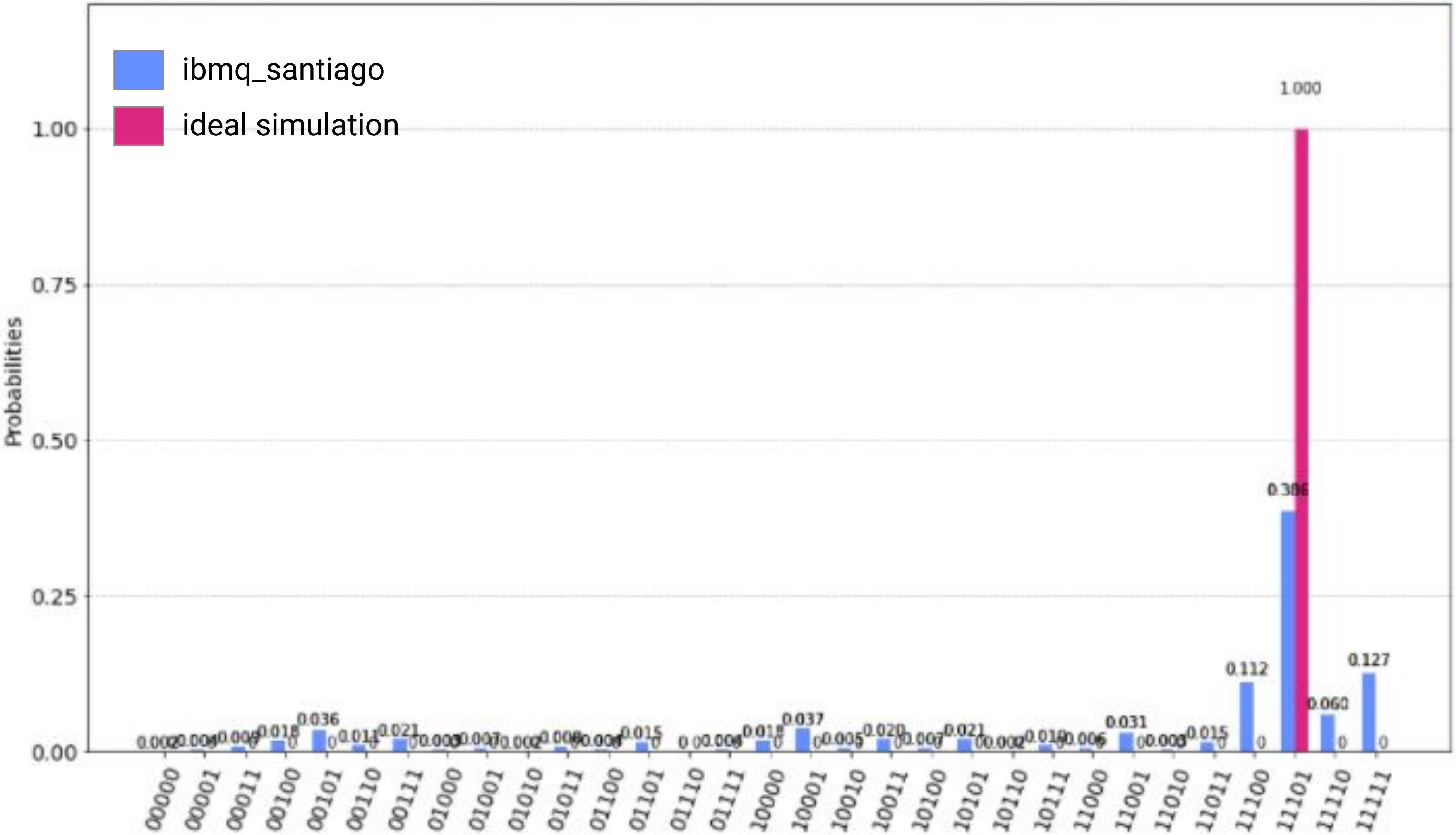


Source: qiskit.org



Solving a QUBO on a real quantum device

Result on the 5-qubits device ibmq_santiago



Computational feasibility

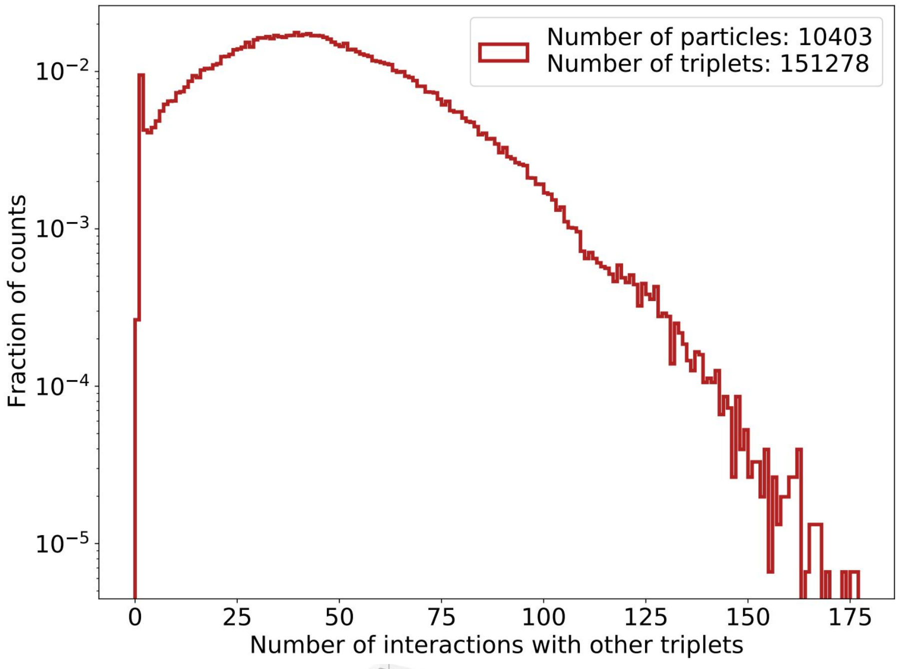
Restricting to a smaller example

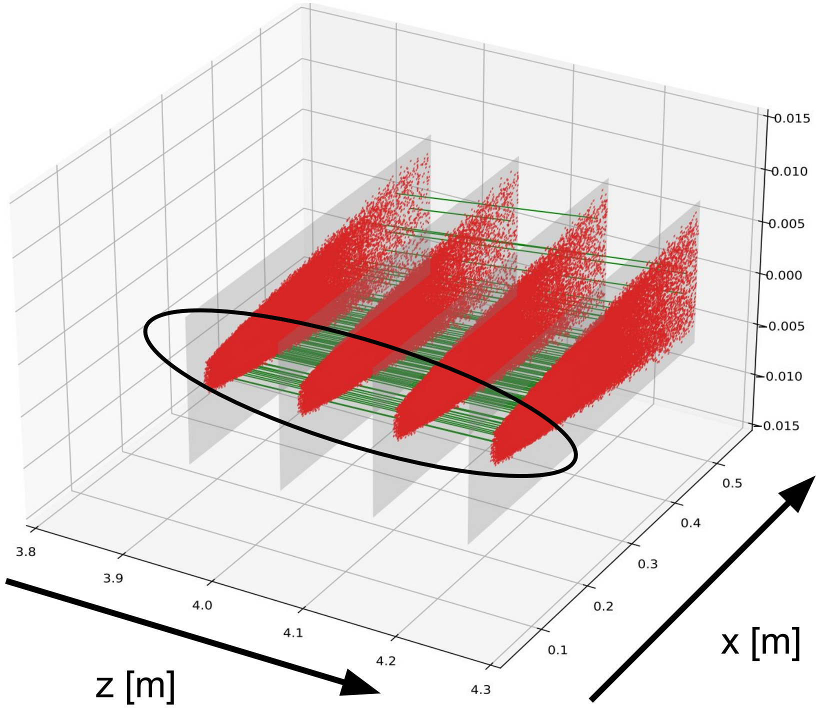
Real quantum devices are still rather small to process big hamiltonians

Proving the concept with 500 and 1000 particles with the highest energies respectively

Simulation of a quantum device consumes a lot of computational resources

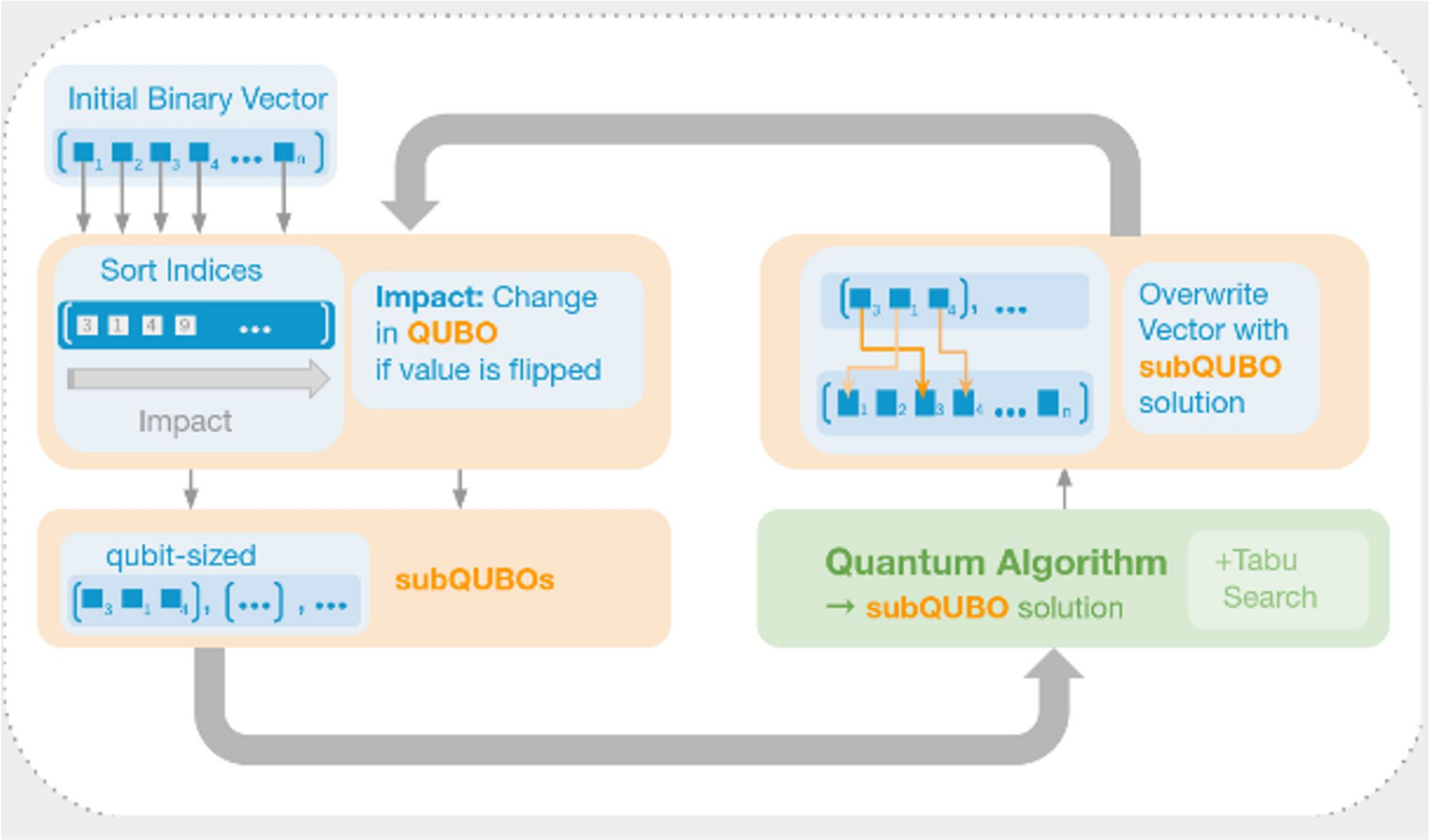
→ Using 7 qubit system and introduce subQUBOs concept





SubQUBOs

Partitioning the QUBO into small pieces



Source: arXiv: 2202.06874

Performance

Track level efficiency and fake rate

Define a correct track as all four hits matched to the same generated particle

$$\text{Efficiency} = \frac{N_{\text{tracks}}^{\text{matched}}}{N_{\text{tracks}}^{\text{generated}}} \qquad \text{Fake rate} = \frac{N_{\text{tracks}}^{\text{fake}}}{N_{\text{tracks}}^{\text{reconstructed}}}$$

Comparing conventional tracking (CKF), GNN and quantum approach for different ξ-values

Exact solution for the QUBO via diagonalizing the hamiltonian (Eigensolver)

→ Only computational feasible for subQUBOs or very small hamiltonians (~20 qubits)

→ Using Eigensolver to evaluate performance of the global optimization algorithm (subQUBO approach)

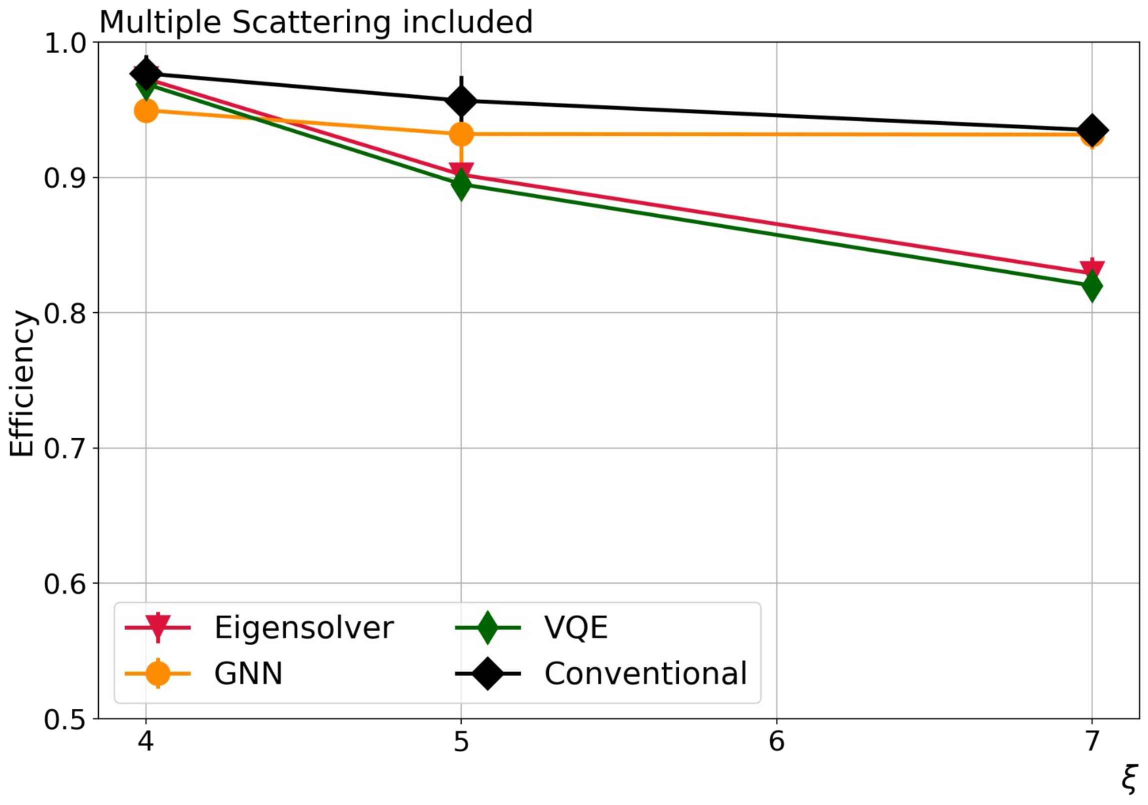
Noisy simulation and computation on a real quantum device were only tested on a smaller scale

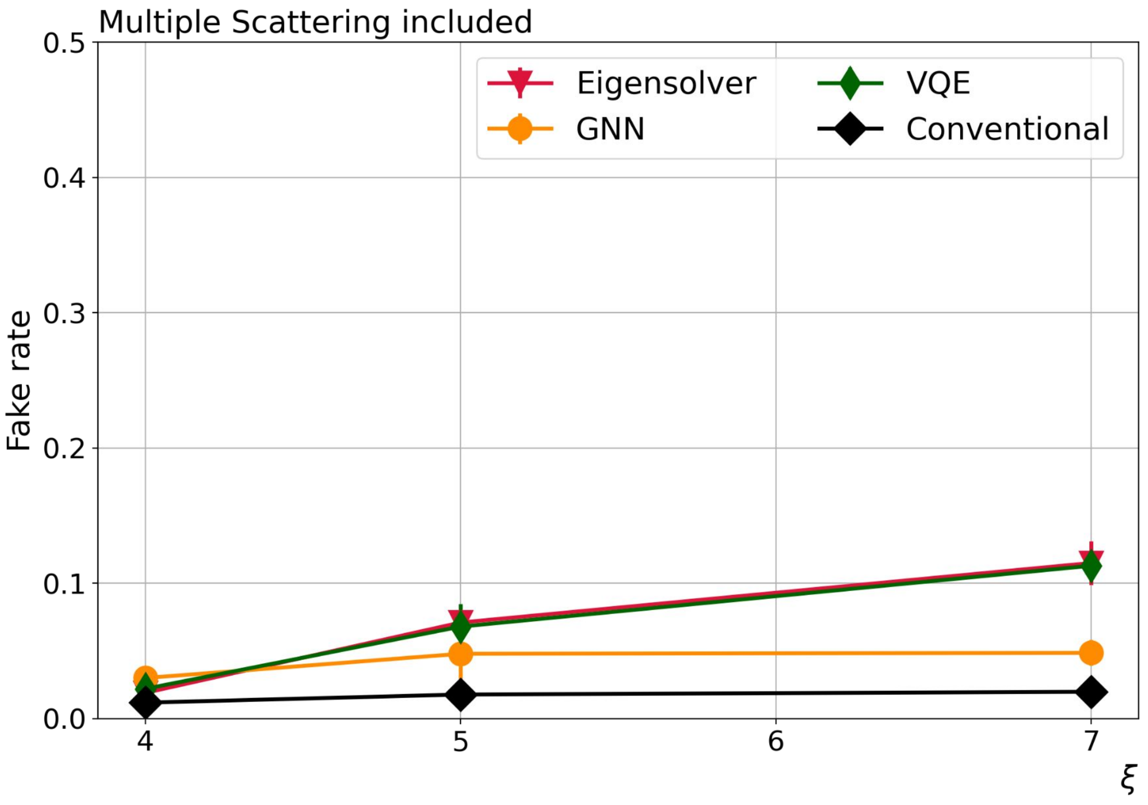
500 tracks from simplified simulation

Phase 0 - 40TW laser

Eigensolver: performance limit with respect to the global optimisation algorithm

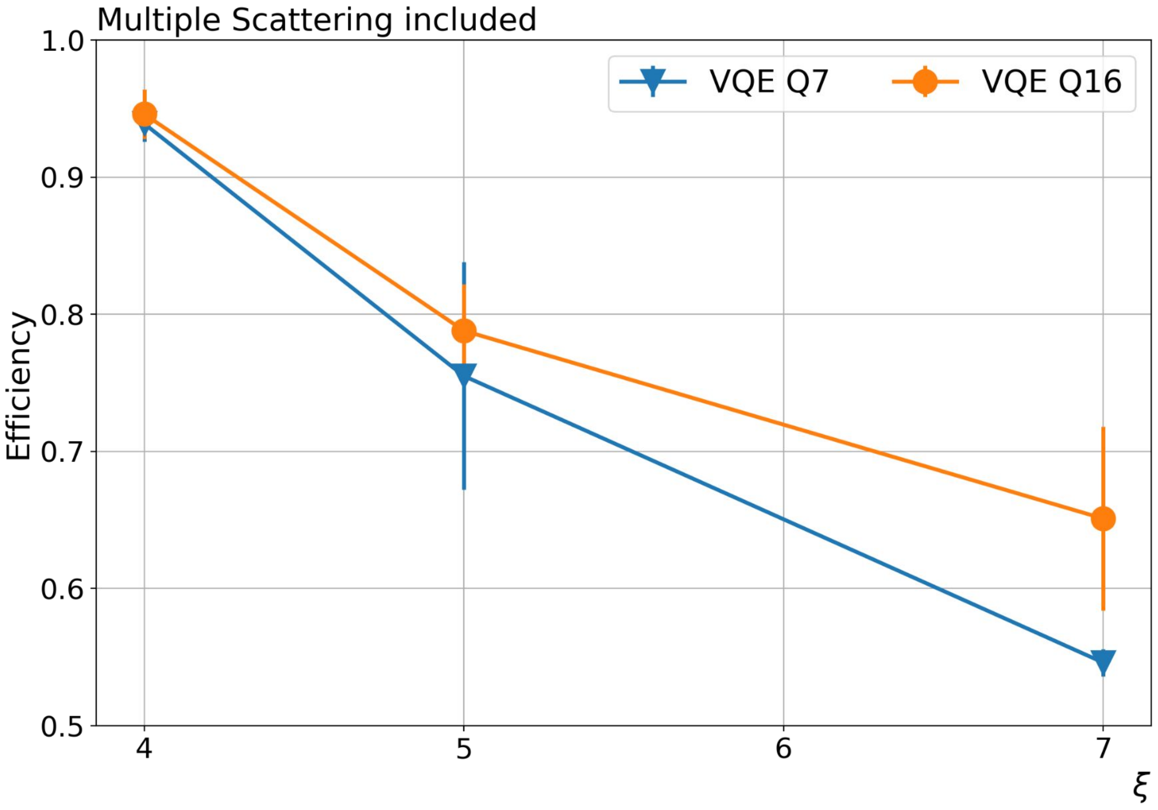
VQE: performance limit with respect to the Eigensolver

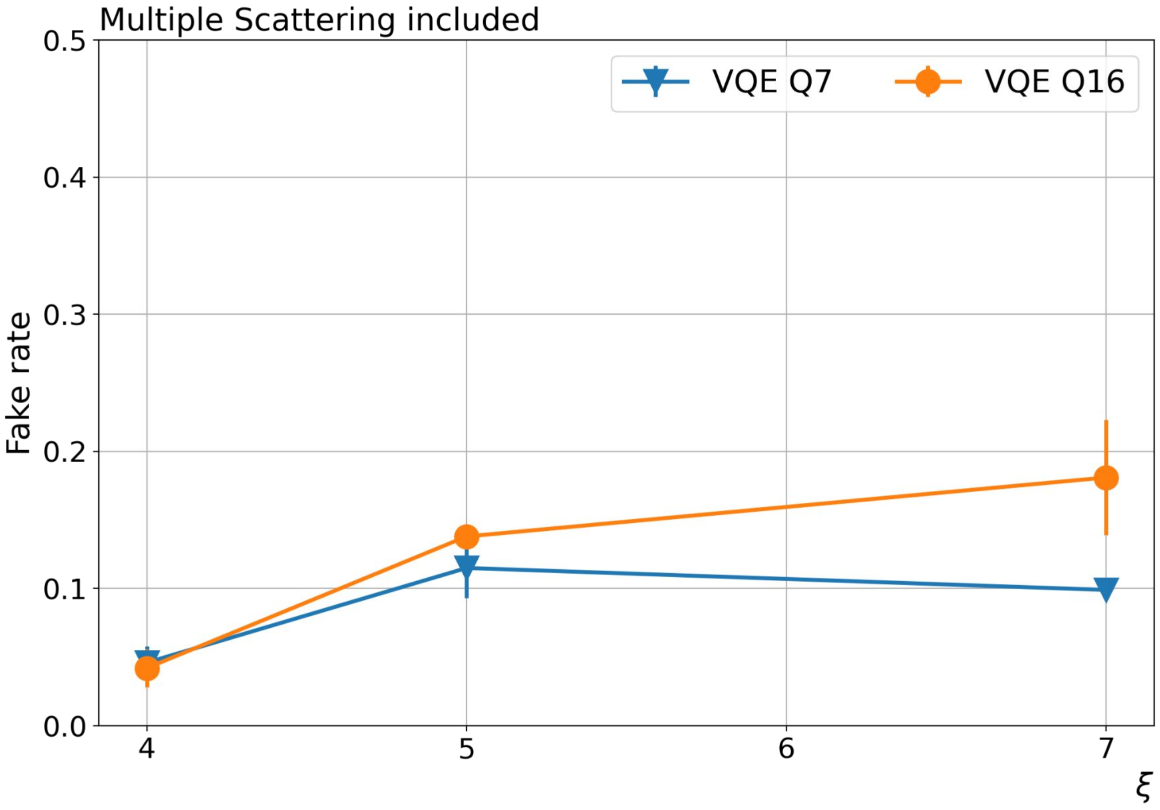




SubQUBO size dependency for 1000 tracks

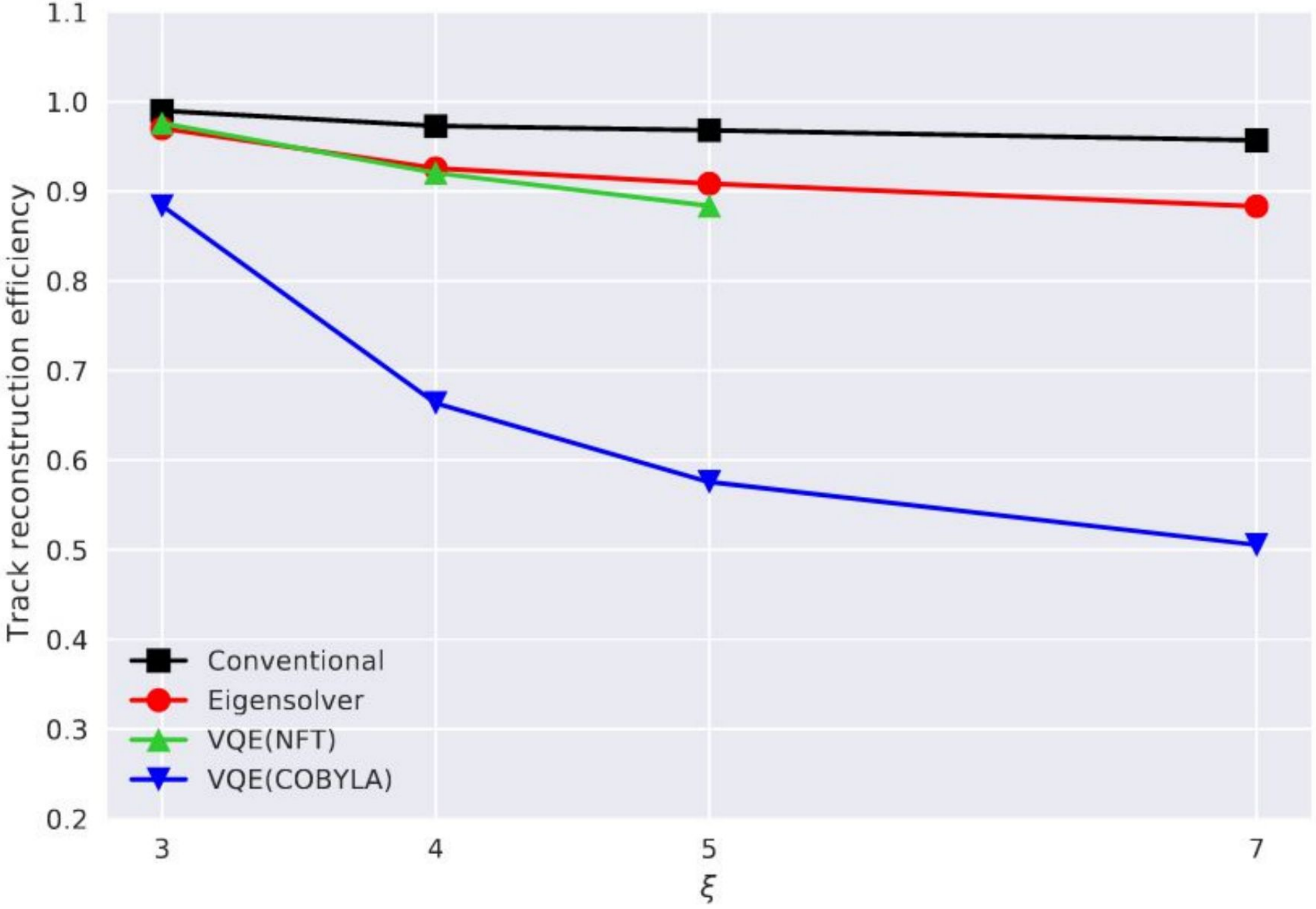
Phase 0 - 40TW laser





Choice of optimizer for 500 tracks

Phase 1 - 350TW laser

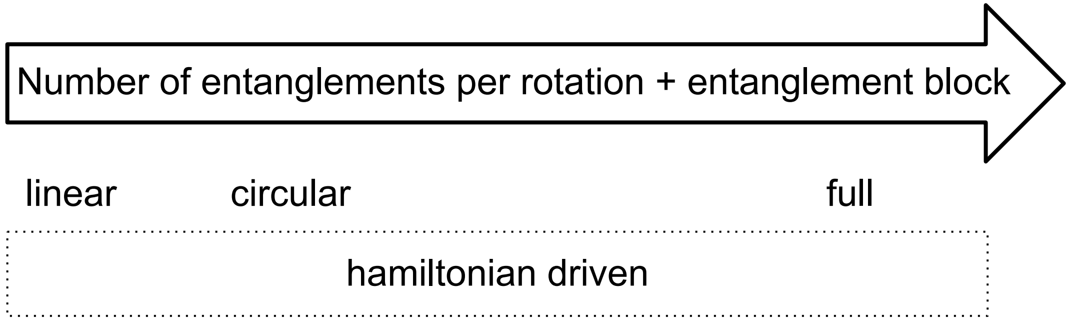


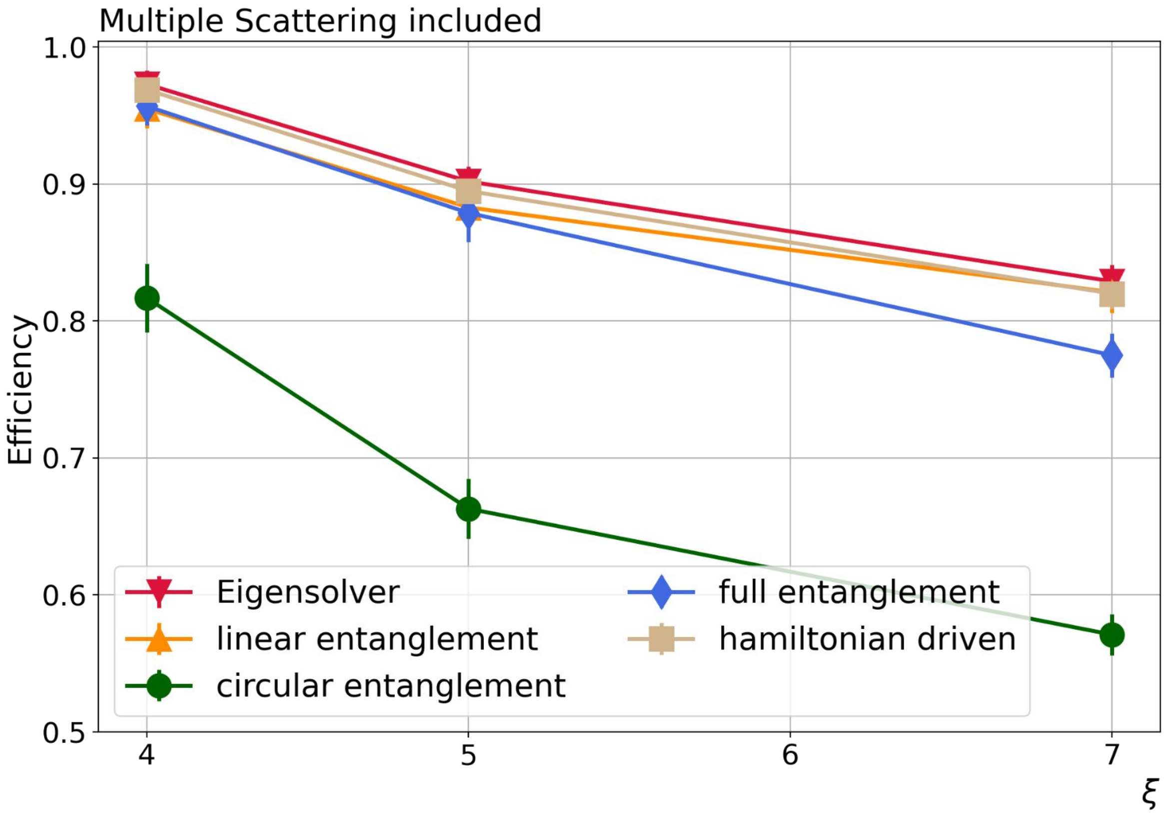
NFT: Nakanishi-Fujii-Todo

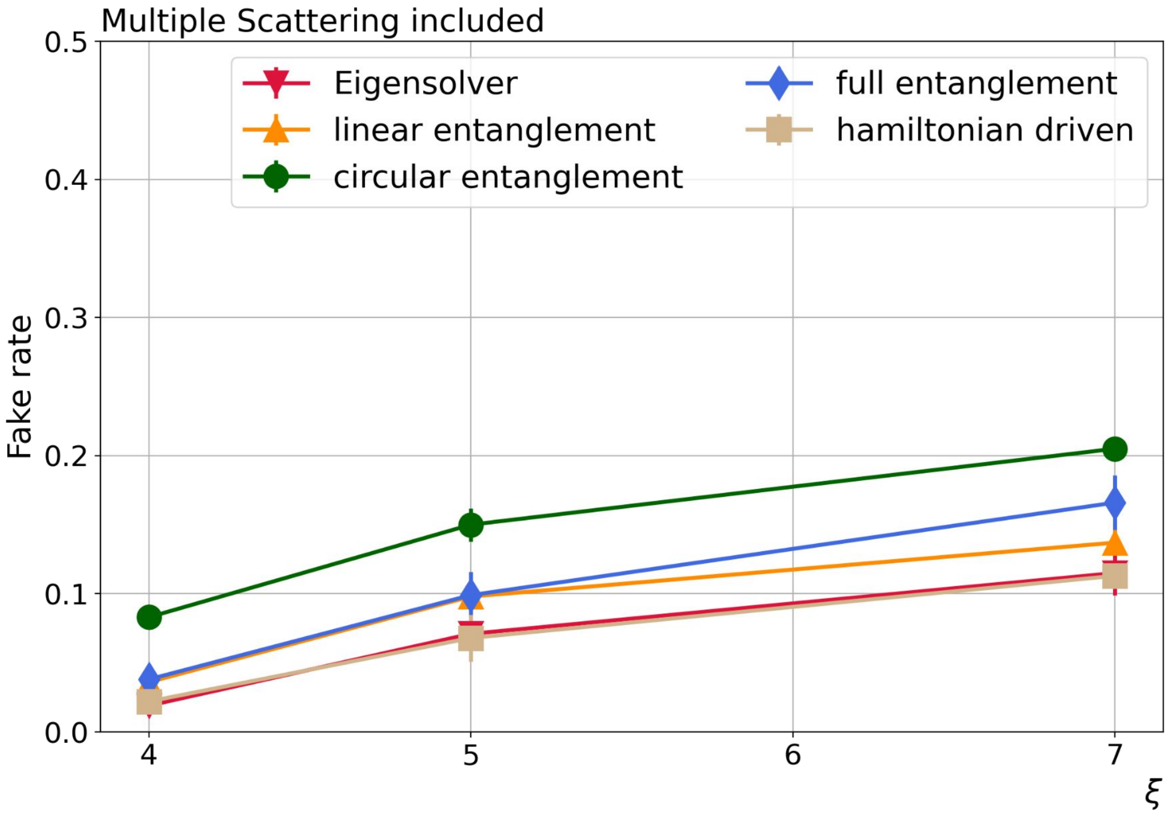
Cobyla: Constrained optimization by linear approximation

Ansatz circuit variations

Varying entanglement structure - Phase 0







Summary

Our conclusions

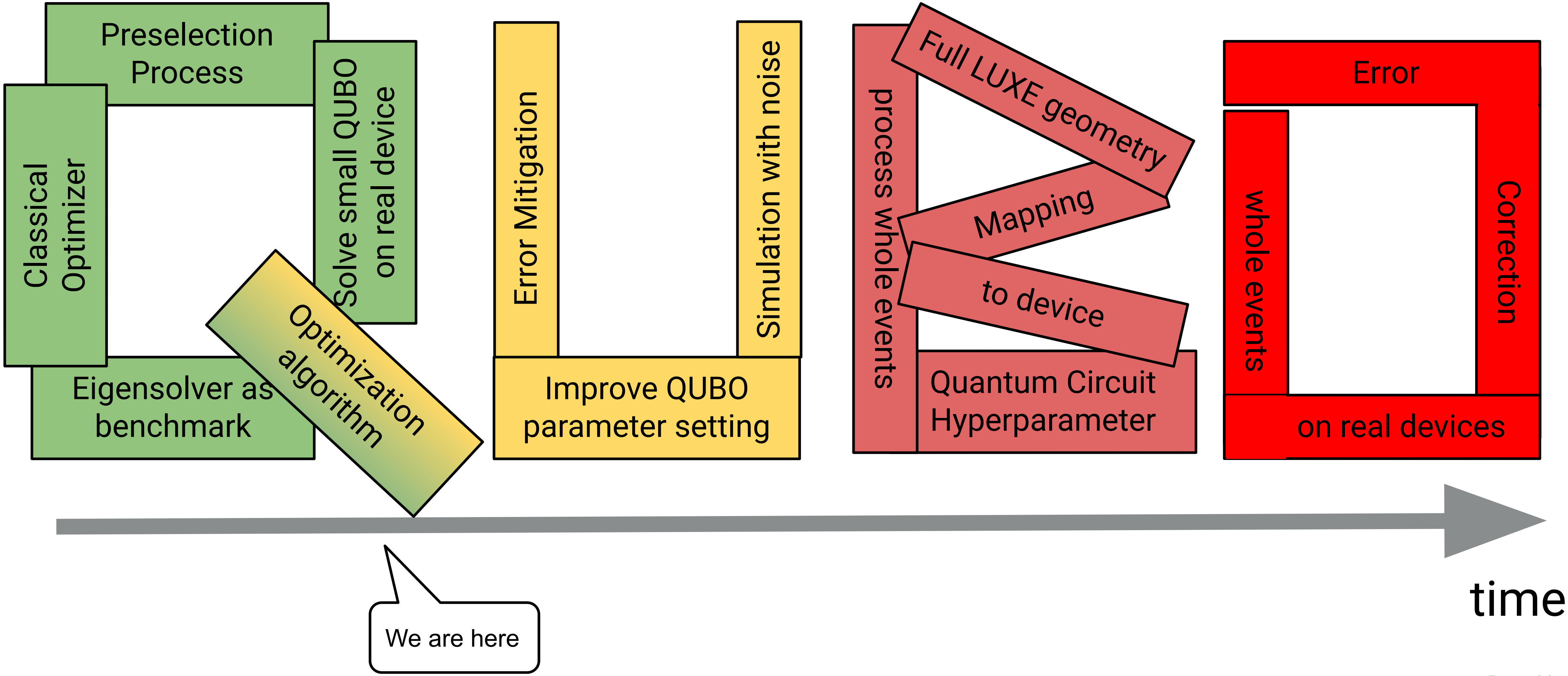
Track reconstruction with hybrid quantum-classical algorithms is possible and has great potential.

At the moment there are limiting factors e.g. the size and availability of quantum devices which makes workarounds necessary (subQUBOs).

There are a lot of parameters to optimize so we are confident to match with GNN and conventional tracking in the future.

Outlook

What's done, what's next?



Thank you very much!

Backup 1: GNN Details

- ADAM optimizer with learning rate: 1e-3 and batch size: 1
- Weighted binary cross entropy loss function. Weights are obtained after preprocessing.

  e.g. ξ=5.0 with NS and 500 HE → Fake edge weights: 0.587, True edge weights: 3.369

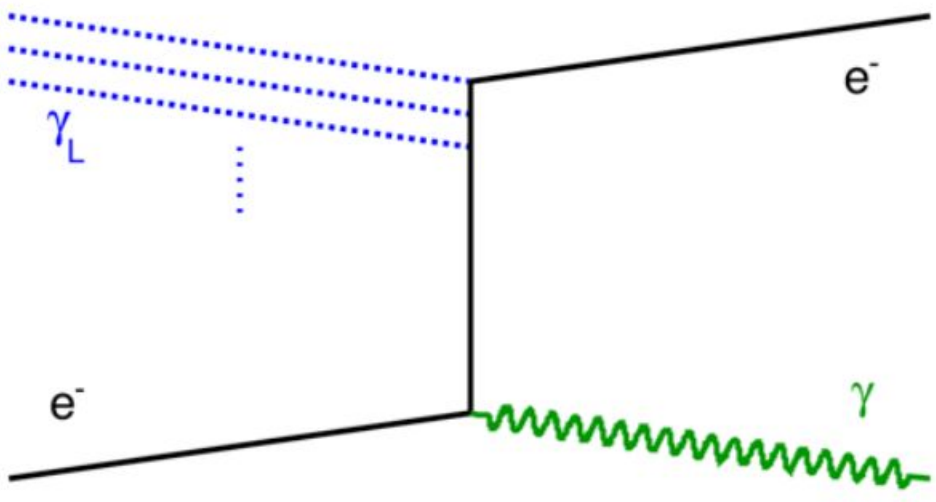
- For each setting 100 BXs are used, Train set: 90 BX, Test set: 10 BX
- GNN implemented with 4 iterations and 128 hidden dimension, following definitions of: arXiv:1810.06111

→ The implementation followed is one of the first proposals, meaning that there is a lot of room for improvement.

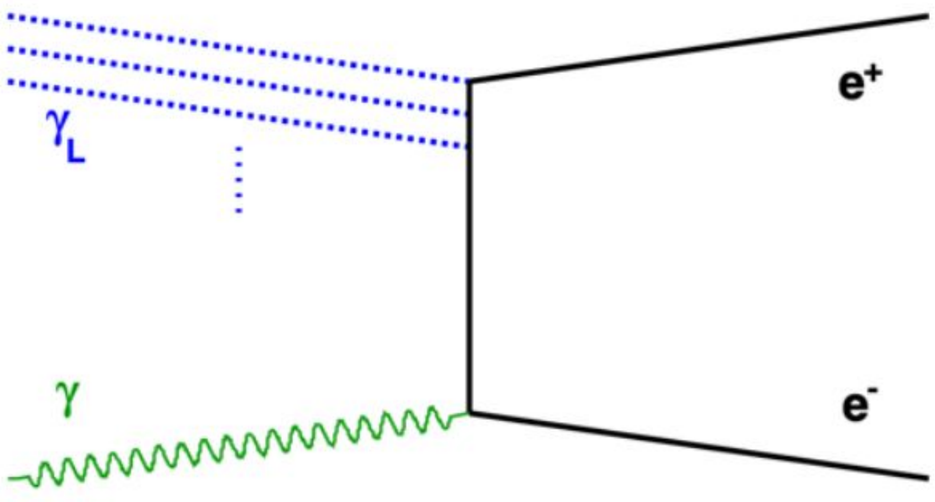
→ Track building is performed by choosing the shared hit with a larger output value. More sophisticated algorithms can be employed to further improve the performance.

Backup 2: LUXE processes

non-linear Compton scattering

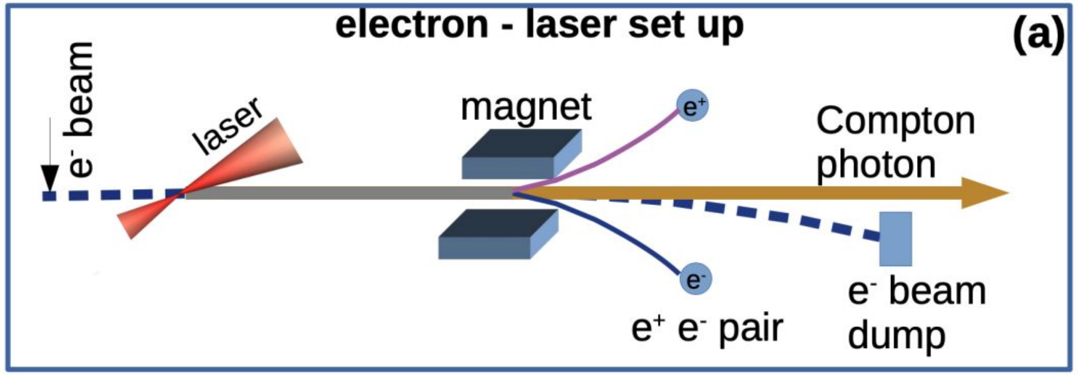


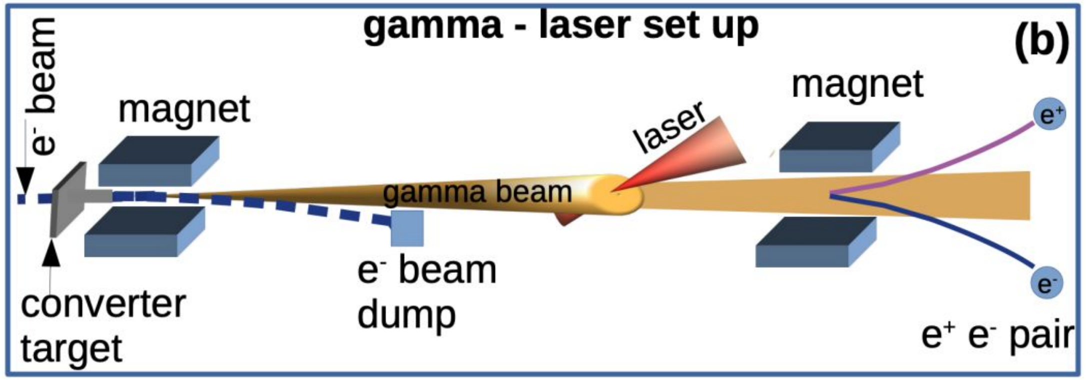
Breit-Wheeler pair production

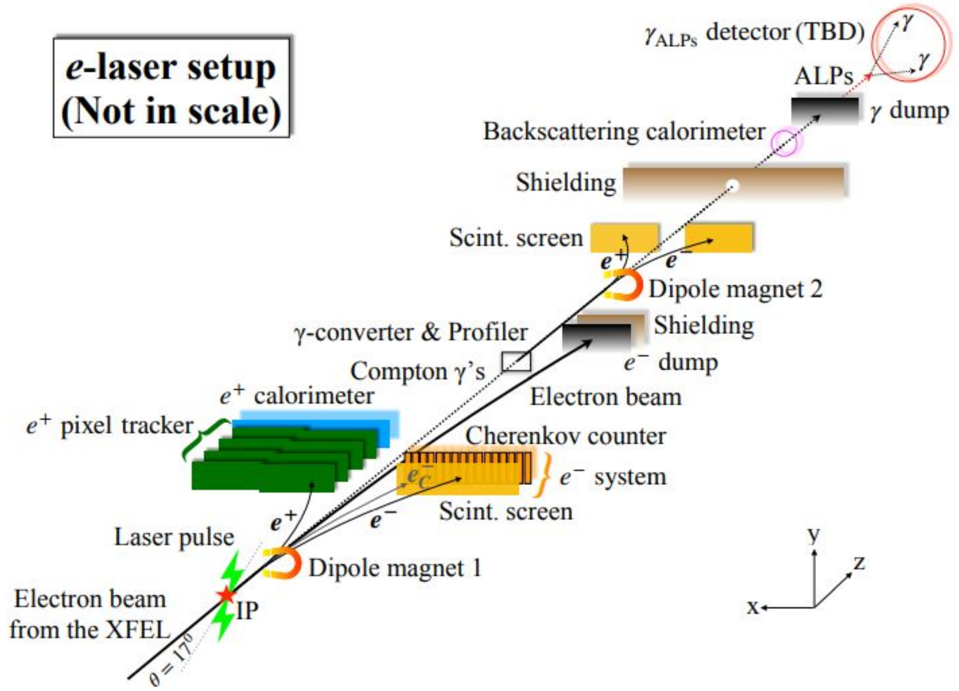


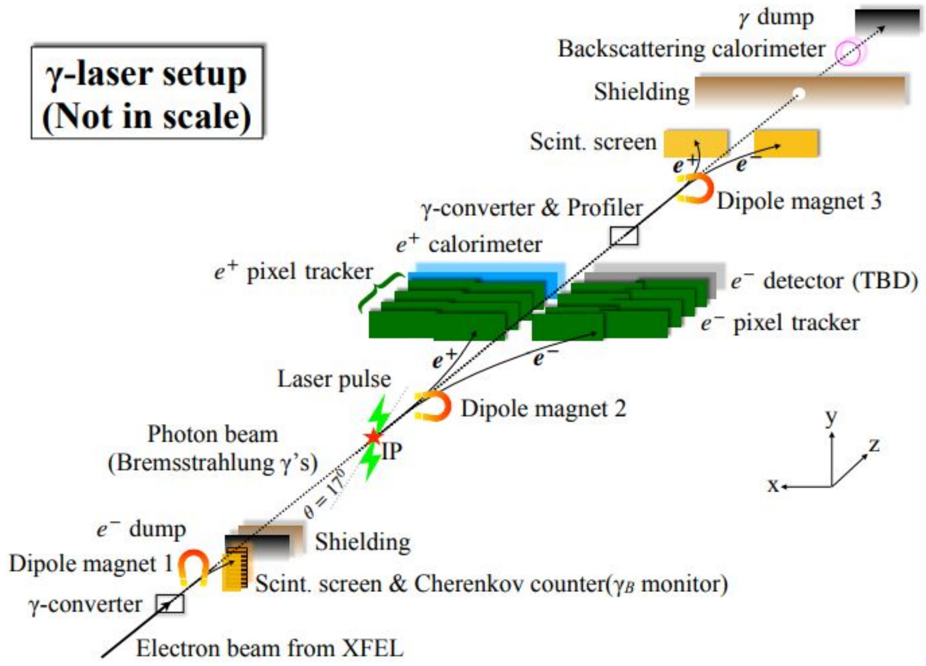
Source: LUXE CDR

Backup 3: LUXE setups









Source: LUXE CDR

Backup 4: Triplet interactions vs. xi (phase 0)