Quantum Computing at DESY and the LUXE Experiment

Federico Meloni (DESY)

World Quantum Day 2023

With special focus on arXiv: 2304.01690

Quantum algorithms for charged particle track reconstruction in the LUXE experiment

Arianna Crippa[1,2], Lena Funcke[3,4], Tobias Hartung[5], Beate Heinemann[6,7], Karl Jansen[1,8], Annabel Kropf[6,7], Stefan Kühn[1,8], Federico Meloni[6], David Spataro[6,7], Cenk Tüysüz[1,2] and Yee Chinn Yap[6]

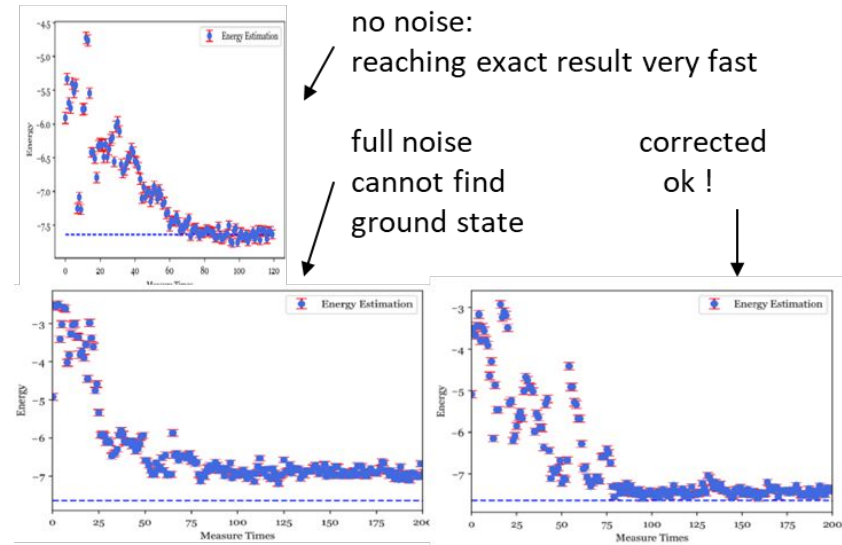
[1] Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany
[2] Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany
[3] Transdisciplinary Research Area "Building Blocks of Matter and Fundamental Interactions" (TRA Matter) and Helmholtz Institute for Radiation and Nuclear Physics (HISKP), University of Bonn, Nußallee 14-16, 53115 Bonn, Germany
[4] Center for Theoretical Physics, Co-Design Center for Quantum Advantage, and NSF AI Institute for Artificial Intelligence and Fundamental Interactions, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
[5] Northeastern University - London, Devon House, St Katharine Docks, London, E1W 1LP, United Kingdom
[6] Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
[7] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3a, 79104 Freiburg, Germany
[8] Computation-Based Science and Technology Research Center, The Cyprus Institute, 20 Kavafi Street, 2121 Nicosia, Cyprus

From general methods…

Increase the reliability of Quantum Computing Calculations

DESY has a rich (and expanding) set of quantum computing activities

$$H = \sum_{i=1}^{N} \beta \left[\sigma_x(i)\sigma_x(i+1) + \sigma_y(i)\sigma_y(i+1) + \sigma_z(i)\sigma_z(i+1)\right] + J\sigma_z(i)$$



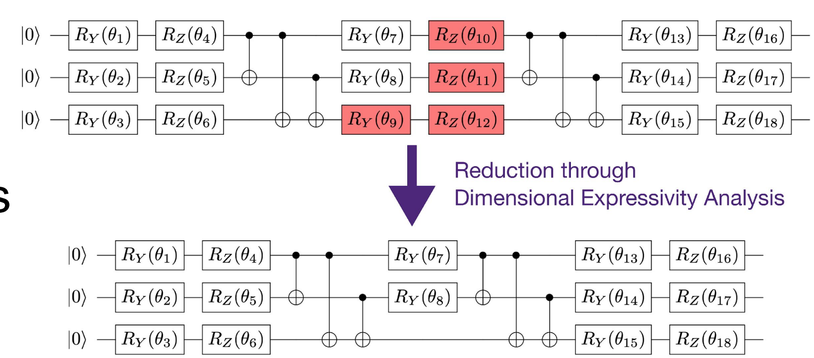
Error Mitigation in VQS

1-Dimensional Heisenberg model

- Very sensitive to QC noise
- Developed error mitigation methods

Optimization of Dimensional Expressivity of a Quantum Circuit

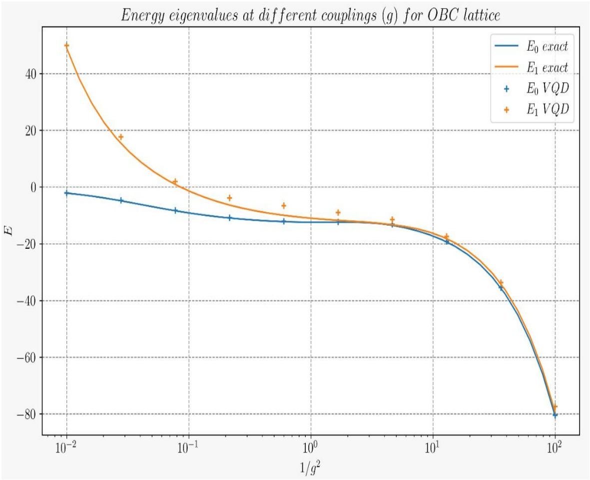
- Dimensional Expressivity Analysis
- Generate as many/complicated states as possible as little gates as possible



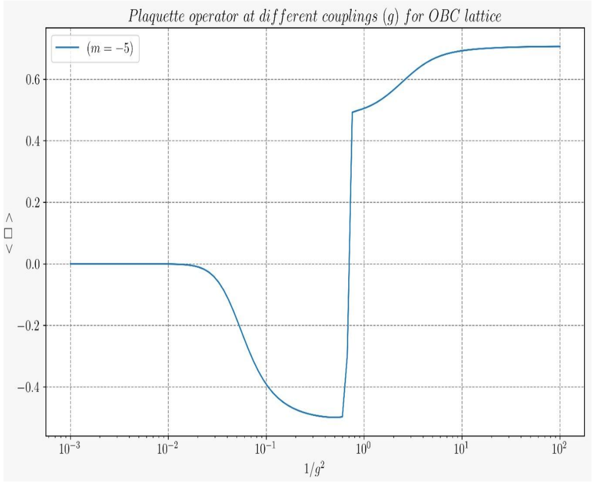
… to theory and applications

From QED in 2+1 dimensions to simulations for HEP

Variational Quantum Simulations (VQCS) for QED



Particle Mass
$\Delta = E_1 - E_0$

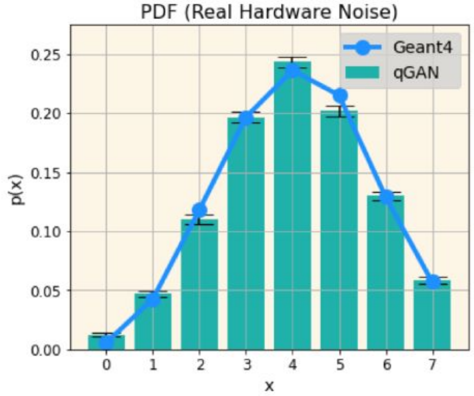


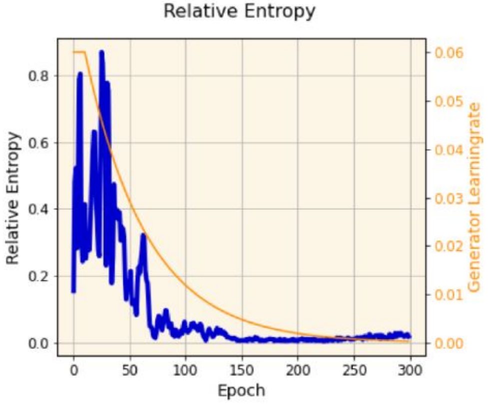
Detecting a phase transition at negative mass

- **not possible with MC methods**

Methods and Quantum Machine Learning applications

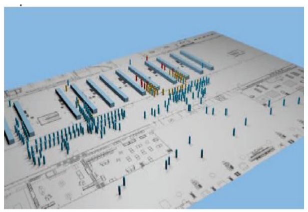
- Robust against noise
- Q-GAN simulations for detectors at High-Luminosity LHC

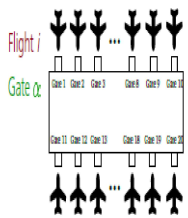


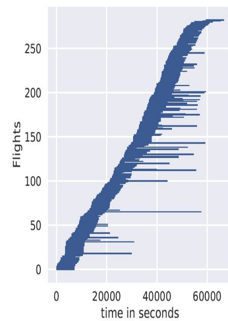


Classical optimization problems

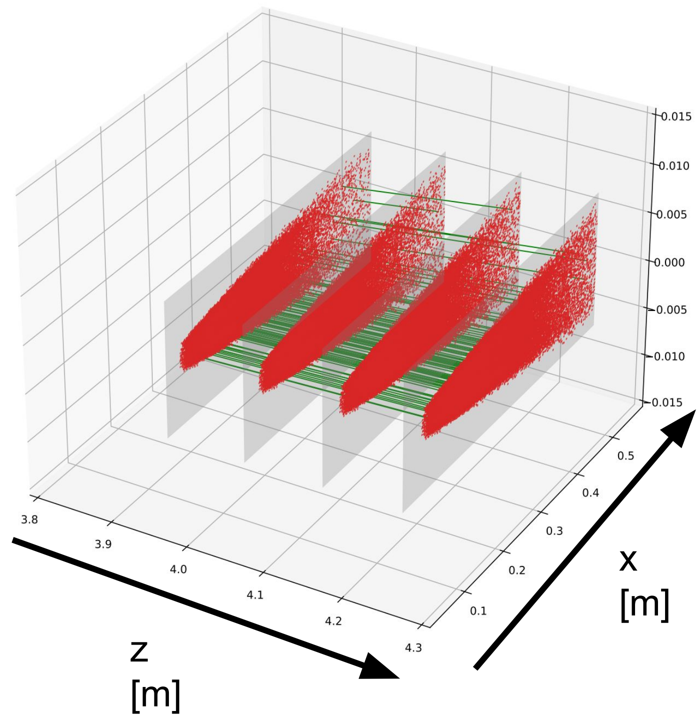
From logistics to particle tracking







$$H = \sum_{j=1}^{n} Q_{jj}\sigma_j^z + \sum_{\substack{j,k=1 \\ j<k}}^{n} Q_{jk}\sigma_j^z \otimes \sigma_k^z$$



Flight Gate Assignment

find lowest energy ⇔ shortest path

- Same mathematics for problems in traffic, logistics, aerospace, ...

Particle tracking

We only observe particles through their interaction with detectors

- Need to single out each particle's trajectory from a cloud of hits

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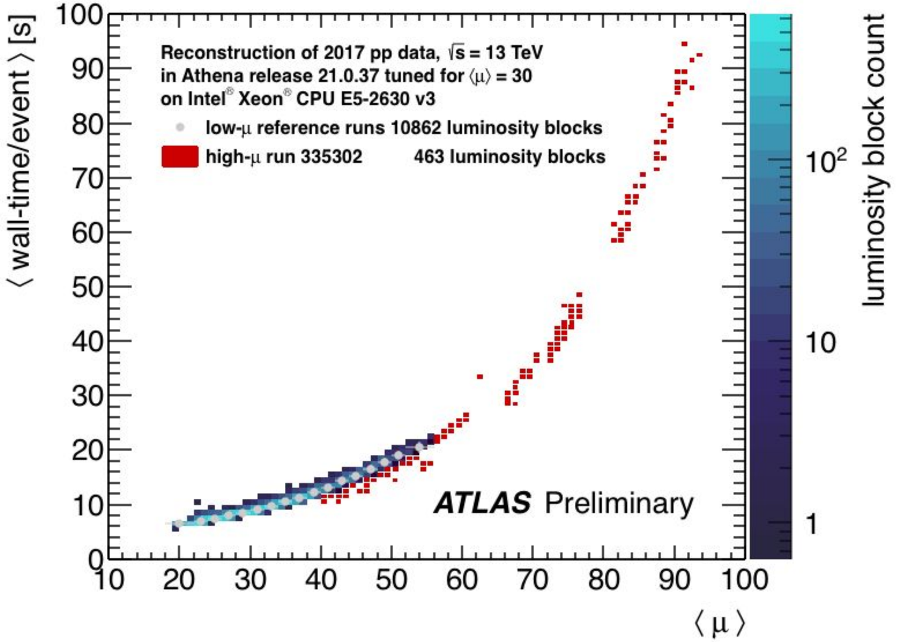
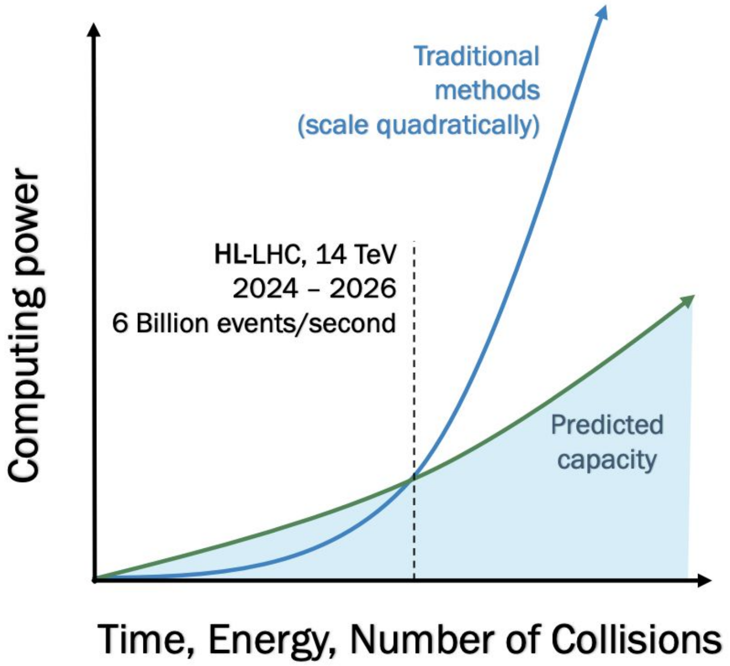
Why study quantum algorithms for tracking?

Tracking is a **hard combinatorial problem**

The CPU needs of HEP will keep growing in the coming years

- We are looking for efficient algorithms and technologies to go forward



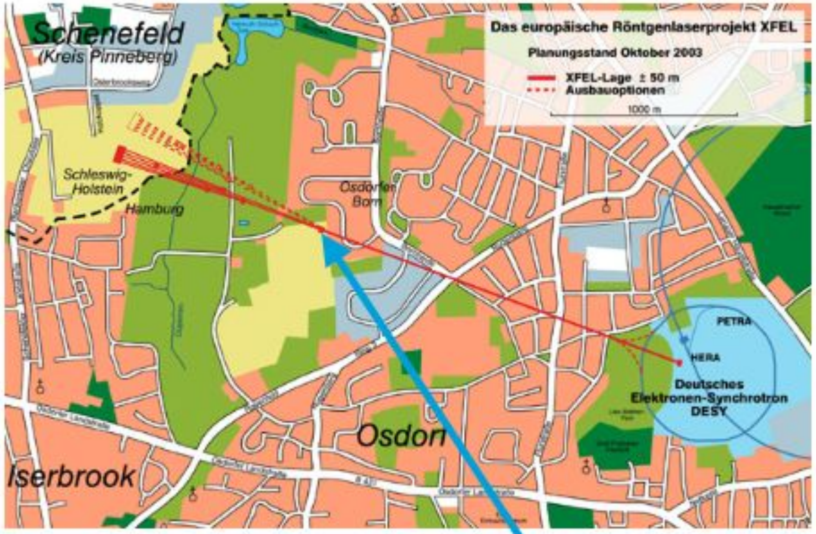


Sketch credit: X. Ju, S. Murnane

The LUXE experiment

LUXE

LASER Und XFEL Experiment



LUXE is a new experiment at DESY and Eu.XFEL

- Collisions of electron beam and a high-power laser
- **First time study non-perturbative QED**

The extreme dynamic range (10^{-4} - 10^{6} particles per event) makes LUXE a **good case study for other colliders**

LUXE (worst case) = **100 hits/mm^2**

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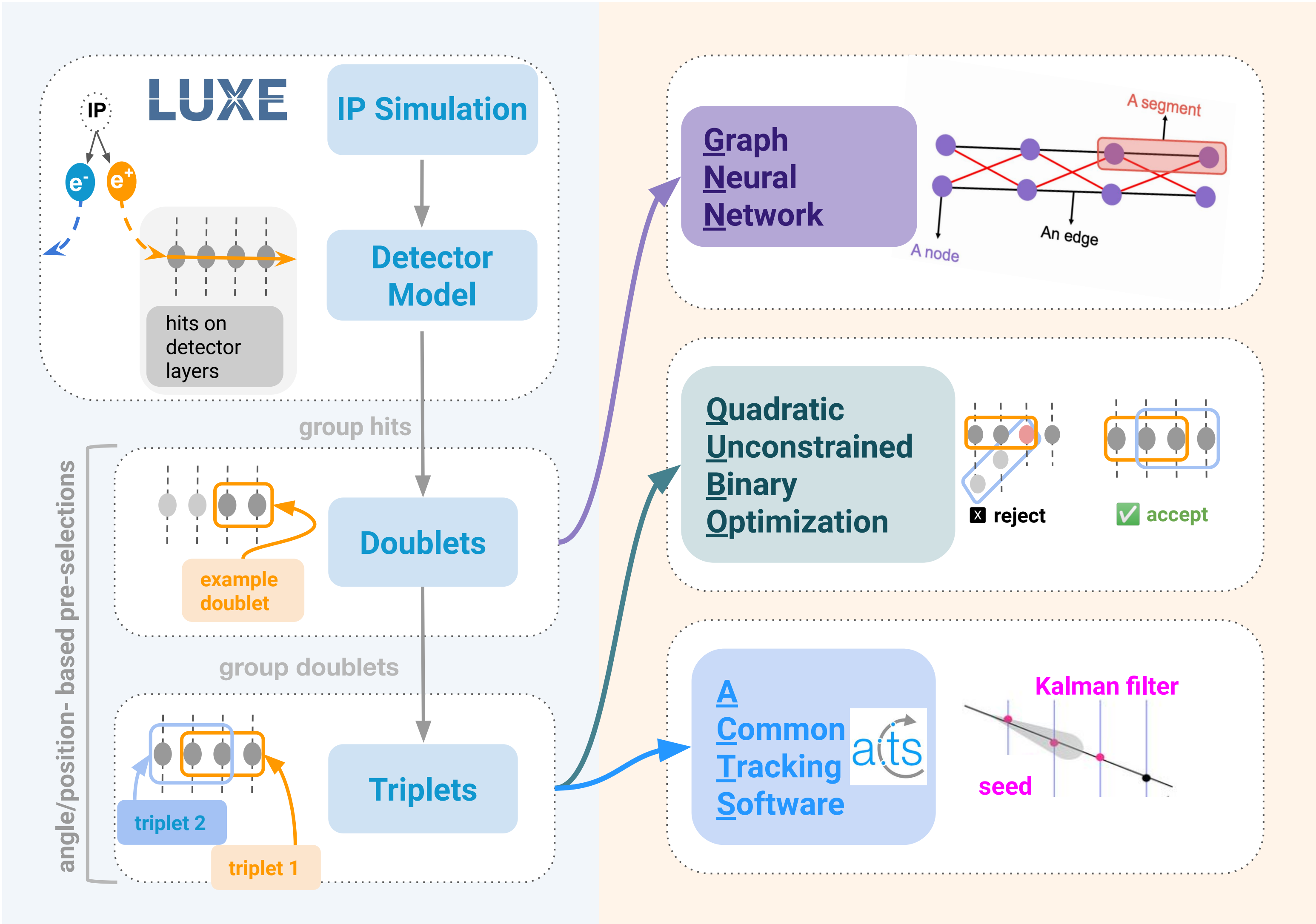
Detector Reference	MCD	Hit Density [mm^{-2}] ATLAS ITk	ALICE ITS3
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

Track reconstruction

Comparing different approaches

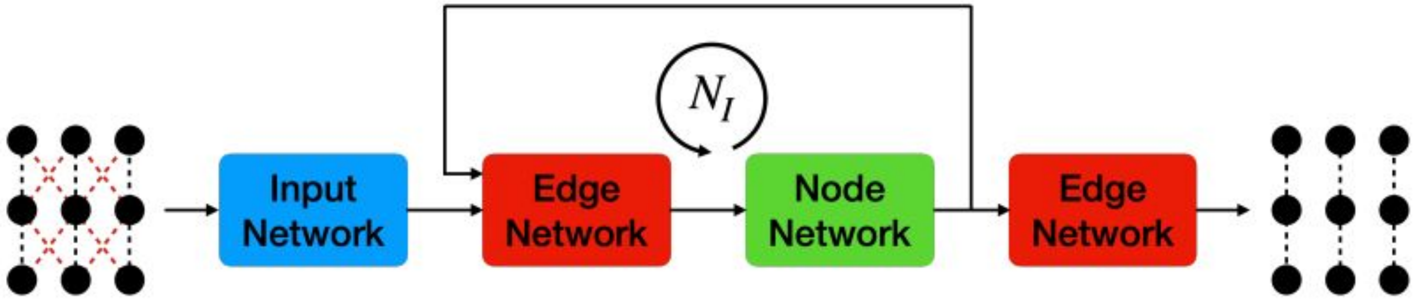


Hep.TrkX
1810.06111
Exa.TrkX
2103.06995
Q.TrkX
2109.12636

1902.08324
2202.06874
2304.01690

ACTS
2106.13593

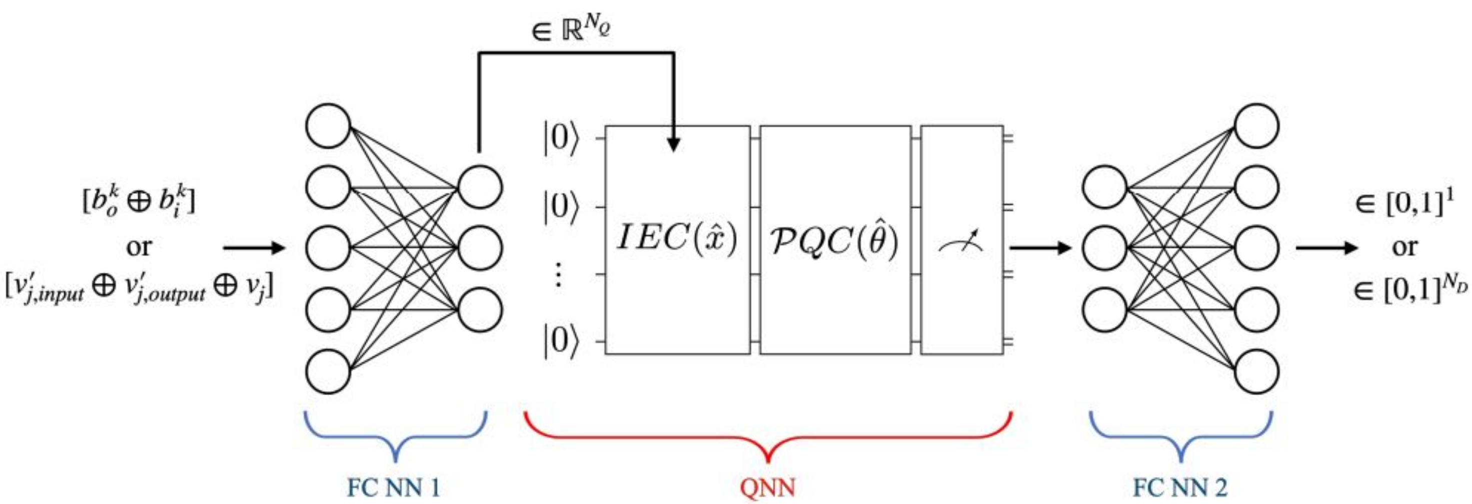
Quantum Graph Neural Network



Input network encodes information (10 hidden features)

Edge and node nets applied 4 times (as many as the tracker layers)

Retain edges with scores above fixed threshold

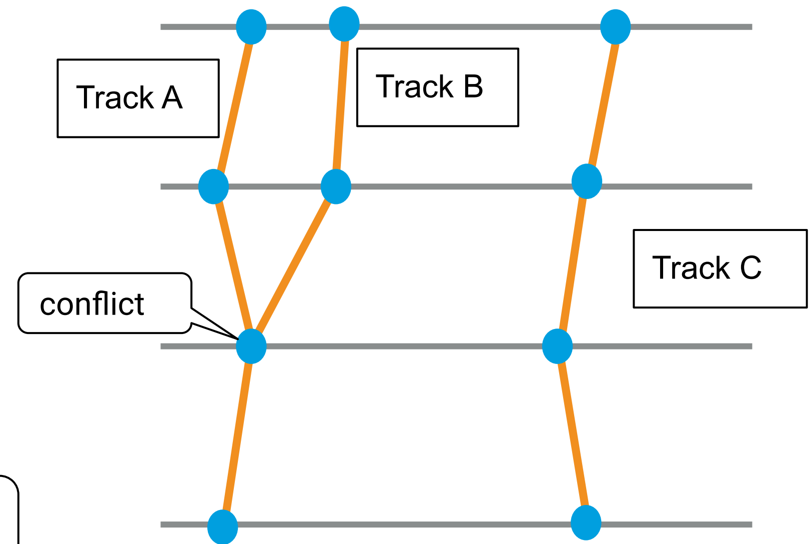


Quadratic Unconstrained Binary Optimisation

Each triplet is represented as a binary quantity $T_i, T_j \in \{0, 1\}$

Minimising an objective function equals to finding the optimal solution

The selected T_i are used to form tracks



"connection term" "quality term"

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

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

O can be mapped to an Ising Hamiltonian and evaluated with a quantum computer

$$T_i \rightarrow (1 + Z_i)/2$$

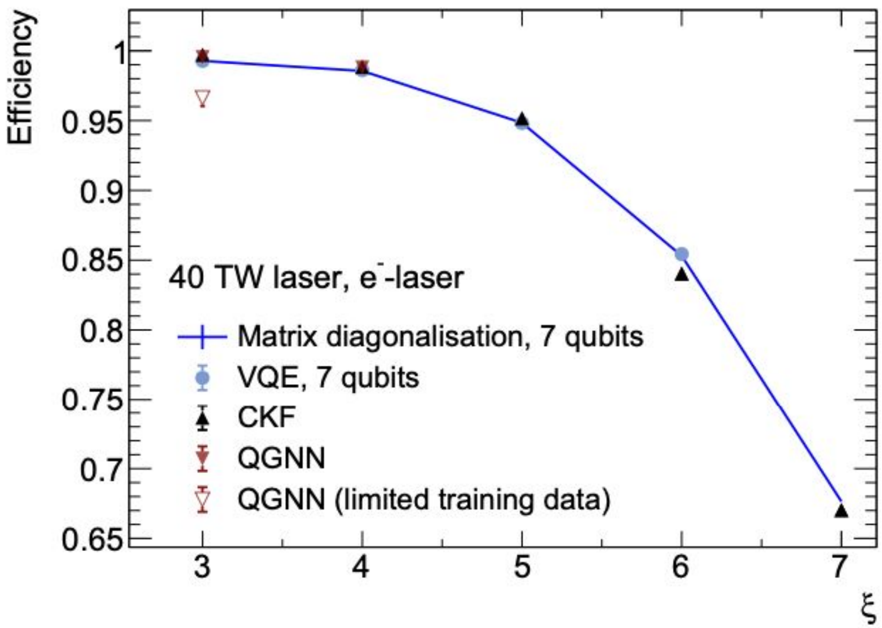
Find ground state with VQE!

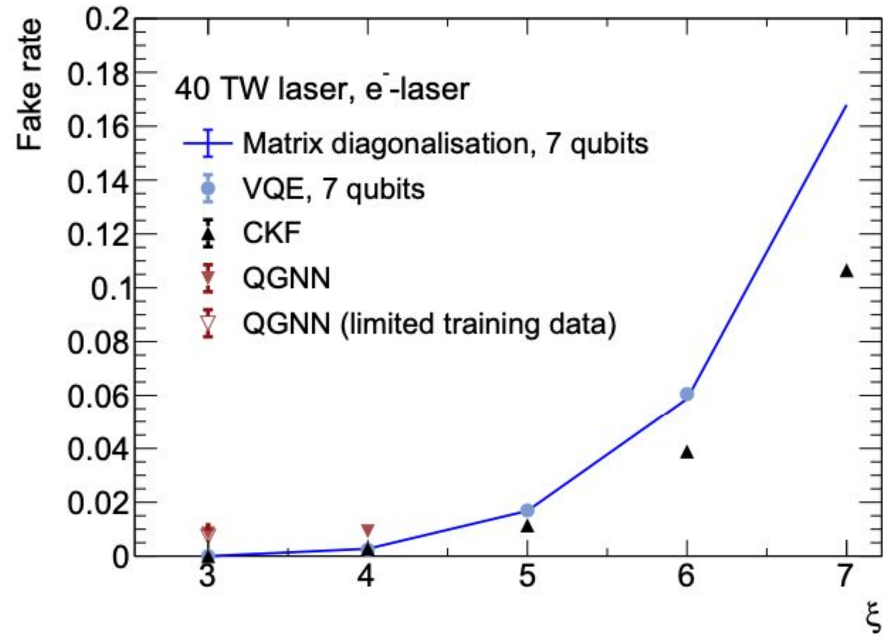
Algorithmic performance

Based on ideal classical simulations of quantum circuits

$$\text{Efficiency} = \frac{N^{\text{matched}}_{\text{tracks}}}{N^{\text{generated}}_{\text{tracks}}}$$

$$\text{Fake rate} = \frac{N^{\text{fake}}_{\text{tracks}}}{N^{\text{reconstructed}}_{\text{tracks}}}$$





Excellent performance, in line with state-of-the-art classical tracking

- Quantum algorithms have higher efficiency but ~2x fakes

Not all methods available for each value of ξ (due to computational limitations)

Performed also tests with quantum hardware (ibm_nairobi)

Summary

LUXE will probe a new regime of quantum physics!

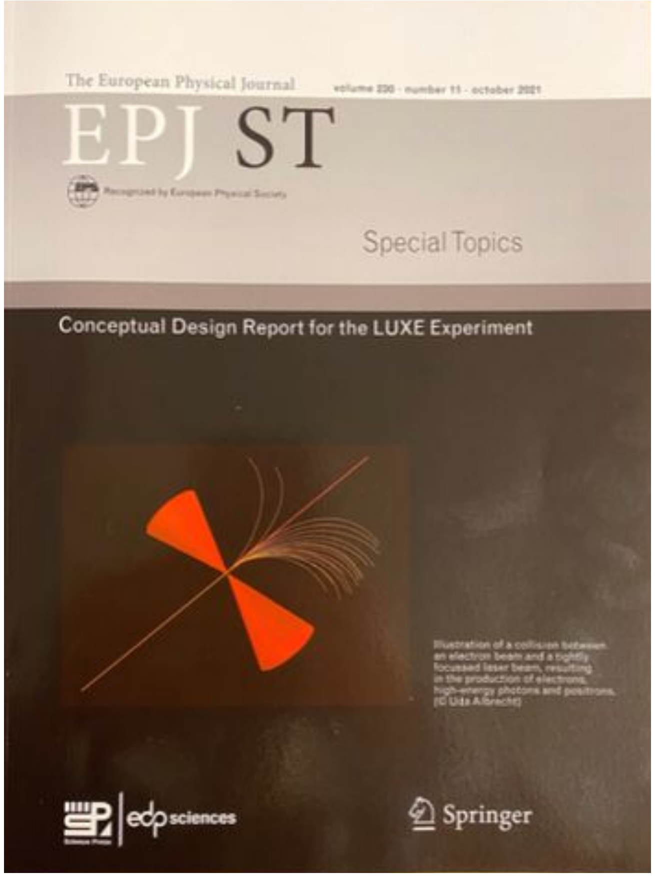
- Huge particle rate range allows to develop and test new reconstruction algorithms

Demonstrated the feasibility of tracking using quantum algorithms

- Similar performance as classical tracking

Next: optimise for larger and real devices

Plenty of space to experiment with new ideas!



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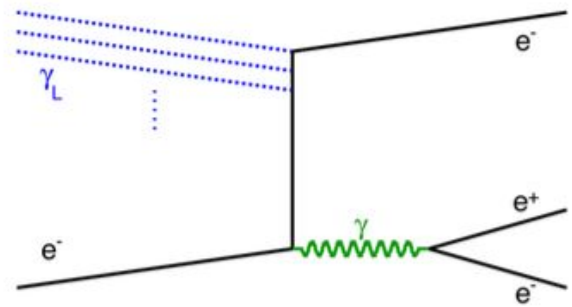
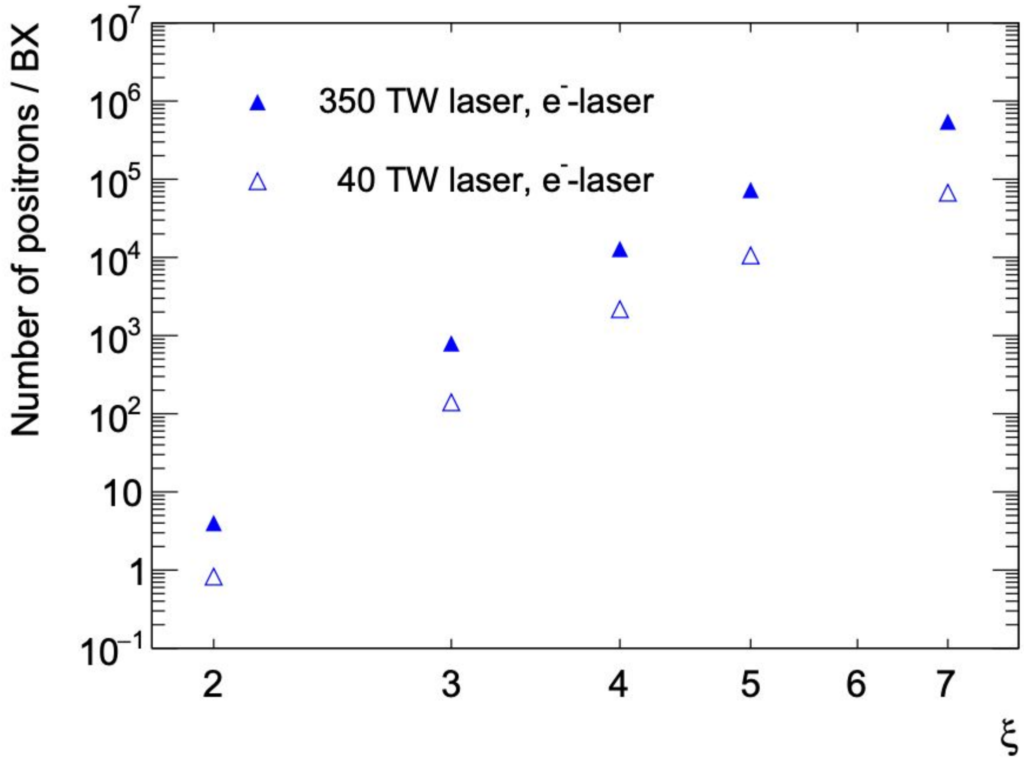
Thank you!

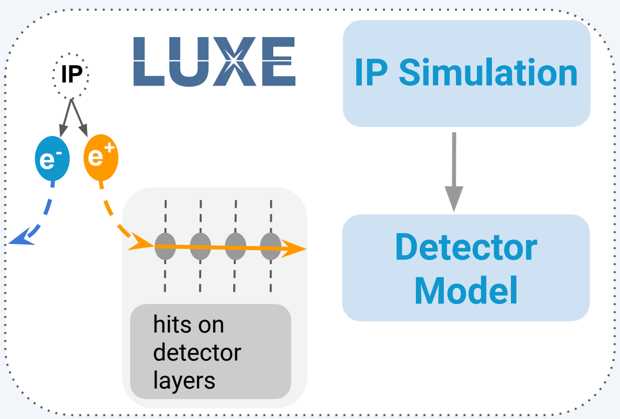
Key observable

$$e^- + n\gamma_L \rightarrow e^- + e^+ + e^-$$



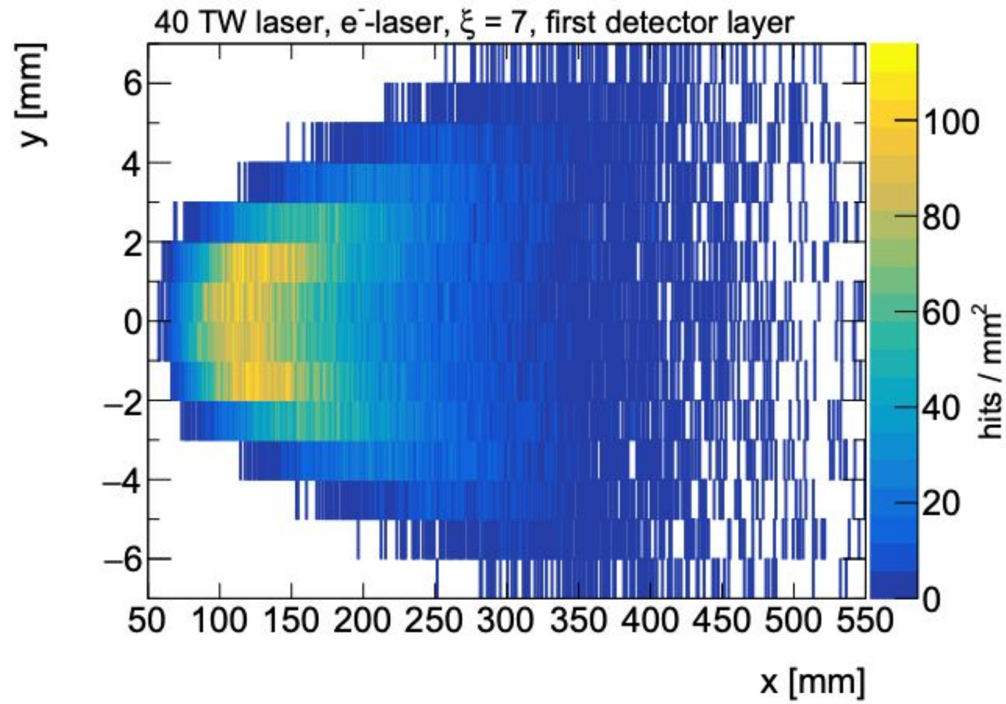


LUXE as test-case for other trackers



The extreme dynamic range (10^{-4} - 10^{6} particles per event) makes LUXE a **good case study for other colliders**

$N_{positrons} \approx 7 \cdot 10^4$



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Detector Reference	Hit Density [mm^{-2}] MCD	ATLAS ITk	ALICE ITS3
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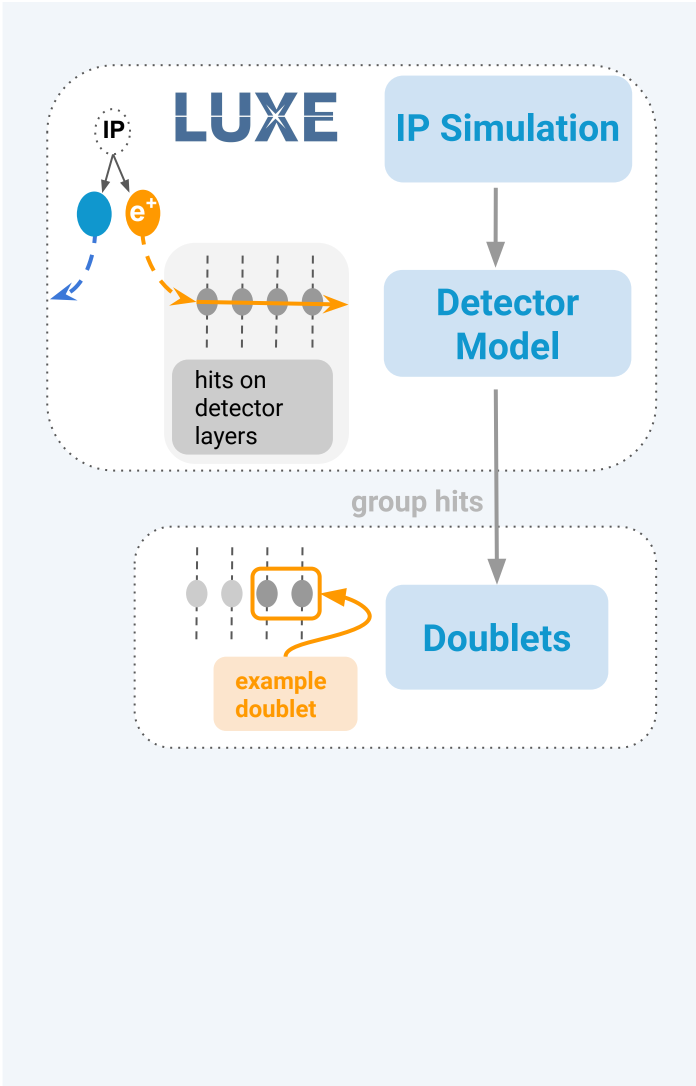
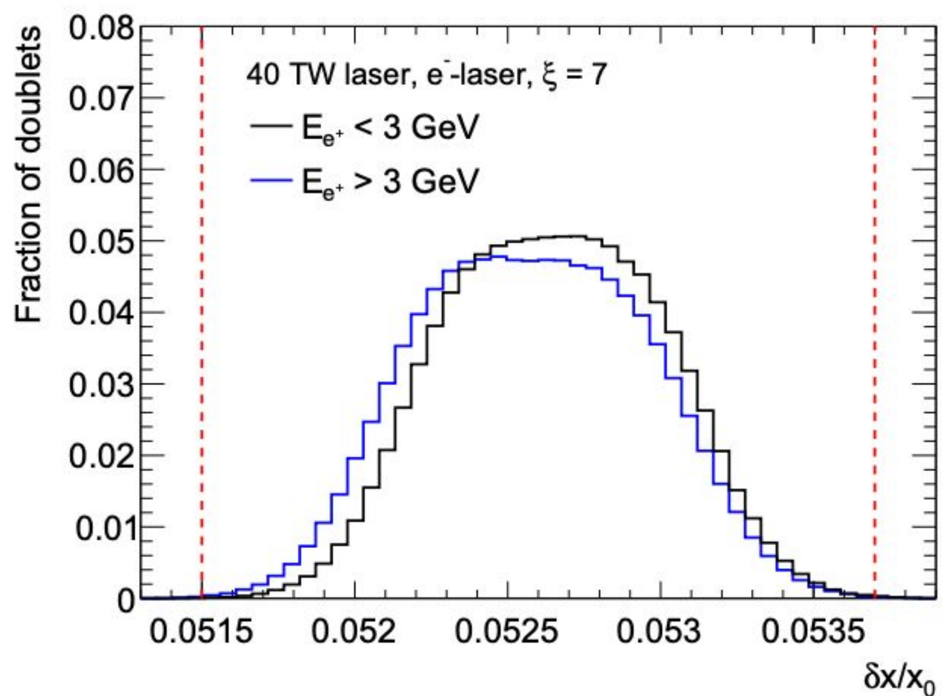
Track reconstruction

Selecting the inputs

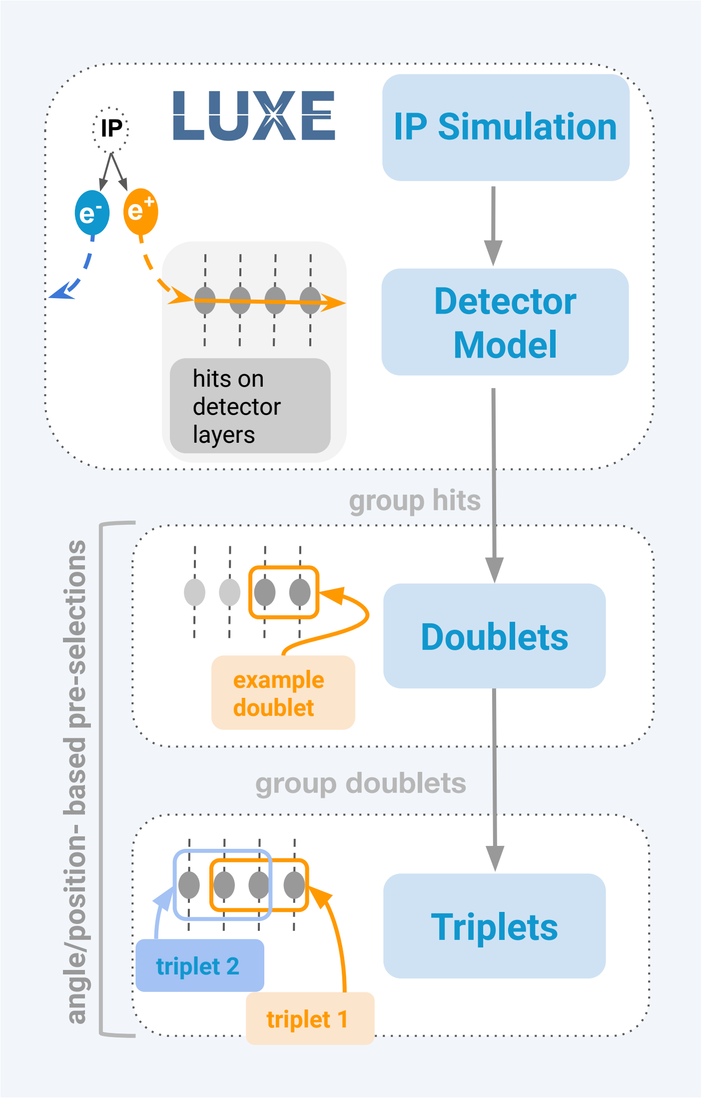


Select doublets based on the ratio $\delta x/x_0$ where $\delta x = x_{i+1} - x_i$, while x_0 indicates the x_i on the detector layer closest to the IP.



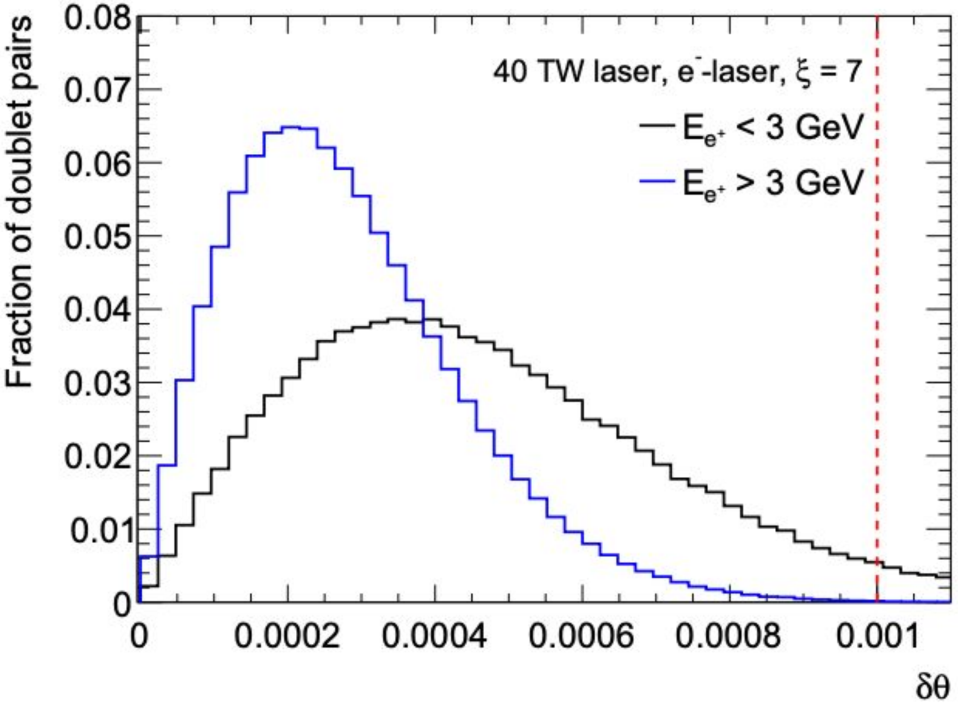
Track reconstruction

Selecting the inputs



Select triplets based on the alignment of the constituent doublets

- maximum angle difference $\delta\theta < 1$ mrad



Performance

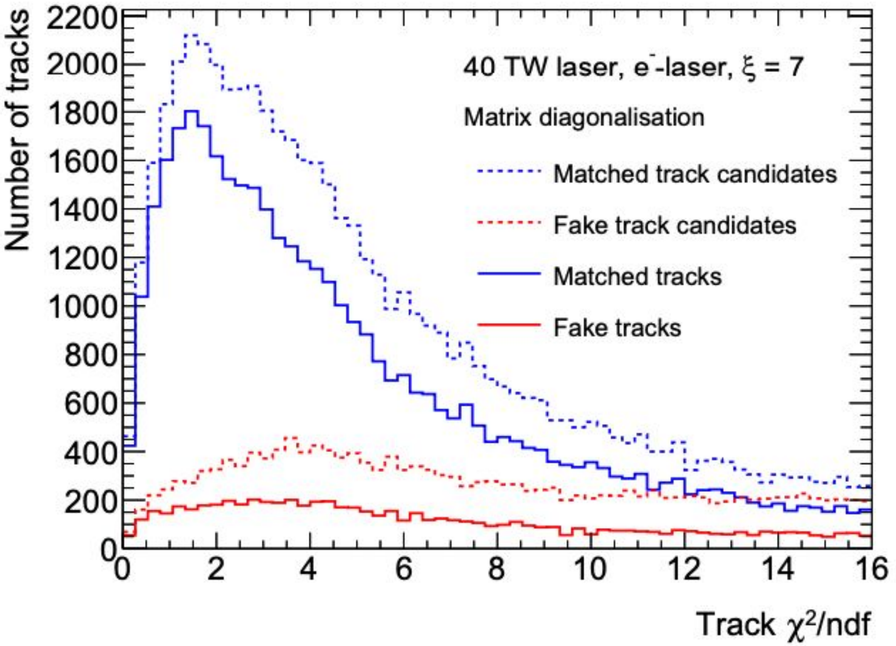
Track level efficiency and fake rate

The output track candidates from the three methods are fitted

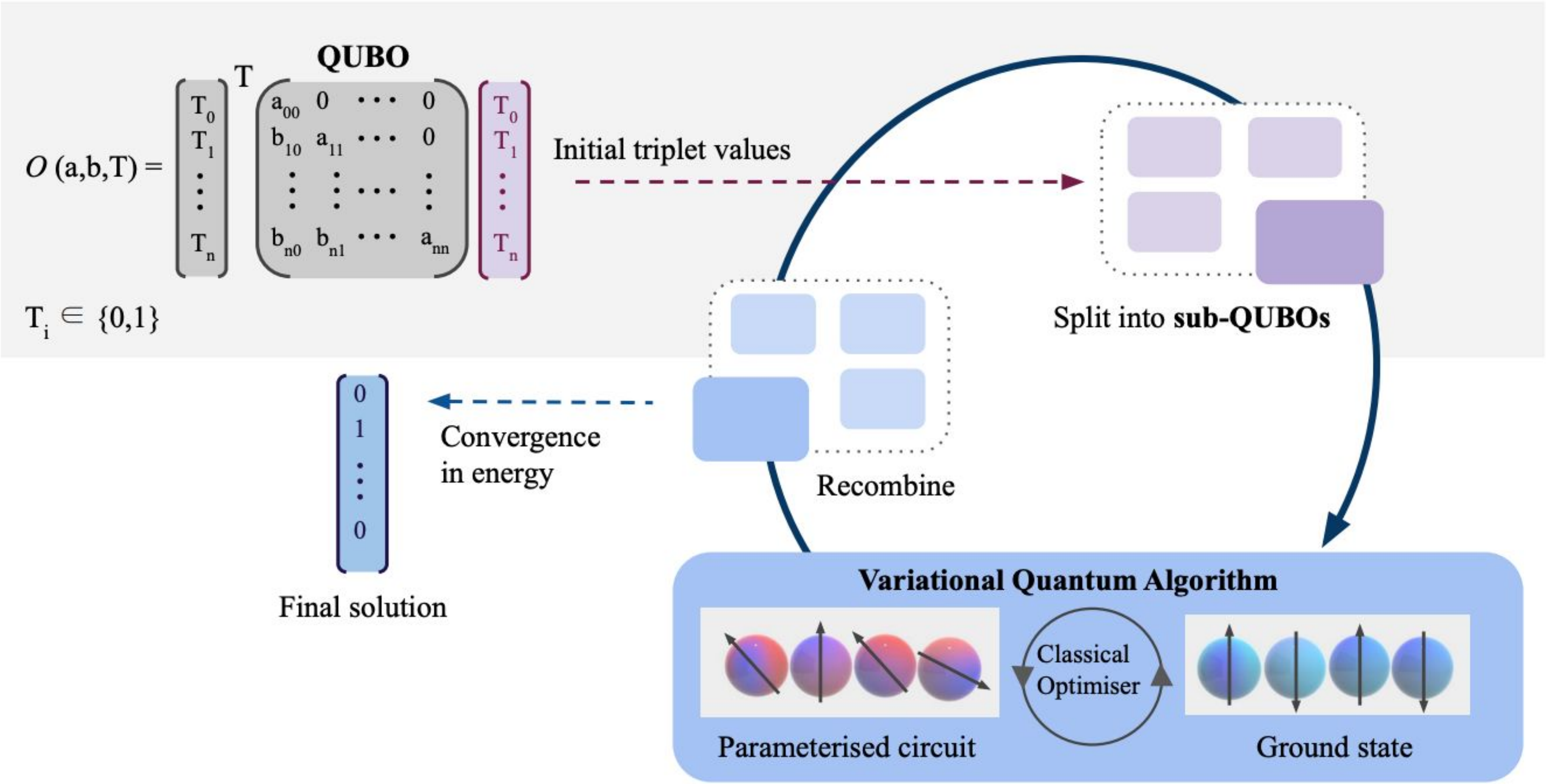
- Track χ^2 only considered in removal of reconstruction ambiguities

$$\text{Efficiency} = \frac{N_{\text{tracks}}^{\text{matched}}}{N_{\text{tracks}}^{\text{generated}}}$$

$$\text{Fake rate} = \frac{N_{\text{tracks}}^{\text{fake}}}{N_{\text{tracks}}^{\text{reconstructed}}}$$



Variational Quantum Eigensolver



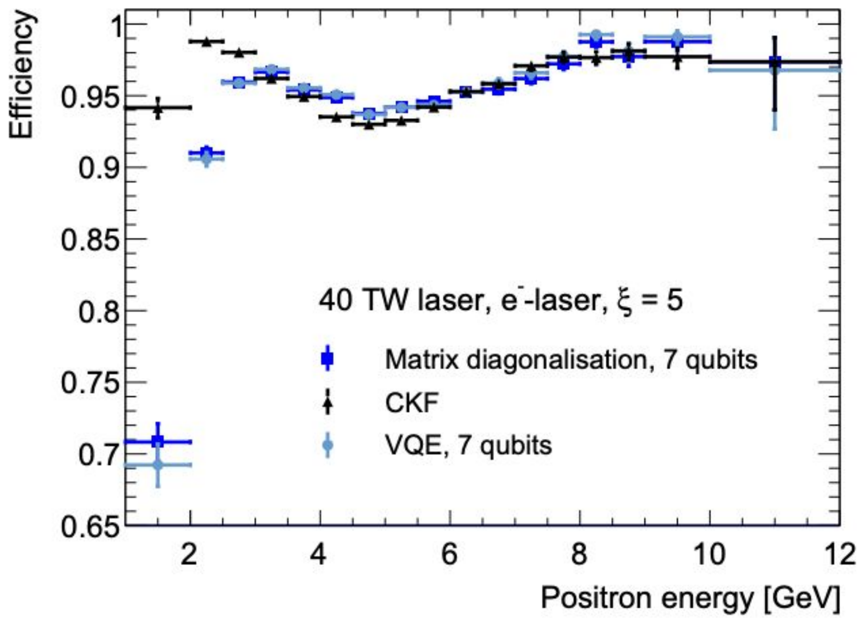
Exact matrix diagonalisation
used as benchmark

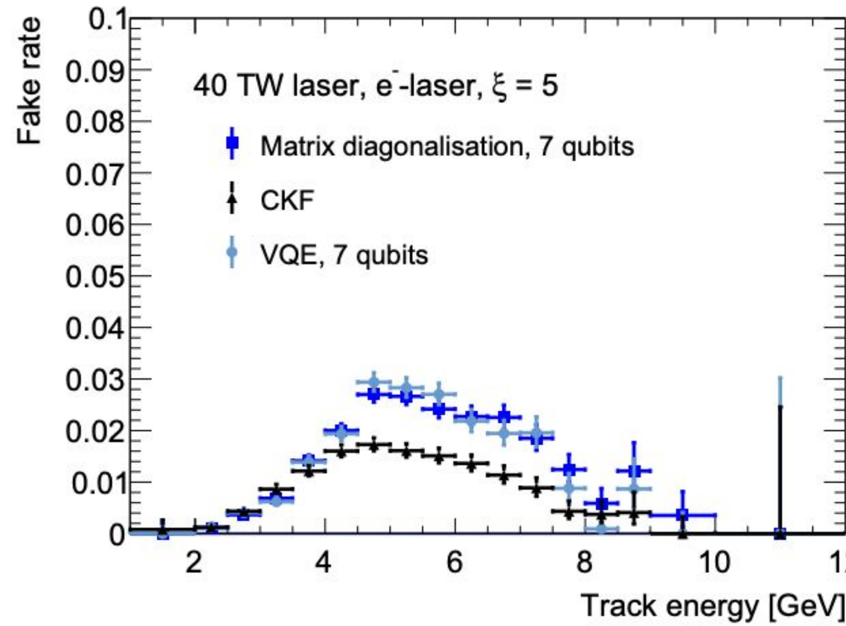
Algorithmic performance

Differential efficiency and fake rate

$$\text{Efficiency} = \frac{N_{\text{tracks}}^{\text{matched}}}{N_{\text{tracks}}^{\text{generated}}}$$

$$\text{Fake rate} = \frac{N_{\text{tracks}}^{\text{fake}}}{N_{\text{tracks}}^{\text{reconstructed}}}$$





Similar performances across methods

- Difference is maximal in high-density region
- QGNN missing because of choice of $\xi = 5$

Tests with quantum hardware

Tested performance on 7-qubit device (ibm_nairobi)

Additional complications arising from gate noise, quantum decoherence, readout and state preparation errors

- Adopted calibration matrix-based readout error mitigation

Results relatively stable

- Minimum 10 shots to find correct result