EPS HEP2023 HAMBURG

25th August 2023

QUANTUM ALGORITHMS FOR CHARGED PARTICLE TRACK RECONSTRUCTION IN THE LUXE EXPERIMENT

Based on arXiv:2304.01690

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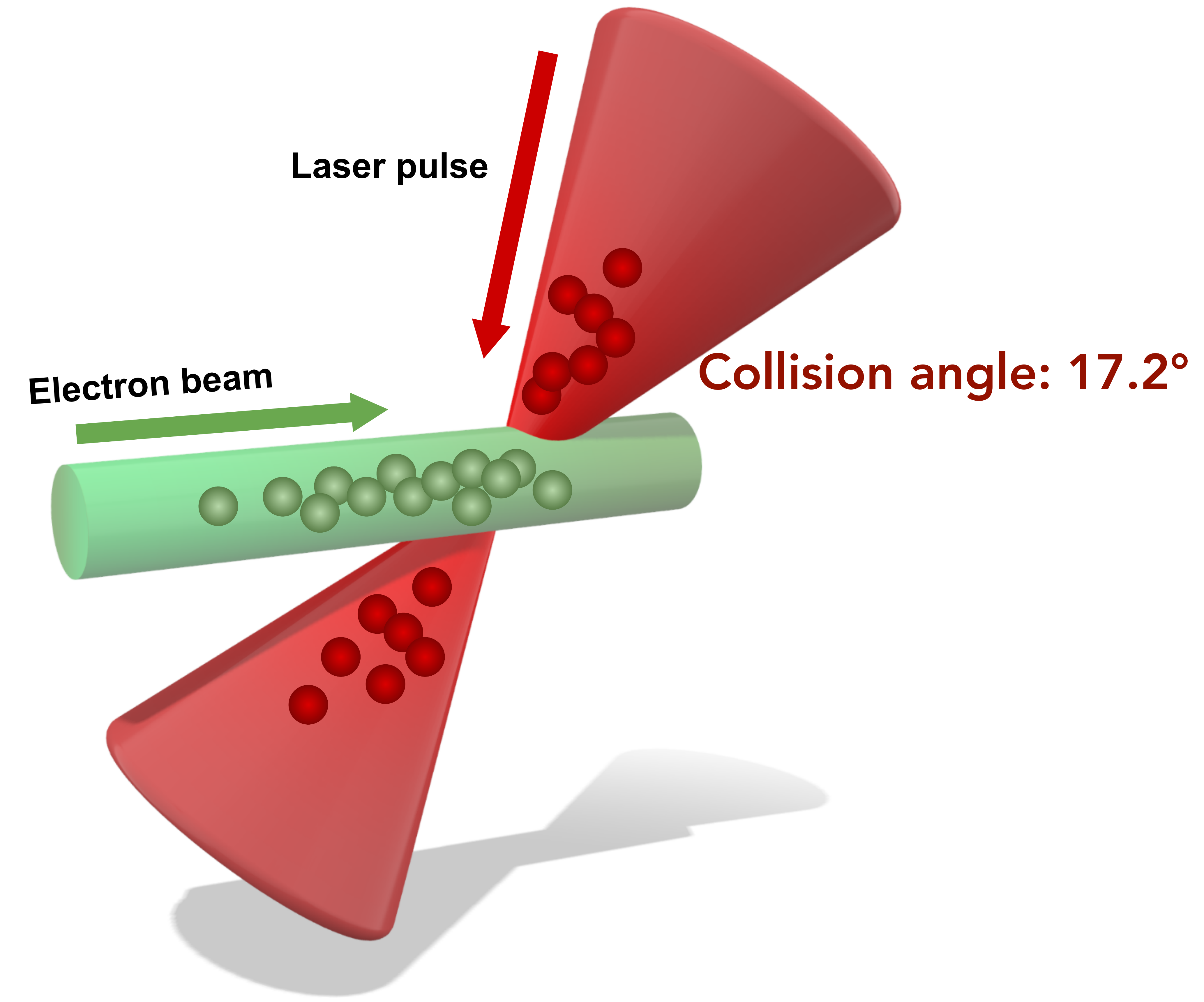
DESY. FTX HELMHOLTZ

LUXE: LASER UND XFEL EXPERIMENT

- Experiment in planning at DESY and European XFEL to study collisions of high-energy XFEL electron beam and high-power laser.



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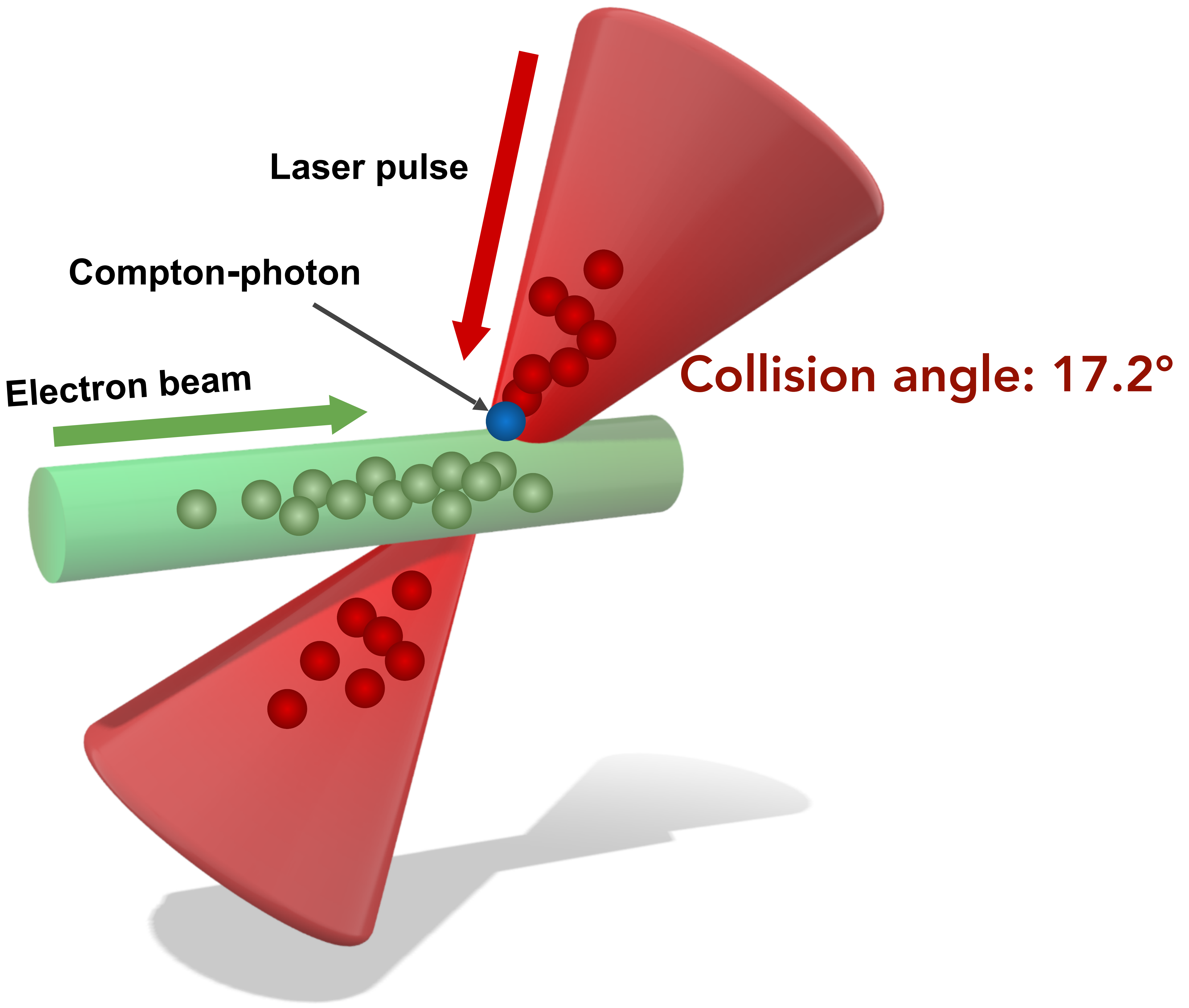
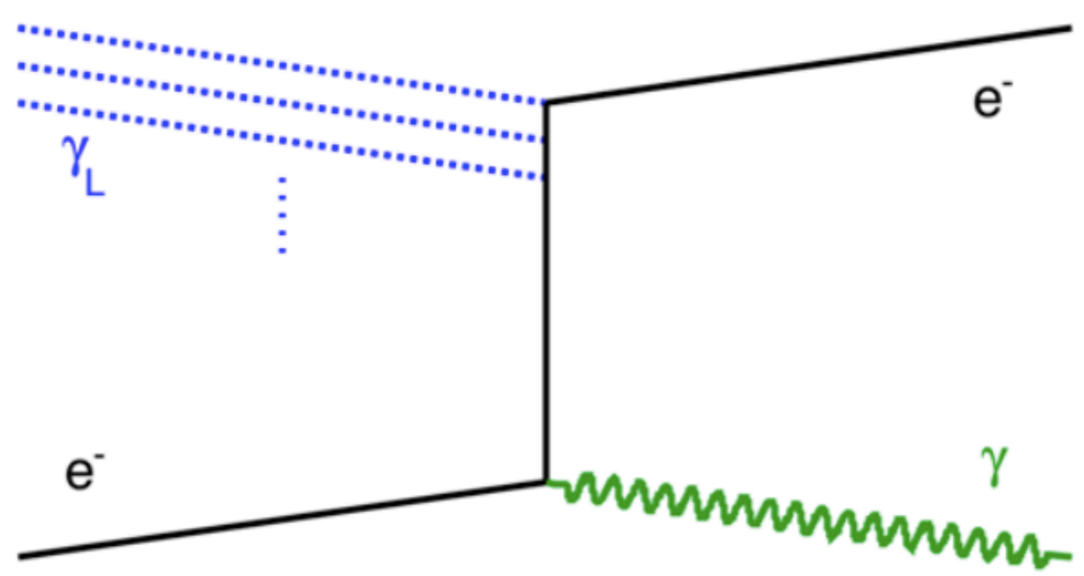


Non-linear Compton scattering:

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



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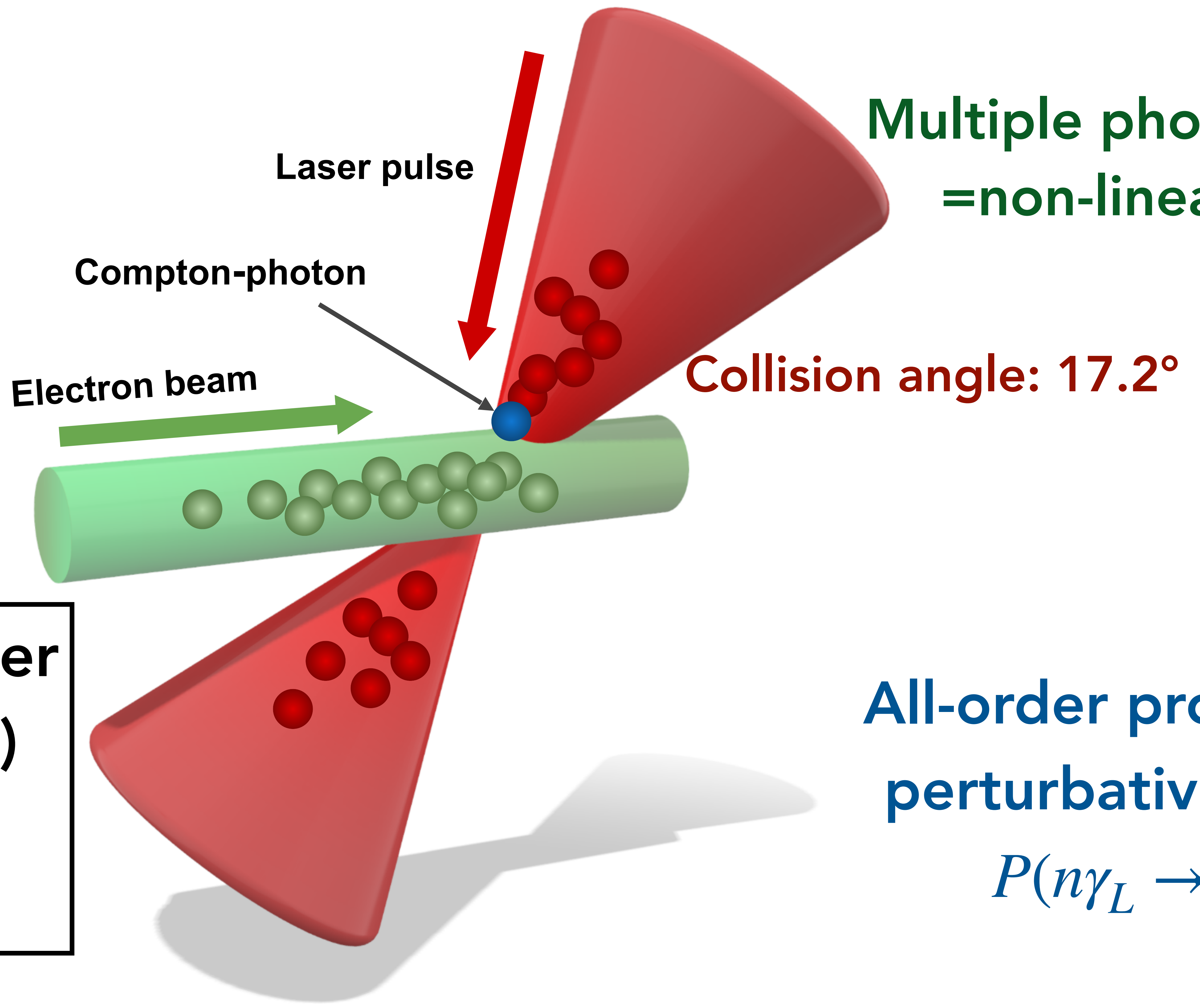
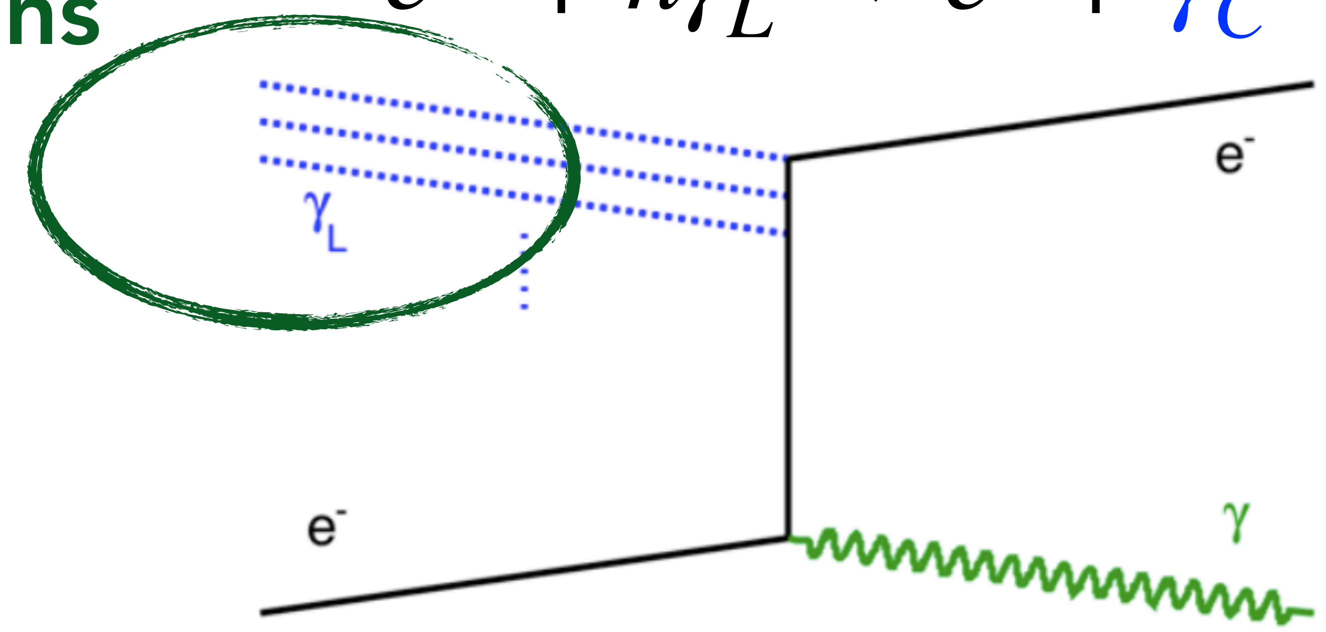


Non-linear Compton scattering:

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

Multiple photons =non-linear



Field intensity parameter (charge-field coupling)

$$\xi = \frac{m_e}{\omega_L}\frac{E_L}{E_{cr}}$$

All-order process, i.e. non-perturbative for $\xi \sim O(1)$

$$P(n\gamma_L \rightarrow \gamma) \propto \alpha\xi^{2n}$$

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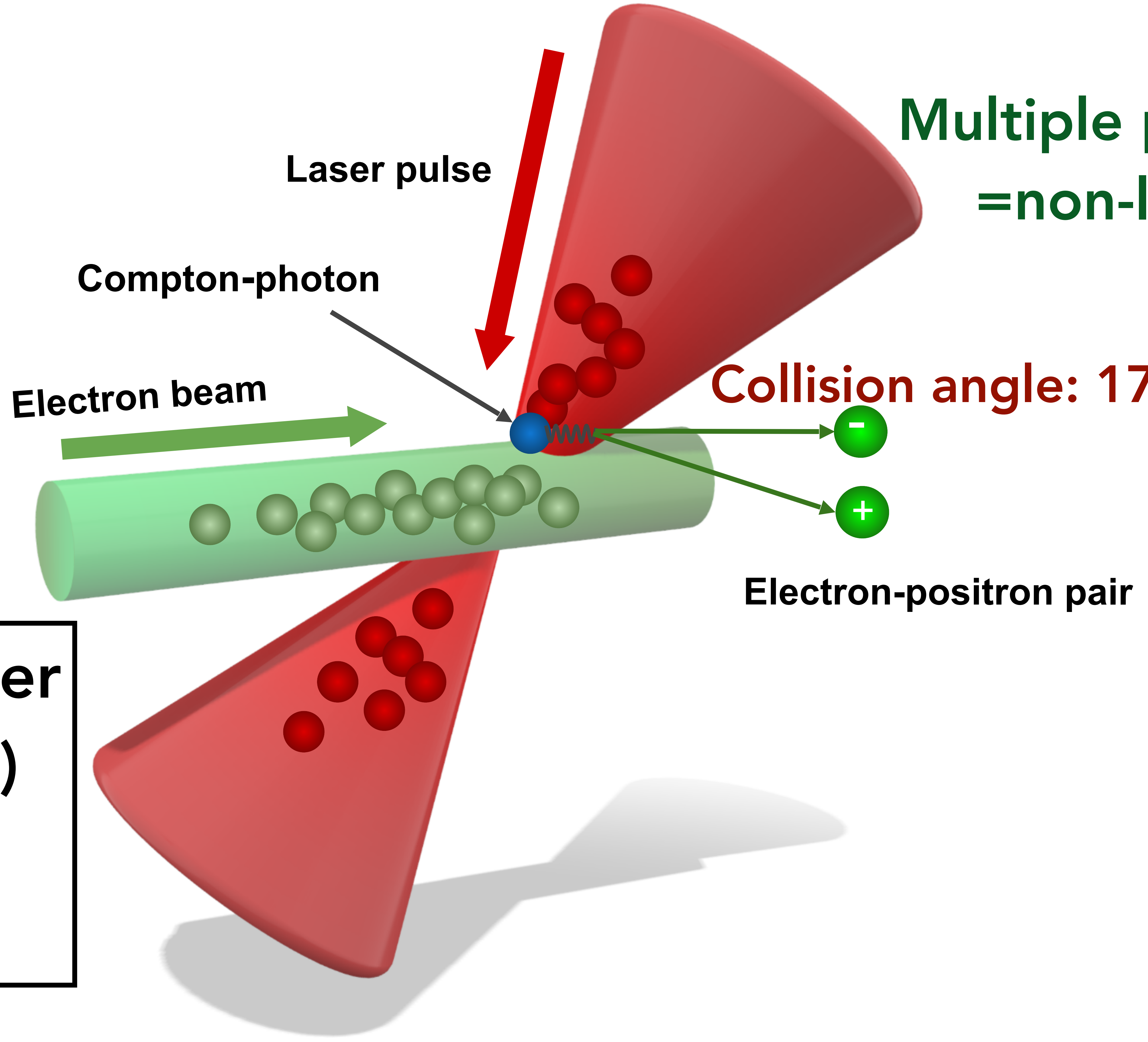

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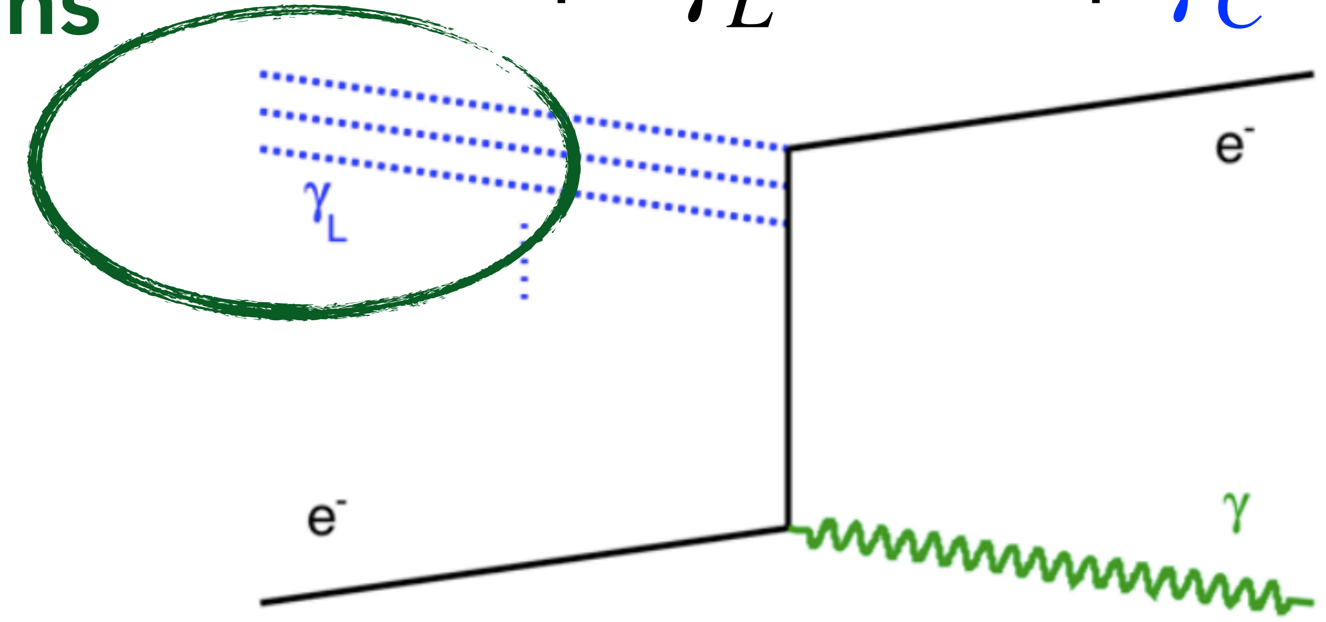
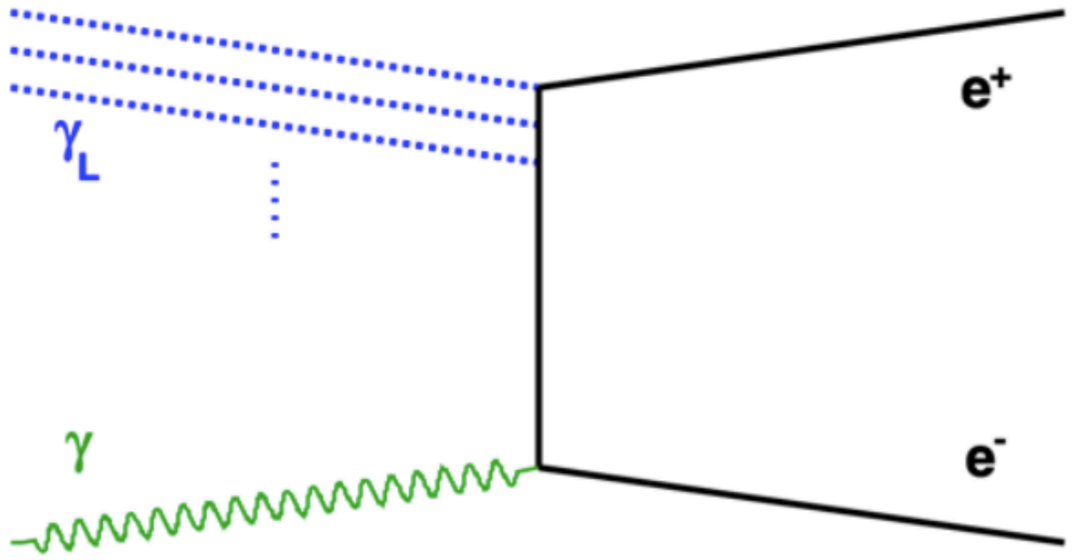


Non-linear Breit Wheeler:

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



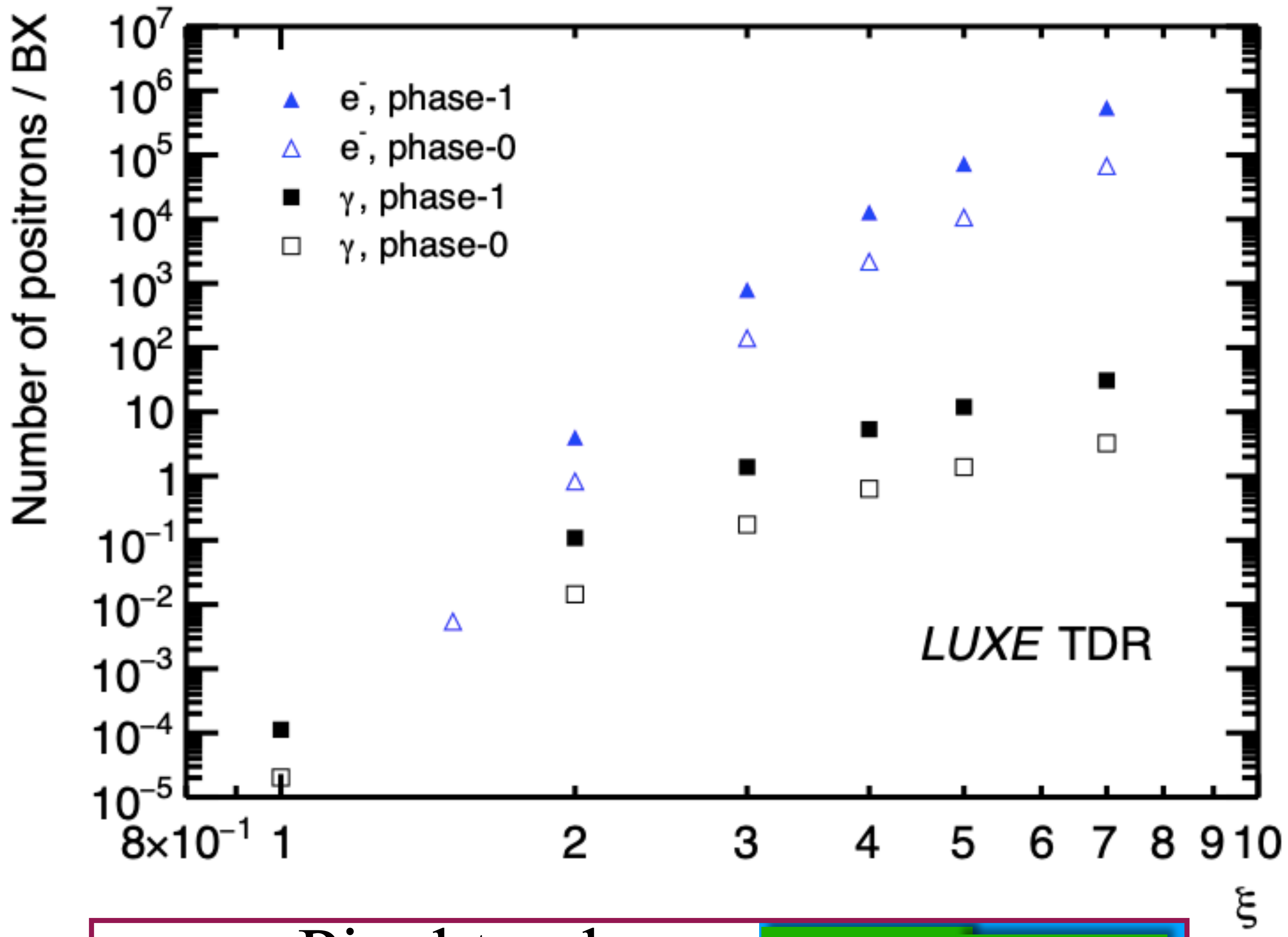
LUXE: LASER UND XFEL EXPERIMENT

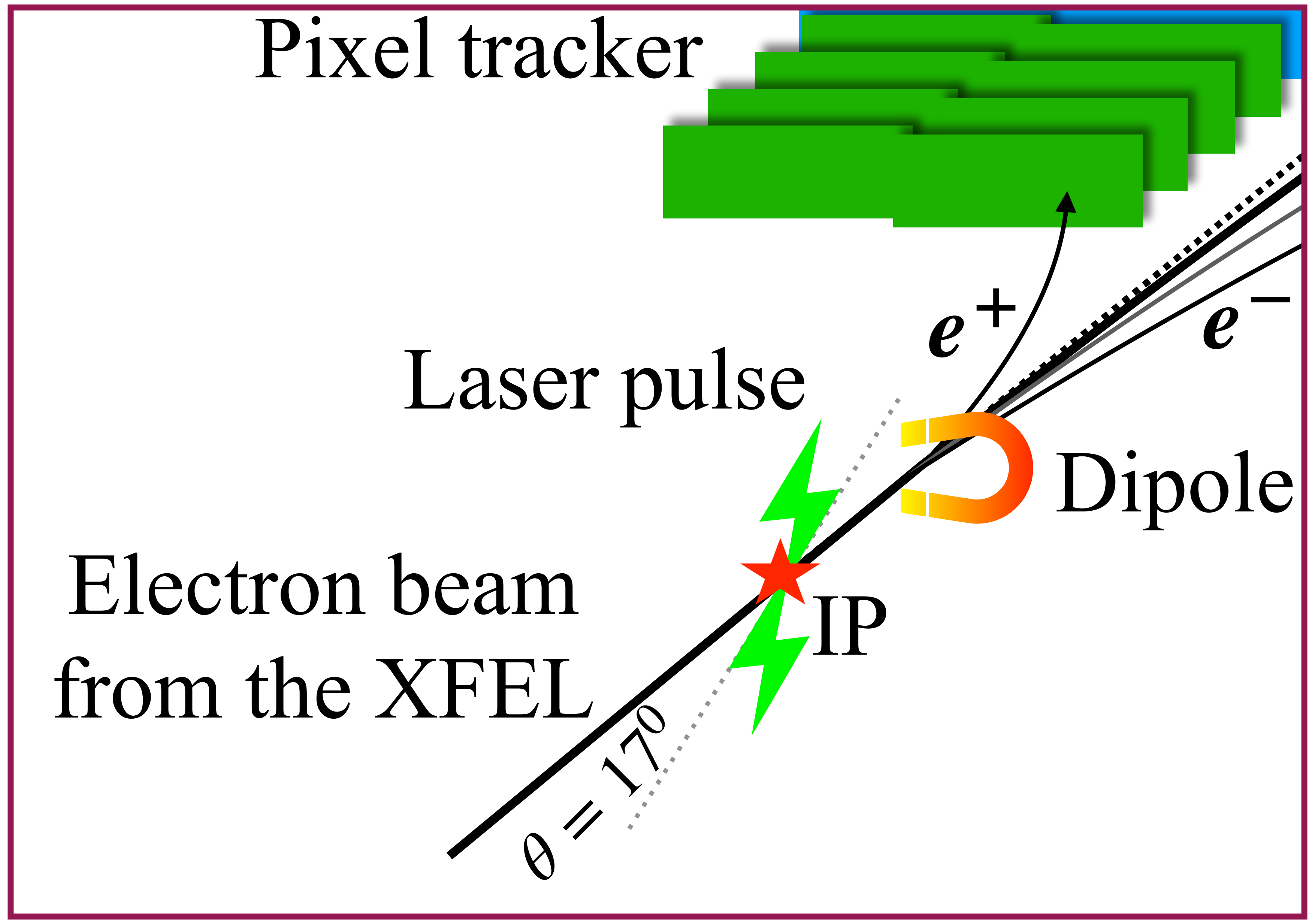
- 2 running modes: electron-laser and photon-laser.
- Planned in 2 phases (40 vs 350 TW laser).
- TDR: arXiv:2308.00515 NEW
- Other LUXE talks @ EPS:
  - General physics (Fri 09:42) by E. Ranken
  - Detector challenges (Fri 08:30) by O. Borysov
  - High-rate electron detectors (Thu 09:10) by A. Athanassiadis
  - BSM programme (Thu 09:00) by N. Trevisani

Focus on phase-0 (40 TW laser) e-laser in this talk

MEASUREMENT

- LUXE aims to make **precision measurements** in a **transition** from perturbative to non-perturbative QED.
    - One such measurement is **positron rate vs ξ**, which spans over 10 orders of magnitudes.
- For precise positron rate measurement, reconstruct particle path with tracking.
    - Acts as a magnetic spectrometer where lower energy positrons are deflected more.
- Detector: 4 layers of 50 x 1.5 cm Silicon pixel tracker using ALPIDE sensors with pixel size 27 x 29 μm².





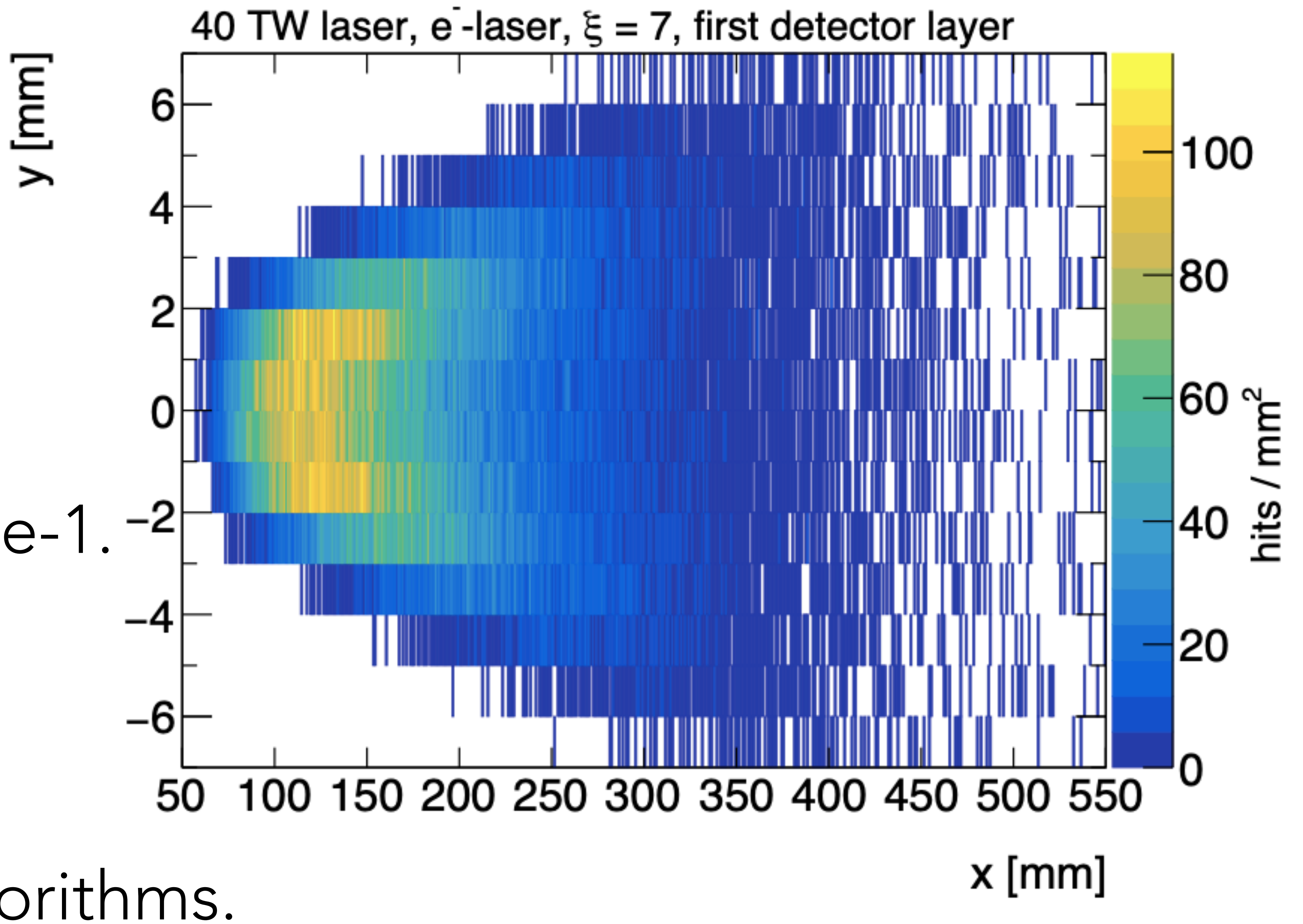
LUXE TRACKING CHALLENGE

- Tracking at LUXE becomes challenging due to combinatorics at high track multiplicities.

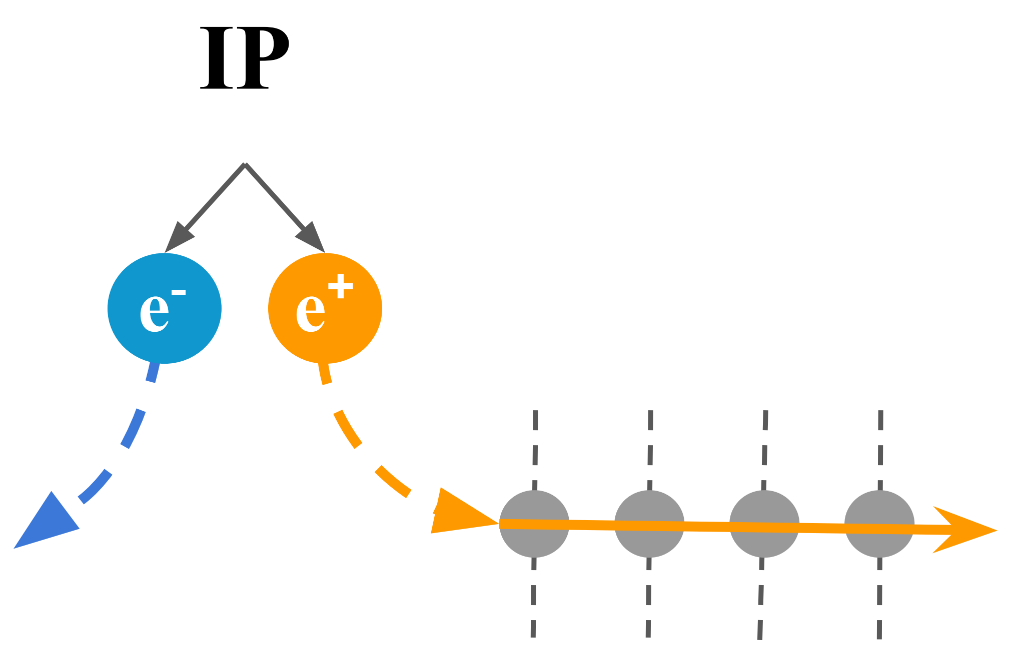
- At phase-0 (40 TW laser), **occupancies** at the pixel detector reach 100 particles/mm^2.
  - Orders of magnitudes higher than other planned HEP experiments, e.g. HL-LHC.

- Even higher occupancies can be expected in phase-1.

- Quantum computing may offer an advantage. In our paper (arXiv:2304.01690), we study various tracking methods using quantum and classical algorithms.



OVERVIEW OF THE WORKFLOW



Interaction Point simulation

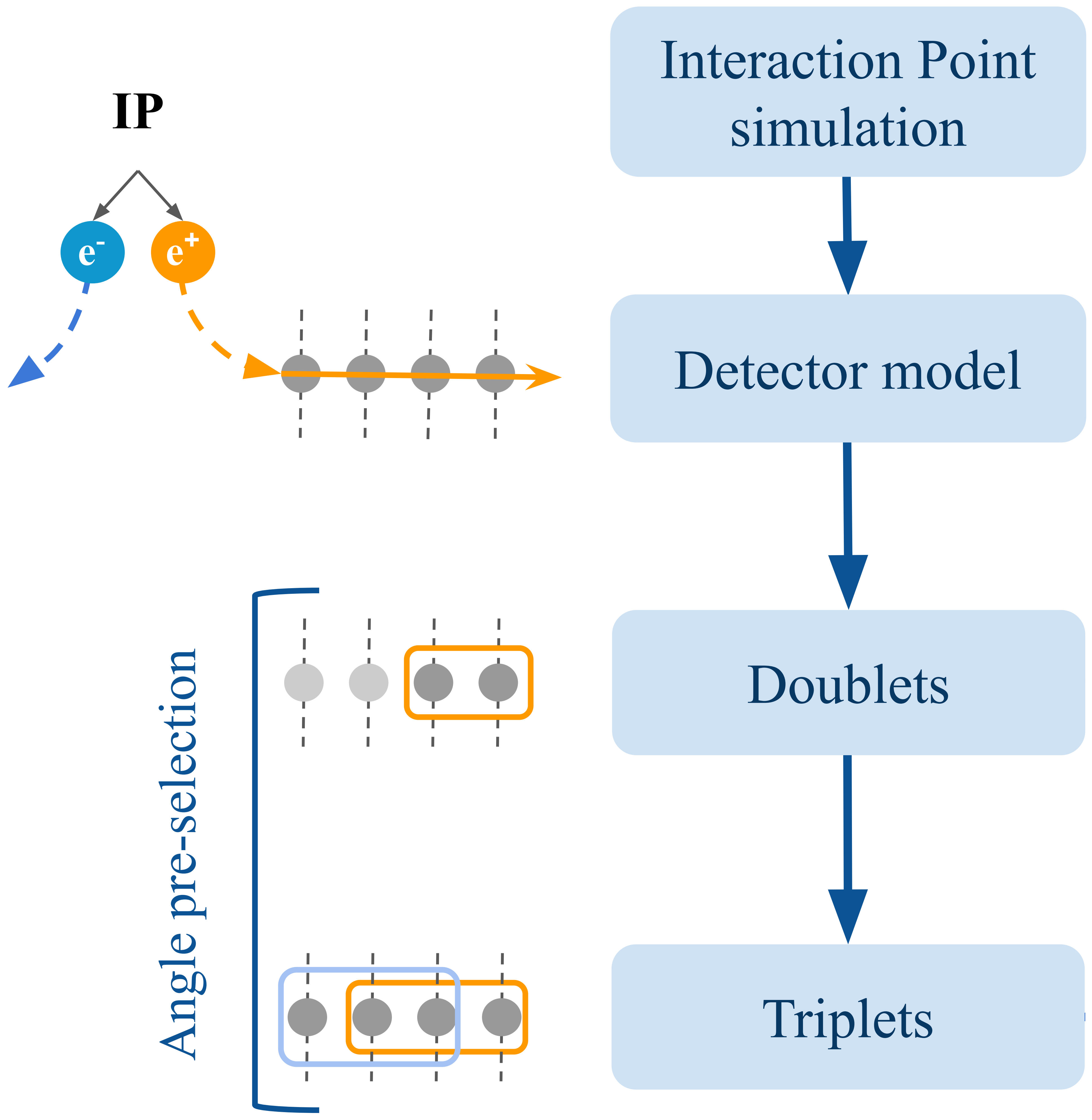
↓

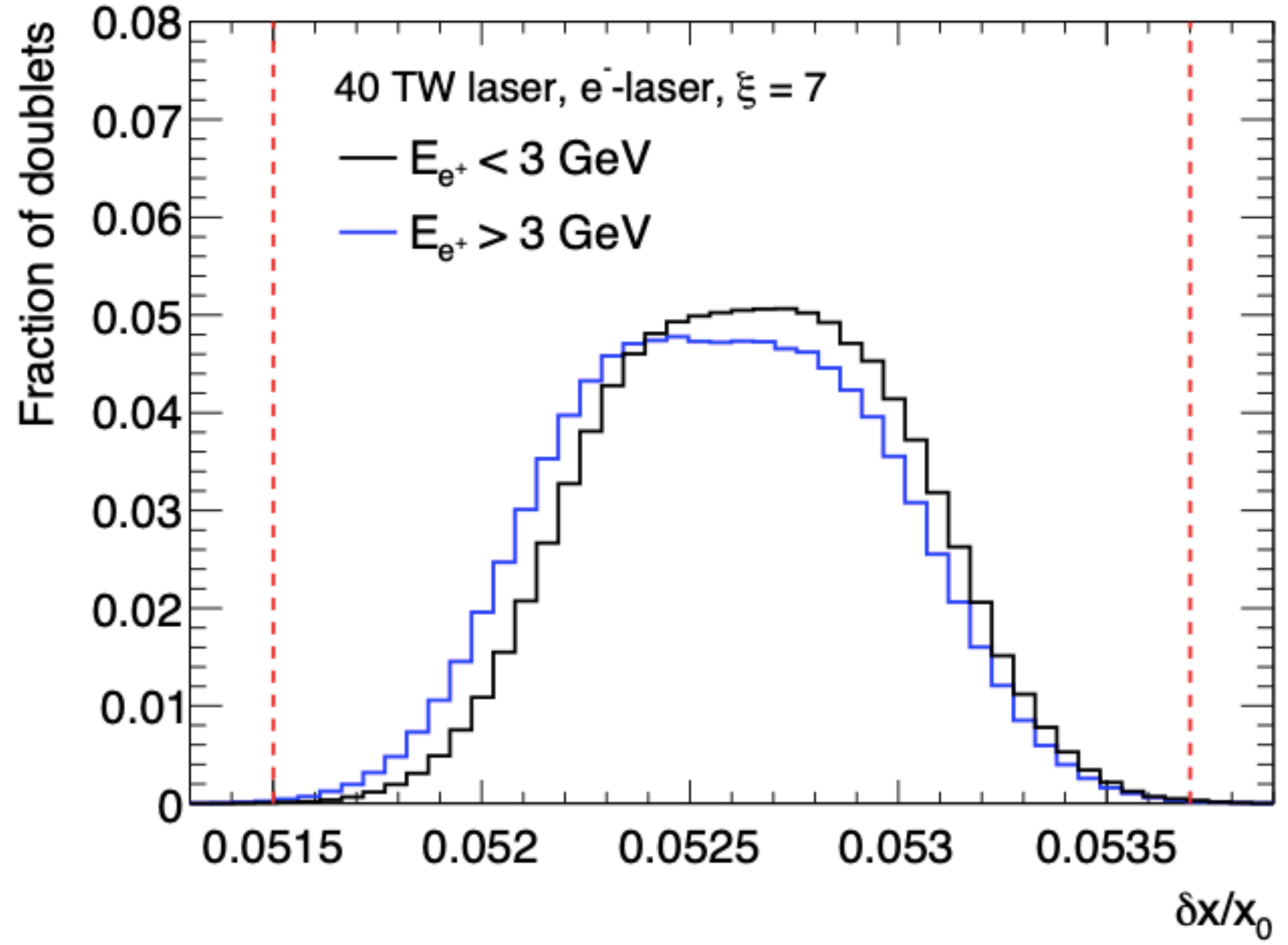
Detector model

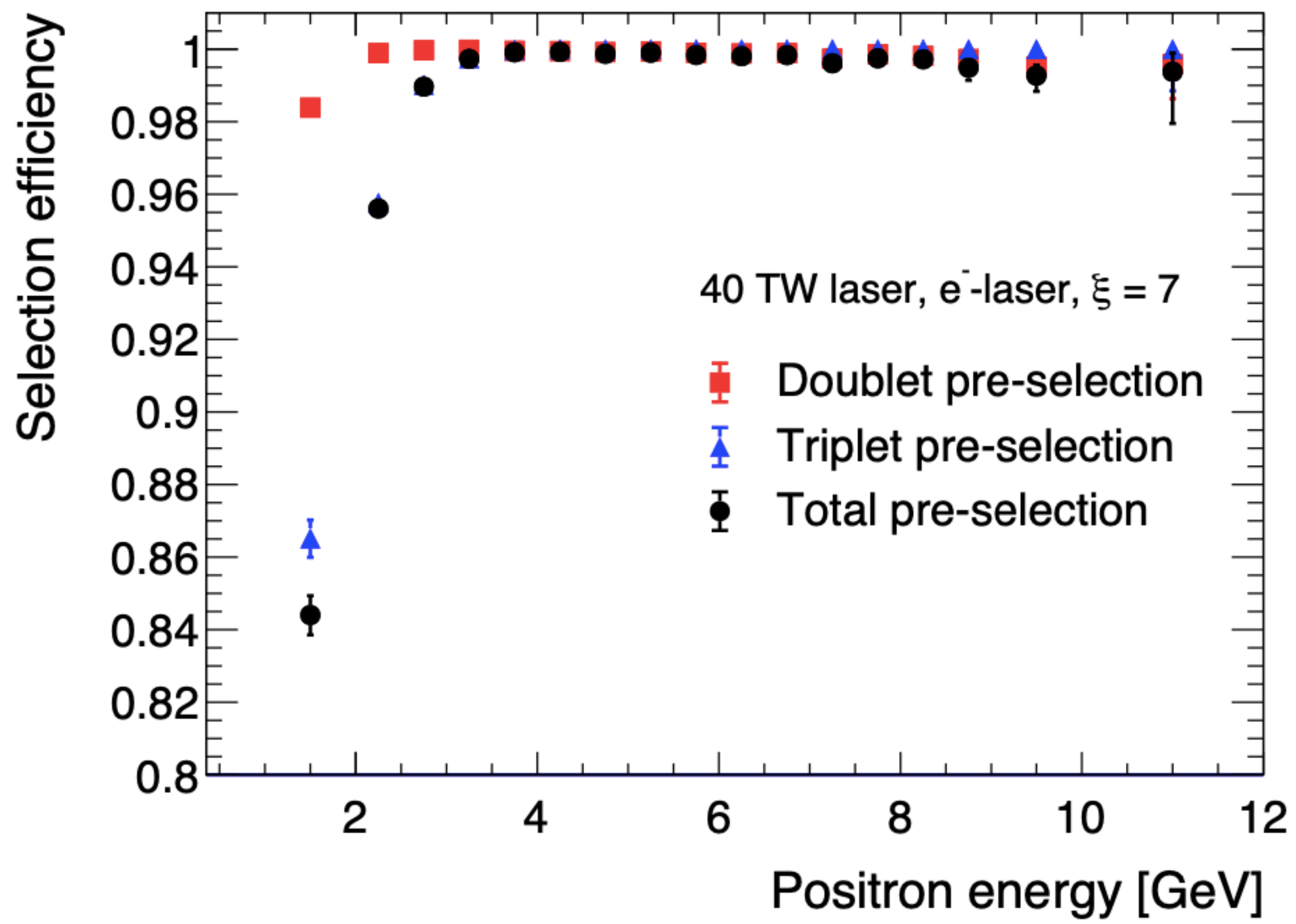
PTARMIGAN arXiv:2108.10883

Custom fast tracker simulation with simplified detector setup

OVERVIEW OF THE WORKFLOW







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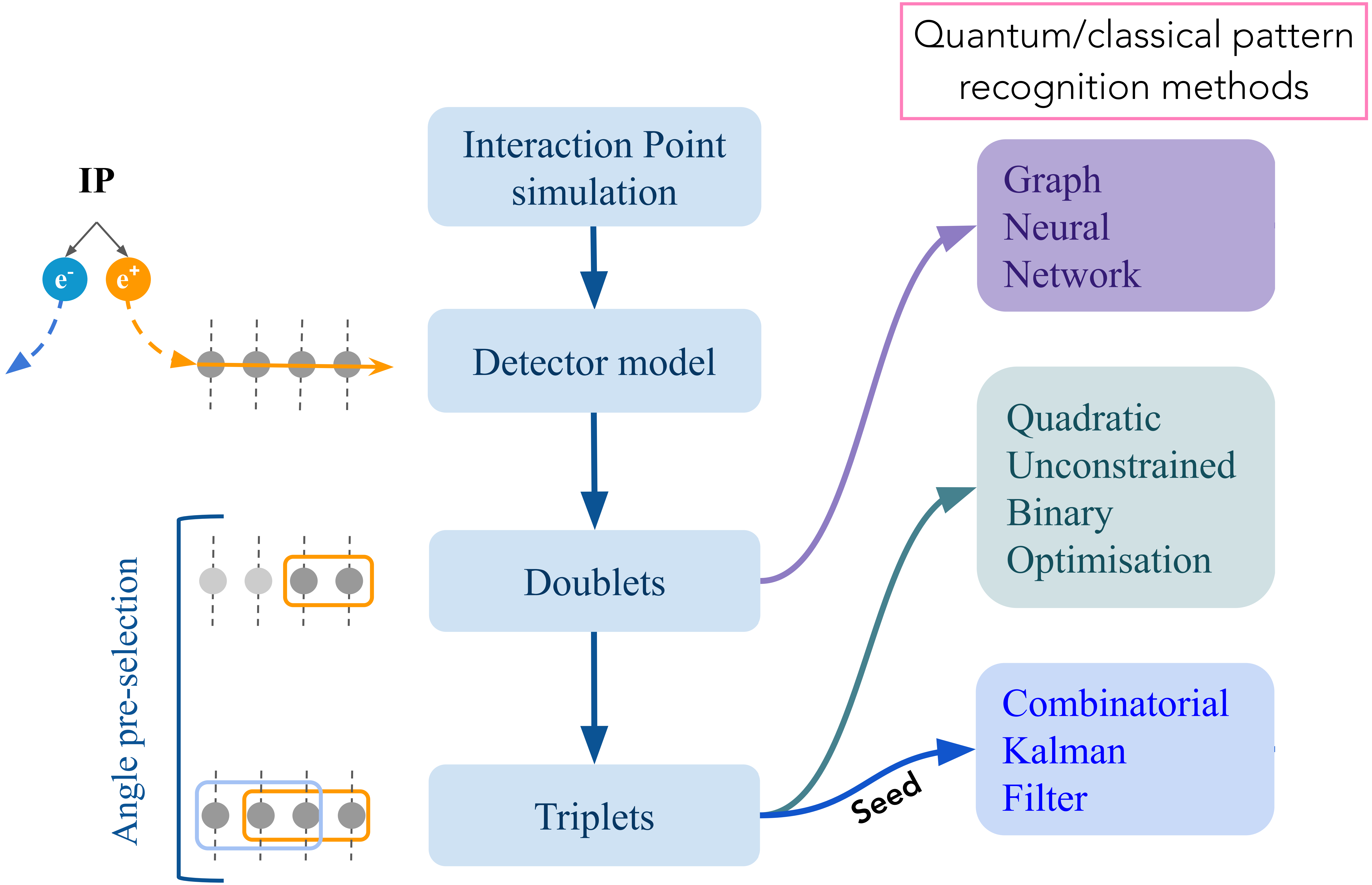

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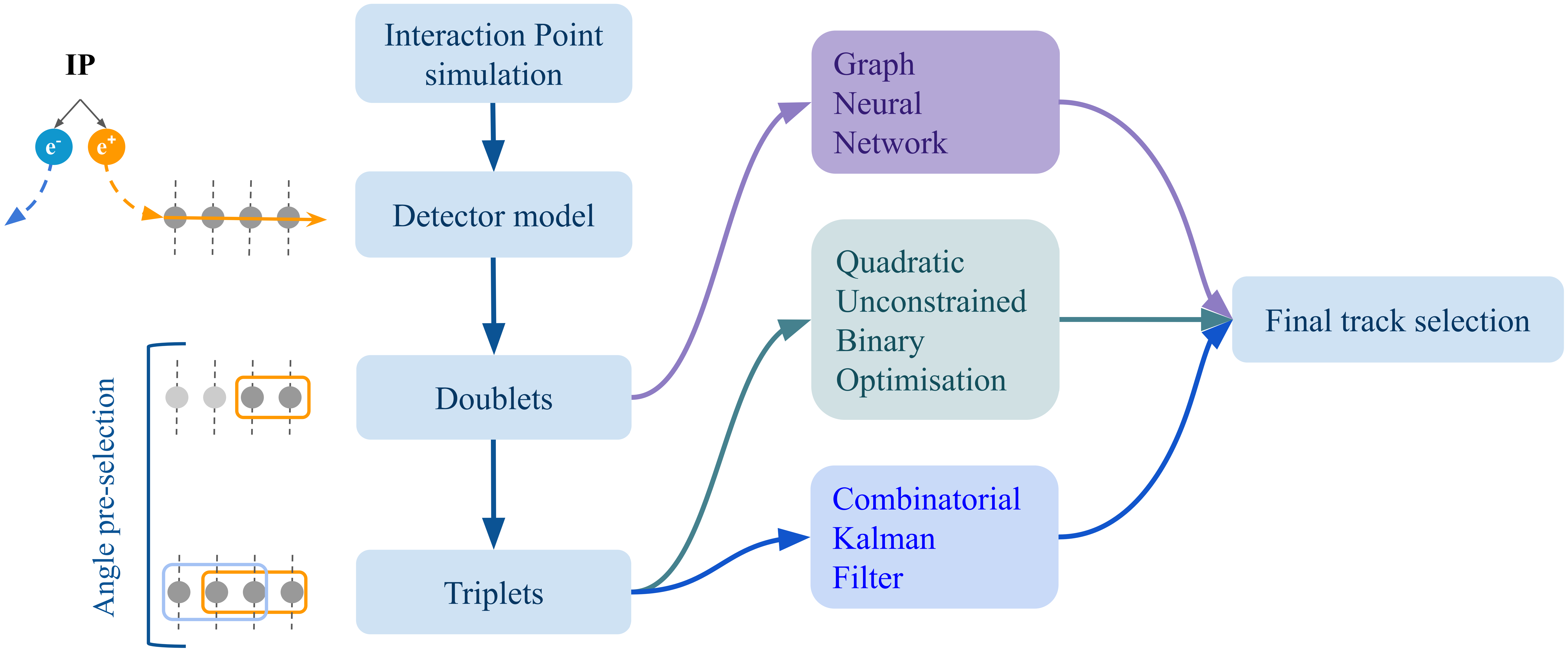
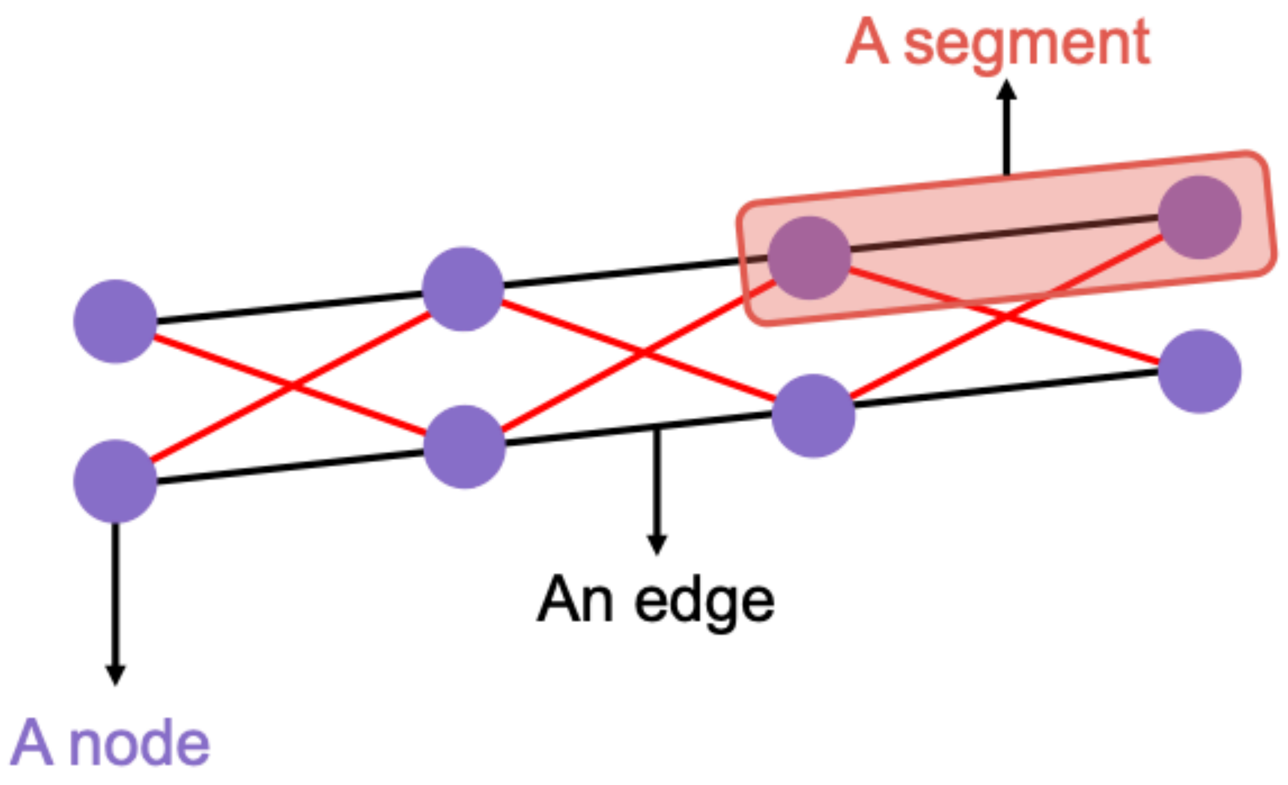
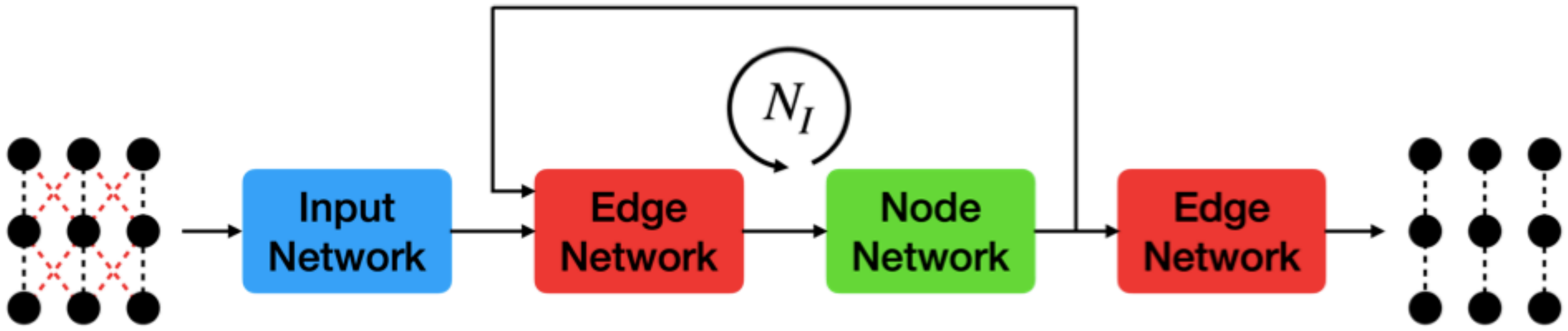


QUANTUM GRAPH NEURAL NETWORK (GNN)

- Doublet classification.



- Graph constructed from doublets, where the hits are nodes and the connections between the hits are edges.
- Hybrid quantum-classical model with 10 hidden features (qubits).
- N_I iterations of alternating edge and node networks applied.



- Edge/doublet with scores above threshold are retained to form track candidates.

HEP.TrkX: arXiv:1810.06111, Exa.TrkX: arXiv:2103.06995, Q.TrkX: arXiv:2109.12636

QUBO

Quadratic
Unconstrained
Binary
Optimisation

- Triplet classification.
  - Find the best set of triplets which can form tracks by minimising the QUBO, given by the states of T_i, T_j.

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

Weighting triplet T_i with quality a_i

Compatibility b_{ij} between two triplets

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

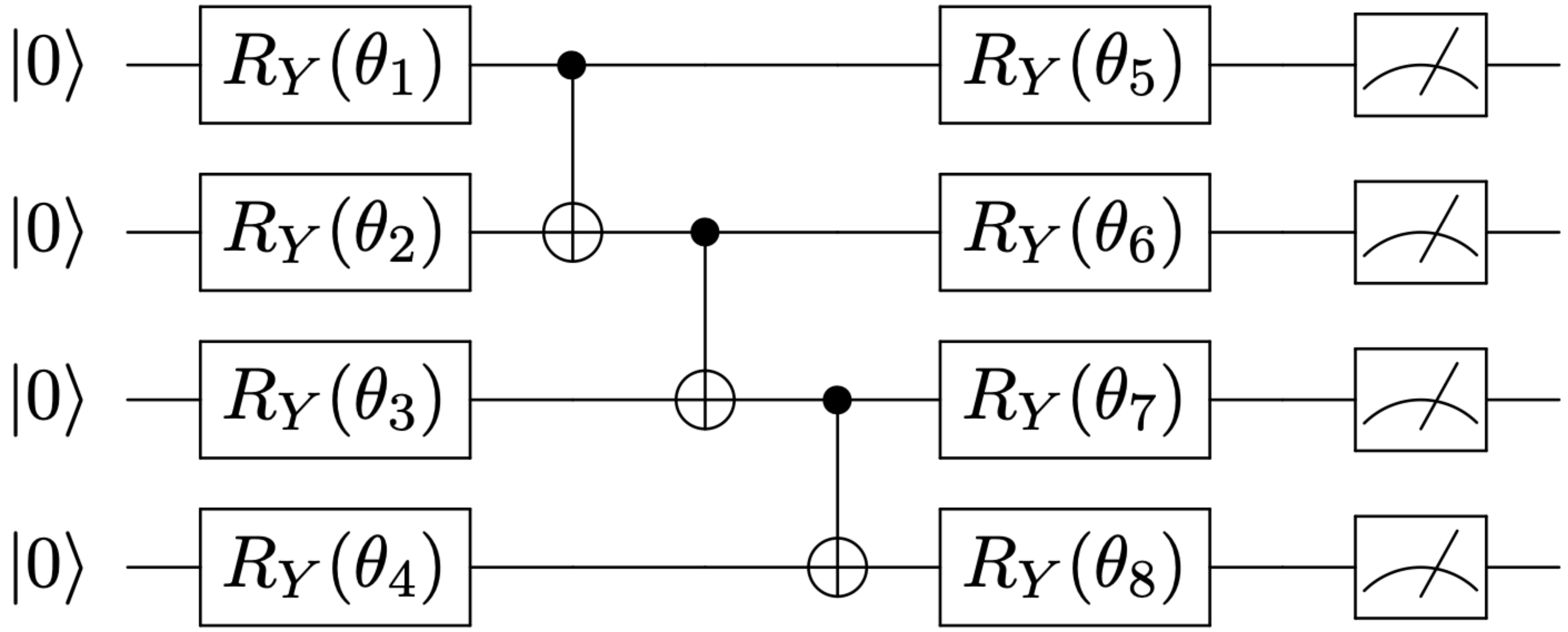
- The QUBO can be mapped to an Ising Hamiltonian.

- Minimising the QUBO is equivalent to finding the ground state of the Hamiltonian.

Find T_i, T_j that minimises QUBO!

QUBO

- The ground state is found using **Variational Quantum Eigensolver (VQE)**, a hybrid quantum-classical algorithm.
  - Nakanishi-Fujii-Todo (NFT) optimiser used.



- QUBO is partitioned into sub-QUBOs of the size of the quantum device (7 qubits assumed) to be solved iteratively.

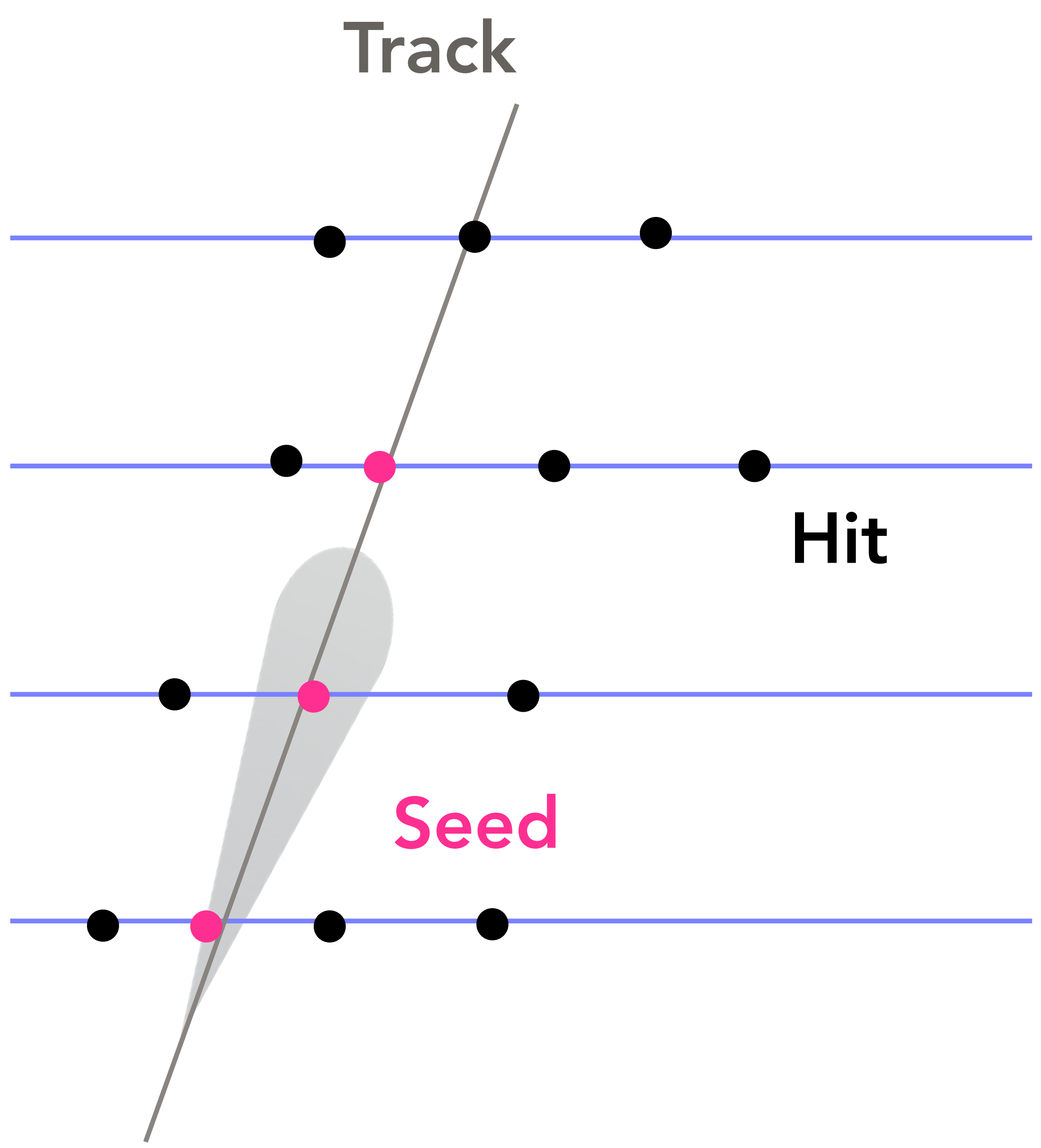
- Exact solution using **matrix diagonalisation** used as benchmark.

- Another method of finding the ground state is with quantum annealing, see poster by A. Kropf titled "Assessing the potential of quantum annealers for track reconstruction at LUXE".

For extension of this method to 4D tracking, see D. Spataro's talk afterwards

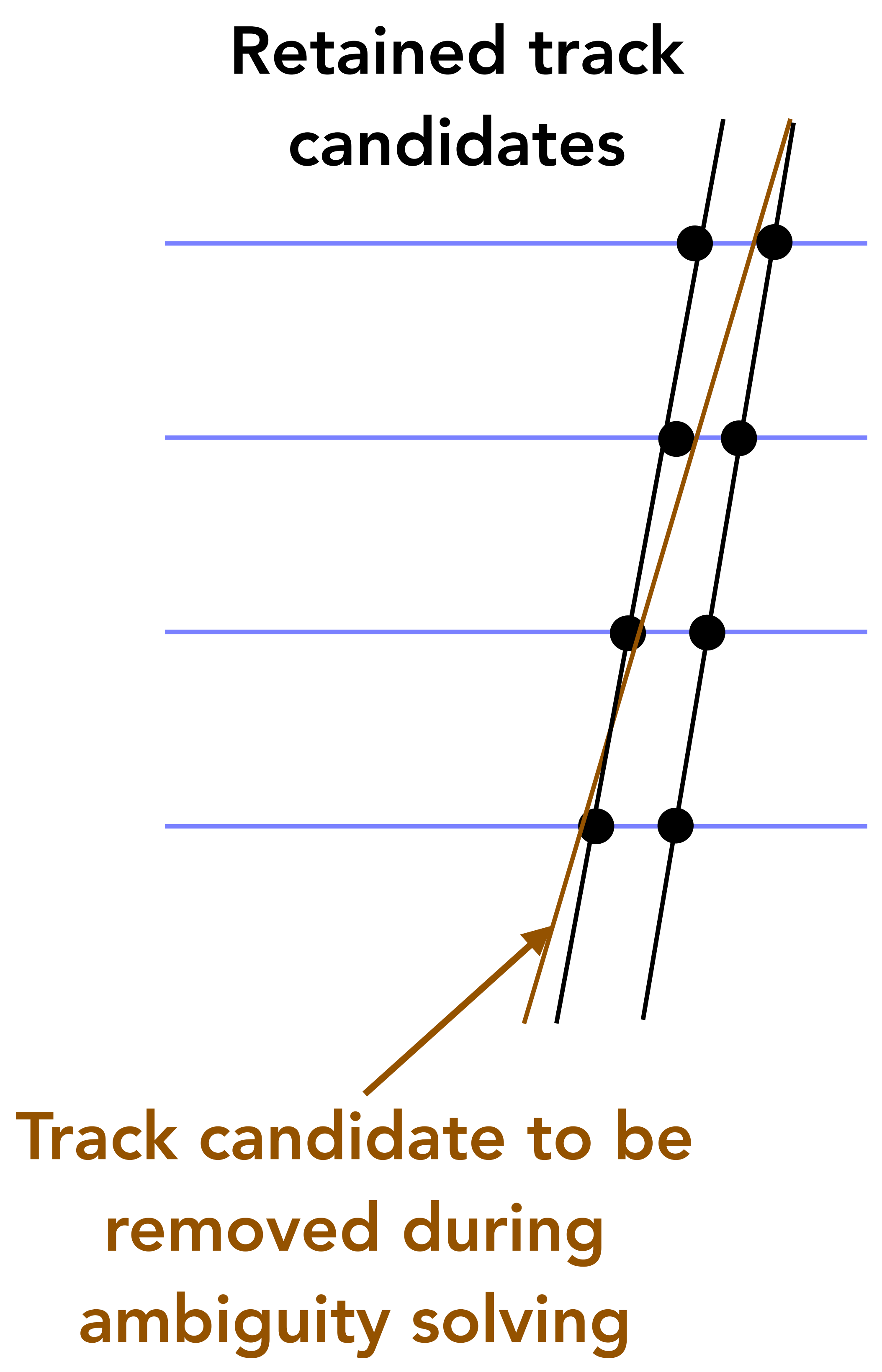
COMBINATORIAL KALMAN FILTER (CKF)

- CKF in a common tracking software (ACTS) used.
- Triplets from first three layers are used as seeds.
- Track parameters estimated from seeds used to steer the tracking.



FINAL TRACK SELECTION

- Tracks are required to have 4 hits.
- Found either directly with classical CKF tracking or by combining selected doublets/triplets into quadruplets in the GNN/QUBO approaches.
- Tracks are fitted and ambiguity solving applied to remove worse quality tracks with shared hits from the track collection.
  - No track is allowed to have more than 1 shared hit.



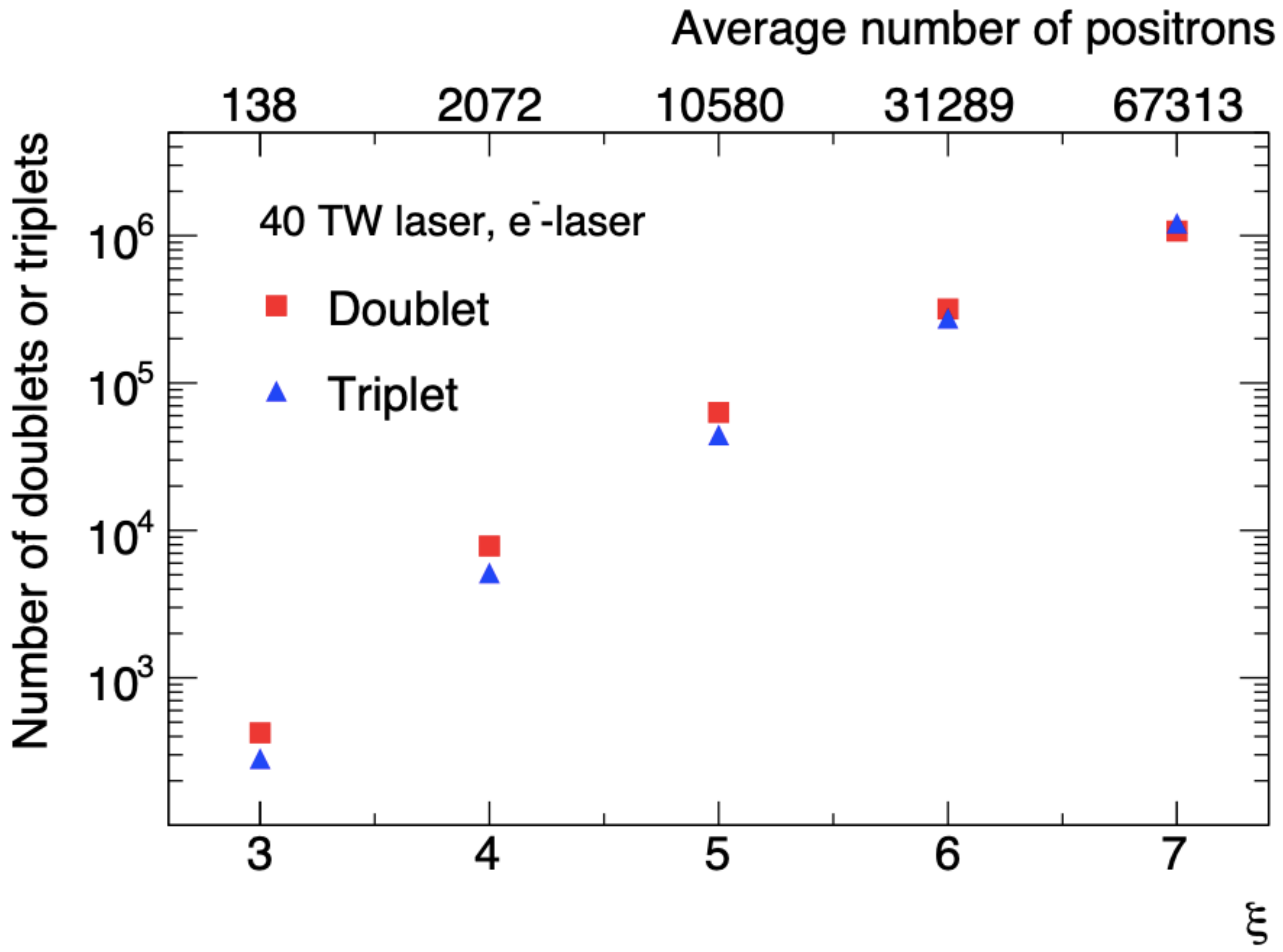
PERFORMANCE

- Compare performance of these tracking methods for ξ = 3 – 7 in LUXE phase-0 e-laser interactions, where the number of positrons are between 140 and 67,000.

- Two metrics:

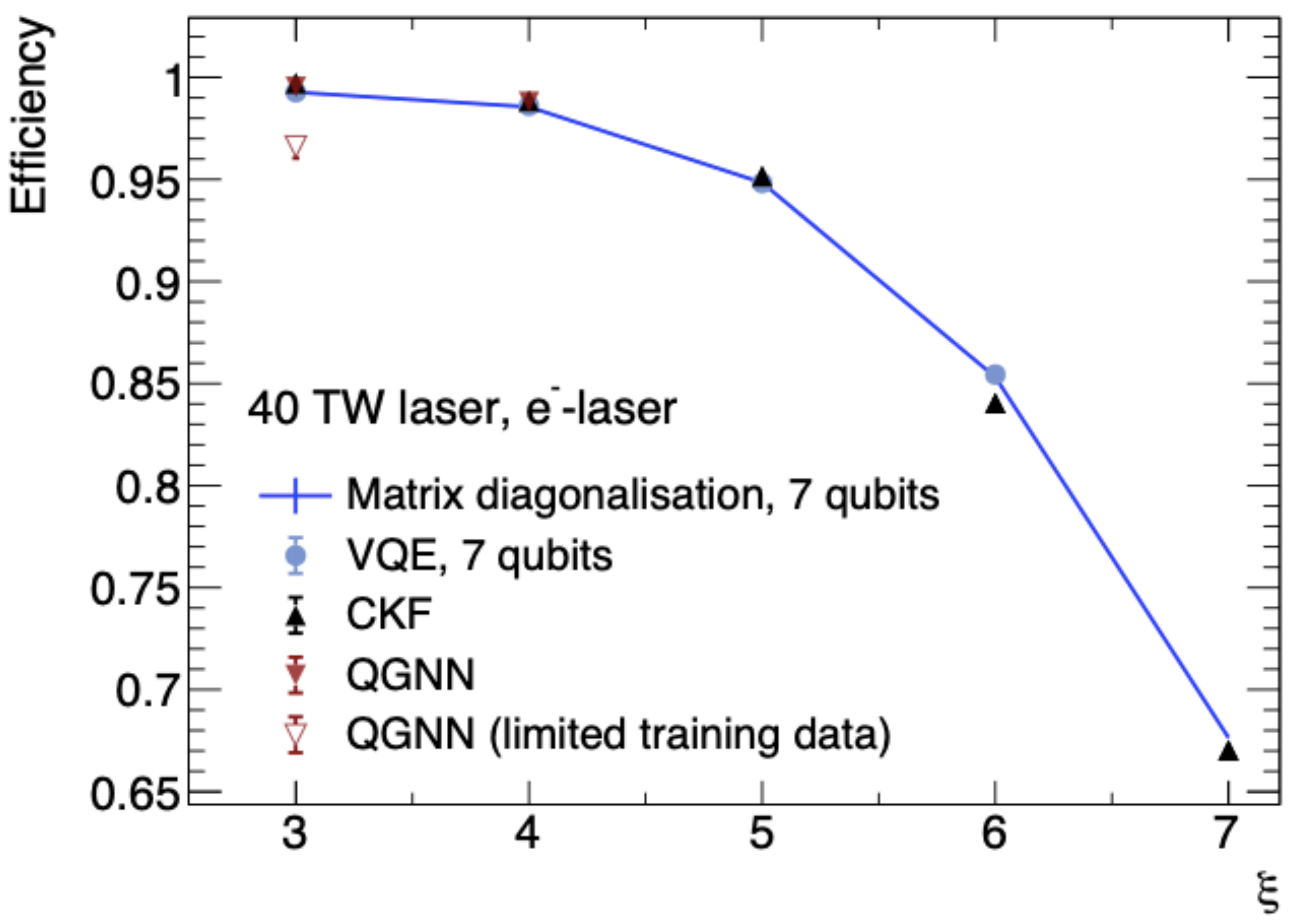
$$\text{Efficiency} = \frac{N_{\text{tracks}}^{\text{matched*}}}{N_{\text{tracks}}^{\text{generated}}}$$

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

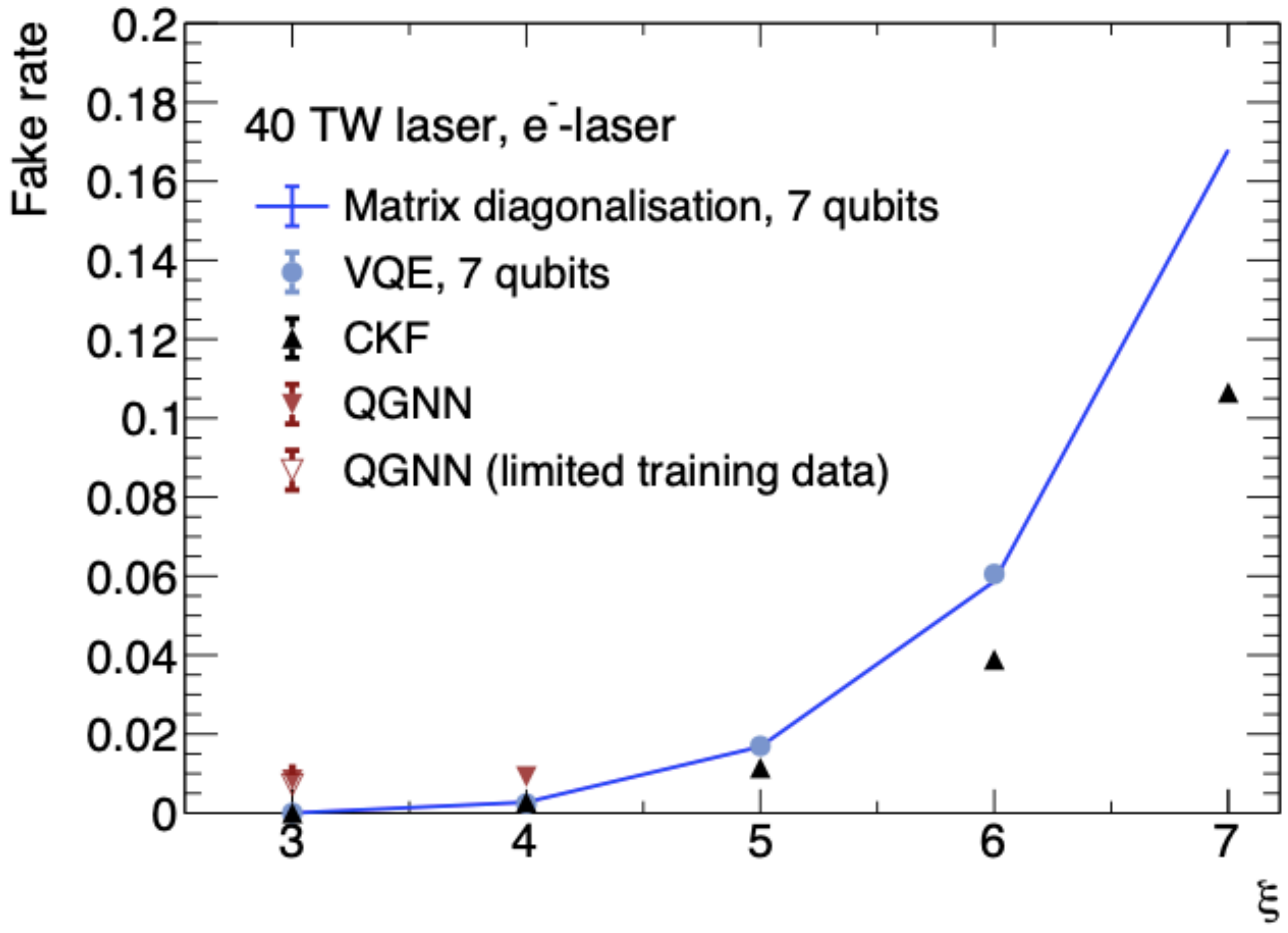


*A track is considered matched if the majority of its hits belong to the same particle (i.e. at least 3 out of 4 hits).

RESULTS



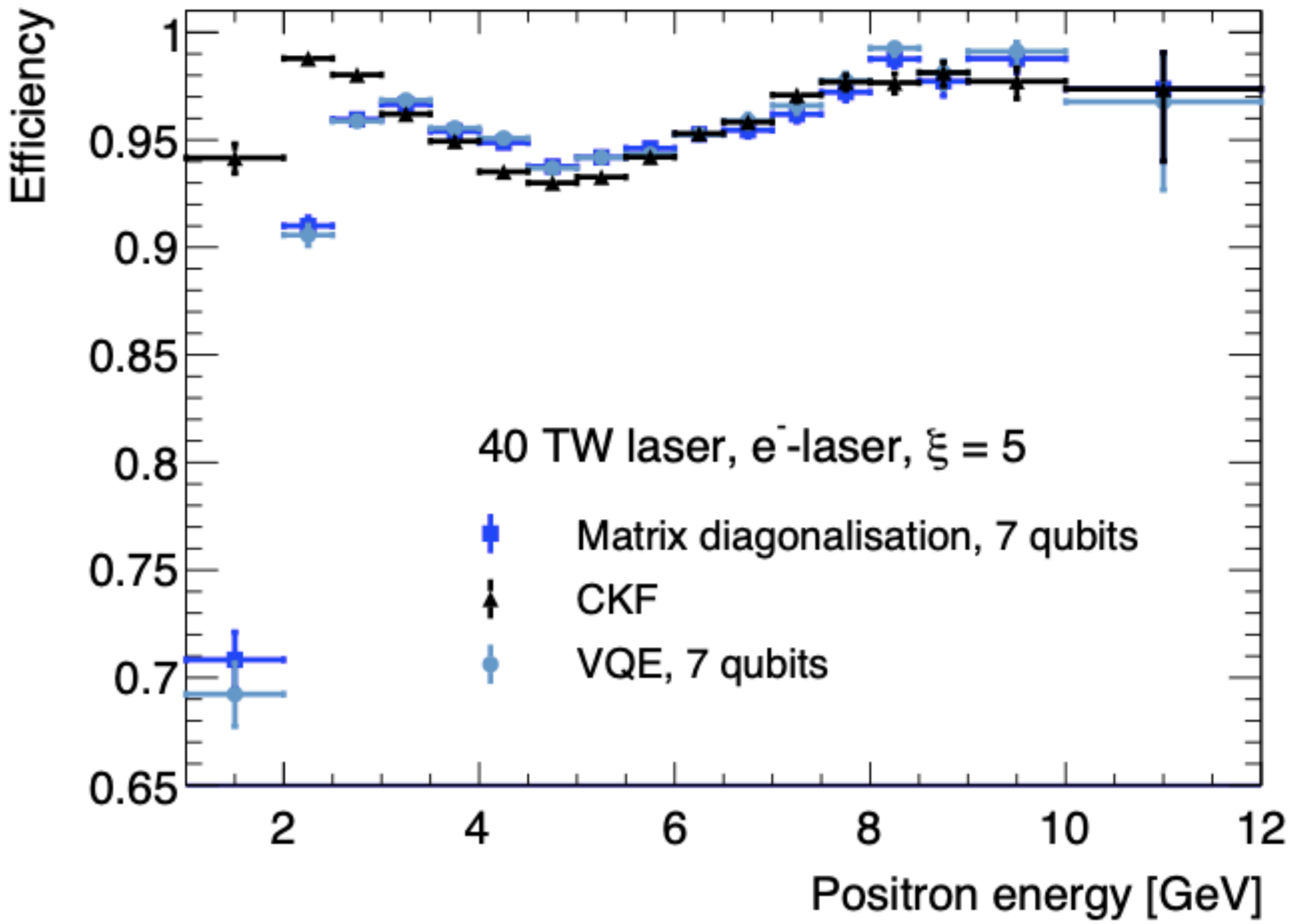
Efficiency
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
3
4
5
6
7
ξ
40 TW laser, e⁻-laser
Matrix diagonalisation, 7 qubits
VQE, 7 qubits
CKF
QGNN
QGNN (limited training data)

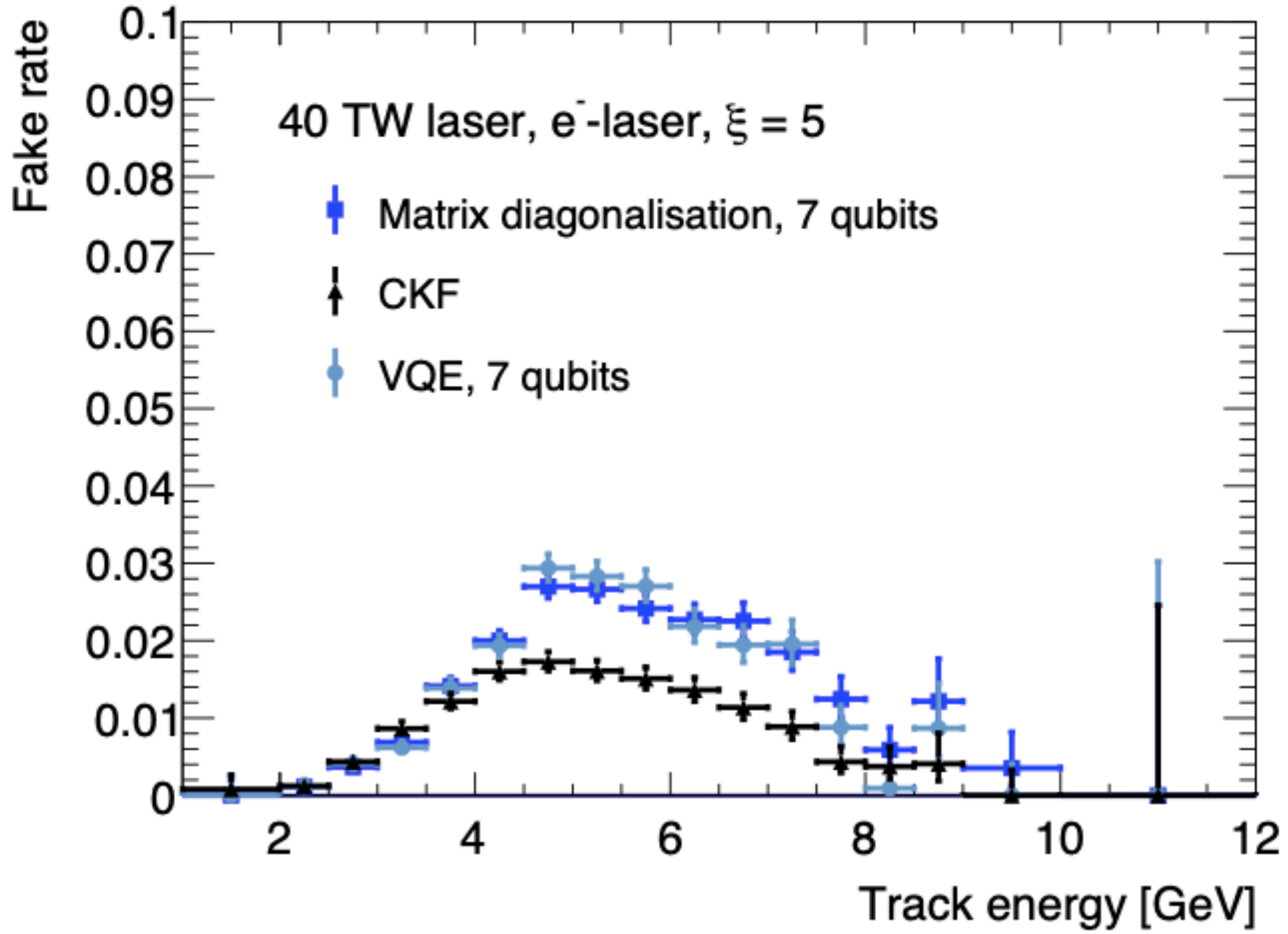


Fake rate
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
3
4
5
6
7
ξ
40 TW laser, e⁻-laser
Matrix diagonalisation, 7 qubits
VQE, 7 qubits
CKF
QGNN
QGNN (limited training data)

PERFORMANCE VS ENERGY

GNN results not available



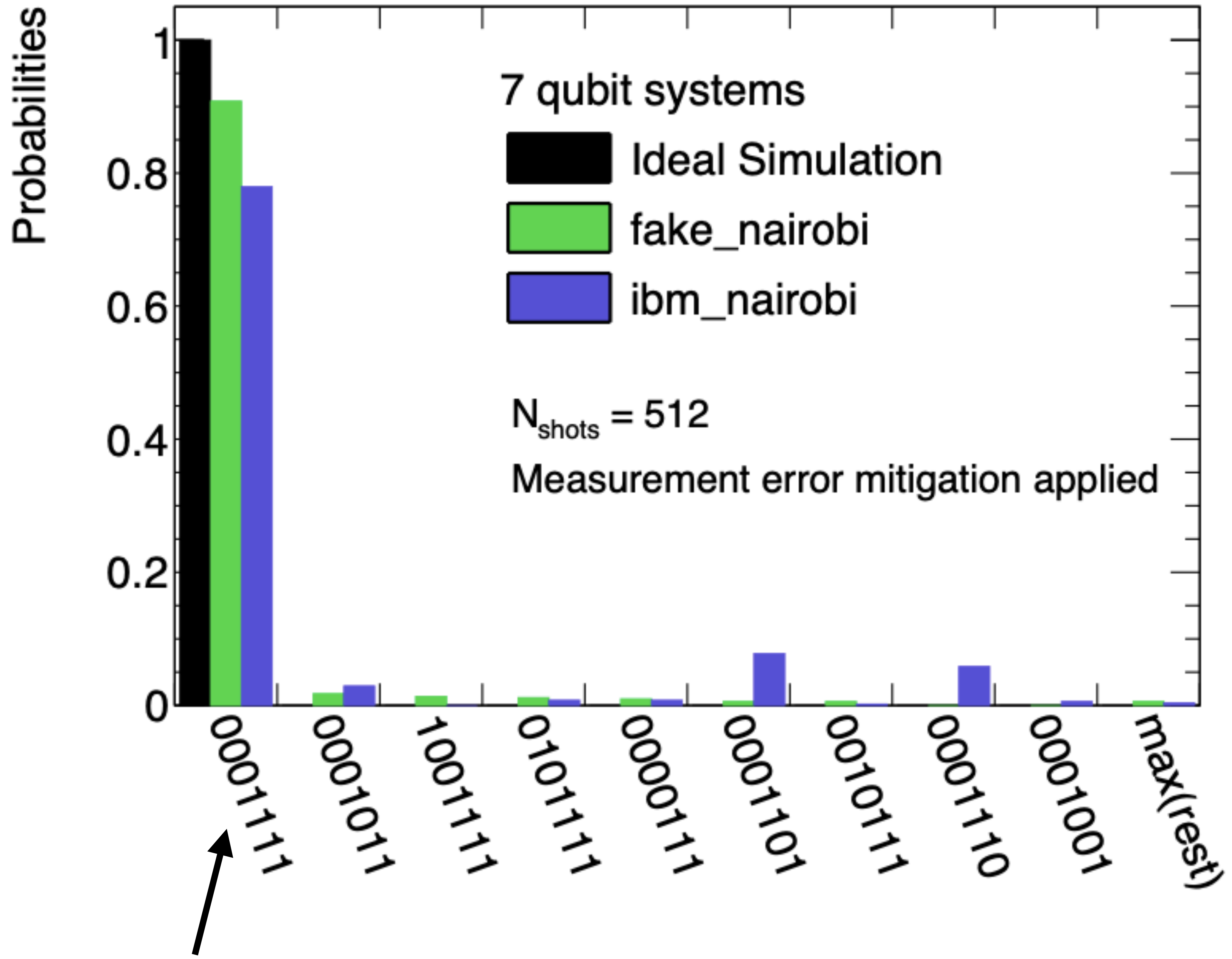


TEST ON REAL QUANTUM HARDWARE

- Results shown so far obtained using classical simulations of quantum hardware without noise.

- To study how well VQE works, we study an example with 7 triplets (matching the #qubits of the device tested).

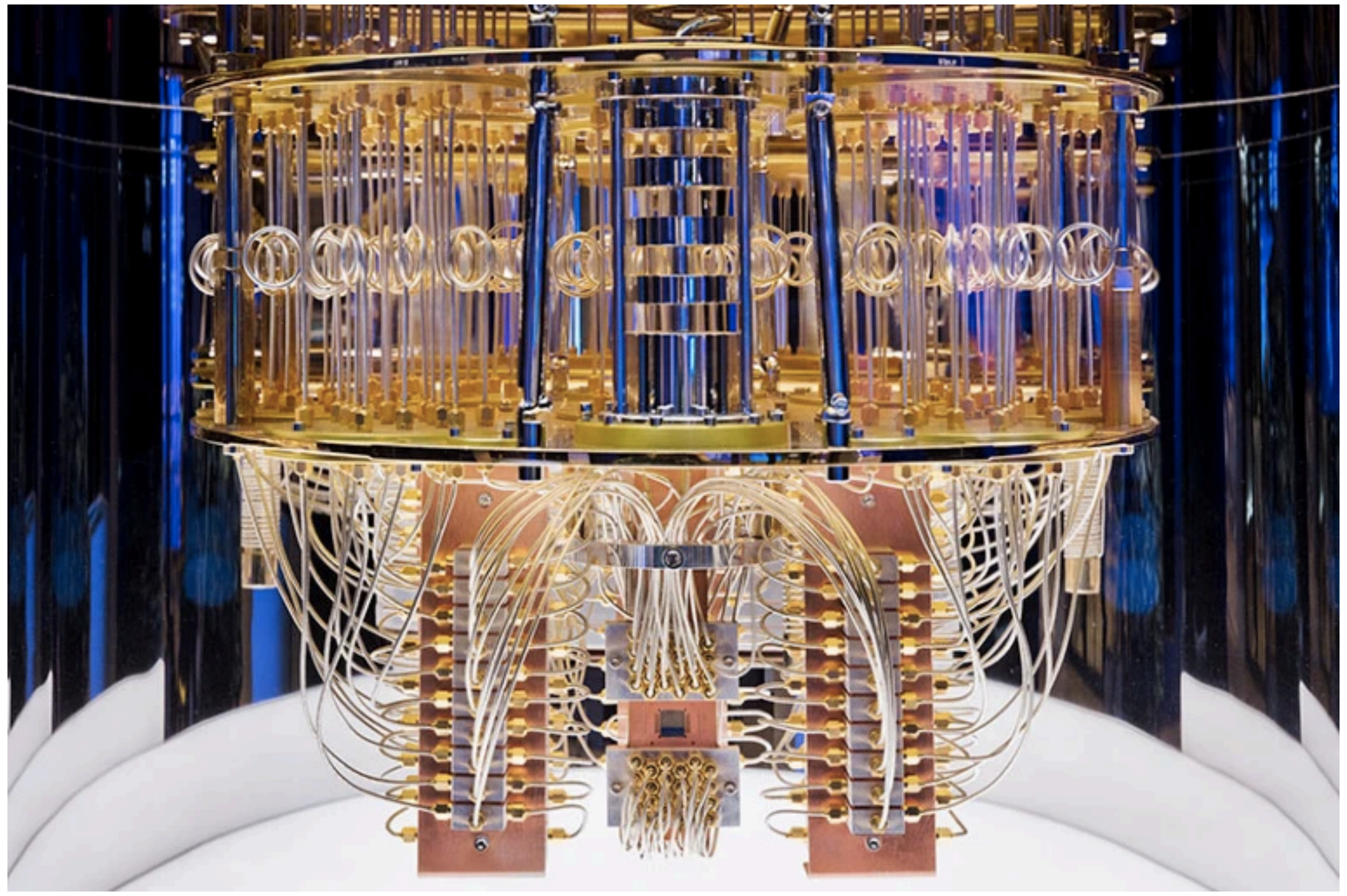
- Compare results from running on **quantum hardware (IBM Nairobi)** to **ideal simulation** as well as a **simulated device with noise**.



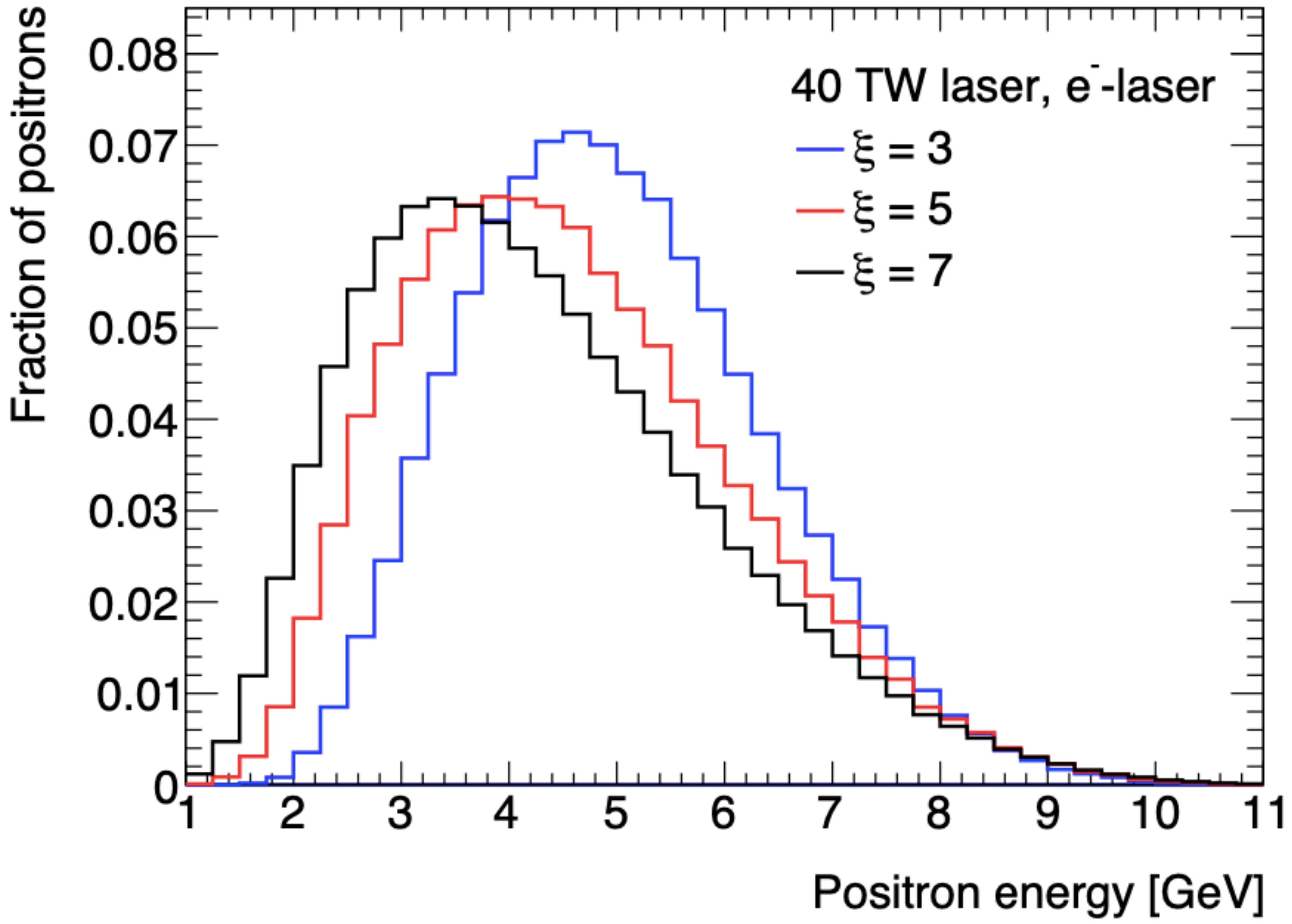
Correct solution

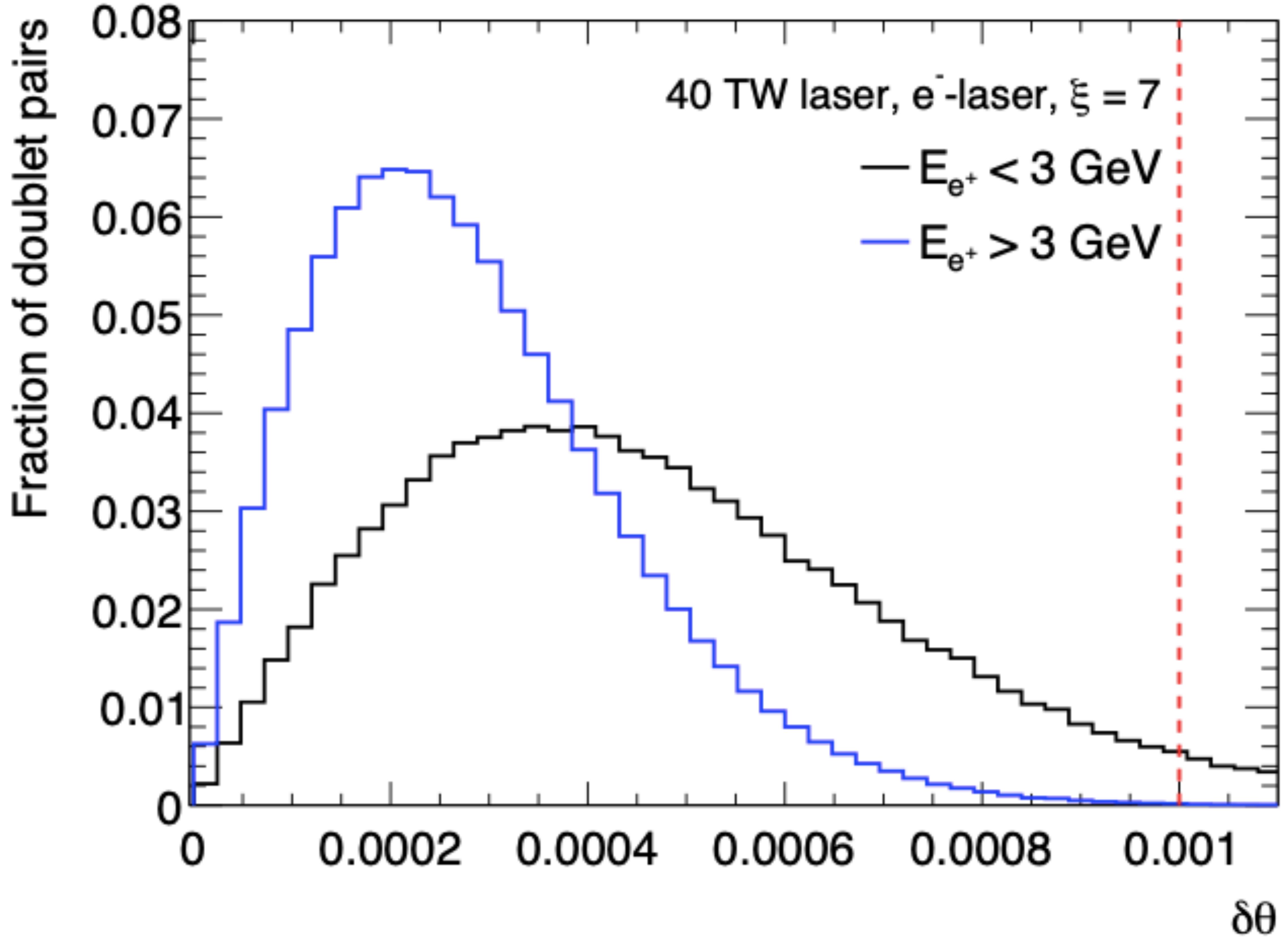
SUMMARY AND OUTLOOK

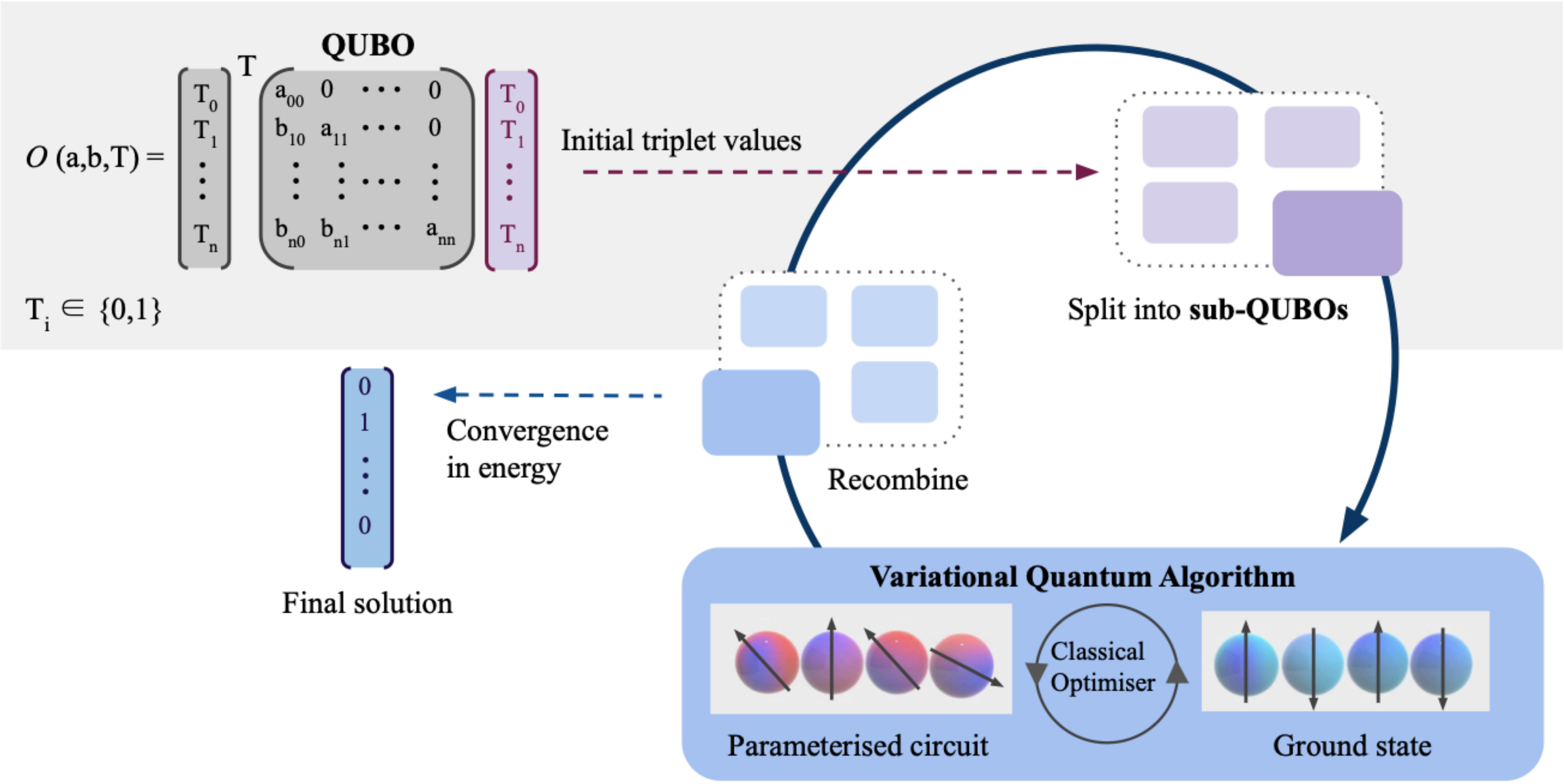
- LUXE will study strong-field QED in an unprecedented regime using high-intensity optical laser pulse and 16.5 GeV XFEL electron beam.
- Demonstrated the feasibility of tracking using a quantum approach.
  - Achieved similar performance as classical tracking.
- Next steps:
  - More systematic study of these algorithms using Noisy Intermediate Scale Quantum (NISQ)-era devices.
  - Study even more extreme environments and explore regions where quantum computing could outperform traditional methods.



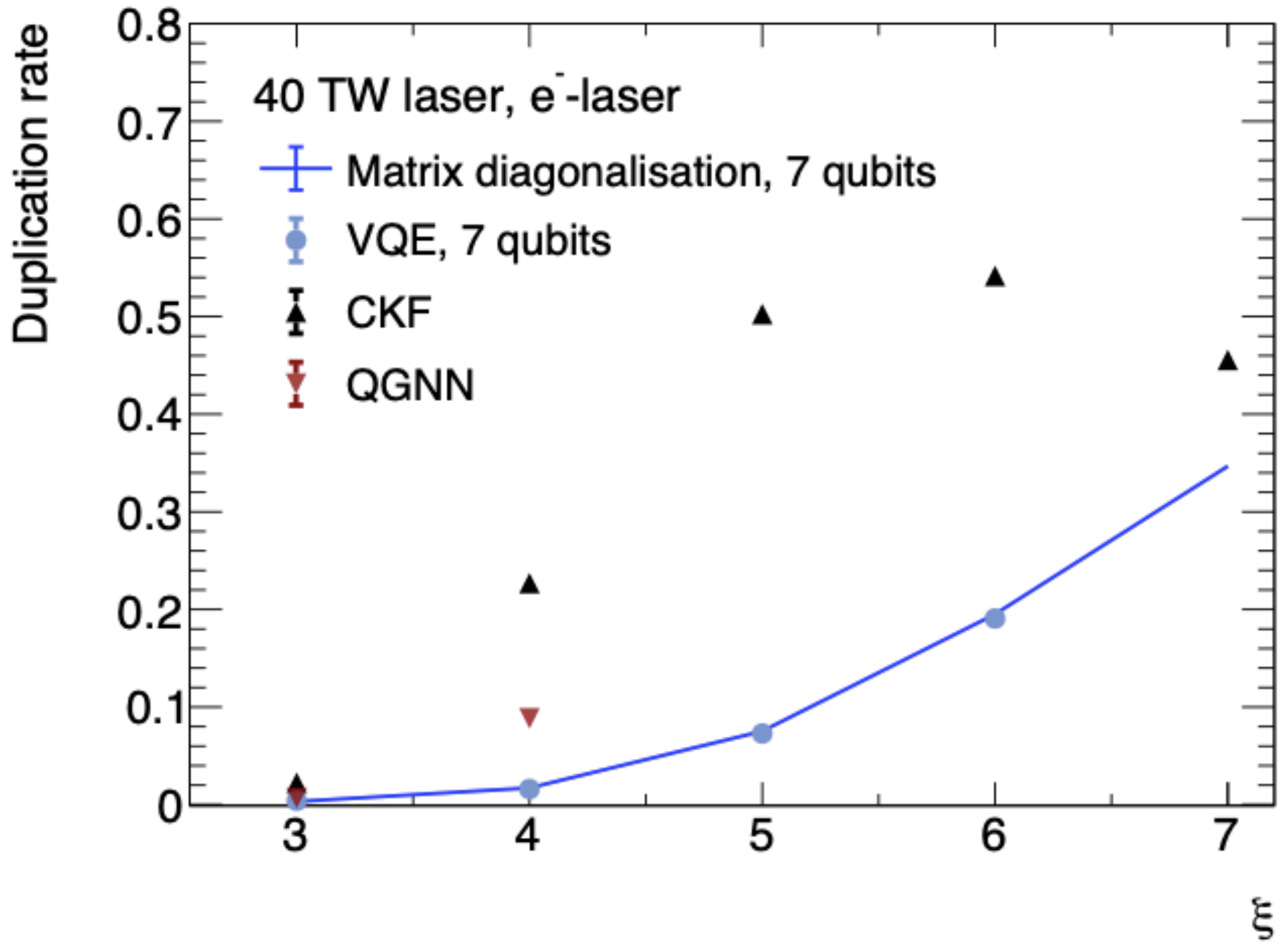
BACK-UP

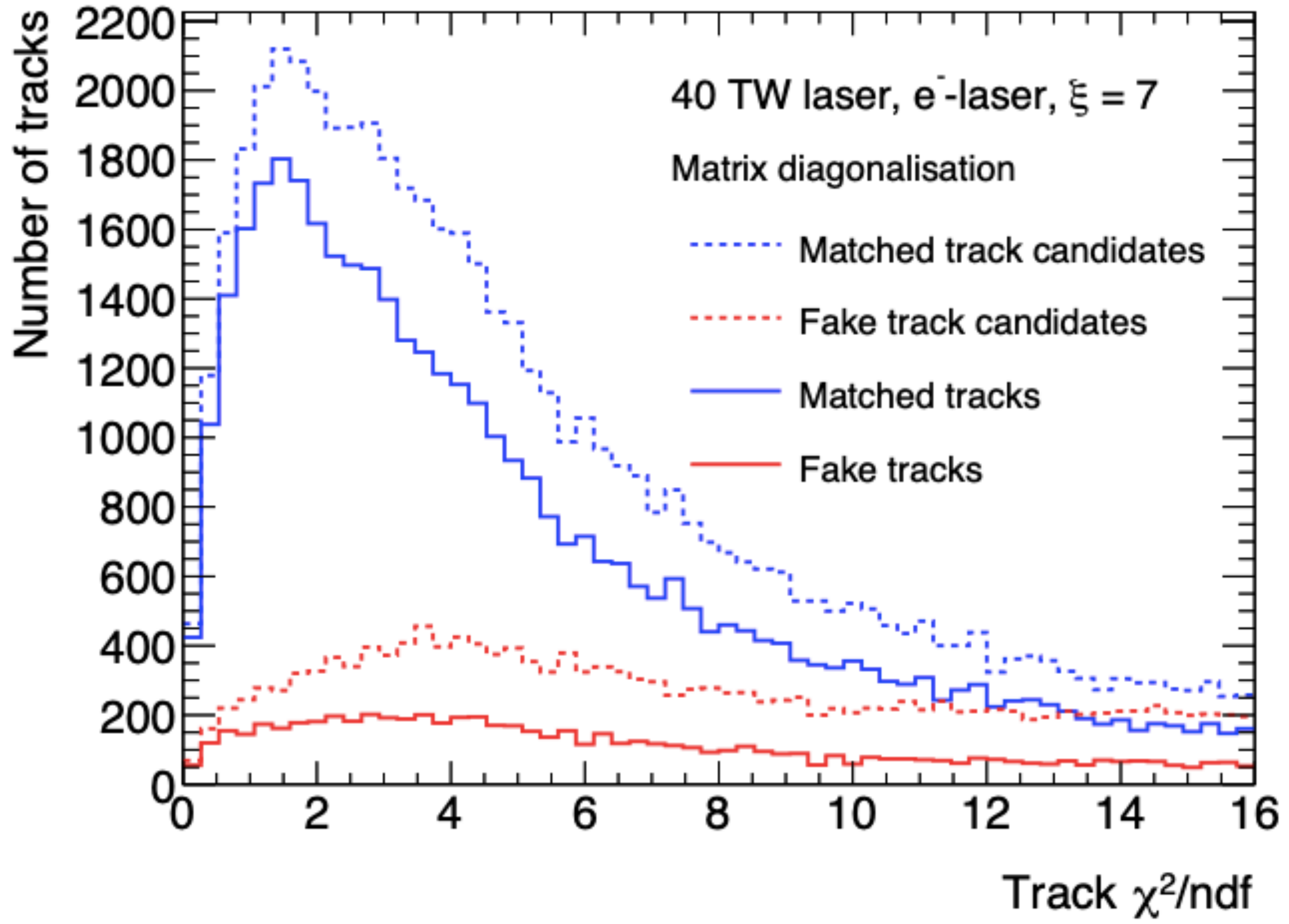

40 TW laser, e⁻-laser
ξ = 3
ξ = 5
ξ = 7
Fraction of positrons
Positron energy [GeV]
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
6
7
8
9
10
11


40 TW laser, e⁻-laser, ξ = 7
E_e+ < 3 GeV
E_e+ > 3 GeV
Fraction of doublet pairs
δθ
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.0002
0.0004
0.0006
0.0008
0.001


QUBO
$O\,(a,b,T) = \begin{bmatrix} T_0 \\ T_1 \\ \vdots \\ T_n \end{bmatrix}^T \begin{bmatrix} a_{00} & 0 & \cdots & 0 \\ b_{10} & a_{11} & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ b_{n0} & b_{n1} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} T_0 \\ T_1 \\ \vdots \\ T_n \end{bmatrix}$
$T_i \in \{0,1\}$
Initial triplet values
Split into sub-QUBOs
Recombine
Convergence
in energy
0
1
0
Final solution
Variational Quantum Algorithm
Classical
Optimiser
Parameterised circuit
Ground state

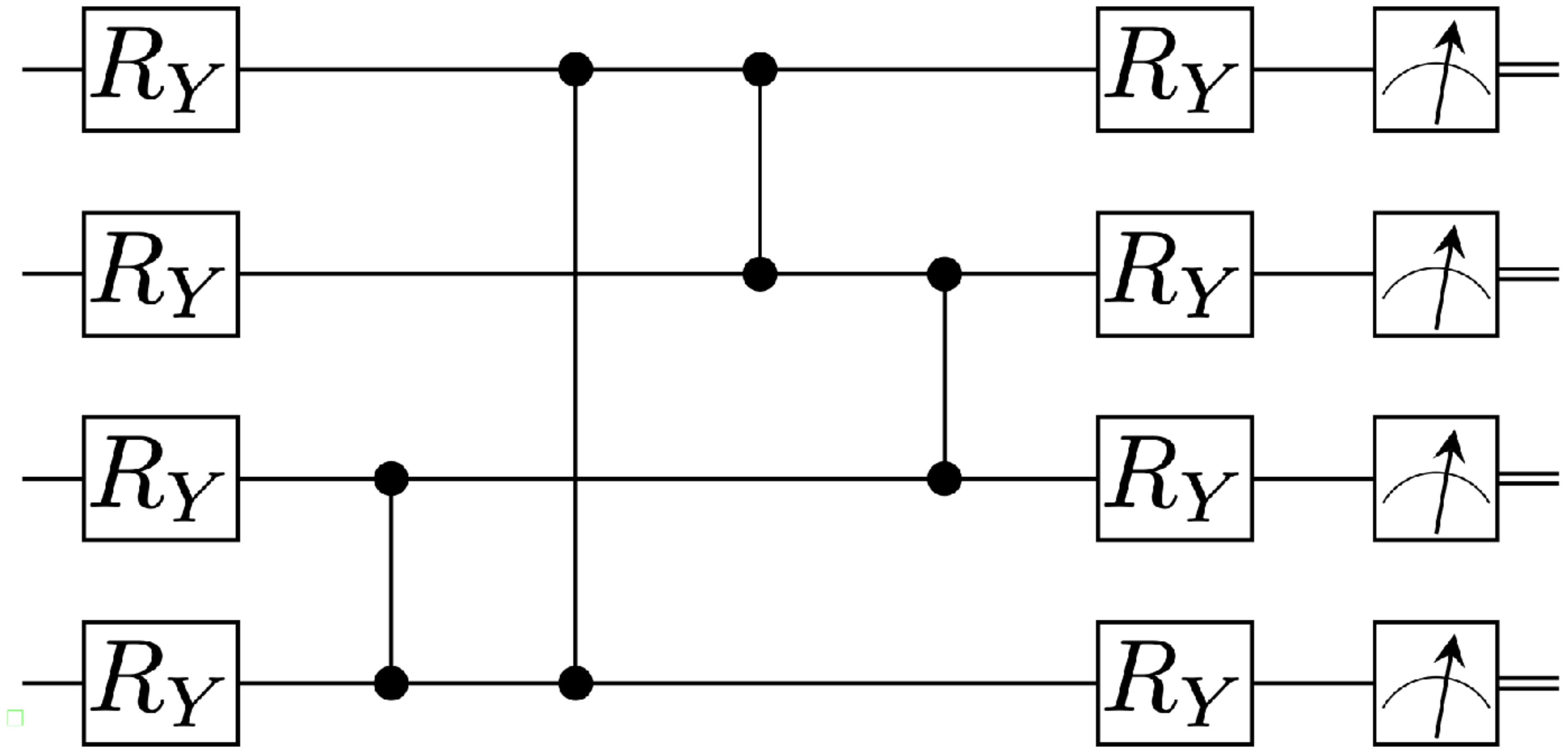
TRACK POST PROCESSING





GNN

- Circuit 10 with two layers and 10 qubits used.



(d) Circuit 10 in four qubits and single layer configuration. Adapted from Sim et al. (2019).

- EdgeNet and the NodeNet are applied alternately four times to allow the node features to be updated using farther nodes, as determined in a scan of the optimal model parameters.

GNN

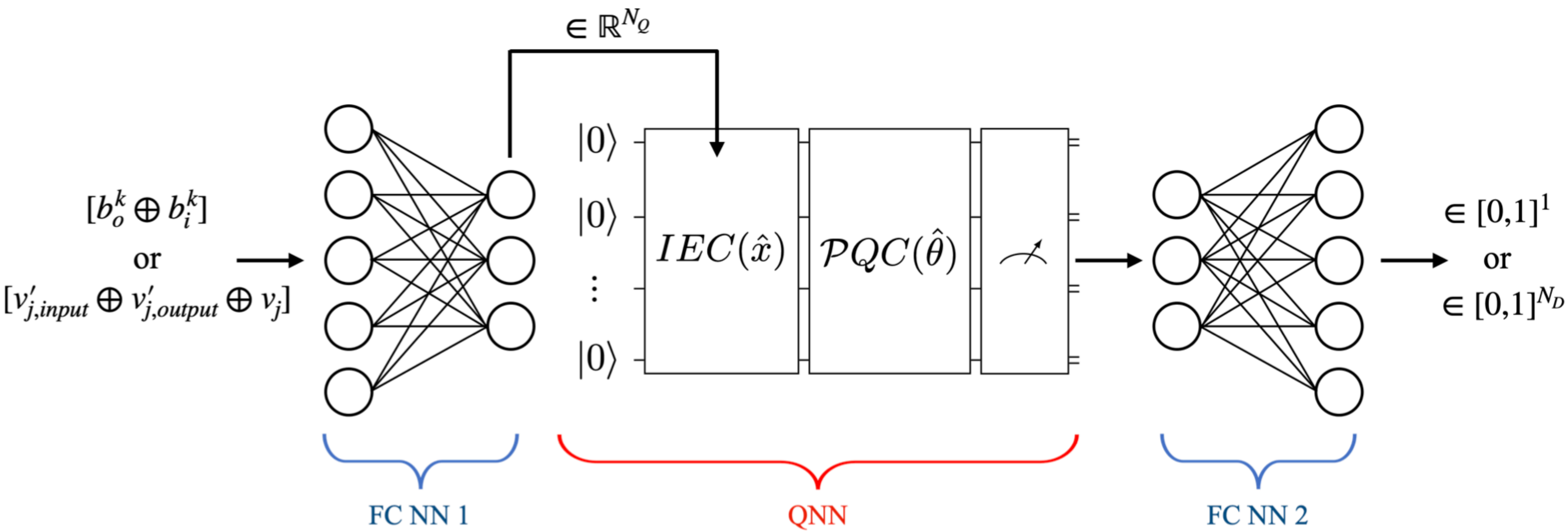
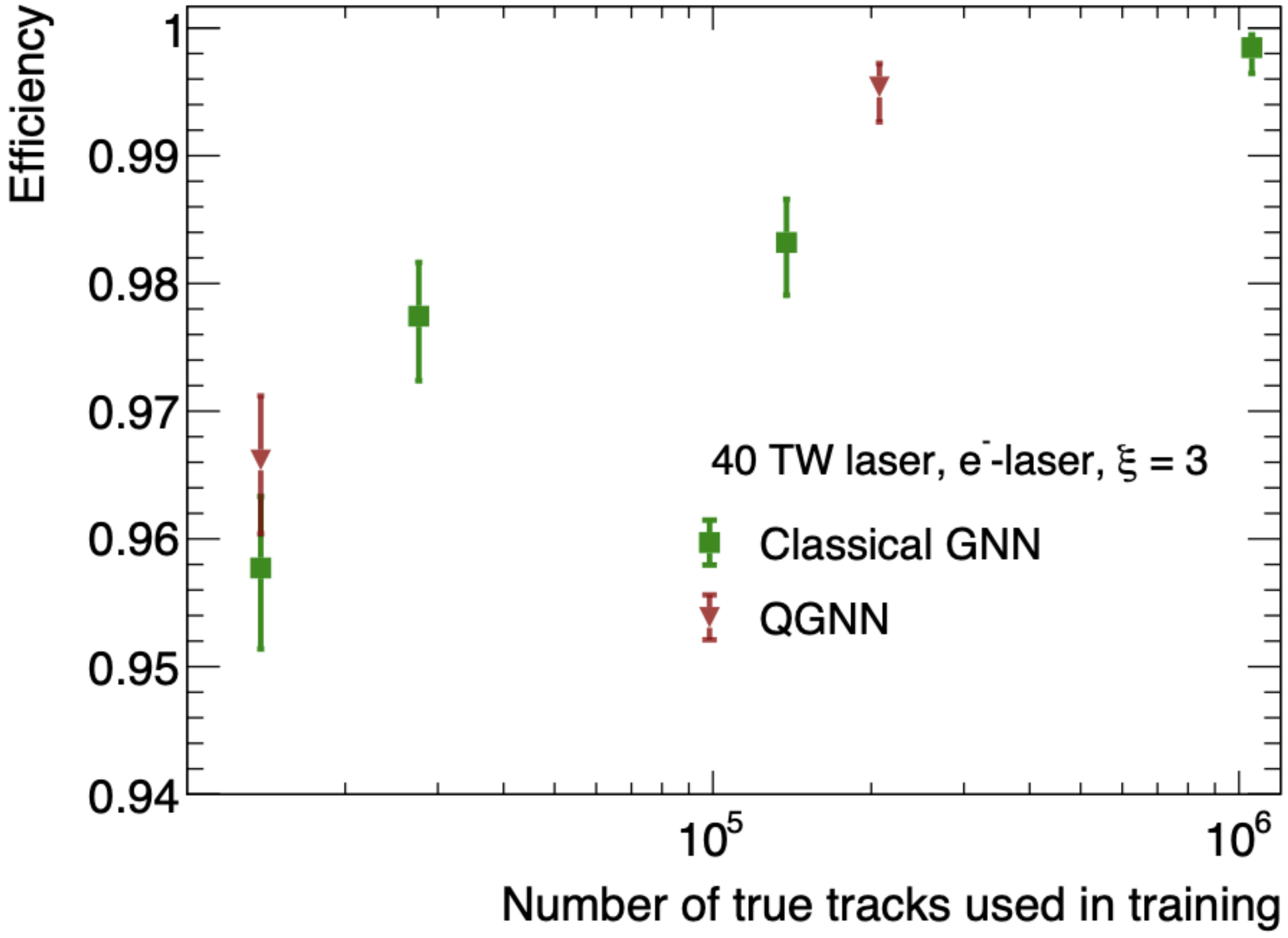


Fig. 6 The Hybrid Neural Network (HNN) architecture. The input is first fed into a classical fully connected Neural Network (FC NN) layer with sigmoid activation. Then, its output is encoded in the QNN with the Information Encoding Circuit (IEC). Next, the Parametrized Quantum Circuit (PQC) applies transformations on the encoded states. The output of QNN is obtained as expectation values for each qubit that is measured. A final FC NN layer with sigmoid activation is used to combine the results of different qubit measurements. The same HNN architecture is used in Edge (upper input and output dimension) and Node Networks (lower input and output dimension) with different parameters. The input and output dimension sizes change according to the network type. Details of the dimensions of each layer are given in Table 1.

GNN


Efficiency
1
0.99
0.98
0.97
0.96
0.95
0.94
10^5
10^6
Number of true tracks used in training
40 TW laser, e^--laser, $\xi = 3$
Classical GNN
QGNN

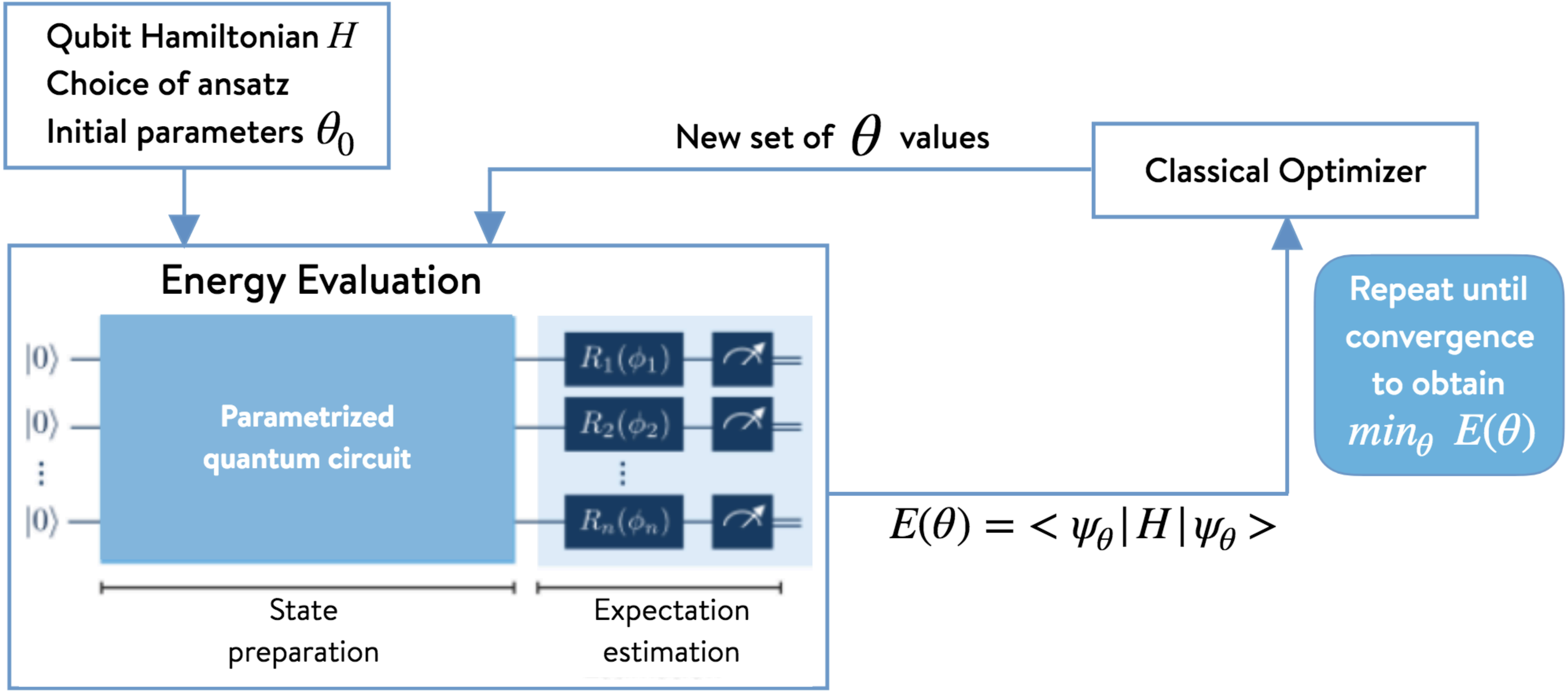


Image from http://openqemist.1qbit.com/docs/vqe_microsoft_qsharp.html

METHOD COMPARISON

Methods	GNN	QUBO	CKF
Starting point	Doublet	Triplet	Seed
Local/global	Global	Global	Local
Scope	Pattern recognition only	Pattern recognition only	Pattern recognition + track fitting
Classical benchmark	Classical GNN	Matrix diagonalisation	-