Positron Track Reconstruction for LUXE using a Quantum Computer

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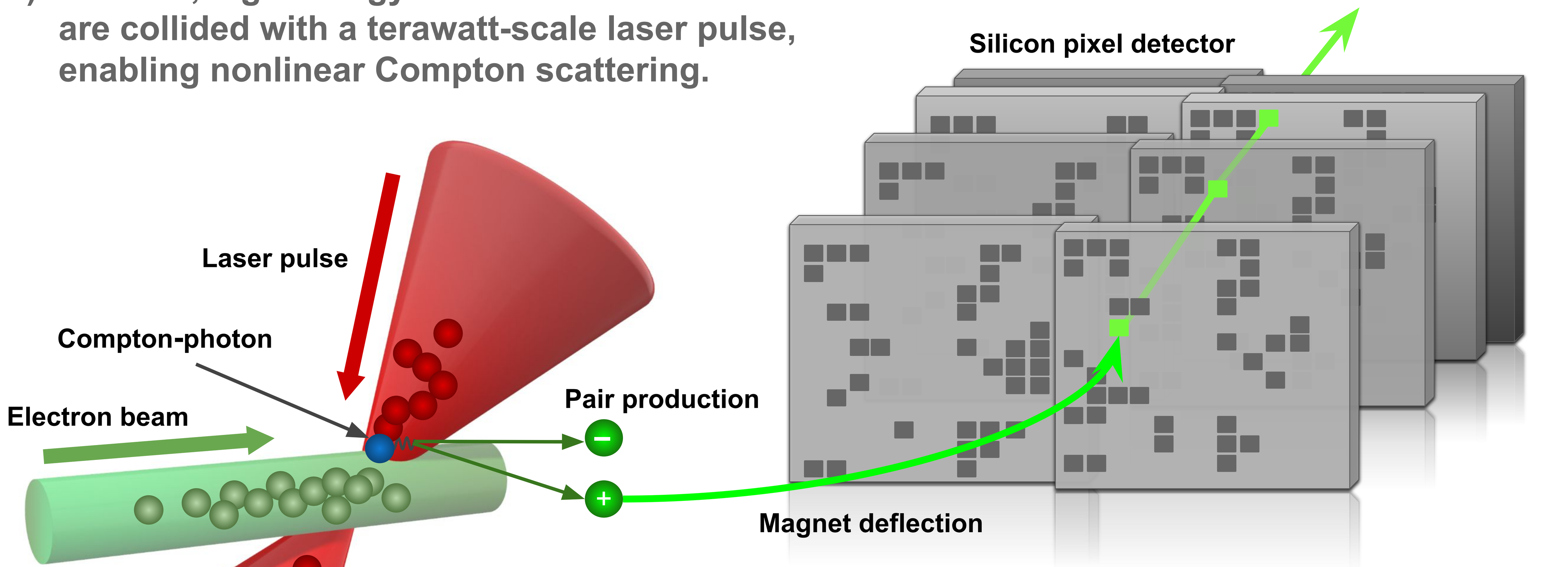
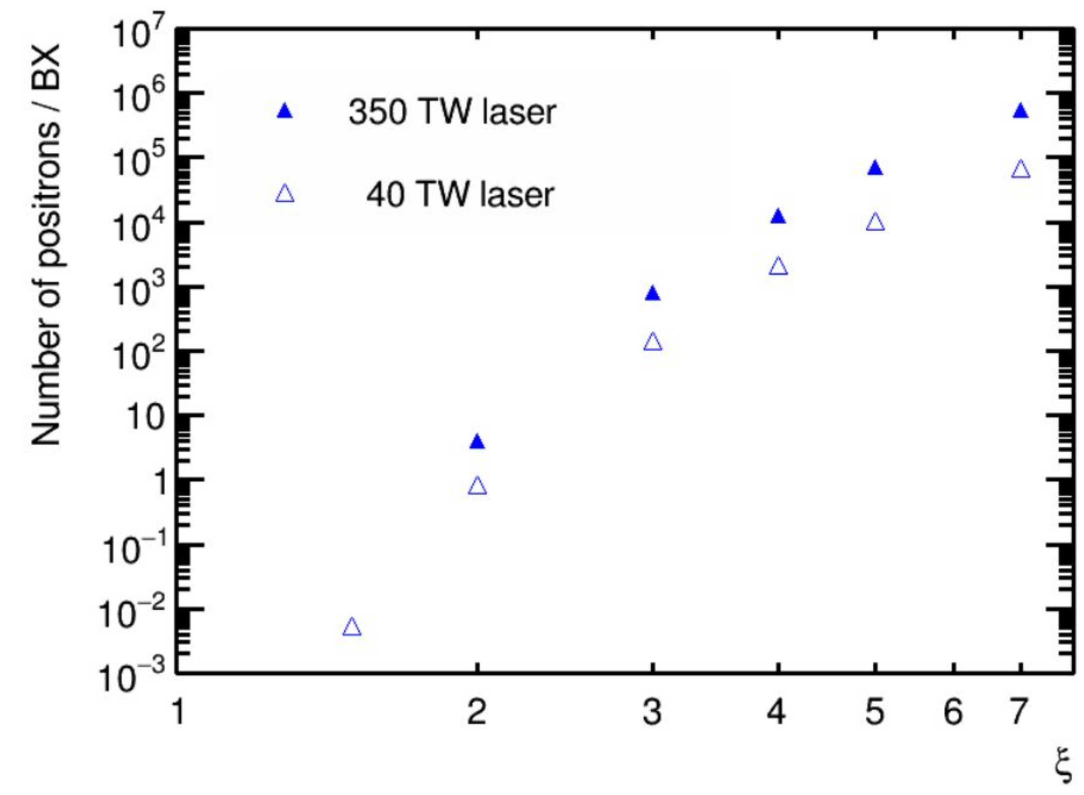
1.) In LUXE, high-energy electrons from XFEL are collided with a terawatt-scale laser pulse, enabling nonlinear Compton scattering.





2.) A subsequent e^+e^- pair is created via Breit Wheeler pair creation. Positrons then impinge on a four-layered Silicon pixel detector.

3.) One goal is to measure the positron rate as a function of the laser intensity parameter

$$\xi = \frac{m_e \epsilon_L}{\omega_L \epsilon_{cr}}$$

m_e : electron mass
ω_L : laser frequency
$\epsilon_{L,cr}$: laser/critical field strength

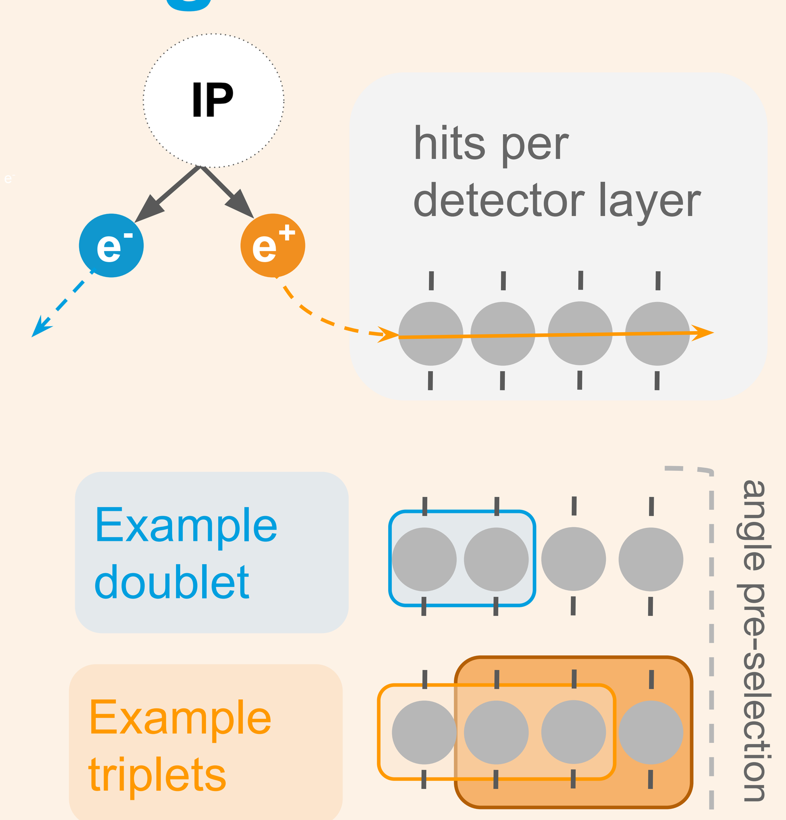
4.) LUXE aims to investigate the transition into the high-energy, non-perturbative regime of QED. Theoretically, a *lower* positron production rate is expected after the critical field is reached compared to perturbative predictions.

LUXE Model Building.

Monte Carlo generated event samples
+
custom detector simulation

Two consecutive hits are grouped into doublets

Two doublets form one triplet



Triplets as QUBO input.

Quadratic Unconstrained Binary Optimisation

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

Weighting triplet T_i with quality a_i

Compatibility b_{ij} between two triplets

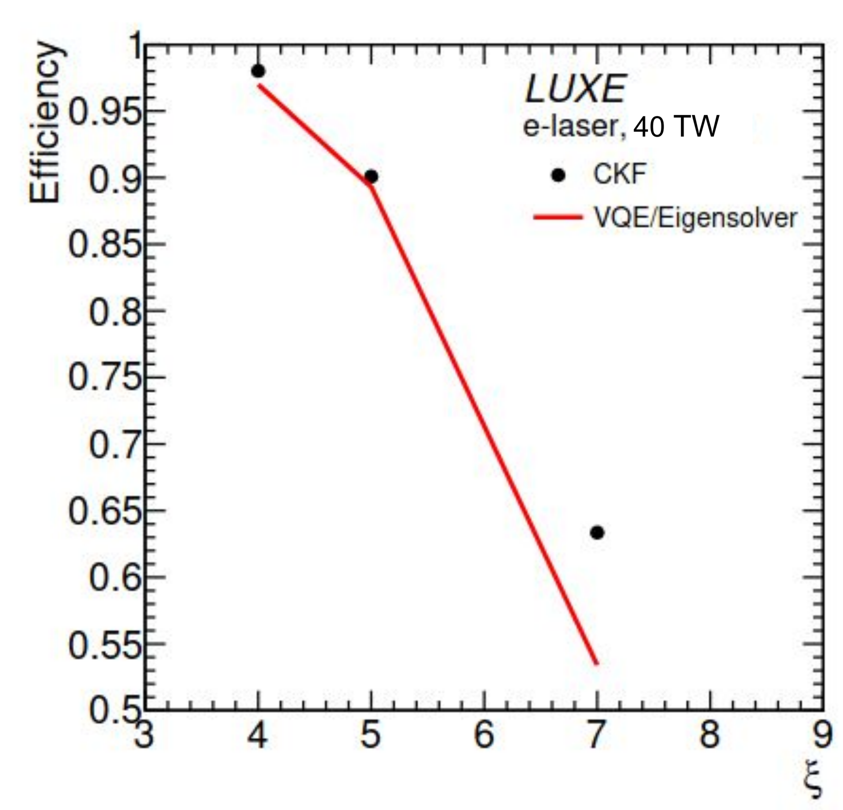
$$b_{ij} = \begin{cases} -S(T_i, T_j), & \text{if } (T_i, T_j) \text{ form a quadruplet,} \\ \zeta & \text{if } (T_i, T_j) \text{ are in conflict,} \\ 0 & \text{otherwise.} \end{cases}$$

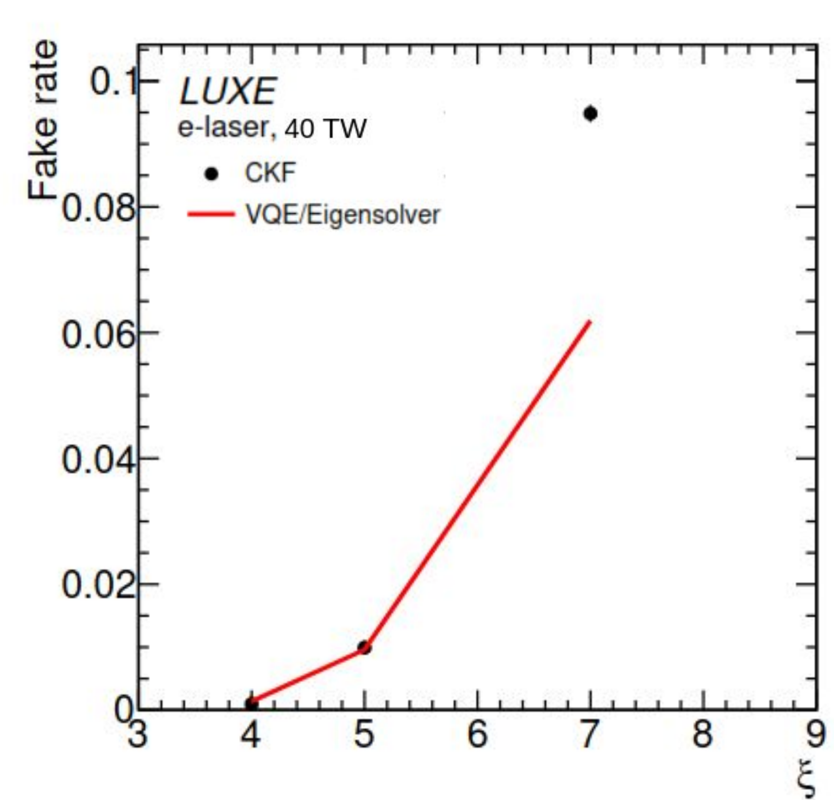
The ground state of the QUBO returns the best set of triplets.

Quantum Simulator. The QUBO is mapped onto a quantum computer (here: simulator) and minimized using the Variational Quantum Eigensolver (VQE). Additionally, the QUBO is analytically solved using the eigensolver.

Goal. Benchmark performance against conventional methods using Graph Neural Network (GNN) or a Combinatorial Kalman Filter.

Results. Efficiency and fake rate are compared for full bunch crossings of up to ~68 000 particles for ξ=7.





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

Key questions.

- How does the performance depend on ξ?
- What are the quantum computer requirements to run efficiently?
- How does quantum noise affect the results?
- What quantum algorithm is optimal?
- How does the choice of quantum computer affect the results?

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Learn more:

Studying quantum algorithms for particle track reconstruction in the LUXE experiment. (2022) *arXiv*. https://doi.org/10.48550/arXiv.2202.06874

Track reconstruction at the LUXE experiment using quantum algorithms. (2022) *arXiv*. https://doi.org/10.48550/arXiv.2210.13021

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