SECOND DMLAB MEETING, 13TH DECEMBER 2022

LUXE AND QUANTUM COMPUTING

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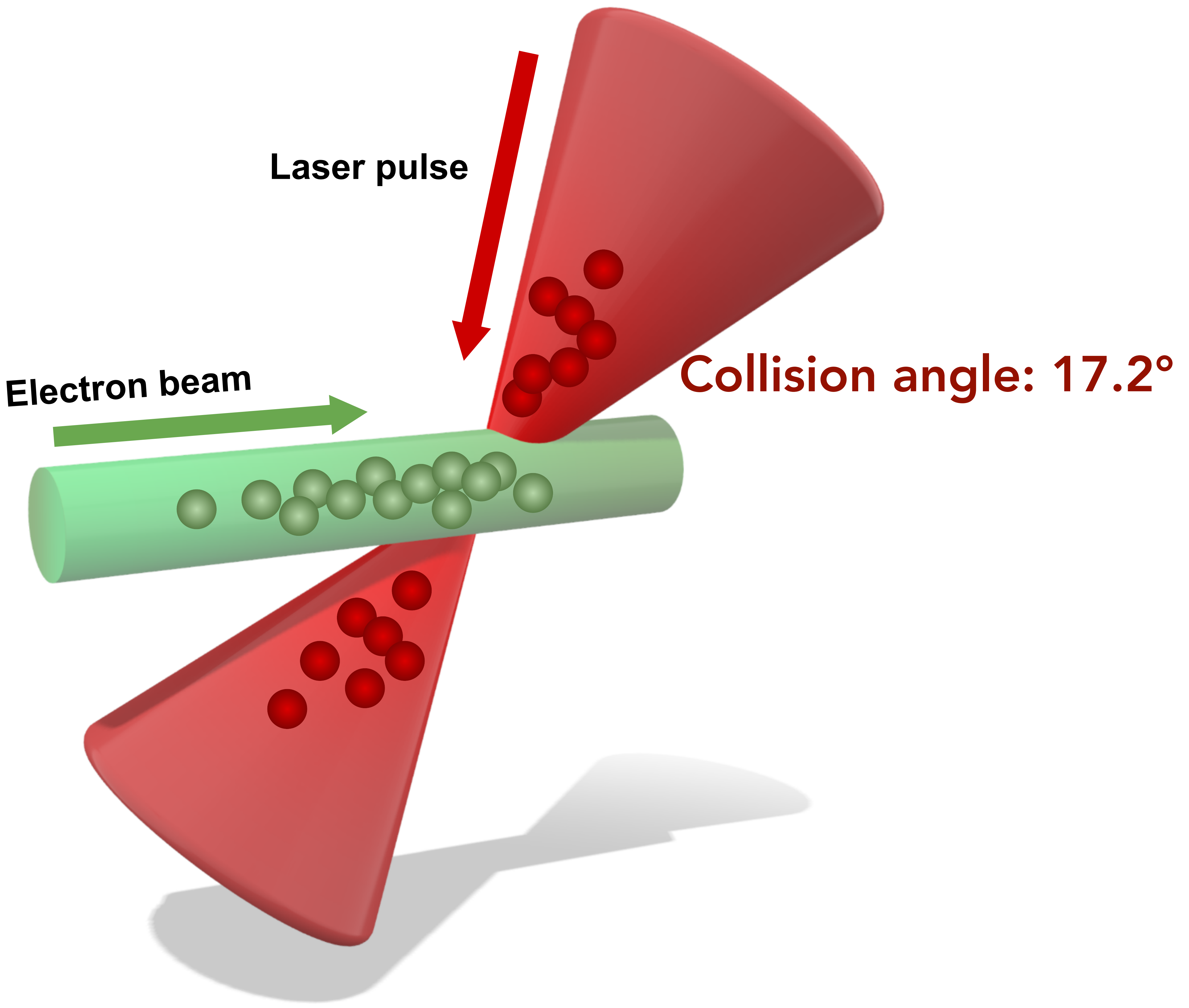
[4]*Massachusetts Institute of Technology*
[5]*Northeastern University London*
[6]*Albert-Ludwigs-Universität Freiburg*

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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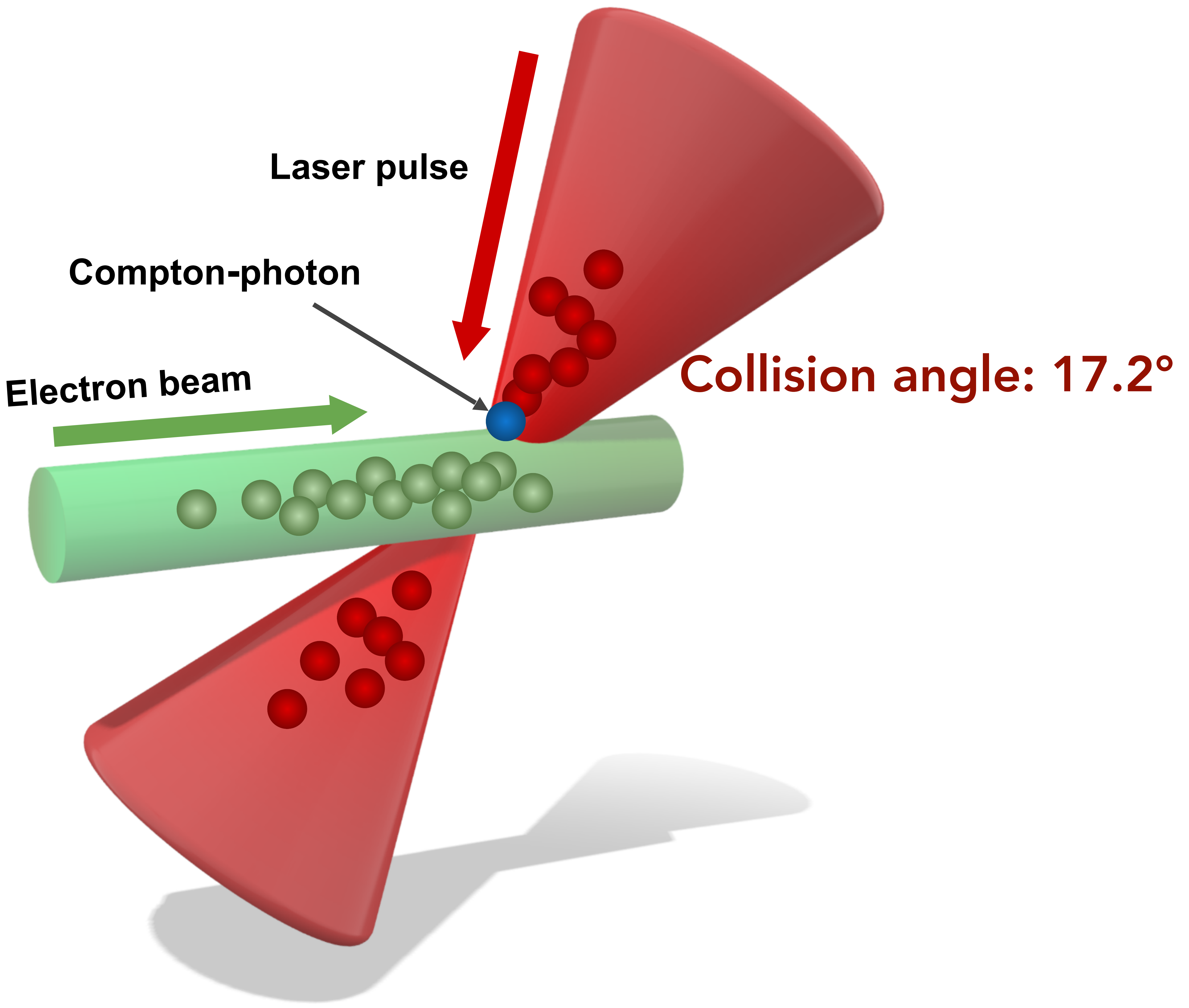
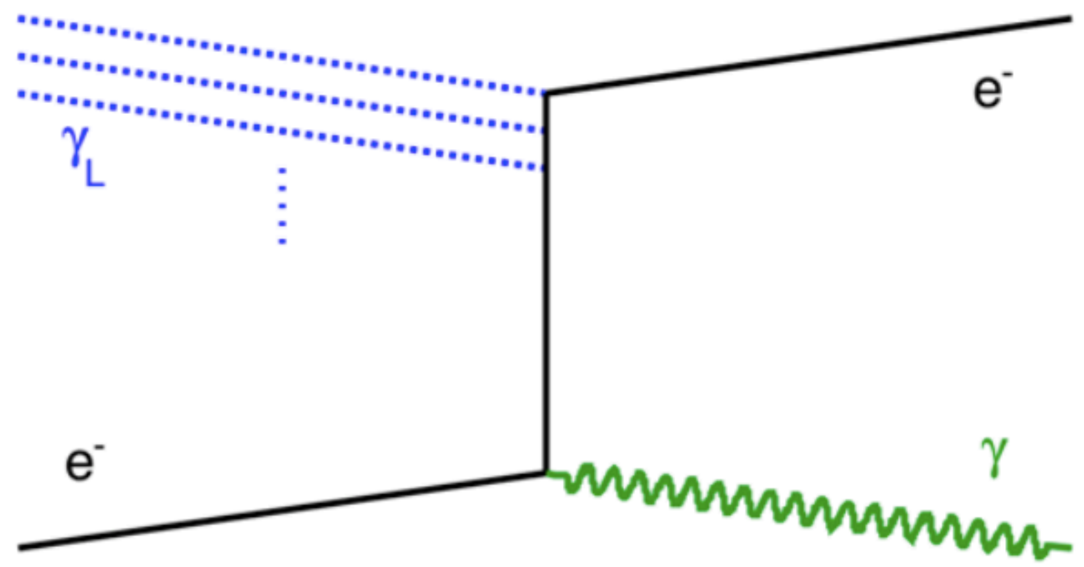


Non-linear Compton scattering:

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



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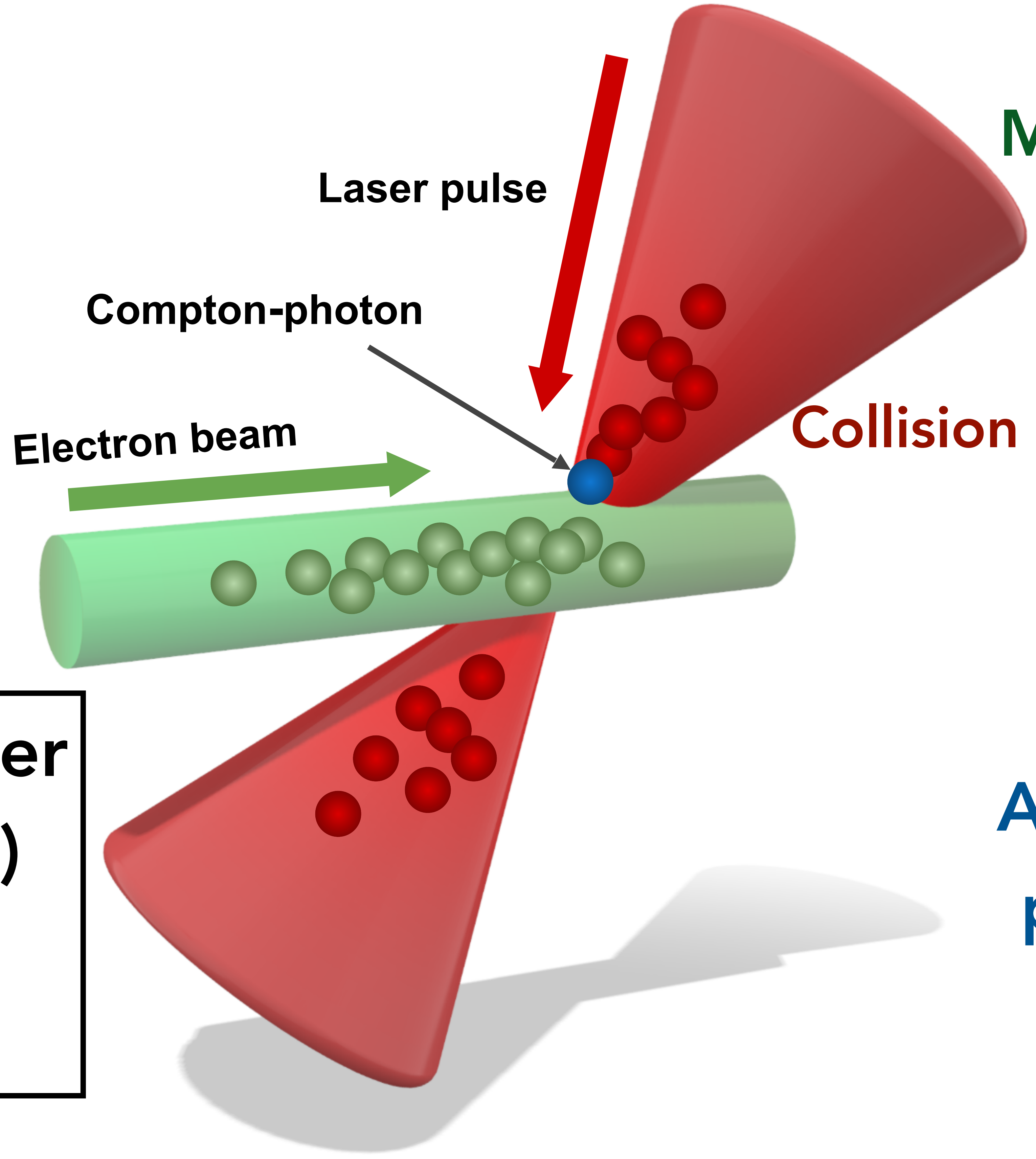
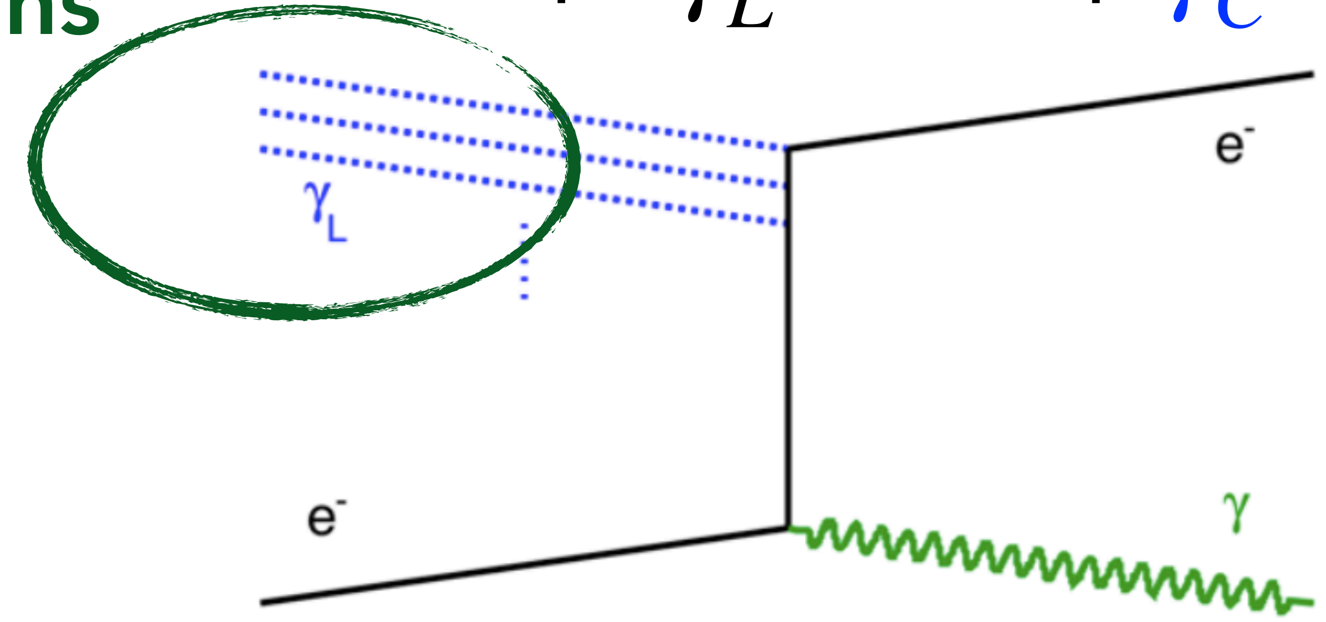


Collision angle: 17.2°

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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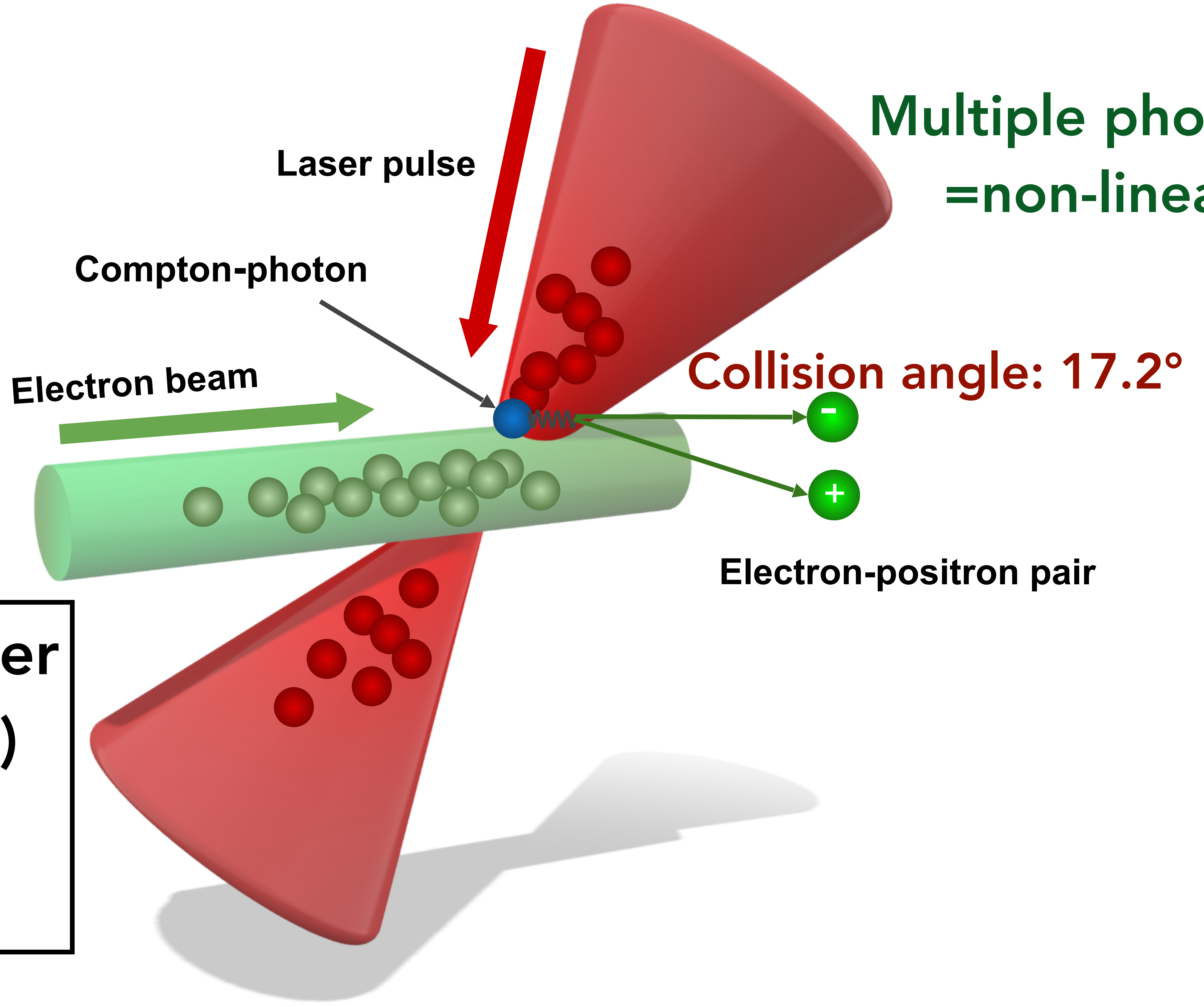

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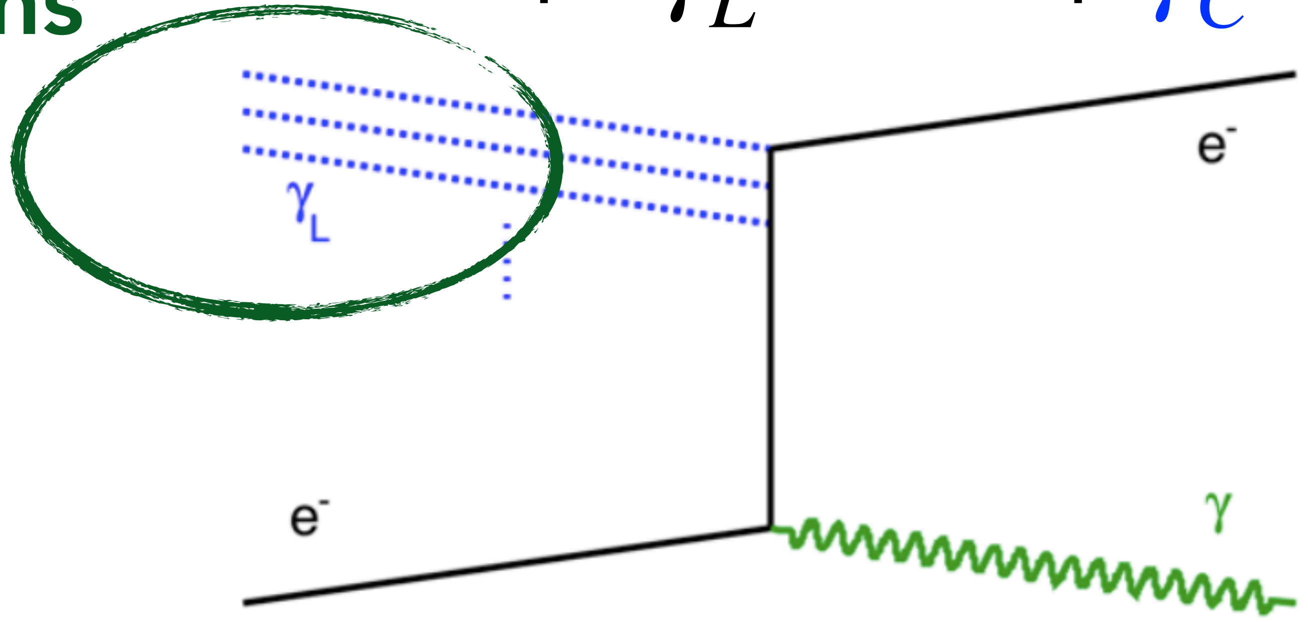
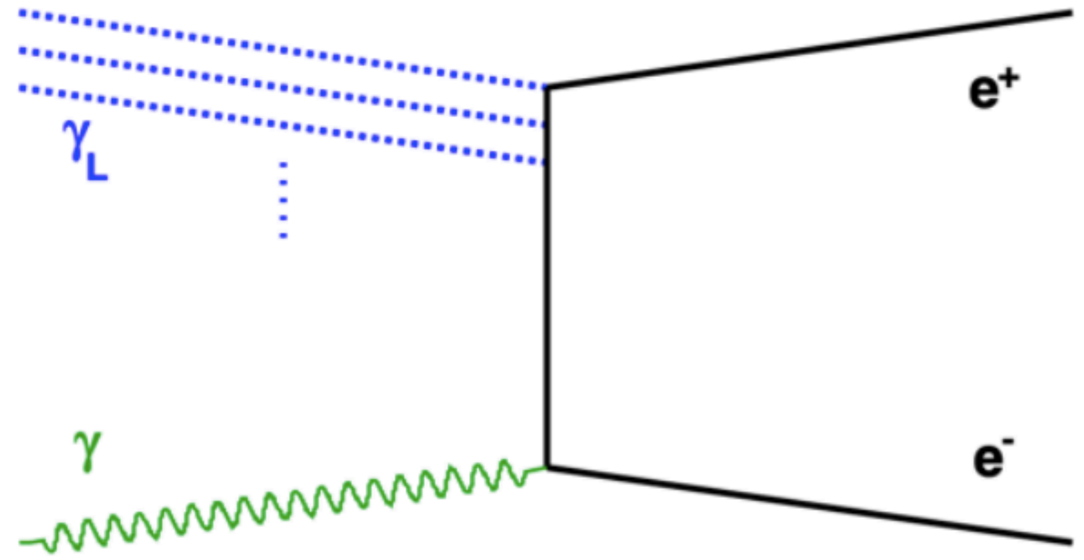


Non-linear Breit Wheeler:

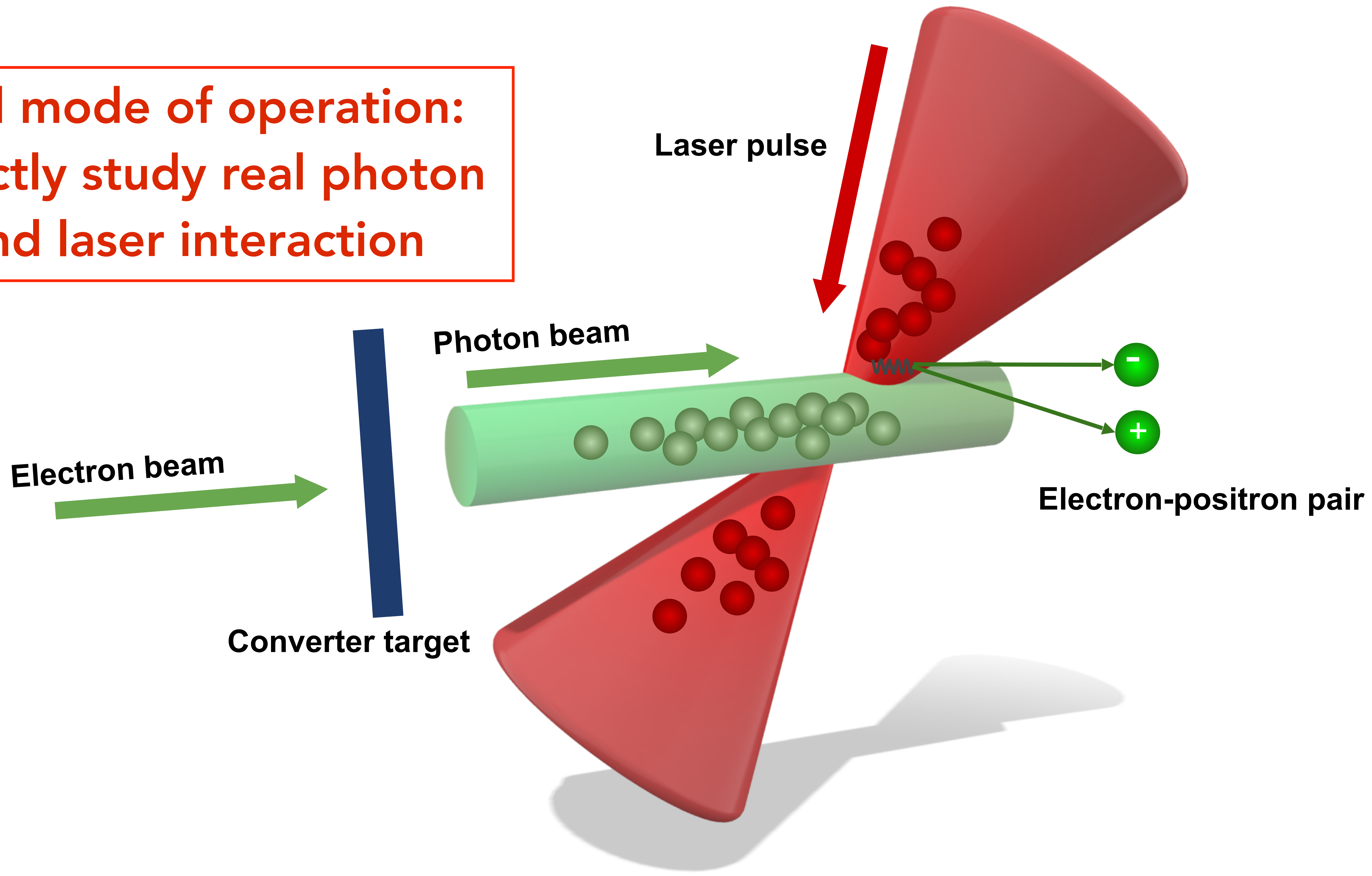
$$\gamma_C + n'\gamma_L \rightarrow e^+ + e^-$$



LUXE: LASER UND XFEL EXPERIMENT

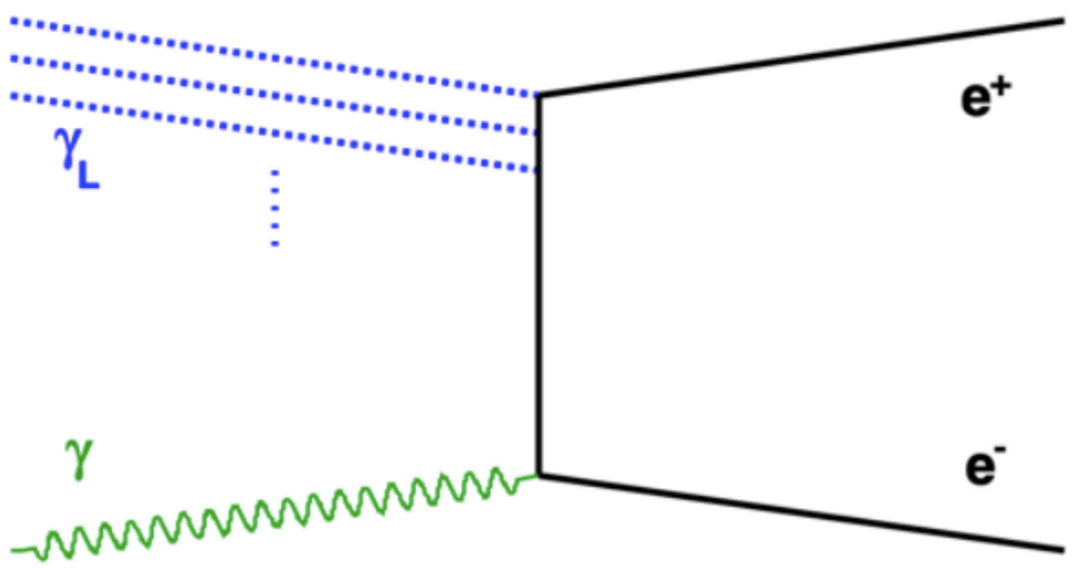
- Experiment in planning at DESY and European XFEL to study collisions of high-energy XFEL electron beam and high-power laser.

2nd mode of operation: directly study real photon and laser interaction



Non-linear Breit Wheeler:

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

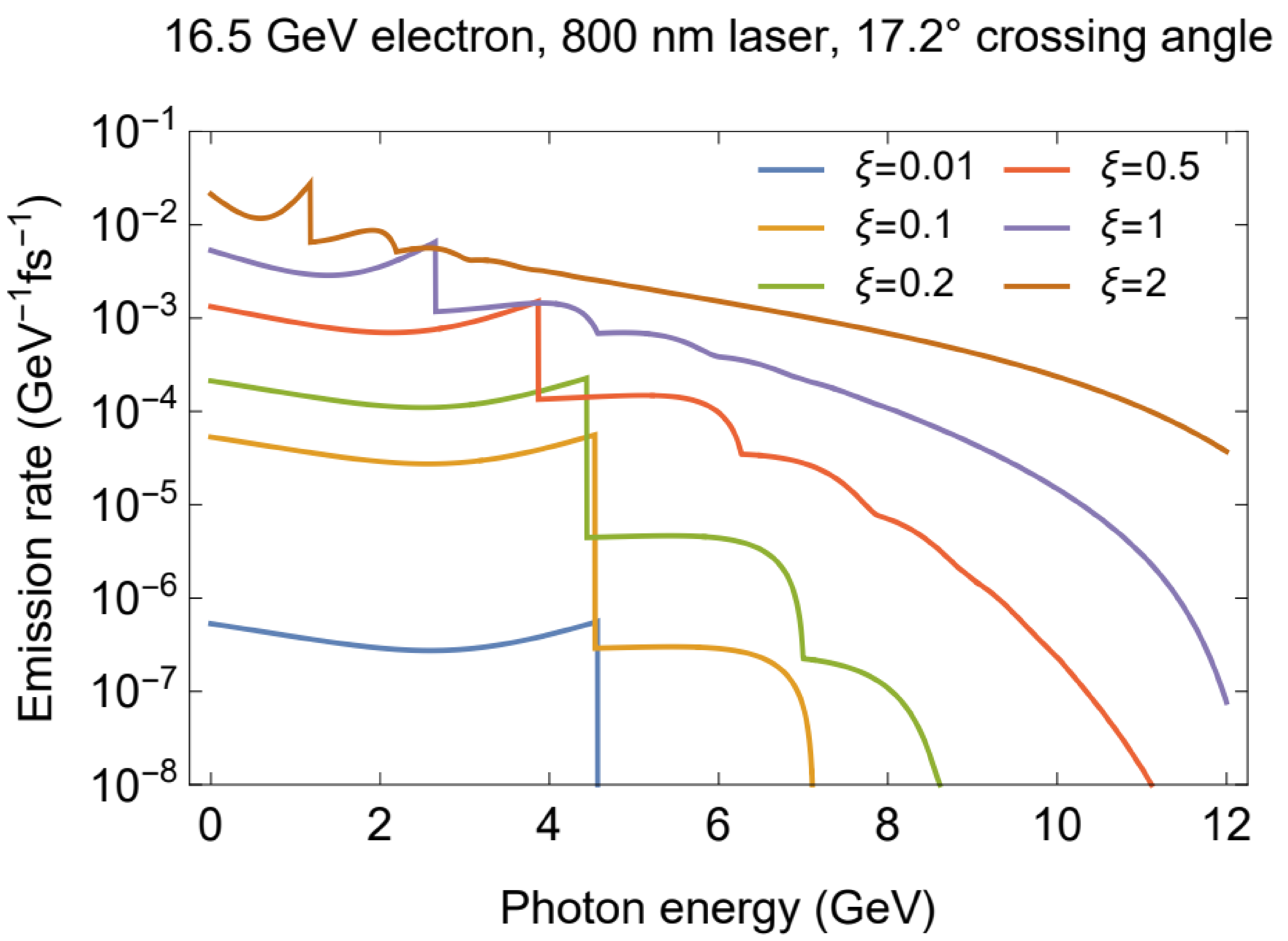


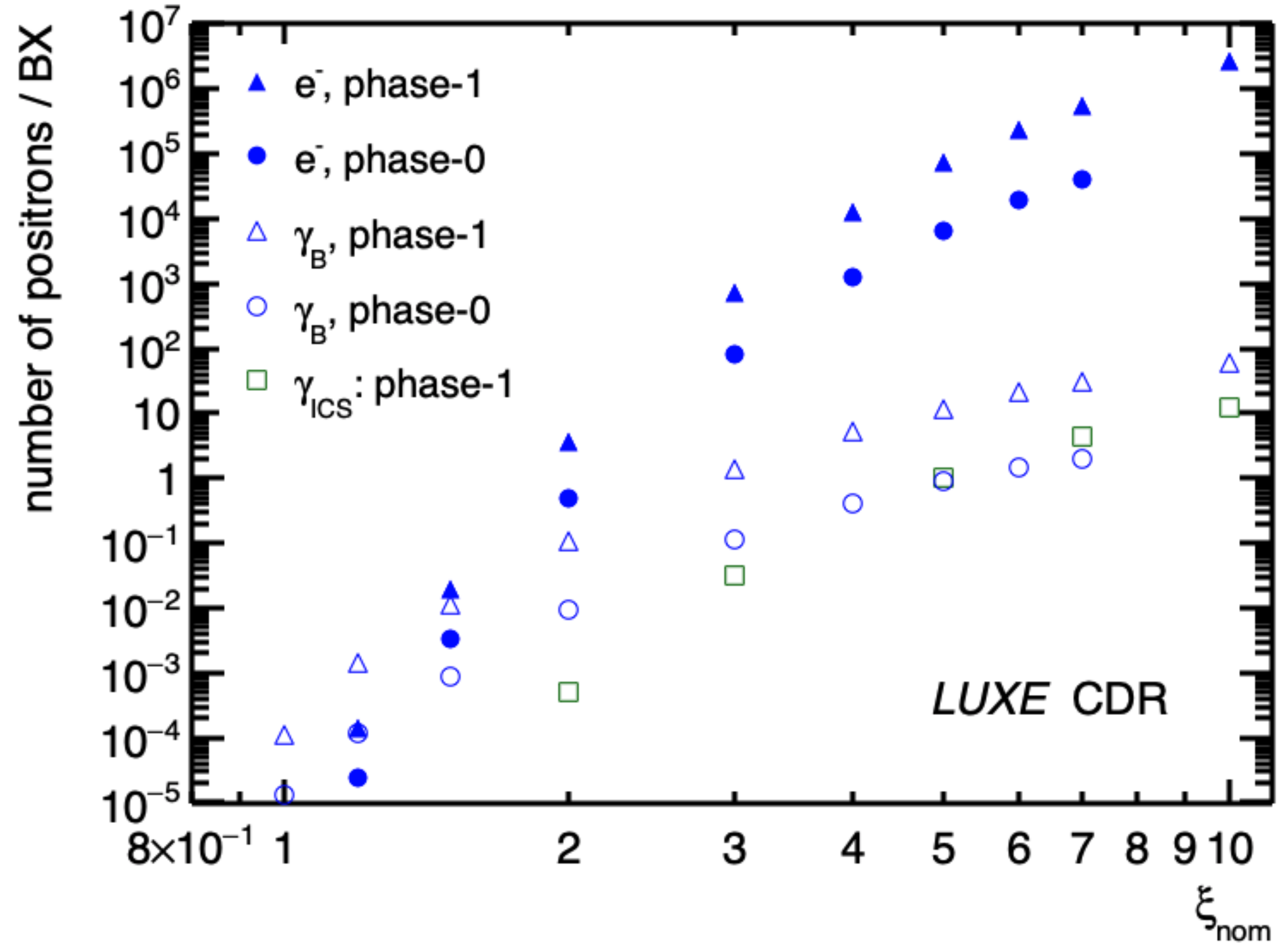
LUXE

- CDR: Eur.Phys.J.ST 230 (2021) 11, 2445-2560
- Website: https://luxe.desy.de
- Obtained CD1 approval from DESY directorate recently.
- Besides 2 running modes, also planned in 2 phases (40 vs 350 TW laser).

PHYSICS MEASUREMENTS

- LUXE aims to make **precision measurement** in a **transition** from perturbative to non-perturbative.
- **Measure** as a function of ξ:
  - Position of Compton edge (determined from e and γ energy spectra).
  - Number of photons radiated per electron.
  - Positron rate (variation spans over 10 orders of magnitude).
- **BSM programme***: high photon flux, ALPs can be produced in an optical dump, LUXE sensitivity competitive with other ongoing/planned experiments.



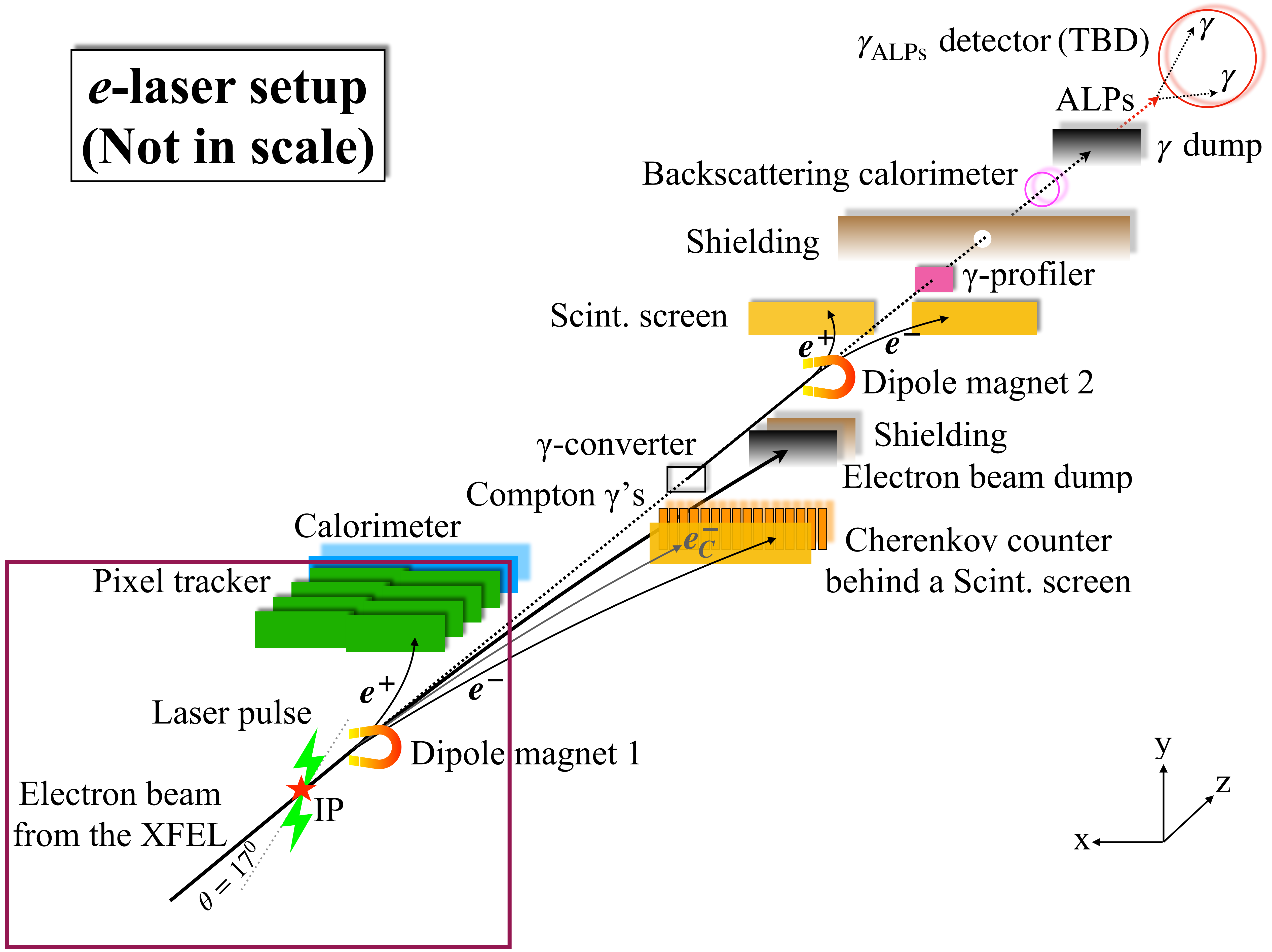


*arXiv:2107.13554

DETECTORS

- Different detectors to measure electron, positron and photon with suitable technologies for the expected range of flux, resolution and other requirements.

POSITRON RATE MEASUREMENT



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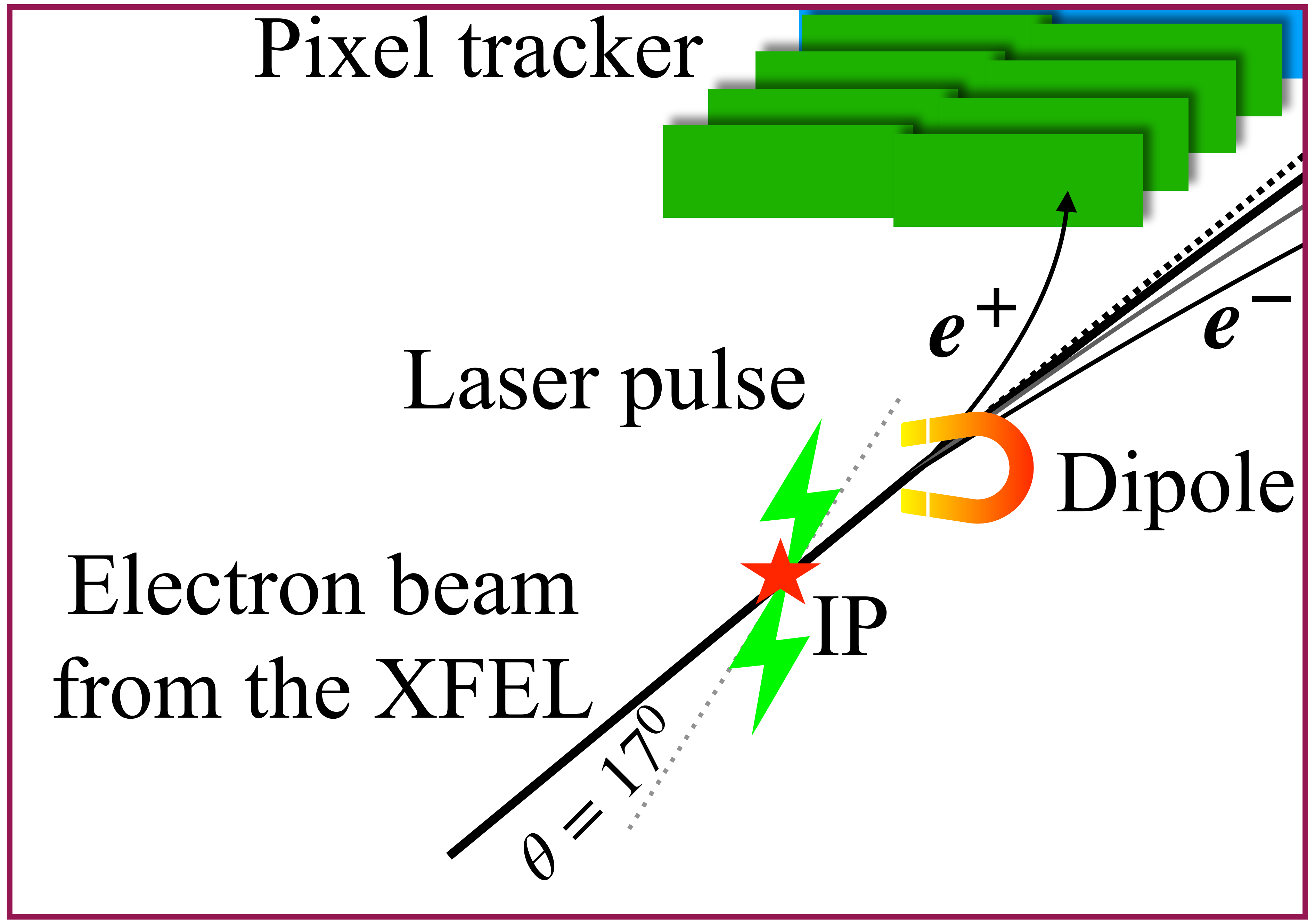
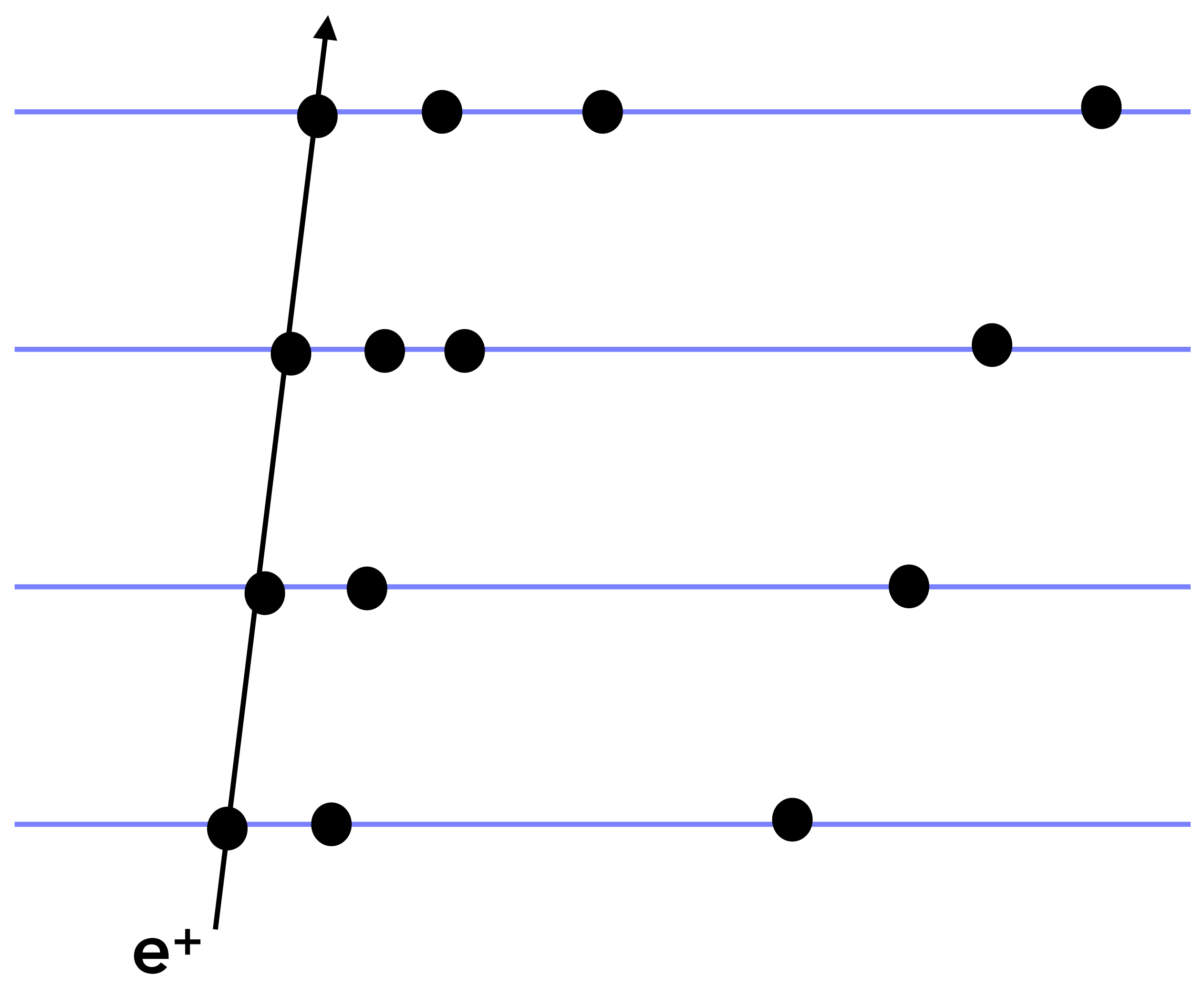


- For precise positron rate measurement, use tracking to reconstruct particle path.
- 4 layers of 50 x 1.5 cm Silicon pixel detector using ALPIDE sensors with pixel size 27 x 29 μm^2.
- Tracking becomes challenging due to combinatorics at high track multiplicities.
- Quantum computing may offer an advantage.

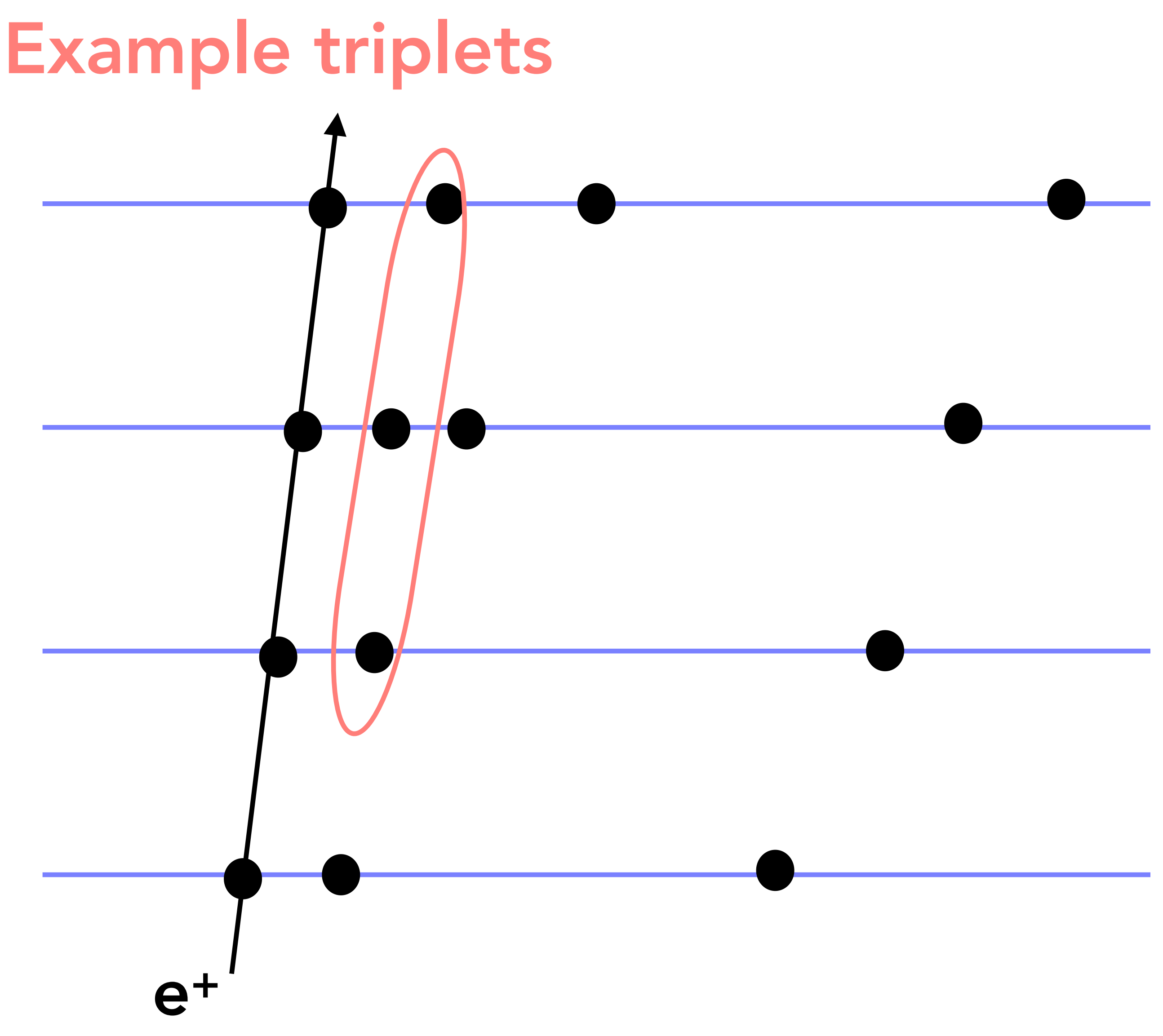
TRACKING USING QUANTUM COMPUTING



TRACKING USING QUANTUM COMPUTING

Step 1: form triplets

satisfying pre-selection



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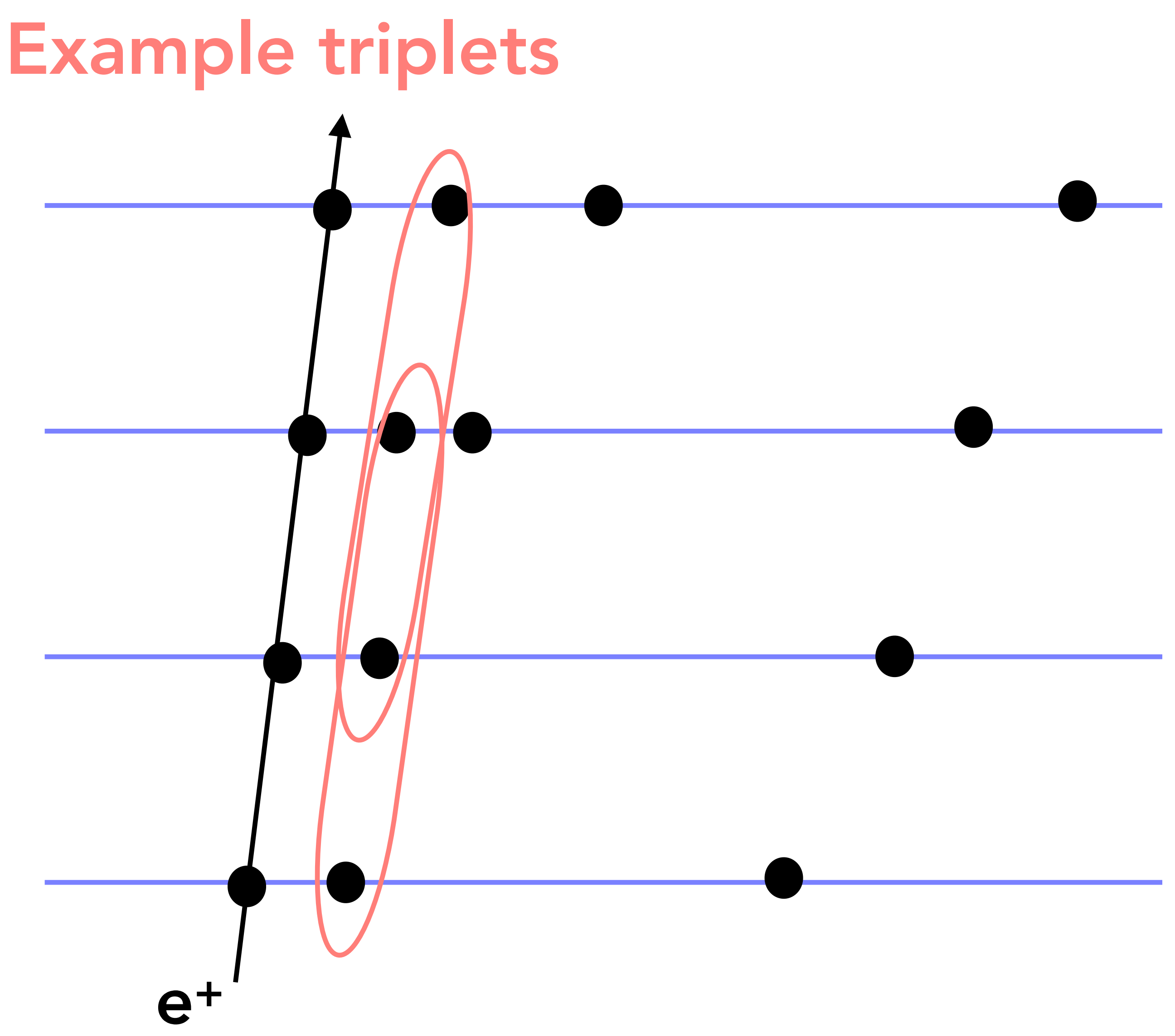

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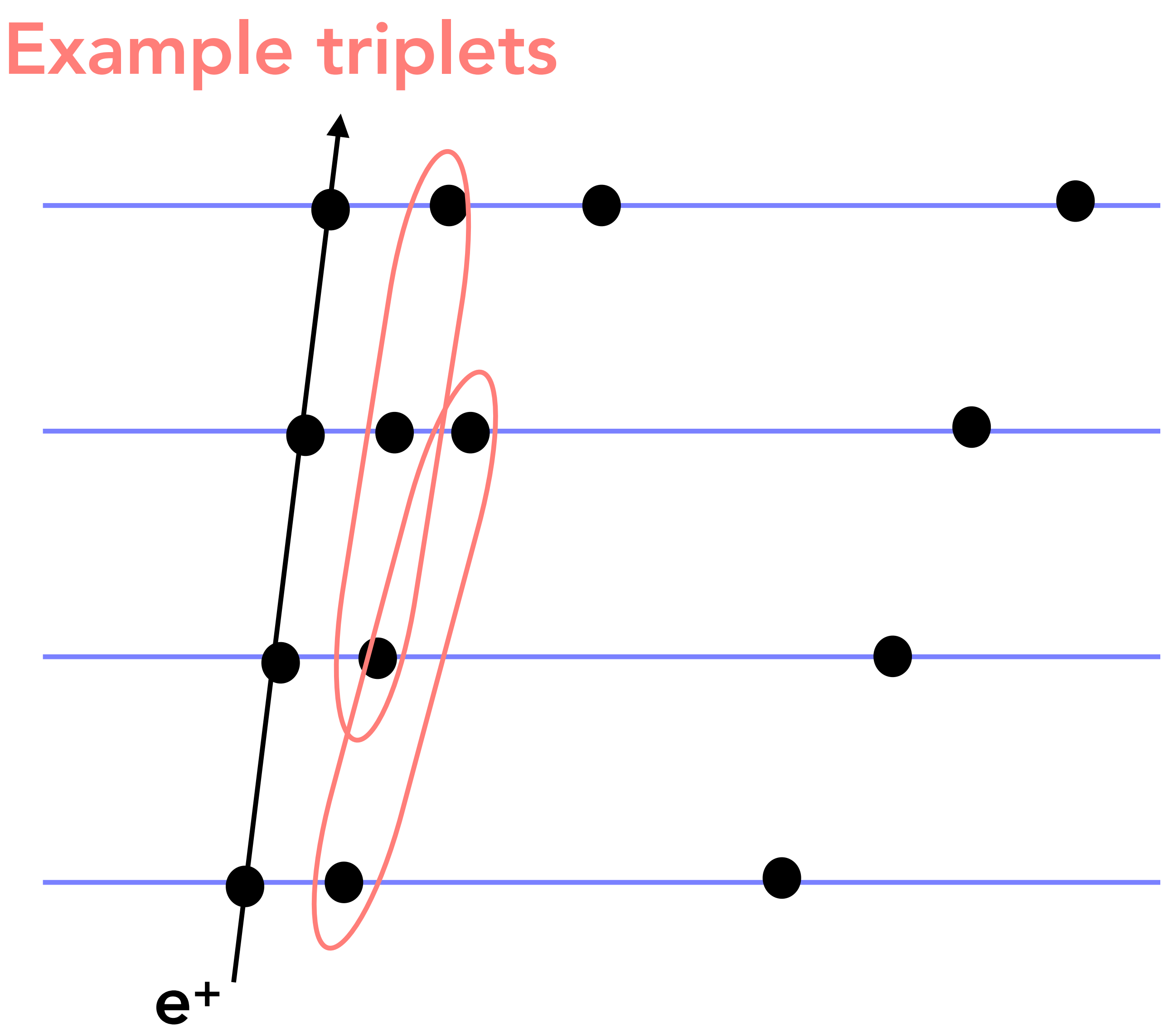

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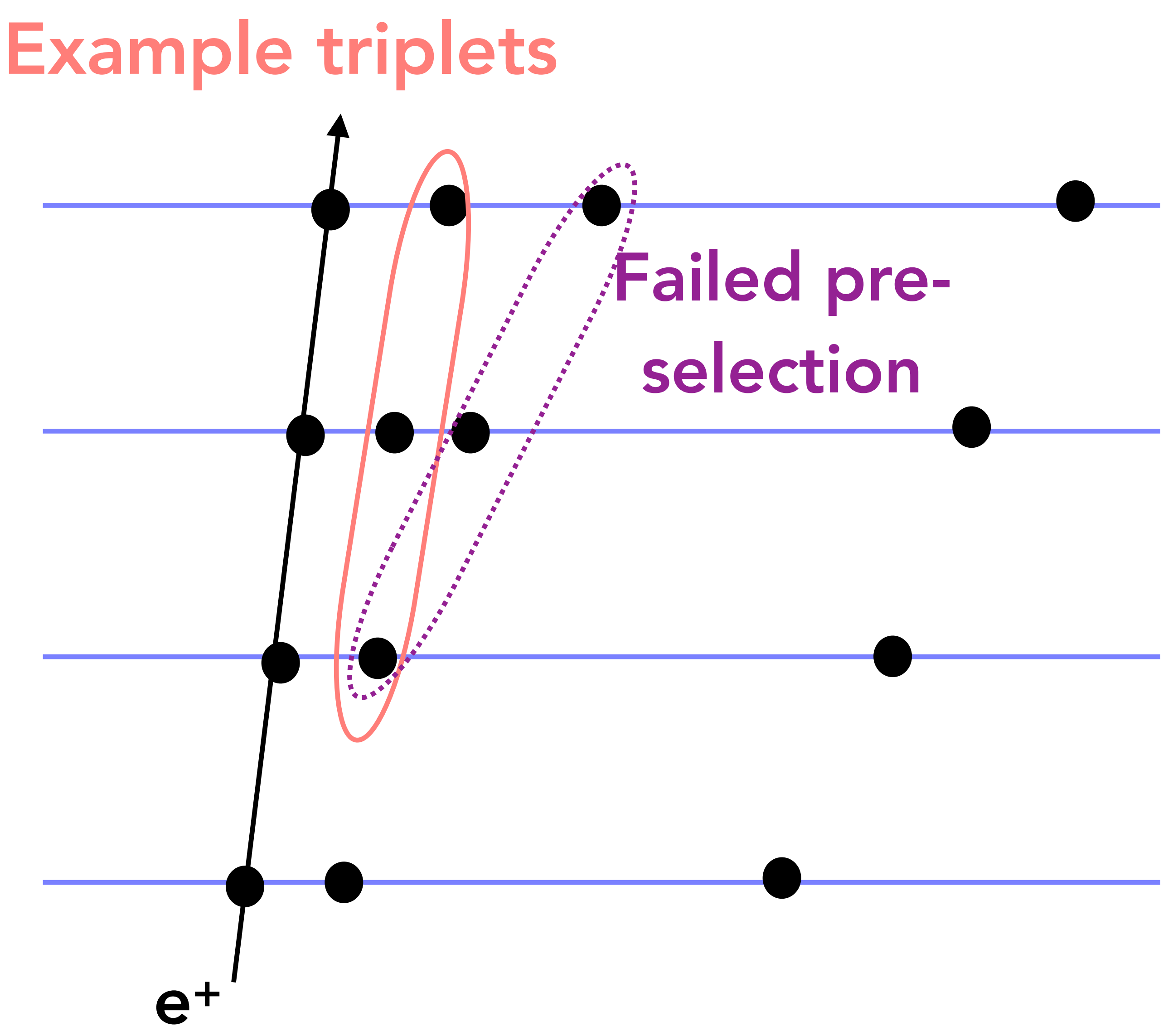

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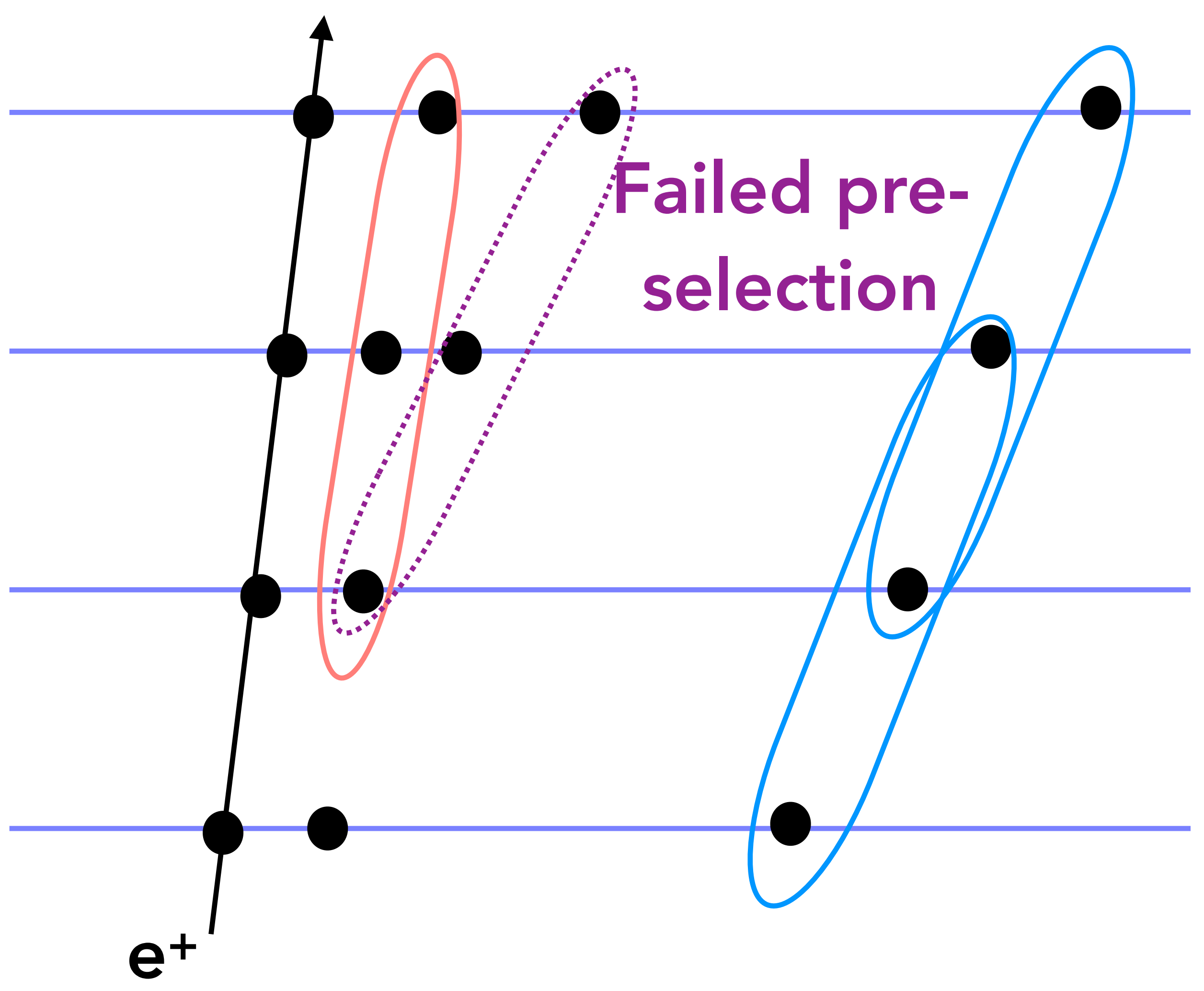


Step 2: find the best sets of triplets
by minimising the QUBO Hamiltonian

Quadratic
Unconstrained
Binary
Optimisation

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

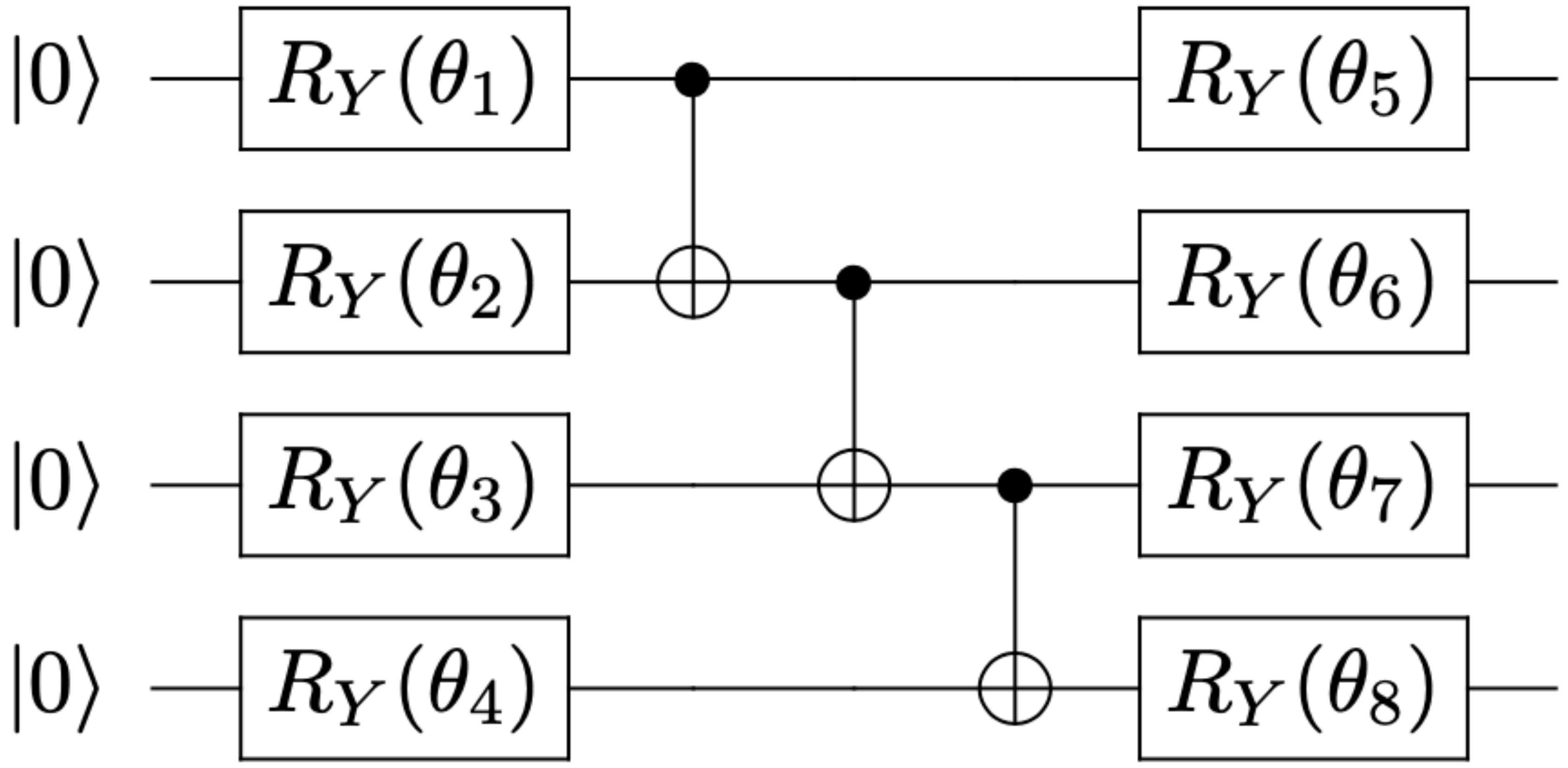
Weighting triplet T_i with quality a_i

Compatibility b_{ij} between two triplets

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

TRACKING USING QUANTUM COMPUTING

- The QUBO is mapped onto a quantum computer (or simulator as done here) and minimised using **Variational Quantum Eigensolver (VQE)** with Nakanishi-Fujii-Todo (NFT) optimiser.



- Due to limited size of currently available devices, QUBO is partitioned into sub-QUBOs of the size of the quantum device (7 qubits assumed) to be solved.

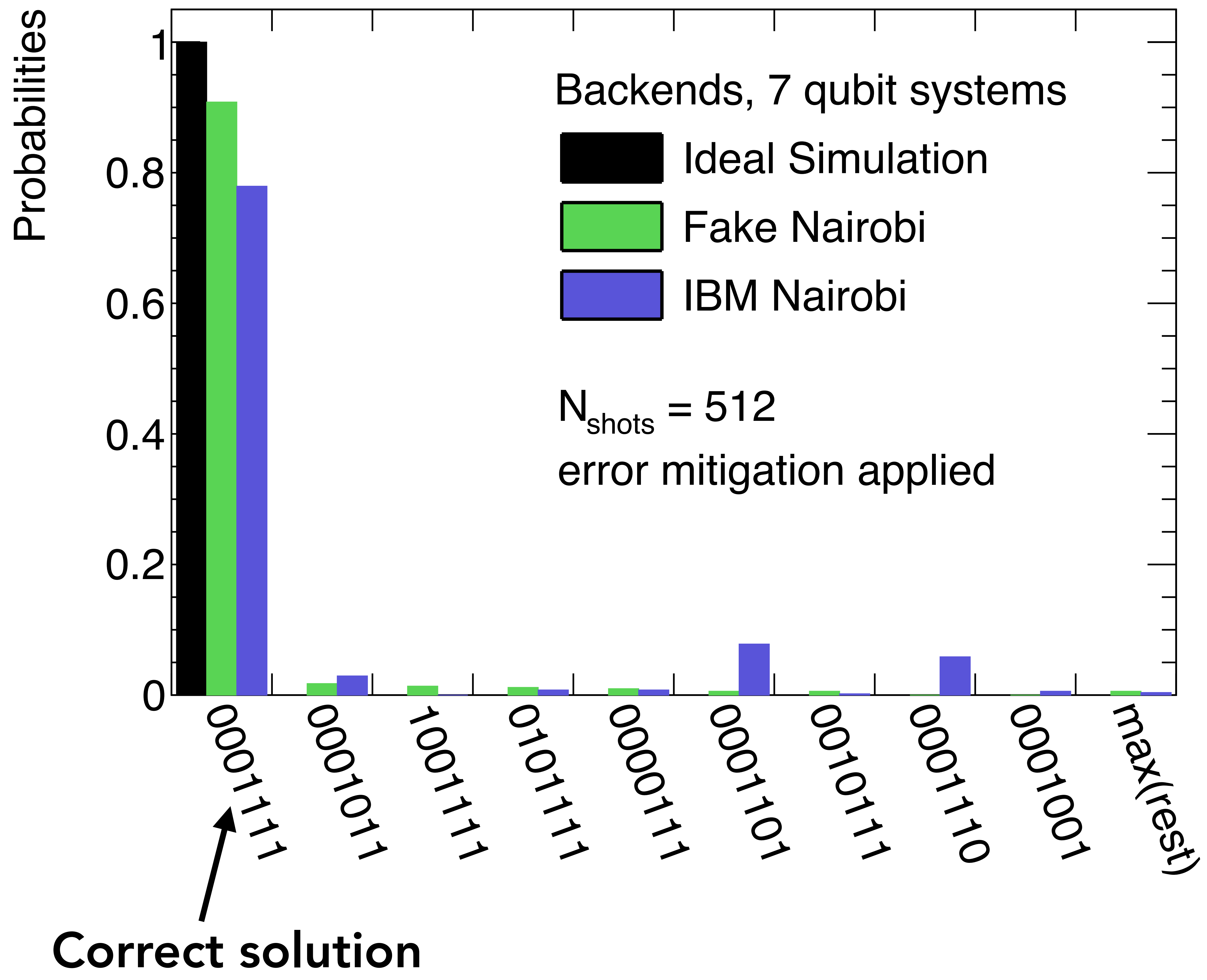
- Exact solution using matrix diagonalisation (**Eigensolver**) used as benchmark.

TEST ON REAL QUANTUM HARDWARE

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

- Results I'll show later are based on ideal simulation of a quantum device but real device is subject to noise.

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



OTHER TRACKING METHODS

- **Combinatorial Kalman Filter (CKF)** in a common tracking software (ACTS)
  - Track parameters estimated from triplet seeds used to steer the tracking.

[1]arXiv:1810.06111, [2]arXiv:2103.06995, [3]arXiv:2109.12636

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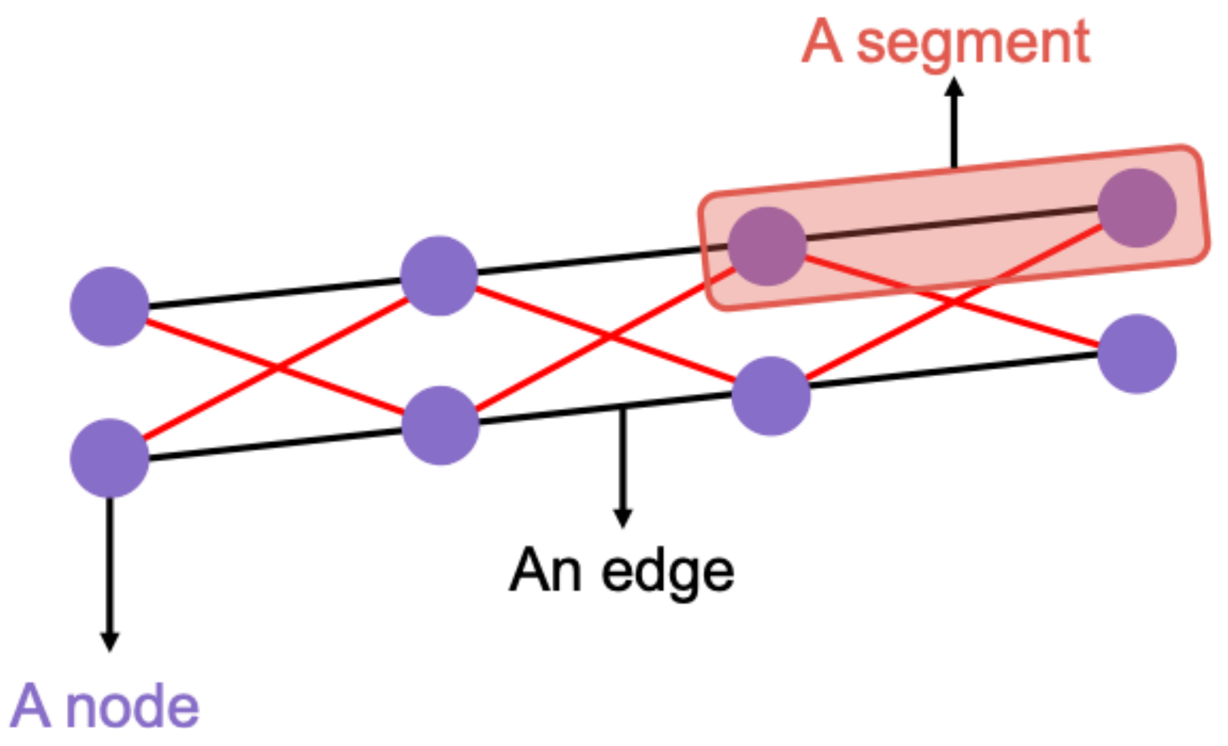
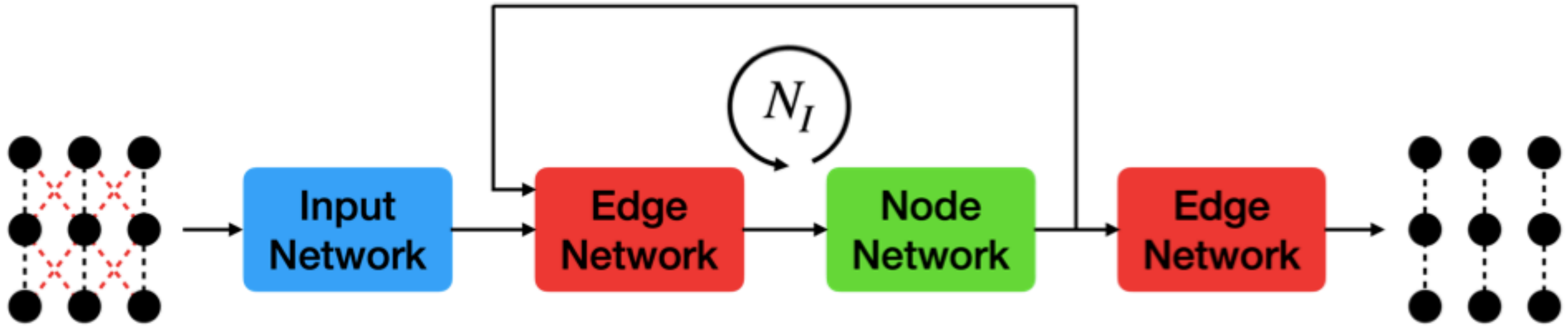


- **Graph Neural Network (GNN)**[1,2]
  - Graph constructed from doublets. N_I iterations of alternating edge and node networks applied.



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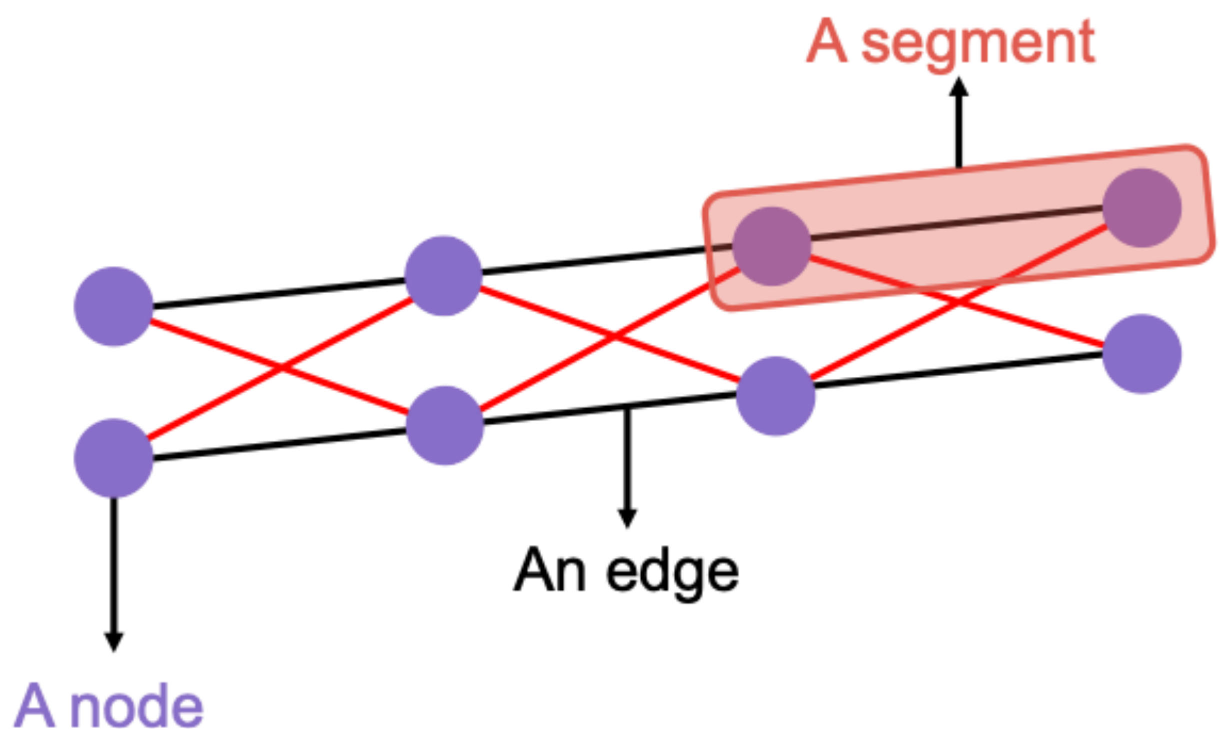
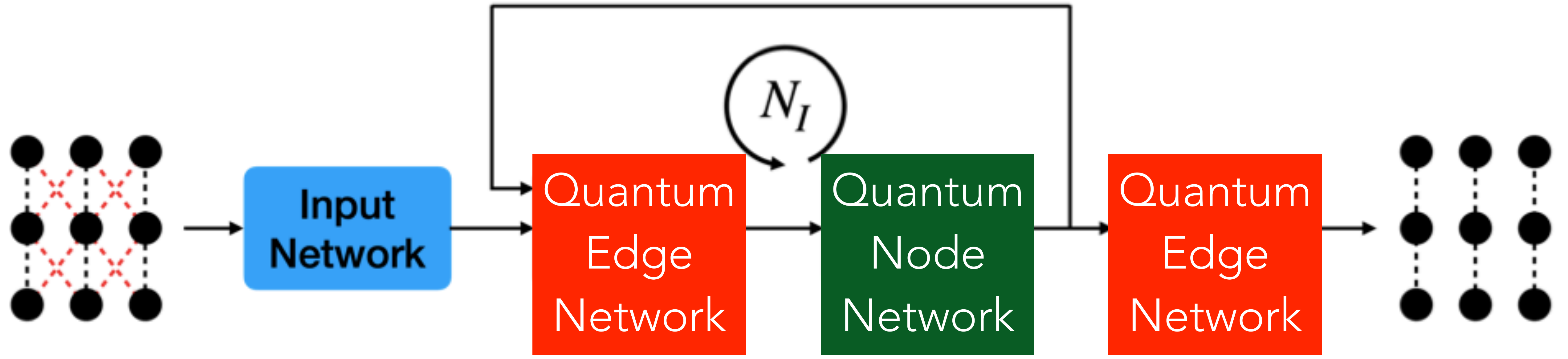


- **Graph Neural Network (GNN)**[1,2]
  - Graph constructed from doublets. N_I iterations of alternating edge and node networks applied.
- **Quantum GNN**[3]
  - Hybrid quantum-classical model.



  - 10 hidden features (qubits) compared to 128 for classical.

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PERFORMANCE

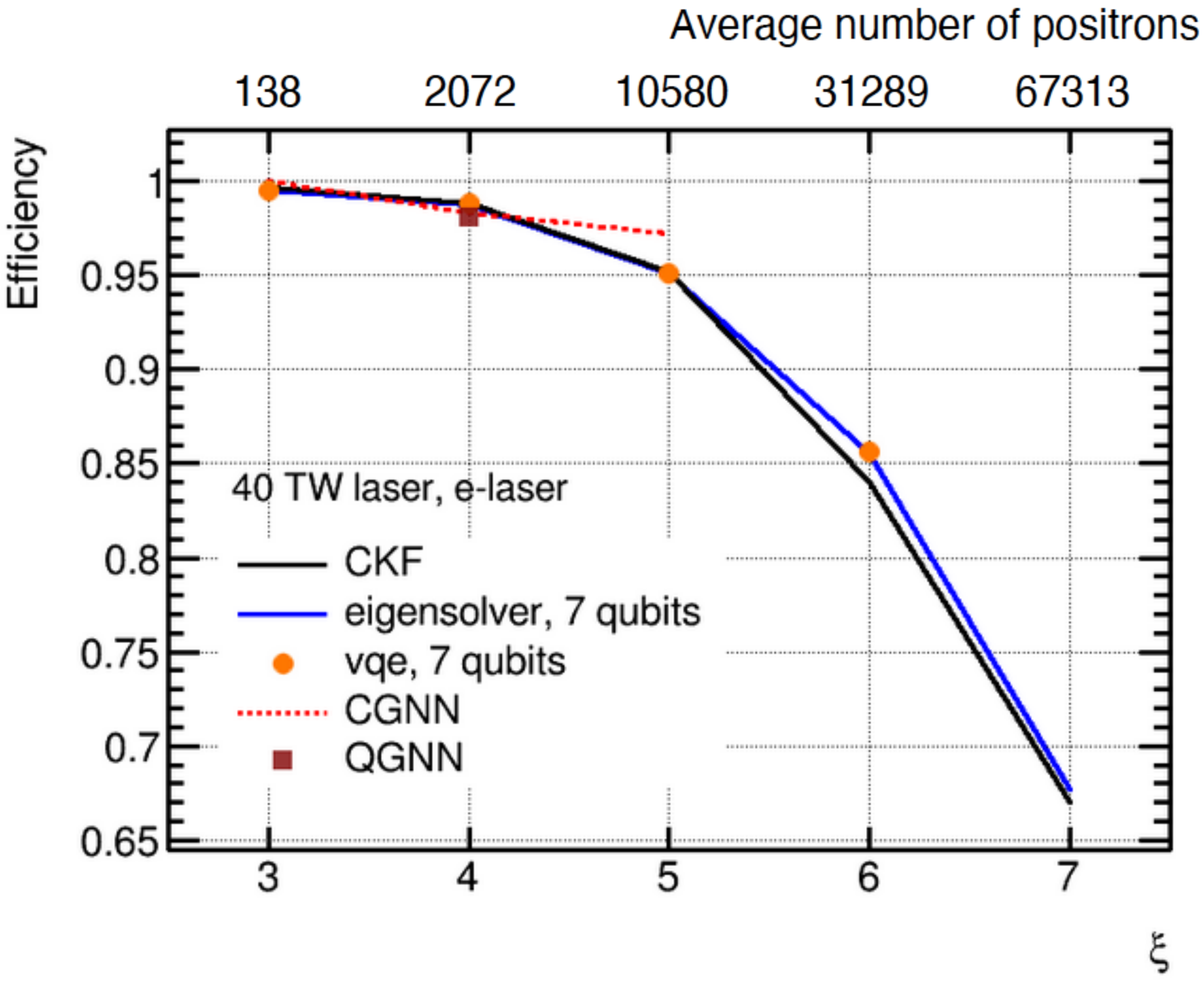
- Compare performance of these tracking methods for $\xi = 3 - 7$ in phase-0, where the number of positrons are between 140 and 67,000.

- Two metrics:

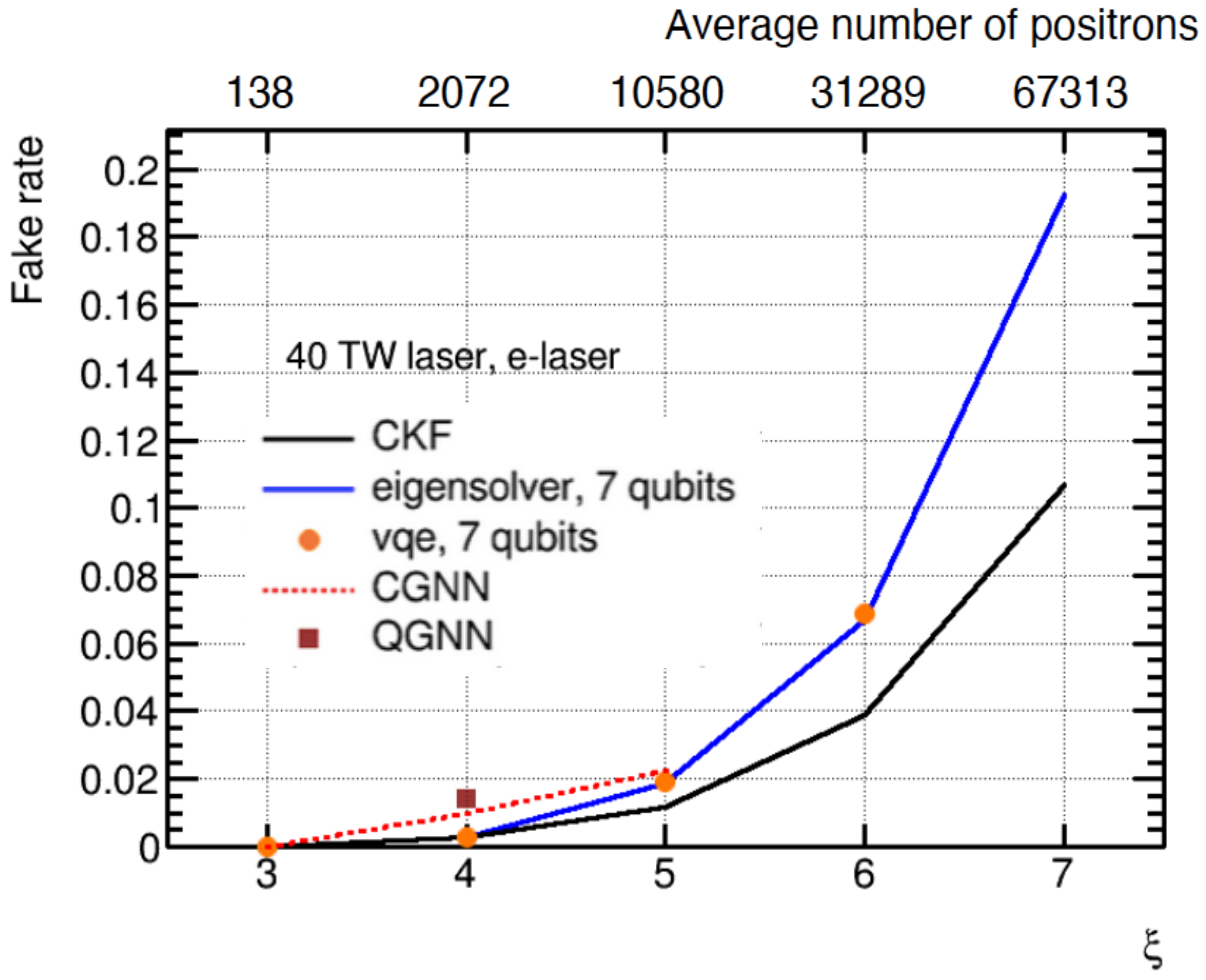
$$\text{Efficiency} = \frac{N_{\text{tracks}}^{\text{matched*}}}{N_{\text{tracks}}^{\text{generated}}} \qquad \text{Fake rate} = \frac{N_{\text{tracks}}^{\text{fake}}}{N_{\text{tracks}}^{\text{reconstructed}}}$$

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

RESULTS



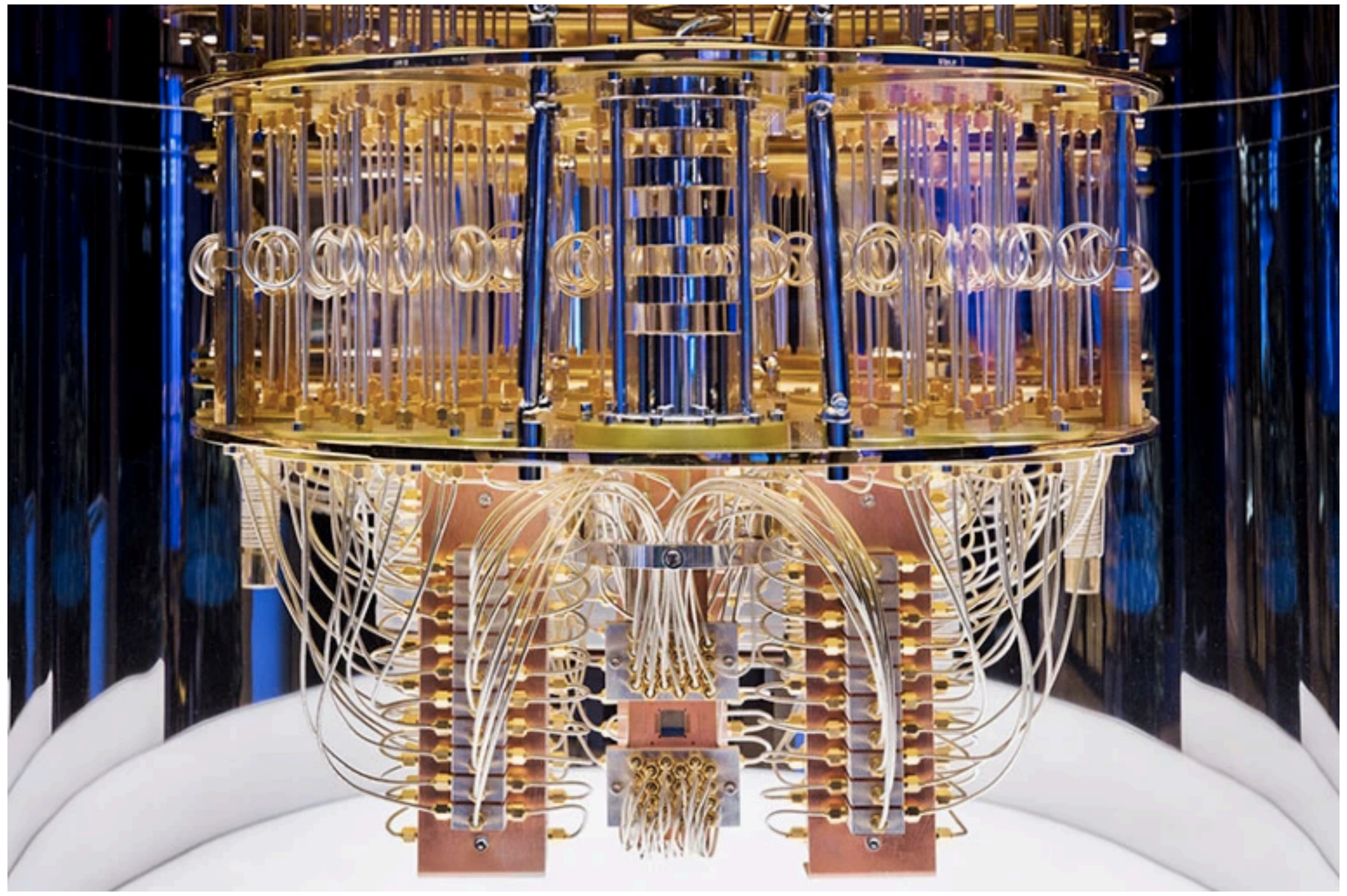
Average number of positrons
138
2072
10580
31289
67313
Efficiency
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
40 TW laser, e-laser
CKF
eigensolver, 7 qubits
vqe, 7 qubits
CGNN
QGNN
3
4
5
6
7
ξ



Average number of positrons
138
2072
10580
31289
67313
Fake rate
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
40 TW laser, e-laser
CKF
eigensolver, 7 qubits
vqe, 7 qubits
CGNN
QGNN
3
4
5
6
7
ξ

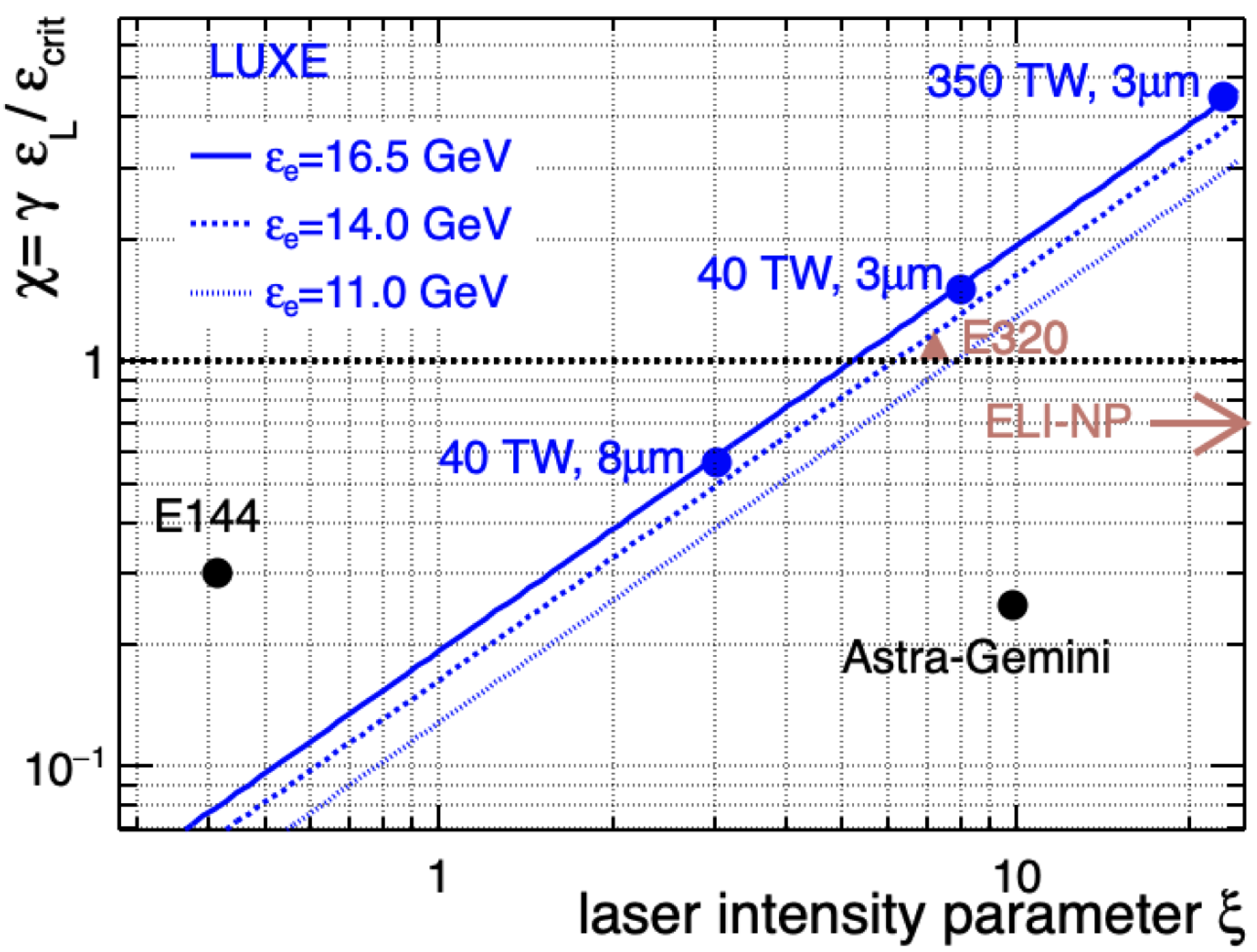
SUMMARY AND OUTLOOK

- 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:
    - Move from quantum computer simulator to real device and apply noise mitigation.
    - Study even more extreme environments and explore regions where quantum computing could outperform traditional methods.

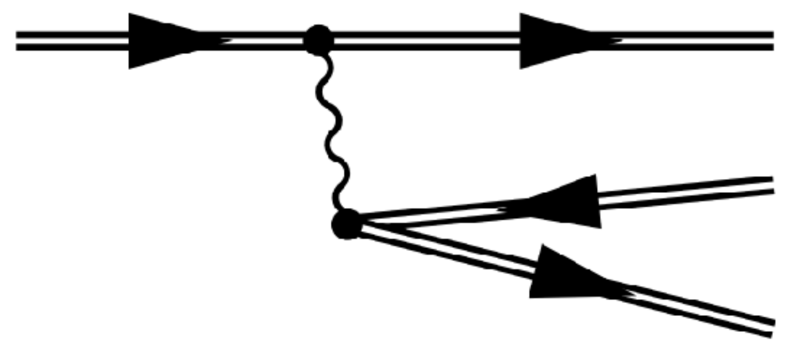


BACK-UP

LUXE PARAMETER SPACE



- SLAC Experiment 144 in the 90s
  - reached $\chi_e \leq 0.25$, $\xi<0.4$, within perturbative regime, but with observable non-linear effects.
  - observed $e^- + n\gamma_L \rightarrow e^- e^+ e^-$ trident process.



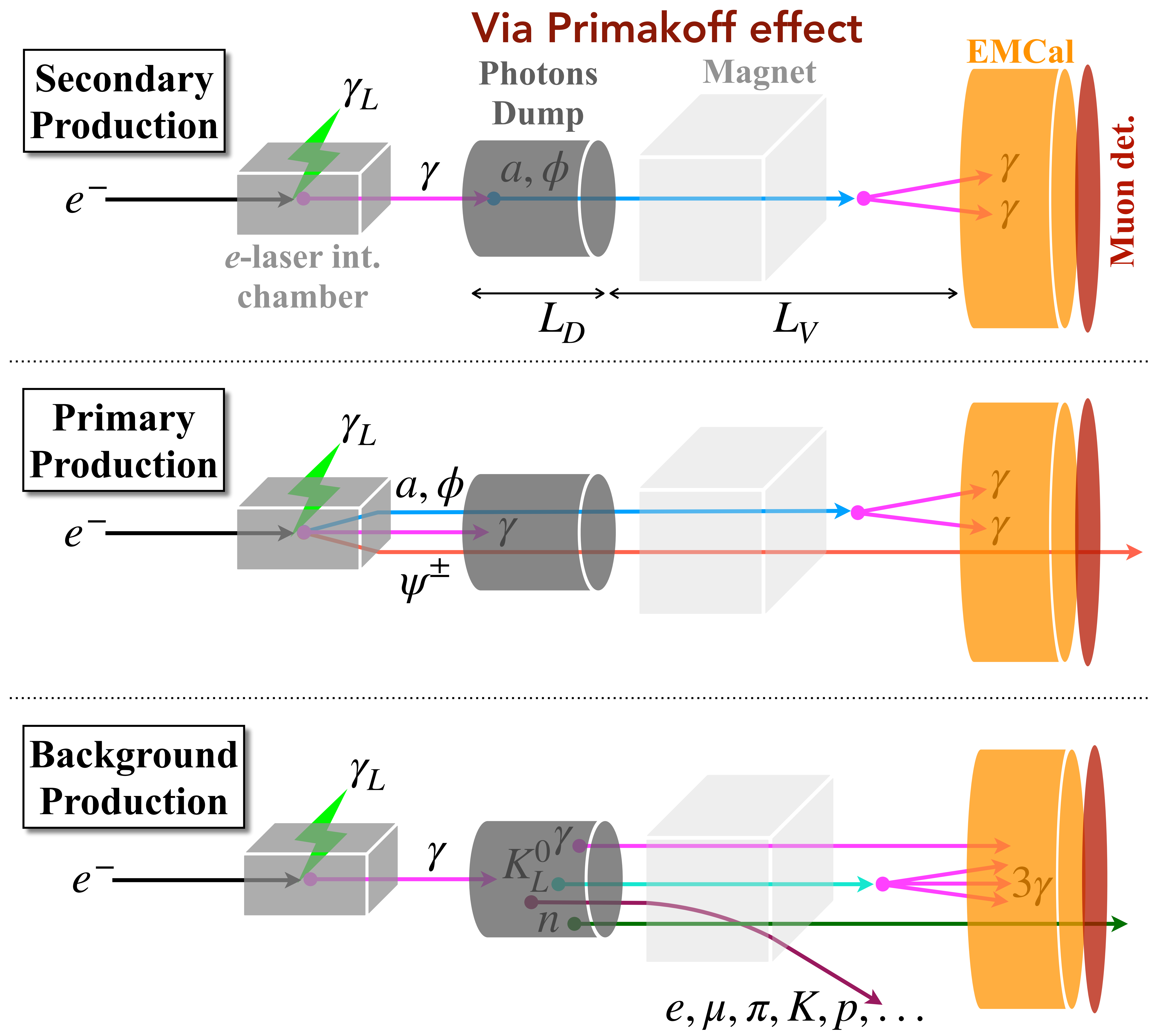
- Other ongoing/proposed experiments: SLAC-E320 (US), Astra-Gemini (UK), ELI-NP (RO)

LASER

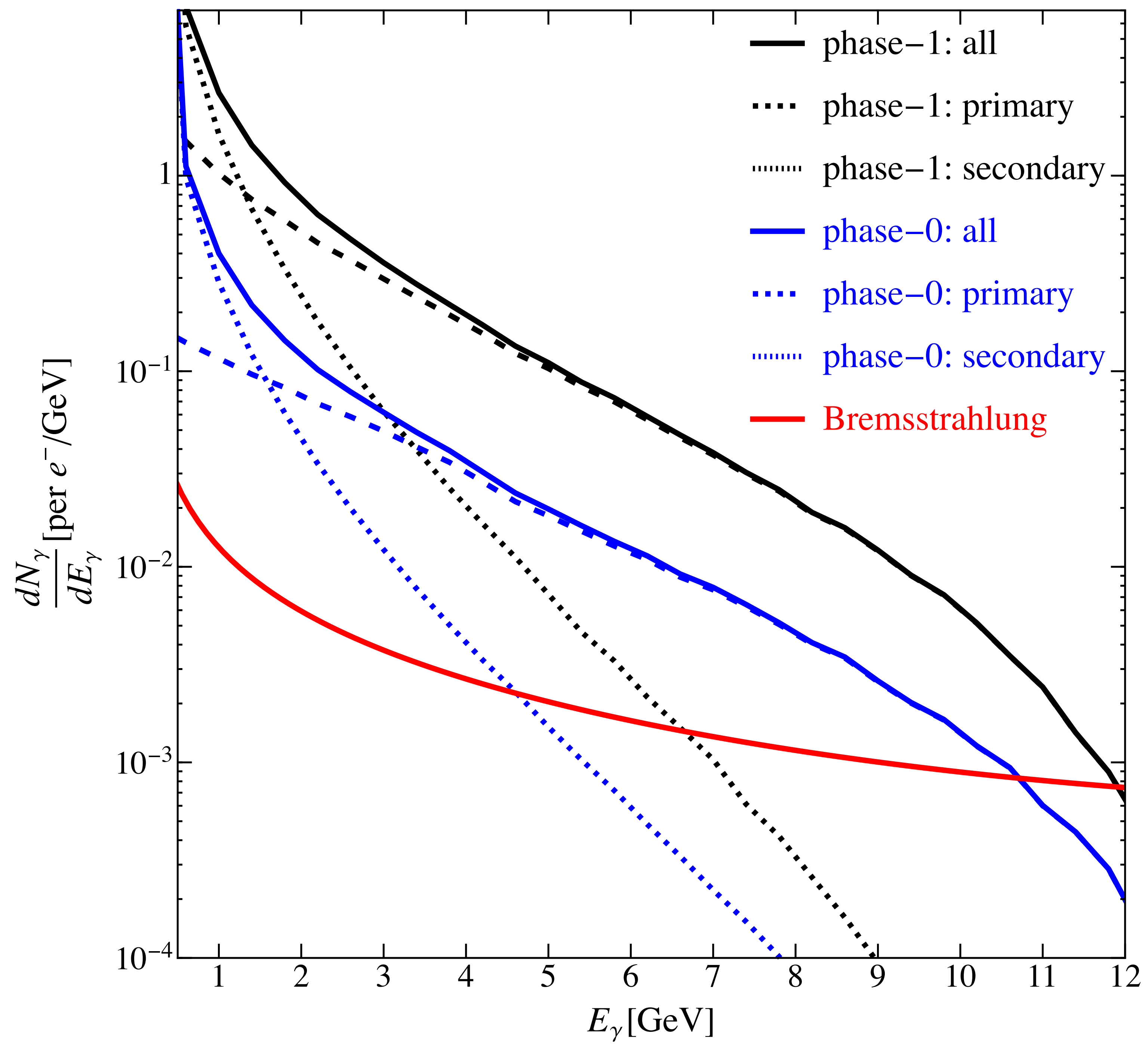
- Titanium:Sapphire laser based on chirped pulse amplification (CPA) technology. Laser photon wavelength 800 nm (or 1.55 eV).
- Different ξ values can be reached by focussing/defocussing the laser.
- Need exceptional shot-to-shot stability (1%).

	Phase-0	Phase-1
Laser power (TW)	40	350
Peak intensity in focus (x10^{20}W/cm^2)	<1.33	<12
Dimensionless peak intensity ξ	<7.9	<23.6
Quantum parameter χ_e for E_e=16.5 GeV	<1.5	<4.45
Laser focal spot waist (μm)	≥3	
Laser pulse duration (fs)	30	

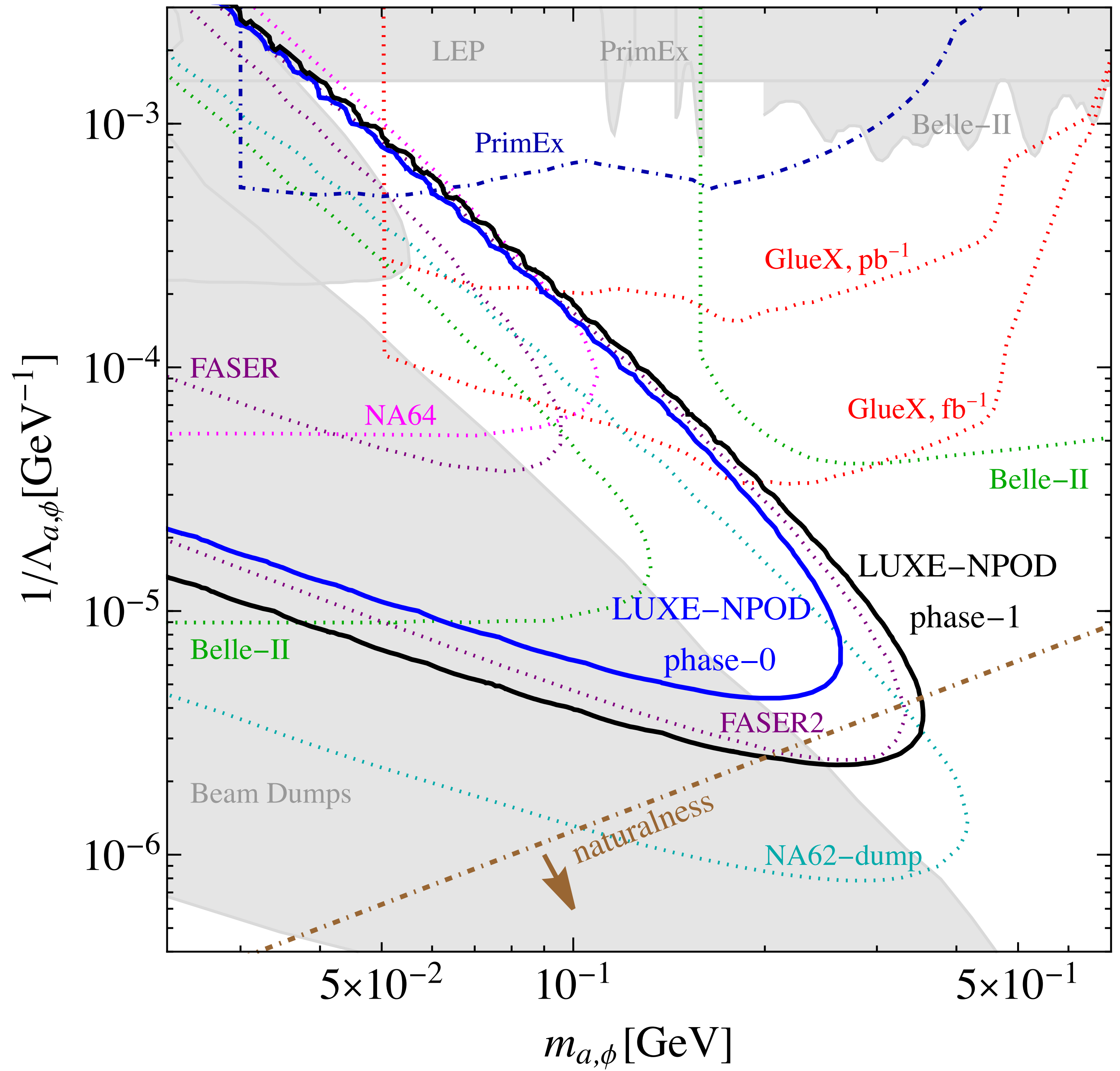
BSM SEARCH



Via Primakoff effect
Secondary Production
Primary Production
Background Production
Photons Dump
Magnet
EMCal
Muon det.
e-laser int. chamber
L_D
L_V
$e, \mu, \pi, K, p, \ldots$



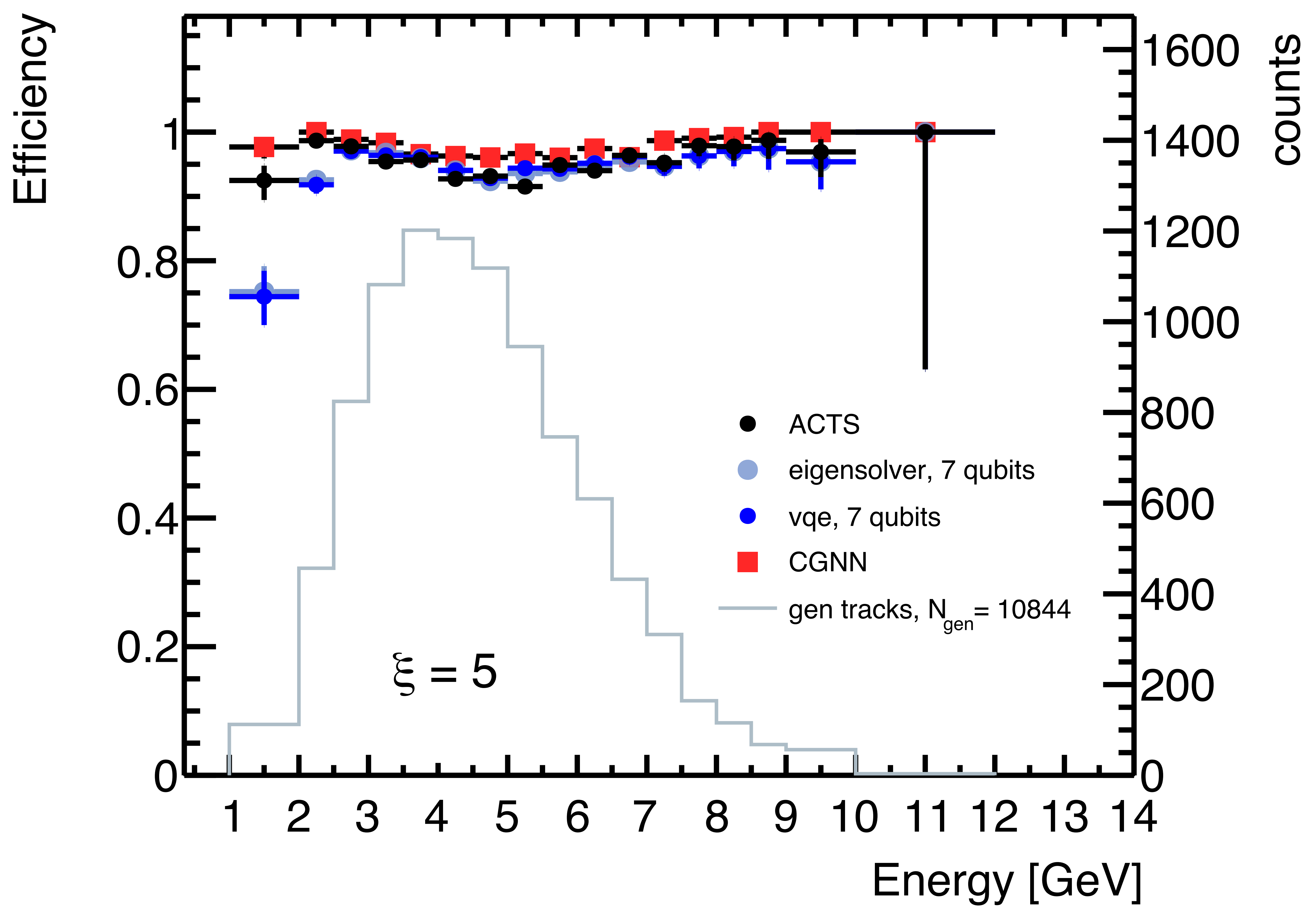
phase−1: all
phase−1: primary
phase−1: secondary
phase−0: all
phase−0: primary
phase−0: secondary
Bremsstrahlung
$\frac{dN_\gamma}{dE_\gamma}$[per e^-/GeV]
E_γ[GeV]

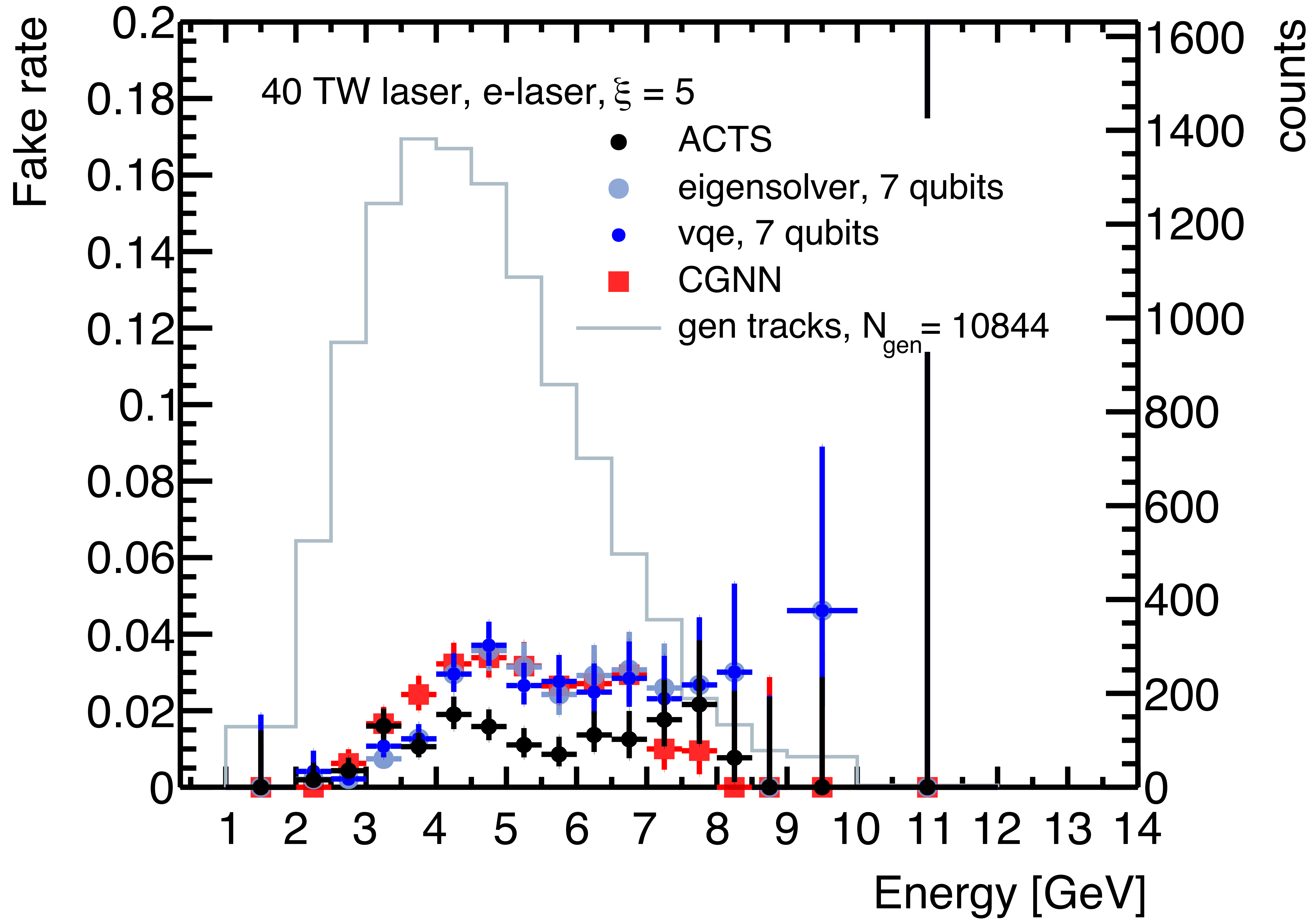


LEP
PrimEx
Belle−II
GlueX, pb^{-1}
GlueX, fb^{-1}
FASER
NA64
LUXE−NPOD phase−1
LUXE−NPOD phase−0
FASER2
Beam Dumps
naturalness
NA62−dump
$1/\Lambda_{a,\phi}$[GeV^{-1}]
$m_{a,\phi}$[GeV]


Toy Model
Hits
Doublets
Group
Triplets
Pre-selection
QUBO
Initial Binary Vector
Sort Indices
Impact
Impact: Change in QUBO if value is flipped
qubit-sized
subQUBOs
Overwrite Vector with subQUBO solution
Quantum Algorithm → subQUBO solution
+Tabu Search
Triplets (kept, rejected)
Trajectories
Real, Fake, Missed
Model Building
subQUBO Solver
Processing

PERFORMANCE VS ENERGY





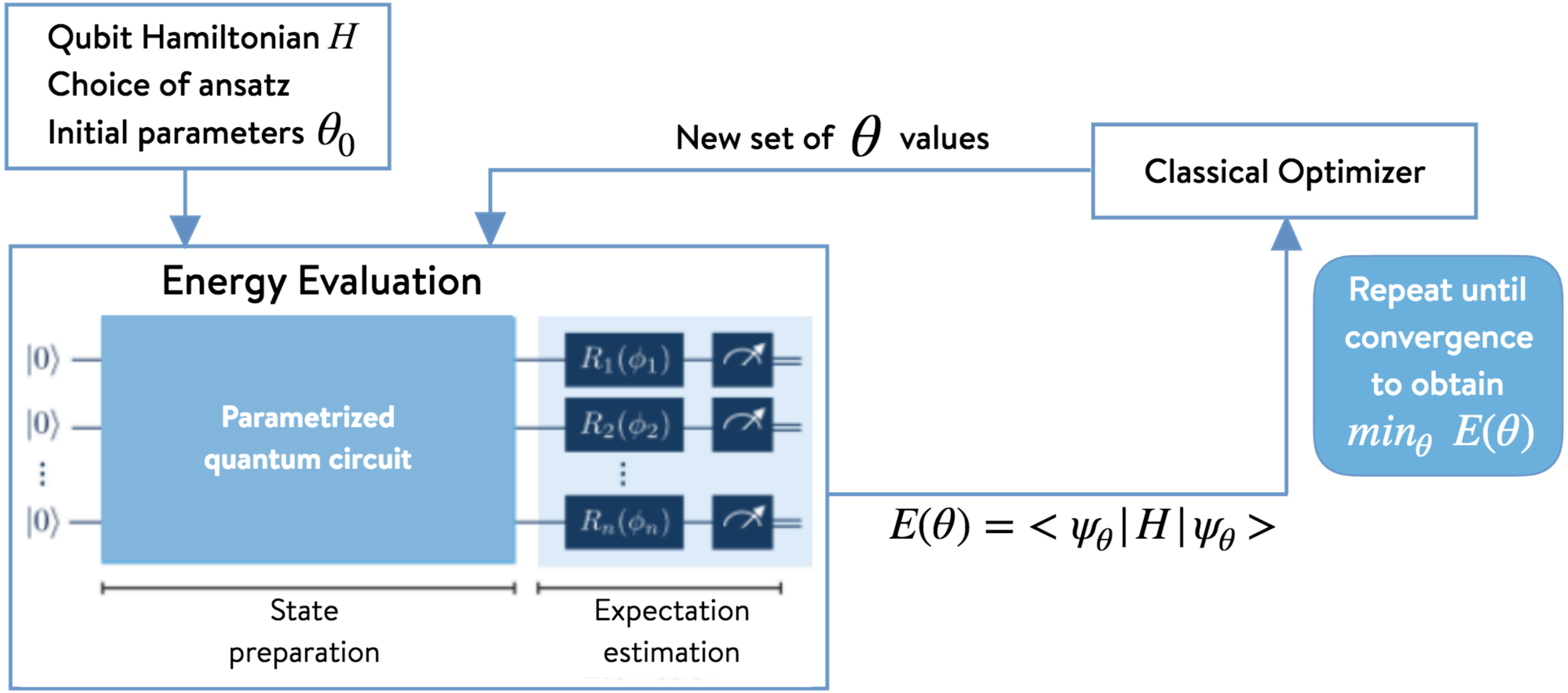


Image from http://openqemist.1qbit.com/docs/vqe_microsoft_qsharp.html

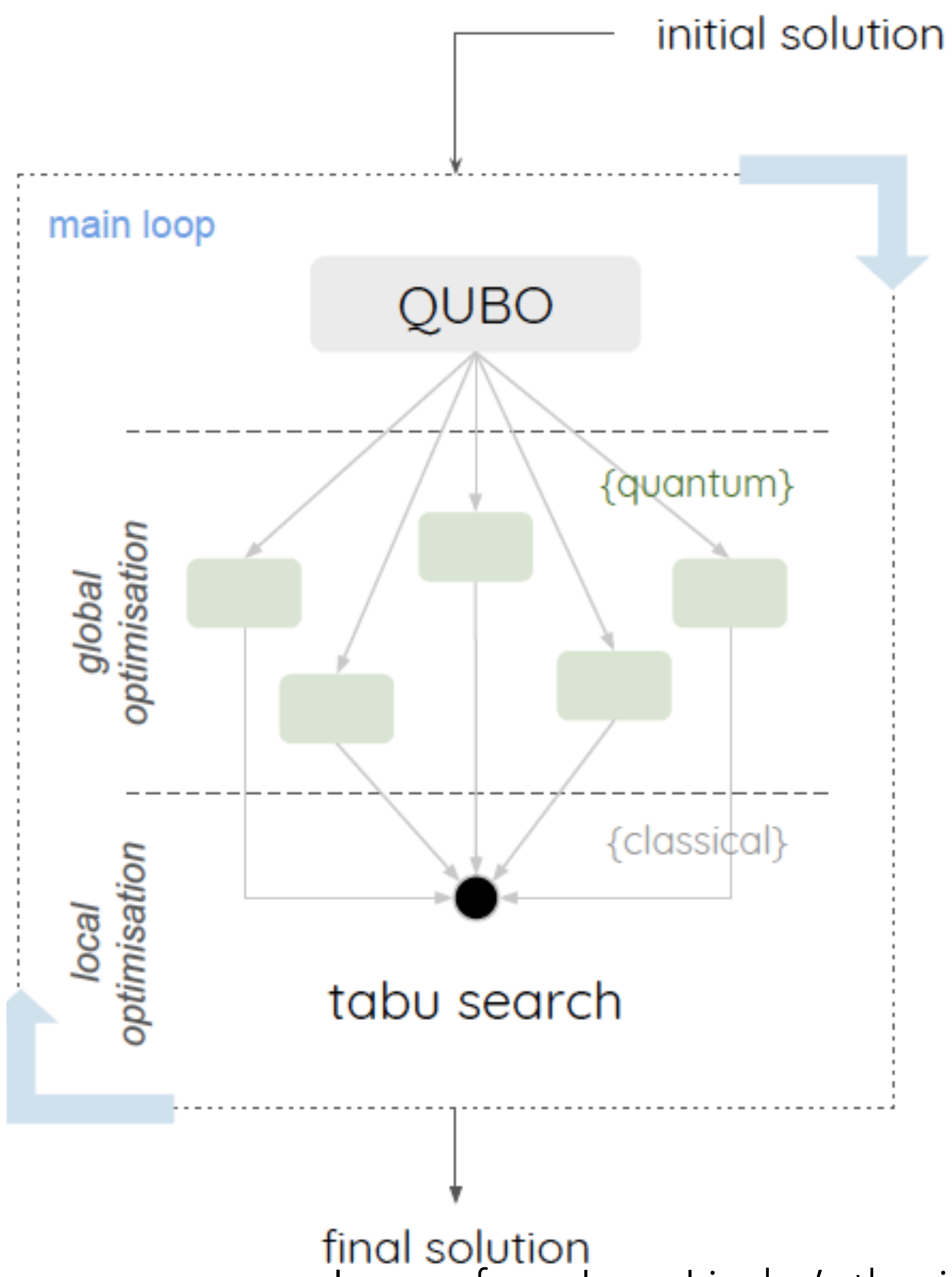


Image from Lucy Linder's thesis