Particle Tracking with a Quantum Computer

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Particle Physics Experiments

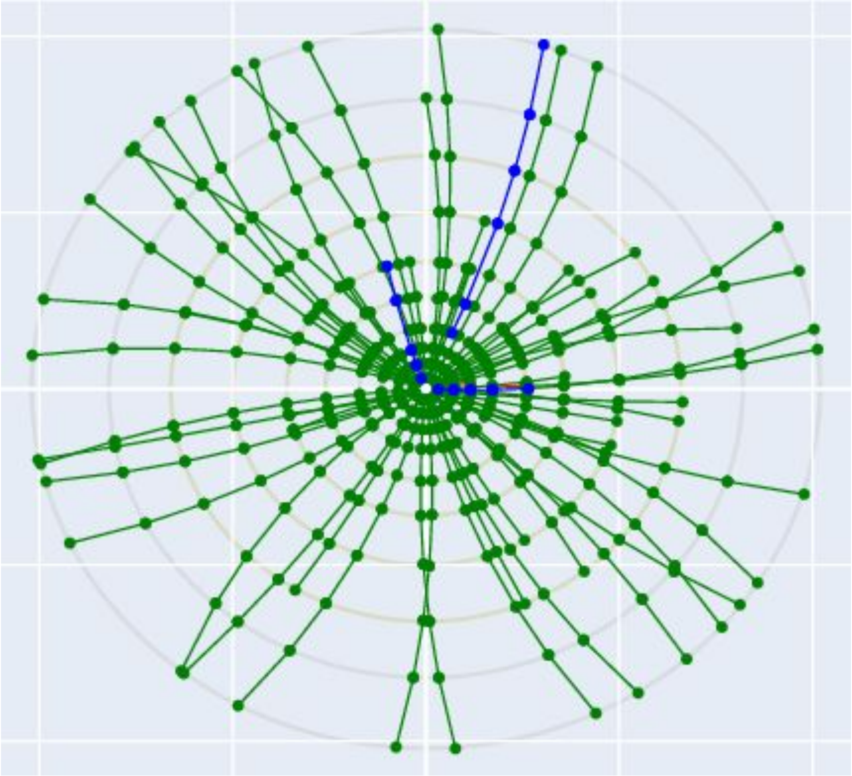
- **Motivation:** study Standard Model of Particle Physics + search for new physics

- Aftermath of collision/interaction between particles lets us infer the structure of the fundamental components

- As particles move through detector, it deposits energy ("**hit**") in each layer

- The path the particle takes depends on the particle's characteristic and detector

- **Goal:** Reconstruct trajectories of multiple particles from a set of hits

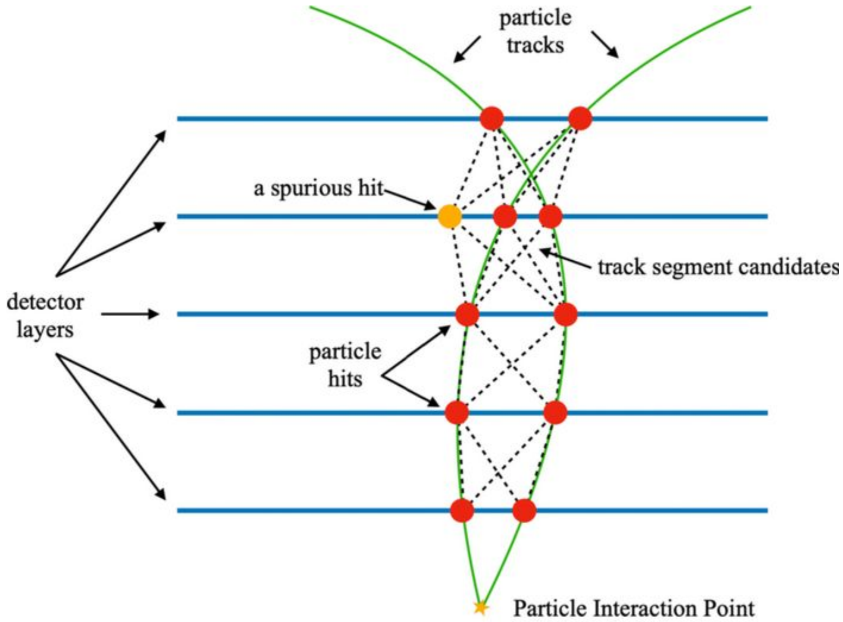


Challenges in track reconstruction

- Large data volume
- High density of hits
- Noise and false signals
- imperfect hardware leads to inaccuracies
- Complex trajectories

Innovative and effective track reconstruction techniques required

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

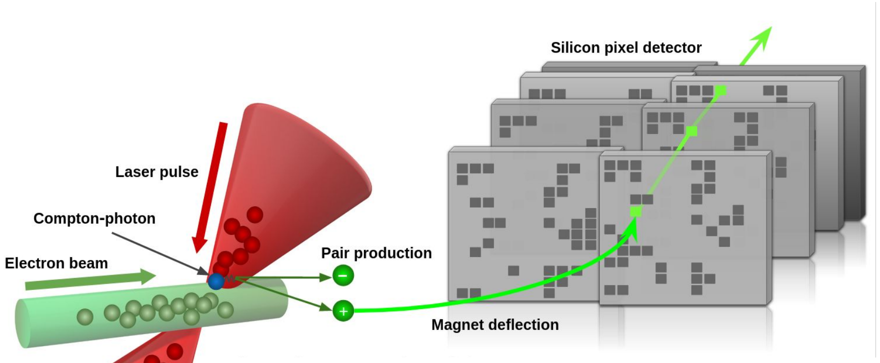


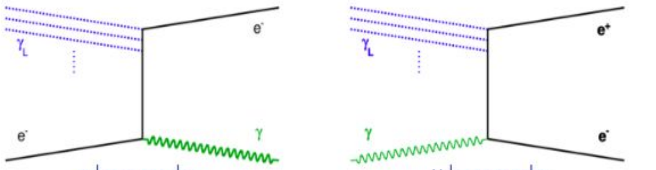
LUXE: Laser und XFEL Experiment

- Investigate transition from QED to strong-field QED (black holes, neutron stars)

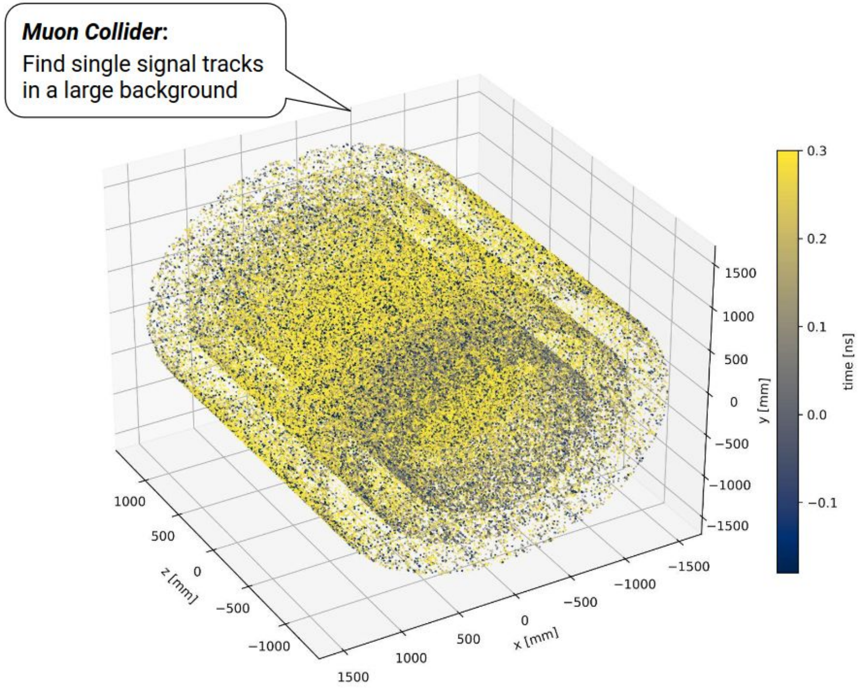
- **Detect:** Straight positron tracks in four-layered pixel detector (no timing info)

- **Challenge**:
  Large range of positrons
  Dense detector regions





Muon Colliders



- Next gen experiment for high-energy collisions (cleaner collisions, less background)

- **Detect:** range of particles with detector system (timing info)

- **Challenge**:
  - Large background

LUXE

- Investigate transition from QED to strong-field QED (black holes, neutron stars)

- **Detect:** Straight positron tracks in four-layered pixel detector (no timing info)

- **Challenge**:
  - Range of positrons
  - Dense detector regions

Muon Colliders

- Next gen experiment for high-energy collisions

- **Detect:** range of particles with detector system (timing info)

- **Challenge**:
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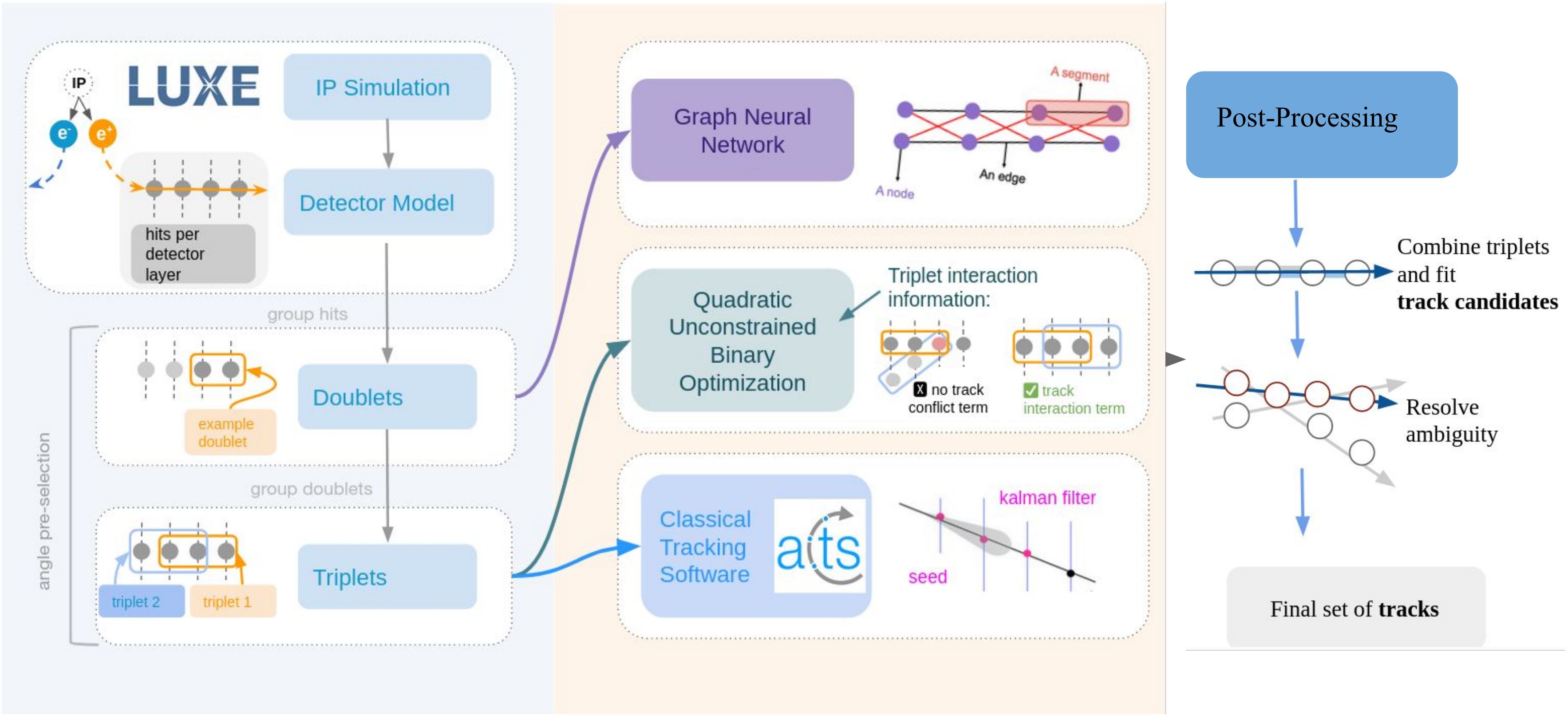
Overview: quantum tracking project



https://doi.org/10.48550/arXiv.2304.01690

QUBO Quadratic Unconstrained Binary Optimization

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

Binary:

0: discarded

1: kept

QUBO Quadratic Unconstrained Binary Optimization

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weigh
triplets by a_i

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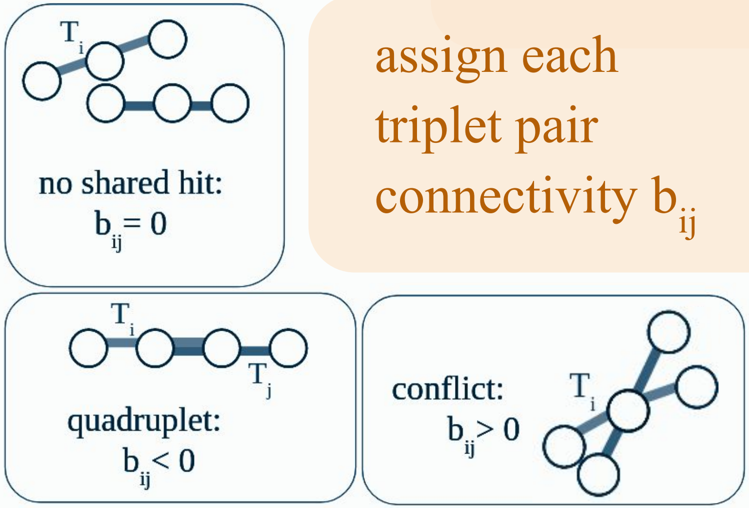
assign each triplet pair connectivity b_{ij}



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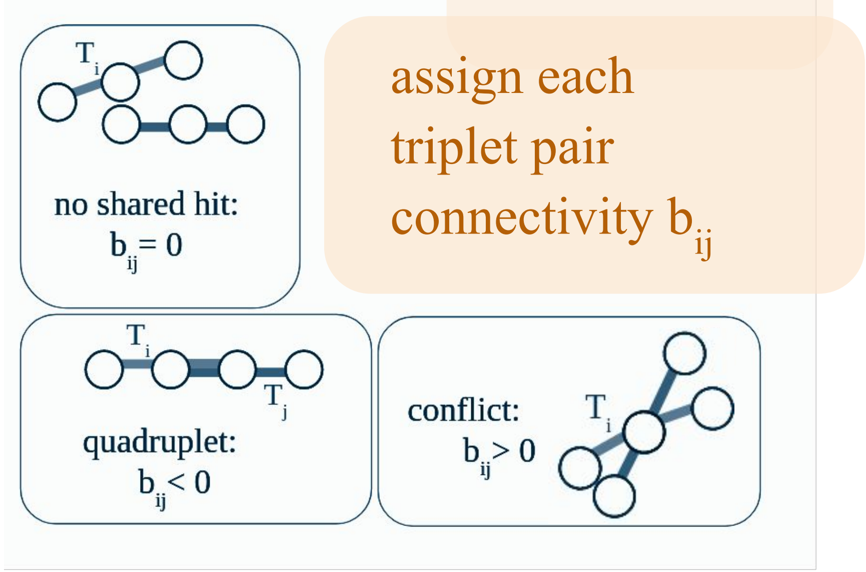
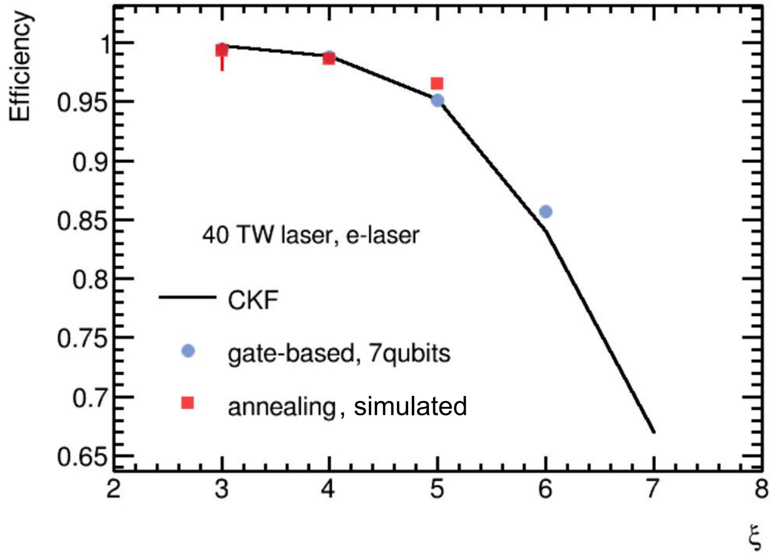
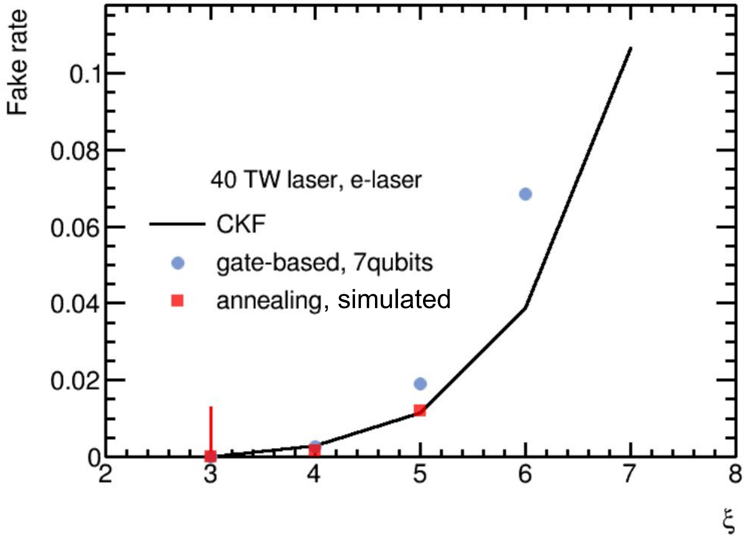


- **Empirically** derived
- **Goal:** maximize good quadruplets and minimise conflicts
- **Ground state** of QUBO gives us our optimal set of triplets

Annealing and Gate-based Simulator: LUXE results





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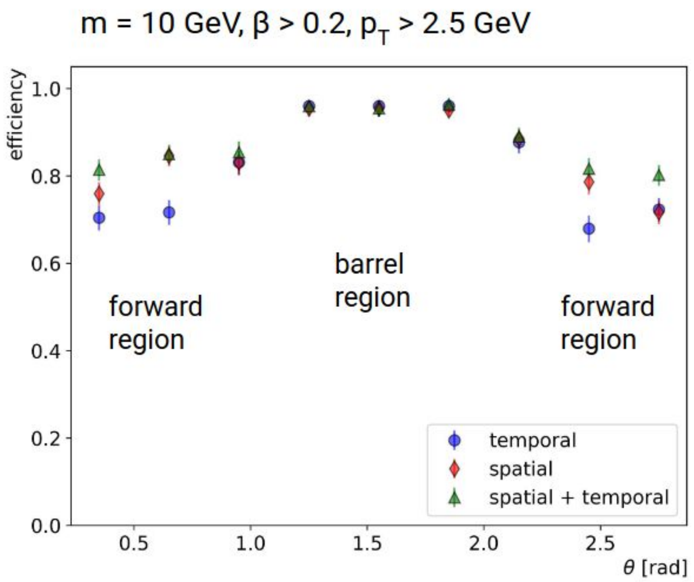
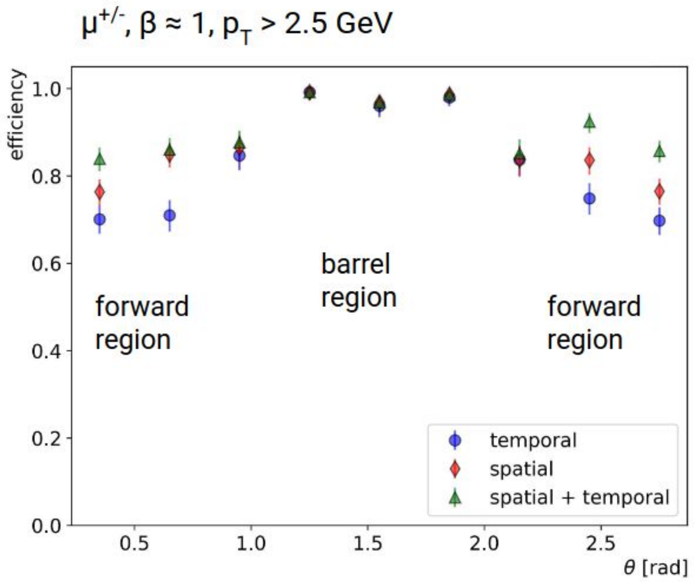
Gate-based Simulator: Muon collider results





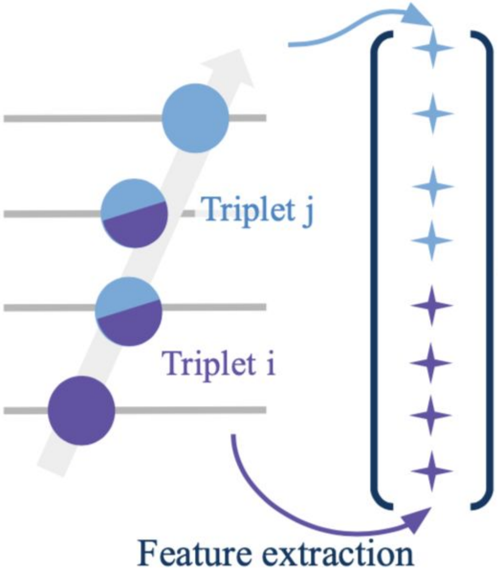
$$\text{Efficiency} = \frac{N_{\text{tracks}}^{\text{matched}}}{N_{\text{tracks}}^{\text{generated}}}$$

Summary and Outlook

- ❖ Difficult tracking environments ask for new tracking algorithms
- ❖ SA, simulated gate-based and CKF show comparable performance
- ❖ QC may be leveraged for highly entangled or complex tracking problems
- ❖ Learn QUBO formulation for data directly

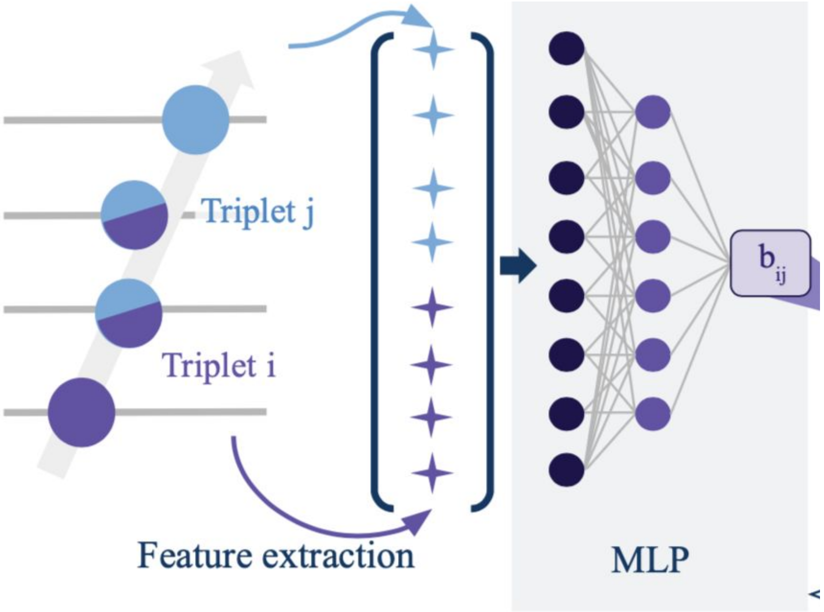
Experience

Learned QUBO encodings



- QUBO entries are difficult to derive analytically or empirically
- Learn encoding from data directly
- QUBOs can be used for all problems that can formulated as a binary decision

Learned QUBO encodings



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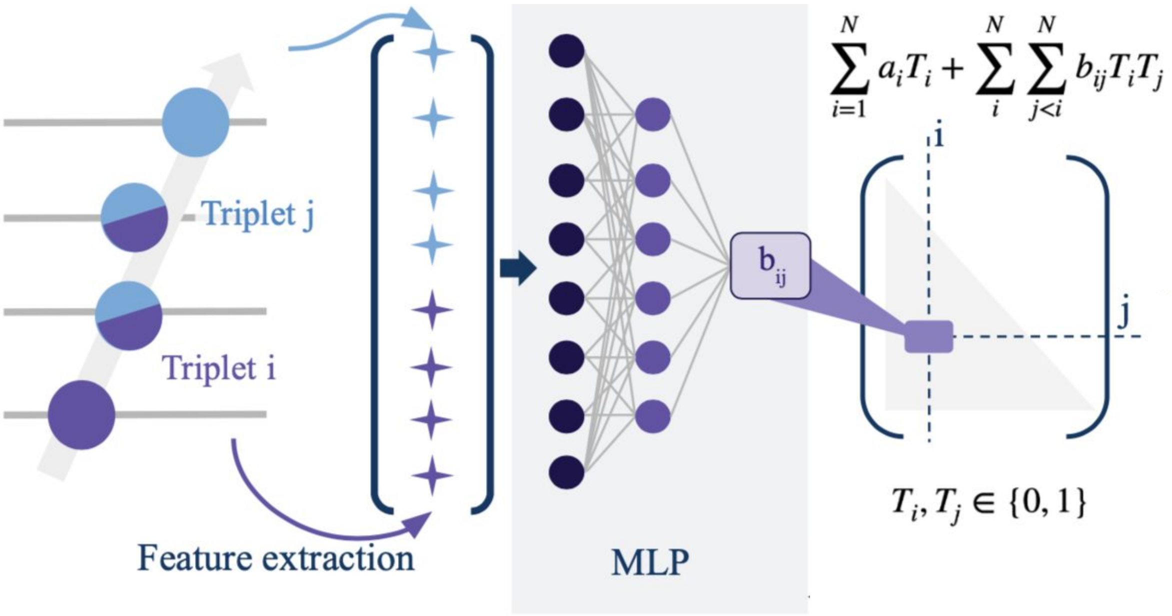

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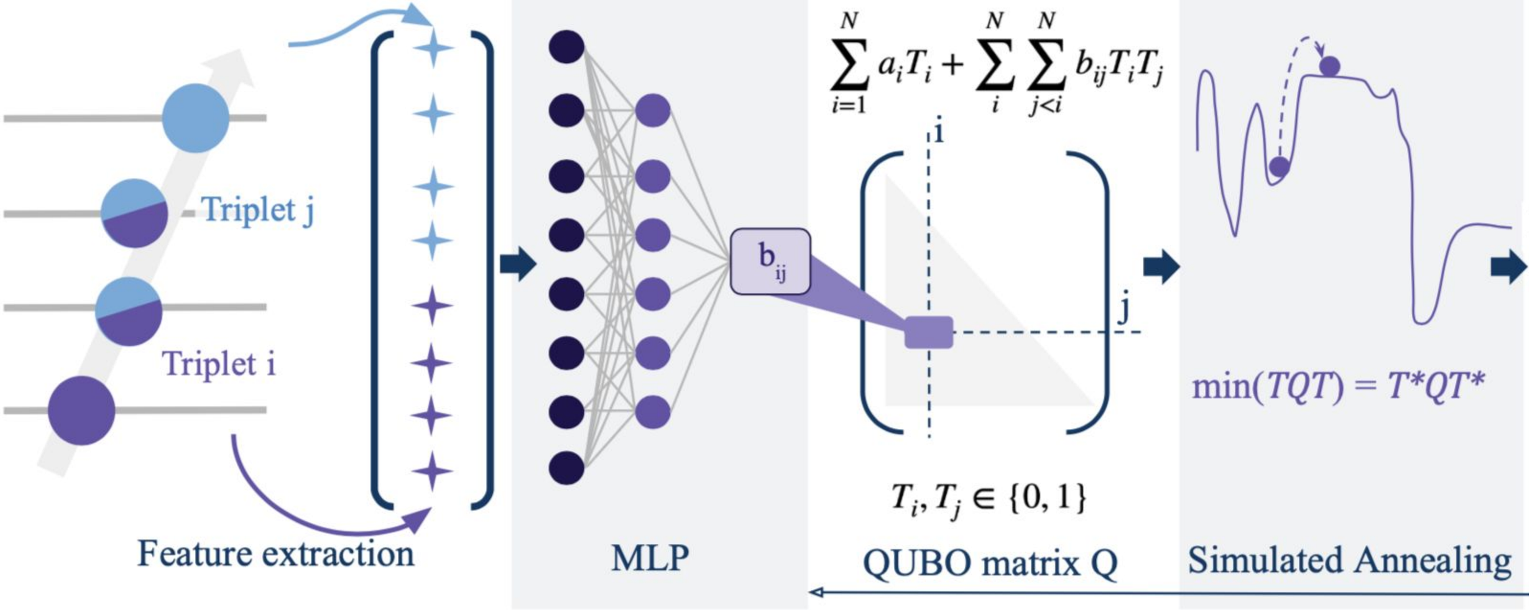

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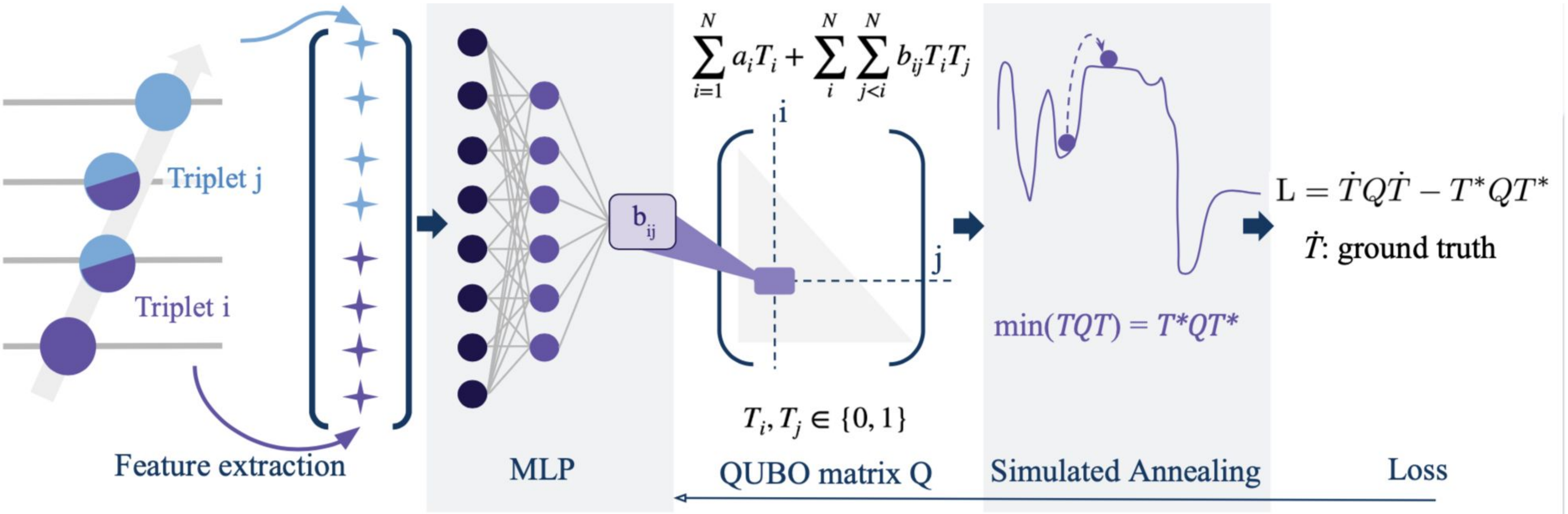
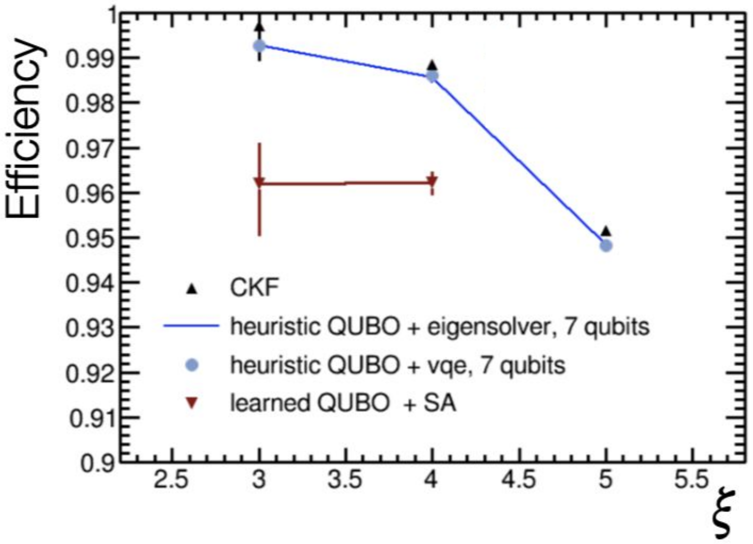
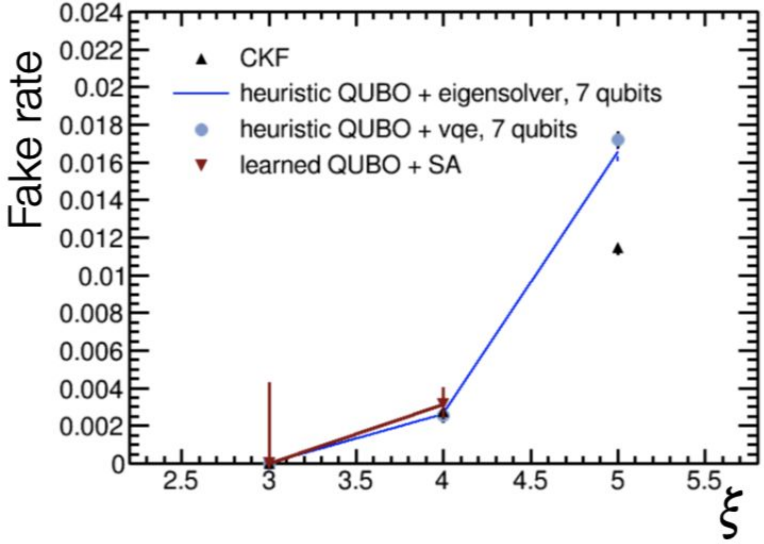


Learned QUBO encodings: Results





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Thank you!