COMBINING QUBO WITH CLASSICAL APPROACH TO PARTICLE TRACKING

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INTRODUCTION

- Various tracking methods (quantum or classical) were explored to reconstruct positron tracks in the LUXE experiment in arXiv:2304.01690:
  - (Quantum) Graph Neural Network
  - Combinatorial Kalman Filter (CKF)
  - Quadratic Unconstrained Binary Optimisation (QUBO)

Quantum algorithms for charged particle track reconstruction in the LUXE experiment

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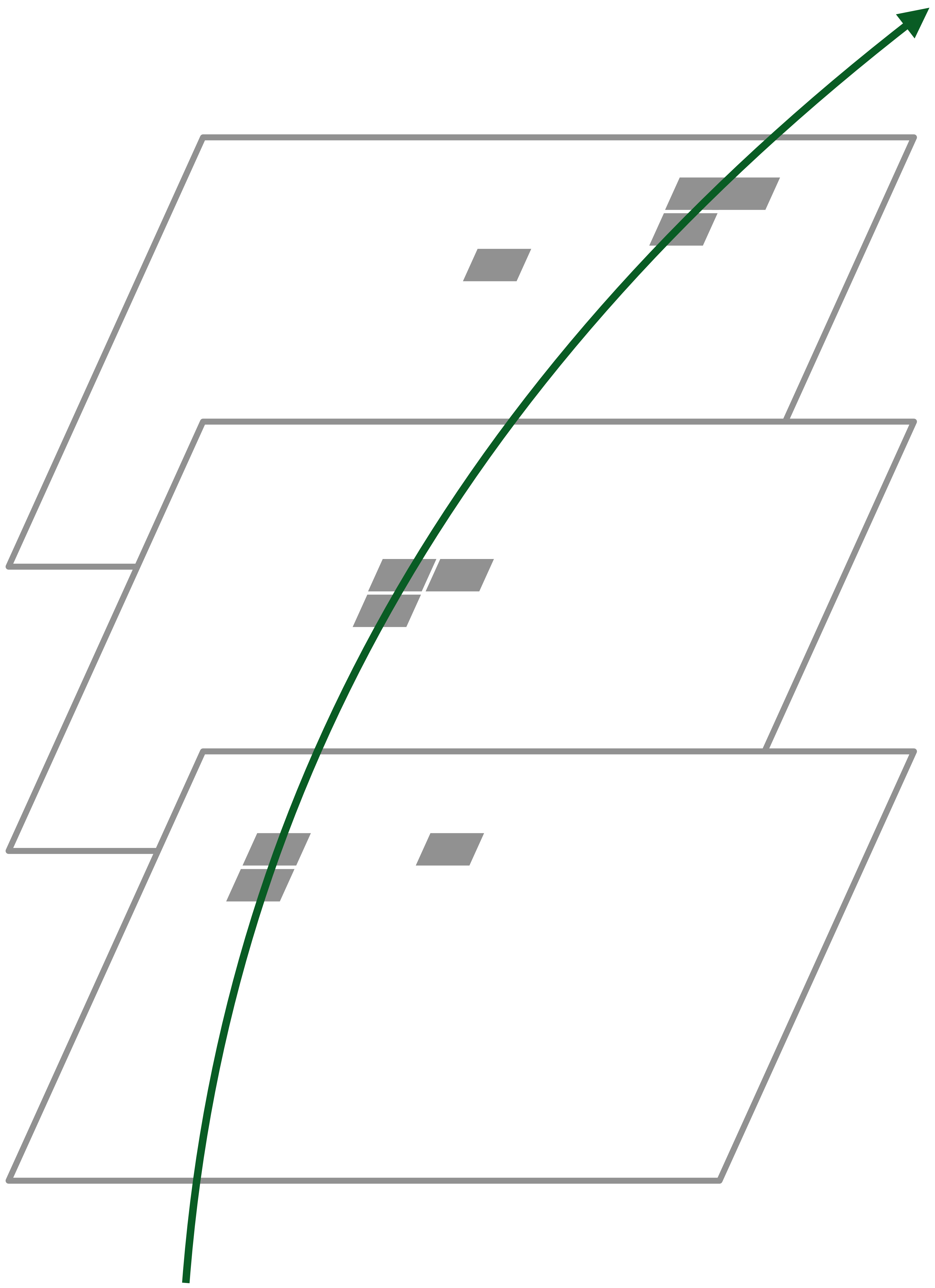
- Present the various discussions our team had on how to leverage/combine the latter two methods.

- Very speculative!

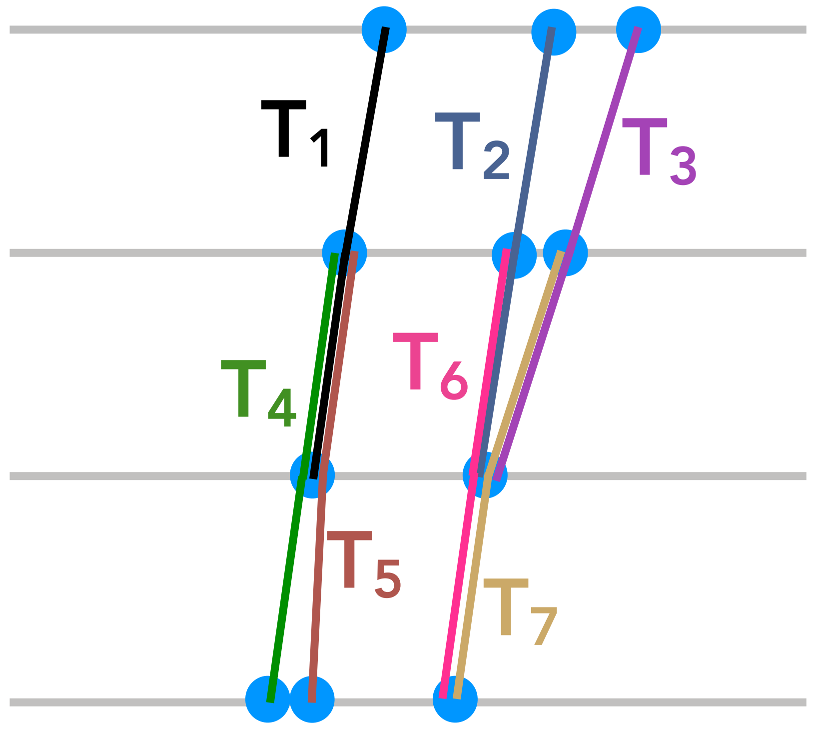
PARTICLE TRACKING

- Tracking = reconstructing the trajectory (or track) of charged particles in a particle detector known as a tracker.
- Particles leave traces of their passage through the tracker by their interactions with the materials in the tracker -> hits.
- If magnetic field is present, momentum of the particle can be determined from the curvature of the track, knowing the electric charge.
- Study tracking in two different proposed particle physics experiments: LUXE and muon collider.
  - Multi-layer silicon detector.



QUBO

- Formulate the tracking problem as a QUBO.
- First reduce the number of considered triplets with a pre-selection.
- Then, 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

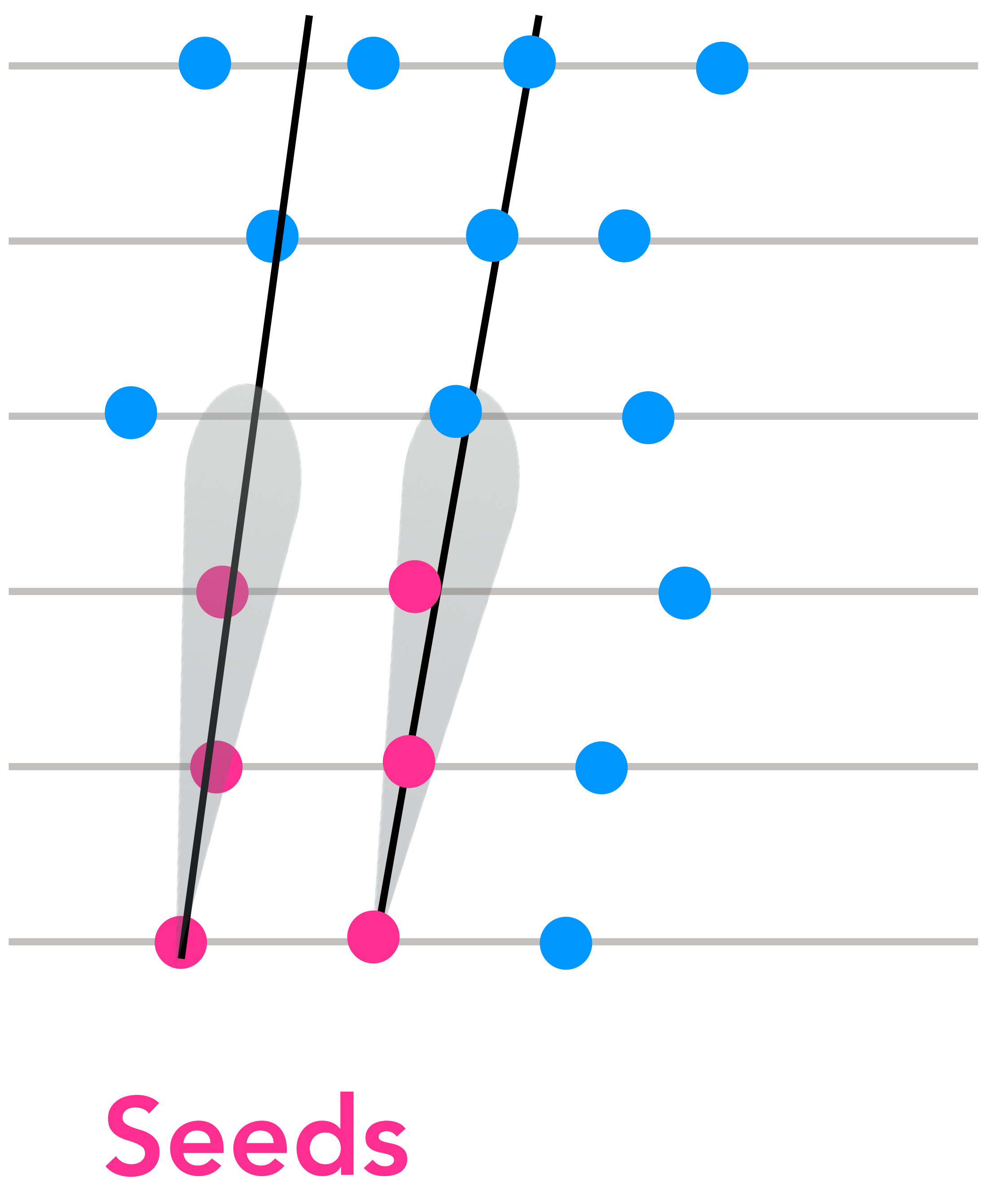
$$b_{ij} = \begin{cases} -S(Ti,Tj), & \text{if } (T_i,T_j) \text{ form a quadruplet}, \\ \zeta & \text{if } (T_i,T_j) \text{ are in conflict}, \\ 0 & \text{otherwise.} \end{cases}$$

- Solution can be found with VQE or quantum annealing.

Find T_i, T_j that minimises QUBO!

CKF

- Combinatorial Kalman Filter is an extension of Kalman Filter that combines track finding and track fitting.
- Starts with a seed (triplet), usually from the innermost layers.
- Estimate trajectory based on a given seed and find more hits to complete the track, fitting and improving the prediction along the way.



QUBO VS CKF

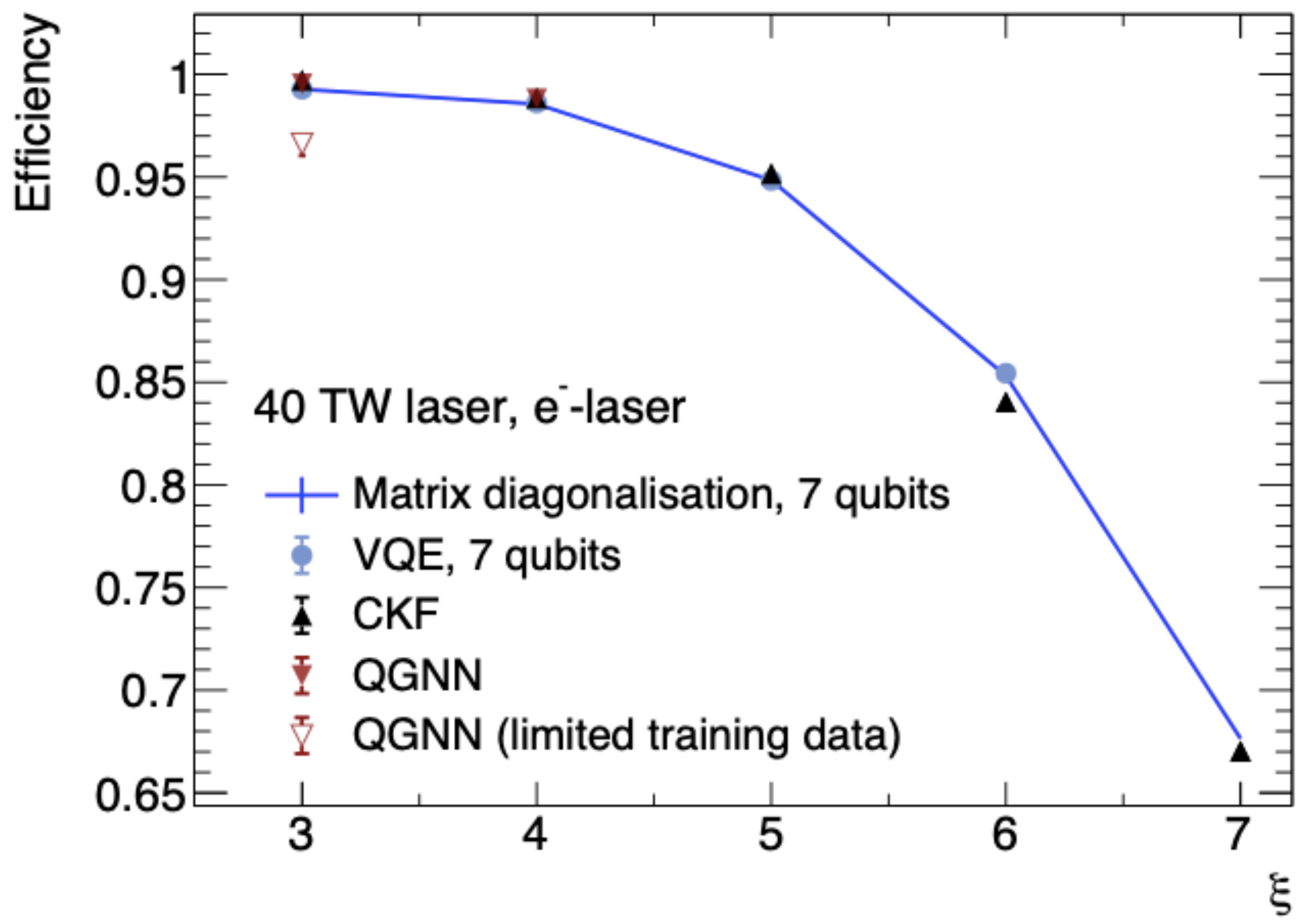
- QUBO selects globally the best triplets to form well aligned tracks while minimising conflicts/hit sharing while CKF only finds local hits matching the initial seed, and is unaware of other seeds.

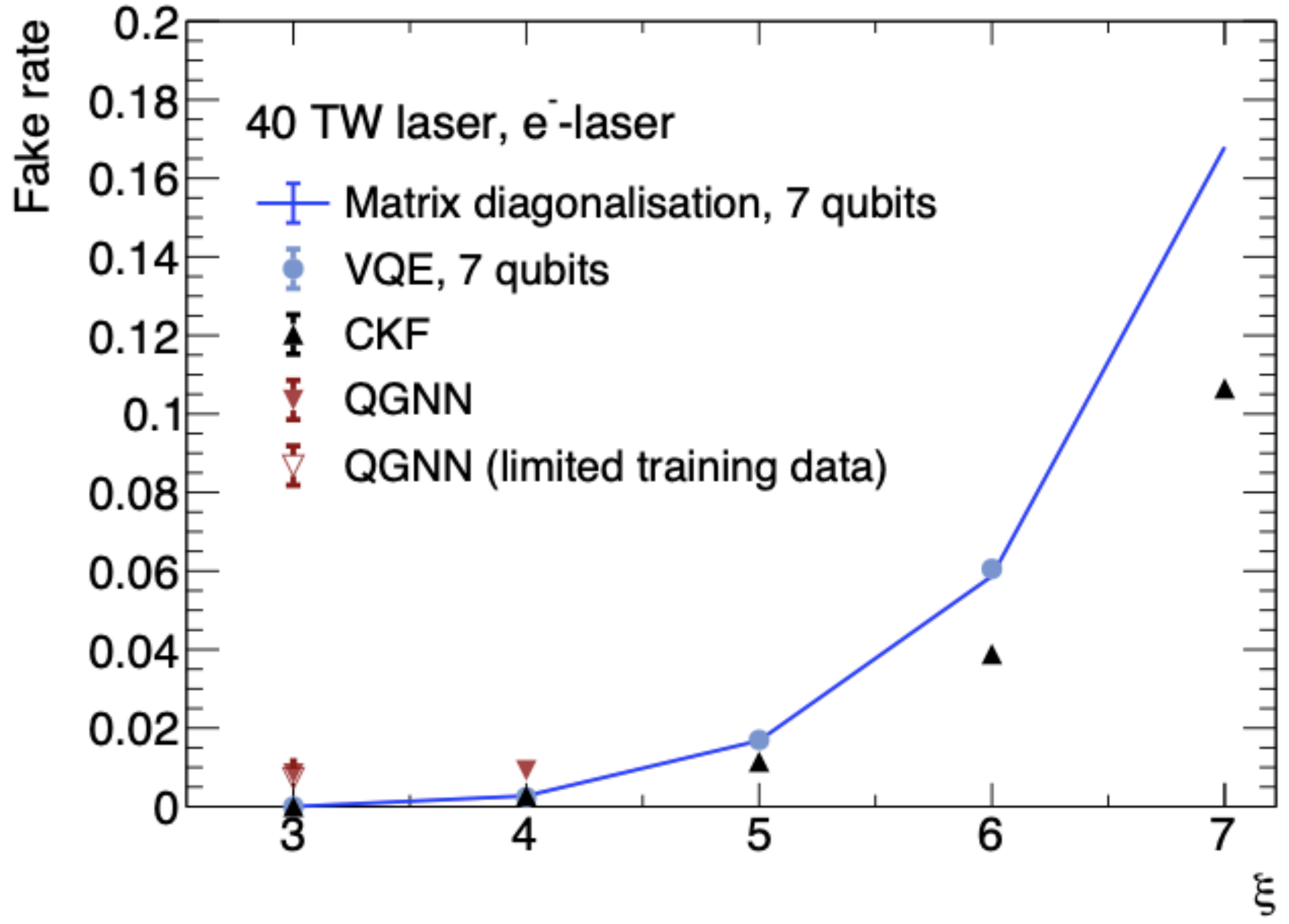
- CKF can easily handle detector inefficiency such as holes (missing hits) in a track while triplets will need to be defined differently for QUBO to account for this.

Methods	QUBO	CKF
Starting point	Triplet	Seed (can be triplet)
Local/global	Global	Local
Scope	Pattern recognition only	Pattern recognition + track fitting

PAPER RESULTS

- Performance of QUBO compared to CKF (and QGNN) for the LUXE experiment in arXiv:2304.01690.
- Comparable performance. But given how different the approaches are, combining them may lead to improved performance.



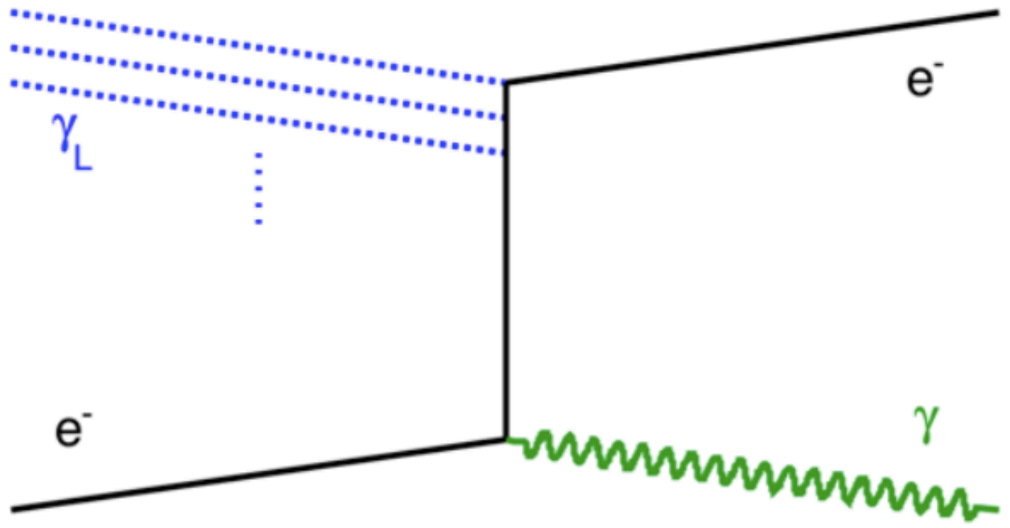


LUXE: LASER UND XFEL EXPERIMENT

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

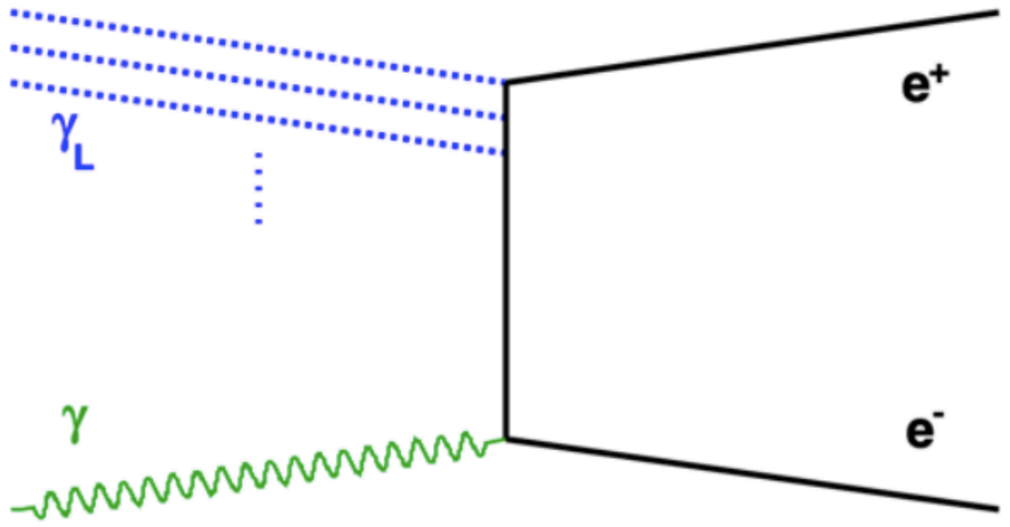
Non-linear Compton scattering:

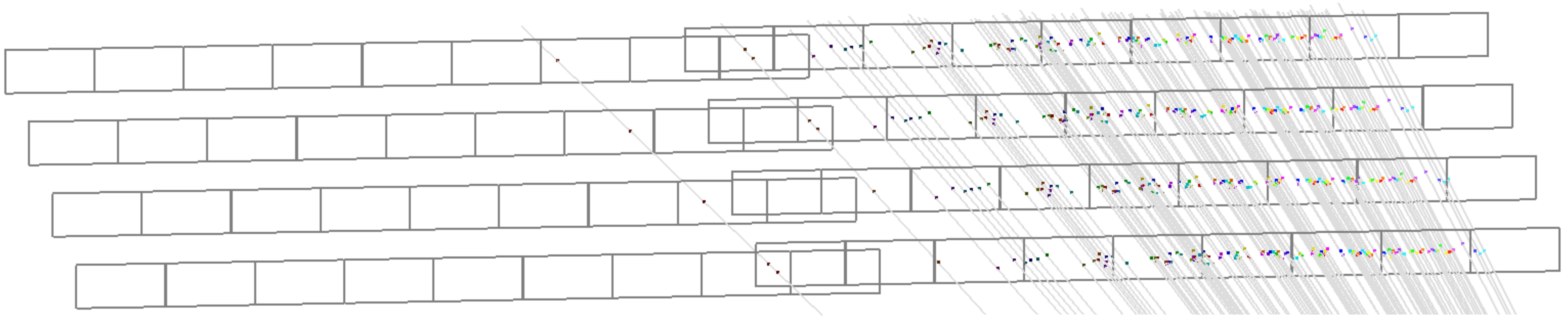
$e^- + n\gamma_L \rightarrow e^- + \gamma_C$



Non-linear Breit Wheeler:

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

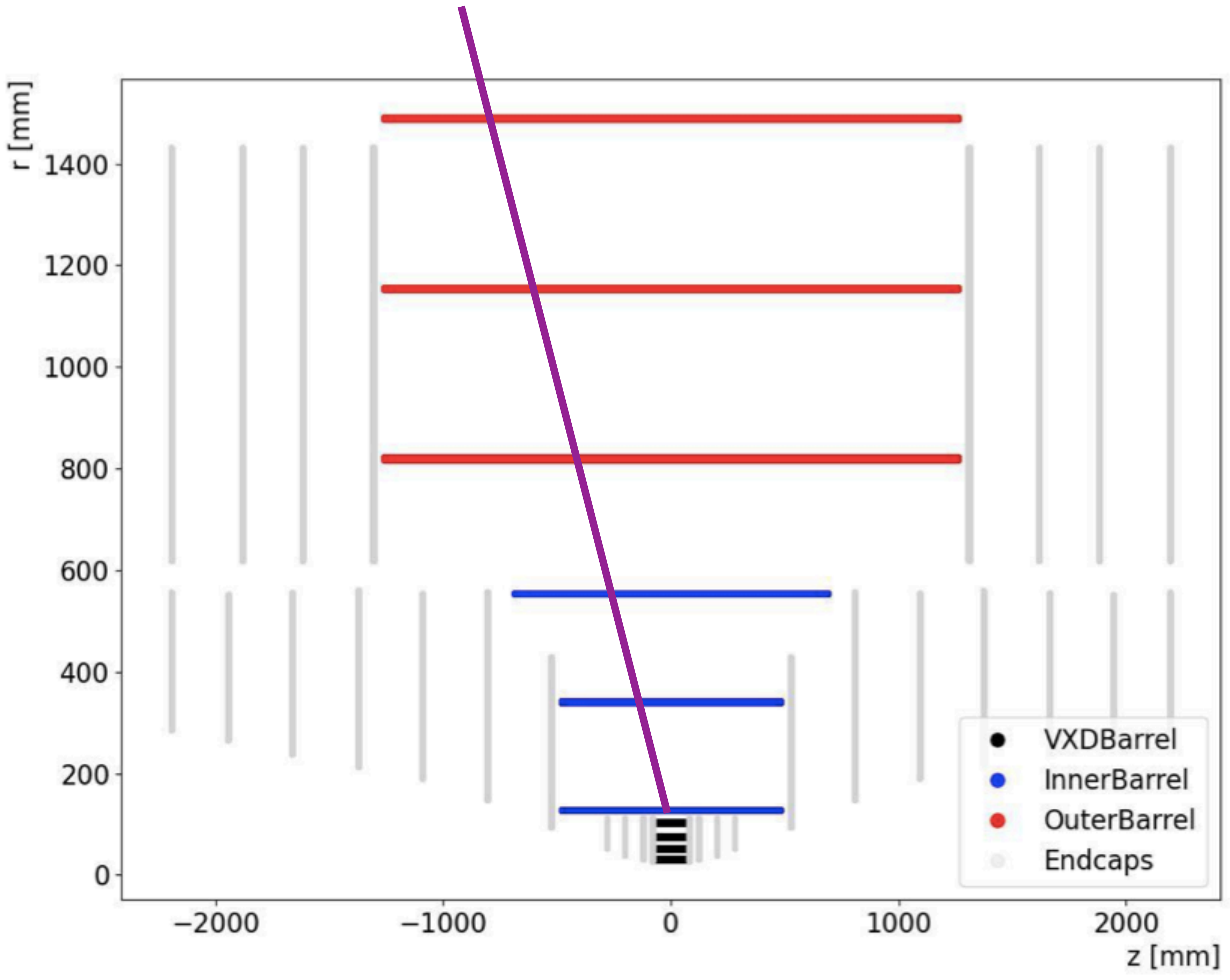




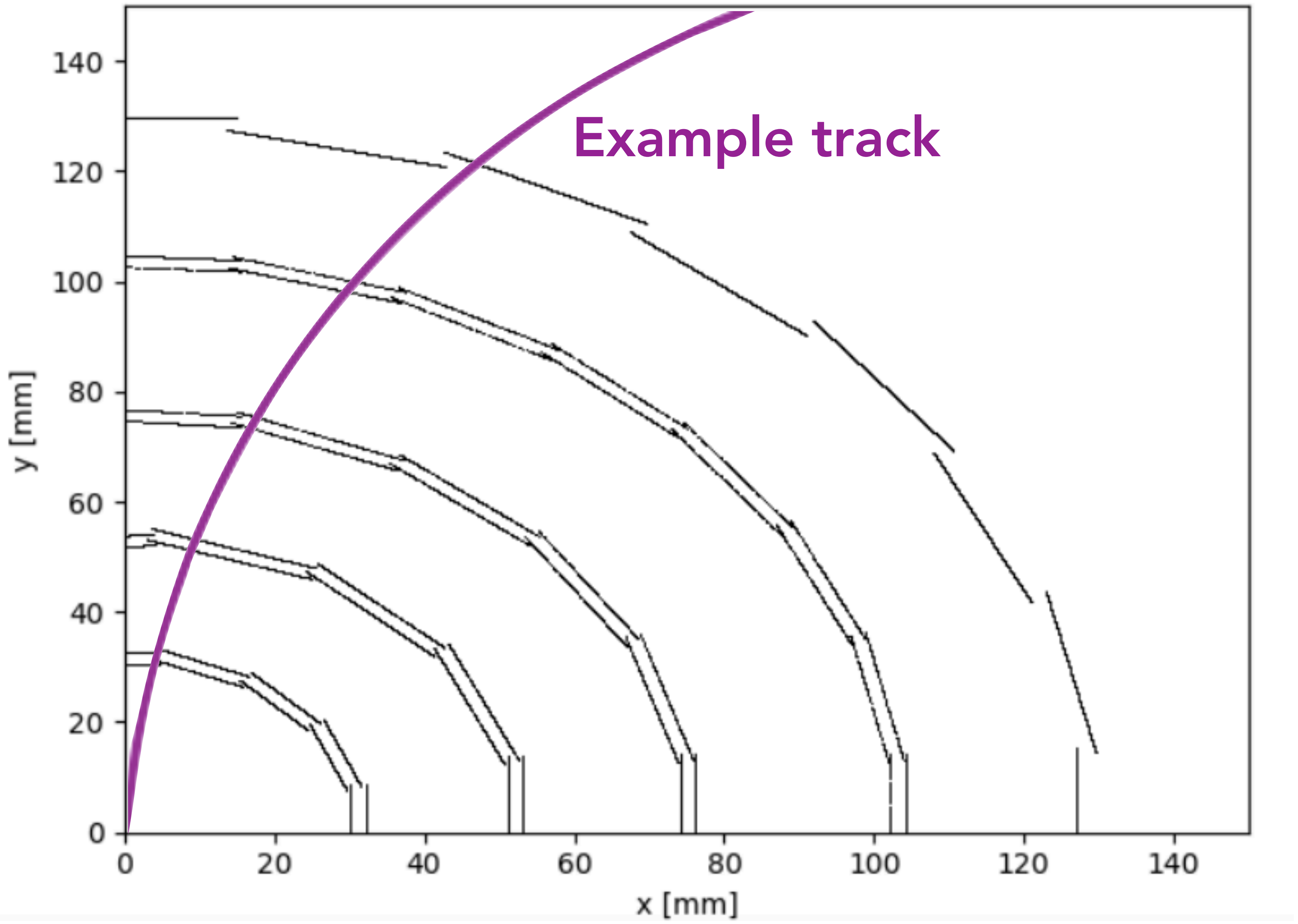
How positron tracks look like at the tracker

MUON COLLIDER

- Proposed future particle collider, less synchrotron radiation than electron but short lifetime. Huge beam-induced background.
- Classic onion shape detector with tracker closest to the collision region.



Vertex detector. Latest design has 1 double layer and 3 single layers



LUXE VS MUON COLLIDER

	LUXE	Muon collider
Detector	4 layers of double staves	Vertex, inner and outer trackers, +endcaps
Timing resolution	μs	30-60 ps
Background	~constant and uniform (~7,000 clusters per layers)	~500,000 hits in innermost layer
Signal	$10^{-3} - 10^{6}$	$O(10^{2})$
Occupancy	Could reach 100% in some scenarios	No more than few %
Discriminating feature	Point to the interaction point	Small impact parameter, in time
B field	0 T, but dipole field before tracker deflecting particles like a spectrometer	3.57 T solenoid
Tracks	Straight, ~4 hits	Curved, >10 hits can be expected

HOW TO COMBINE?

- **Mixed QUBO/CKF track finding (promising for LUXE)**

PARALLEL

- e.g. QUBO for some triplet clusters, CKF for others
  - Triplet cluster is a group of triplets that interact with one another.

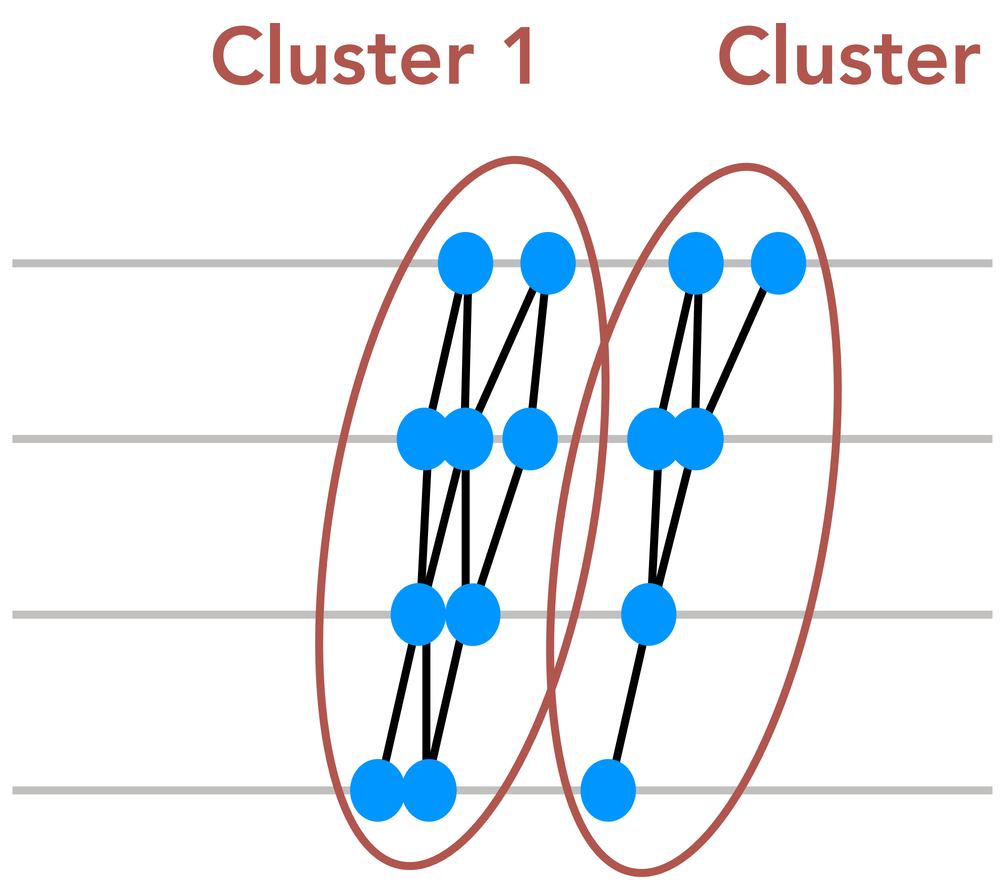
- **QUBO for seeding (promising for Muon collider)**

SEQUENTIAL

- First identify track segments (formed combining 2 or more selected triplets) with the QUBO method then run CKF with them as seeds.
  - Could identify track segments efficiently and reduce number of seeds in CKF dramatically.
  - Less limiting seeding.
  - CKF helps to recover missing hits from QUBO.

MIXED QUBO/CKF TRACK FINDING

- What kind of clusters are better solved with QUBO? Complicated highly entangled ones with many triplets interacting with one another, many conflicts?
- Quantify with e.g. #track candidates/#triplets. Perhaps there's a threshold over which QUBO performs better than CKF?
- Benefits of dividing the problem into clusters and solving them separately:
  - Less qubits needed to fit entire QUBO
  - Less empty entries in the QUBO
  - Faster



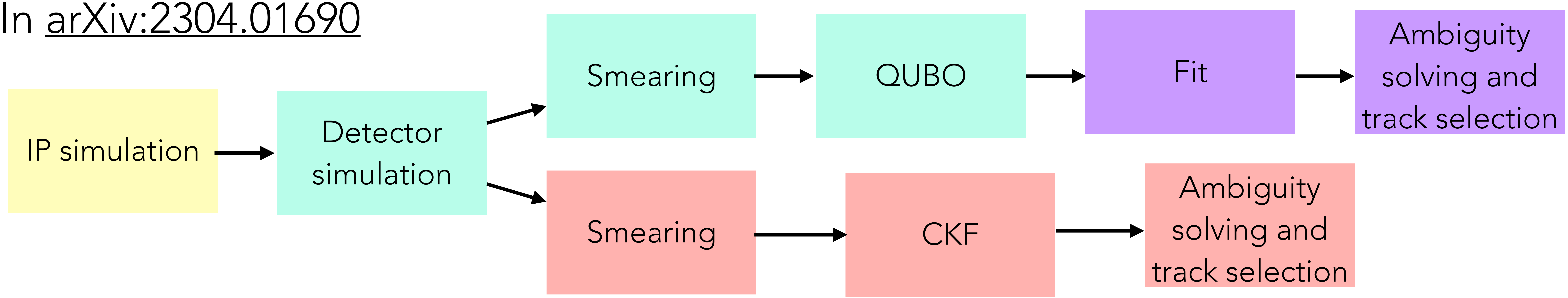
DIVIDE AND CONQUER

MIXED QUBO/CKF TRACK FINDING

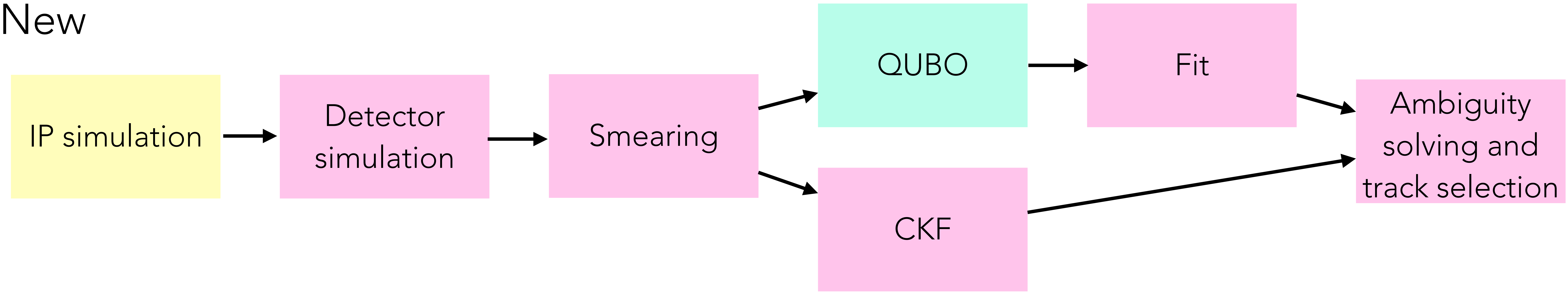
- To investigate the advantage of this hybrid method, need to find out in which cases/phase space QUBO performs better than CKF.
- To make this comparison seamless, want to make sure we can compare the resulting track candidates properly and consistently, by processing the track candidates in a uniform way (same fit, same ambiguity resolving).
- Done within a software framework with the event data model planned for LUXE.

WORKFLOW

In arXiv:2304.01690

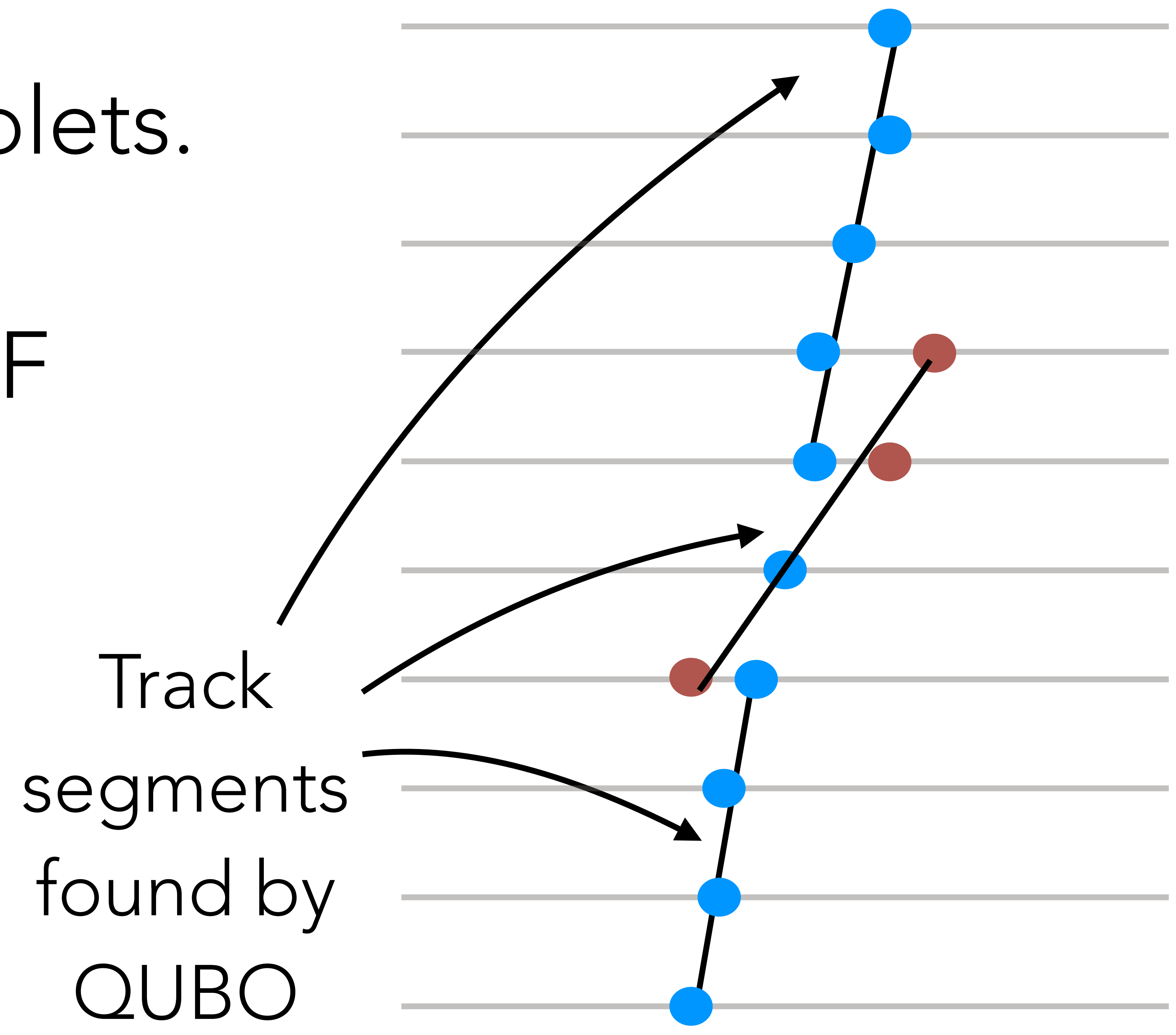


New



QUBO FOR SEEDING

- QUBO method may fail at identifying the entire track pattern and only get track segments (from 2 or more triplets).
  - e.g. due to failing pre-selection or competing triplets.
- Track segments can be used instead as seeds in CKF to recover the entire track pattern.
- Additional benefit that holes are also allowed.



QUBO FOR SEEDING

- Currently, 10^5 seeds are found per muon collider event for CKF, large majority of which are fakes.
  - Using track segment found by QUBO could reduce this drastically by several orders.

- More general than outside-in or inside-out tracking since the seeds found by QUBO can be anywhere and not restricted to just the first or last few tracking layers.
  - Not missing exotic signatures like displaced vertex and disappearing track.

SUMMARY

- QUBO and CKF are two very different tracking methods.
- Presented two ways of combining QUBO and CKF where the two methods are used in parallel or sequentially.
- Any other ideas?