Track reconstruction of charged particles using a 4D quantum algorithm

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DPG Spring Meeting, Dresden
21.3.2023

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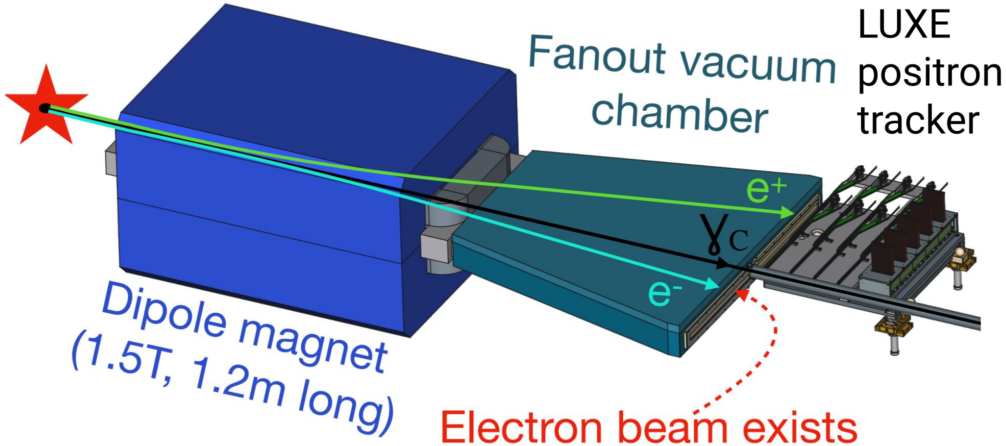
HELMHOLTZ

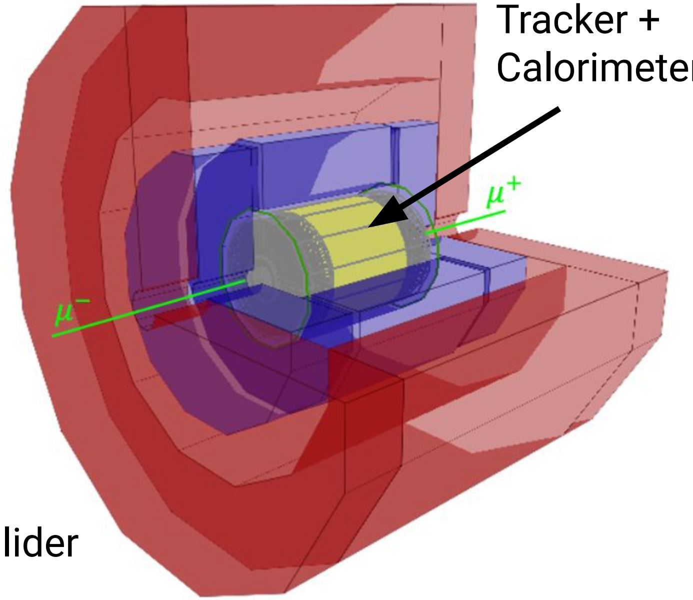
Track reconstruction

- Extract physics properties from particle tracks
- Allows for projection to or through other detectors, e.g Calorimeter, Cherenkov Detector
- Identify secondary decays



Challenges:

- Identify signal tracks within a large background (Muon-Collider)
- Match tracks to detector hits in high occupancy regions (LUXE)



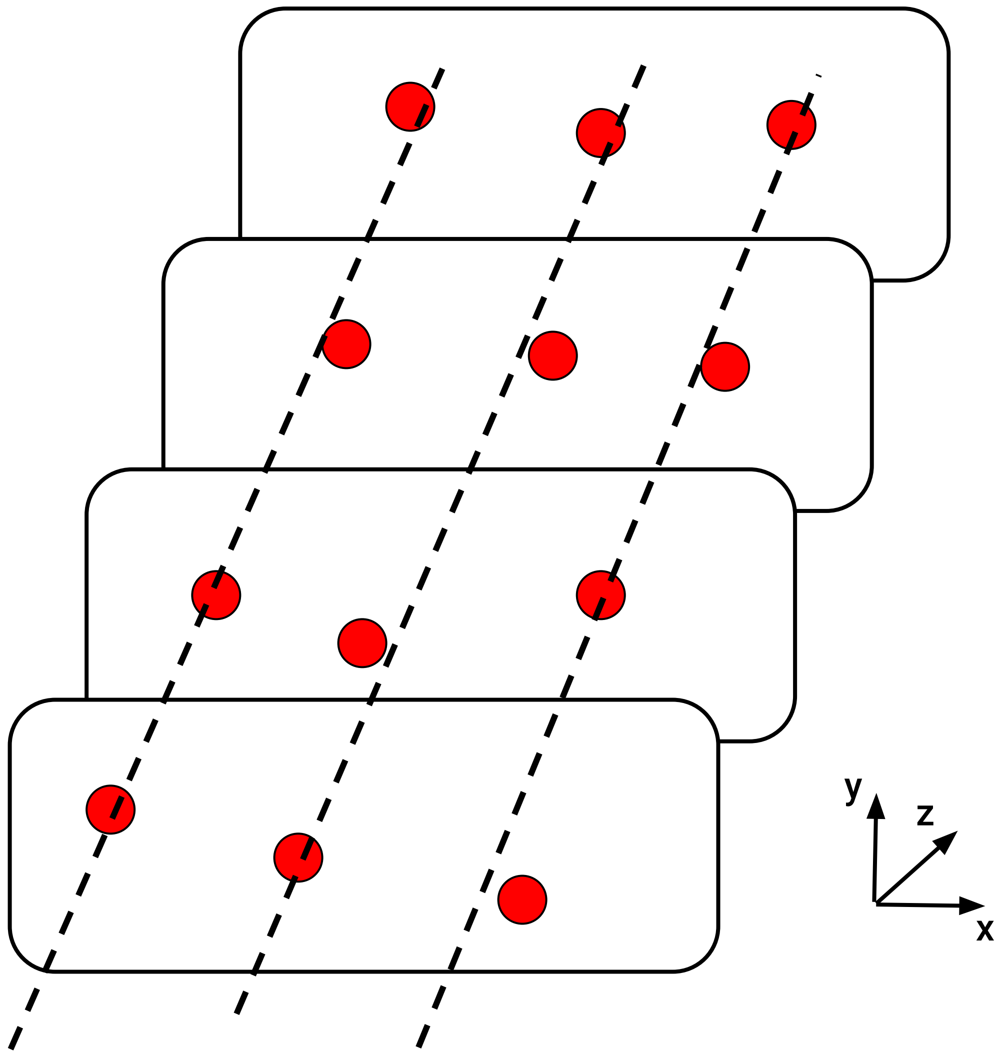
Muon Collider Detector

Source: https://muoncollider.web.cern.ch

Pattern Building for Track Reconstruction

particle hit on detector

true particle track



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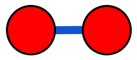
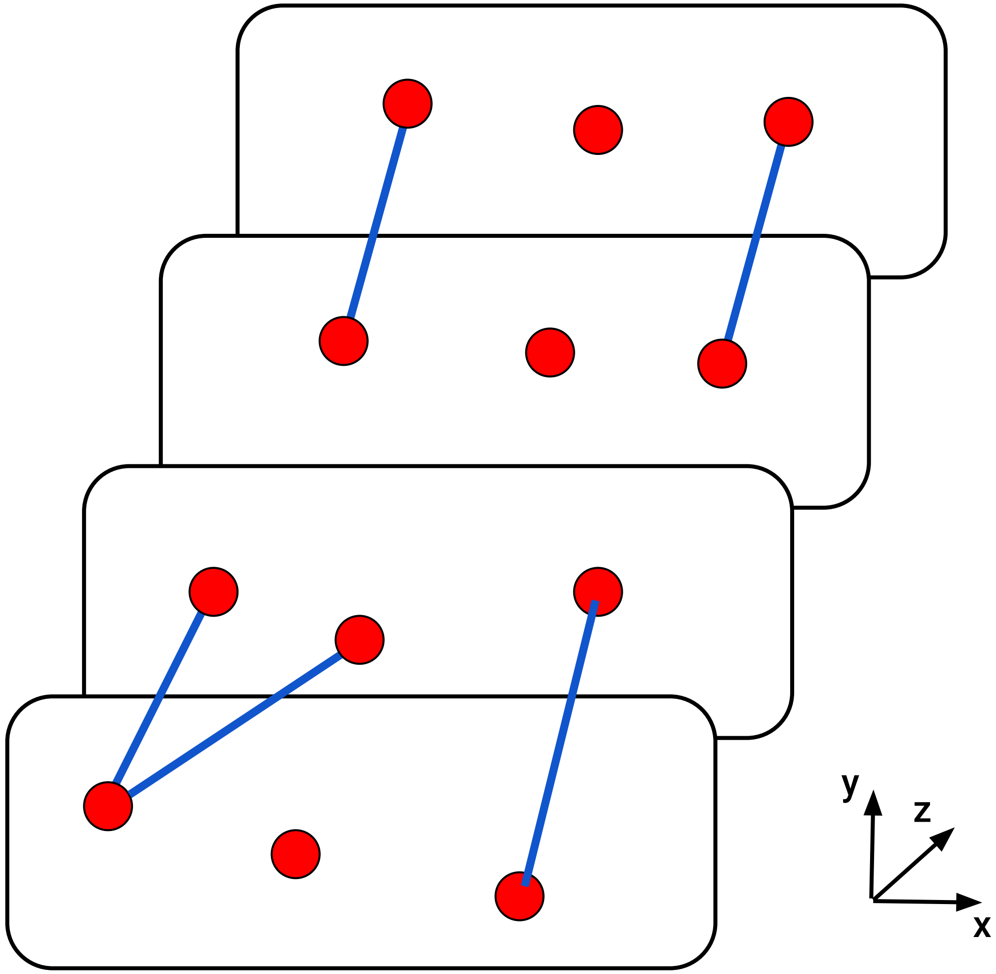


Build patterns from detector hits:

- doublets



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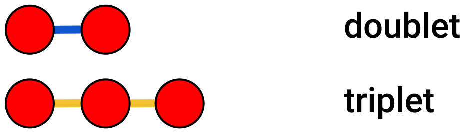
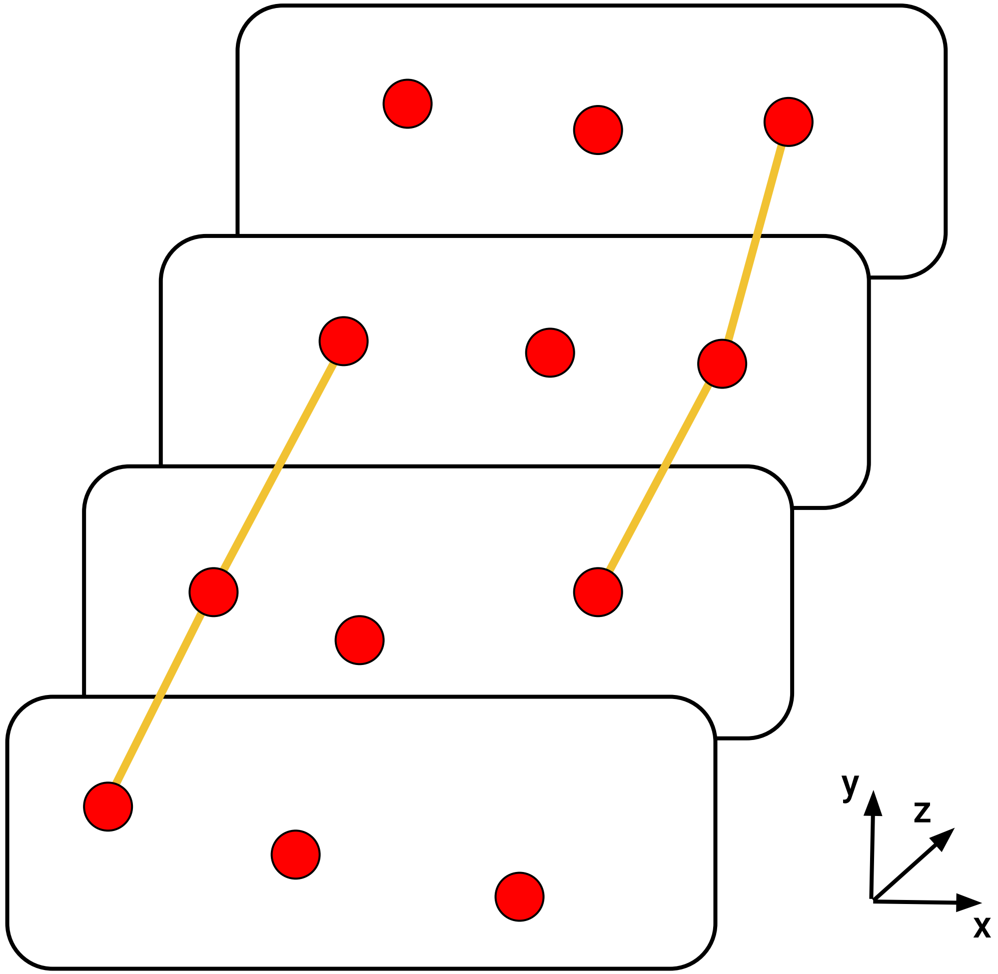
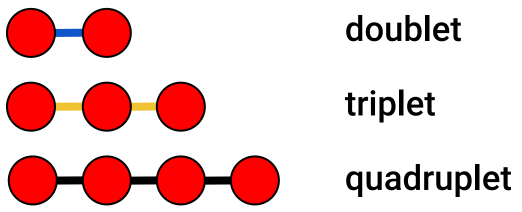


Build patterns from detector hits:

- doublets
- triplets

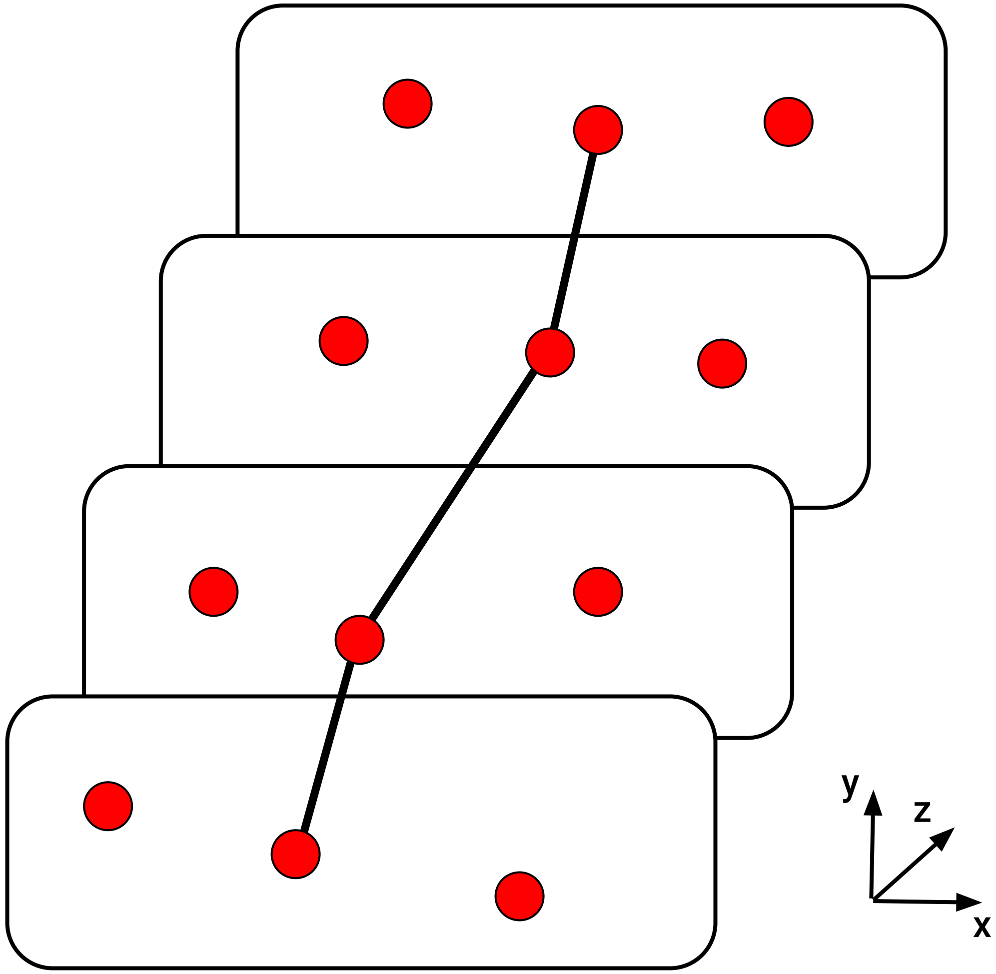


Pattern Building for Track Reconstruction

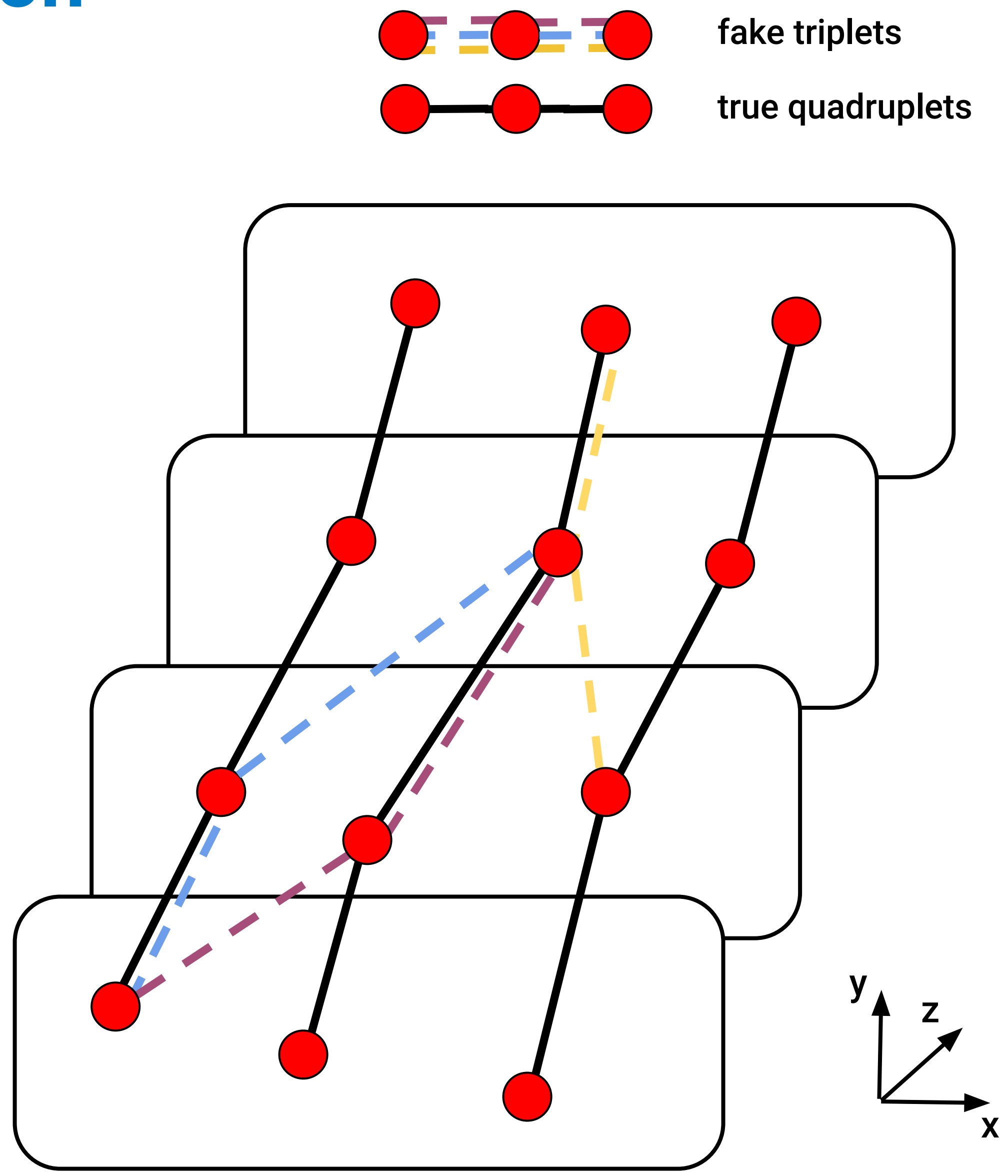


Build patterns from detector hits:

- doublets
- triplets
- quadruplets



Pattern Building for Track Reconstruction



Build patterns from detector hits:

- doublets
- triplets
- quadruplets

Pattern building is a purely combinatorial task
→computationally costly for a high number of particles

Goal: Identify patterns stemming from a single particle

Measuring Track Reconstruction

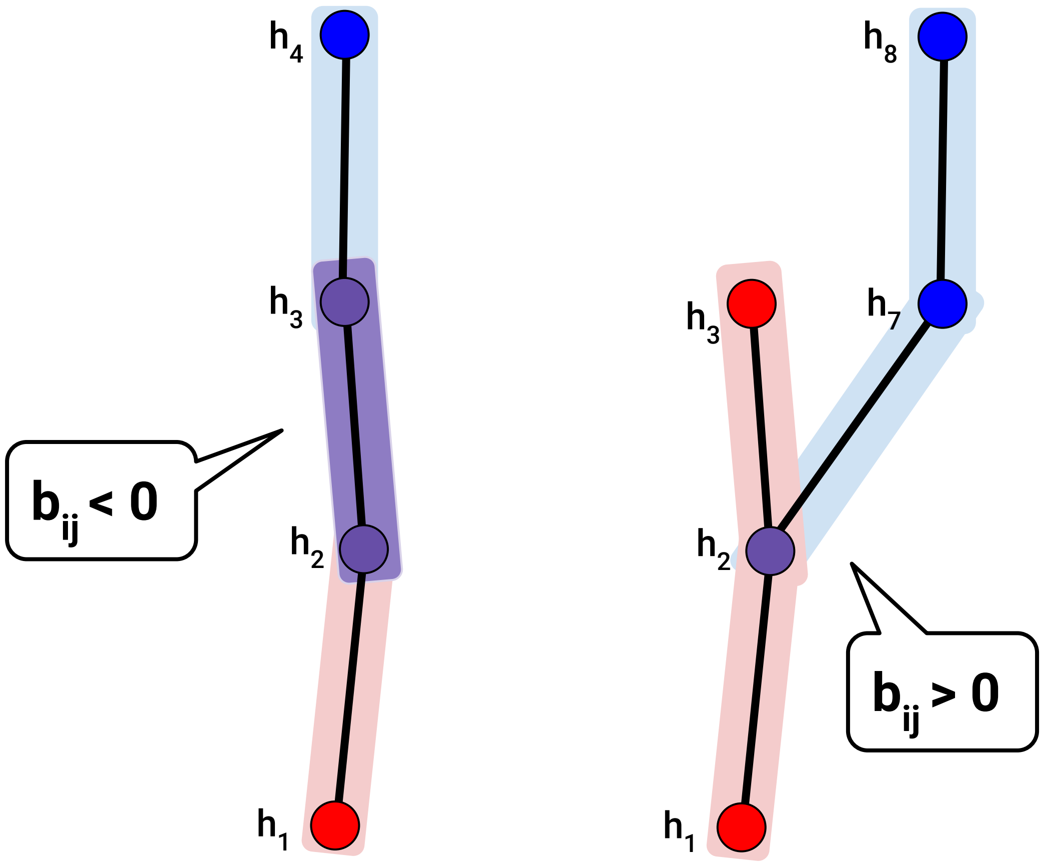
Quadratic ***U***nconstrained ***B***inary ***O***ptimisation as Hamiltonian formulation of the track reconstruction:

- $\mathbf{T_i} \in \{0, 1\}$ as binary representation of a triplet
  $\mathbf{t_{bin}}$: $[T_1, T_2, T_3, \dots, T_N] \rightarrow [0, 1, 1, \dots, 0]$
- $\mathbf{b_{ij}}$ as interactions of triplets
- $\mathbf{a_i}$ as quality of a triplet

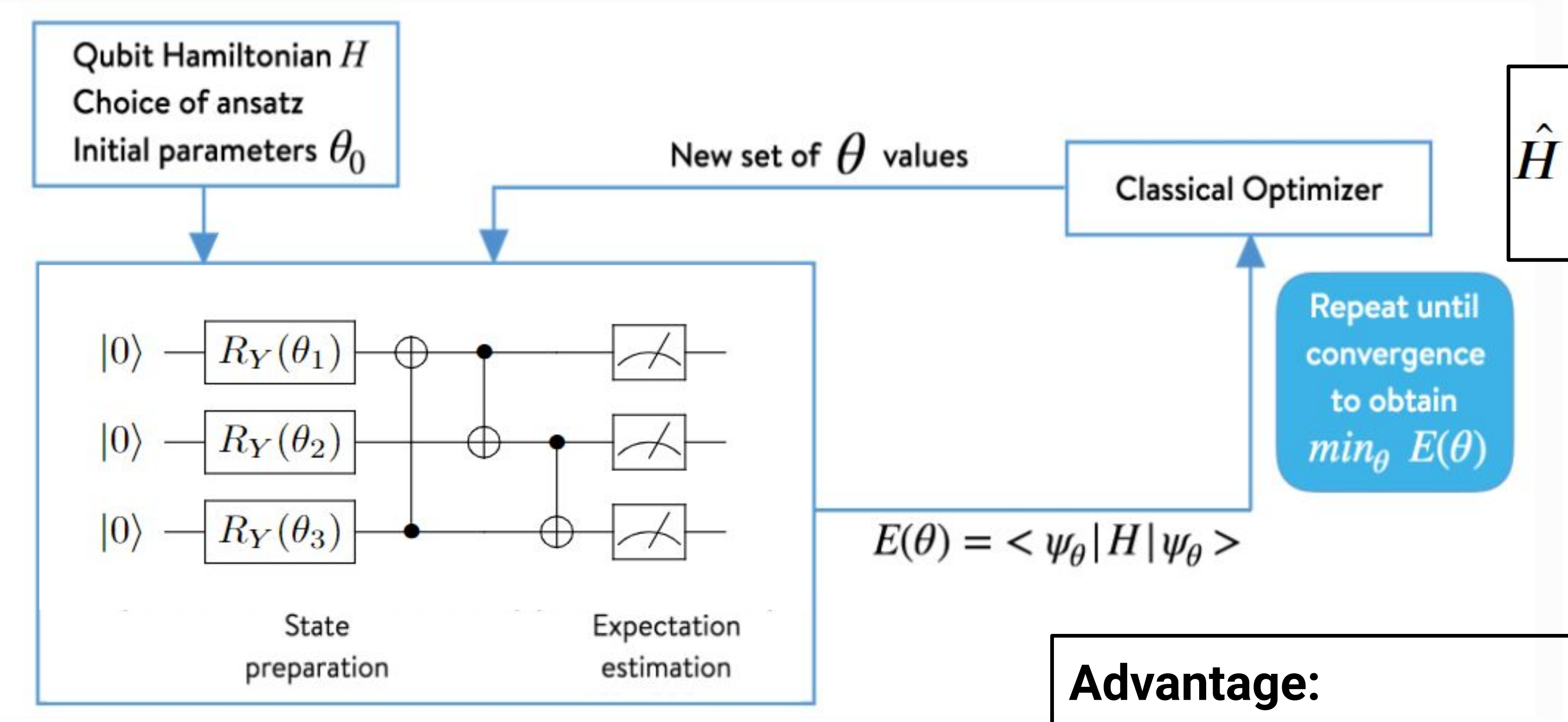
Ground state of the Hamiltonian is the optimal solution of the track reconstruction task

→ resulting binary vector $\mathbf{t_{bin}}$ tells which triplets to keep

$$\hat{H} = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i$$



VQE - *V*ariational *Q*uantum *E*igensolver



Source: edited from http://openqemist.1qbit.com/

$$\hat{H} = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i$$

Advantage:

dim(H) = 2^n x 2^n, then <ψ|H|ψ> needs

- $O(2^{2n})$ operations classically
- O(Poly(n)) operations with a quantum computer

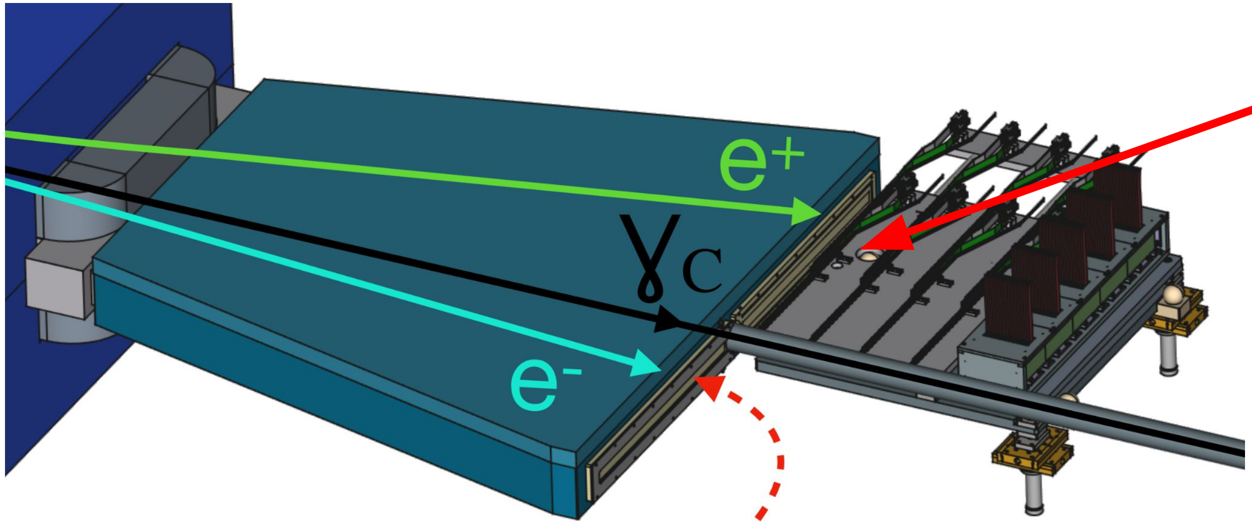
Reconstruction of positron tracks in LUXE

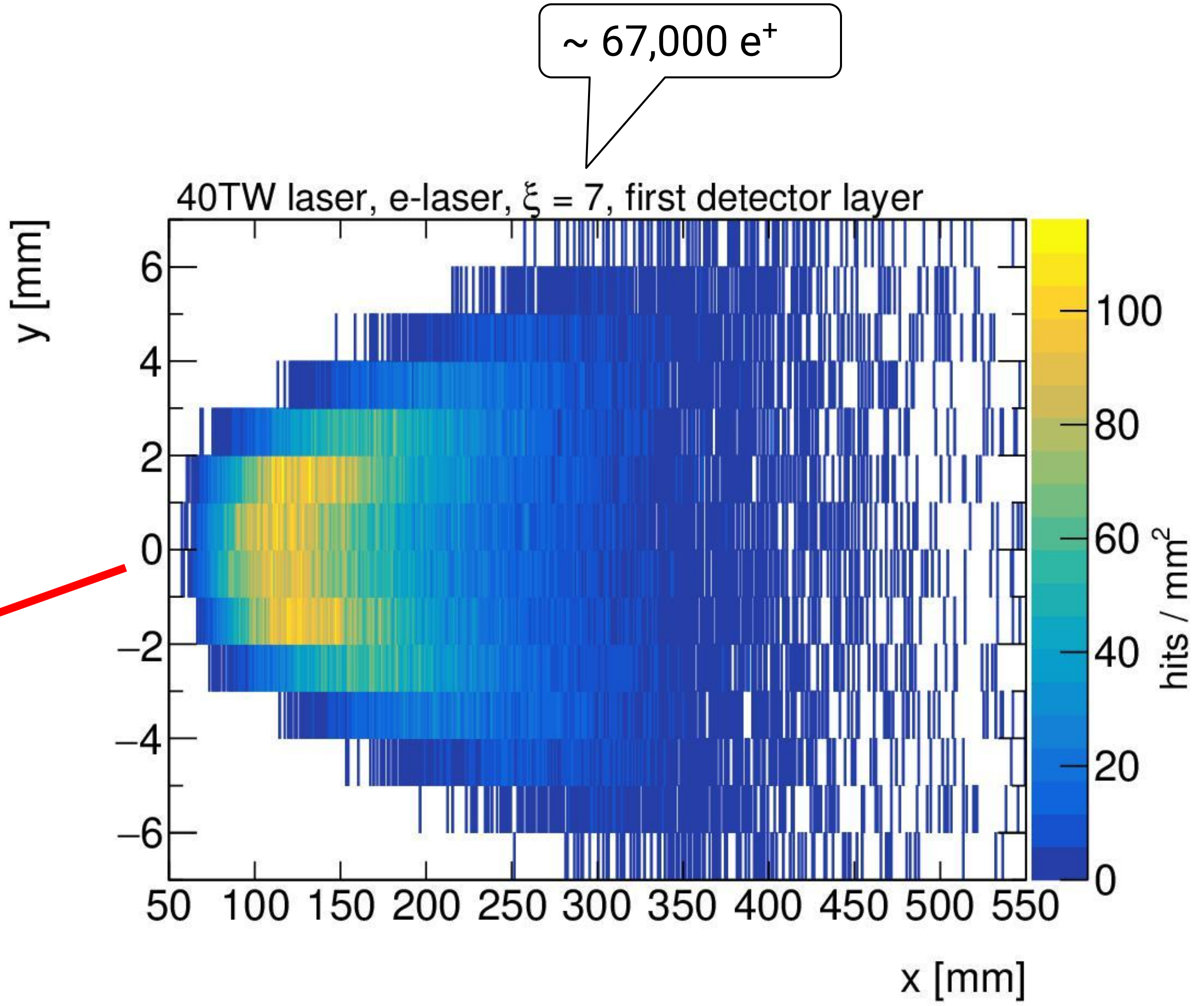
Tomorrow at 11am by Ruth Jacobs:
LUXE – A new experiment to study non-perturbative QED in electron-laser and photon-laser collisions

LUXE: e^+e^- pair creation through electron-laser and photon laser collisions

→ separated with a strong dipole magnet

Challenge: Track reconstruction at high occupancy



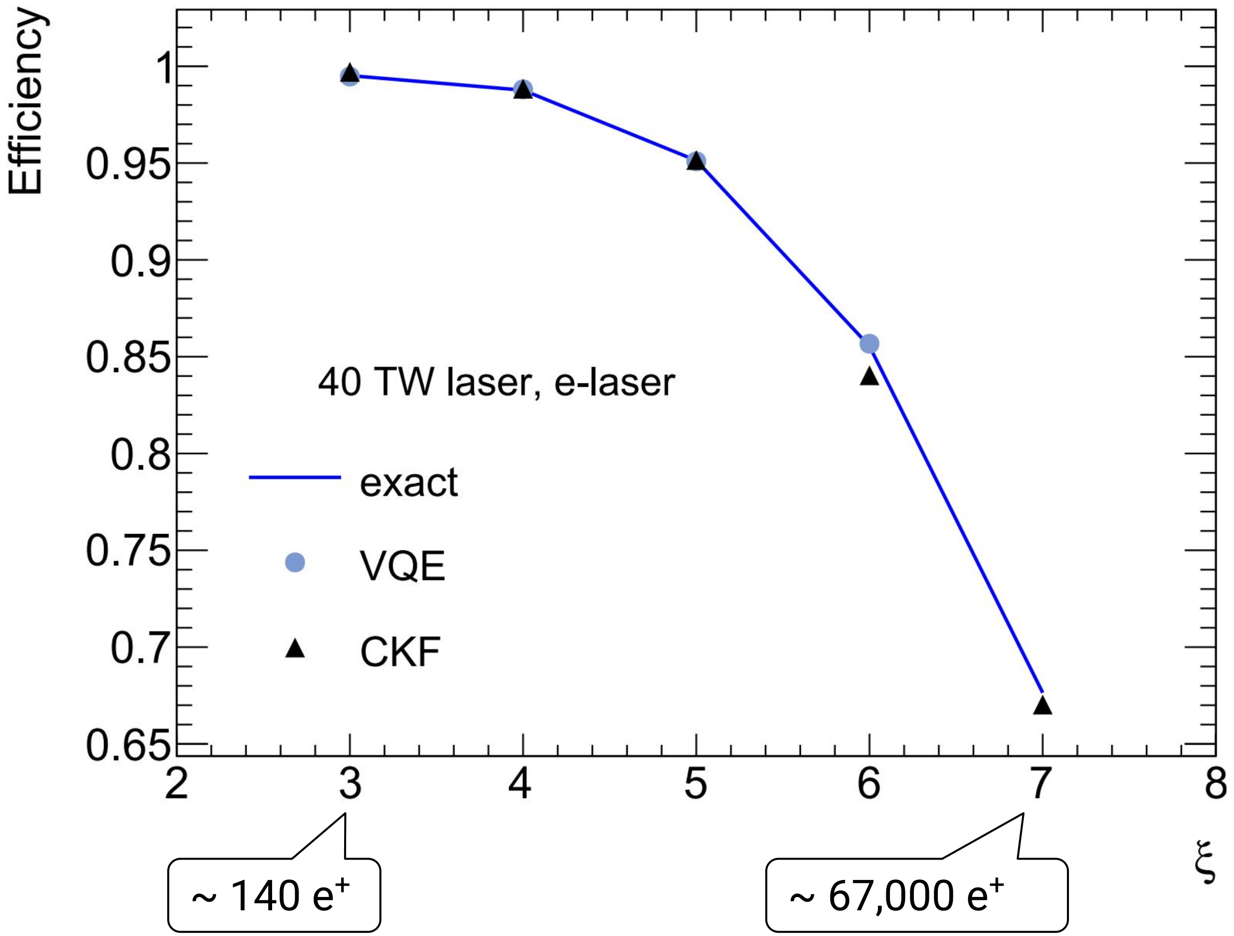


Track level efficiency

Compare three different solving methods

- ***C****ombinatorial* ***K****alman* ***F****ilter*
- ***V****ariational* ***Q****uantum* ***E****igensolver (Simulation)*
- Exact Matrix Diagonalisation

VQE and exact diagonalisation: QUBO partitioned into smaller parts (sub-QUBOs) corresponding to a 7 qubit system and solved sequentially.

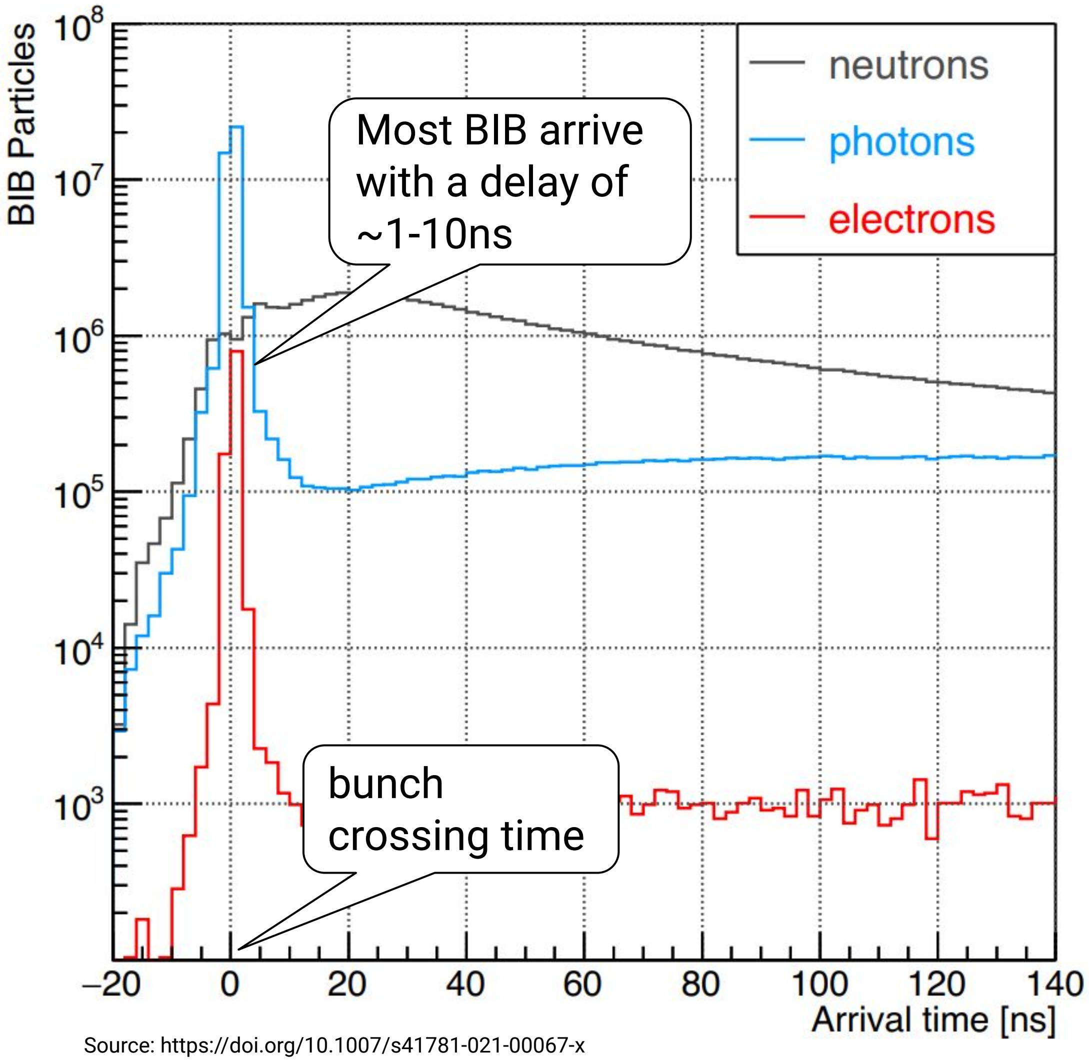


Tracking challenge in Muon Colliders

Myon decays result in secondary and tertiary particles (***B***eam-***I***nduced-***B***ackground)

Challenge: Identify signal tracks within a large background

Time information is a crucial component to suppress BIB particles



Source: https://doi.org/10.1007/s41781-021-00067-x

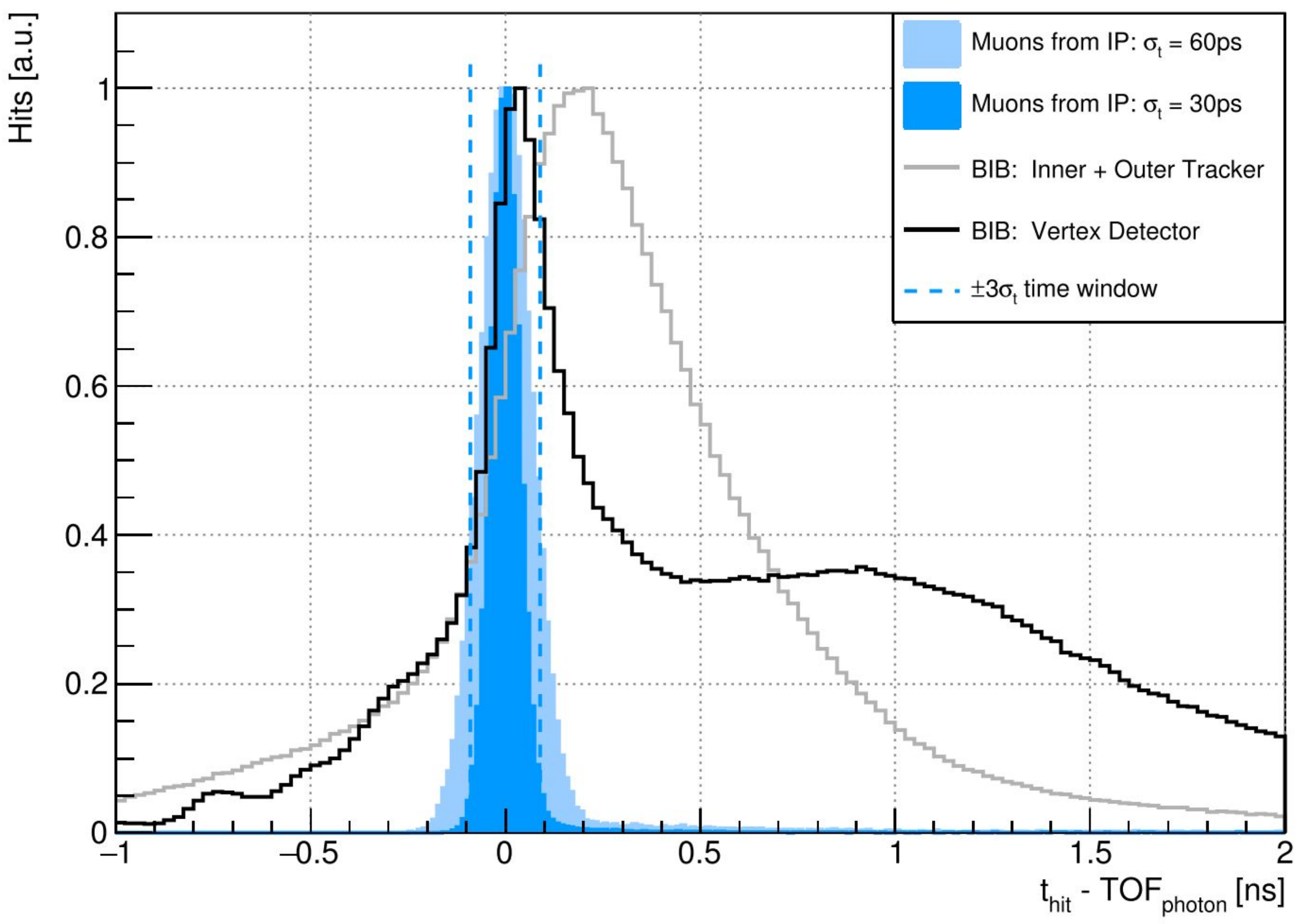
Pattern building with time information

TOF corrected time of hits in the tracking detector

Idea: Include time information when building patterns → 4D quantum algorithm:

- Veto patterns with time information
- Include time information into a_i and b_{ij}

$$\hat{H} = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i$$



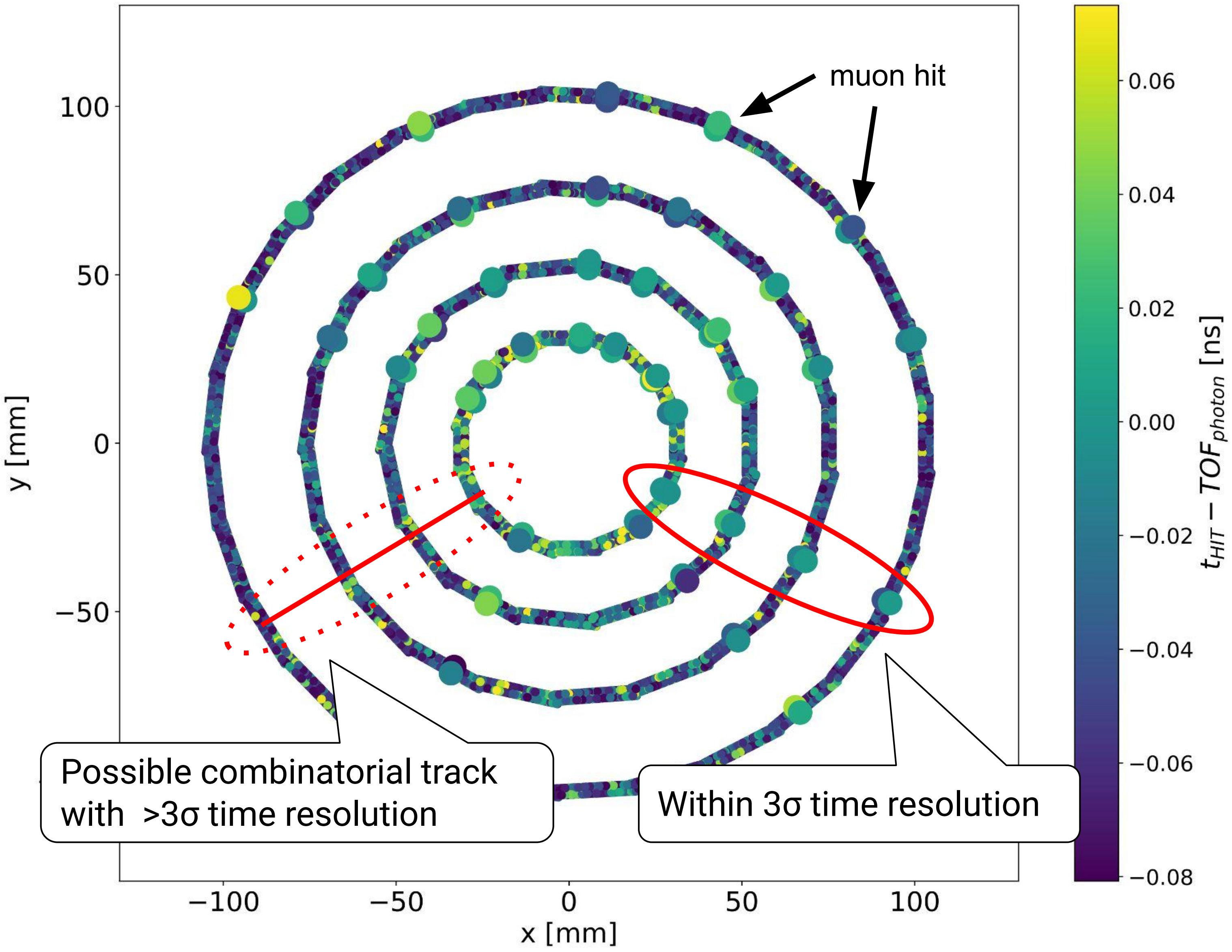
Time + Position Information

Vertex detector: four double layers

Muons shot from (0,0,0) overlayed with background

→ find muon tracks in background

Focus on detector hit time spread of track candidates



4D QUBO

Setup:

- 250 events per energy, event: single muon + 10% background
- Matched track: 8 hits, majority of hits stemming from same particle
- 3σ time window for doublet creation

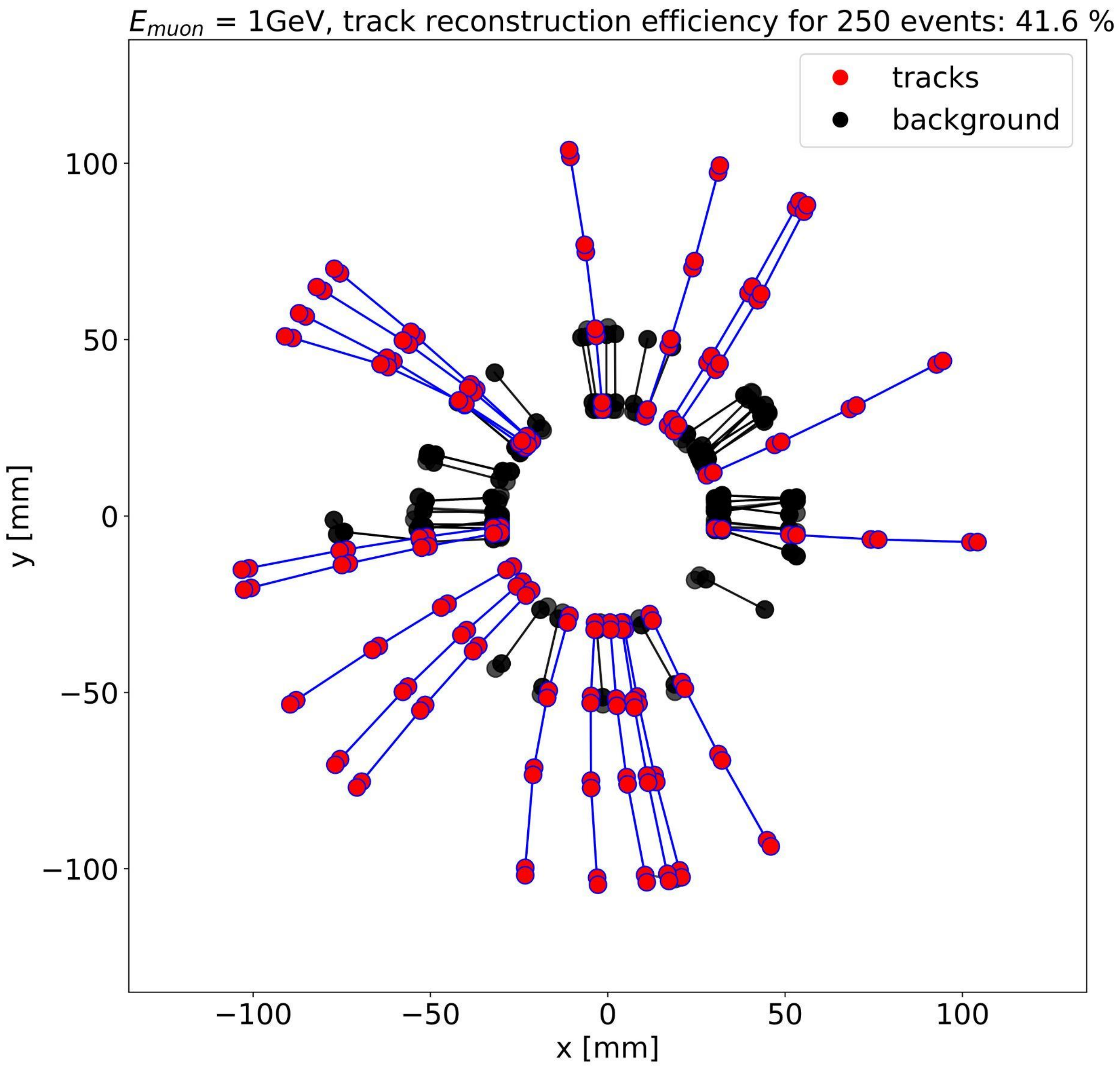
Results:

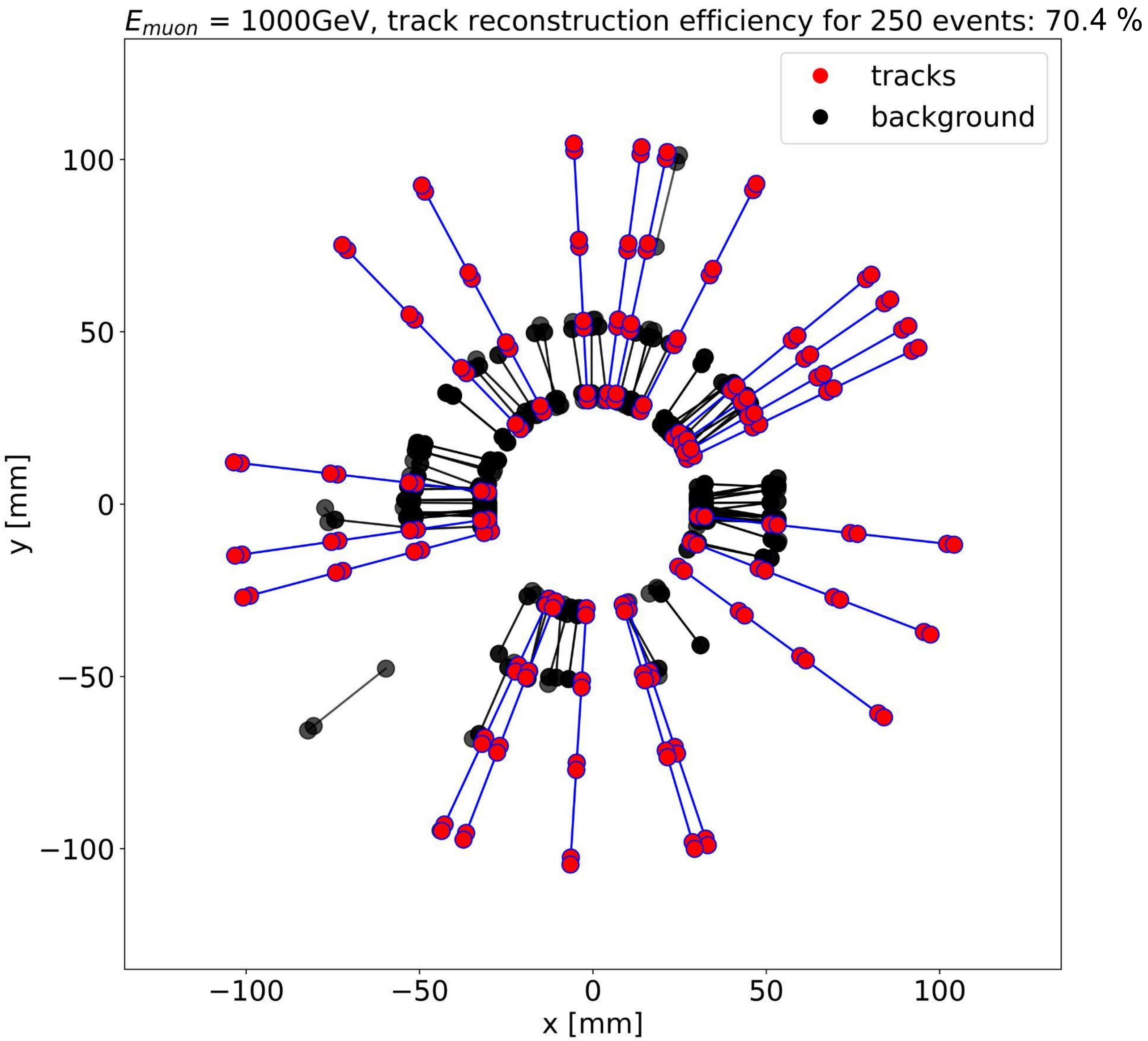
- > 50% reduction of track candidates
- All found tracks are matched tracks

Pre selection and + pattern creation parameters probably too tight, will be optimised in future studies!

Muon Energy [GeV]	Reconstruction efficiency
1	41.6 ± 4.4%
10	60.8 ± 3.9%
100	64.8 ± 3.8%
1000	70.4 ± 3.6%

4D QUBO results - 25 example tracks





Summary and Outlook

Demonstrated track reconstruction using the QUBO formulation on whole LUXE events → competitive with CKF

Using time information for the QUBO approach enables 4D track reconstruction with quantum algorithms → reduces computational costs

Next steps:

- Integrate time information directly into QUBO parameters
- Use 100% of background

Thank you!

Bonus: VQE result from a real quantum computer

Calculations on a quantum device are noisy:

- → Error mitigation
- → Error correction

10 shots (number of circuit evaluations) sufficient for 99% success rate