Track reconstruction of charged particles using a 4D quantum algorithm

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HELMHOLTZ

Track reconstruction

Why it is important

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

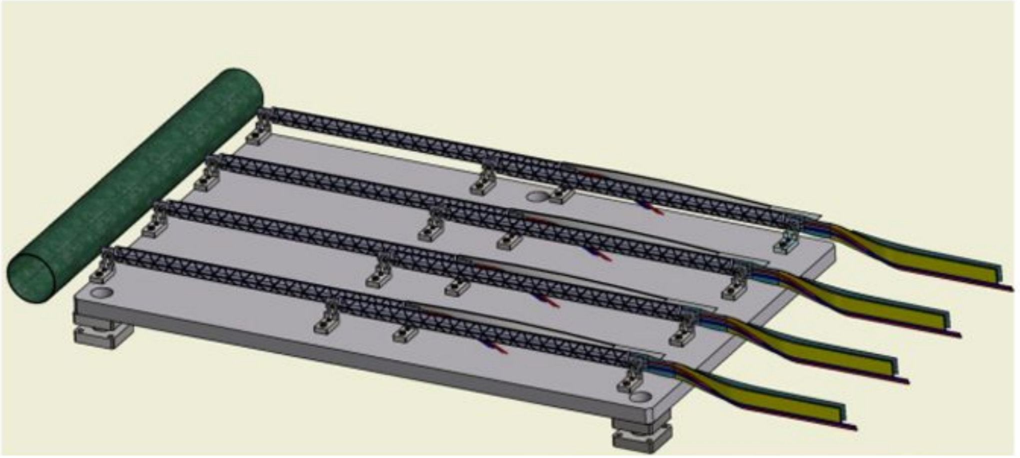
→ Identify secondary decays

→ Reconstruct whole events

Challenges:

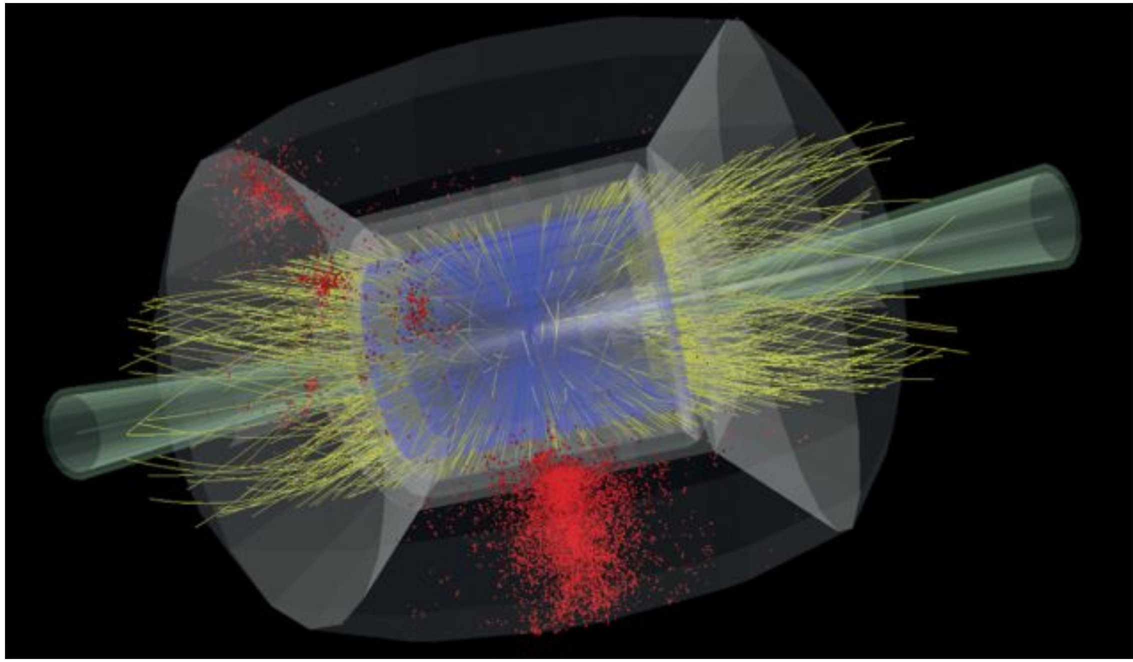
a) Find single signal tracks in a huge background

b) Match tracks to hits in high occupancy regions



Source: LUXE CDR

LUXE positron detection system

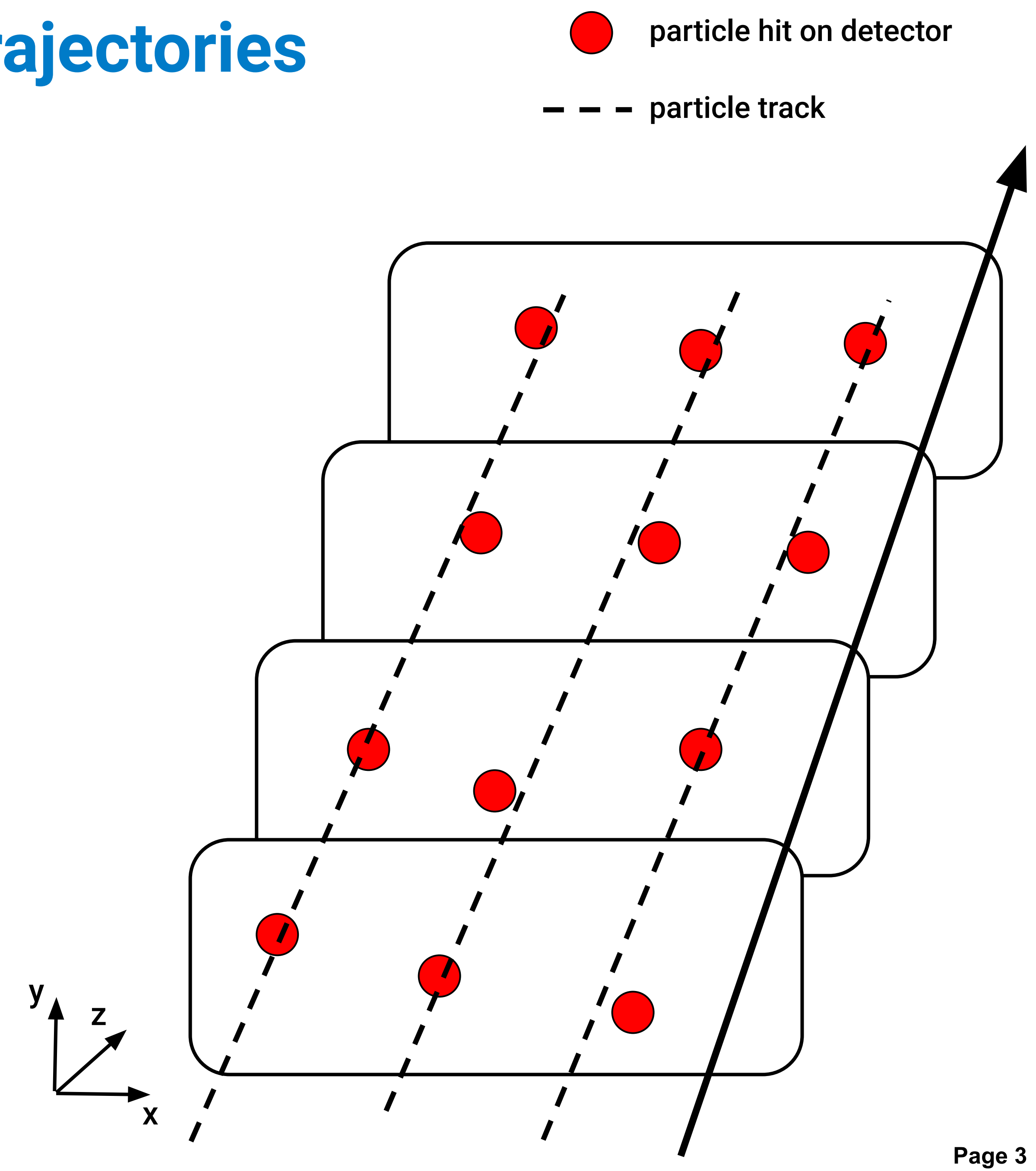


Source: cerncourier, Credit: D Lucchesi *et al*

Higgs decay in the Muon Collider

Pattern Recognition of Particle Trajectories

Encoding detector data into patterns

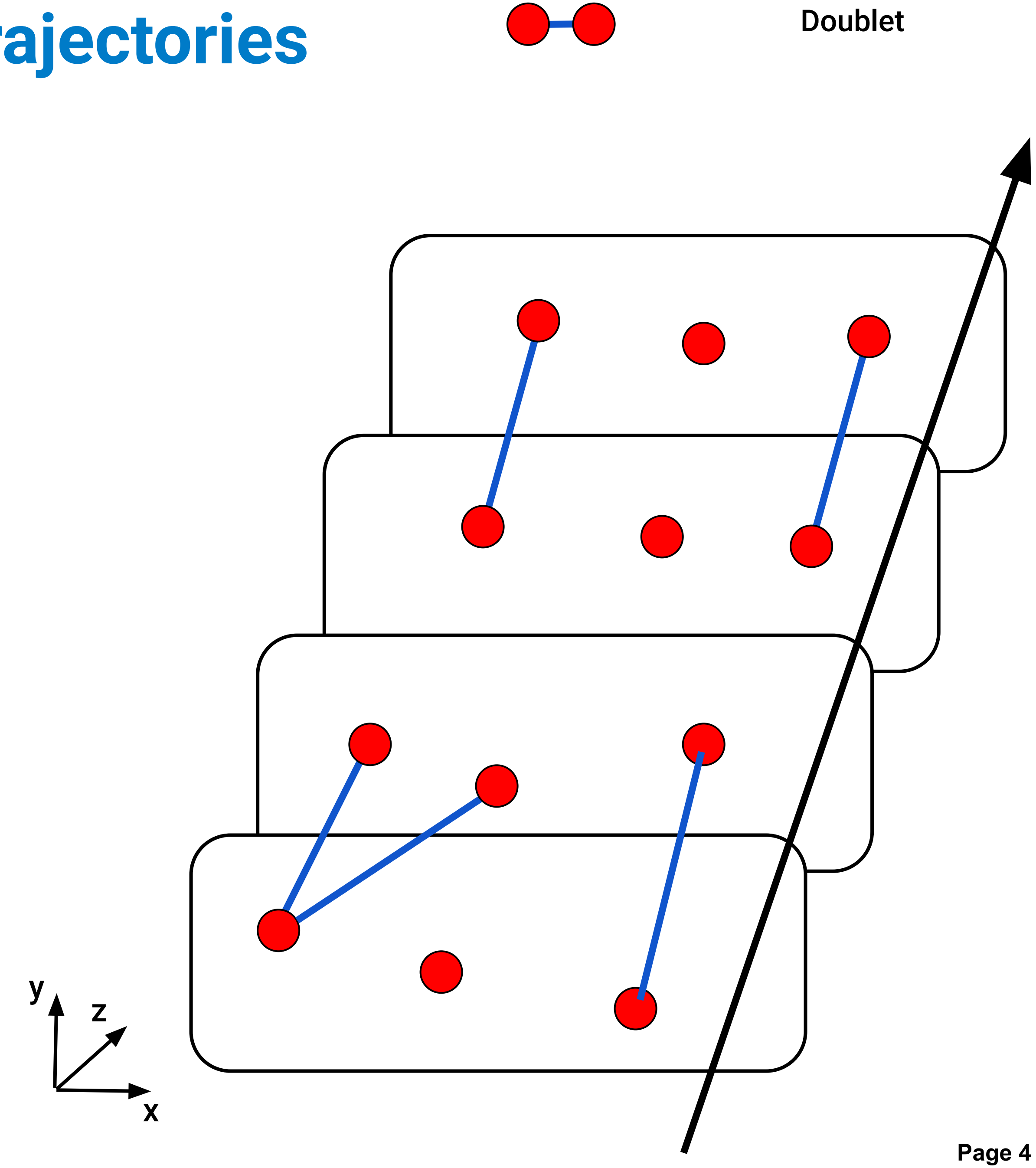


Pattern Recognition of Particle Trajectories

Encoding detector data into patterns

Xplets as elementary patterns:

- Doublets

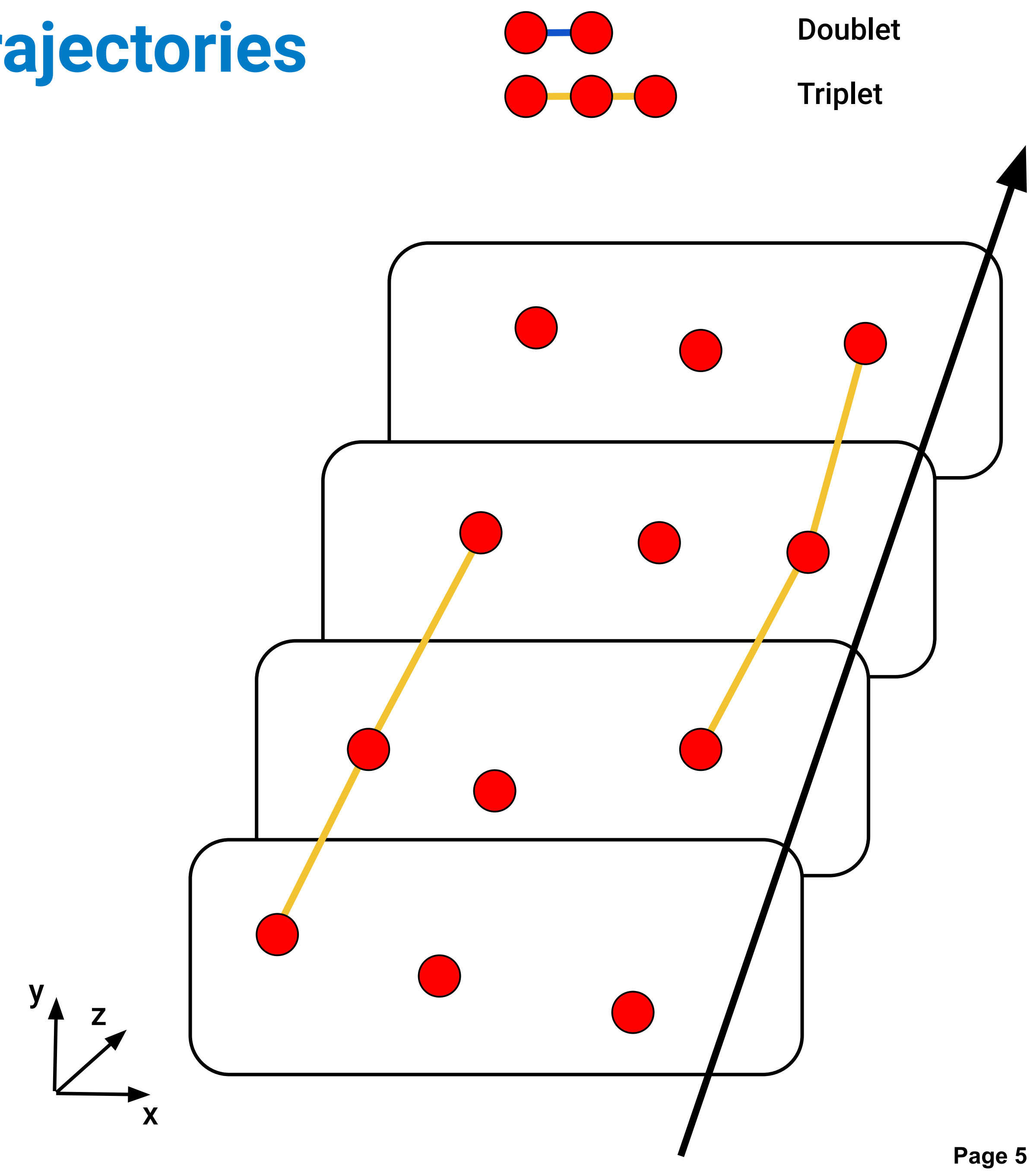


Pattern Recognition of Particle Trajectories

Encoding detector data into patterns

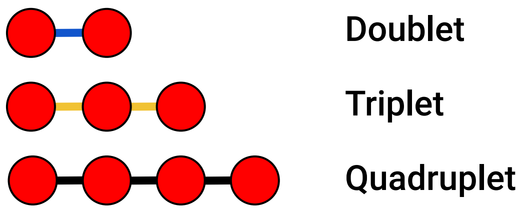
Xplets as elementary patterns:

- Doublets
- Triplets



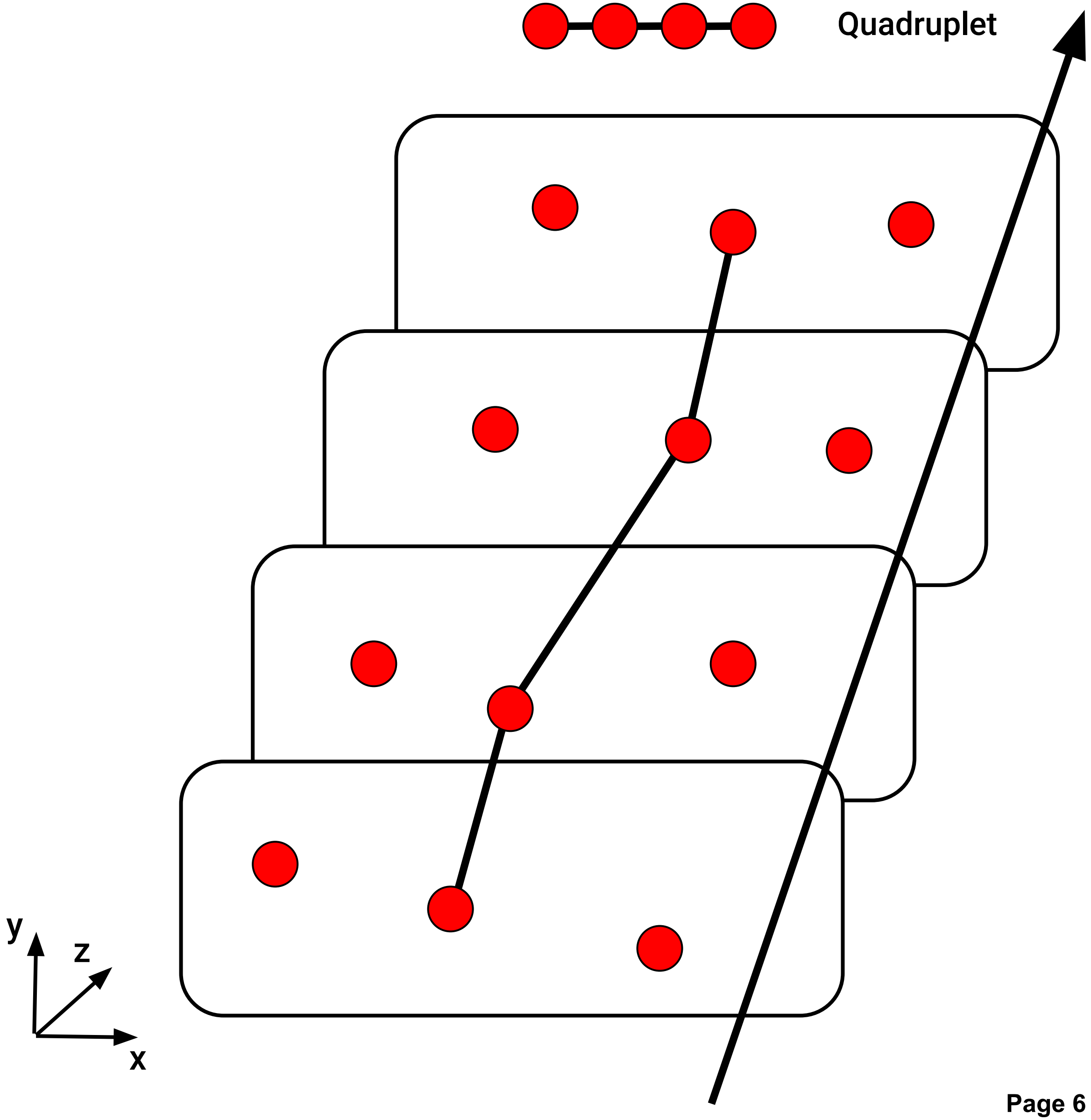
Pattern Recognition of Particle Trajectories

Encoding detector data into patterns



Xplets as elementary patterns:

- Doublets
- Triplets
- Quadruplets



Pattern Recognition of Particle Trajectories

Encoding detector data into patterns

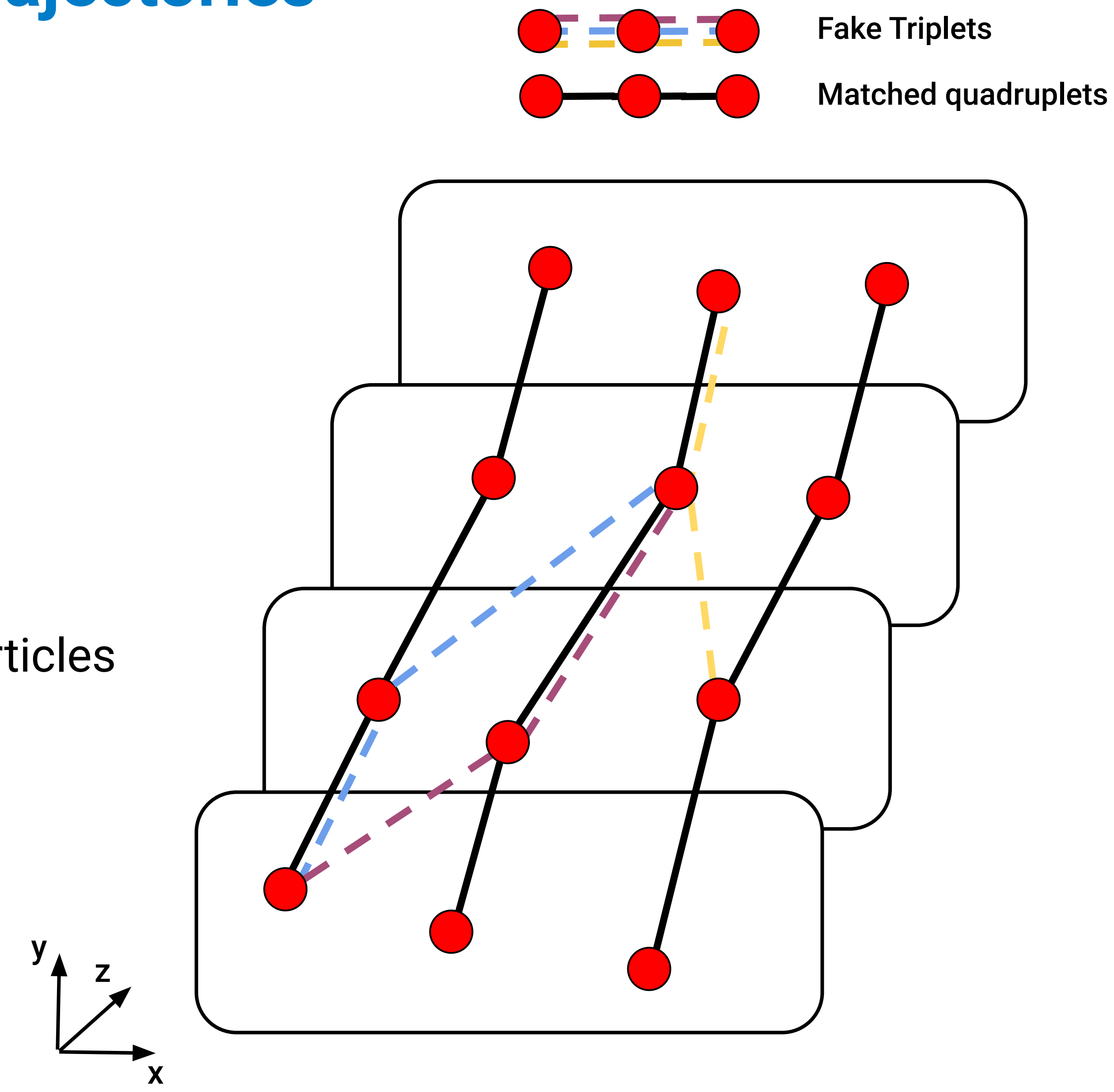
Xplets as elementary patterns:

- Doublets
- Triplets
- Quadruplets

Forming Xplets is a purely combinatorial task

→computationally costly for a high number of particles

Goal: Identify Xplet patterns stemming from a single particle



QUBO - Quadratic Unconstrained Binary Optimisation

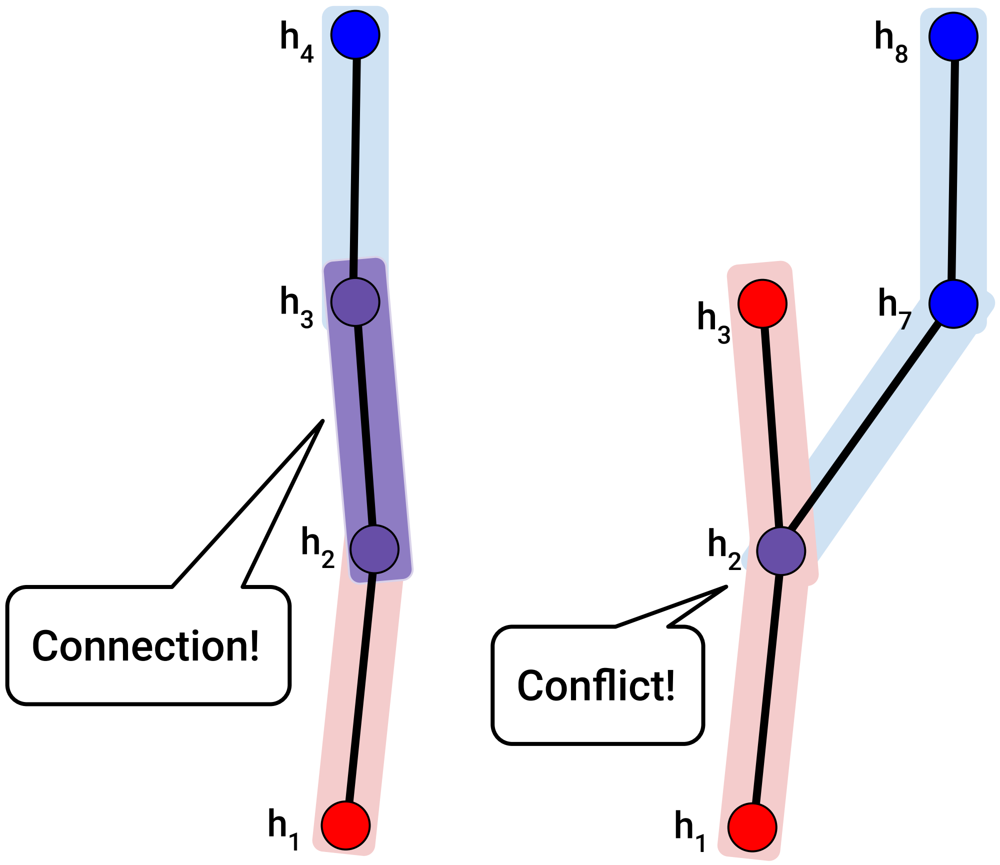
The positive twin of the Ising model

Hamiltonian formulation for the system:

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

- Quality a_i of a triplet
- Interaction b_{ij} with other triplets

with $T_i \in \{0, 1\}$ as binary triplet representation



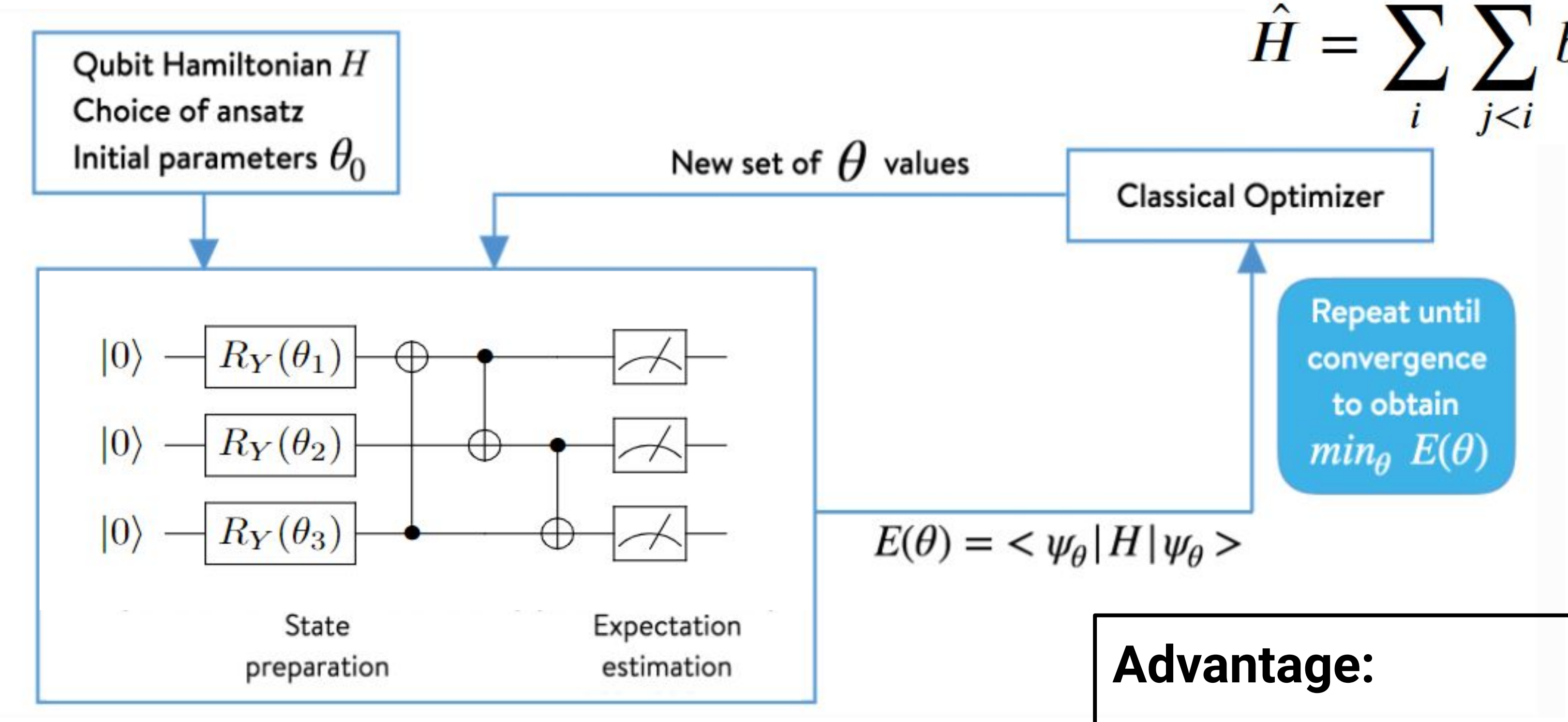
Goal: Minimise the Hamiltonian

→ Binary vector as result with 1 for keeping and 0 for discarding a triplet

VQE - Minimising the QUBO

Hybrid classical-quantum algorithm

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



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

Advantage:

dim(H) = $2^n \times 2^n$, then <ψ|H|ψ> needs

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

Track reconstruction challenges in LUXE

Positron detection system

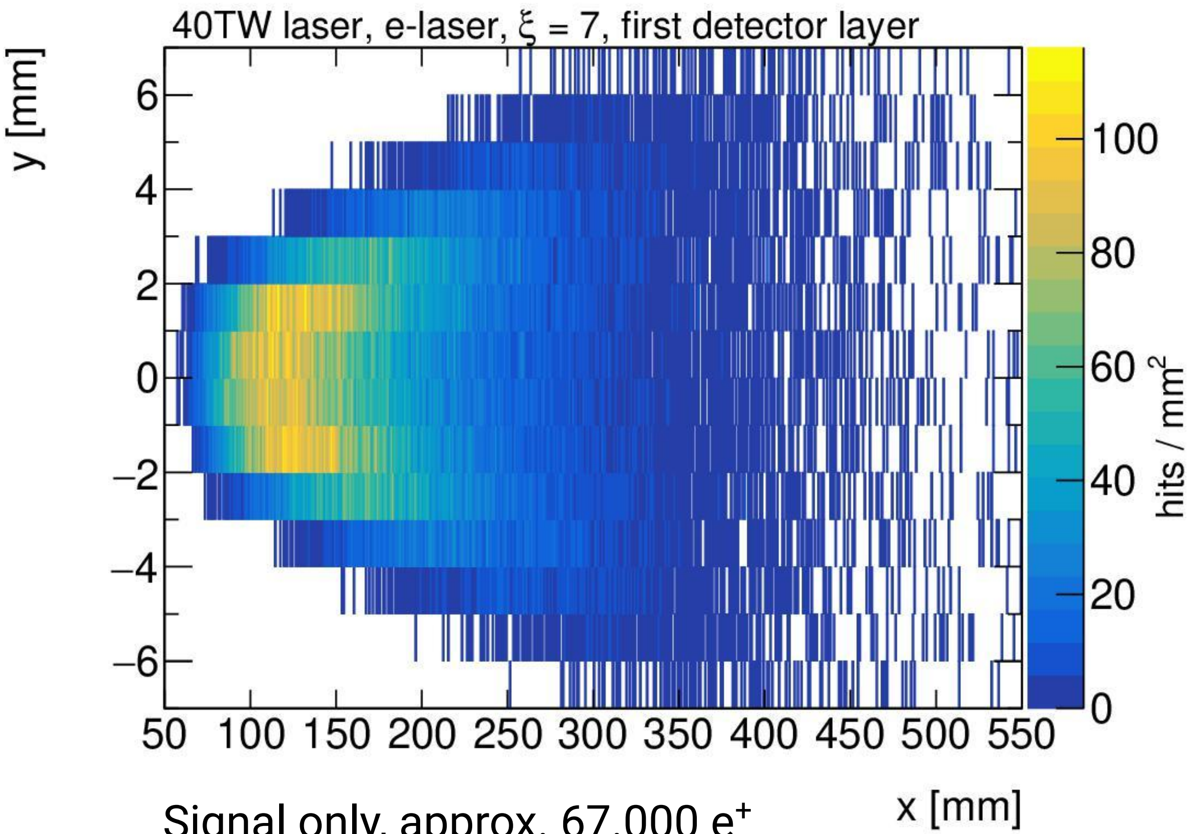
Tomorrow at 11am by Ruth Jacobs:
LUXE – A new experiment to study non-perturbative QED in electron-laser and photon-laser collisions

Four layered tracking system, based on ALPIDE silicon pixel sensor, 27 x 29 μm^2 pixel size

Expect 10^{-3} to 10^6 positrons per BX, background $O(10^3)$, no magnetic field in tracking system

Challenges:

a) Track reconstruction at high occupancy
b) Find single positron tracks in dominant background



Signal only, approx. 67.000 e^+

Performance

Track level efficiency and fake rate

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

$$\text{Fake rate} = \frac{N_{\text{tracks}}^{\text{fake}}}{N_{\text{tracks}}^{\text{reconstructed}}}$$

Approx number of positrons:

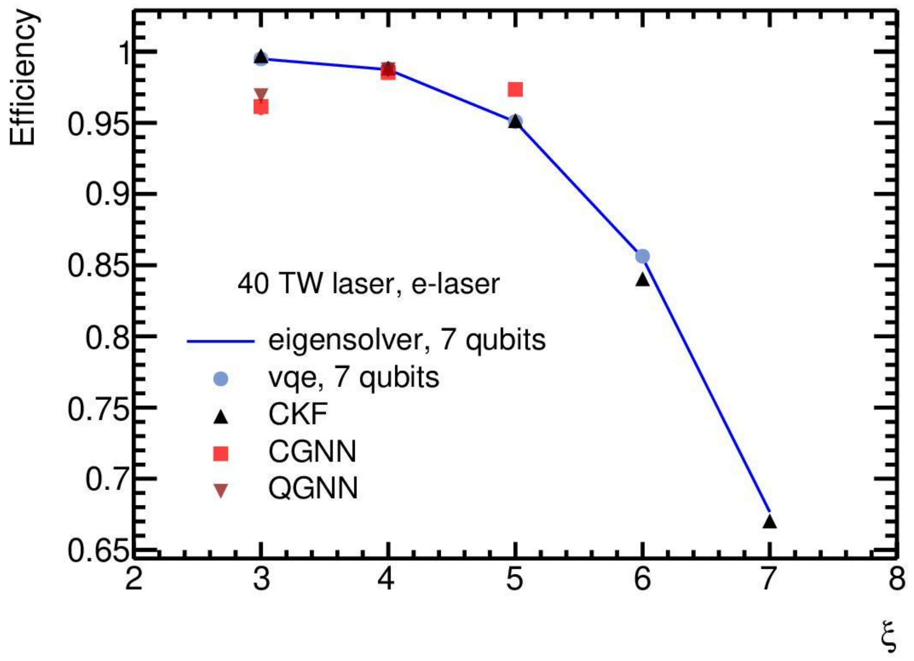
ξ=3: 140 e^+

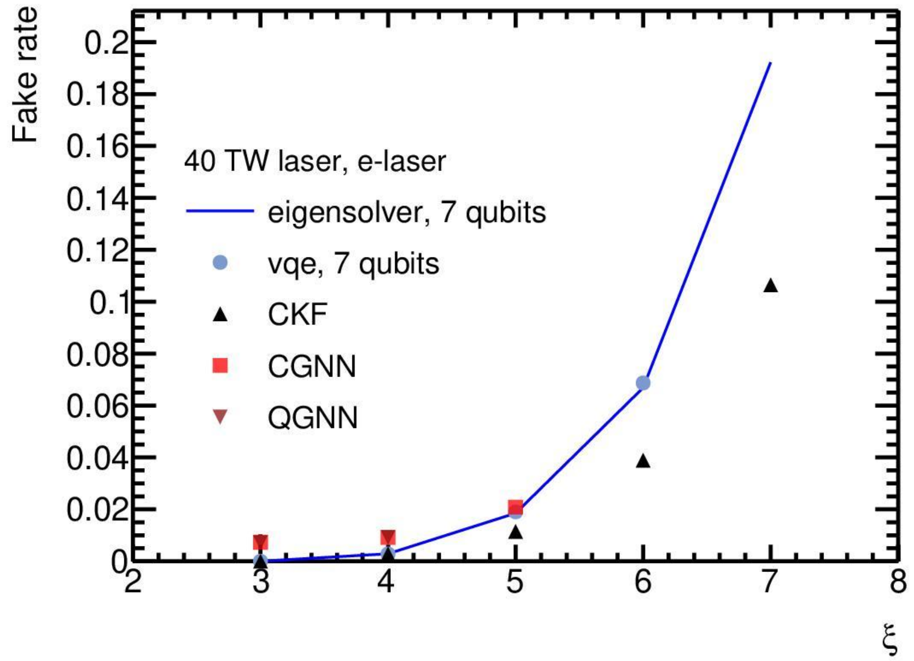
ξ=4: 2,100 e^+

ξ=5: 10,500 e^+

ξ=6: 31,000 e^+

ξ=7: 67,000 e^+





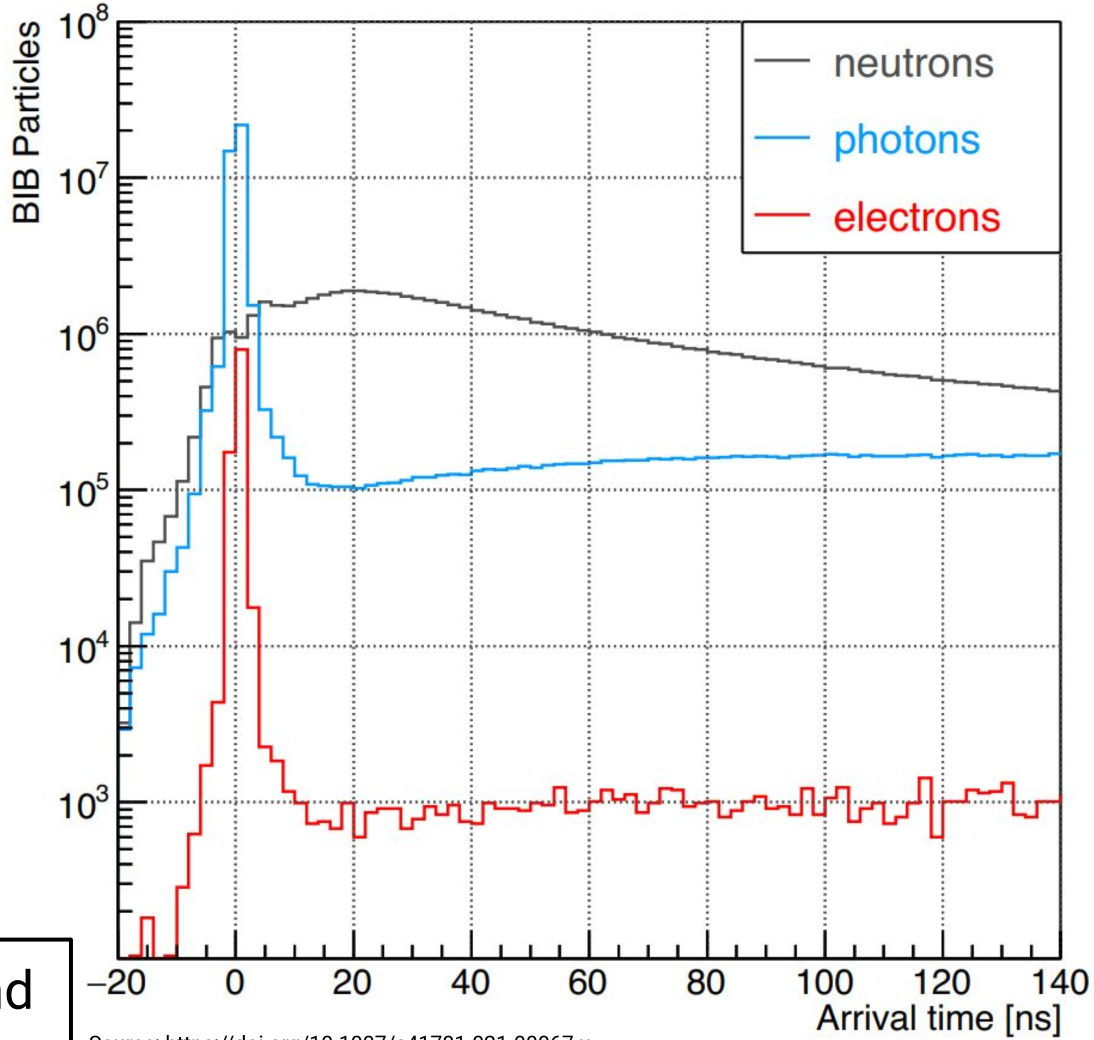
Tracking challenges in Muon Colliders

Muon Collider

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

- electrons
- synchrotron radiation
- hadrons produced by photo-nuclear interactions
- …

Also: magnetic field in tracking region



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

Challenge: Find single signal tracks in a huge background

Detector hits time information

Time information as separation power

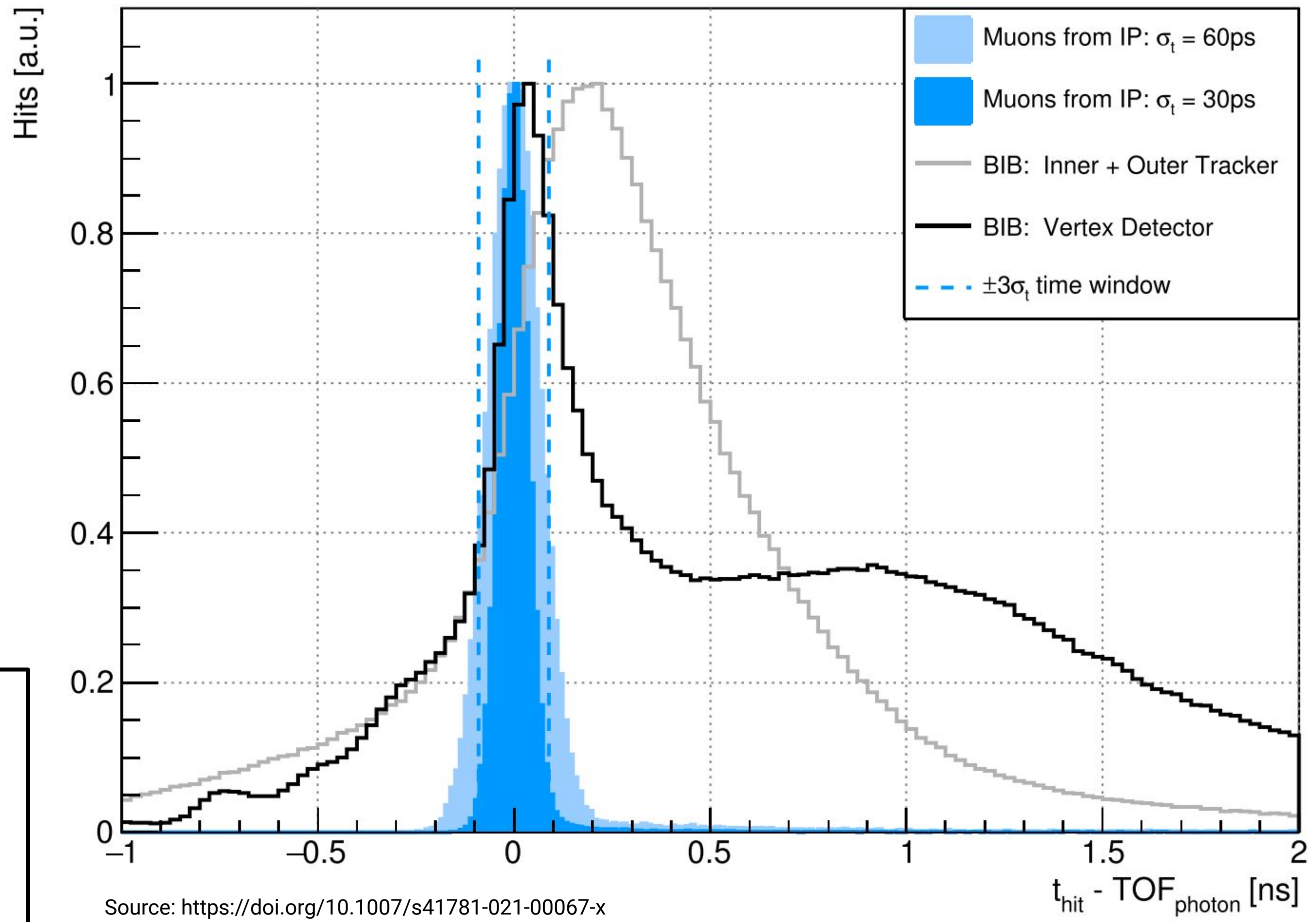
Time resolution:

- Vertex Tracker : 30ps
- Inner + Outer Tracker: 60ps

Natural approach: use time information

to veto detector hits.

Idea: Xplet pattern building with respect to time information + include time to set QUBO coefficients a_i and b_{ij}

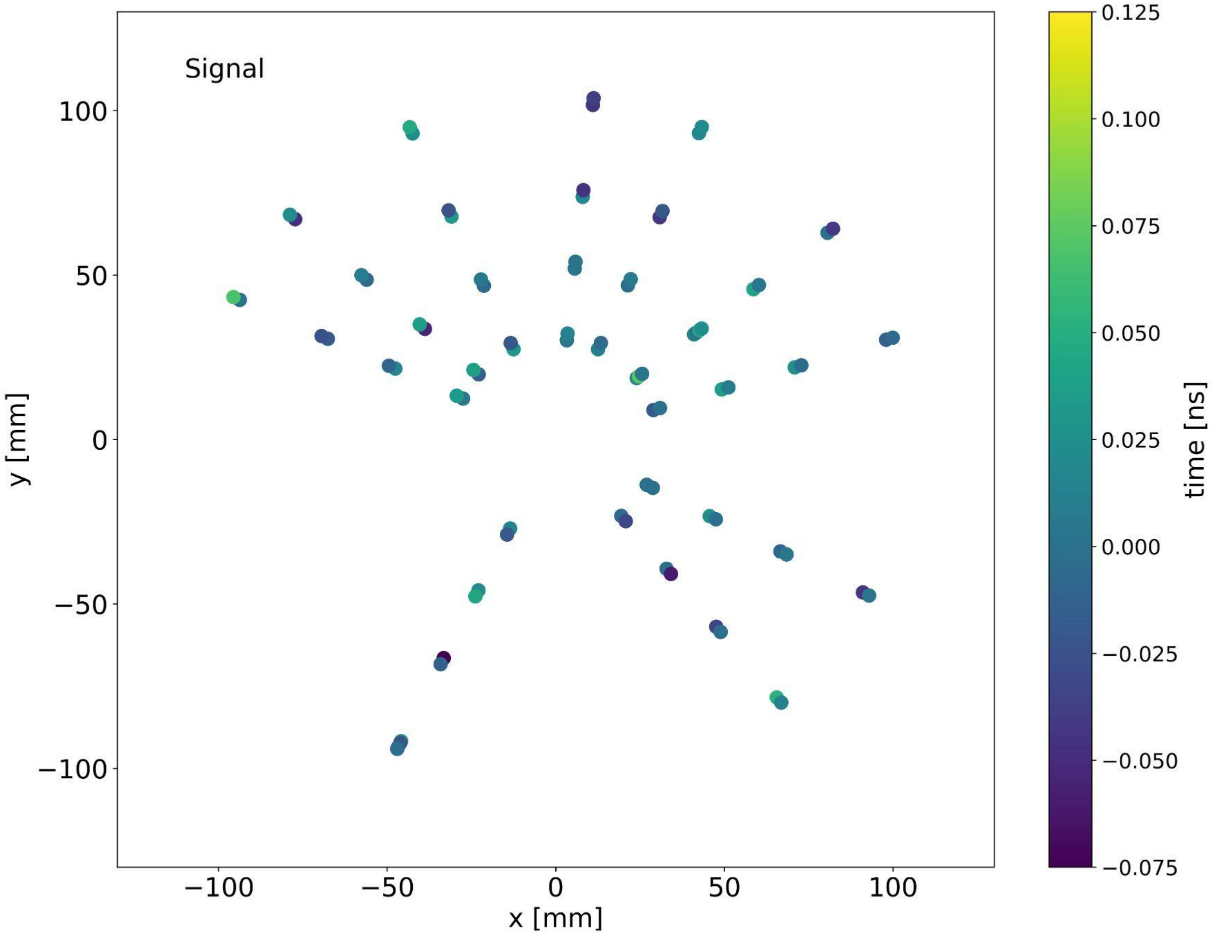


Source: https://doi.org/10.1007/s41781-021-00067-x

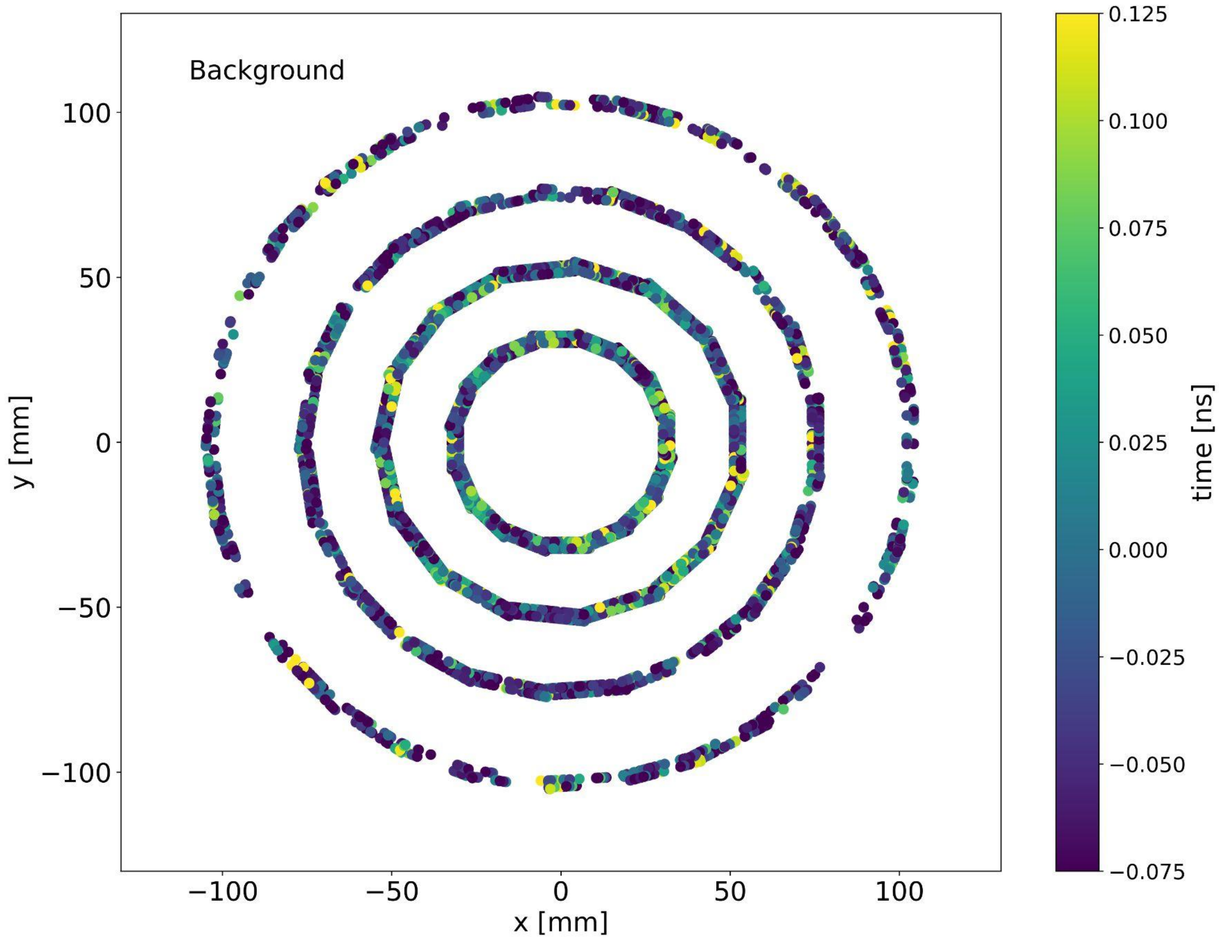
Muon Collider Setup

Find a single muon event in a huge background

Single muons from a particle gun



Approx. 10% of the expected background



4D QUBO tracking

Time-dependent pre-selection

Discard doublets if the hits are not in a certain time window (ToF_{photon} ± 2σ time resolution)

→ Less doublets

→ Less triplets

→ Less computational costs in the optimisation process

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

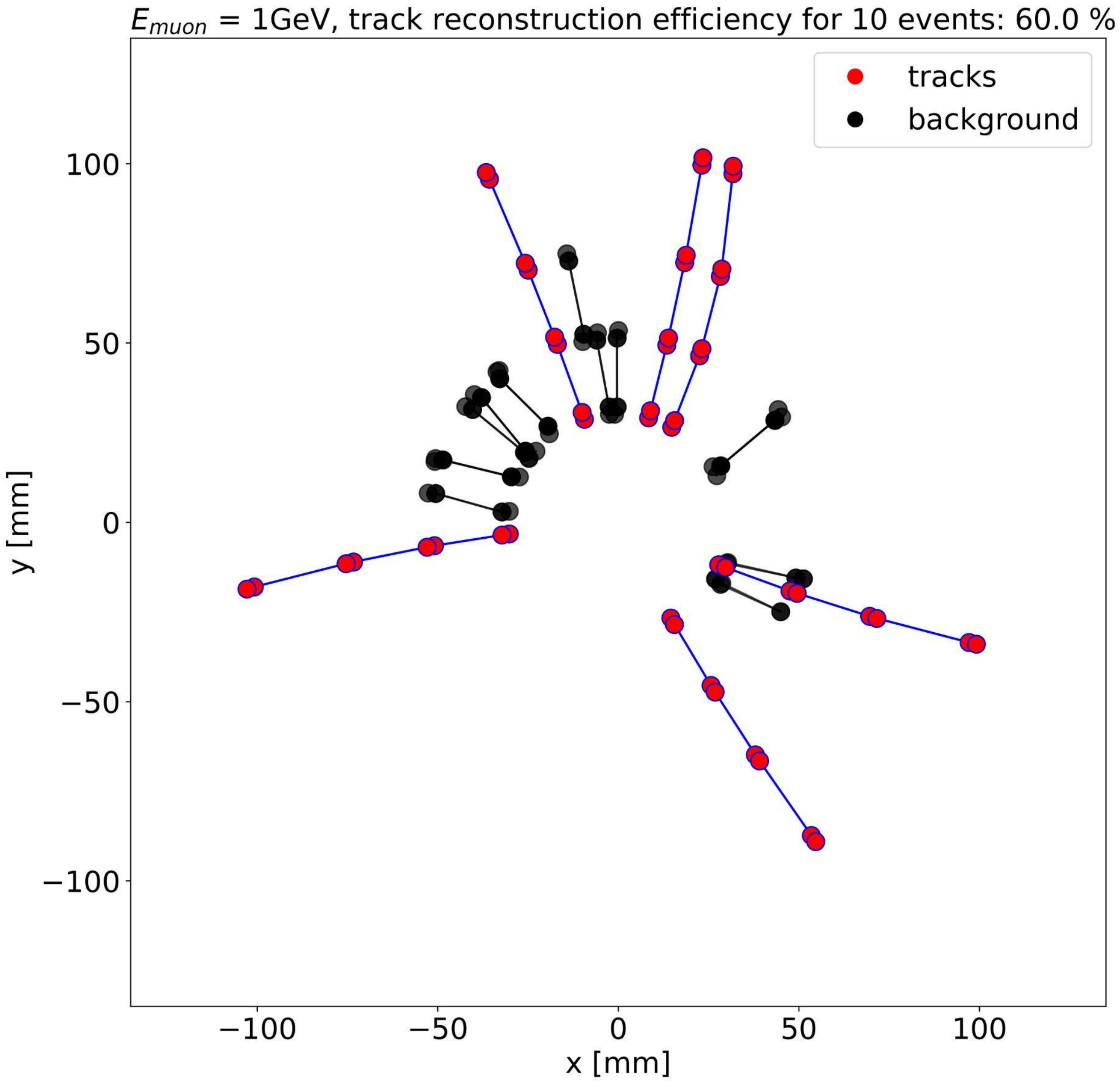
Adding time information to the existing geometrical preselection reduces number of triplets by an additional 30%!

Not yet implemented: Use time information to set QUBO coefficients

4D QUBO tracking

Let’s find the the muon tracks!

Muon Energy [GeV]	Reconstruction efficiency
1	60%
10	90%
100	70%
1000	80%



Summary and next steps

Adding time information to the QUBO enables 4D track reconstruction with quantum algorithms

Including time information reduces computational costs

Next steps are:

a) Include time information to set QUBO parameters

b) Approach full background usage

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