Track reconstruction of charged particles using a 4D quantum algorithm

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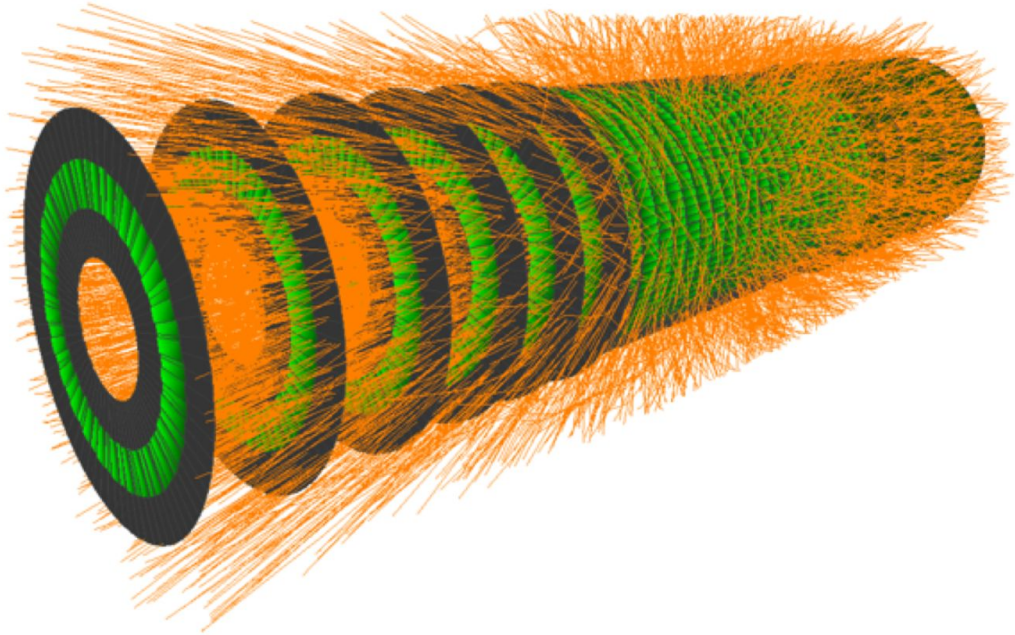
Track reconstruction

Reconstruct full events:

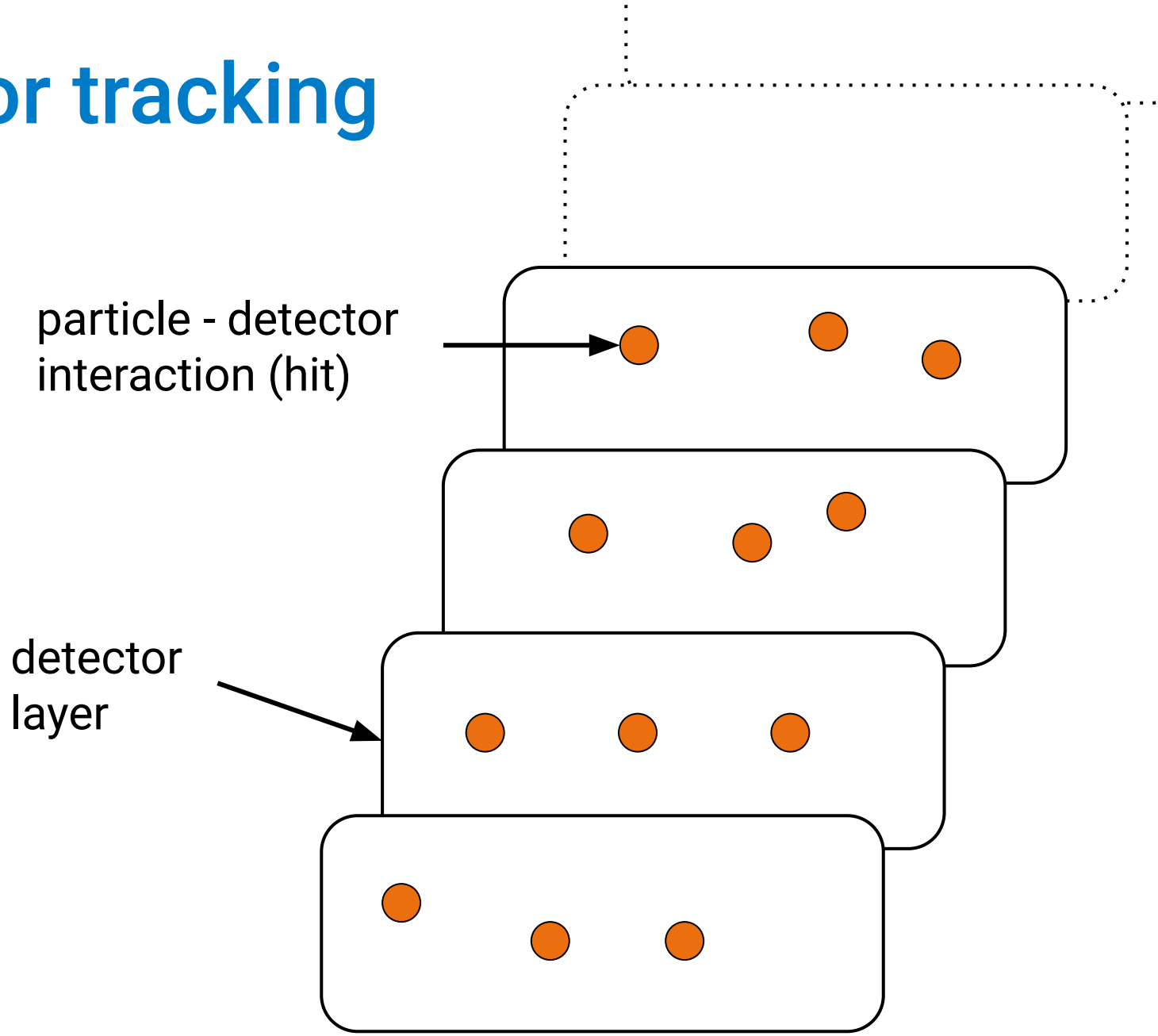
- Measuring particle energy
- Determine particle type
- Projection to/through other detector parts
- Identify/reconstruct secondary decays



Source: TrackML Challenge
https://www.kaggle.com/competitions/trackml-particle-identification/overview/description

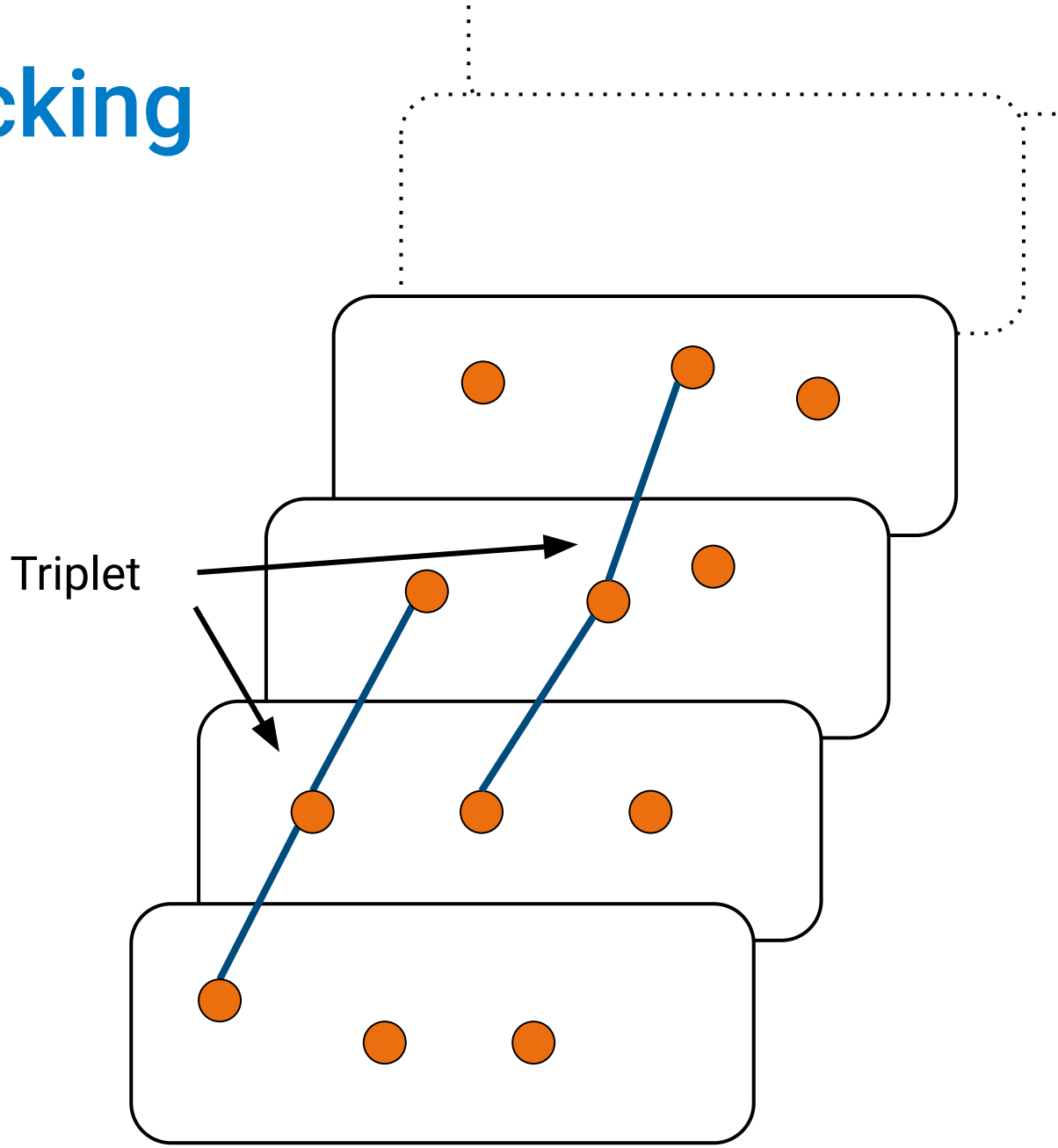
… but can become computationally very costly!

Pattern recognition for tracking



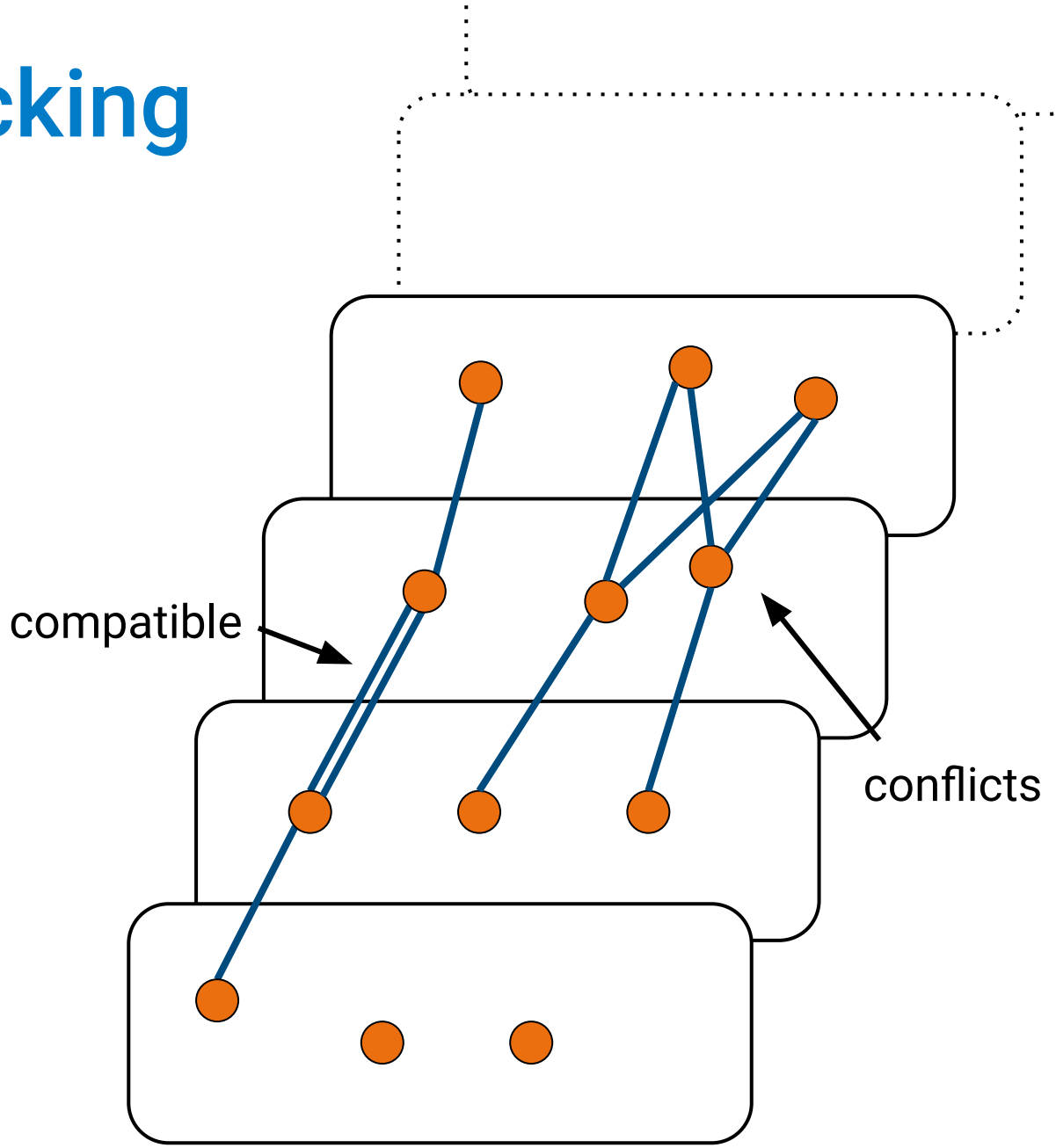
Pattern recognition for tracking

- **Triplets** as elementary patterns



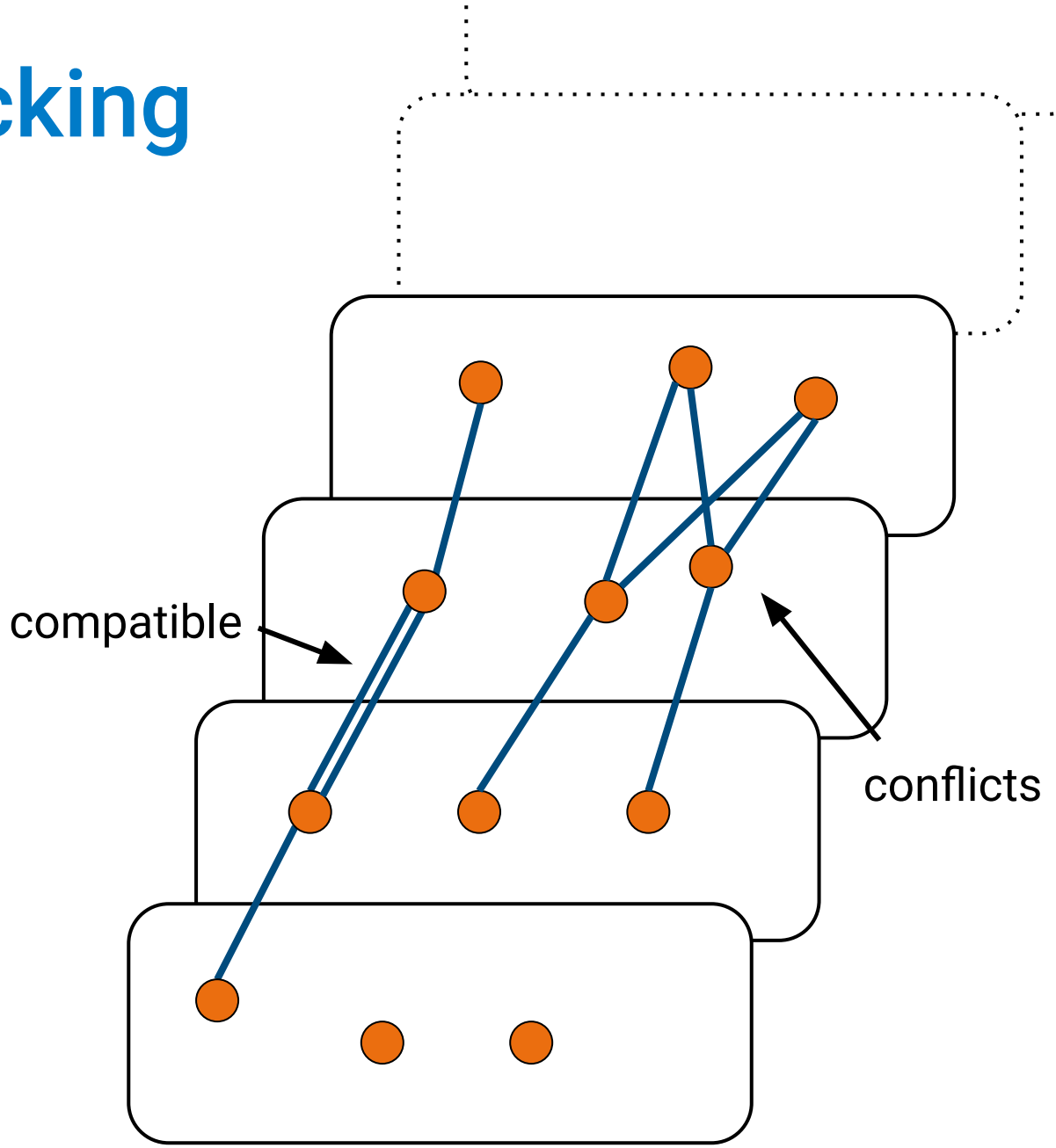
Pattern recognition for tracking

- **Triplets** as elementary patterns
- **Interactions** between triplets



Pattern recognition for tracking

- **Triplets** as elementary patterns
- **Interactions** between triplets



Goal:

Identify triplets stemming from a single particle

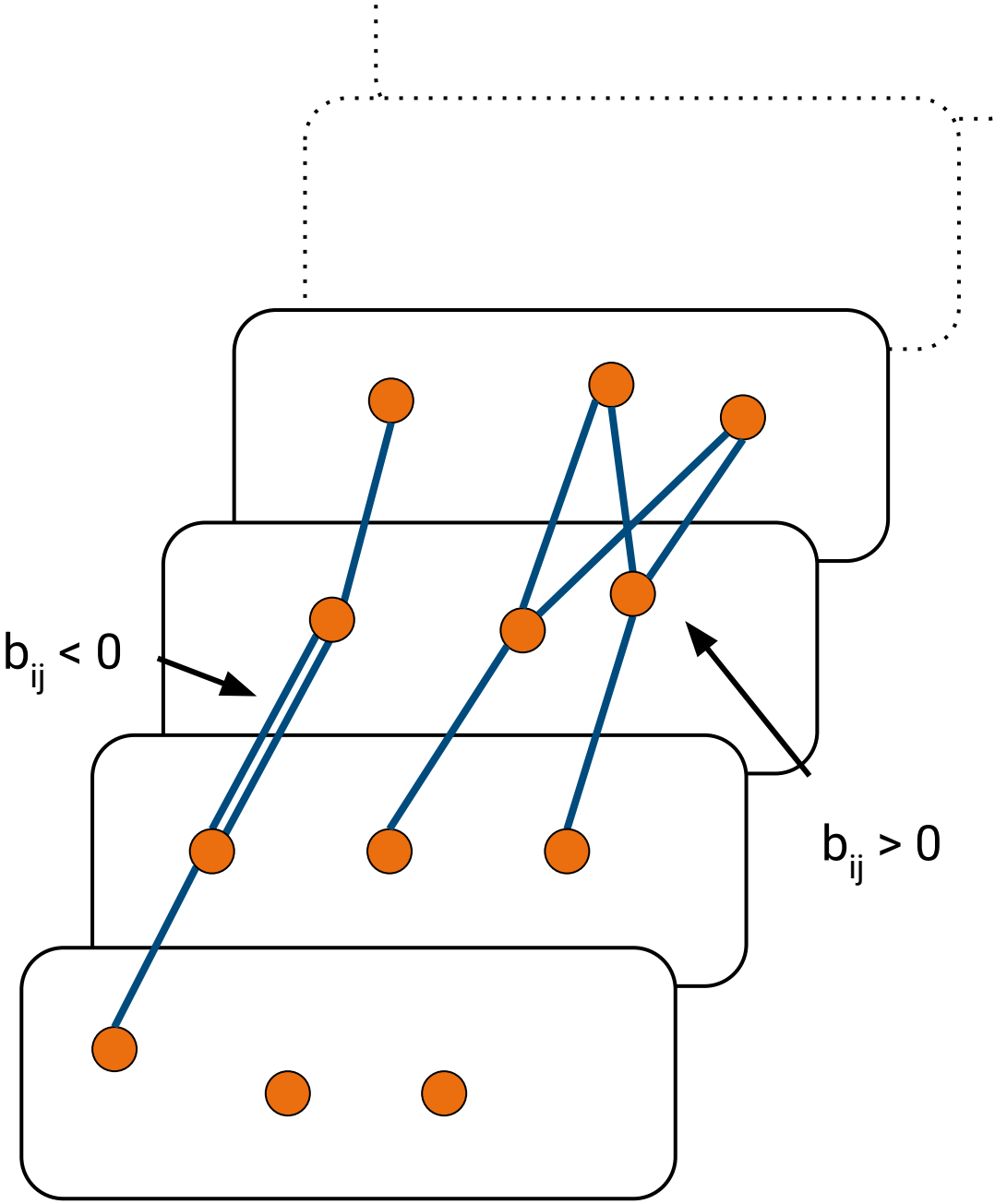
→ build tracks from kept triplets

QUBO

Quadratic Unconstrained Binary Optimisation

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

- $\mathbf{T_i} \in \{0, 1\}$
- $\mathbf{b_{ij}}$: interaction
- $\mathbf{a_i}$: quality
- $\mathbf{v_{binary}}$: $[T_1, T_2, T_3, \dots, T_N] \rightarrow [0, 1, 1, \dots, 0]$



QUBO

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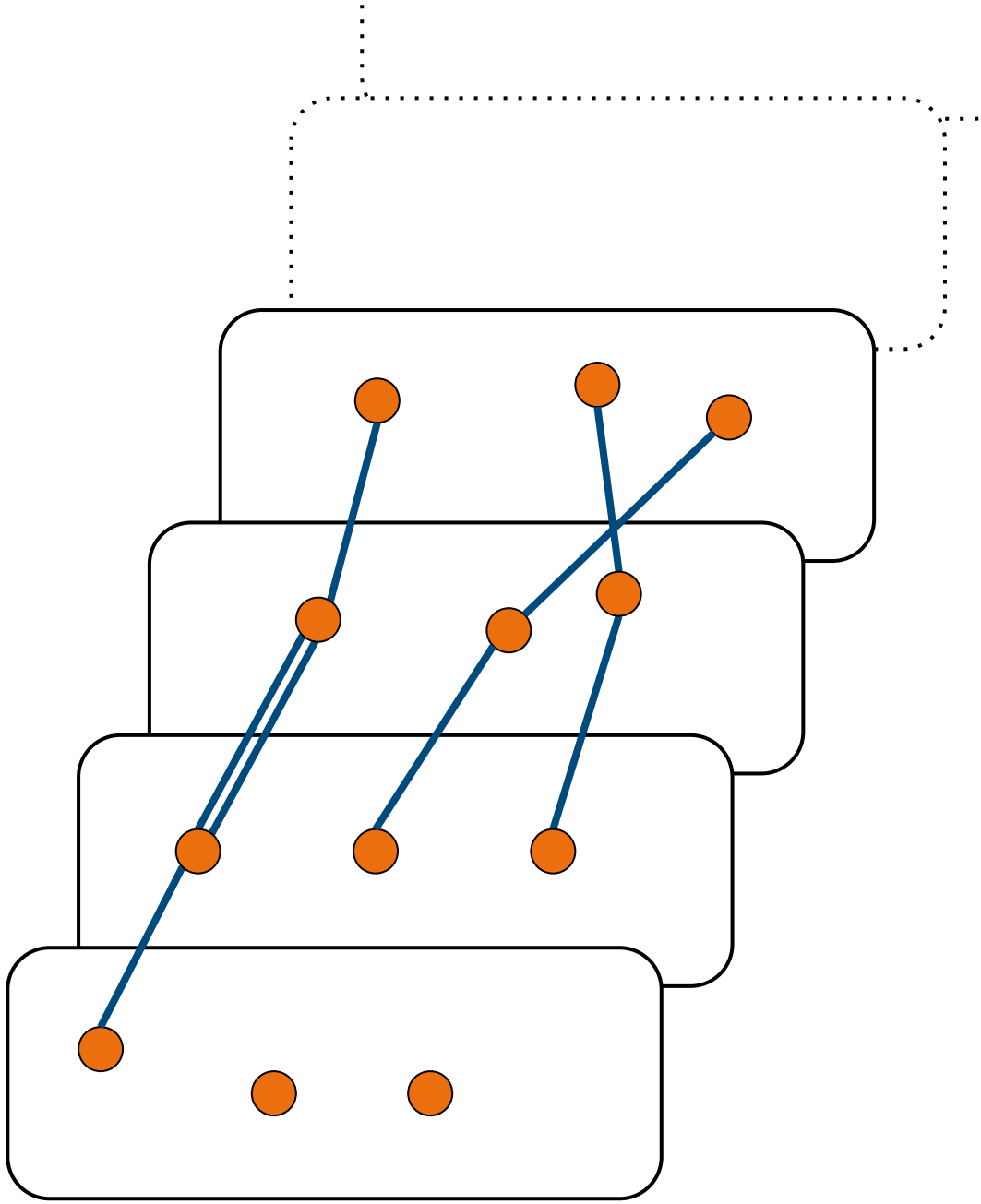


Ground state of the Hamiltonian

→ optimal set of triplets

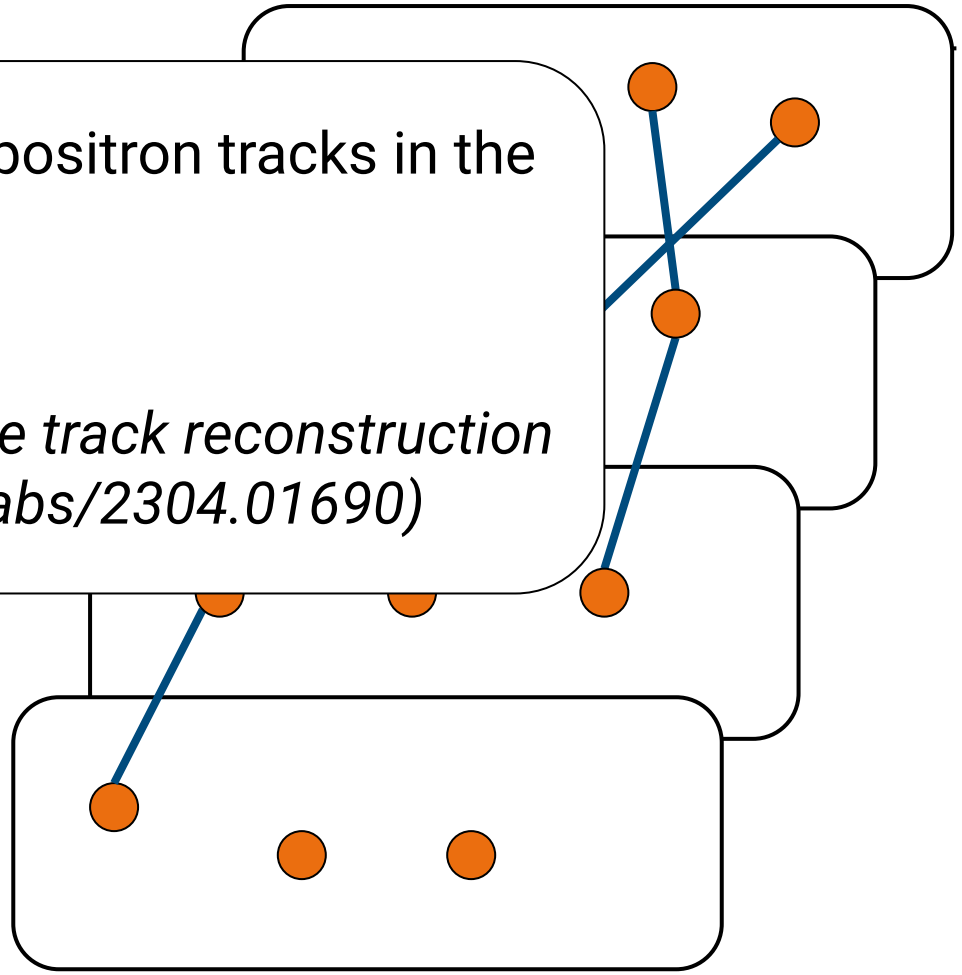
QUBO

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

- $\mathbf{T_i} \in \{0$
- $\mathbf{v_{binary}}$
- $\mathbf{b_{ij}}$: int
- $\mathbf{a_i}$: quality

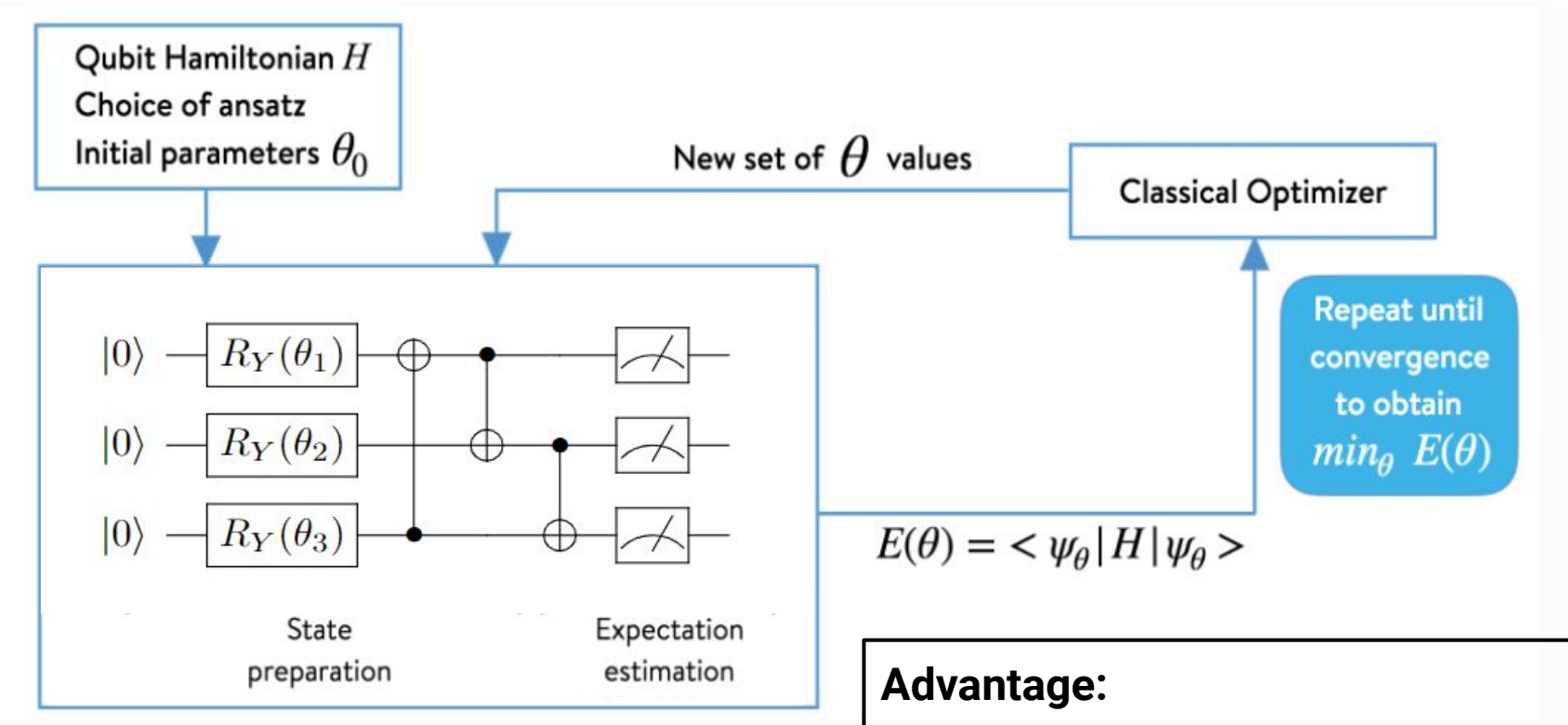
Approach investigated for reconstructing positron tracks in the Laser Und XFEL Experiment (LUXE):

→ Yee Chinn Yap's talk
→*"Quantum algorithms for charged particle track reconstruction in the LUXE experiment" (https://arxiv.org/abs/2304.01690)*



Minimise Hamiltonian → optimal set of triplets

VQE - Variational Quantum Eigensolver



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

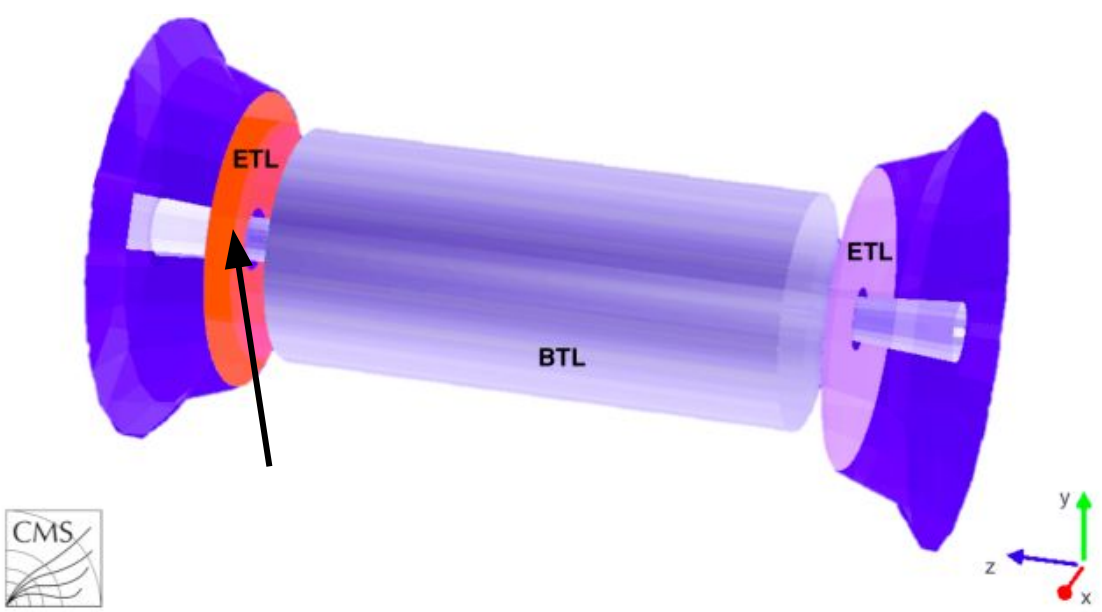
Advantage:

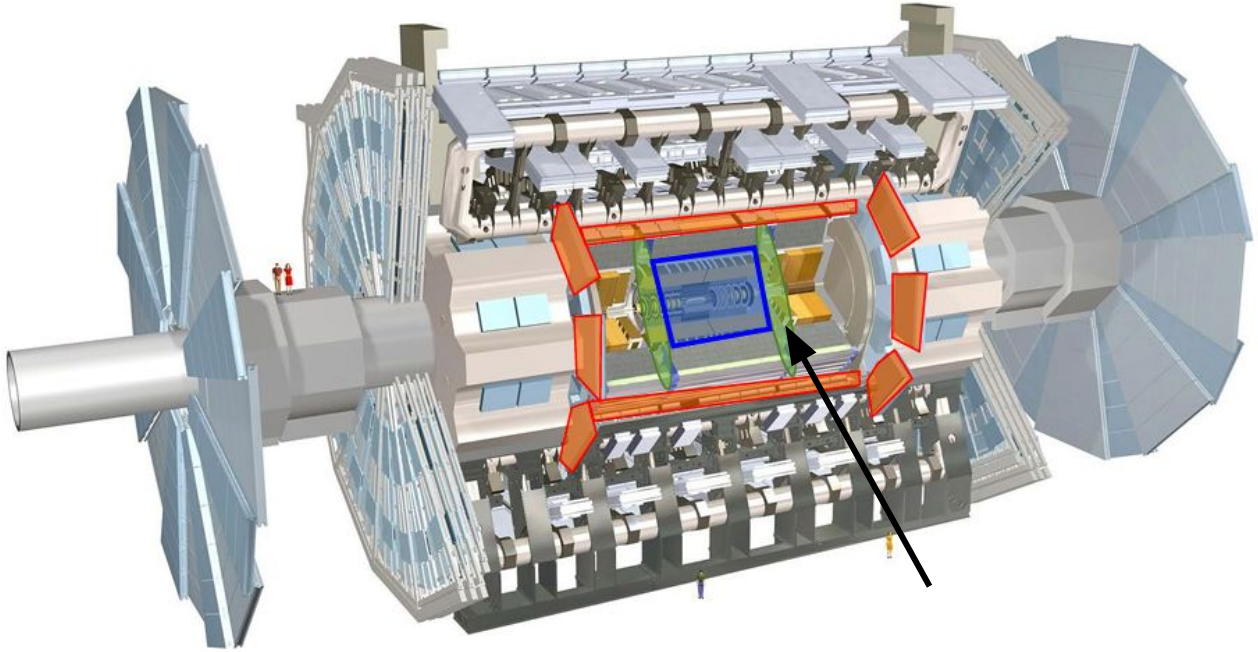
dim(H) = 2^n x 2^n, then <ψ|H|ψ> needs

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

Timing information used for particle tracking

- Reduce background and sharpening resolution
- ATLAS: High Granularity Timing Detector
- CMS: Minimum Ionising Particle Detector





Source: https://cds.cern.ch/record/2667167?ln=de

Source: https://cds.cern.ch/record/2799535/files/Affolder-ATLAS_upgrade-v6.pdf

Timing information used for particle tracking

- Reduce background and sharpening resolution
- ATLAS: High Granularity Timing Detector
- CMS: Minimum Ionising Particle Detector
- Next generation of detectors will (probably) have timing in every layer

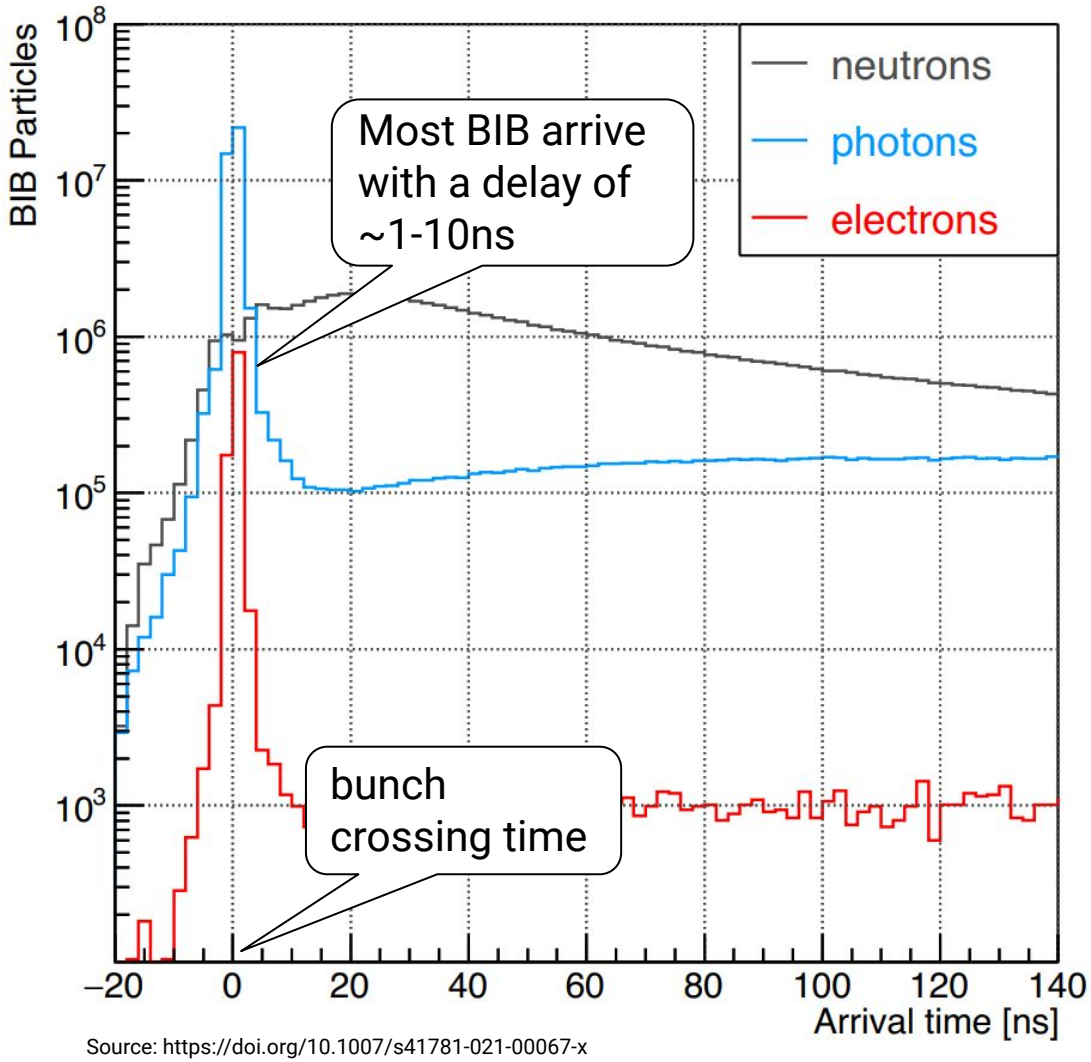
Pattern recognition in Muon Colliders

Beam muons decays induce secondary particle showers that reach the detector (**B**eam-**I**nduced-**B**ackground)

Time information as a crucial component to suppress BIB particles

4D tracking with QUBO:

Include time information directly into pattern recognition



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

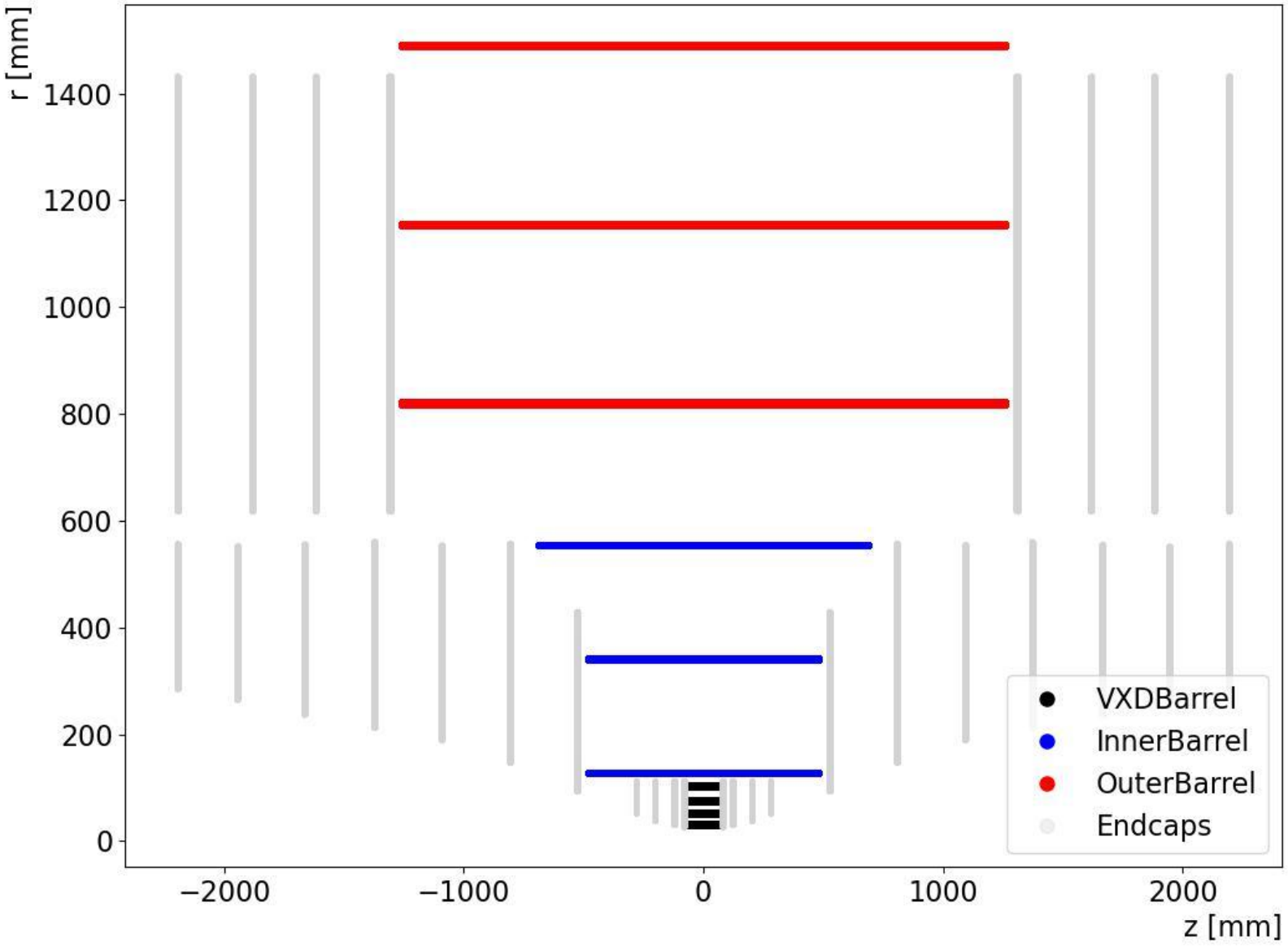
4D QUBO

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

Interaction $b_{ij,\,total}$:

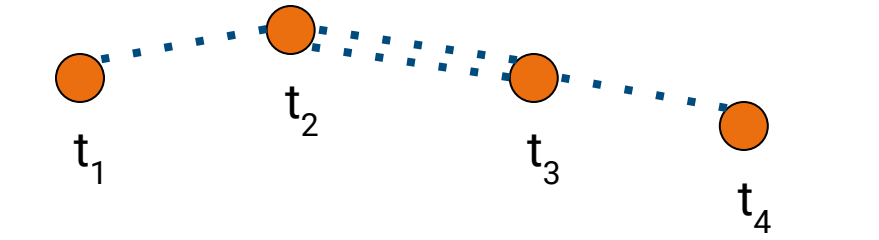
- curvature
- scattering
- time

→ **4D modeling of interactions**

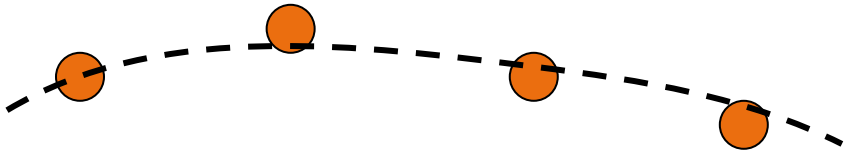


Time component of b_{ij}

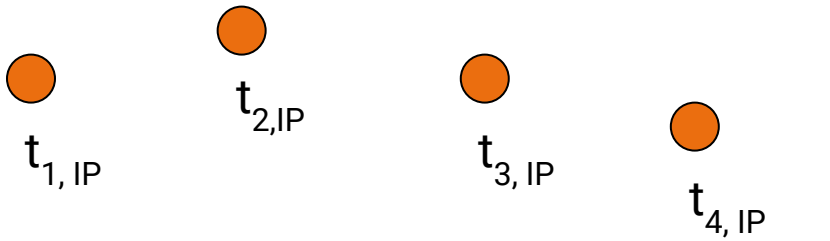
Raw time from data



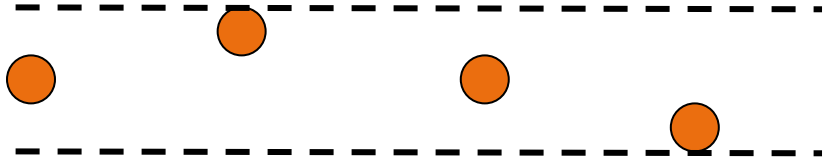
p_T / curvature



Time of hits at IP



Time compatibility



"time spread window"

Time component of b_{ij}

Raw time from data

↓

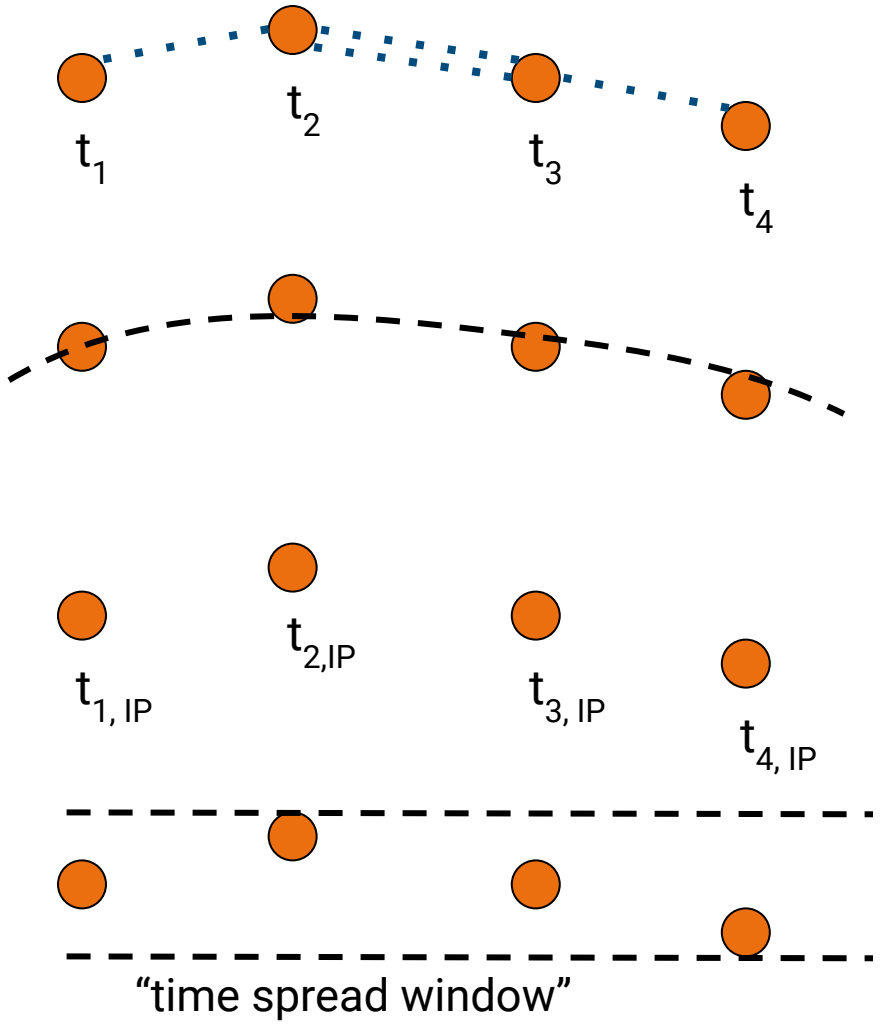
p_T / curvature

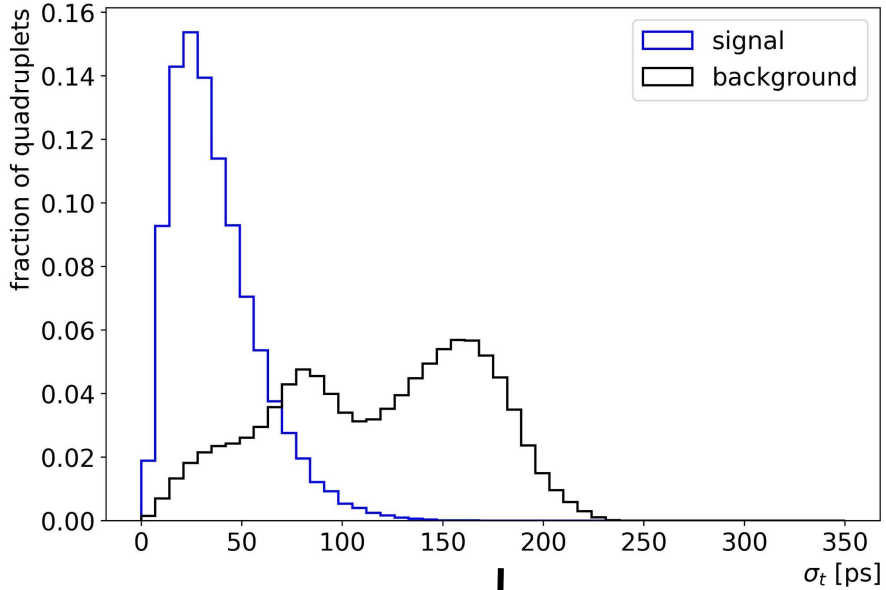
↓

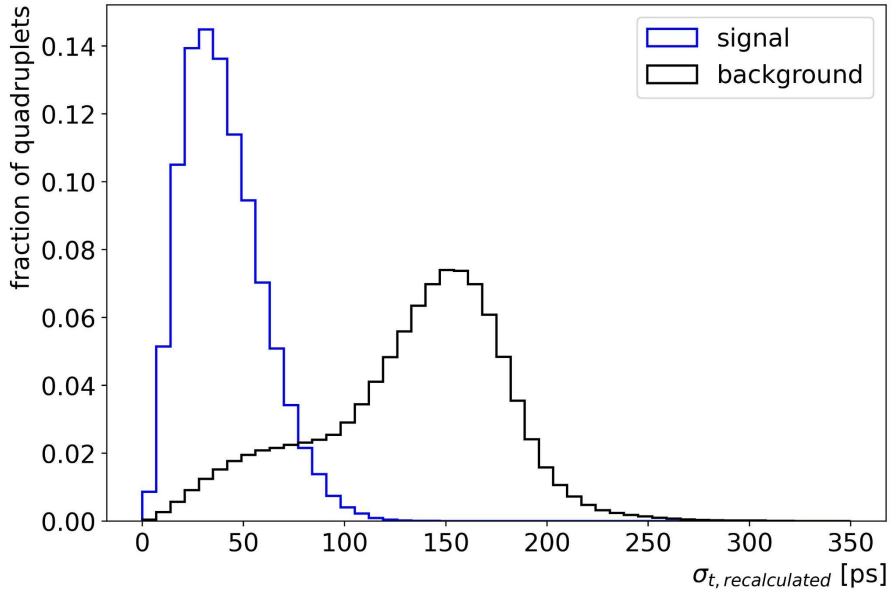
Time of hits at IP

↓

Time compatibility







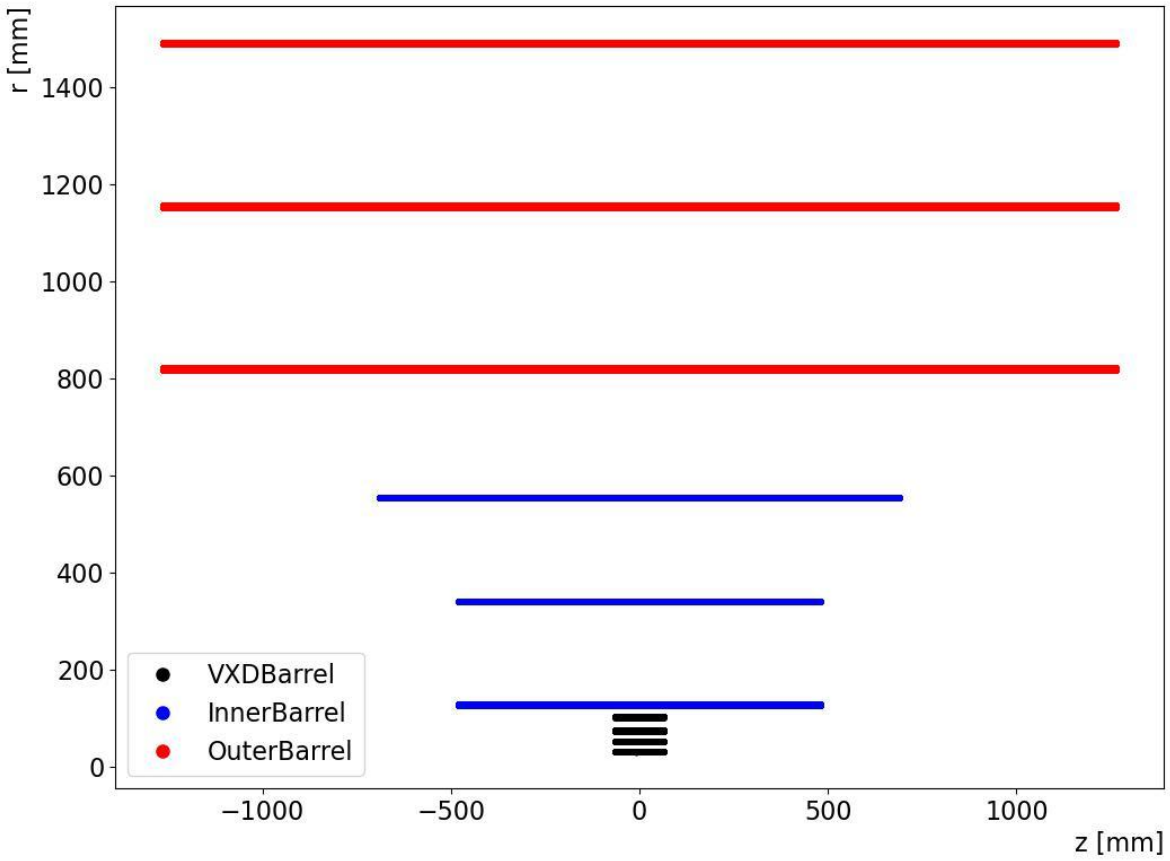
Single muon track within a large BIB

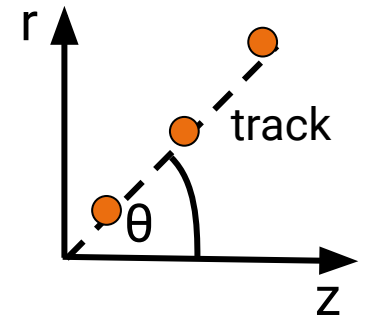
Pre-selection + QUBO coefficients

- Signal-only events to determine pre-selection values
- QUBO coefficients studied on single muon events overlaid with BIB

Tracking:

- Focus on barrel region
- O(10^6) background hits
- $\theta = 90°$, $\varphi \in [0, 2\pi]$

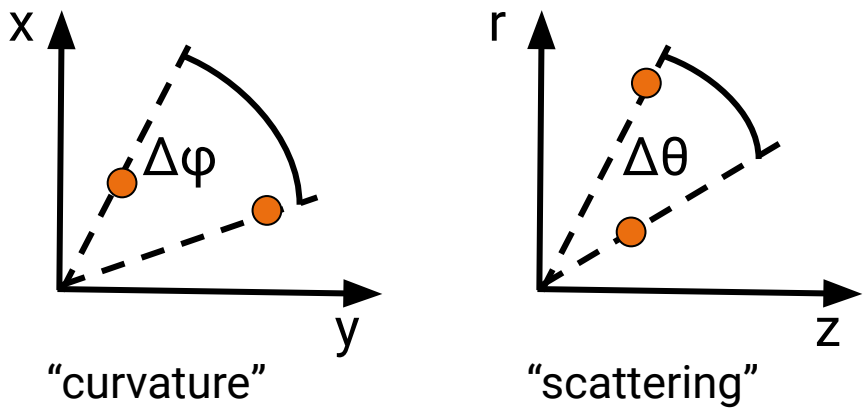


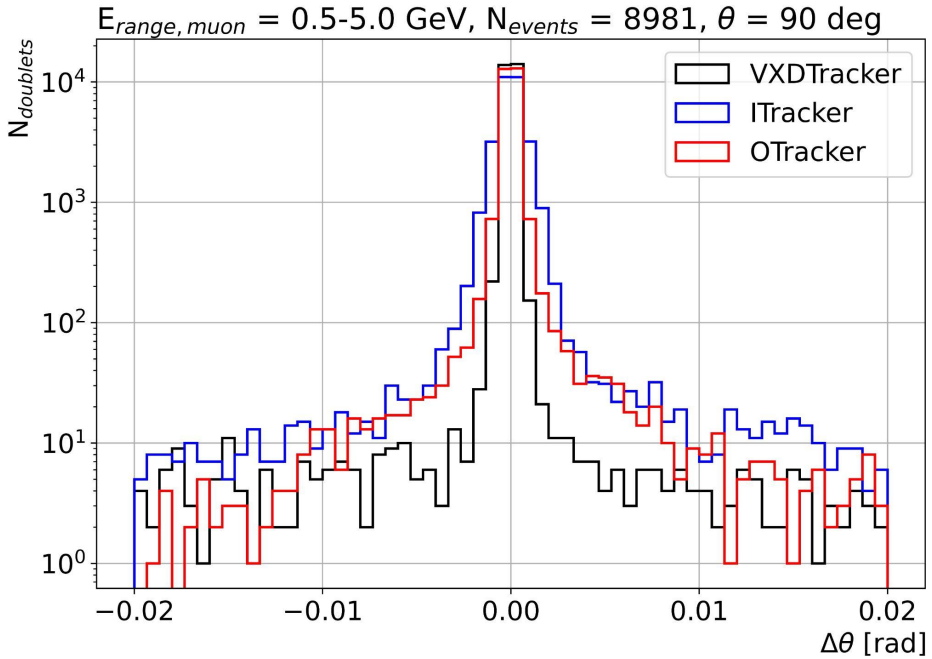


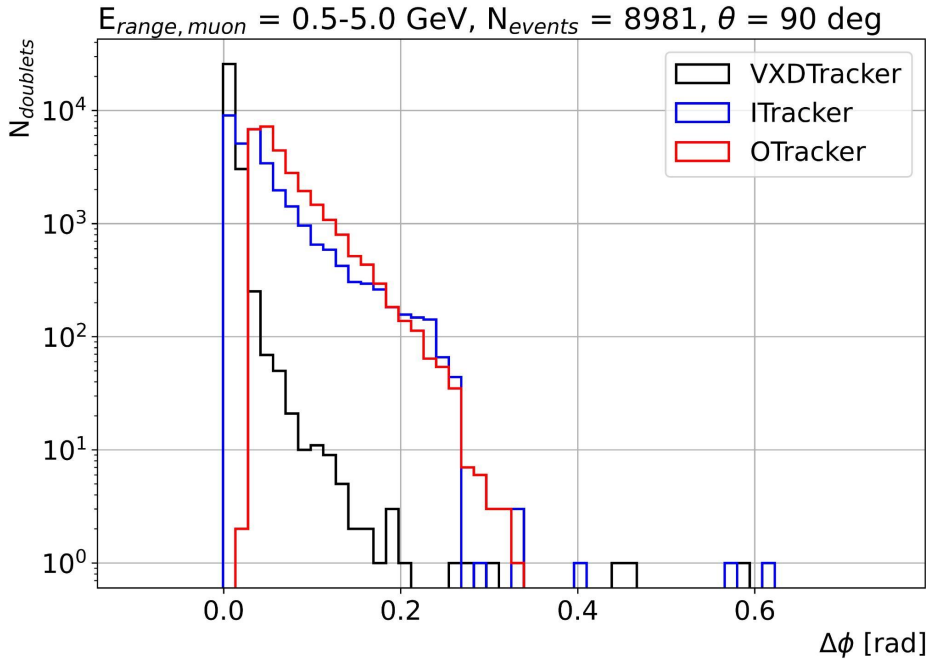
Preselection

Pre-selection

- **Doublet** pre-selection on **Δθ** and **Δφ**



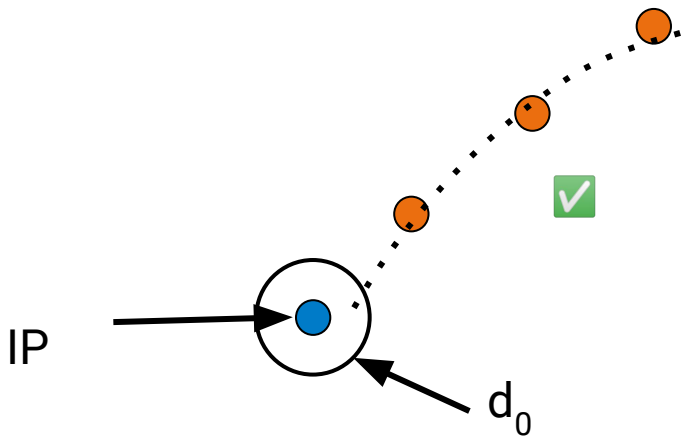


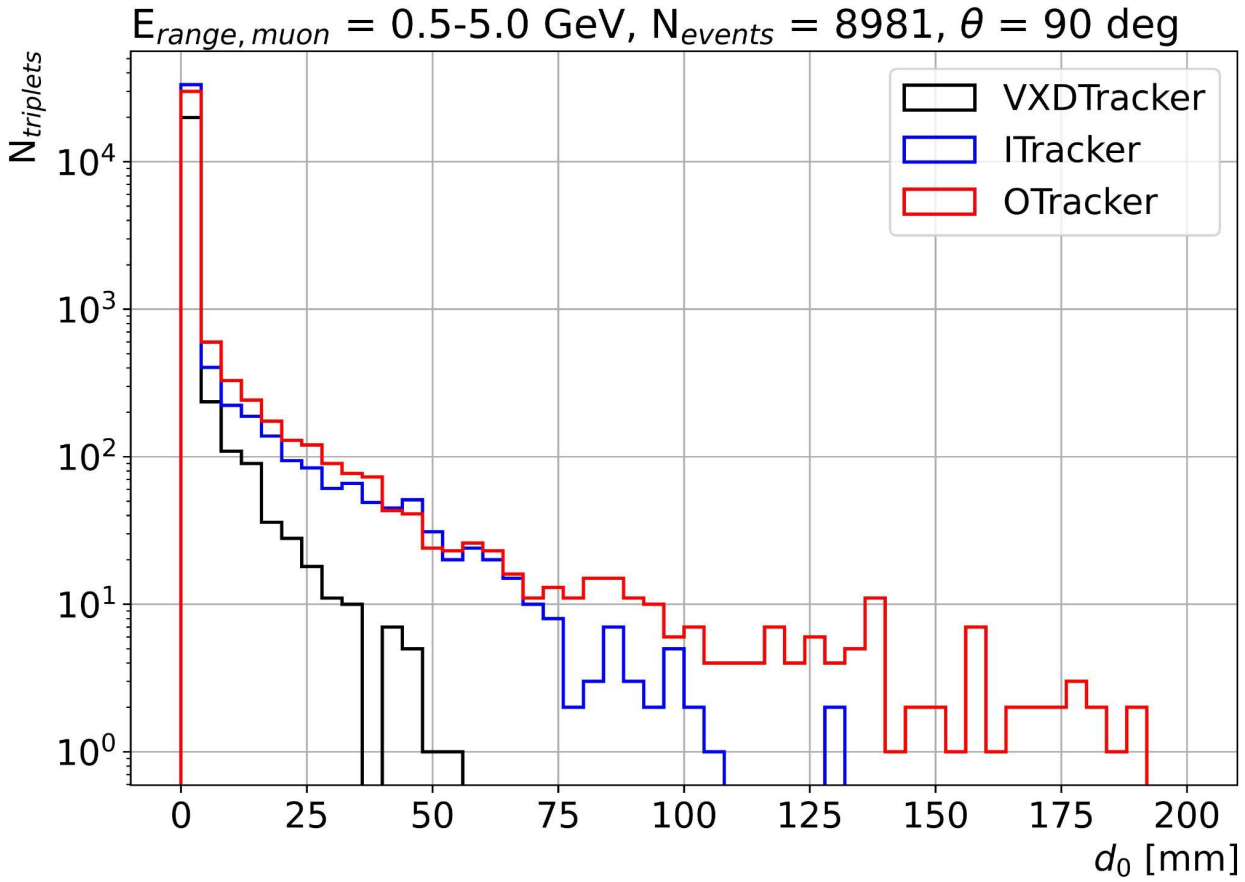


Preselection

Pre-selection

- **Doublet** pre-selection on **Δθ** and **Δφ**
- **Triplet** pre-selection on trajectories having a small $|\mathbf{d_0}|$ w.r.t. the IP





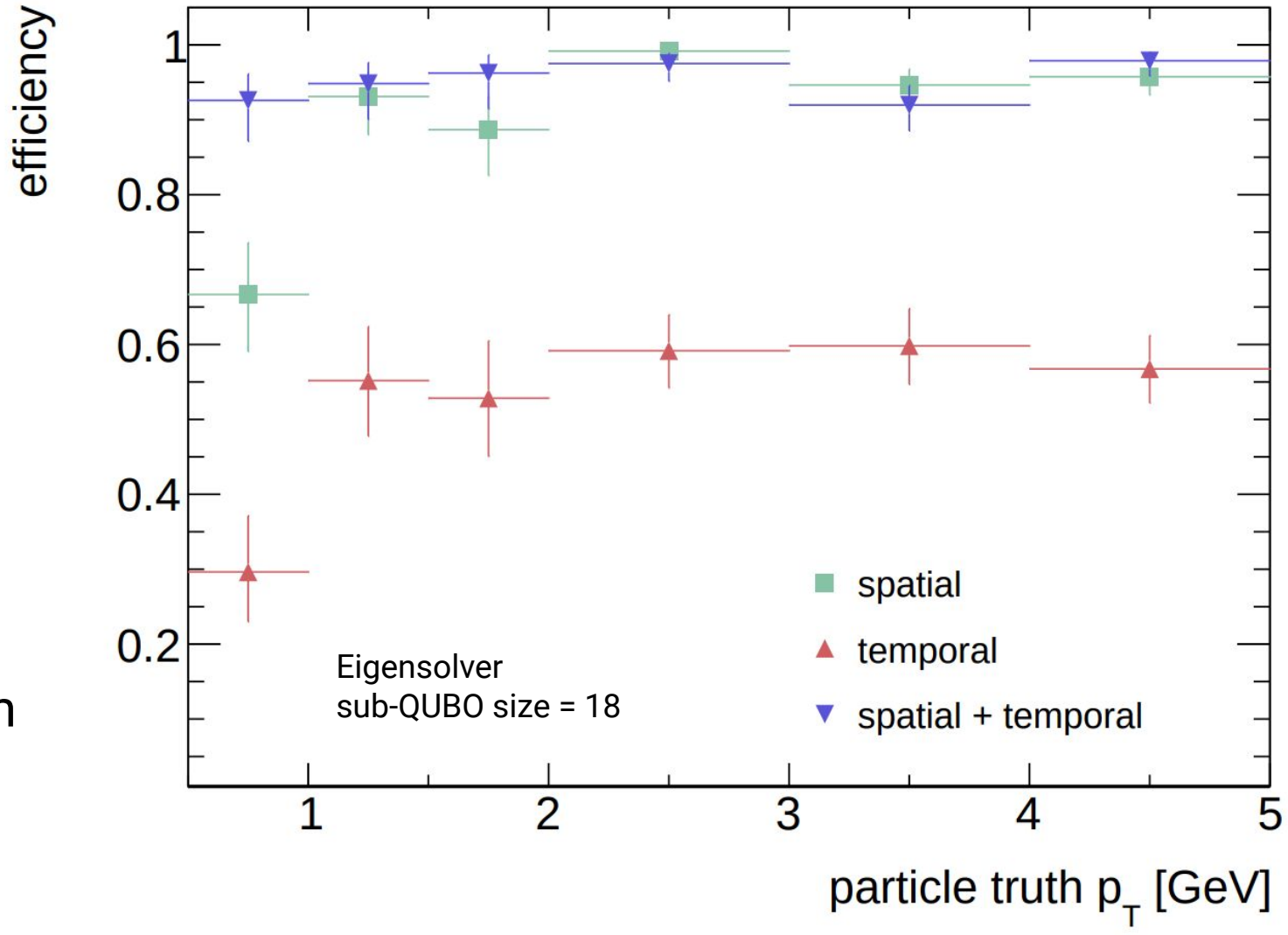
Efficiency vs. p_T

Reconstruction mode

- Pattern building in a θ-slice around muon track

Track selection

- At least 6 hits in a row
- Matched if majority of hits from signal else fake



Summary

- First implementation of a 4D-QUBO is in place
- Focus on barrel region of the Muon Collider detector
- Adding time information to the QUBO parameters b_{ij} is likely to improve track reconstruction efficiency especially at low p_T

Thank You!

Next steps

- Performance vs θ, additionally including endcap regions
- Optimise QUBO parameter modelling, e.g. weighting of time/spatial parts
- Optimise track selection and fitting, e.g. number of hits required:

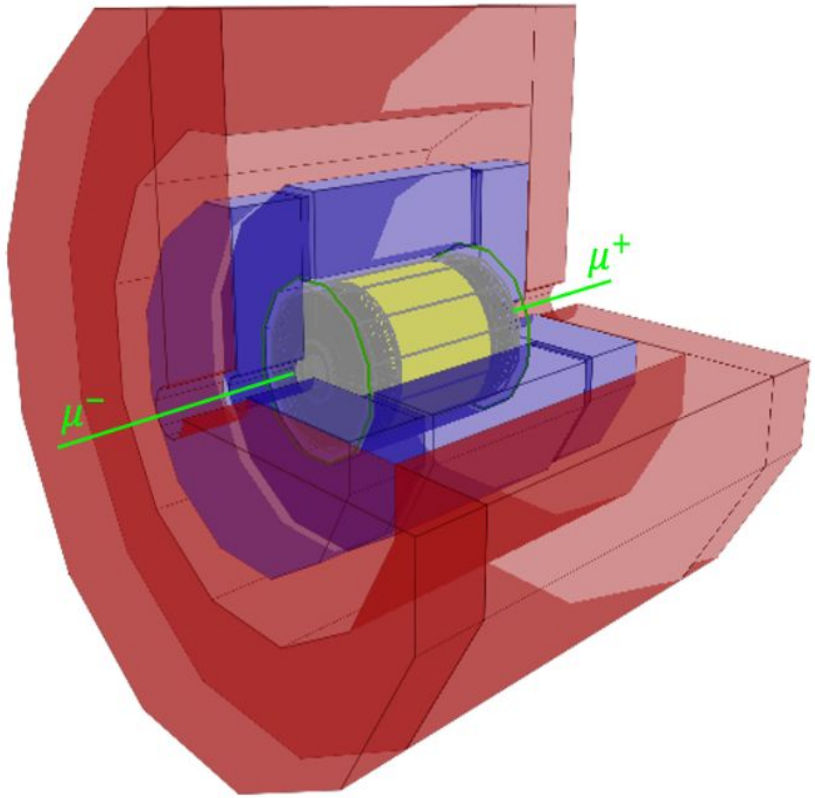
  χ^2 , p_T reconstruction…
- Number of fake tracks per event before / after χ^2

Muon Collider

Why Muon Colliders?

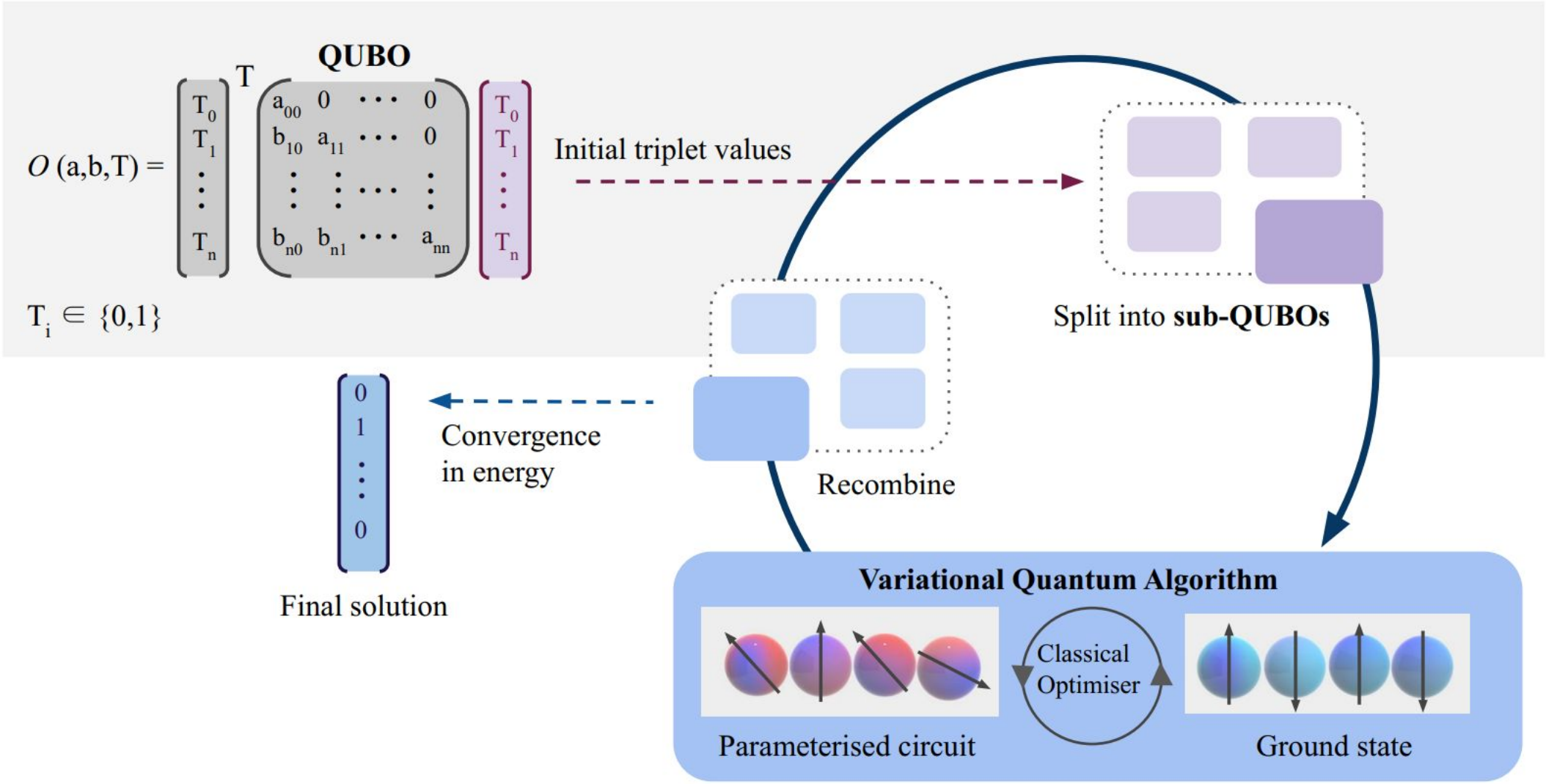
- Muons are heavier than electrons

  → higher energy reach, less synchrotron radiation,
- Higgs precision measurements
- Complementary research on pp and e^+e^- colliders



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

Sub-QUBOs



Source: https://arxiv.org/pdf/2304.01690.pdf

Appendix: QUBO parameter settings

Trivial

- -1 if connection possible

Spatial

compatible curvature: c=1
contrary curvature: c=2

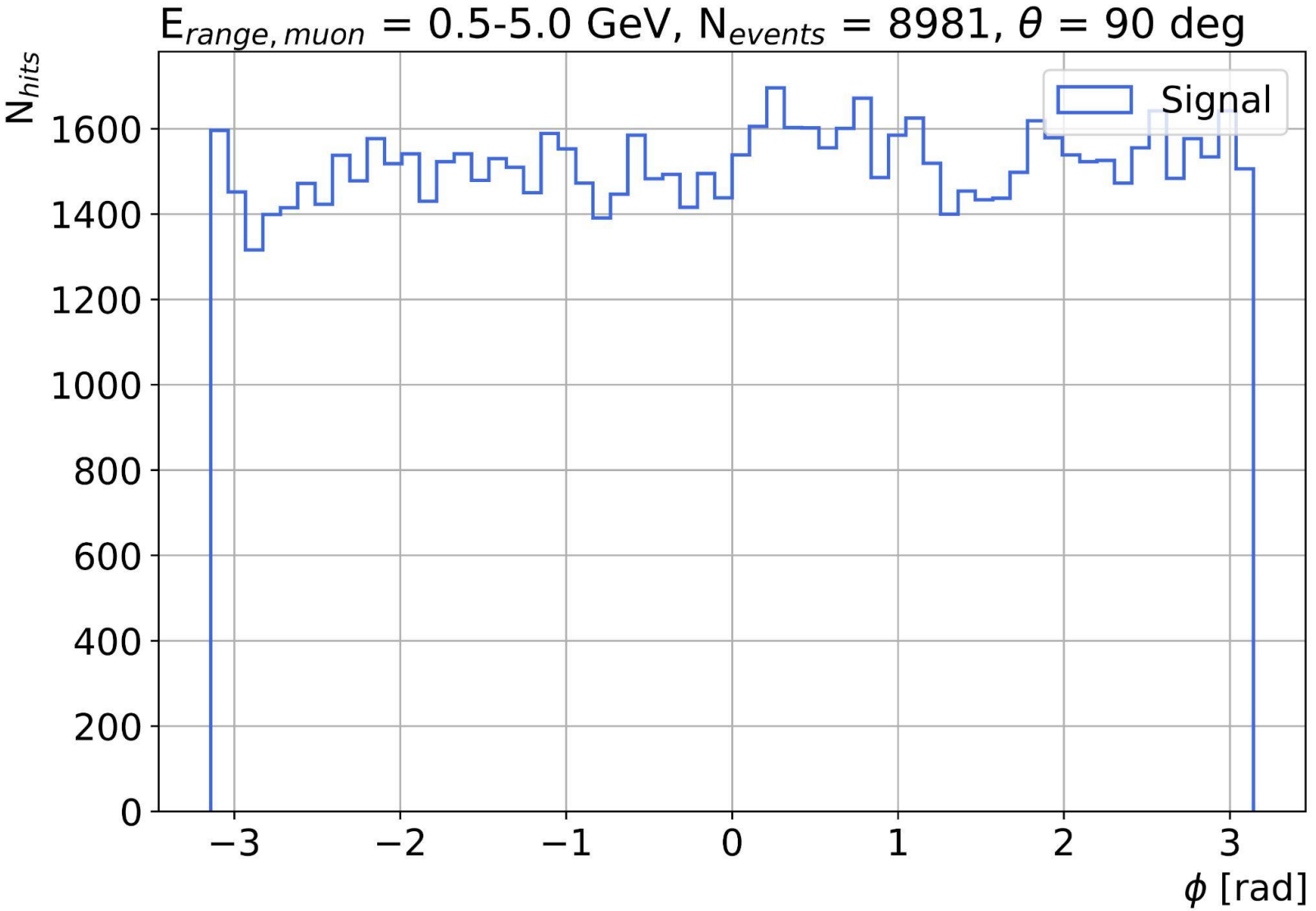
- $f(q/p_T) : 0.5 \cdot (c - \min([pT_{\text{triplet 1}}\ pT_{\text{triplet 2}}]) / \max([pT_{\text{triplet 1}}\ pT_{\text{triplet 2}}])) \rightarrow$ **[0, 1]**
- $\max(\Delta\theta / 0.01) \rightarrow$ **[0, 1]**
- average of both is spatial value

Temporal

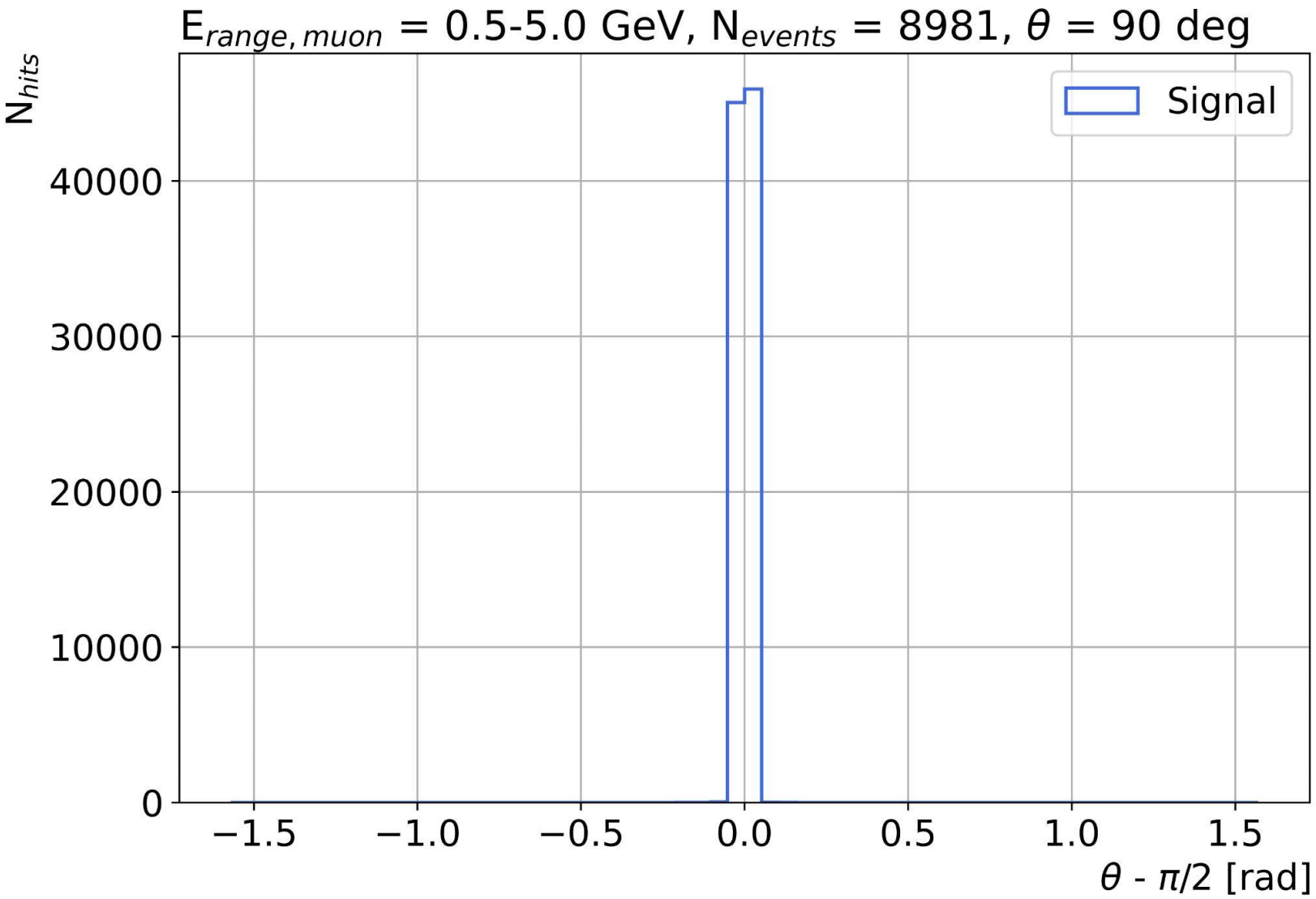
- $\min(\sigma(t_{\text{hits}}) / 250\ [\text{ps}]\ , 1) \rightarrow$ **[0, 1]**

Connections are rescaled to be inside **[-1.0, -0.9]**

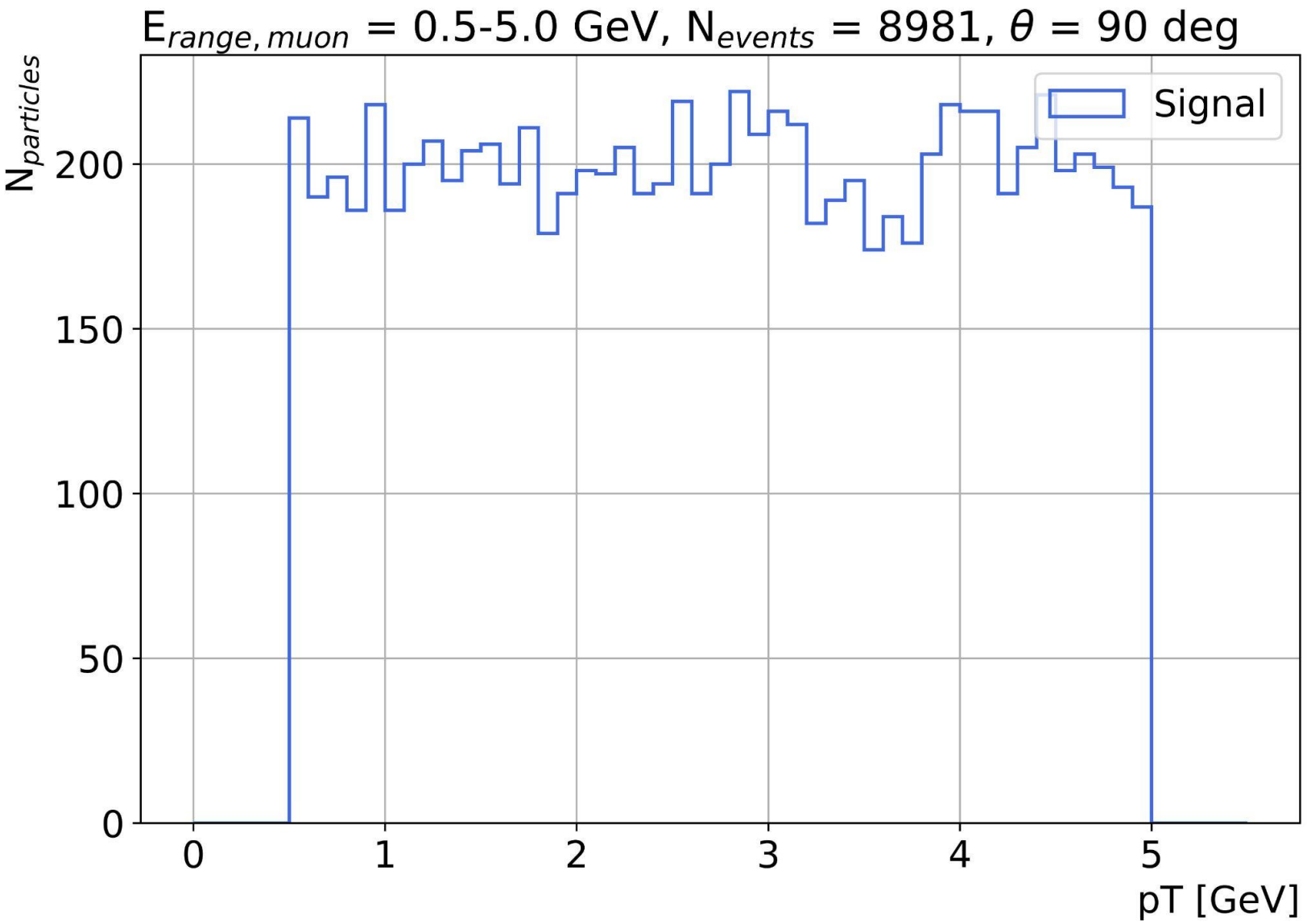
Appendix: Signal only - φ



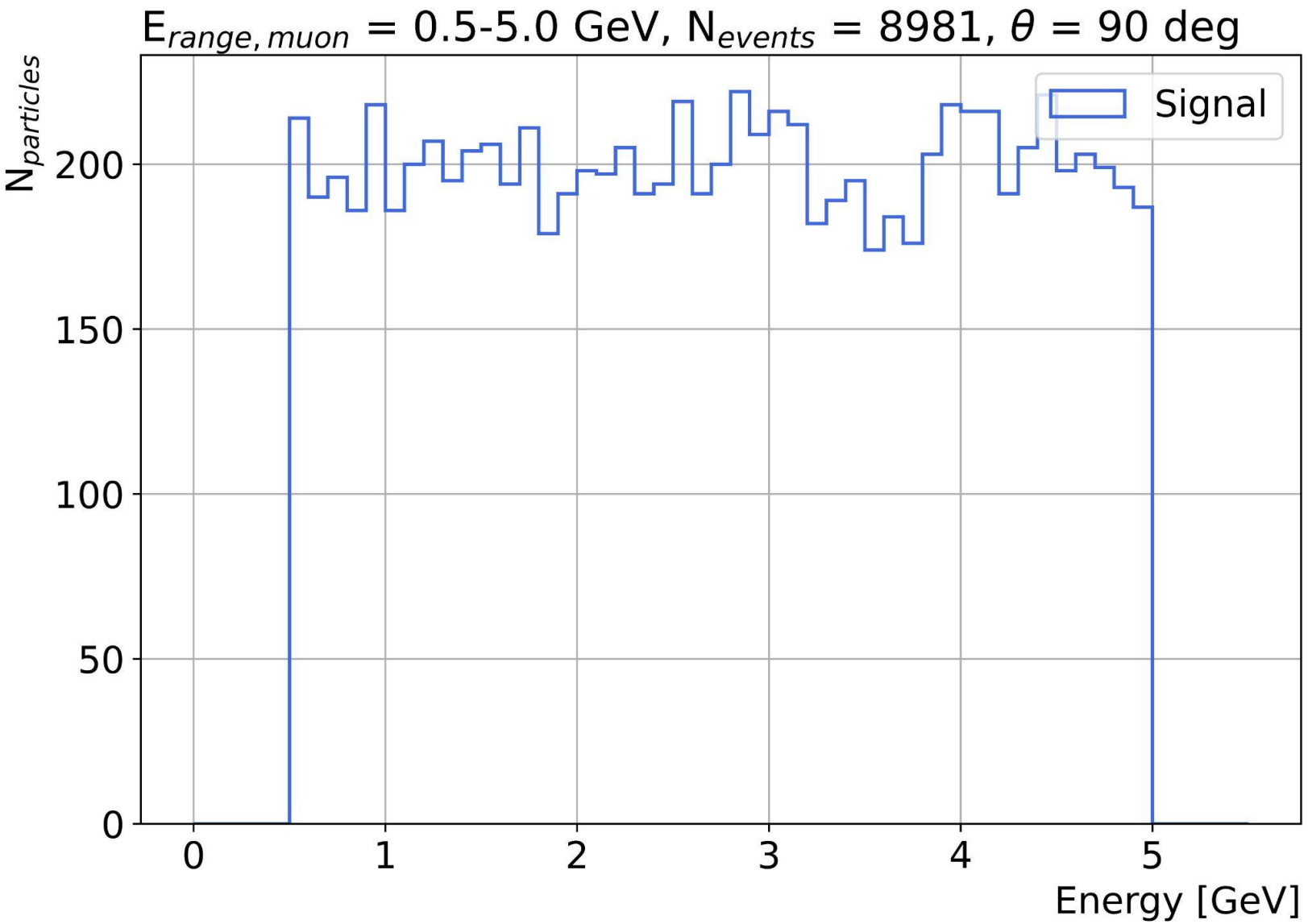
Appendix: Signal only - θ



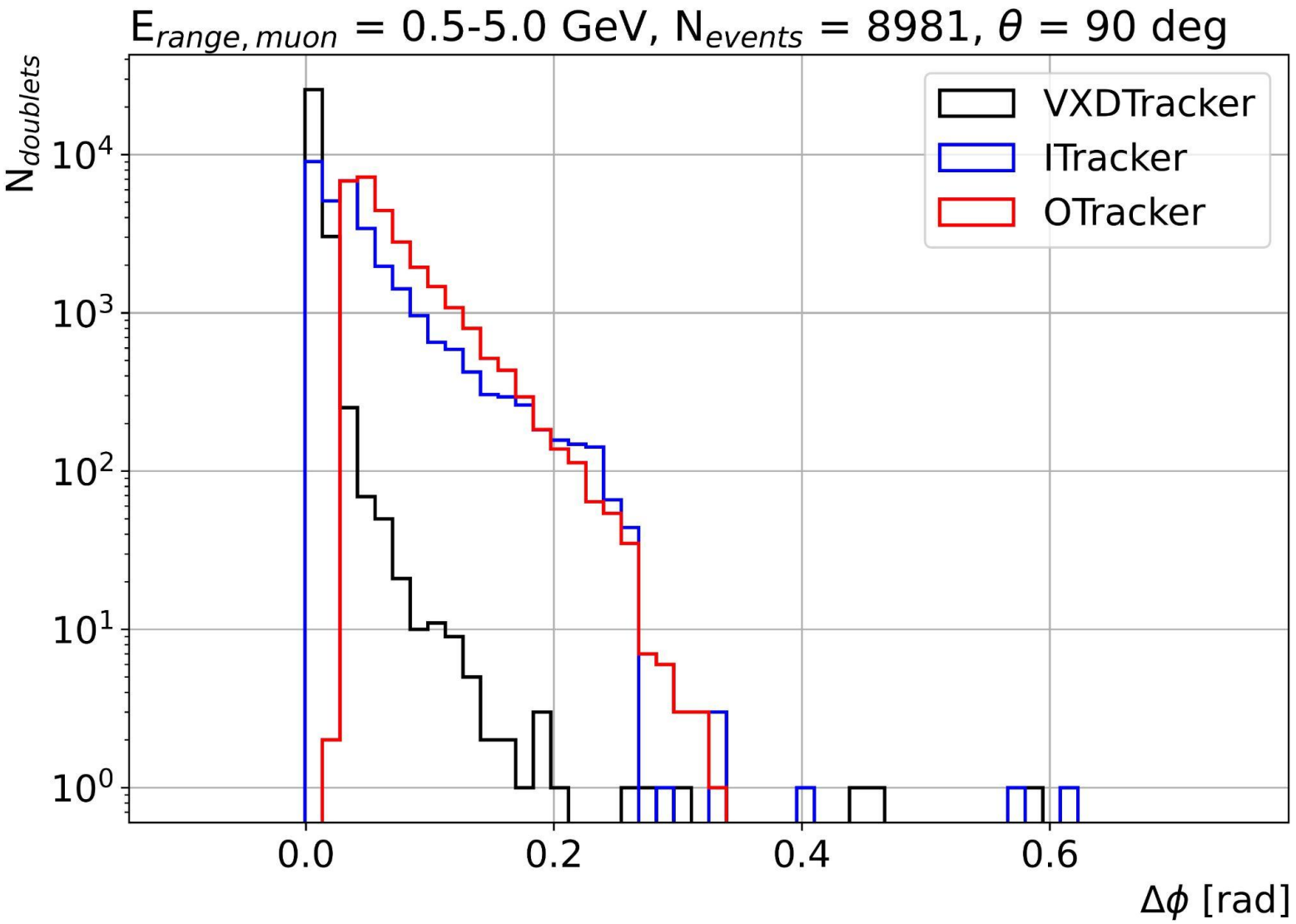
Appendix: Signal only - p_T



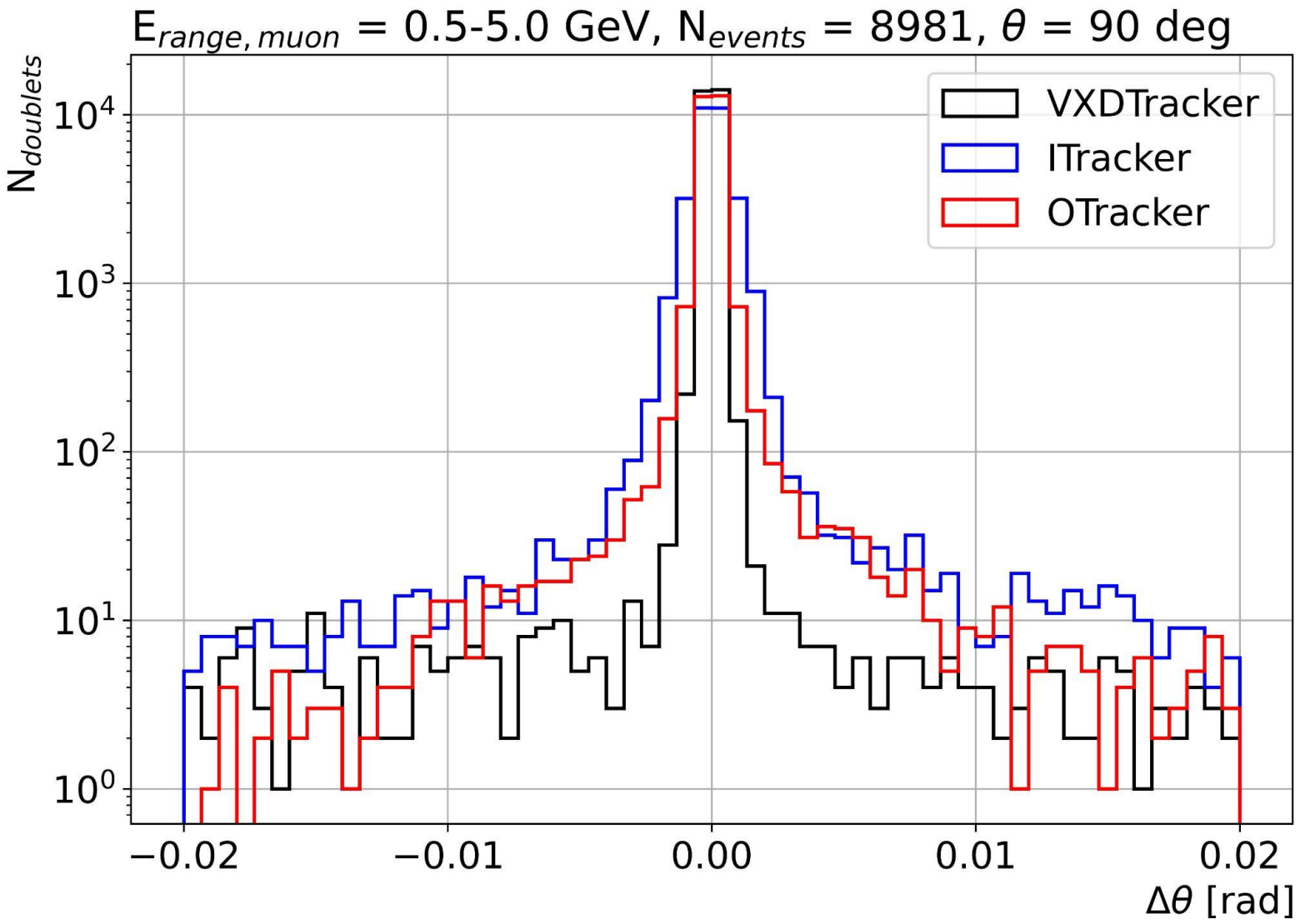
Appendix: Signal only - energy



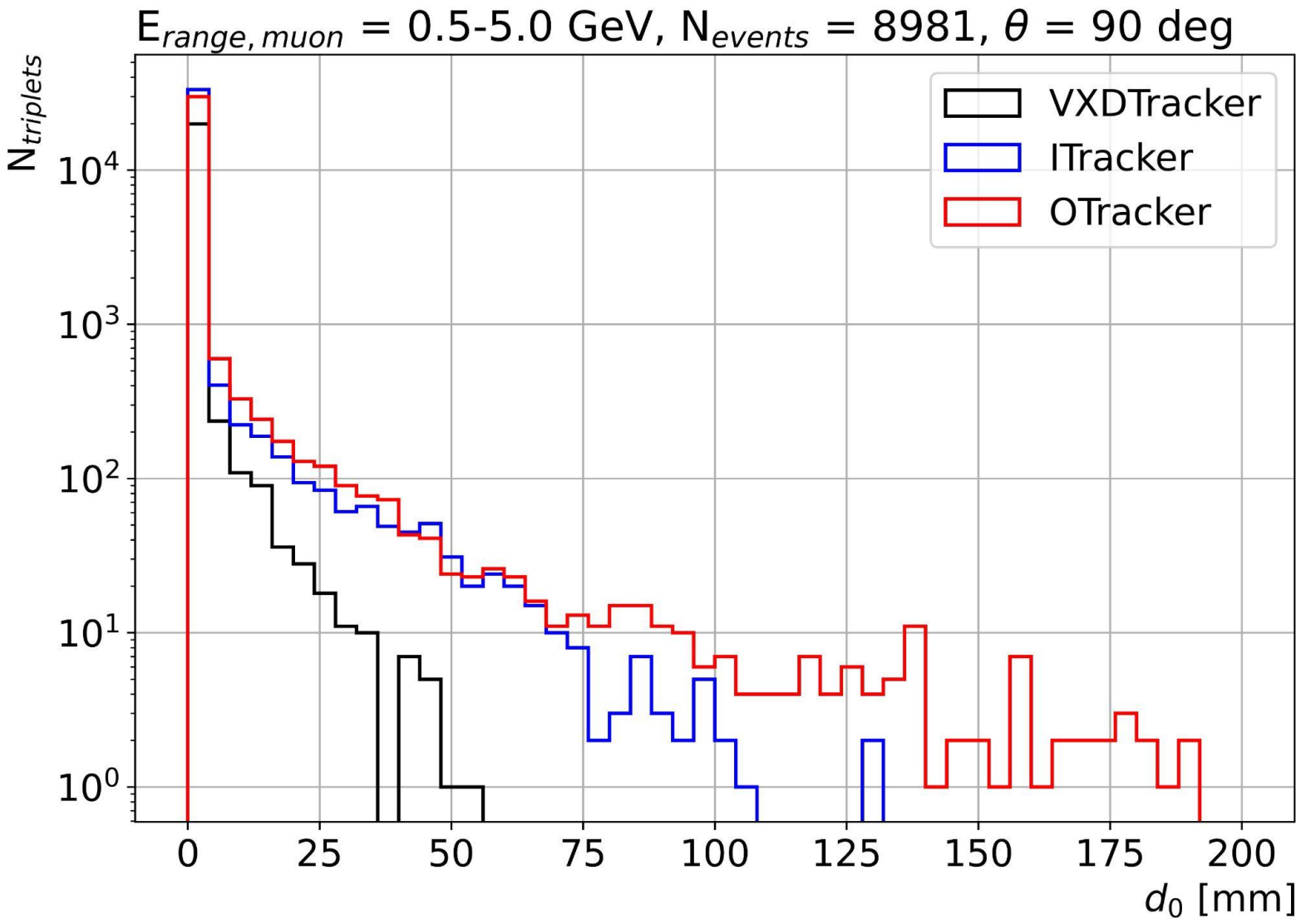
Appendix: Signal only - Δφ



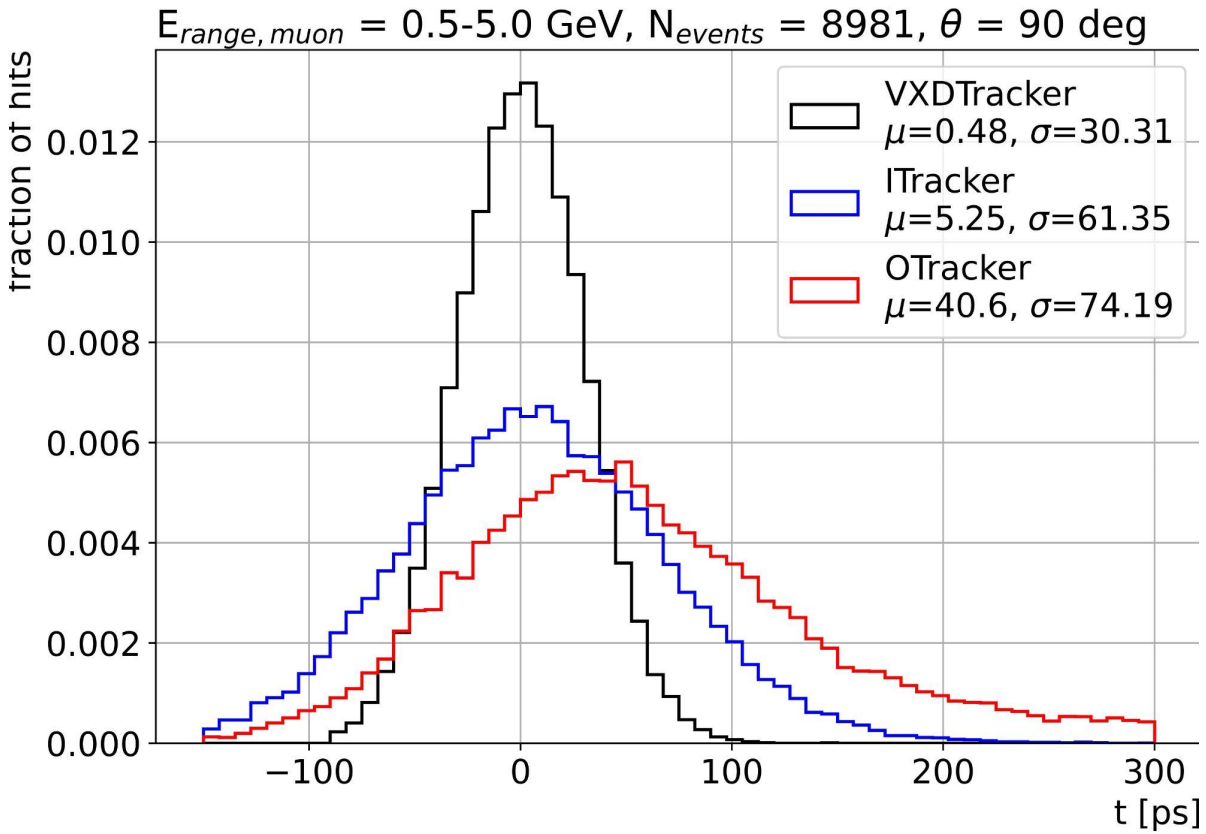
Appendix: Signal only - Δθ



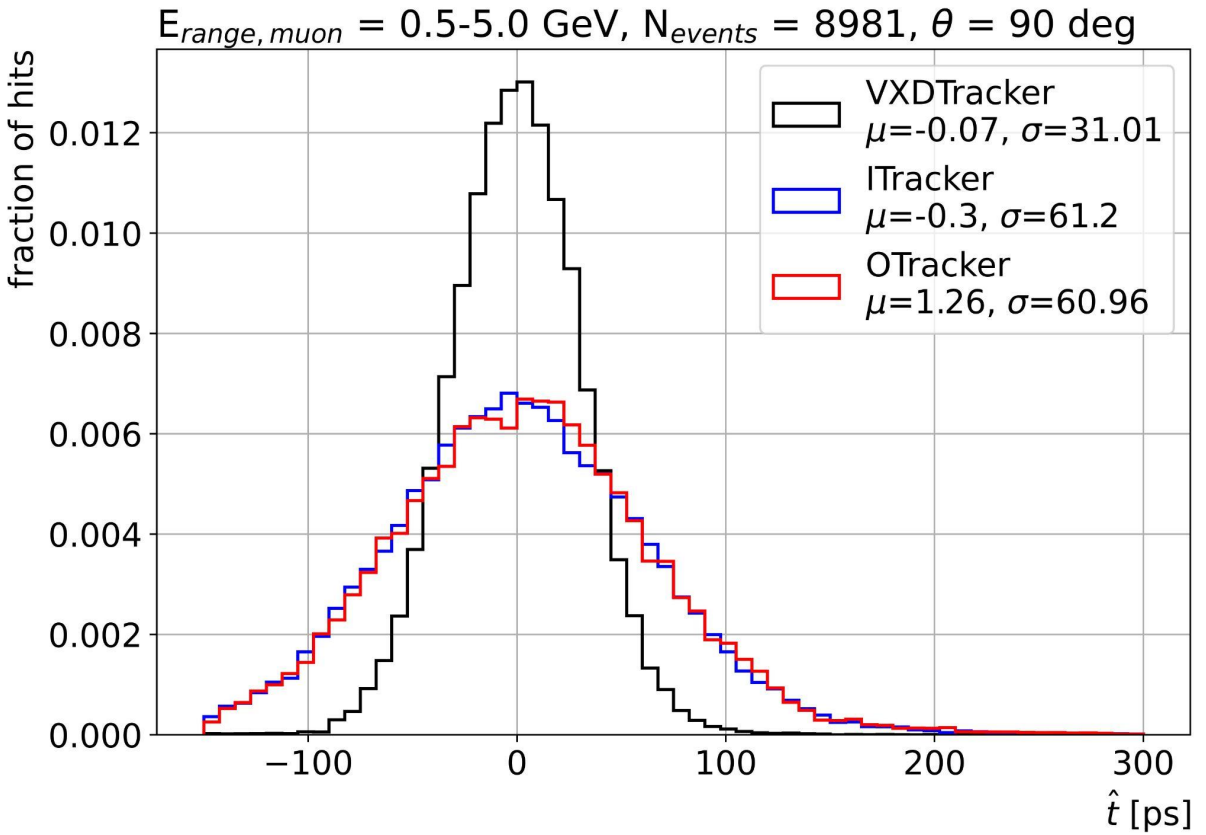
Appendix: Signal only - d_0



Appendix: Signal only - t_{hits}



t - tof_{photon}



t - $tof_{curvature}$

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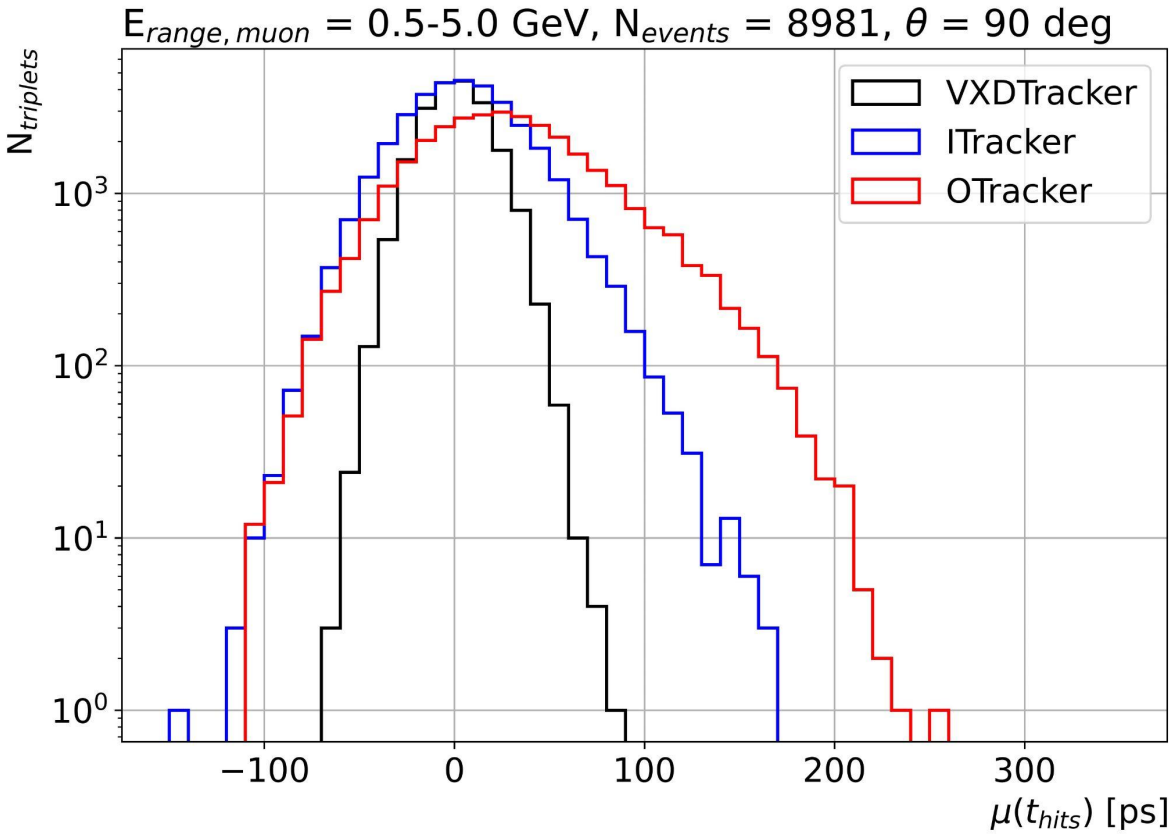
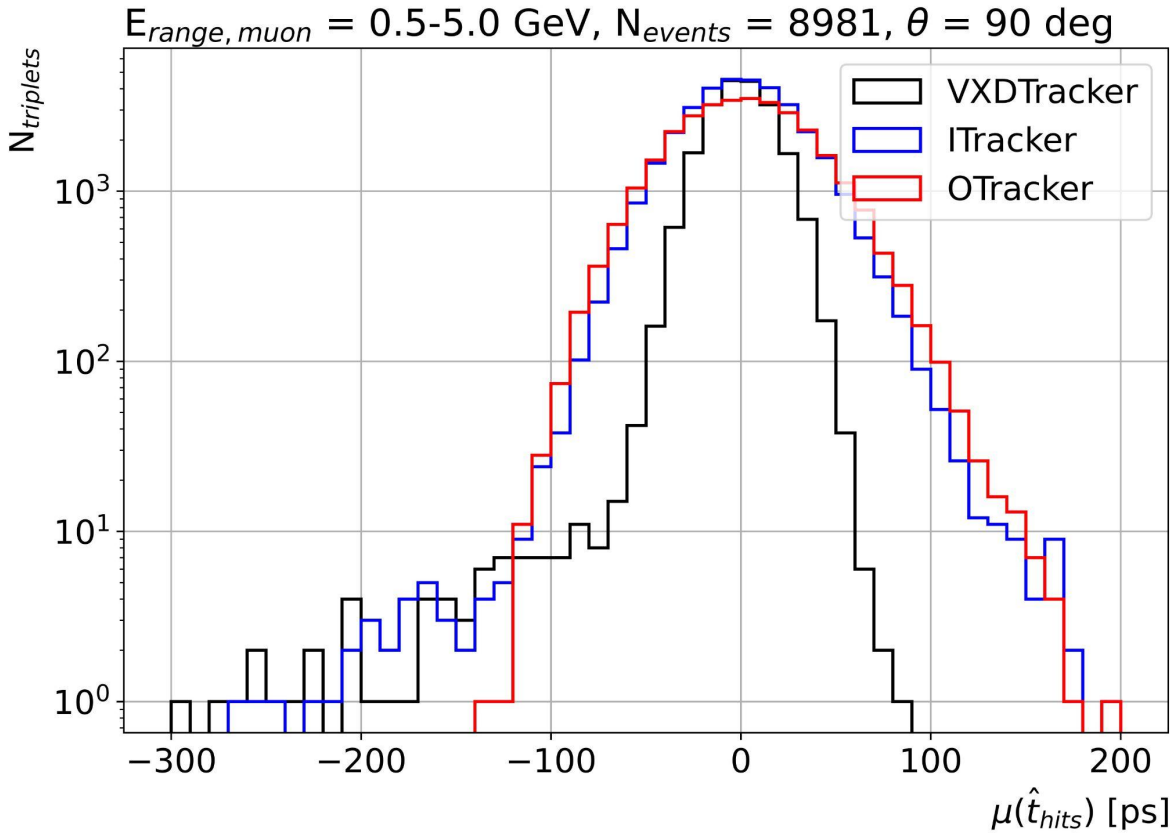
Appendix: Signal only - $\mu(t_{hits,\ triplet})$



t - tof_{photon}



t - $tof_{curvature}$

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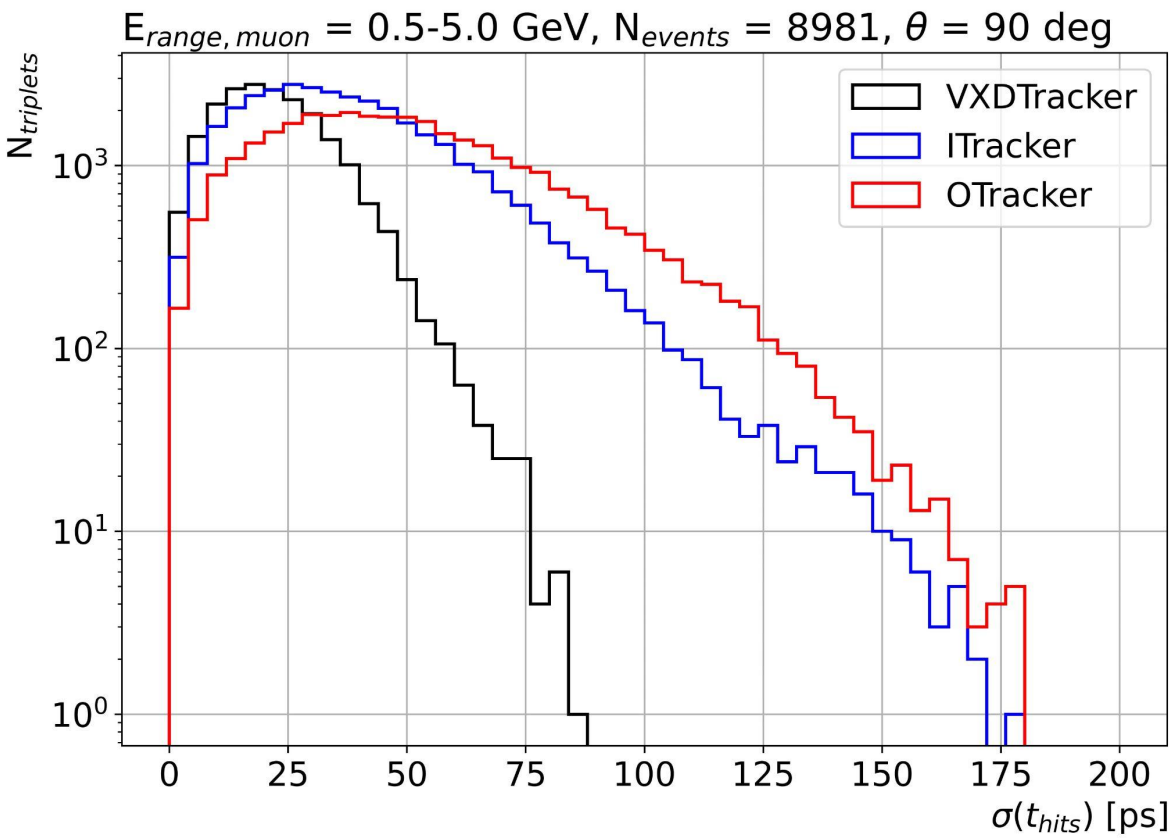
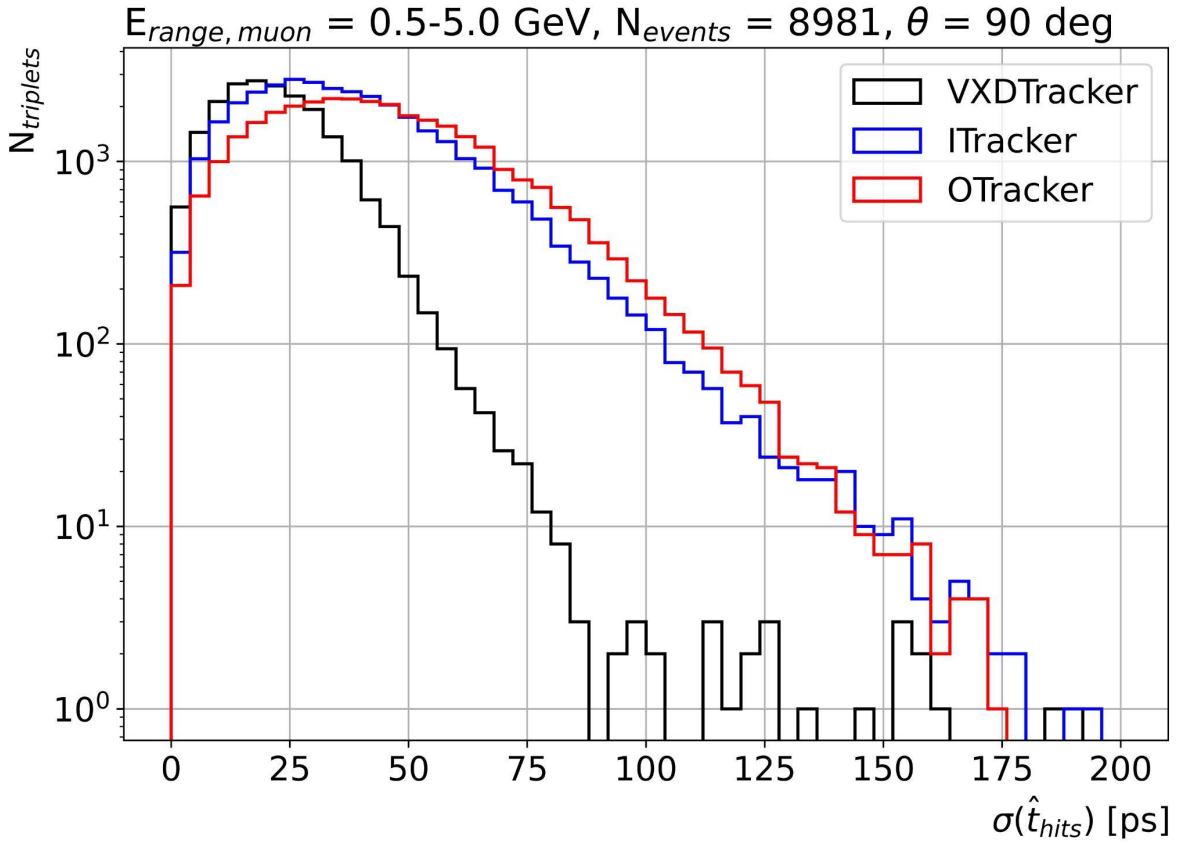
Appendix: Signal only - $\sigma(t_{hits,\ triplets})$



t - tof_{photon}



t - $tof_{curvature}$

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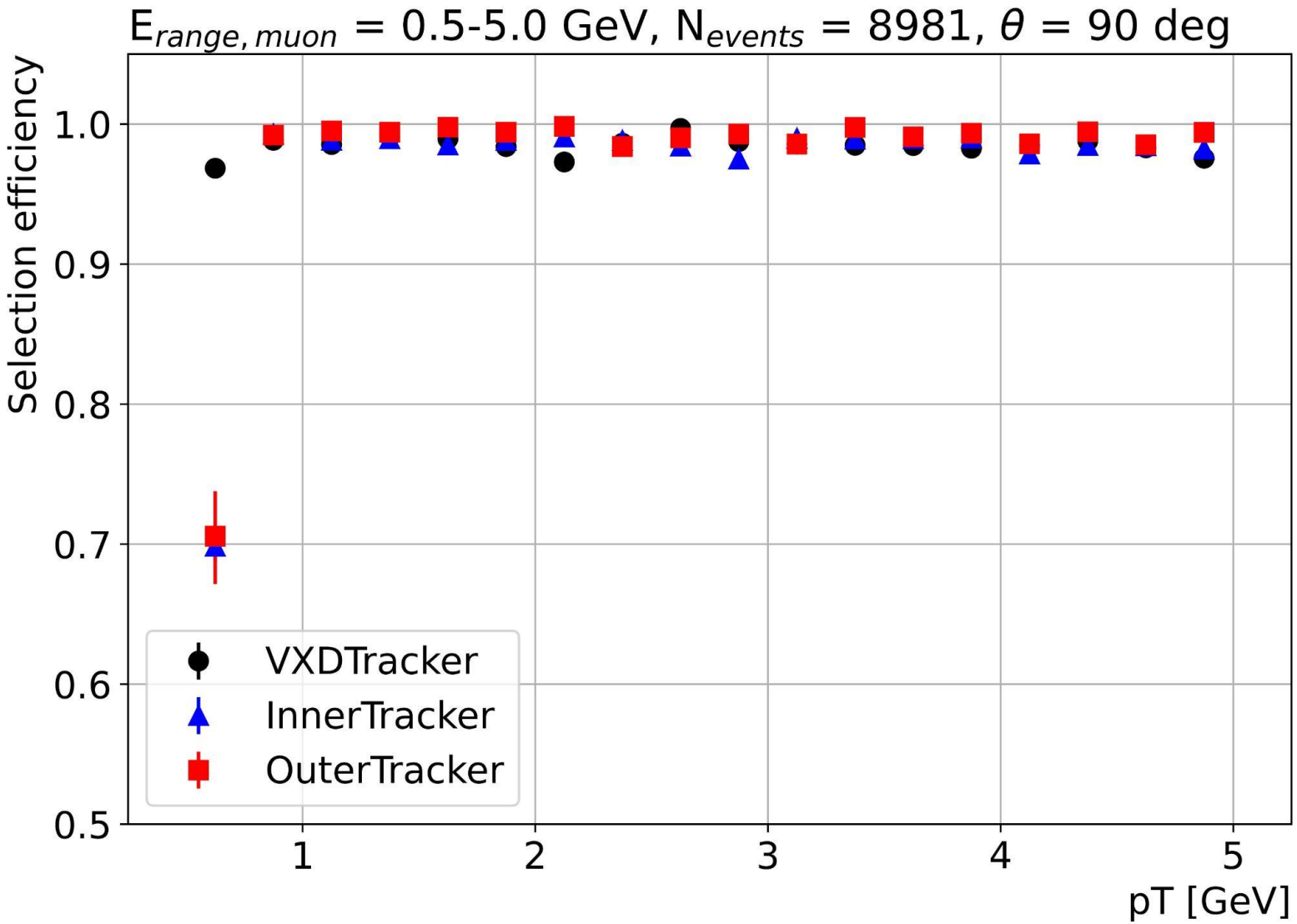
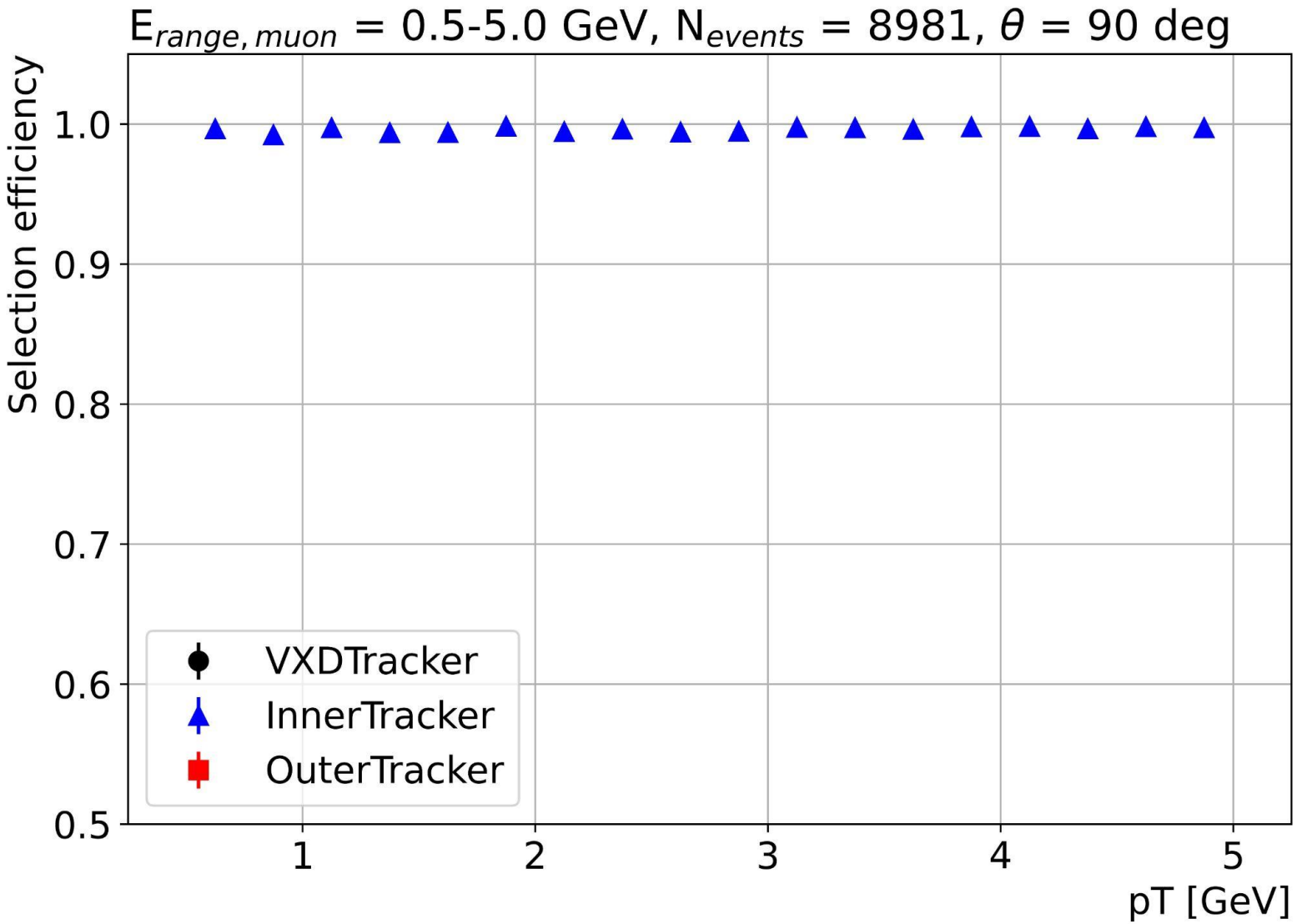
DESY.

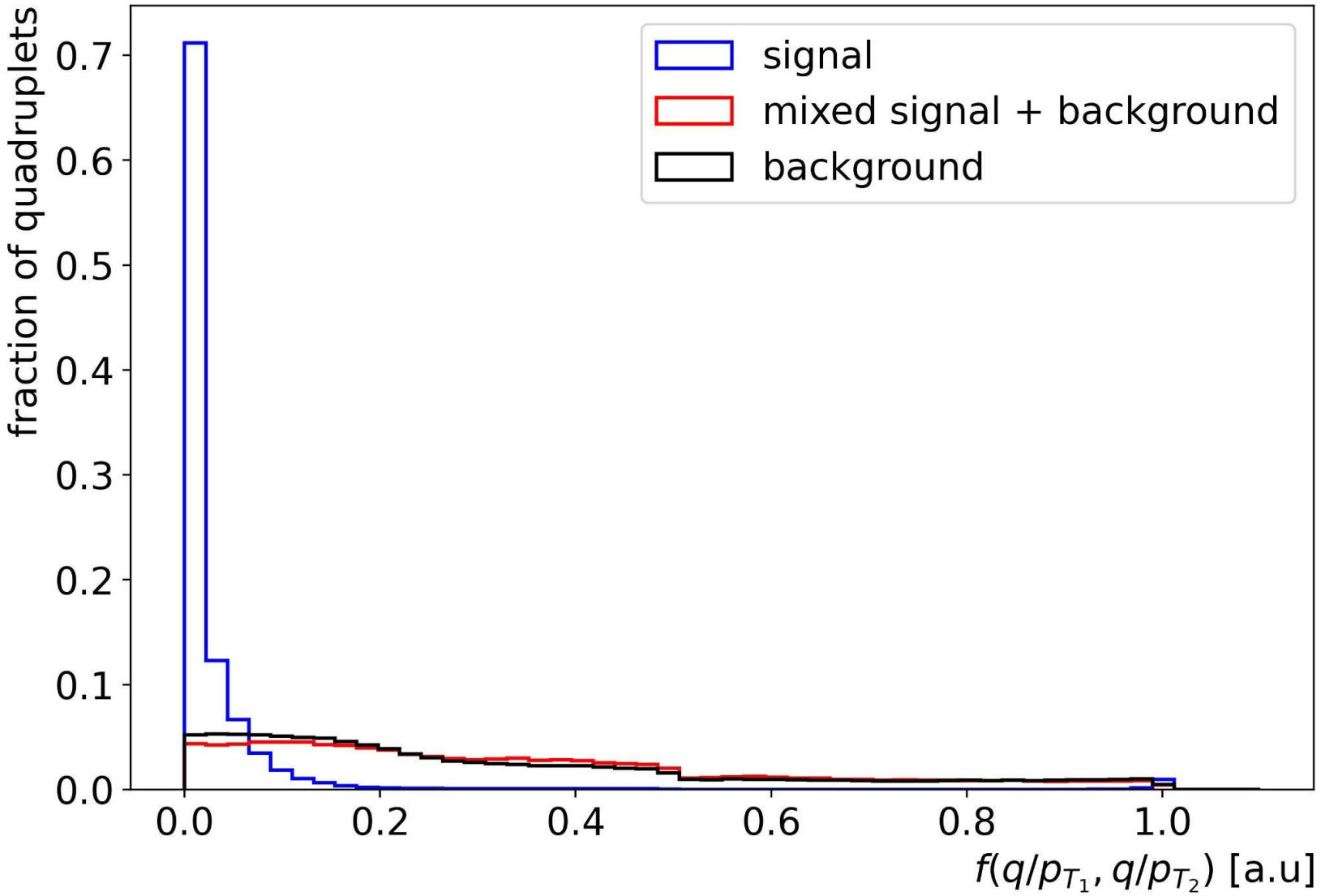
Appendix: Signal only - doublet pre-selection



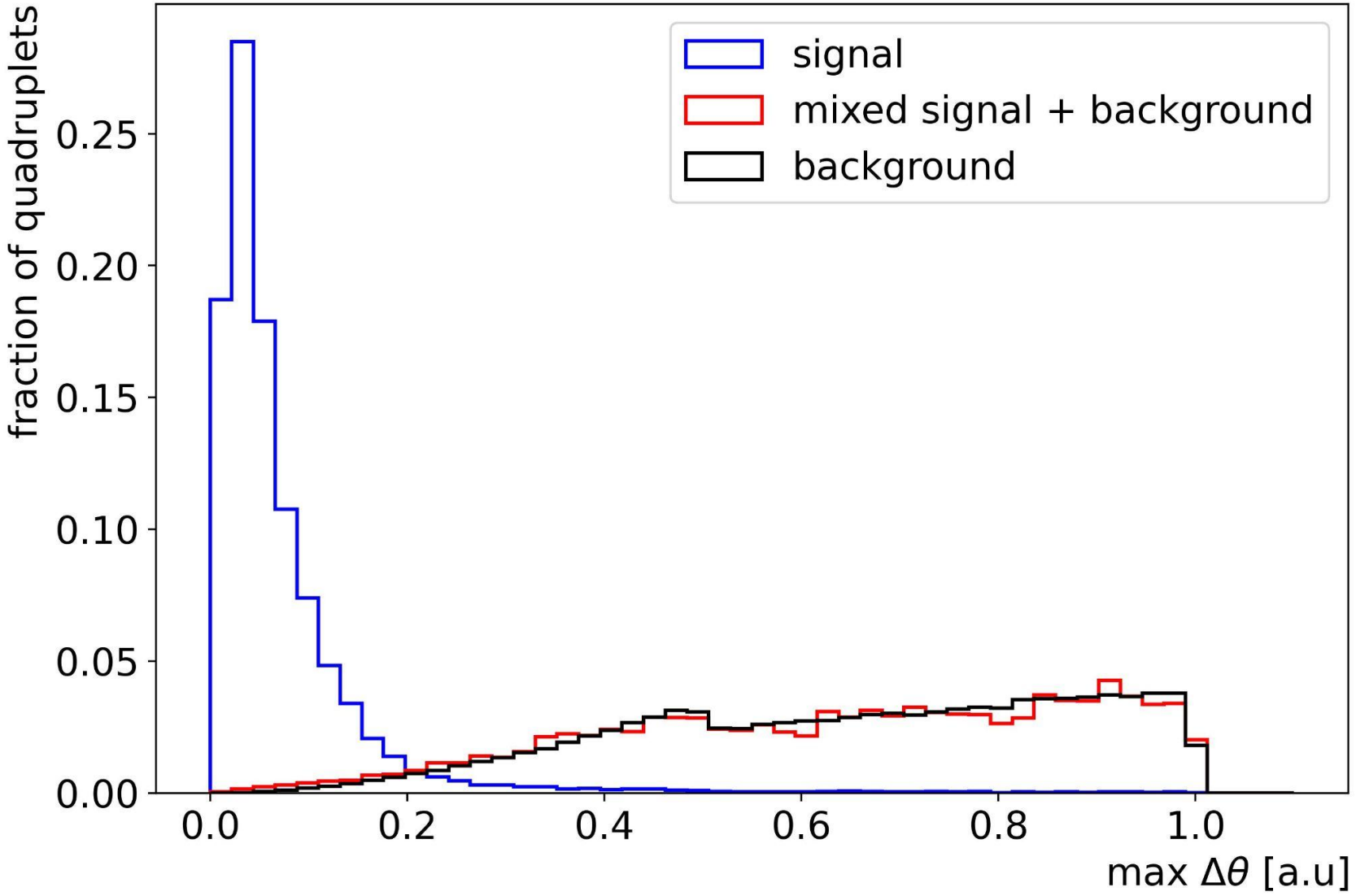
Appendix: Signal only - triplet pre-selection



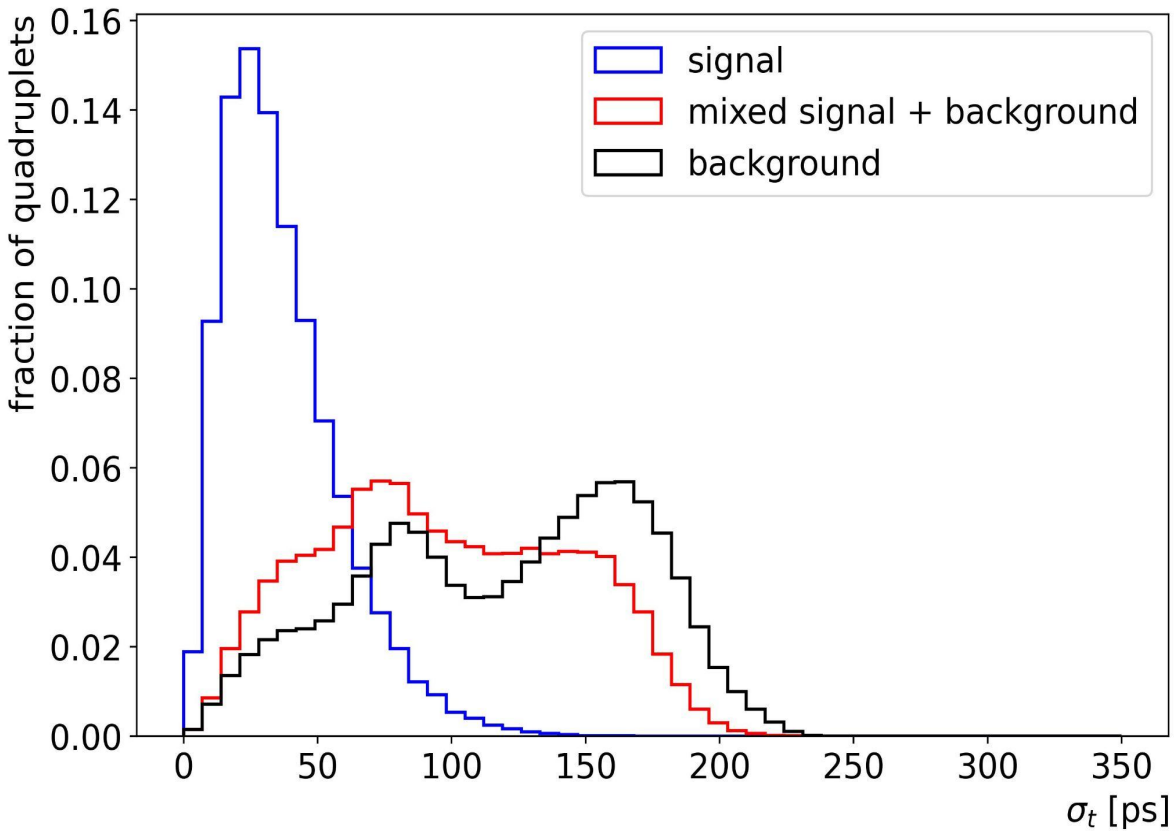
Appendix: QUBO-coefficients - curvature



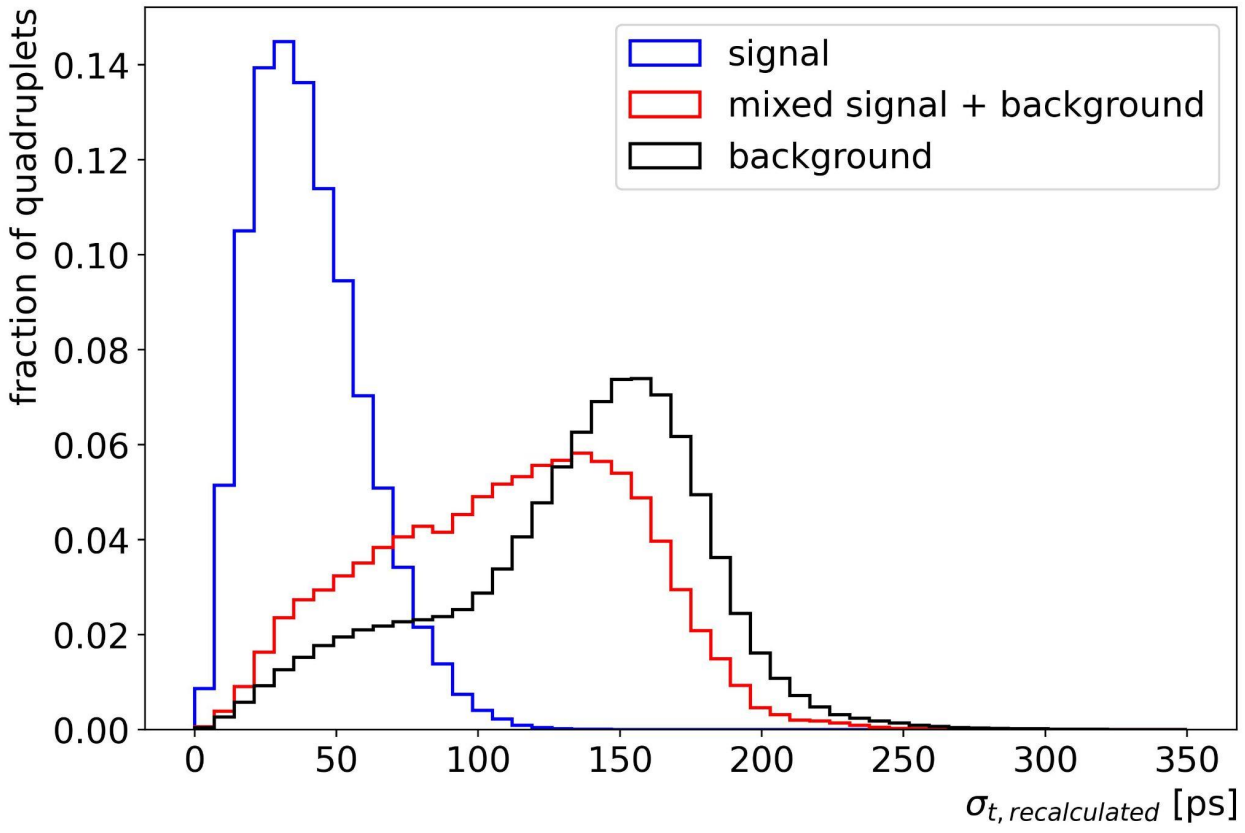
Appendix: QUBO-coefficients - max(Δθ)



Appendix: QUBO-coefficients - $\sigma(t_{hits,\ qudruplet})$



t - tof_{photon}



t - $tof_{curvature}$

HELMHOLTZ

DESY.

Appendix: Preselection values

VXD:	$\Delta\varphi = 0.05$	$\Delta\theta = 0.01$	d0 = 15mm
ITracker:	$\Delta\varphi = 0.2$	$\Delta\theta = 0.01$	d0 = 50mm
OTracker:	$\Delta\varphi = 0.25$	$\Delta\theta = 0.005$	d0 = 50mm

Appendix: Triplet statistics

N_{events} = 538,

$N_{triplets}$ = 15087781 → 28044 / event

$N_{triplets,\ signal}$	= 5048	→ 9	/ event
$N_{triplets,\ majority\ signal}$	= 40137	→ 75	/ event
$N_{triplets,\ majority\ background}$	= 278561	→ 518	/ event
$N_{background}$	= 14764025	→ 27442	/ event

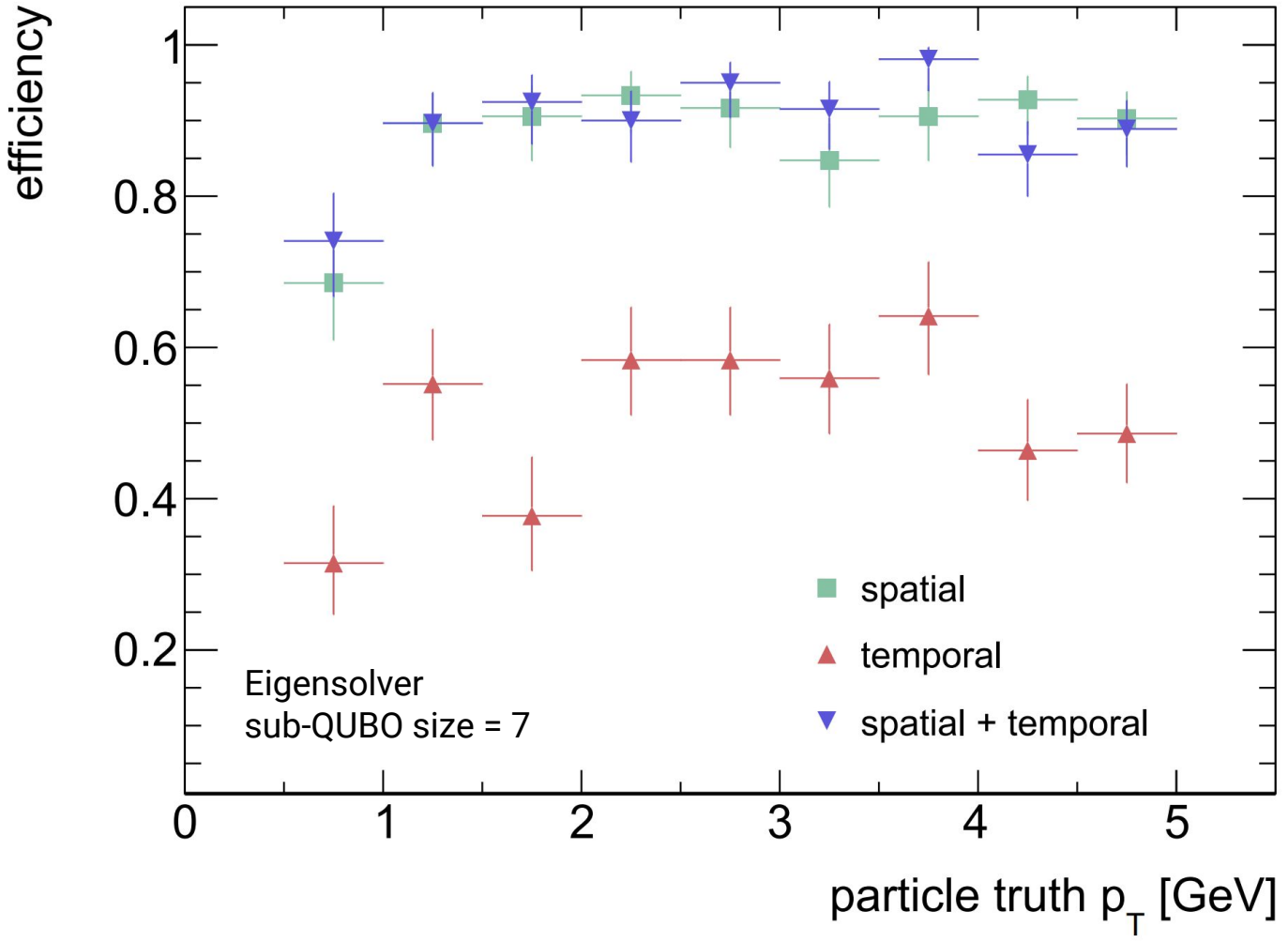
Efficiency vs. p_T

Reconstruction mode

- Pattern building in a θ-slice around muon track

Track selection

- At least 6 hits in a row
- Matched if majority of hits from signal else fake



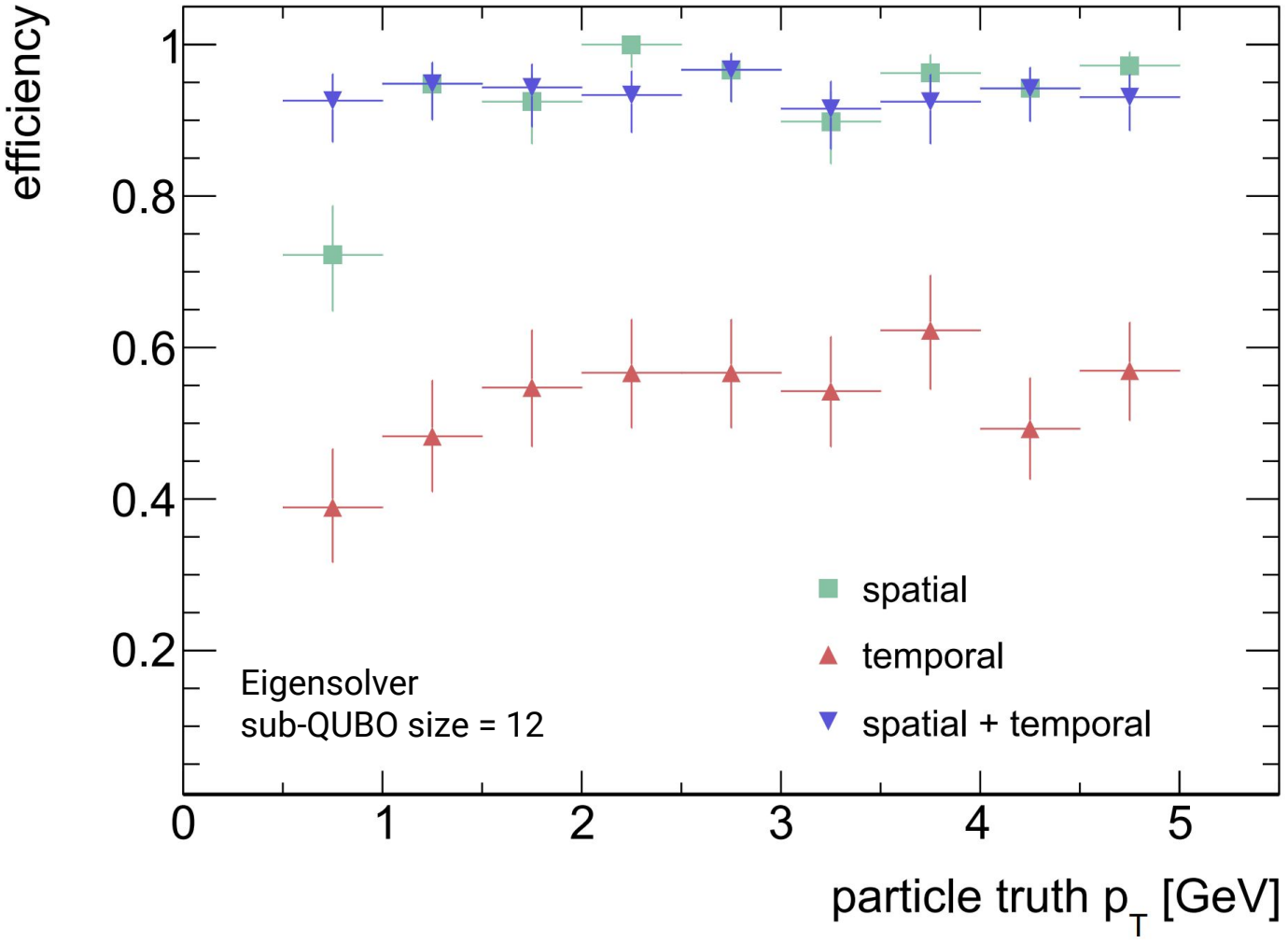
Efficiency vs. p_T

Reconstruction mode

- Pattern building in a θ-slice around muon track

Track selection

- At least 6 hits in a row
- Matched if majority of hits from signal else fake



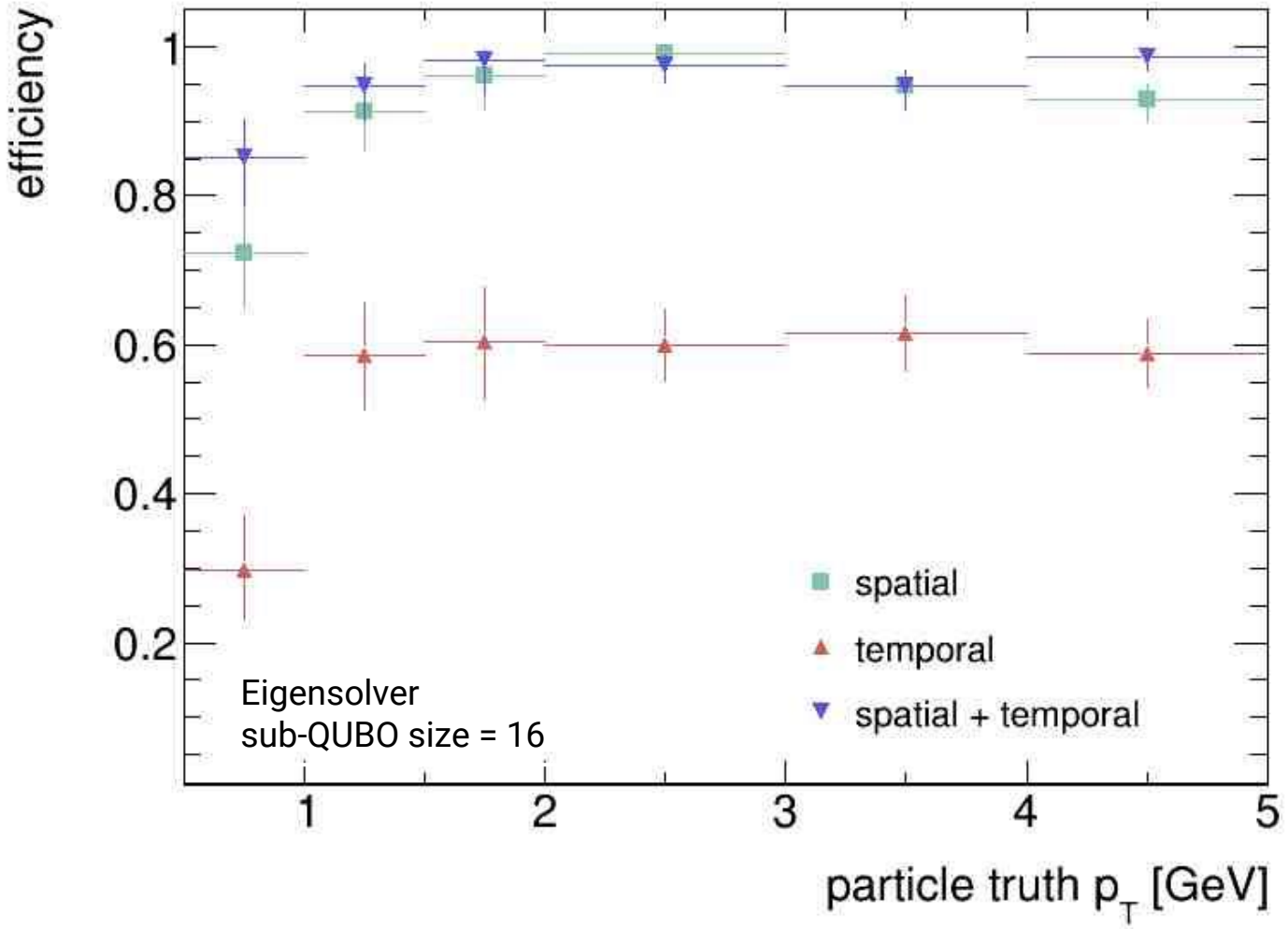
Efficiency vs. p_T

Reconstruction mode

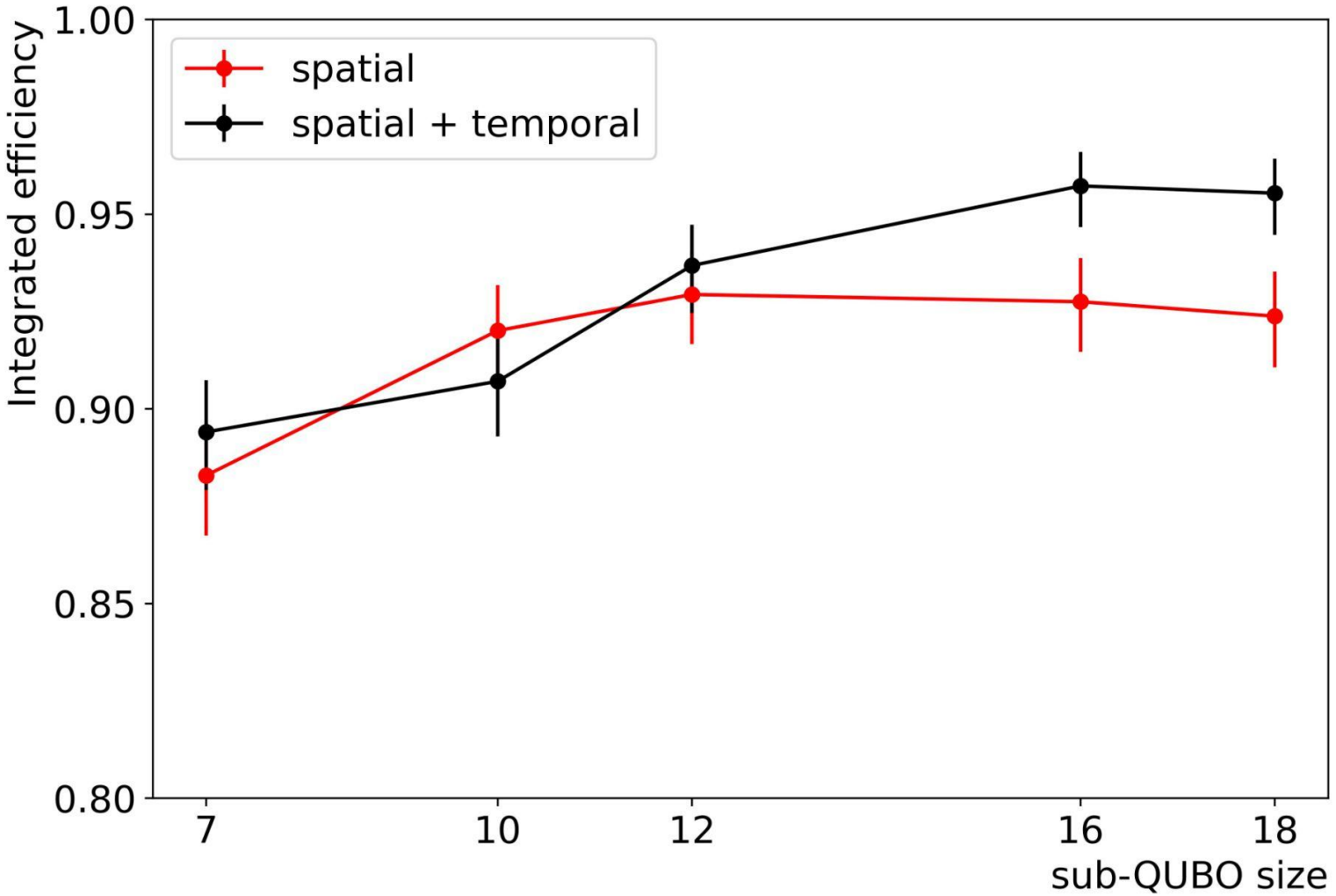
- Pattern building in a θ-slice around muon track

Track selection

- At least 6 hits in a row
- Matched if majority of hits from signal else fake

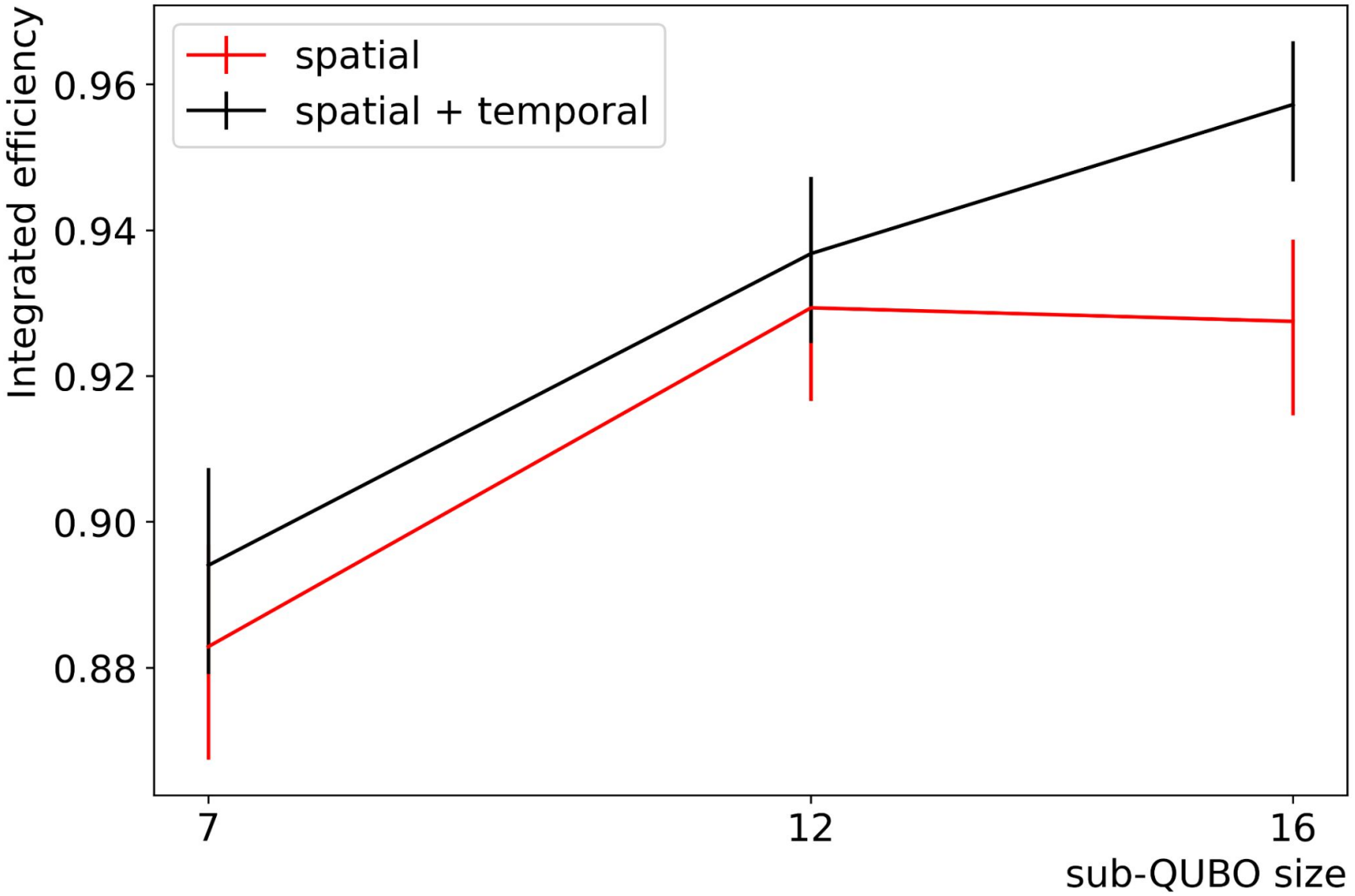


Efficiency vs. sub-QUBO size

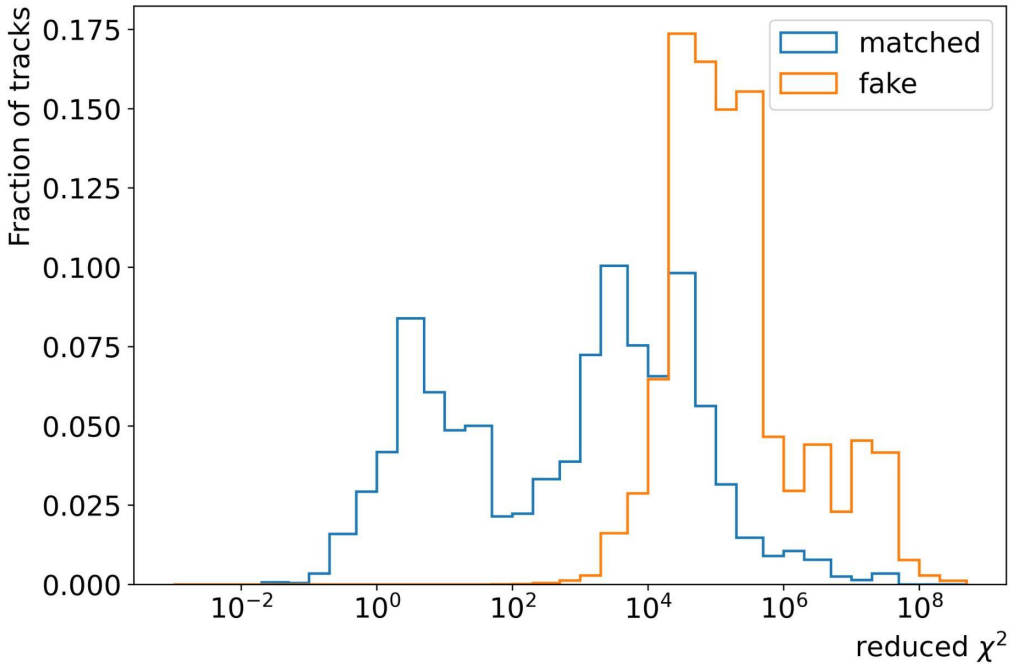


Not finished plots and not understood results

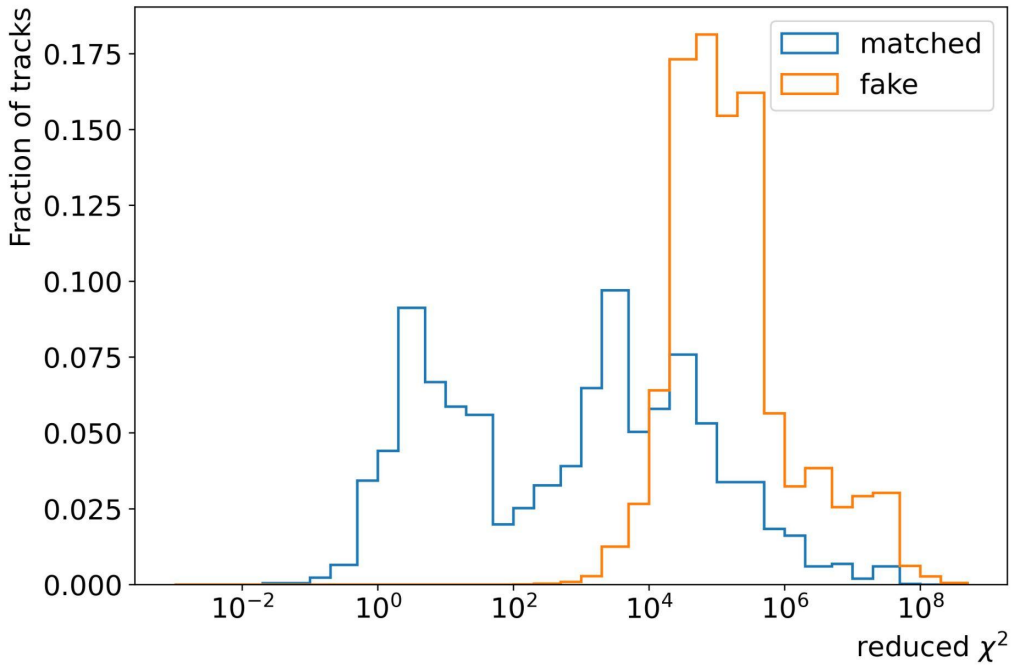
Integrated efficiency vs sub-QUBO size



Appendix: χ^2 - before final track selection



spatial



spatial + temporal