Graph Neural Networks and Multi-Objective Optimization for Coded-Mask Prompt-Gamma Imaging within the SiFi-CC Collaboration

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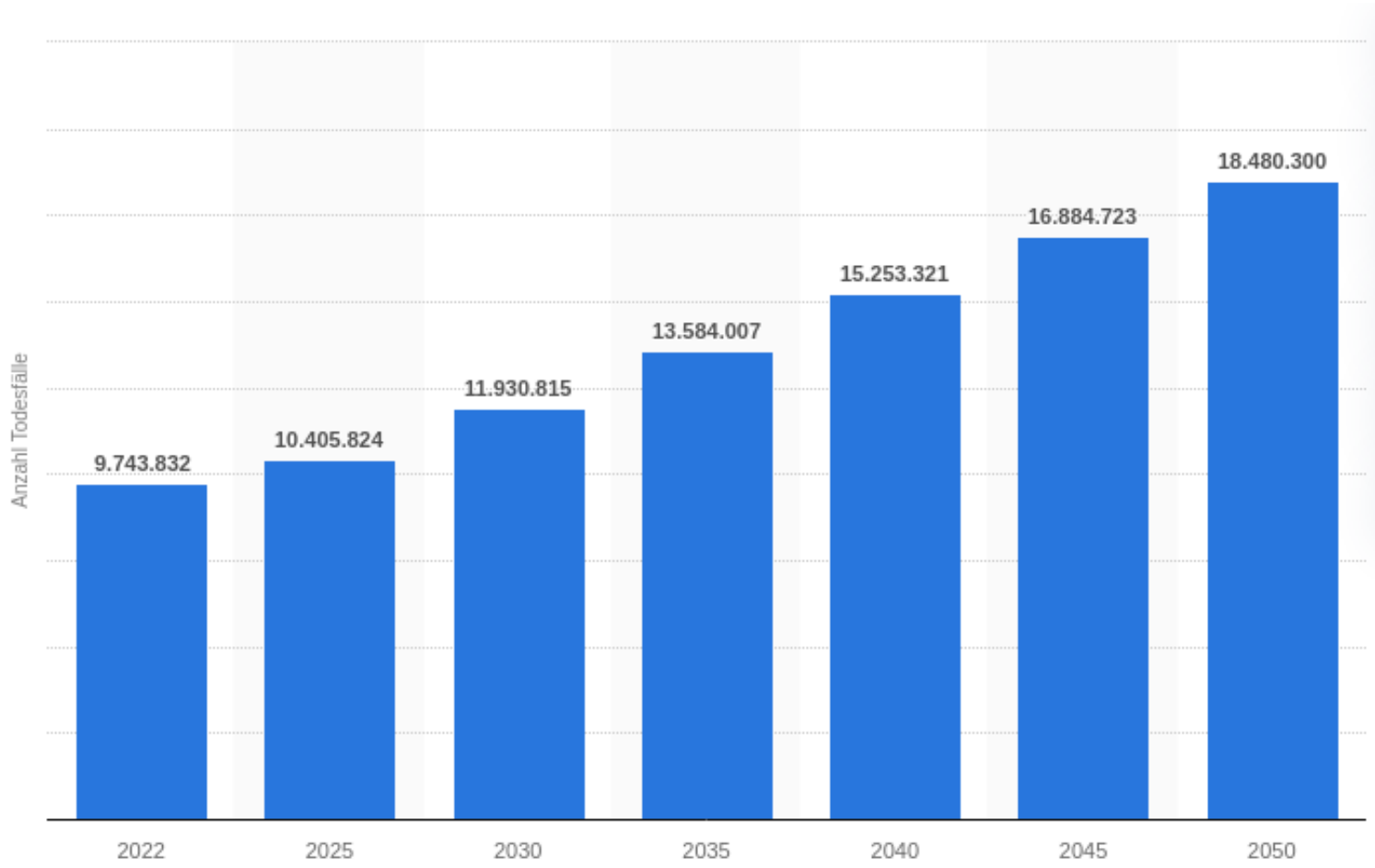
Supervisor: Aleksandra Wrońska

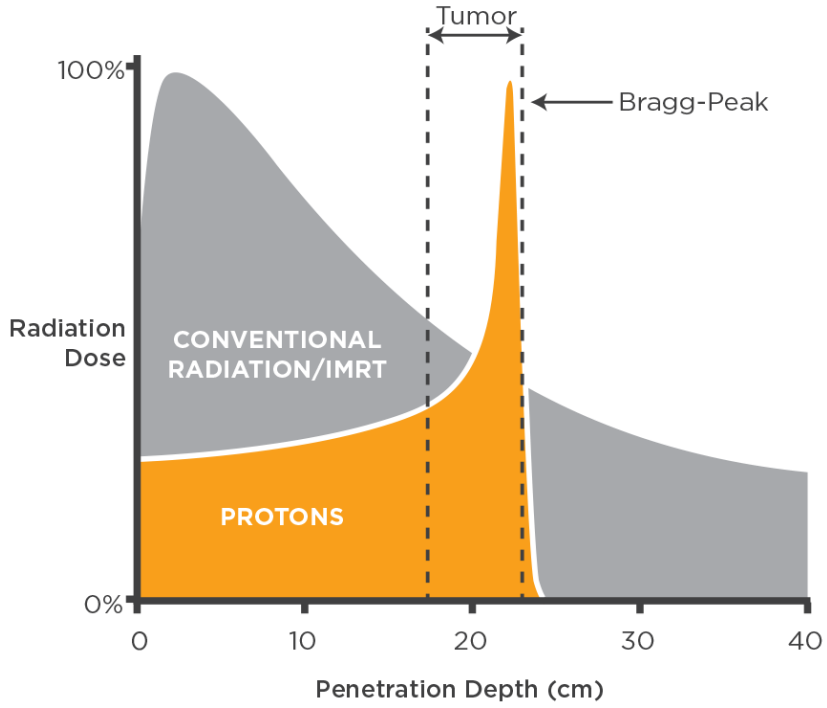
Cancer



International Agency for Research on Cancer

Proton therapy

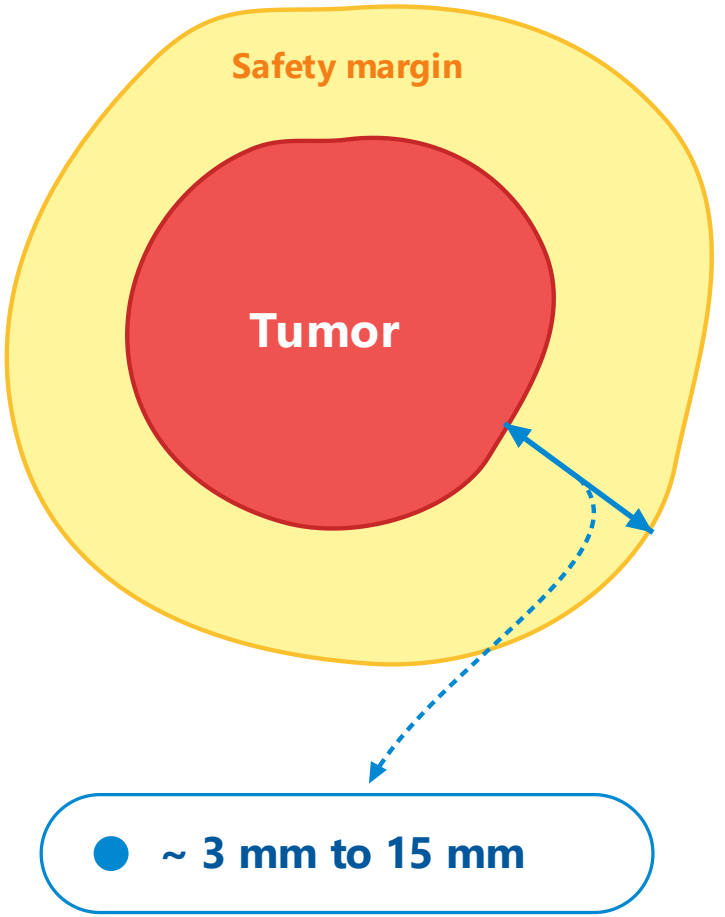
- X-rays have attenuation
- Proton energy loss peaks at track end (Bragg peak)



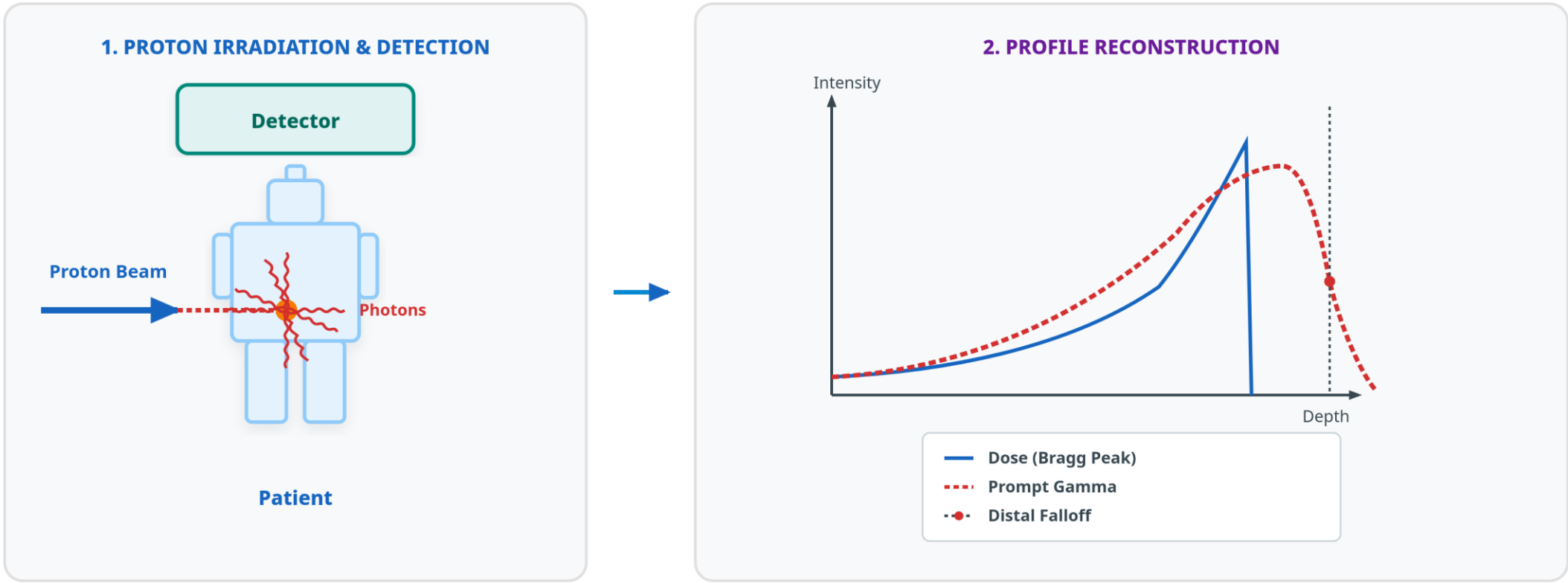
Knoxville proton

Why monitor proton therapy?

- Safety margins
  - Additional tissue irradiated to make sure the whole tumor gets dose
- Reduce safety margins
  - Reduce negative impact on patients
  - Improve outcomes and effectiveness

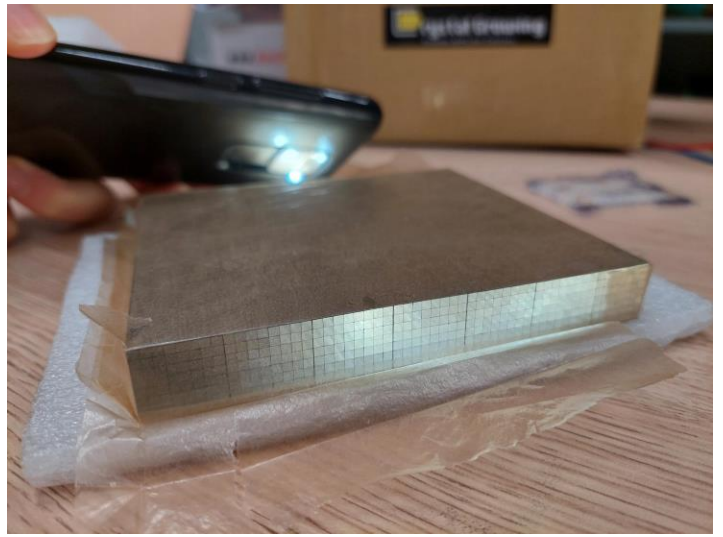


Prompt gamma imaging (PGI)



The SiFi detector module

- Scintillating fibres 1.94 x 1.94 x 100 mm³
  - Made from LYSO = heavy scintillator
  - Wrapped in aluminum foil to prevent crosstalk
  - Glued together to create module
  - Final module 14 x 110 x 100 mm³

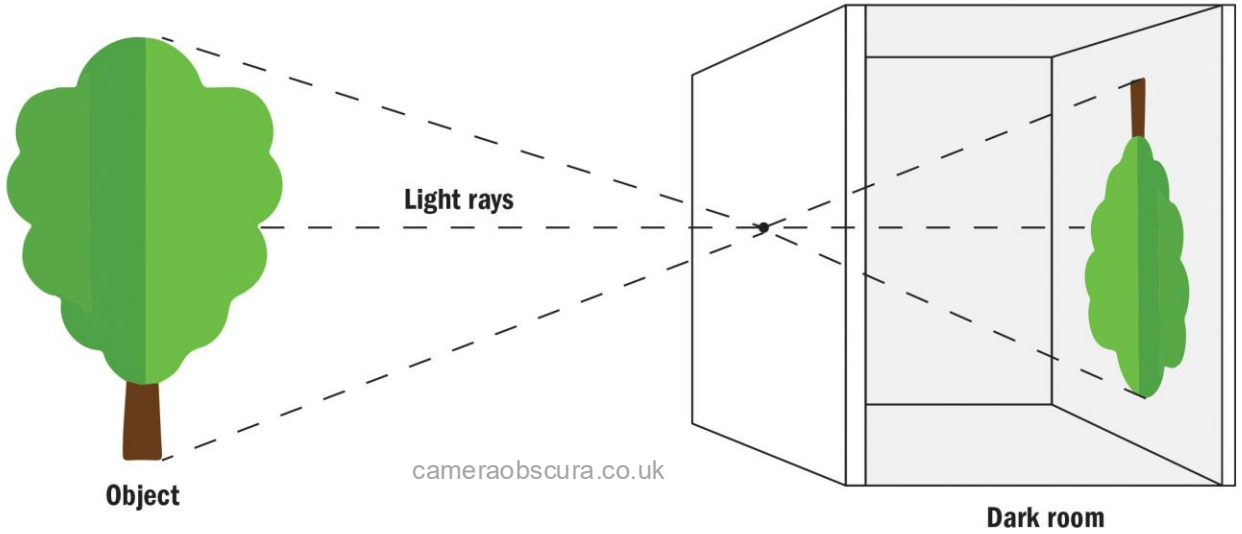


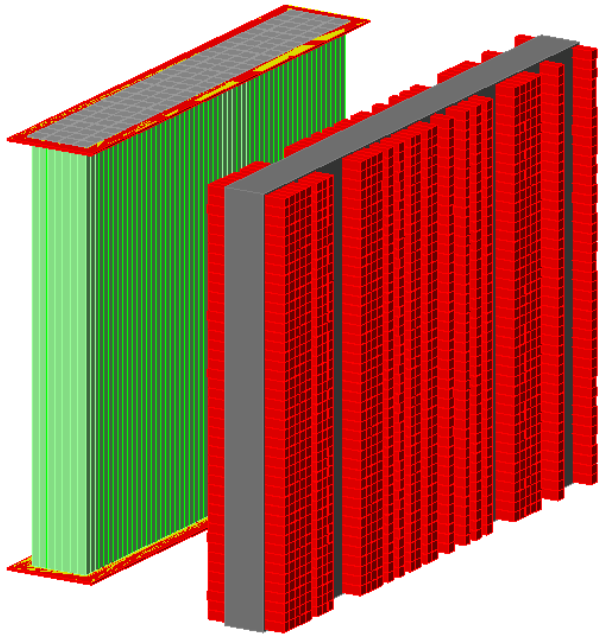
Coded Mask detector principle

Pinhole camera

(Camera obscura)

- Overlaying many pinholes
- More light passing through
- Image will be convoluted

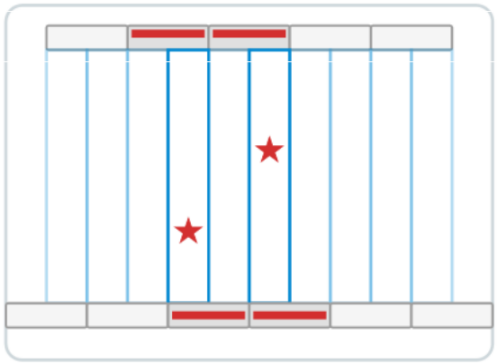


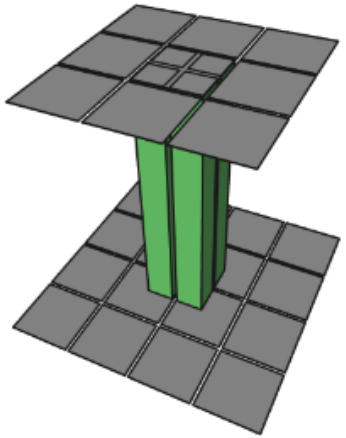


Ronja Hetzel

Near-field coded-mask technique and its potential for proton therapy monitoring (2023)

4-to-1 Coupling



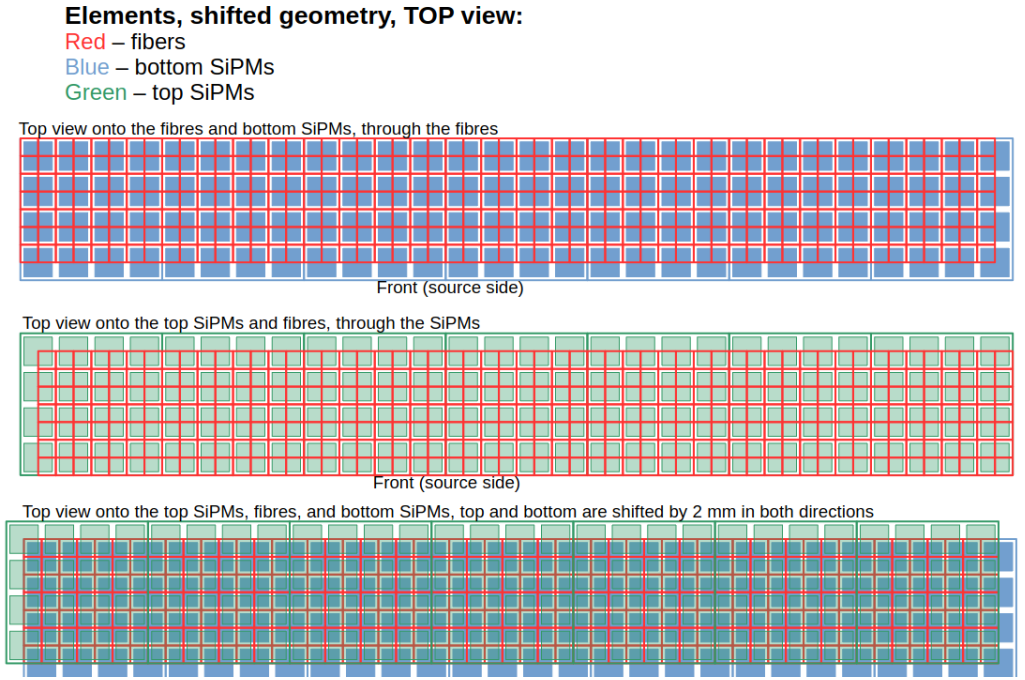


• Red Stars = Gamma Interactions

- 1 SiPM – 4 Fibers

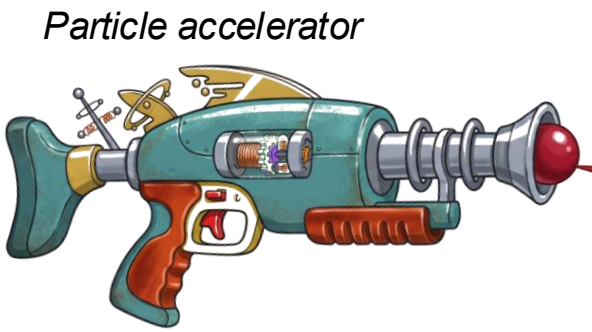
- Reduce number of channels
- Make final detector cheaper

- Leads to some ambiguity



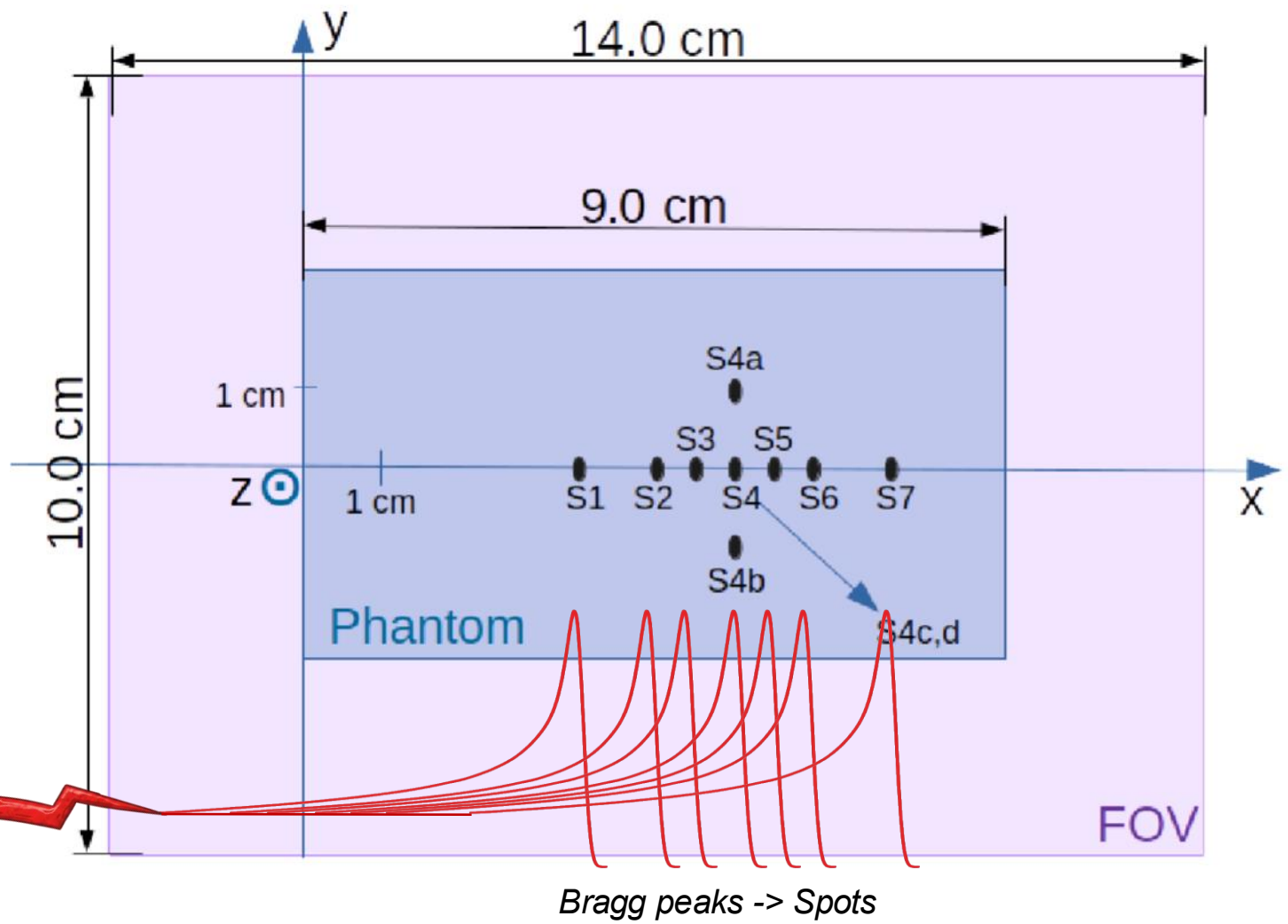
Irradiation plan

- Irradiation at 7 depths
- Sideways shifts in the middle position to investigate systematics



Particle accelerator

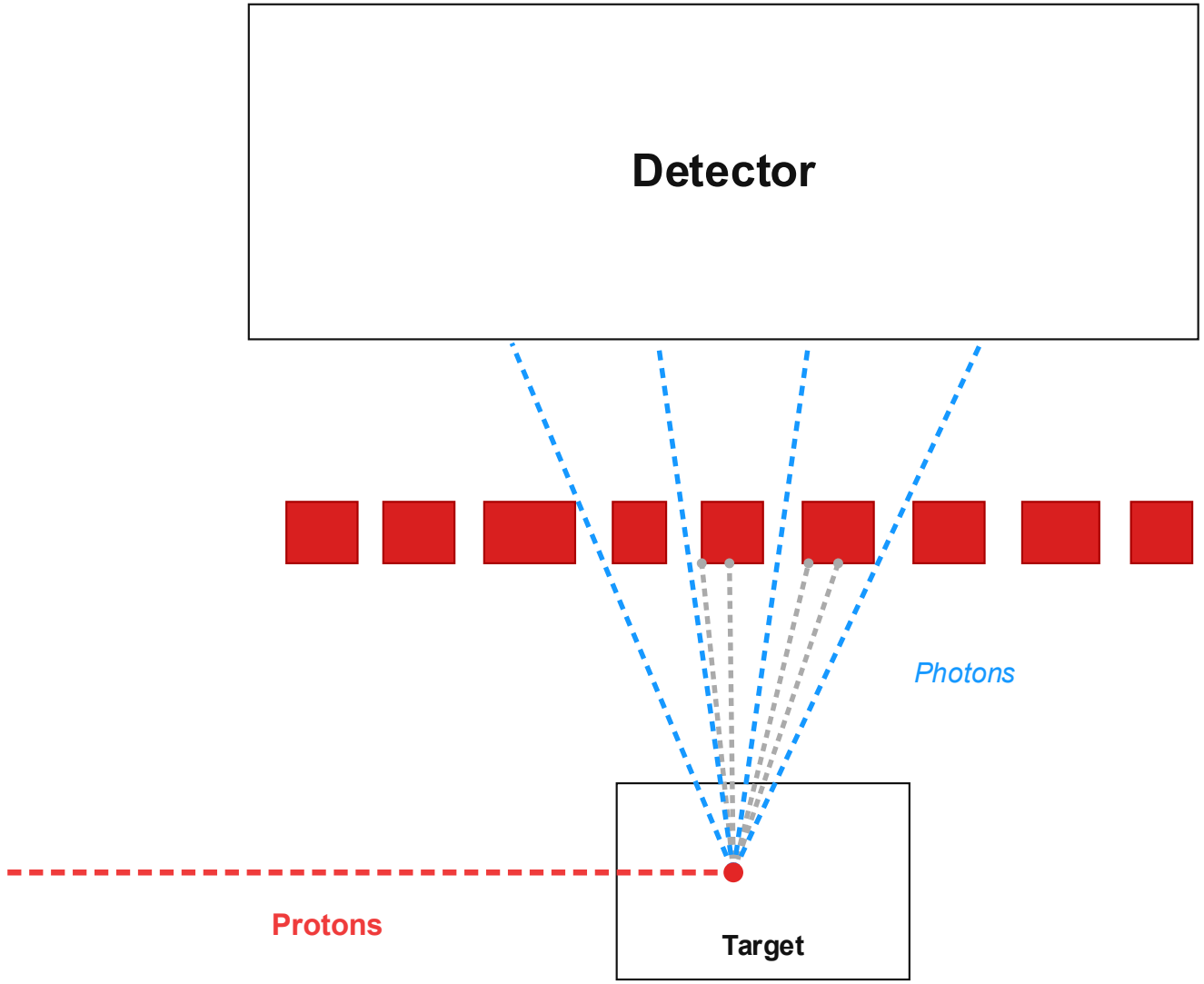
Protons

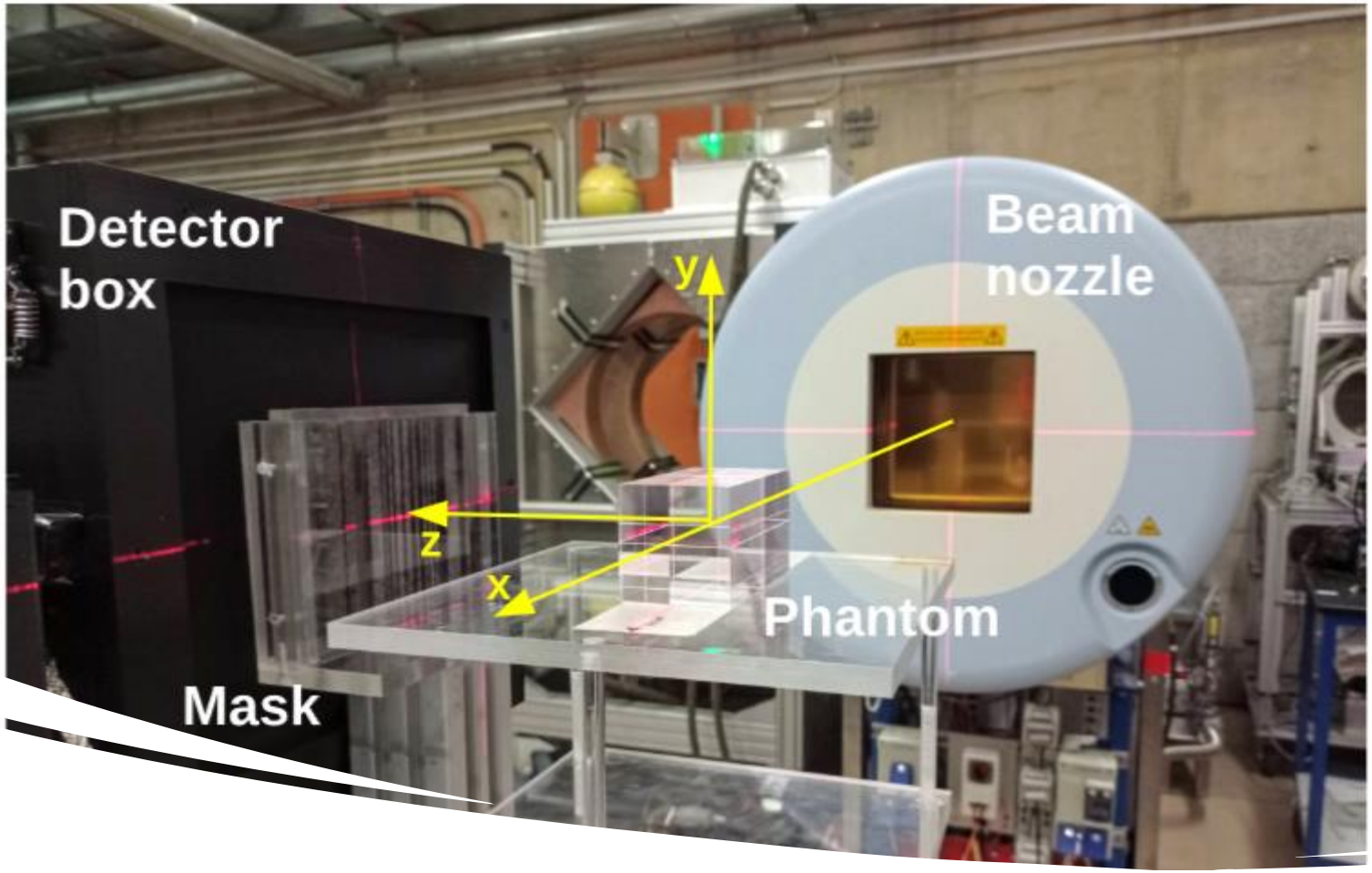


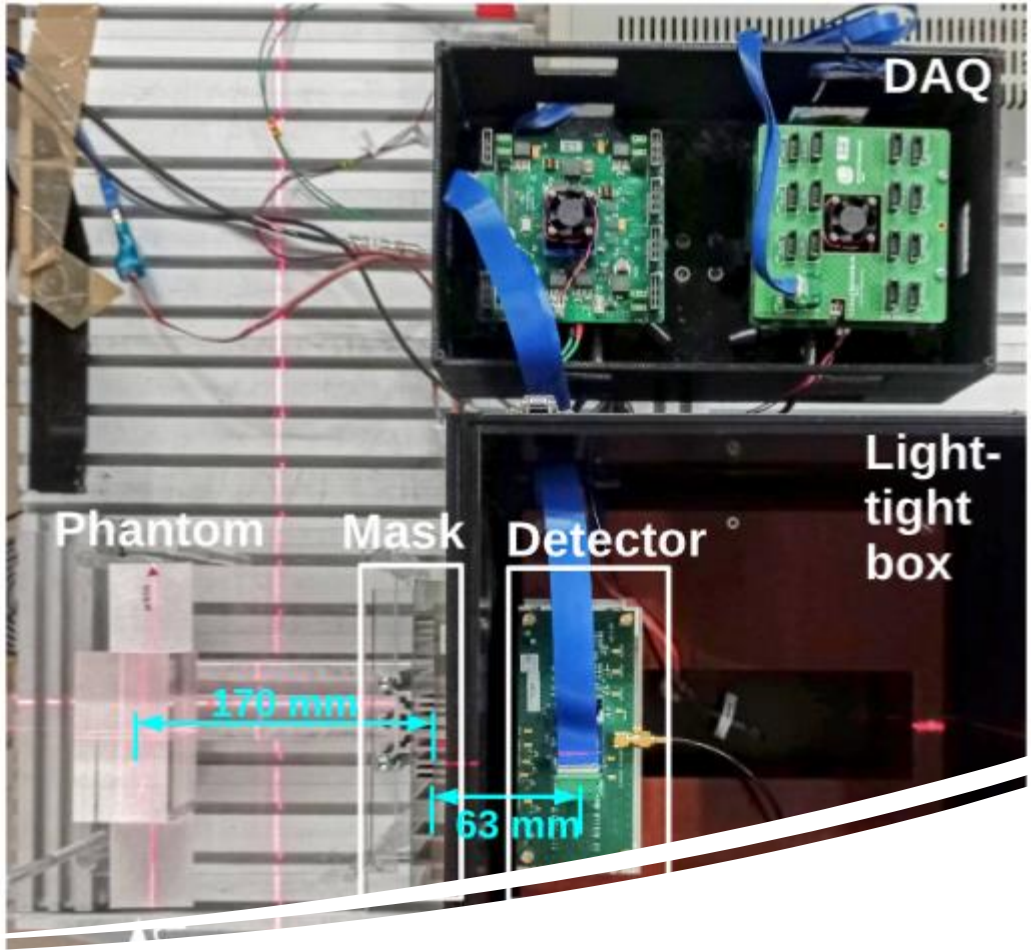
Bragg peaks -> Spots

Simulation

- Developed within the SiFi collaboration
- Provides SiPM response, fibre response, information used for training





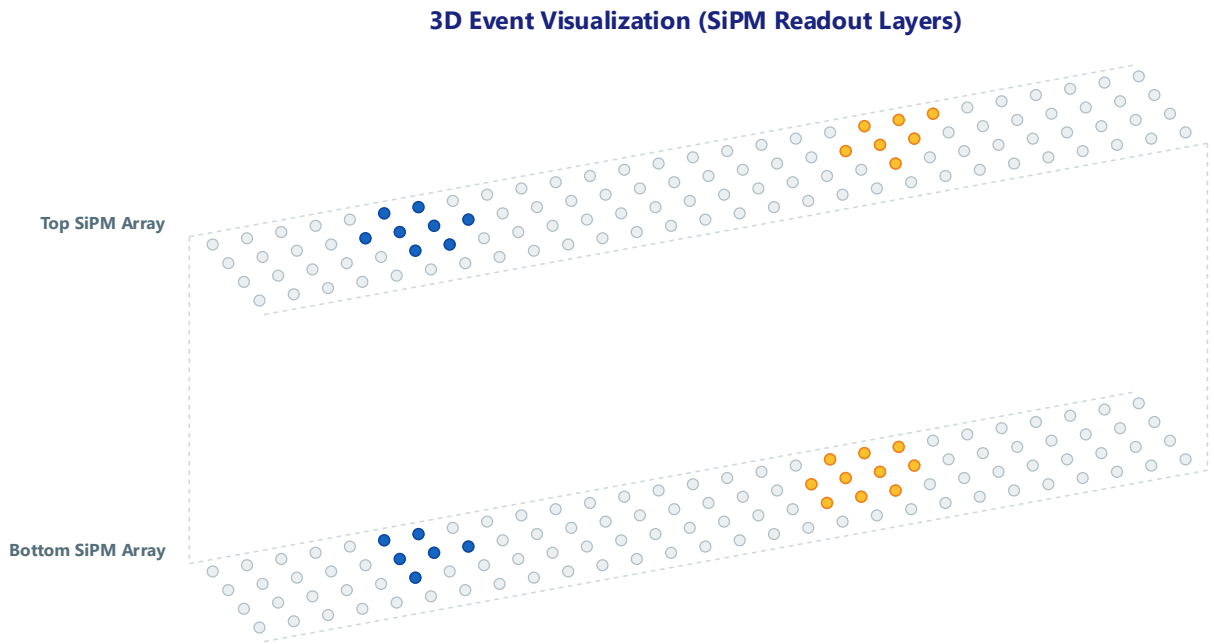


Experimental setup

HIT
Heidelberger Ionenstrahl-Therapiezentrum

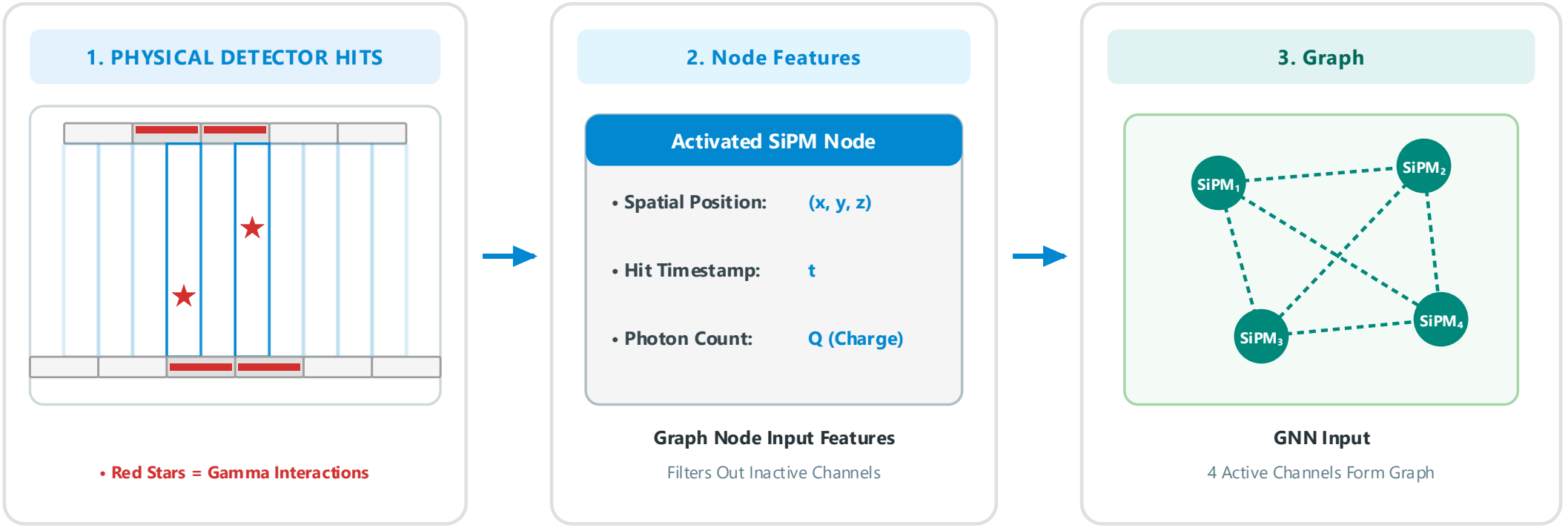
Clustering

- Event windows have 15ns and can have more than one interaction.
- Clustering method developed by Magdalena Kołodziej
  1. Find SiPM clusters on each side
  2. Find superclusters ("Clustered SiPM clusters")

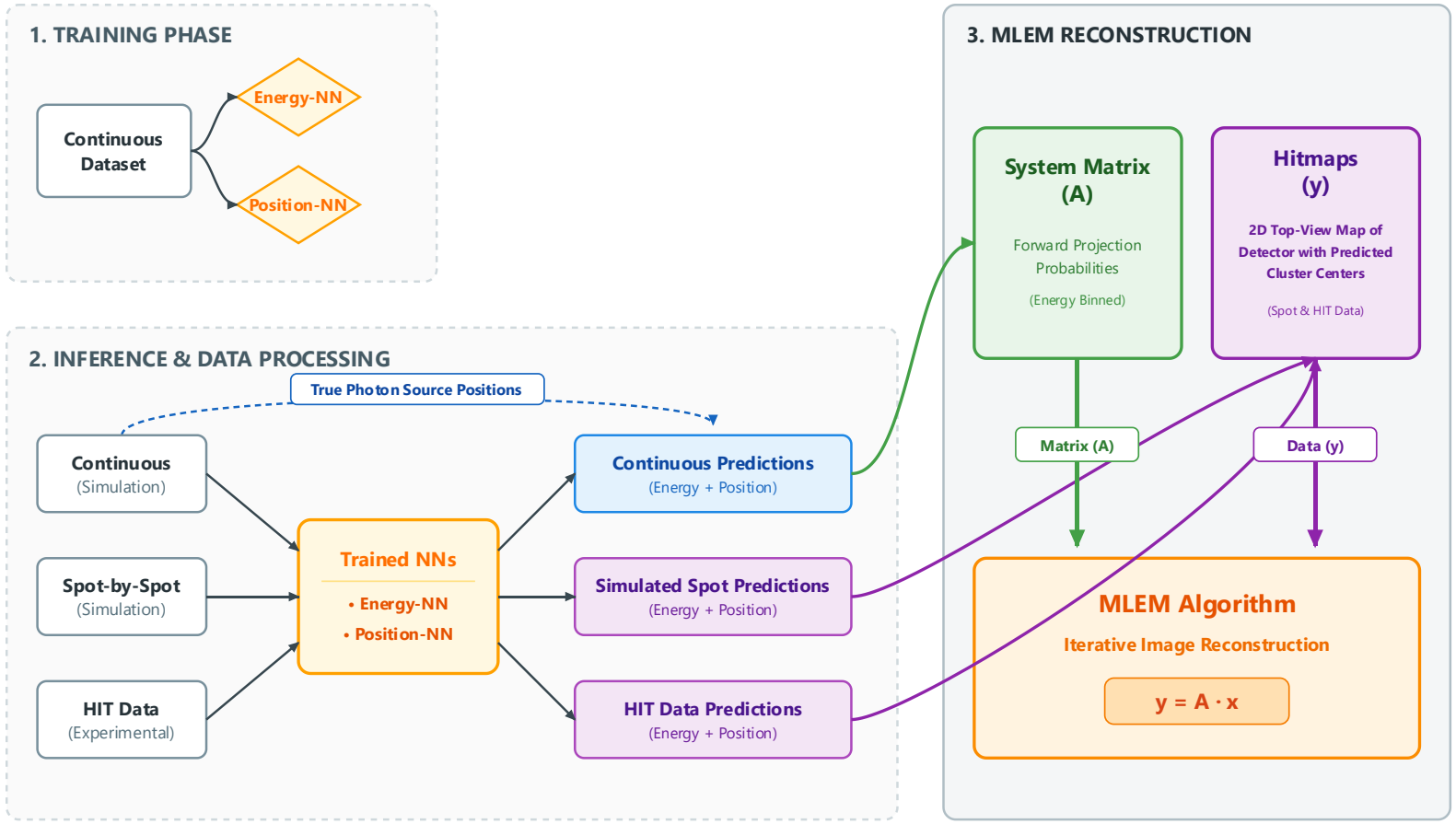


Creating graphs

- Detector has many channels corresponding to SiPMs.
- SiPM hits from simulations (GEANT4) or experiments form graph nodes.
- Node features capture crucial info like position, timestamp, and photon count.
- Edges connect all nodes (active SiPMs) in the graph.
- The goal is accurate interaction reconstruction (position and energy).

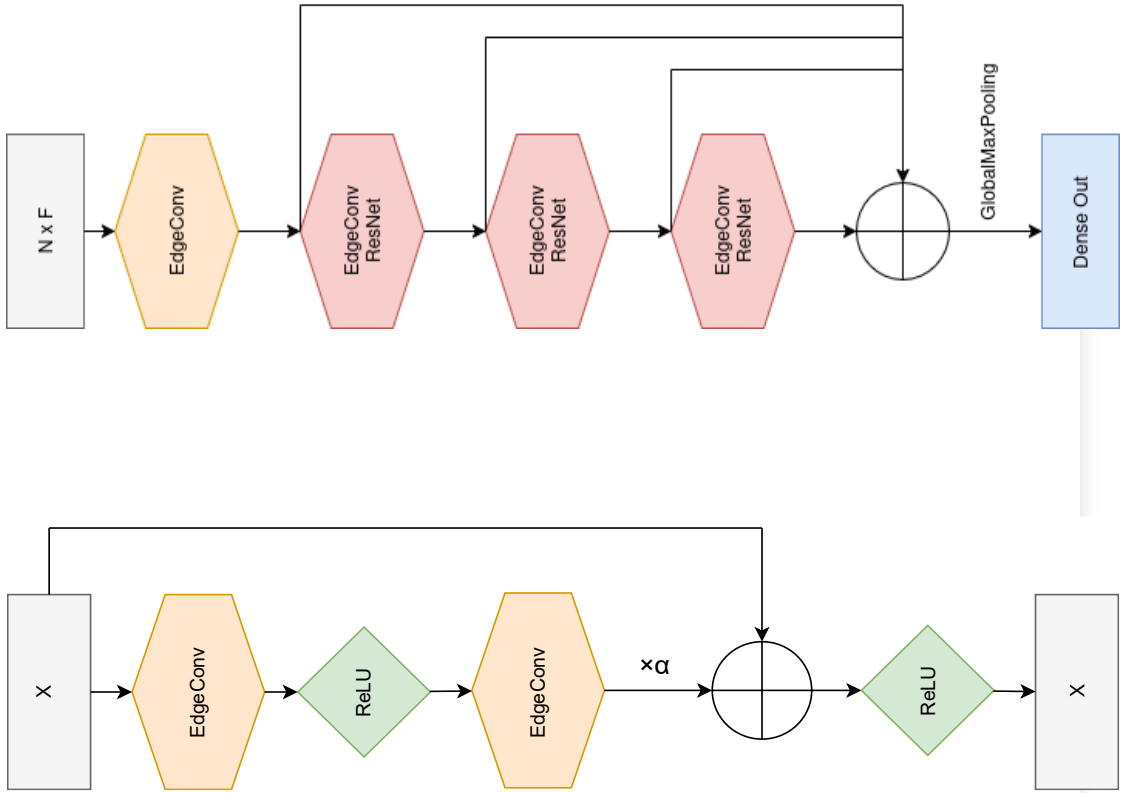


Network Usage

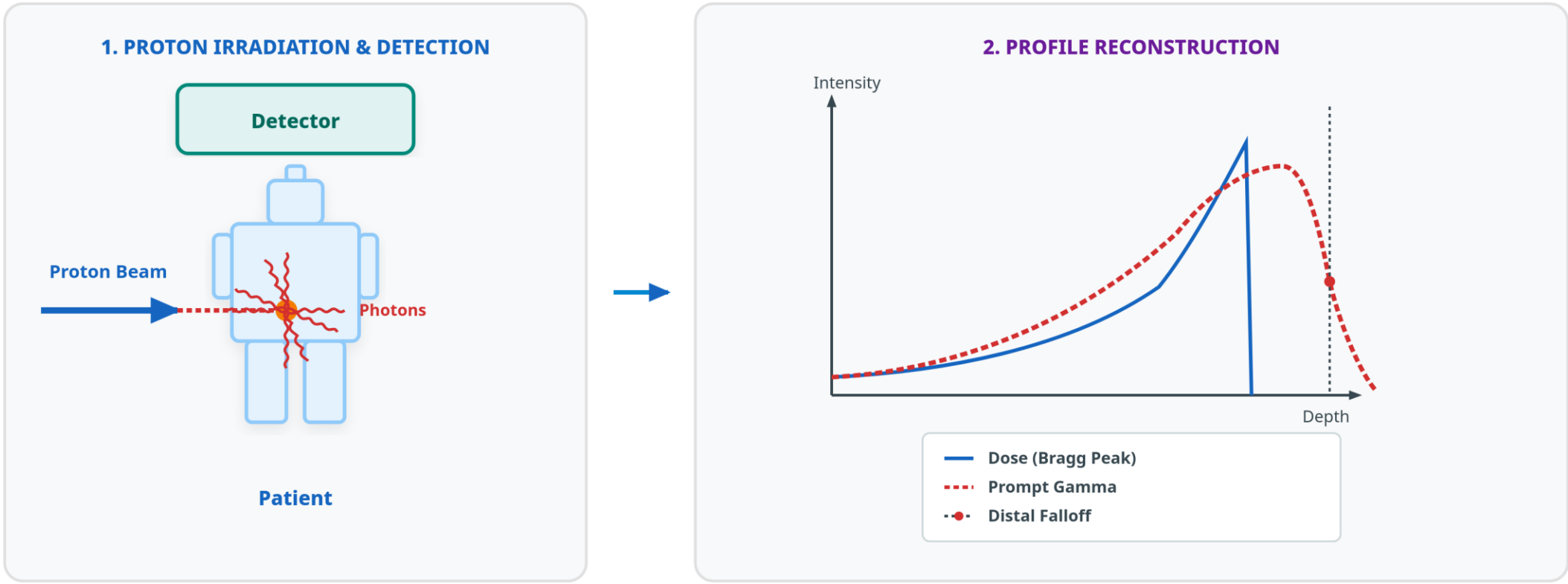


Network architecture

- EdgeConv layers
  - Infer features of the edges from nodes (SiPM data -> fibers)
  - ResNet architecture
  - Use repeating blocks with a skip connection
- ReZero layer
  - Add a weight to the skip connection



Recap: PGI


1. PROTON IRRADIATION & DETECTION
Detector
Proton Beam
Photons
Patient
2. PROFILE RECONSTRUCTION
Intensity
Depth
Dose (Bragg Peak)
Prompt Gamma
Distal Falloff

Towards image reconstruction

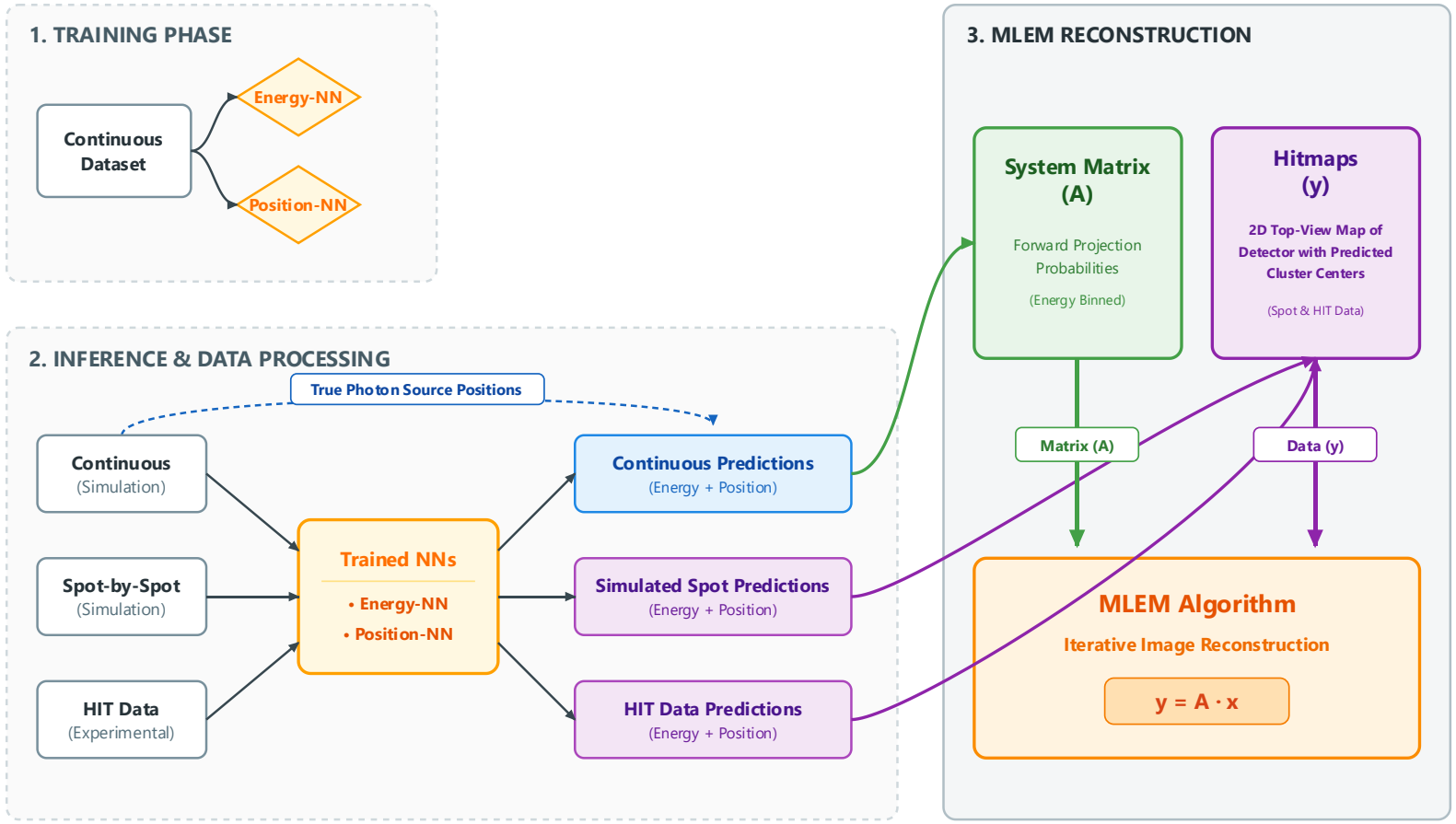
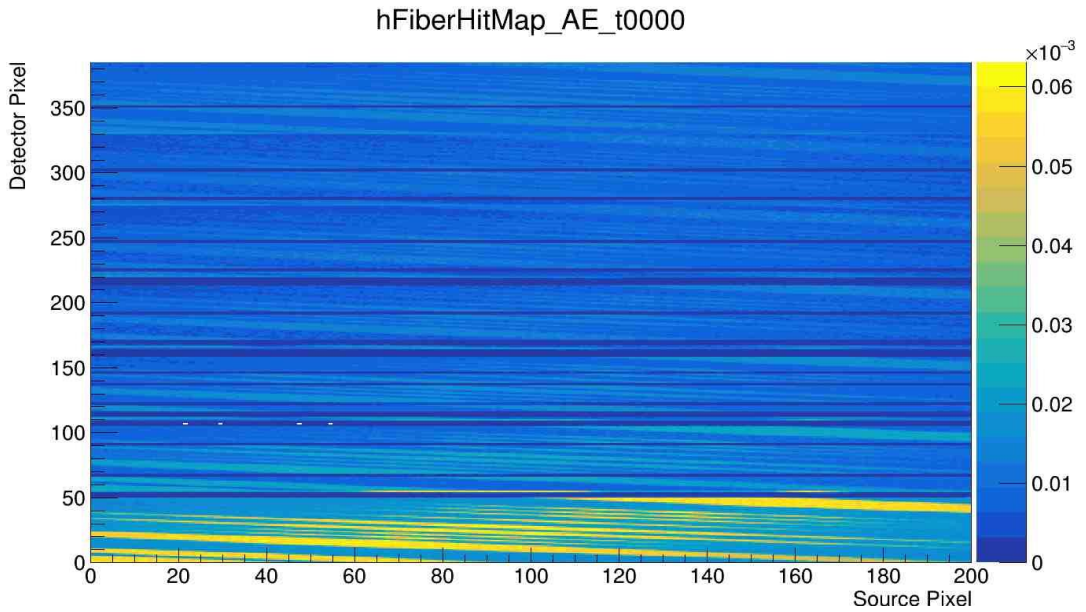
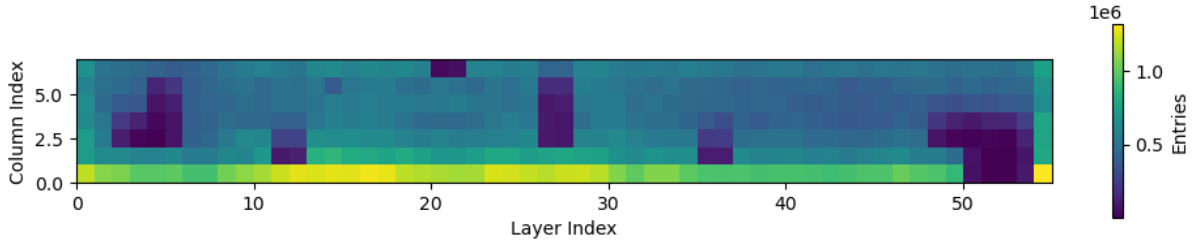


Image reconstruction

- Hitmap collects information about all reconstructed hit positions
- System matrix holds information about geometrical mapping and probabilities
- MLEM returns contributions of different source positions

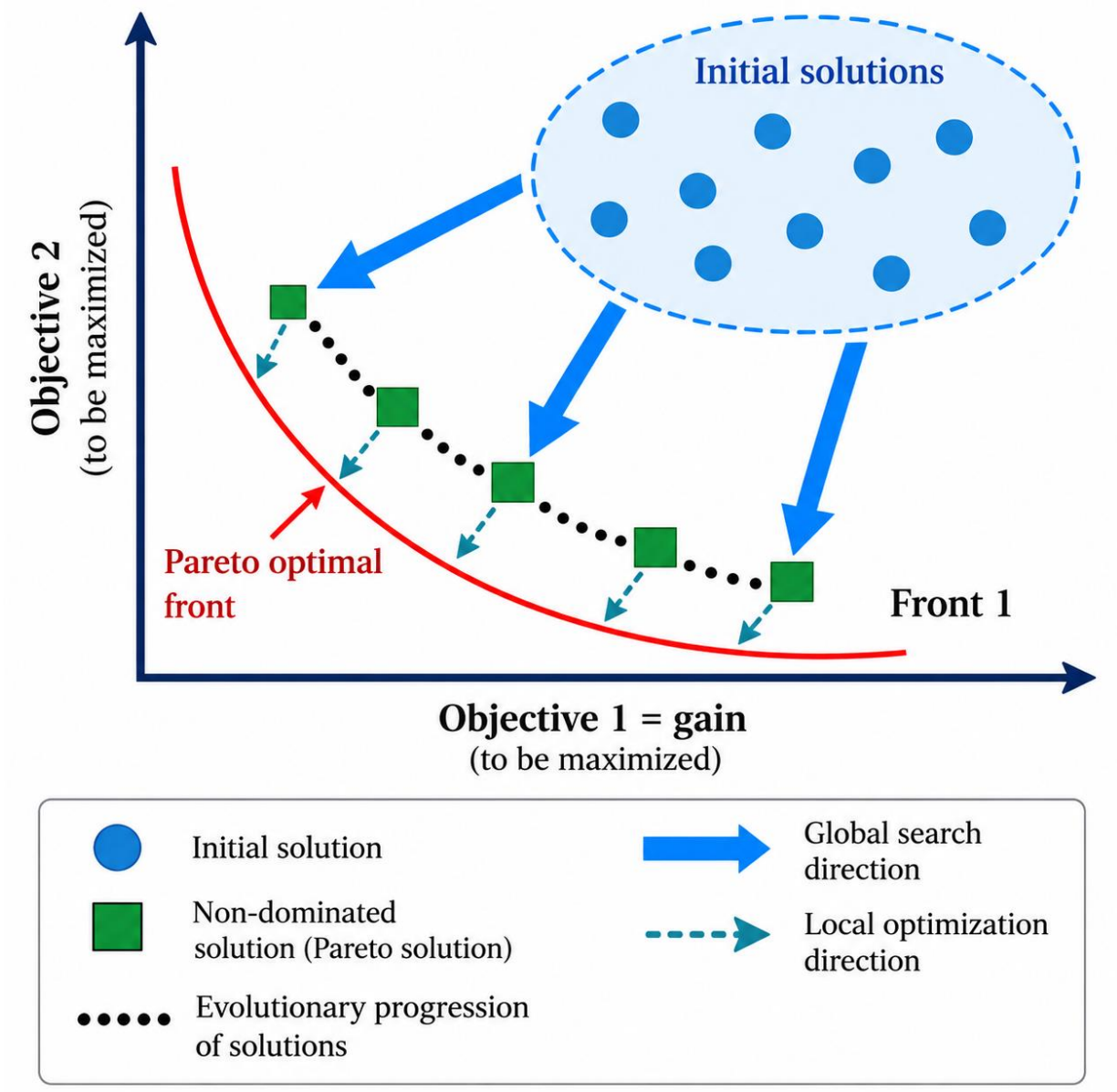




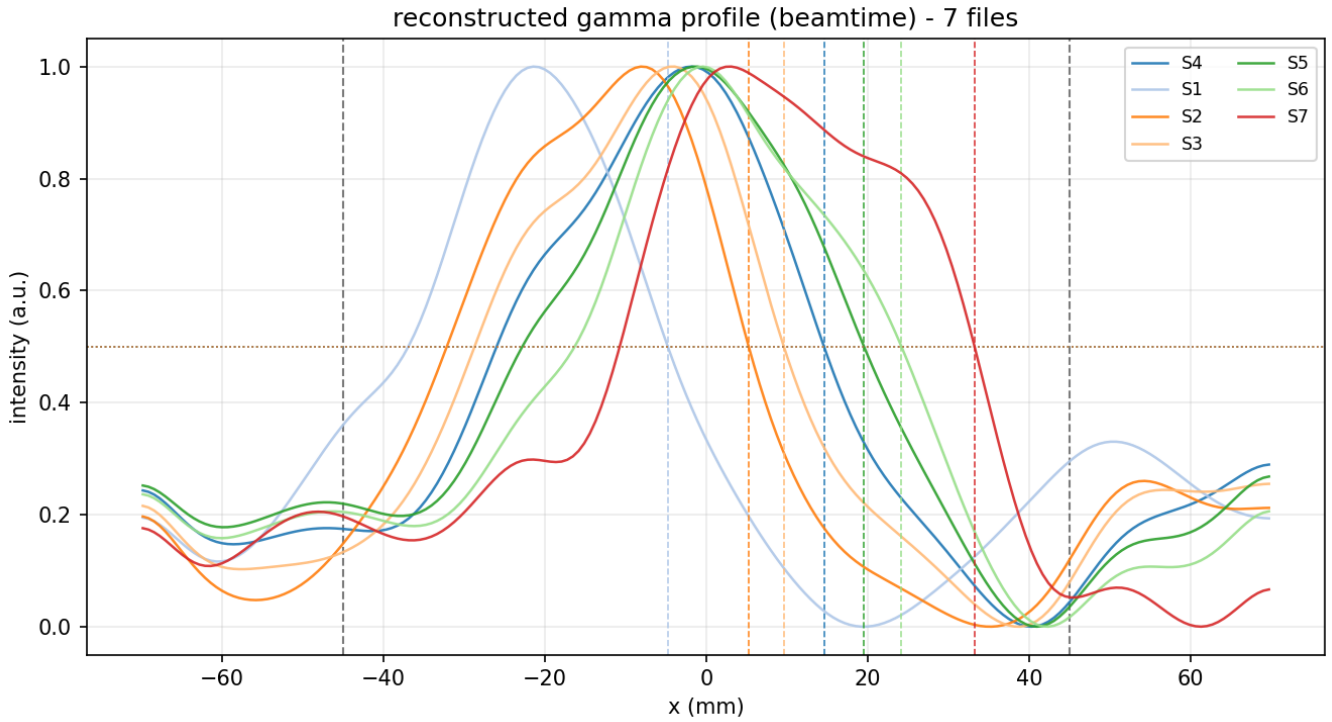
Issue: Some SiPMs not soldered correctly

Optimizing the image reconstruction

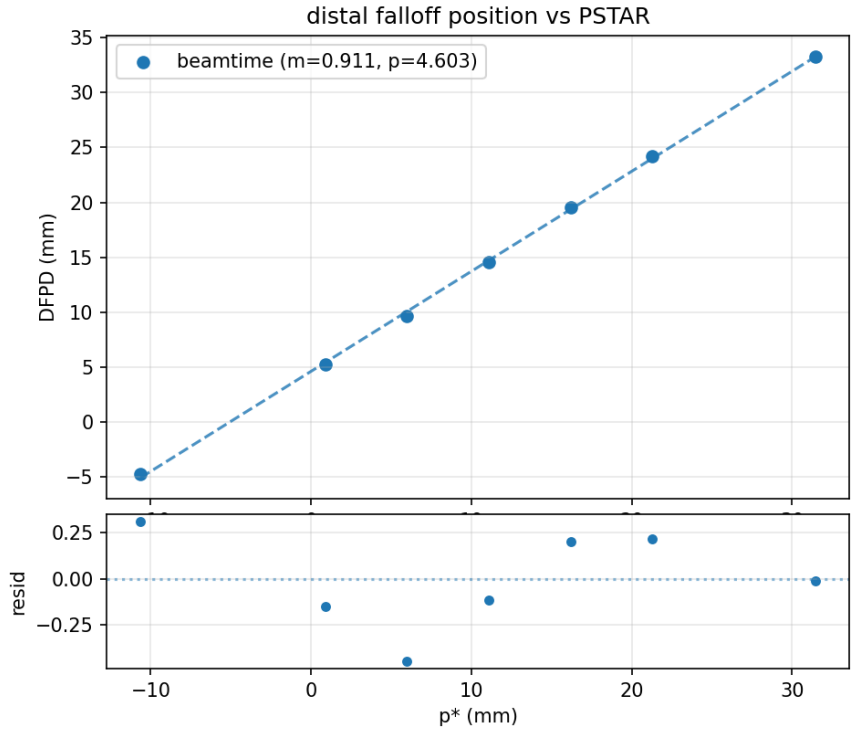
- Systematic approach needed to tune all parameters (Excluded detector parts, number of iterations, smoothing,…)
- Genetic algorithm
  - Use 6 metrics (RMSE, PCC, R^2,χ^2/ndf, $(\text{Slope}-1)^2$, uncertainties of spots at the same depth)
  - Too many dimensions for single optimum, but reduces number of competitors by giving Pareto front runs



Results (preliminary)



Proton beam direction



Comparison

First experimental test of a coded-mask gamma camera for proton therapy monitoring

Magdalena Kołodziej*, Stephan Brons, Mikołaj Dubiel, George N Farah, Alexander Fenger, Ronja Hetzel, Jonas Kasper, Monika Kercz, Barbara Kołodziej, Linn Mielke, Gabriel Ostrzołek, Magdalena Rafecas, Jorge Roser, Katarzyna Rusiecka*, Achim Stahl, Vitalii Urbanevych, Ming-Liang Wong and Aleksandra Wrońska ▲ Hide full author list

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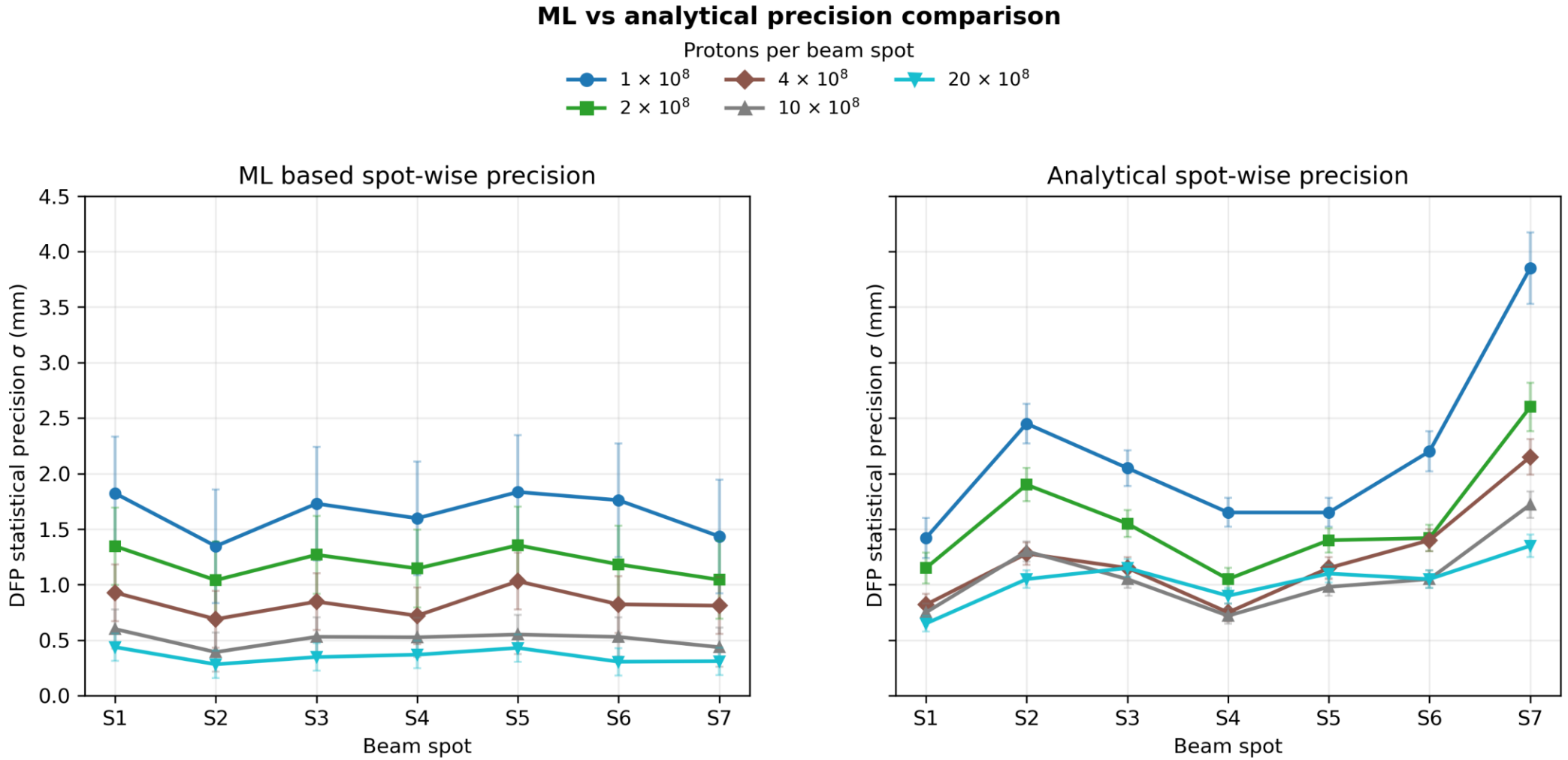
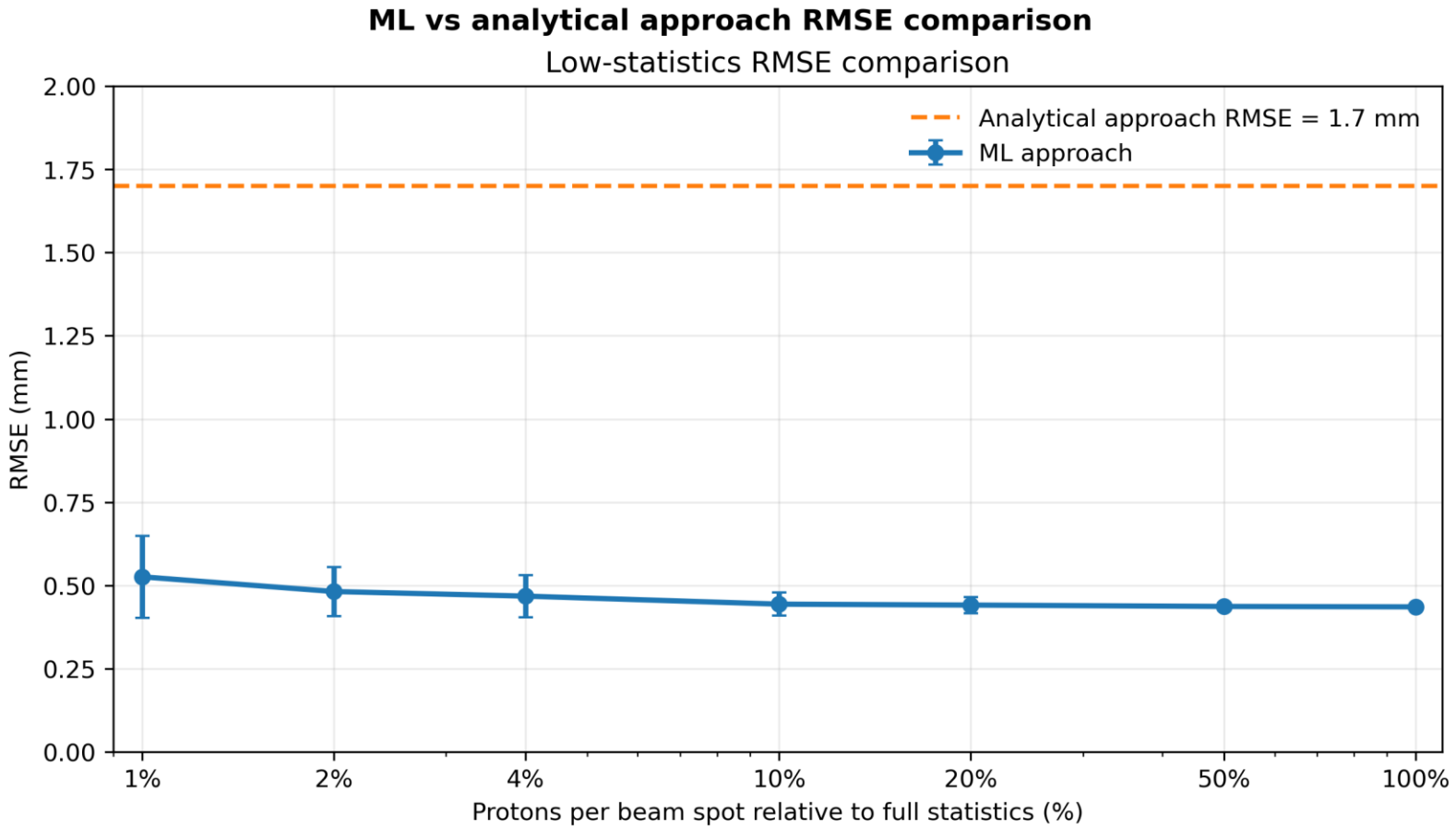
Statistical precision comparison (preliminary)





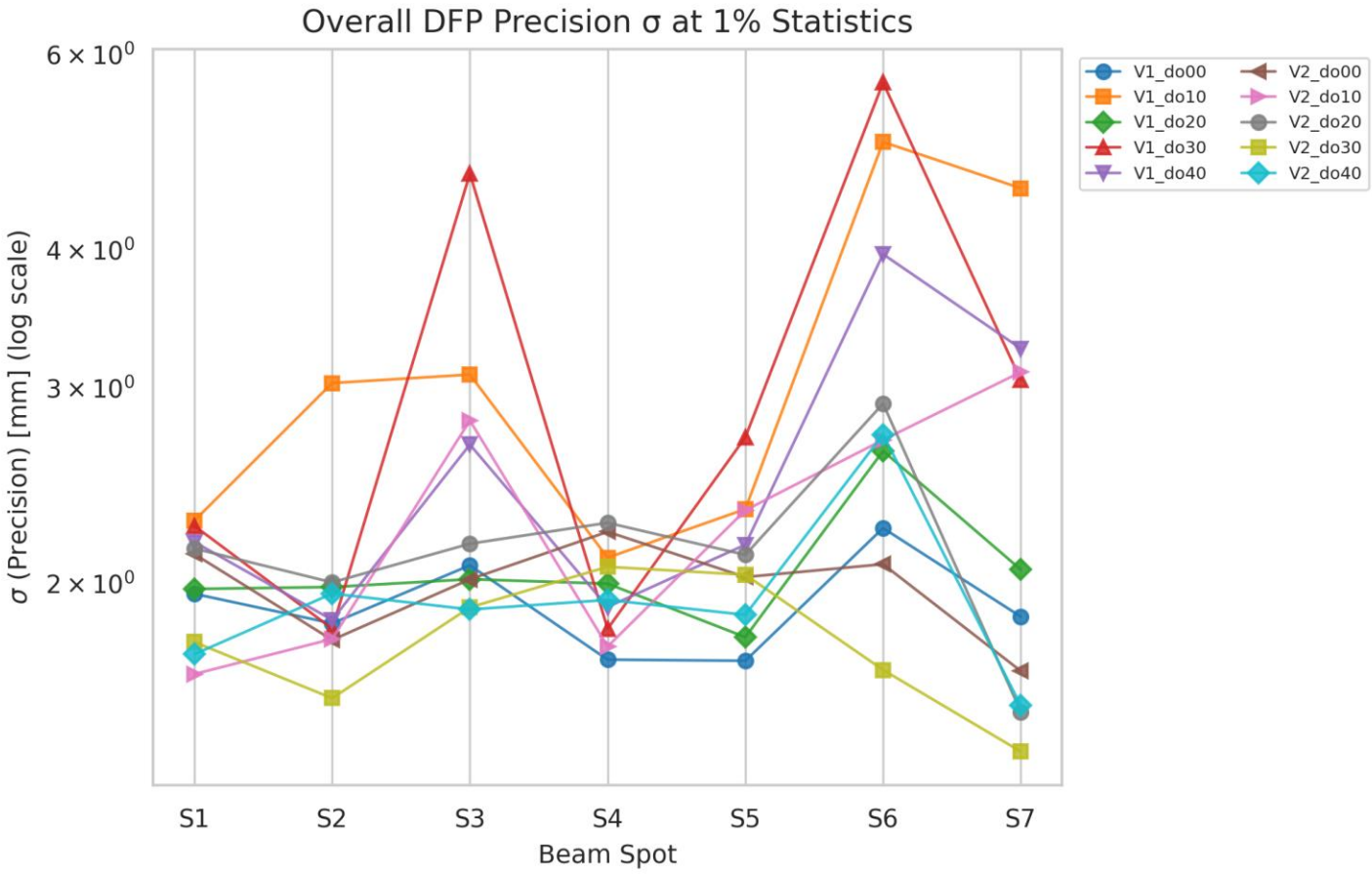
Root mean square error (RMSE) comparison (preliminary)

Thank you for your attention!

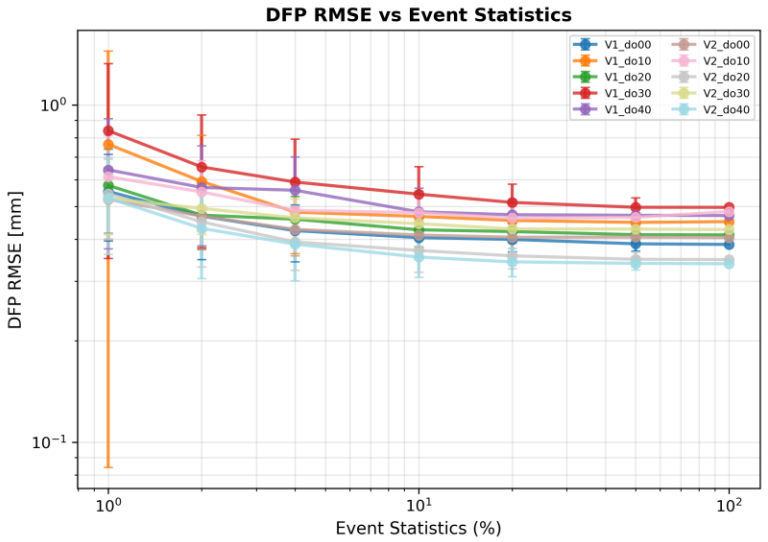
SiFi-CC

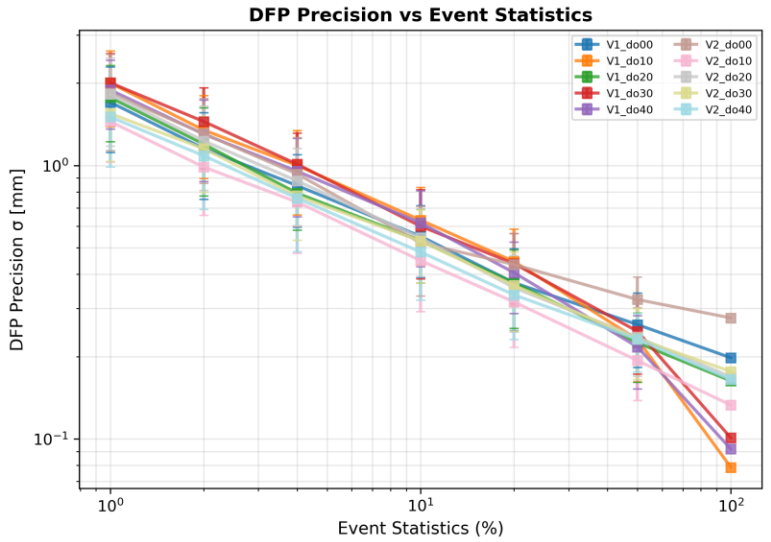
Collaboration Website

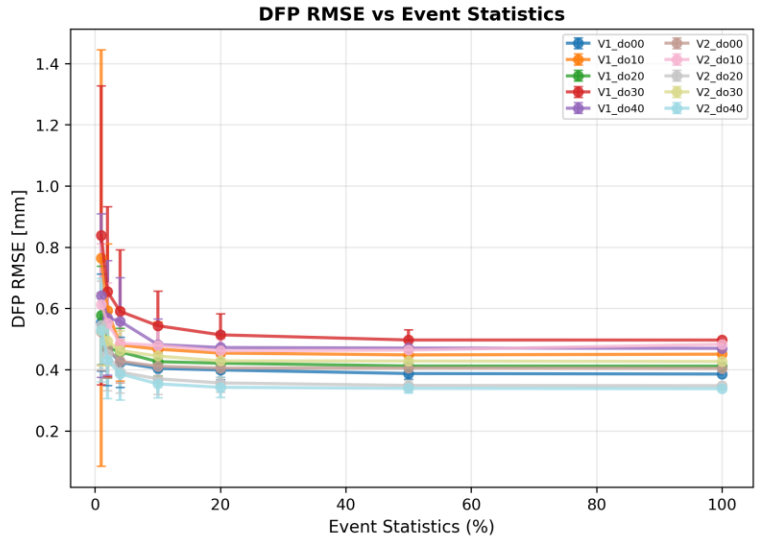
Results

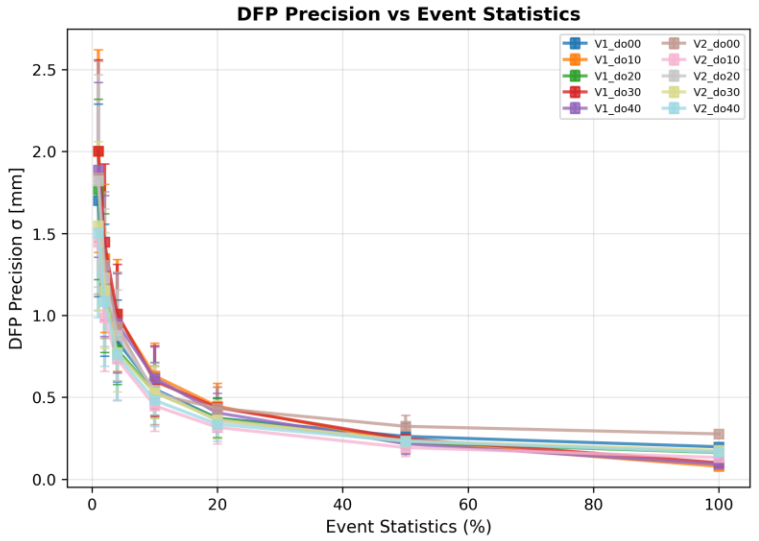

Overall DFP Precision σ at 1% Statistics
σ (Precision) [mm] (log scale)
6 × 10^0
4 × 10^0
3 × 10^0
2 × 10^0
S1
S2
S3
S4
S5
S6
S7
Beam Spot
V1_do00
V1_do10
V1_do20
V1_do30
V1_do40
V2_do00
V2_do10
V2_do20
V2_do30
V2_do40

Results

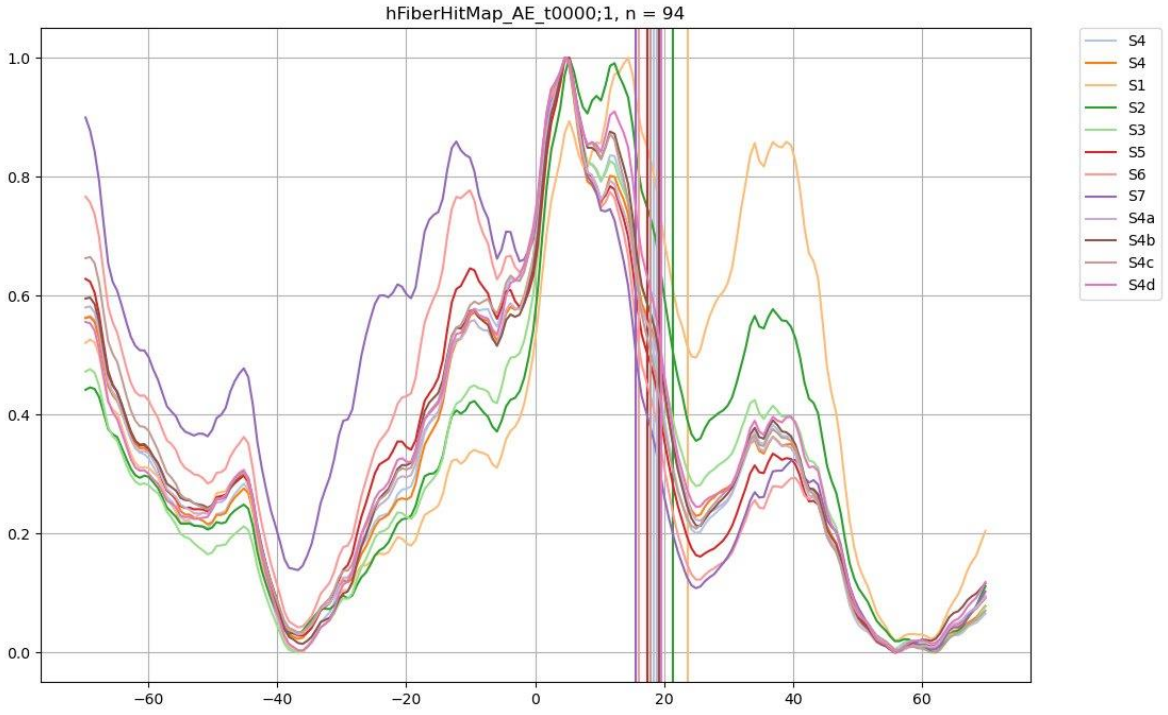

DFP RMSE vs Event Statistics
DFP RMSE [mm]
Event Statistics (%)
V1_do00
V1_do10
V1_do20
V1_do30
V1_do40
V2_do00
V2_do10
V2_do20
V2_do30
V2_do40

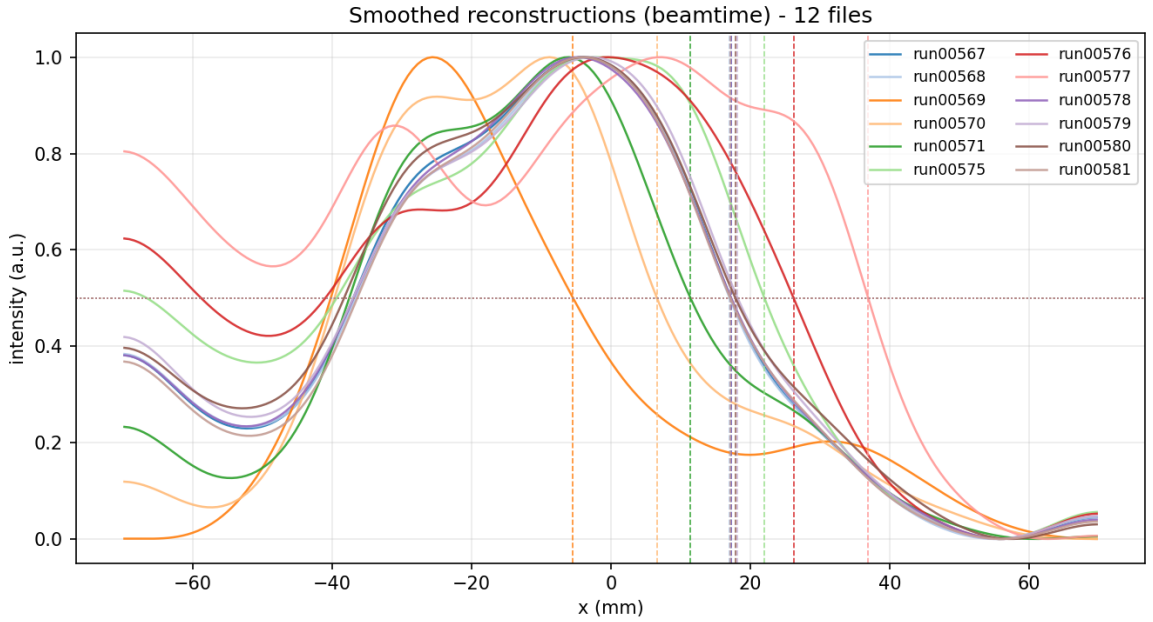

DFP Precision vs Event Statistics
DFP Precision σ [mm]
Event Statistics (%)
V1_do00
V1_do10
V1_do20
V1_do30
V1_do40
V2_do00
V2_do10
V2_do20
V2_do30
V2_do40

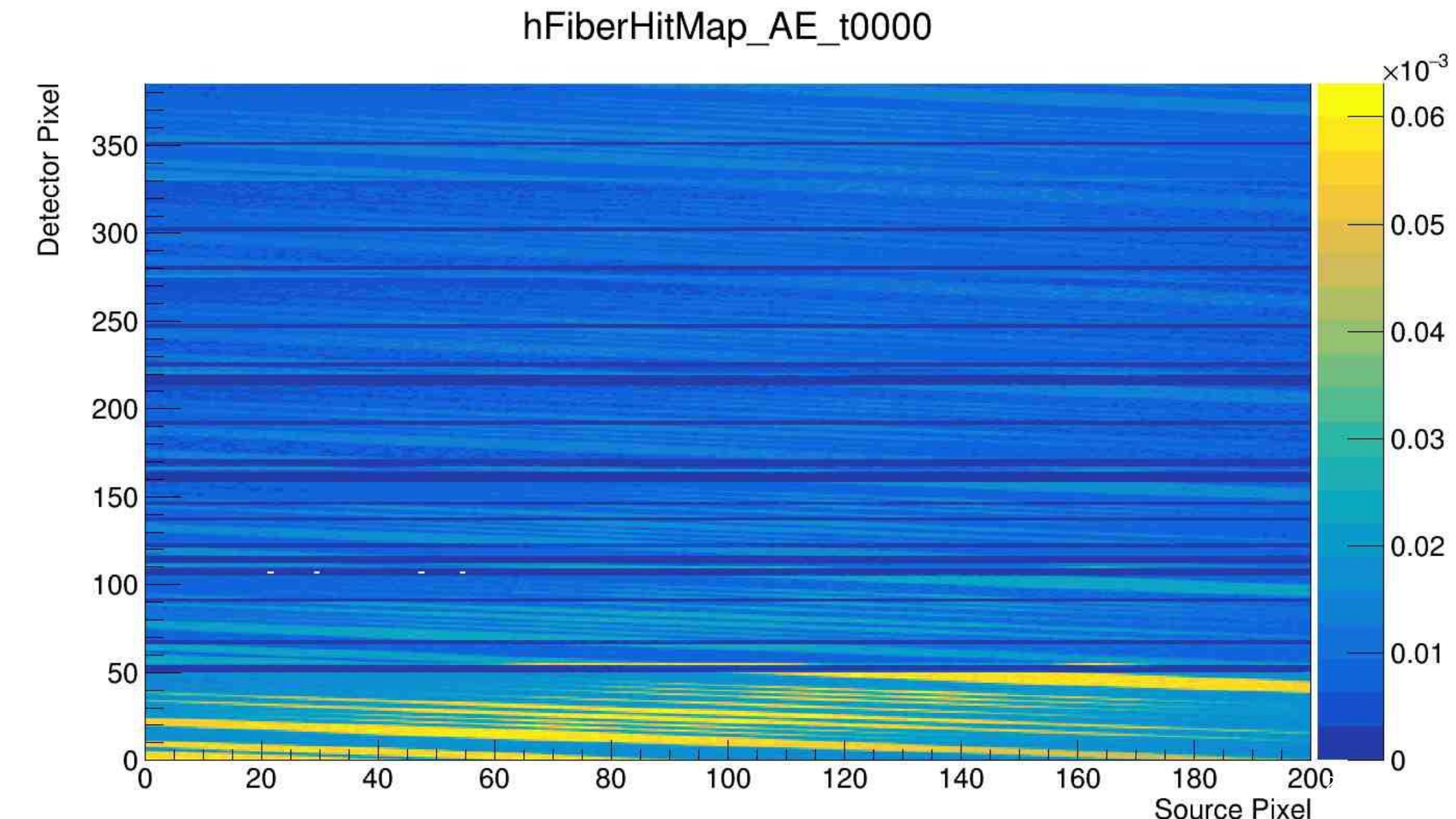

DFP RMSE vs Event Statistics
DFP RMSE [mm]
Event Statistics (%)
V1_do00
V1_do10
V1_do20
V1_do30
V1_do40
V2_do00
V2_do10
V2_do20
V2_do30
V2_do40

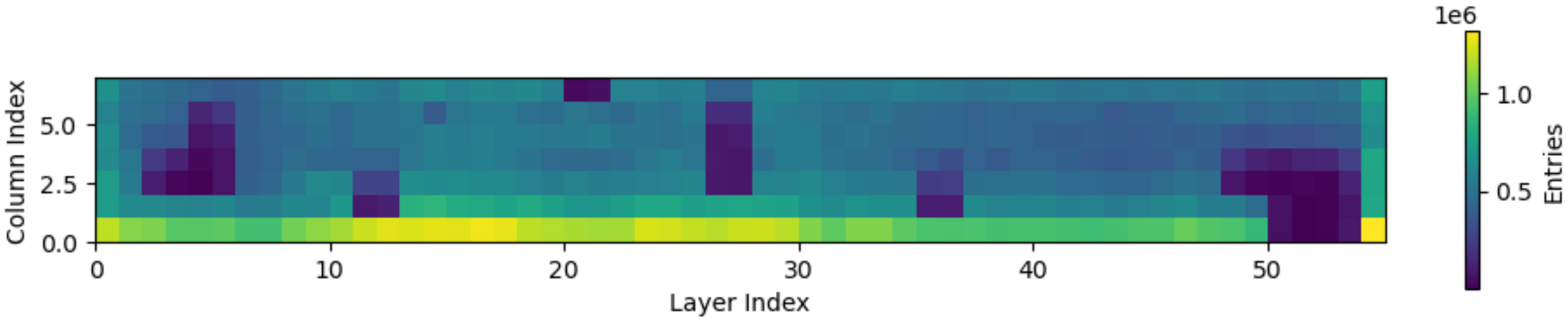

DFP Precision vs Event Statistics
DFP Precision σ [mm]
Event Statistics (%)
V1_do00
V1_do10
V1_do20
V1_do30
V1_do40
V2_do00
V2_do10
V2_do20
V2_do30
V2_do40

Comparison to previous work






hFiberHitMap_AE_t0000
Detector Pixel
Source Pixel
×10⁻³
0
50
100
150
200
250
300
350
0
20
40
60
80
100
120
140
160
180
200
0
0.01
0.02
0.03
0.04
0.05
0.06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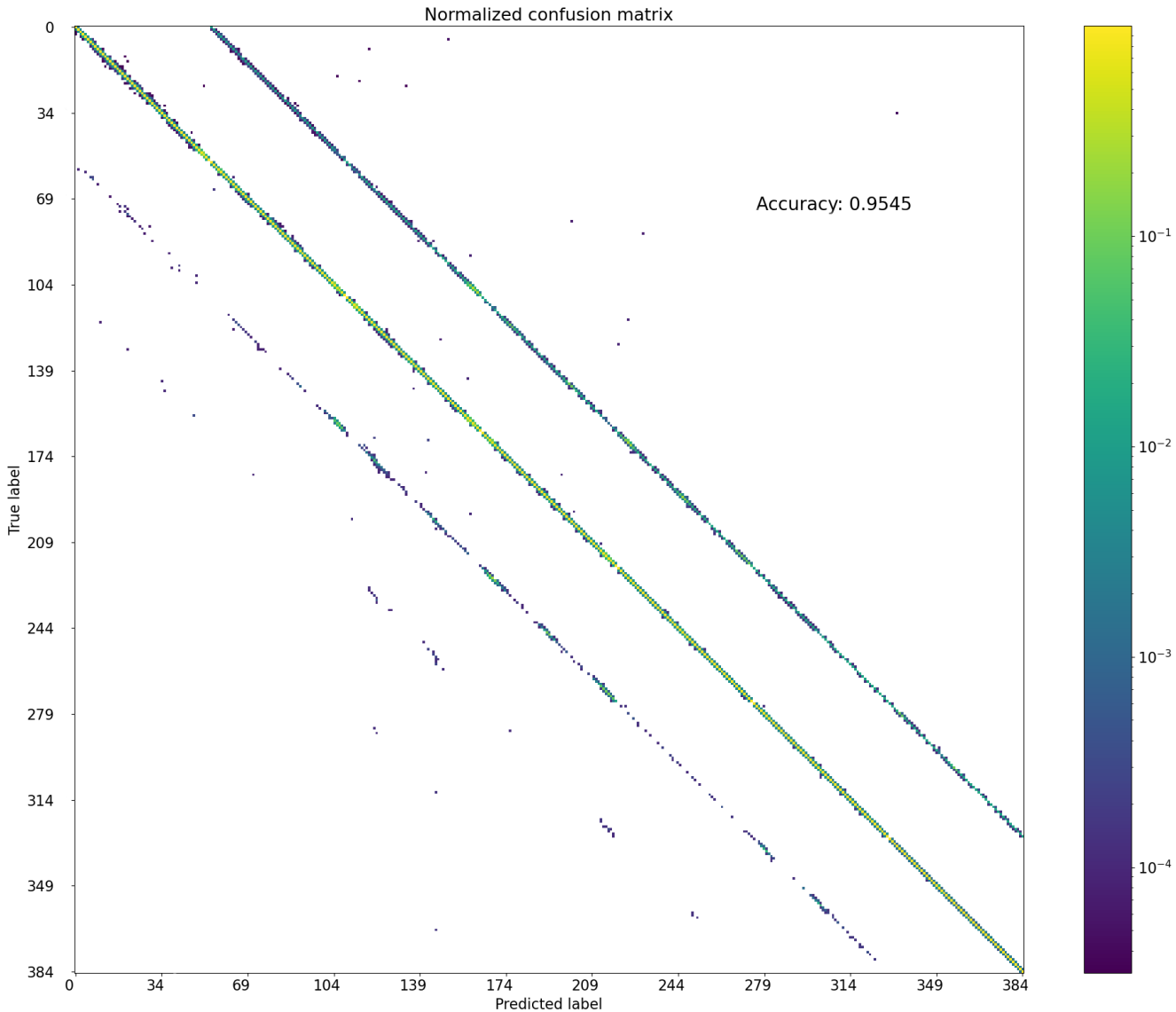
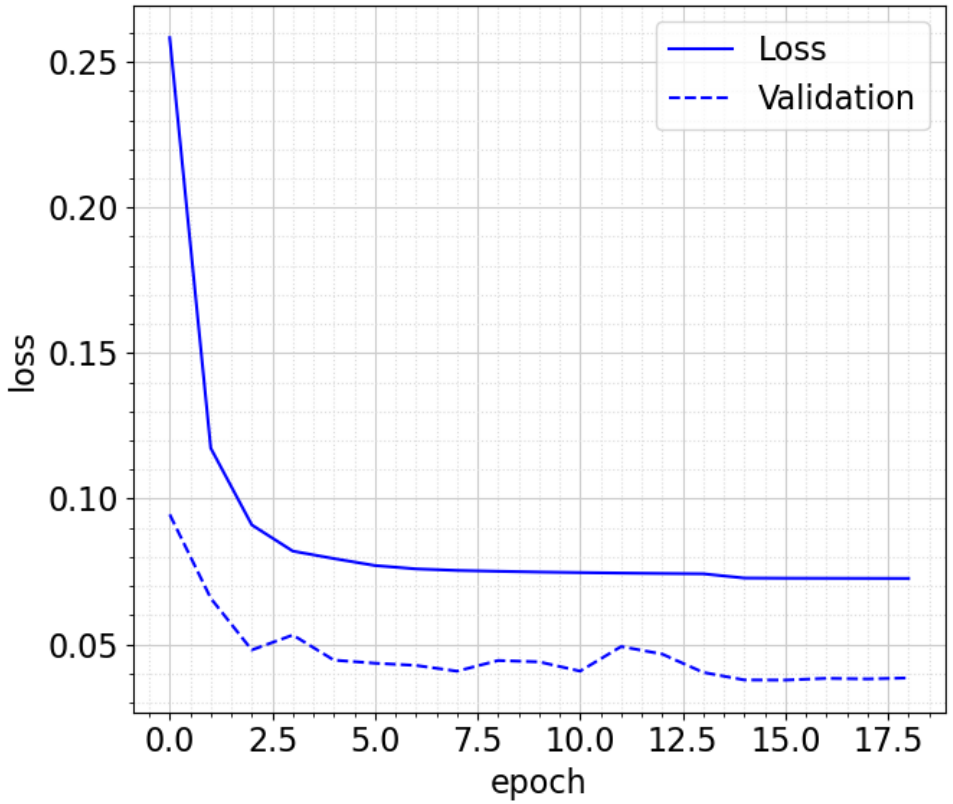
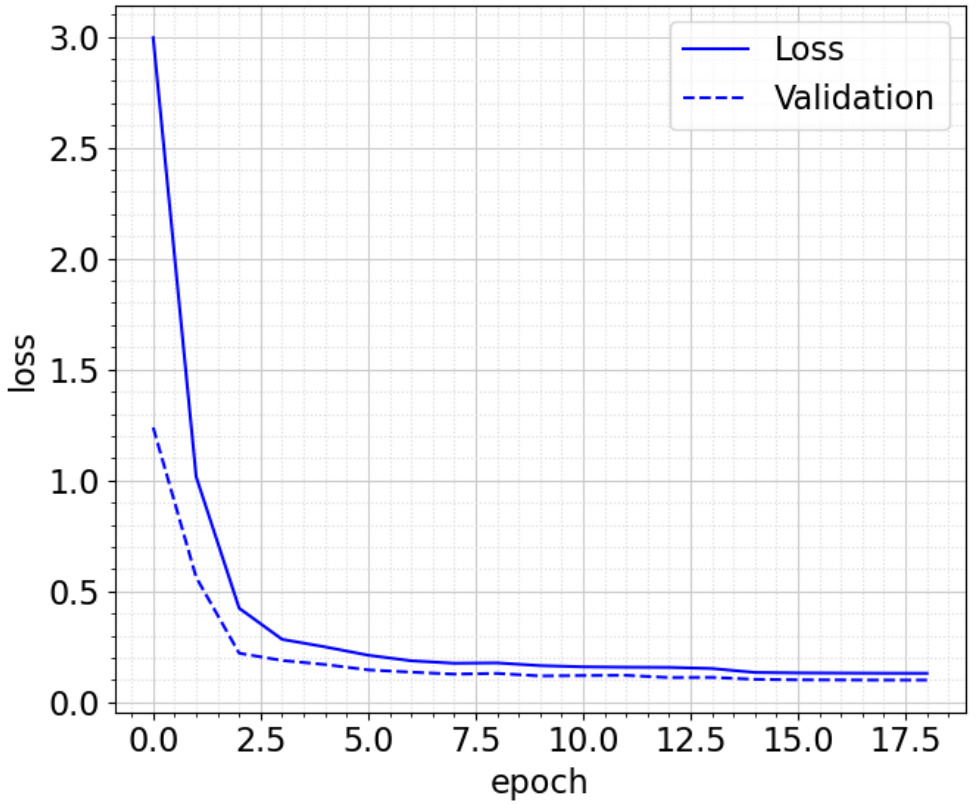
0
10
20
30
40
50
Layer Index
1e6
1.0
0.5
Entries

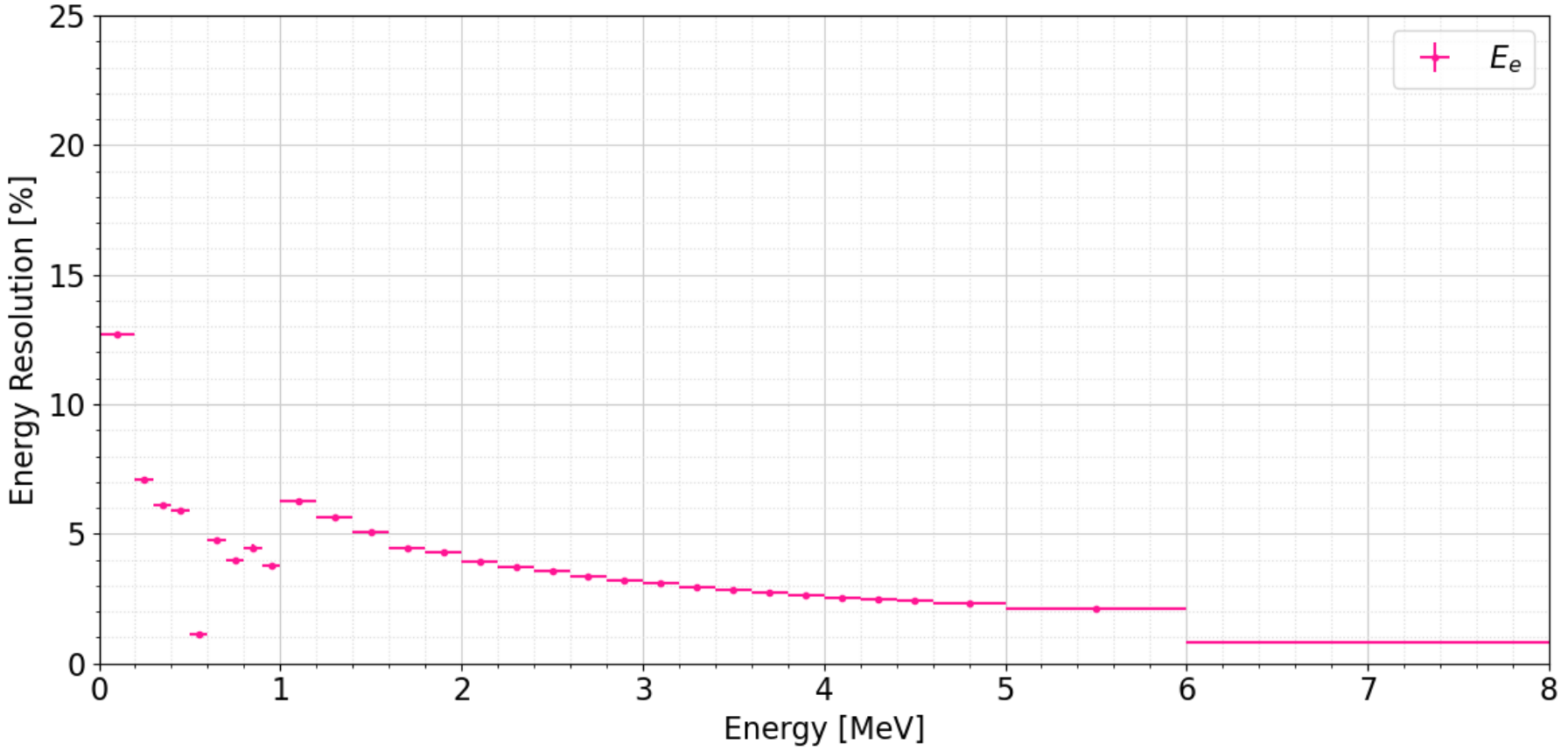

Normalized confusion matrix
Accuracy: 0.9545
True label
Predicted label
0
34
69
104
139
174
209
244
279
314
349
384
10^{-1}
10^{-2}
10^{-3}
10^{-4}

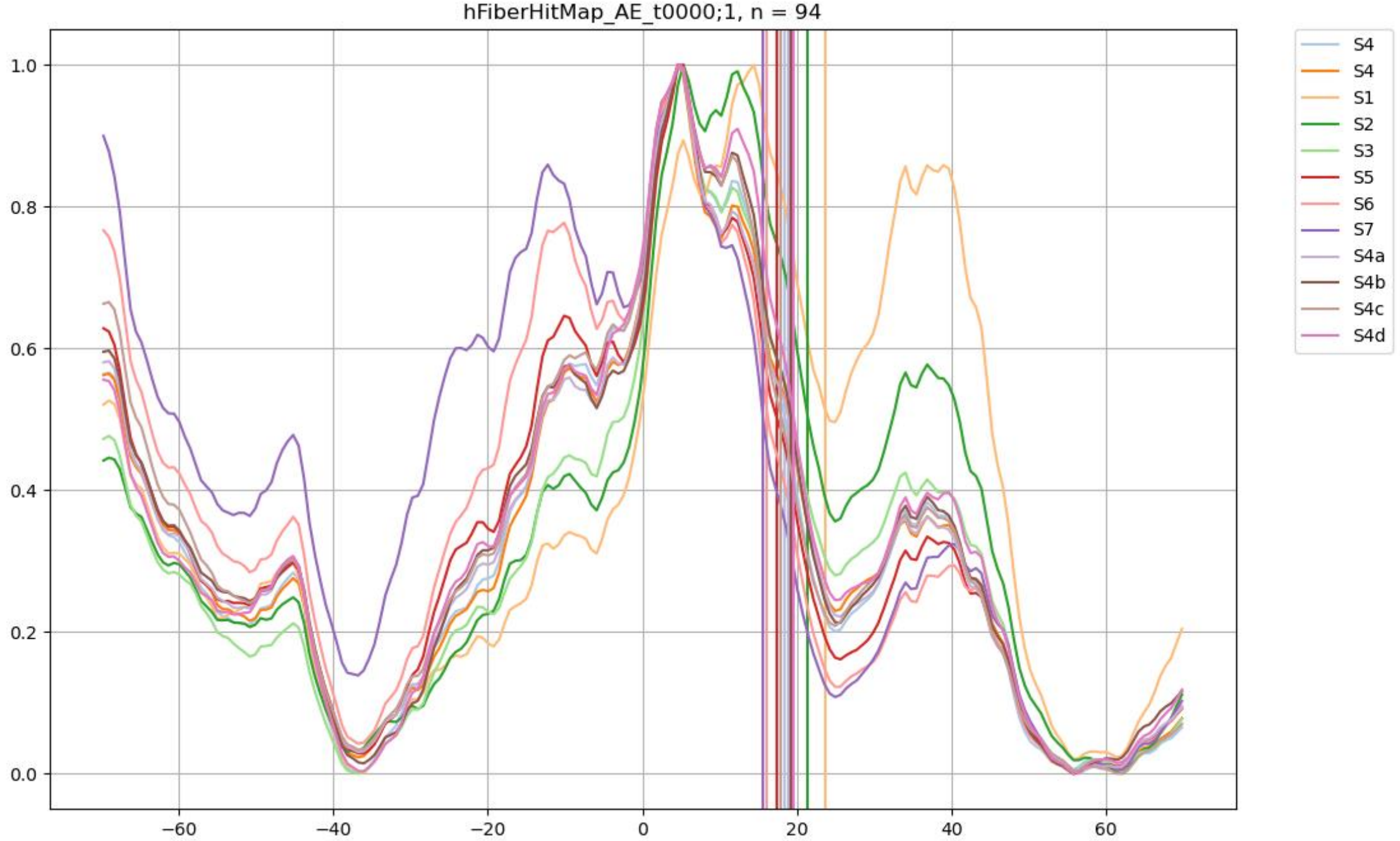
CM learning curves





CM

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0.8
0.6
0.4
0.2
0.0
−60
−40
−20
0
20
40
60
S4
S4
S1
S2
S3
S5
S6
S7
S4a
S4b
S4c
S4d