Proton Computed Tomography for Hadron Therapy

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Bergen pCT Collaboration

Talk overview

- Cancer
- Cancer treatments
- Hadron therapy
- pCT
- Machine learning
- Tracking
- Energy prediction
- Image reconstruction

Cancer

What we know about it (in short)

History

- 30th century BC: Egyptians write about it.
- 5th century BC: Hippocrates names this disease.
- 18th century AD: John Hunter propose surgery
- Early 20th century AD: First radiotherapy
- Mid 20th century AD: Chemotherapy

Categories of cancer

Types

Carcinoma	• Cancer that originates from epithelial tissues. For example: skin
Sarcoma	• Bones and soft tissues
Melanoma	• Starts from the skin
Leukemia	• Cancer in the blood cells
Lymphoma	• Cancer in the immune system
Mix of above	

Stages

Stage one

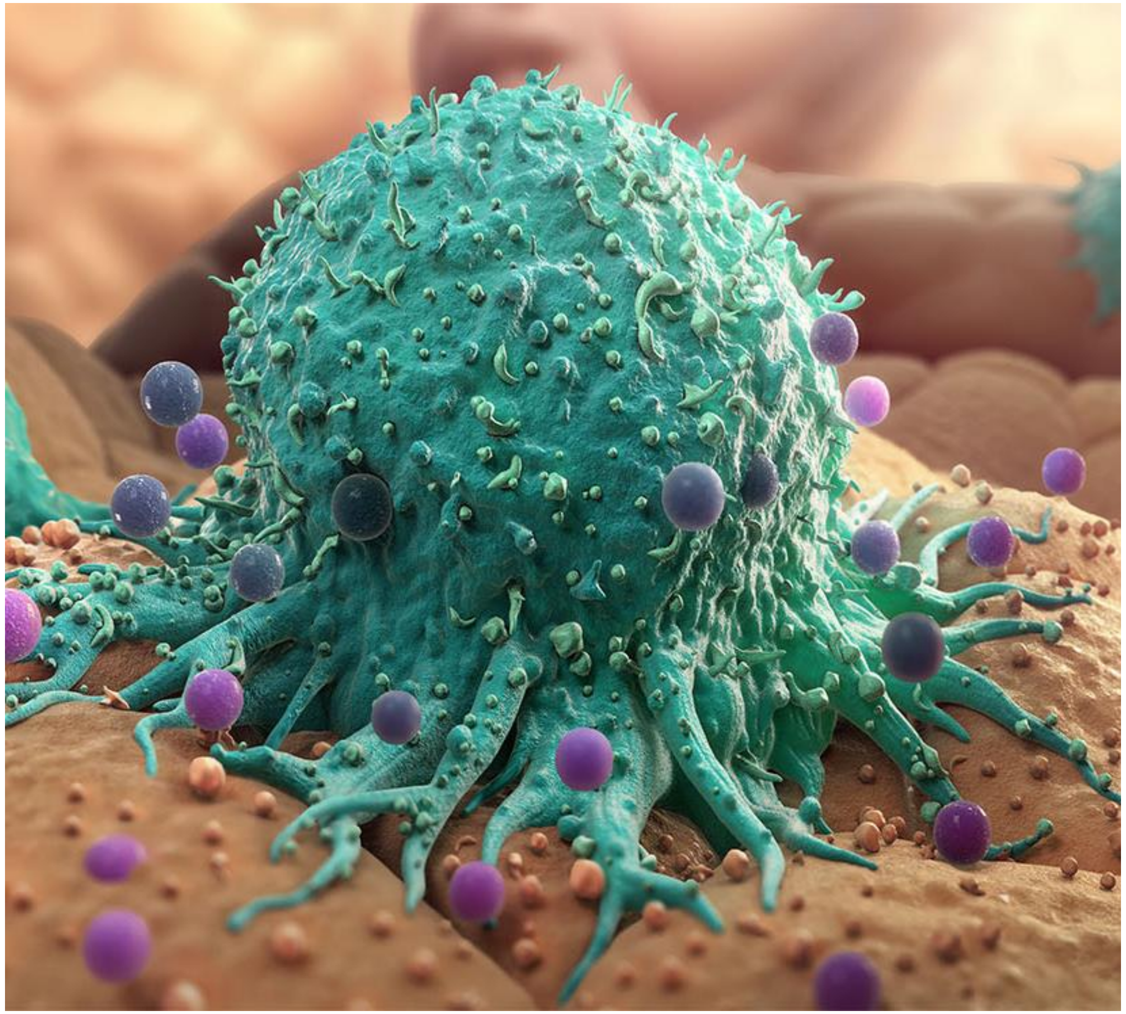
Stage two

Stage three

Stage four

What is Cancer

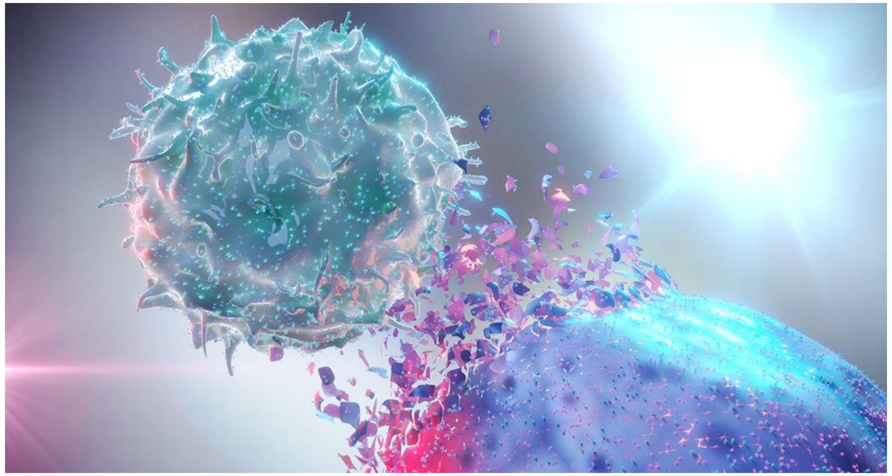
- Mutated/damaged cells.
- Growing constantly, even when they shouldn’t.
- Don’t stop growing when signaled do to so.
- Spreading through the body.
- Hide from immune system.
- Always grow, eat a lot.



Cancer treatments

Possible ways to deal with this disease

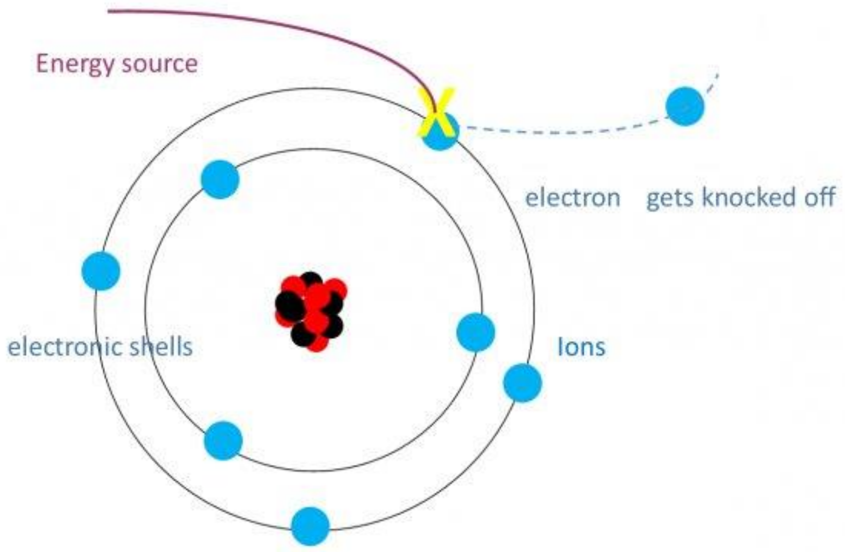
Possible treatments



Radiotherapy

Uses ionizing particles

Radiotherapy

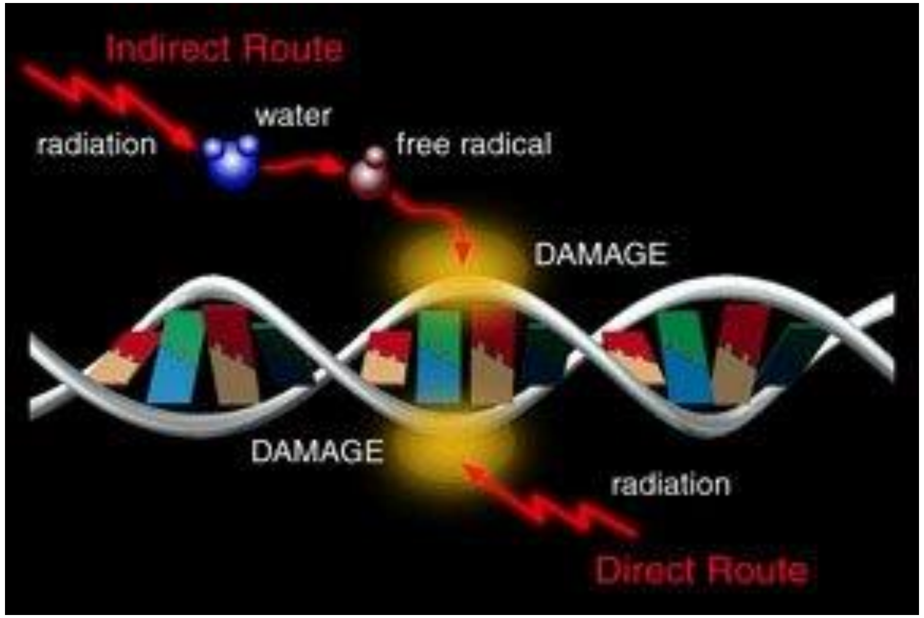


Uses ionizing particles

↓

Ionisation: a particle with sufficient kinetic energy kicks out an electron from an atom so it becomes charged (ionized)

Radiotherapy



Uses ionizing particles

↓

Ionisation: a particle with sufficient kinetic energy kicks out an electron from an atom so it becomes charged (ionized)

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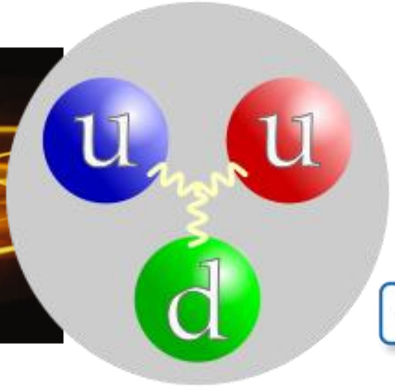
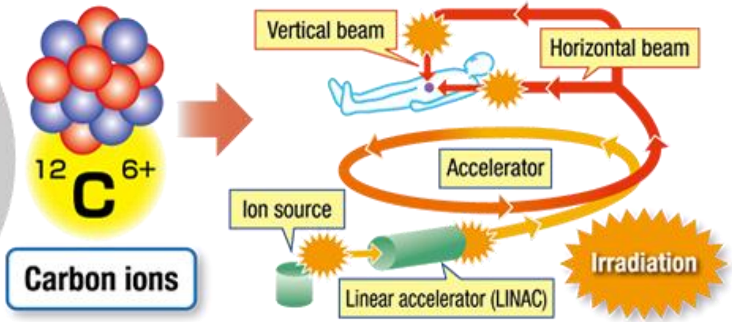
DNA is made of atoms, so ionization changes its structure, it gets damaged

Radiotherapy

Uses ionizing particles

Photons | Protons | Heavy ions



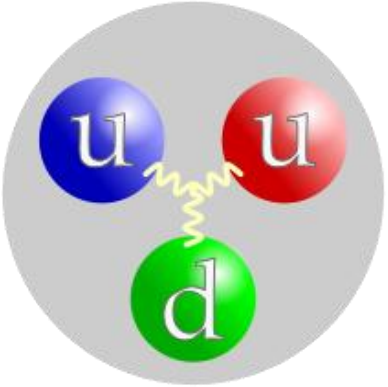


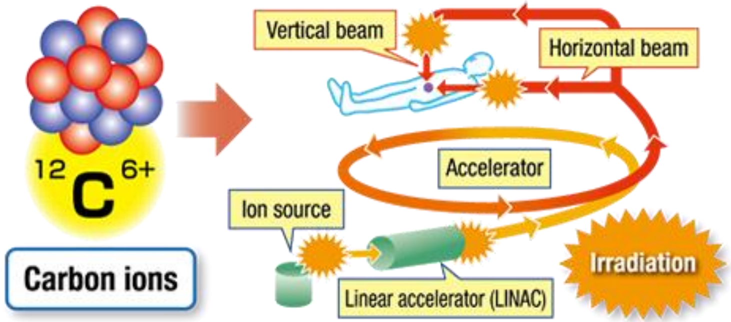
Radiotherapy

Protons

Heavy ions

HADRONS



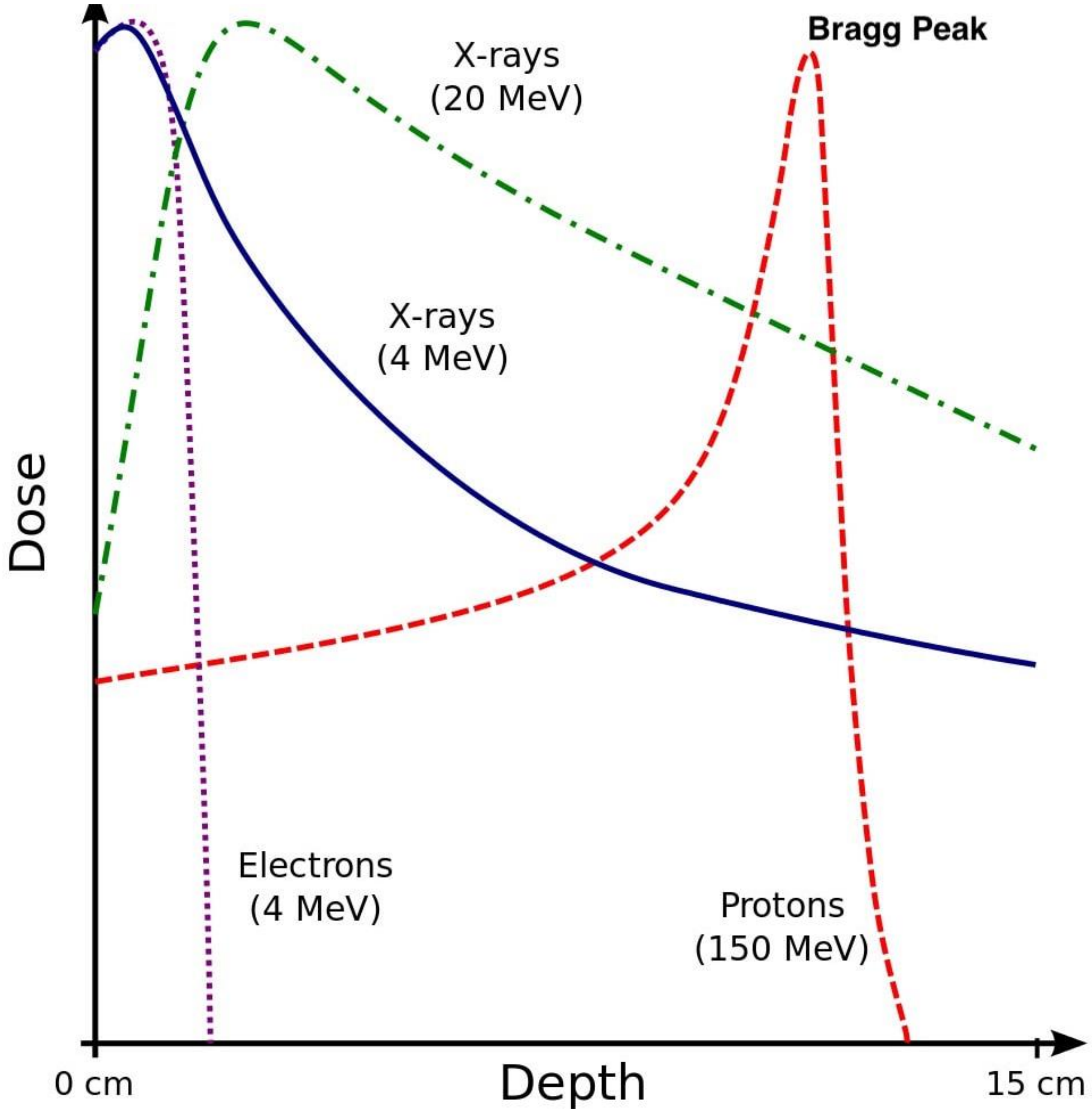


Hadron therapy

A special version of radiotherapy

Properties

- Radiation based cancer therapy.
- Using charged particles for more concentrated dose (compared to X-ray) - Bragg peak.
- Ambulant treatment.
- Current medical devices were not made for charged particles (protons in our case).
- Medical imaging needs to be fast to optimal treatment.



pCT

Medical Imaging, Proton Computed Tomography

Why do we need imaging?

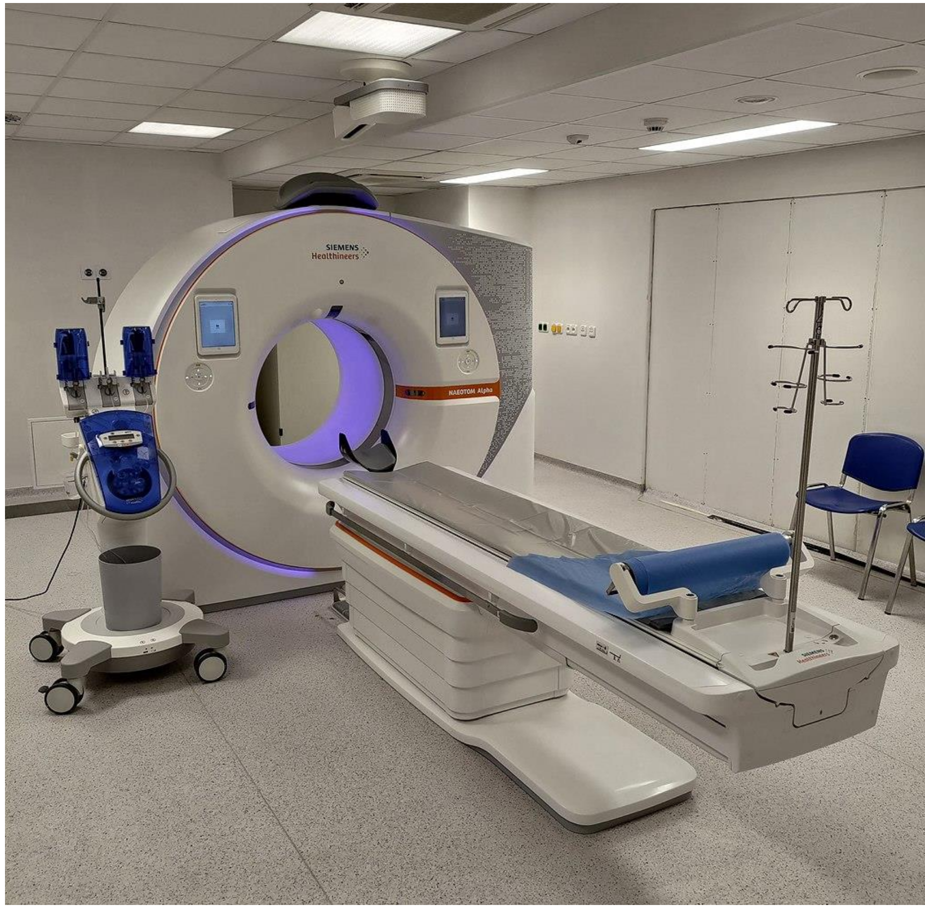
- Before the treatment, we need information of the patient's anatomy
- Contouring, dosage planning
- Currently: mostly (X-ray) CT imaging before the treatment
- Our goal: as accurate and fast imaging as possible (better imaging = better treatment)

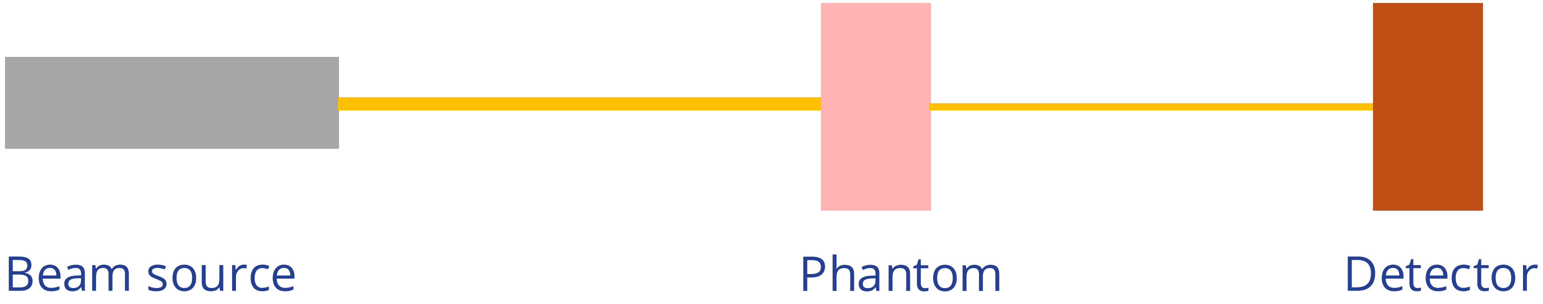
Fun fact: to test imaging systems, we use so-called phantoms

(this is a very advanced, Erler-Zimmer head phantom)

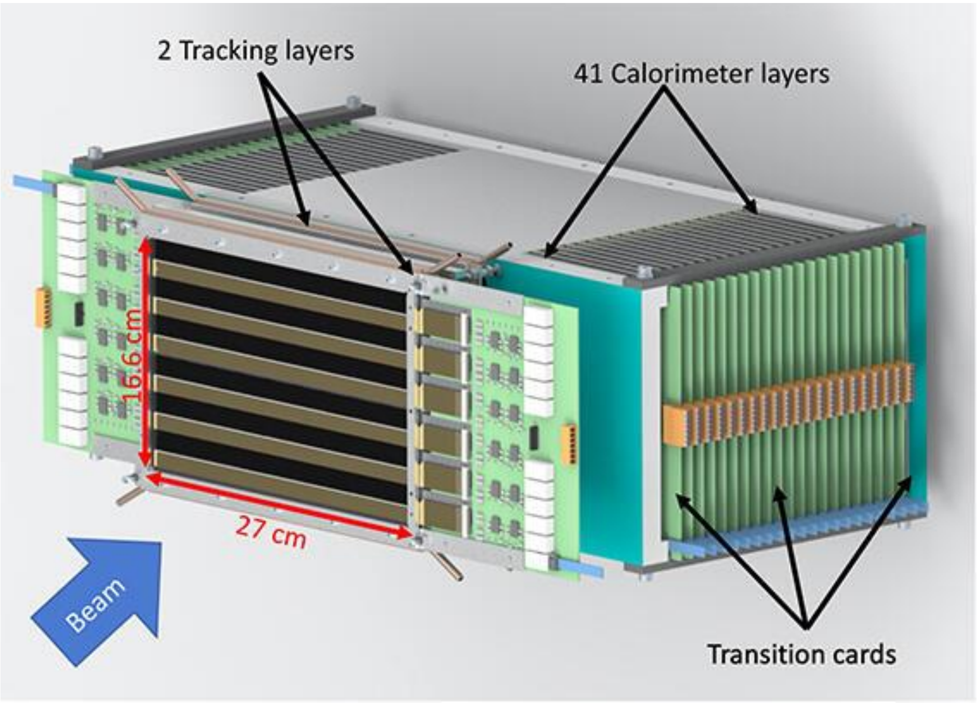
Computed Tomography

- Rotating X-ray around the patient.
- Detector in the other side.
- Measuring incoming beam intensity.
- Not designed for protons.
- Can’t calculate proton stopping power.

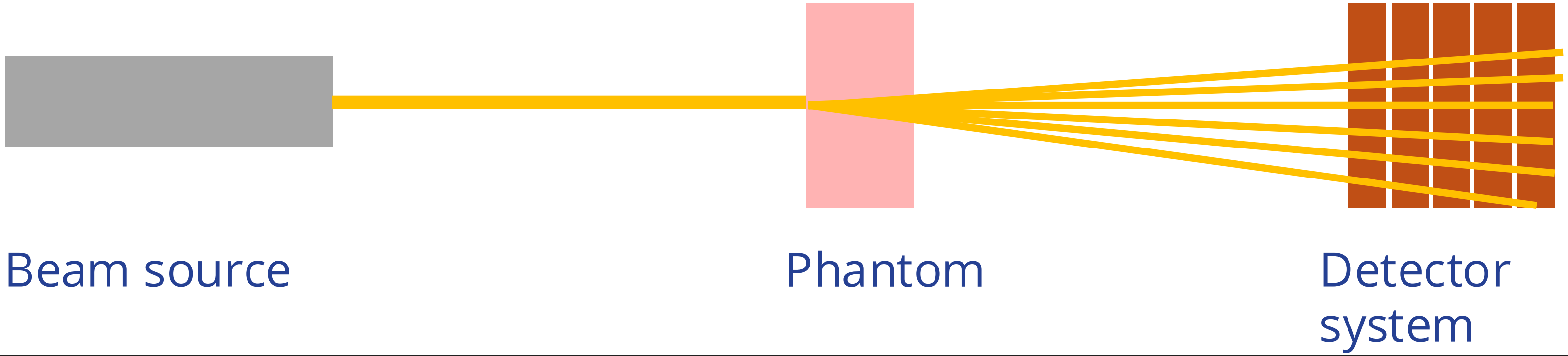




Proton CT



- Beam in protons.
- High energy protons (not to hurt patient).
- Measure proton scattering (need more detector).
- Need to reconstruct particle trajectories.
- We can calculate scattering angles and energies.
- Rotating around detector system to have 3D image.



Process of pCT

Beam in high energy protons

- High enough to not harm the patient.

Detecting particle hits in detector system

- Using the pCT detector system.

Charged particle track reconstruction

- Track trajectories and initial kinetic energy prediction (~100 particle at once).

Medical image generation

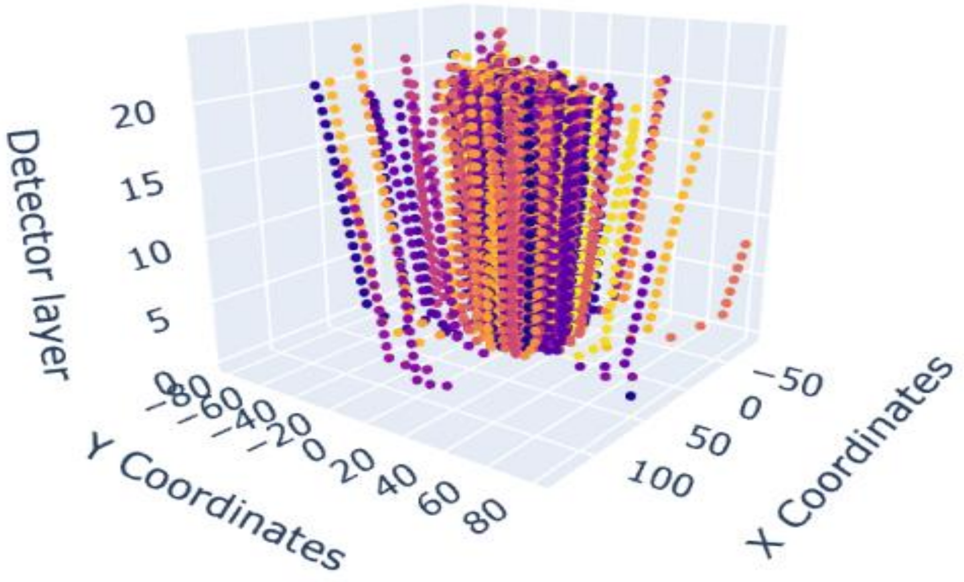
- Based on scattering angles and kinetic energies doing tomography.

Tracking

Reconstruction of particle paths

Explain the problem

- Have to reconstruct particle path in detector system.
- There are a lot of particles very close to each other.
  - Hard to find based on distance.
- Particles can cross each others' path.
  - Crossing track can confuse algorithms.
- There are existing methods in HEP.
  - Too computational heavy/too slow.
- We have to process data quickly for medical imaging.



Machine learning

Curing cancer with AI

History

1955: John McCarthy
„Artificial Intelligence”

1958: Perceptron model

1974-1980: AI witner

1986: Multi layer perceptron

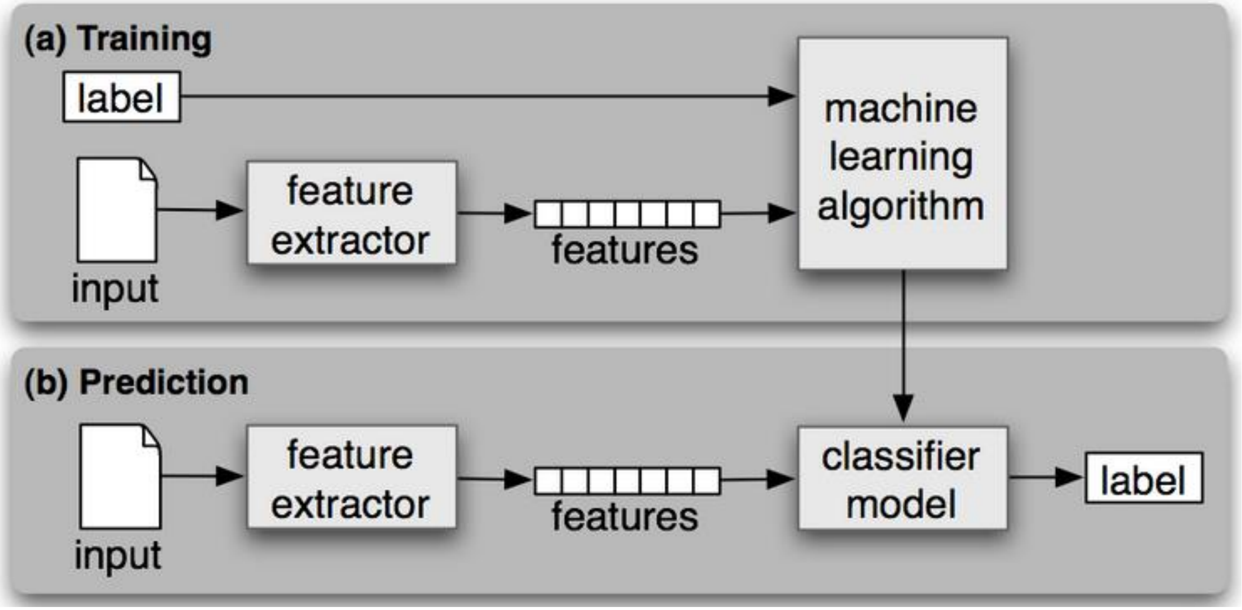
1998: Yann LeCunn Deep Learning

2017: Attention Is All You Need

2022: OpenAI ChatGPT

Fundamentals

- There is a relation between some features and a target.
  - House prices, computer electricity consumption, etc…
- We can approximate it with a defined model.
  - Universal Approximation theory
- Model parameters are tuned.
  - Objective function.
  - Gradient descent etc.



Why ML?

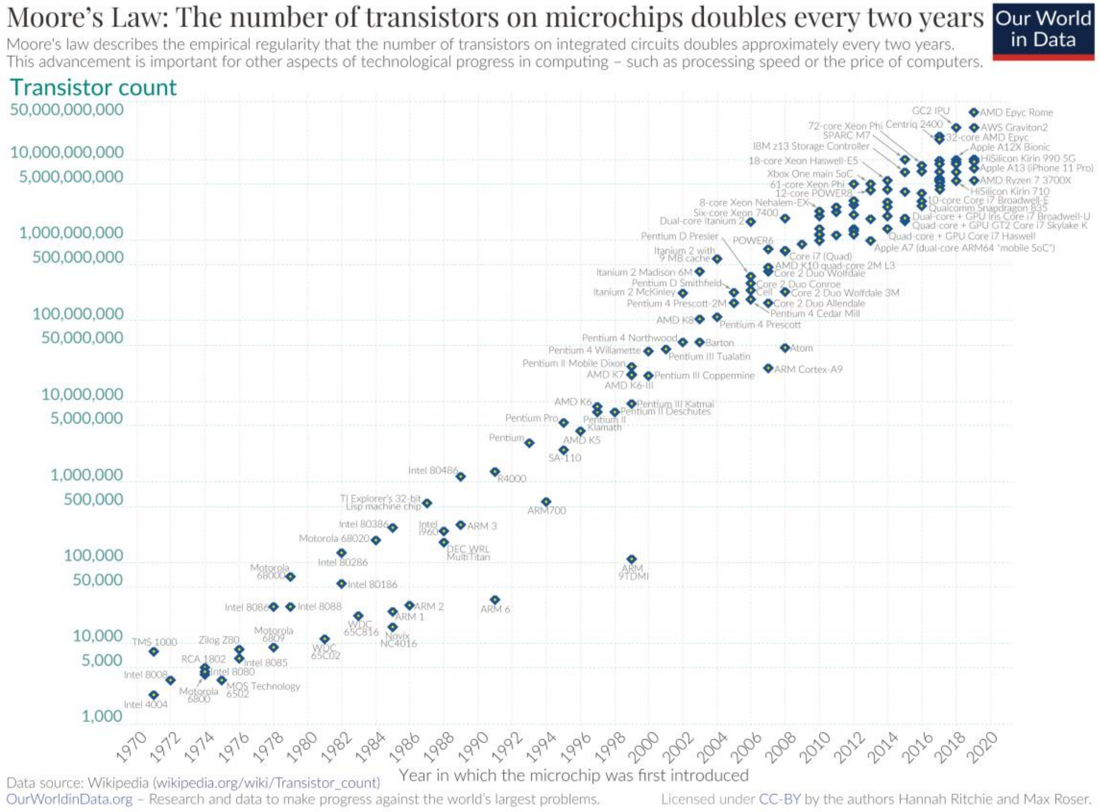
- What if we can't define this rule?
- Or it is too complicated to define?
- How to find differences?
- Machine learning is not about explicit rule definition.
  - It's about learning the rules that gives us the connection.

How to write a program that defines cats and dogs?

How to write a program as recognize all of this as car?

Why we want it?

- By nature these evaluate fast.
  - – GPU property.
  - – Paralellized.
  - – Needs to run in medical device.
- pCT medical imaging – iterative reconstruction methods can be used.
  - – Can be sped up with ML.
- pCT tracking must be very fast.
  - – Traditional particle track reconstruction is slow.
  - – And we can't really define rules of matching.

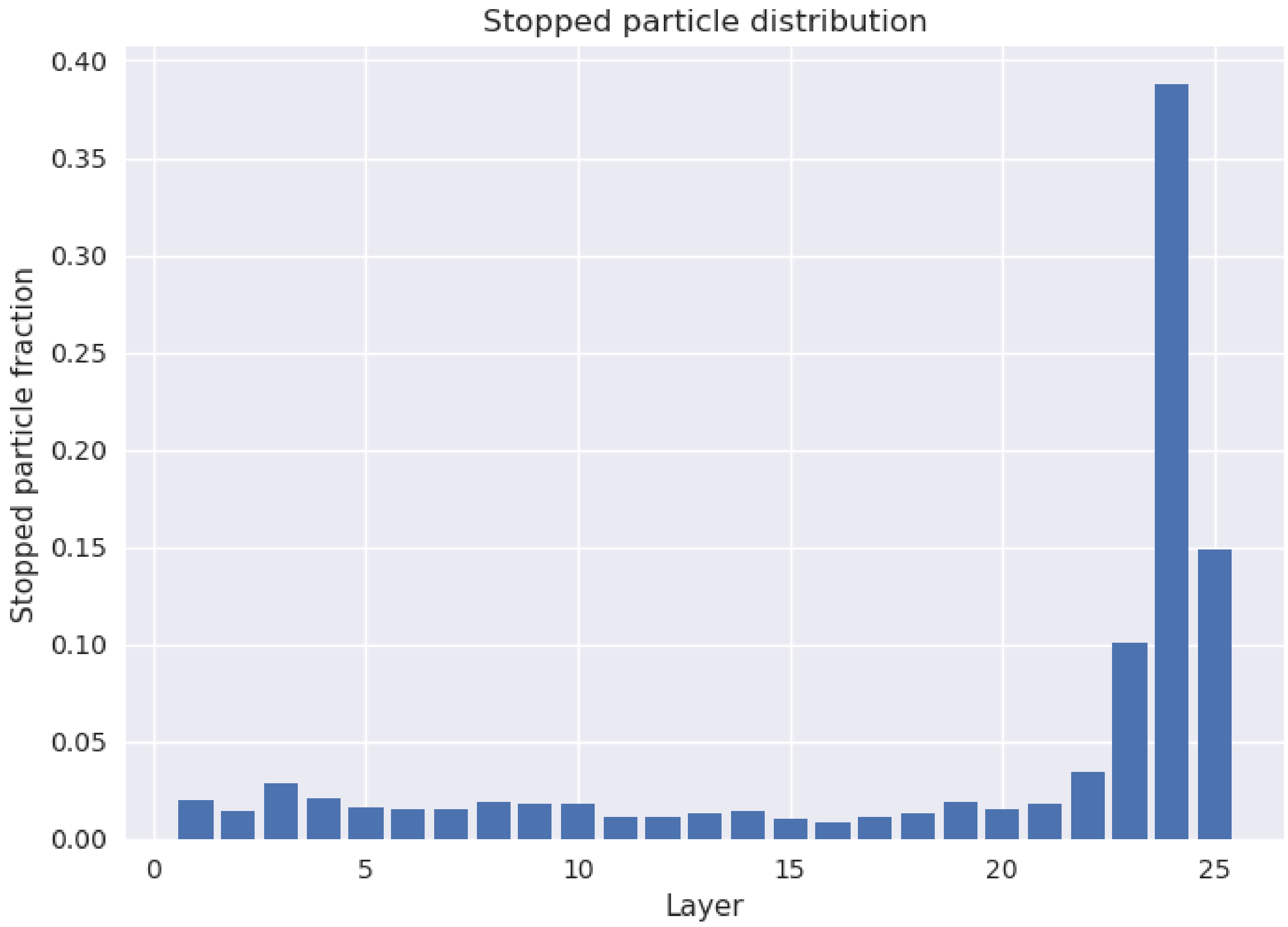


Tracking - Energy prediction

This is the easiest part, can be done by simple machine learning algorithms

Energy prediction

- Small neural network to approximate energies.
- Filter data around expected Bragg peak.
- In evaluation, we don't know expected.



Energy prediction

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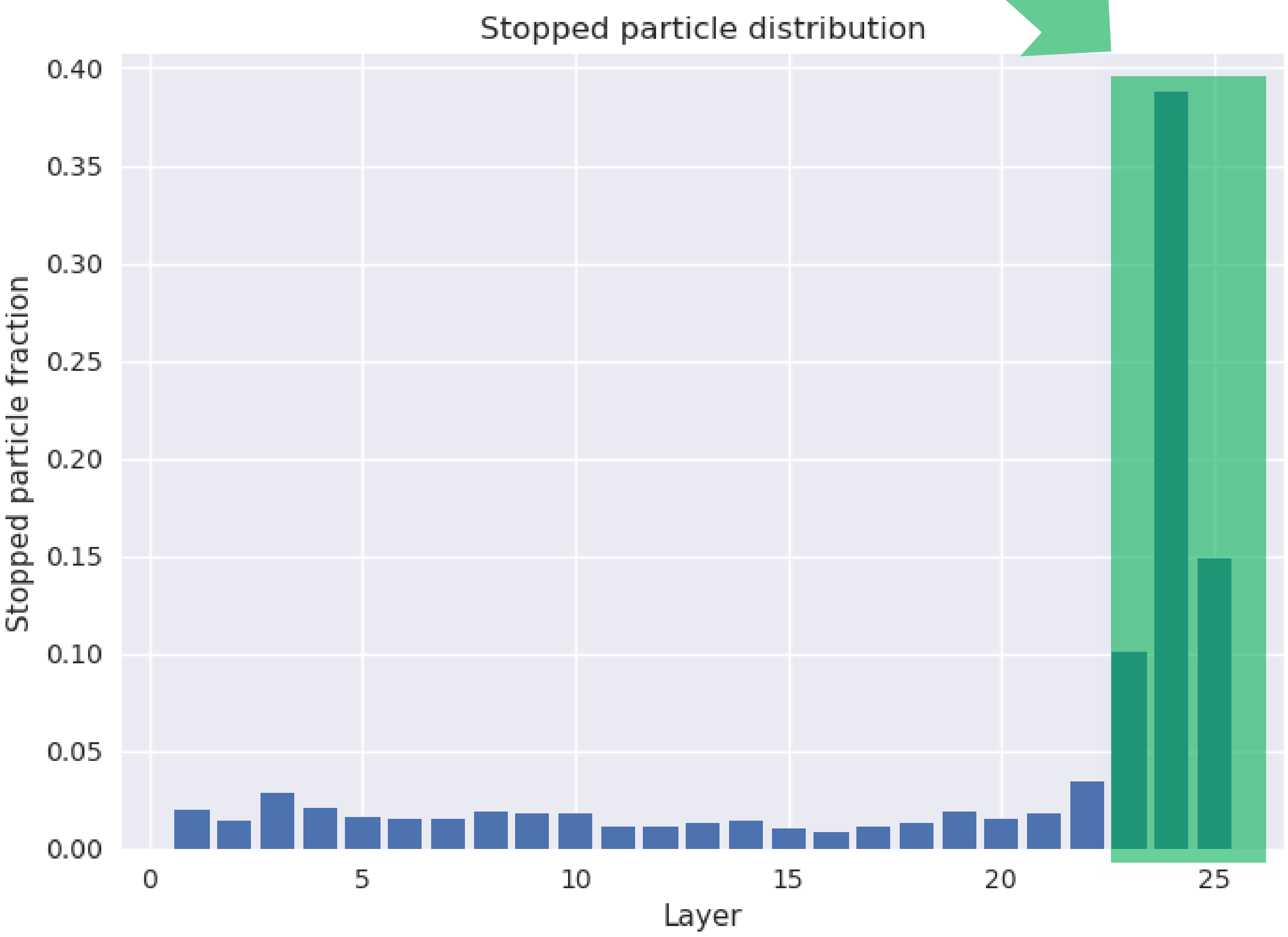
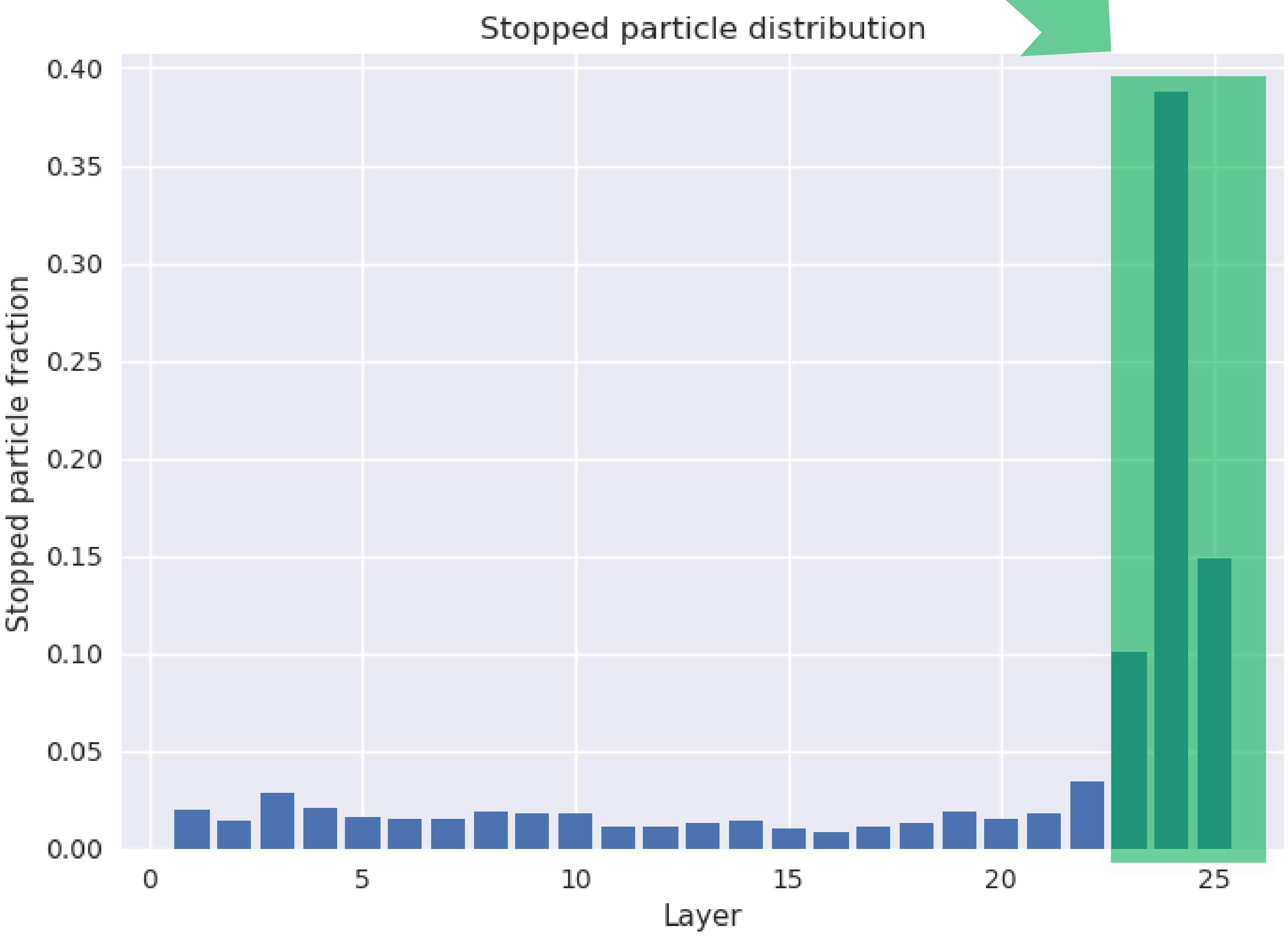
We want to work with these!



Energy prediction

- Approximated from already reconstructed tracks.
- Last particle with not 0 energy.
- This will be our ,,expected Bragg peak”.
- Particles leaving the detector system are uniformly occurred everywhere.
- These usually make the prediction worse.
- With the maximum position we can make an assumption on the initial beam energy.

We want to work with these!



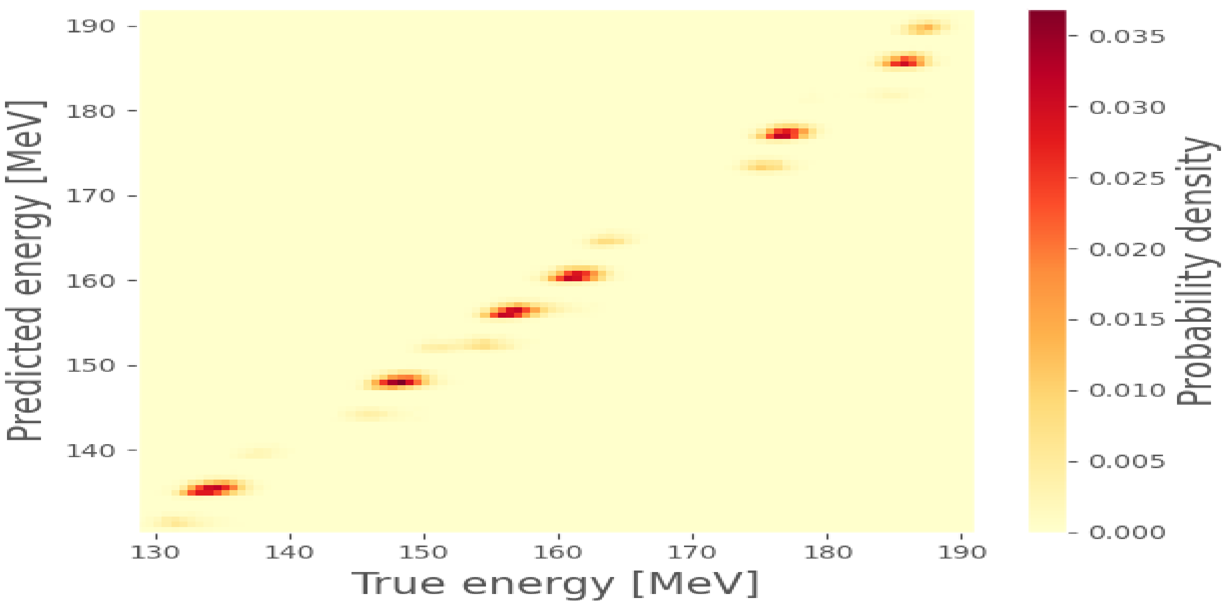
Energy prediction

- Small neural network to approximate energies.
  - Originally linear regression was very close.
  - Deep neural nets slightly better.
  - Possible to merge NN with other subtasks.

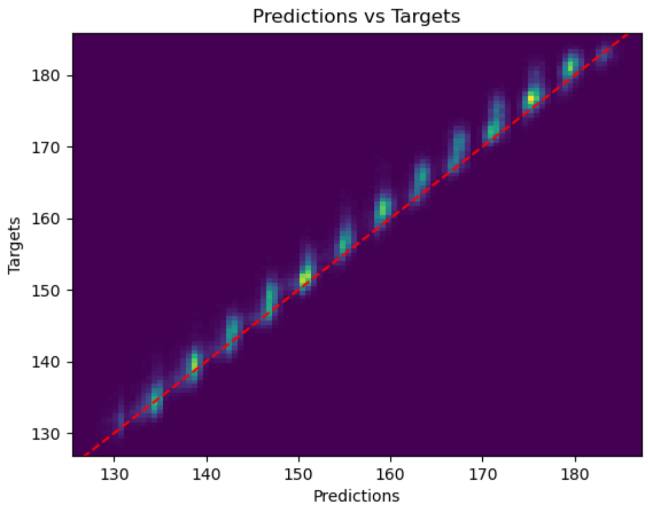
- Input of the model is:

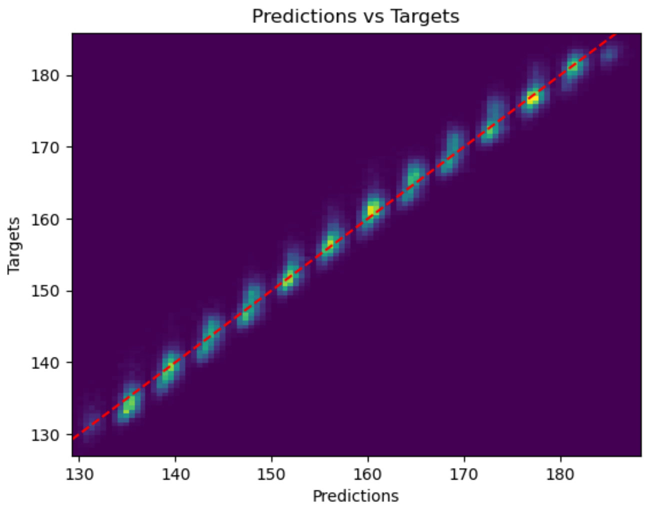
$$\hat{X} = (L_B, E_{B-1}/E_B, E_{b+1}/E_B)$$

- Where E_B is the energy deposition on the ,,expected'' Bragg peak, L_B the normalized position of the Bragg peak.
  - Some embedding might improve.
  - But currently this is enough for reconstruction.



[M. Aehle et al, Reconstruction of proton relative stopping power with a granular calorimeter detector model]





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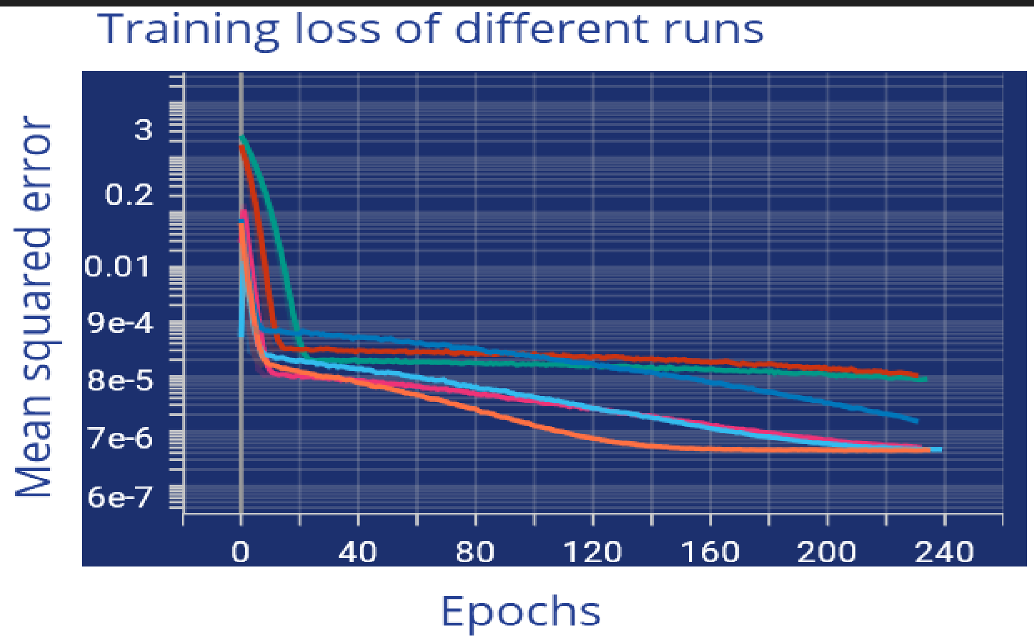
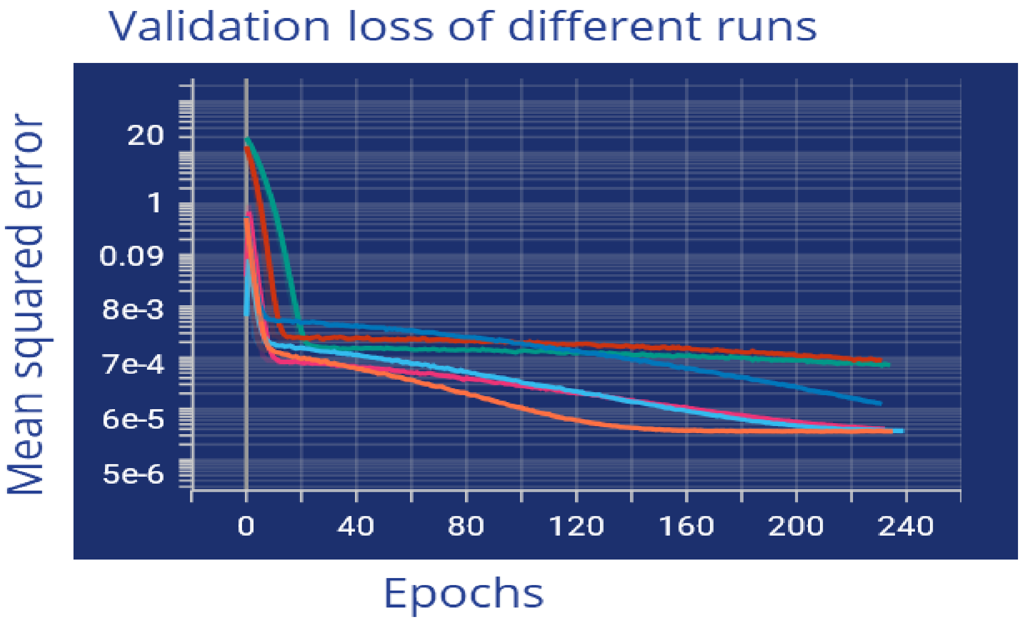
- Where E_B is the energy deposition on the ,,expected" Bragg peak, L_B the normalized position of the Bragg peak.
  - Some embedding might improve.
  - But currently this is enough for reconstruction.
- We obtain around 1MeV precision.
- Colors indicate hyperparameter configs



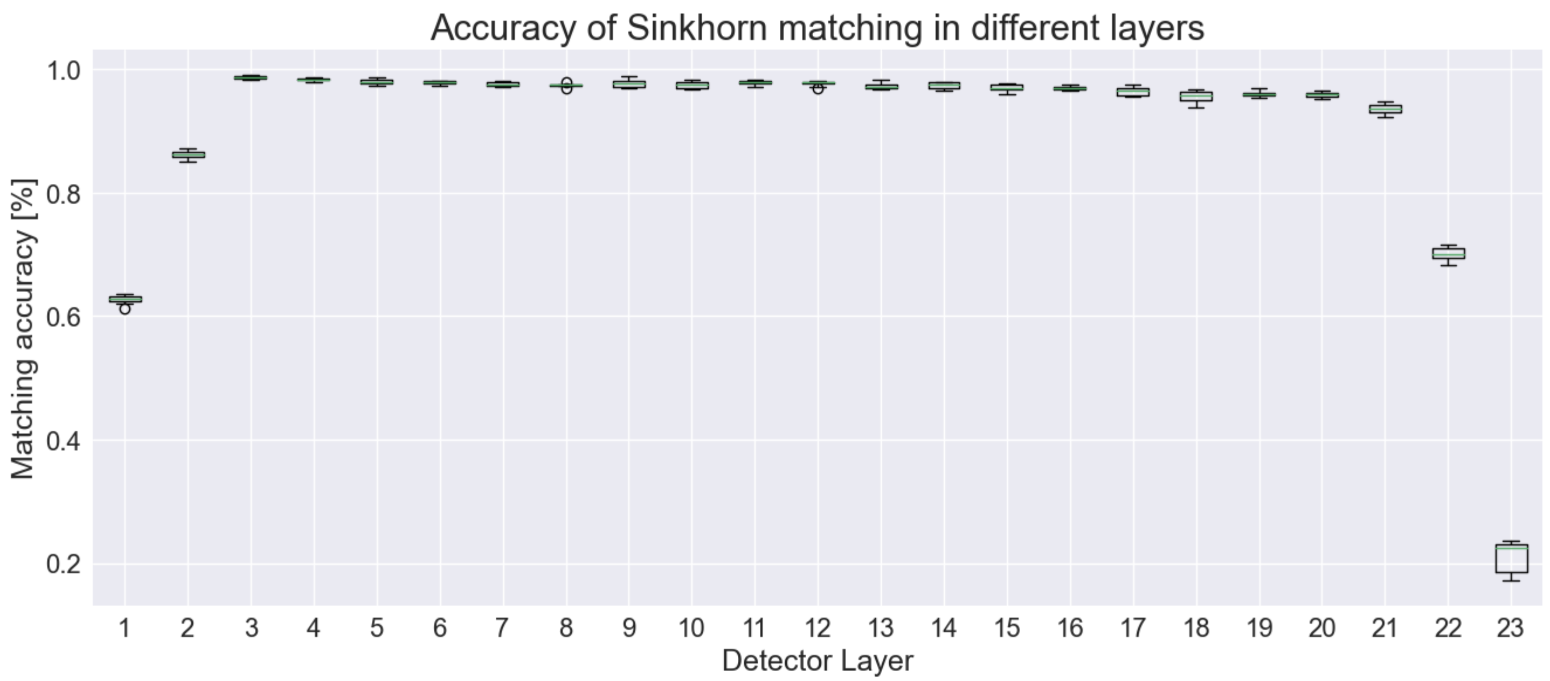


Tracking – Particle matching

I have 2 proposed system for particle trajectory reconstruction. One is to help traditional algorithms, one is to replace them

Particle matching

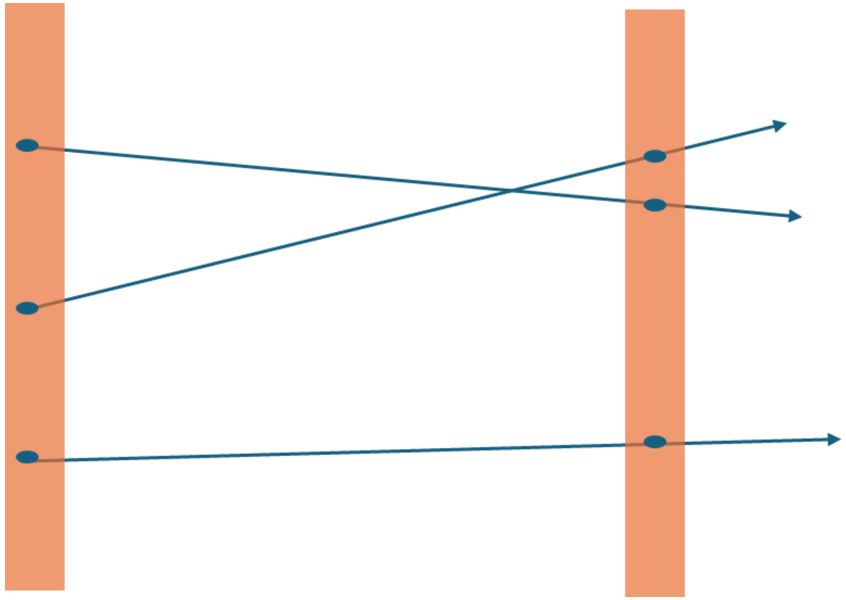
- Need match particles to recreate trajectories.
- Matching in the calorimetric layers is very efficient.
  - For technical reasons we pad the trajectories.
  - This leads to small accuracy later.
  - This can be filtered in track reconstruction.
- We have 2 approaches to this problem.
  - Position correction.
  - Matching Neural Network.



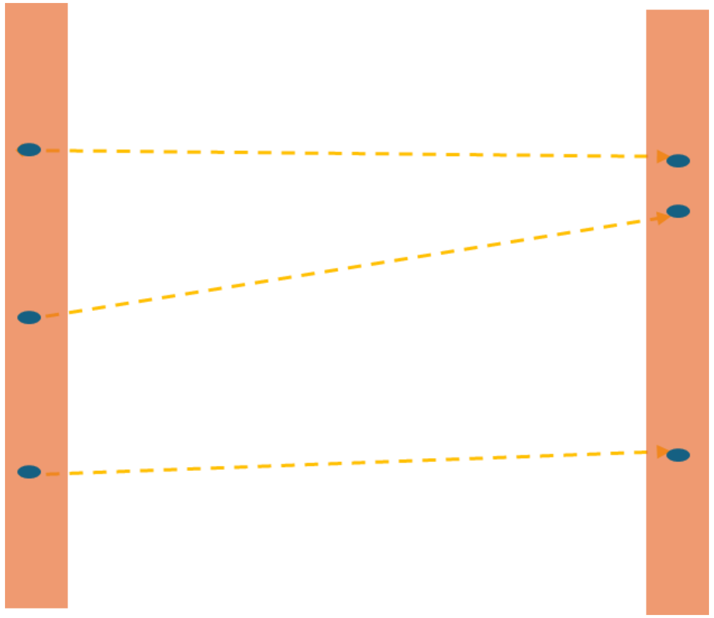
- Closest particle matching around: 54%
- Sinkhorn matching is around: 65%
- The whole track reconstruction is even worse.

Position projection

- Scattering and path crossing is very common.
- Distance based algorithms can’t correct this.
- We created a neural network that predicts expected position.



Real trajectories



Reconstructed

Position projection

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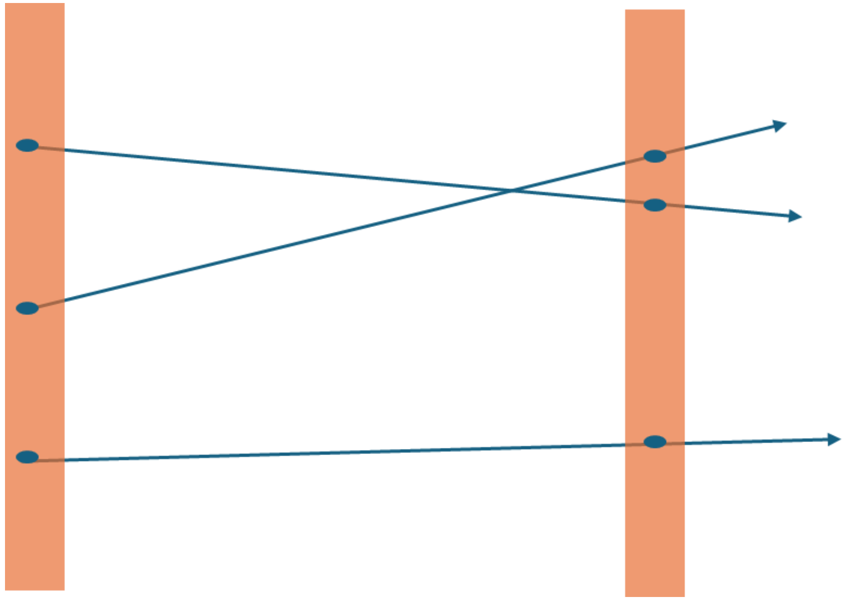
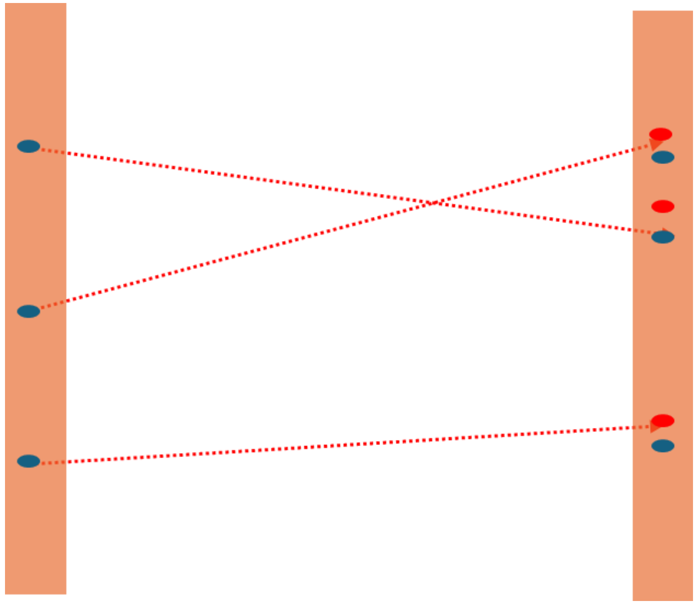


Real trajectories



Expected positions

Position projection

- Scattering and path crossing is very common.
- Distance based algorithms can’t correct this.
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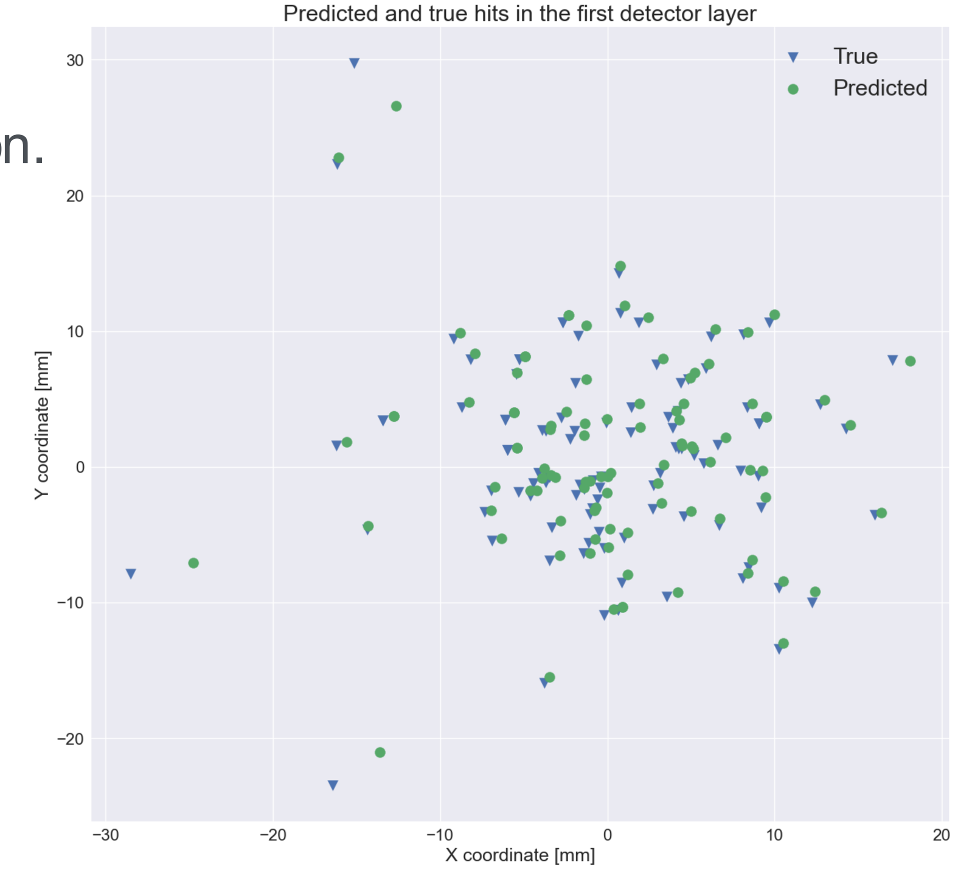
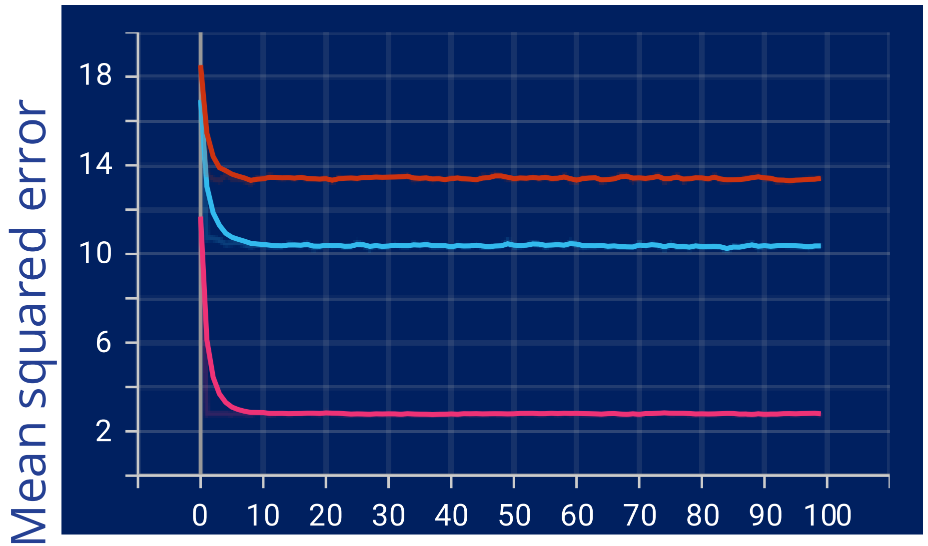


Position projection

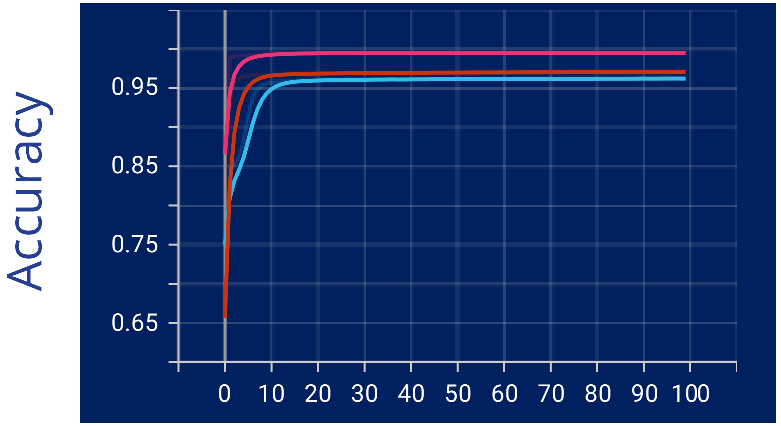
- We start from the end of the detector system.
  - Few particles, that are very easy to match.
  - In calorimetric layers we can do very good matching.
- Based on previous position we predict an expected position.
- We want to match expected position with the real one.
- One-one model for the first 3 layers.

Training loss for position prediction



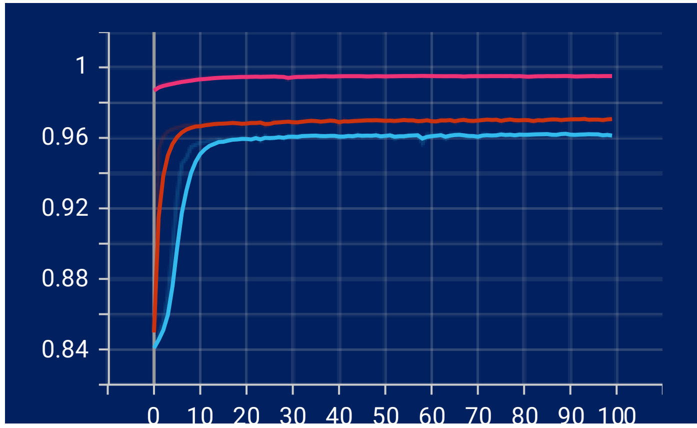
- Layer 3 to 2 prediction
- Layer 2 to 1 prediction
- Layer 1 to 0 prediction

Training accuracy



Epochs

Validation accuracy



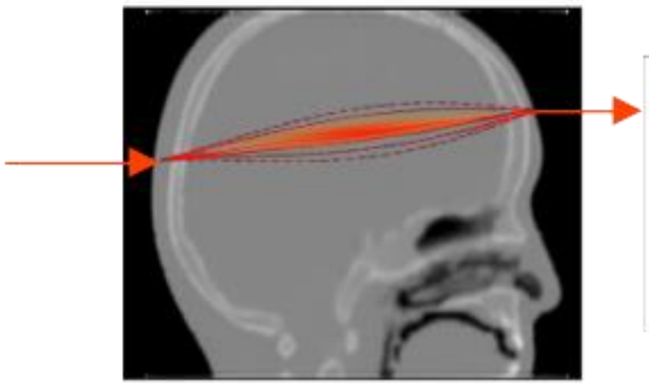
Epochs

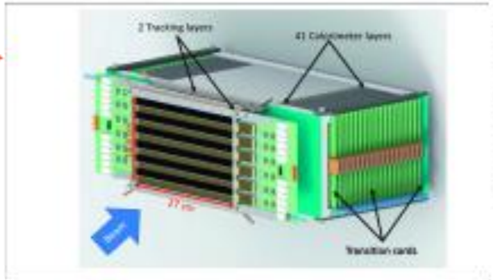
Image Reconstruction

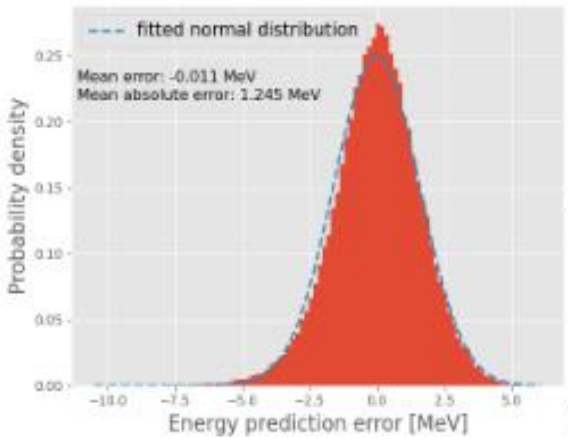
We already developed an algorithm that can reconstruct Relative Stopping Power maps. We are currently developing an AI based system, for more accuracy and less computational time.

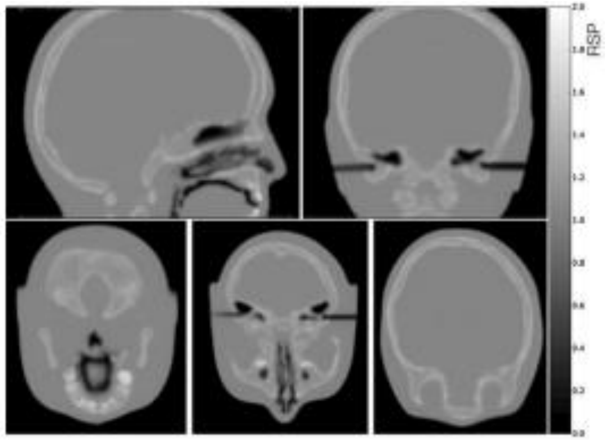
Image Reconstruction

Recall - how did we get the picture?









Irradiating phantom with high energy (~100 MeV) protons

Detector system senses the signals

Processing the signals (reconstructing trajectories from hits + predicting energies)

Reconstructing the image (some kind of image reconstruction algorithm needed)

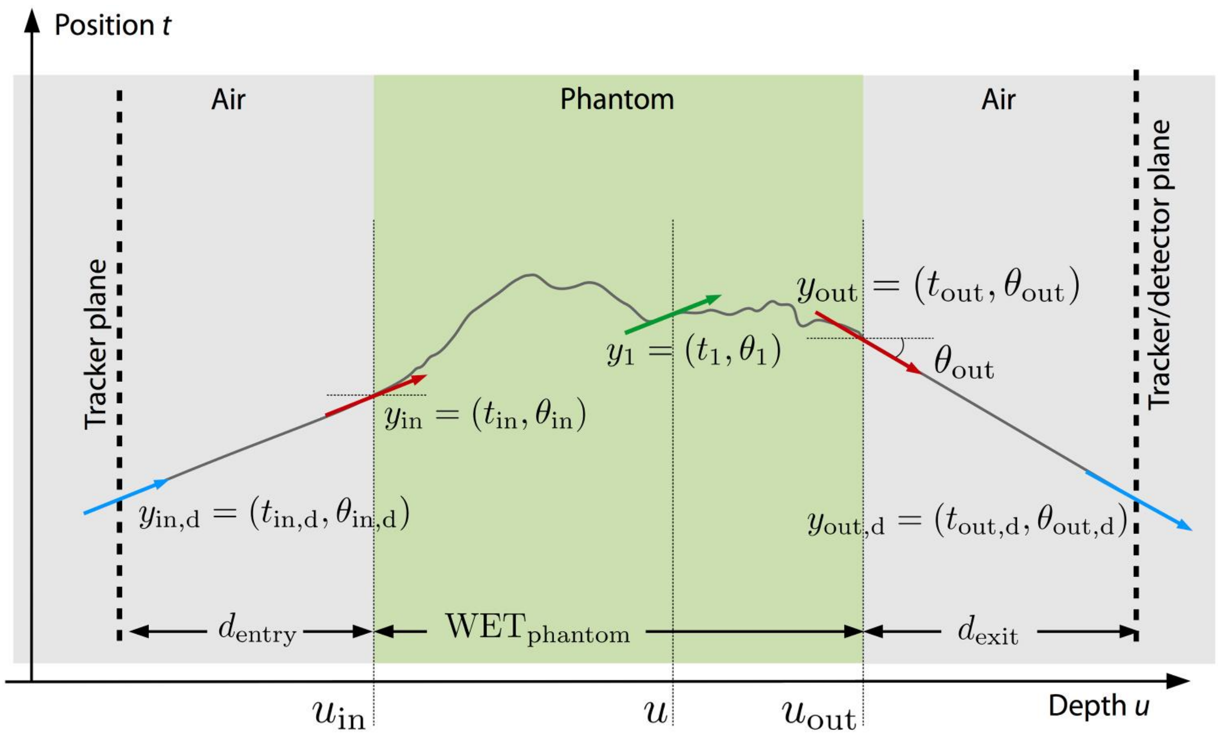
Image reconstruction methods

Integral transformations (Radon, Inverse Radon)

- Easy, but cannot be used for protons

Iterative reconstruction methods

- Solving a linear equation system



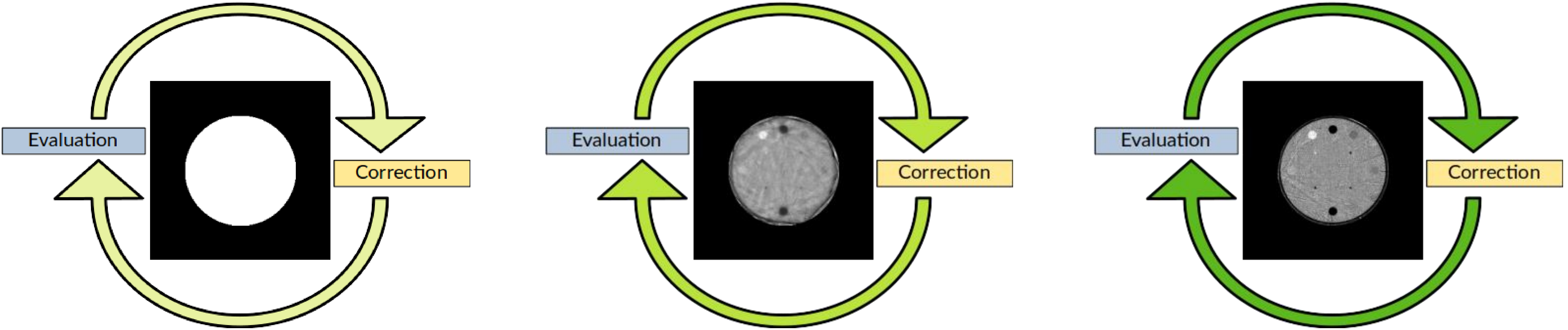
$$\boldsymbol{A} \times x = y$$

Matrix containing interaction coefficients between protons and pixels

Estimated Relative Stopping Power values

Water Equivalent Path Length values (from detector)

Iterative reconstruction techniques



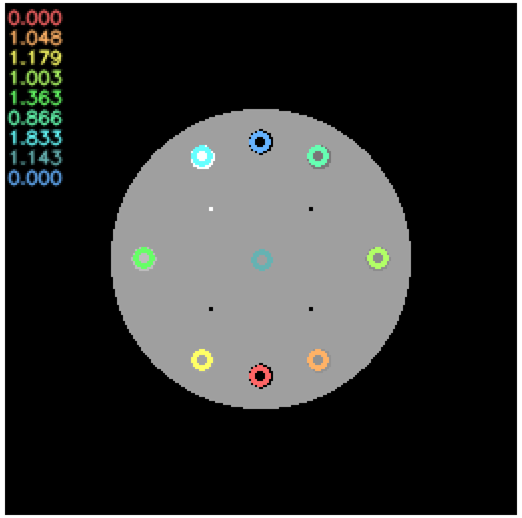
Currently being developed and used: Richardson-Lucy algorithm

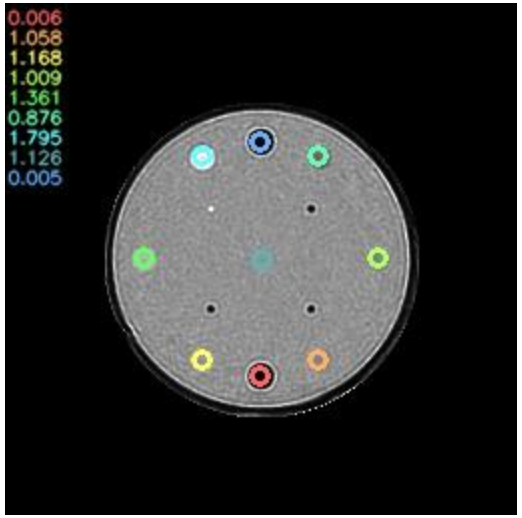
- Originally used in optics, not for medical imaging
- Technical challenge (~millions of proton trajectories)
- Currently sped up with GPU, but there is room for further improvement (AI)

Some of our latest results

CTP404 phantom:

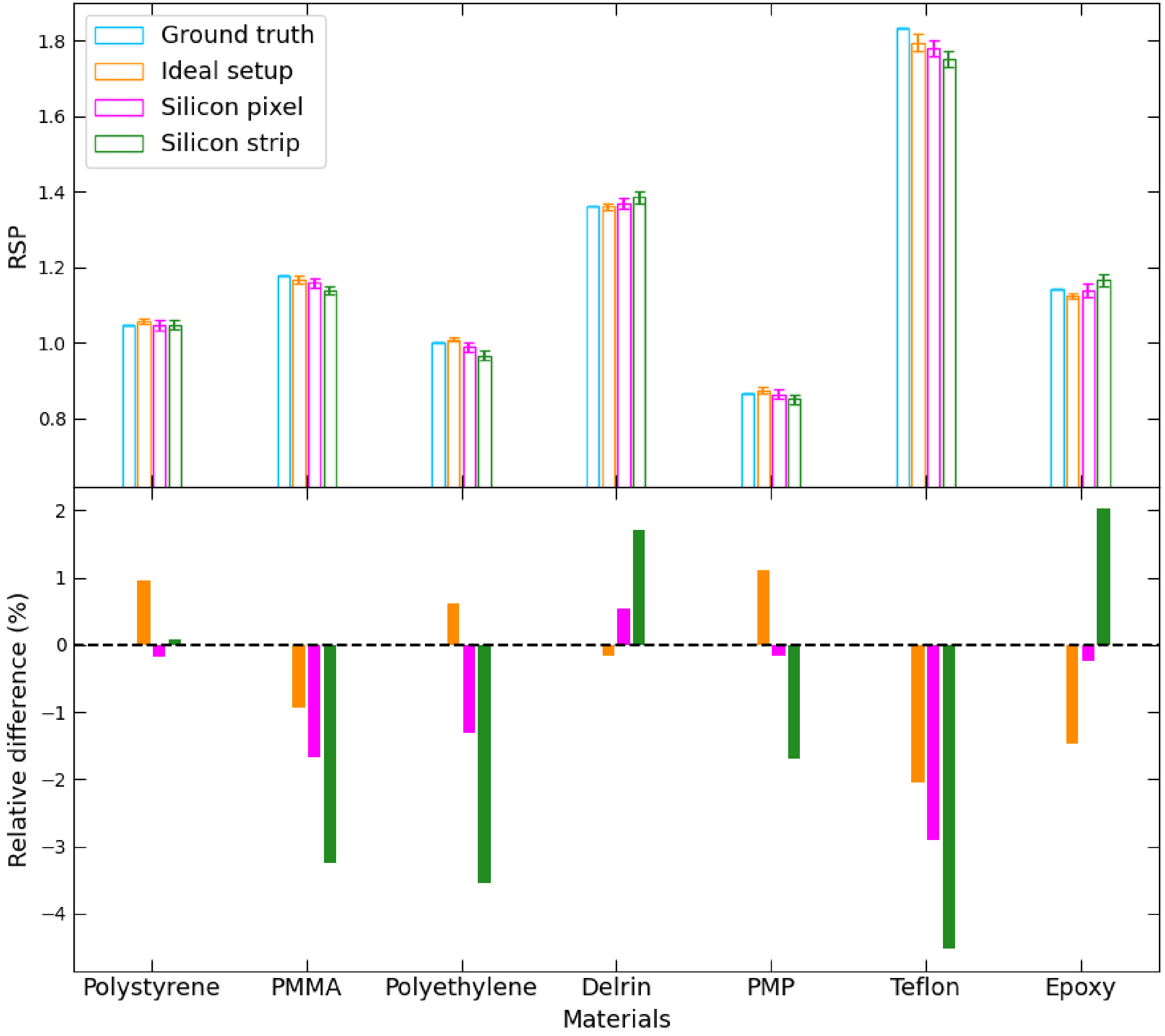
- Used for testing proton RSP reconstruction accuracy (basically density reconstruction)
- Has 8 inserts made of materials with different density
- 3 different setups tested, ~4% relative difference achieved between ground truth and reconstructed values





"Ground truth" image

Reconstructed image



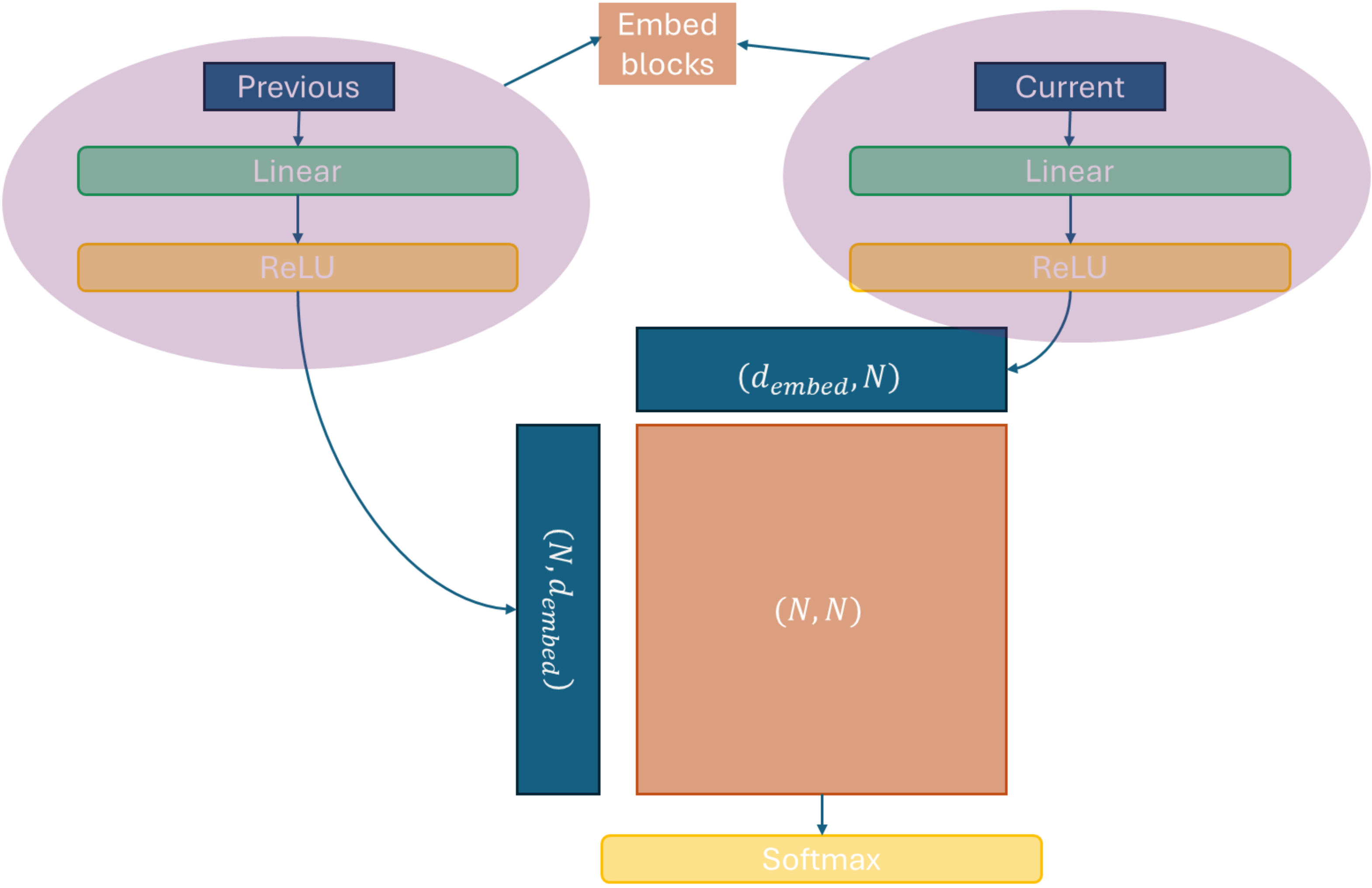
Proton Computed Tomography

- Hadron therapy is an outstanding way to treat cancer...
- But it requires very specific imaging.
- Proton Computed Tomography is a promising method.
- Machine learning could be implemented at many parts of the imaging process.
  - Charged particle tracking in pCT detector system.
  - Medical image generation.

Thank you for your attention!

Backup

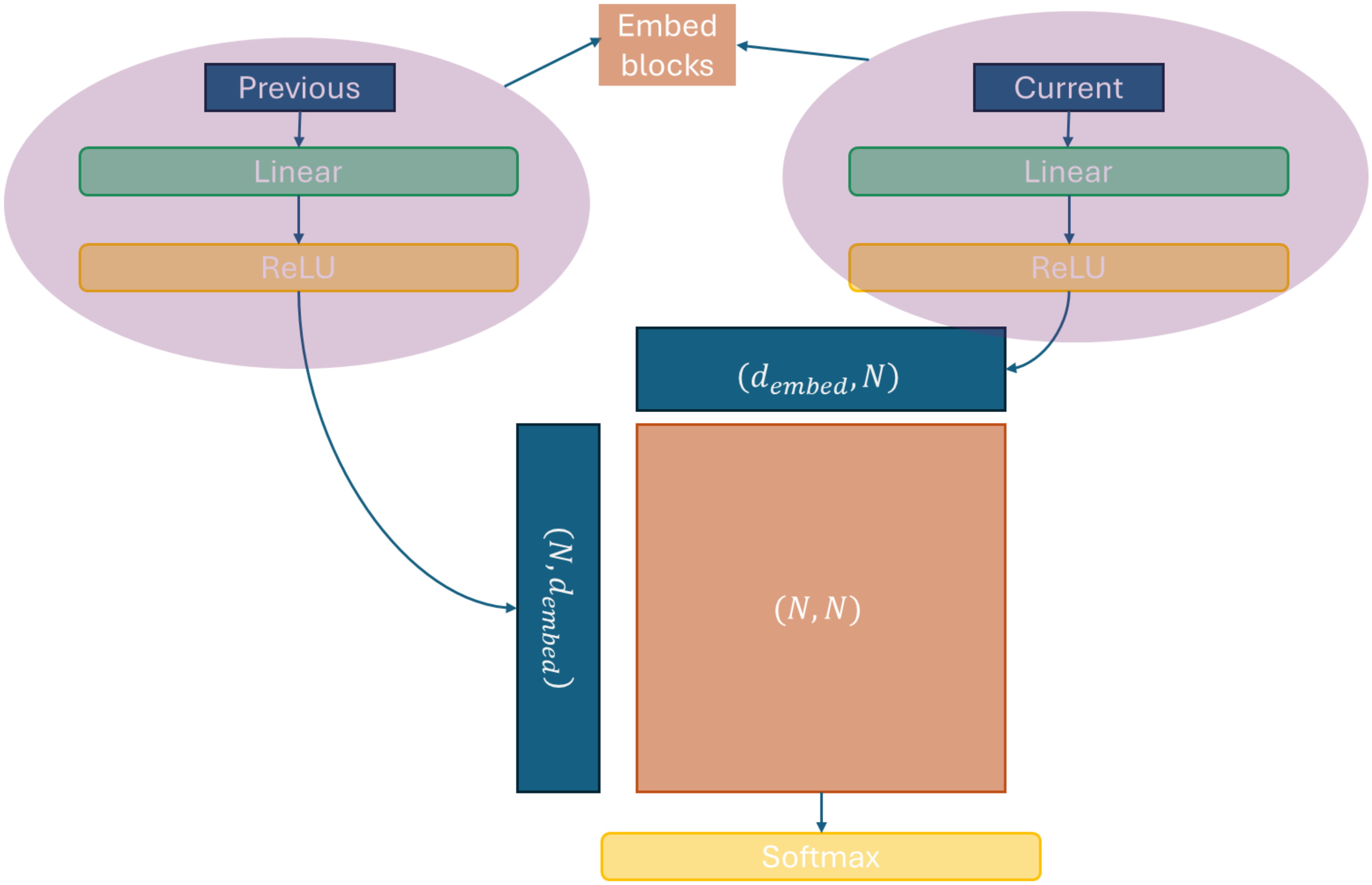
Deep particle matching



Connection Probability Matrix

Deep particle matching

- Normalize input before giving it to the model.
- Creating a high dimensionel embeddig from input.
- Shallow linear block don't break normalization.
- Multiply them with each other.
  - The closer they are the bigger the matrix element value.
  - Similar to attention.

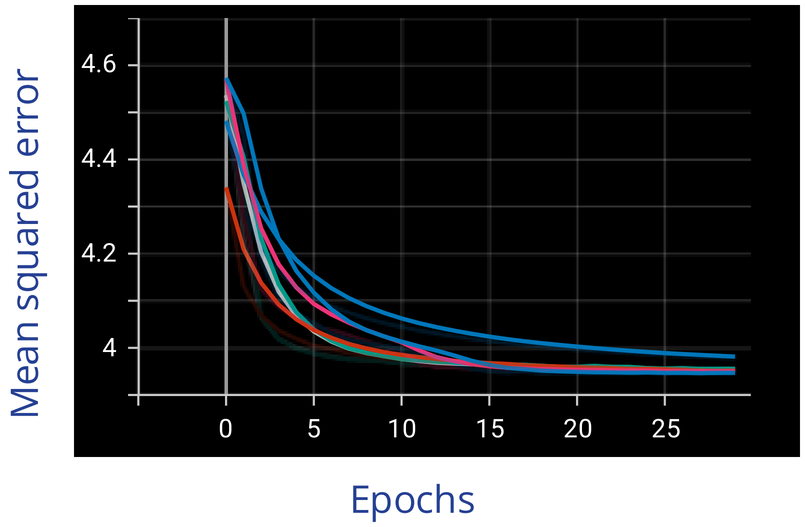


Connection Probability Matrix

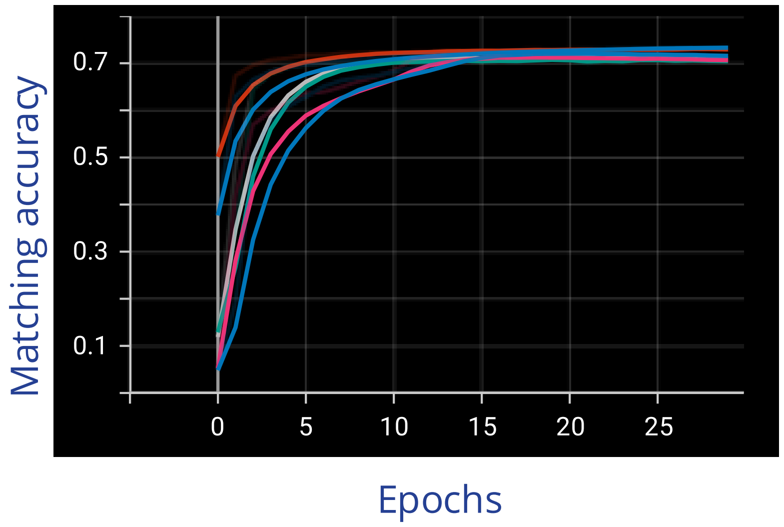
Deep particle matching

- Connection between two detector layer hits.
- Deep neural nets evaluate quick.
- Currently overperforms every traditional algorithm.
  - 72% compared to 65%
- Colors indicate different hyperparameters.
  - As you can see end up with very similar results.

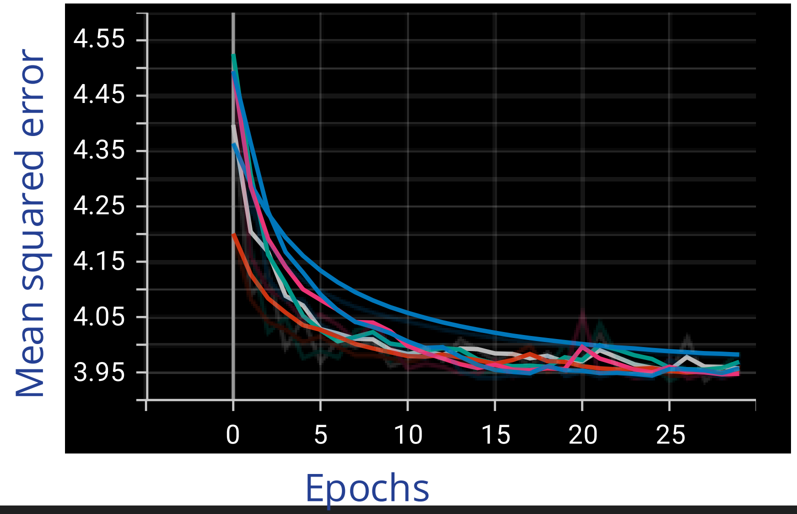
Training loss of different runs



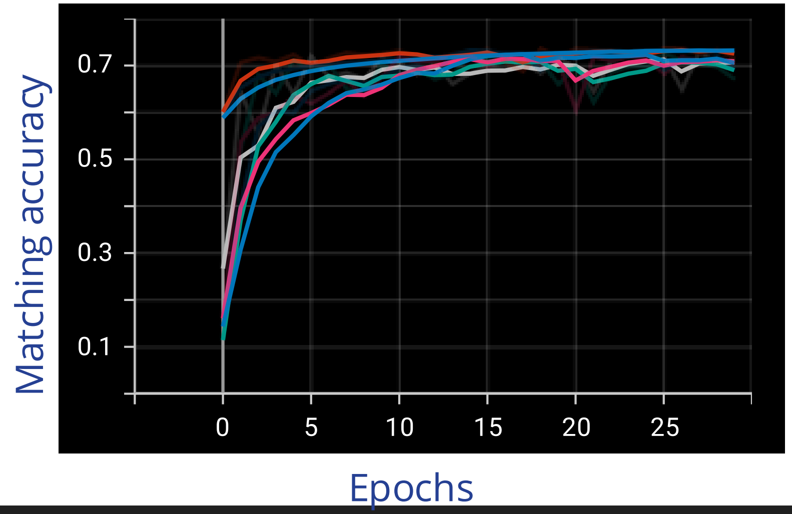
Matching accuracy on training



Validation loss of different runs

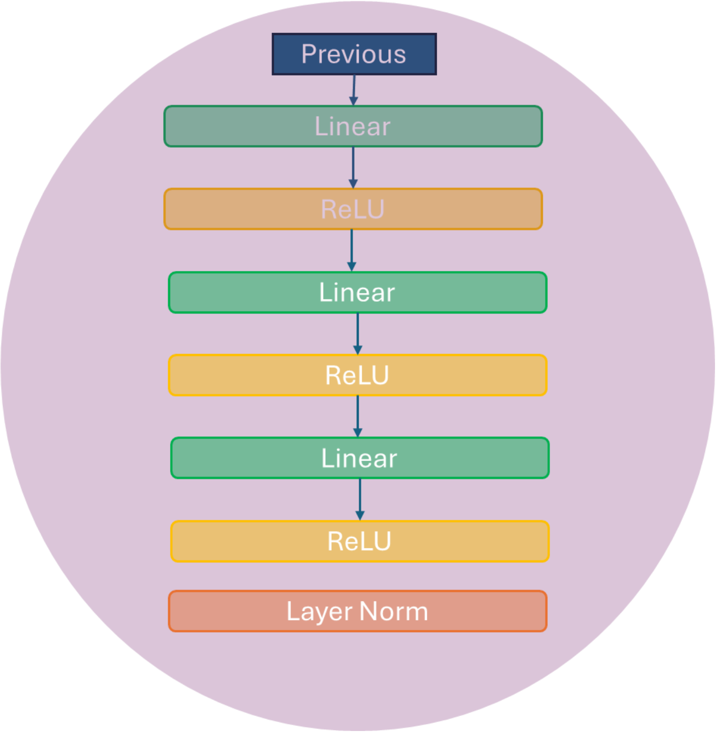


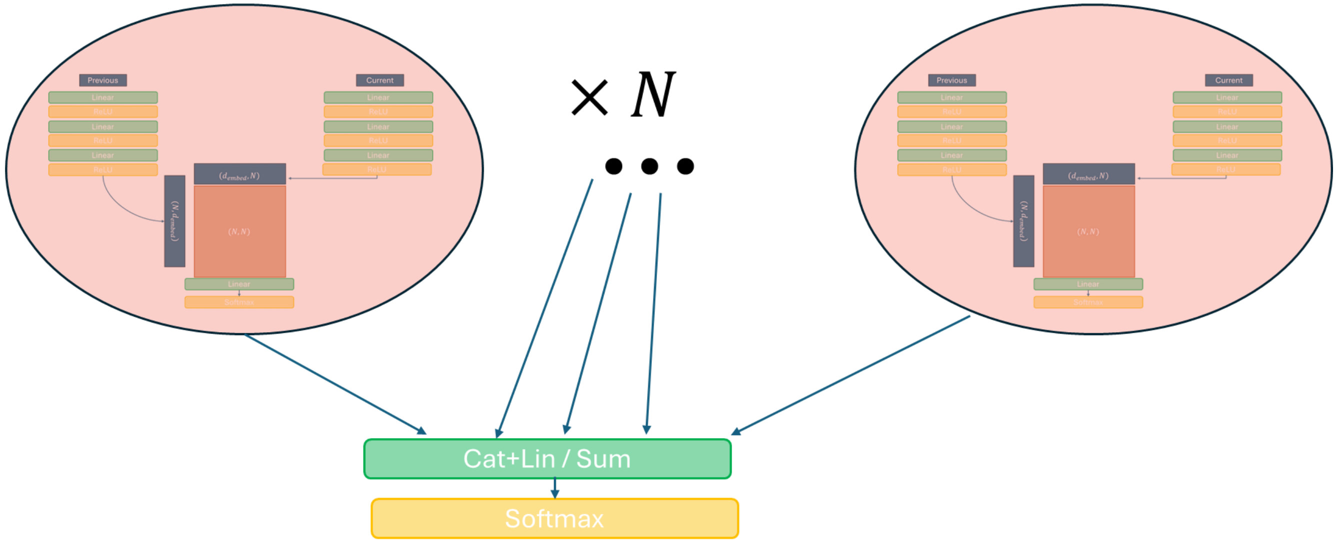
Matching accuracy in validation



Possible improvements

- Multi head attention doesn't show improvement.
- Trying to add multiple normalization step to enforce 1-1 matching.
  - The problem is that the gradients are vanishing.
- Deeper embedding blocks are not making improvement.
- Plans to do position projection in latent dimension and apply match block there.





Process of pCT

Beam in high energy protons

Detecting particle hits in detector system

Charged particle track reconstruction

Medical image generation

These take the most computational time.

Process of pCT

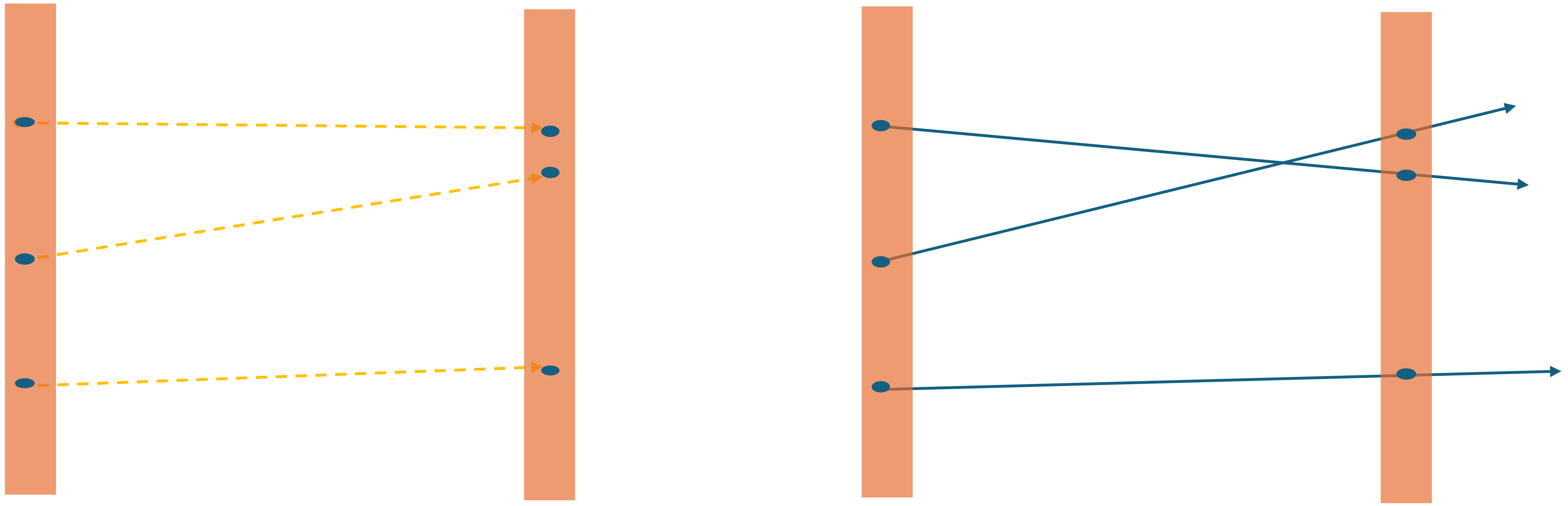
Beam in high energy protons

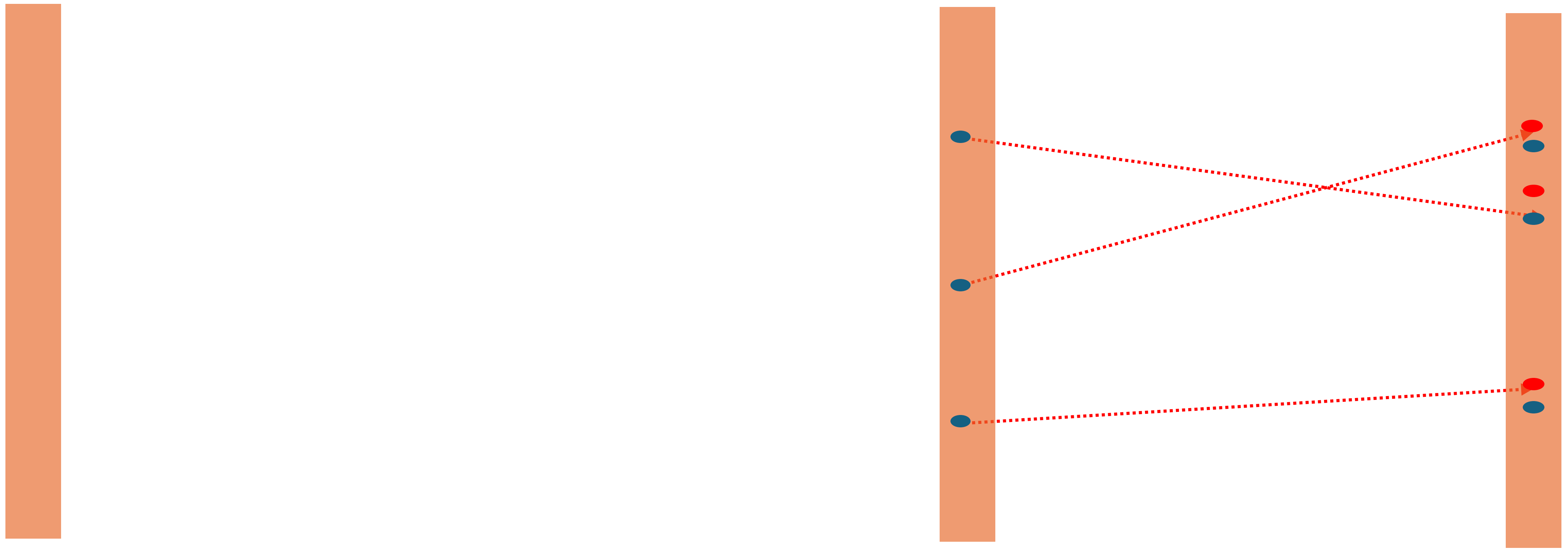
Detecting particle hits in detector system

Charged particle track reconstruction

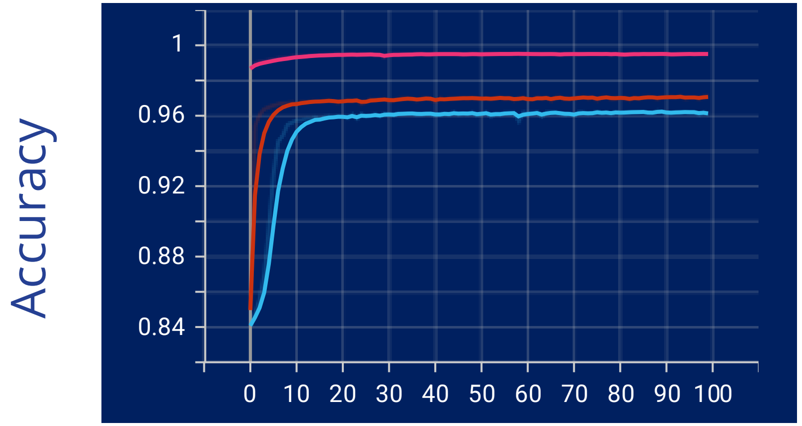
Medical image generation

I concentrate on this.





Validation accuracy



Epochs

- Layer 3 to 2 prediction
- Layer 2 to 1 prediction
- Layer 1 to 0 prediction