17th May 2022

CALOR 2022

Proton energy reconstruction with ASTRA a novel detector concept for pCT

César JESÚS-VALLS IFAE UAB

cesar.jesus@cern.ch

On behalf of M. Granado-González, Dr. T. Lux, Dr. T. Price & Prof. F. Sánchez

Partially based on: *Phys.Med.Biol.* 67 (2022) 3, 035013 • e-Print: 2109.03452.

Outline

1: Introduction

- Proton beam therapy.
- Proton computerized tomography.

2: ASTRA

- Detector concept.
- Reconstruction.
- Proton energy reconstruction by range.
- Imaging results.

3: Calorimetry

- Proton energy reconstruction with calorimetry.
- Calorimetric based tracking using Deep Neural Networks.
- Online reconstruction and data compression processing.
- Proton energy reconstruction by range.
- Imaging results.

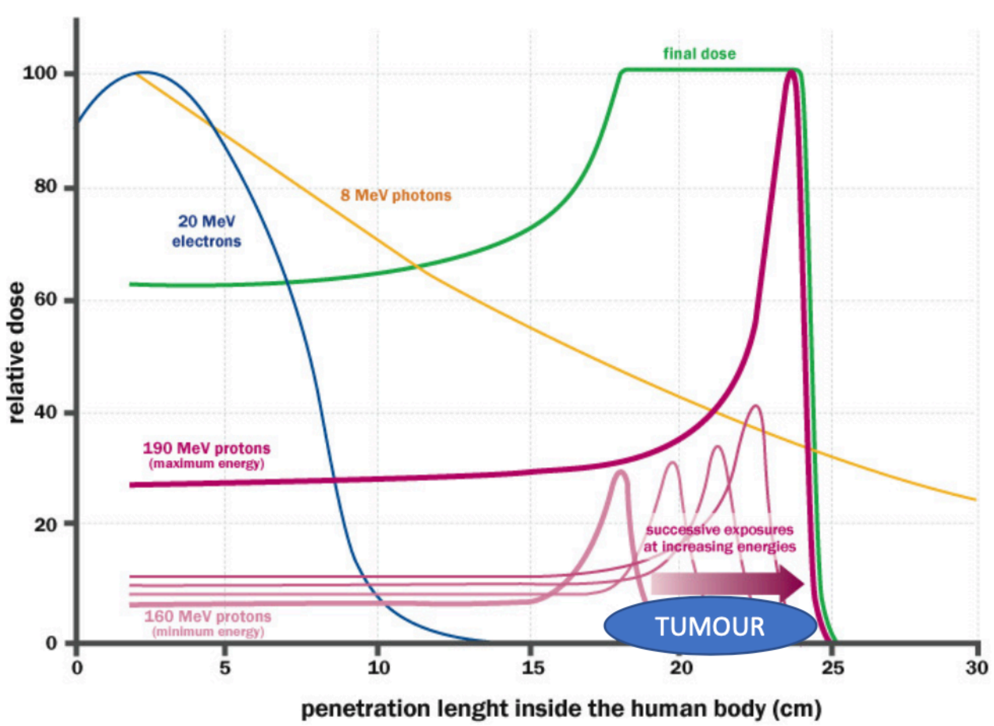
4: Conclusions

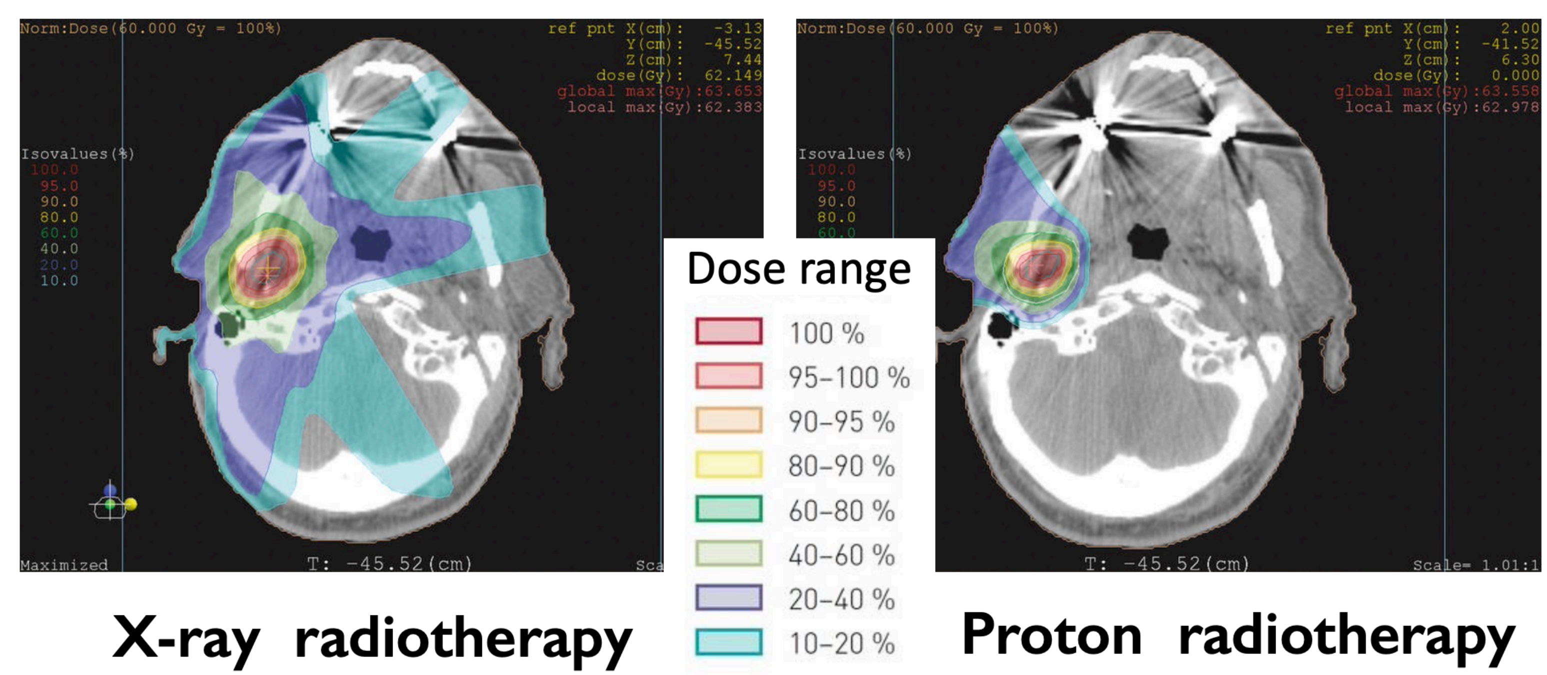
Beam therapy

- Beam therapy consists on the treatment of cancers by using a beam of particles.
- The standard method radiotherapy is x-rays radiotherapy.

Proton beam therapy:

- Proton beam therapy (PBT) was first proposed in 1946.
- Compared to x-rays radiotherapy, PBT is far more localized.





Computed Tomography (pCT)

- In Computed Tomography (CT) a 3D image is made combining 2D images taken at different angles.

The necessity of pCT

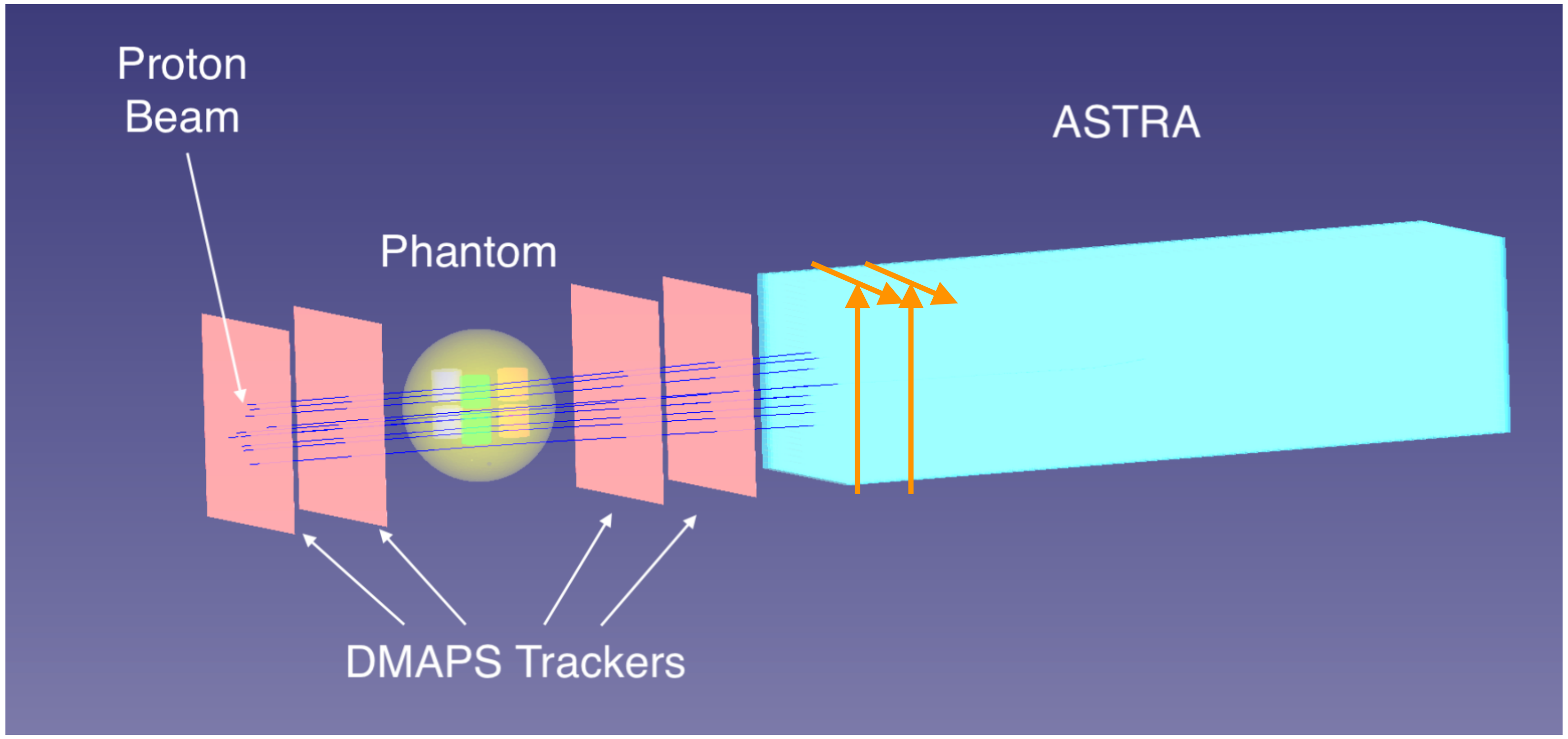
- Existing standard CT systems are based on x-rays.
- To address PBT treatment planning images need to be converted into a Relative Stopping Power (RSP) map, introducing uncertainties.
- Doing the CT scan directly with protons (pCT) might overcome this issue and reduce the imaging toxicity.

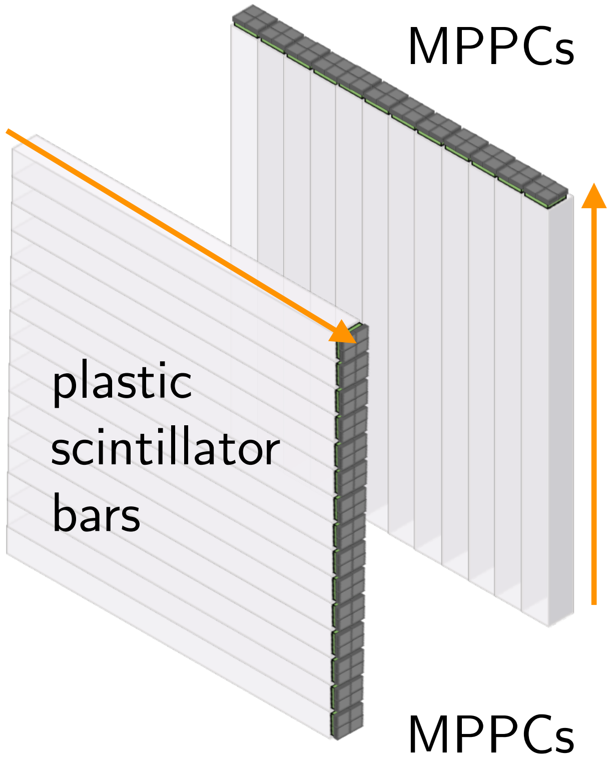
Limitations of exiting pCT systems (Goals)

- Difficulty to cope with high rates >O(MHz). → **O(100 MHz)**
- Inefficient when dealing with proton pile-up. → **Deal with multiple protons.**
- Limited residual proton energy resolution. → **$\leq$ 1% energy resolution.**

ASTRA: A novel energy tagger for pCT

Detector Concept

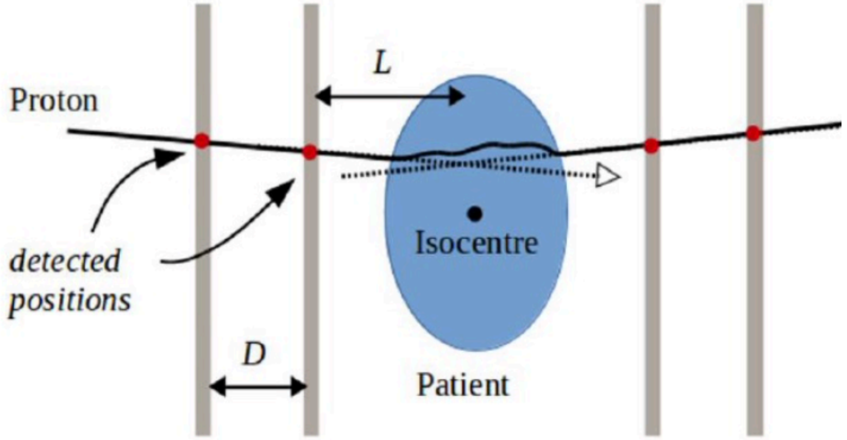




- Tracker made up of 4 Depleted Monolithic Active Pixels Sensors (**DMAPS**).
  TJ Monopix: pixels size 40×40μm^2. Aim at 10×10cm^2 readout area.

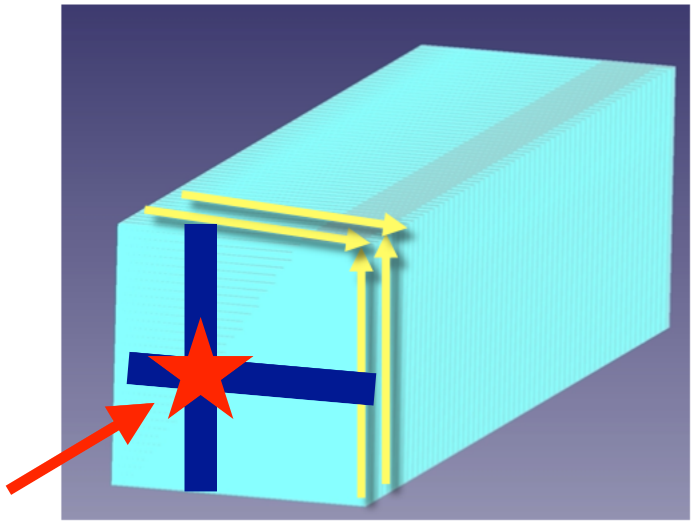
- Proton energy tagger: A Super Thin RAnge telescope (**ASTRA**).
  It combines several technological developments made in the context of the T2K neutrino experiment:
  - **3×3mm^2 bars** of plastic scintillator.
  - Electronics based on **CITIROC ASIC** (continuous readout every 2.5ns + ToT calorimetry).
  - Plastic choice **EJ-200** (rise time 0.9ns, decay time 2.1ns).
  - MPPCs with fast response(e.g **Onsemi's MicroFJ SiPMs)** coupled directly to the plastic bulk

Reconstruction



DMAPS tracking

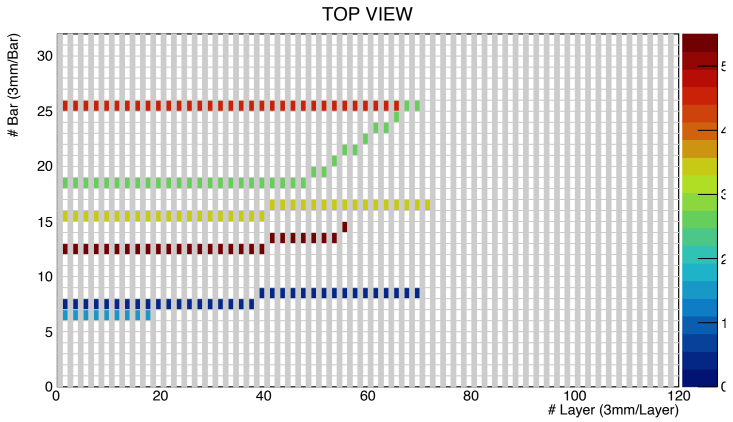
- Hit combinations that minimize the total χ^2 under the assumption of a straight trajectory.

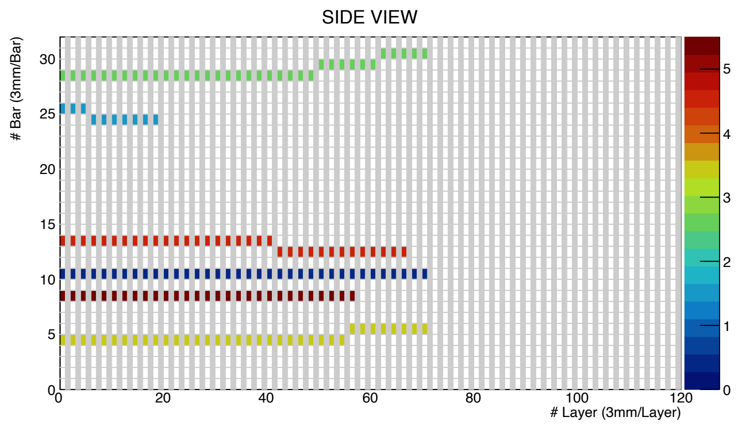


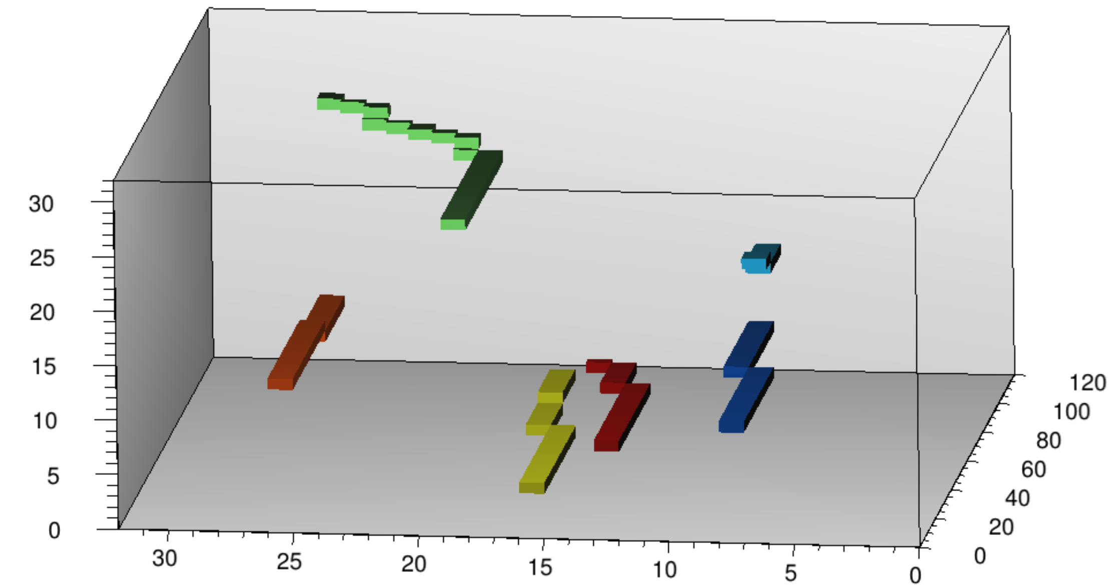
ASTRA tracking

- DMAPS trajectory is projected to ASTRA in if a set of 2 bar hits is found to match the prediction a 3D point is formed, which is propagated forward.

Example of a reconstructed event



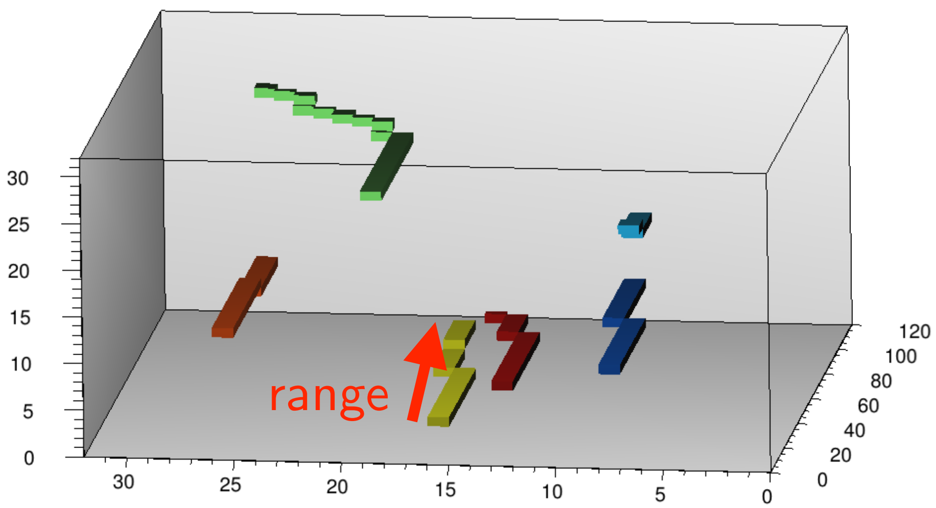




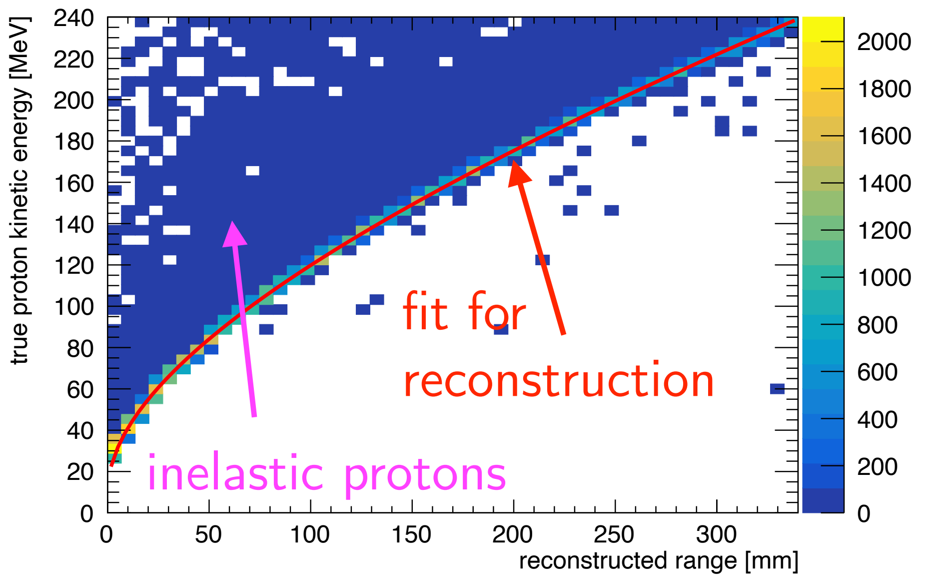
ASTRA energy resolution (by range)

Energy reconstruction solely by range

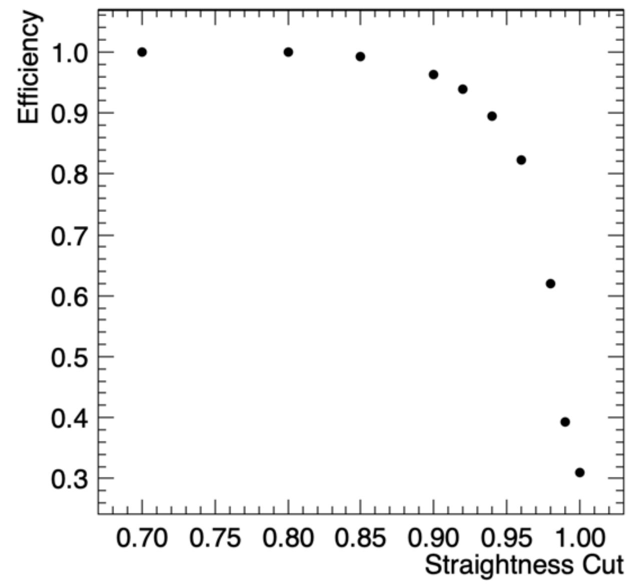
Compute range for each reconstructed track



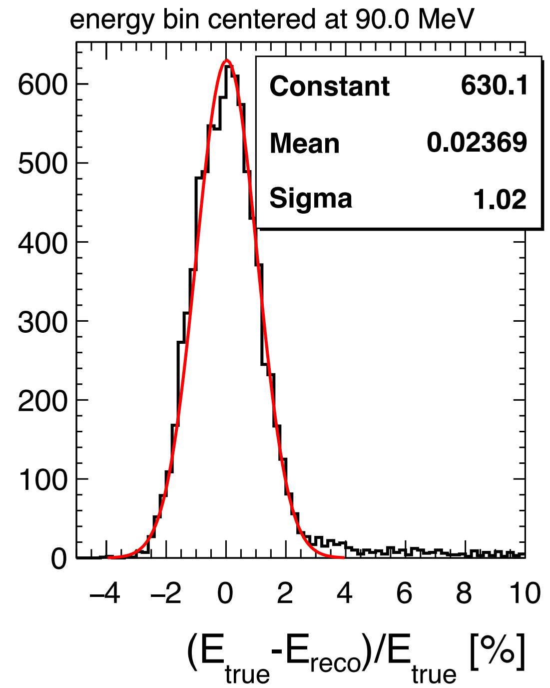
Build a map from reconstructed range to true energy

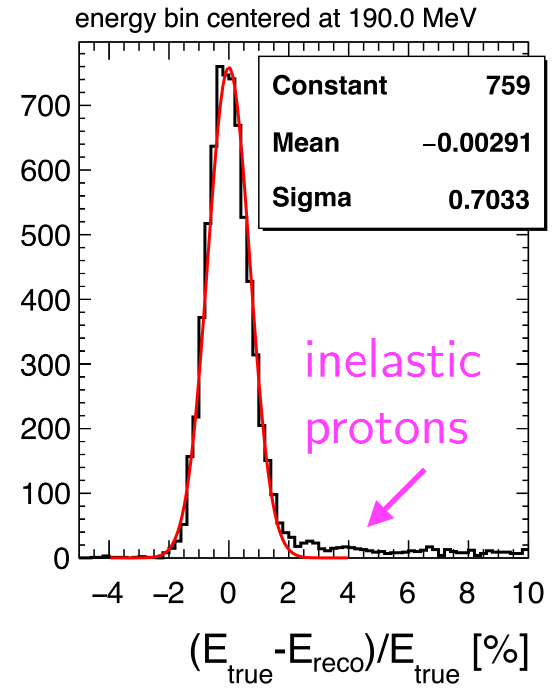


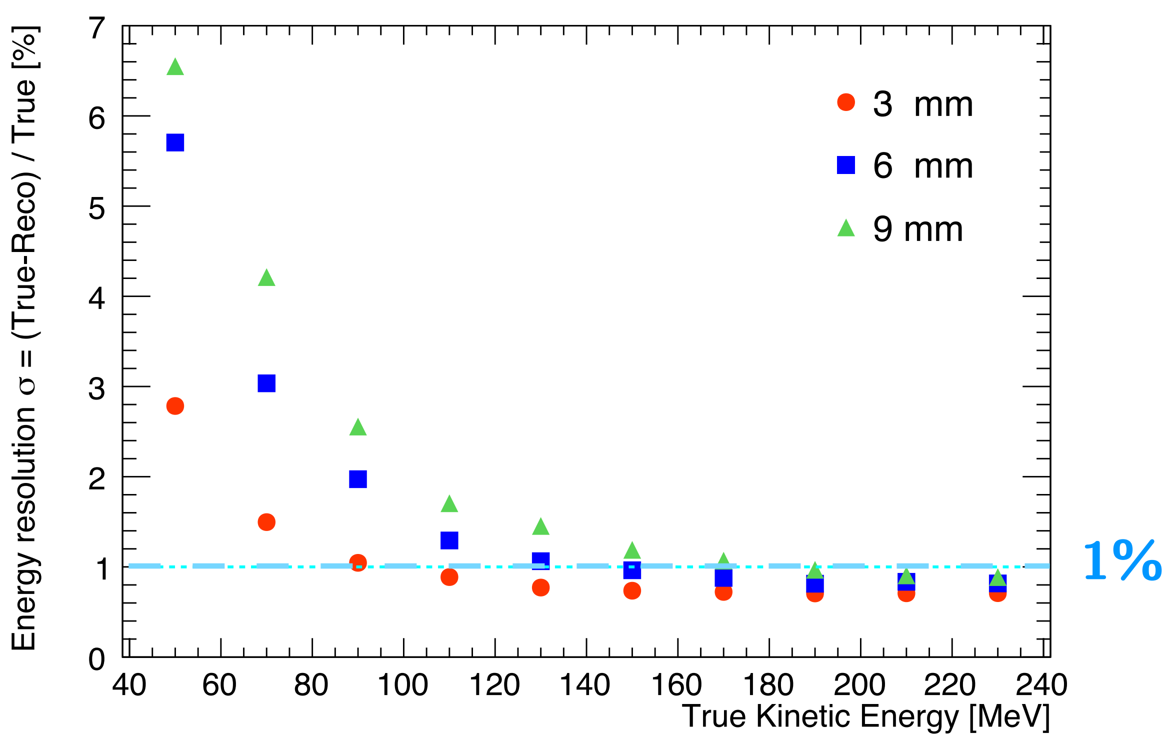
Inelastic protons easy to identify using track's straightness



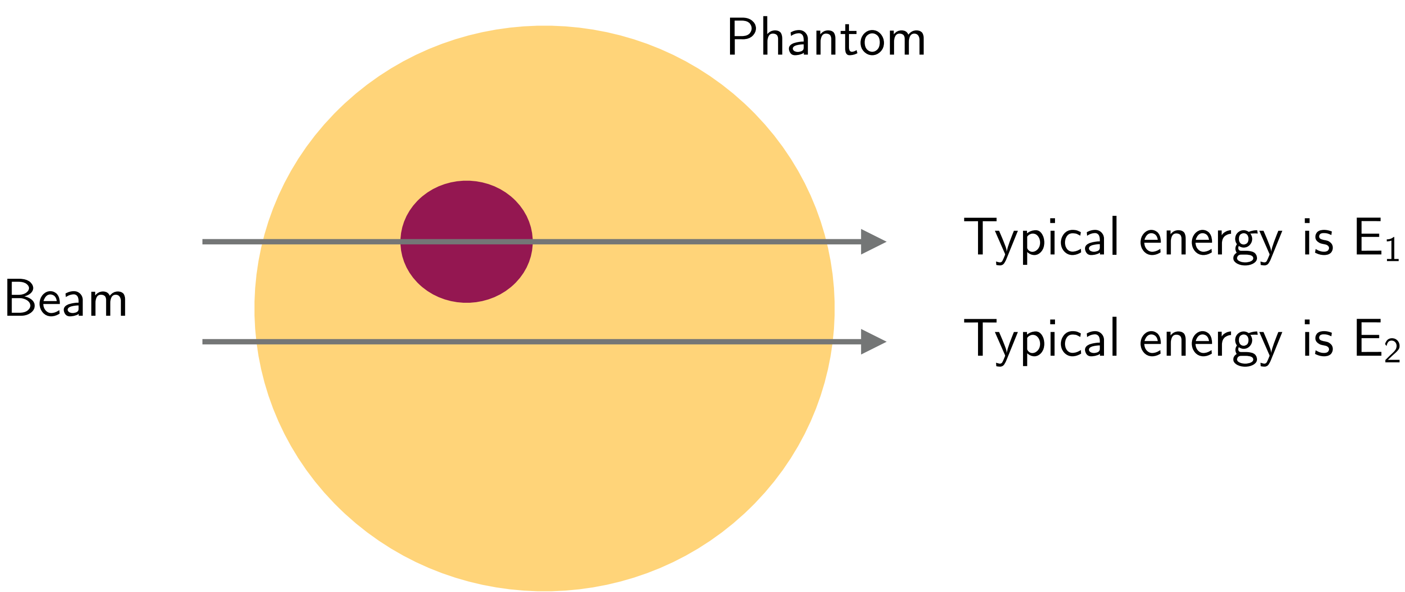
Performance:



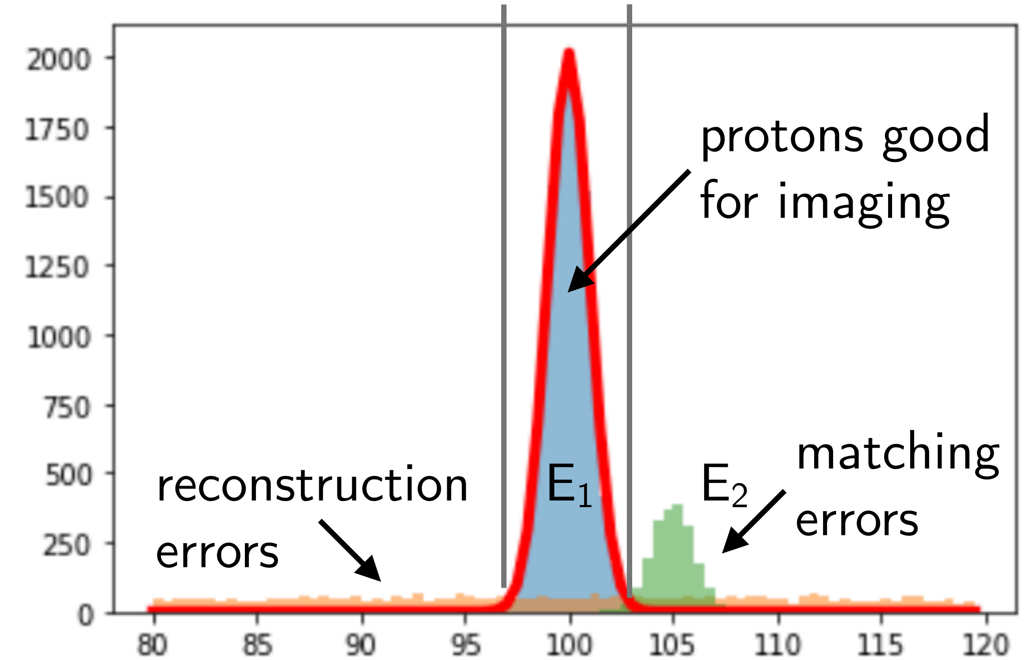




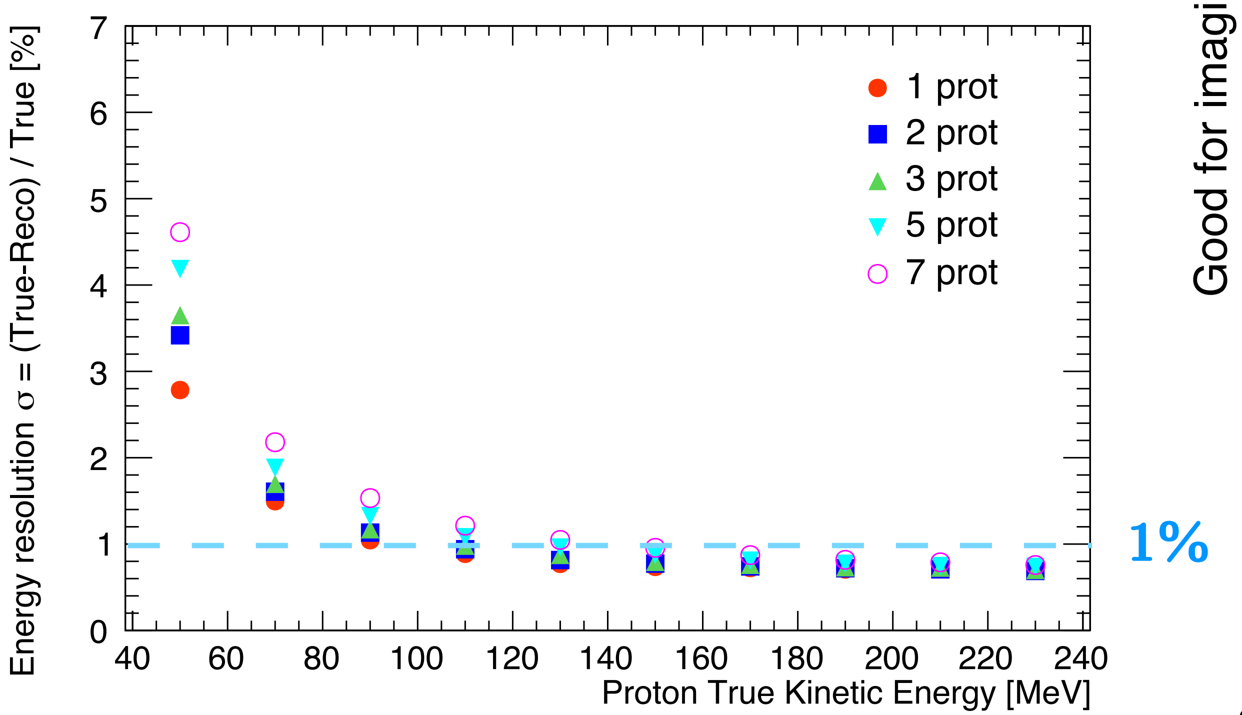
pCT, impact of reconstruction errors

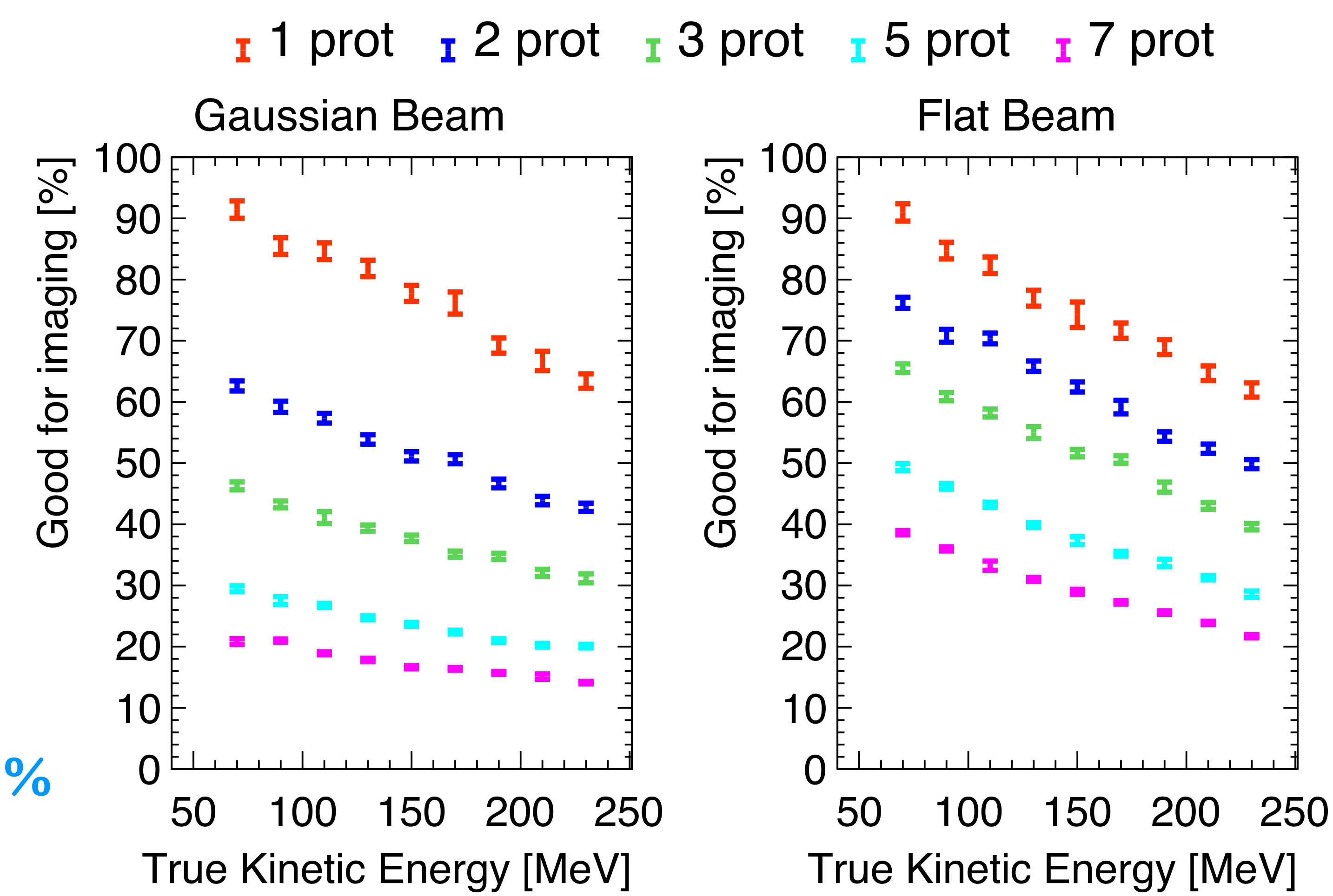


*idealized sketch



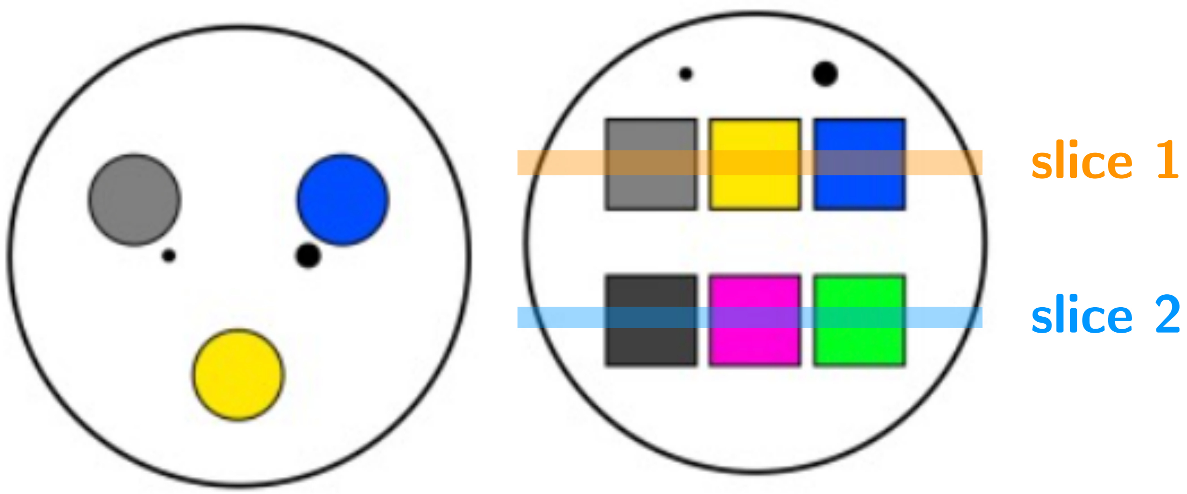
- Protons in gaussian regime are considered good for imaging.

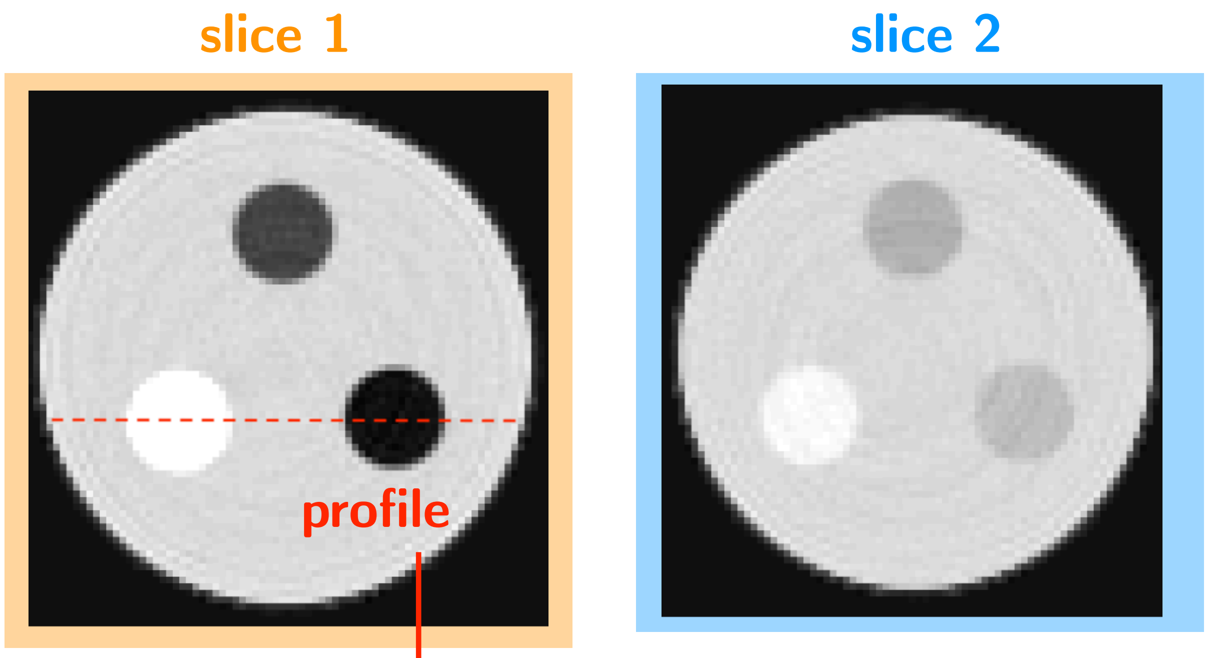




Slope: Longer range → higher proportion of inelastic protons.

Imaging





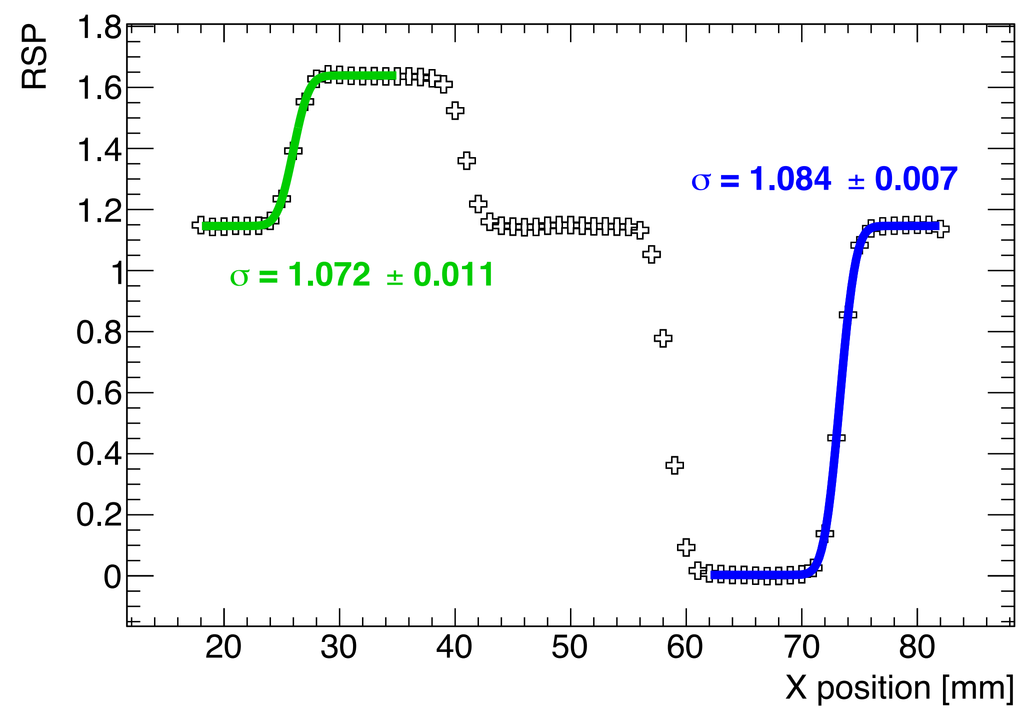
Reconstructed RSP

- Realistic clinical beam profile (Gaussian beam $\sigma = 10$ mm).

Material	RSP (Reco)	RSP (True)	%diff	RSP (Reco 3p)	%diff (True)
Water	0.992 ± 0.002	0.994 ± 0.002	0.201	1.033 ± 0.002	3.924
Air	0.009 ± 0.002	0.008 ± 0.002	-12.5	0.076 ± 0.006	850
Adipose	0.916 ± 0.006	0.917 ± 0.005	0.109	0.96 ± 0.02	3.60
Rib bone	1.325 ± 0.003	1.326 ± 0.001	0.075	1.34 ± 0.04	1.06
HC bone	1.641 ± 0.003	1.646 ± 0.002	0.304	1.66 ± 0.02	0.85
Perspex	1.144 ± 0.004	1.149 ± 0.002	0.455	1.14 ± 0.01	-0.78
Lung	0.302 ± 0.003	0.302 ± 0.002	0.000	0.35 ± 0.02	15.89

- Excellent RSP results (<1%) paired with 1mm position resolutions.
- Results show potential to deal with pile-up events.

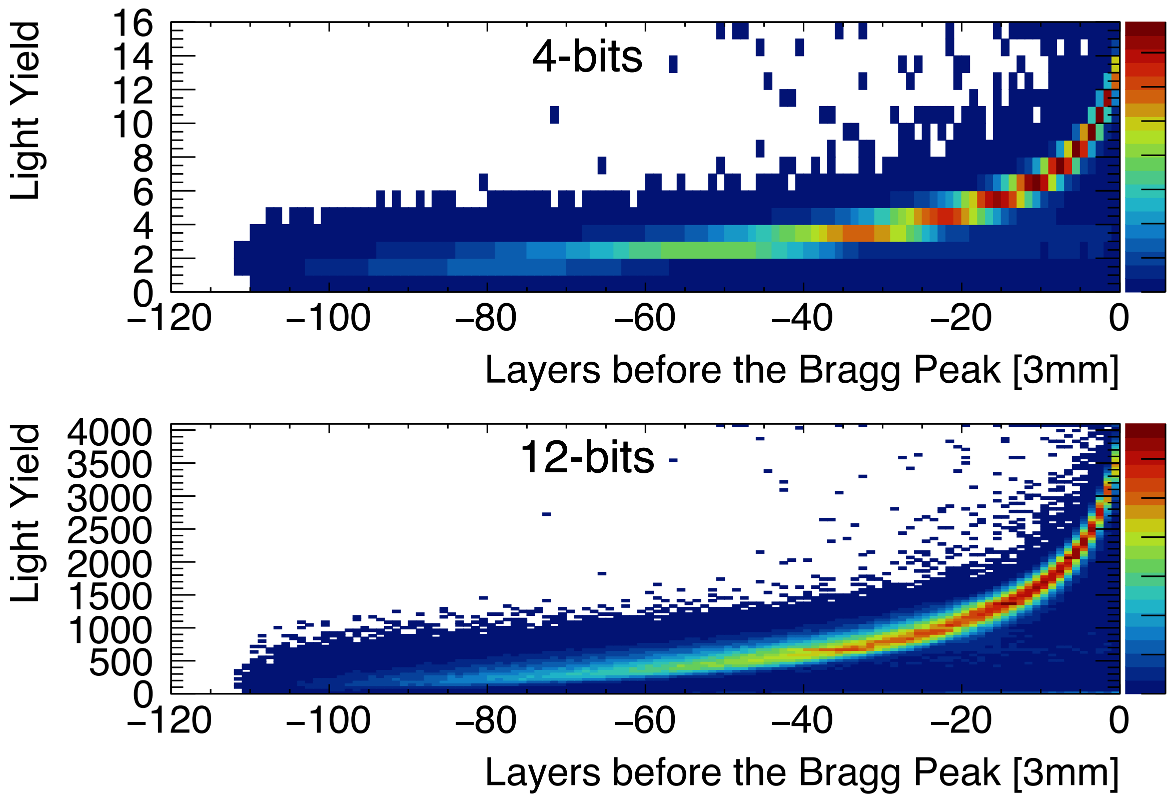
Reconstructed position

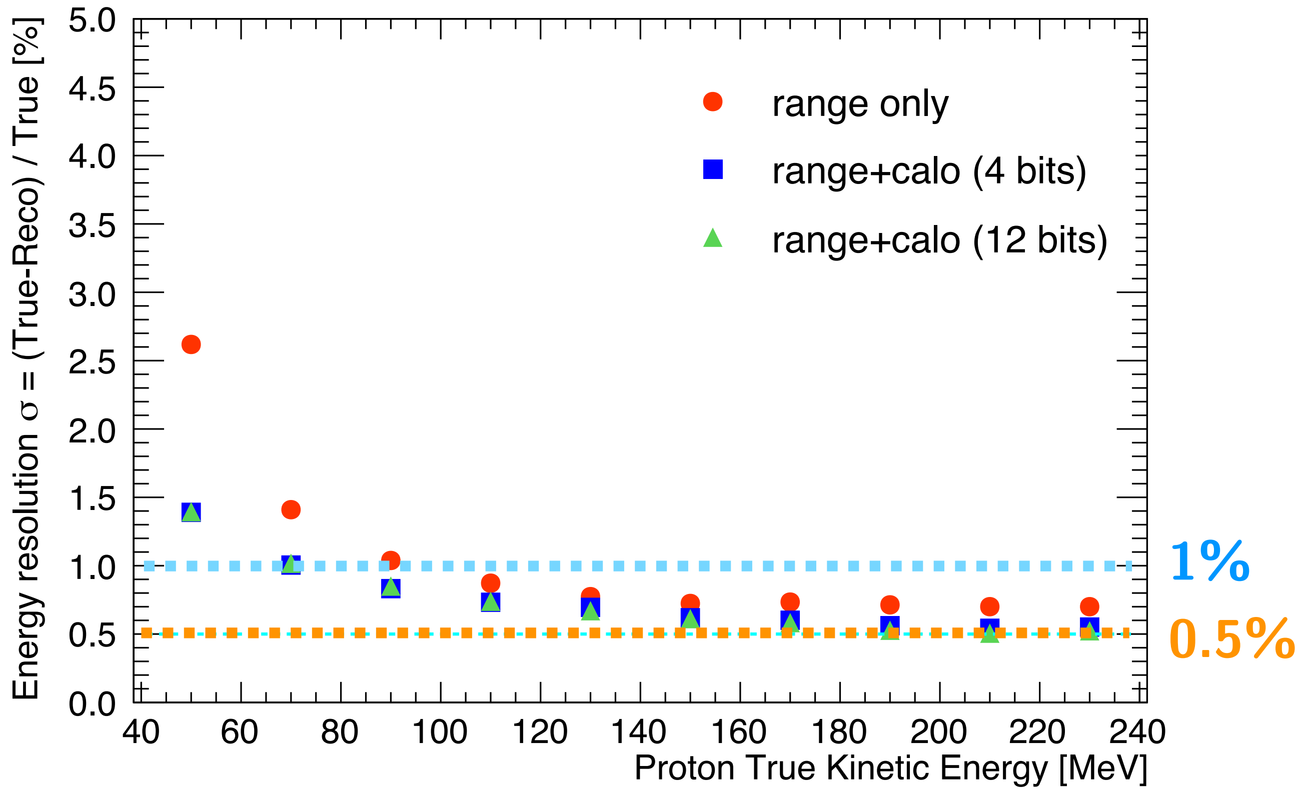


ASTRA calorimetry

Motivations:

- Improve the energy resolution.
- Improve reconstruction for inelastic protons.
- Help tracking of pile-up events.





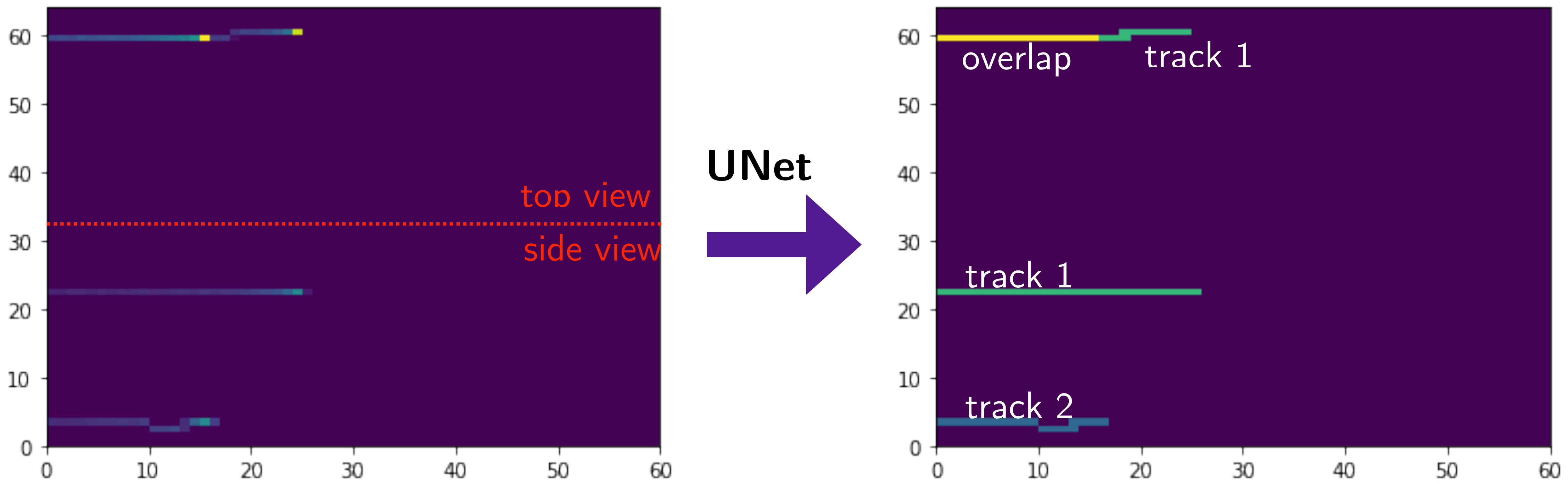
Caveats:

- Total data rate for calorimetric information is a challenge.

Calorimetric based tracking using DNN

Idea:

- Use deep neural networks (DNN) to perform the tracking.
- Overlaps can be solved thanks to calorimetry.



Benefits:

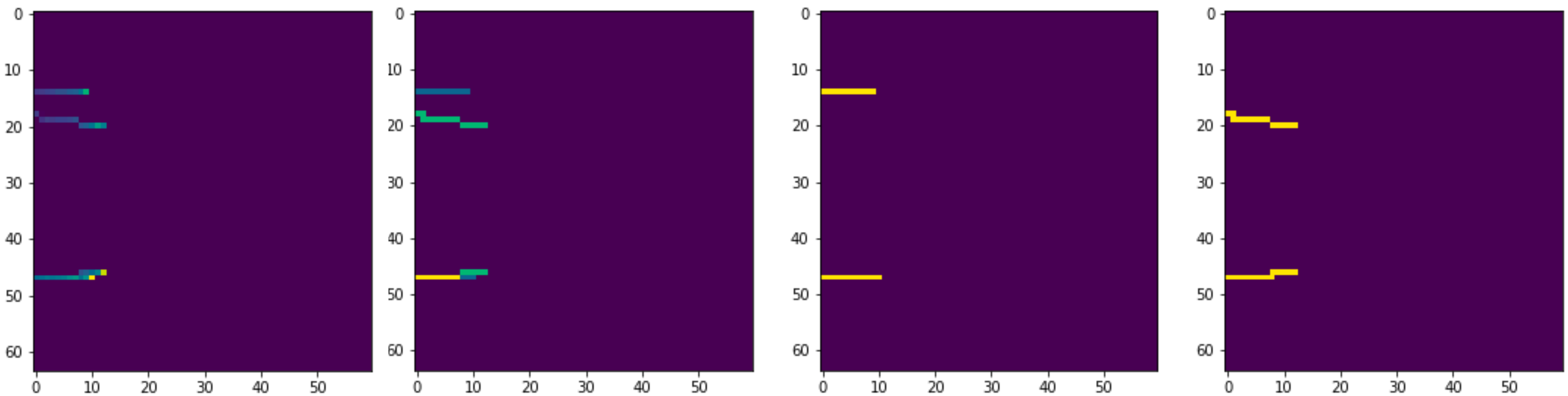
- No need of developing time-consuming custom tracking algorithms.
- DL can often outperform conventional alternatives.
- NN evaluation times are very fast.

Calorimetric based tracking using DNN

preliminary (work ongoing)

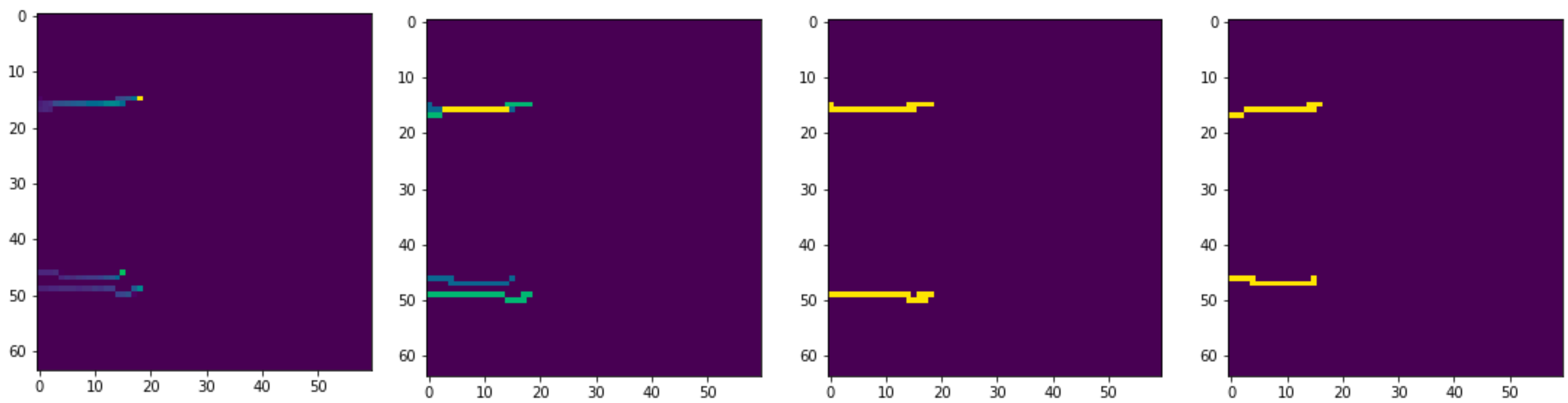
Example A

Input: | Truth | Predicted Track 0 | Predicted Track 1



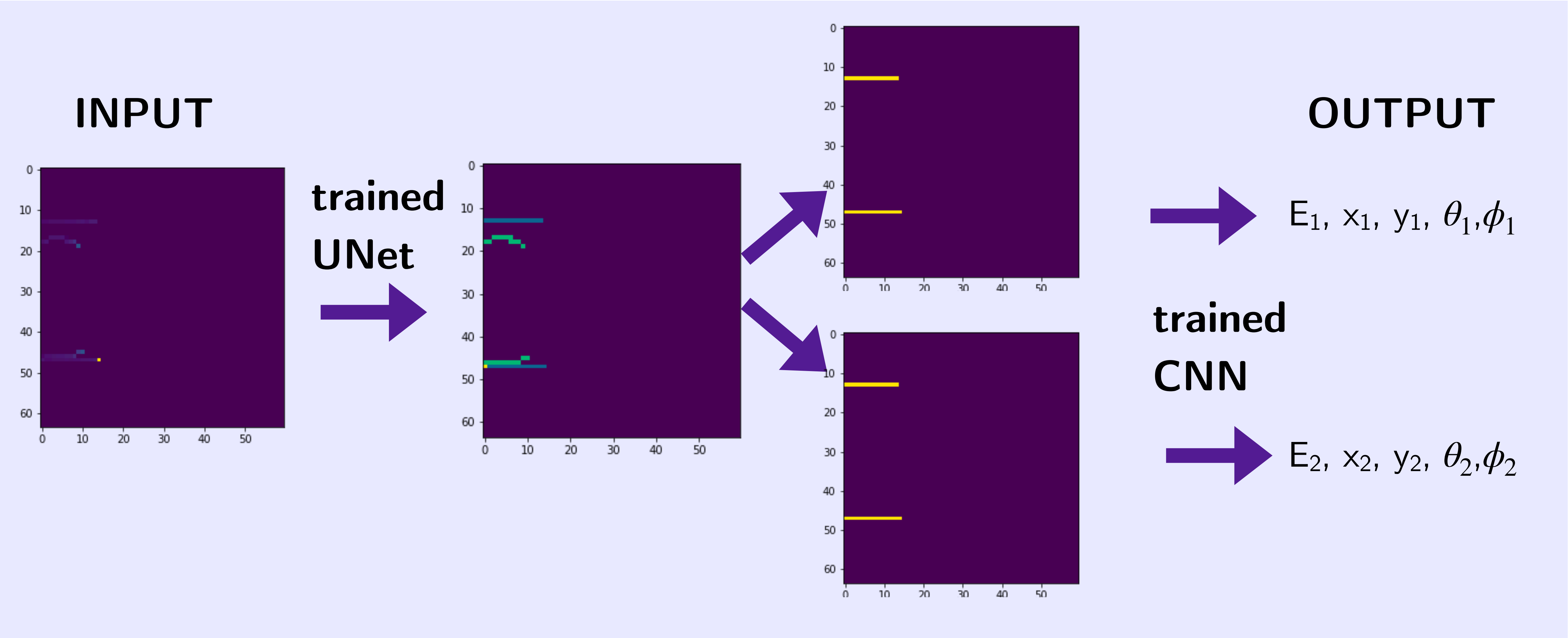
Example B

Input: | Truth | Predicted Track 0 | Predicted Track 1



Reconstruction and Data Reduction

Idea: End-to-end DL reconstruction



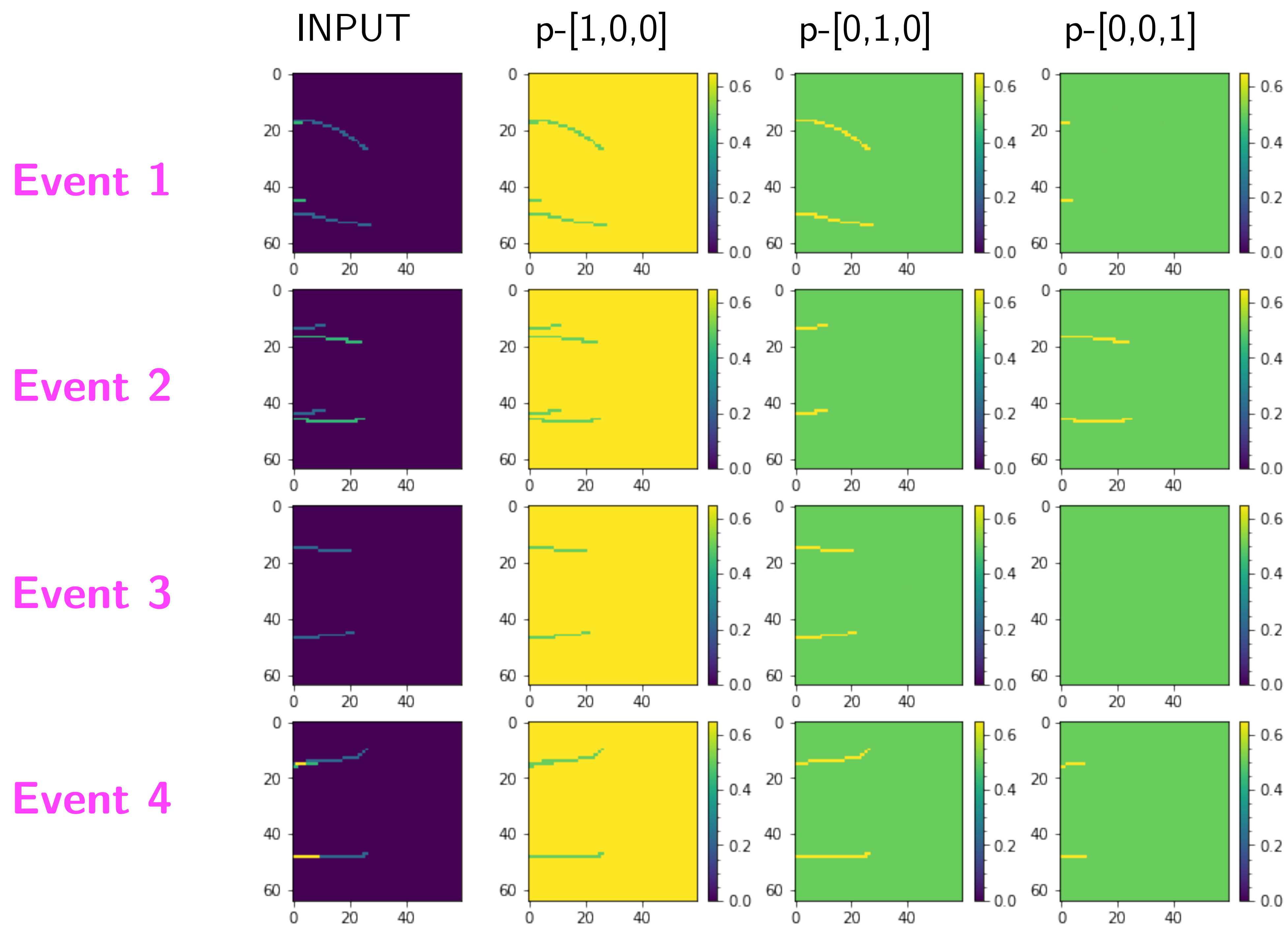
Benefits:

- Tracking outputs can be input to a CNN to get only the values of interest.
- Running the former algorithm in several GPUs in parallel might help to deal with high the data rates.

Conclusions

- ASTRA is a novel detector concept to perform protonCT.
- MC shows exciting potential for this device even without calorimetry.
- The addition of calorimetry opens the door to significant enhancements, including:
  - Better energy resolution.
  - Higher efficiency for inelastic protons.
  - Much better multi-proton tracking.
- Efforts are underway to get funding to build a first prototype.

Calorimetric based tracking using DNN



- Current approach uses multi-label classification, and returns probability 'p':
  Background: p-[1,0,0]
  Track 1: p-[0,1,0]
  Track 2: p-[0,0,1]