The use of CNN for multi-proton events at the ASTRA range telescope for pCT

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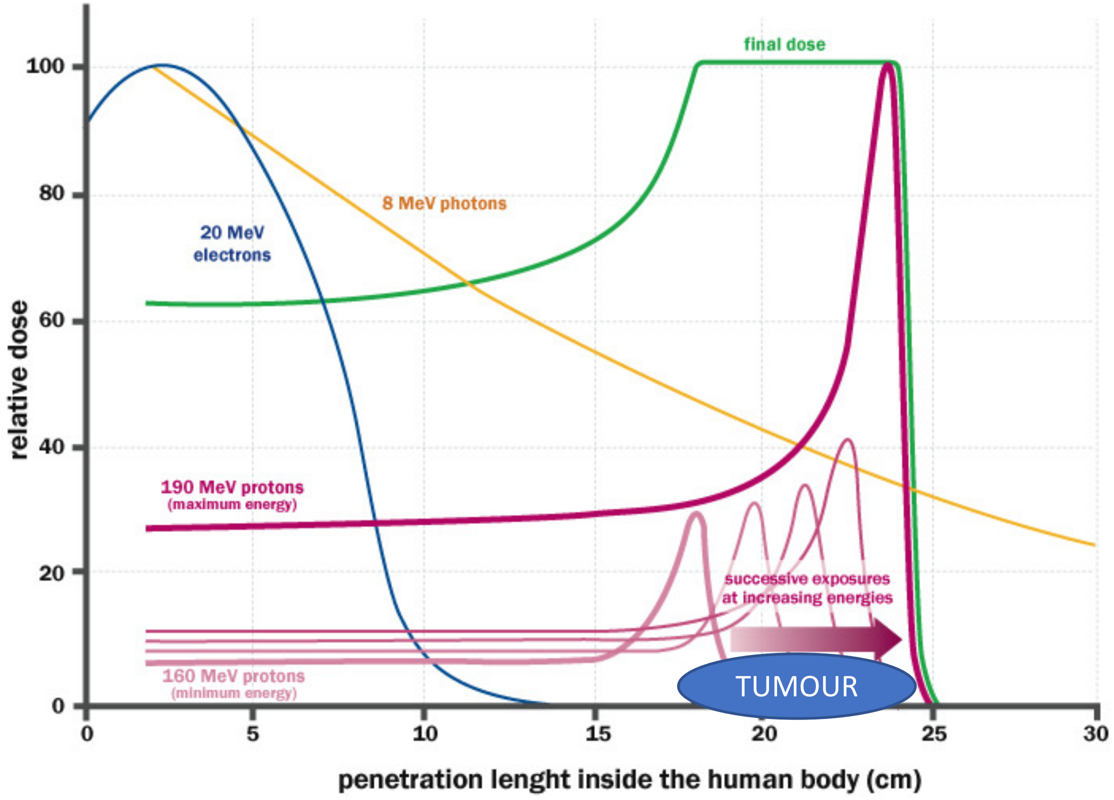
Overview

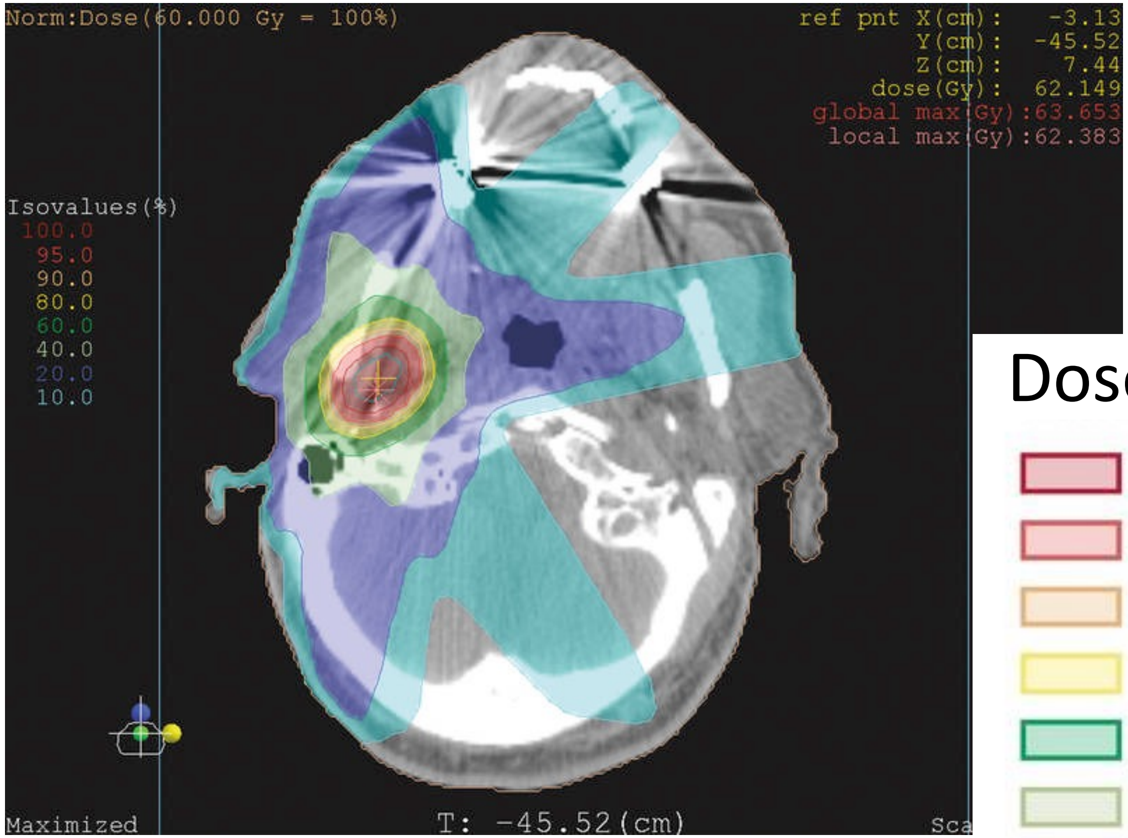
- Motivation protons vs X-rays for
  - Treatment
  - Imaging
- Simulated setup
- Classic algorithms analysis
- CNN for multi-proton tracking
- Energy reconstruction with NN
- Conclusions

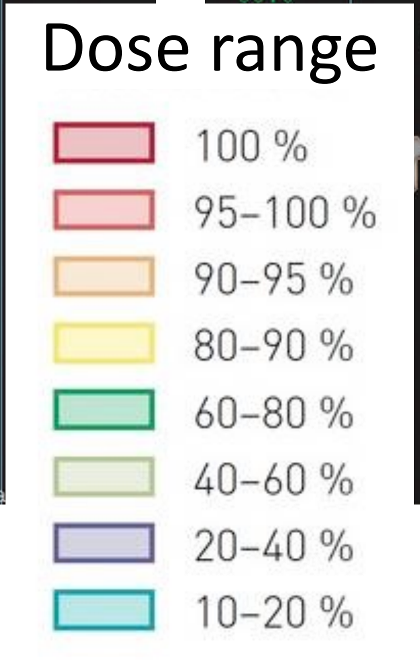
Robert Wilson circa 1946

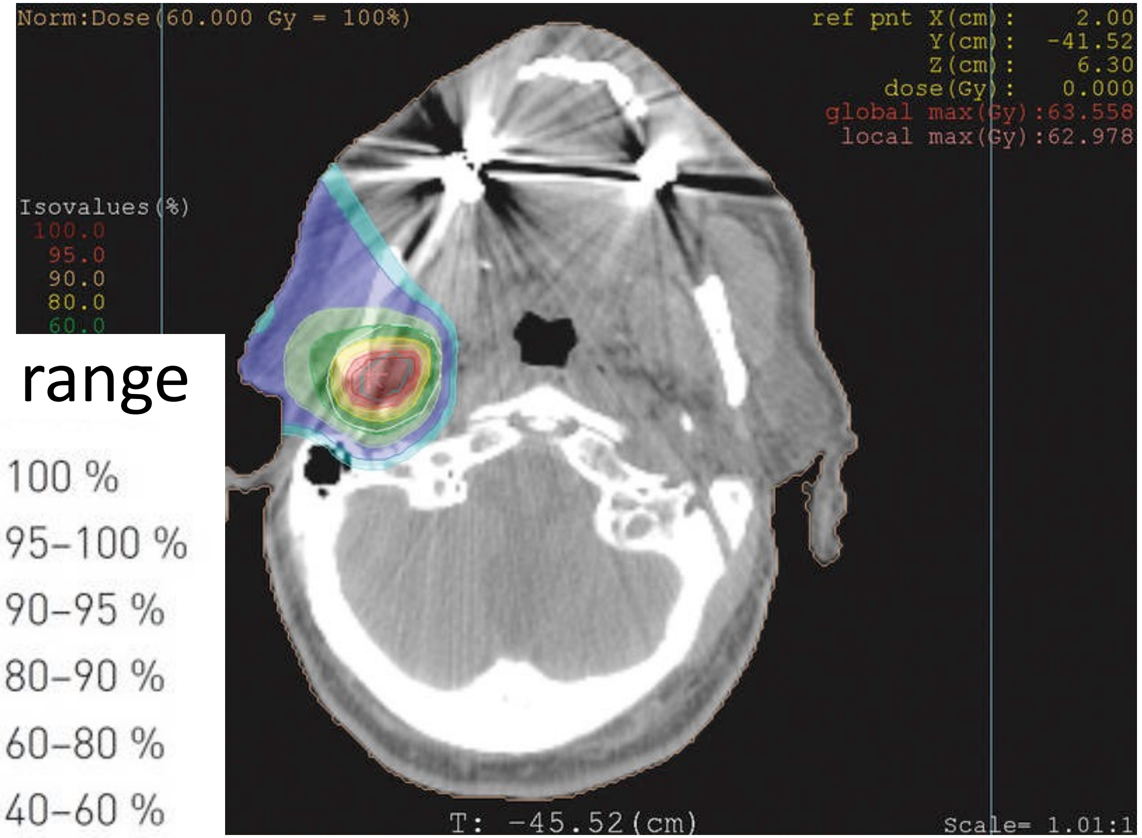
Proton vs X-rays on treatment



- A beam of photons will deposit energy all along its path following an exponential law
- A proton will lose energy via the Bethe-Bloch formula and as such exhibit a Bragg Peak (BP)
- Most of the energy is deposited just before a proton stops
- Range of charge particle and therefore position of BP set by initial particle energy and materials to be traversed
- No dose deposited after the BP
- Lower dose to healthy tissue reduces the risk of complications in later life and allows for treatment of cancers close to critical organs

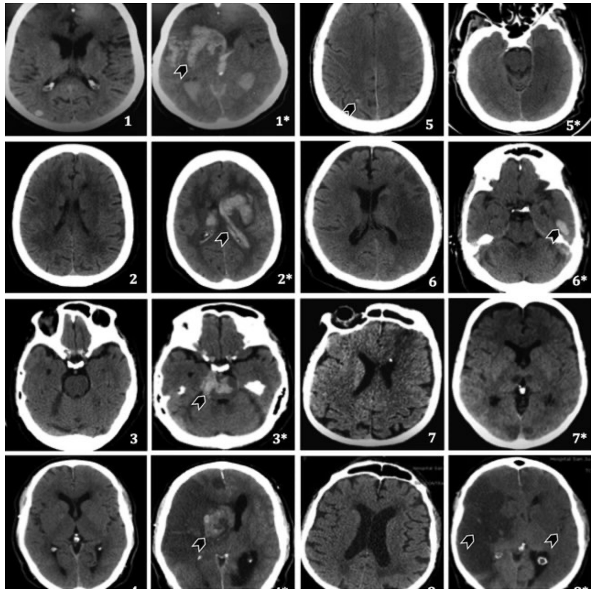






X-ray radiotherapy **Proton radiotherapy**

Computed Tomography



- Bragg peak: **With great power comes great responsibility**
- Very localised dose deposition needs from very low uncertainty in range (energy).
- So far, stopping power and ionisation potentials of materials are extracted from a conventional x-ray CT scan –> BIG uncertainties!
  - New results with Double Energy CT achieve better resolutions but compatible with pCT
- If we treat with protons, lets image with protons!

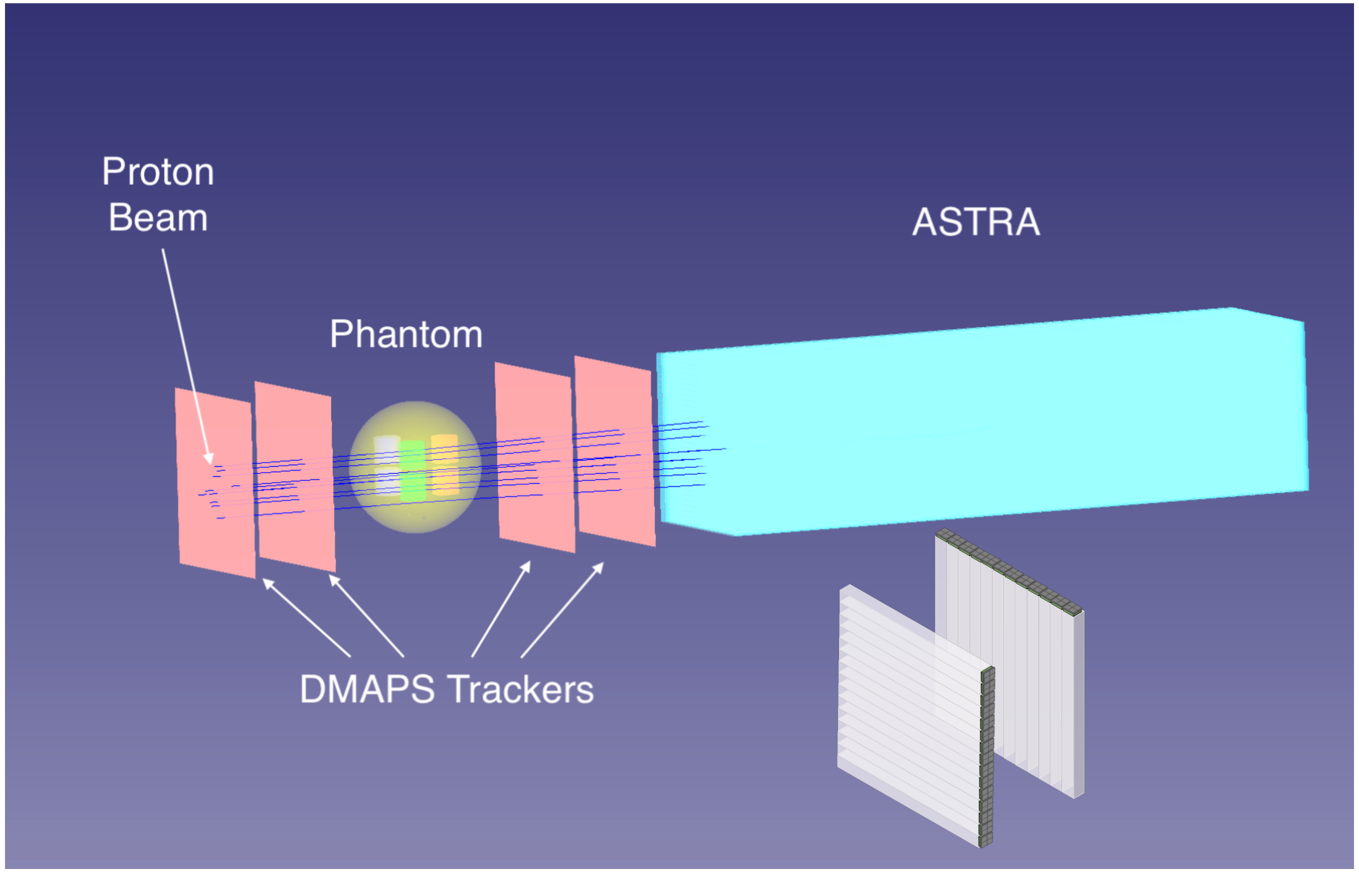
	Uncertainties in SPR estimation (1σ)		
Uncertainty source	Lung (%)	Soft (%)	Bone (%)
Uncertainties in patient CT imaging	3.3	0.6	1.5
Uncertainties in the parameterized stoichiometric formula to calculate theoretical CT numbers	3.8	0.8	0.5
Uncertainties due to deviation of actual human body tissue from ICRU standard tissue	0.2	1.2	1.6
Uncertainties in mean excitation energies	0.2	0.2	0.6
Uncertainties due to energy dependence of SPR not accounted by dose algorithm	0.2	0.2	0.4
Total (root-sum-square)	5.0	1.6	2.4

Simulation work for pCT

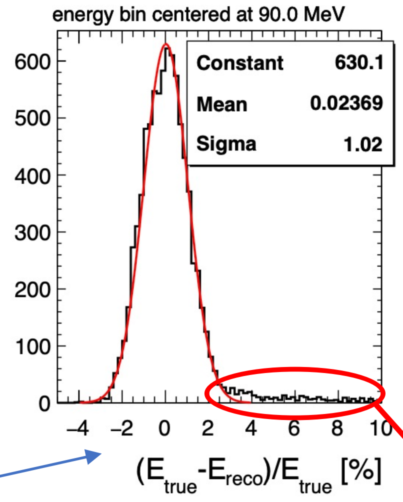
- **Proton tracking:**
  - **DMAPS** [3,4,5] with for the front (2) and back (2) tracking system with pixels of 40x40 μm^2 and a full size of 10x10 cm^2.

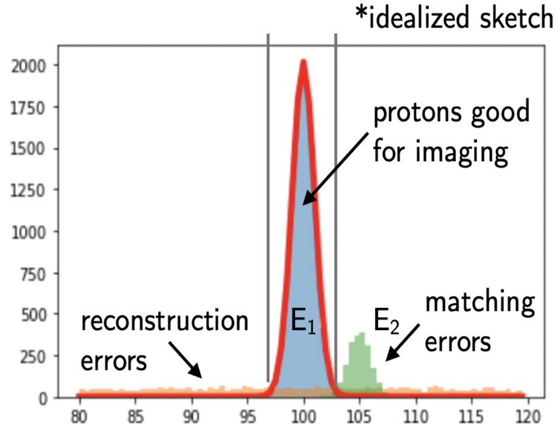
- **Energy tagging:**
  - **ASTRA** for the residual energy measurement with 120 layers of 36 bars of 96x3x3 mm^2 inspired on the FGD at T2K [6].

The technologies, presented in [2], simulated with **Geant4/10.06.p03** and the physics package **QGSP_BIC** at the BlueBear computer.



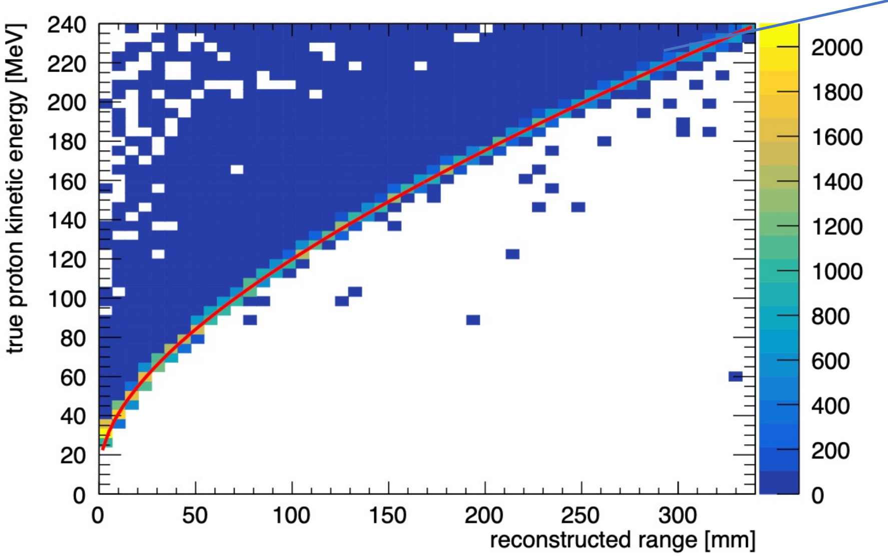
Resolution & efficiency





- Energy reconstructed (purely by range) using range reconstructed by the length of each track from **1 M** simulated protons with **no phantom** and beam energies ranging between **80 to 180 MeV**
- Long tails due to hard scattering.
  - Tracks above the fitted line

Segmentation → Length of track rather than depth/layer



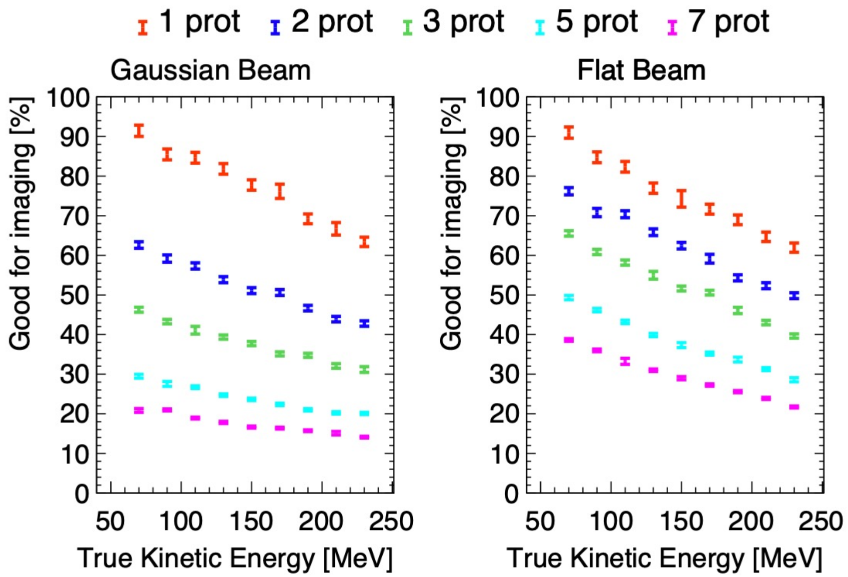
- Sub 1% resolution for protons above 100 MeV.

The beam profiles used were:

- Gaussian with **σ = 10 mm**
- 75 × 75 mm^2 square.

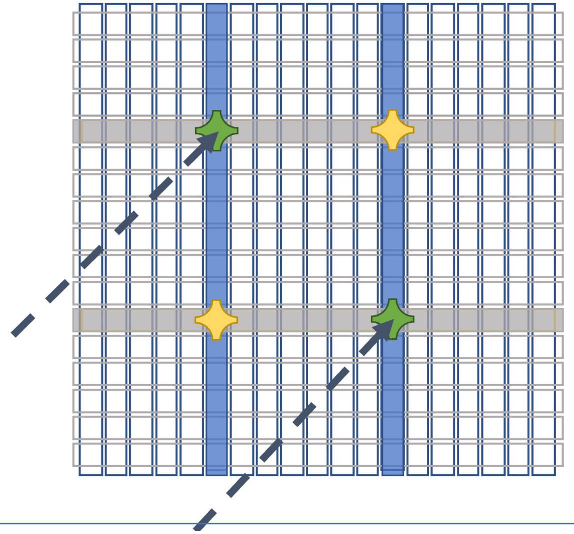
Two important factors:

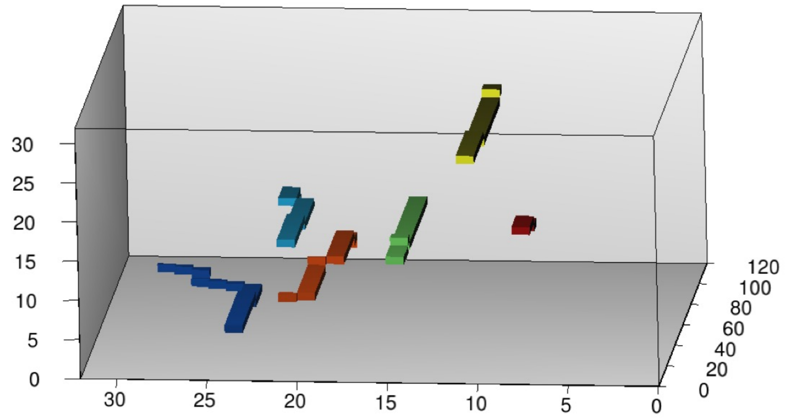
- **Energy reconstruction**
- **Matching**

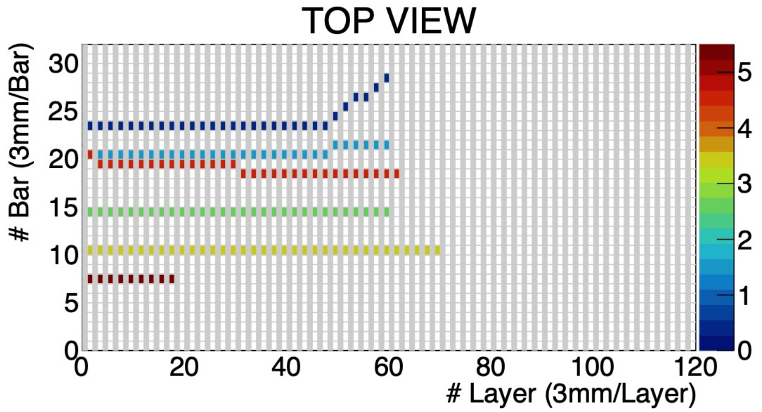


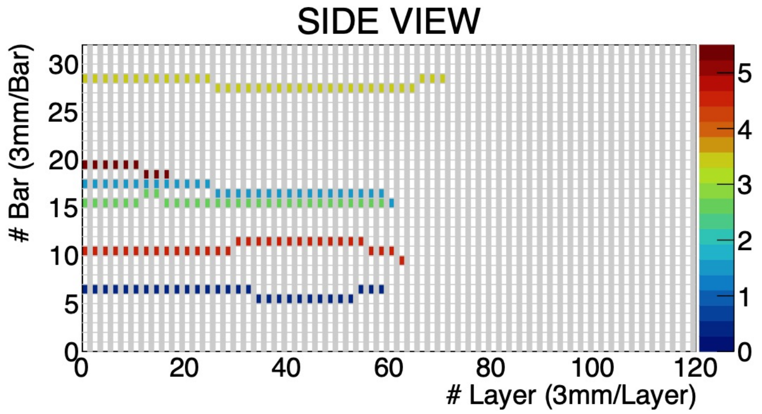
Ambiguities on multi-proton events

- The small crossectional area of the ASTRA bars allows multi-proton tracking but:
    - If two protons hit two layers of the detector two hits and two ghost hits (ambiguities) are generated
    - Both combinations of hits are indistinguishable

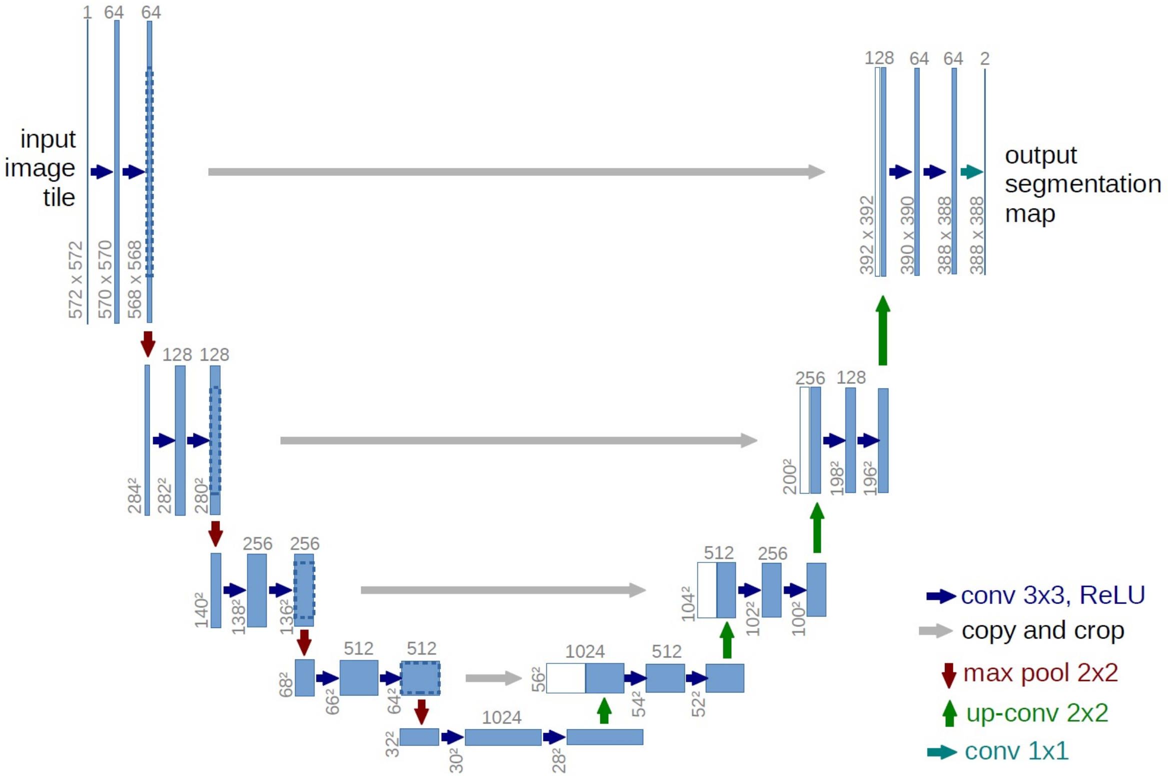


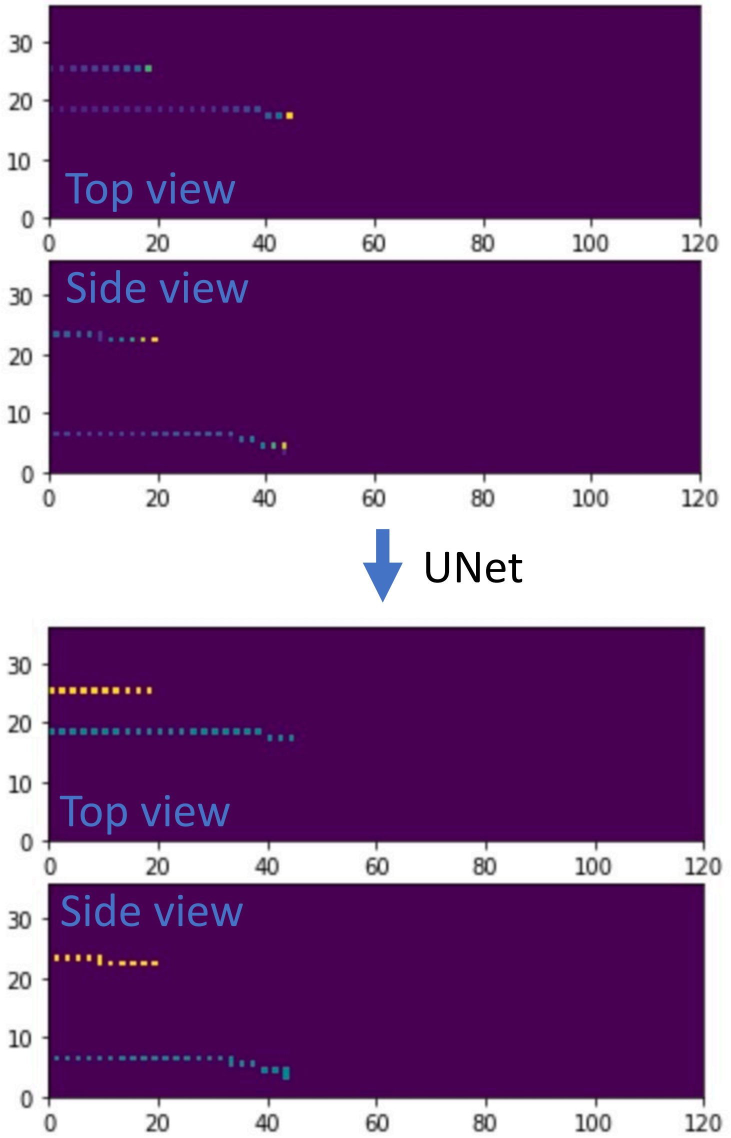






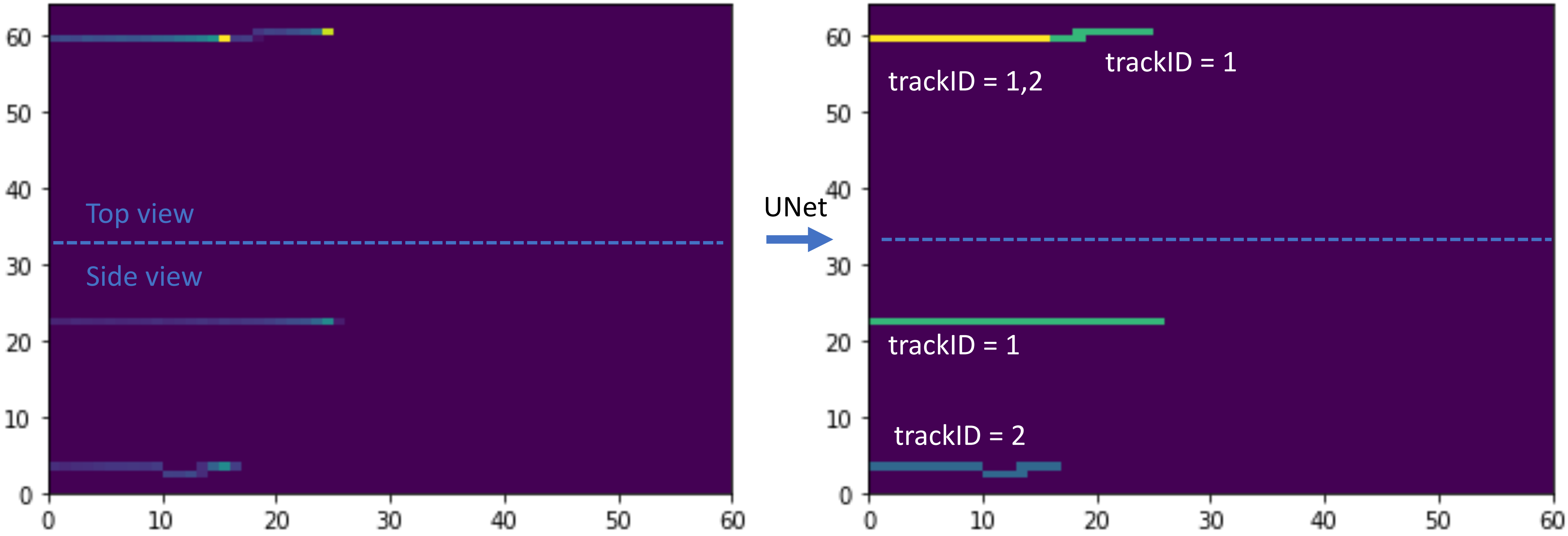
1 M events **2 protons** per event. **No phantom** and beam energies ranging between **80 to 180 MeV** to train a **UNet** using the edep information at each ASTRA bar.
1 M events with 1 proton to check with Classic Algorithms





Input structure

- The input is the energy deposited (edep) and the output the different categories (track id = 1, 2 and overlap [1,2])
- The data is prepared into 60x64 pixel images merging vertical (top) and horizontal (bottom) projections.



Reconstruction

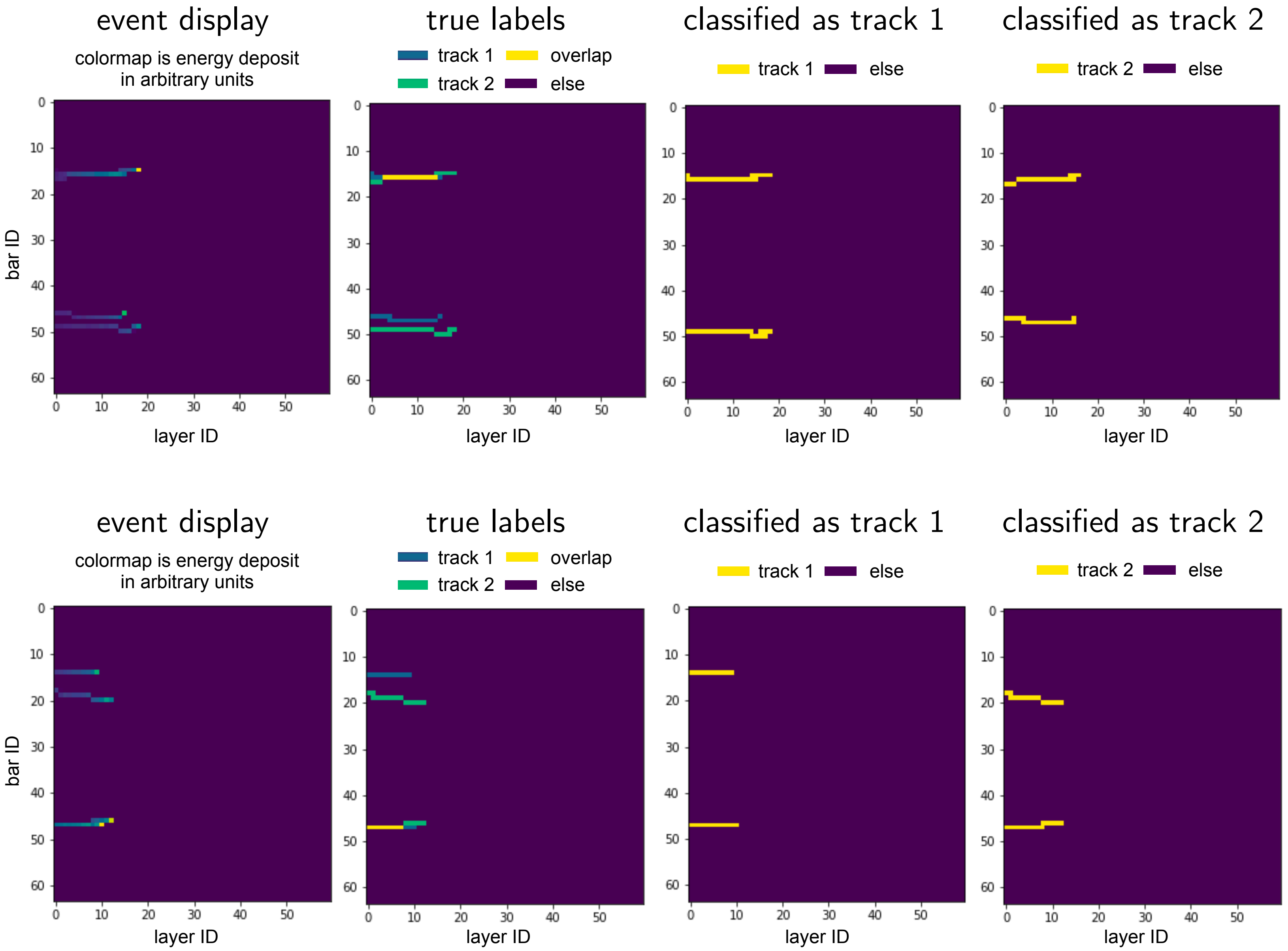
Signal segmentation with multi-label at pixel level!

Background = [1, 0, 0]

TrackID1 = [0, 1, 0]

TrackID2 = [0, 0, 1]

Overlap12 = [0, 1 ,1]



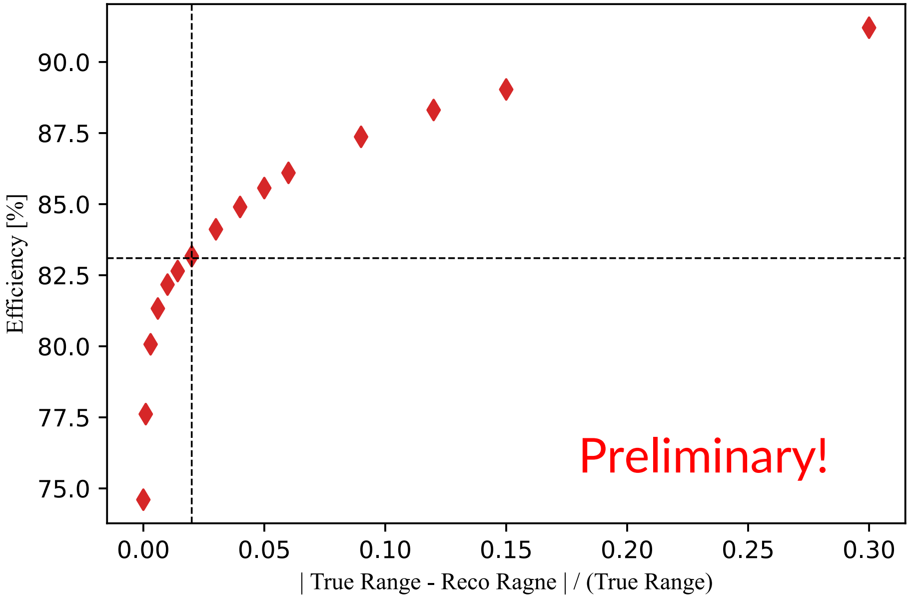
Efficiencies

Tracking efficiency an protons good for imaging (**pGfI**)

Algorithm	1p Track eff [%]	1p pGfI [%]	2p Track eff [%]	2p pGfI [%]
Classic	97	80	69	55
UNet	97	80	**82**	**68**

A **13 % improvement over all range of energies** is observed when using the Unet with 2 proton events.

Still **20 %** of the tracks are lost due to inelastic interactions. **Extra layer of NN to recover them!**

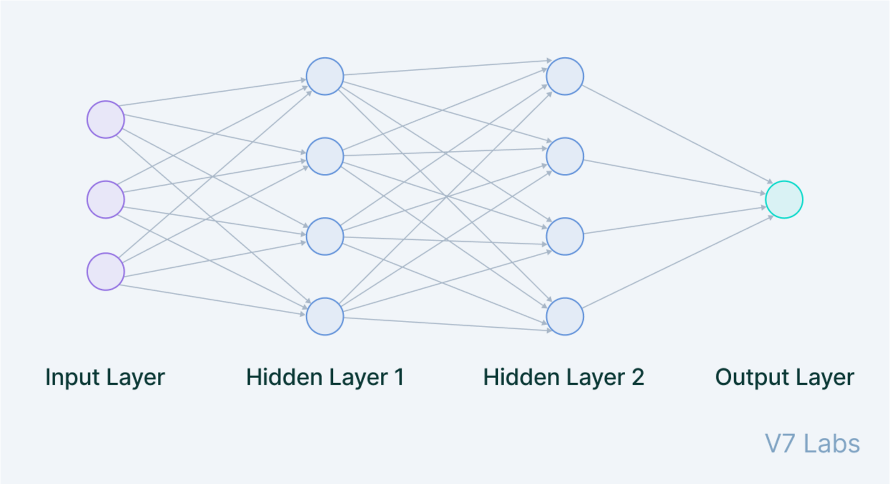


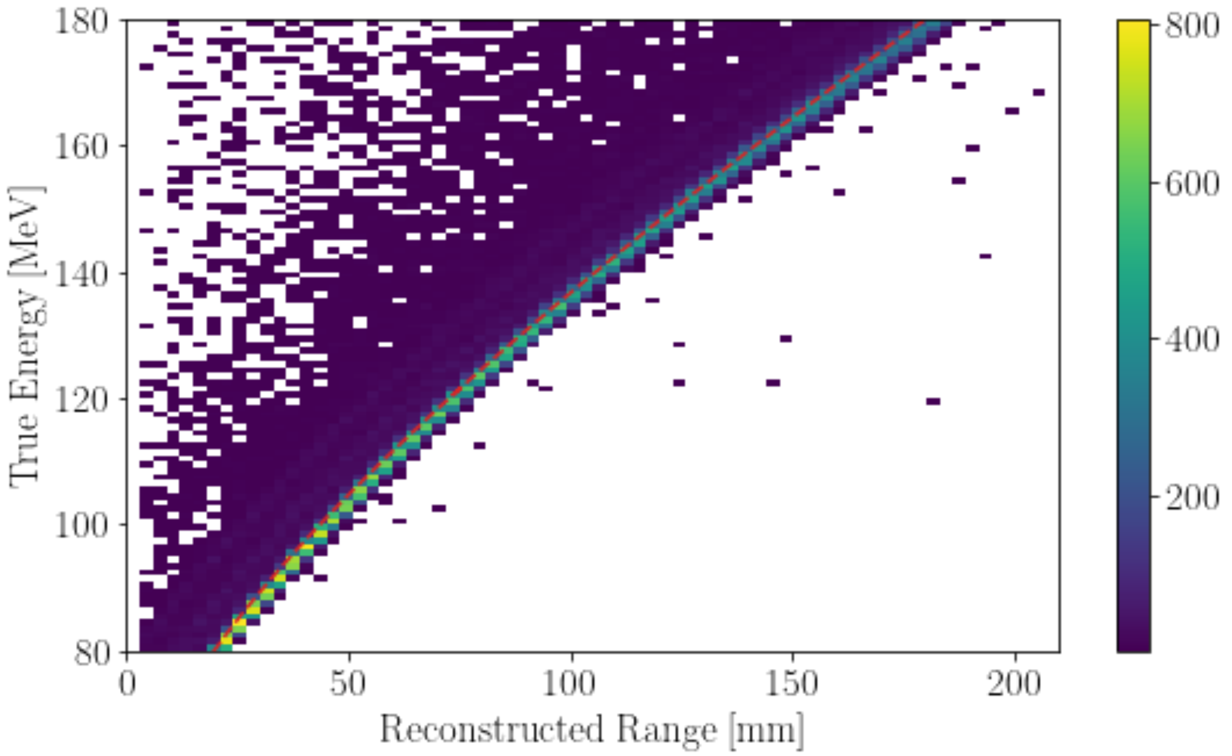
Proton selection for training the NN:

In order to perform a proper training the hits that suffer inelastic scattering.

Any good reconstruction of the energy obtained from these events would imply an increase in efficiency.

Use of NN for **regression problems**:





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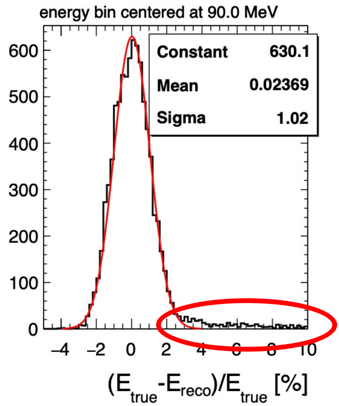

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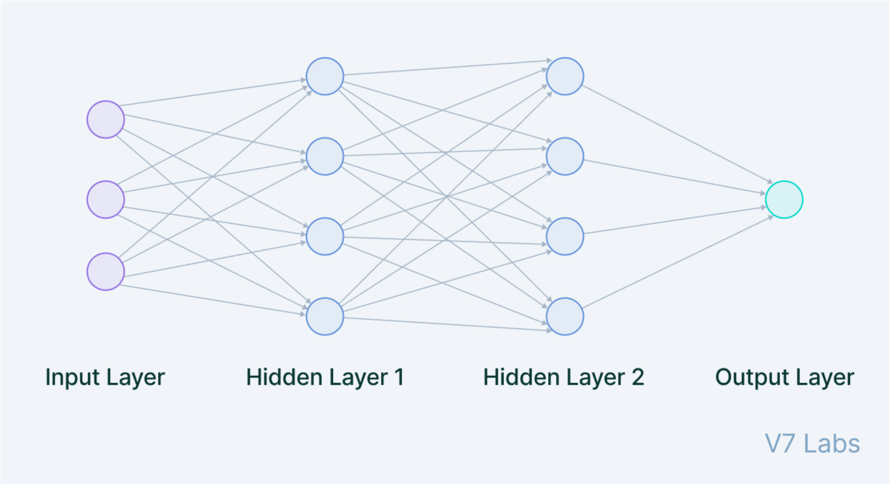
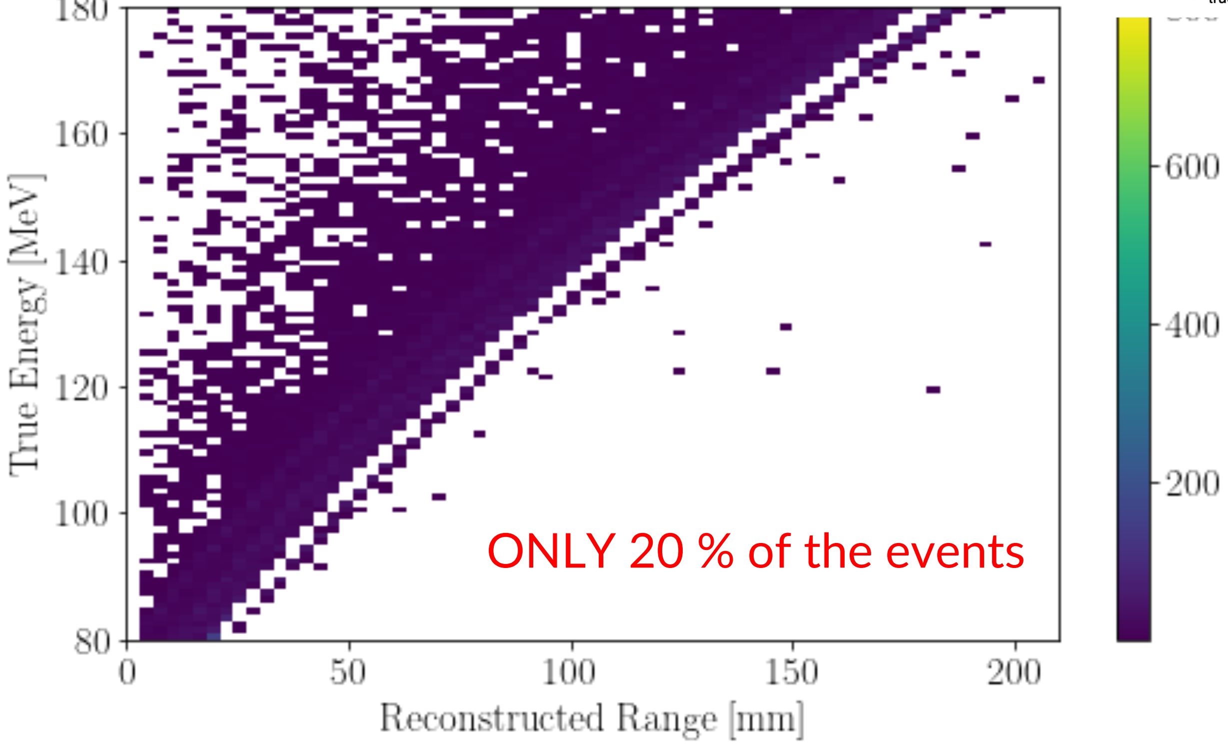


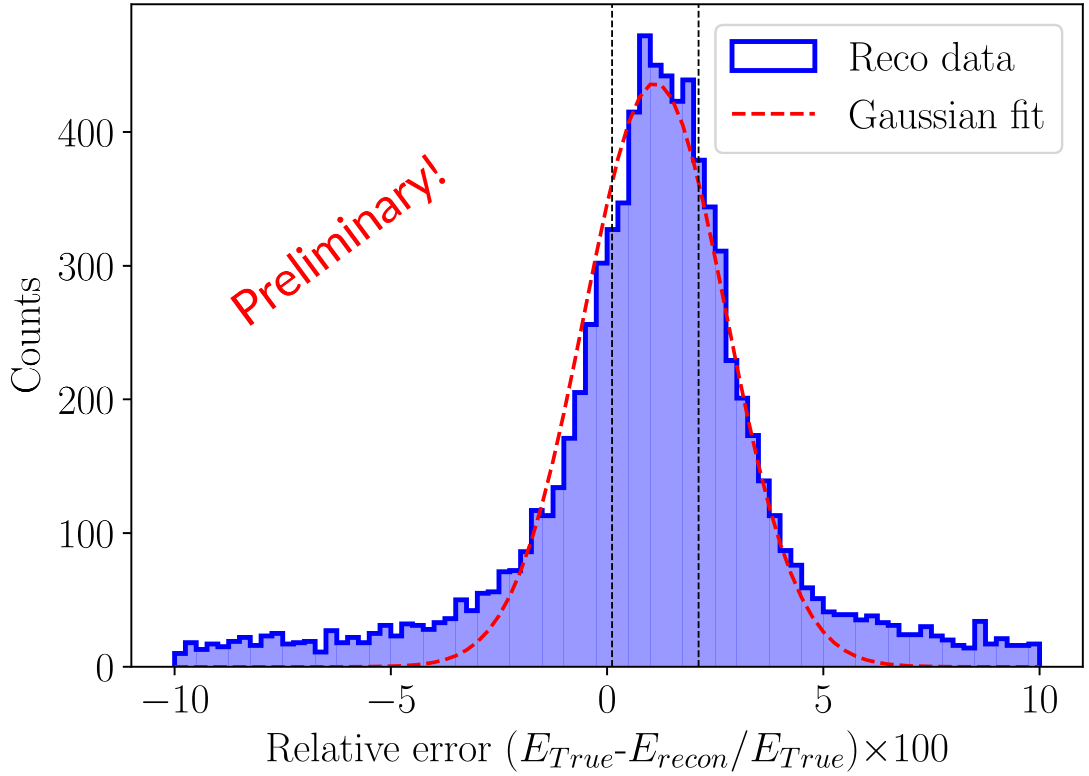


Efficiency of the NN for energy recontruction

The relative error has a small bias that can be easily corrected.

The sigma of the distribution is 1.65 %, very close to the 1 % resolution obtained with the “normal tracks”.

Taking $\pm\,\sigma$ (pGfI) 46 % of the rejected tracks are recovered **9.2 % improve in total efficiency**.



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Conclusions:

- Tracking with CNN:
  - Single proton results are recovered.
  - With two proton tracks **82 % found within 1 %** error in range **13 % improvement on tracking efficiency** compared to classic algorithms
- An extra analysis using NN has been performed with the inelastic events that are not good for imaging when reconstructed by range.
  - The current status shows results with 1.65 % energy resolution
    - **10 % increase in efficiency** compared with respect not using this layer.
- Using the UNet for tracking and the NN for energy reconstruction is a gain (for 2 protons) from **55 %** efficiency to **78 %** → almost 50% more data!
- The increase in efficiency could result in the reduction of the dose received by the patient during the pCT by a **third of the total dose.**
- Feasable technology based on existing and modules tested with **Geant4** and **BlueBear** cluster.
- Ther is a current search for funding in order to build a prototype for he **ASTRA** system.

References

[1] M. Esposito *et al.*, "Pravda: The first solid-state system for proton computed tomography," *Physica Medica*, vol. 55, pp. 149–154, 2018.

[2] M. Granado-González, C. Jesús-Valls, T. Lux, T. Price, and F. Sánchez, "A novel range telescope concept for proton CT," *Physics in Medicine &amp Biology*, vol. 67, p. 035013, feb 2022.

[3] H. Pernegger *et al.*, "First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors," *JINST*, vol. 12, no. 06, p. P06008, 2017.

[4] W. Snoeys, G. Aglieri Rinella, H. Hillemanns, T. Kugathasan, M. Mager, L. Musa, P. Riedler, F. Reidt, J. Van Hoorne, A. Fenigstein, and T. Leitner, "A process modification for cmos monolithic active pixel sensors for enhanced depletion, timing performance and radiation tolerance," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 871, pp. 90–96, 2017.

[5] T. Wang *et al.*, "Development of a Depleted Monolithic CMOS Sensor in a 150 nm CMOS Technology for the ATLAS Inner Tracker Upgrade," *JINST*, vol. 12, no. 01, p. C01039, 2017.

[6] P. A. Amaudruz *et al.*, "The T2K Fine-Grained Detectors," *Nucl. Instrum. Meth. A*, vol. 696, pp. 1–31, 2012.

Thank you for your attention!

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Backup

Proton radio therapy

- Treat the tumour with a proton beam
- Proton Radio Therapy (PRT) first proposed in 1946 by Robert Wilson
- First proton therapy treatment was in 1954 at Berkeley Radiation Laboratory
- The world’s first proton therapy treatment in a hospital occurred at the Clatterbridge Cancer Centre in 1989

The phantom

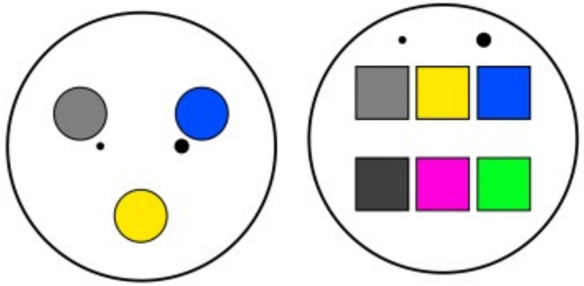
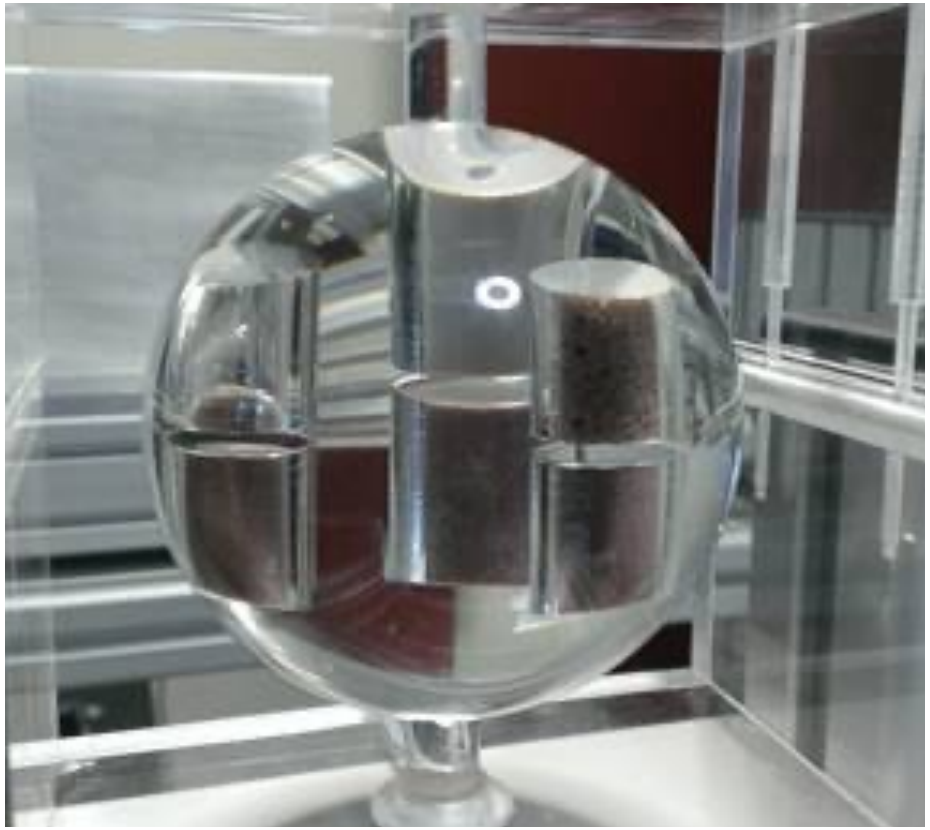
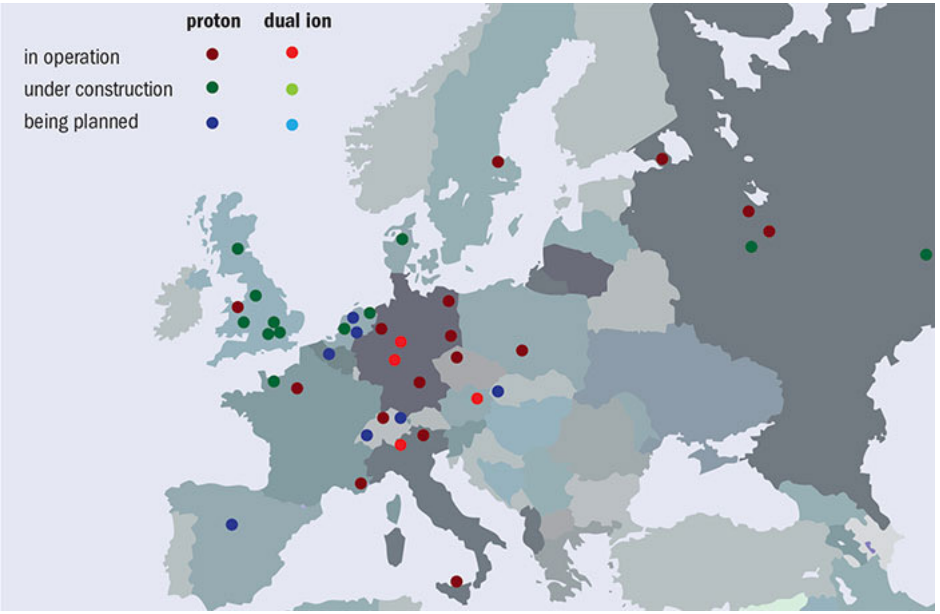


FIG. 3: *The 75 mm-diameter phantom used in simulations, representative of the experimental PRaVDA phantom: a PMMA sphere containing six cylinders, of cortical bone (dark grey), lung (pink), air (green), rib bone (light grey), adipose (yellow), water (blue) and with two balls of tungsten carbide (black). The sphere is depicted viewed from above (left image) and from the side (right image).*

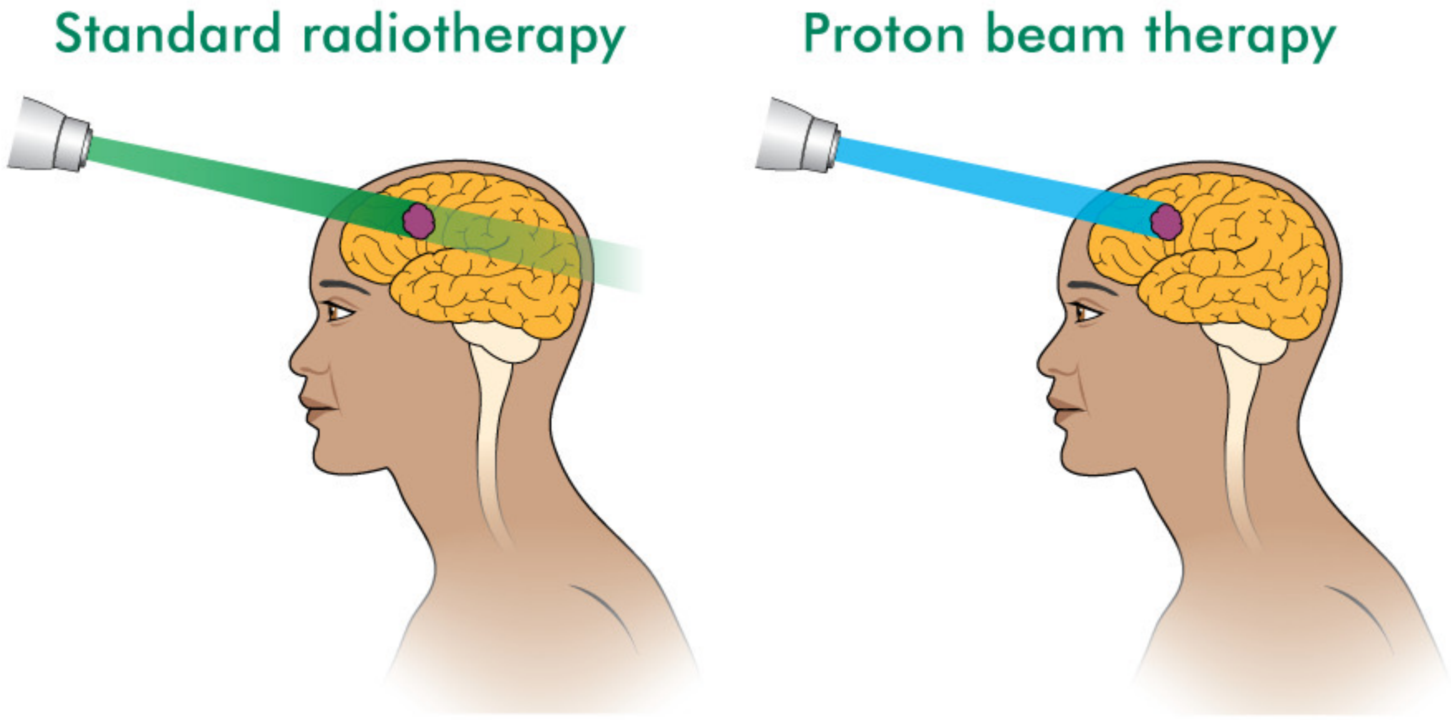


Proton radio therapy

- Rapidly growing and evolving field due to benefits to head and neck cancers and in paediatrics.
- There are currently over **89 proton therapy** sites operational worldwide with a **41 more planned**
- Considerable developments in the UK and Spain over recent years
  - In the UK 2 proton therapy centres Manchester and London
  - 2 centres in Madrid and 10 more to be build in Spain in the following years.
- By the end of 2021, over **170,000** had received proton radiotherapy worldwide



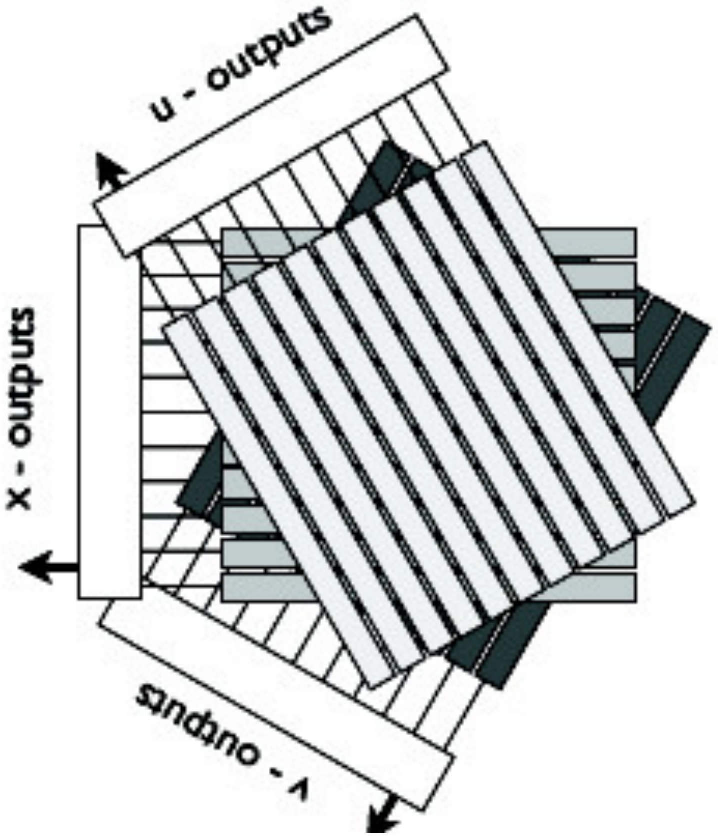
Proton vs X-rays



The differences with how protons and x-rays interact with matter affect dramatically the treatment's toxicity

State of the art on pCT

- **Position trackers:**
  - Old technologies (30 years old). Strips sensors (**1D resolution!**) are used in order to track the protons before and after trespassing the phantom.
  - Hybrid sensors with large budget material.
  - Big modules with larger amounts of data.
  - Hard to decouple ambiguities.

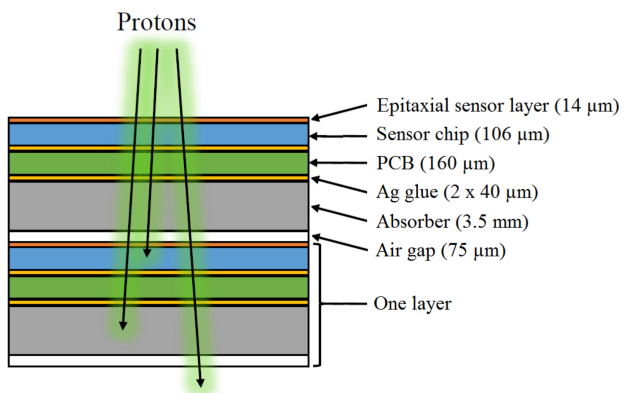


PRaVDA tracking module

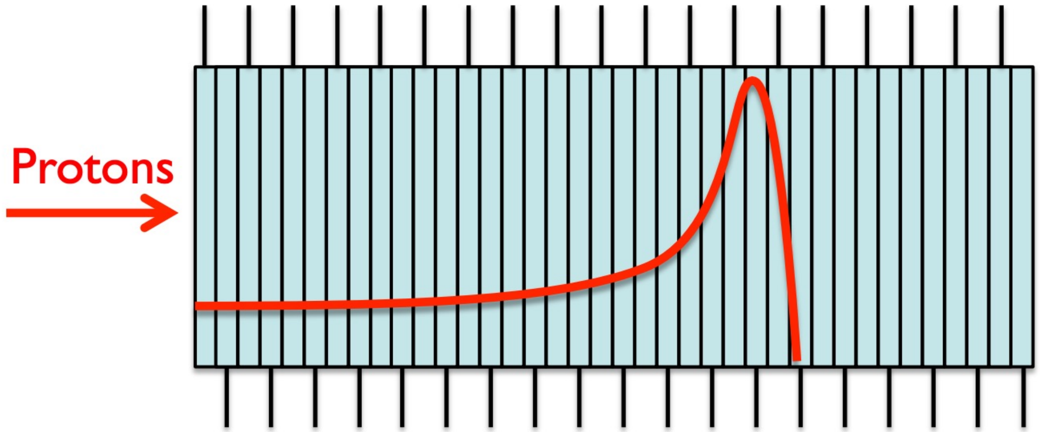
State of the art on pCT

- **Energy tagging:**
  - New technologies under development example
    - **ALPIDE** based calorimeters.
      - Expensive (silicon)
      - **Slow sampling rate** few micro seconds.
    - The plastic scintillator design from **Loma Linda** or the **SUPER-NEMO** based range telescope.
      - Layers of plastic scintillator
      - **Not capable to deal with multi protons**
      - Unable to deal with “kinks”

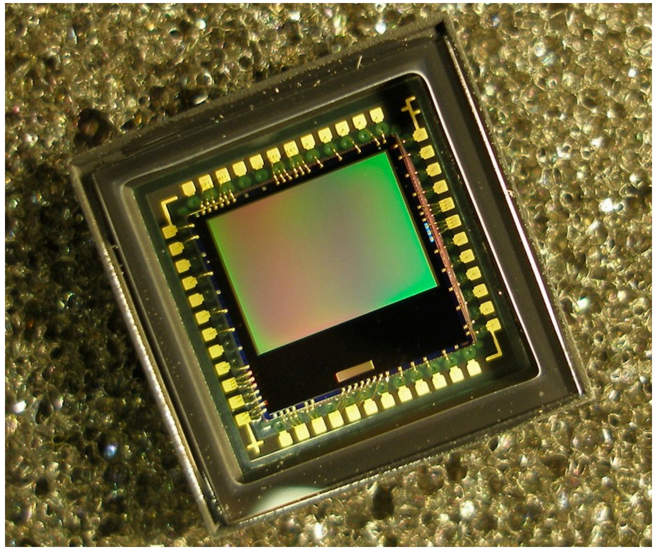
ALPIDE based module



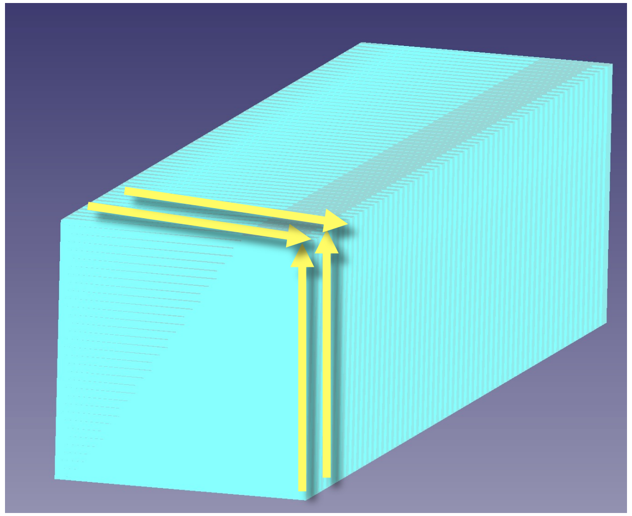
SUPER-NEMO based RT



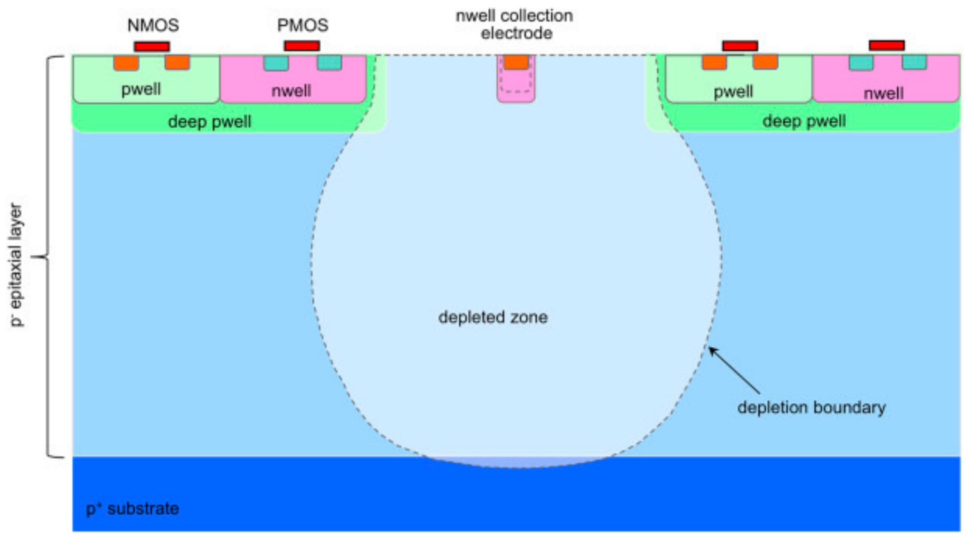
New technologies



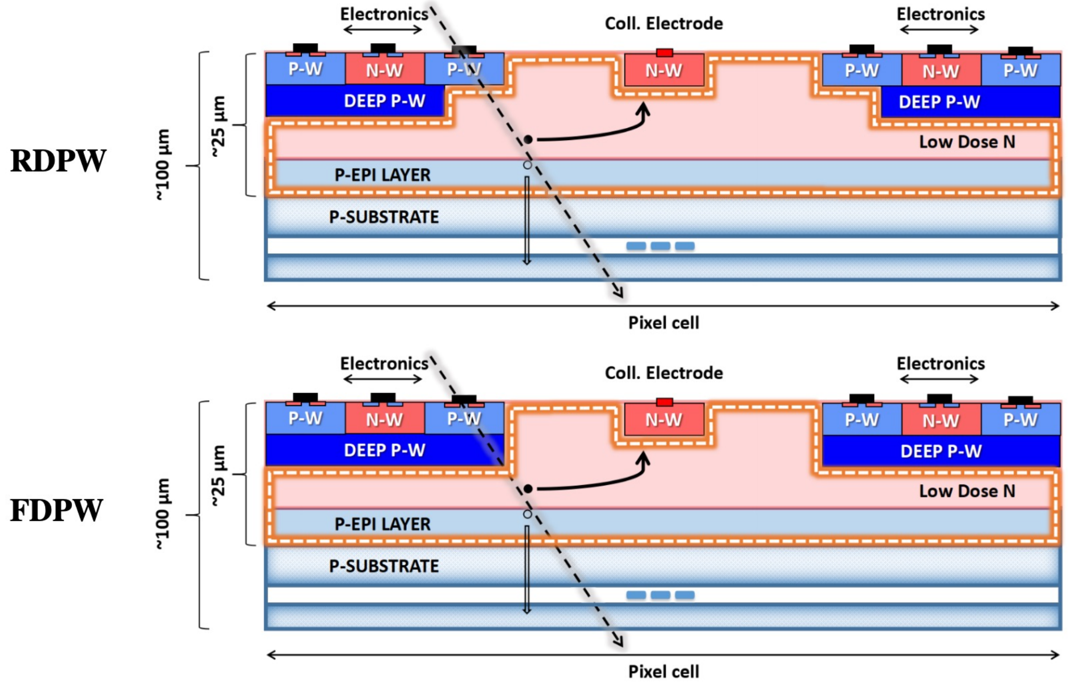
- Depleated Active Pixel Sensors (DMAPS) are a modification of MAPS but faster and able to cope with radioactive environments.
    - Same tech you have in your phone, but cooler.
- **A S**uper **T**hin plastic **RA**nge telescope:
    - Fine segmentation achieving 1D resolution to be able to track individual protons.
    - ASTRA module segmented in bars oriented in perpendicular directions to the beam.



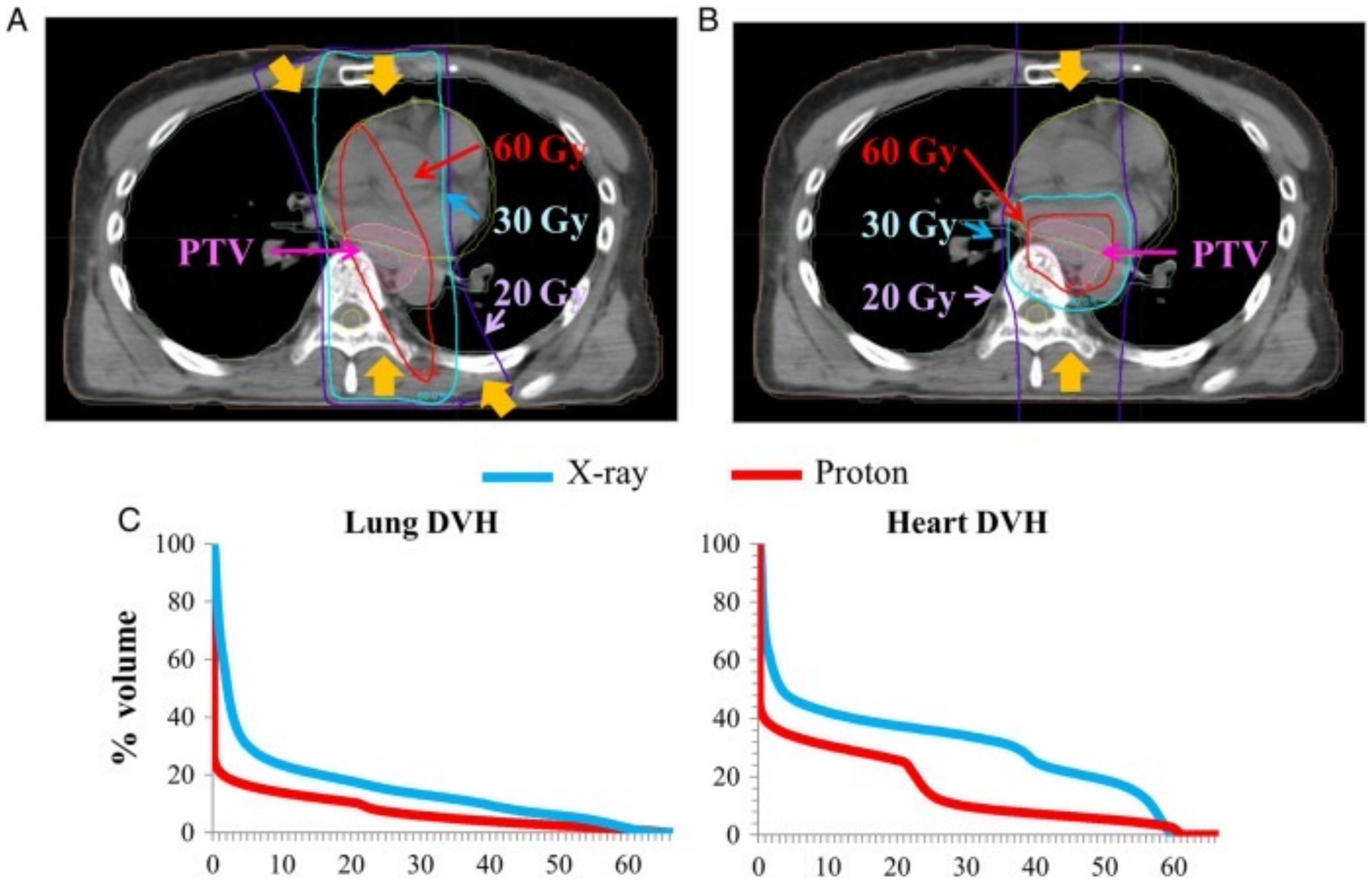
MAPS and DMAPS



Sketch of a transverse of an Active Pixel Sensor structure showing the depleted boundary.



Sketch of the structure of the TJ-monopix (DMAPS) chip with a partially Removed Deep P-Well (RDPW) (top) and Full Deep P-Well (FDPW) (bottom) [1]


A
B
60 Gy
30 Gy
PTV
20 Gy
X-ray
Proton
C
Lung DVH
Heart DVH
% volume
100
80
60
40
20
0
0
10
20
30
40
50
60

Imaging with x-rays

- Bragg peak: **With great power comes great responsibility**
- Very localised dose deposition needs from very low uncertainty in range (energy).
- So far, stopping power and ionisation potentials of materials are extracted from a conventional x-ray CT scan –> BIG uncertainties!
- Imaging with x-rays, but treating with protons!

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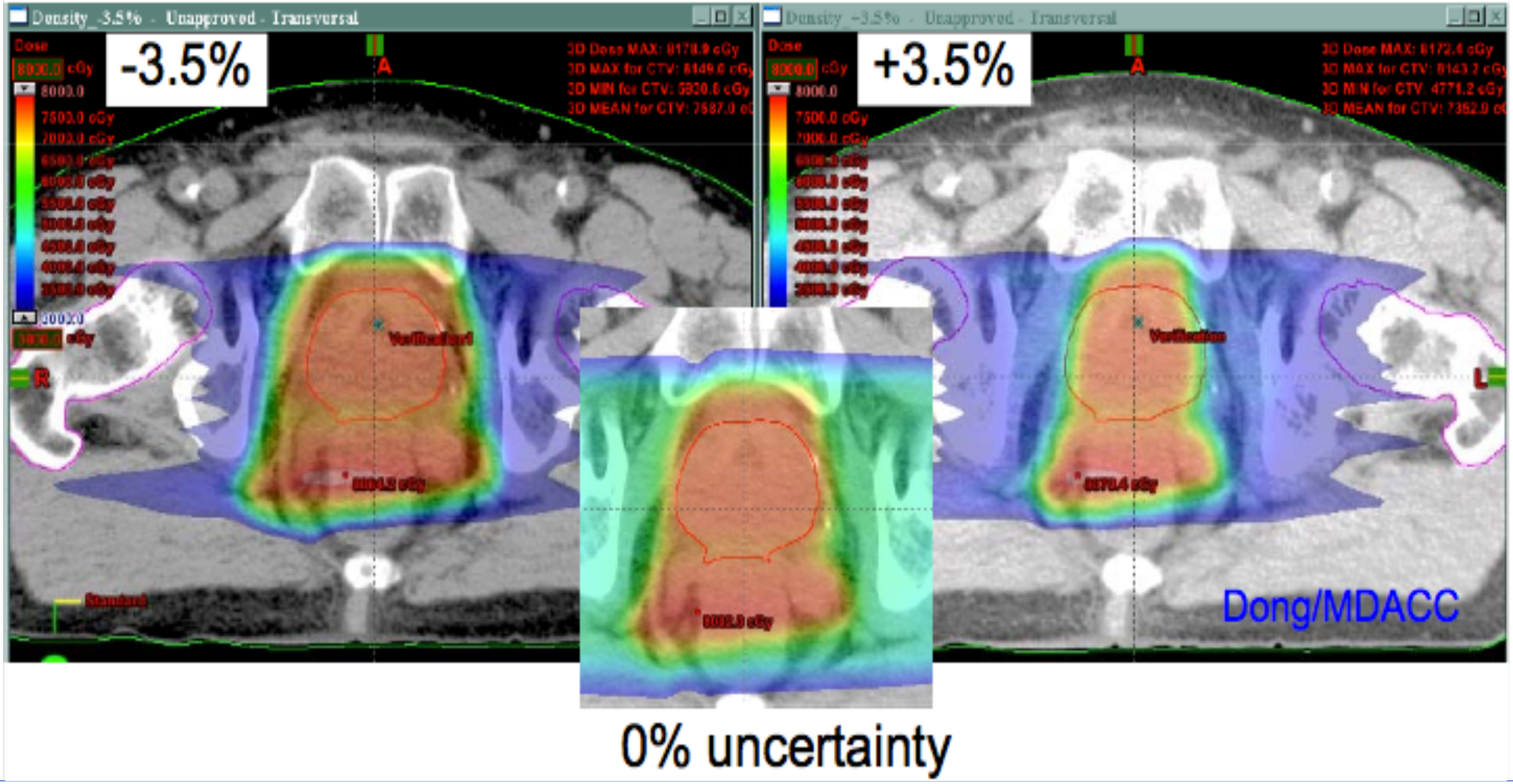
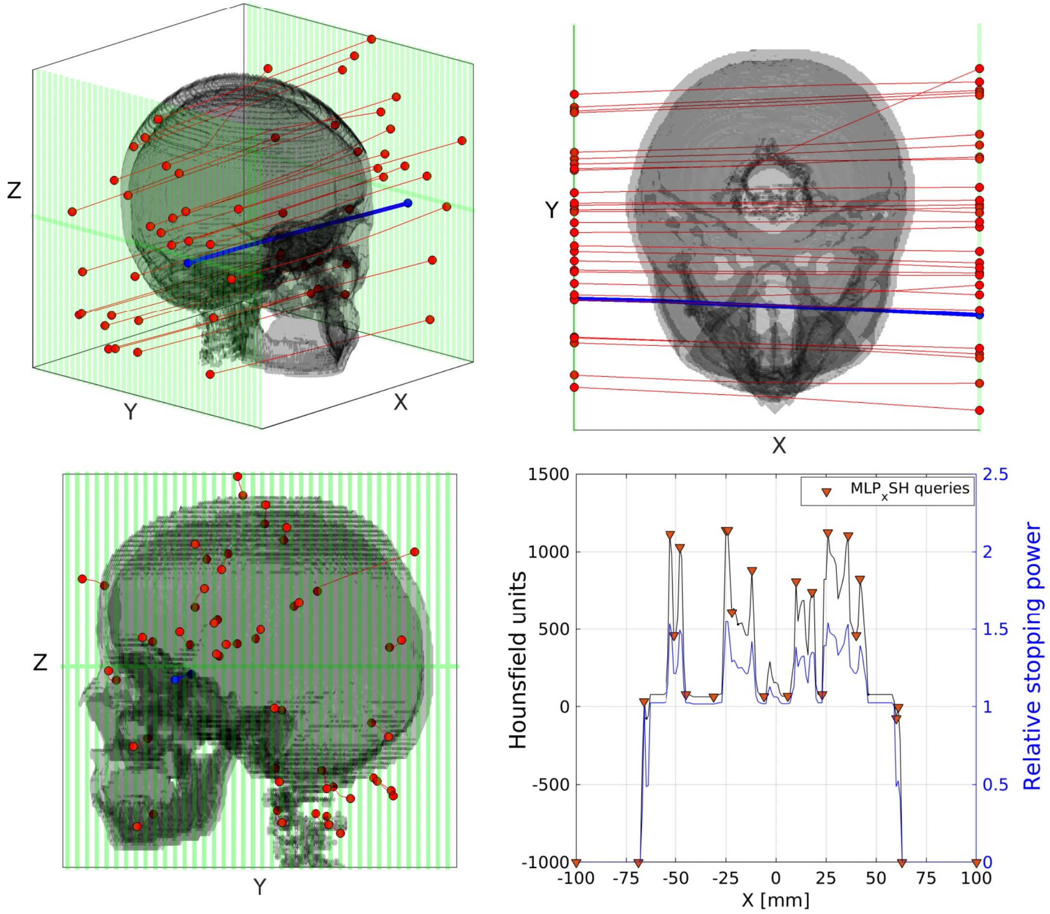
Total (root-sum-square)	5.0	1.6	2.4

Consequences of big uncertainties



Resolutions needed

- A technique able to measure directly the Proton Stopping Power or the Relative (to water) Stopping Power **RSP**
- When treating with protons, image with protons → **pCT**
- Range or energy resolution below 1%
- Position resolution (voxel size) of ≤ 1 mm

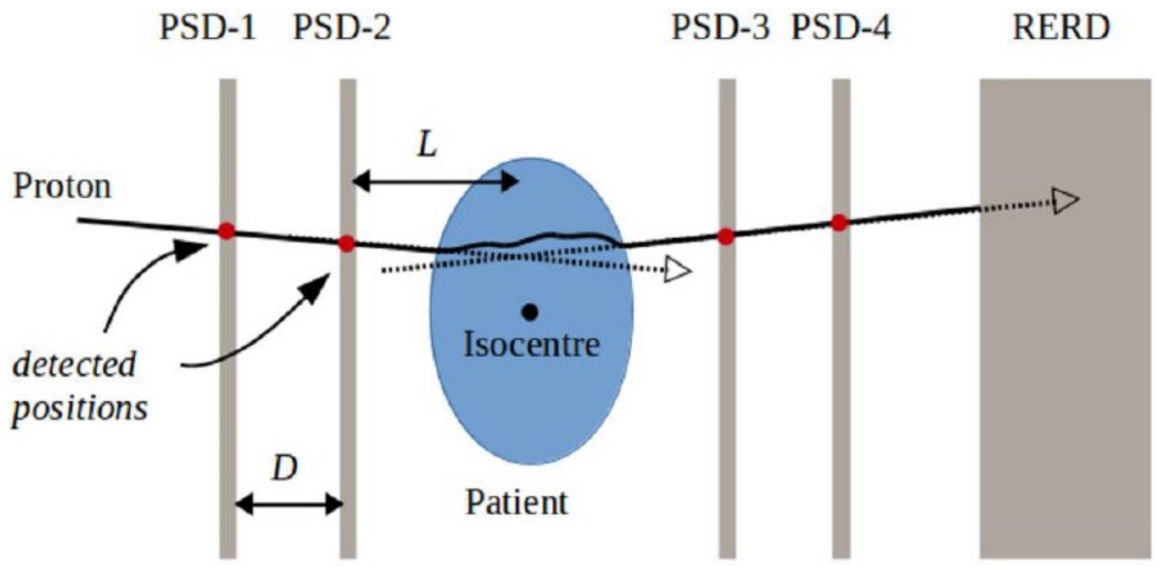


Needs for proton CT

In order to obtain a proton Computed Tomography (pCT) one needs to know:

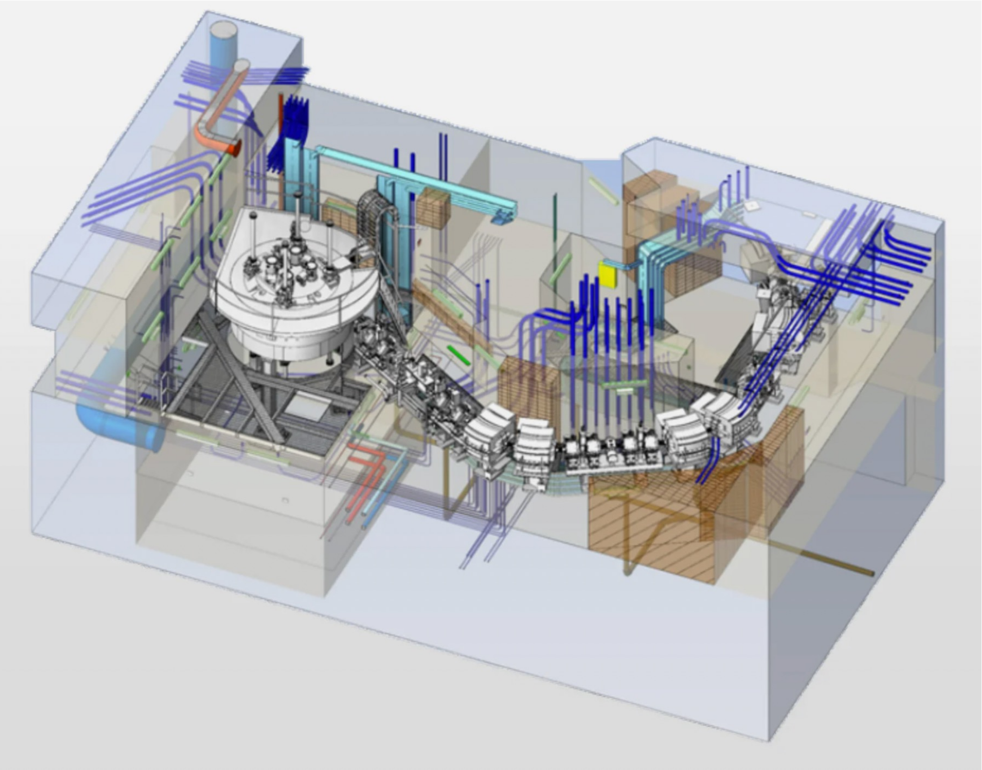
- The protons' entering and exiting points of the imaged body.
- The residual energy after trespassing the phantom.
- How to reconstruct the path within the patient/phantom.

Note: For this work, a Most Likely Path (MLP) algorithm written for the PRaVDA collaboration was used. This algorithm requires from energy measurements.



State of the art on pCT

- Clinical beam using energies up to 250 MeV
- The currents provided by the clinical beams during treatment are of the order of 10^9 protons/s:
  - These values aim to be reduced for imaging purposes but there are limitations due to the accelerator properties.
  - Beam time is gold so the faster the better.
- Proton bunch density follows a Poisson distribution.
- Pencil beam used for imaging → Gaussian beam with $\sigma \leq 10\ \mathrm{mm}$

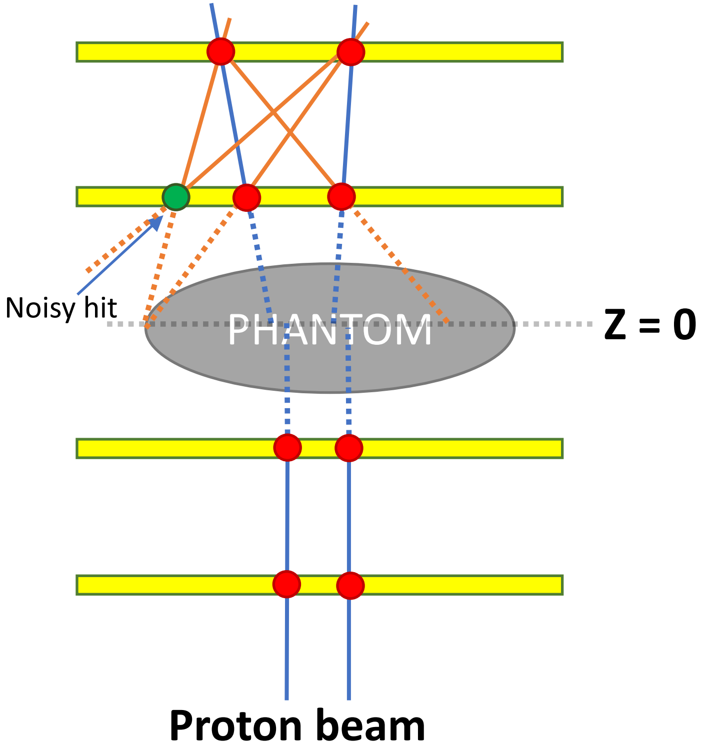


Matching tracks

The tracking algorithm builds all possible 3D lines with hits in 2 first planes, same in the 2 last planes, look for combinations of lines (4 points) that minimize global χ^2(to straight lines) for single proton events.

The XY distance between front and back projections at Z = 0 as the key parameter to select the tracks in multi proton events.

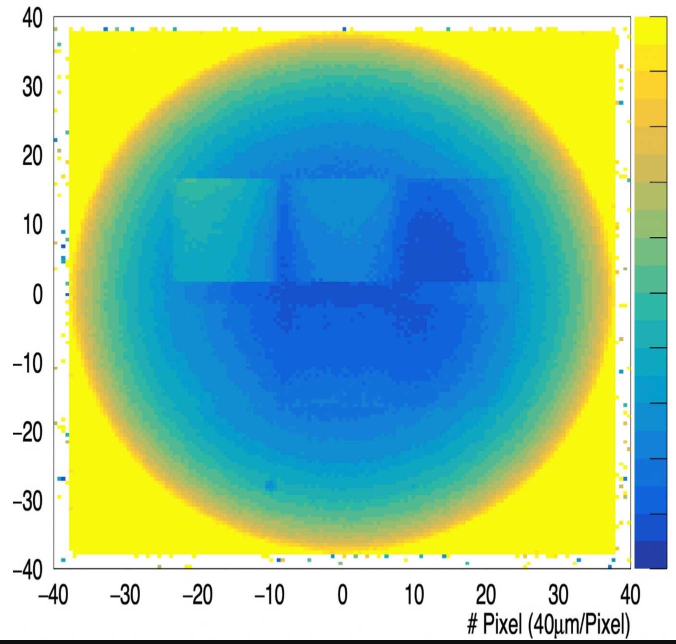
This results in a rise of the purity in matching front and back tracks, when finding 2.

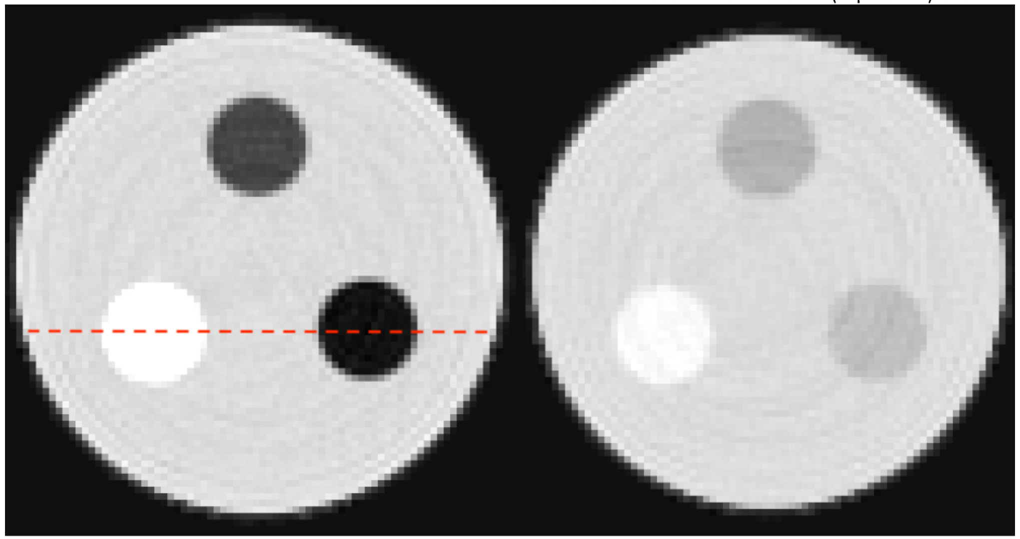


Example of the algorithm reconstruction for two tracks with proton hits in red, noisy hits in green, accepted tracks in blue and bad reco tracks in orange

Image simulation specifics

- The imaged phantom was a recreation of the PRaVDA phantom [1] consisting on a sphere with 6 inserts of 6 different materials.
- 180 radiographies:
    - 10^6 protons per radiography divided in,
    - 9x9 steps of a pencil beam with $\sigma = 10$ mm
    - 180 MeV protons
- For each radiography the phantom was rotated by 1 degree.
- The simulations were performed with Geant4 v4.10.05.p01 and the physics package QGSP_BIC at the BlueBear computer.





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Efficiency and purity

The figure of merit for the front tracker is $Purity \times Efficiency$ defined as:

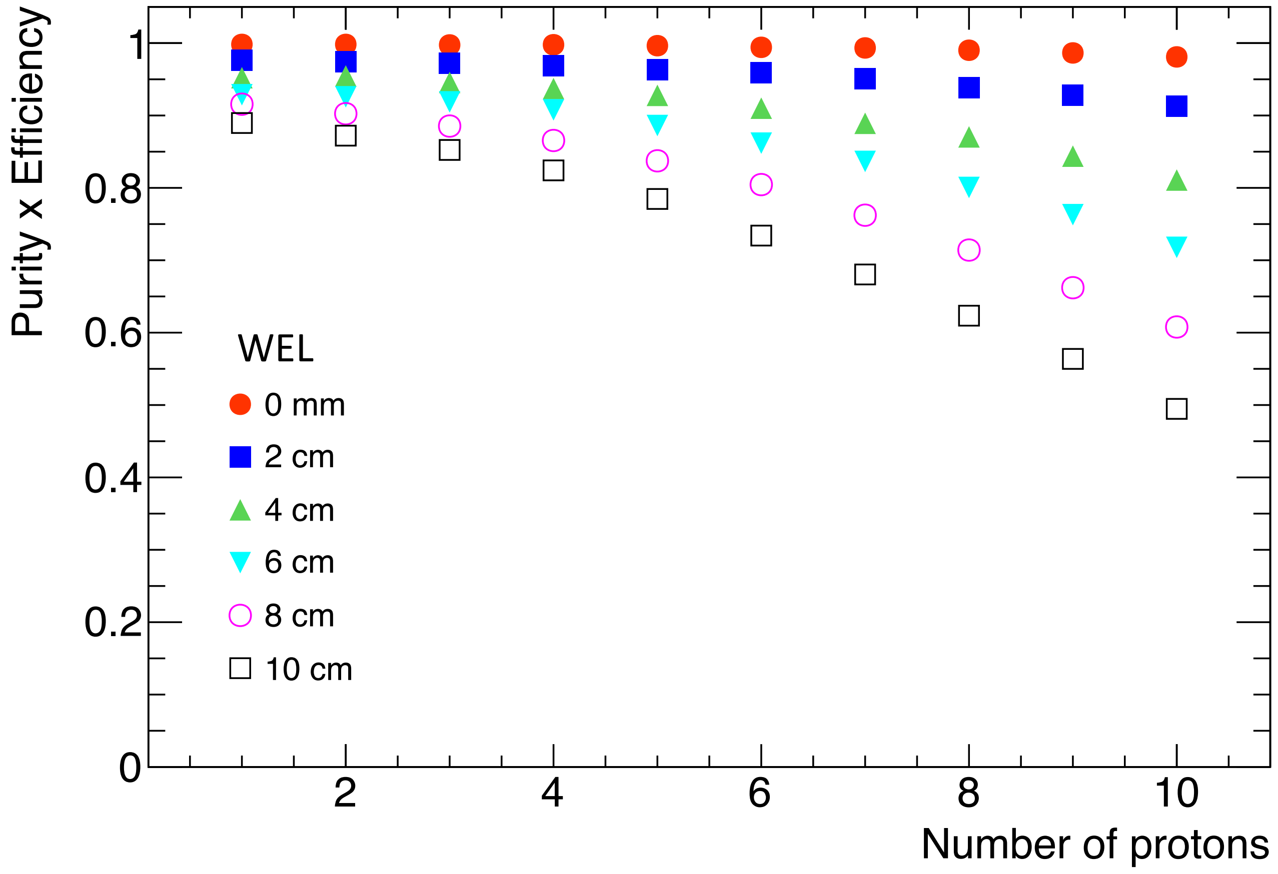
$$Purity = \frac{Well\ Reco\ Tracks}{Total\ Reco\ Tracks}$$

$$Efficiency = \frac{Total\ Reco\ Tracks}{Total\ \ Tracks}$$

Plotted as function of the number of protons per event for different water equivalent lengths (WEL).

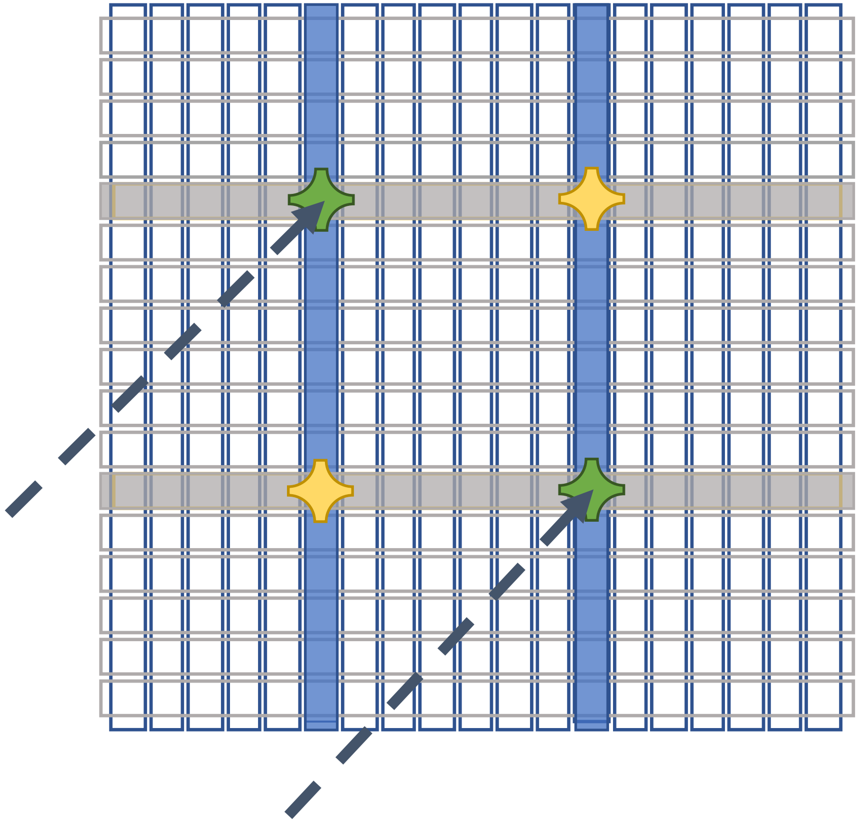
180 MeV protons with a Gaussian beam distribution with $\sigma = 10$ mm.

Note that MCS will affect on the efficiency (lost protons) and purity (crossed tracks).

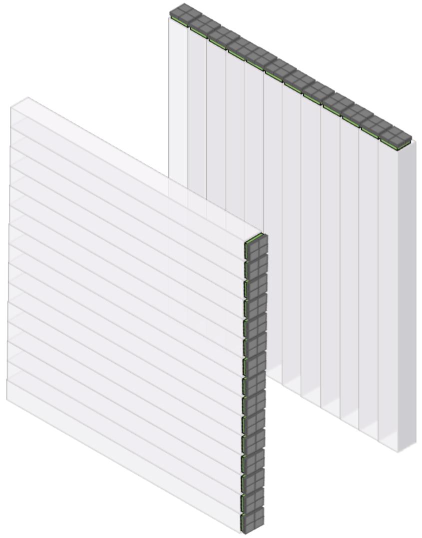


Ambiguities on multi-proton events

- If two protons hit two layers of the detector two hits and two ghost hits (ambiguities) are generated
- Both combinations of hits are indistinguishable

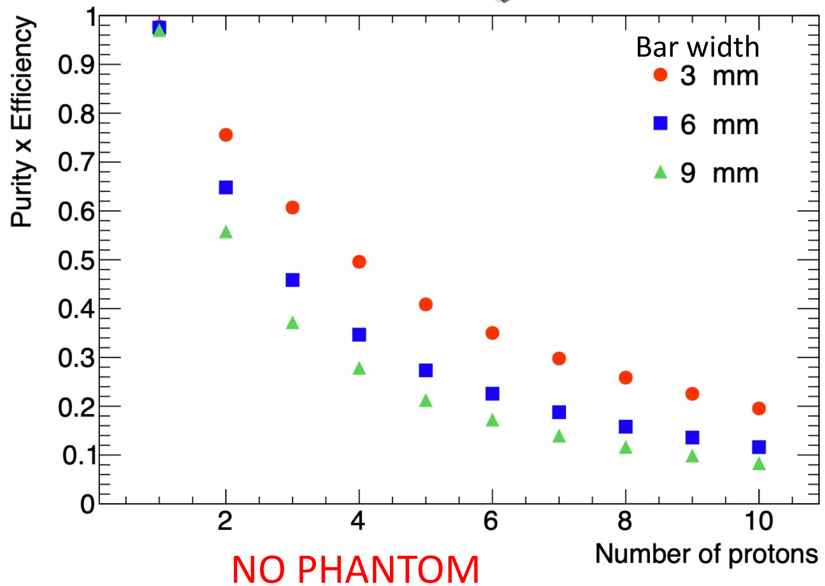


Matching tracks with ASTRA



- Project DMAPS tracks into ASTRA first 2 layers (3D seeding points in ASTRA), connect trajectories that are closer.
- For the seeding points, assume that the track goes forward, look for the next closer 3D point and propagate forward. Hits can not be shared between tracks.
- Different bar sizes where tested trying to study costs and figures of merit such as $Purity \times Efficiency$ and energy resolution.

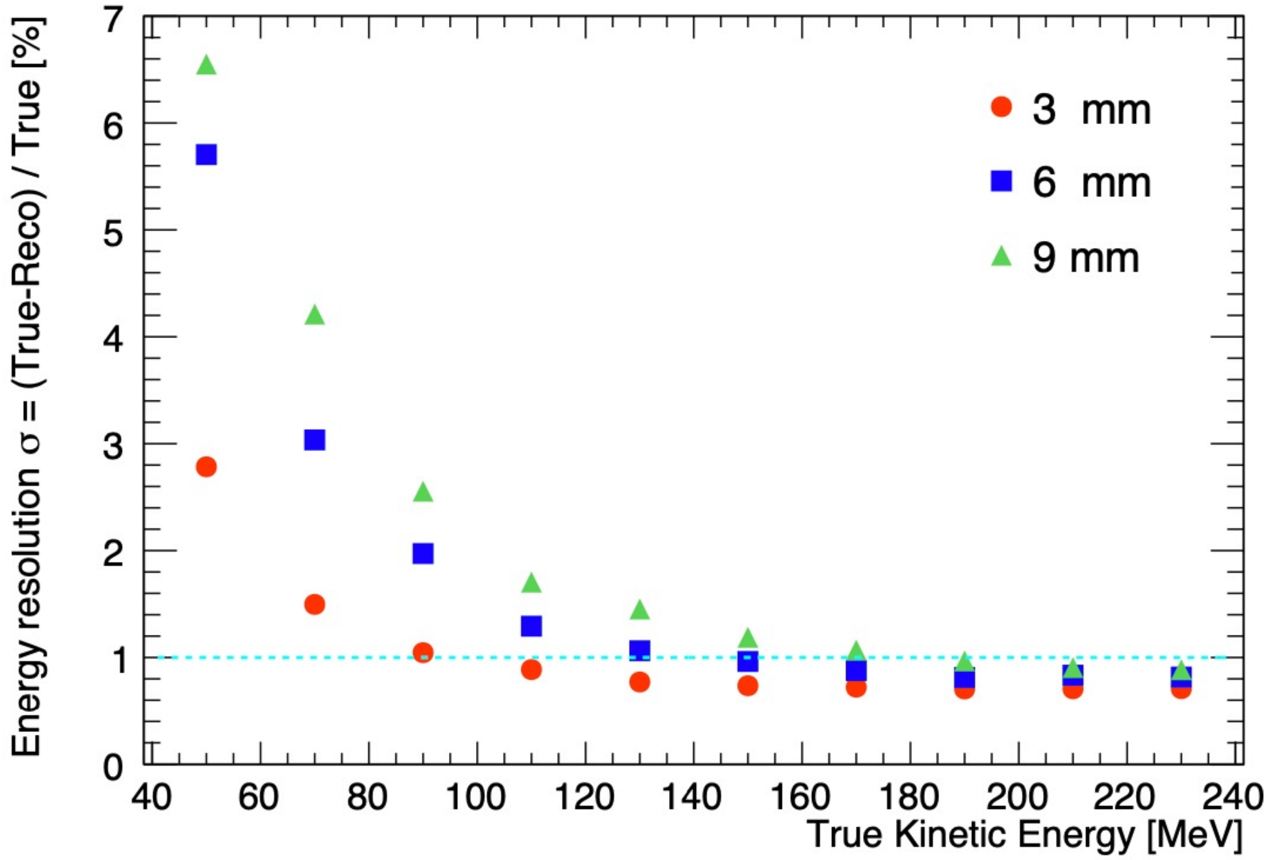
NOTE: The reconstruction can be improved in the future with dedicated work, we only built a minimal version to show the concept.



NO PHANTOM

Energy resolution

- Sub 1% resolution for protons above 100 MeV.
- The effect of the bars size is clear on low energy protons.
- 3 mm bars were used for the further studies.



Resolution & efficiency

The profiles of the beam affect dramatically on the % of good protons in multi-proton events even with no phantom.

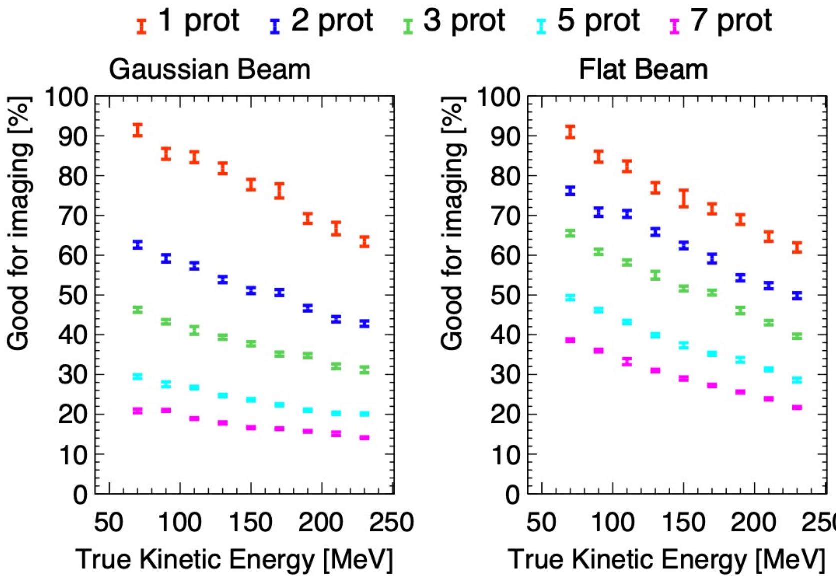
Beams used in clinical facilities are Gaussian with $\sigma \leq 10$ mm.

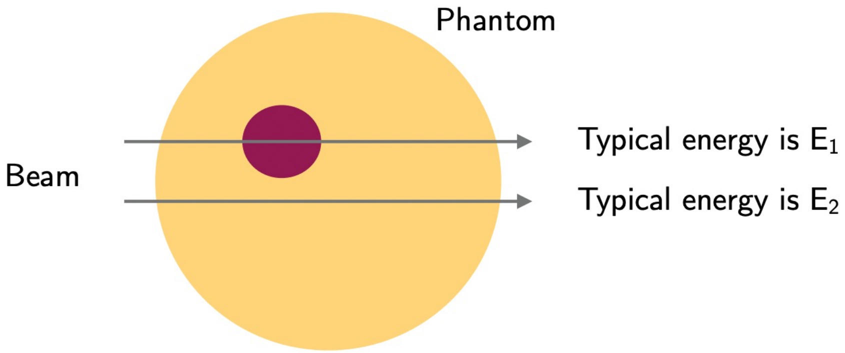
The beam profiles used were:

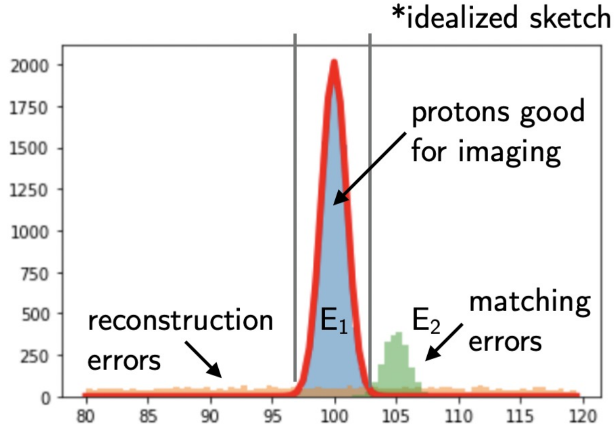
- Gaussian with σ = 10 mm
- 75 × 75 mm^2 square.

Two important factors:

- **Matching**
- **Energy reconstruction**







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Reconstructed vs true energy:

The correlation between the reconstructed and true energy is not 1 to 1 (red line).

This implies that an extra transformation for the reconstructed energy could lower the error at each energy reducing the energy resolution.

Linear or polynomial fit have potential to improve the results.

The model could be improved to do so?