The Bergen proton CT project

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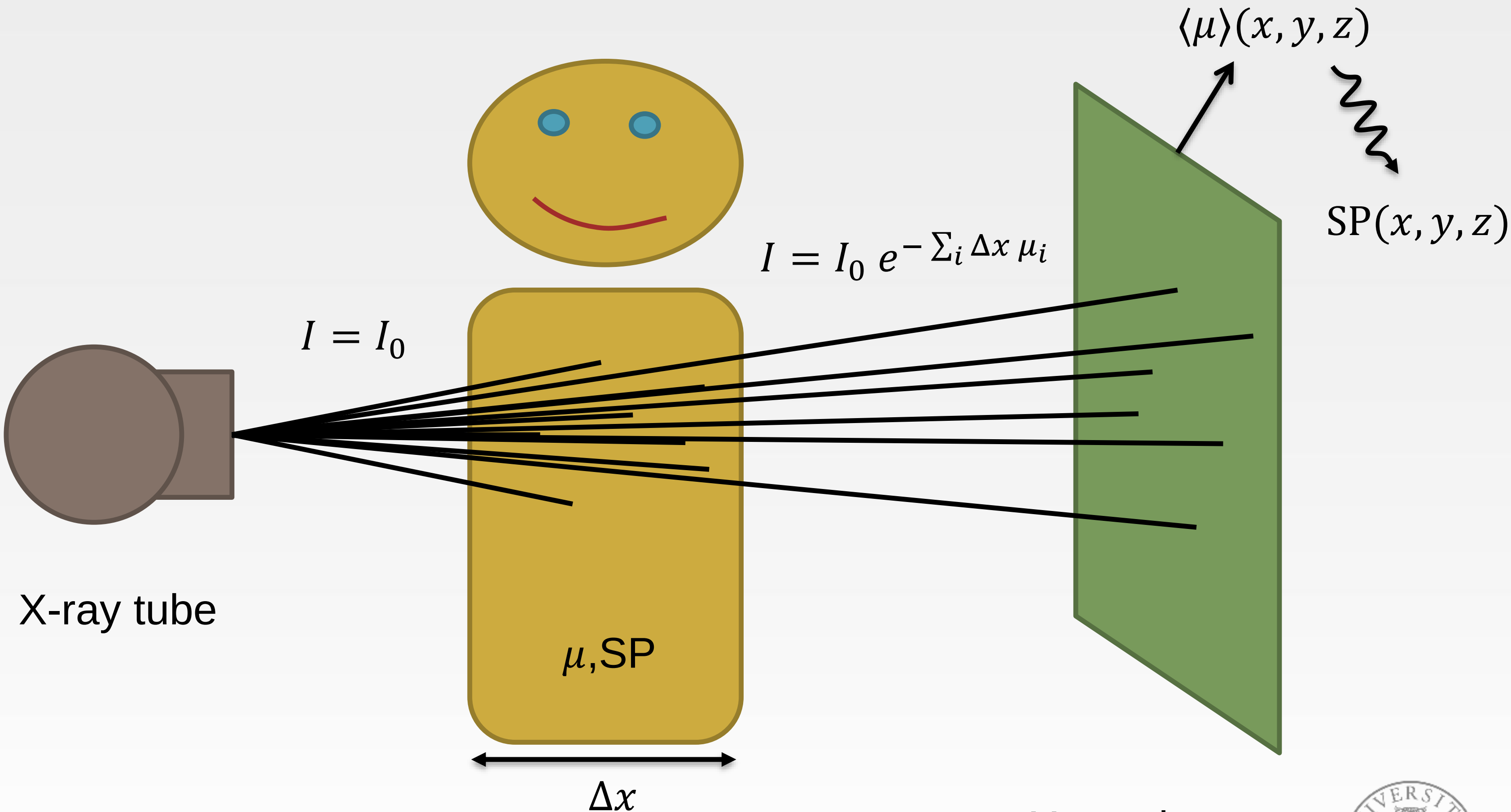
UNIVERSITY OF BERGEN

3-slide introduction if Pierluigi did bad

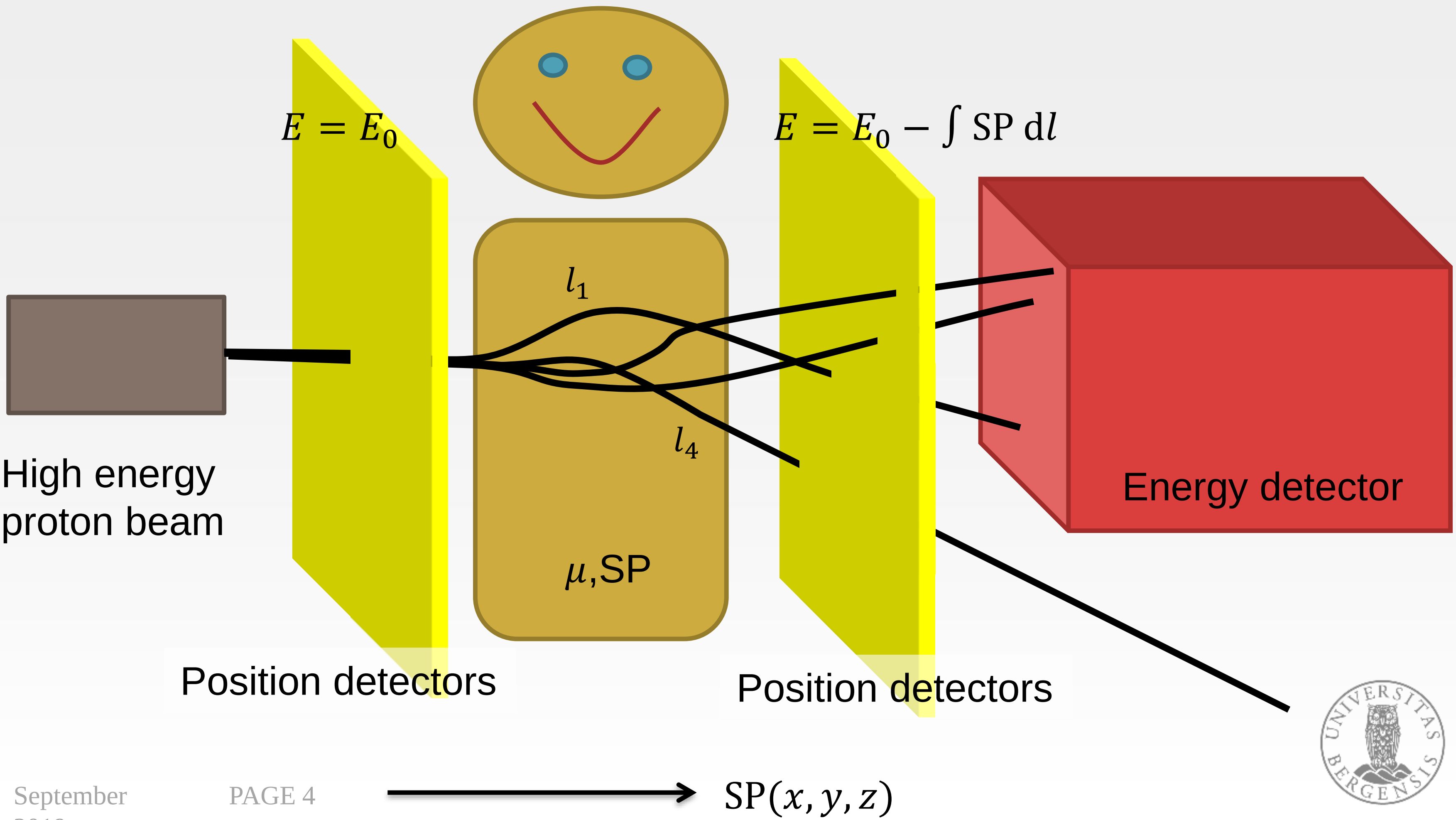
Proton Computed Tomography

X-ray CT



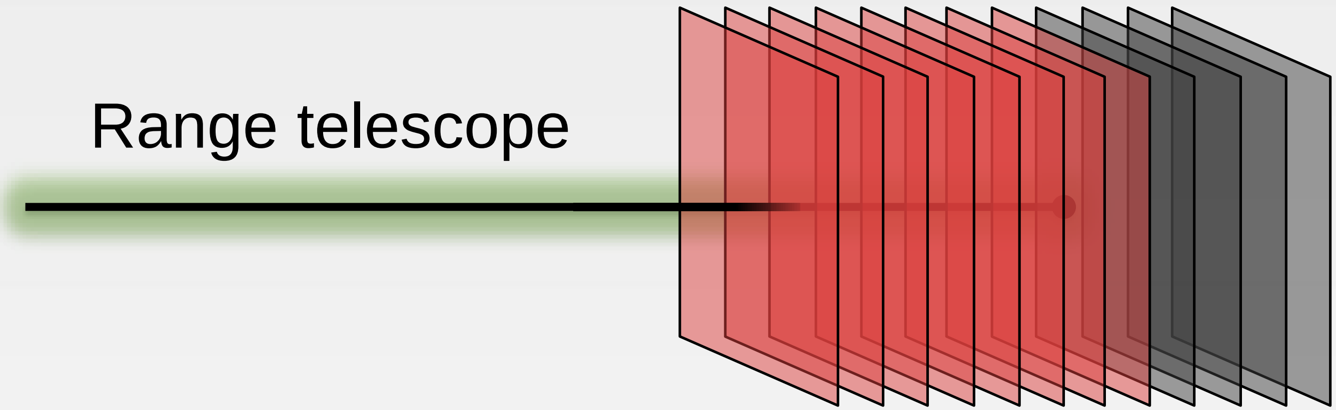
$\langle\mu\rangle(x,y,z)$
$\mathrm{SP}(x,y,z)$
$I = I_0\, e^{-\sum_i \Delta x\, \mu_i}$
$I = I_0$
X-ray tube
μ,SP
Δx
X-ray detector

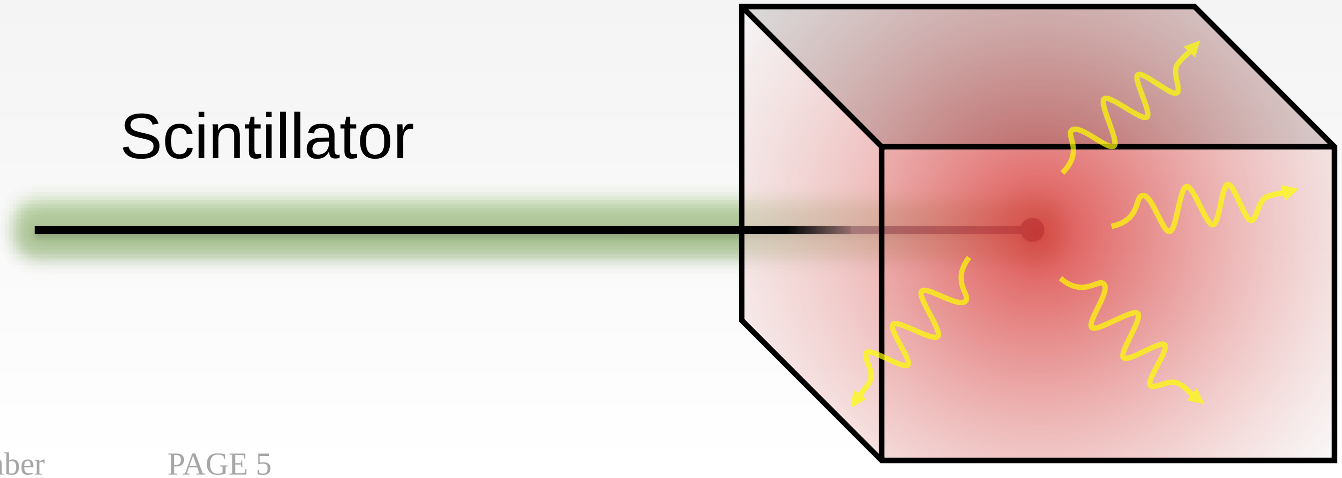
Proton CT



$E = E_0$
$E = E_0 - \int \mathrm{SP}\, \mathrm{d}l$
l_1
l_4
High energy proton beam
μ,SP
Energy detector
Position detectors
Position detectors
$\mathrm{SP}(x, y, z)$

The energy detector

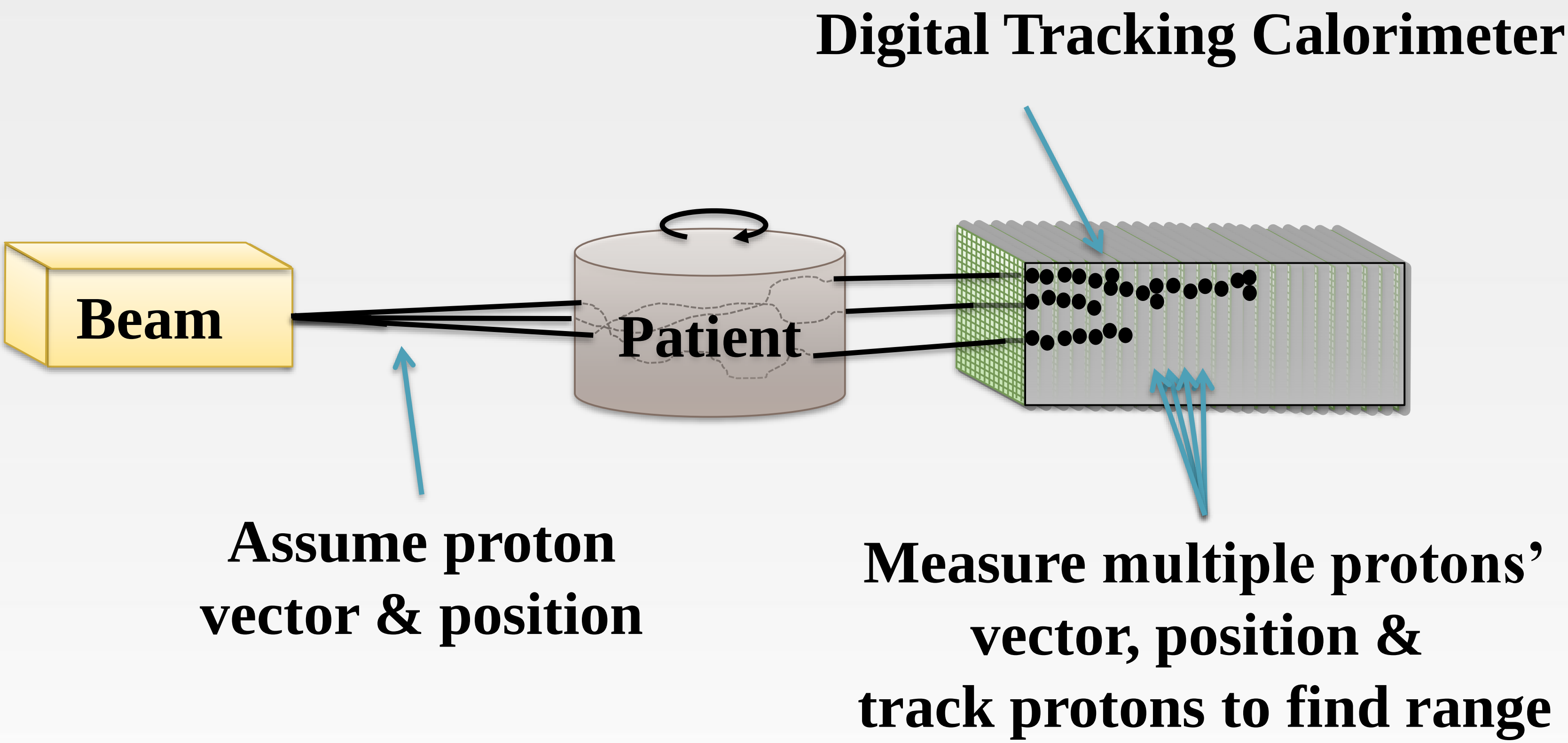




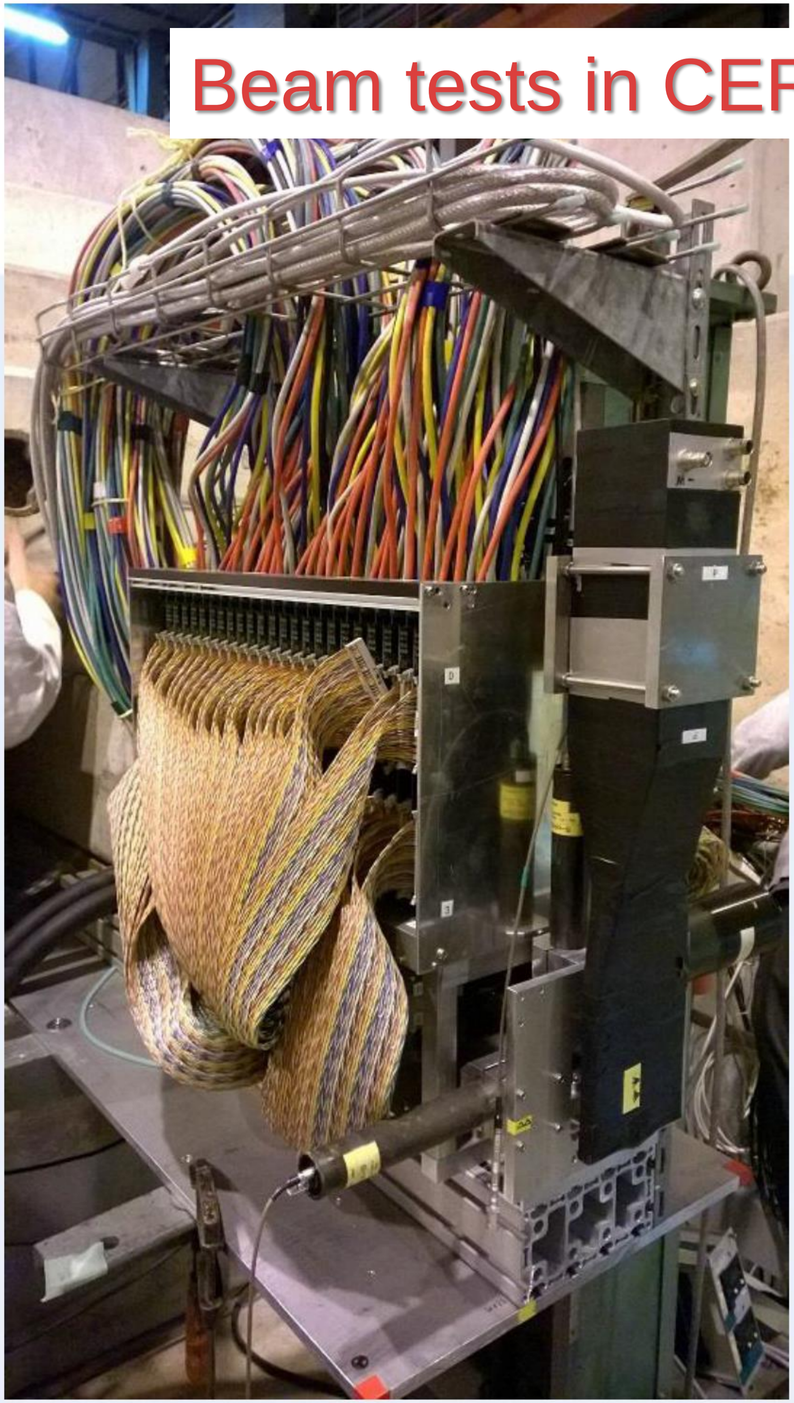
Proton CT with a Digital Tracking Calorimeter

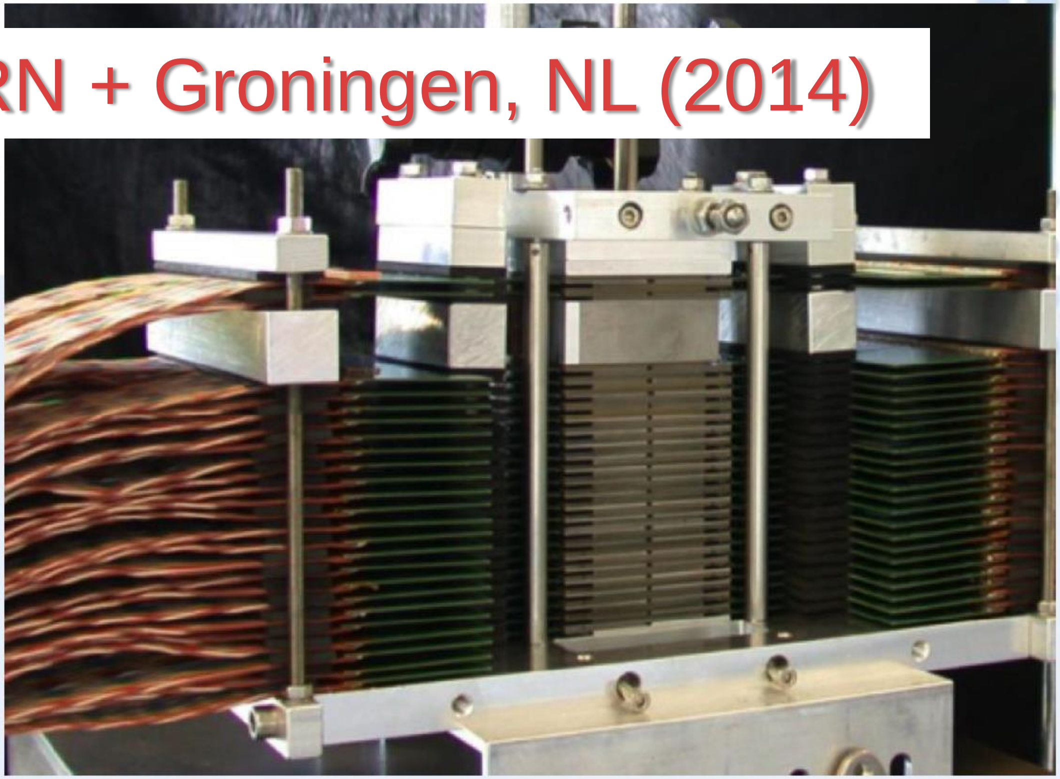
First proof-of-concept detector

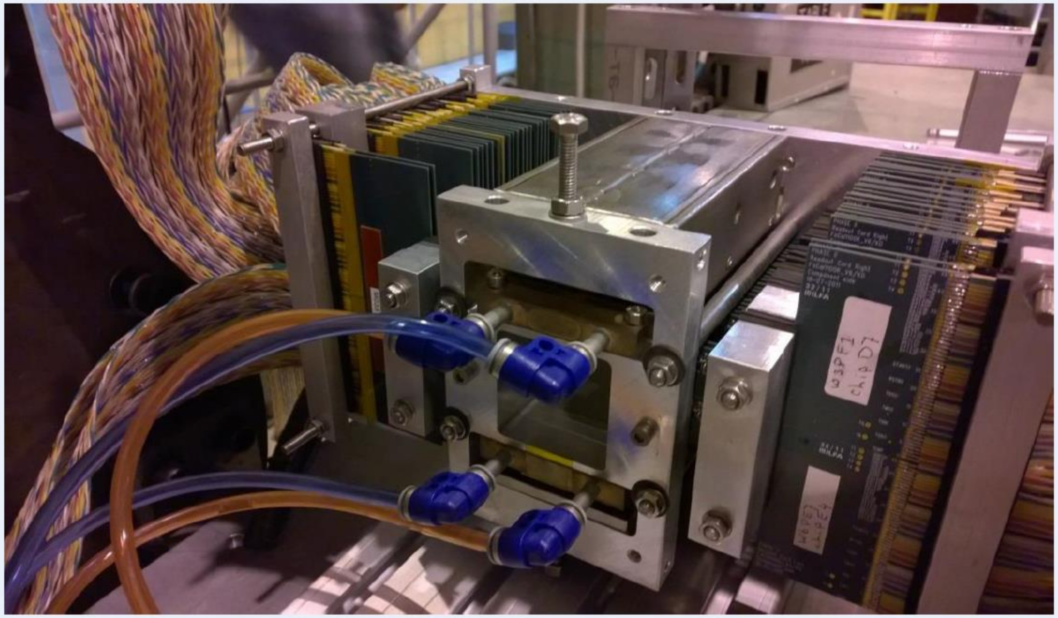
pCT – Digital Tracking Calorimeter



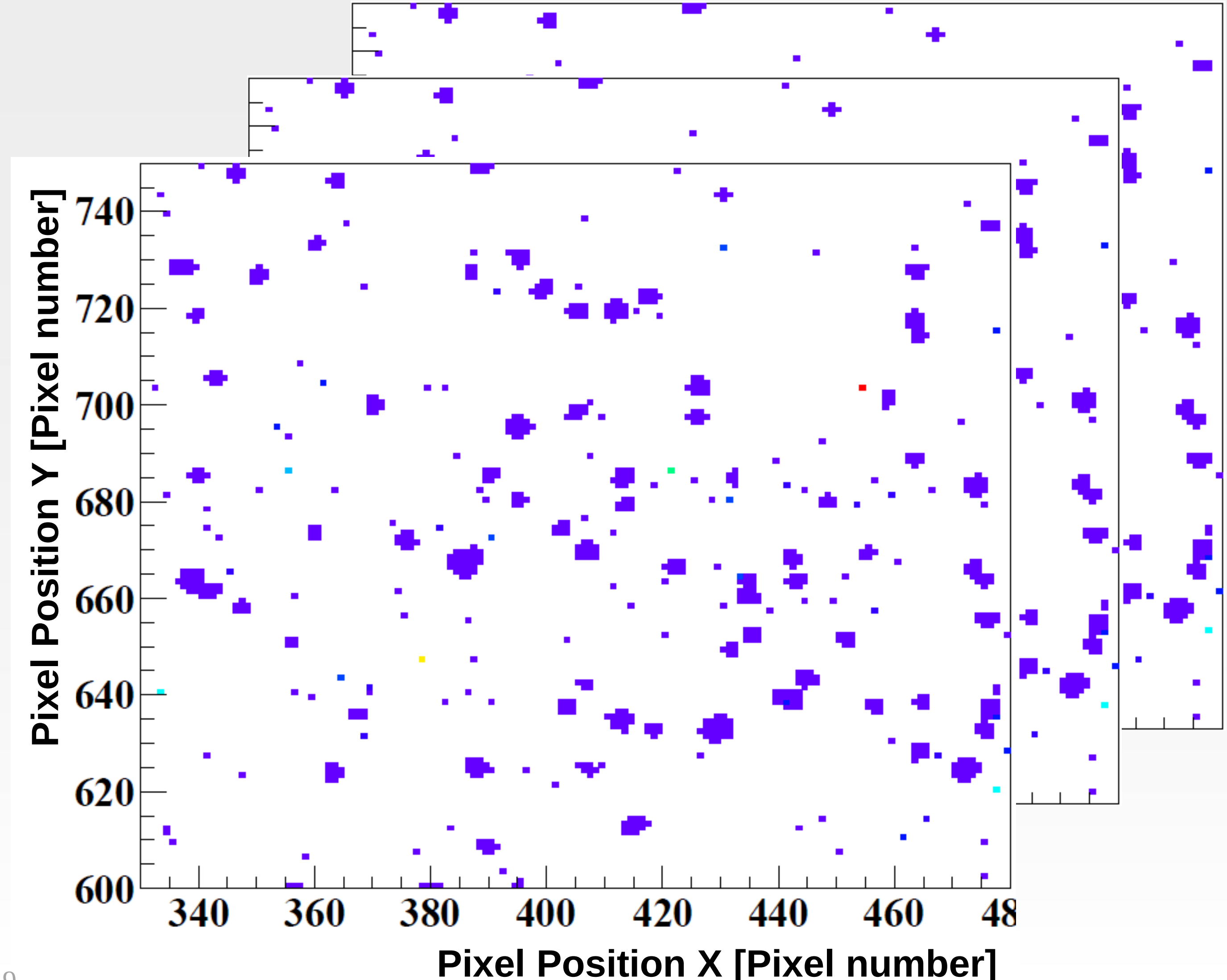
Beam tests in CERN + Groningen, NL (2014)







Protons hitting the pixel detectors



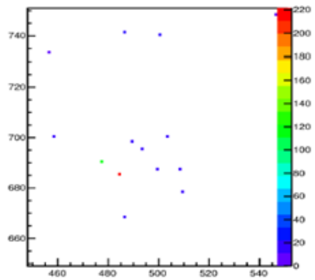
Analysis workflow

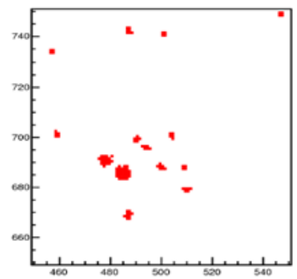
Data readout
MC, MC + truth, exp.

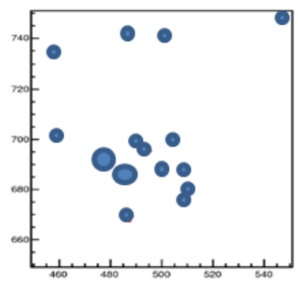
Pixel diffusion modelling (MC only)

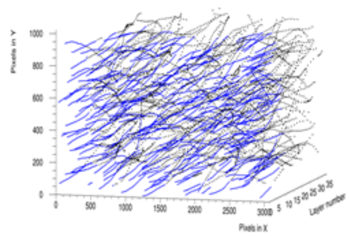
Cluster identification

Proton track reconstruction





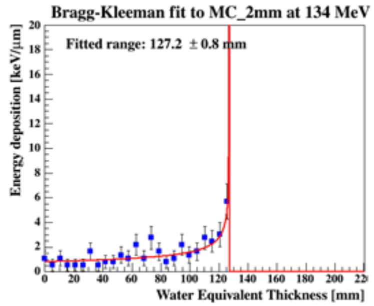


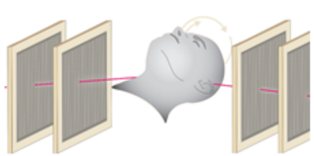


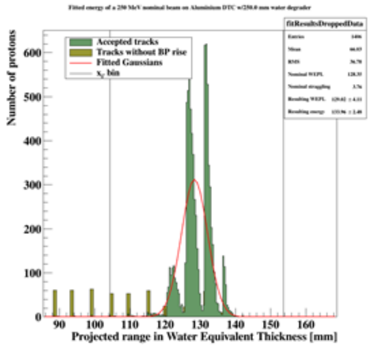
Individual track – energy loss fitting

If 3D reconstruction: MLP estimation

Residual range calculation







Proof-of-concept: ALICE-FoCal

- From 2013: Analysis + beamtests with the ALICE-FoCal detector for pCT
- Expectedly poor resolution
- Track reconstruction possible at high rates
  – ~1 million/s across 16 cm^2 @ 2 kHz readout

Proton CT with a Digital Tracking Calorimeter

Second prototype

Alice Pixel Detector (ALPIDE)

More on ALPIDE in 34 minutes!

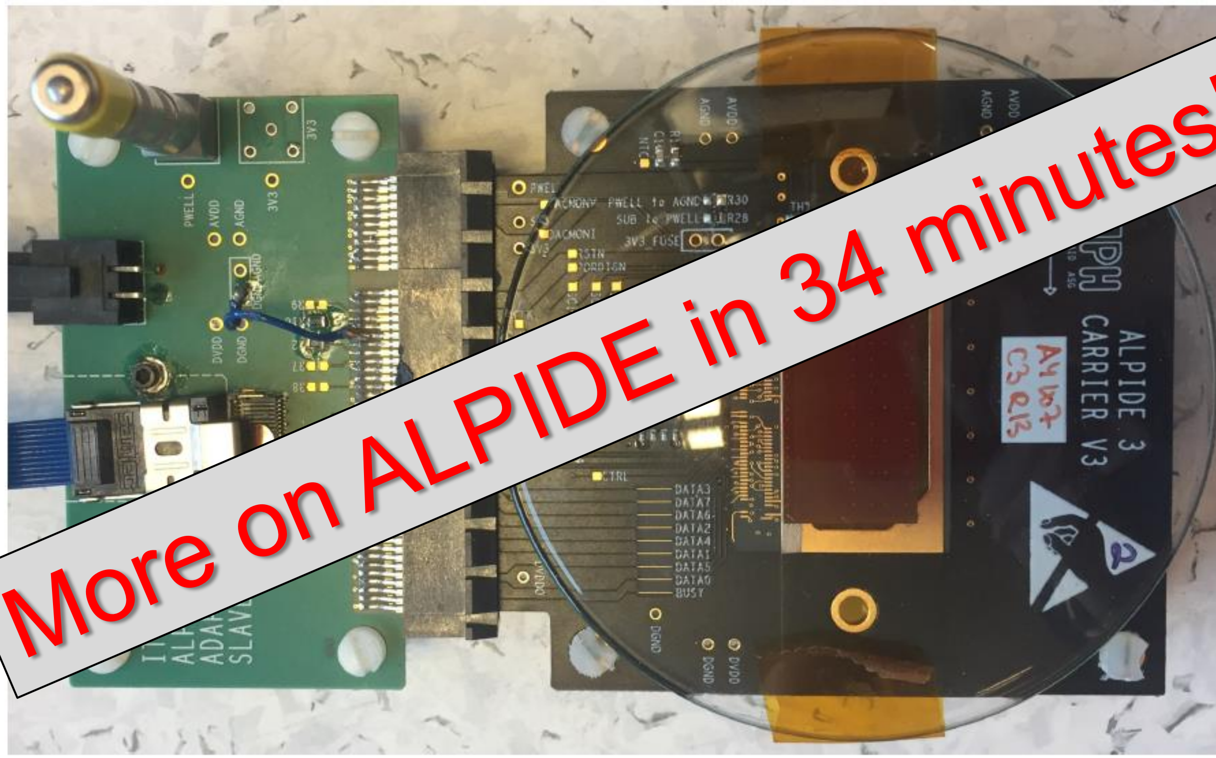
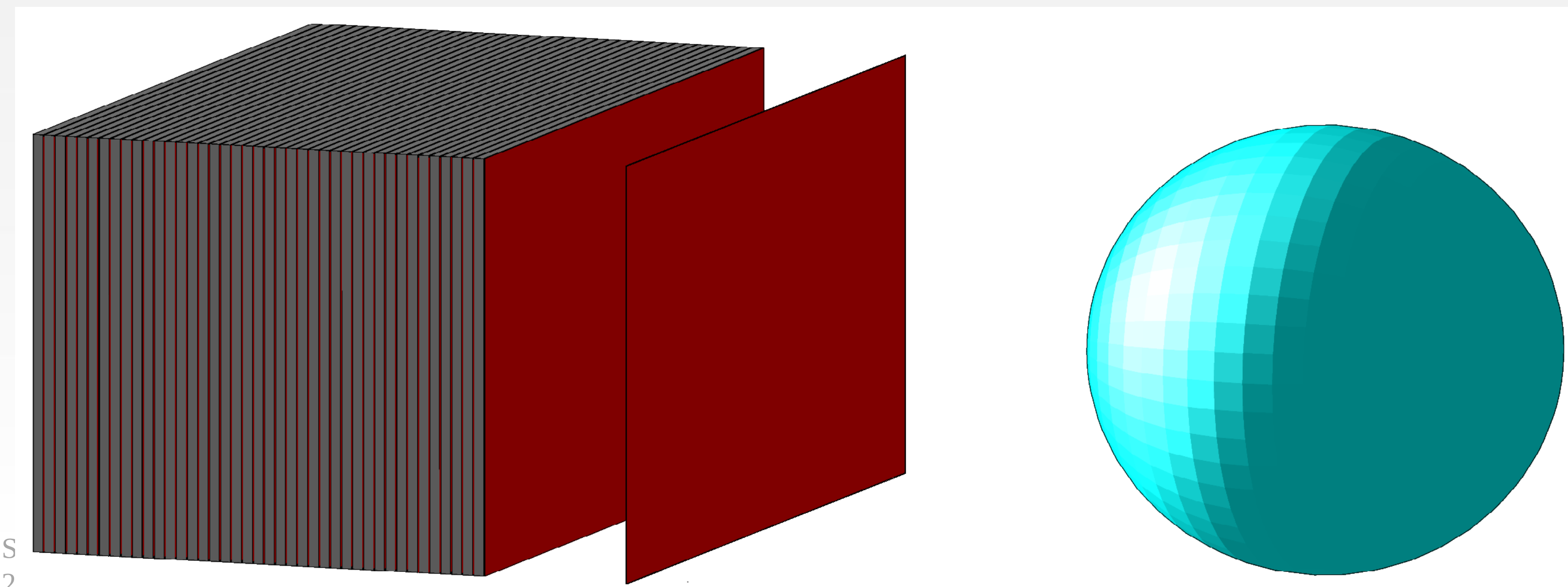


Figure 4.6: On the right: The ALPIDE carrier card. On the left: the ALPIDE adaptor slave.

http://bora.uib.no/handle/1956/16041: **Design of High-Speed Digital Readout System for Use in Proton Computed Tomography**

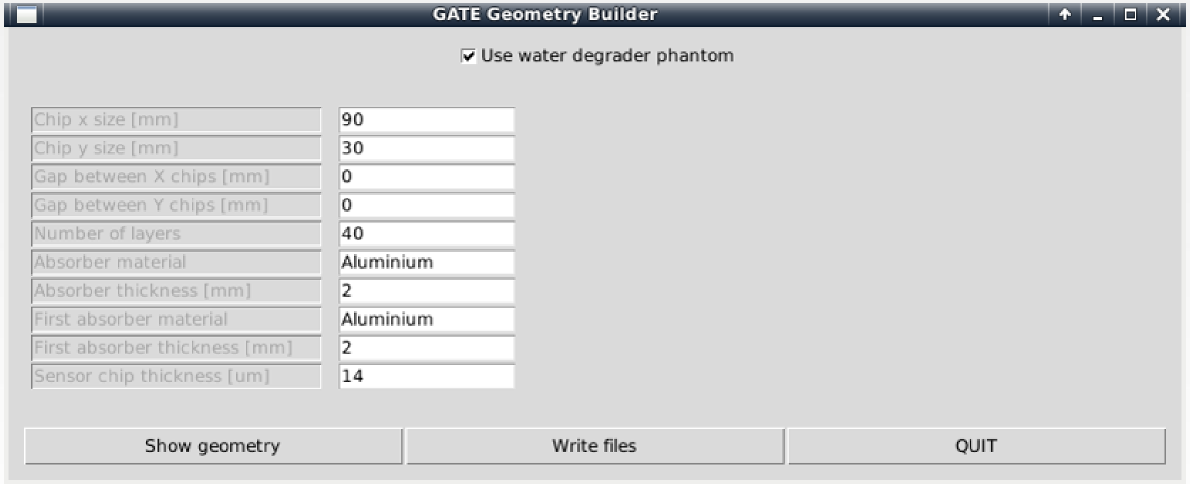
Monte Carlo simulations

- A *very* important tool in detector development
  - Define geometry, materials, beam, readout…
  - Simulation of how the particles interact and how energy is deposited



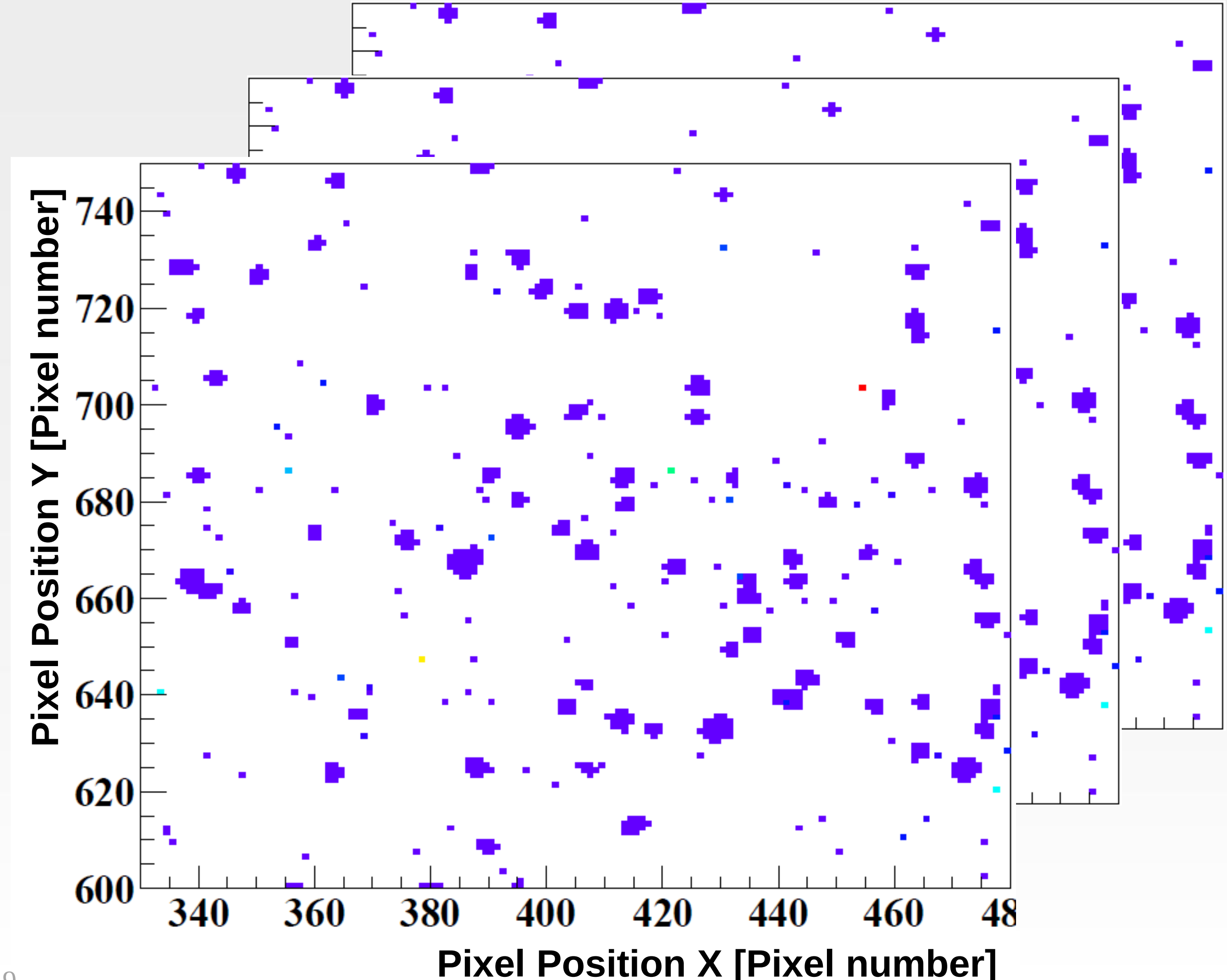
GATE

- Geant4-based MC framework
- Macro-based, simple to automate, e.g. to test iterative designs:

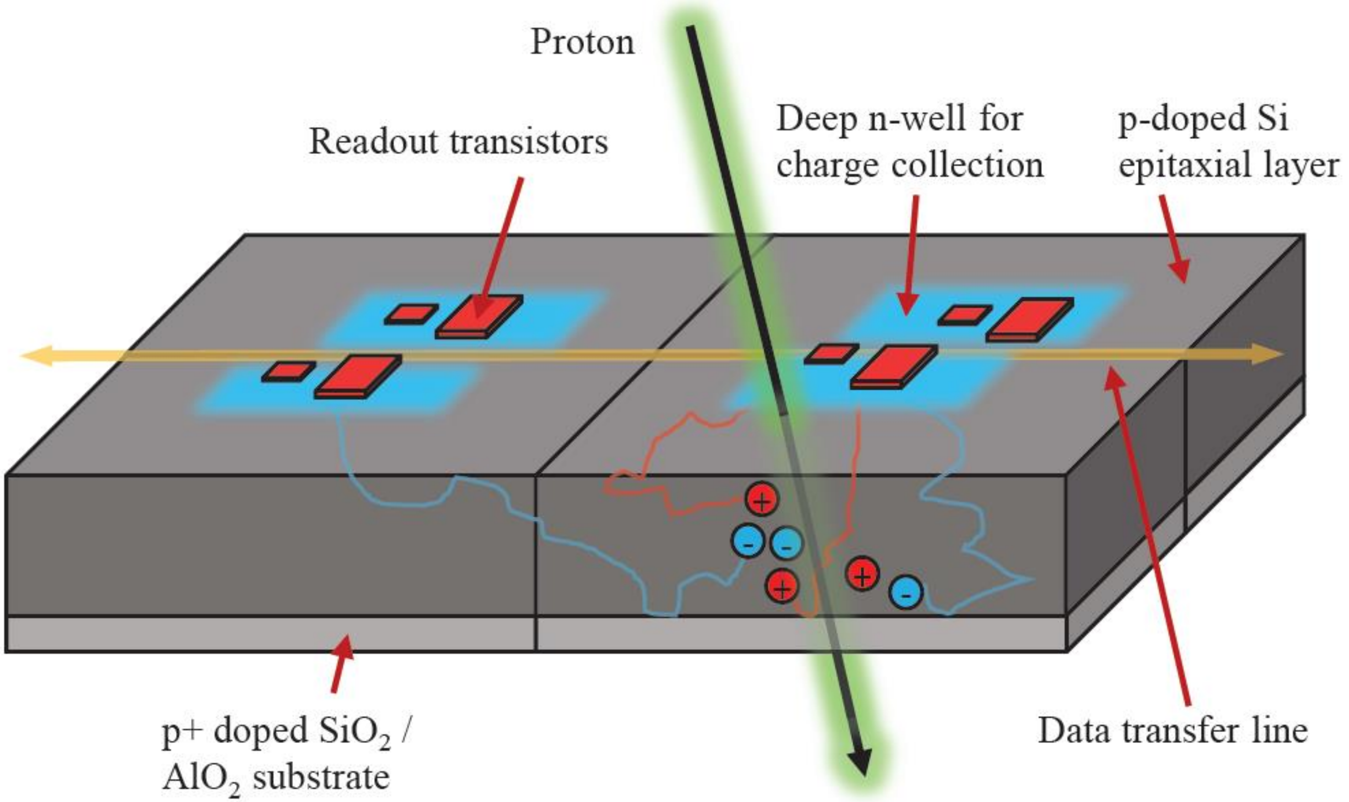


Charge diffusion from proton tracks

Protons hitting the pixel detectors



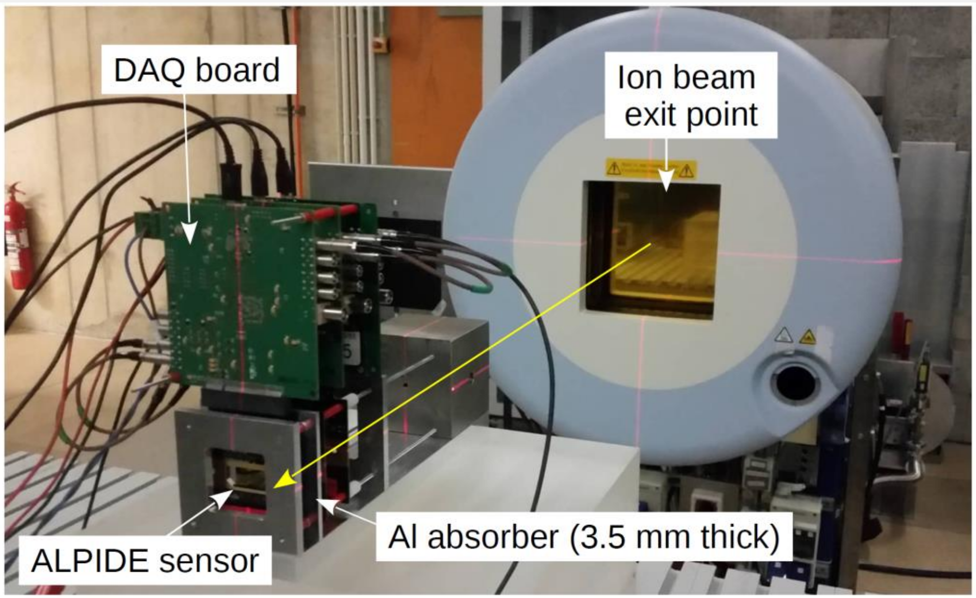
Charge diffusion in pixels



Pettersen, H.E.S., 2018. PhD thesis

Heidelberg beam test: 2018

- A list of 15 000 «good» clusters
- + Calculation of the ions' E_D



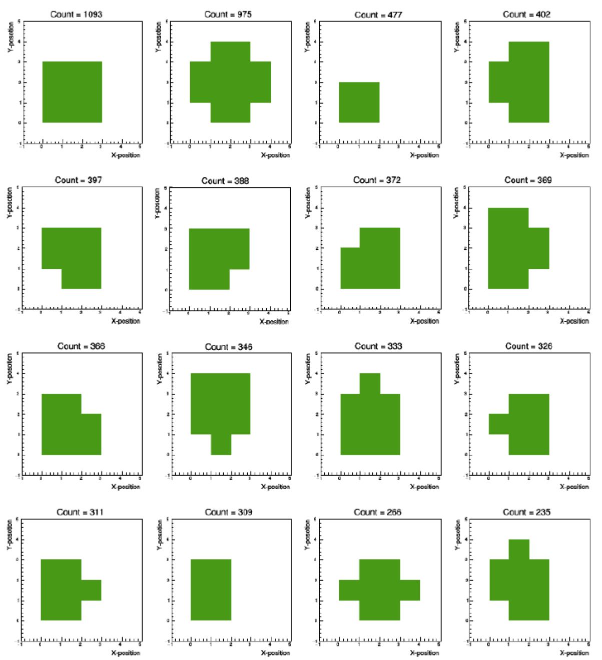
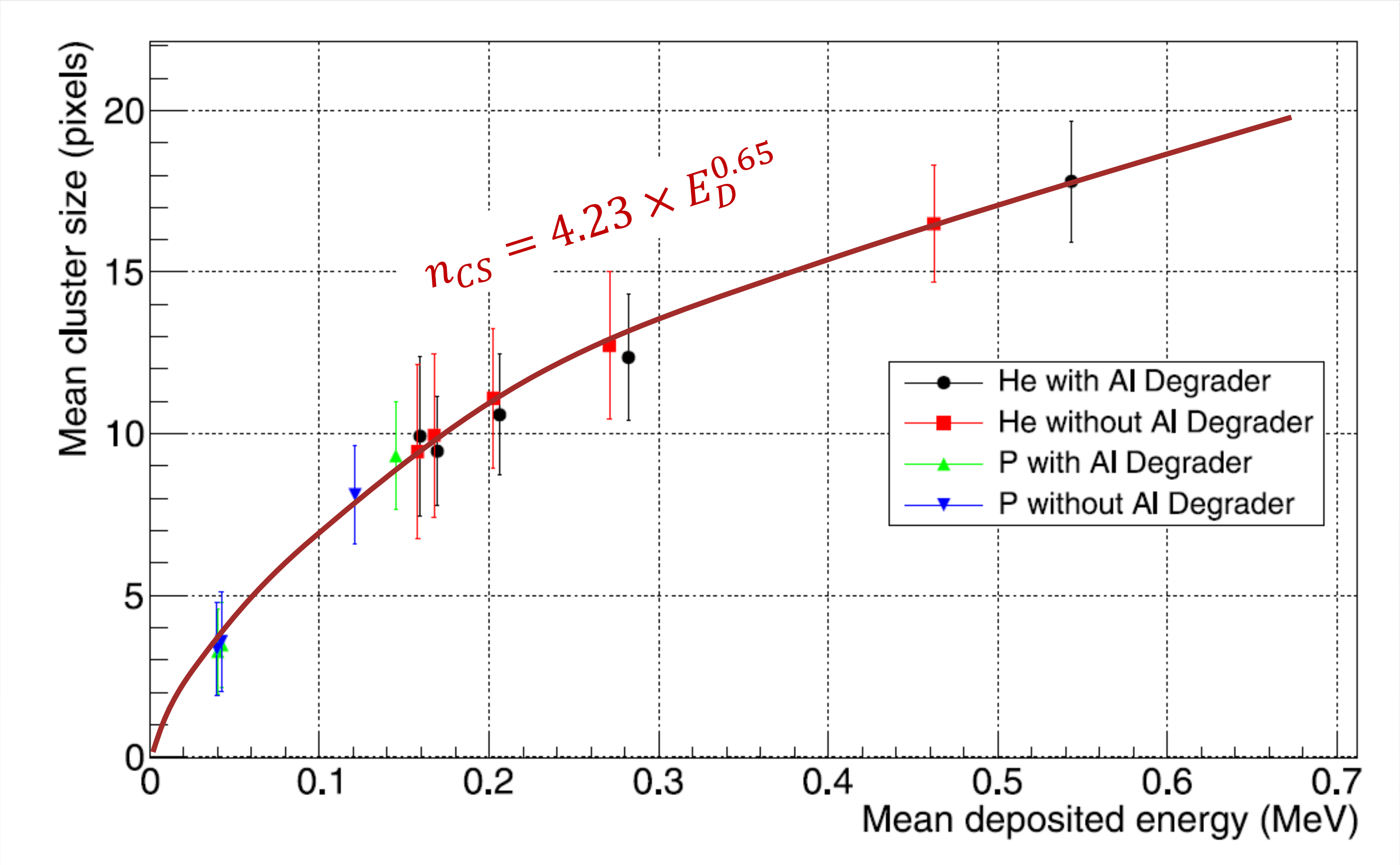


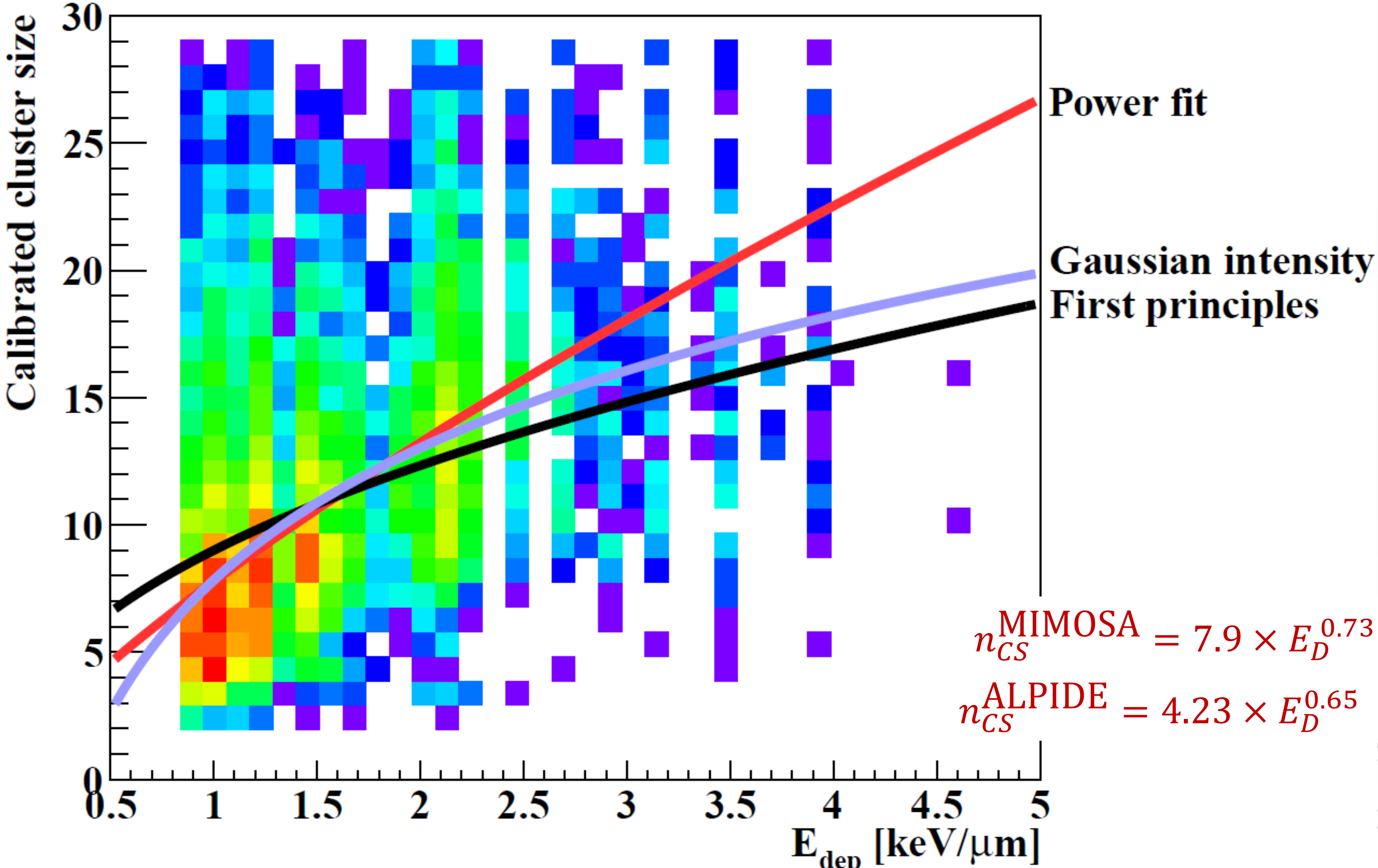
Figure 3.11: 16 most frequent clusters in the data collection.

Grimstad, S., 2019. MSc: *Simulation and analysis of clustering for proton CT*
Tambave, G. et al., 2019. Nucl Instr And Meth in Phys Res A; 162626



Tambave, G. et al., 2019. Nucl Instr And Meth in Phys Res A; 162626

Compare this to MIMOSA (PoC)



$$n_{CS}^{\mathrm{MIMOSA}} = 7.9 \times E_D^{0.73}$$

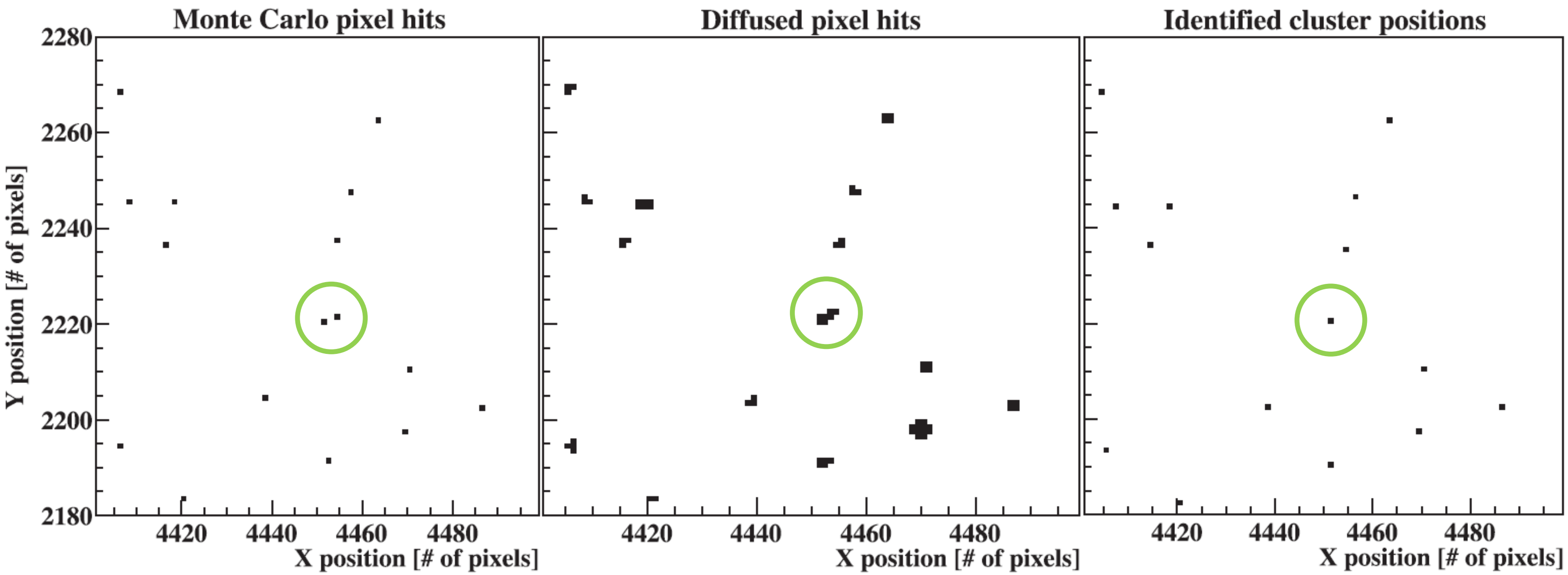
$$n_{CS}^{\mathrm{ALPIDE}} = 4.23 \times E_D^{0.65}$$

Pettersen, H.E.S., 2018. PhD thesis

MC modeling of Cluster Sizes

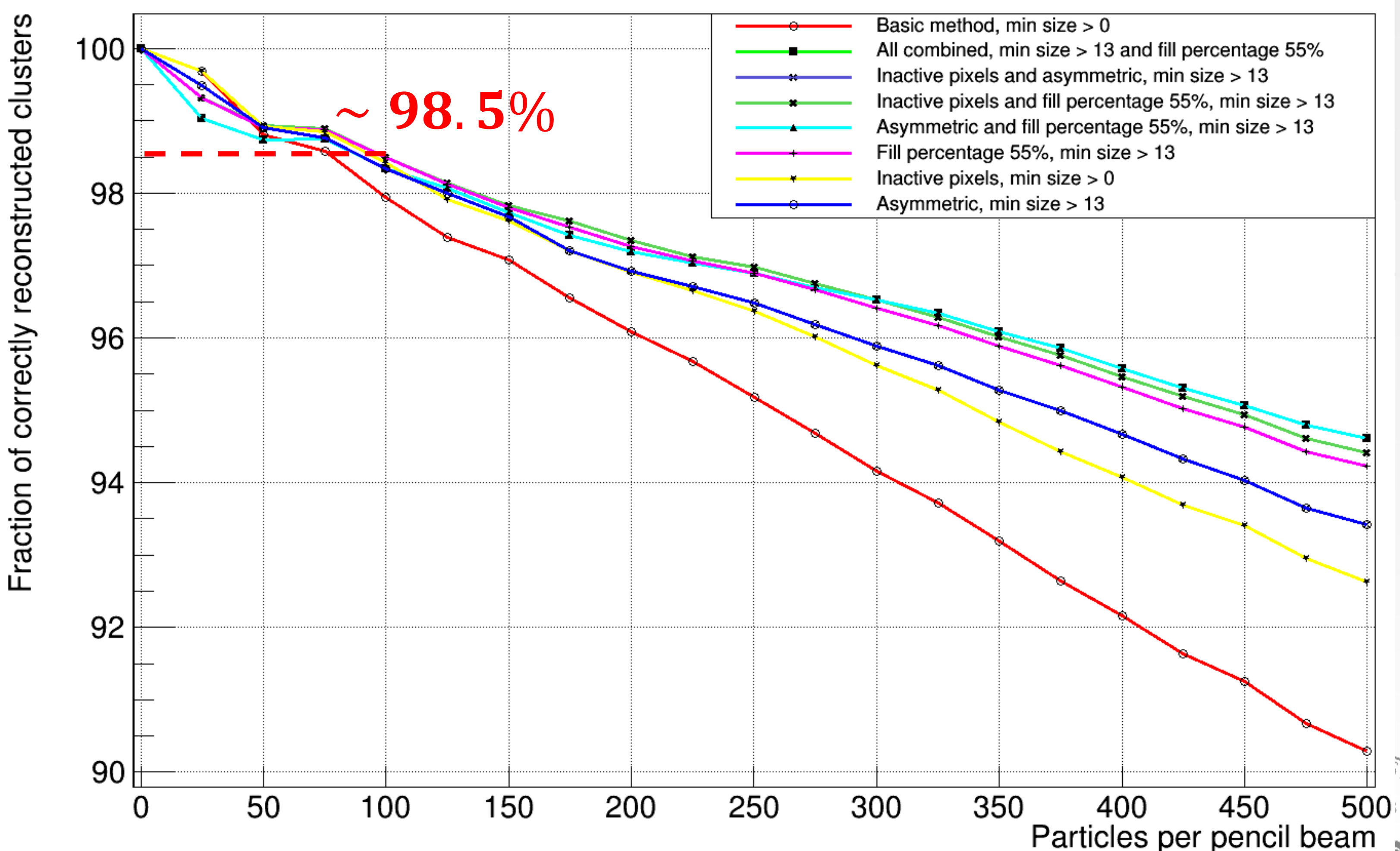
- Not feasible to directly simulate in MC
- MSc of Silje Grimstad:

1. Use n_{CS}, E_D relashionship from Heidelberg data
2. Use collected library of clusters, sorted by n_{CS}
3. MC → Find E_D in pixel → Sample random cluster with correct n_{CS}
4. Paint cluster around hit position
5. Do cluster analysis (hit position from cluster…)



Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.

Accuracy of cluster reconstruction



Grimstad, S., 2019. MSc: *Simulation and analysis of clustering for proton CT*

Track reconstruction

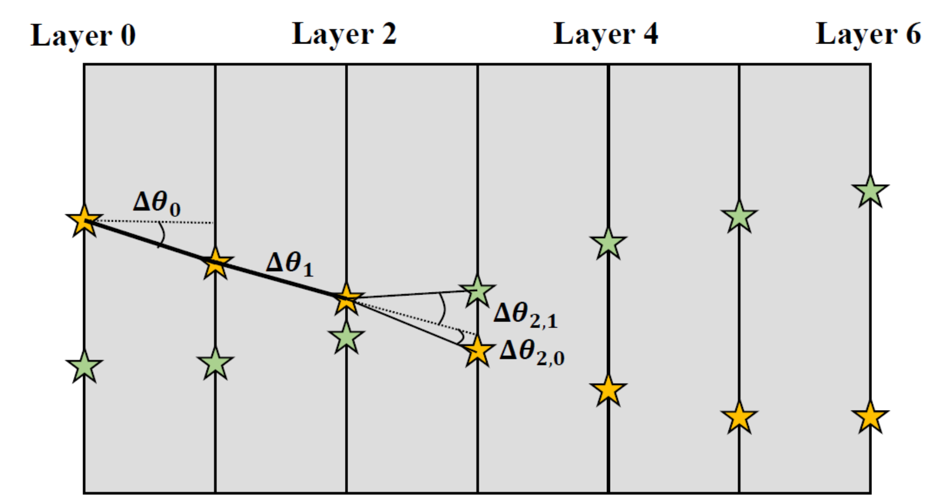
Proton track reconstruction

- With a DTC-type detector:
  - – Possible to reconstruct many protons in a single readout
  - – All proton hits throughout the detector must be «de-spaghetti-fied» into tracks

Tracking algorithm

1. Identify all hits in first/last layer
2. Find angular change $\Delta\theta_0$ in all possible combinations of hits in first/last + next layer.

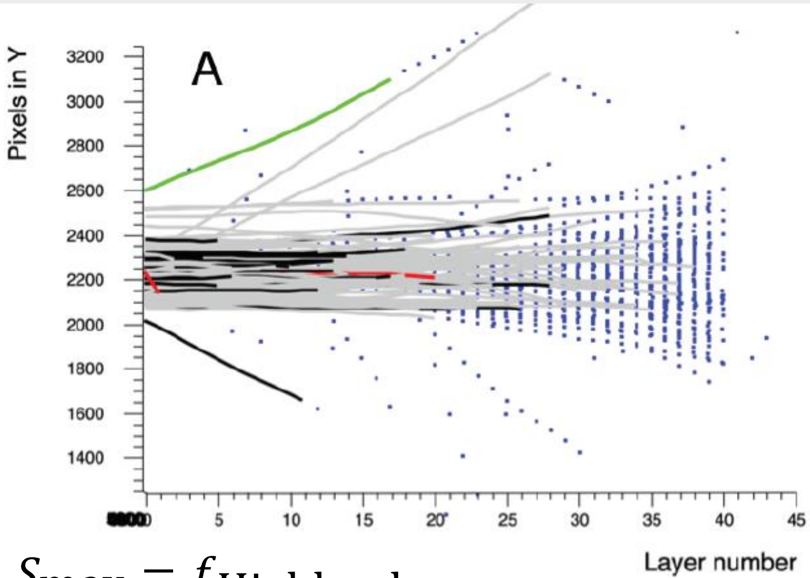
   Accumulate $\Delta\theta_i$: $S_n^{(i)} = \sqrt{\sum_{\text{layer}}^{n} \left(\Delta\theta_{\text{layer}}\right)^2}$ for pair i
3. Identify all tracklet candidates where $S_n < S_{\text{max}}$. Keep the best (or the two best if sufficiently similar).
4. Recursively grow the tracklet tree to reconstruct all tracks



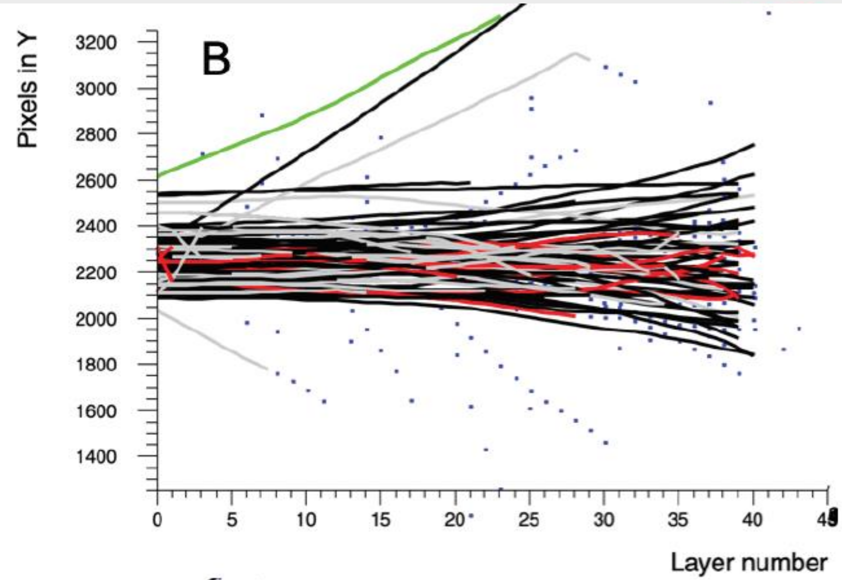
Pettersen, H.E.S. et al., 2019. EPJ WoC (in press).

Stuff we've tried

- Backwards + forwards tracking
  - Backwards slightly better
- $\Delta\theta > K$ scoring w/per-layer Highland
- Follow all tracks where $\Delta\theta < K$
  - Scales «poorly» with nlayers and ntracks
- Track-splitting corrections; cluster merging corrections
- Kalman filtering: MCS uncertainties too large compared to measurement uncertainties



$s_{max} = f_{Highland}$



$s_{max} = 4f_{Highland}$

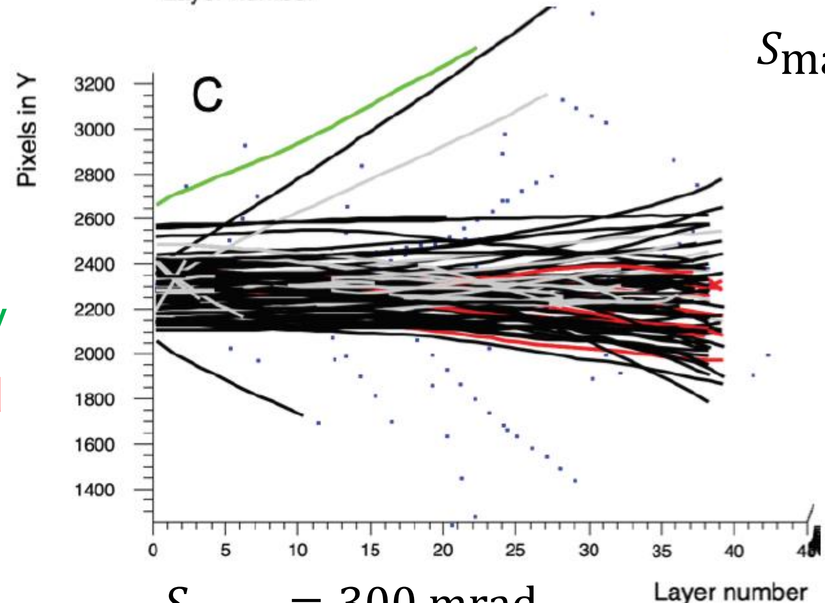
Good track

Incomplete track

Unfiltered secondary

Two tracks confused

Unused cluster



$s_{max} = 300 \text{ mrad}$

Garcia-Santos, A., 2019. Utrecht University, Delft. MSc: Optimization of the Track Reconstruction Algorithm in a Pixel Based Range Telescope for Proton Computed Tomography

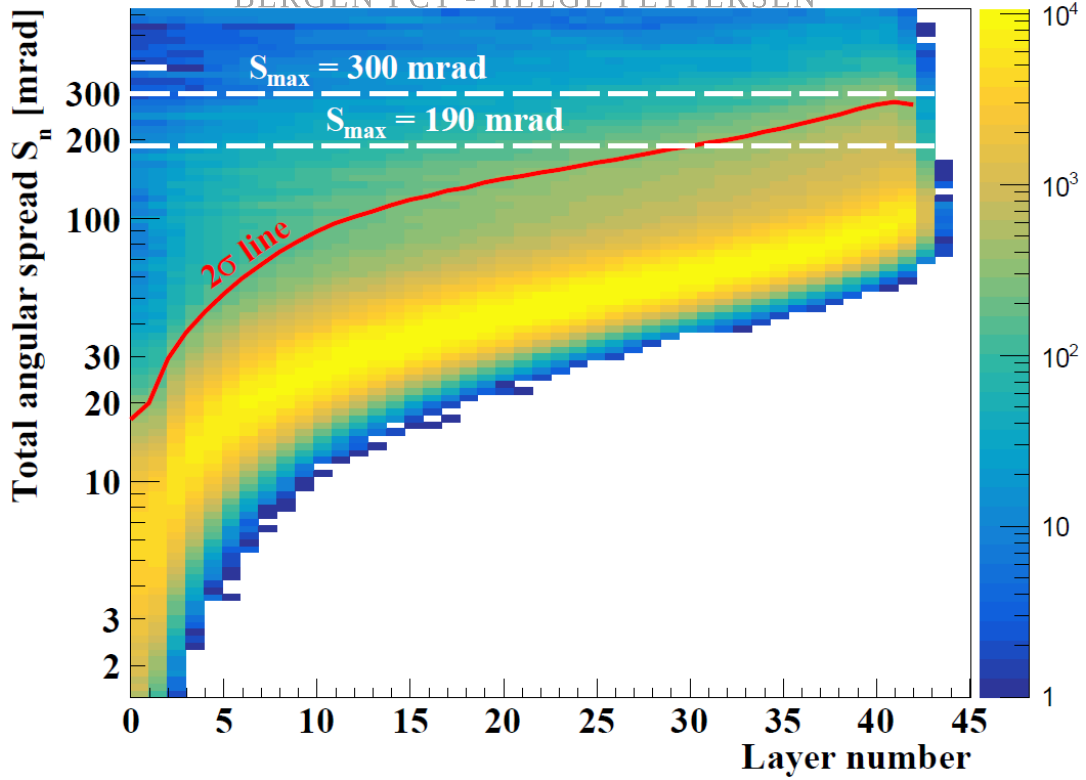
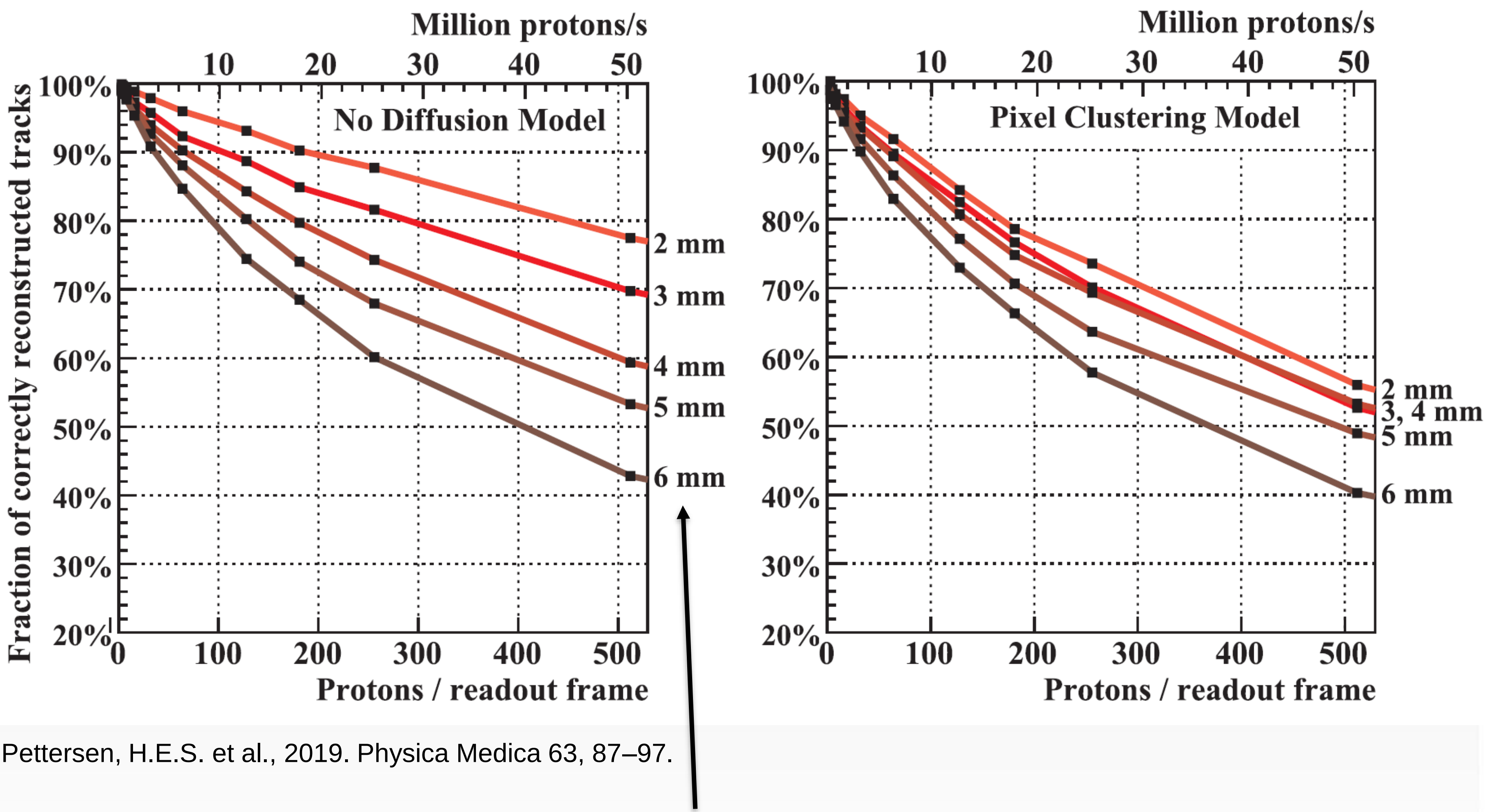


Figure 5. Distribution of actual $S_n = \sqrt{\sum_{\text{layer}}^{n}(\Delta\theta_{\text{layer}})^2}$ values from tracks reconstructed using MC truth. The empirical 2σ value of the distribution as well as two different S_{max} thresholds are shown.

Pettersen, H.E.S. et al., 2019. EPJ WoC (in press).

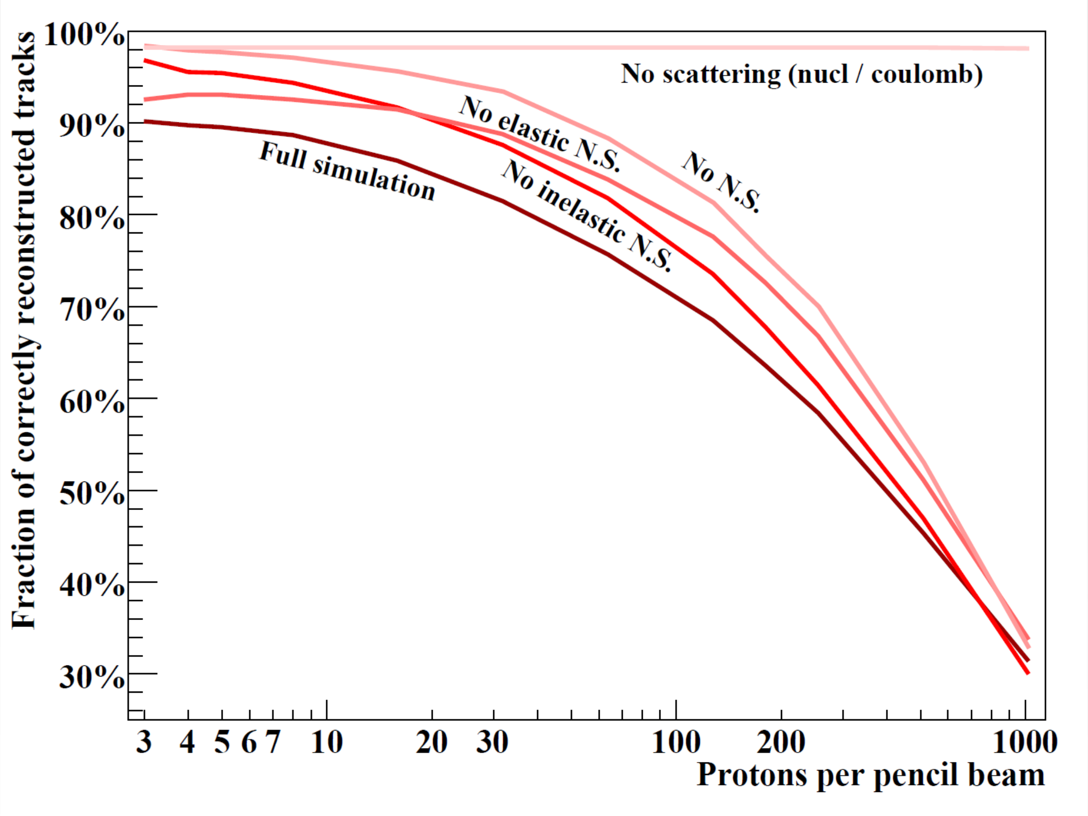
Now assuming a $\sigma = 3\text{ mm}$ pencil beam & 10 µs integration time



Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.

Aluminum absorber thickness (final = 3.5 mm)

What are the degrading effects?



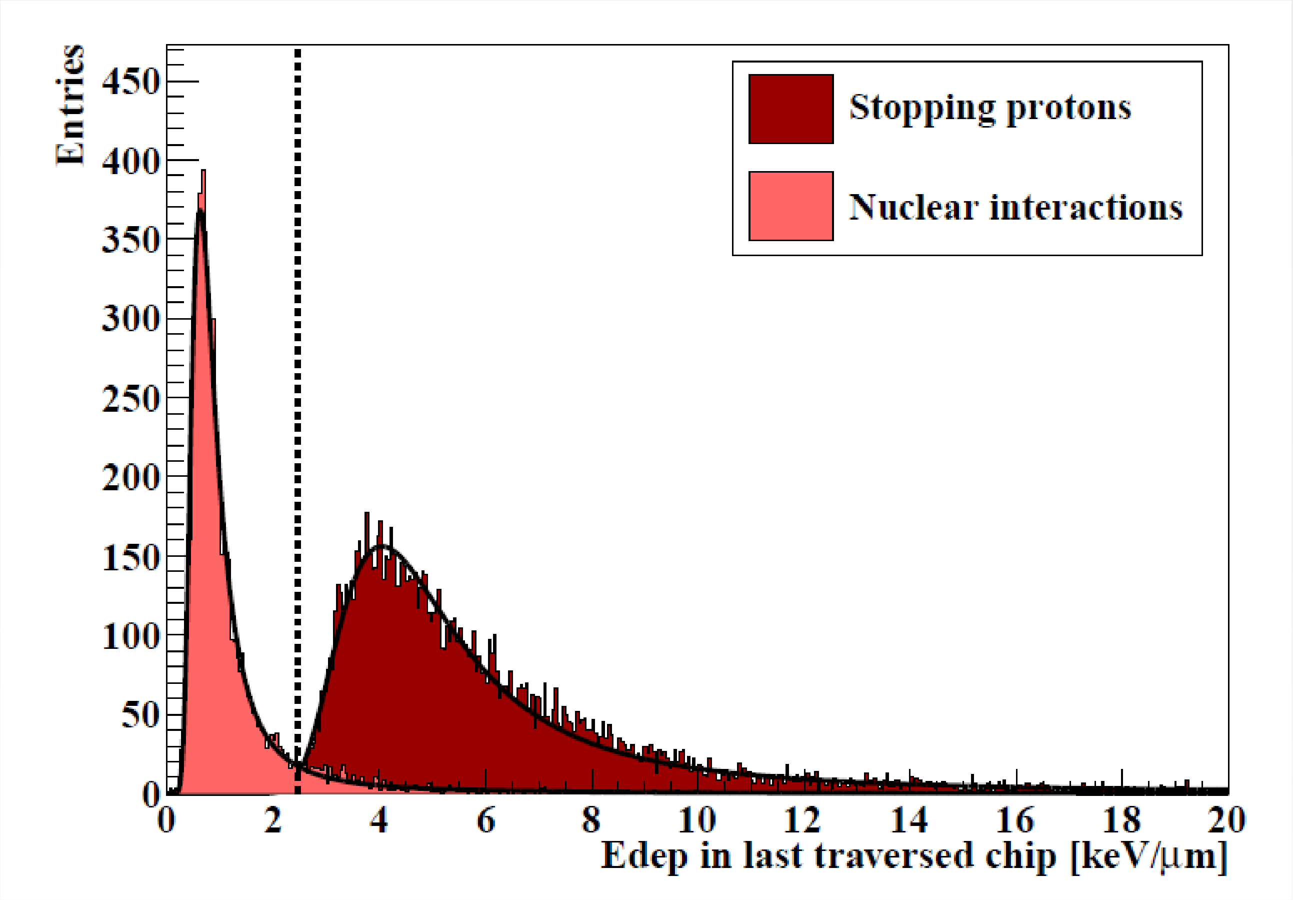
Pettersen, H.E.S. et al., 2019. EPJ WoC (in press).

Track filtering

- Need filter nuclear interactions in detector/patient
  - 3 sigma angular filter
  - 3 sigma filter on range per beam / voxel
  - Filter on E_D in the last layer

	Number of tracks	2nd removed	2nd remaining
Reconstructed tracks	483,287	–	28.0%
After removing high angle tracks	421,810	64.5%	22.7%
After removing short tracks	324,793	53.4%	13.5%
After removing low E_D tracks	281,925	25.7%	11.6%

Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.



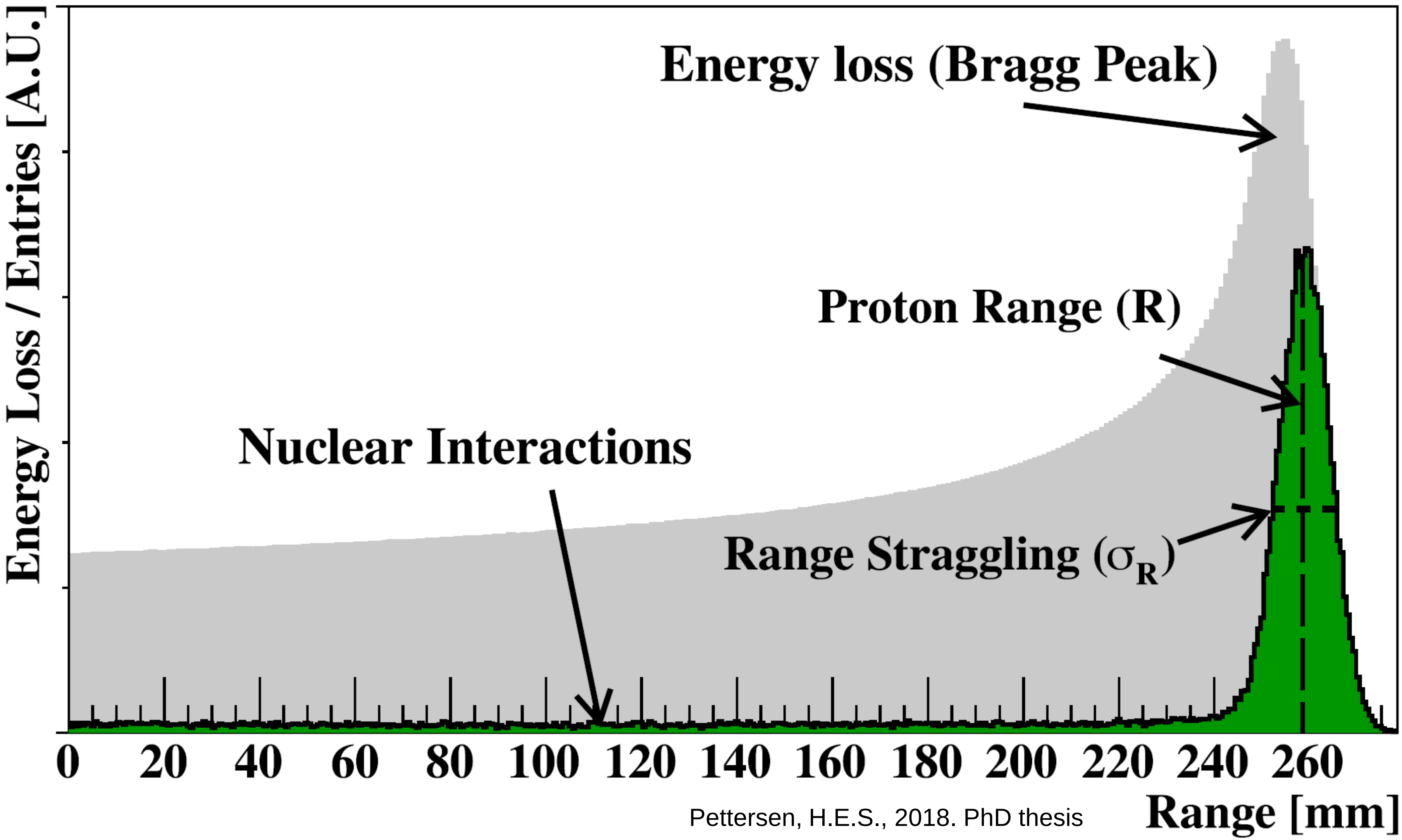
Pettersen, H.E.S., 2018. PhD thesis

Volz, L. et al., 2019. Phys. Med. Biol. 64, 15NT01
→ uses E_D filtering to remove 2ndies in He beam

What happens to bad tracks?

- 500,000 protons tracked with $n_p = 100$
- 286,925 remaining after filtering (w/ 11.5% 2nd)
- 84% are correctly reconstructed:
  - 10% of the tracks are confused (>70 % due to cluster merging)
    - *Image noise*
  - 5% are incomplete
    - *Systematic lower WEPL*
  - 1% are confused + incomplete
    - *Image noise*

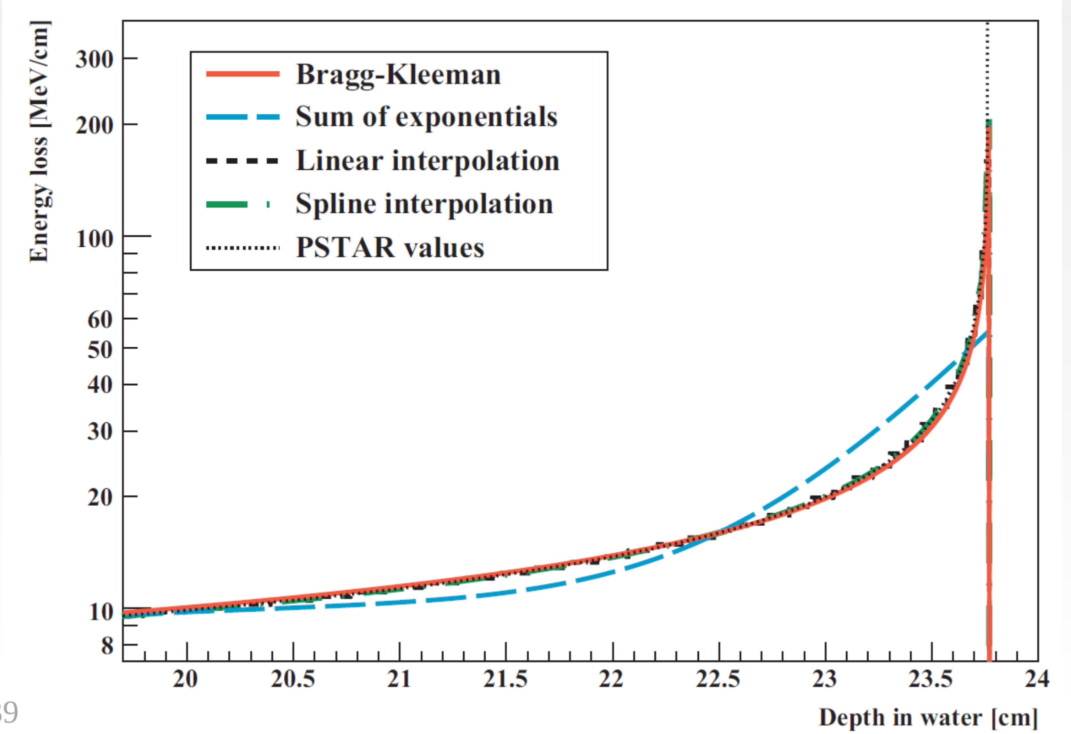
Range calculation



Pettersen, H.E.S., 2018. PhD thesis

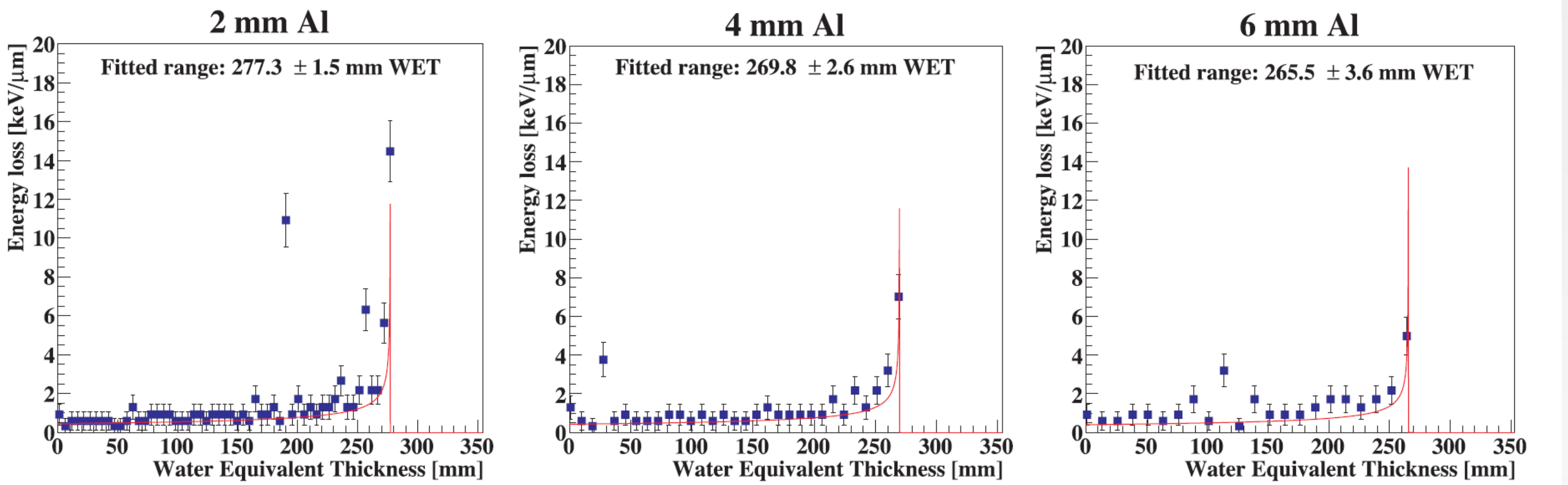
- The Bragg-Kleeman range-energy relationship, $R = \alpha E^p$, can be rewritten to give an accurate depth-dose curve for a *single* proton:

$$\frac{\mathrm{d}E}{\mathrm{d}z} = \frac{(R - z)^{1/\mathrm{p}-1}}{p\alpha^{1/\mathrm{p}}}$$



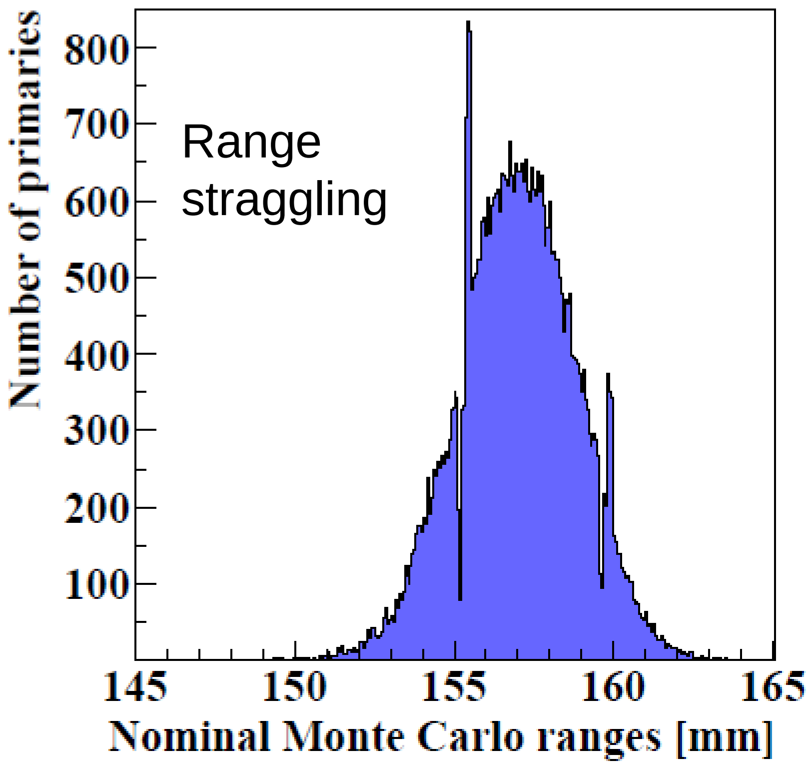
Pettersen, H. E. S. et al., 2018. Radiat. Phys. Chem. 144, 295–297.

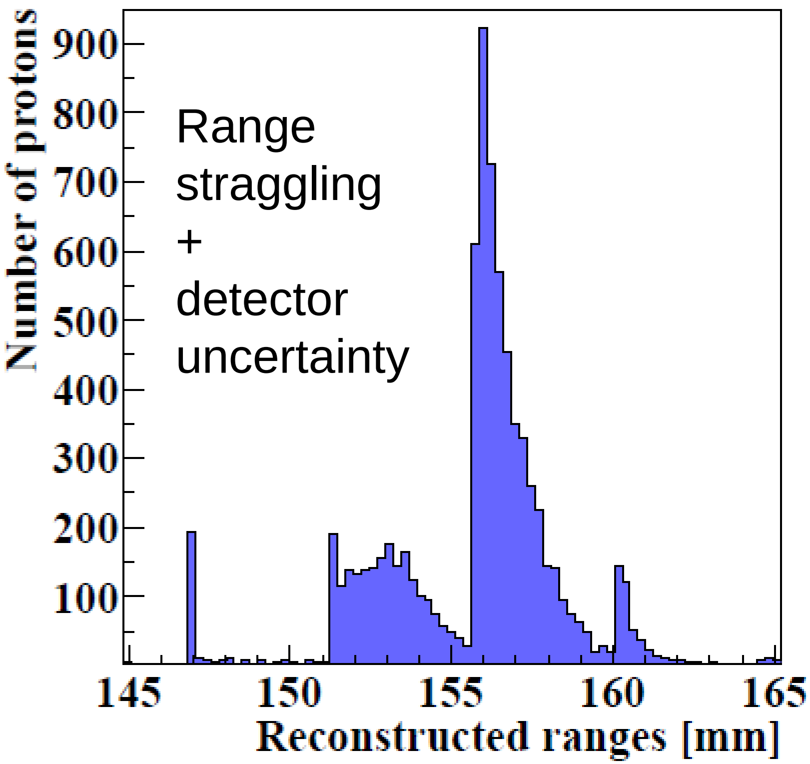
Range resolution from individual tracks



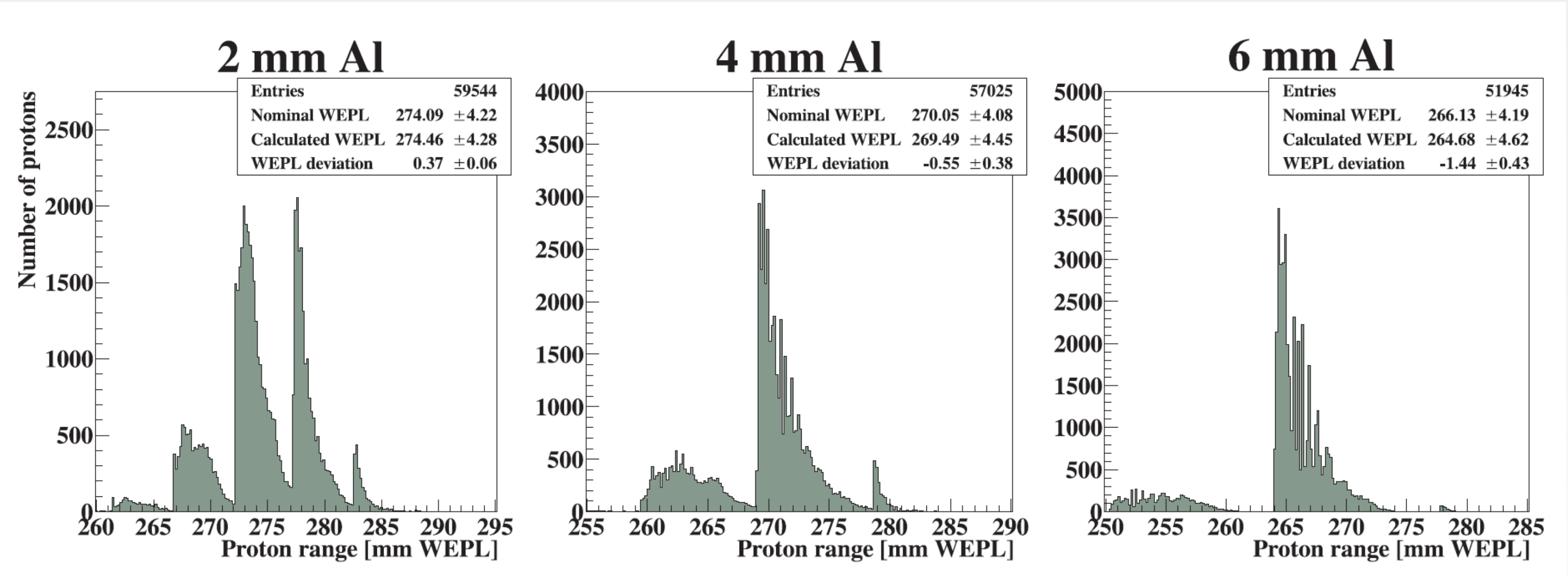
Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.

Range accuracy and precision

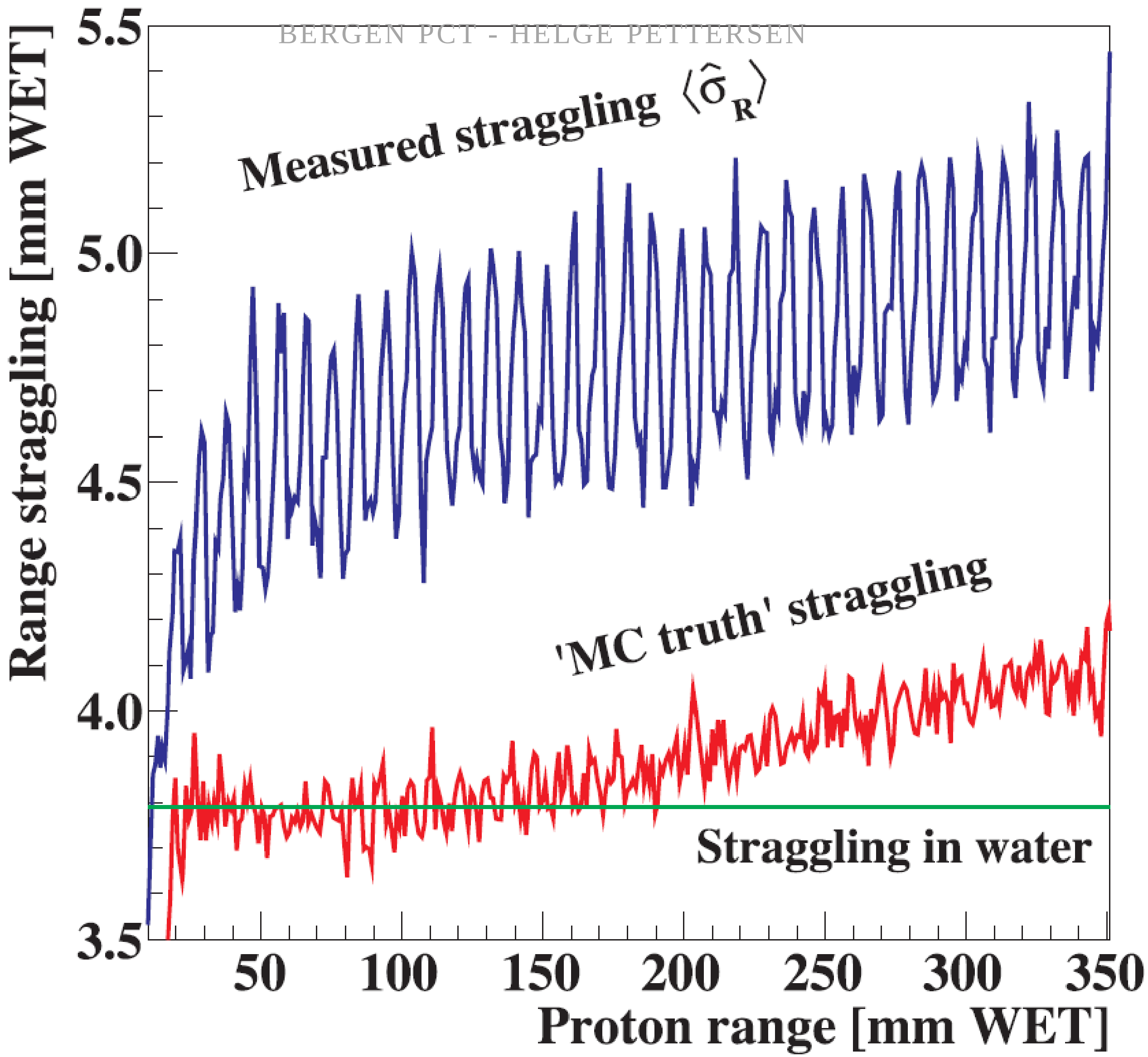




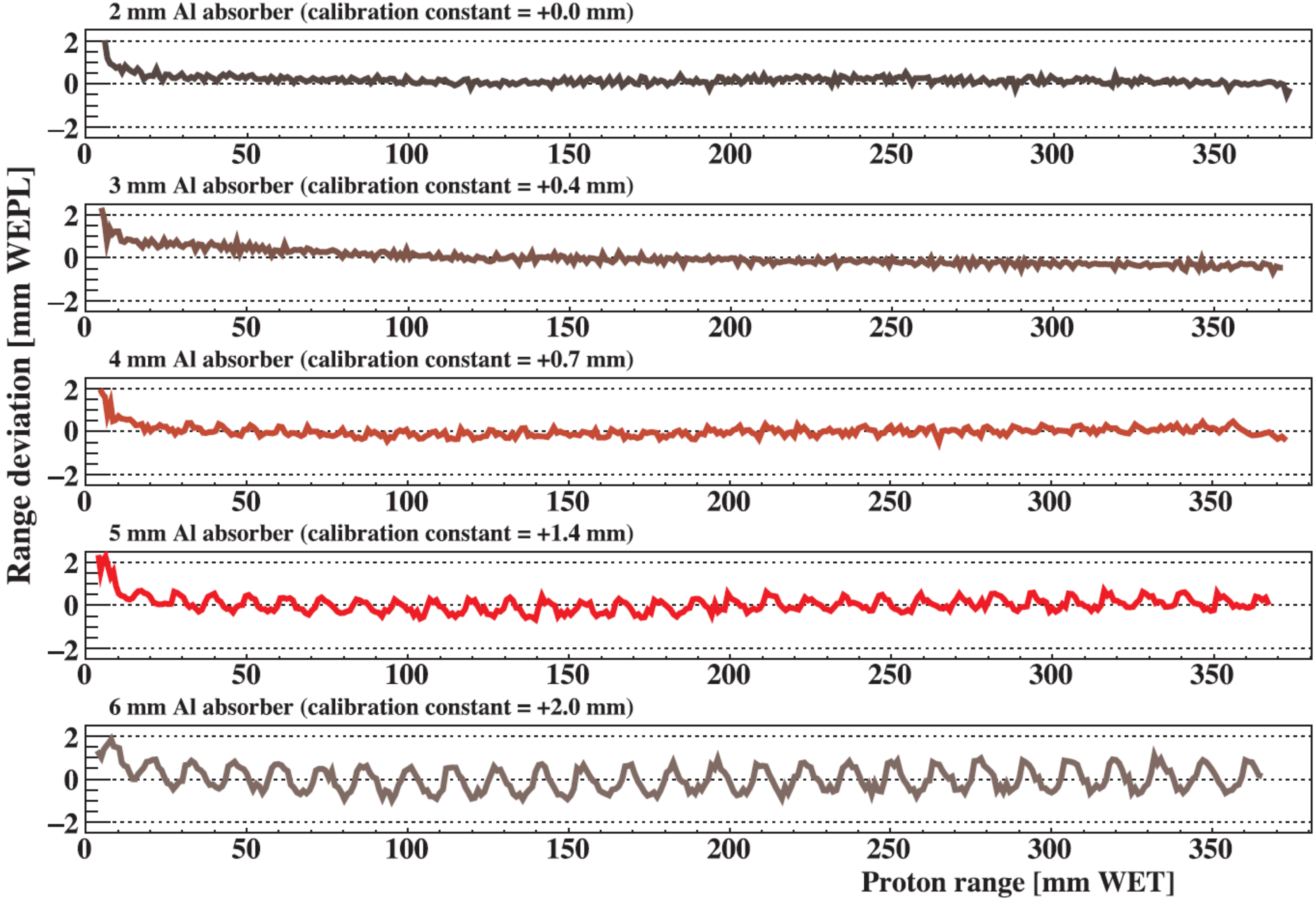
Range distribution per beam energy



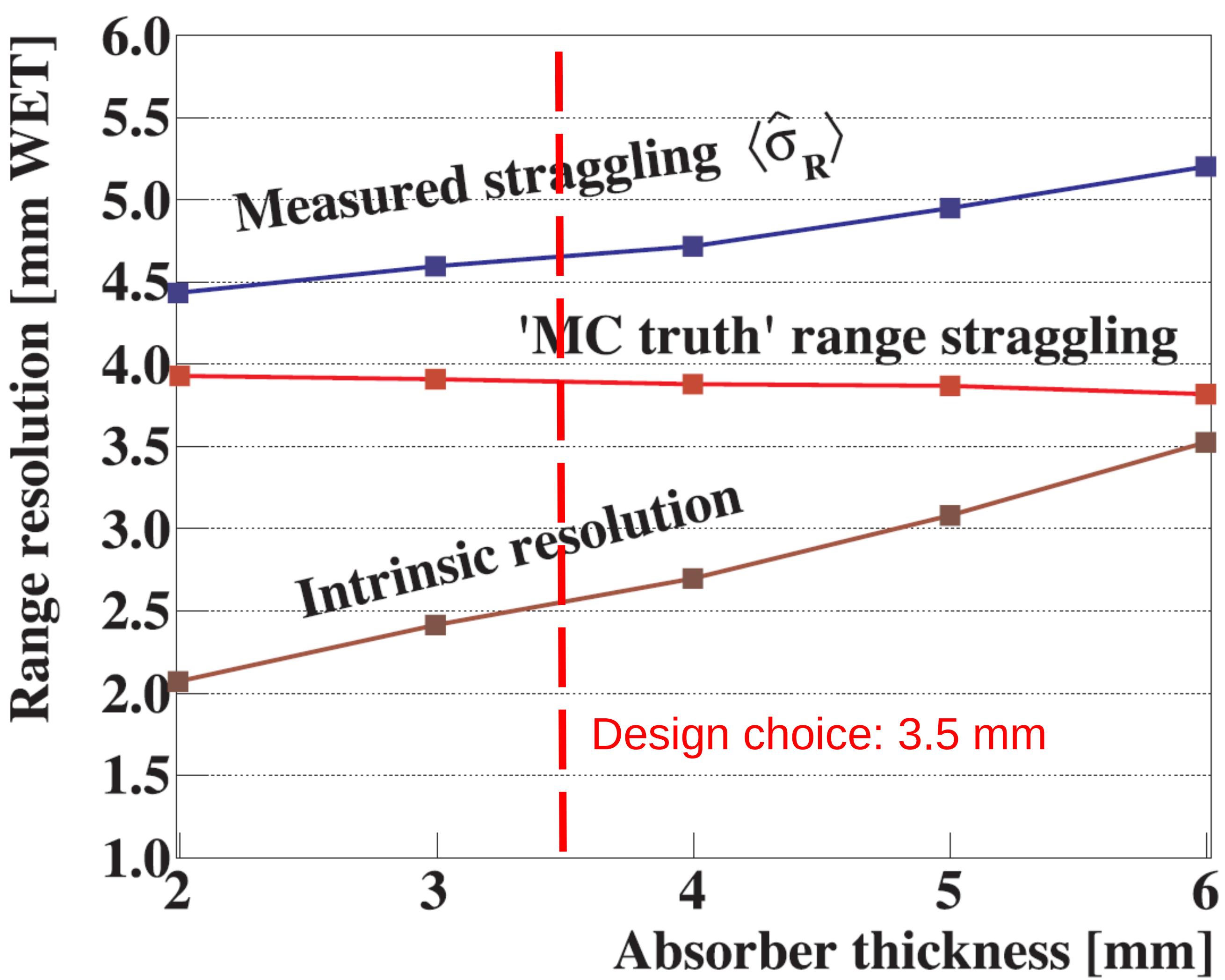
Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.



Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.



Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.



Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.

Number of layers needed

Table 2
The number of layers needed to contain a proton beam of 200 MeV and 230 MeV, in the different geometries, when a necessary extra margin corresponding to a distance of three times the range straggling is added [7].

Absorber thickness [mm]	2	2.5	3	3.5	4	4.5	5	5.5	6
Layers needed (250 MeV)	74.9	62.4	53.8	46.8	42.0	37.8	34.5	31.8	29.4
Layers needed (230 MeV)	65.9	54.7	47.0	41.1	36.8	33.1	30.3	27.9	25.8
Layers needed (200 MeV)	52.4	43.7	37.7	32.9	29.5	26.6	24.3	22.5	20.7

Pettersen, H.E.S. et al., 2019. Physica Medica 63, 87–97.

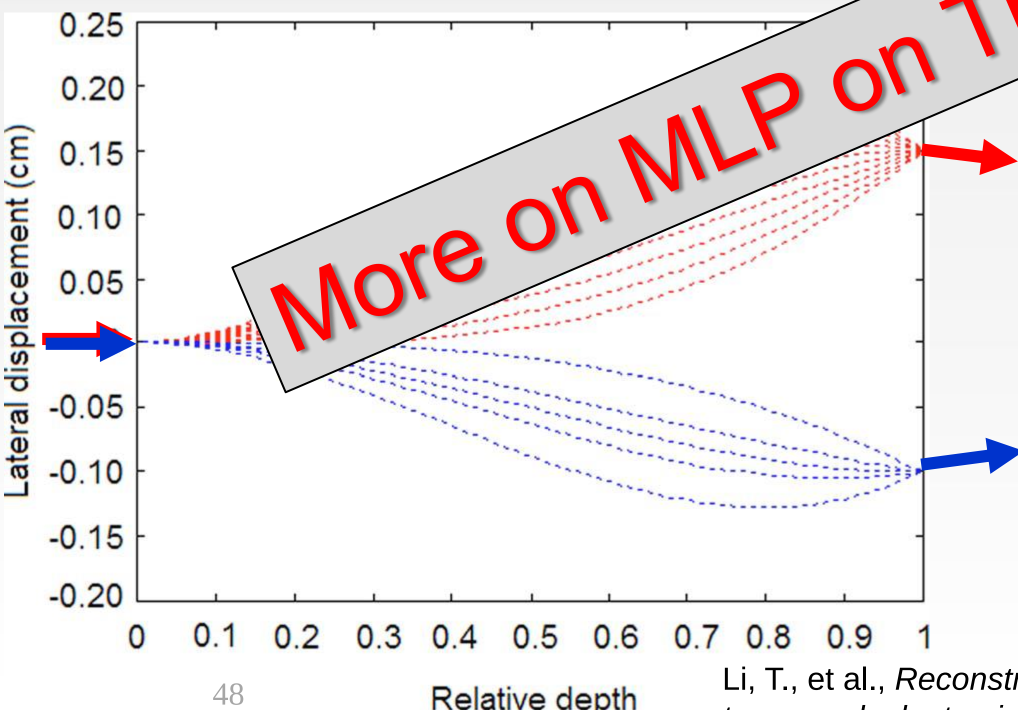
What about images?

The Most Likely Path scheme

The **Most Likely Path** (MLP) of the proton through the object

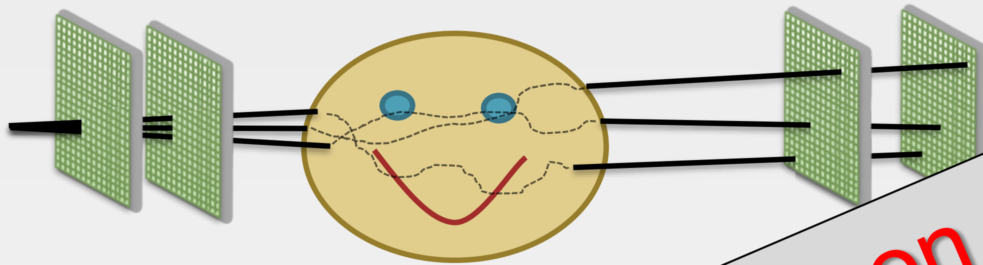
- A model fit to the entry and exit angle/position
- Use the curves for image reconstruction

More on MLP on Thursday!



Li, T., et al., *Reconstruction for proton computed tomography by tracing proton trajectories: a Monte Carlo study.* Med Phys, 2006. **33**(3): p. 699-706

How to find the entrance position?



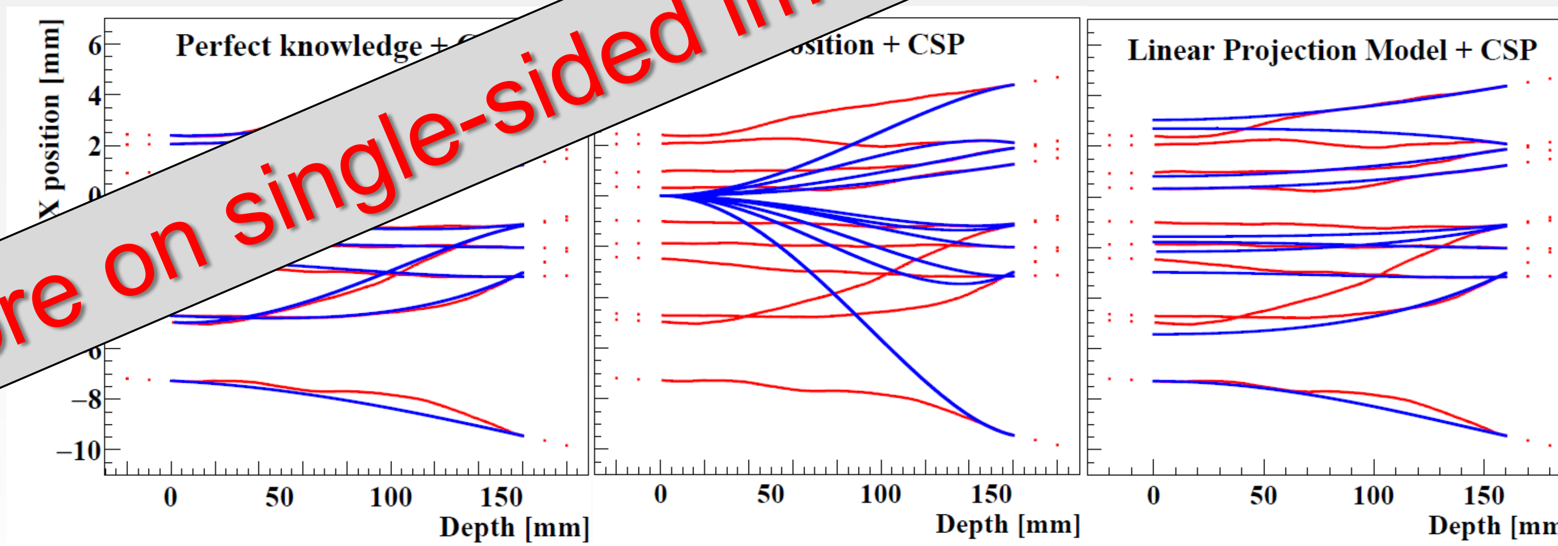
Measure before the patient…

Use m… …n

Estimate from front position (not too bad eh!)

MC tracks

Estimated tracks



More on single-sided imaging on Friday!

Krah N *et al.* (2018) PMB 63 (13)

Also Pettersen HES, Volz L *et al.* Rejected by *Phys Med Biol* ☹

References

- Garcia-Santos, A. (2019). **MSc: Optimization of the Track Reconstruction Algorithm in a Pixel Based Range Telescope for Proton Computed Tomography**. Utrecht University.
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- Pettersen, H.E.S. (2018**). PhD: A Digital Tracking Calorimeter for Proton Computed Tomography**. University of Bergen.
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- Pettersen, H.E.S., Alme, J., Barnaföldi, G.G., Barthel, R., van den Brink, A., Chaar, M., Eikeland, V., García-Santos, A., Genov, G., Grimstad, S., et al. (2019a). **Design optimization of a pixel-based range telescope for proton computed tomography.** Physica Medica *63*, 87–97.
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