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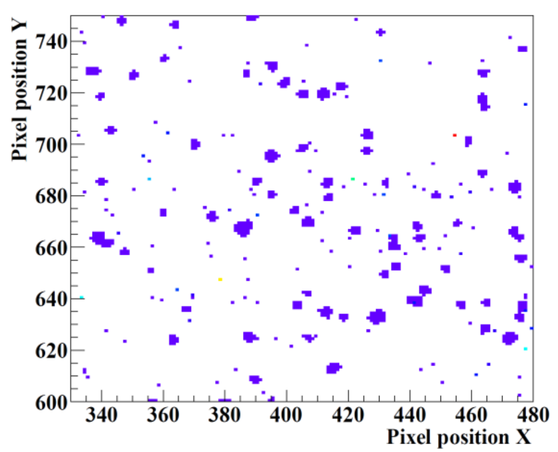
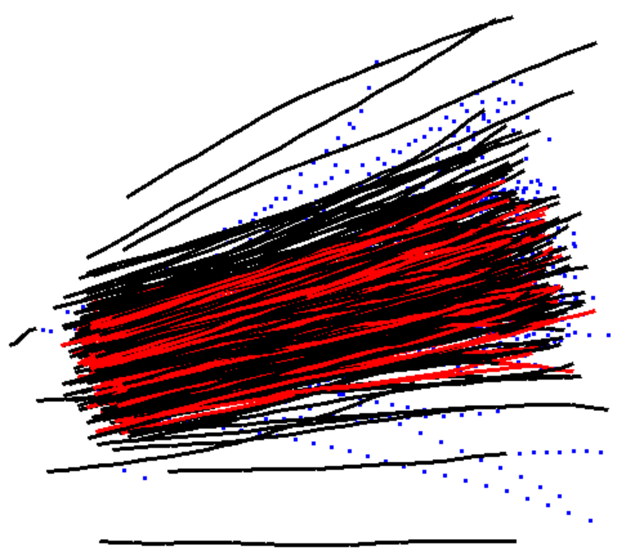
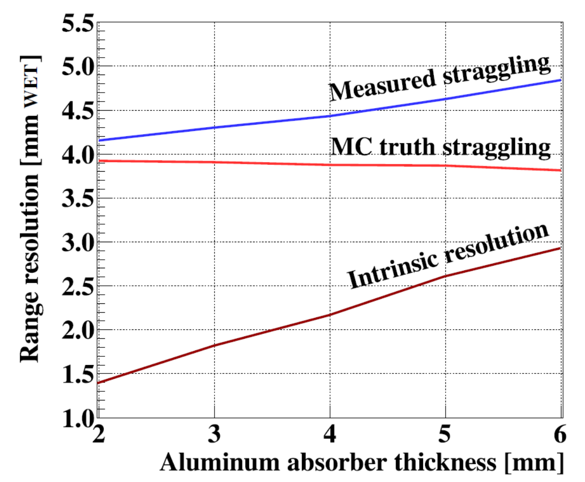
UNIVERSITY OF BERGEN

WP1 Detector Design Recommendations





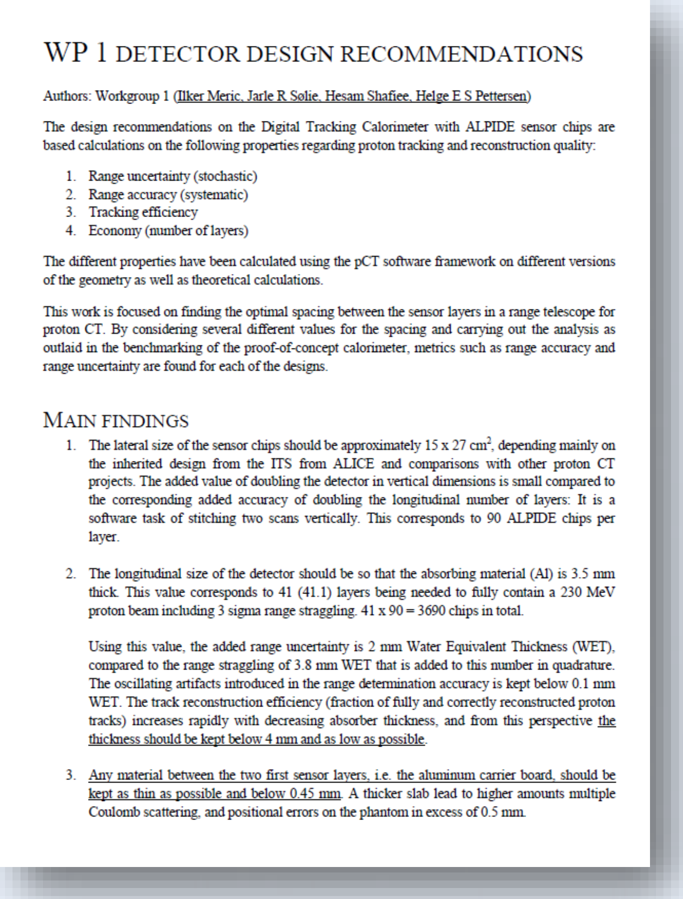


Helge Pettersen
pCT workshop, March 2018
UiB

In this presentation:

- Summary of MC simulations & very brief overview over analysis
- Analysis performed on different geometries
- In the end a design recommandation is made

More details in WP1 design report & (submitted) thesis



WP 1 DETECTOR DESIGN RECOMMENDATIONS

Authors: Workgroup 1 (Ilker Meric, Jarle R Sølie, Hesam Shafiee, Helge E S Pettersen)

The design recommendations on the Digital Tracking Calorimeter with ALPIDE sensor chips are based calculations on the following properties regarding proton tracking and reconstruction quality:

1. Range uncertainty (stochastic)
2. Range accuracy (systematic)
3. Tracking efficiency
4. Economy (number of layers)

The different properties have been calculated using the pCT software framework on different versions of the geometry as well as theoretical calculations.

This work is focused on finding the optimal spacing between the sensor layers in a range telescope for proton CT. By considering several different values for the spacing and carrying out the analysis as outlaid in the benchmarking of the proof-of-concept calorimeter, metrics such as range accuracy and range uncertainty are found for each of the designs.

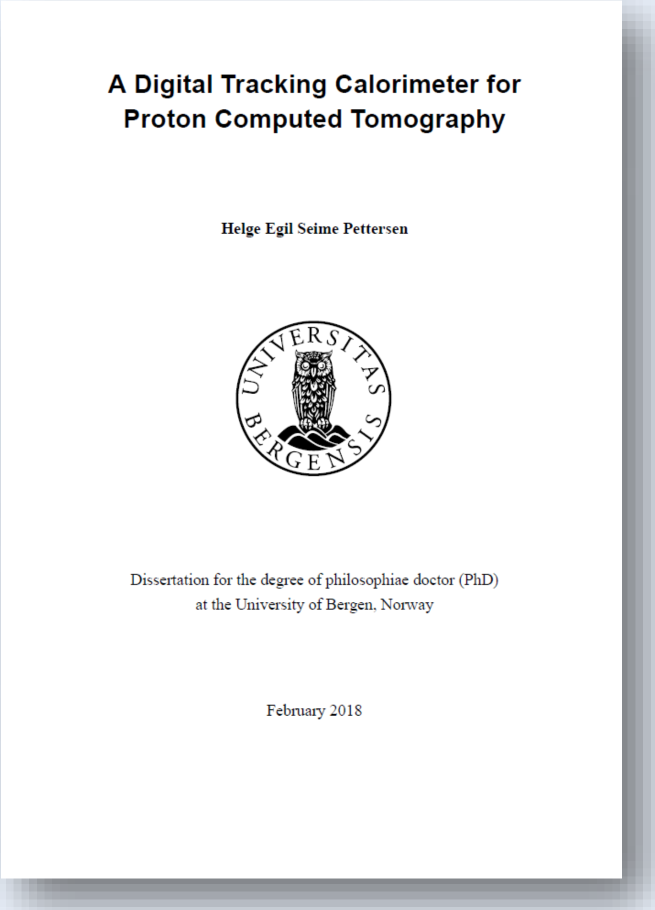
MAIN FINDINGS

1. The lateral size of the sensor chips should be approximately 15 x 27 cm^2, depending mainly on the inherited design from the ITS from ALICE and comparisons with other proton CT projects. The added value of doubling the detector in vertical dimensions is small compared to the corresponding added accuracy of doubling the longitudinal number of layers: It is a software task of stitching two scans vertically. This corresponds to 90 ALPIDE chips per layer.

2. The longitudinal size of the detector should be so that the absorbing material (Al) is 3.5 mm thick. This value corresponds to 41 (41.1) layers being needed to fully contain a 230 MeV proton beam including 3 sigma range straggling. 41 x 90 = 3690 chips in total.

   Using this value, the added range uncertainty is 2 mm Water Equivalent Thickness (WET), compared to the range straggling of 3.8 mm WET that is added to this number in quadrature. The oscillating artifacts introduced in the range determination accuracy is kept below 0.1 mm WET. The track reconstruction efficiency (fraction of fully and correctly reconstructed proton tracks) increases rapidly with decreasing absorber thickness, and from this perspective the thickness should be kept below 4 mm and as low as possible.

3. Any material between the two first sensor layers, i.e. the aluminum carrier board, should be kept as thin as possible and below 0.45 mm. A thicker slab lead to higher amounts multiple Coulomb scattering, and positional errors on the phantom in excess of 0.5 mm.

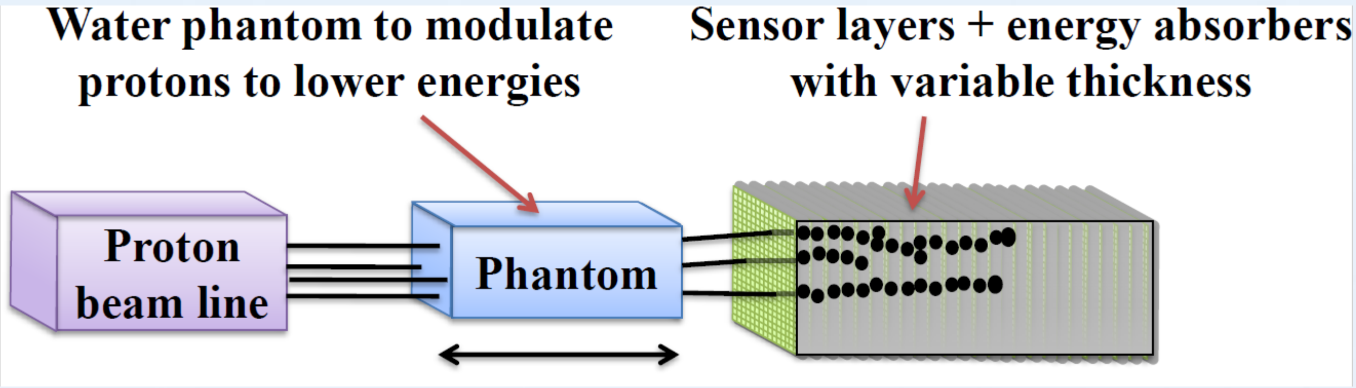


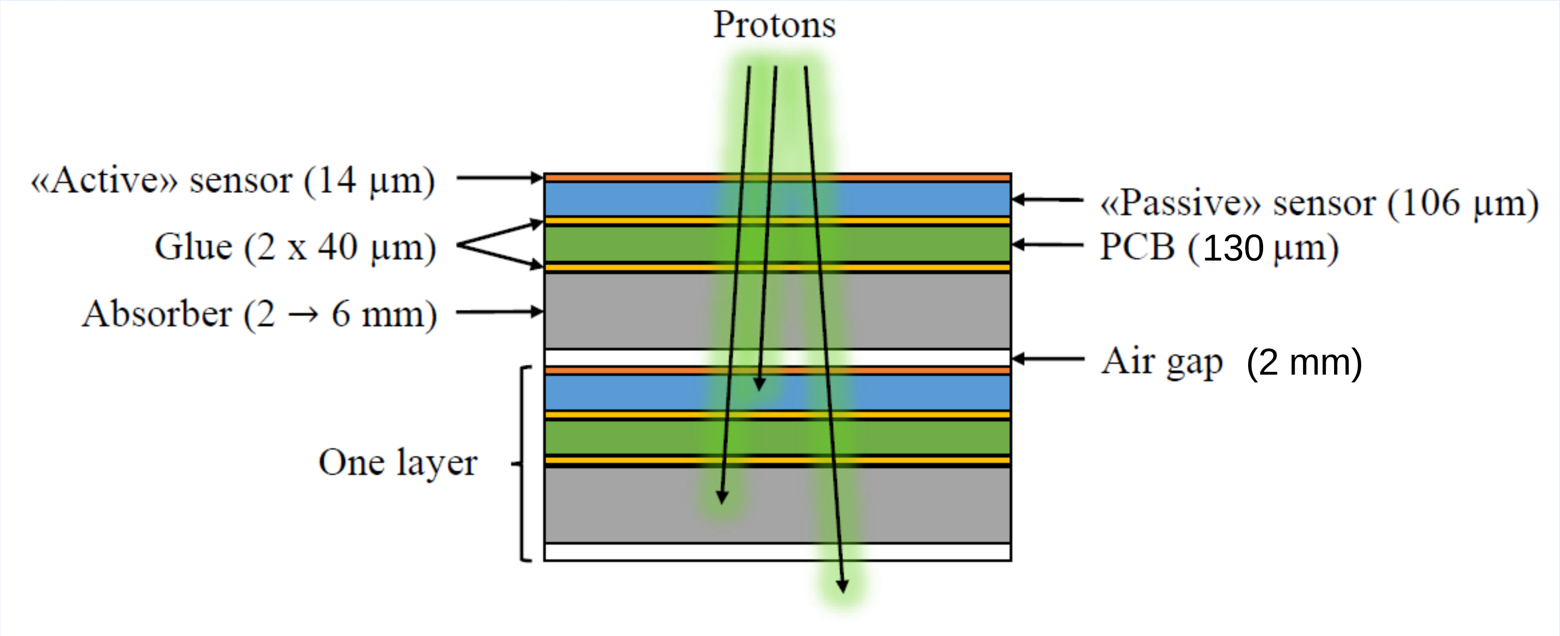
A Digital Tracking Calorimeter for Proton Computed Tomography

Helge Egil Seime Pettersen

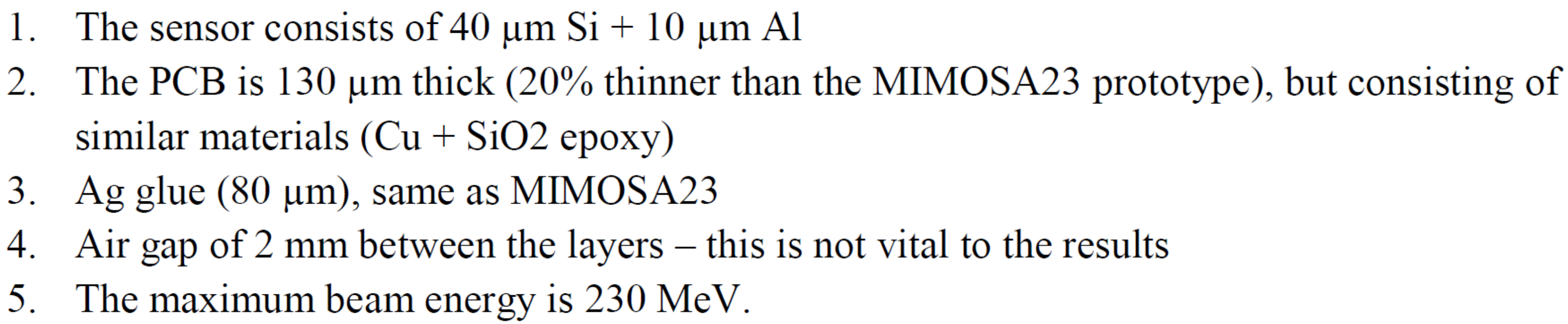
Dissertation for the degree of philosophiae doctor (PhD)
at the University of Bergen, Norway

February 2018


Water phantom to modulate protons to lower energies
Sensor layers + energy absorbers with variable thickness
Proton beam line
Phantom


Protons
«Active» sensor (14 μm)
Glue (2 x 40 μm)
Absorber (2 → 6 mm)
One layer
«Passive» sensor (106 μm)
PCB (130 μm)
Air gap (2 mm)

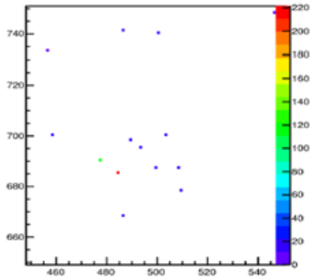
Some assumptions



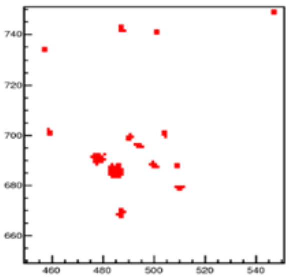
1. The sensor consists of 40 µm Si + 10 µm Al
2. The PCB is 130 µm thick (20% thinner than the MIMOSA23 prototype), but consisting of similar materials (Cu + SiO2 epoxy)
3. Ag glue (80 µm), same as MIMOSA23
4. Air gap of 2 mm between the layers – this is not vital to the results
5. The maximum beam energy is 230 MeV.

Analysis workflow

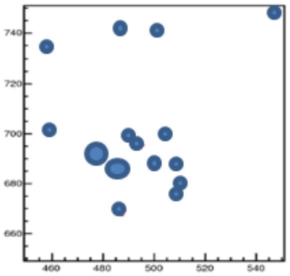
Data readout
MC, MC + truth, exp.



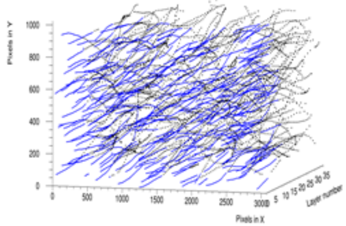
Pixel diffusion modelling (MC only)



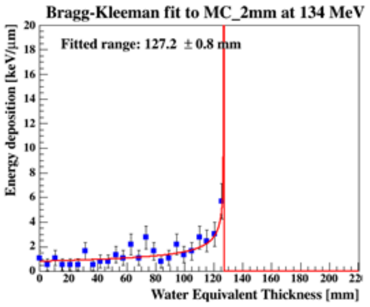
Cluster identification



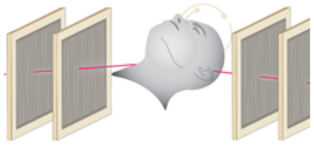
Proton track reconstruction



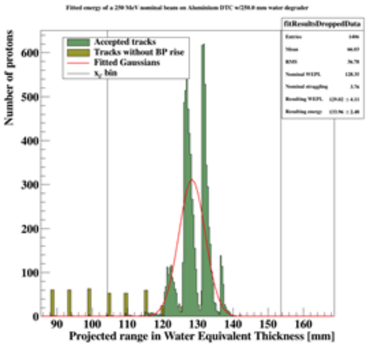
Individual track – energy loss fitting

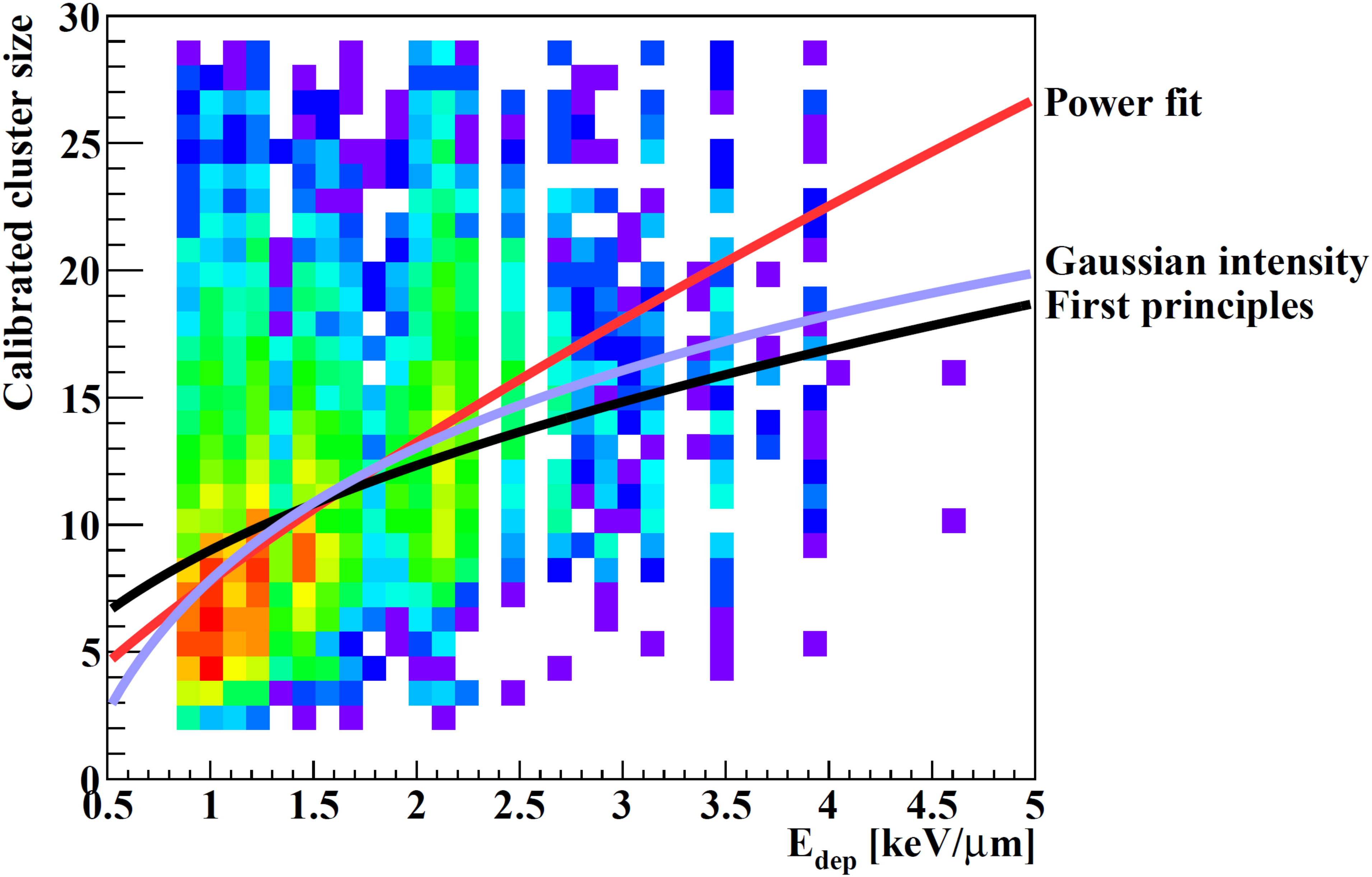


If 3D reconstruction: MLP estimation



Residual range calculation




Calibrated cluster size
0
5
10
15
20
25
30
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_{dep} [keV/µm]
Power fit
Gaussian intensity
First principles

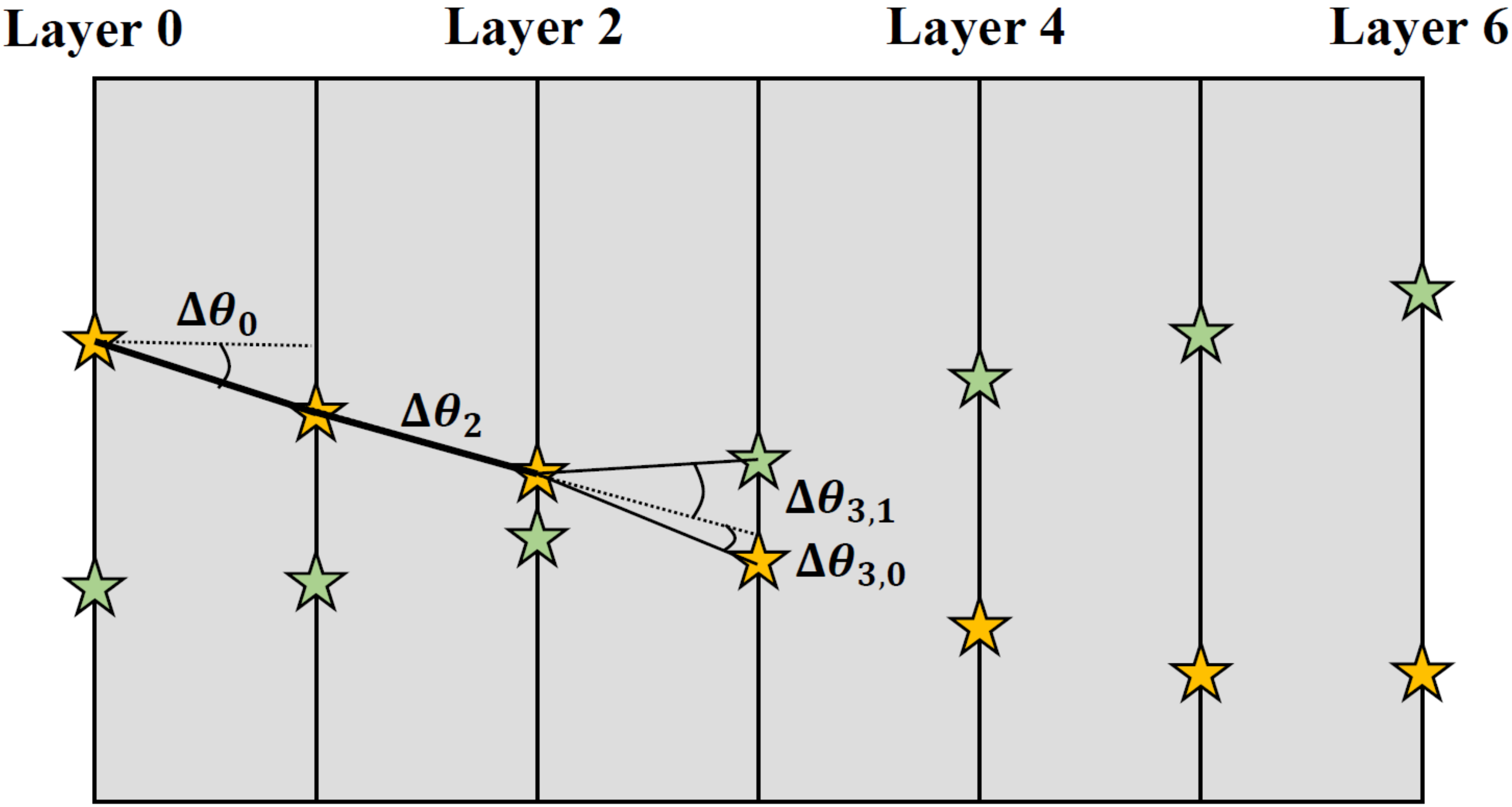
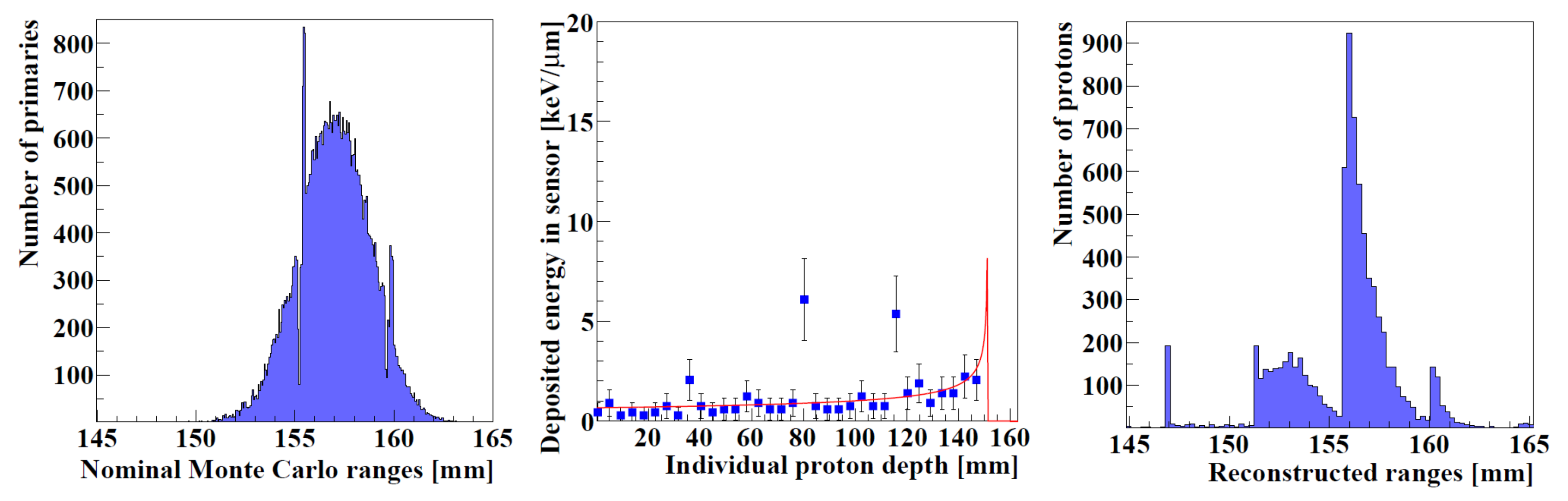


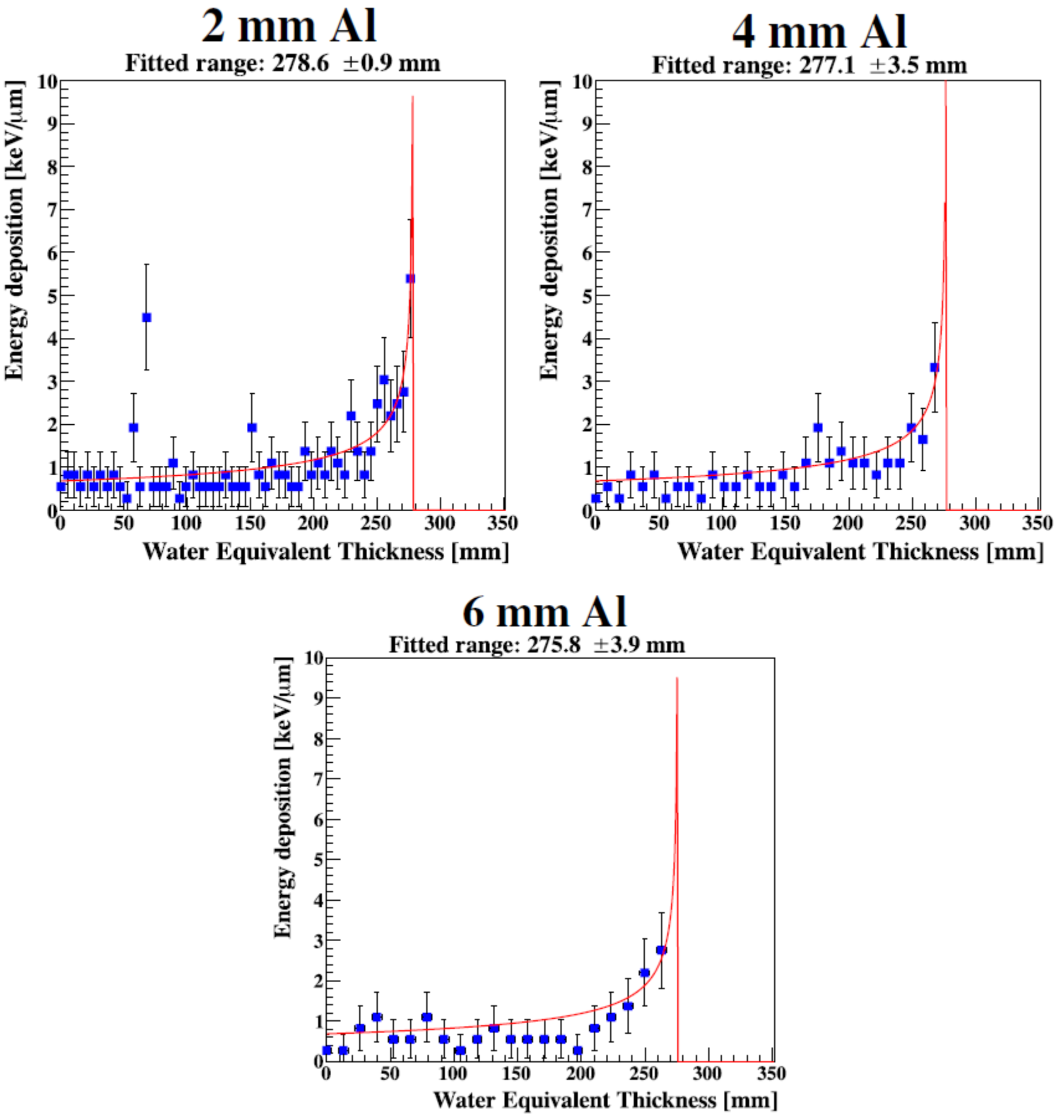
Figure 2: Track Reconstruction Example: Here $\Delta\theta_{3,0} \ll \Delta\theta_{3,1}$ and the former is chosen at the single next track segment.

Range resolution



- Range <u>accuracy</u> (bias, systematic errors)
- Range <u>uncertainty</u> (in addition to range straggling)

Range resolution from individual tracks



2 mm Al

Fitted range: 278.6 ±0.9 mm

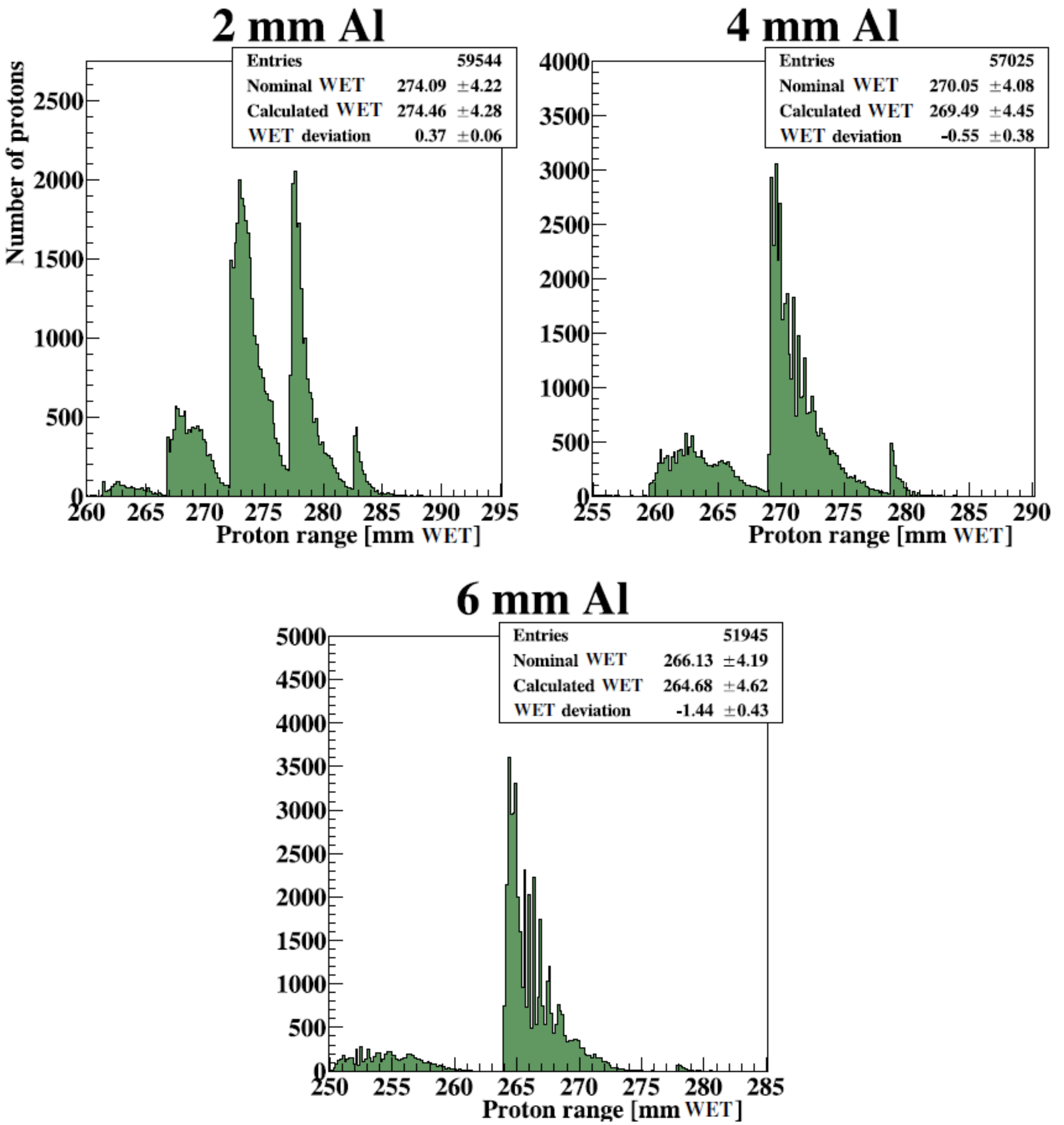
4 mm Al

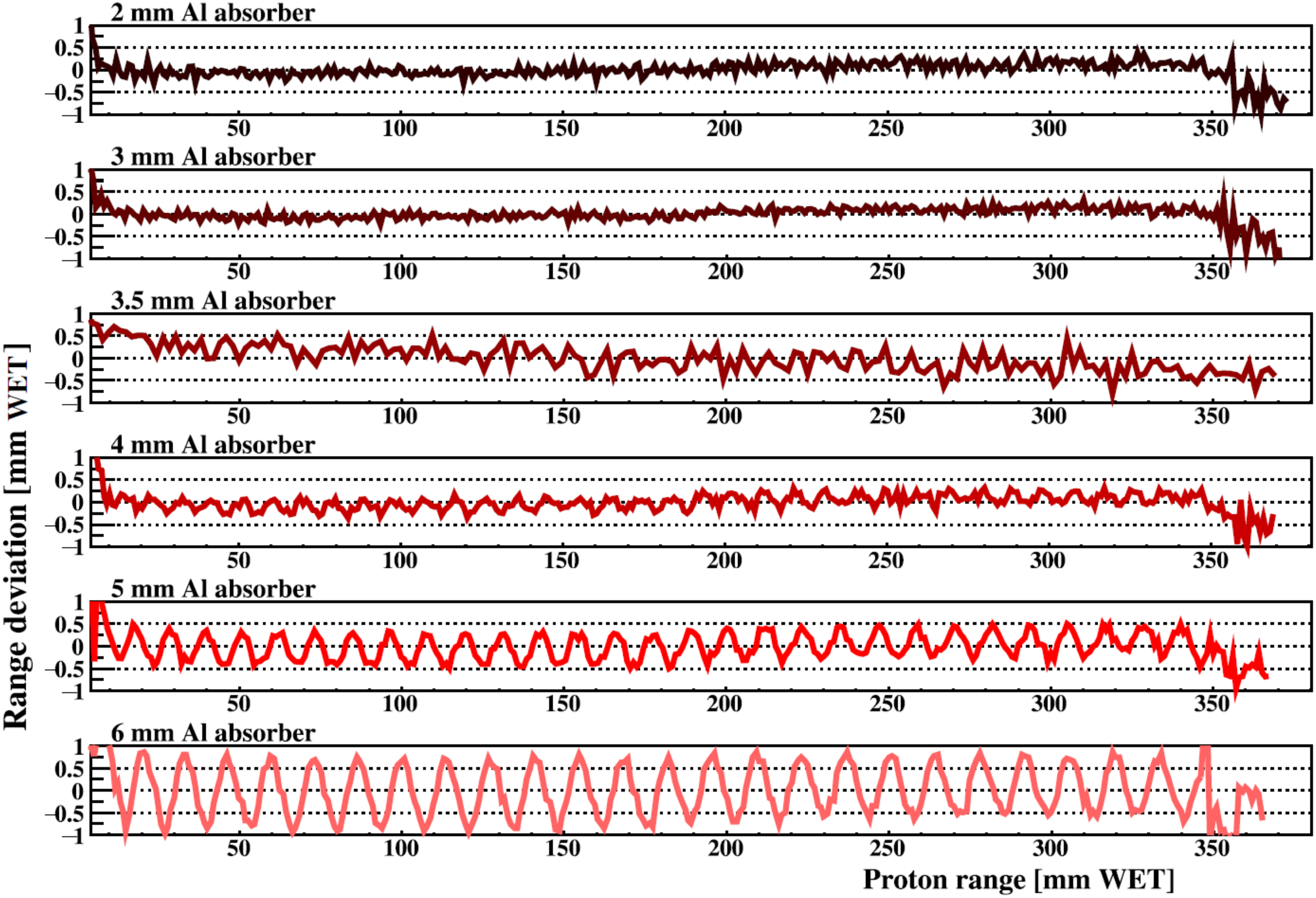
Fitted range: 277.1 ±3.5 mm

6 mm Al

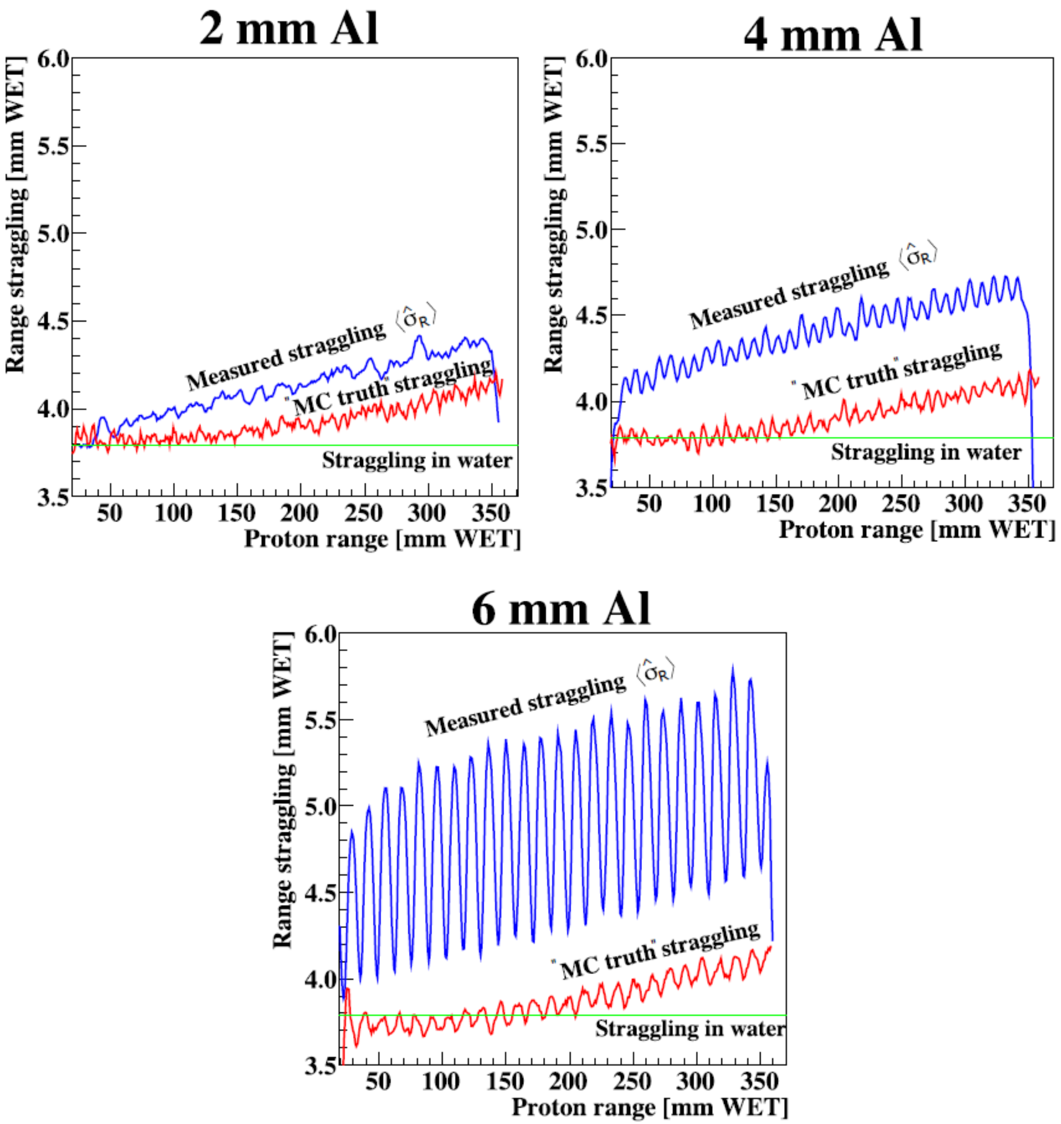
Fitted range: 275.8 ±3.9 mm

Range distribution per beam energy (/voxel)

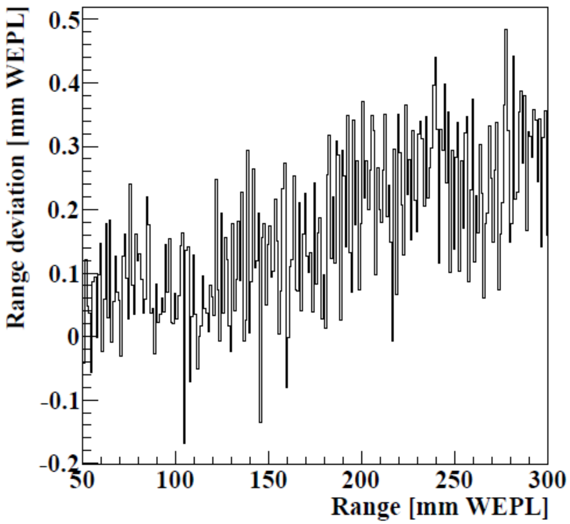


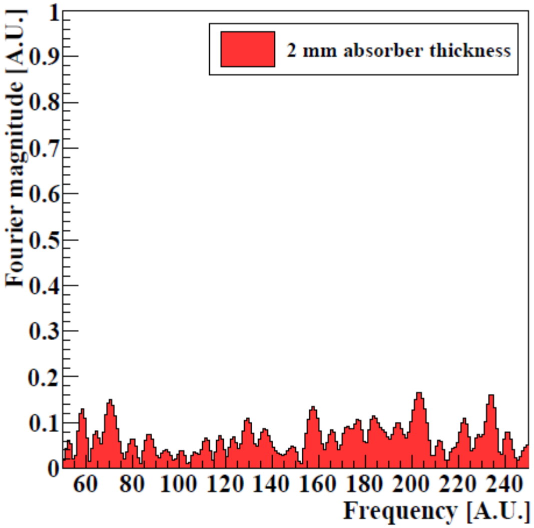

2 mm Al absorber
3 mm Al absorber
3.5 mm Al absorber
4 mm Al absorber
5 mm Al absorber
6 mm Al absorber
1
0.5
0
−0.5
−1
50
100
150
200
250
300
350
Range deviation [mm WET]
Proton range [mm WET]

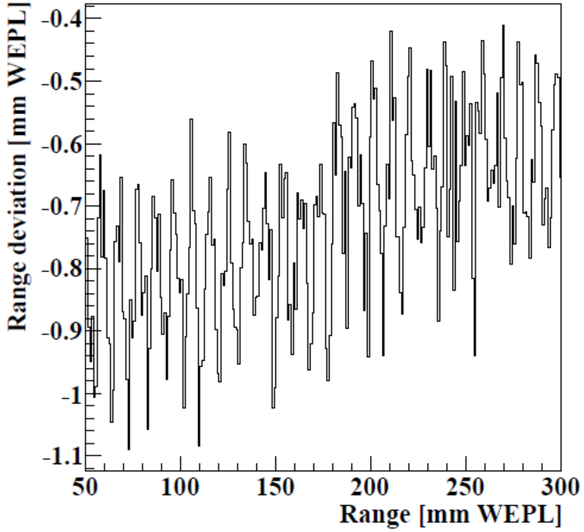
Range uncertainty

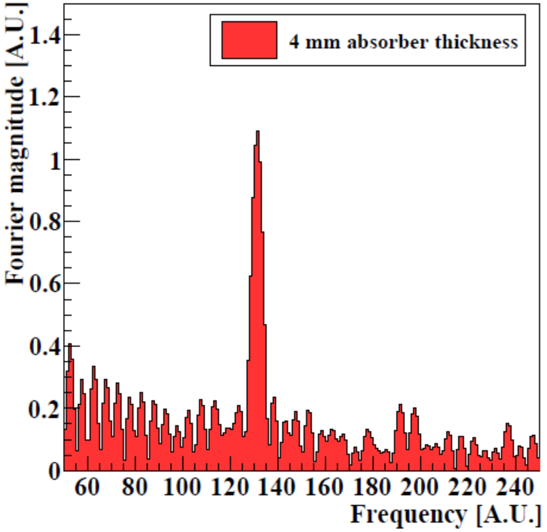


Oscillatory range error – Systematic uncertainty

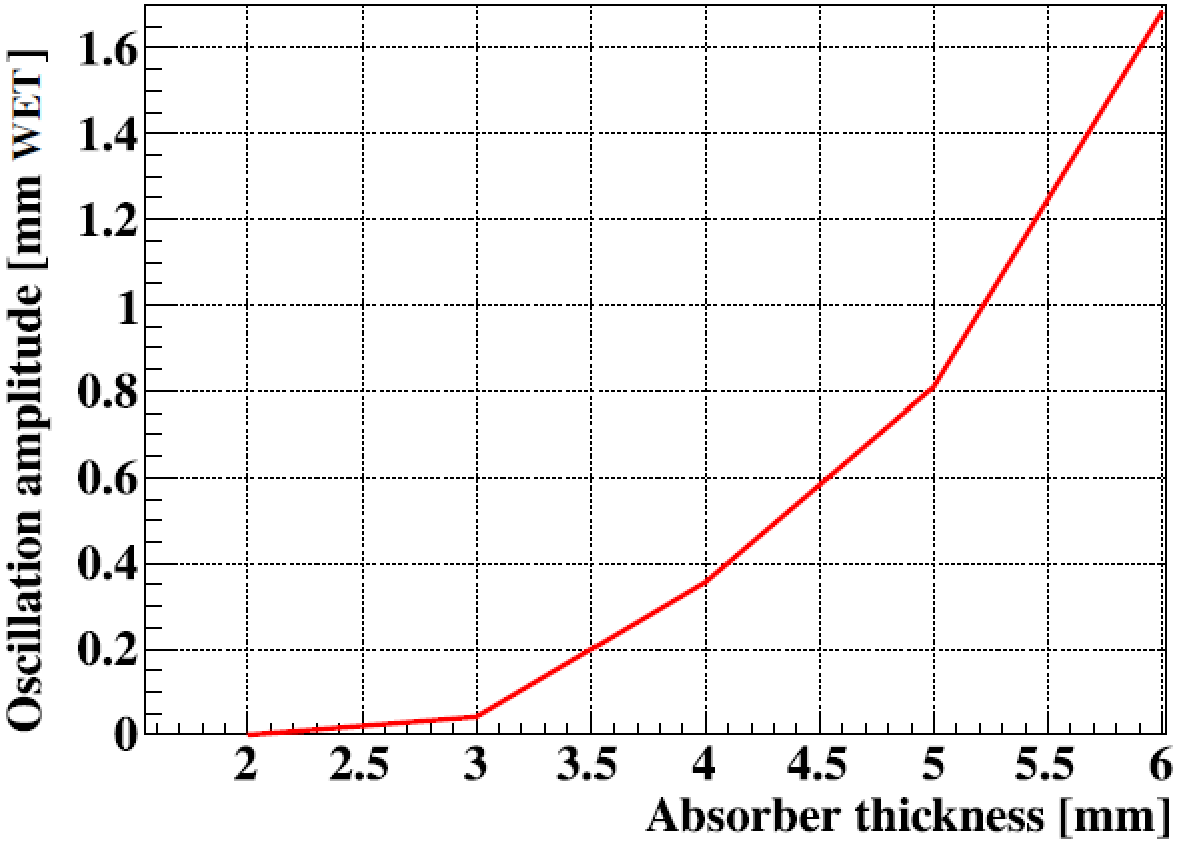








Oscillatory range error – Systematic uncertainty



Compare this to the FoCal prototype…

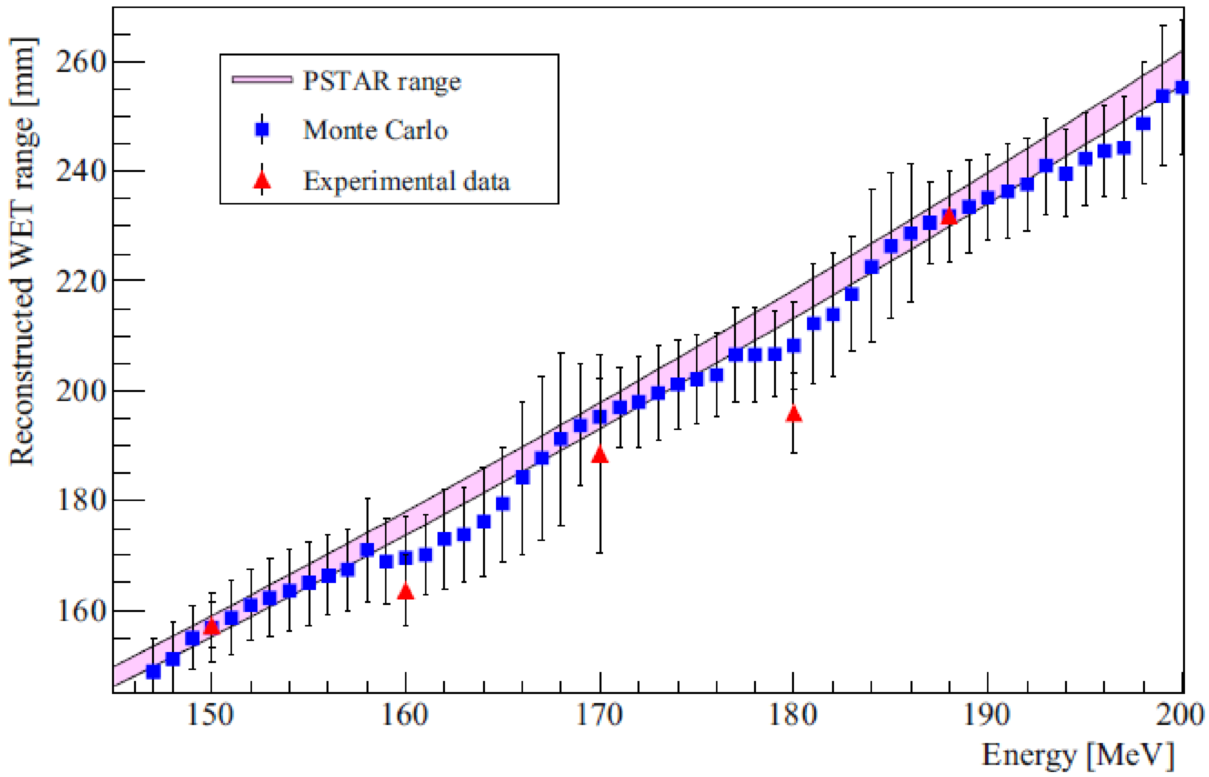
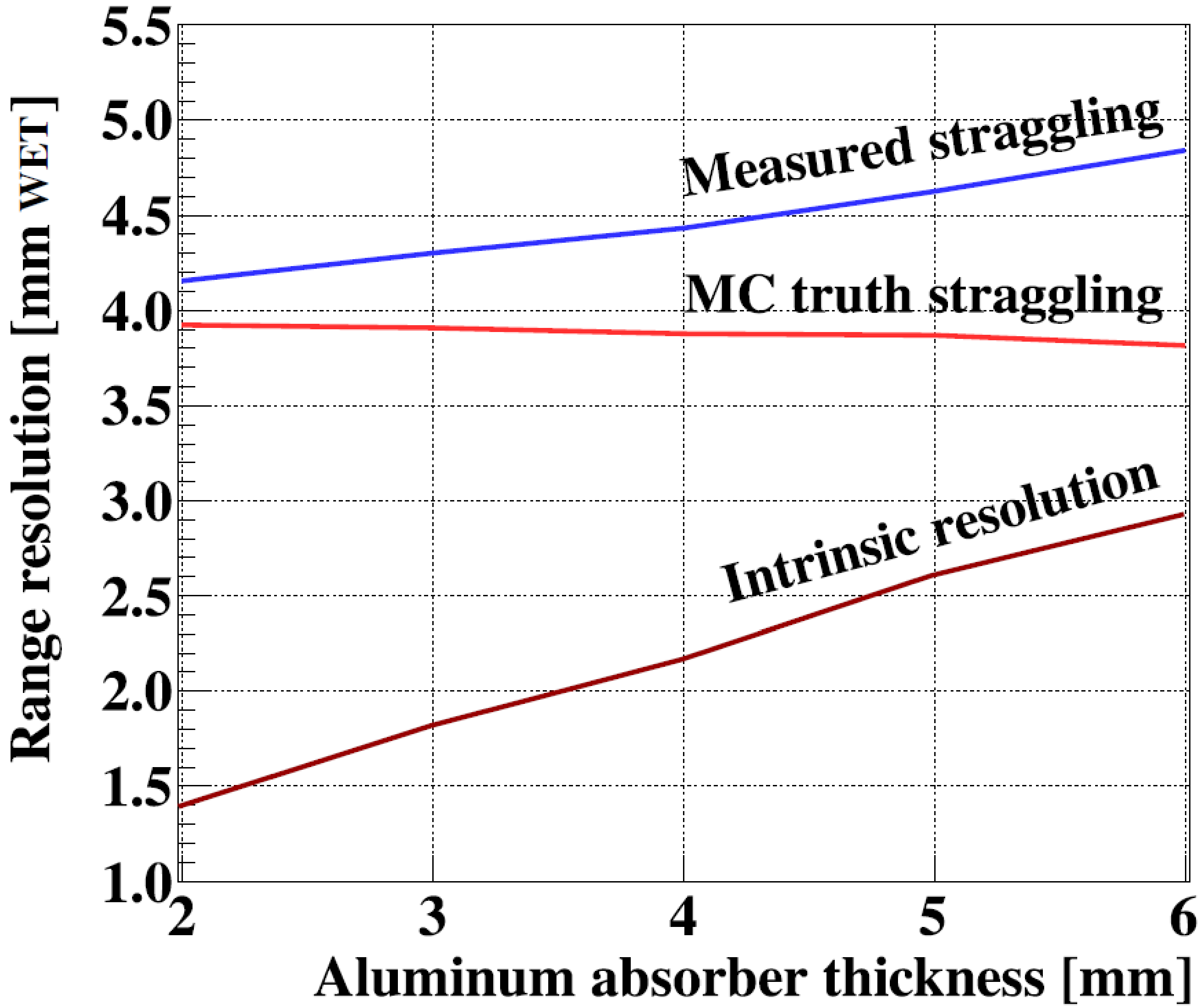
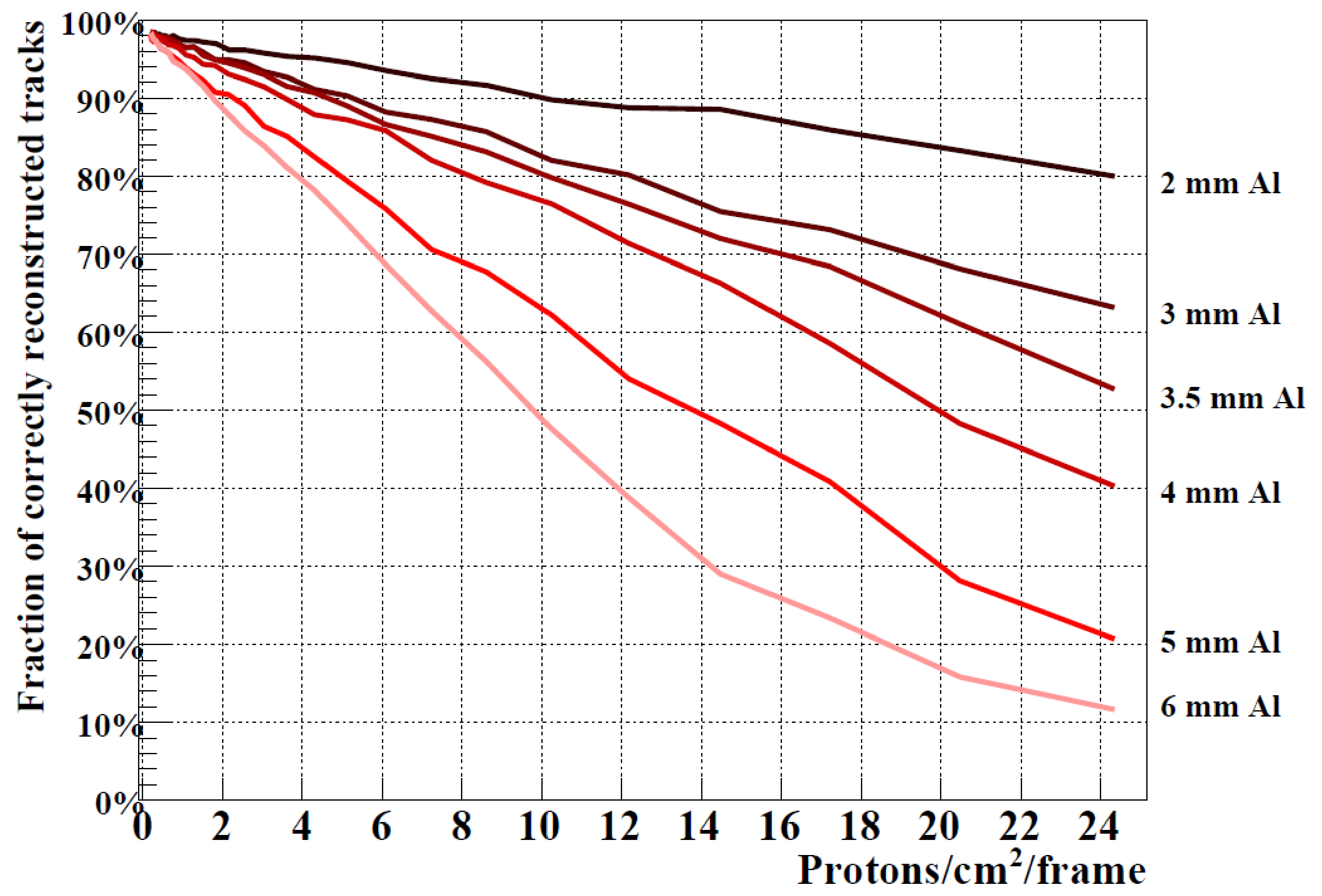


Fig. 7. Reconstructed ranges $\langle \hat{R_0} \rangle$ of proton beams with different energies. Results from both the MC simulations and from the experimental measurements are displayed on the plot. The PSTAR range is displayed using a band representing the expected range straggling. Average numbers for the deviations between R_0 and $\langle \hat{R_0} \rangle$ as well as the corresponding resolution $\langle \hat{\sigma} \rangle$ are presented in Section 6.3.

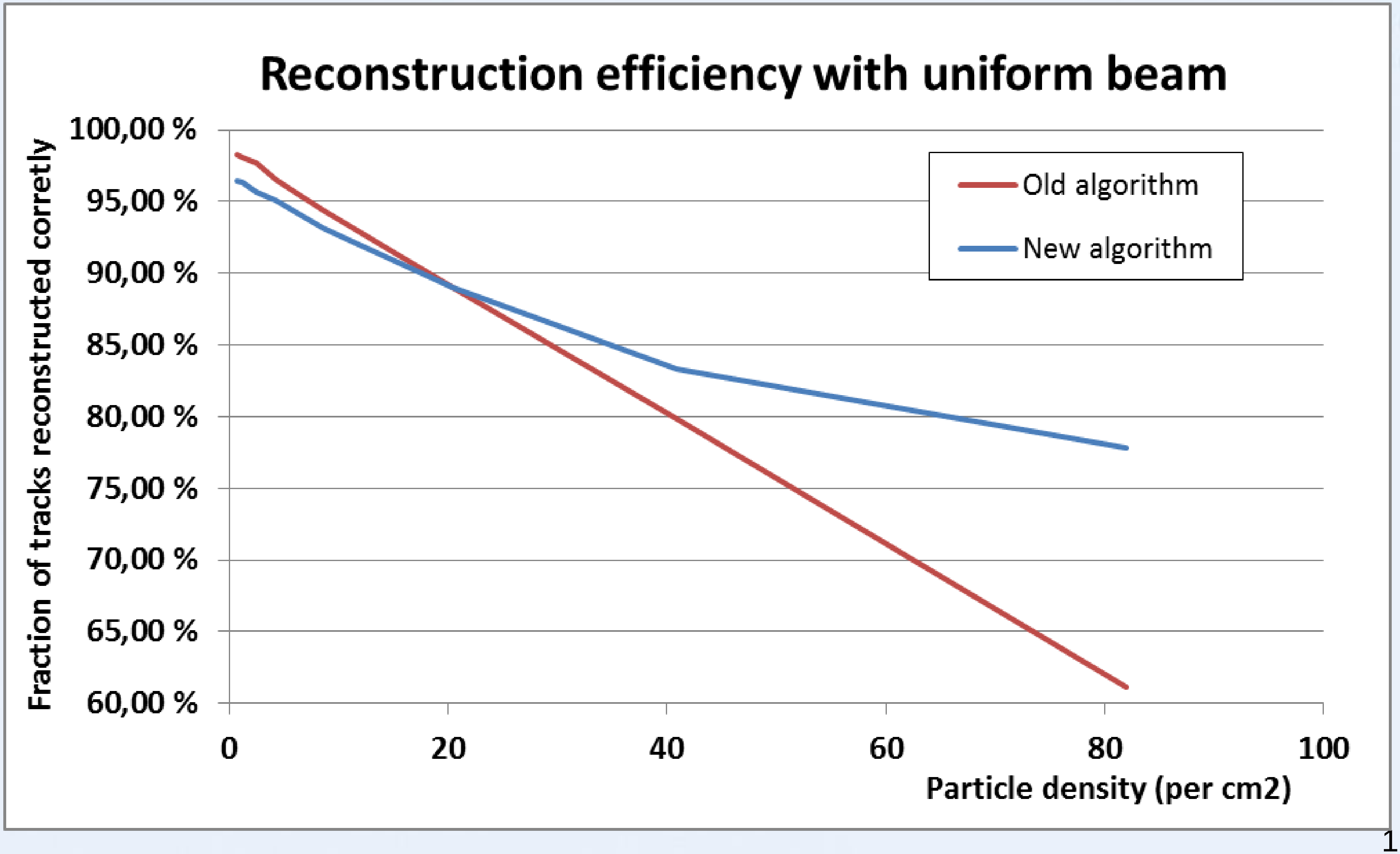
Width of range distribution – stochastic uncertainty



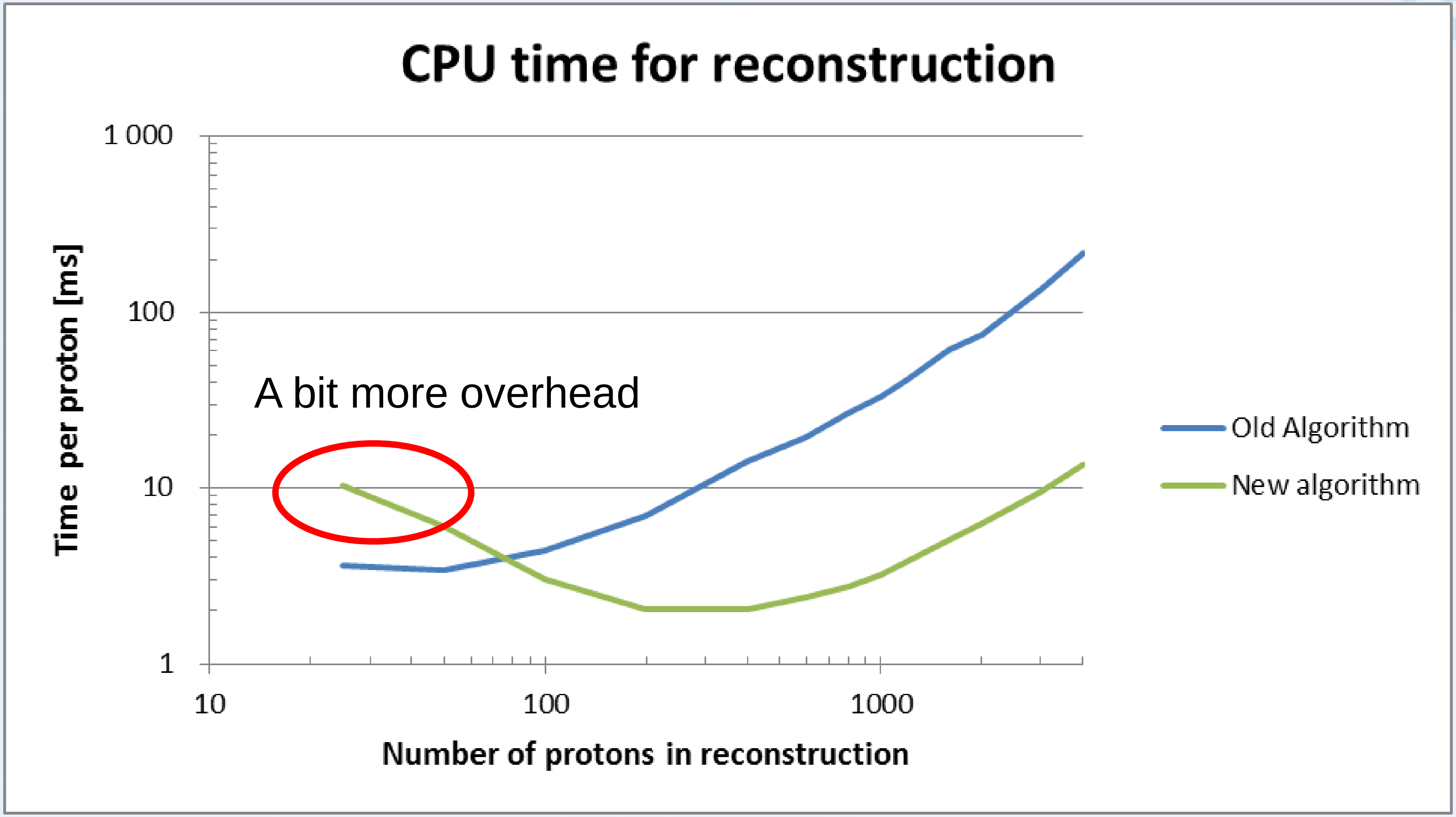
Track reconstruction efficiency (old algorithm)



New track reconstruction algorithm …



New track reconstruction algorithm …



A bit more overhead

Some Pencil Beam considerations

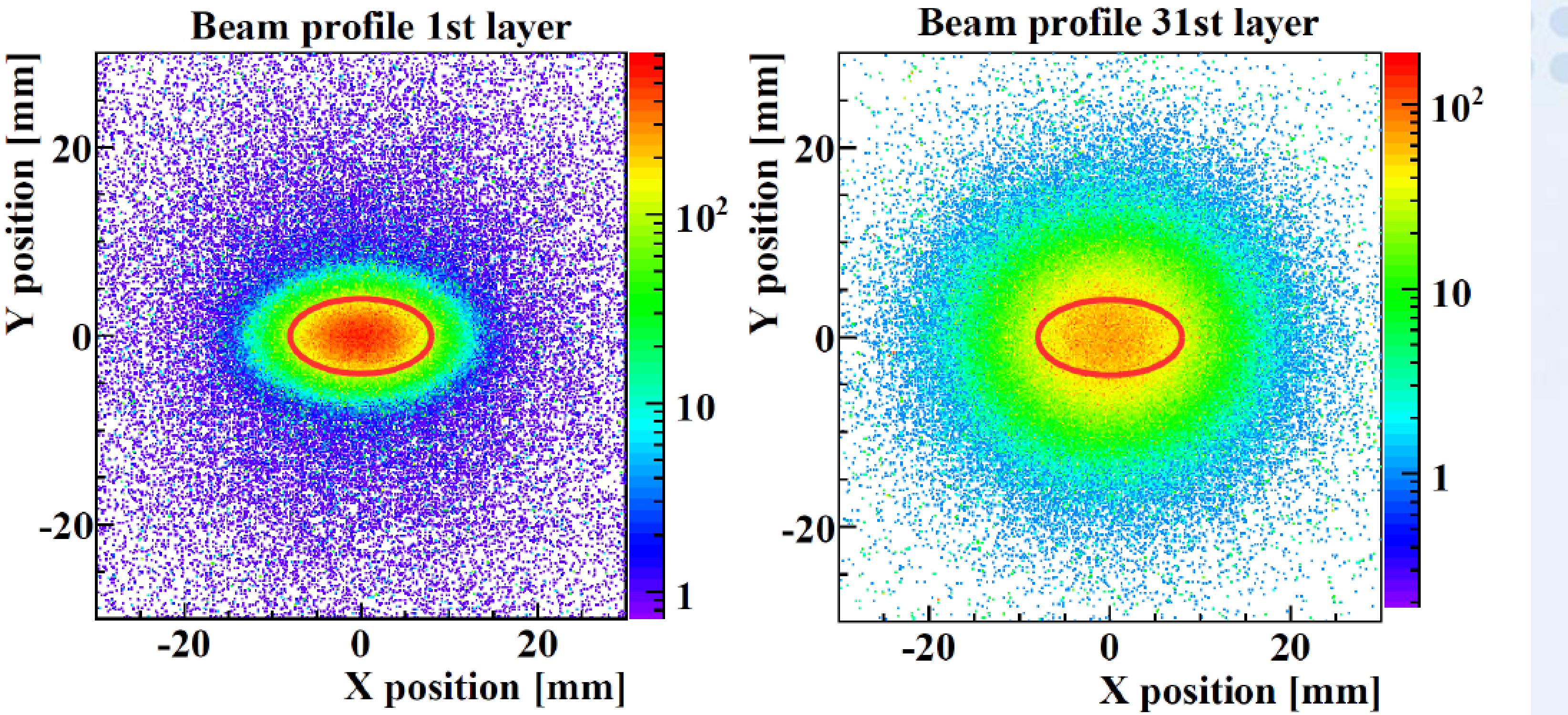
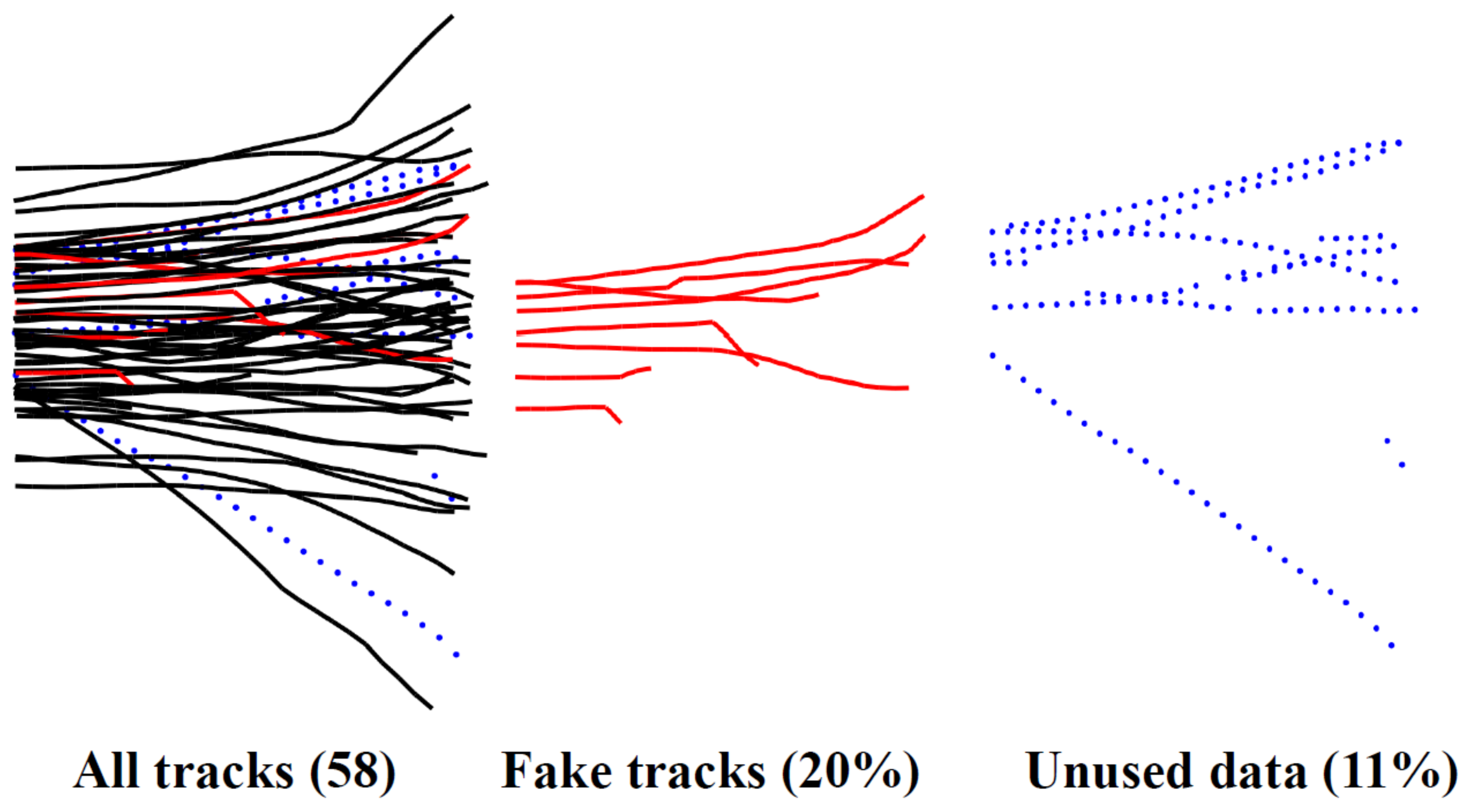


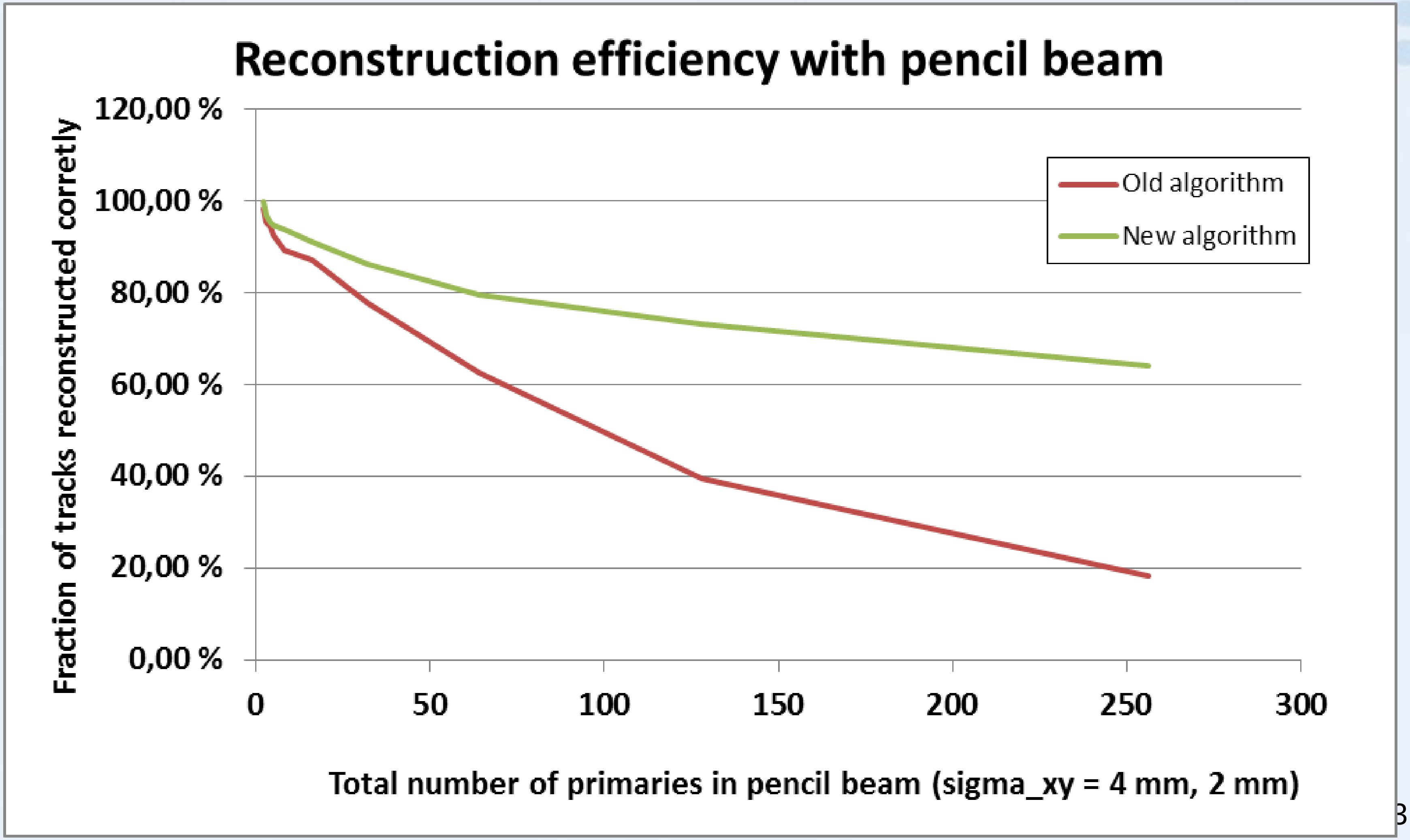
Figure 5.8: *Beam profile in the DTC at two different positions. A 250 MeV pencil beam is shown first after traversing 10 cm water, then after traversing 30 layers of the DTC. The pencil beam is defined by the parameters* $\sigma_x = 4\,mm$, $\sigma_y = 2\,mm$ *and an angular spread of* $\sim$*4 mrad. The red ellipse is the* 2σ *value of the original pencil beam profile.*

Some Pencil Beam considerations

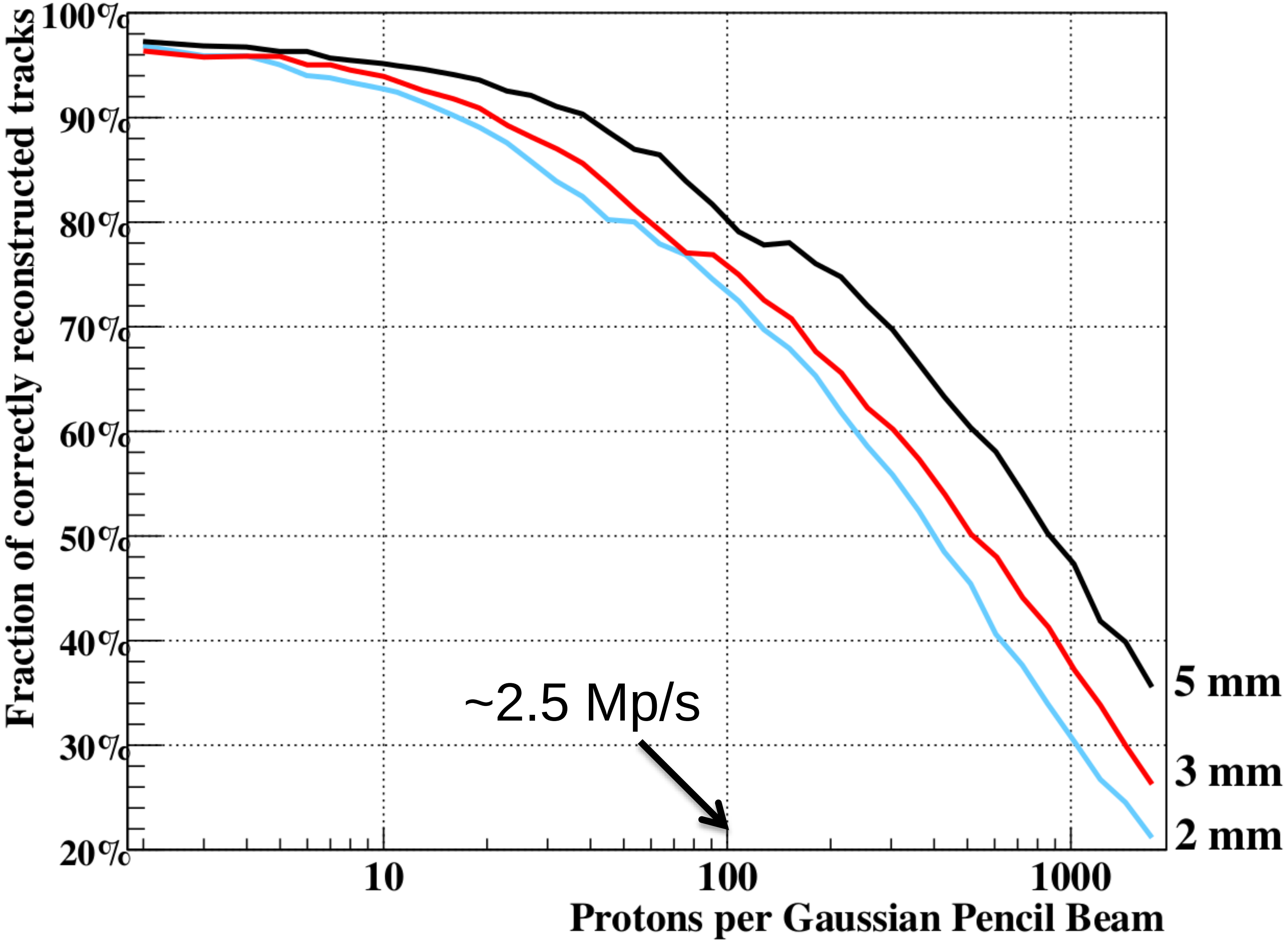


$\sigma_x = \sigma_y = 3\ \mathrm{mm}$; 250 MeV beam degraded by 16 cm water

New track reconstruction algorithm …

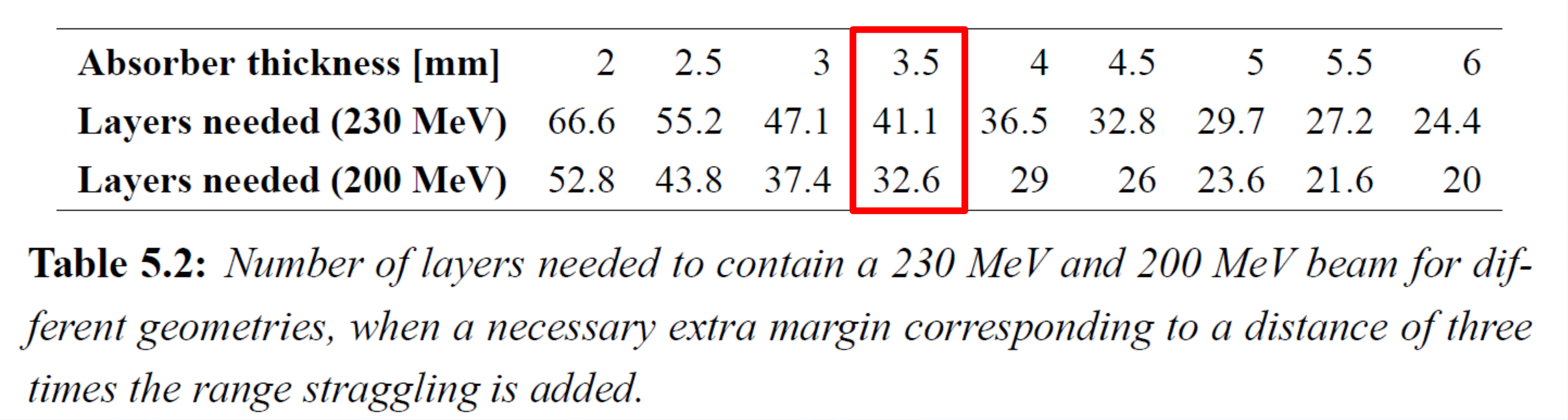


Reconstruction efficiency with different spot sizes ($\sigma_{x,y}$)



~2.5 Mp/s

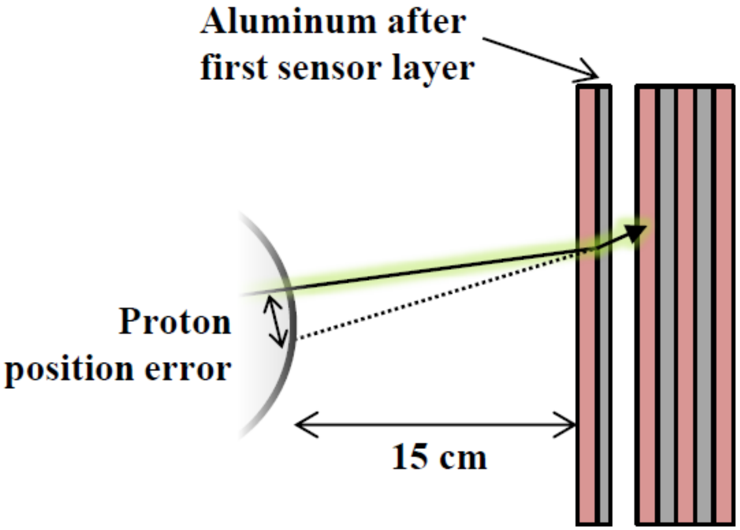
How many layers are needed for the different configurations?

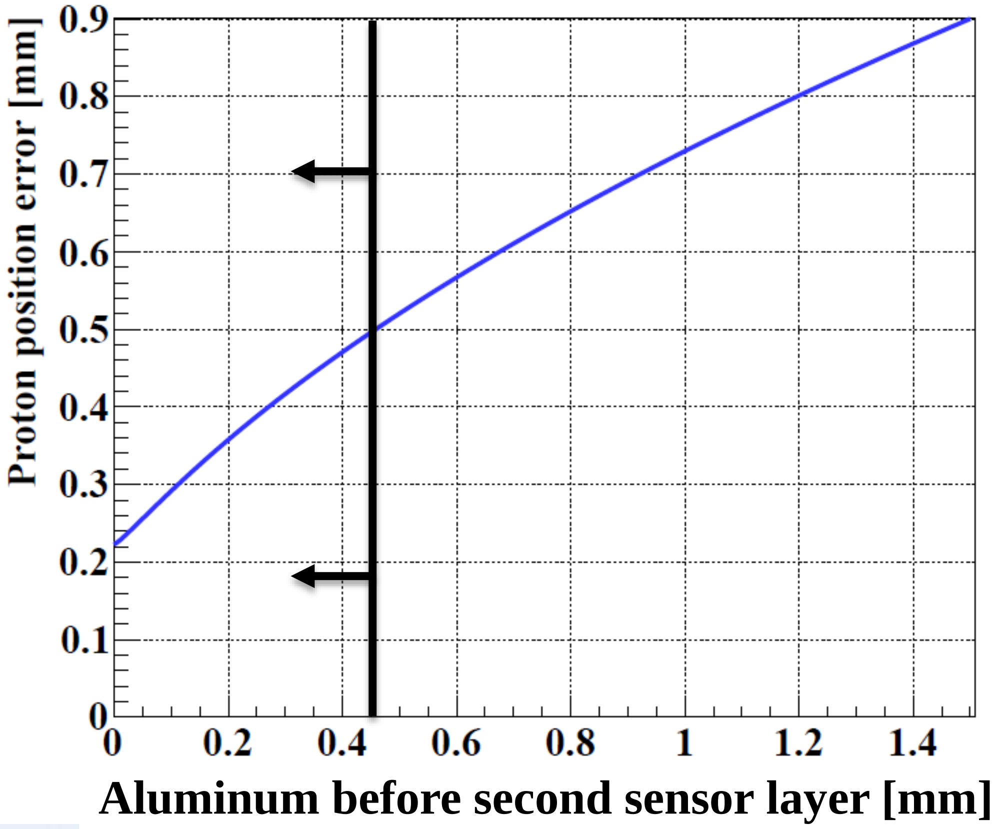


Absorber thickness [mm]	2	2.5	3	3.5	4	4.5	5	5.5	6
Layers needed (230 MeV)	66.6	55.2	47.1	41.1	36.5	32.8	29.7	27.2	24.4
Layers needed (200 MeV)	52.8	43.8	37.4	32.6	29	26	23.6	21.6	20

Table 5.2: *Number of layers needed to contain a 230 MeV and 200 MeV beam for different geometries, when a necessary extra margin corresponding to a distance of three times the range straggling is added.*

Scattering in first layers

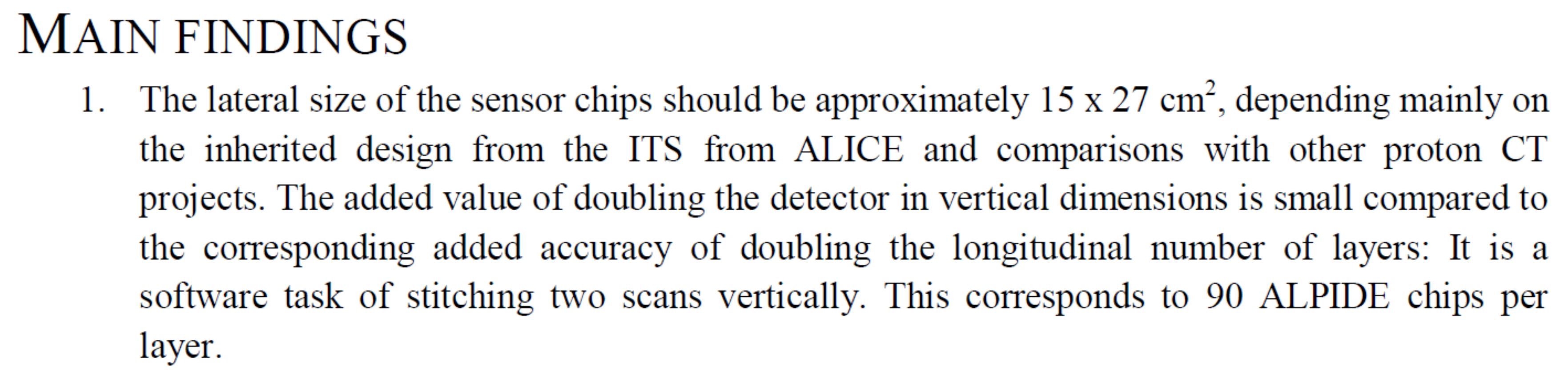




$$\theta_0 \simeq \frac{14.1\ \mathrm{MeV}}{p_1 v_1} \sqrt{\frac{x}{X_0}} \left(1 + \frac{1}{9} \log_{10} \frac{x}{X_0}\right)$$

Detector size recommendations

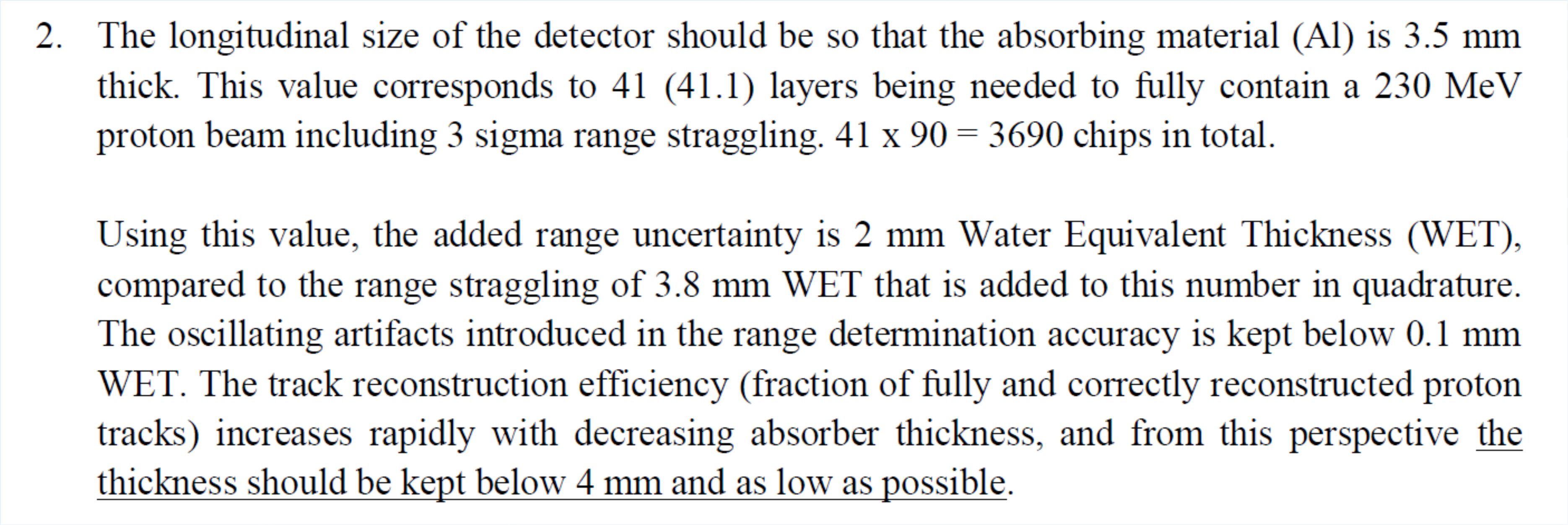
(from pCT-WP1-Report1)



MAIN FINDINGS

1. The lateral size of the sensor chips should be approximately 15 x 27 cm^2, depending mainly on the inherited design from the ITS from ALICE and comparisons with other proton CT projects. The added value of doubling the detector in vertical dimensions is small compared to the corresponding added accuracy of doubling the longitudinal number of layers: It is a software task of stitching two scans vertically. This corresponds to 90 ALPIDE chips per layer.

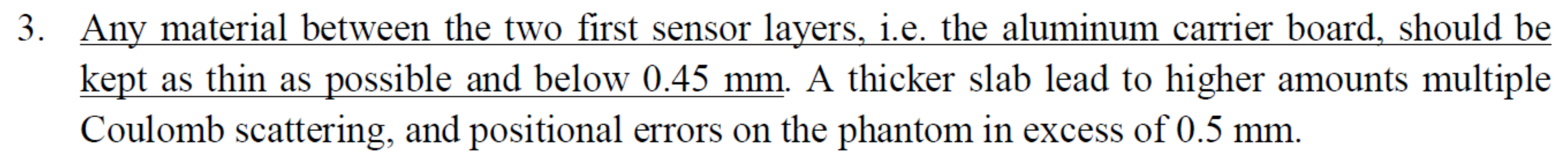
Detector size recommendations



2. The longitudinal size of the detector should be so that the absorbing material (Al) is 3.5 mm thick. This value corresponds to 41 (41.1) layers being needed to fully contain a 230 MeV proton beam including 3 sigma range straggling. 41 x 90 = 3690 chips in total.

   Using this value, the added range uncertainty is 2 mm Water Equivalent Thickness (WET), compared to the range straggling of 3.8 mm WET that is added to this number in quadrature. The oscillating artifacts introduced in the range determination accuracy is kept below 0.1 mm WET. The track reconstruction efficiency (fraction of fully and correctly reconstructed proton tracks) increases rapidly with decreasing absorber thickness, and from this perspective the thickness should be kept below 4 mm and as low as possible.

Detector size recommendations



3. Any material between the two first sensor layers, i.e. the aluminum carrier board, should be kept as thin as possible and below 0.45 mm. A thicker slab lead to higher amounts multiple Coulomb scattering, and positional errors on the phantom in excess of 0.5 mm.

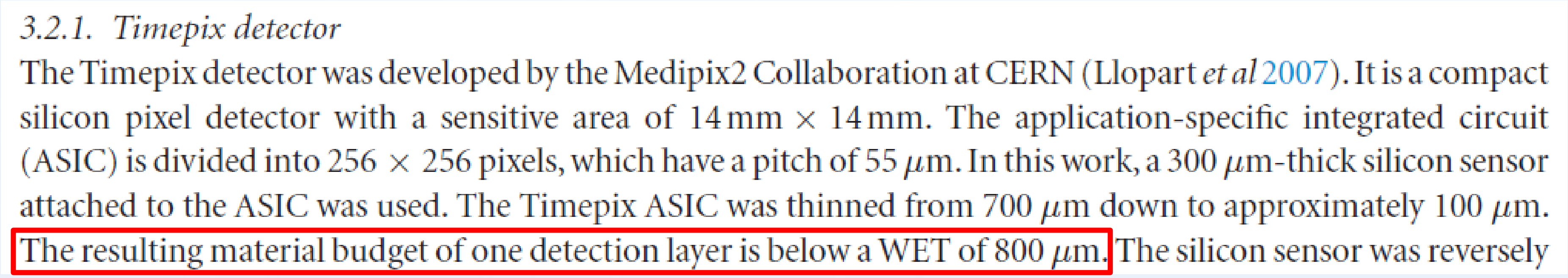
Tracking layers – comparison with other projects

Scattering in first layers – HIT pRG

Theoretical and experimental comparison of proton and helium-beam radiography using silicon pixel detectors

T Gehrke[1,2,3,4], C Amato[2,3,5], S Berke[2,3] and M Martišíková[2,3]

Phys. Med. Biol. 63 (2018) 035037 (18pp)

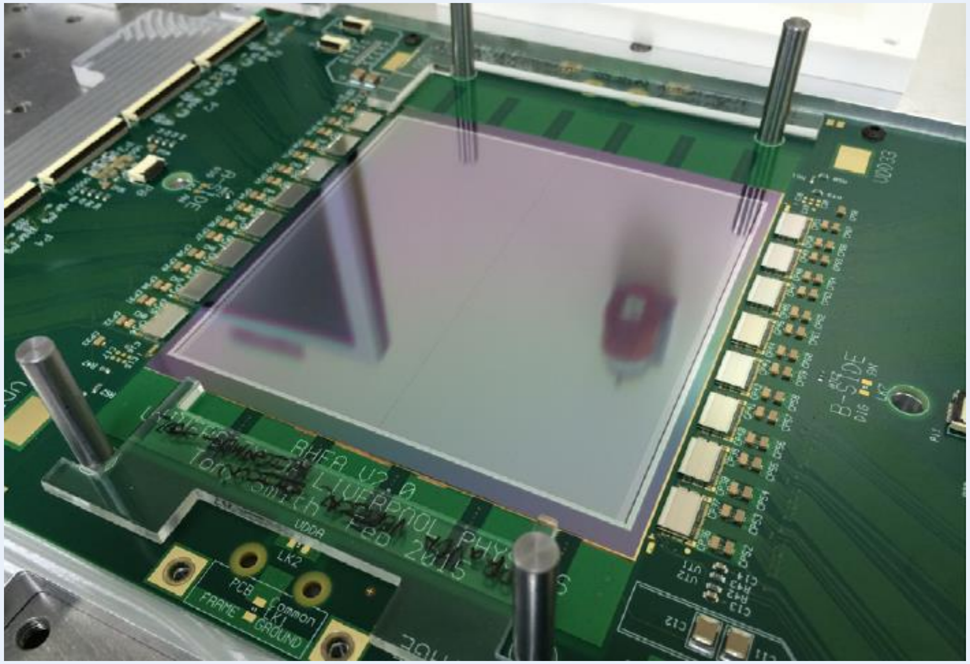


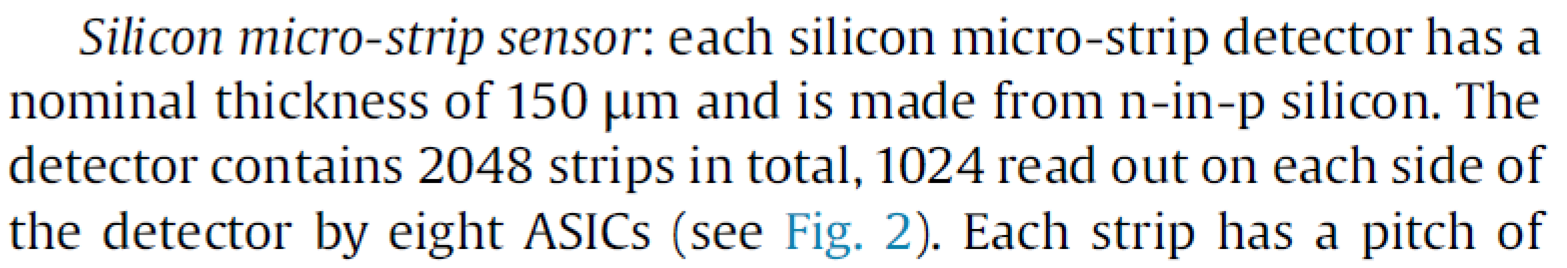
3.2.1. *Timepix detector*

The Timepix detector was developed by the Medipix2 Collaboration at CERN (Llopart *et al* 2007). It is a compact silicon pixel detector with a sensitive area of 14 mm × 14 mm. The application-specific integrated circuit (ASIC) is divided into 256 × 256 pixels, which have a pitch of 55 μm. In this work, a 300 μm-thick silicon sensor attached to the ASIC was used. The Timepix ASIC was thinned from 700 μm down to approximately 100 μm. The resulting material budget of one detection layer is below a WET of 800 μm. The silicon sensor was reversely

(800 µm WET = 380 µm Al)

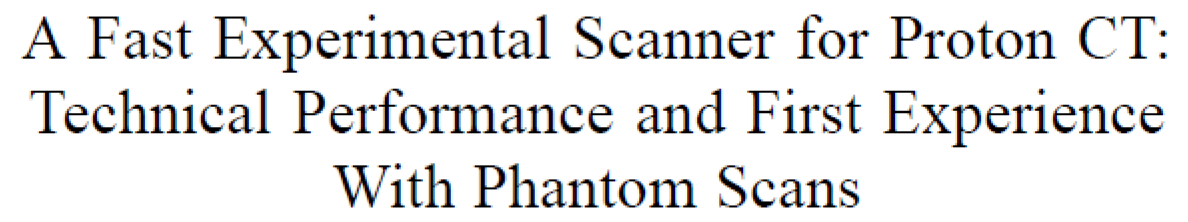
Scattering in first layers – PRaVDA



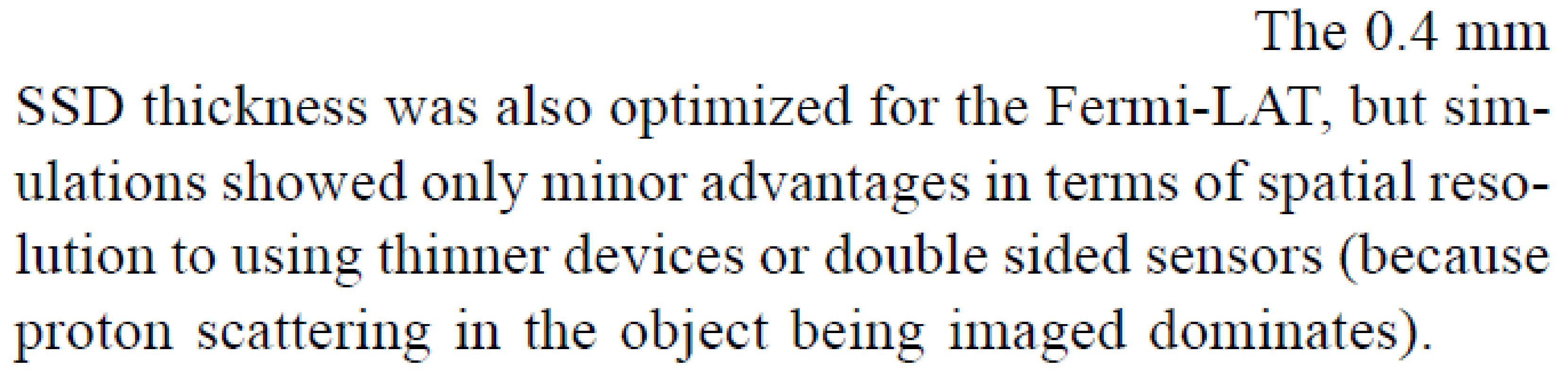


Silicon micro-strip sensor: each silicon micro-strip detector has a nominal thickness of 150 µm and is made from n-in-p silicon. The detector contains 2048 strips in total, 1024 read out on each side of the detector by eight ASICs (see Fig. 2). Each strip has a pitch of

Scattering in first layers – Lomda Linda



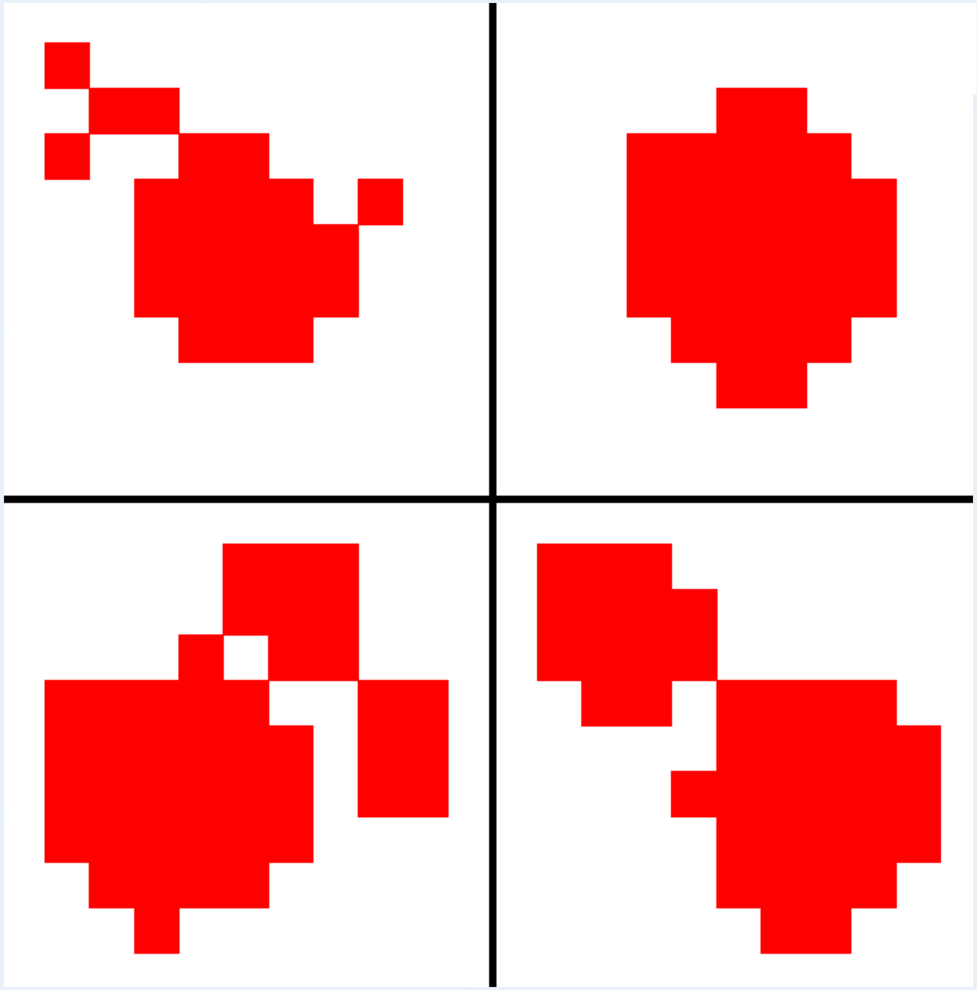
A Fast Experimental Scanner for Proton CT: Technical Performance and First Experience With Phantom Scans



The 0.4 mm SSD thickness was also optimized for the Fermi-LAT, but simulations showed only minor advantages in terms of spatial resolution to using thinner devices or double sided sensors (because proton scattering in the object being imaged dominates).

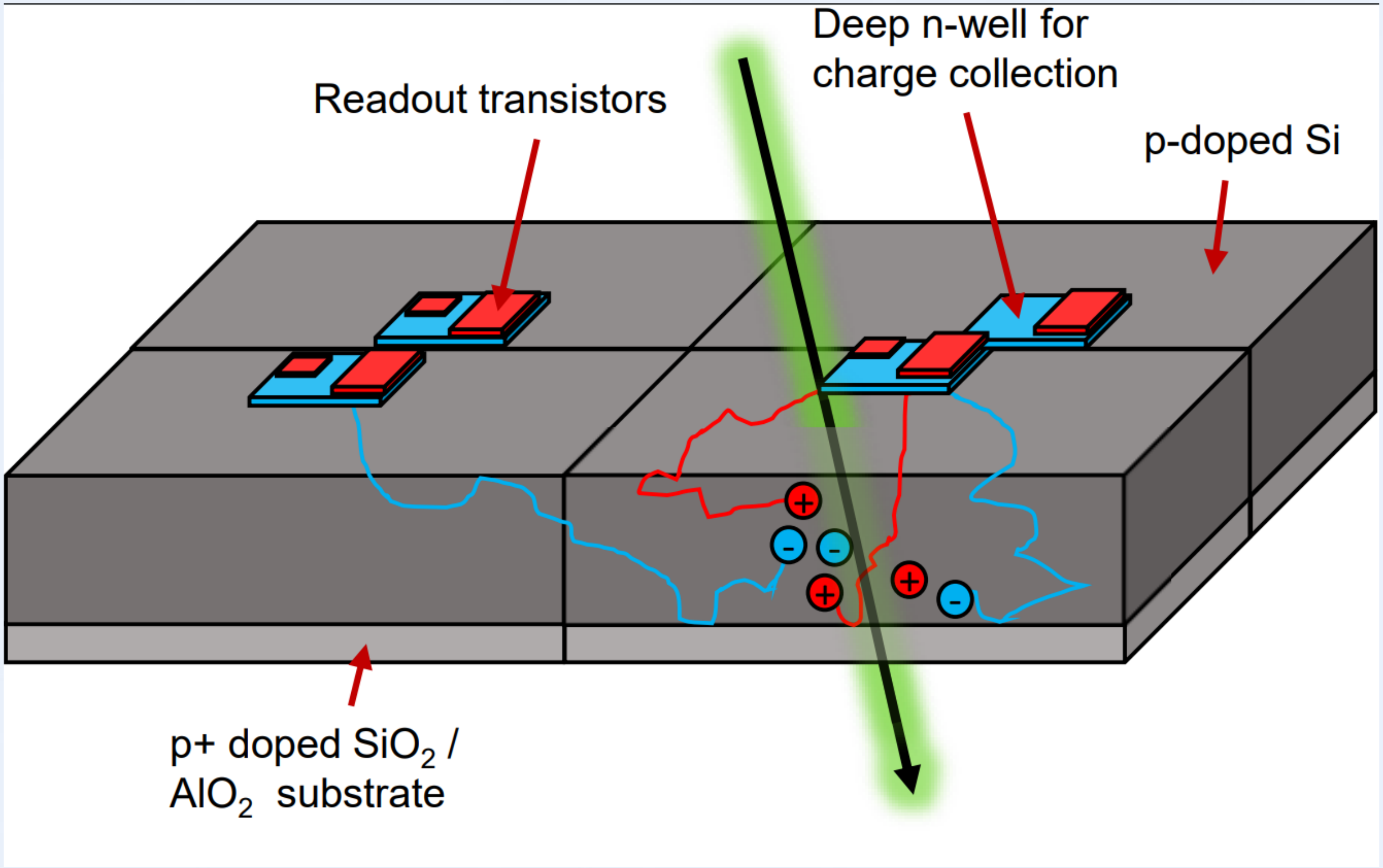
BACKUP SLIDES – ANALYSIS

Charge diffusion



Charge clustering model

Each proton track creates charge diffused pixel clusters



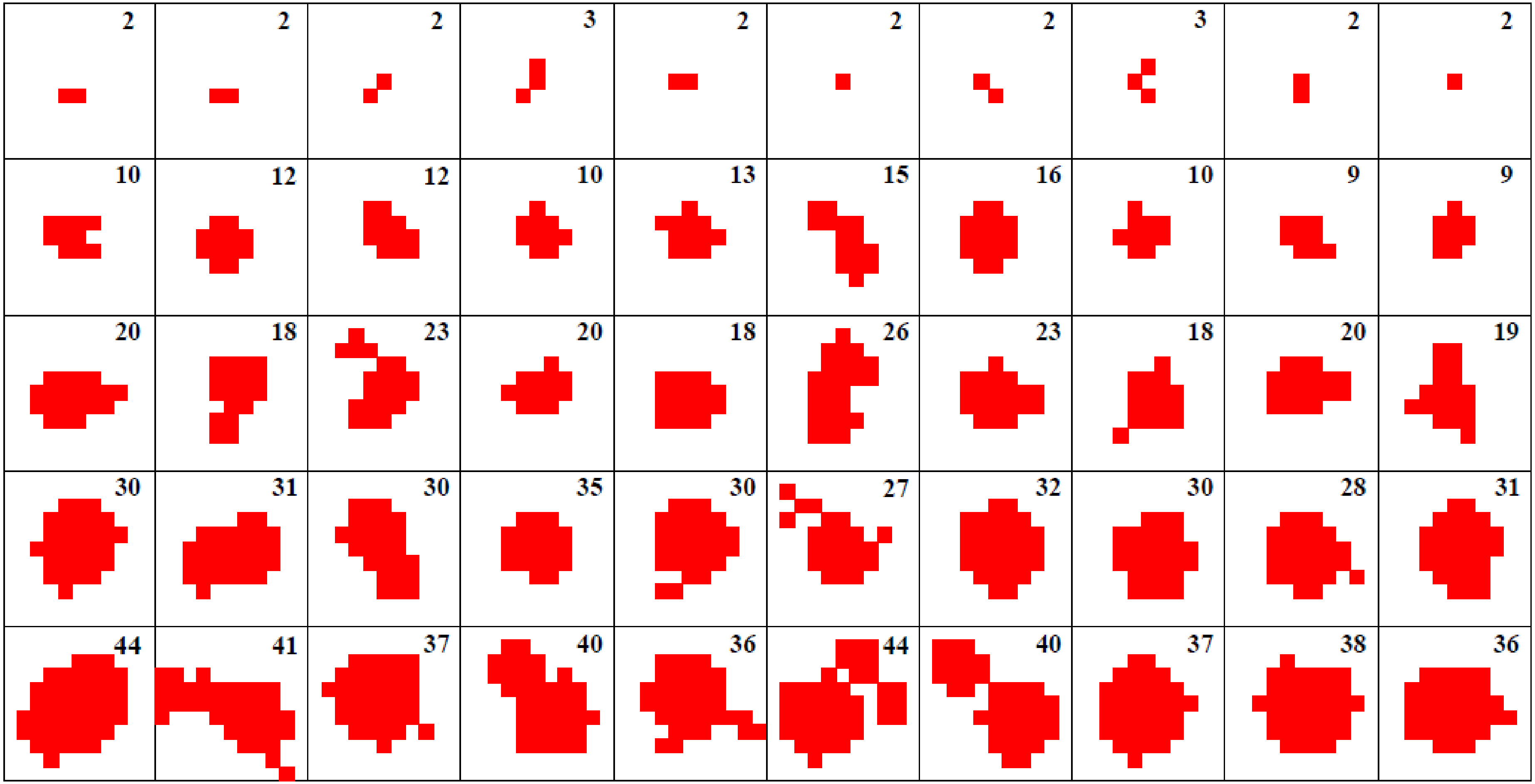


Figure 4.4: Examples of charge diffused pixel clusters, grouped by their cluster size (number of activated pixels in cluster). The cluster size is shown in the corner of each figure. Note that some of the larger clusters actually are wrongly identified smaller clusters, located very close to each other.

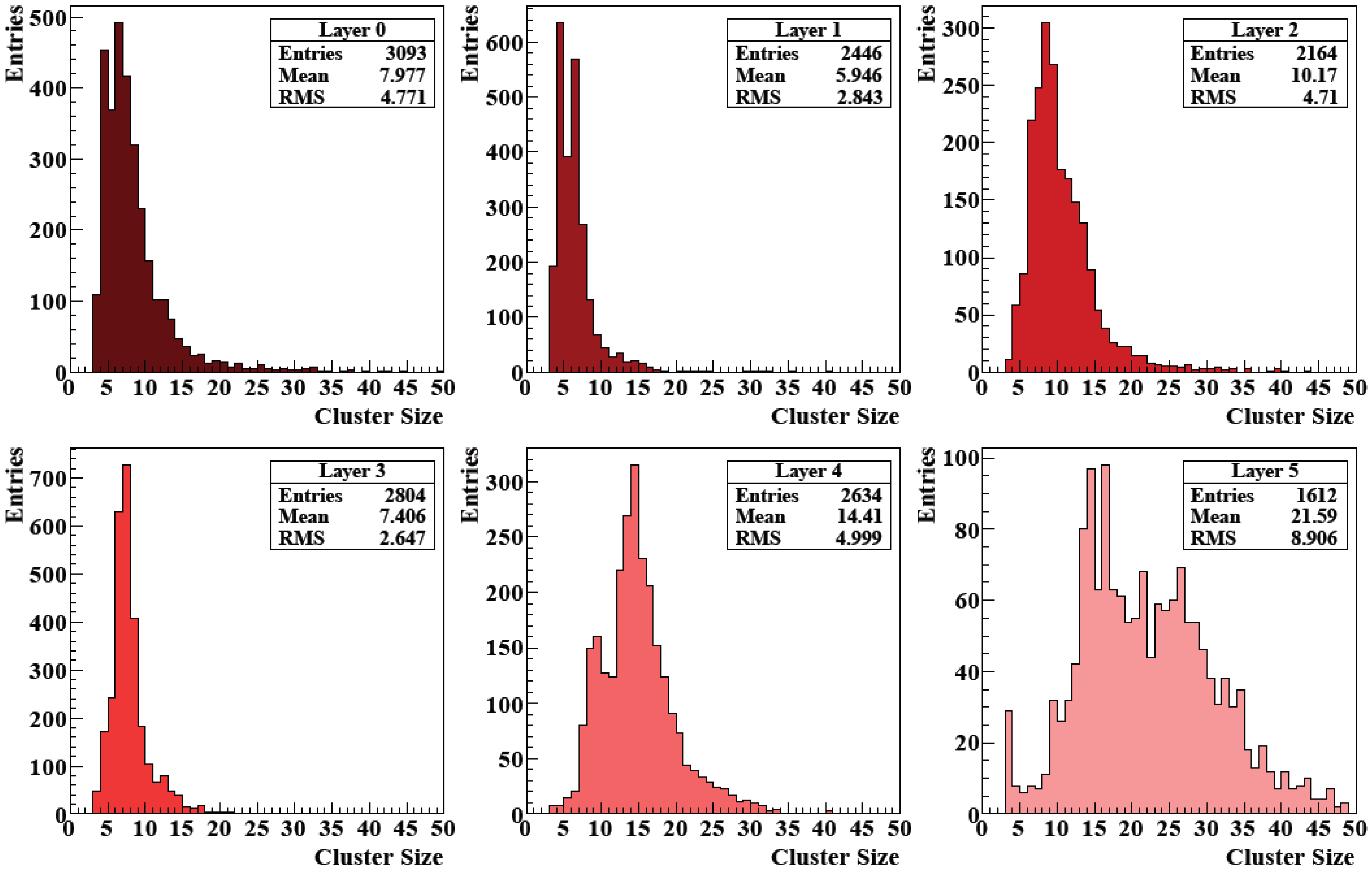
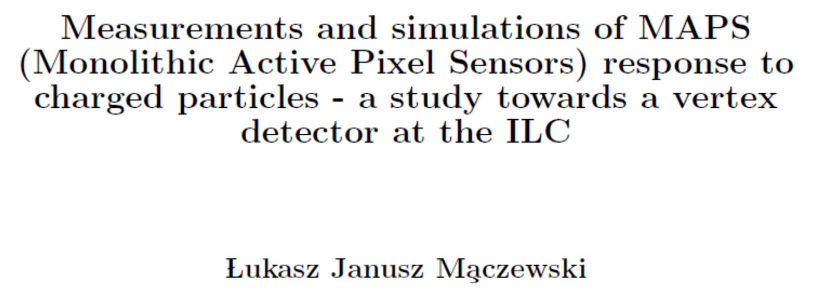


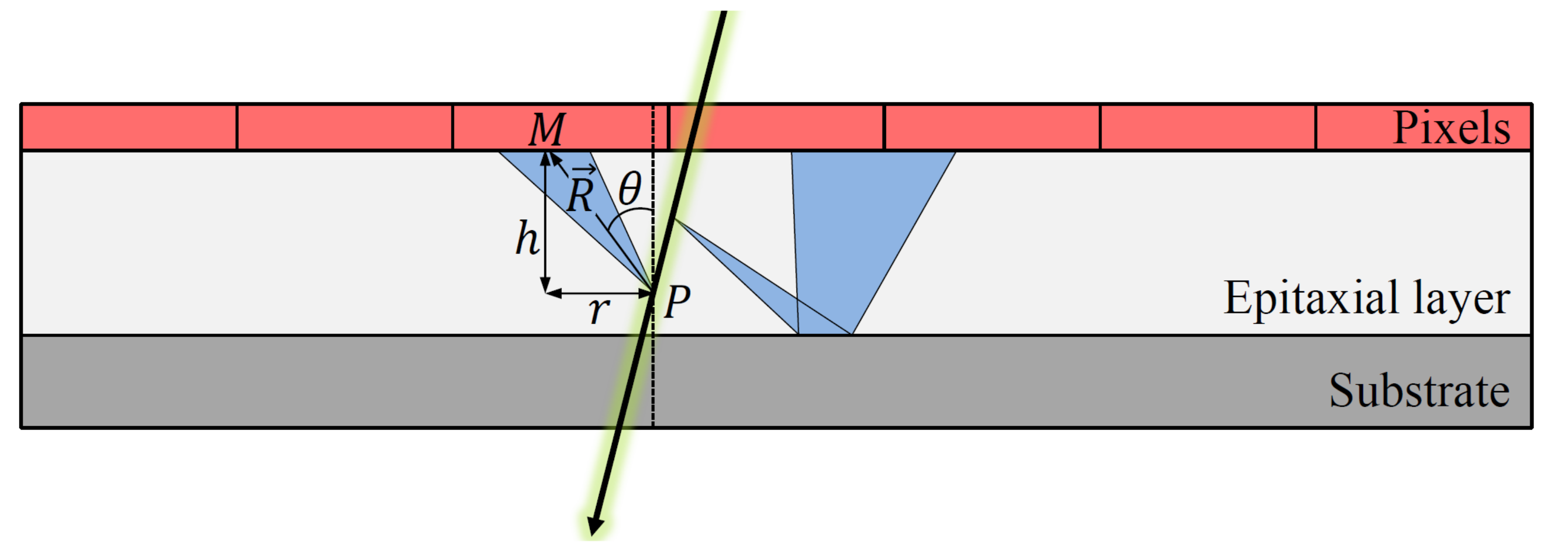
Figure 4.6: Cluster size distributions in the various sensor layers, from the 170 MeV beam test data.

Analytical model

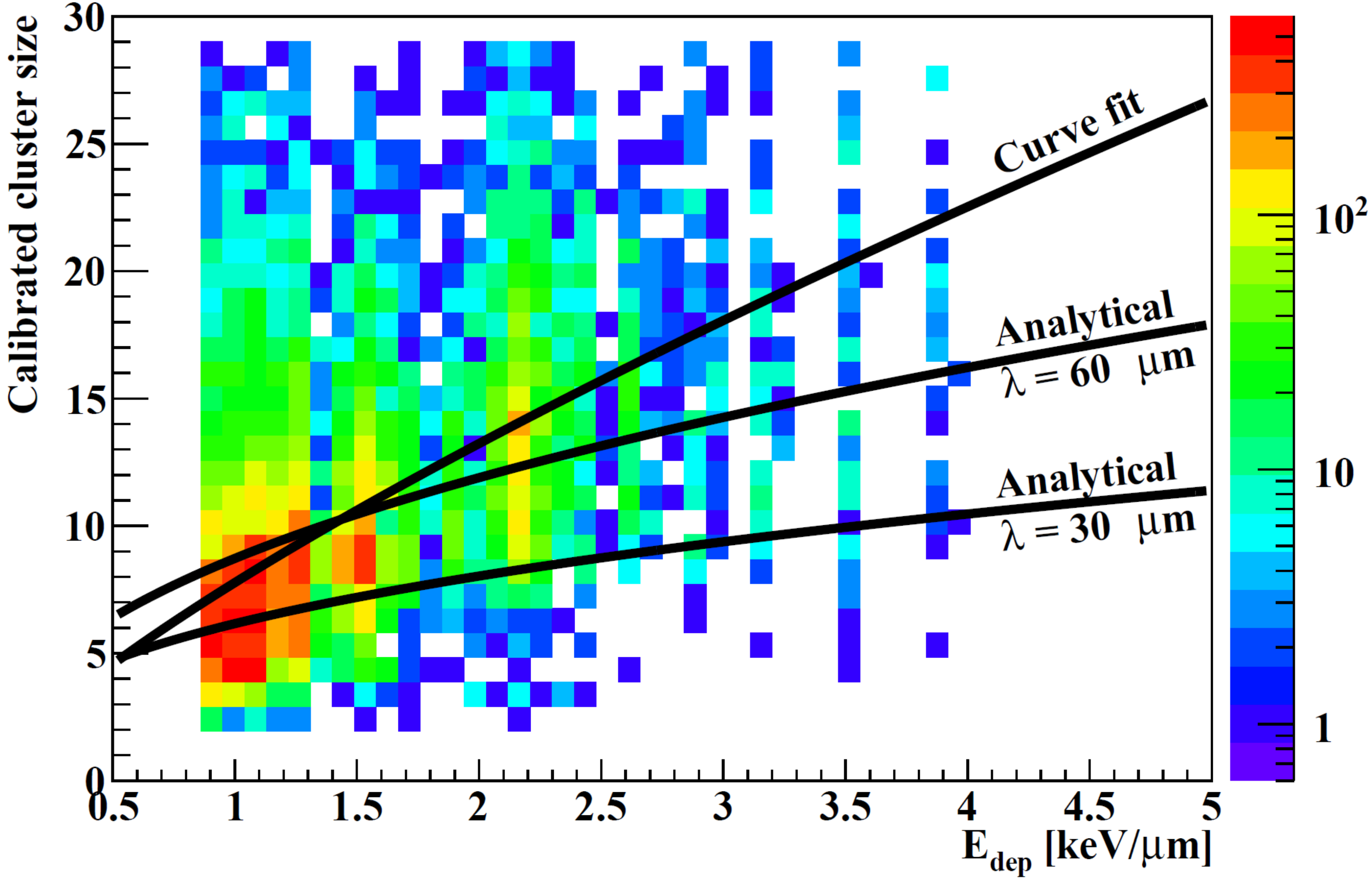


Measurements and simulations of MAPS (Monolithic Active Pixel Sensors) response to charged particles - a study towards a vertex detector at the ILC

Łukasz Janusz Mączewski

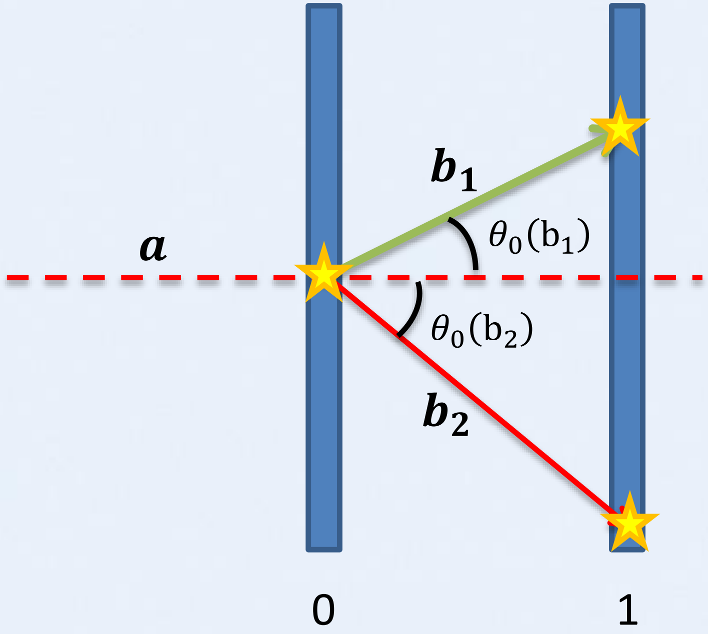


$$\rho(\vec{R})\mathrm{d}r\mathrm{d}\phi = \frac{\mathrm{d}\Omega}{4\pi} \cdot \exp\left(-\frac{|\vec{R}|}{\lambda}\right) = \frac{hr}{4\pi|\vec{R}|^3} \cdot \exp\left(-\frac{|\vec{R}|}{\lambda}\right) \mathrm{d}r\mathrm{d}\phi,$$


Calibrated cluster size
0
5
10
15
20
25
30
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_{dep} [keV/μm]
Curve fit
Analytical
λ = 60 μm
Analytical
λ = 30 μm
1
10
10^2

Tracking algorithm

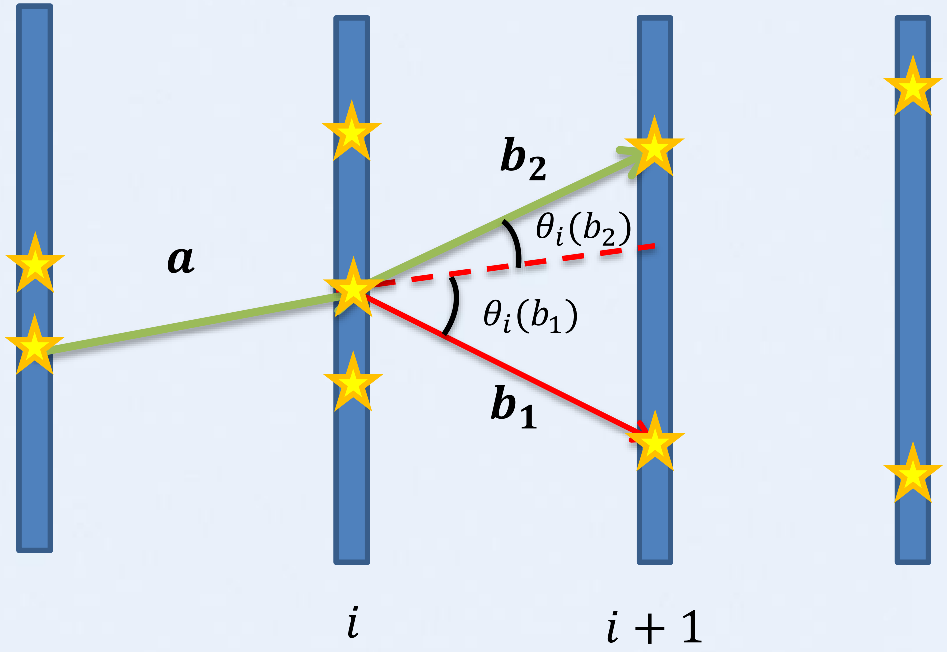
1. Use all hits in first layer as seeds
2. Test all seeds against hits in next layer:
    1. Evaluate: Find change in direction θ_0 in first sensor layer (assume parallel beam here) against all hits in next layer
    2. Compare θ_0 against a threshold value: If below, keep the hit in next layergiving rise to lowest θ_0: Here it's $\boldsymbol{b_1}$.



$$\theta_0(\boldsymbol{x}) = \cos^{-1}\left[\frac{\boldsymbol{a}\cdot\boldsymbol{x}}{|\boldsymbol{a}|\cdot|\boldsymbol{x}|}\right]$$

Tracking algorithm

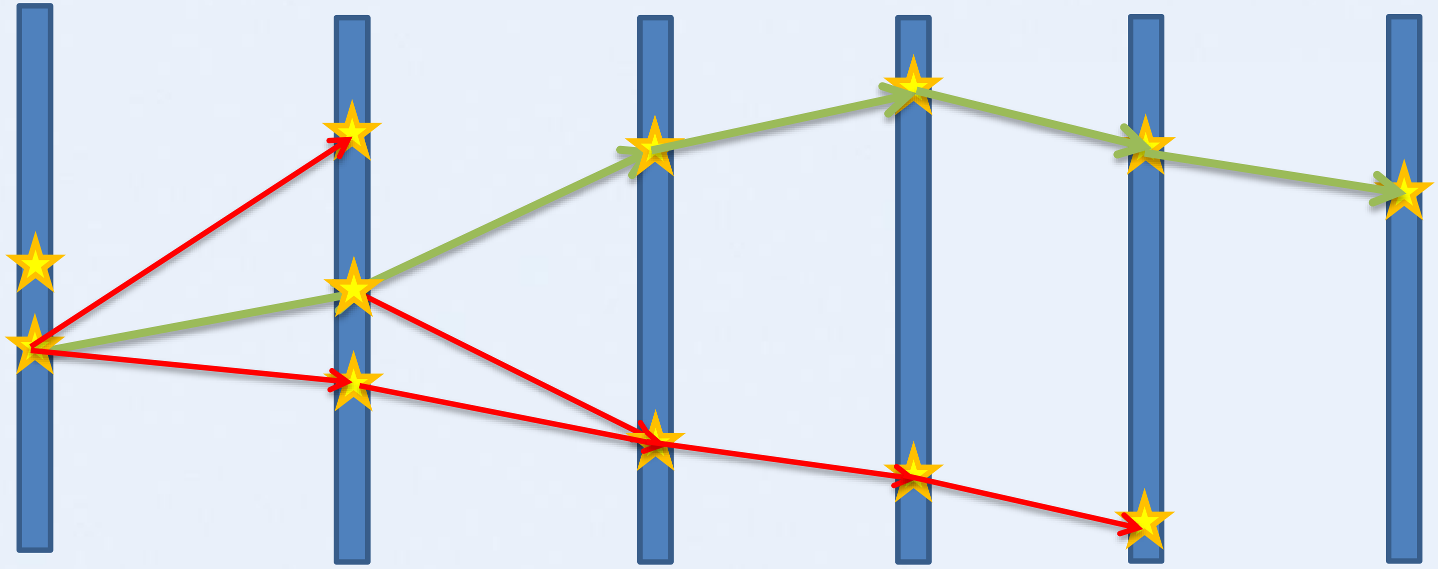
1. For all next layers, find angular change θ_i and append the hit with «lowest-scattering» cluster.



$$\boldsymbol{\theta_i(b_1) > \theta_i(b_2) \rightarrow \textbf{Use } \mathbf{b_2}}$$

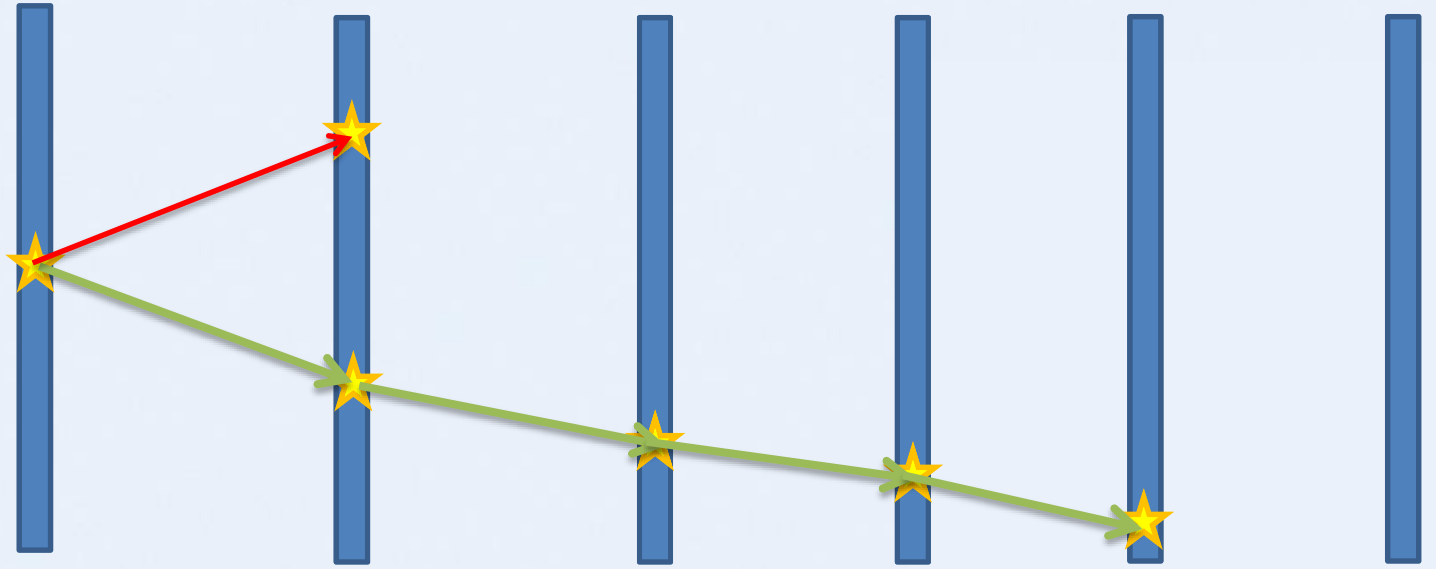
Tracking algorithm

1. When a few tracks are made from the same seed pair, find the best one using different scoring criteria (total angular change, length, existence of Bragg Peak, etc.)
2. Keep the track (green) and remove all hits connected to it



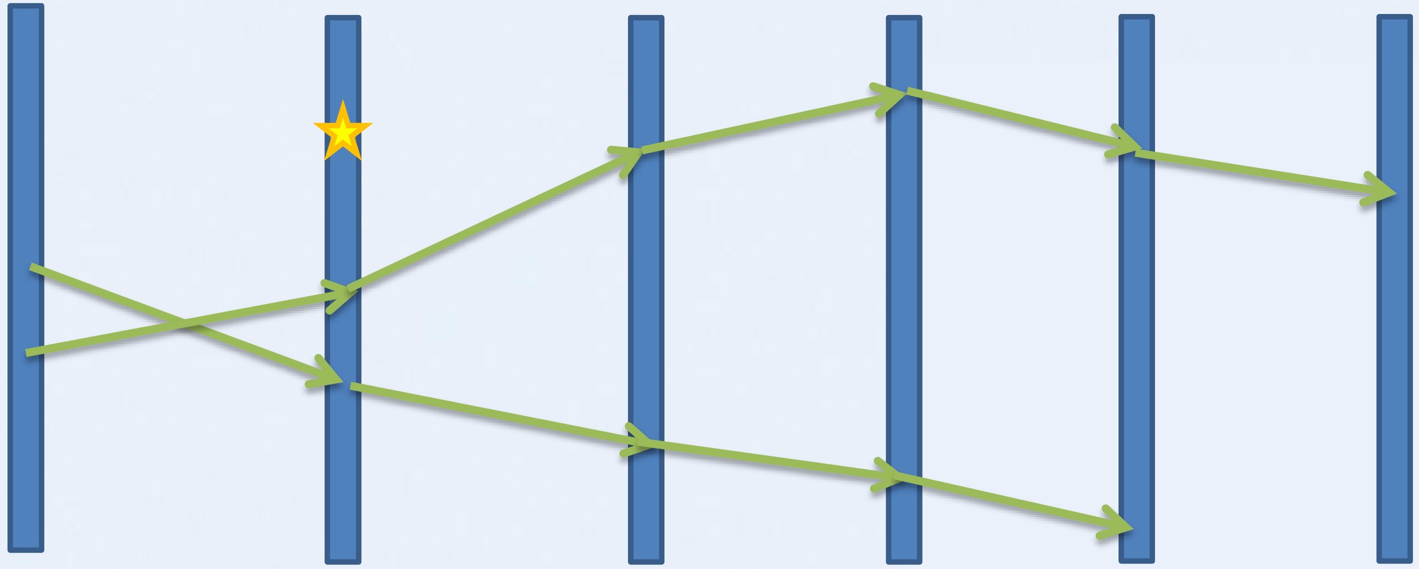
Tracking algorithm

1. Redo the tracking on the reduced data



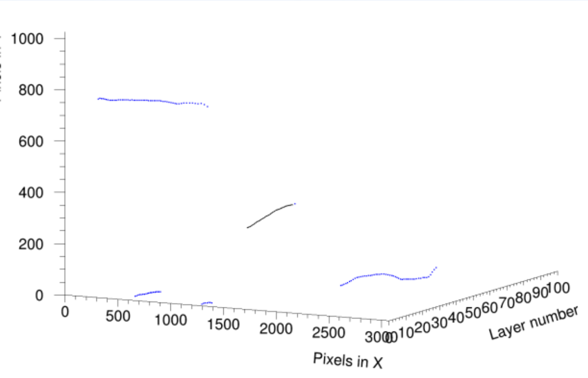
Tracking algorithm

1. Voilà, all tracks are reconstructed

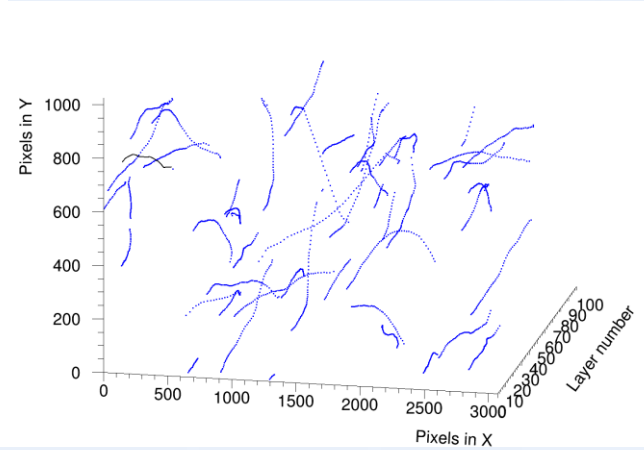


Proton tracking – Accuracy

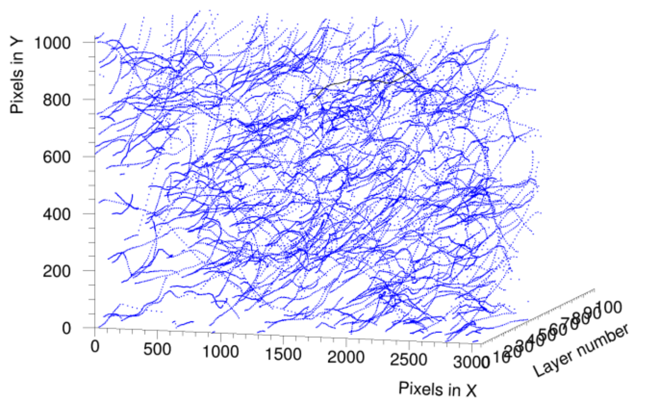
The more protons to be reconstructed at the same, the smaller the probability of finding the correct track



5



50

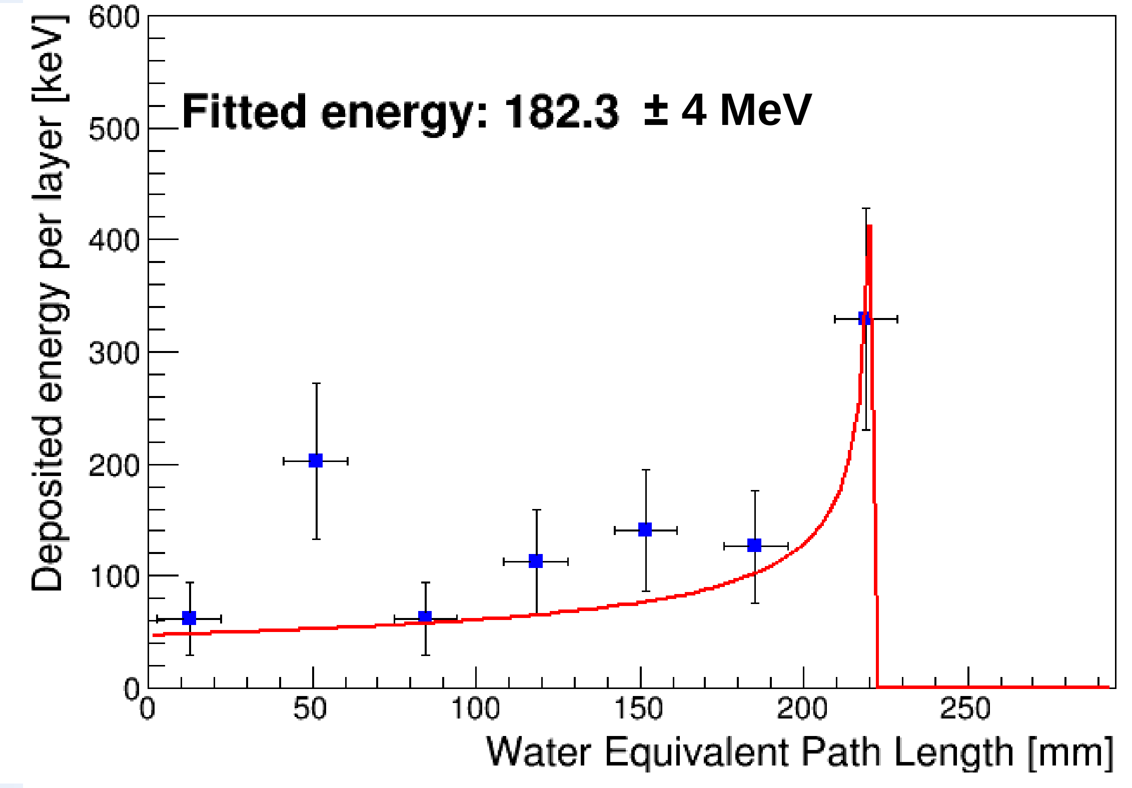


500

Finding the range

For each proton it's possible to plot proton depth vs E_{dep}

And do model fitting with Bortfeld's Bragg Curve $R = \alpha\, E^{p}$



Bortfeld, T. *An Analytical approximation to the Bragg curve for therapeutic proton beams.* Med. Phys 24 2024-33 (1997)