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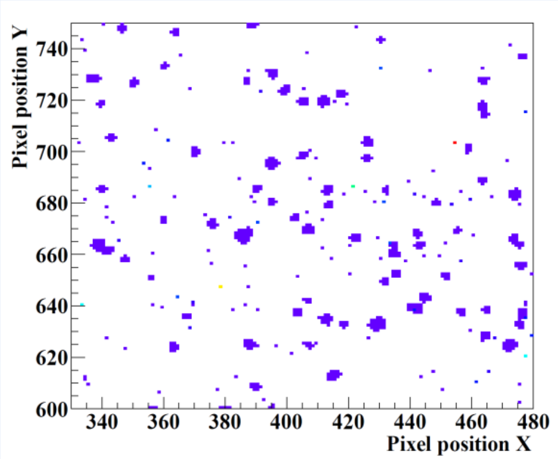
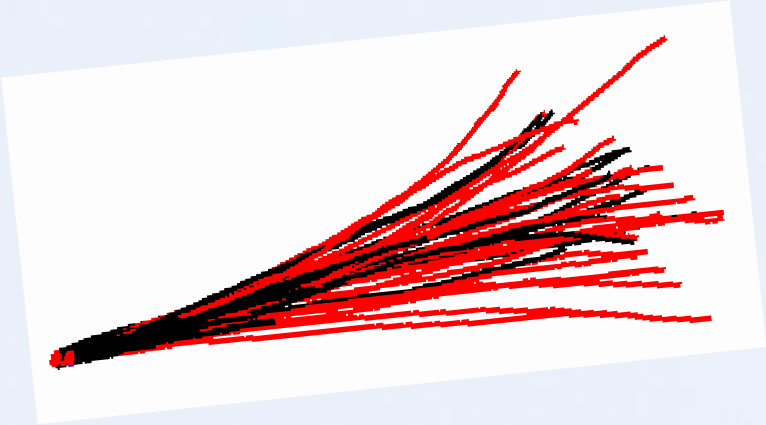
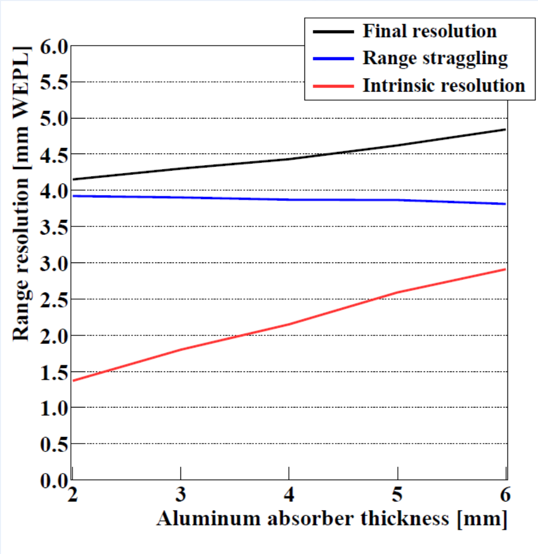
Detector layout specification







Helge Egil Seime Pettersen
PhD student
pCT workshop, november 2017
UiB

Overview

1. Overview of the data analysis
    1. Charge diffusion model
    2. Track reconstruction inside the calorimeter
    3. Bragg Peak fitting
2. The design optimization method
    1. Range accuracy
    2. Range uncertainty
3. Results -- recommendations

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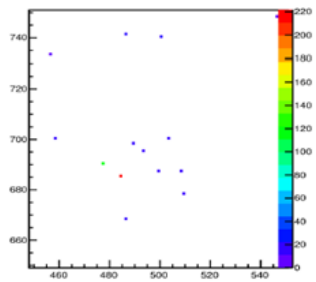
Analysis workflow

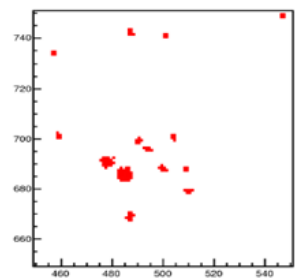
Data readout
MC, MC + truth, exp.

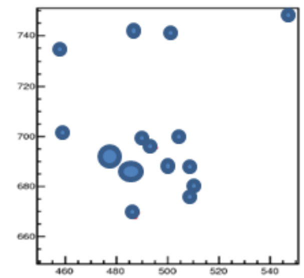
Pixel diffusion modelling (MC only)

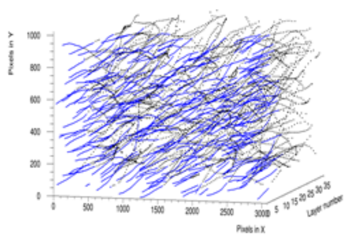
Cluster identification

Proton track reconstruction





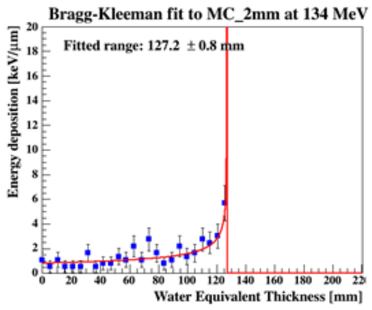


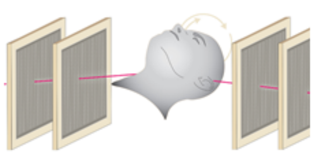


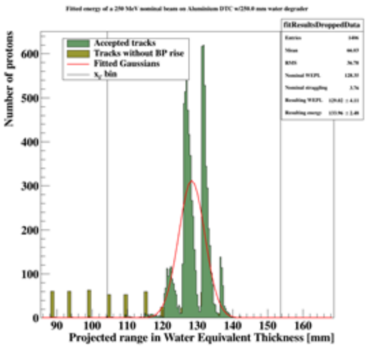
Individual track – energy loss fitting

If 3D reconstruction: MLP estimation

Residual range calculation







Data analysis

This process is thorougly explained in our 2017 NIMA paper (and even thoroughlier in my upcoming thesis)

Nuclear Instruments and Methods in Physics Research A 860 (2017) 51–61

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journal homepage: www.elsevier.com/locate/nima

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Proton tracking in a high-granularity Digital Tracking Calorimeter for proton CT purposes

CrossMark

H.E.S. Pettersen[a,b,*], J. Alme[b], A. Biegun[e], A. van den Brink[c], M. Chaar[b], D. Fehlker[b], I. Meric[d], O.H. Odland[a], T. Peitzmann[c], E. Rocco[c], K. Ullaland[b], H. Wang[c], S. Yang[b], C. Zhang[c], D. Röhrich[b]

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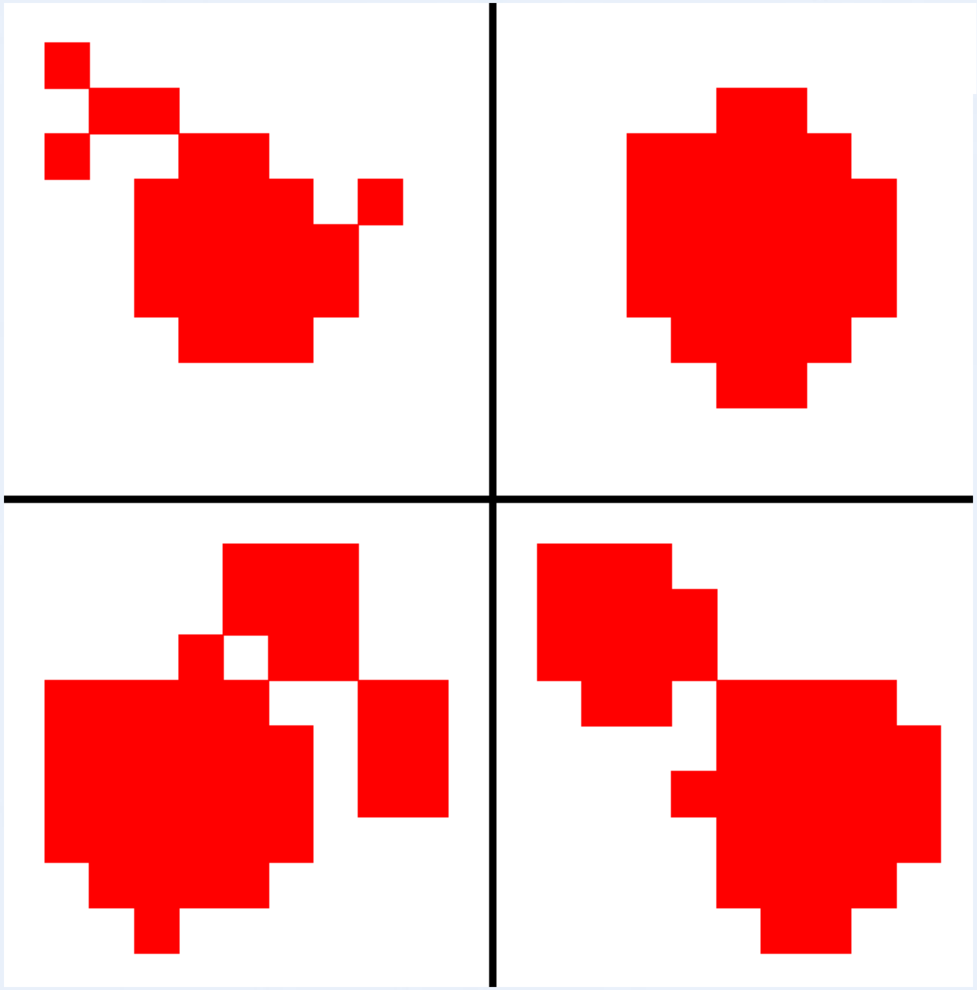
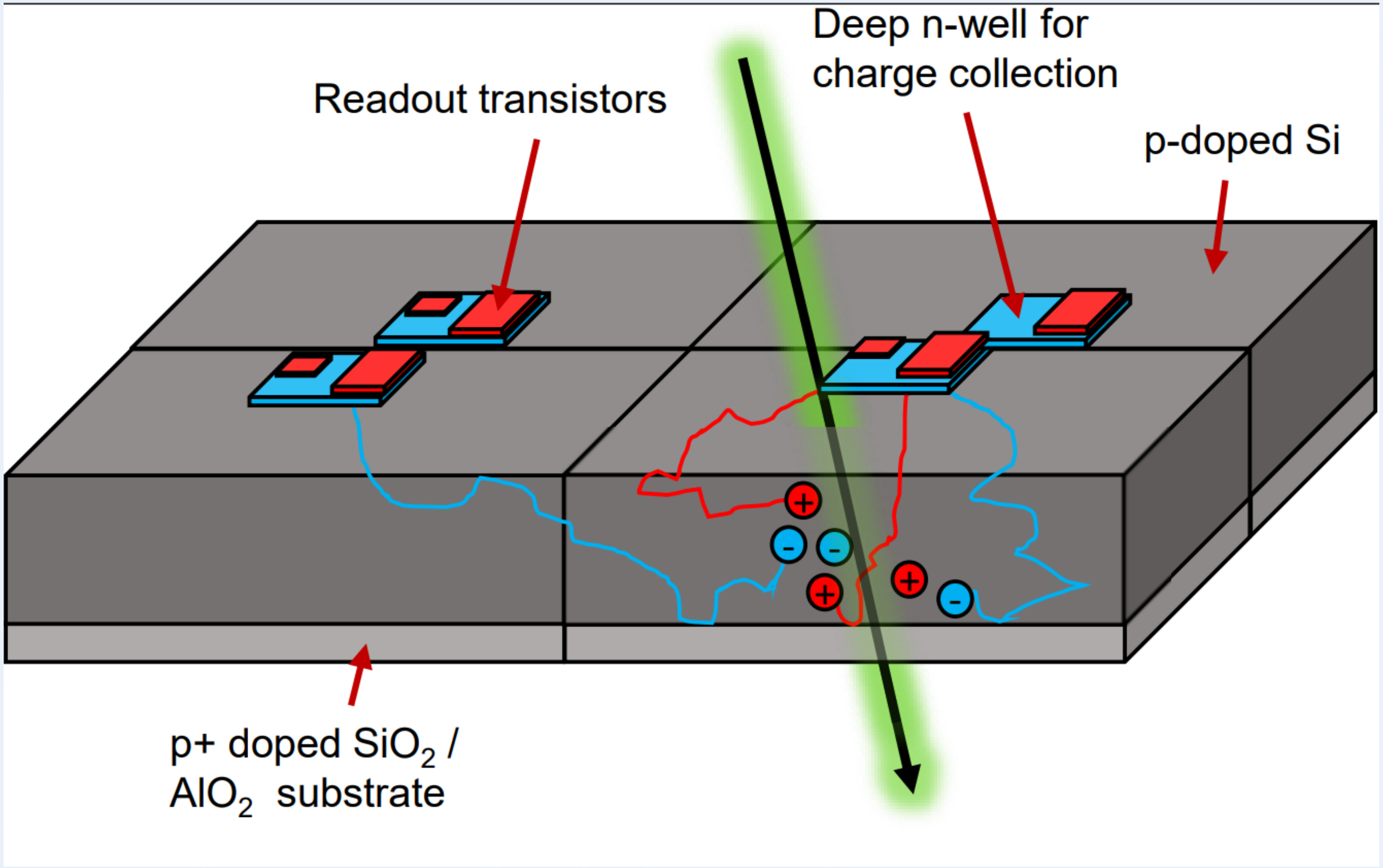
[e] *Kernfysisch Versneller Instituut, University of Groningen, NL-9747 AA Groningen, The Netherlands*

Charge diffusion



Charge clustering model

Each proton track creates charge diffused pixel clusters



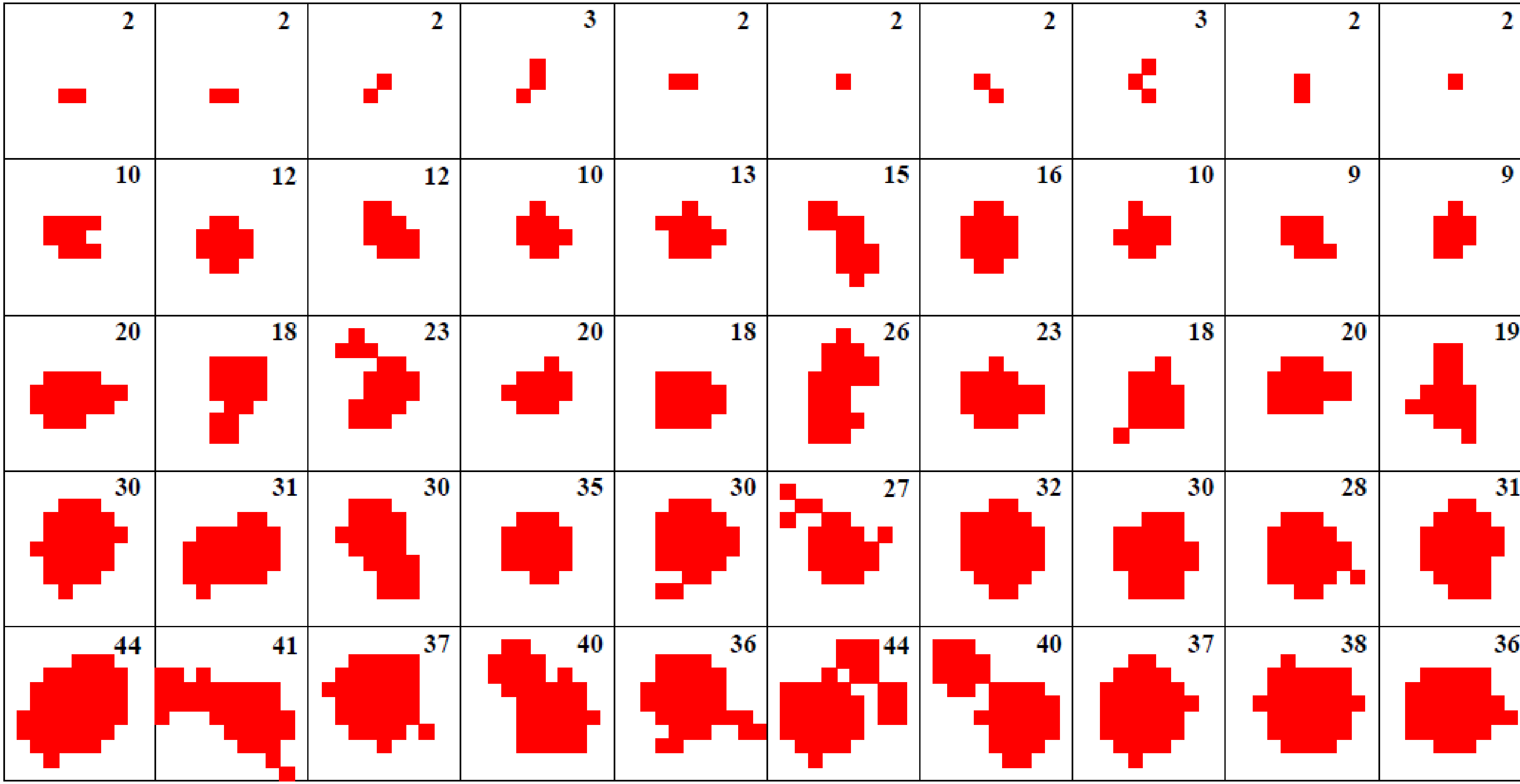


Figure 4.4: Examples of charge diffused pixel clusters, grouped by their cluster size (number of activated pixels in cluster). The cluster size is shown in the corner of each figure. Note that some of the larger clusters actually are wrongly identified smaller clusters, located very close to each other.

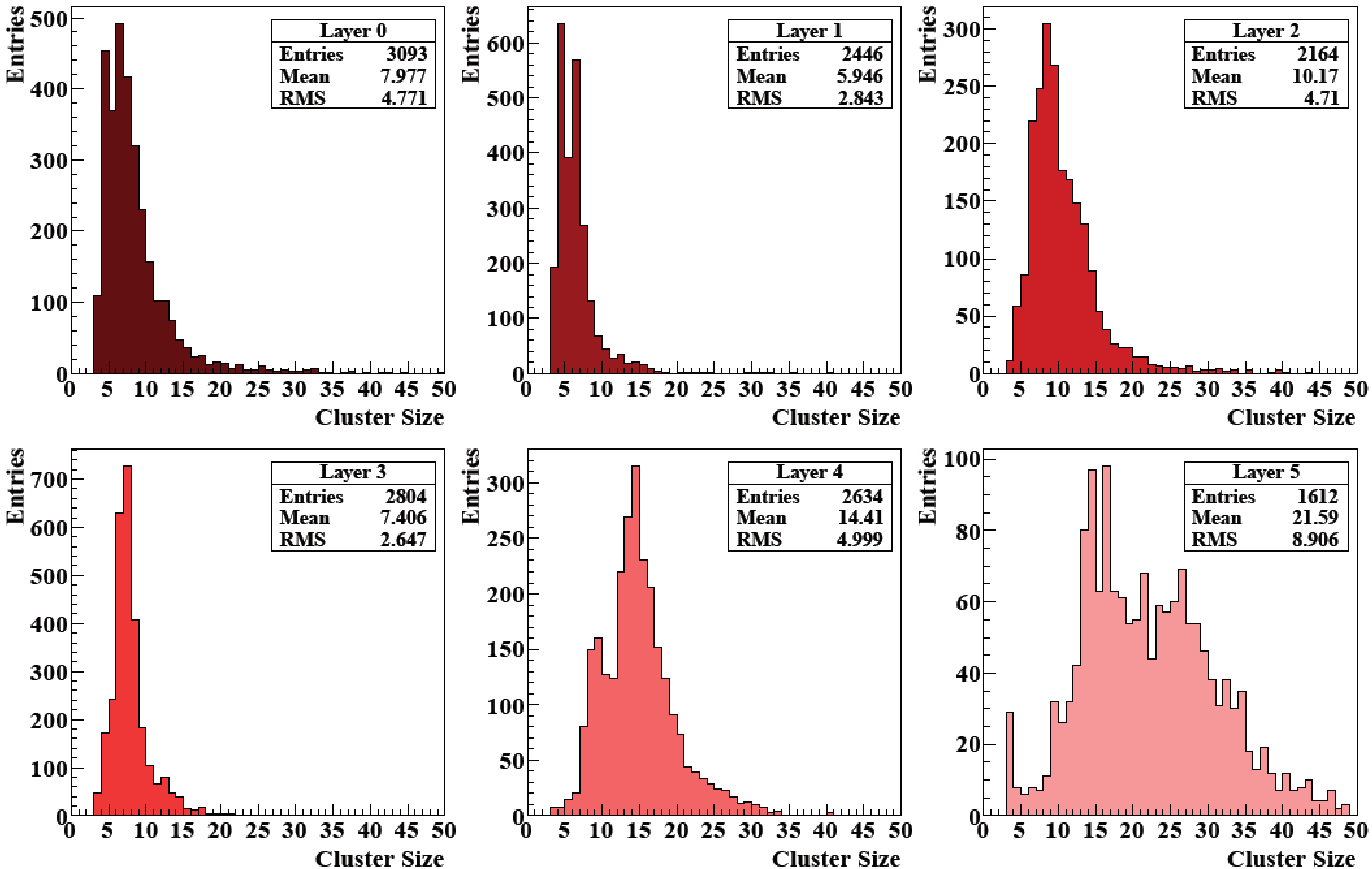
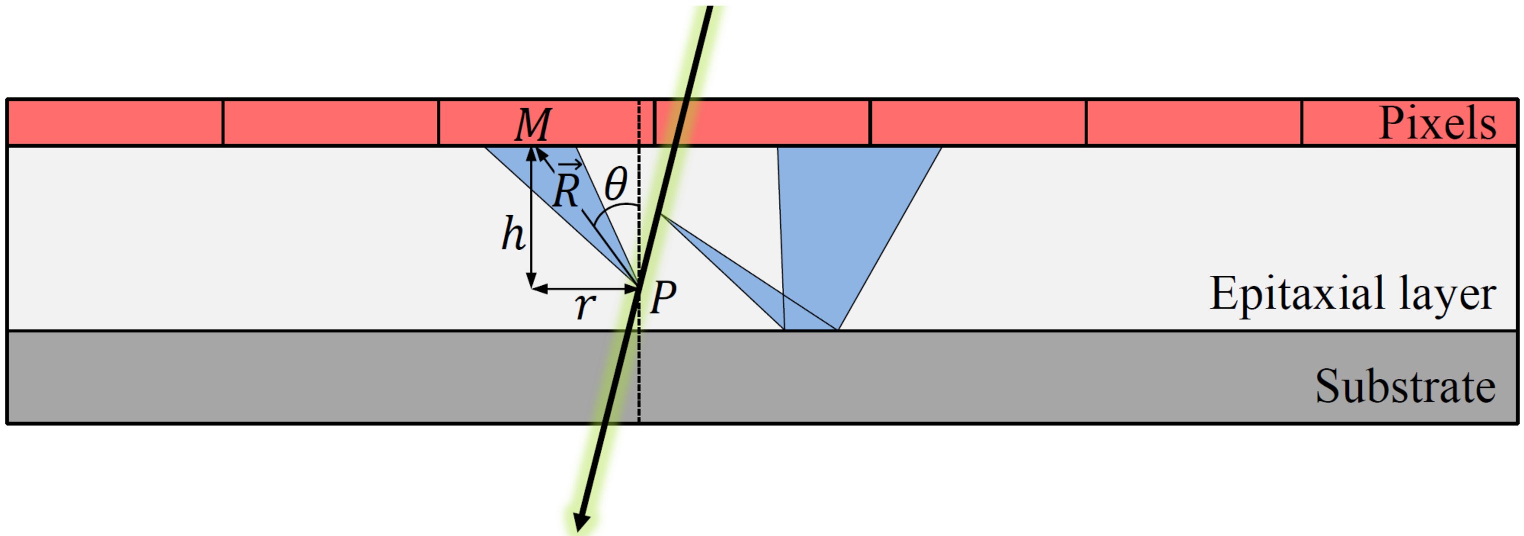


Figure 4.6: Cluster size distributions in the various sensor layers, from the 170 MeV beam test data.

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



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

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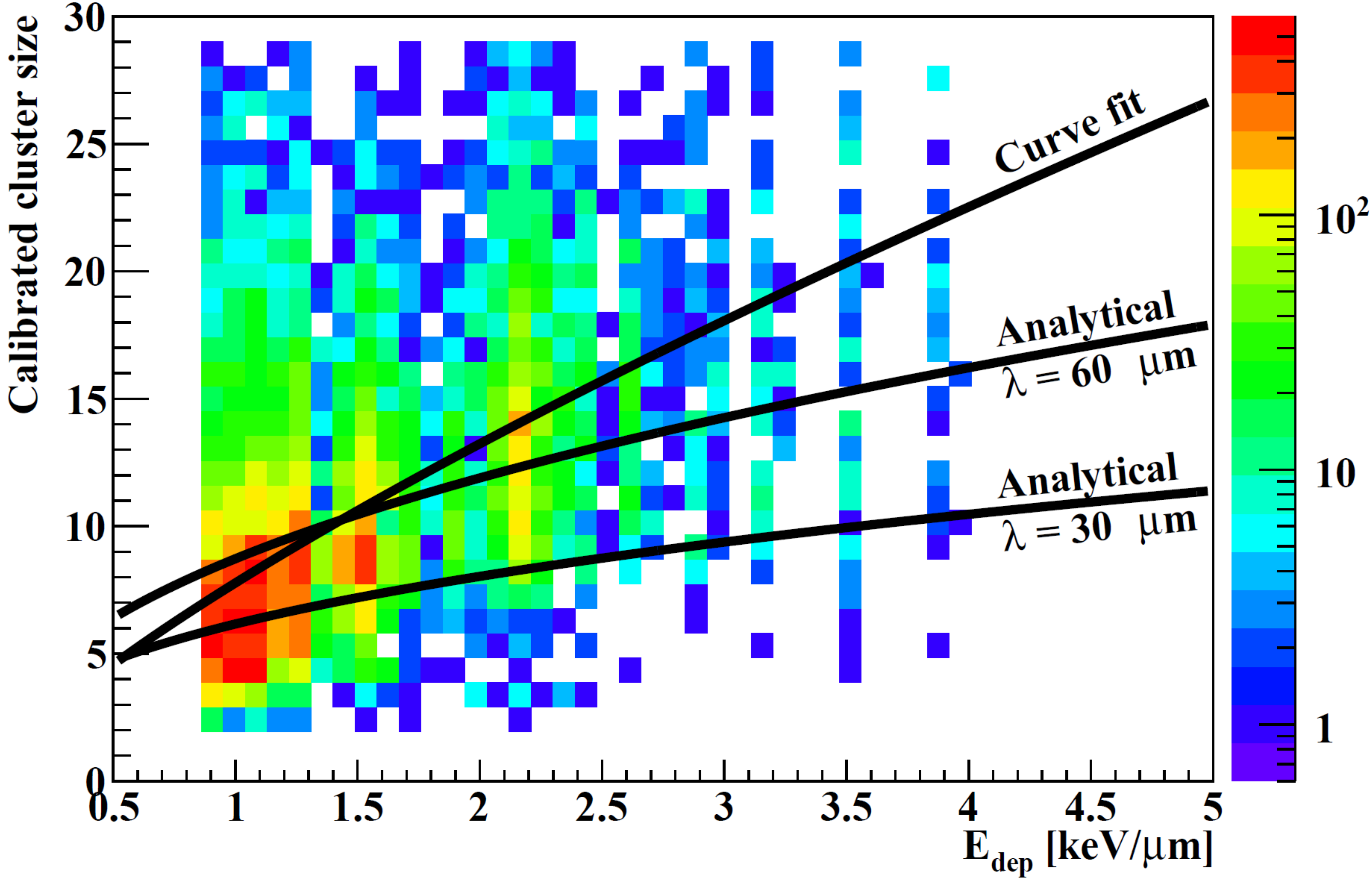

Outlook

- Charge diffusion in ALPIDE
  - Time dependence (~5 μs)
  - Bias voltage
  - Why model?? (increased range resolution)

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Particle tracking

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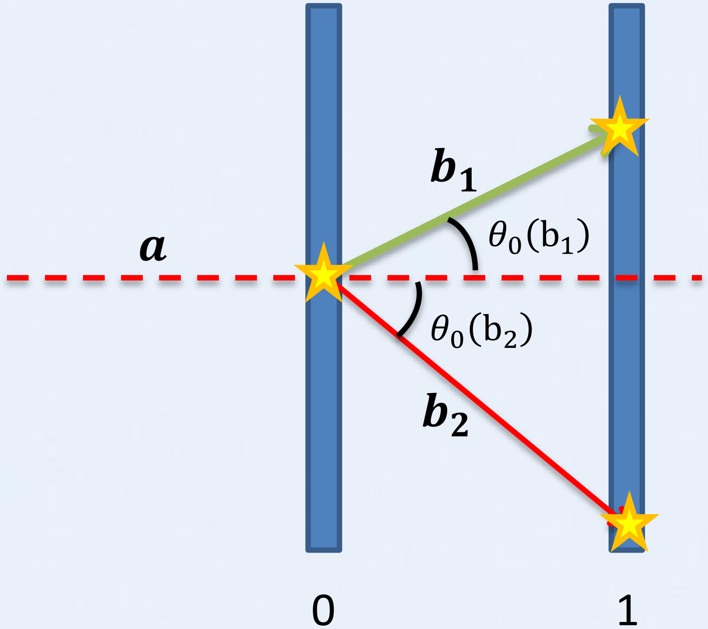
Tracking algorithm

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 $\boldsymbol{b_1}$.



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

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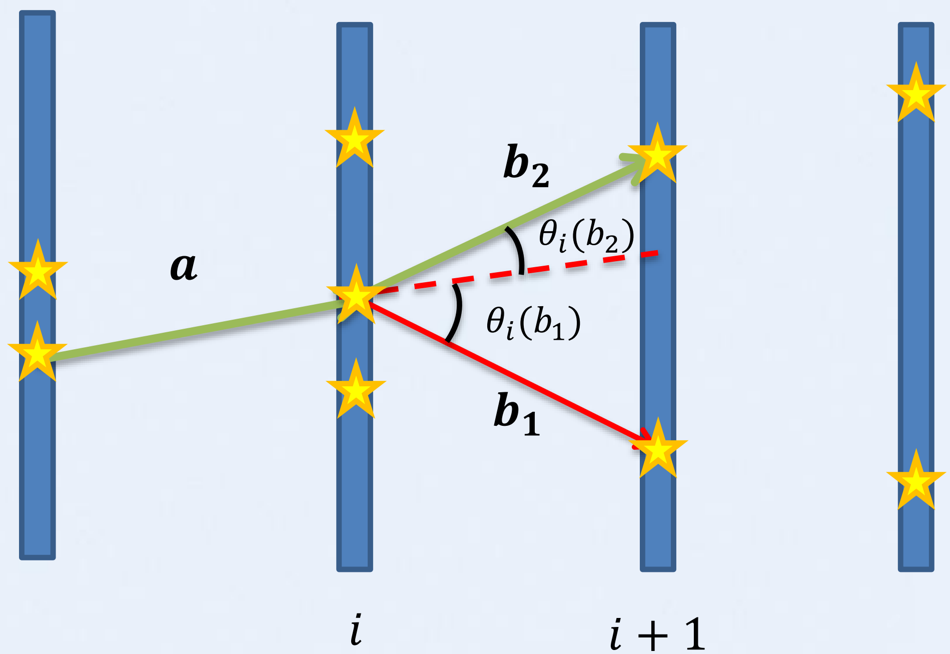
Tracking algorithm

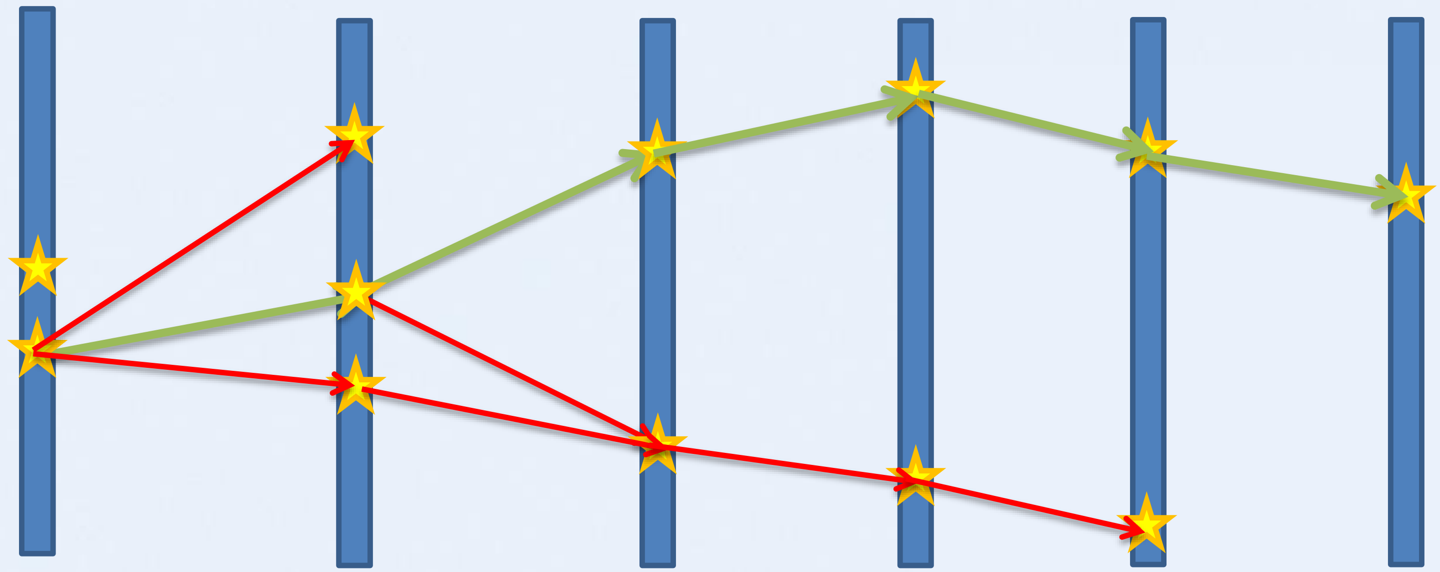
1. For all next layers, find angular change θ_i and append the hit with «lowest-scattering» cluster.



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

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



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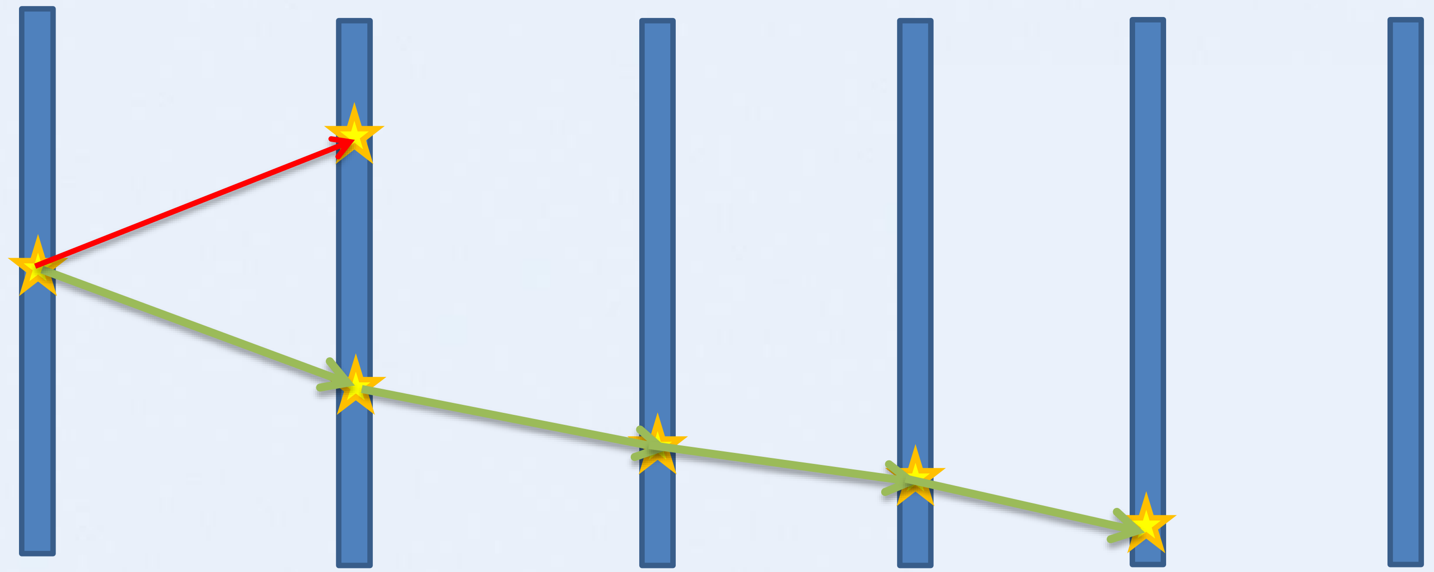
Tracking algorithm

1. Redo the tracking on the reduced data



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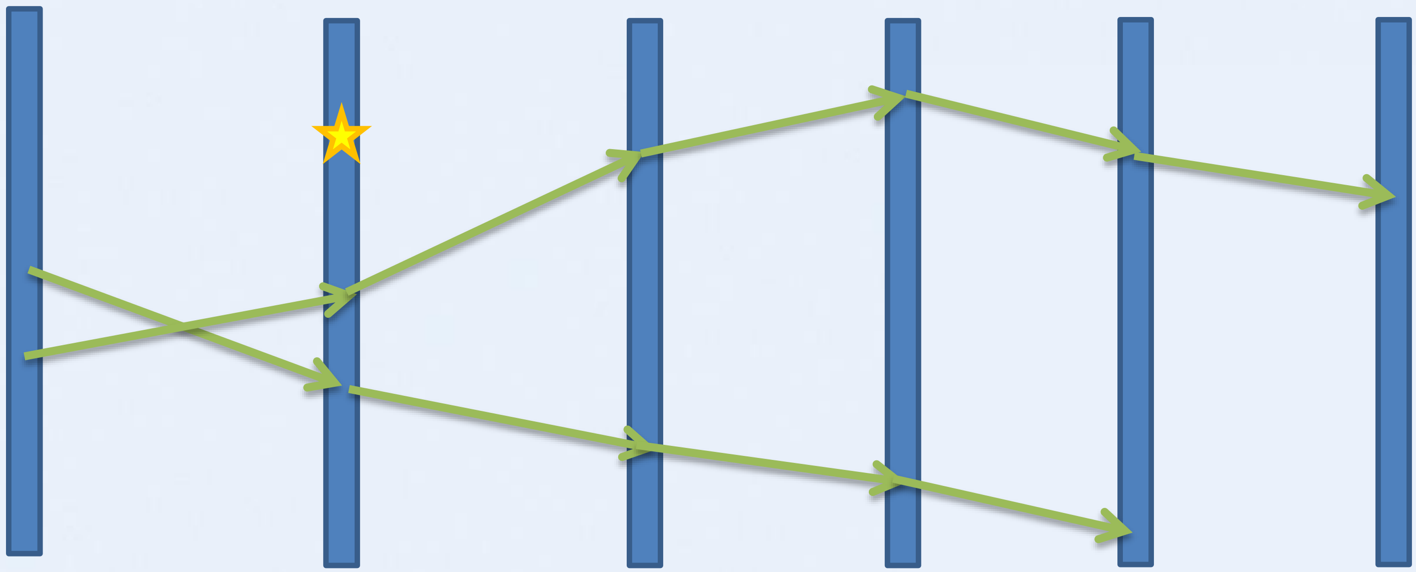
Tracking algorithm

1. Voilà, all tracks are reconstructed



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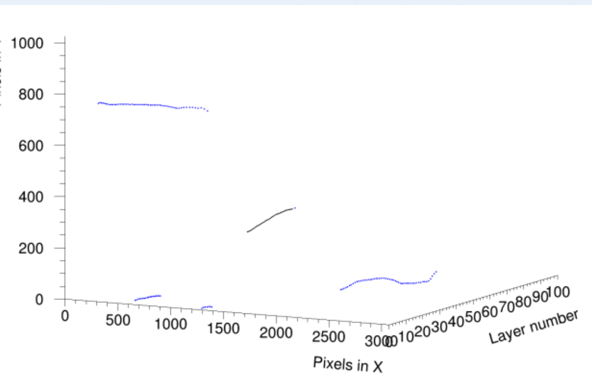
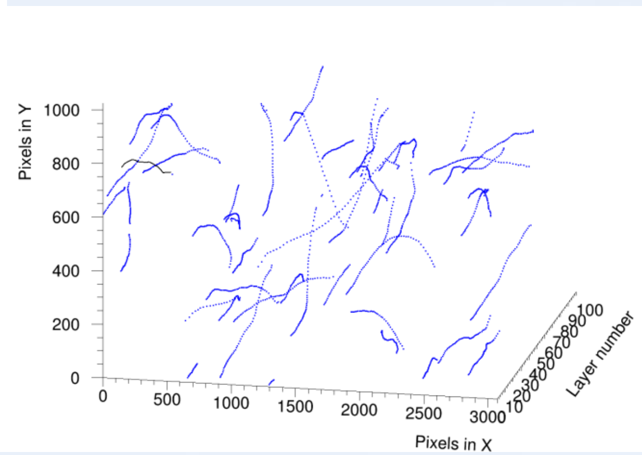
Proton tracking – Accuracy

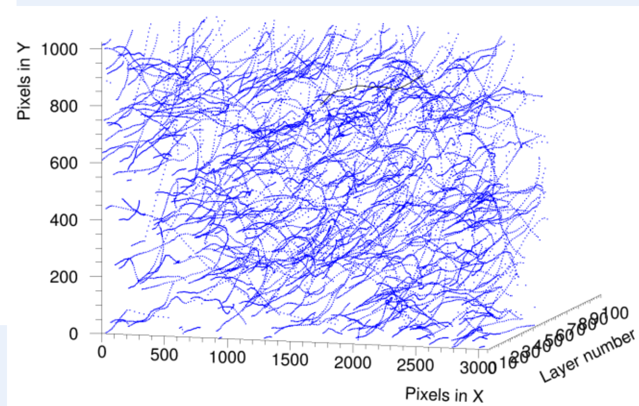
The more protons to be reconstructed at the same, the smaller the probability of finding the correct track



5

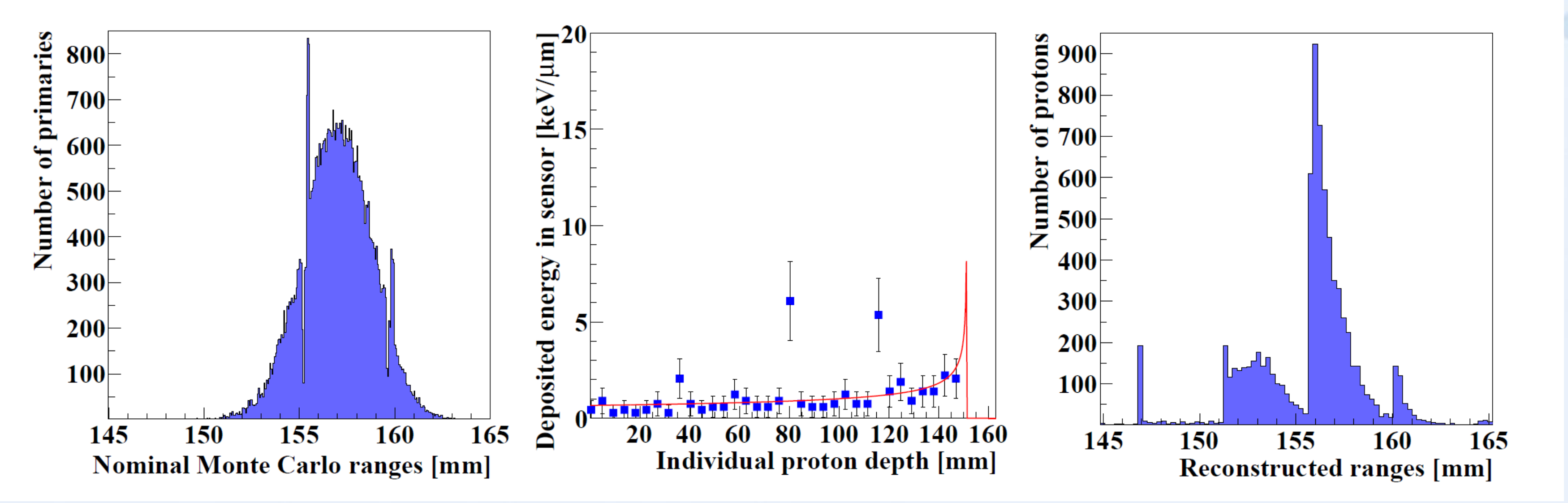


50



500

Range resolution

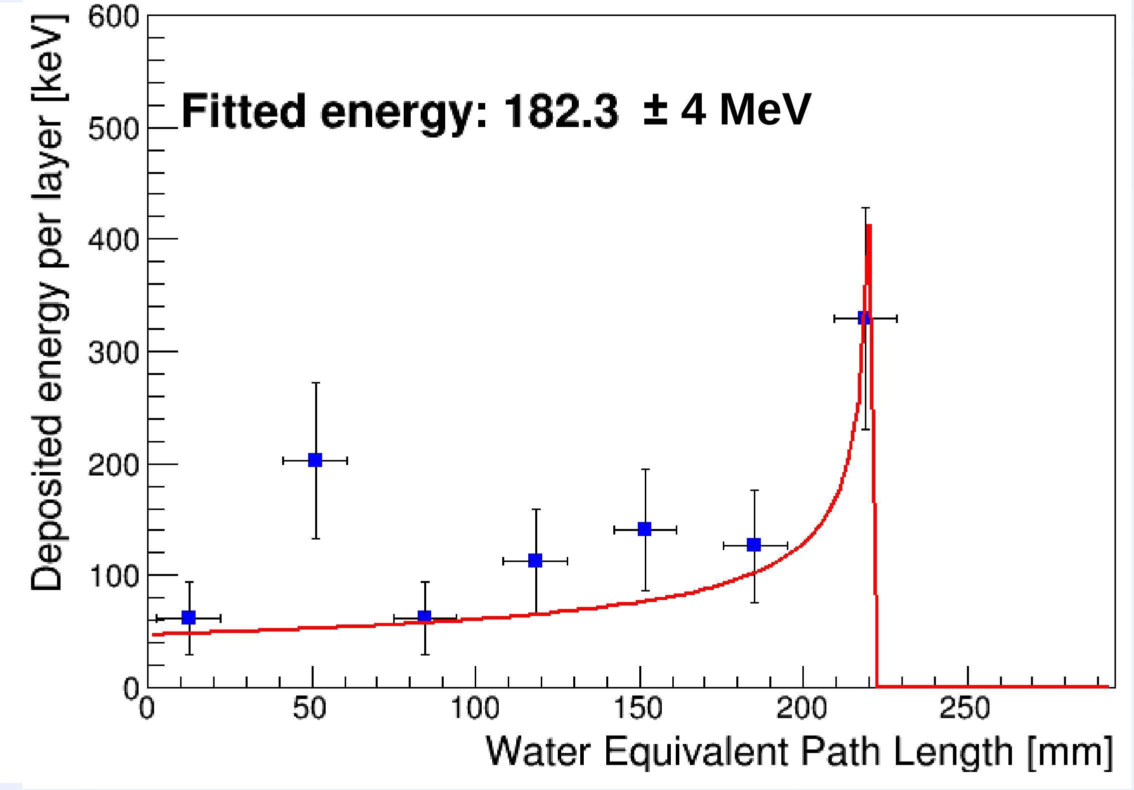


- Range <u>accuracy</u> (bias, systematic errors)
- Range <u>uncertainty</u> (in addition to range straggling)

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)

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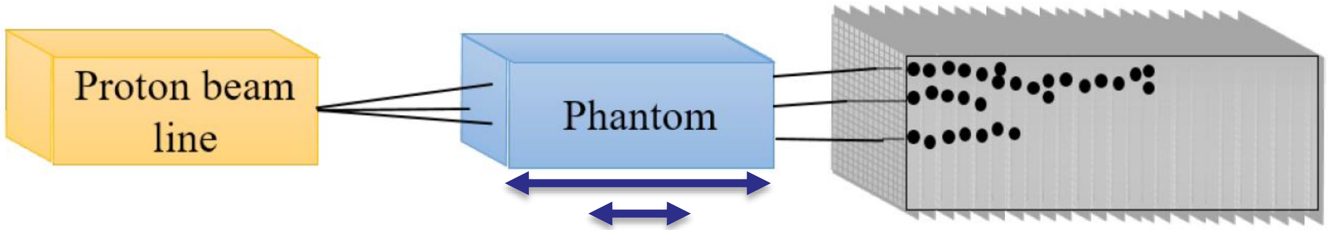
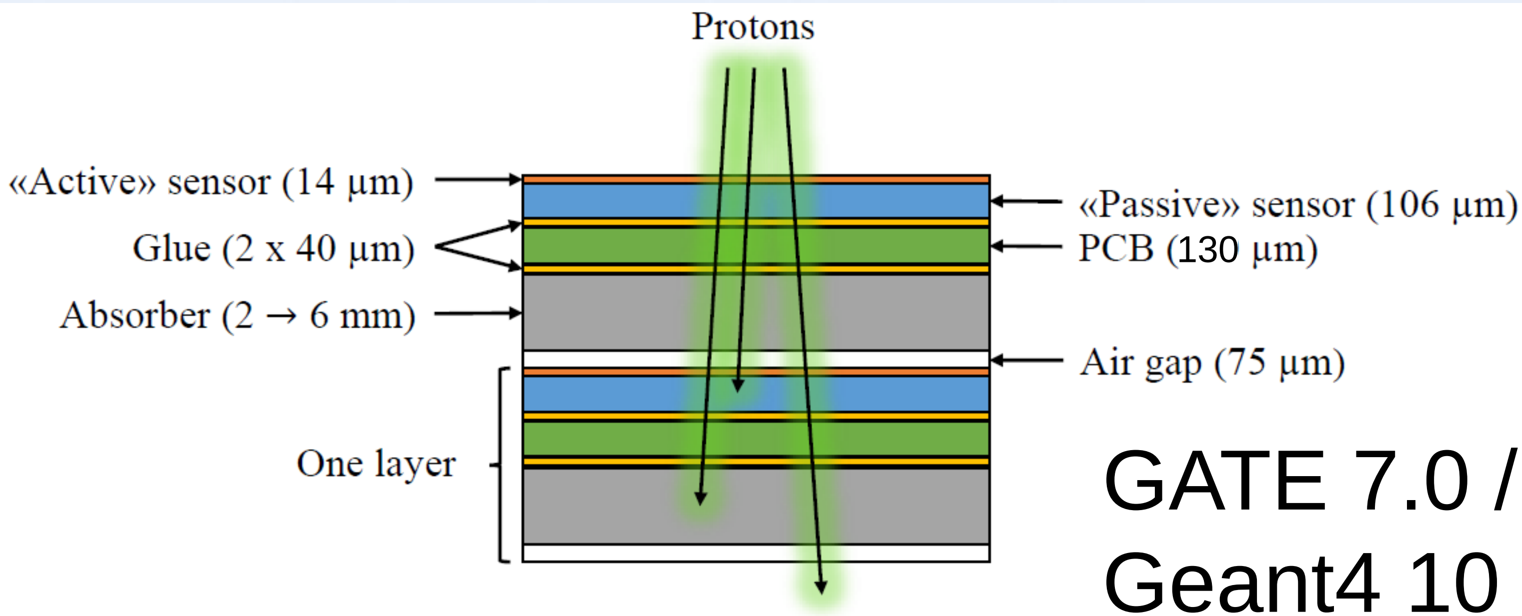
Simulation procedure for design evaluation





GATE 7.0 / Geant4 10

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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 + SiO_2 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.

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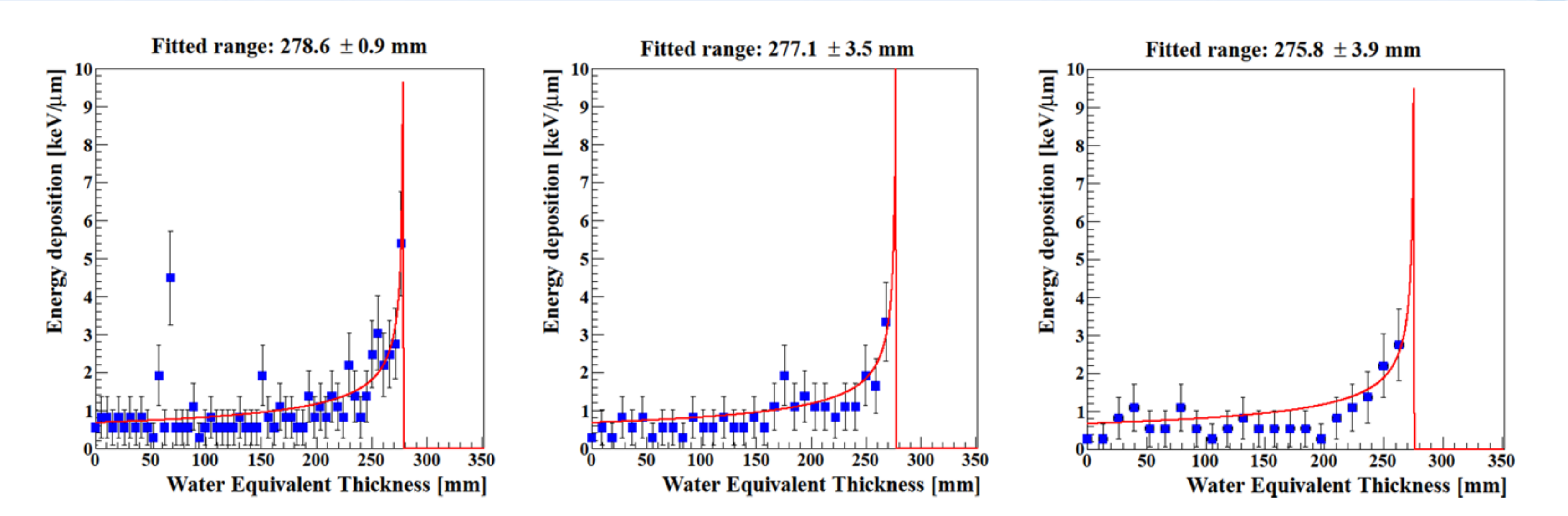
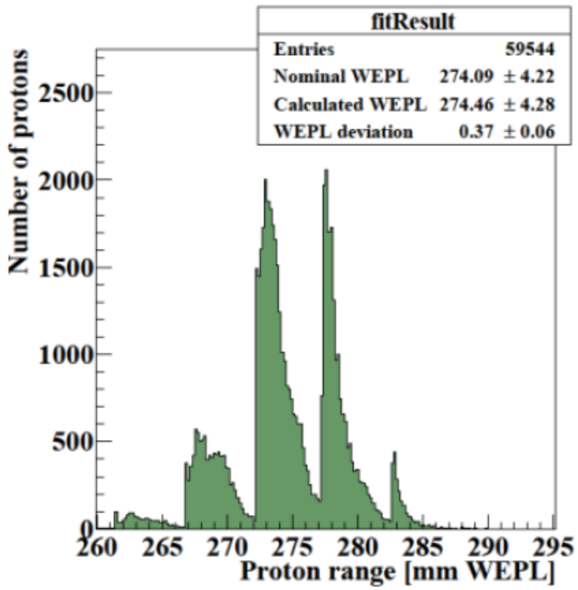
Range resolution from individual tracks

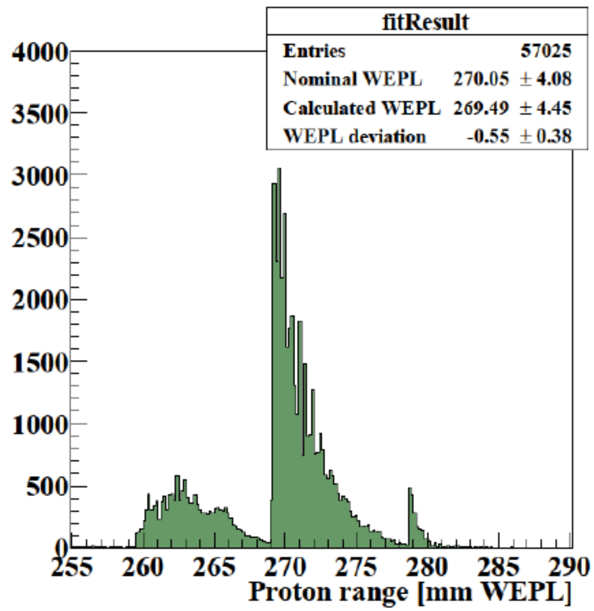


2 mm Al　　4 mm Al　　6 mm Al

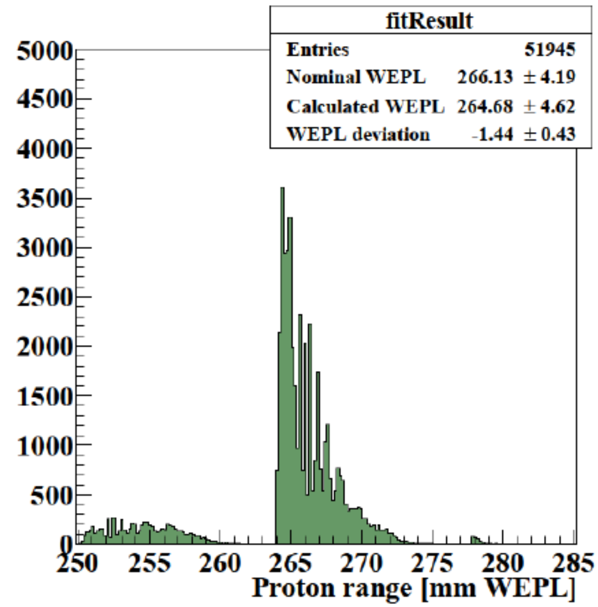
Range distribution per beam energy (/voxel)



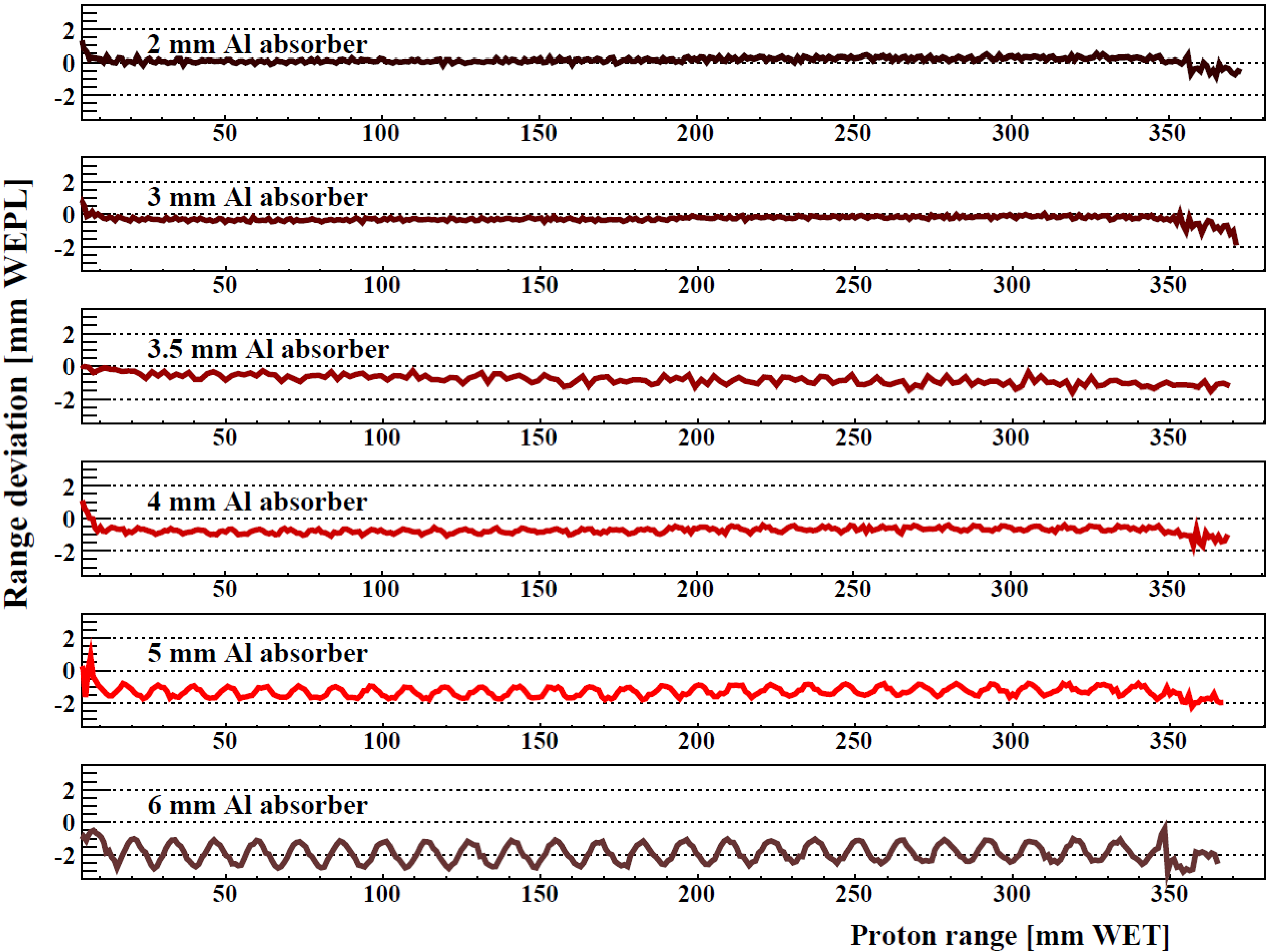
2 mm Al



4 mm Al



6 mm Al



Range deviation [mm WEPL]
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
2
0
-2
50
100
150
200
250
300
350
Proton range [mm WET]

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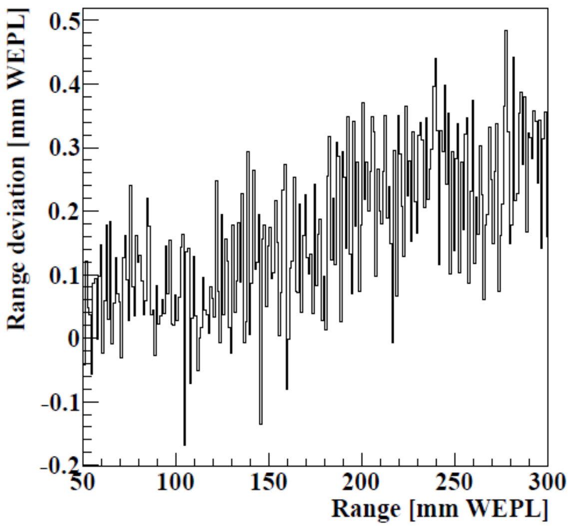
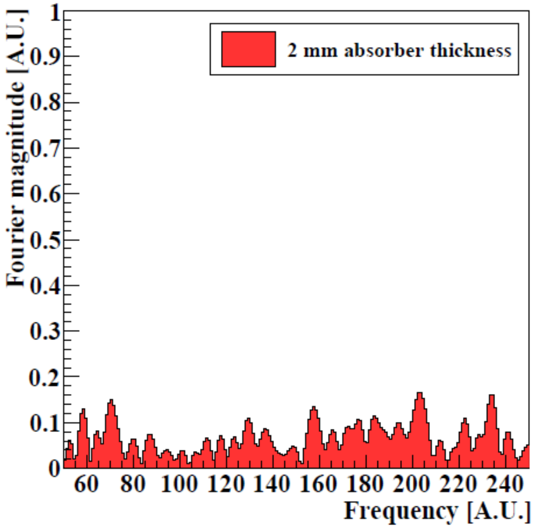
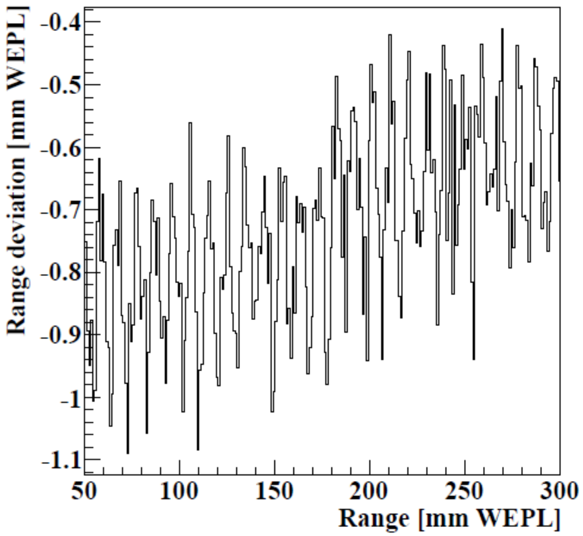
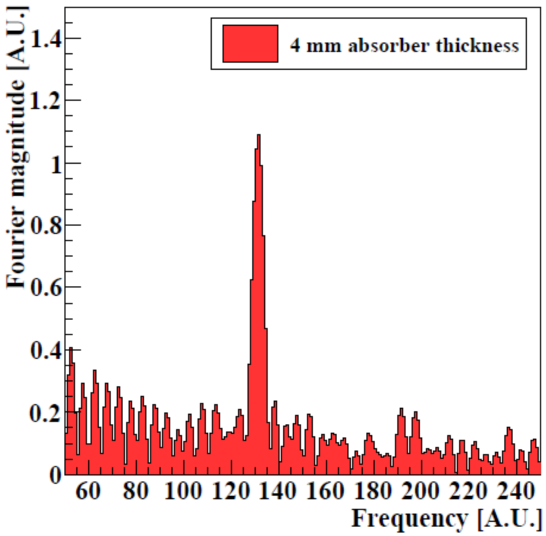
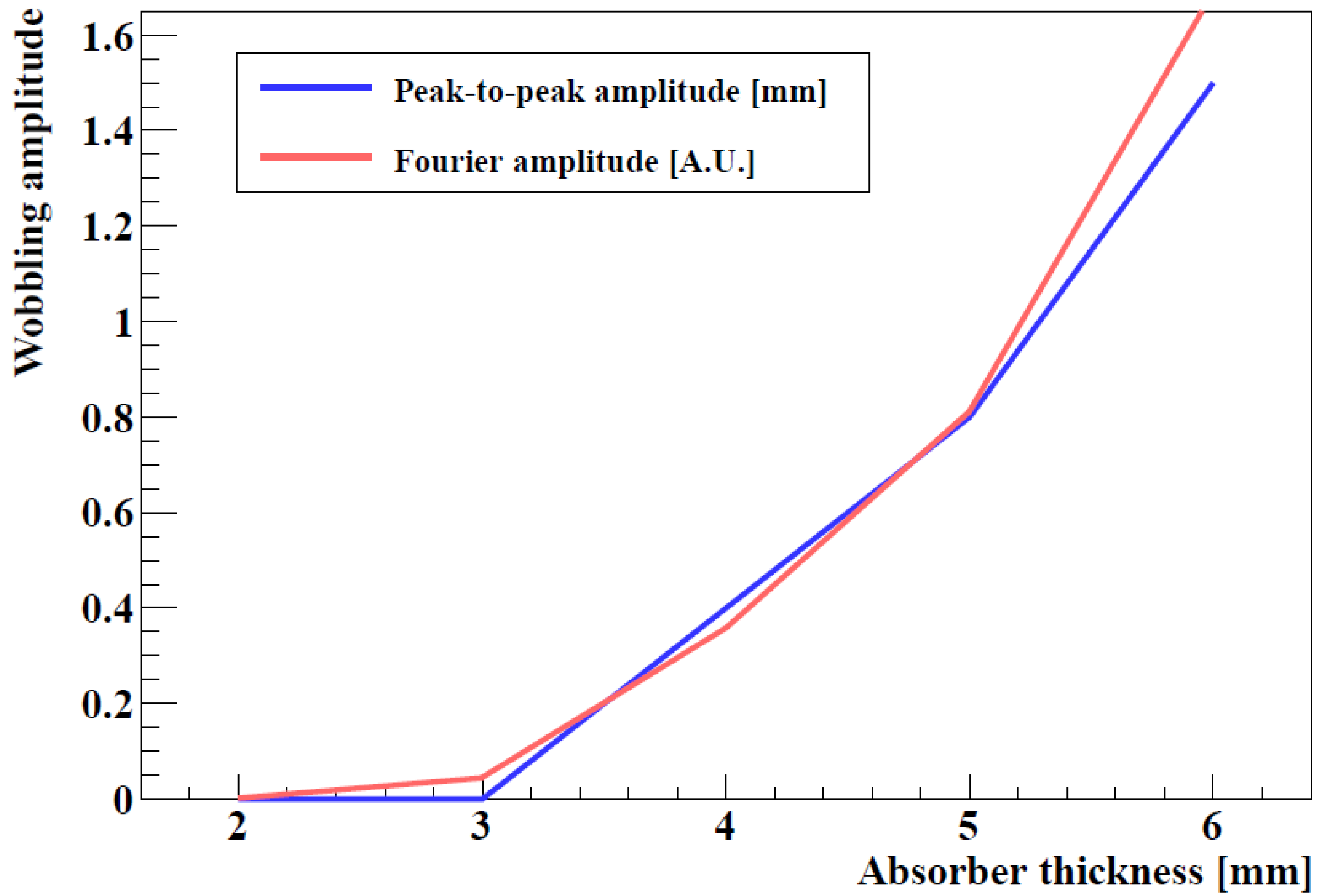
Characterizing the systematic oscillatory range error










Wobbling amplitude
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2
3
4
5
6
Absorber thickness [mm]
Peak-to-peak amplitude [mm]
Fourier amplitude [A.U.]

Compare this to the FoCal prototype…

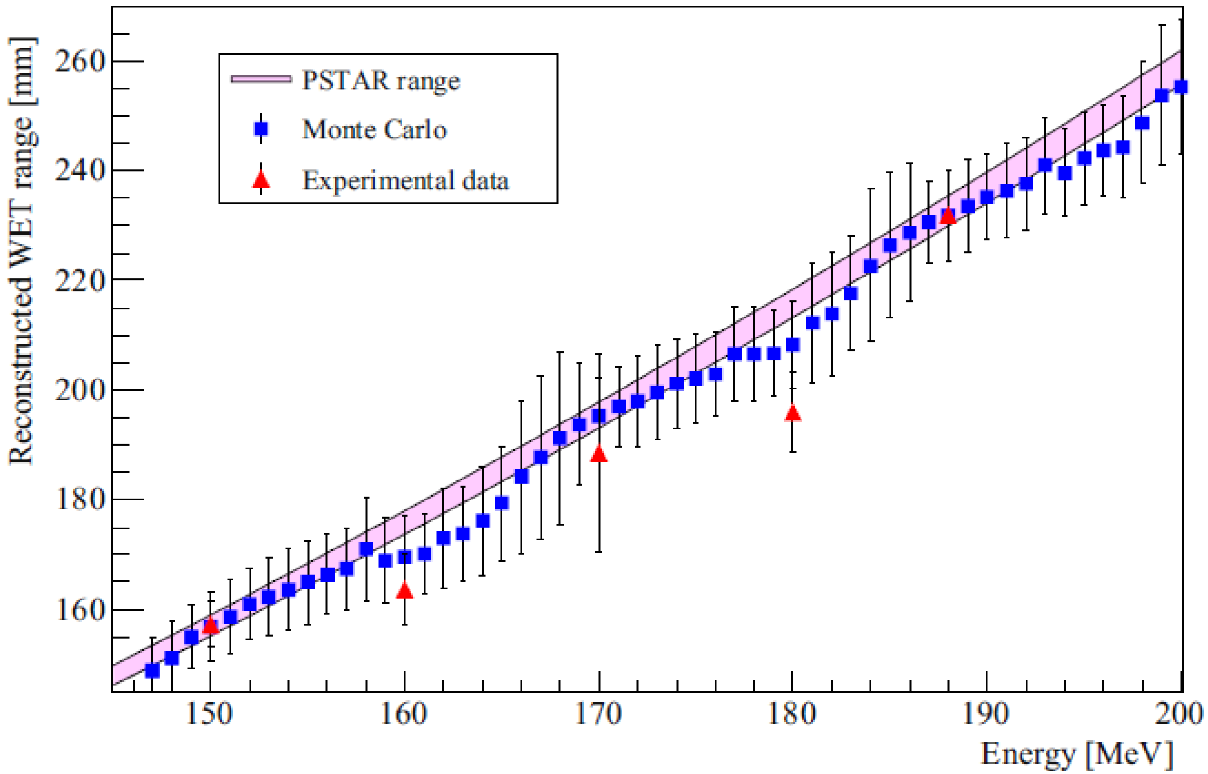
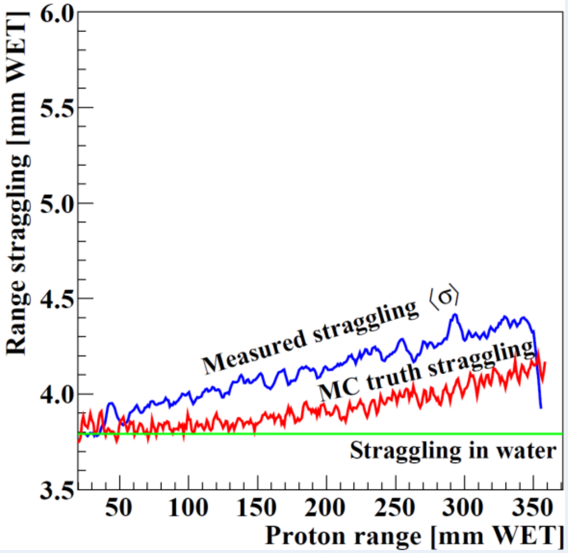
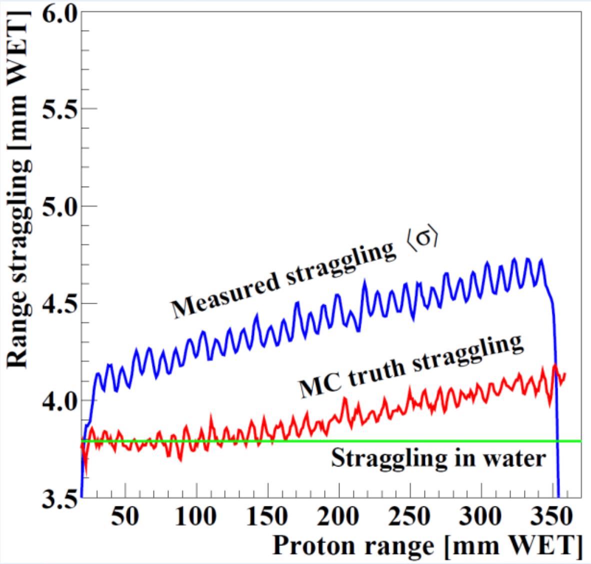


Fig. 7. Reconstructed ranges $\langle \hat{R_0} \rangle$ of proton beams with different energies. Results from both the MC simulations and from the experimental measurements are displayed on the plot. The PSTAR range is displayed using a band representing the expected range straggling. Average numbers 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.

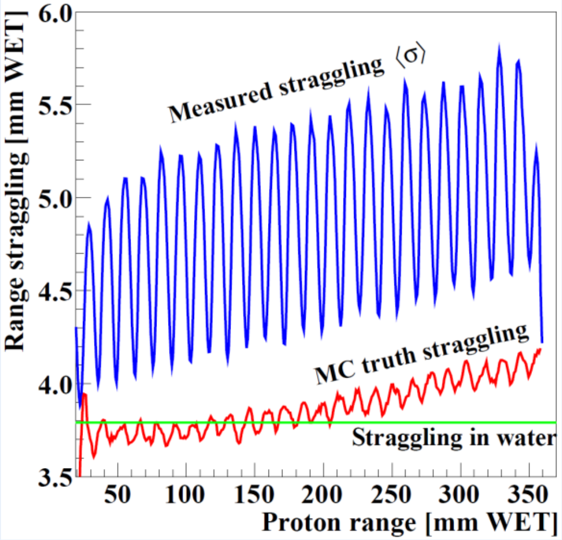
Range uncertainty



2 mm

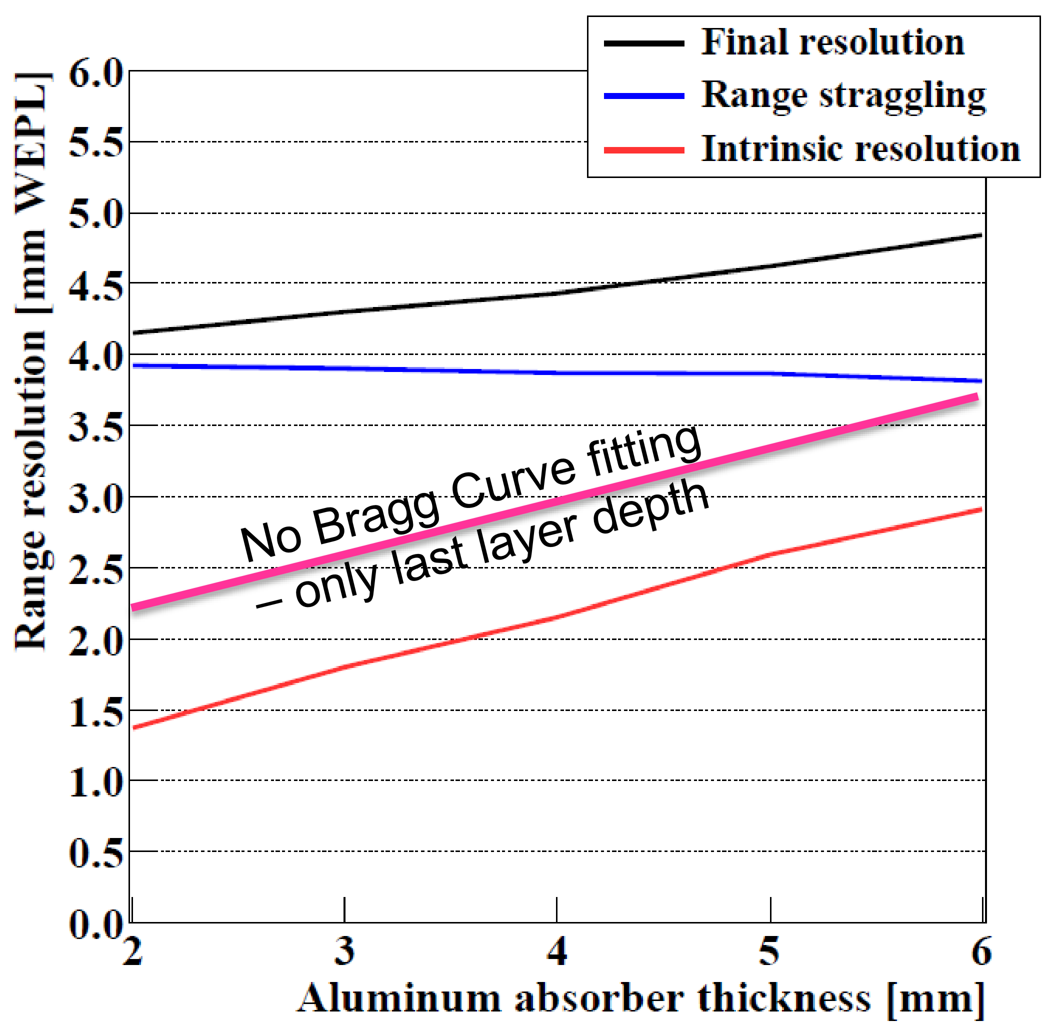


4 mm



6 mm

Range uncertainty



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 230 MeV (mean range)	65,3	54	46	40,1	35,5	31,9	29	26,5	24,4
Layers 230 MeV (+ 3 sigma)	66,6	55,2	47,1	41,1	36,5	32,8	29,7	27,2	25,1
Layers 200 MeV (mean range)	51,5	42,6	36,3	31,7	28	25,2	22,8	20,9	19,3
Layers 200 MeV (+ 3 sigma)	52,8	43,8	37,4	32,6	29	26	23,6	21,6	20

Table 1 *Number of layers needed to contain a 230 and 200 MeV beam, with and without a 3 sigma range straggling addition, for different absorber thicknesses.*

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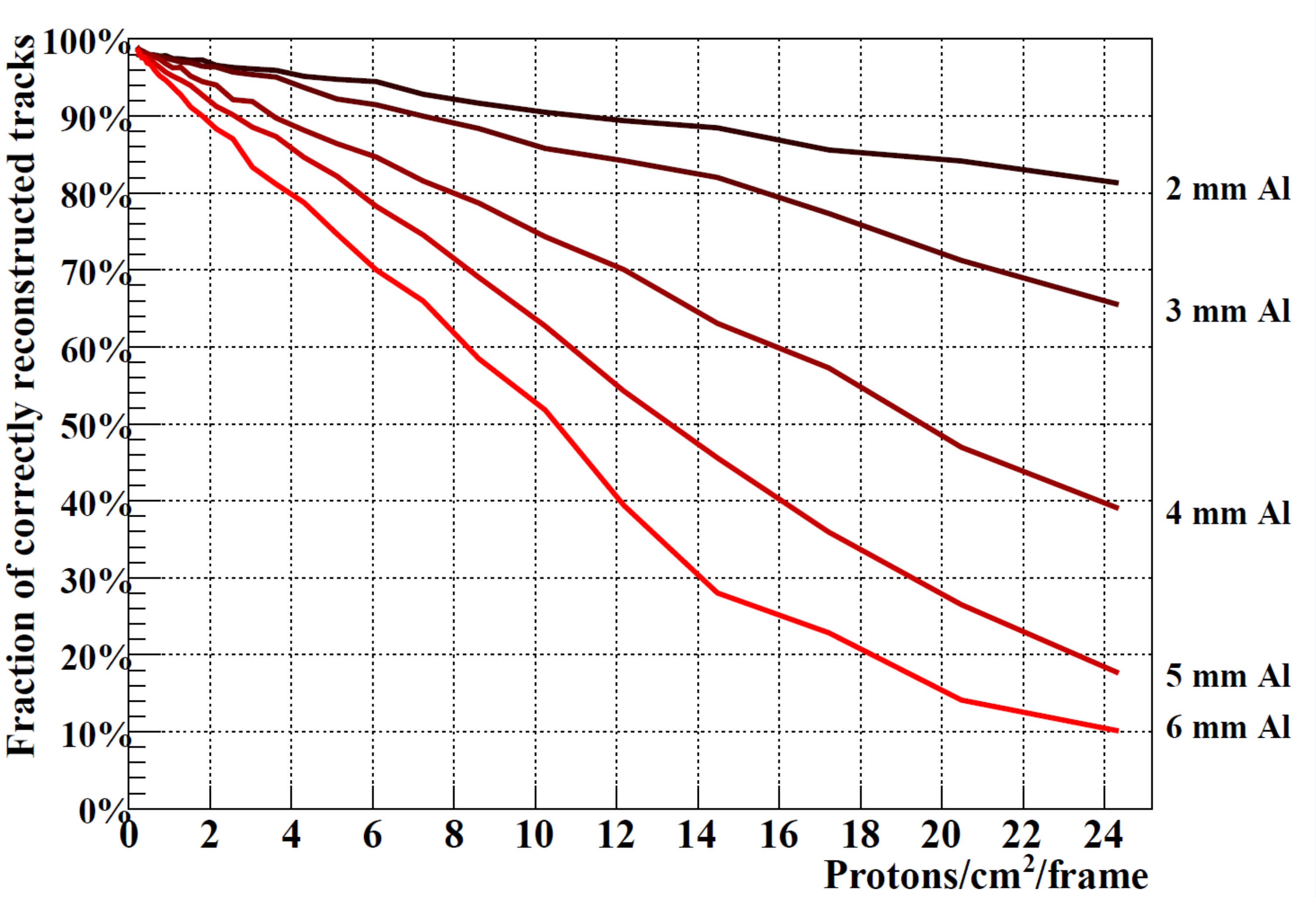
Some simulation results
Track reconstruction efficiency



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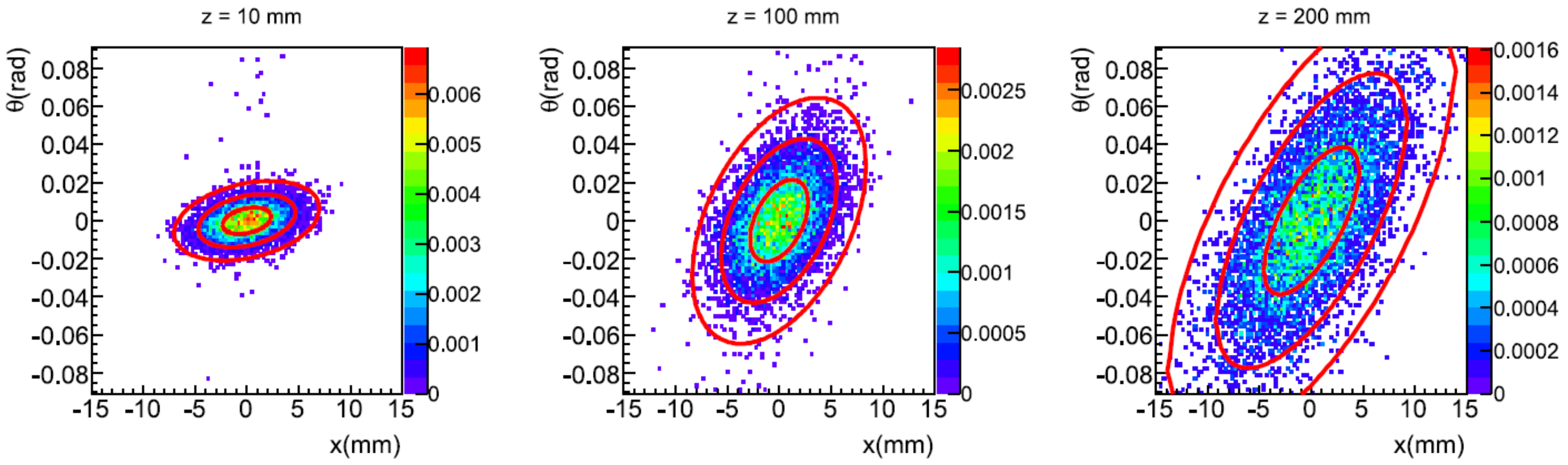
Expected beam density



(a) (b) (c)

FIG. 3. Beam ellipse area in the phase space for three different water depths (a) $z = 10$ mm, (b) $z = 100$ mm, and (c) $z = 200$ mm. The colored scale refers to the normalized proton probability density function from the Monte Carlo sample. The contour lines represent the 1-, 2-, and 3-σ of the normalized bivariate Gaussian distribution predicted analytically.

A pencil beam approach to proton computed tomography

Regina Rescigno,[a] Cécile Bopp, Marc Rousseau, and David Brasse
Université de Strasbourg, IPHC, 23 rue du Loess, Strasbourg 67037, France and CNRS, UMR7178, Strasbourg 67037, France

Detector size recommendations

- Longitudinal size = 41 layers w/ 3.5 mm Al absorbers
- Lateral size of ALPIDE chip = 3 x 1.5 cm, to be stiched in 9 x (2 * 5) fashion: 27 x 15 cm^2
    - Horizontal size covers head-sized phantoms ++
        - Head phantoms usually with 16 cm diameter
        - Body phantoms with 32 cm diameter
    - Vertical size → Stitch images vertically through multiple scans (as with clinical full-body projection x-ray or concurrent pCT prototypes)
    - LLUMC prototype: 36 x 8.6 cm laterally (w/stiching)
- 41 * 90 = 3700 chips

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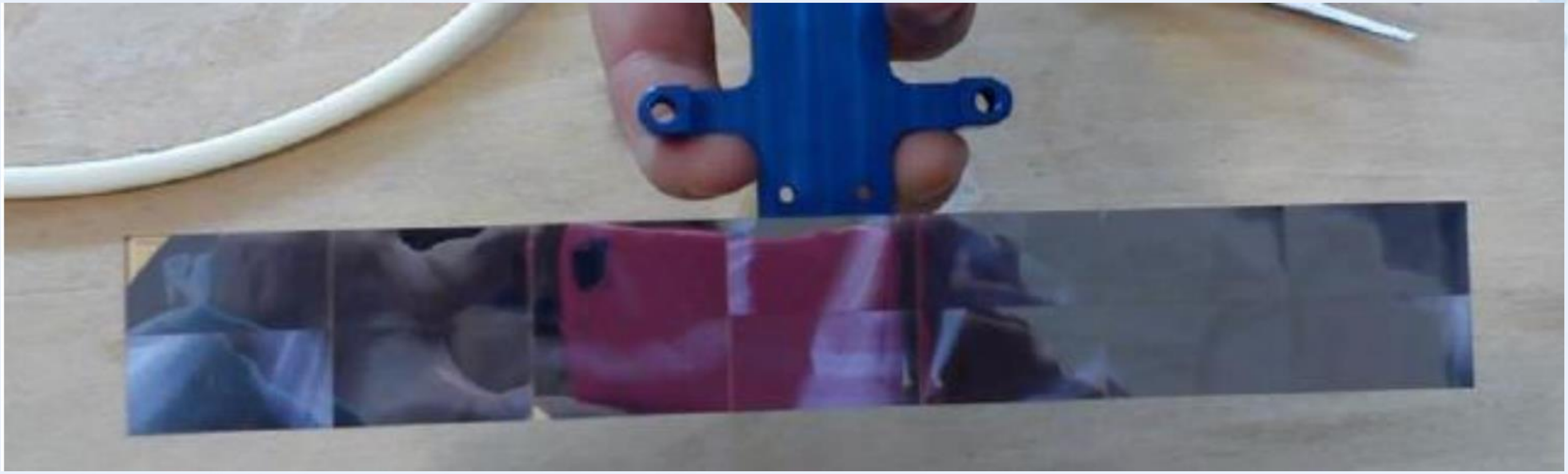
Detector size recommendations



Shown: 7x2 chip array -> 21 x 3 cm^2

We want 9x(2x5) chip array → 27 x 15 cm^2

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Other considerations

- No energy absorbers between first two layers
    - Tracking layer with incoming vector determination
- If tracker in front of patient:
    - Tough task to ID > 5 particles per readout due to in-patient scattering
    - Optimal positioning of layers etc.: Already a study by Bopp et al. (PMB 59:23 N197 (2014))
- Cooling and absorber material / shape: ~35 mW per cm^2 * 41 layers * (27 x 15 cm^2) = 600 W @ ITS readout density (15 W per layer)

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Conclusion next prototype

- Track 2 M protons/s/cm^2 with 80% reconstruction efficiency
  - This number to increase with better algorithms than mine
- Range uncertainty per proton = 13 % above range straggling
  - (2 mm added width, 3.8 mm range straggling = 4.3 mm total)
- Oscillation artefact below 0.1 mm
- <0.5 mm systematic error from 20 mm WET to full detector length (containing a 230 MeV beam)