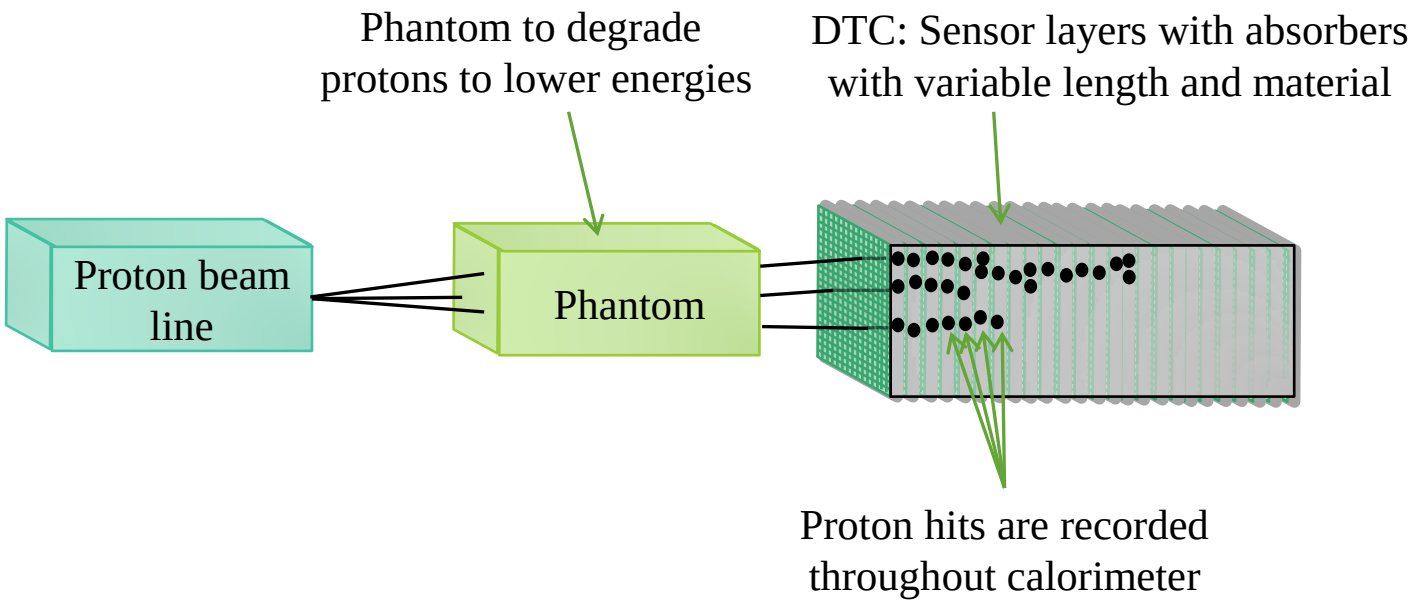
Optimizing the DTC

2017-03-03

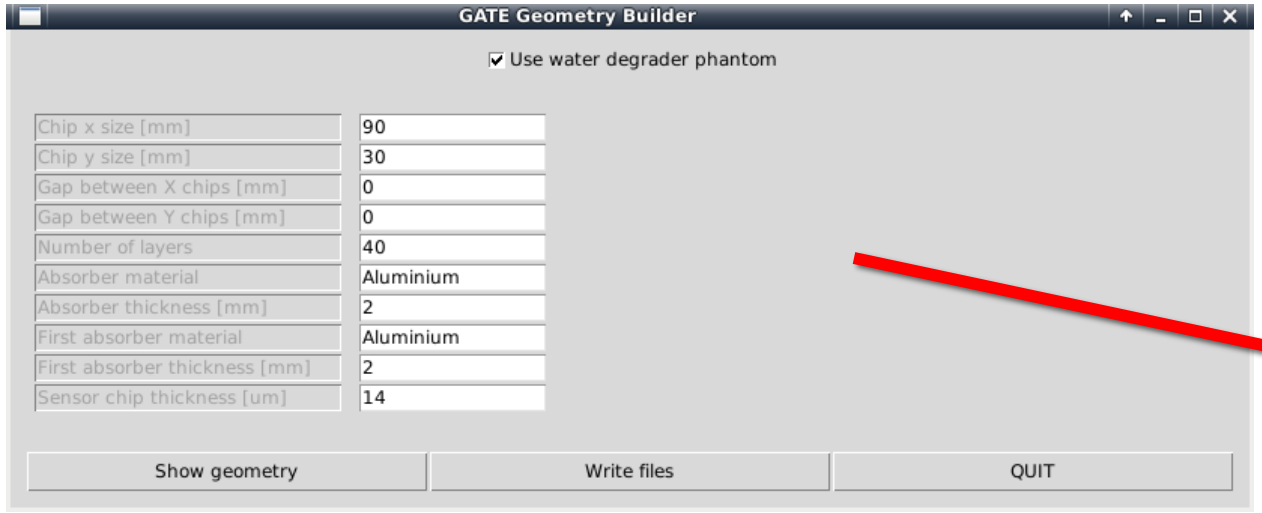
Goals

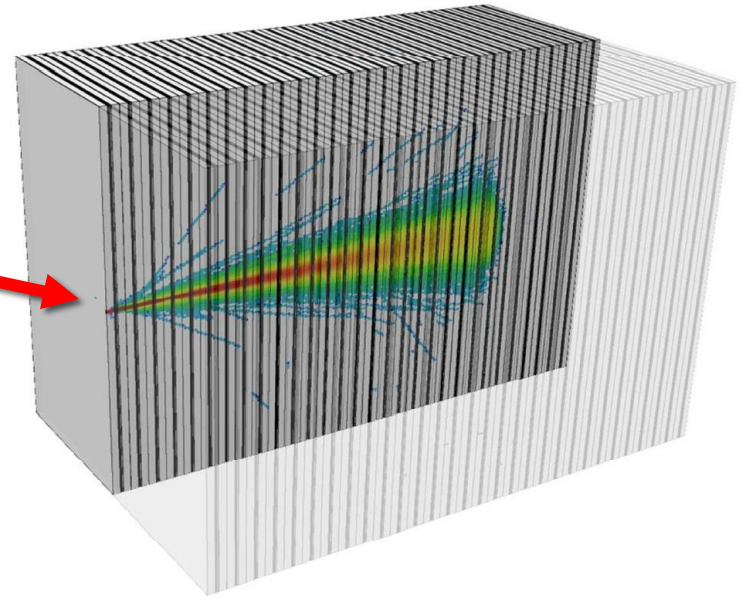
1. To find the best possible design for the range calorimeter part of DTC
2. Constrained by $$$ and Range Straggling
    1. Need to contain a 250 MeV proton beam
    2. Linear resolution to be limited somewhat by range straggling ~ 1 %

Method


Phantom to degrade protons to lower energies
DTC: Sensor layers with absorbers with variable length and material
Proton beam line
Phantom
Proton hits are recorded throughout calorimeter

GATE setup



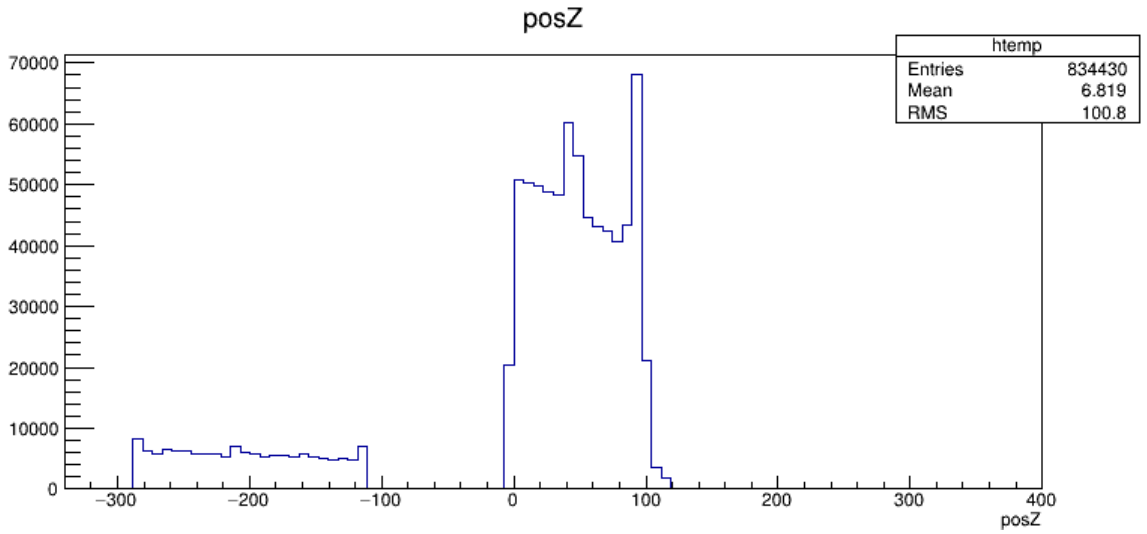


For example, with a 3 mm degrader, and simulating a 250 MeV beam passing through a phantom of 50, 55, 60, 65 and 70 mm water:

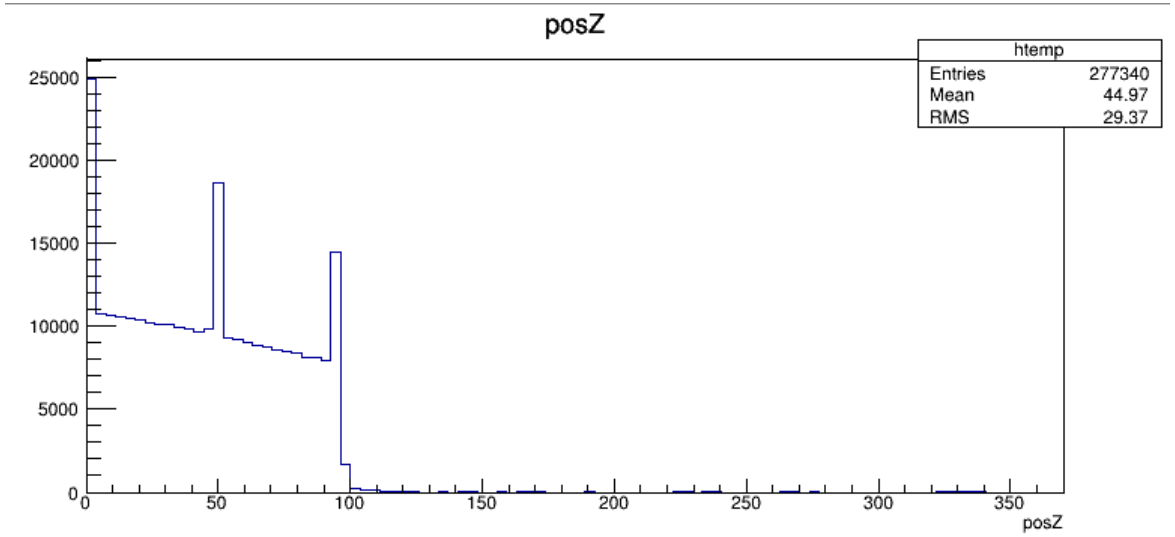
```
[gate/python] $ sh runDegrader.sh 3 50 5 70
```

Monte Carlo simulations

Full simulation: Record everything: 5’ primaries/energy



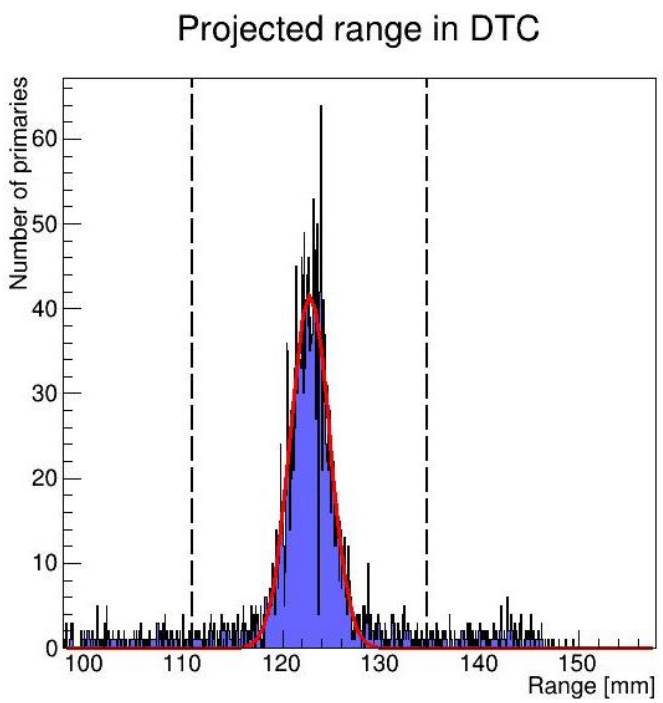
Chip simulation: Record only events in sensors: 15’ primaries/energy

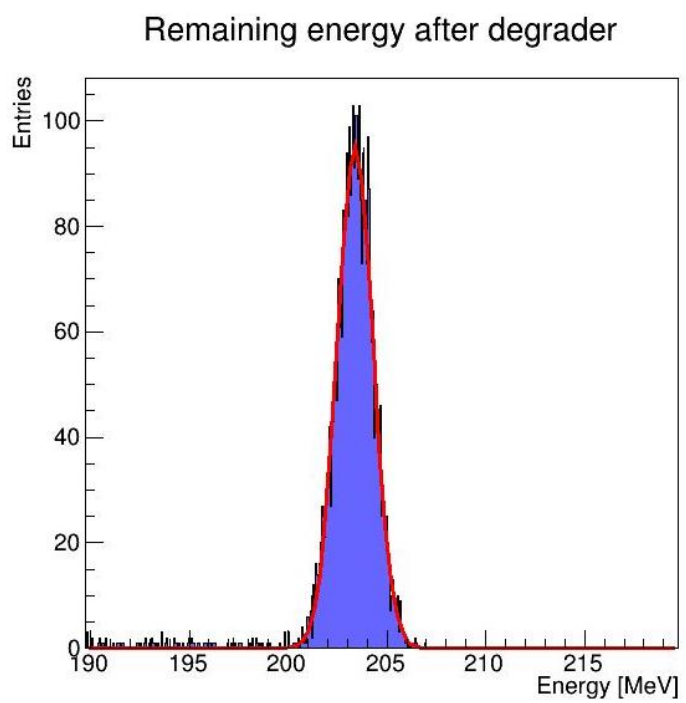


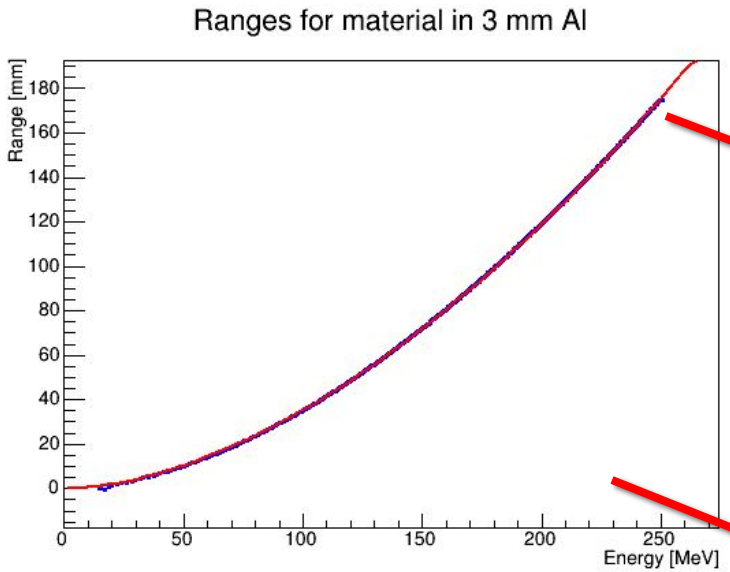
Full MC simulations

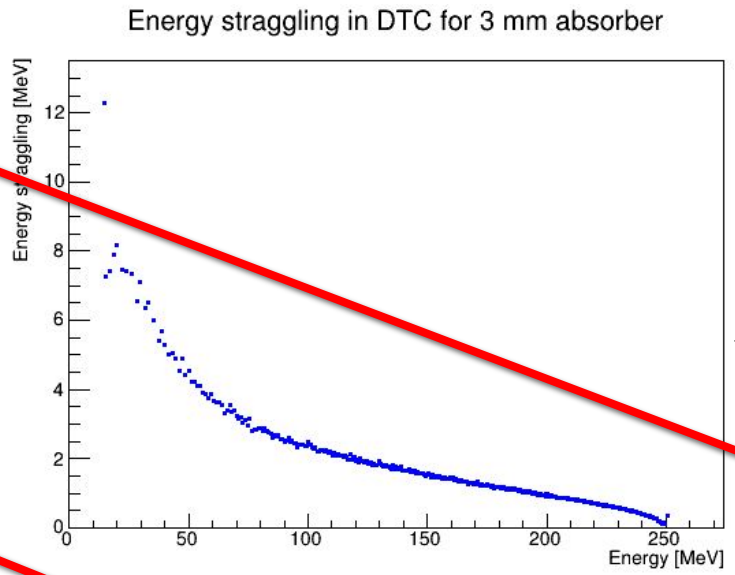
The «Gold standard» in this context

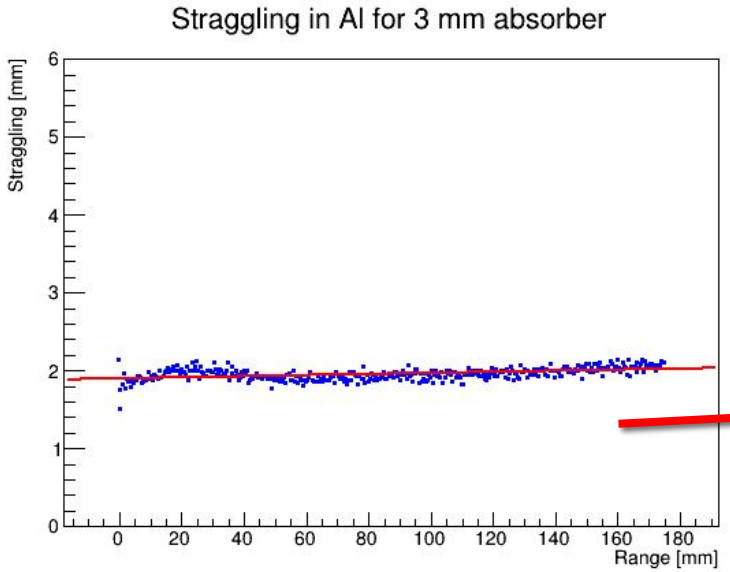
1. Range for each water phantom thickness and geometry configuration
2. Range straggling
3. Energy spread distal to DTC

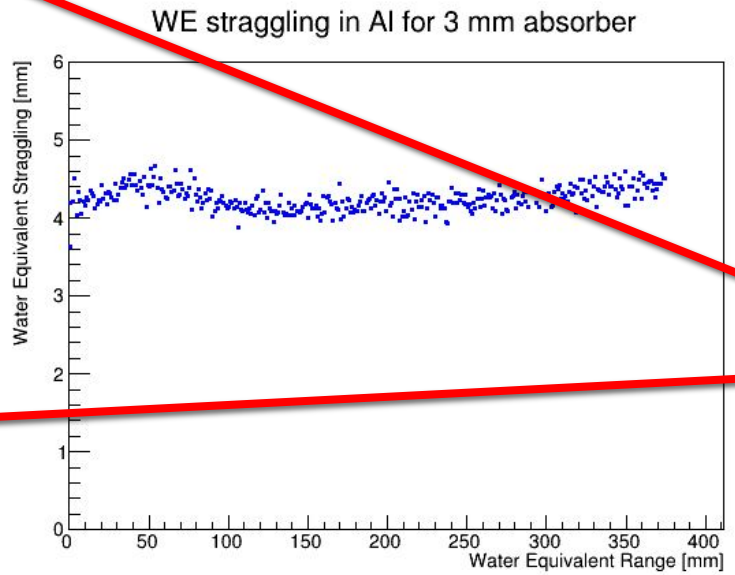













```
 1 # ENERGY RANGE
 2 14.845 0.056788
 3 15.3795 0.104973
 4 17.2187 -0.215777
 5 18.6584 0.855986
 6 20.1045 1.2952
 7 22.0102 1.93137
 8 23.889 2.34508
 9 25.8993 2.82206
10 28.2813 3.44492
```

In addition, the following parameters should be extracted:

```
Bragg-Kleeman parameters: R = 0.011626 E ^ 1.743151
Straggling = 1.8568 + 0.000856 R
```

Configuring the chip MC simulations

```
81  void createSplines() {
...
107    else if (kAbsorbatorThickness = 3) {
108       in.open("Data/Ranges/3mm_Al.csv");
109    }
...
192    else if (kAbsorbatorThickness = 3) {
193       alpha_aluminum = 0.011626;
194       p_aluminum = 1.743151;
195       straggling_a = 1.8568;
196       straggling_b = 0.000856;
197    }
```

Or in the corresponding material (alpha_pmma, alpha_carbon, etc.) and absorbatorthickness lines.

And in the file `DTCToolkit/Scripts/makePlots.C`, put the \alpha, p parameters.

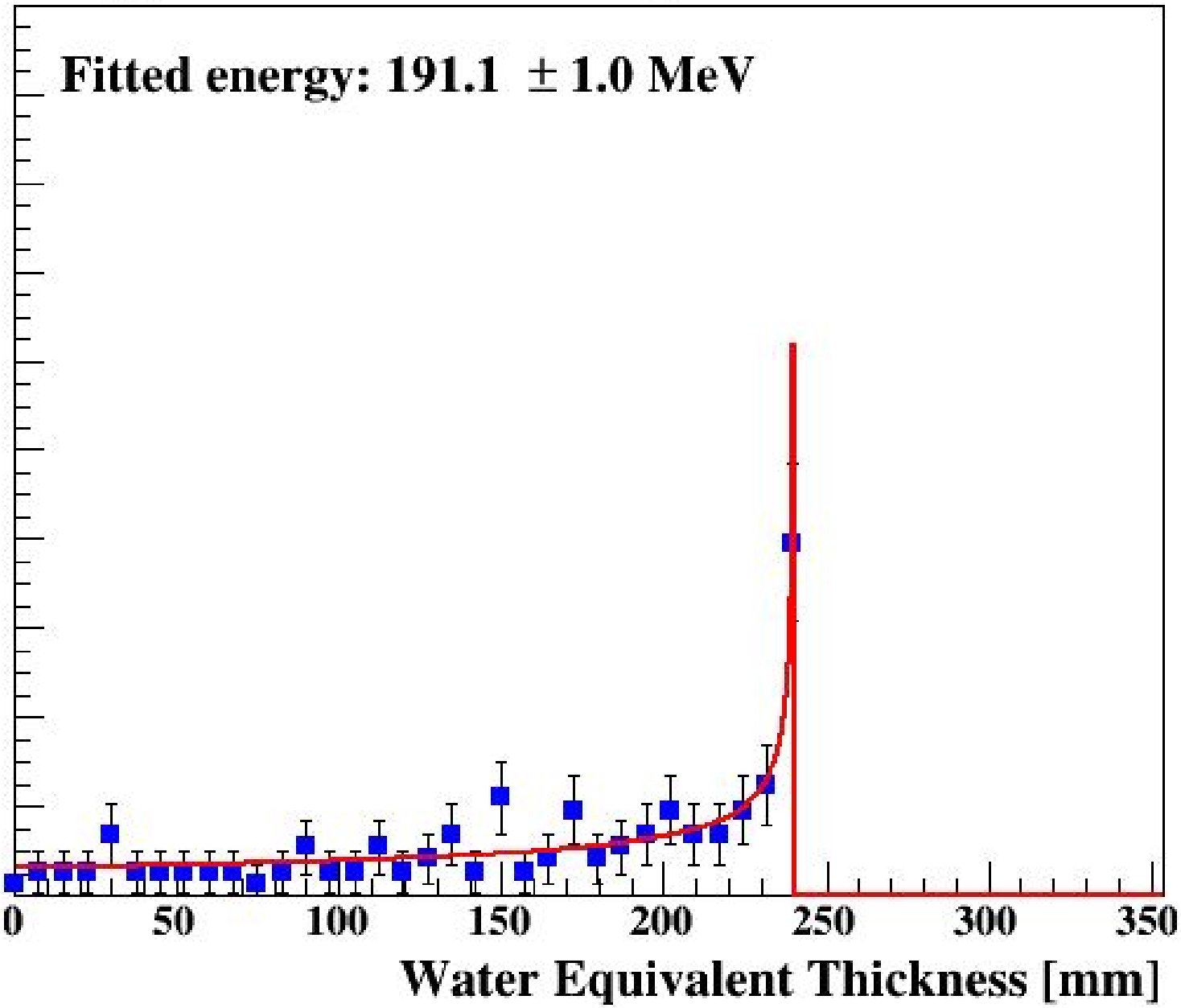
```
144   else if (absorberThickness == 3) {
145      a_dtc = 0.011626;
146      p_dtc = 1.743151;
147    }
```

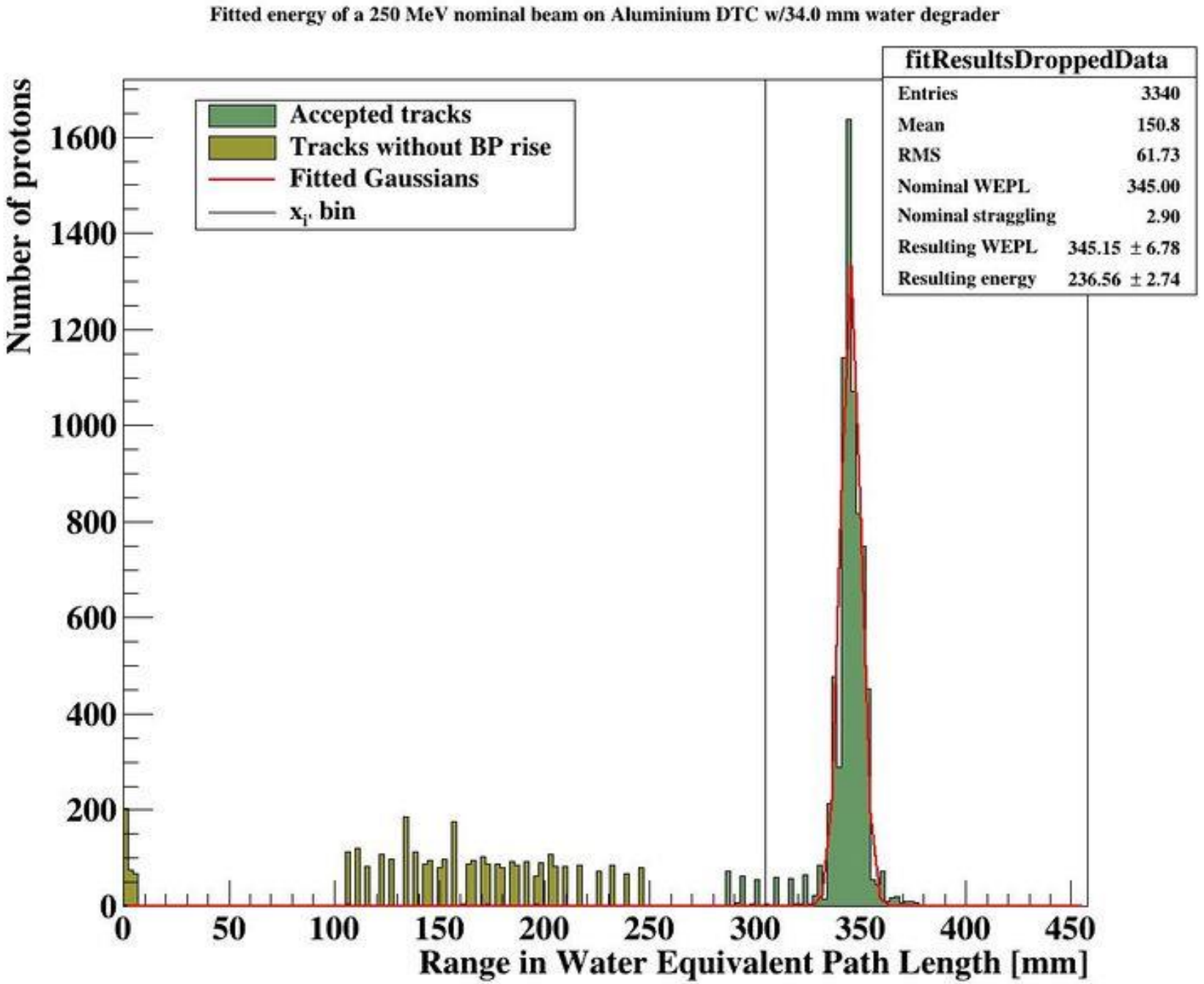
Chip MC simulations

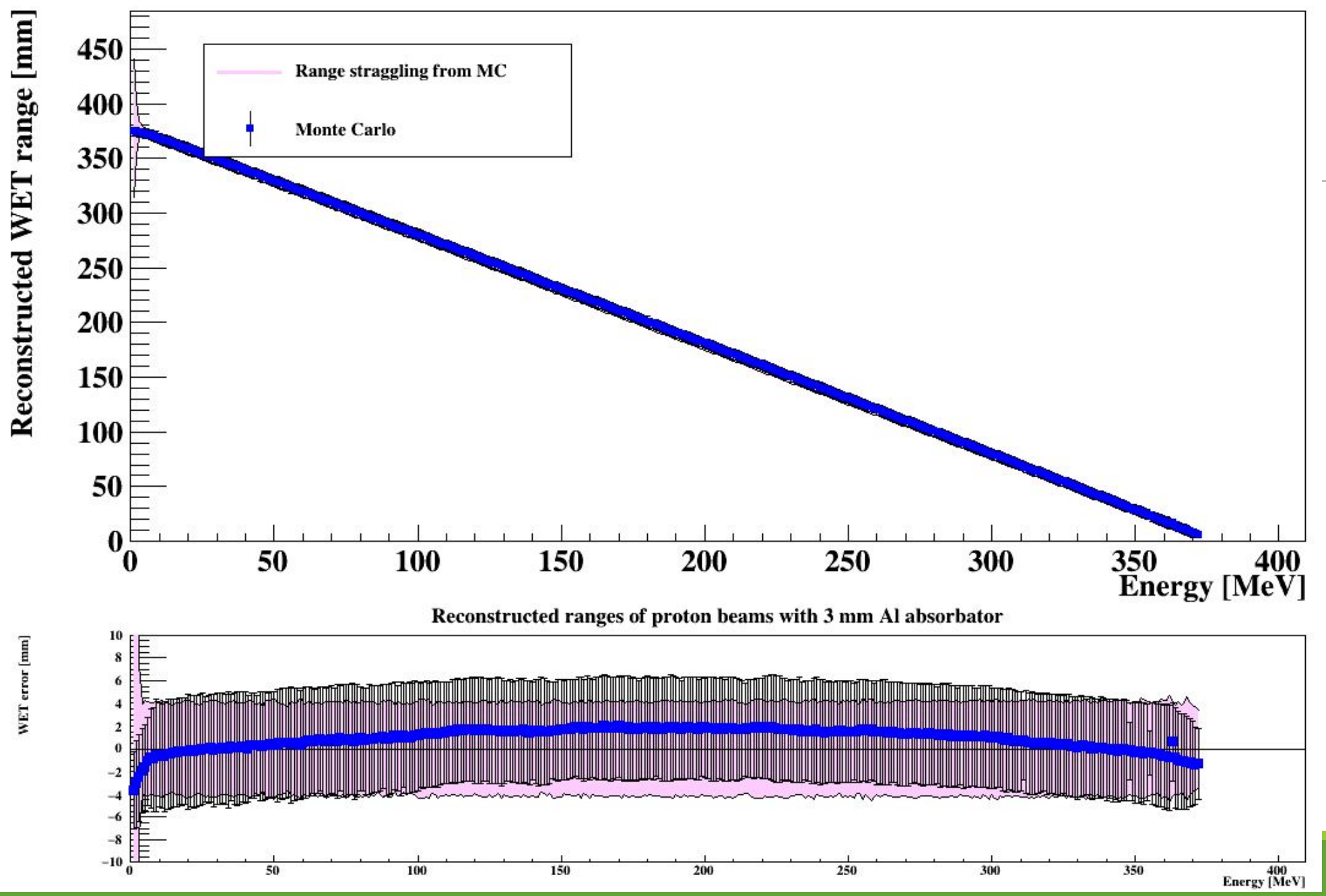
From the GATE data, we do:

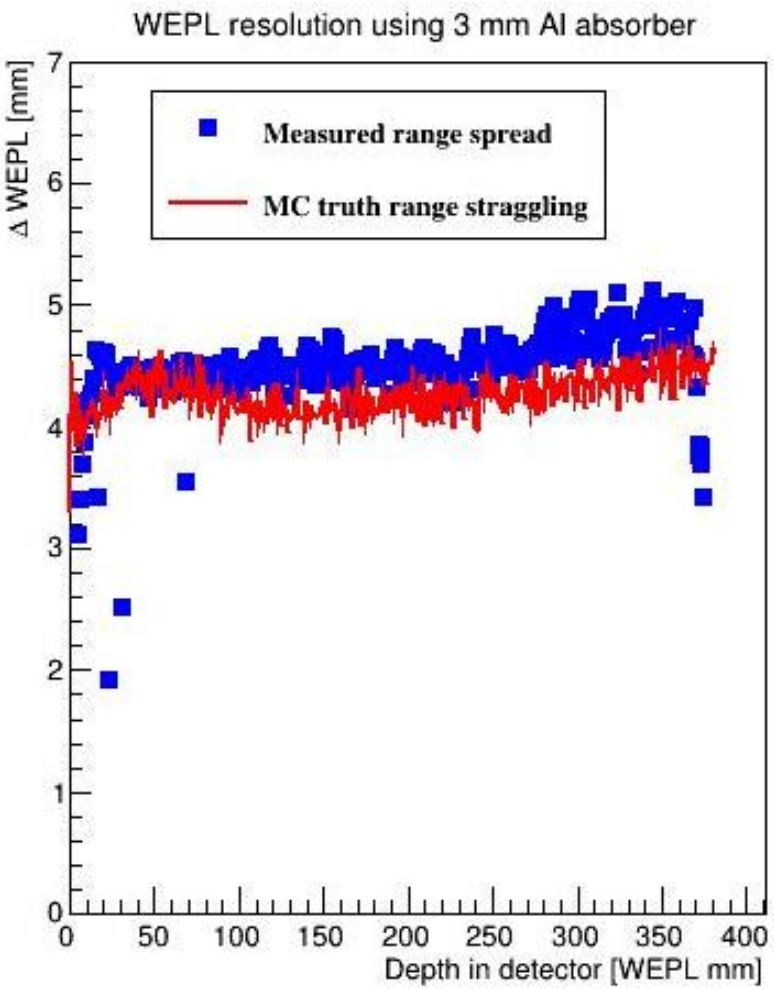
1. Make Cluster objects containing (x,y,layer,edep,eventID) from the MC ROOT files **(simplified)**
2. Make Tracks using the eventID **(simplified)**
3. Find optimal range for each track using Bragg curve model fit with layer/edep
4. Find Mean and Width of the range distribution of all proton tracks
    1. Mean: DTC Accuracy
    2. Width: DTC Resolution
5. Repeat for all water degrader thicknesses ($\simeq 400$ energies per geometry)
6. Make plot of the variation of Accuracy and Resolution with water degrader thicknesses

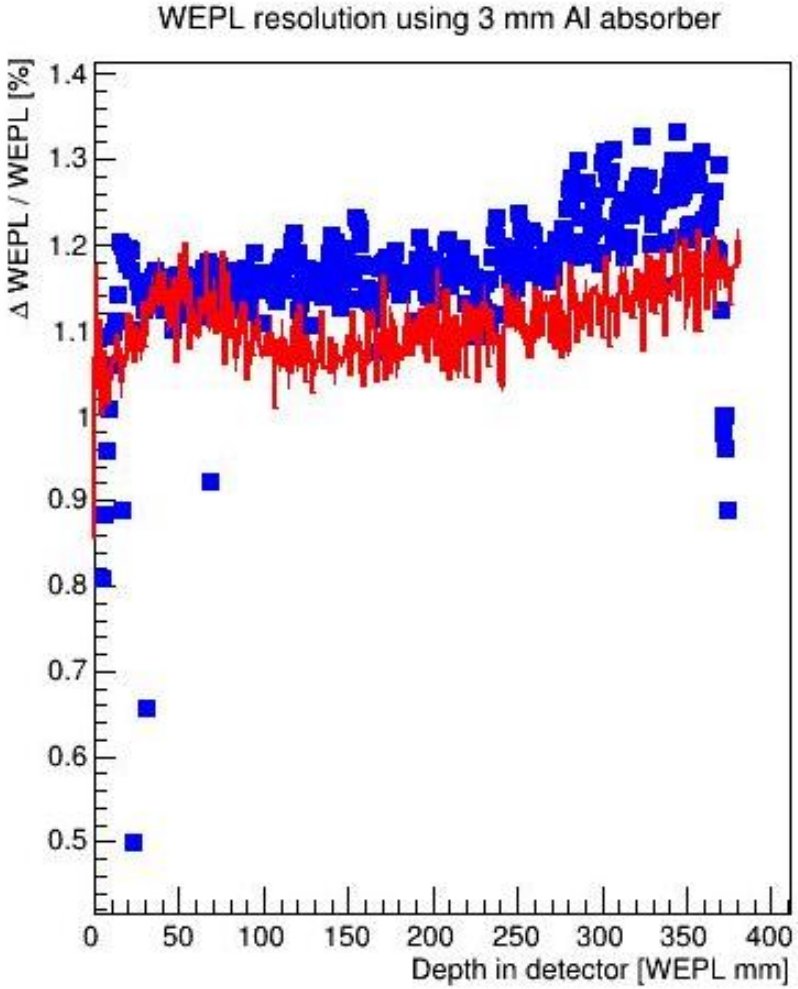
Bragg-Kleeman fit to exp. data at 192 MeV

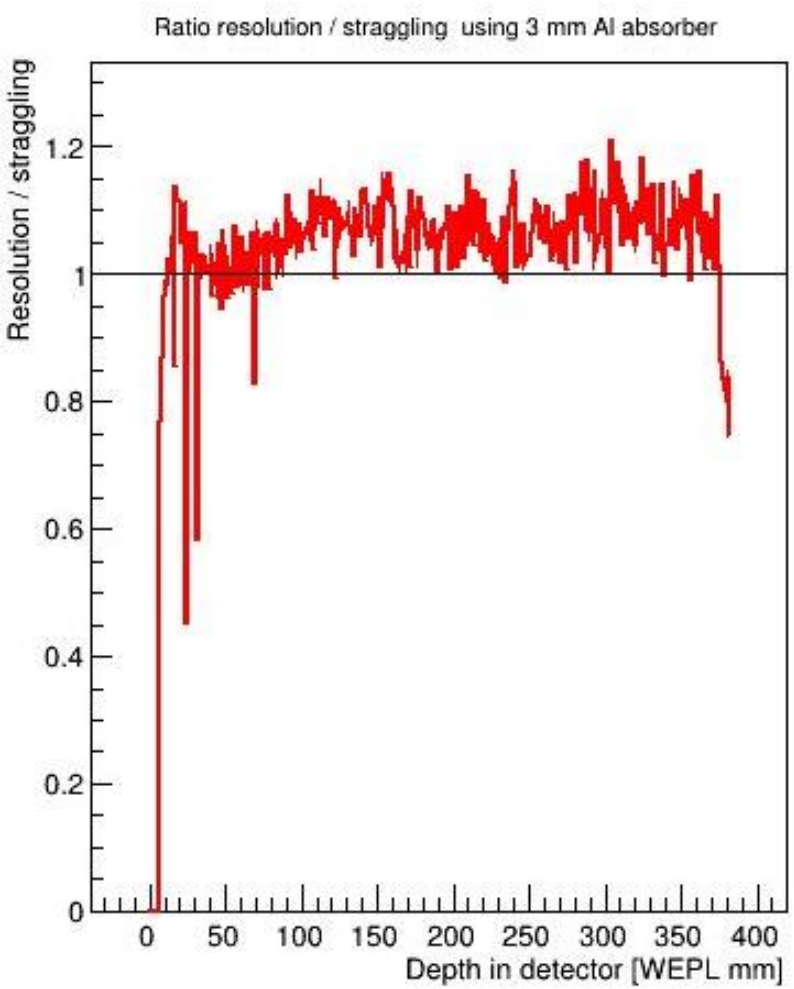



Fitted energy of a 250 MeV nominal beam on Aluminium DTC w/34.0 mm water degrader
fitResultsDroppedData
Entries 3340
Mean 150.8
RMS 61.73
Nominal WEPL 345.00
Nominal straggling 2.90
Resulting WEPL 345.15 ± 6.78
Resulting energy 236.56 ± 2.74
Accepted tracks
Tracks without BP rise
Fitted Gaussians
x_i, bin
Number of protons
0
200
400
600
800
1000
1200
1400
1600
0
50
100
150
200
250
300
350
400
450
Range in Water Equivalent Path Length [mm]


Reconstructed ranges of proton beams with 3 mm Al absorbator
Reconstructed WET range [mm]
Range straggling from MC
Monte Carlo
Energy [MeV]
Reconstructed ranges of proton beams with 3 mm Al absorbator
WET error [mm]
Energy [MeV]


WEPL resolution using 3 mm Al absorber
Measured range spread
MC truth range straggling
Δ WEPL [mm]
Depth in detector [WEPL mm]


WEPL resolution using 3 mm Al absorber
Δ WEPL / WEPL [%]
Depth in detector [WEPL mm]

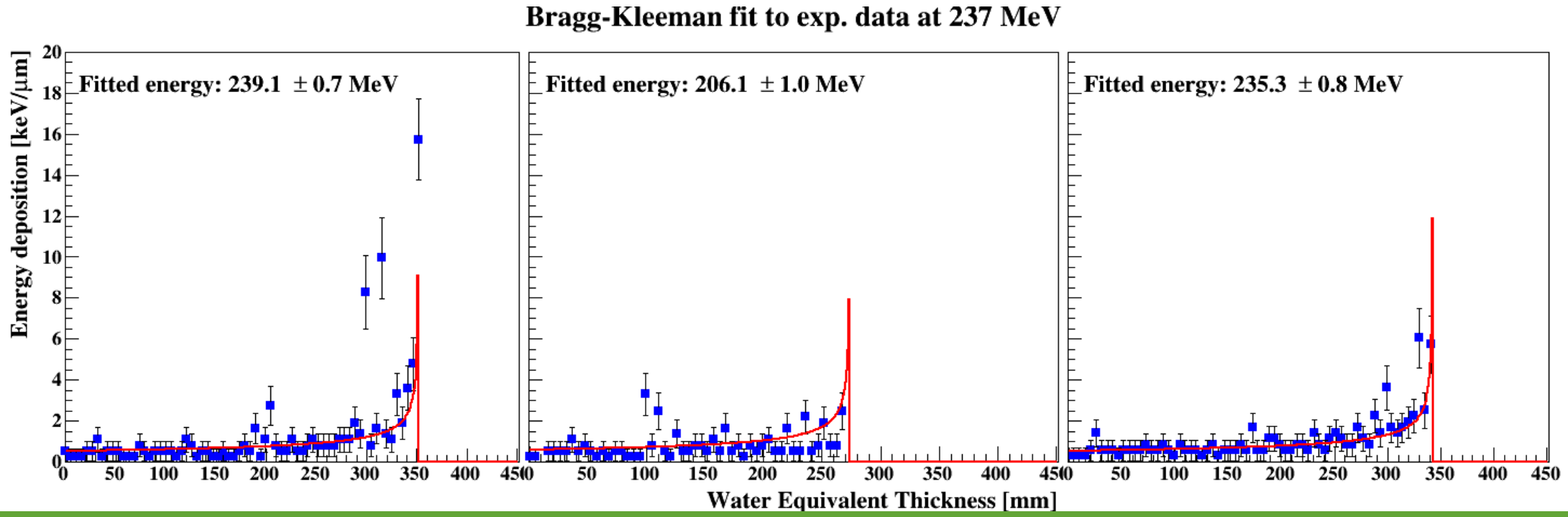

Ratio resolution / straggling using 3 mm Al absorber
Resolution / straggling
Depth in detector [WEPL mm]

Points to discuss

1. Approaches to the analysis
2. Resolution determination
3. Features we **understand** and **don’t understand**

Approaches to the analysis

1. How to properly fit the Bragg Peak?
   - **Choice of limits (currently: 0 to last recorded hit + 1 layer)**
   - **Choice of bias (currently: Start of range fit is last recorded hit + 0.5 layer)**
   - Choice of variables to fit (currently: Only range. More spread out if scale is included)



Approaches to the analysis

1. How to properly fit the Bragg Peak?
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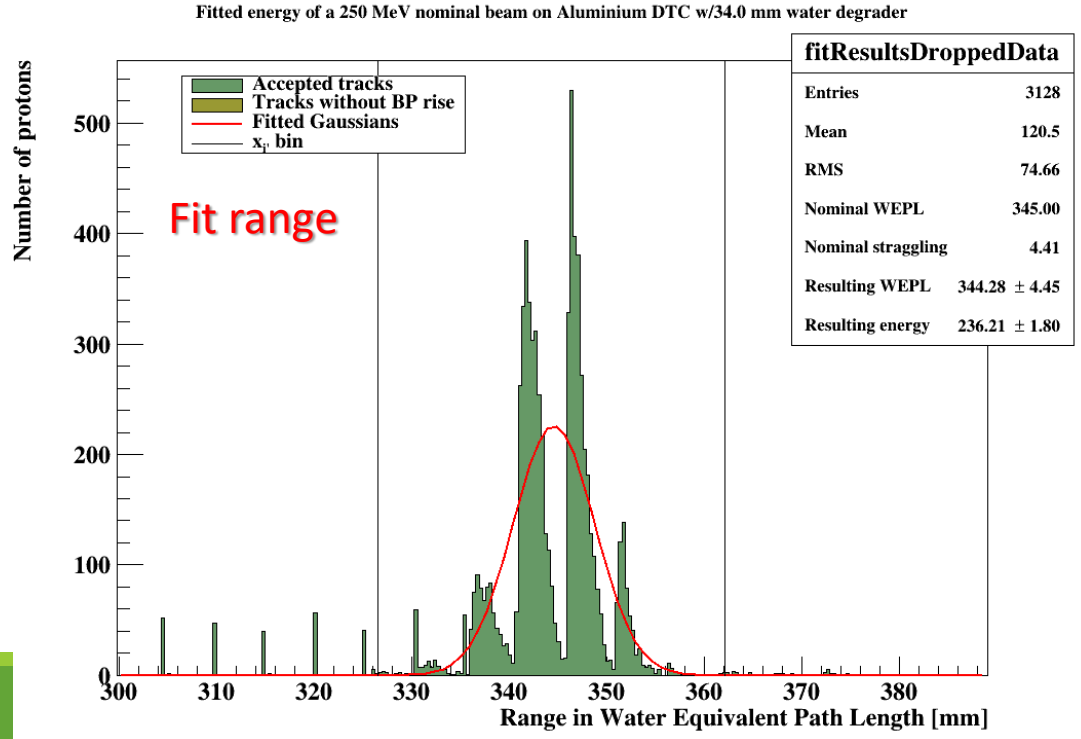
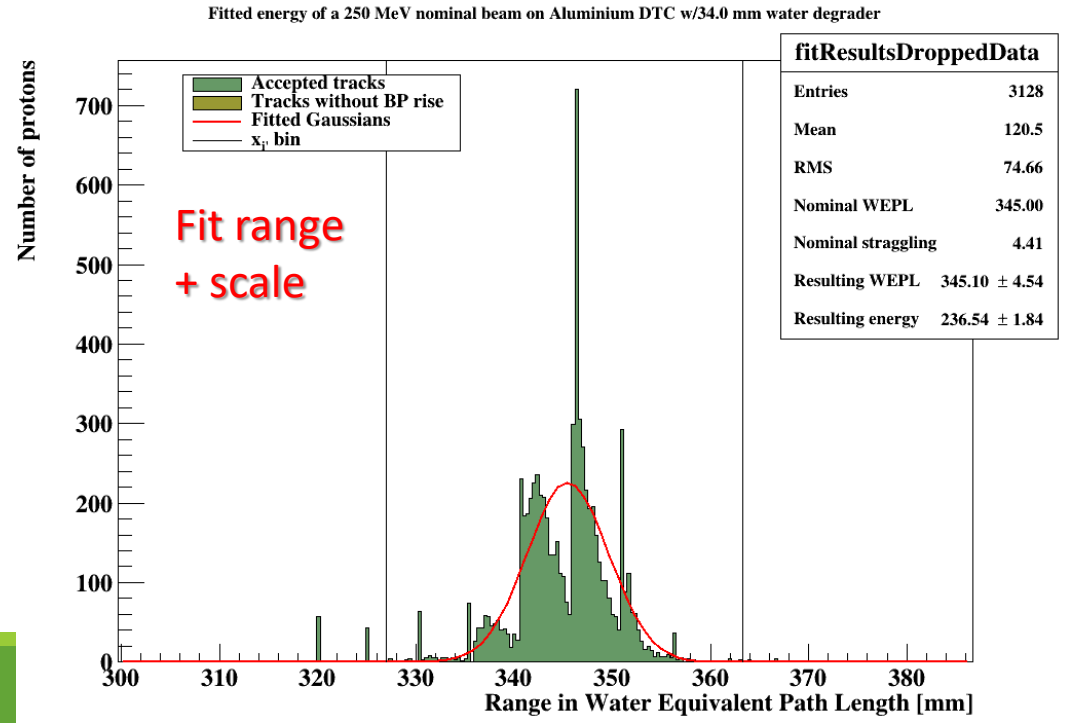




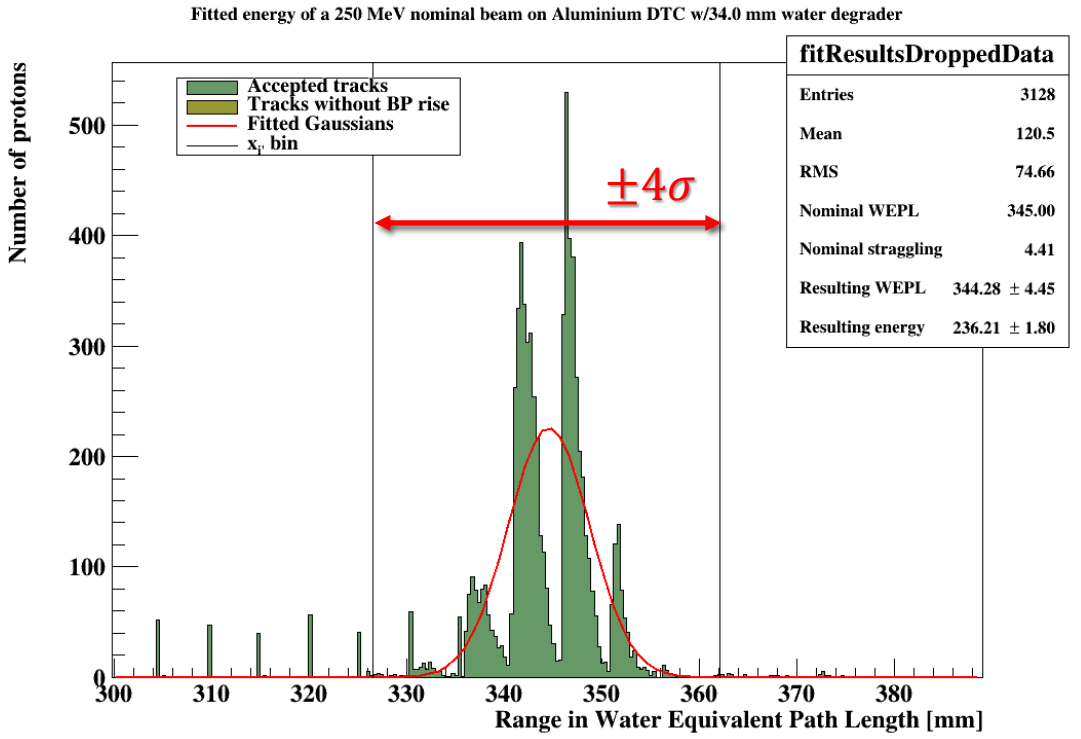
Approaches to the analysis

2. How to determine Mean and Width of range distribution?
   1. Gaussian fit parameters (NO) or empirical summed values (YES)

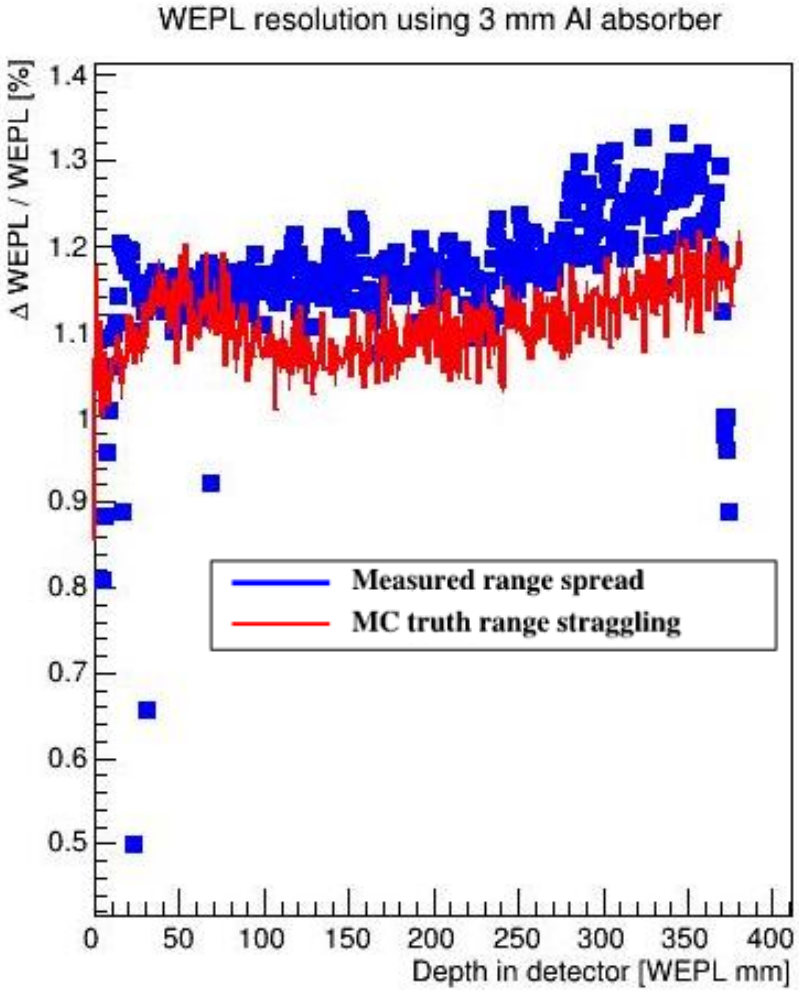
$$\left[\widehat{R_0}\right]_A = \sum_{-4\sigma}^{+4\sigma} \frac{R_i w_i}{w_i}$$

$$\left[\widehat{R_0}\right]_B = \mathrm{Gauss}_\mu$$

   2. Limits of empirical summed values? (currently: $\pm 4\sigma$ from fitted Gaussian)
   3. Q: How many layers in one «straggling» to best find the Range? 4-5? Better than FoCal's 1-2.

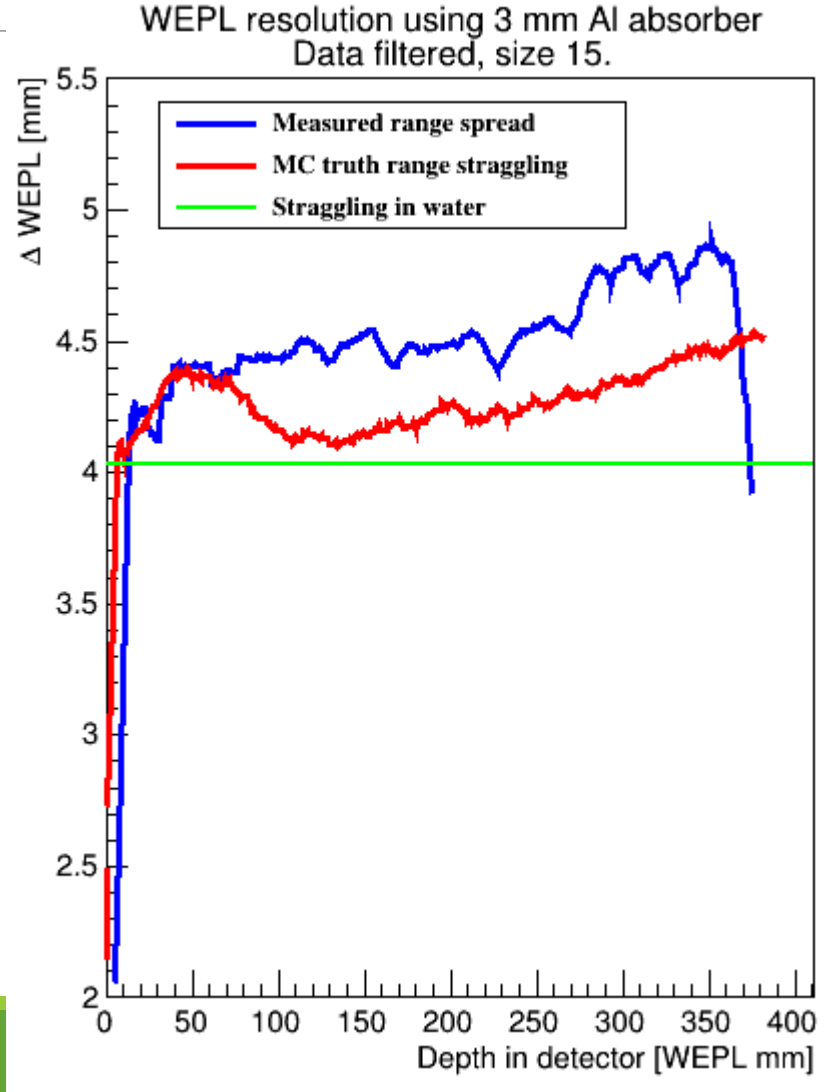


Resolution determination



TOO NOISY!!

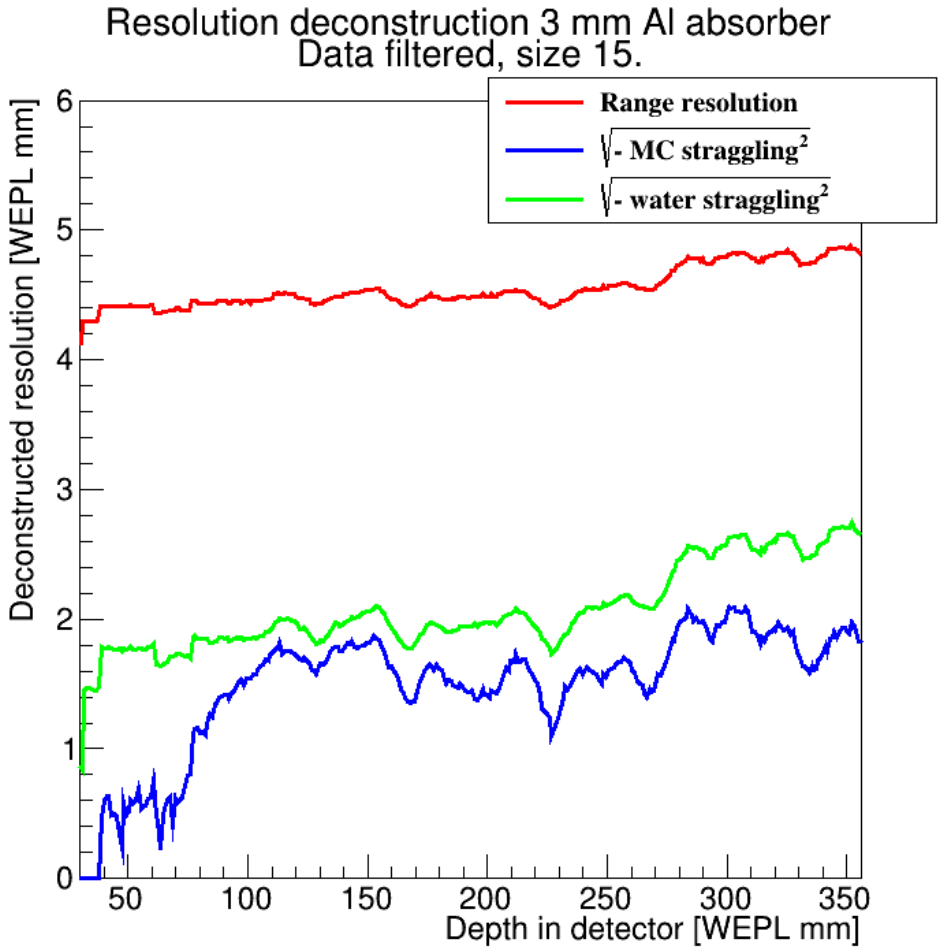
```
for (Int_t i=0; i<arraySize; i++) {
   value = 0;
   n = 0;

   for (Int_t j=i-filterSize/2; j<=i+filterSize/2; j++) {
      if (j<0 || j>=arraySize) {
         continue;
      }
      value += array[j];
      n++;
   }

   value /= n;
   tempArray[i] = value;
}
```



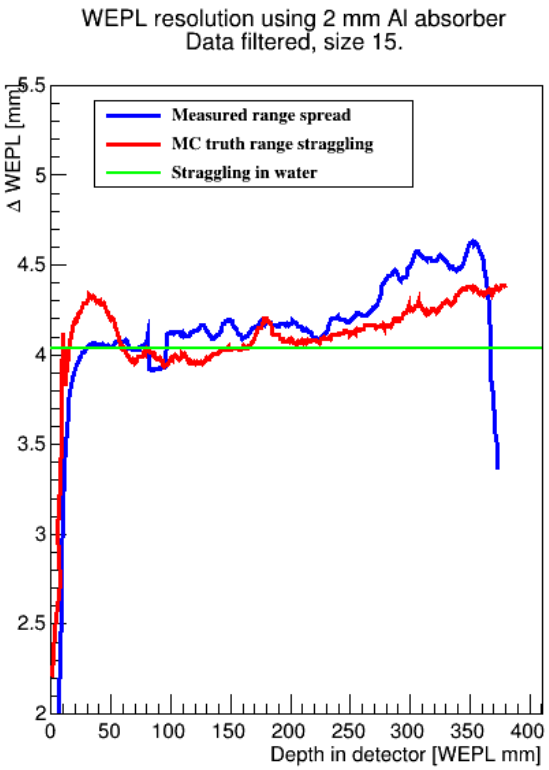
Resolution determination

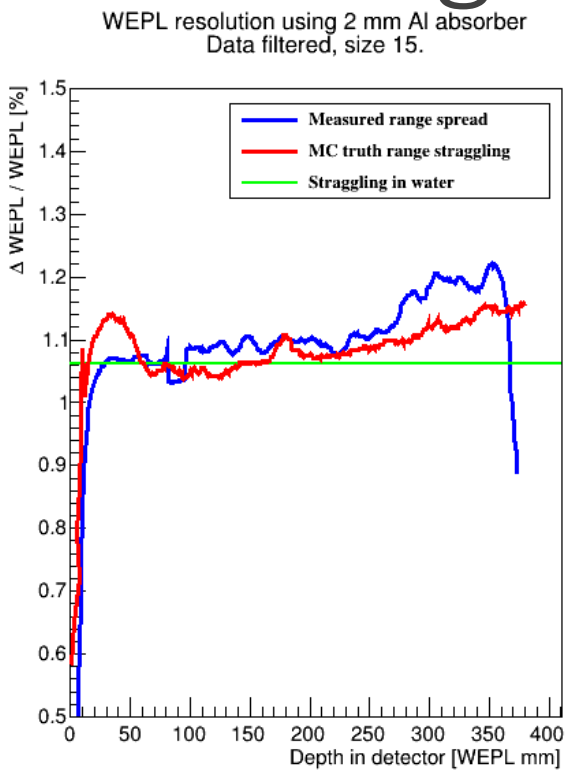
So… Lets do some calculations

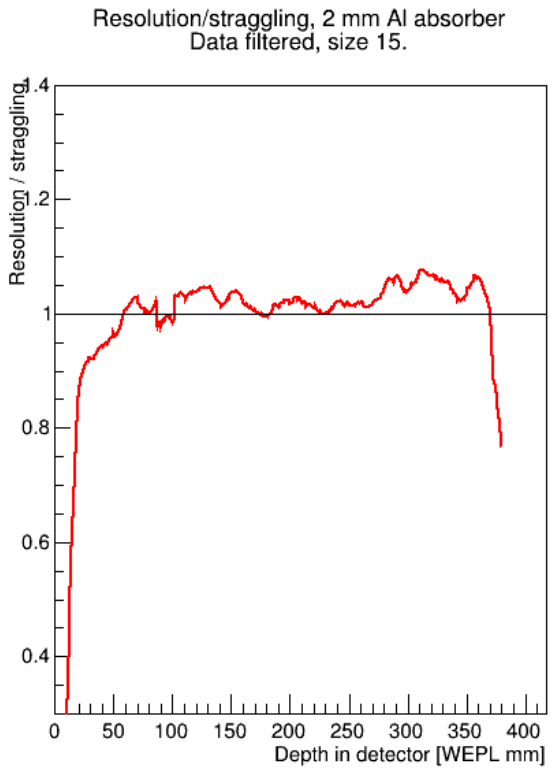
1. Resolution can be added quadratically
2. We can remove the different (known) components by removing also in quadrature
3. Let’s stay in the stable region of the detector (30 – 360 mm)

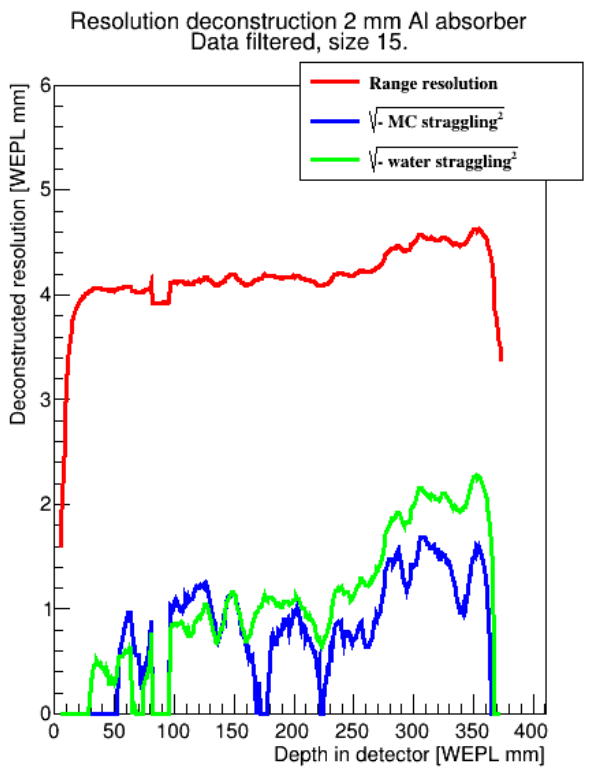


For the different geometries

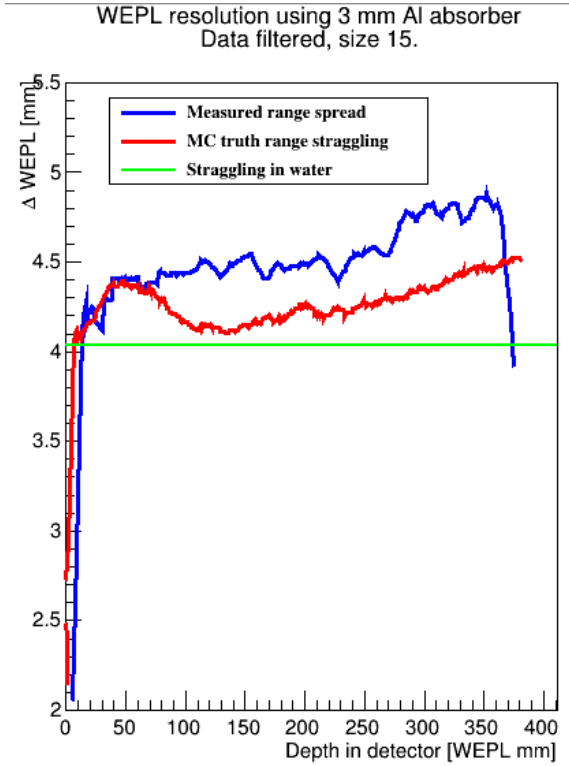


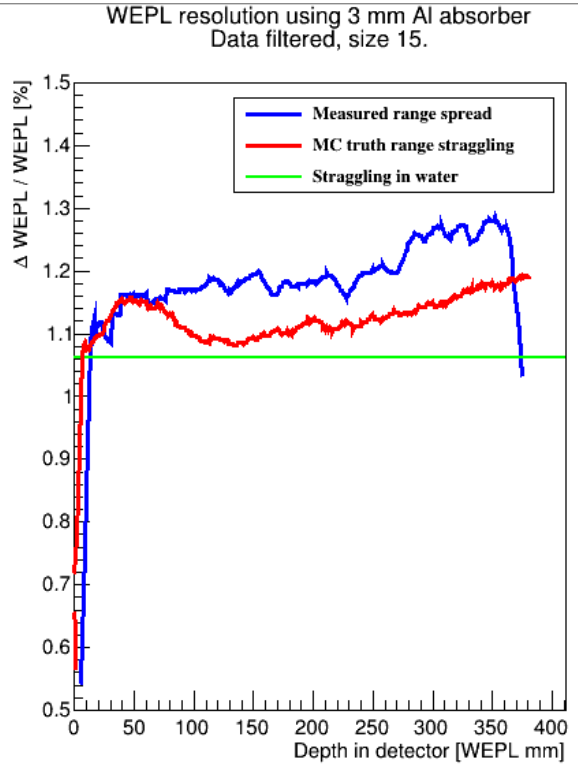


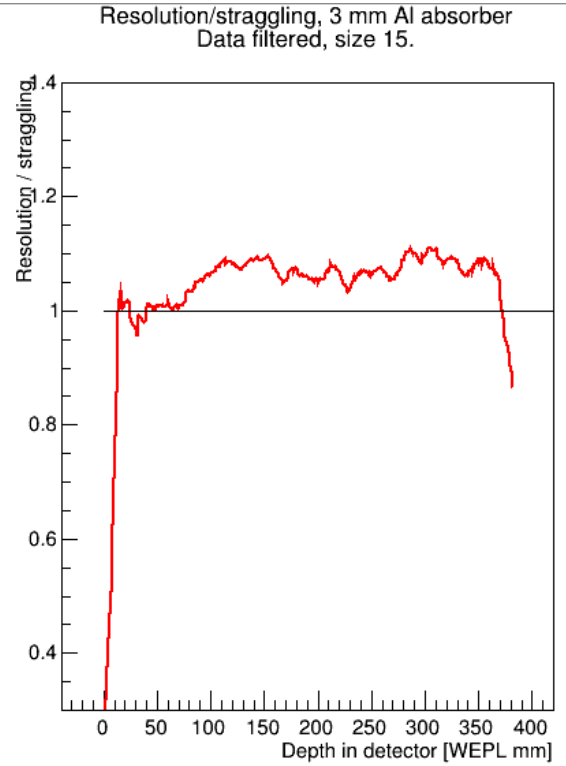


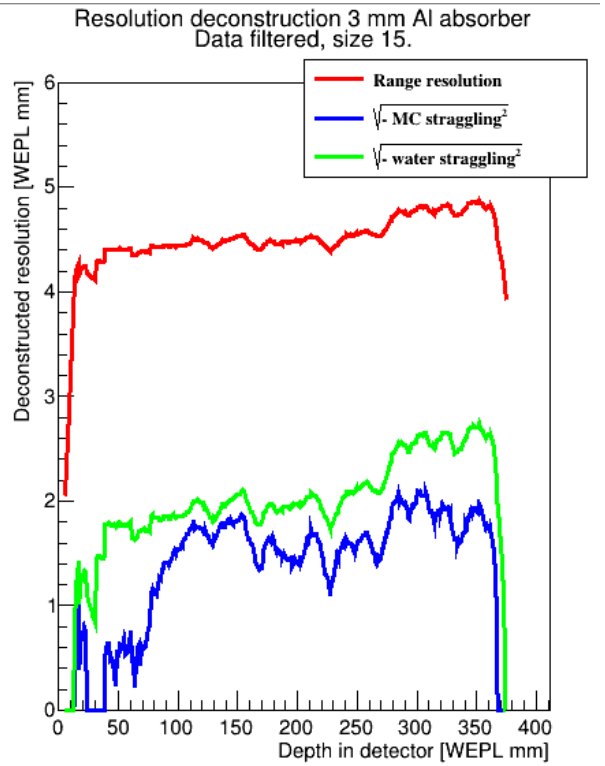


For the different geometries

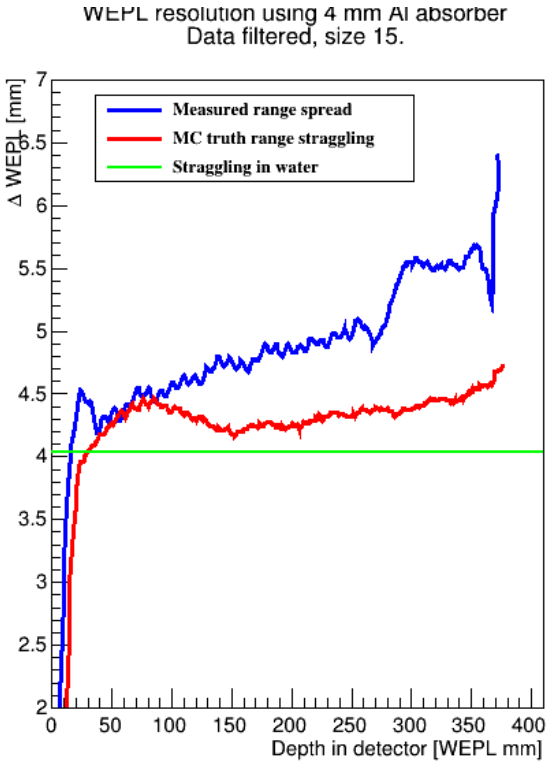


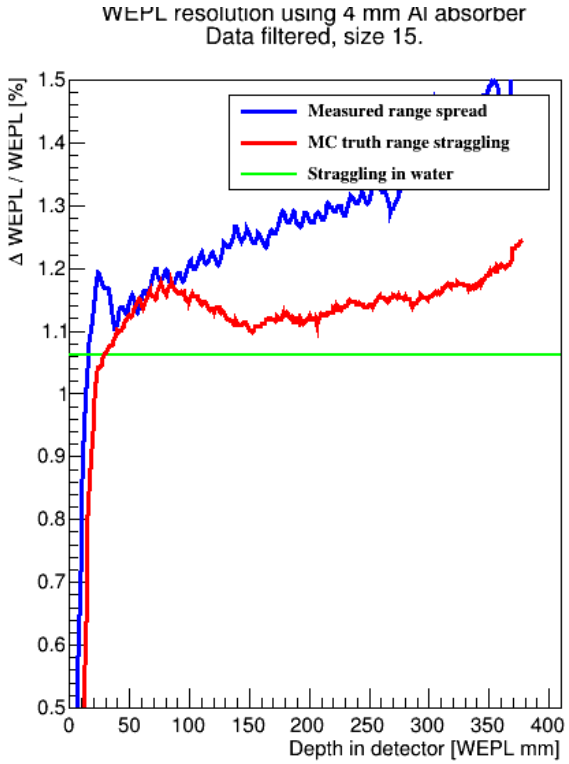


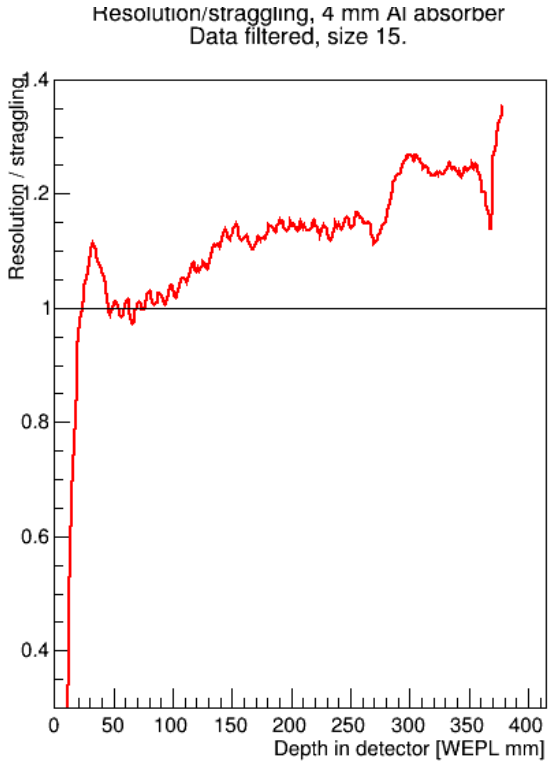


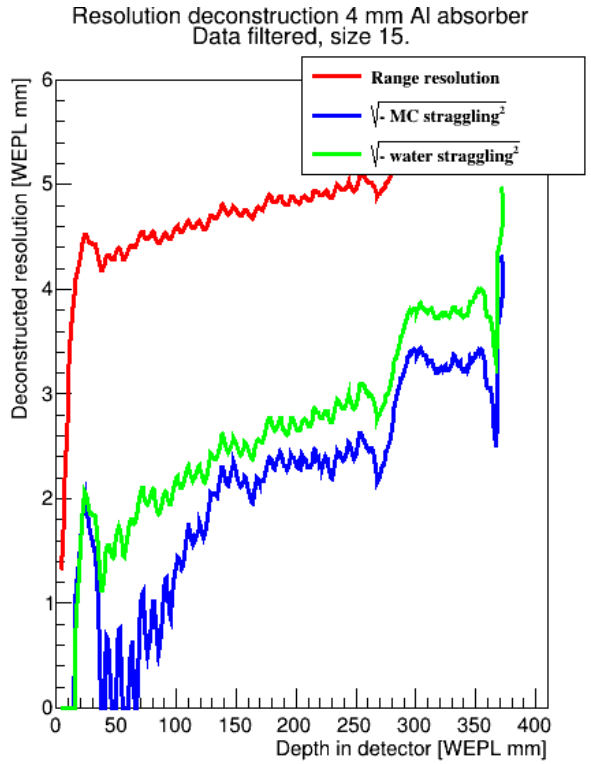


For the different geometries









NOTE: This time the DTC had too few layers, so the deepest results are not OK

Resolution determination

So… Lets do some calculations

Setup	**Average Resolution**	**Res. ⊖ MC strag.**	**Res. ⊖ H_2O strag.**
2 mm	4.20 mm (1.11%)	1.03 mm	0.76 mm
3 mm	4.55 mm (1.19%)	1.37 mm	1.98 mm
4 mm	4.89 mm (1.29%)	2.10 mm	2.67 mm
Loma Linda (@ 200 MeV)	4.1 mm (2.19%)?		3.00 mm (1.16%)?
FOCAL @ 188 MeV	9.6 mm (4%) !!		

Remember…

:ope. For the discretization uncertainty to be sub-dominant to range straggling, we would require $\Delta/\sqrt{12} < 3$ mm (Table 4).

The WEPL factor is approx. 2.18

At 2 mm: 4.4 / sqrt(12) = 1.27 ✓

At 3 mm: 6.54/sqrt(12) = 1.89 ✓

At 4 mm: 8.72/sqrt(12) = 2.51 ✓

At 5 mm: 10.9/sqrt(12) = 3.14 ✗

3 * sqrt(12) / 2.18 = 4.76

Poludniowski, G., Allinson, N.M., Evans, P.M., 2015. Proton radiography and tomography with application to proton therapy. The British Journal of Radiology 88, 20150134. doi:10.1259/bjr.20150134

Interpreting the Loma Linda results…

IV. Five-Stage Detector Performance

When we look at just the signals in the first stage from 200 MeV protons passing through a 2 cm square in the center of the 5-stage detector (with no phantom in place), we find a Gaussian distribution with $\sigma = 3.0\%$. Since Geant-4 simulations [18] predict $\sigma = 2.8\%$ just from variations in the energy deposition, by subtracting the two numbers in quadrature we estimate that the detector resolution is around 1%, more than adequate for this application.

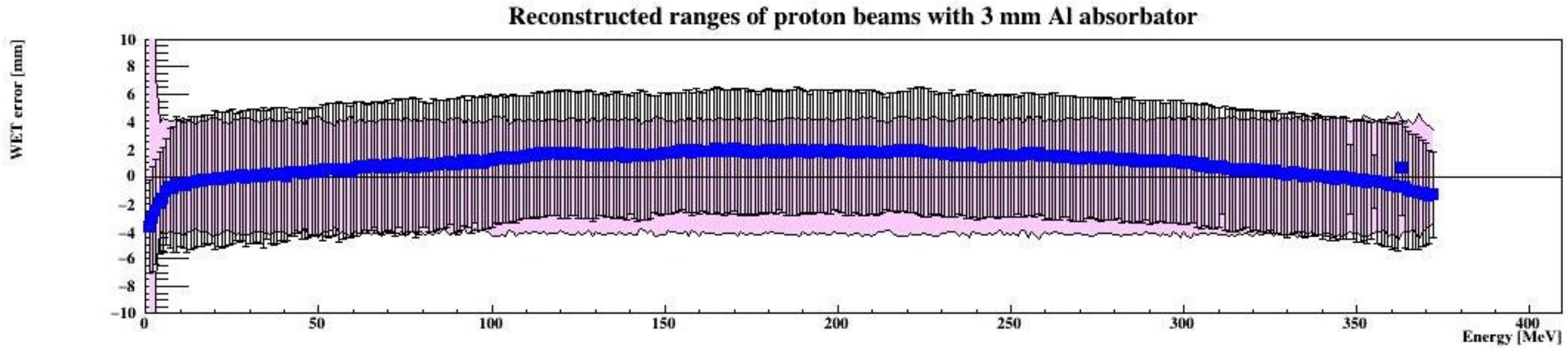
in 6.35 mm steps. From those data we derive the calibration constants needed for scanner operation. We have verified that this procedure yields a WEPL resolution that is approximately 3 mm rms for all values of WEPL, only slightly higher than the predicted lower limit of 2.8 mm that arises from range straggling of 200 MeV protons.

200 MeV -> 259 mm
3 mm is 1.16 %

BUT… Is that after subtracting the expected straggling..? Do they do that twice??

R. P. Johnson, V. Bashkirov, L. DeWitt, V. Giacometti, R. F. Hurley, P. Piersimoni, T. E. Plautz, H. F. W. Sadrozinski, K. Schubert, R. Schulte, B. Schultze, A. Zatserklyaniy, 2016. A Fast Experimental Scanner for Proton CT: Technical Performance and First Experience With Phantom Scans. IEEE Transactions on Nuclear Science 63, 52–60. doi:10.1109/TNS.2015.2491918

Features we don’t understand



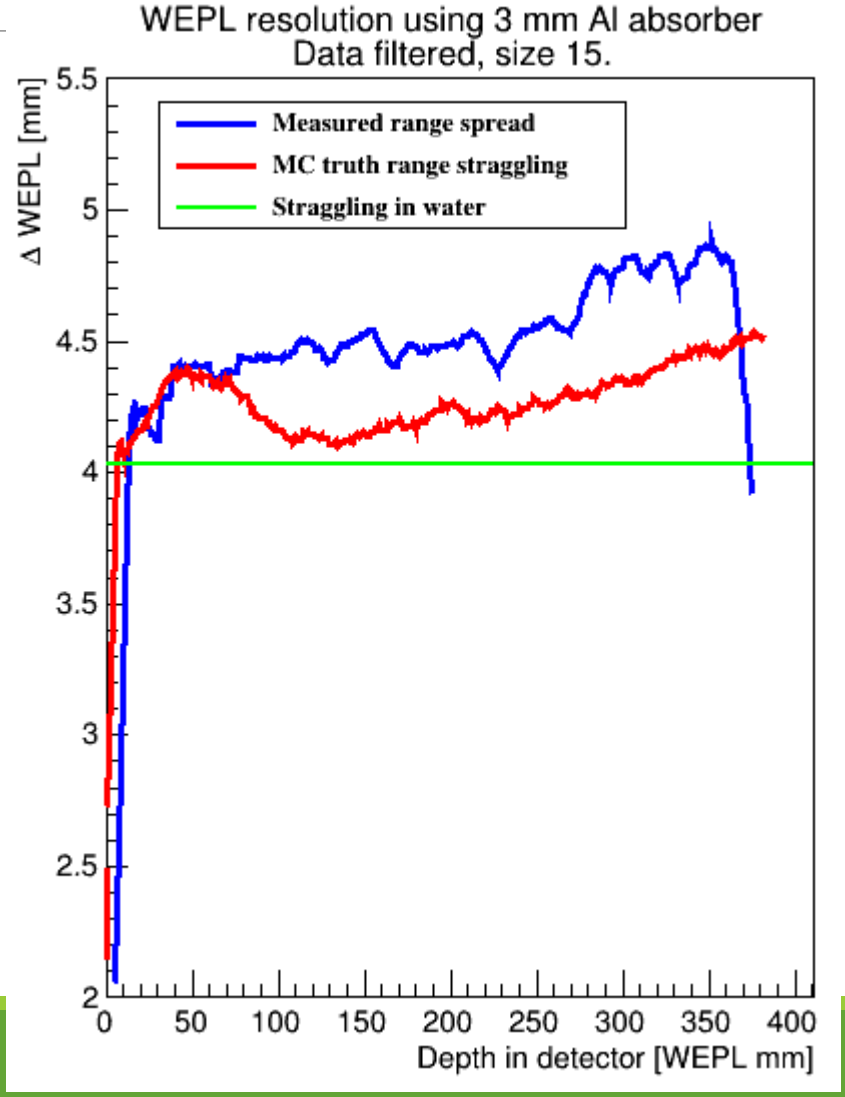
Why do we have these «nice» systematic errors in range determination?

- Looks like Bragg-Kleeman-type error of range-energy,
  but I can’t think of any place I use the equation… (I use LUTs to calculate this)

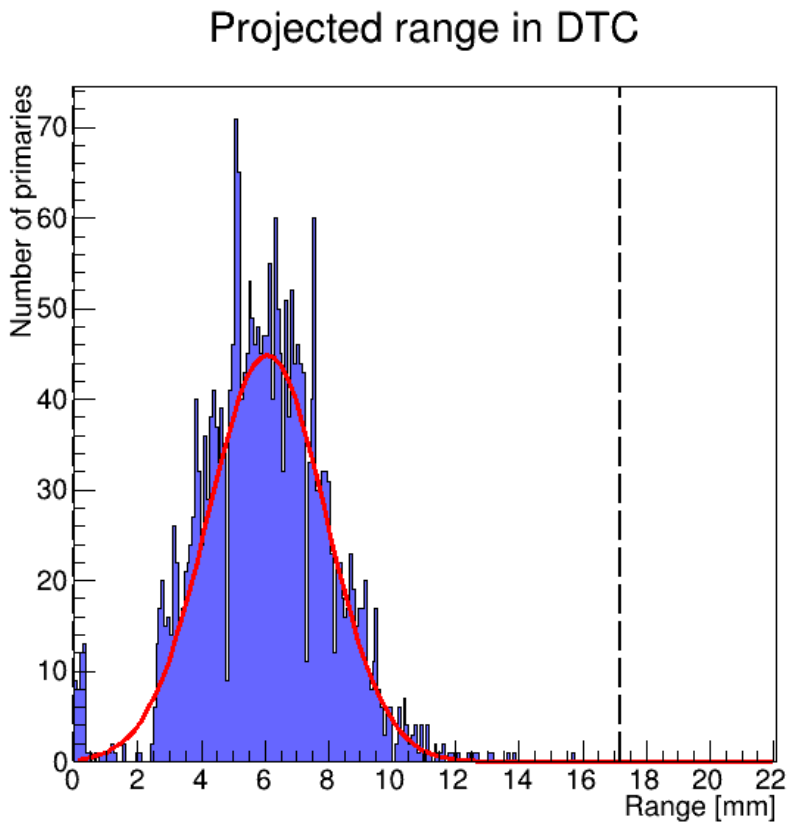
Features we don't understand

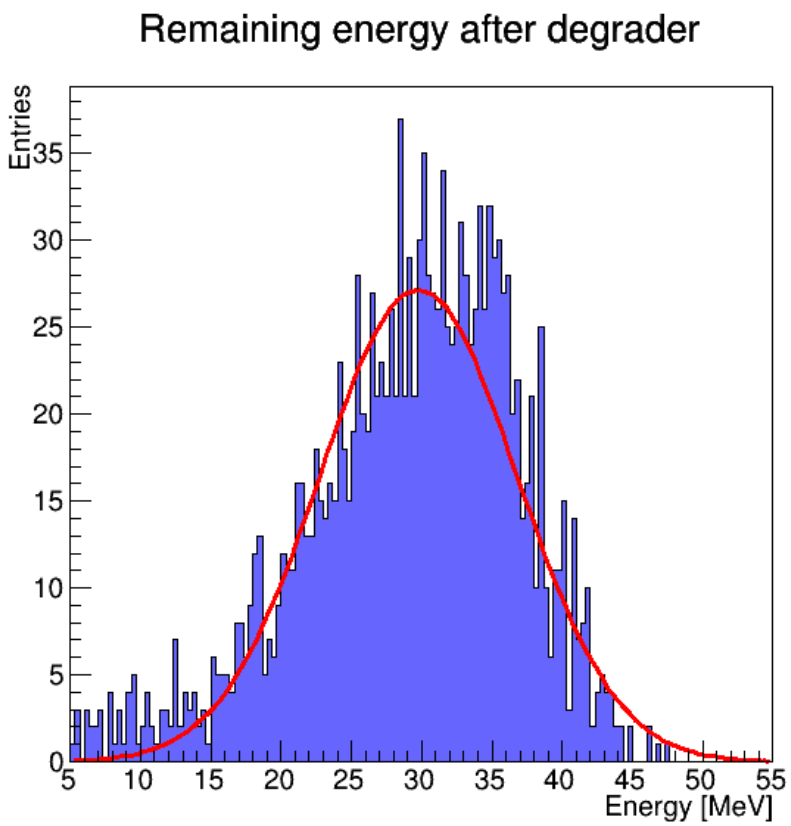
What about the «bump» in the MC truth range straggling here? It's in the raw data as well

1. Edge effects from the proton beam hitting the DTC just before the Bragg Peak?
2. It's not mis-fits (I've studied the range distribution data)
3. We expect the MC truth range straggling to start at the water straggling levels (since beam passes through 99% water at that point), and increase when the fraction of the beam traversing the DTC increases.
4. I'll try anchoring the water phantom just proximal to the first layer, and not to its midpoint



Animation of the straggling raw data





Bump at 5-30 mm with peak at 18 mm

NOTE: It's the Gaussian σ that is used, not a histogram sum

Going forward

1. We need to fully understand the artifacts before going through with a full scan of all geometries and materials, otherwise it's wasted effort
2. All code is located at github: http://github.com/HelgeEgil/focal
3. A full user's guide for its usage is located on the wiki: https://wiki.uib.no/pct/index.php/Software_for_design_optimization

Known bugs

1. It’s still not possible to use geometries with floating point values for absorber thicknesses
2. The DTC geometry creator does NOT propagate the first layer material. We want to use Air (to increase the Dynamic Range at low energies), but it defaults to Aluminium…
   - Solution: Edit the material in *Module.mac* after using *makeGeometryDTC.py*.