Detector simulation and digitization

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CYGNO Collaboration Meeting
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Overview

- **Parameter Optimization and Validation**:
  - Improved digitization parameters using comparisons with iron at various GEM voltages and z-positions.
  - Preliminary comparison data/mc for alpha particles from radon.
- **LIME Gain Saturation Estimation**:
  - Assessed saturation effect at different energies.
- **Future Steps**:
  - Validate results with PMT waveform cross-checks.
  - Extend simulation to Americium data (59 keV ER)

Updates on digitization code (c++ version)

- The digitization code has been rewritten from **Python to C++ (G. Dho and S. Piacentini)**.

Key changes:

- **Performance:**
  - **6 keV ER:** ~1 second / track (was ~10 seconds with Python)
  - **5 MeV NR:** ~1 minute / track(was not possible in Python, max energy was 100 keV)
- **PMT simulation:** Not yet available (soon will be integrated).

Testing:

- The code has been tested for 6 keV ER at various z-values and 20 keV NR.

The code is available on: https://github.com/CYGNUS-RD/digitizationpp

From this point forward, the C++ code is the official version

Data Analysis

Overview

- **Scans:** GEM1V and source position (iron, 6 keV).
- **Run Date:** December 15, 2023 (Run 4 LNGS).

Parameters

- **GEM1 Voltages:** 260 V – 440 V.
- **Source position (z):** 5, 10, 15, 25, 35, 46.5 cm.

Cuts Applied

- sc_length < 500.
- sc_integral / sc_nhits < 100.
- sc_integral < 6e4.
- sc_width / sc_length < 1.
- sc_width / sc_length > 0.5.
- Barycenter outside circle with radius > 750 px.

43050,step 5,260,32/33,101
43049,step 5,280,32/33,105
43048,step 5,300,32/33,102
43047,step 5,320,32/33,102
43046,step 5,340,32/33,103
43045,step 5,360,32/33,102
43044,step 5,380,32/33,102
43043,step 5,400,32/33,103
43042,step 5,420,32/33,103
43041,step 5,440,32/33,103
43040,step 5 PED,260,32/33,105
43039,step 4,260,24/25,104
43038,step 4,280,24/25,105
43037,step 4,300,24/25,102
43036,step 4,320,24/25,102
43035,step 4,340,24/25,101
43034,step 4,360,24/25,101
43033,step 4,380,24/25,104
43032,step 4,400,24/25,103
43031,step 4,420,24/25,103
43030,step 4,440,24/25,103
43029,step 4 PED,260,24/25,106
43028,step 3,260,17/18,104
43027,step 3,280,17/18,102
43026,step 3,300,17/18,103
43025,step 3,320,17/18,103
43024,step 3,340,17/18,101
43023,step 3,360,17/18,101
43022,step 3,380,17/18,103
43021,step 3,400,17/18,103
43020,step 3,420,17/18,103
43019,step 3,440,17/18,102
43018,step 3 PED,440,17/18,104

43017,step 2,260,10/11,105
43016,step 2,280,10/11,102
43015,step 2,300,10/11,103
43014,step 2,320,10/11,103
43013,step 2,340,10/11,102
43012,step 2,360,10/11,103
43011,step 2,380,10/11,104
43010,step 2,400,10/11,103
43009,step 2,420,10/11,102
43008,step 2,440,10/11,102
43007,step 2 PED,260,10/11,106
43006,step 1,260,03/04,102
43005,step 1,280,03/04,101
43004,step 1,300,03/04,103
43003,step 1,320,03/04,102
43002,step 1,340,03/04,102
43001,step 1,360,03/04,102
43000,step 1,380,03/04,102
42999,step 1,400,03/04,103
42998,step 1,420,03/04,101
42997,step 1,440,03/04,101
42996,step 1 PED,260,03/04,101
42995,parking position,260,00/00,101
42994,parking position,280,00/00,102
42993,parking position,300,00/00,101
42992,parking position,320,00/00,100
42991,parking position,340,00/00,105
42990,parking position,360,00/00,101
42989,parking position,380,00/00,103
42988,parking position,400,00/00,102
42987,parking position,420,00/00,105
42986,parking position,440,00/00,101
42985,parking position PED,400,00/00,105

(Around 500 iront spots per run)

Fitting unsaturated integral as a function of z and GEM1V

Given the unsaturated GEM gain:

$$G_{\text{GEM}} = g_0 \cdot e^{\alpha \cdot V_{\text{GEM}}}$$

With **g0** representing a term that accounts for the **deviation from a perfect exponential gain**, we can fit the average sc_integral (under unsaturated conditions: low GEM1V and high z) as a function of GEM1V and z (iron position relative to the GEMs) using the following function:

$$I = I_0 \cdot e^{\alpha \cdot V_{\text{GEM1}}} \cdot e^{-\frac{z}{\lambda}}$$

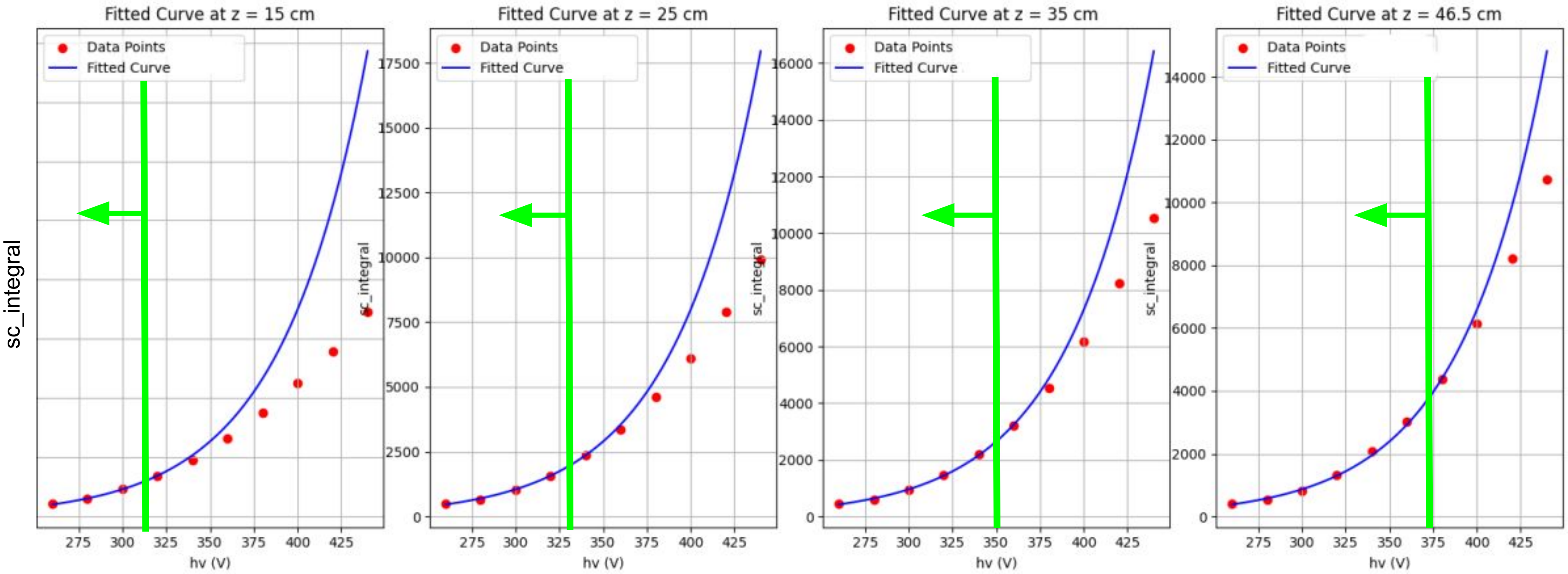
Where λ is the absorption length of primary electrons during their drift in the gas, and I_0 is expressed as:

$$I_0 = \frac{E}{W} \cdot 0.07 \cdot 4 \cdot \Omega \cdot \epsilon_{\text{eff}}^2 \cdot g_0^3 \cdot e^{\alpha \cdot V_{\text{GEM3}}} \cdot e^{\alpha \cdot V_{\text{GEM2}}}$$

photon per electron (0.07) ORCA-Fusion counts per photon (4)

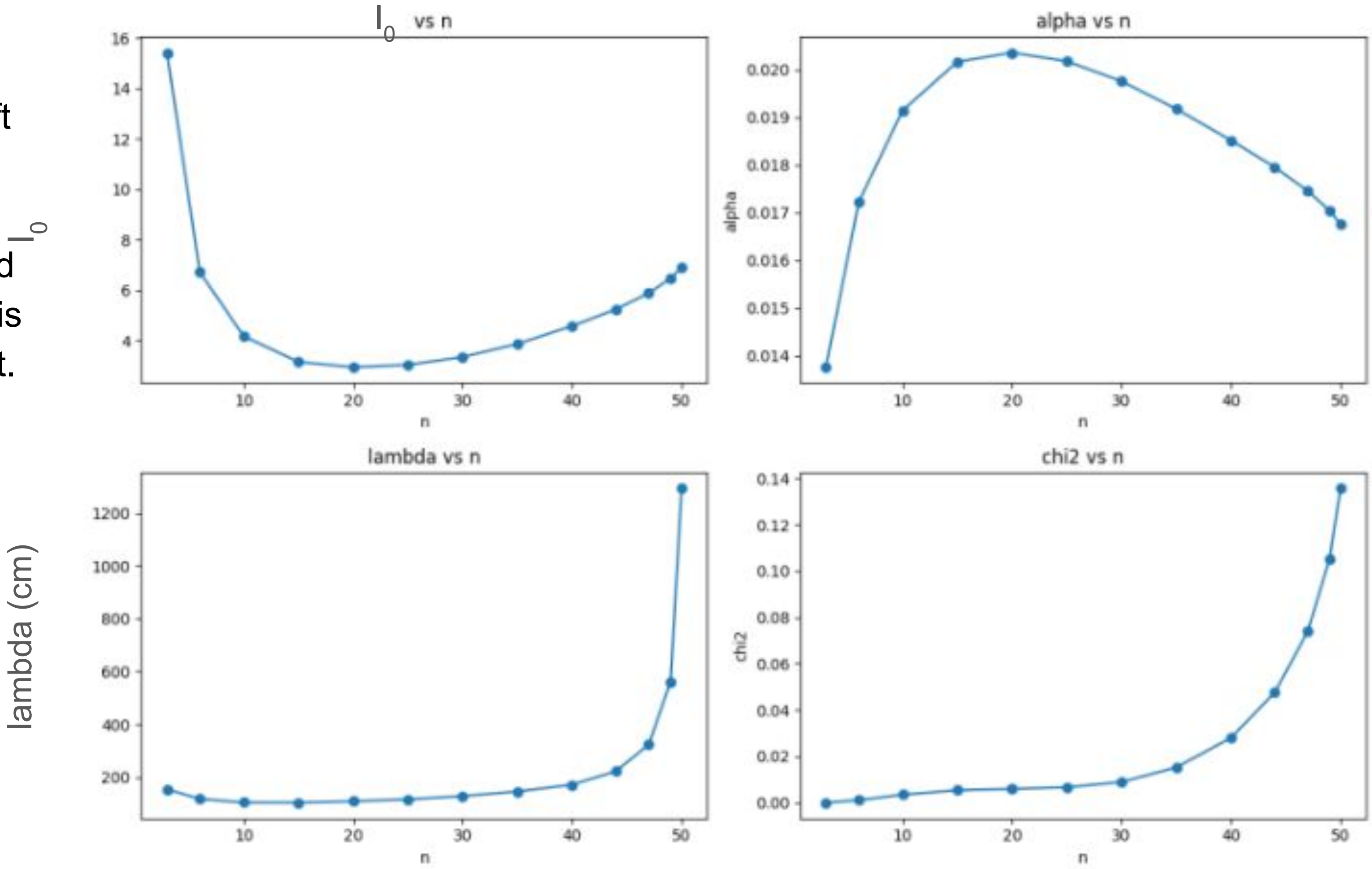
Below is the result of a **simultaneous fit** on **sc_integral** as a function of **z** and **GEM1V (hv)**.
Each (red) data point represents the average of the sc_integral over 500 tracks.

The **'unsaturated' condition** is shown by the (green) threshold: data points to the left



Note: when sc_integral is low (< 2000), the reconstruction of integral is not very efficient, so we applied a correction based on simulation (see here or in backup)

By moving the threshold to the left (right), we can reduce (increase) the number of fitted data points (n). This affects the fit result.



So we perform a fine-tuning around **alpha**, **lambda**, **g0** for our digitization when comparing with data.

Best parameters after fine-tuning

Digitization parameter	LNF calibration (z scan only)	LNGS calibration (z & GEM1V scan)
diff_const_sigma0T (mm^2)	**0.1225**	**0.13475**
diff_coeff_T (mm/sqrt(cm)^2 for 1 kV)	0.013225	0.0143819
diff_const_sigma0L (mm^2)	0.0676	0.0676
diff_coeff_L (mm/sqrt(cm)^2 for 1 kV)	0.00978	0.0103483
ion_pot (keV)	**0.0462**	**0.035**
x_vox_dim (mm)	346/2304	346/2304
y_vox_dim (mm)	346/2304	346/2304
z_vox_dim (mm)	0.1	0.1
A (normalization in saturation)	**1.52**	**1**
beta (saturation)	**1.0e-5**	**0.8e-5**
photons_per_el (photons/electron)	0.07	0.07
counts_per_photon (counts/photon)	**2**	**4**
sensor_size (mm)	14.976	14.976
camera_aperture (N/A)	0.95	0.95
absorption_l (mm)	**1400**	**1350**
alpha (1/V)	0.0209	0.0209
g0	**0.0347**	**0.030**

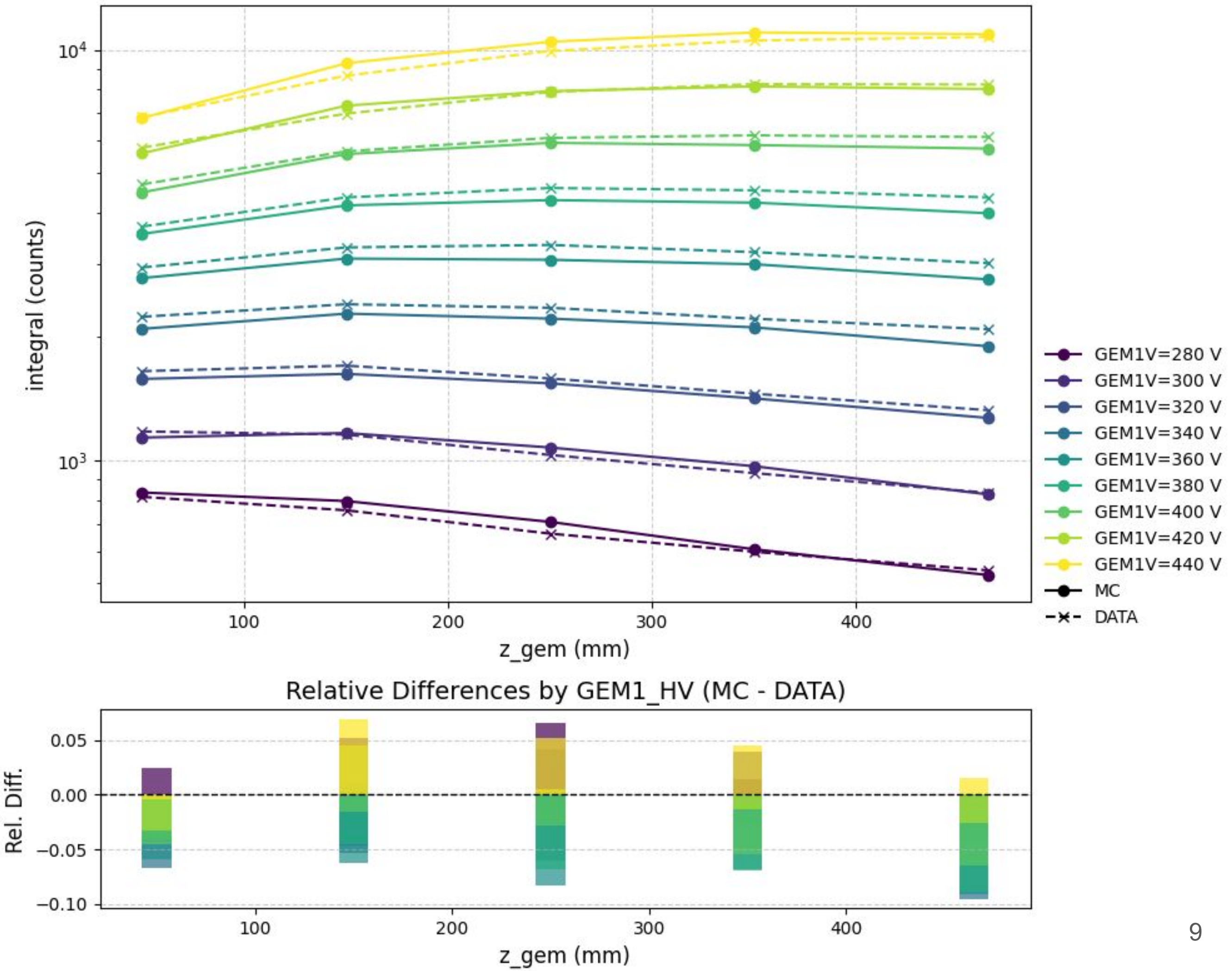
BY FIXING ALL DIGITIZATION PARAMETERS AS IN PREVIOUS SLIDE

Each data point is the average sc_integral.

For MC we have 500 tracks per data point.

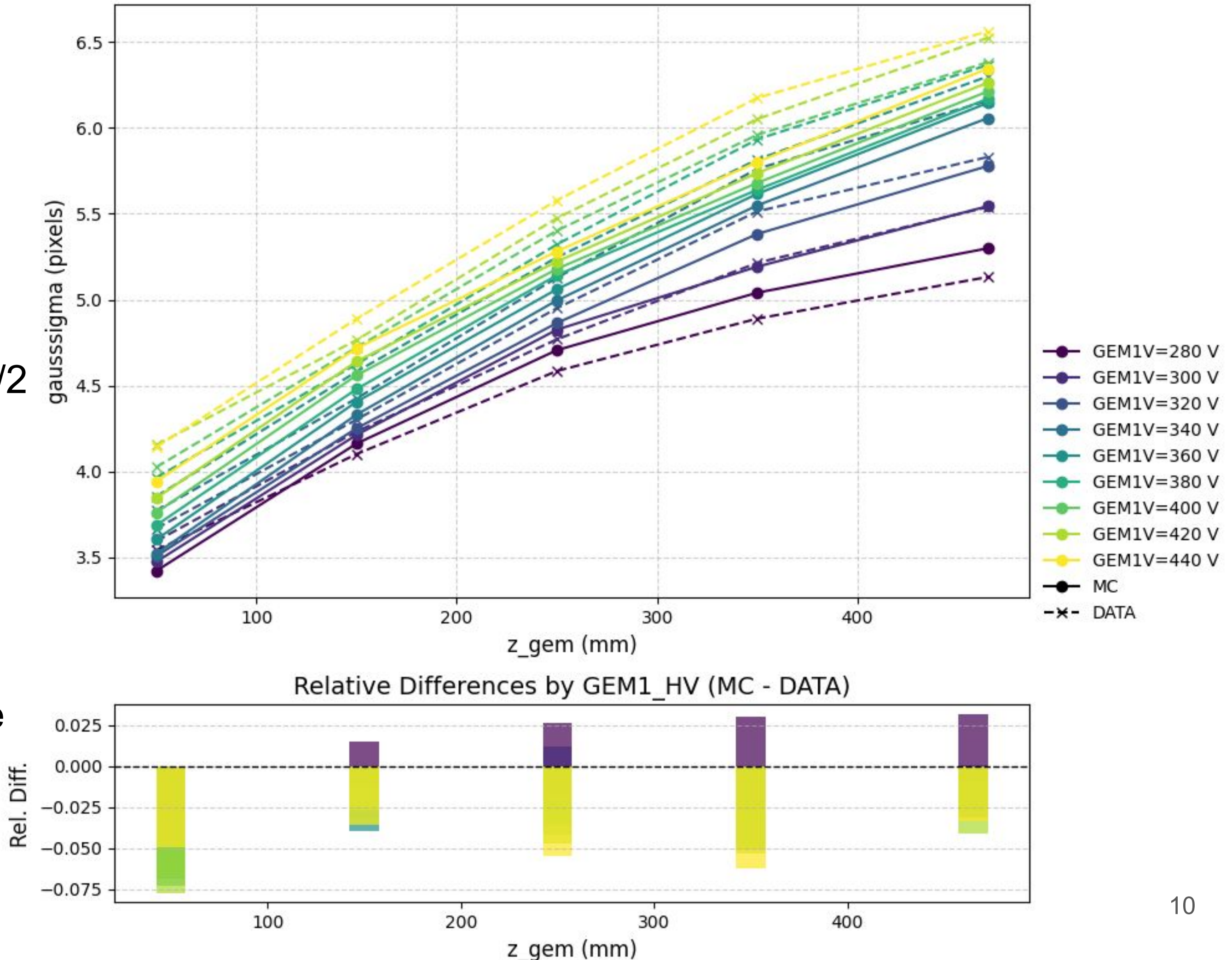
Geant4 tracks are
6 keV electrons
generated isotopically.

5% accuracy across two orders of magnitude!



guasssigma:
(tgausssigma + lgausssigma)/2

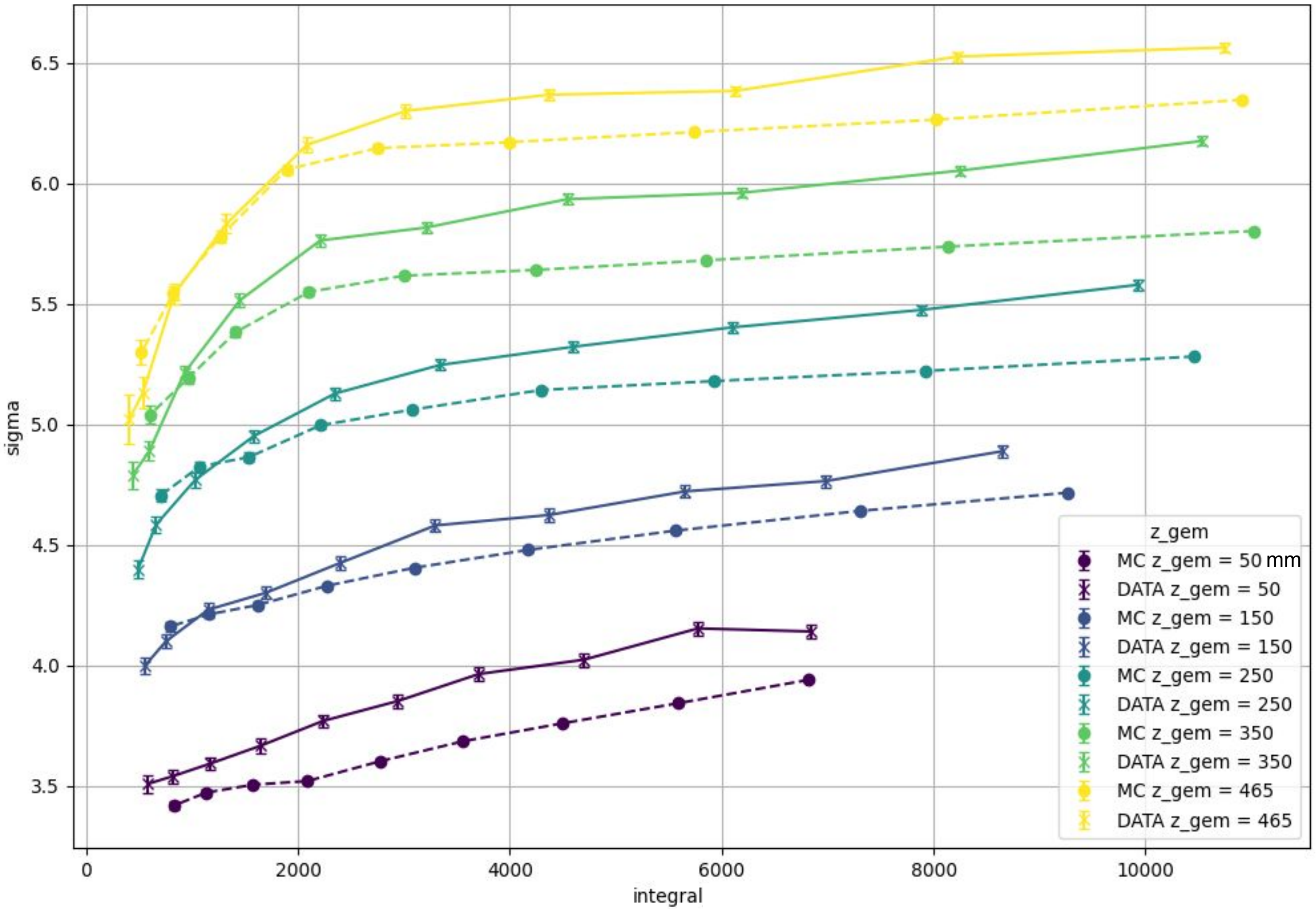
tgausssigma/lgausssigma:
standard deviation of
the Gaussian
transversal/longitudinal profile



guasssigma vs sc_integral

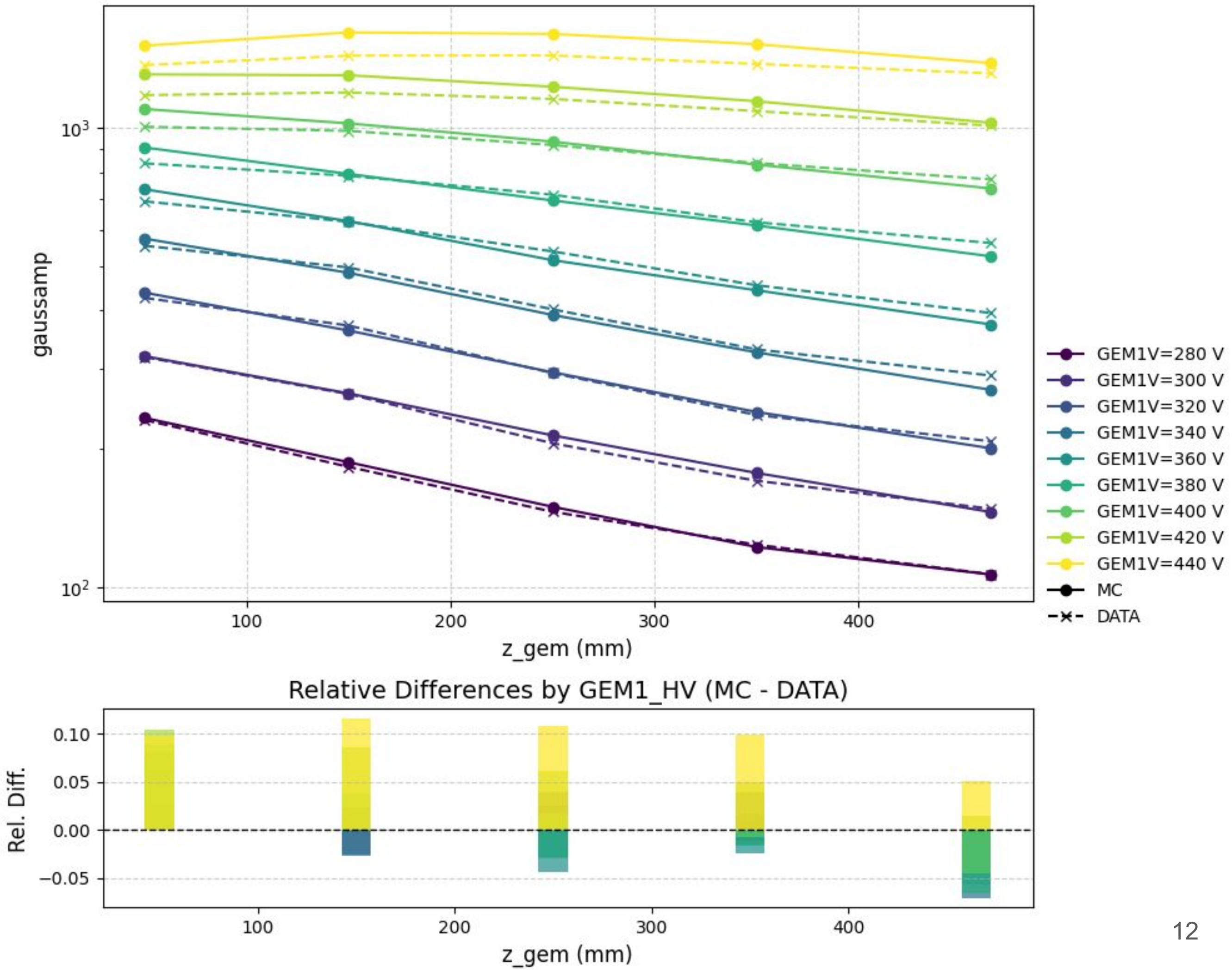
(integral is changing because we change GEMV1)

Note the effect of the reconstruction at low integral (energy)

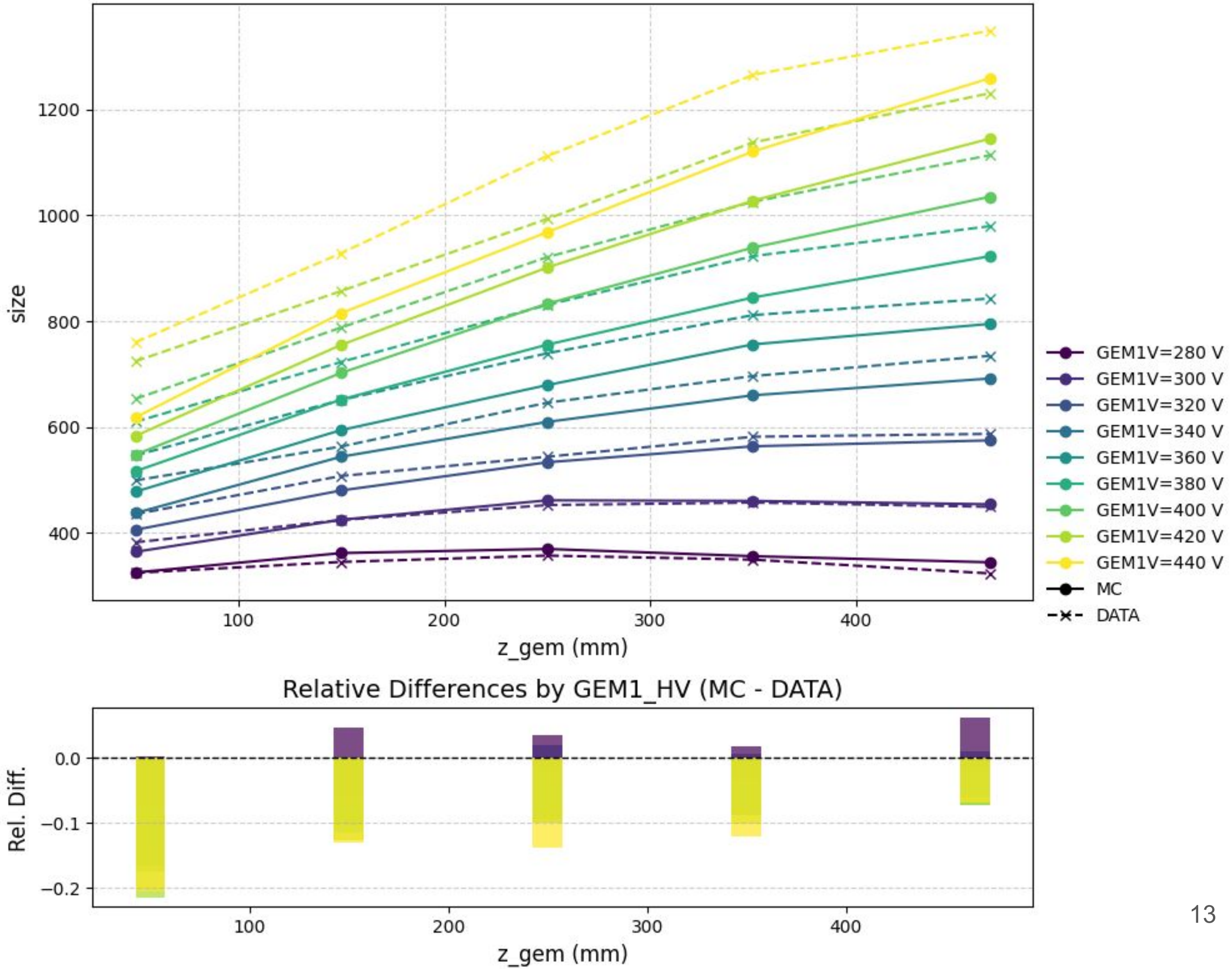


guassamp:
(tgaussamp + lgaussamp)/2

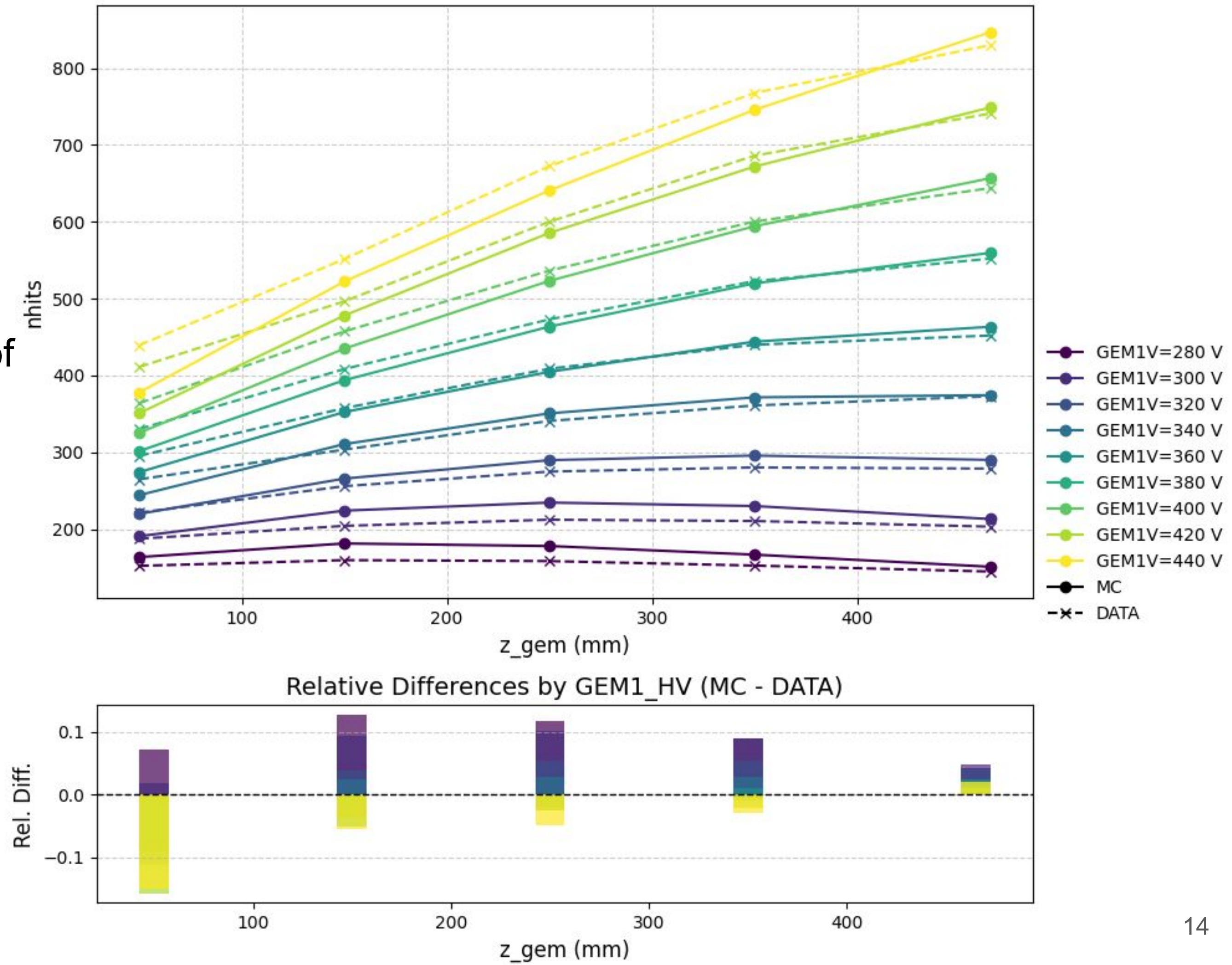
tgaussamp/lgaussamp:
amplitude of the Gaussian transversal/longitudinal profile



sc_size: number of pixels of the cluster, without zero-suppression



sc_nhits: number of pixels of the cluster above zero-suppression threshold



Comparison with alphas from Rn

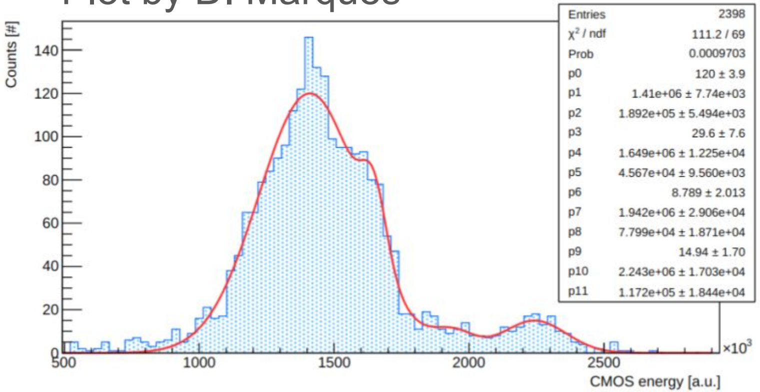
Purpose

- We simulate really well **6 keV ER,** what about 5-8 MeV NR? By fixing the best parameters for iron, we simulate alphas from Rn decay and compare them with data.

Analysis Details

- Data runs: **40919–42848**
  (Close to iron optimization data runs: 43050–42985)
- Analysis performed by **D. Marque (here)**

Plot by D. Marques



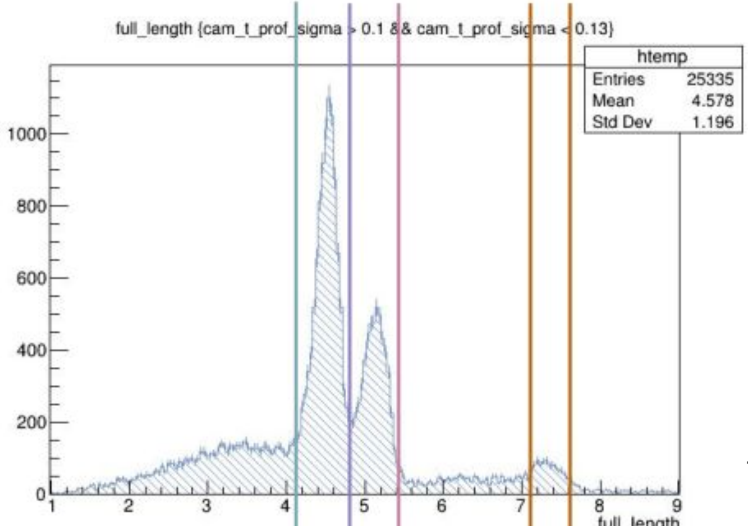
Radon alphas:

^{222}**Rn**: 5.590 MeV (~43 mm)

^{218}**Po**: 6.115 MeV (~50 mm)

^{214}**Po**: 7.833 MeV (~73 mm)

Plot by D. Marques



Rn alpha simulation

Simulation Setup

- **Alpha Particles:** at z = 46.5 cm (we know they mostly come from the cathode).
- **Statistics:** just 10 tracks per energy (but it's enough)
- **Energies:** Simulated using radon alpha energies:
    - 5.590 MeV
    - 6.115 MeV
    - 7.833 MeV

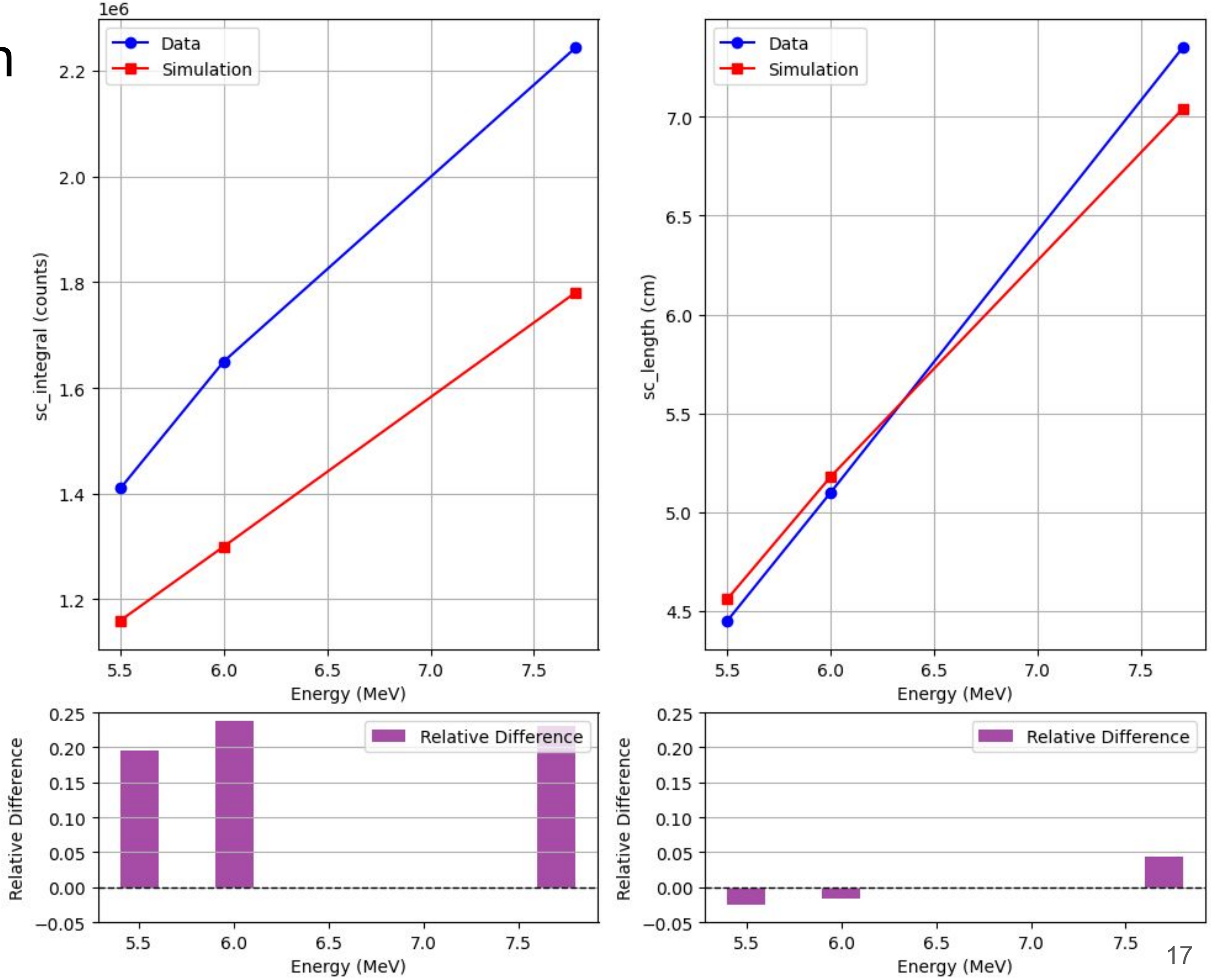
Parameters

- **Consistency:** Same parameters as those used for iron simulation (since iron scans and 'alpha data' are close in time).
- **Direction:** tracks were simulated parallel to the GEMs.

Preliminary comparison

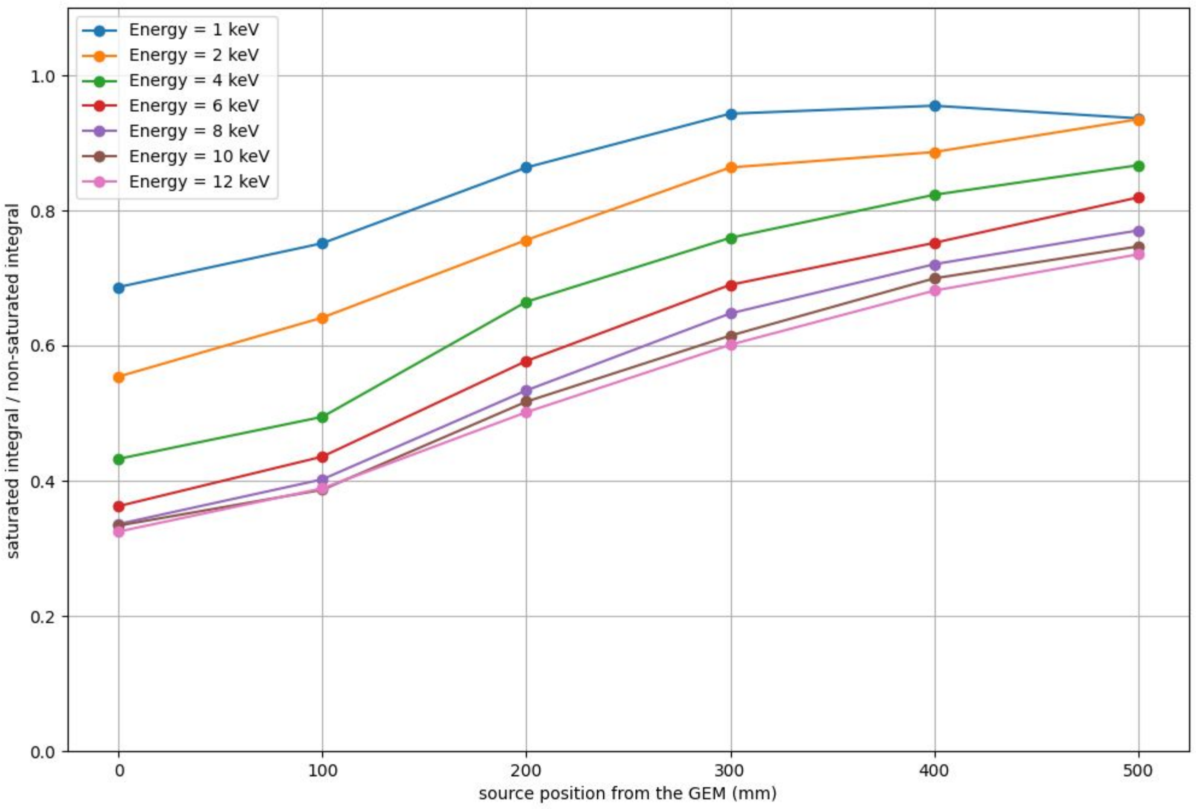
A 25% difference in integral seems a first good result since digitization was calibrated on o(keV) tracks and it seems to reproduce o(MeV)

sc_length very nice!



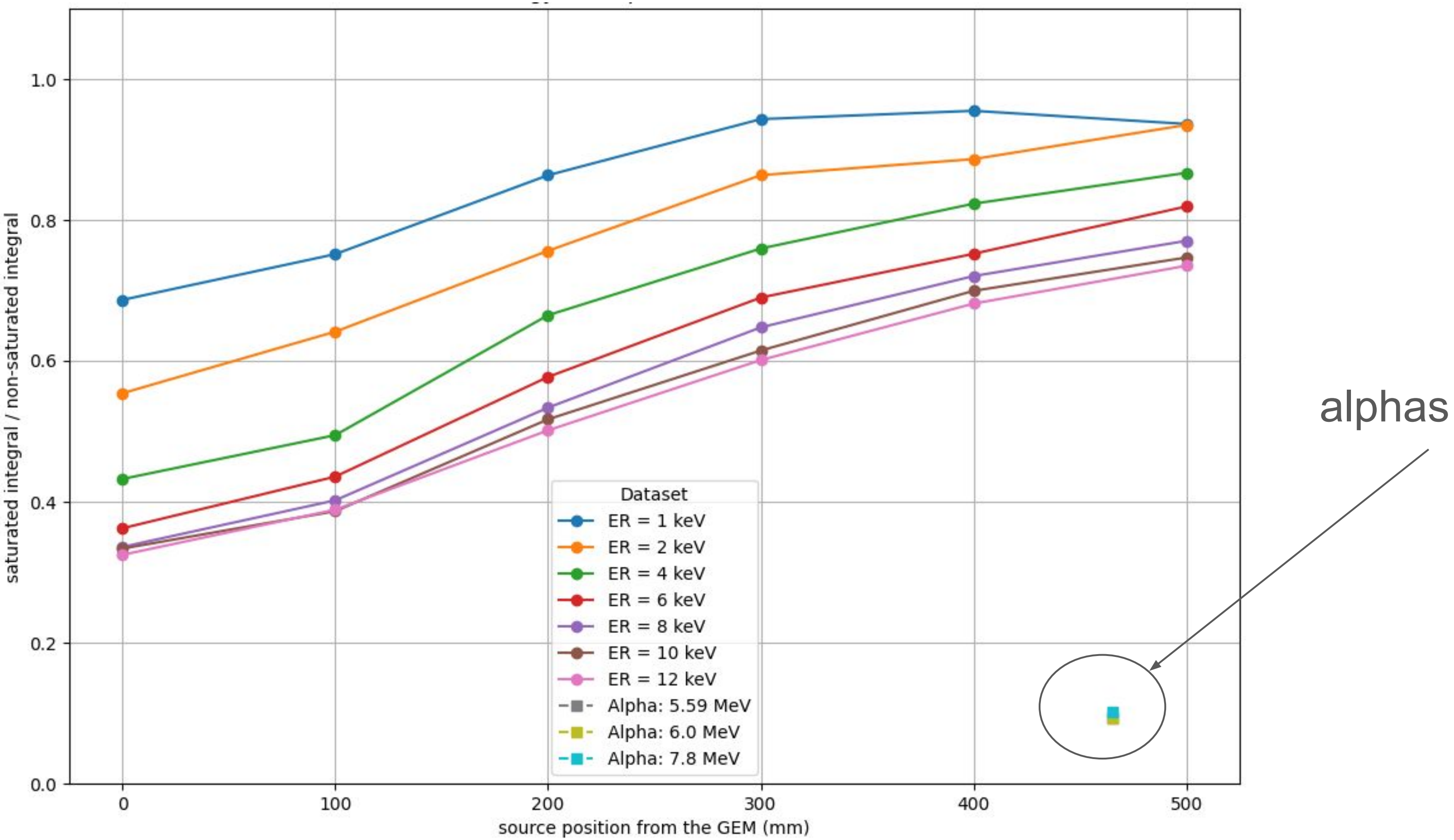
Saturation vs energy in simulation **(ER 1-12 keV)**

- We compute the ratio between **saturated integral** and **unsaturated integral** in simulation. Average integral over 500 tracks, not reconstructed (real integral)
- If we trust our **simulation**, this gives an estimate of the **saturation effect** at various energies in LIME. But it seems we are **saturating even at 1 keV at high z.**
- Saturation trend is similar for energies > 8 keV since tracks get longer



The ratio between the Cu peak (8 keV) and Fe (6 keV) in LIME also seems comparable with data in LIME

And alphas…



saturated integral / non-saturated integral
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
source position from the GEM (mm)
Dataset
ER = 1 keV
ER = 2 keV
ER = 4 keV
ER = 6 keV
ER = 8 keV
ER = 10 keV
ER = 12 keV
Alpha: 5.59 MeV
Alpha: 6.0 MeV
Alpha: 7.8 MeV
alphas

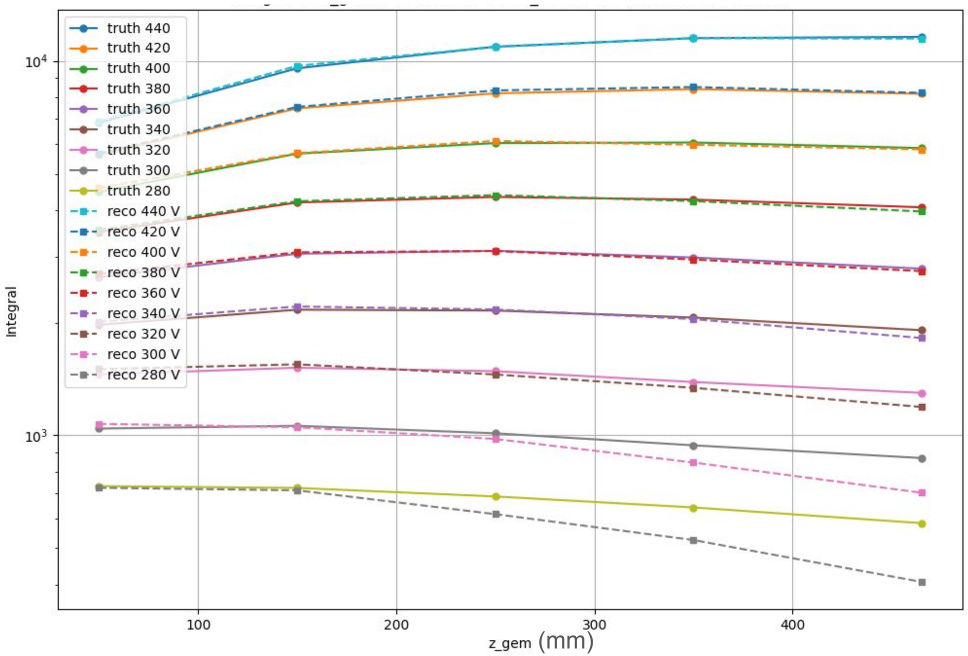
Conclusions

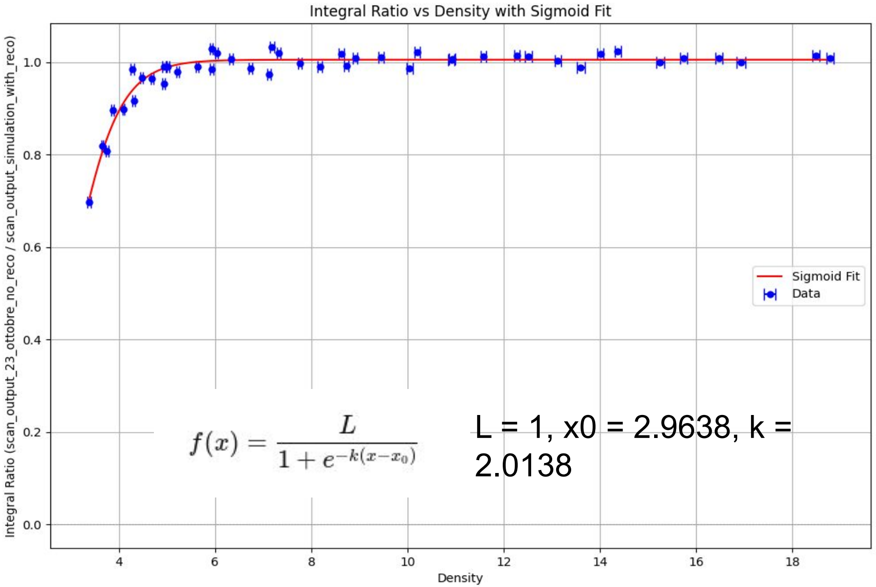
- **Fine-tuning digitization parameters**:
  - Accurate simulation of iron at different GEM voltages and z-positions.
  - **sc_integral** within 5%, other features within 10%.
- **Comparison with Radon alphas**:
  - Preliminary results suggest slight **over-saturation** in the simulation.
  - 25% accuracy on the comparison seems a good first result
- **PMT cross-check**:
  - Next step: Validate results by cross-checking with both iron and alpha **PMT waveforms**.
- **Americium simulation**:
  - Plan to simulate **59 keV gamma rays**
- **Optimization scope**:
  - Current optimization based on a specific set of runs. Some **fine-tuning** may be required for different time periods (only for **g0** and **lambda** parameters).
- **Proposing Iron calibration at low GEMV:**
  - We propose to change current Fe calibration by adding a low V scan

Thanks for the attention

Low integral - low density correction, from simulation

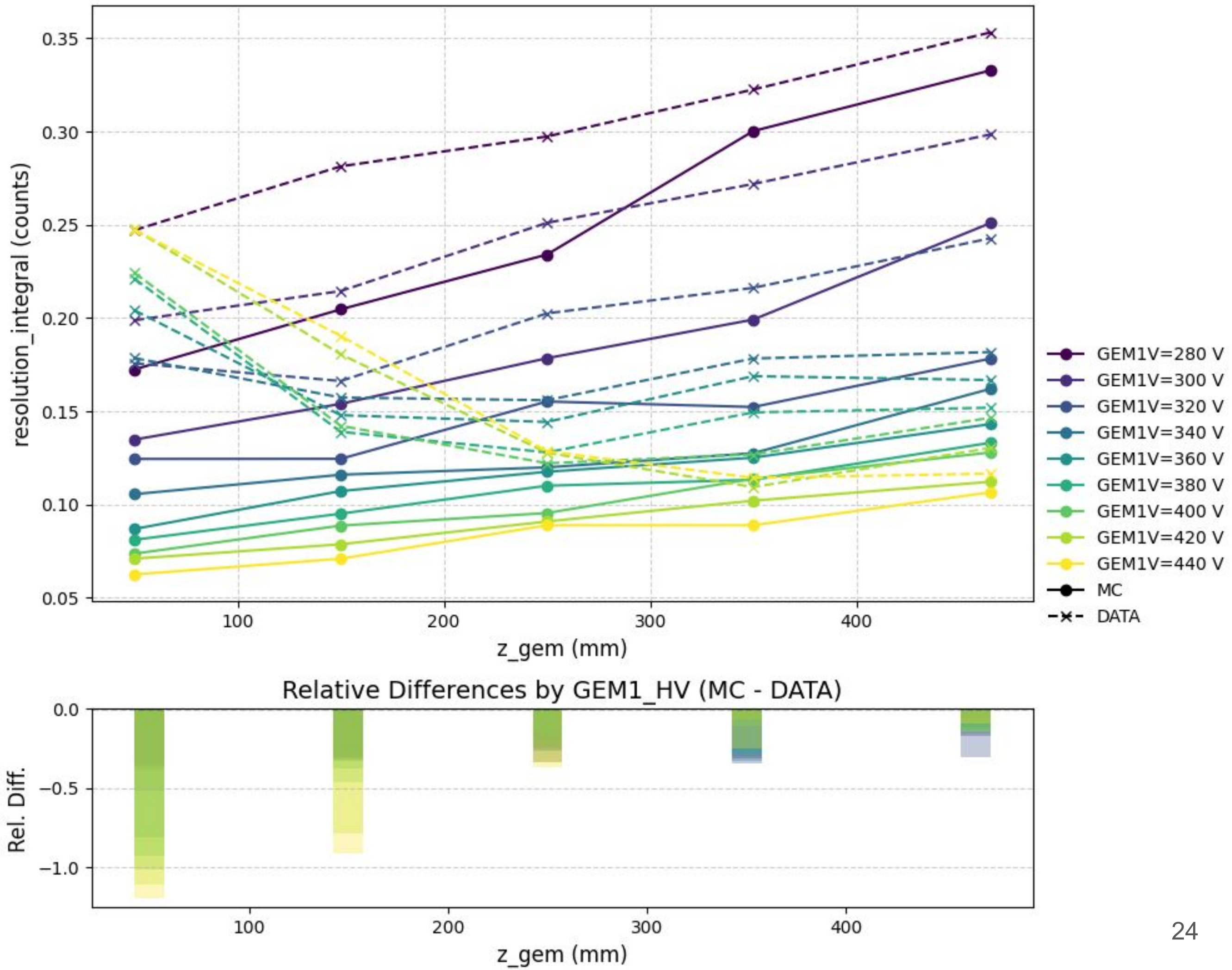
(density is defined as: sc_integral / sc_nhits)





$$f(x) = \frac{L}{1 + e^{-k(x - x_0)}}$$

L = 1, x0 = 2.9638, k = 2.0138


resolution_integral (counts)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
100
200
300
400
z_gem (mm)
GEM1V=280 V
GEM1V=300 V
GEM1V=320 V
GEM1V=340 V
GEM1V=360 V
GEM1V=380 V
GEM1V=400 V
GEM1V=420 V
GEM1V=440 V
MC
DATA
Relative Differences by GEM1_HV (MC - DATA)
Rel. Diff.
0.0
−0.5
−1.0
100
200
300
400
z_gem (mm)