Detector simulation and digitization

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CYGNO Collaboration Meeting
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Overview

- **Digitization Code Improvements**:
  - Rewritten from Python to C++ for better performance.
  - Upcoming PMT waveforms simulation.
- **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 per track (was ~10 seconds with Python)
    - **5 MeV NR:** ~1 minute per 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

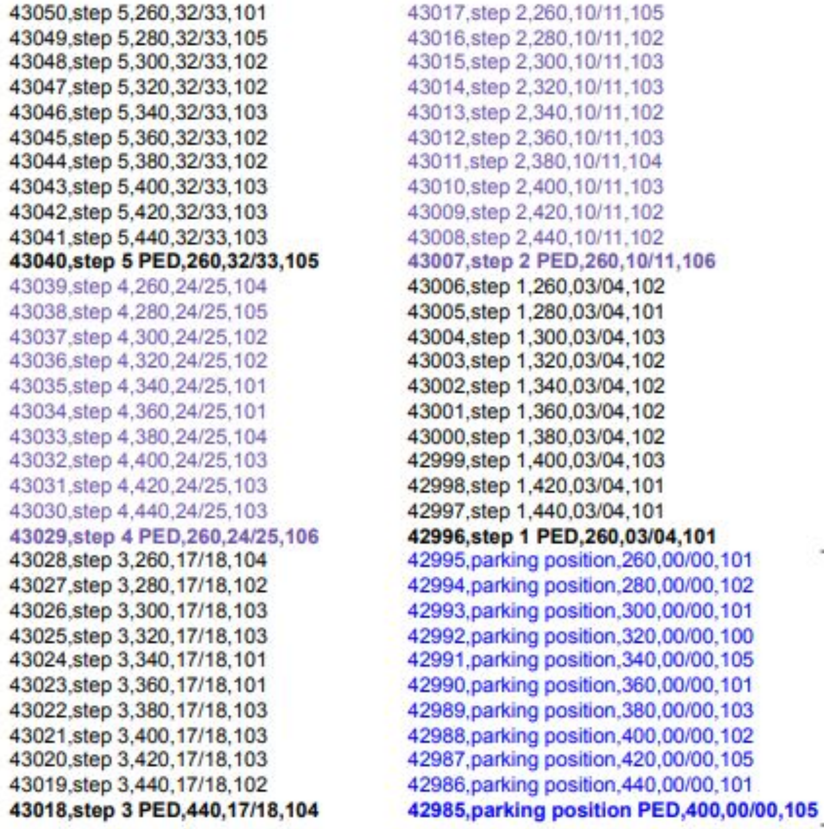
- **Scans:** GEM1V and z over 50 runs.
- **Run Date:** December 15, 2023 (Run 4 LNGS).

Parameters

- **GEM1 Voltages:** 260 V – 440 V.
- **Steps (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.



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43045,step 5,360,32/33,102
43044,step 5,380,32/33,102
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42987,parking position,420,00/00,105
42986,parking position,440,00/00,101
42985,parking position PED,400,00/00,105

Fitting unsaturated integral as a function of z and GEM1V

Given the unsaturated GEM gain:

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

With g0 representing a term that accounts for the deviation from a perfect exponential gain, we can fit 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:

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

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

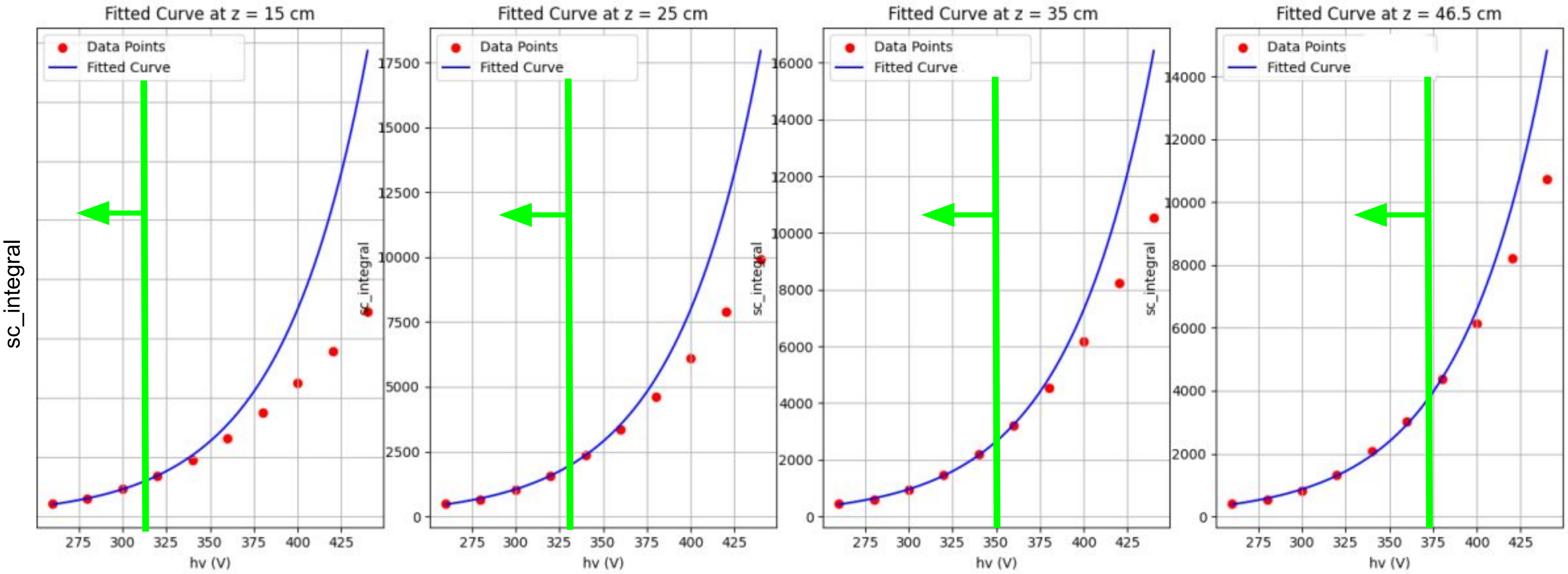
$$I_0 = \frac{E}{W} \cdot 0.07 \cdot 4 \cdot \Omega \cdot \epsilon_{\mathrm{eff}}^2 \cdot g_0^3 \cdot e^{\alpha \cdot V_{\mathrm{GEM3}}} \cdot e^{\alpha \cdot V_{\mathrm{GEM2}}}$$

photon per electron

ORCA-Fusion counts per photon

Below is the result of a **simultaneous fit** on **sc_integral** as a function of **z** and **GEM1V (hv)**.

The choice of the **threshold** (green line) to select the **'unsaturated' condition** influences the fit result. Therefore, we perform some fine-tuning to optimize the results.



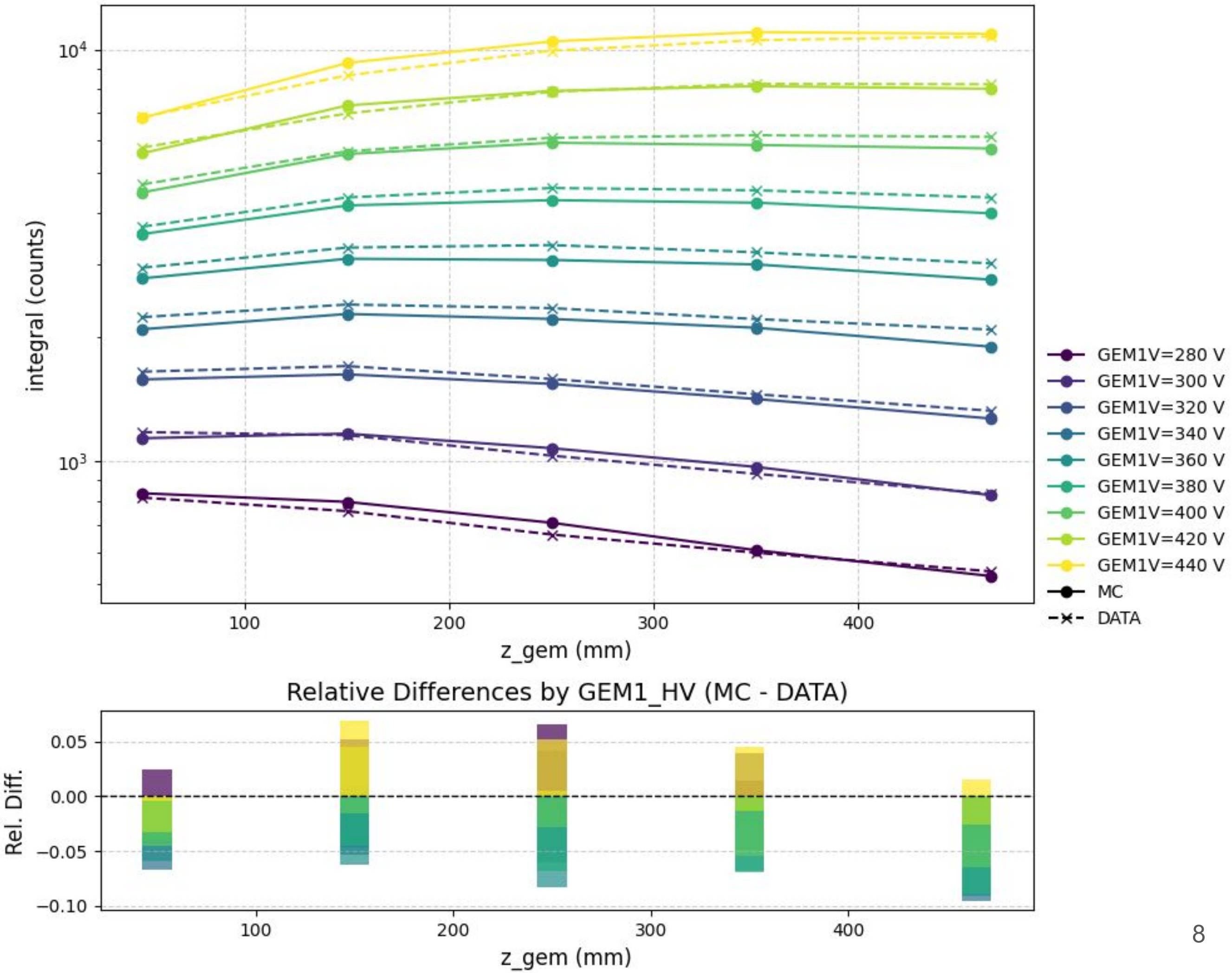
https://agenda.infn.it/event/43875/contributions/246832/attachments/127273/188228/study_of_saturation_params.pdf

Best parameters after fine-tuning on LNGS z-GEMV1 iron scans

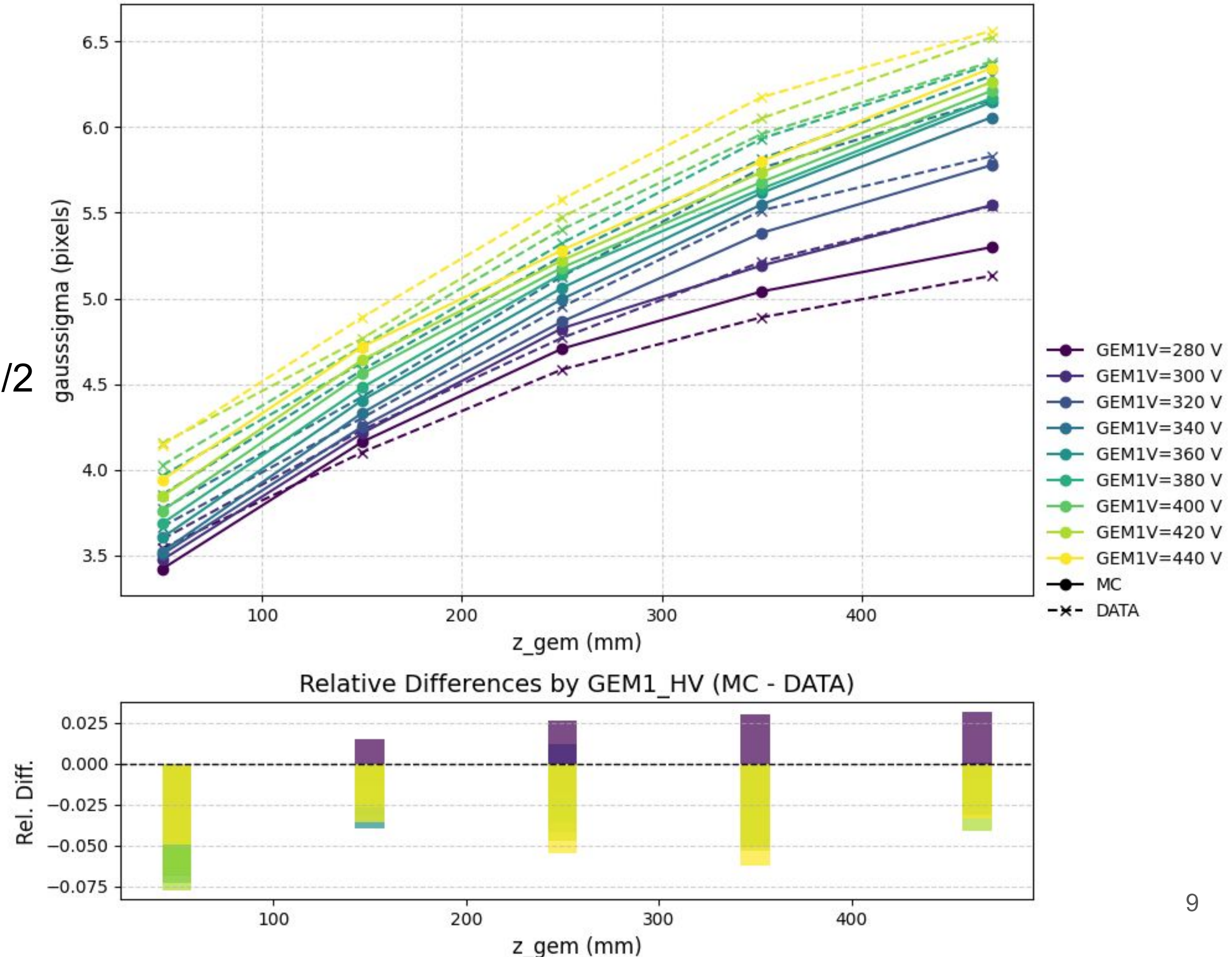
Digitization parameter	**LNF calibration (z scan only)**	**LNGS calibration (z & GEM1V scan)**
diff_const_sigma0T (mm^2)	**0.1225**	**0.13475**
diff_coeff_T (mm/sqrt(cm)^2 for 1 kV)	0.013225	0.0143819
diff_const_sigma0L (mm^2)	0.0676	0.0676
diff_coeff_L (mm/sqrt(cm)^2 for 1 kV)	0.00978	0.0103483
ion_pot (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**

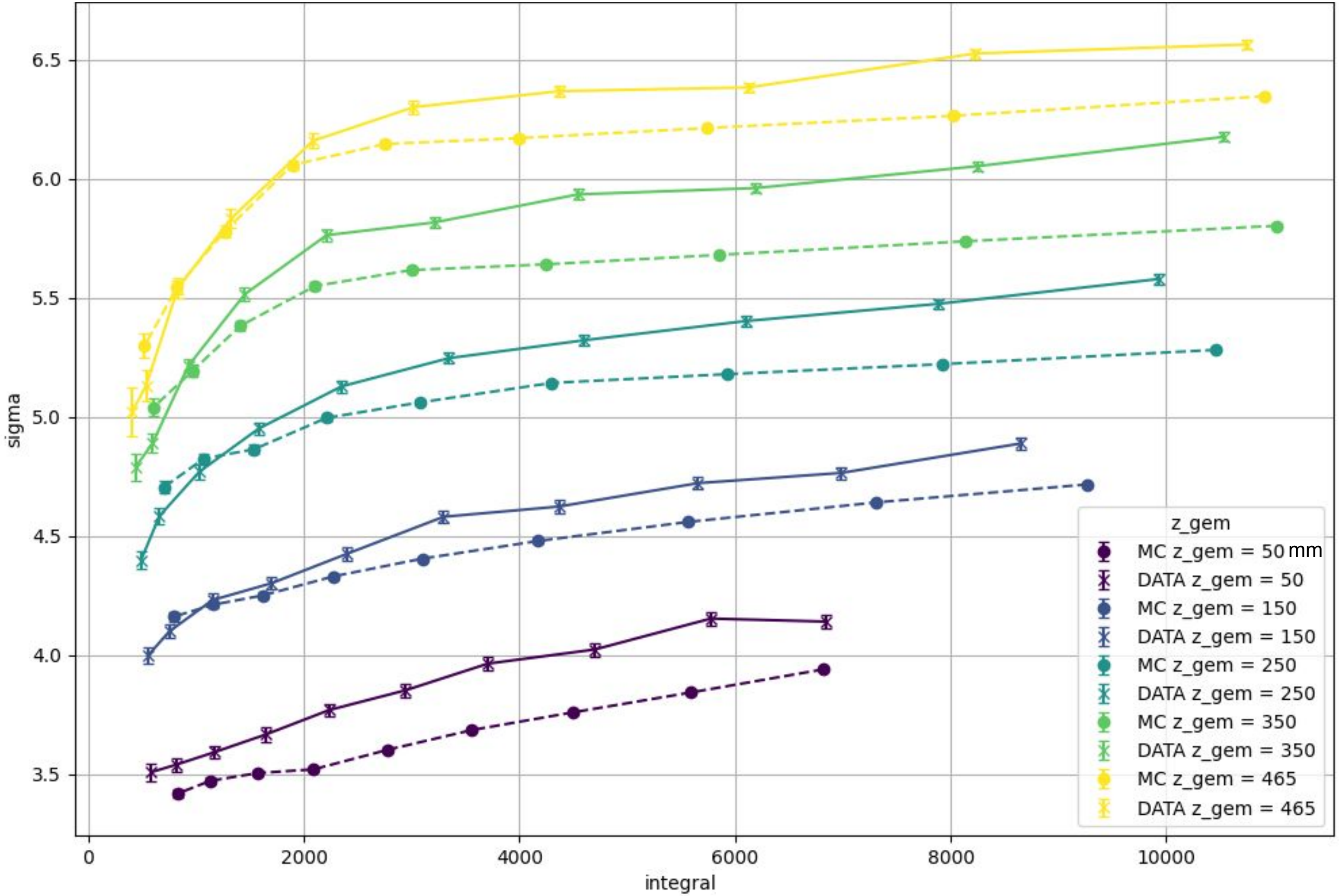
Each data point is the average sc_integral (for MC 500 tracks for data ~500)

Iron spot integrals reproduced within 5% across two orders of magnitude.

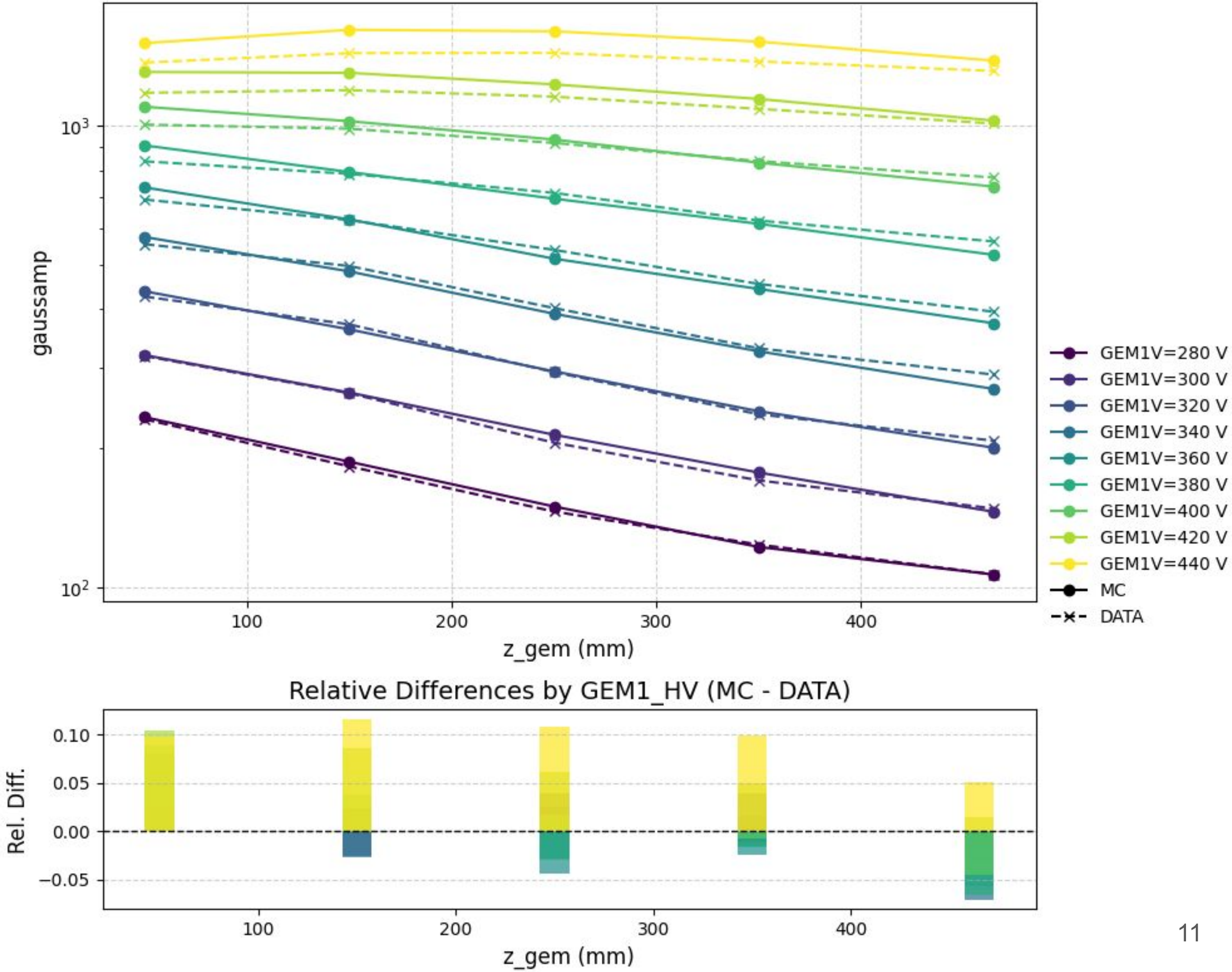


guasssigma:
(tgausssigma + lgausssigma)/2

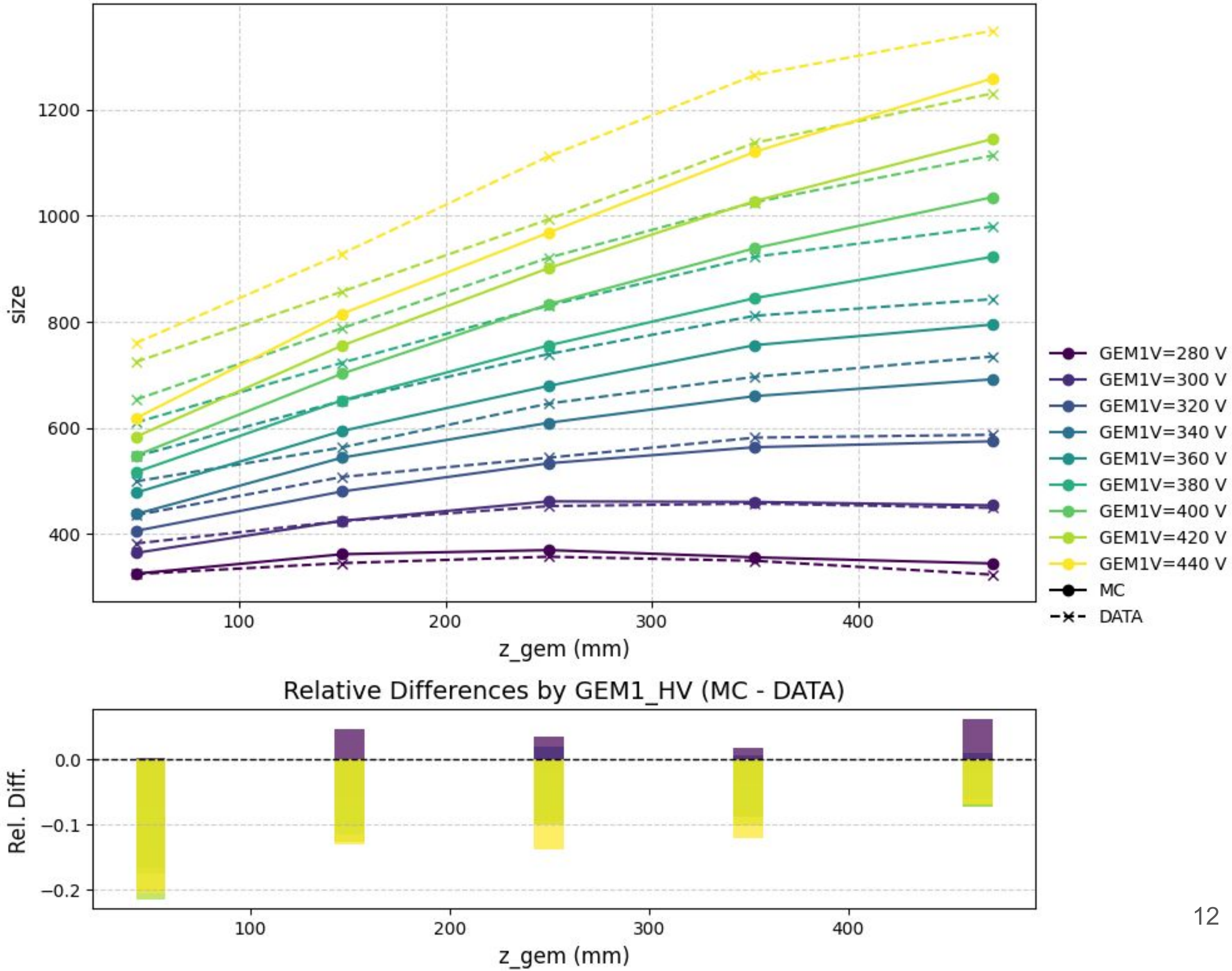



sigma
integral
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0
2000
4000
6000
8000
10000
z_gem
MC z_gem = 50 mm
DATA z_gem = 50
MC z_gem = 150
DATA z_gem = 150
MC z_gem = 250
DATA z_gem = 250
MC z_gem = 350
DATA z_gem = 350
MC z_gem = 465
DATA z_gem = 465

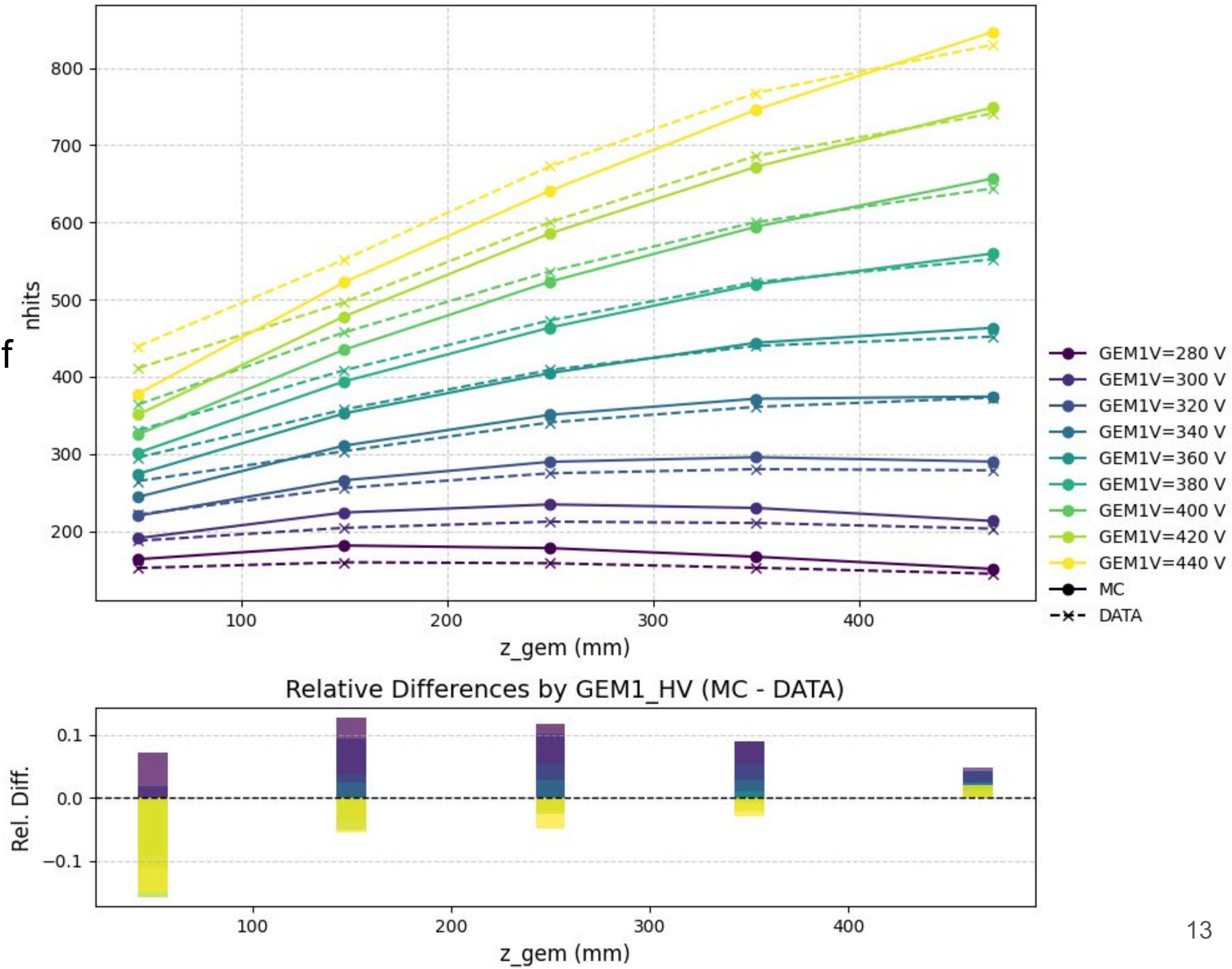
guassamp:
(tgaussamp + lgaussamp)/2



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

- Validate the digitization to simulate tracks of alphas from Rn.

Analysis Details

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

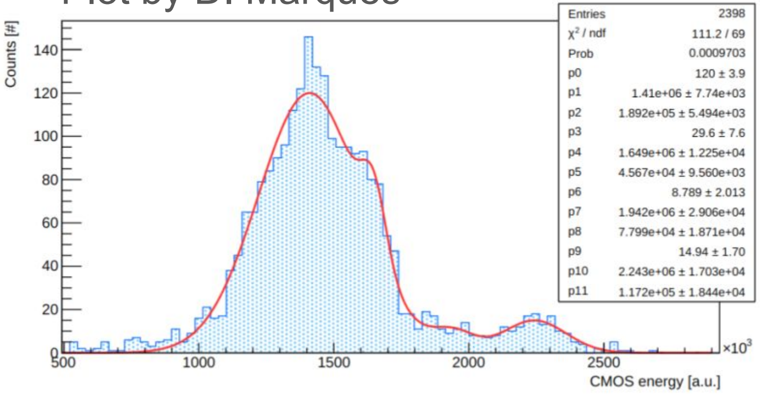
Radon alphas:

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

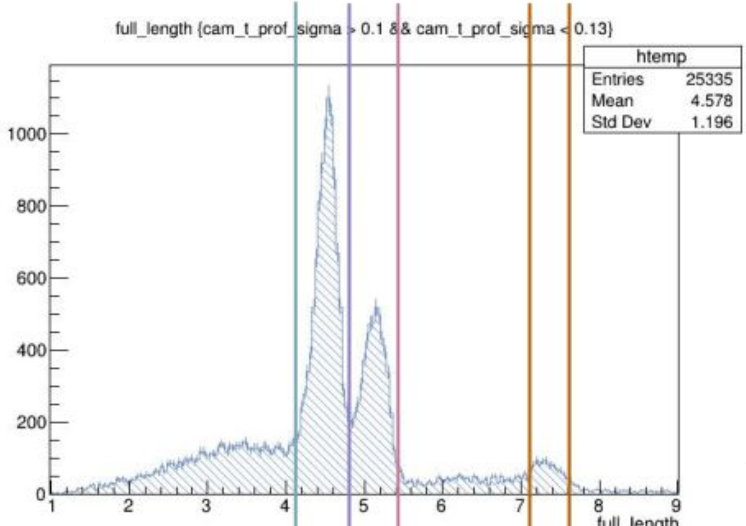
^{218}**Po**: 6.115 MeV (~50 mm)

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

Plot by D. Marques



Plot by D. Marques



Rn alpha simulation

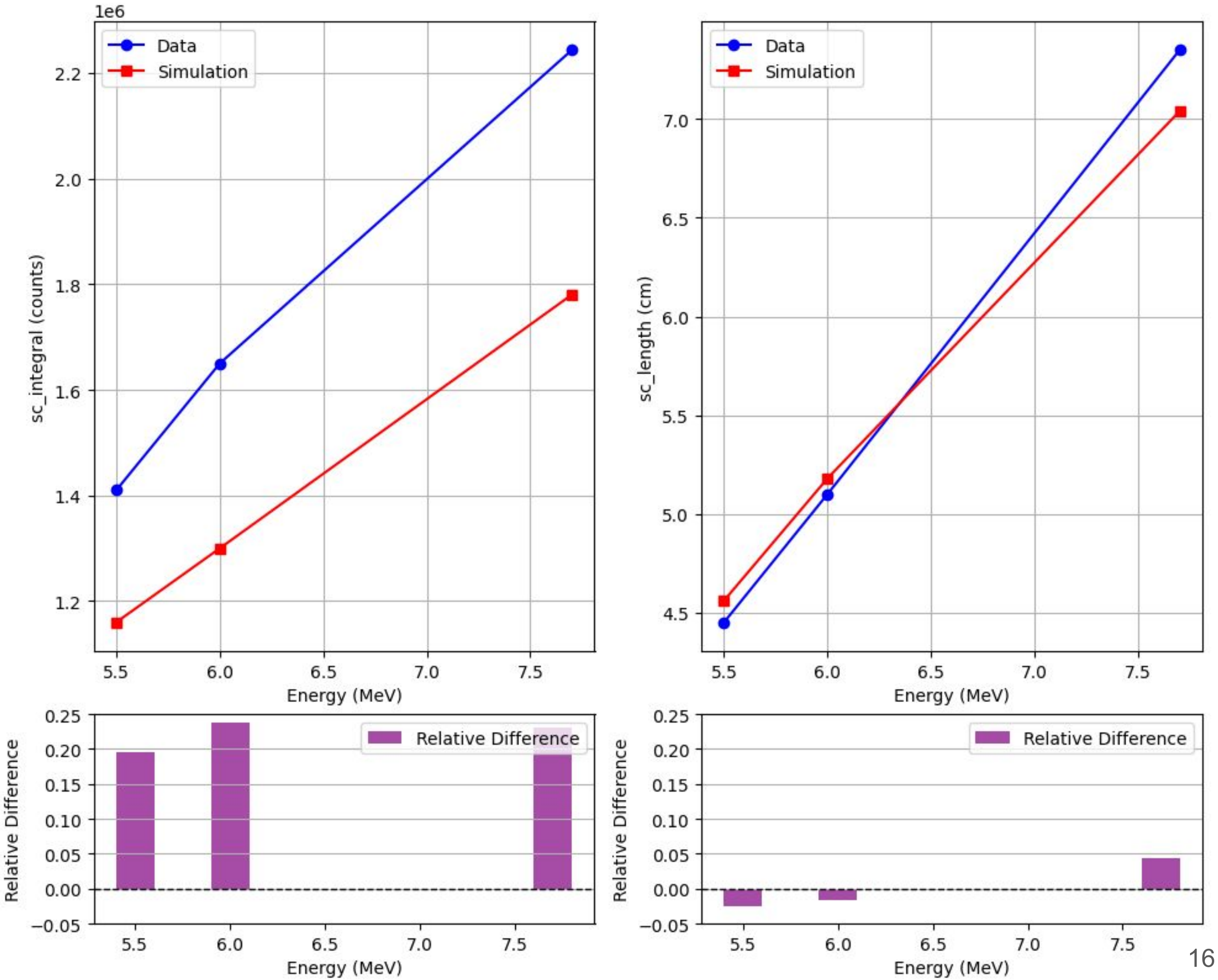
Simulation Setup

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

Parameters

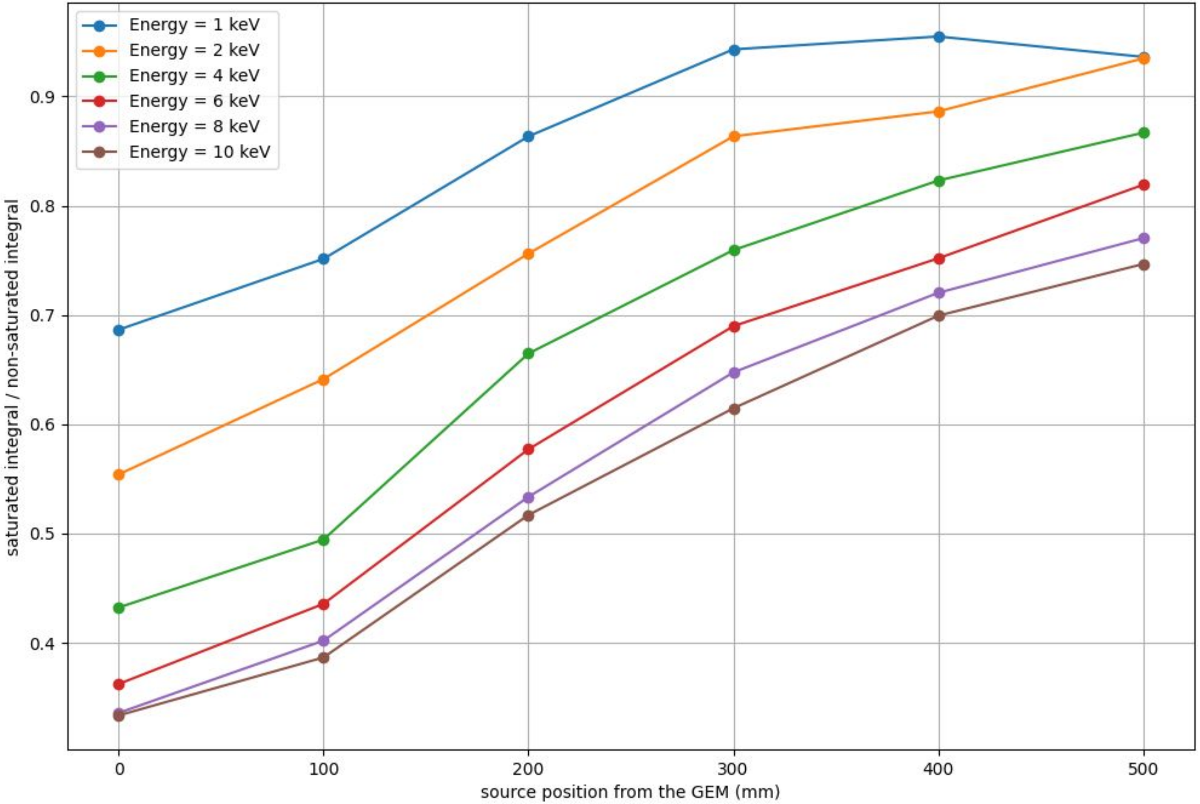
- **Consistency:** Same parameters as those used for iron simulation (since iron scans and ‘alpha data’ are close in time).
- **Direction:** tracks were simulated parallel to the GEMs.

A first comparison with **tguassigma** shows that simulated alphas have a smaller transversal profile (tgausssigma) of ~25 %



How Much Gain Saturation Occurs in LIME GEMs?

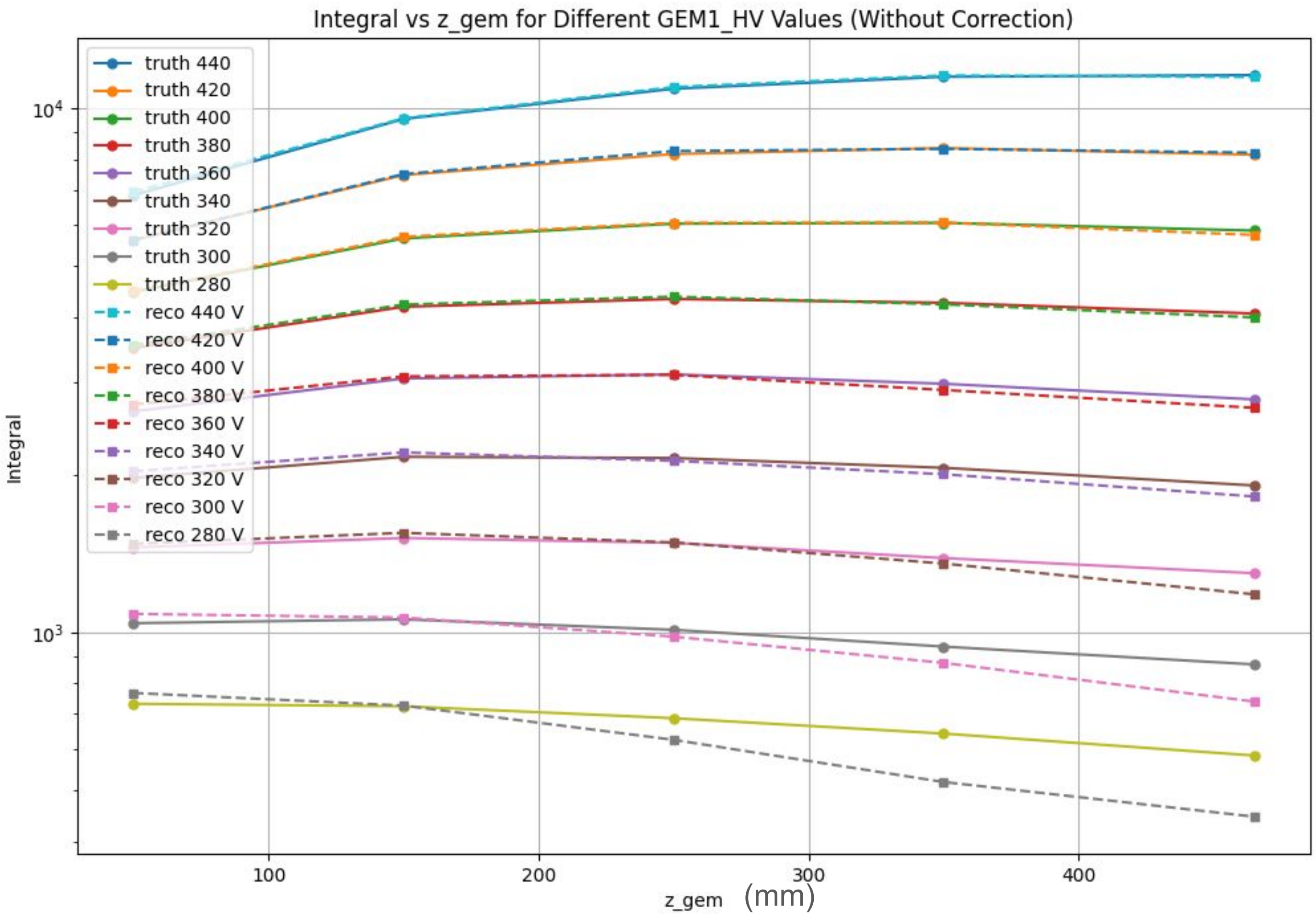
- If we trust our **simulation**, we can estimate the **saturation effect** at various energies in LIME. And it appears we saturate even at 1 keV
- Saturation trend is similar for energies > 8 keV since tracks get longer



Conclusions

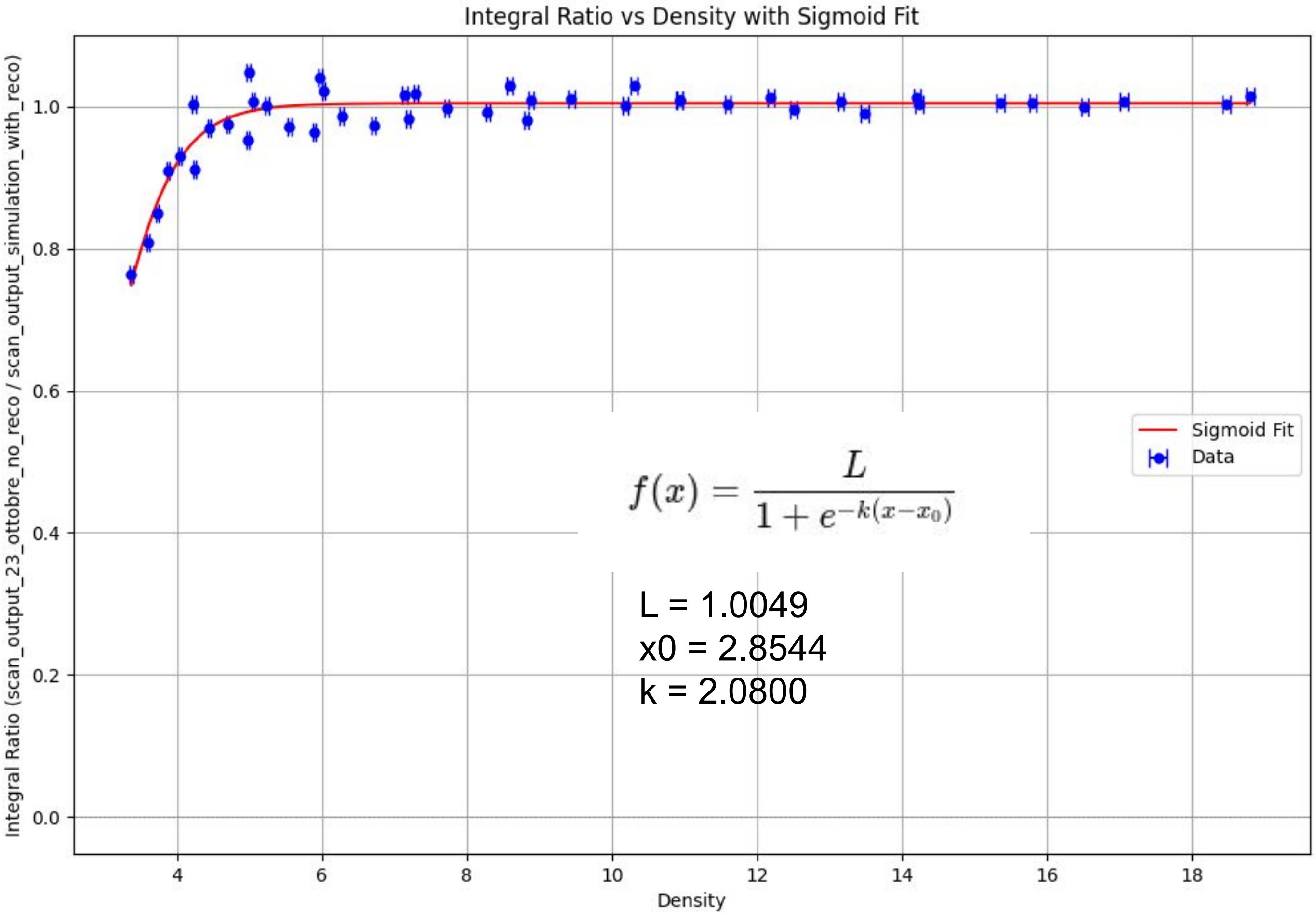
- **Fine-tuning digitization parameters**:
  - Accurate simulation of iron at different GEM voltages and z-positions.
  - **sc_integral** within 5%, other features within 10%.
- **Comparison with Radon alphas**:
  - Preliminary results suggest slight **over-saturation** in the simulation.
- **PMT cross-check**:
  - 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.
  - Further **fine-tuning** may be required for different time periods (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



(mm)

In the low saturation region, we are not reconstructing properly (**note the dependency on the z, that is the density**)

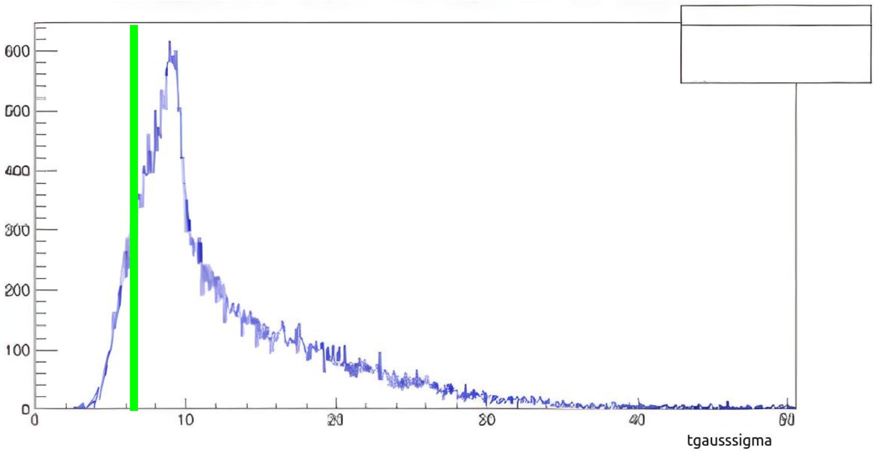


$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}$$

L = 1.0049
x0 = 2.8544
k = 2.0800

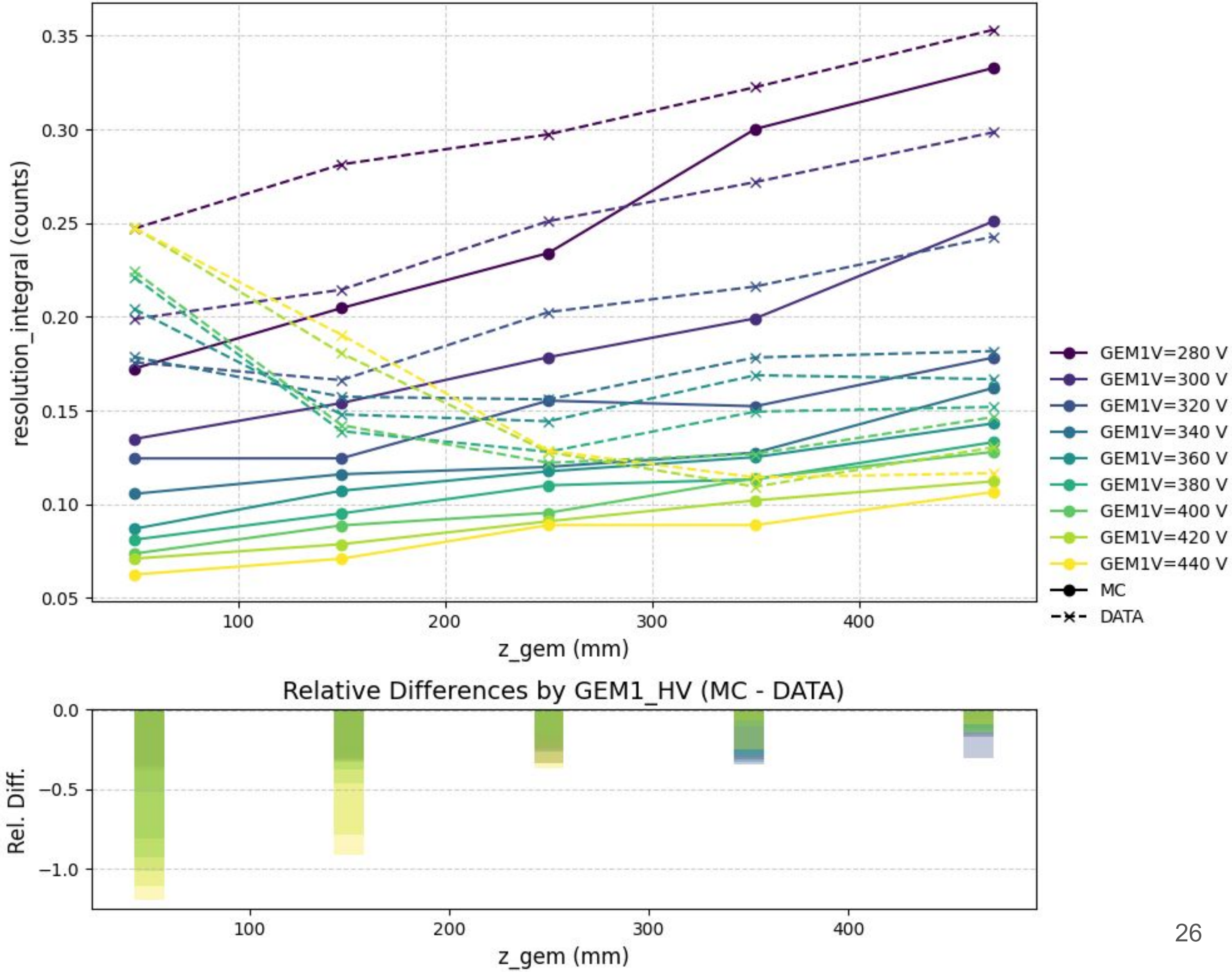
SIGMA PER ALPHA

overlapp histogram of david with my value of 7 pixels



simulted alpha have tgausssigma ~ 7 pixels aggiungi fluttuazioni z ,x y

maybe separate in 2 plots

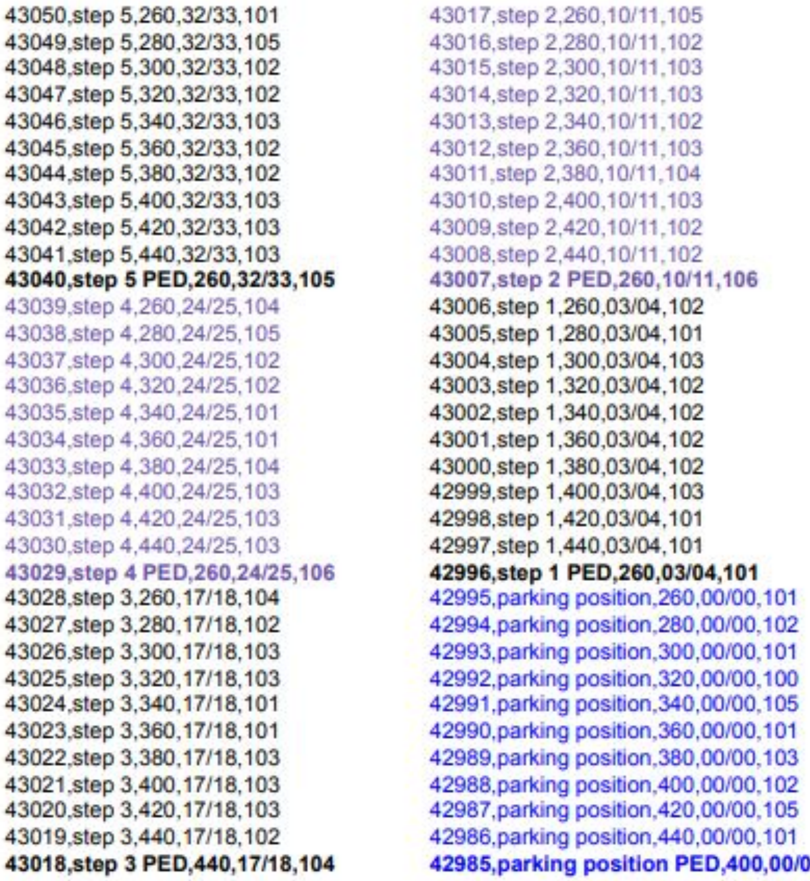


Data and analysis

Scans in HV and z. 50 runs in total.
(**15 dec 2023, RUN 4**)

- 10 GEM1 voltages: (280 V - 440 V)
- Usual 5 steps: 5, 10, 15, 25, 35, 46.5 cm

Cuts: sc_length < 500
sc_integral / sc_nhits < 100
sc_integral < 6e4
sc_width / sc_length < 1
sc_width / sc_length > 0.5
barycenter in circle with radius > 750 px



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