CYGNO collaboration meeting 2021

Gran Sasso Science Institute, L'Aquila, Italy

Detector simulation and saturation

ROMA TRE INFN Roma Tre F. Petrucci

for the "digitization group" (Davide, Giulia, Pietro, …)

20-21 December 2021

Outline

- Detector response
  - Ionization and drift
  - Gain fluctuations
  - Diffusion and smearing
  - Electrons to photons conversion
  - Photons collection
- Saturation effect
- Code improvement
- Data/MC comparison
- Next steps

Detector simulation

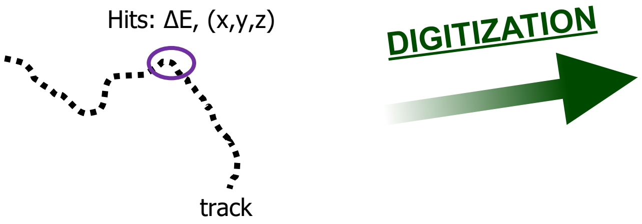
The simulation of an event in the detector, is done in two parts:

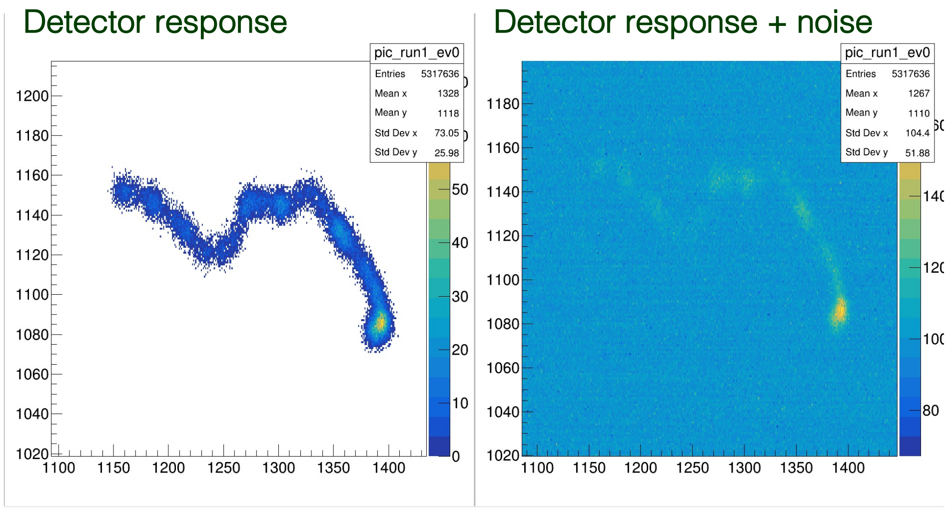
SIMULATION of a primary particle interacting in the gas volume: Geant4 for electron recoils (ER), SRIM for nuclear recoils (NR).

- Along the track:
  - hits energy deposition ΔE
  - hits position coordinates x, y , z

DIGITIZATION: Simulation (modelling) of the detector response returning a 2D image as for real data

G4/SRIM





Digitization

Takes the output of Geant4/SRIM as an input, and returns a “2D image”:
a 2D histogram where each cell contains the number of photons in a CMOS pixel

- The following processes are considered:
  - Ionization
  - Drift of the ionization electrons towards the 3-GEM stack
  - Multiplication in the 3-GEM stack
  - Production of photons in the multiplication process
  - Saturation effect
  - Photon collection on the sensor
  - Smearing of the impact position

- The digitization is a Python code still under development/optimization.
  - Code: https://github.com/CYGNUS-RD/digitization/
  - Wiki documentation: https://github.com/CYGNUS-RD/WIKI-documentation/wiki/Digitization

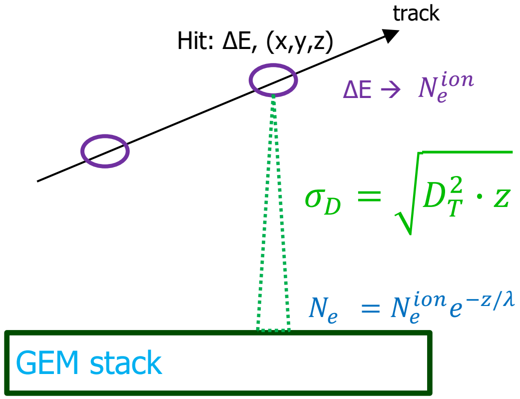
Ionization and drift

1. For each G4/SRIM hit, a mean number of ionization electrons are produced:
   $\overline{N}_e^{ion} = \Delta E / W_i$ (W$_i$=46.2 eV/pair in He/CF$_4$ 60/40)

2. The actual number N_e^{ion} of ionization electrons is obtained from a Poisson distribution with mean = $\overline{N}_e^{ion}$

3. Ionization electrons diffuse in the drift region on the x-y plane of the GEM stack: $\sigma_D^2 = D_T^2 \cdot z$

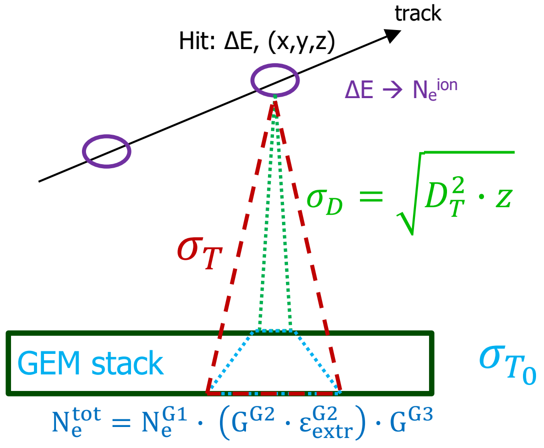
4. Ionization electrons are partially absorbed in the gas:
   $N_e = N_e^{ion} e^{-z/\lambda}$ where z is the distance from the GEM stack



Gain and fluctuations

Ionization electrons arrive at the GEM stack; gain and efficiencies of the 3 GEM foils should be considered.

1. gain fluctuations in the first foil only are relevant:
2. For each ionization electron → $N_e^{G1,k}$ multiplication electrons in the first GEM (k=1, N_e^{ion}) are extracted using an exponential distribution with $\mathrm{mean} = G^{G1}$ (G^{G1} is the gain of the first GEM foil)
3. Total number of multiplication electron for the first foil:
   $N_e^{G1} = \sum N_e^{G1,k} \cdot \varepsilon_{extr}^{G1}$ (ε_{extr}^{G1}: extraction efficiency for the first GEM)



4. The total number of multiplication electrons computed considering the gain of other two GEM foils and the extraction efficiency of the second foil: $N_e^{tot} = N_e^{G1} \cdot (G^{G2} \cdot \varepsilon_{extr}^{G2}) \cdot G^{G3}$

5. Electrons diffuse also in the GEM stack (σ_{T_0}): $\sigma_T = \sqrt{\sigma_{T_0}^2 + \sigma_D^2}$

Photons collection

1. The mean total number of photons is obtained using 0.07 ɣ/e: $N_\gamma^{mean,tot} = N_e^{tot} \cdot 0.07\ ^{\gamma}/_{e}$
2. The number of total photons N_γ^{tot} extracted from a Poisson distribution with mean value $N_\gamma^{mean,tot}$

3. The number of photons hitting the sensor depends on the solid angle ratio Ω: $N_\gamma = N_\gamma^{tot} \cdot \Omega$

   where: $\Omega = \frac{1}{(4(\delta+1)a)^2}$; $\delta = \left(\frac{\text{image size}}{\text{sensor size}}\right) \left(= \frac{350\ \text{mm}}{14.976\ \text{mm}} \text{for ORCA Fusion on LIME}\right)$; $a = 0.95$ aperture

4. ɣ's positions are obtained with random extractions of N_γ positions from a gaussian around the initial hit position, with $\sigma_T = \sqrt{\sigma_{T_0}^2 + \sigma_D^2}$

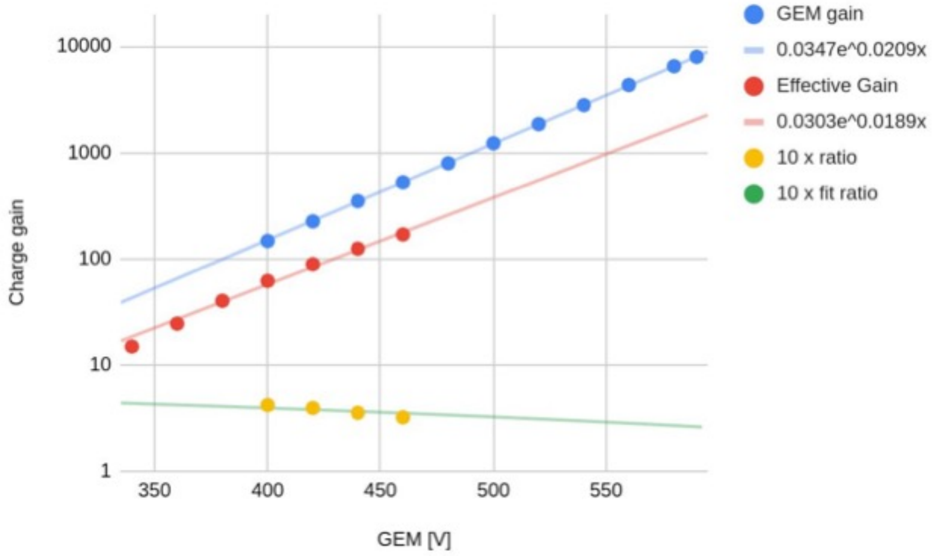
5. The sensor noise is added to the simulation as an image:
   - from a pedestal file (option used so far);
   - from a set of images simulated with the code from the Brazilian colleagues.

GEM gain and efficiency

The GEM gain G and efficiency changes according to operating conditions and detector configuration

Dependence of the gain as a function of HV: $G = 0.347 \cdot e^{0.029 \cdot HV}$

Dependence of the efficiency as a function of HV: $\varepsilon = 0.873 \cdot e^{0.002 \cdot HV}$



- GEM gain from Fernando's measurements
- Efficiency from effective gain measurements from Francesco and Karolina

Gain saturation (in a nutshell)

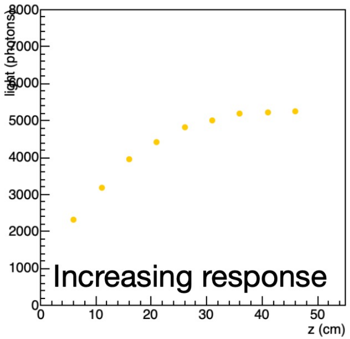
from Davide, see:
https://cernbox.cern.ch/index.php/s/tJIyEZZPLdkSrH6/download

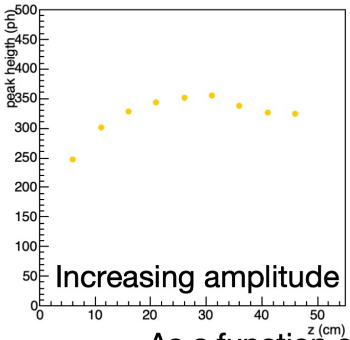
In a real optical TPC: Gain and light yield (ph/e) are not constant → no linearity between light production and ionization

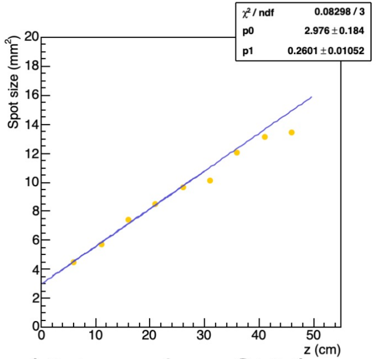
- In an <u>ideal</u> optical TPC:
  - charges are efficiently drifted toward GEM;
  - gain and light yield (ph/e) are constant

- As a function of the distance from the GEM:
- Decreasing of the spot amplitude and increasing of the spot size (becouse of diffusion)

- Observed behaviour:







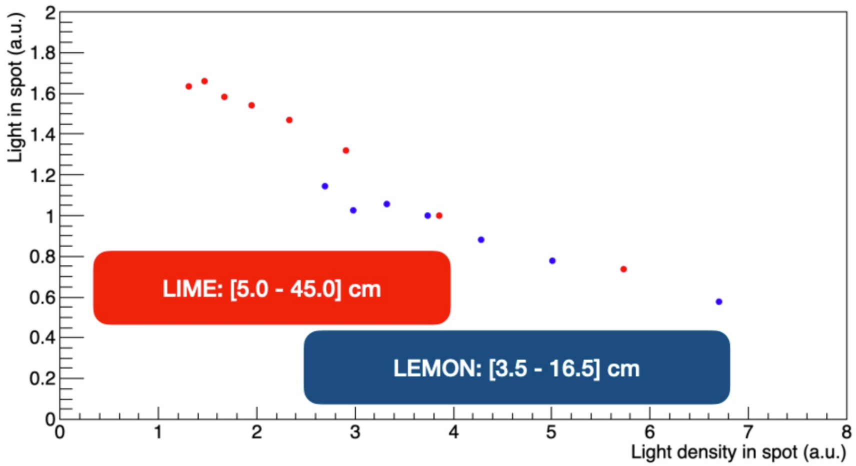
Spot size increasing because of the diffusion

As a function of z (distance from GEM)

Gain saturation (in a nutshell)

from Davide, see:
https://cernbox.cern.ch/index.php/s/tJIyEZZPLdkSrH6/download

^{55}Fe data; expected density evaluated from diffusion parameters (simulations)

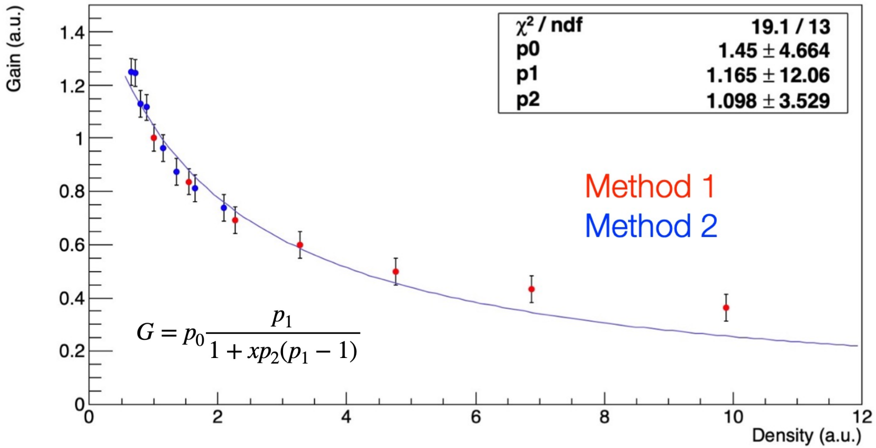


From a "simple" model:

$$G = \frac{Ae^{\alpha V_{GEM}}}{1 + \beta n_0 (e^{\alpha V_{GEM}} - 1)}$$

Charge density on GEM3 can be varied:

- Varying the gain of GEM1; changing the charge (method 1)
- Varying the z; changing the size of the spot (method 2)



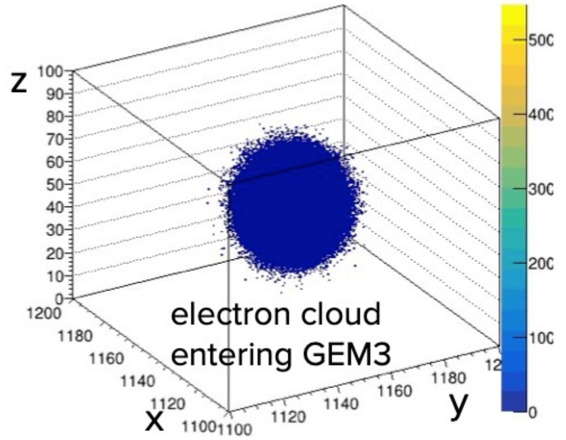
Simulation of the saturation

- The number of electrons entering GEM3 are calculated as before.
- The charge cloud have a 3D gaussian shape:

$$\sigma_T = \sqrt{\sigma_{T_0}^2 + \sigma_{D,T}^2}$$ in the plane of the GEM as before;

$$\sigma_L = \sqrt{\sigma_{L_0}^2 + \sigma_{D,L}^2}$$ along the z axis

- Clouds are divided in voxels (with the size of the pixels in the x-y plane and 2 x GEM thickness in z);



- Non saturated gain in GEM#1 and GEM#2 is assumed;
- the number n of electrons in each voxel is multiplied by a gain

$$G = A\frac{g}{1+\frac{n}{n_h}(g-1)}$$ where g is the no-saturated gain; A is an overall free parameter

- Total number of electrons is the sum of all voxels along z.
- The number of photons (in each x-y bin) is obtained as before (light yield, geometrical efficiency, …).

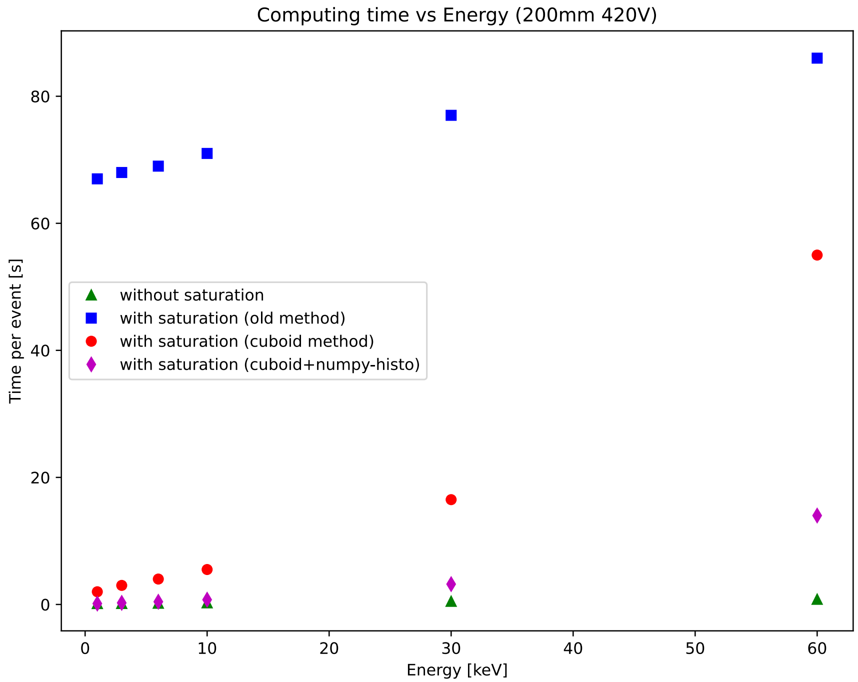
Code optimization

Results from Pietro

The simulation of the saturations resulted to be extremely slow (tens s per events).
Technical, but relevant, improvements to the method are being developed:

- “cuboid” method:
  - The saturation is applied only in a much smaller cuboid around the track, not the full 3D histo
- “cuboid+Numpy–histo”:
  - A smaller numpy histo (with the size of the cuboid) is used. The rest of the blank image is added in the end.

- Another improvement under study, promising for further improvement at high energies.



Data/MC comparison

Data: ^{55}Fe data taking with LIME (April 2021, runs from 4119 to 4190)

- GEM1_HV scan: 350, 386, 406, 420, 431, 440 V
- GEM2_HV = GEM3_HV = 440 V
- Distance from GEM scan: 6, 11, 16, 21, 26, 31, 36, 41, 46 cm

Data and MC reconstructed and analysed with the same code ("autumn21" branch)

Simulation parameters:

- 6 keV electrons
- Saturation: $\beta = \frac{1}{n_h}$=1e-5, A = 1
- Absorption: λ = 1000 mm
- Light yield: 0.07 photons/electrons
- Diffusion parameters:

(from https://arxiv.org/pdf/2007.00608.pdf)

  - σ_{T_0} = 350 μm, σ_T= 0.11 mm/sqrt(cm)
  - σ_{L_0} = 260 μm, σ_L= 0.099 mm/sqrt(cm)

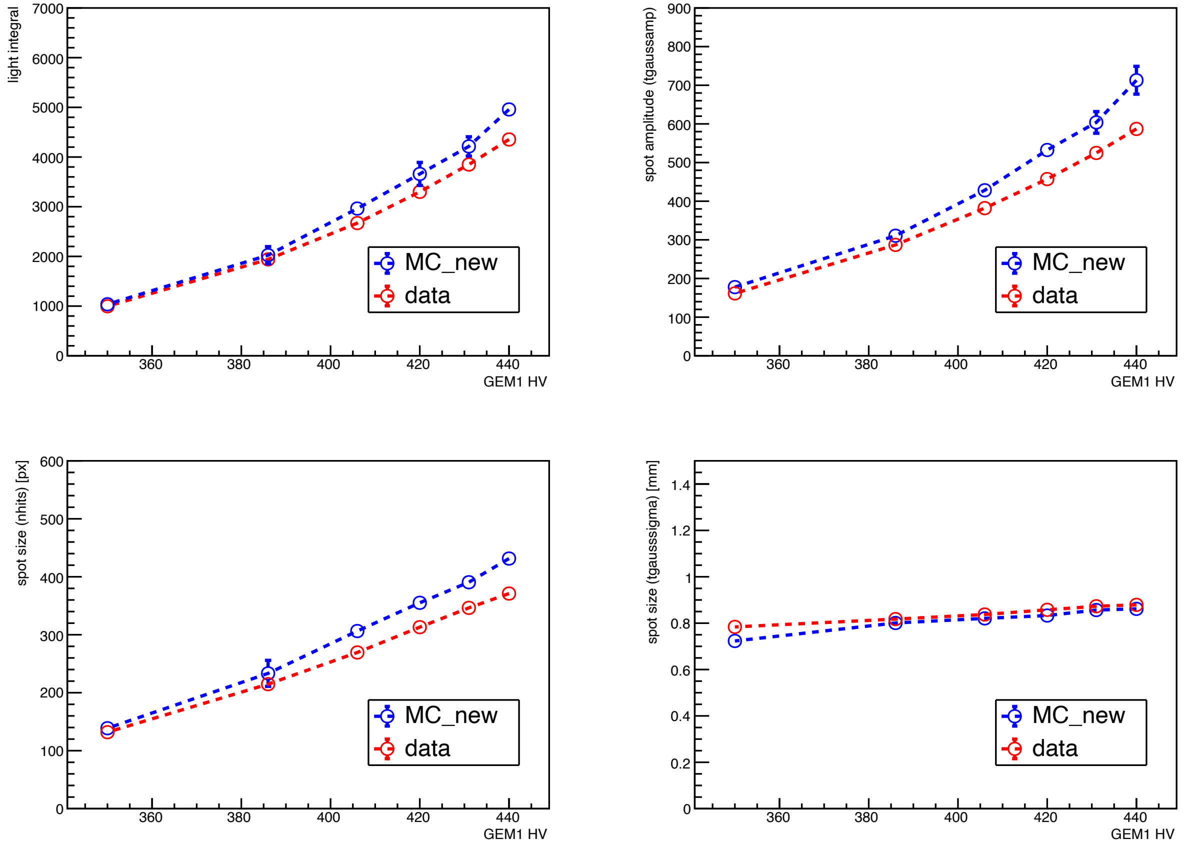
- ORCA Fusion:
  - 2304 x 2304 pixels (1 pixel 6.5 um x 6.5 um)
  - Camera aperture a = 0.95
  - Sensor size: 14.976 mm
  - Sensor calibration → 1 photon = 2 sensor counts
  - Active area: 35 cm x 35 cm
  - $\delta = \frac{350\ \text{mm}}{14.976\ \text{mm}}$

- GEM1_HV=350, 386, 406, 420, 431, 440 V
- GEM2_HV = 440 V, GEM3_HV = 440 V
- Distance from GEM scan: 10, 15, 20, 25, 30, 35, 40, 45 cm

Data/MC comparison

Results from Pietro

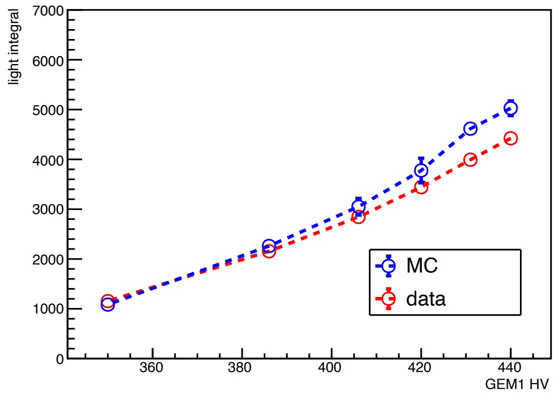
CYGNO Experiment

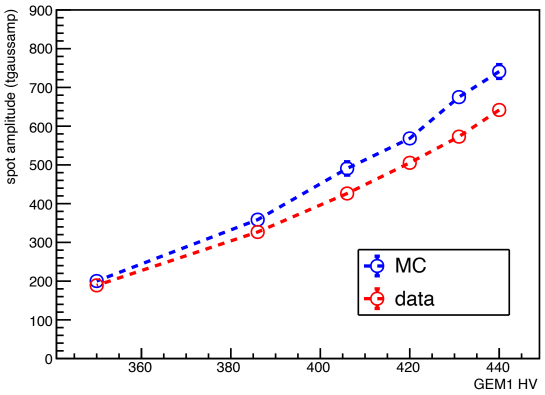


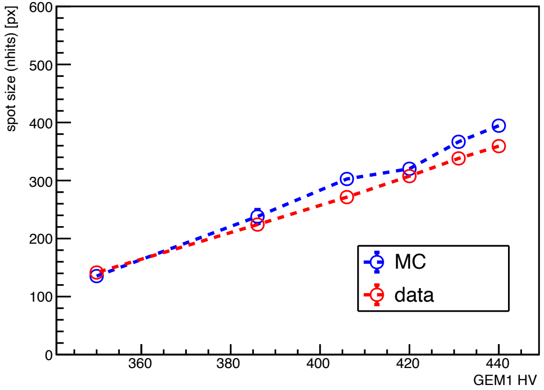
z = 45 cm

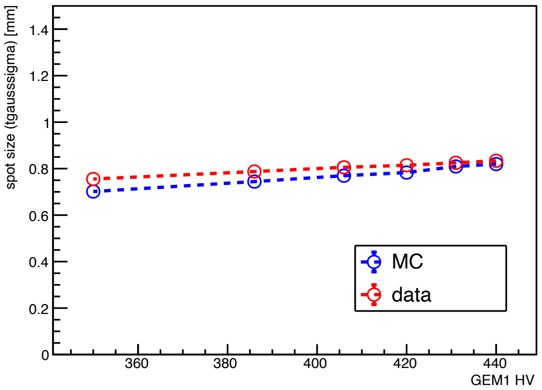
Data/MC comparison

Results from Giulia





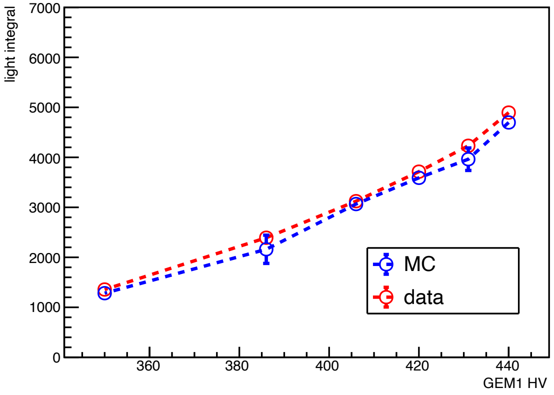


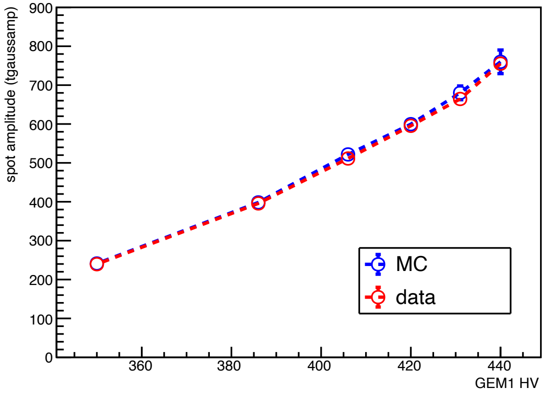


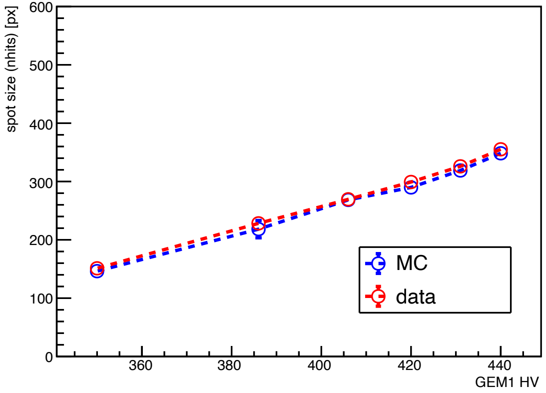
z = 35 cm

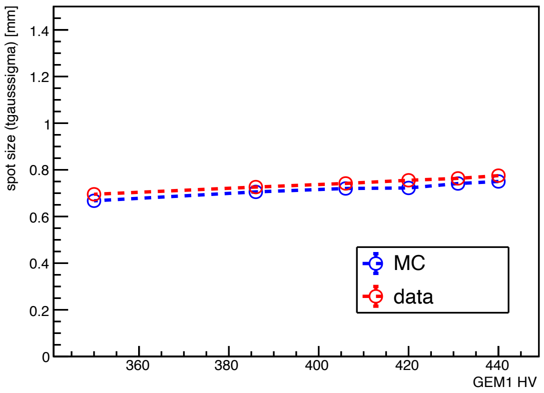
Data/MC comparison

Results from Giulia





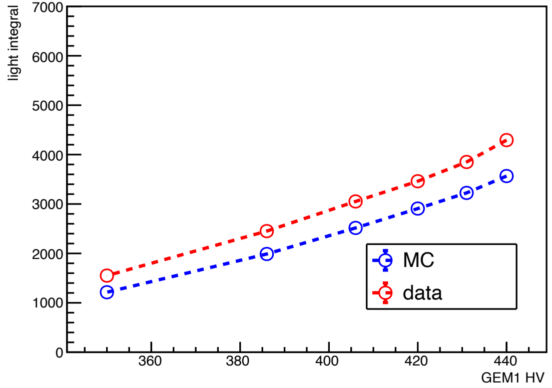


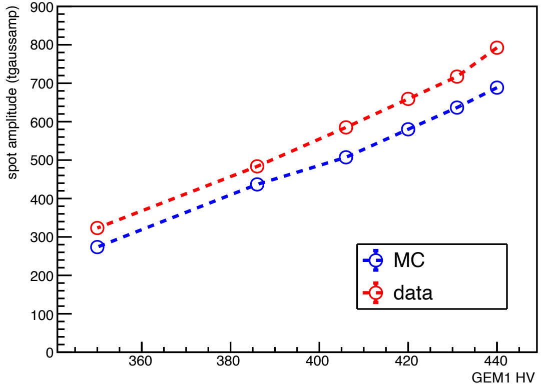


z = 25 cm

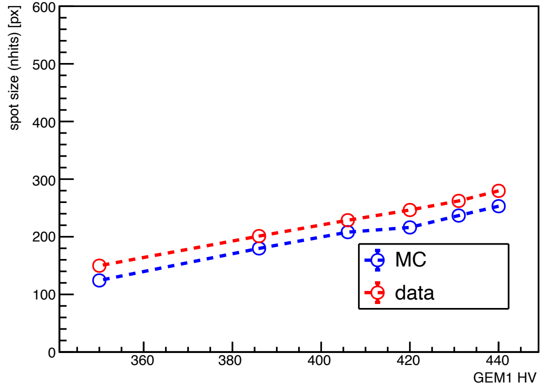
Data/MC comparison

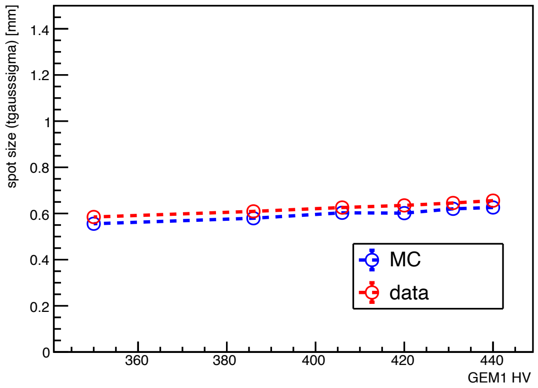
Results from Giulia





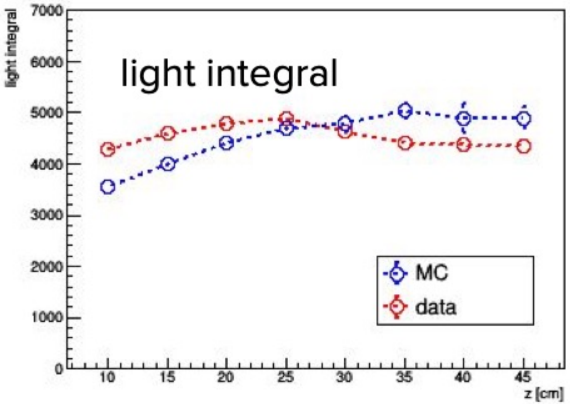
z = 10 cm

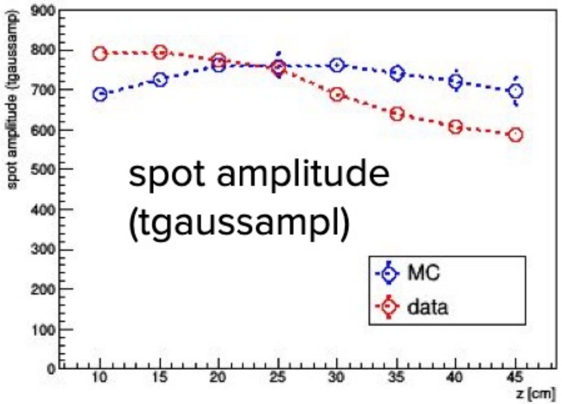


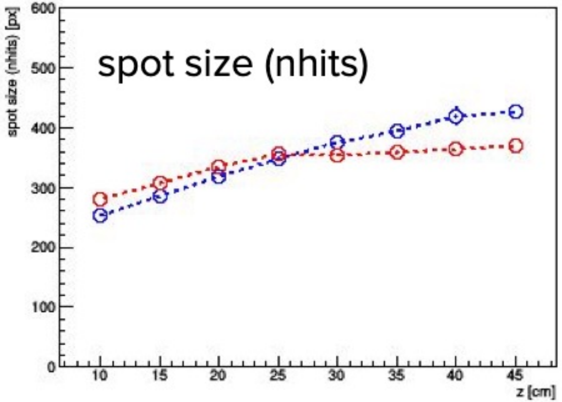


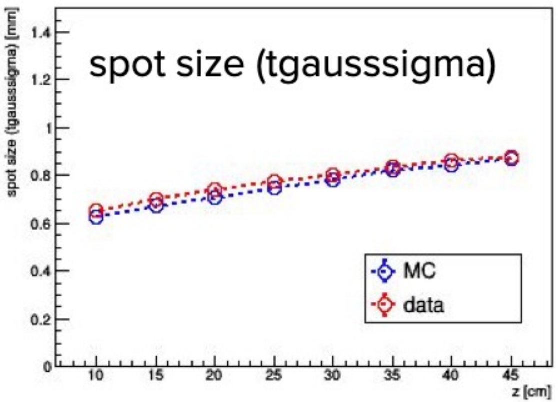
Data/MC comparison

Results from Giulia









HV = 440 V

Summary and next steps

- The digitization is reasonably fast and provides acceptable results.
- Simulation parameters must be tuned in order to improve data/MC agreement.
- Data/MC comparison must be extended:
  - using higher statistics;
  - looking at other reconstructed variables;
  - exploiting data at different energies and with different sources.