

Summary of the detector response simulation



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on behalf of the "digitization group"
(Davide, Giulia, Pietro, Samuele, ...)





CYGNO collaboration meeting 2021
Gran Sasso Science Institute, L'Aquila, Italy

Detector simulation and saturation



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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.



F. Petrucci – Detector simulation and saturation

19

- The overall structure of the detector response simulation is in place since last Collaboration Meeting in december last year.

- Since then, the following steps were (slowly!) taken:

1. Simulation parameters tuning;
2. Data/MC comparison at different energies;
3. Writing a paper summarizing the topic.

PREPARED FOR SUBMISSION TO JINST

Modeling the detector response of the CYGNO optical readout TPC

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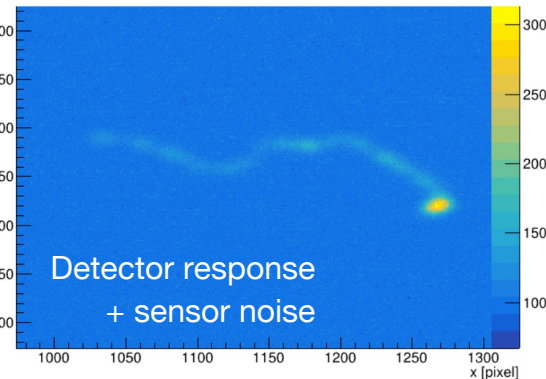
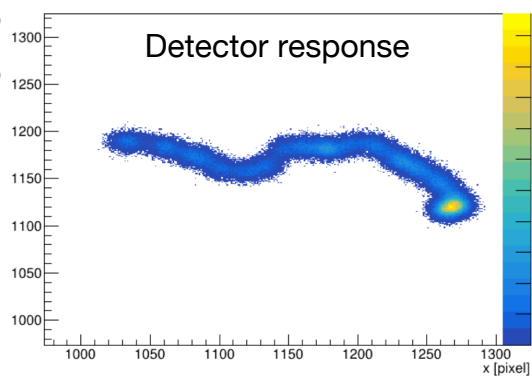
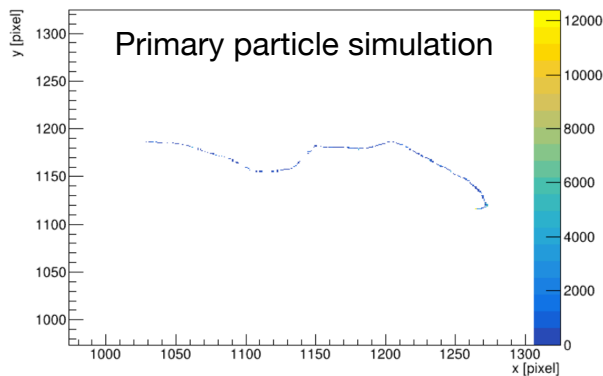
Detector response simulation

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

SIMULATION of a primary particle interacting in the gas volume

DIGITIZATION: Modelling of the detector response to return a 2D image as for real data

30 keV electron



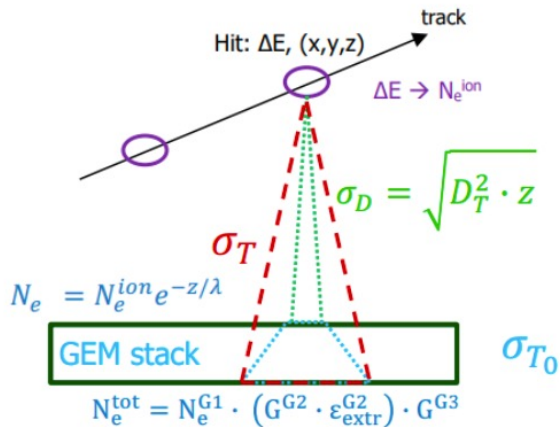
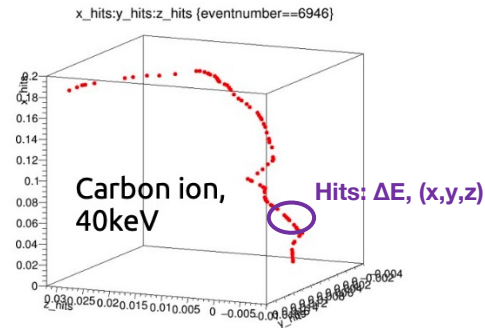
Modelling the detector response

MC simulation of 3D energy deposition:

GEANT4 for ER, SRIM for NR.

For each hit along the track:

- hits energy deposition ΔE
- hits position coordinates x, y, z



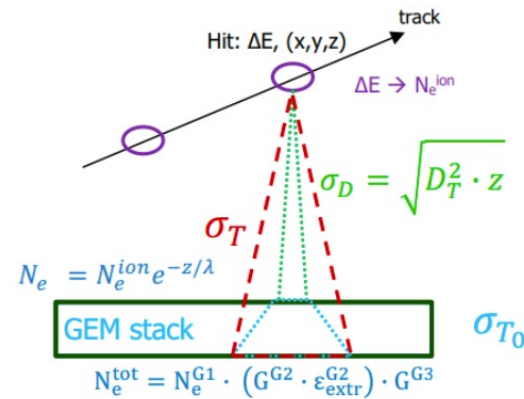
The following processes are considered (including fluctuations):

- Ionization;
- Diffusion (in the gas and in the GEMs);
- Absorption in the gas;
- Multiplication in the 3-GEM stack;
- Gain Saturation effect (depending on the charge density);
- Production and collection of photons in the multiplication process;
- Sensor noise.

- Code: <https://github.com/CYGNUS-RD/digitization/>
- Wiki documentation: <https://github.com/CYGNUS-RD/WIKI-documentation/wiki/Digitization>

Simulation parameters

W_i	46.2 ev/pair	Effective ionization potential
G	$G = 0.0347 \cdot e^{0.0209 \cdot HV}$	Single GEM gain
ϵ	$\epsilon = 0.873 \cdot e^{-0.002 \cdot HV}$	Single GEM Extraction efficiency
k	0.07 ph/e	Ligth yield
Ω	$\frac{1}{(4(\delta+1)a)^2} = 1.19 \cdot 10^{-4}$	Sensor optical acceptance (LIME)
δ	$\left(\frac{\text{image size}}{\text{sensor size}}\right) = \left(\frac{346 \text{ mm}}{14.976 \text{ mm}}\right)$	For ORCA Fusion on LIME
a	0.95	aperture



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

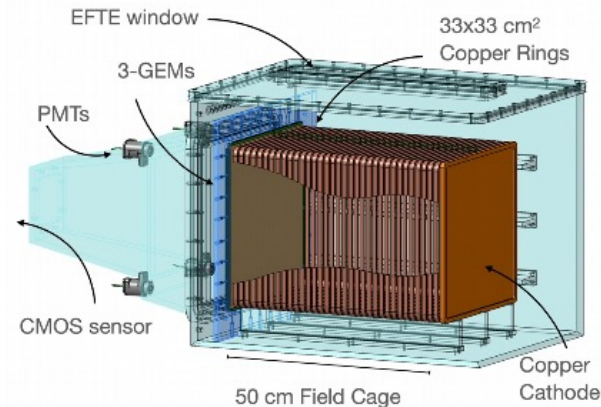
Gas related parameters were checked/tuned with data

σ_{0T}	350 μm	Diffusion parameters
σ_{0L}	260 μm	
σ_T	110 $\mu\text{m}/\sqrt{\text{cm}}$	
σ_L	100 $\mu\text{m}/\sqrt{\text{cm}}$	

λ	1 m	Absorption lenght
β	10^{-5}	Saturation parameters
A	1	
$\Delta x, y_{vox}$	0.13 mm	
Δz_{vox}	0.1 mm	

Data/MC comparison for parameters optimization

- Data taken with LIME, operated for few months @INFN LNF:
 - 50L sensitive volume (33x33 cm² thin GEMs, 50 cm drift);
 - Optical readout:
 - 4 PMTs at the corners;
 - 1 sCMOS camera (Hamamatsu ORCA Fusion);
- Data sample: ⁵⁵Fe X-ray source at different distance from the GEM plane.



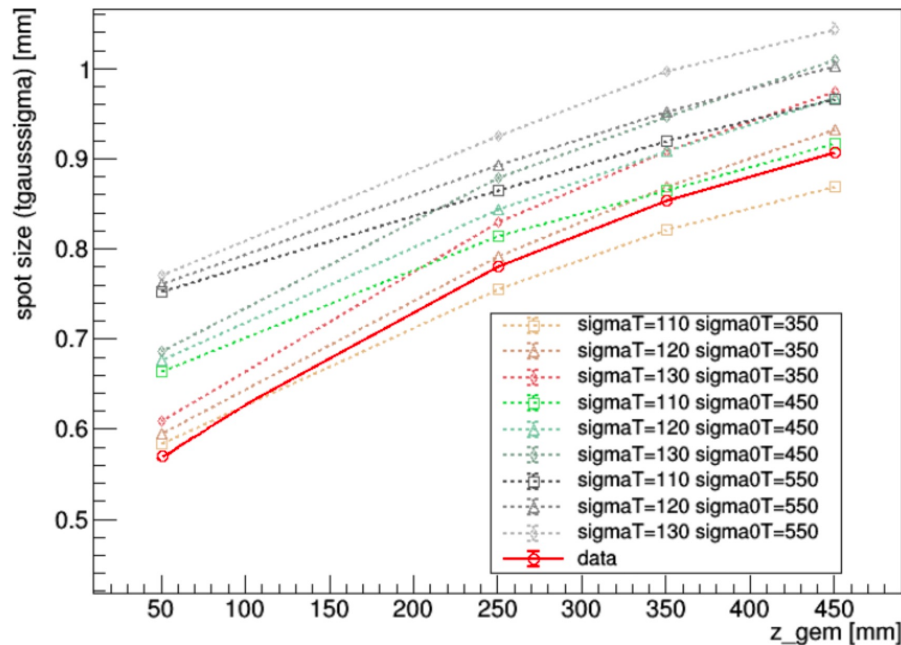
- Simulated samples: 6 keV electrons generated in a specific position;
- Digitization code used exploiting different settings:
 - Different distances from the GEM plane (50, 250, 350 and 450 mm);
 - Different values of the parameters to check consistency.

Data and MC reconstructed with the same code version and configurations.
 Spot properties used for comparison: **total ligth** (integral), **number of pixel** per spot, **gaussian spot profile amplitude and sigma**

Diffusion parameters

- Example for the transversal diffusion parameters: the spot size is the most sensible quantity

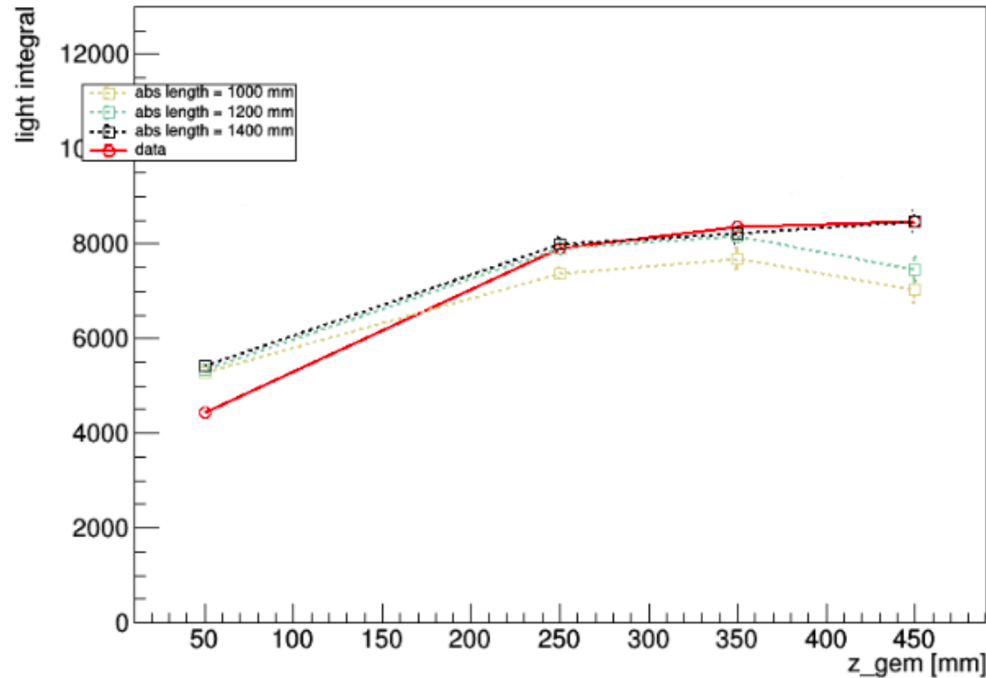
	Initial value	Optimized value
σ_{0T}	350 μm	350 μm
σ_{0L}	260 μm	260 μm
σ_T	110 $\mu m/\sqrt{cm}$	115 $\mu m/\sqrt{cm}$
σ_L	100 $\mu m/\sqrt{cm}$	100 $\mu m/\sqrt{cm}$



Attenuation length

- Total length is the most sensitive variable. Spot size variables (size and number of hits) are almost insensitive)

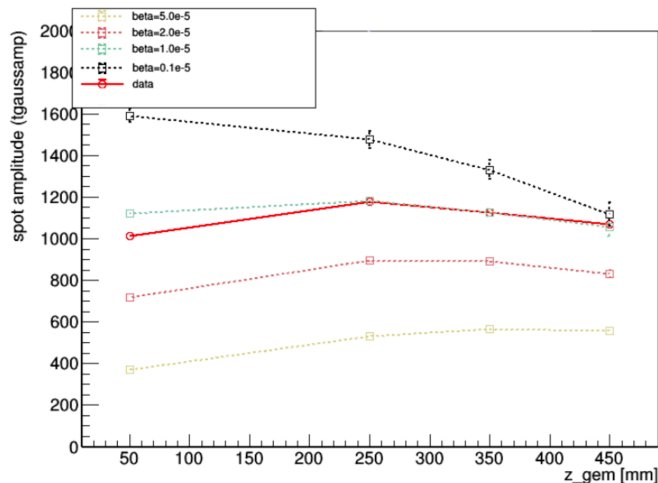
	Initial value	Optimized value
λ	1 m	1.4 m



Saturation parameters

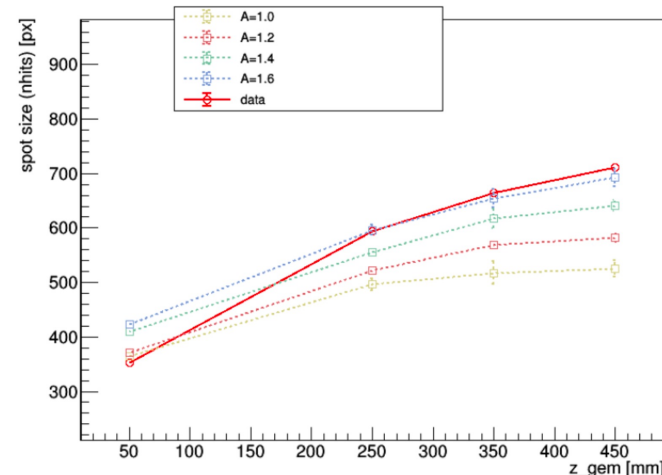
$$G = \frac{Ae^{\alpha V_{GEM}}}{1 + \beta n_0(e^{\alpha V_{GEM}} - 1)}$$

- Spot amplitude: larger beta values increase saturation effect, in particular at low z where the electron cloud is more dense



	Initial value	Optimized value
β	10^{-5}	10^{-5}
A	1	1.5

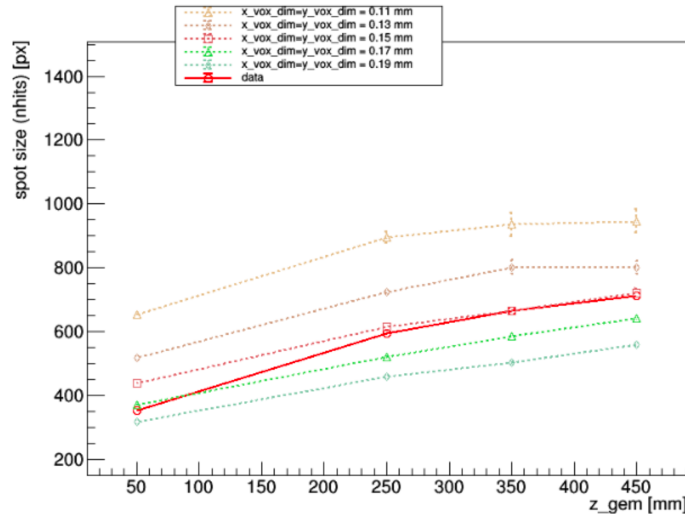
- Spot size: large A values (normalization) is relevant in particular at large distances (photons on the edge of the image)



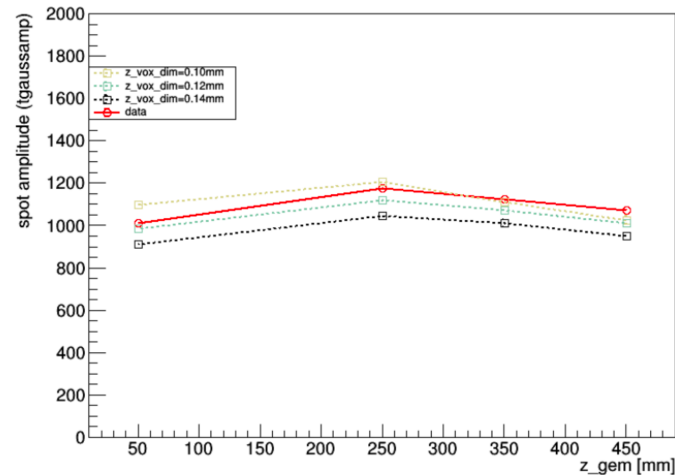
Saturation parameters

	Initial value	Optimized value
$\Delta x, y_{vox}$	0.13 mm	0.15 mm
Δz_{vox}	0.1 mm	0.1 mm

- Spot amplitude: larger beta values increase saturation effect, in particular at low z where the electron cloud is more dense



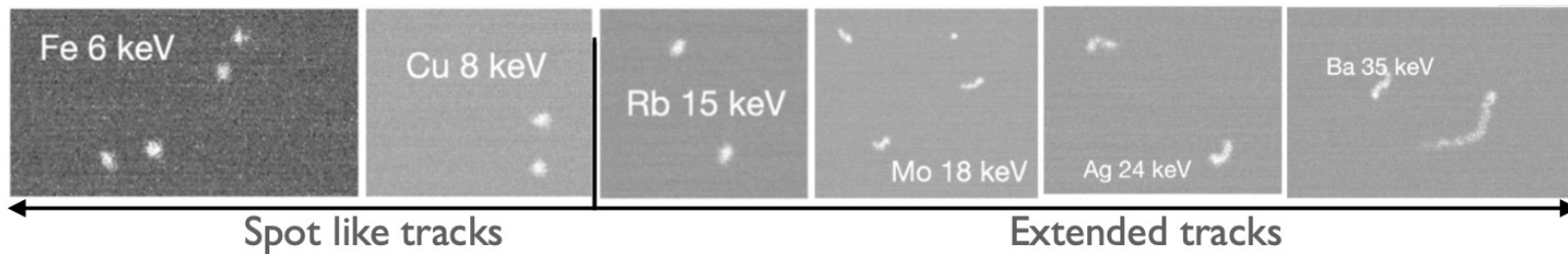
- Spot size: large A values (normalization) is relevant in particular at large distances (photons on the edge of the image)



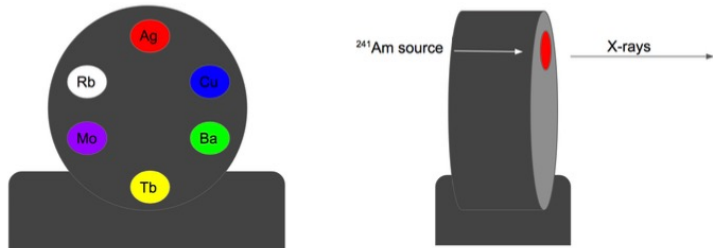
Comparison with data at different energies

Study of linearity and energy resolution overground performed with different X-Ray source:

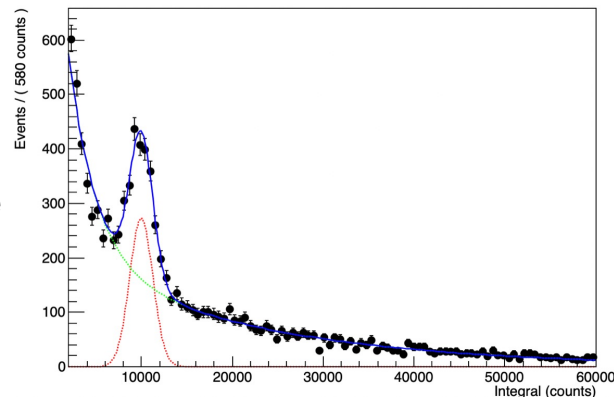
- ^{55}Fe -source for 6 keV;
- Different materials (Cu, Rb, Mo, Ag, Ba, Tb) irradiated by a ^{241}Am -source for higher energies;
- ^{55}Fe on a gypsum (Ca) target for 3.7 keV.



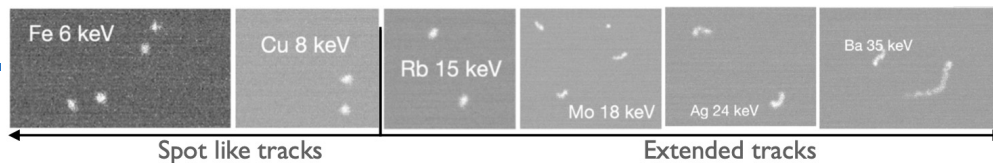
Amersham AMC.2084 X-ray source



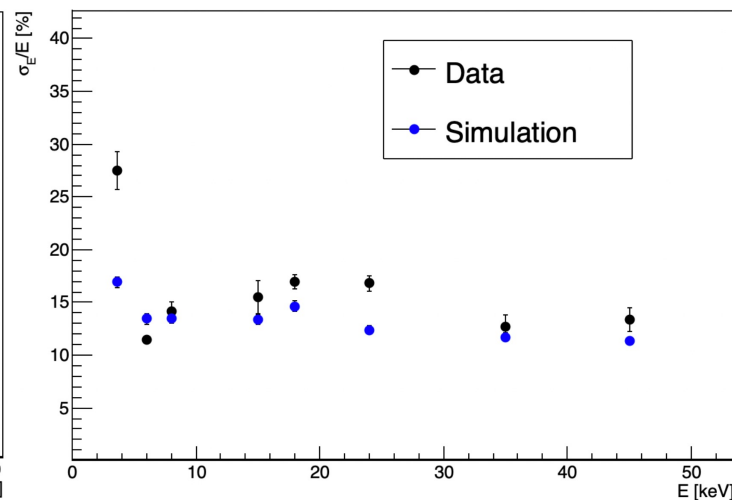
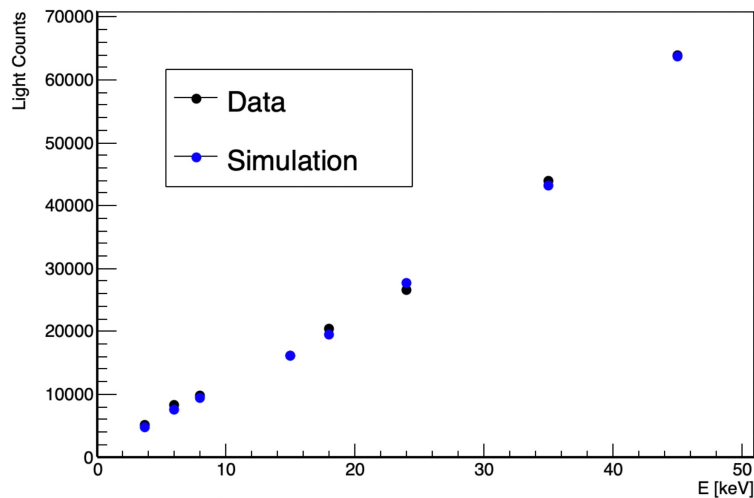
Combined fit
of the source
signal over the
background



LIME performances



- **Linear energy response** was found between 3.7 keV and 44 keV;
- **Energy resolution ~14%** in the whole volume;
- **Very good data-MC agreement.**



Paper contents

- Detailed description of how the different processes were simulated
- Brief description of LIME data (and their analysis) used for comparison. Use reference to the paper on LIME “overground” (in preparation).
- Detailed description of the tuning of the simulation parameters in comparison with data and of data/MC comparison at different energies.

Contents

1 Introduction	2
1.1 Detector concept and design	2
2 Electron recoils track simulation	2
3 Modeling the detector response	3
3.1 Production, drift and diffusion of the ionization electrons	3
3.2 Avalanche multiplication	4
3.2.1 Saturation of the amplification	4
3.3 Image formation	5
3.3.1 Vignetting	6
3.4 Camera background noise	6
4 The LIME prototype, the data samples, and the reconstruction	6
4.1 The LIME prototype	6
4.2 Data samples	7
4.3 Events reconstruction	8
4.4 Data analysis	8
5 Simulation optimization and results	8
5.1 Diffusion parameters	9
5.2 Attenuation length	10
5.3 Saturation parameters	10
5.4 Detector response and simulation comparison	11
6 Conclusions	11

Conclusions

- Digitization software optimized and tested:
 - Code is reasonably fast and reliable;
 - Data/MC agreement is very good.
- Would be important to extend the comparison to nuclear recoil data.
- Preparing a paper summarizing the work presented here; first draft ready for circulation in the coming weeks.

Thanks for your attention!

BACKUP MATERIAL

Ionization and drift

1. For each G4/SRIM hit, a mean number of ionization electrons are produced:

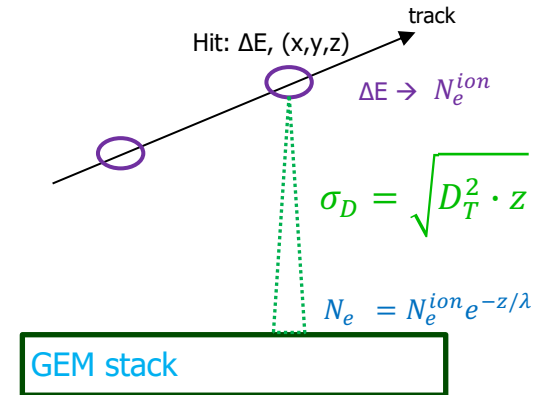
$$\bar{N}_e^{\text{ion}} = \Delta E / W_i \quad (W_i = 46.2 \text{ eV/pair in He/CF}_4 \text{ 60/40})$$

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

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:

$$N_e = N_e^{\text{ion}} e^{-z/\lambda} \quad \text{where } z \text{ is the distance from the GEM stack}$$



Gain and fluctuations

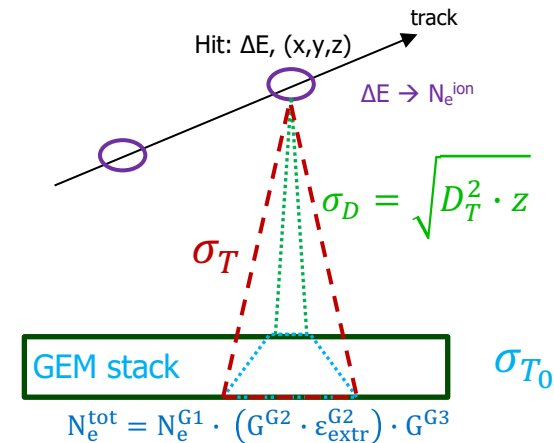
Ionization electrons arrive at the GEM stack; gain and efficiencies of the 3 GEM foils should be considered.

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

$$N_e^{G1} = \sum N_e^{G1,k} \cdot \epsilon_{\text{extr}}^{G1} \quad (\epsilon_{\text{extr}}^{G1}: \text{extraction efficiency for the first GEM})$$

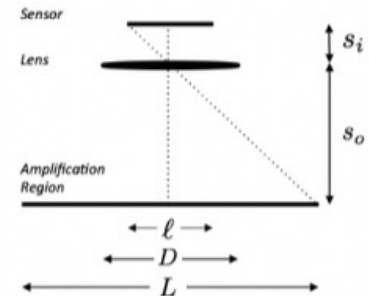
4. The total number of multiplication electrons computed considering the gain of other two GEM foils and the extraction efficiency of the second foil: $N_e^{\text{tot}} = N_e^{G1} \cdot (G^{G2} \cdot \epsilon_{\text{extr}}^{G2}) \cdot G^{G3}$

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 γ /e: $N_Y^{\text{mean,tot}} = N_e^{\text{tot}} \cdot 0.07 \gamma/e$
2. The number of total photons N_Y^{tot} extracted from a Poisson distribution with mean value $N_Y^{\text{mean,tot}}$
3. The number of photons hitting the sensor depends on the solid angle ratio Ω : $N_Y = N_Y^{\text{tot}} \cdot \Omega$
 where: $\Omega = \frac{1}{(4(\delta+1)a)^2}$; $\delta = \left(\frac{\text{image size}}{\text{sensor size}}\right)$ ($= \frac{350 \text{ mm}}{14.976 \text{ mm}}$ for ORCA Fusion on LIME); $a = 0.95$ aperture
4. γ 's positions are obtained with random extractions of N_Y 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.



Optical acceptance:

$$\Omega = \frac{1}{(4(L/\ell + 1)a)^2}$$

GEM gain and efficiency

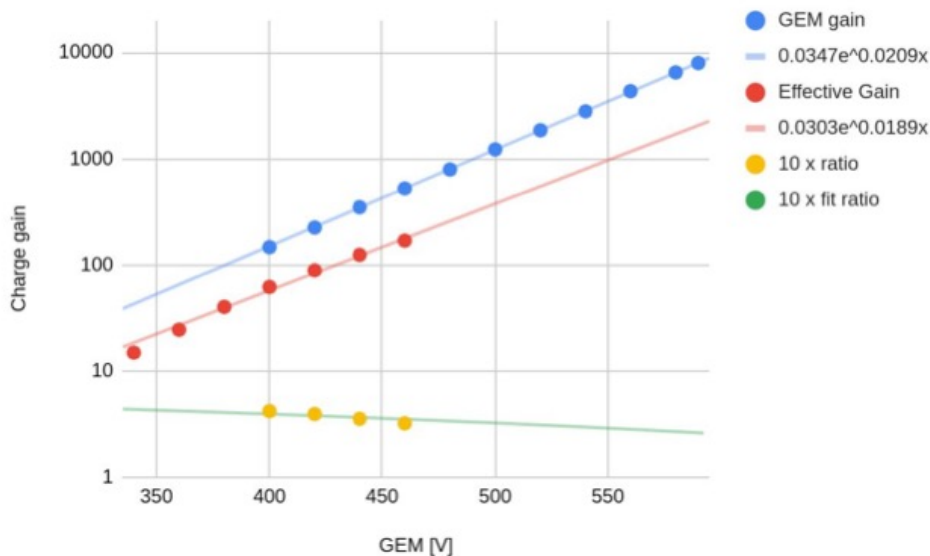
The GEM gain G and efficiency changes according to operating conditions and detector configuration

Dependence of the gain as a function of HV:

$$G = 0.0347 \cdot e^{0.0209 \cdot HV}$$

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/tJlyEZZPLdkSrH6/download>



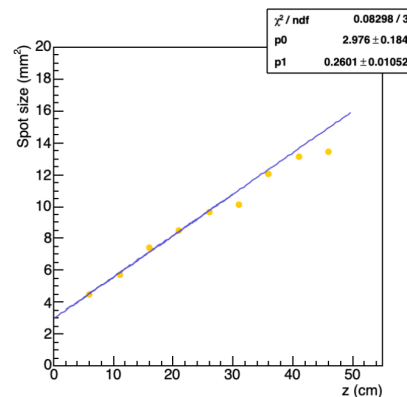
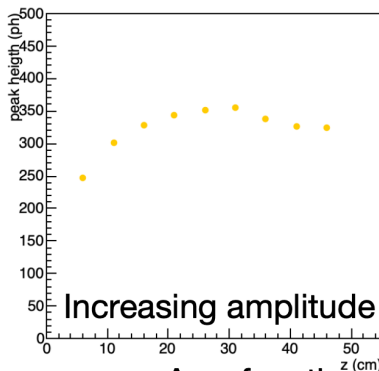
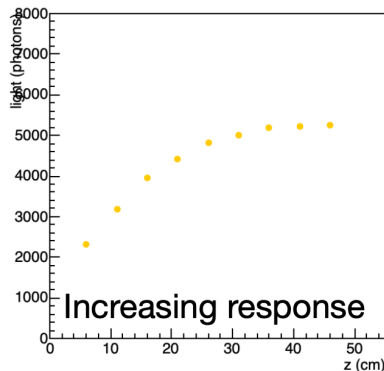
In a real optical TPC: Gain and light yield (ph/e) are not constant → no linearity between light production and ionization.

- In an ideal 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 (because of diffusion)

- Observed behaviour:

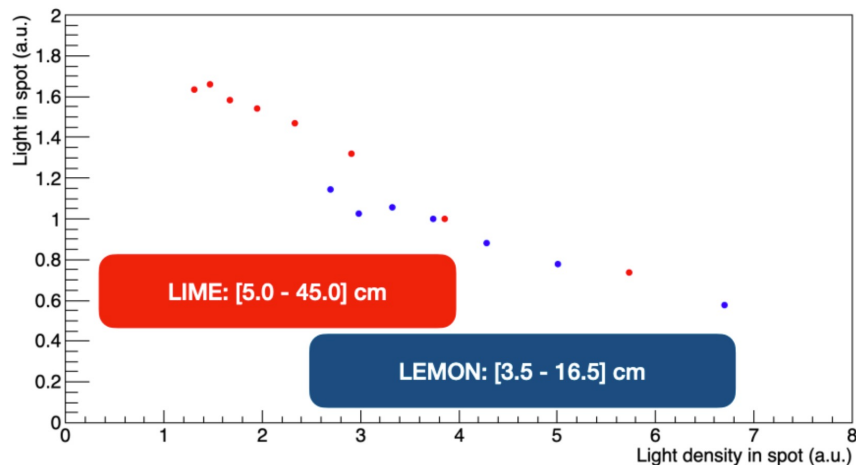


Spot size increasing because of the diffusion

As a function of z (distance from GEM)

Gain saturation (in a nutshell)

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



From a
“simple” model:

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

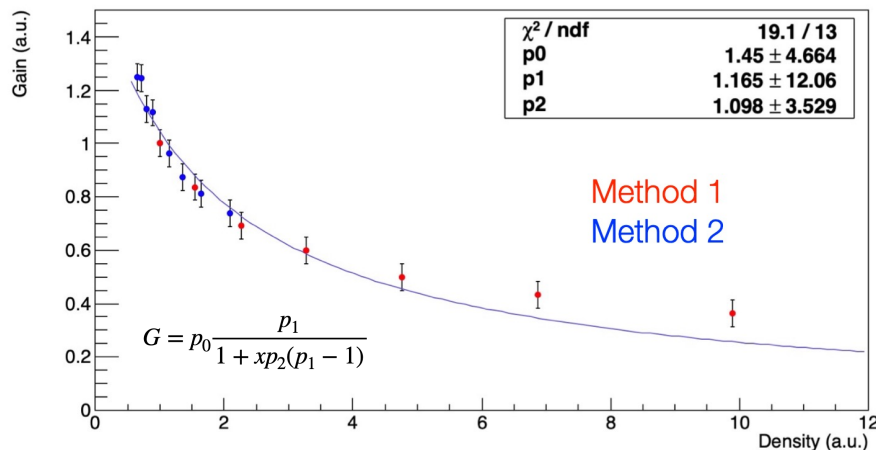
from Davide, see:

<https://cernbox.cern.ch/index.php/s/tJlyEZZPLdkSrH6/download>



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:

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

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

- 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

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

- 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, ...).

