Modelling the response of a TPC with optical readout

Pietro Meloni
on behalf of CYGNO Collaboration

6 dec. 2023

RD51 Collaboration Meeting

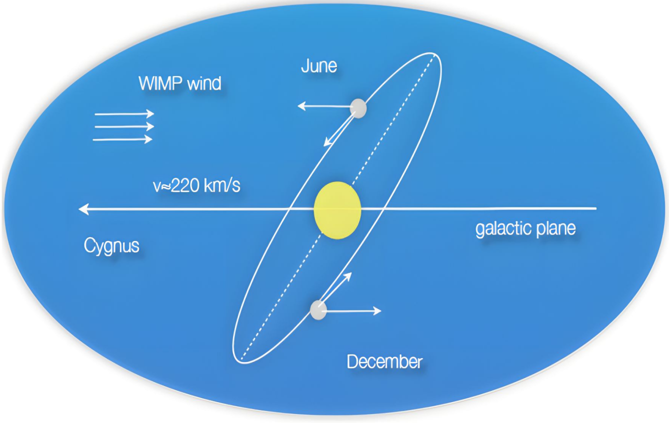
Founded from ERC in Horizon 2020 program (grant agreement 818744)

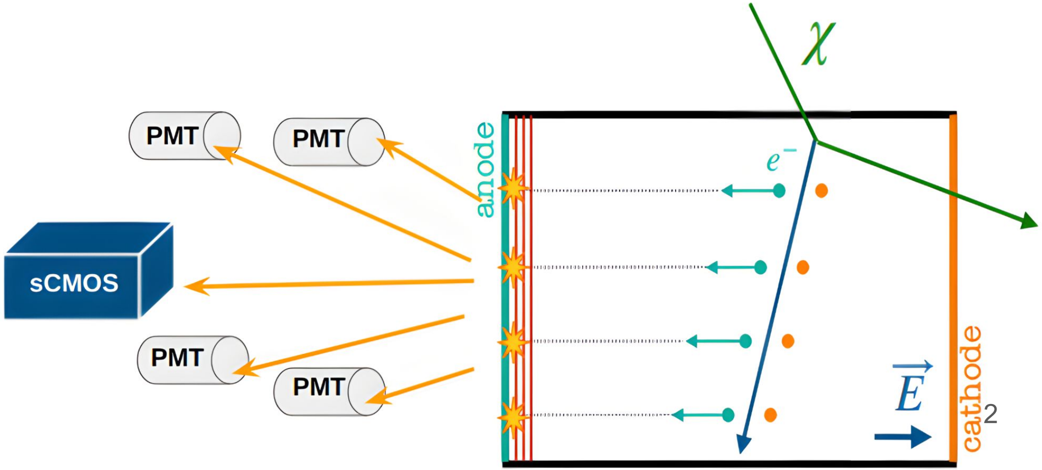
The CYGNO project

Aiming for a large detector for high precision 3D tracking of rare low energy nuclear recoils (keV) possibly induced by dark matter (DM) particles and solar neutrinos.

Strategy: photograph nuclear recoils in a (1 atm) He:CF_4 TPC with a GEM amplification stage.

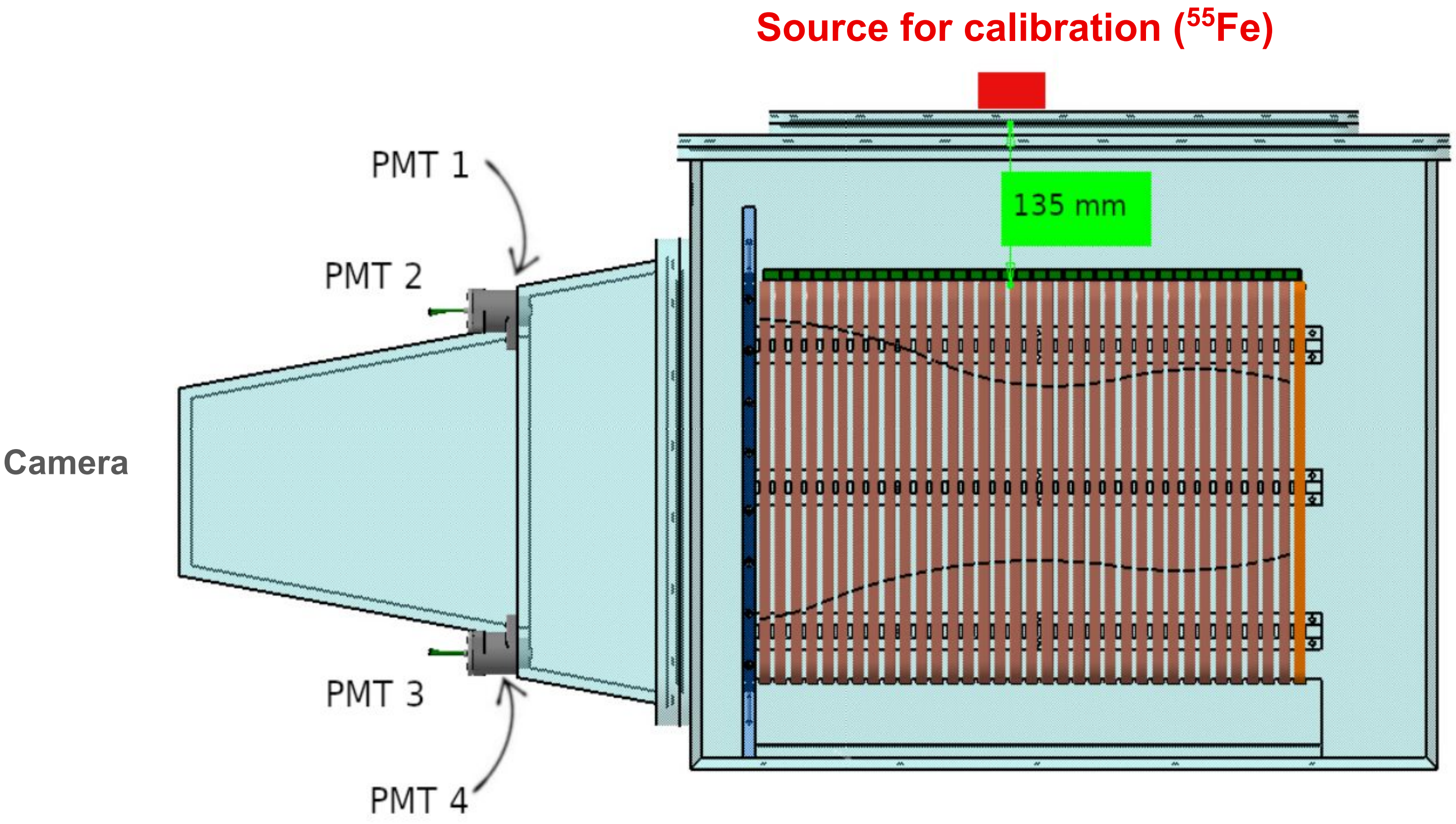
What performances do we need?
Nucleus average range ~ 150 μm
Energy threshold O(keV) for low mass DM





LIME detector [arXiv:2305.06168]

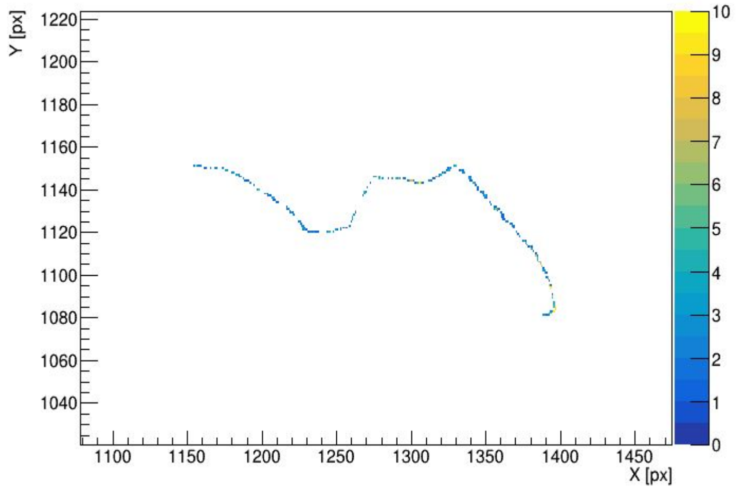
- A 50 liters of He:CF_4 60:40 TPC at 1 atm (50 cm of drift) (1kV/cm)
- 1 sCMOS camera [Hamamatsu Orca-Fusion]
  - 2304 x 2304 pixels
  - readout noise of 0.7 e-/pixel
  - Acquisition time ~ 30-300 ms
- 3 GEMs for a 33x33 cm^2 sensitive area
- 4 PMTs [Hamamatsu R7378]
  - 22 mm diameter
  - ~ns time response


Source for calibration (^{55}Fe)
135 mm
PMT 1
PMT 2
Camera
PMT 3
PMT 4

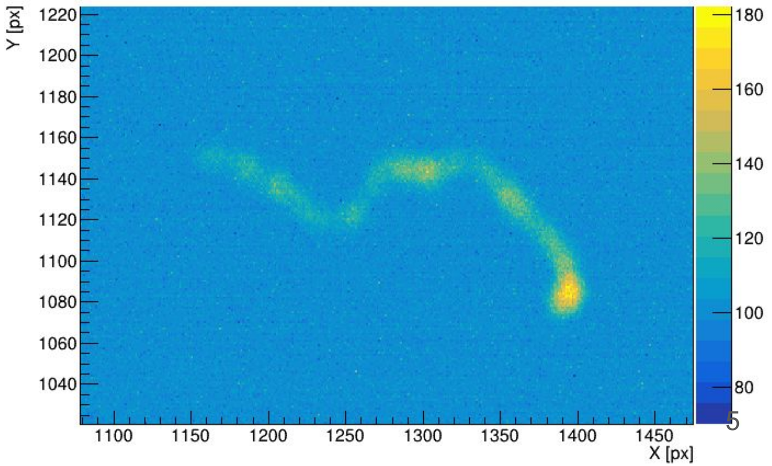
Detector response simulation

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

1. SIMULATION of a primary particle interacting in the gas volume

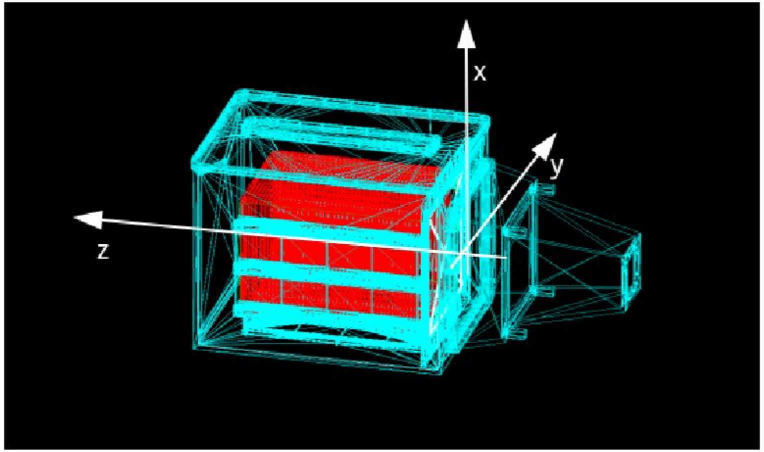


2. DIGITIZATION: Modelling of the detector response to return a 2D image (and soon PMTs too)



Geant4 simulation of Electron Recoils (ER)

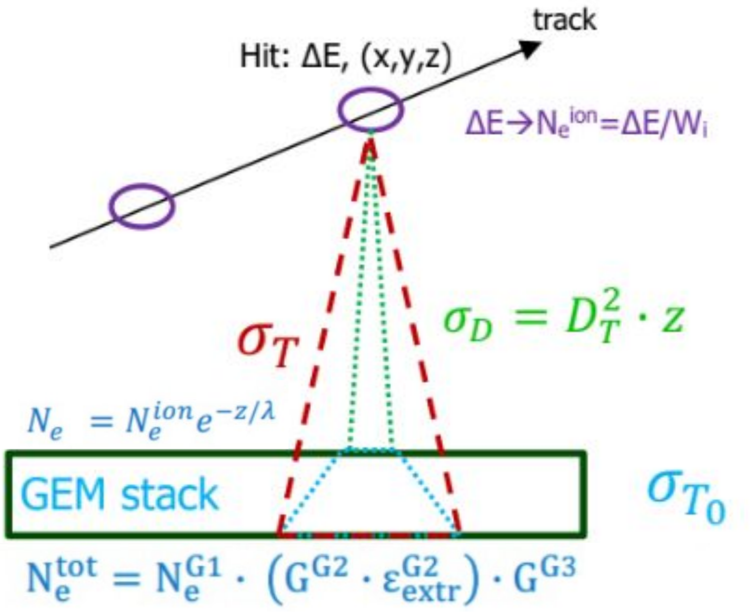
- Electron produced tracks in sensitive volume.
- Physics processes: transportation, Coulomb scattering, ionization, bremsstrahlung
- Save coordinates of tracks (x, y, z), and **energy deposits** (E).
- Electrons are produced with energy **matching X-ray emission peak**
- **Isotropic distribution** at the center of the volume, with subsequent translations to replicate actual spatial distribution.



Detector response simulation (digitization)

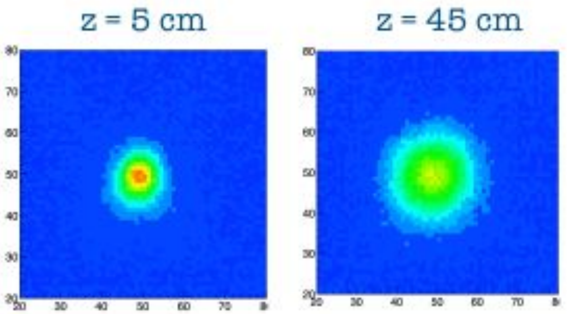
The following processes are considered (including fluctuations):

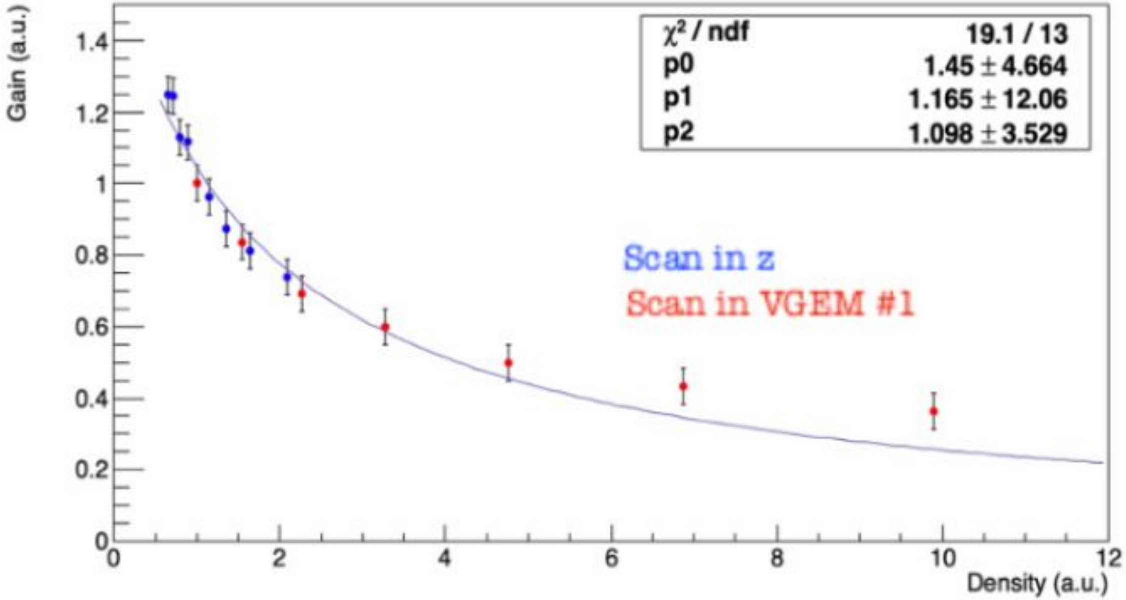
- **Ionization**;
- **Diffusion** (**in the gas** and in the **GEMs**);
- Absorption in the gas;
- **Multiplication in the 3-GEM stack**;
- Gain Saturation effect (depending on the charge density);
- Production and collection of photons in the multiplication process;
- Vignetting effect and other non-uniformities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



Saturation of the GEM gain

- saturation of GEM gain due to positive ions back-flow **screening the electric field**
- denser energy deposits: more charge in the same holes





Gain saturation model

We developed a simple model (modified Townsend model).

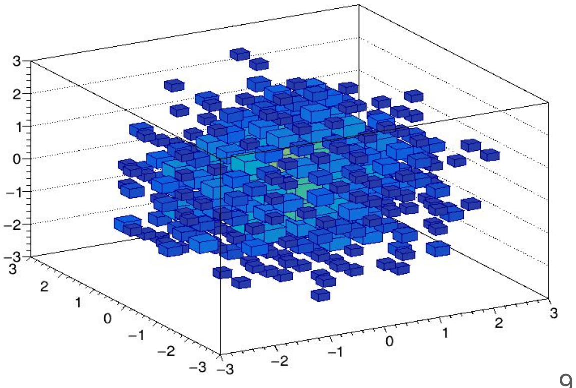
$$\frac{dn}{ds} = \alpha n E(1 - \beta n)$$

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

The electron cloud approaching the **3rd GEM** is divided into **voxels** (volume pixels) to properly evaluate the number of electrons entering each GEM channel.

Then for each channel, we apply the saturated gain.

The saturation effect is simulated only on the 3rd GEM where the electron cloud is more dense.

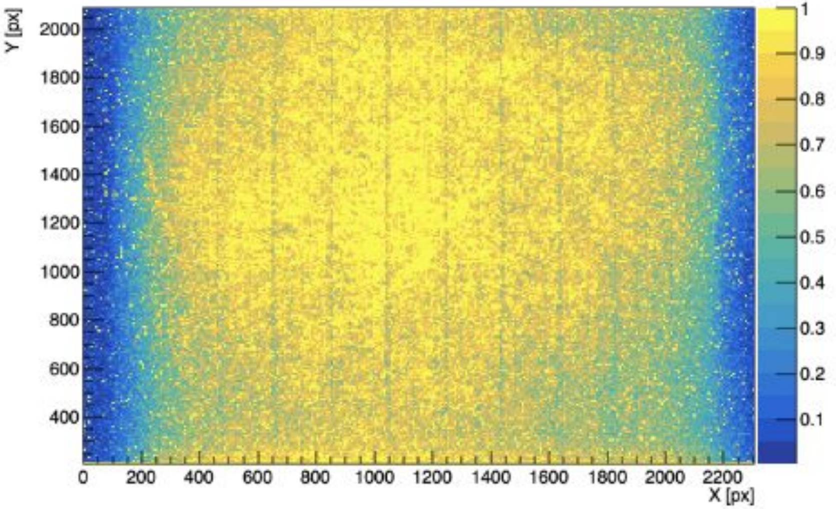


Vignetting effect and gain non-uniformity

Darkening of an image in the corners with respect to its center.

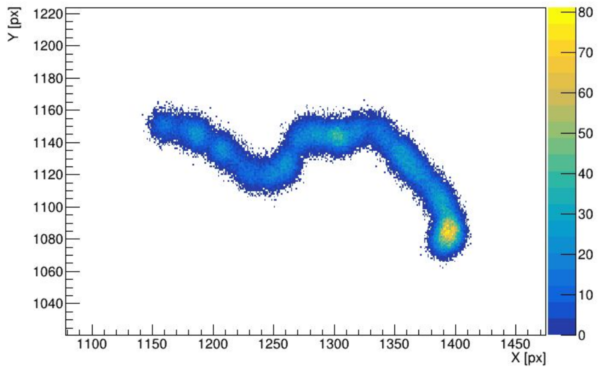
To take this into account, we apply to simulated tracks a map.

The map is produced by summing real pictures of natural radioactivity. The map also allow reproducing the non-uniformity of GEM gain.

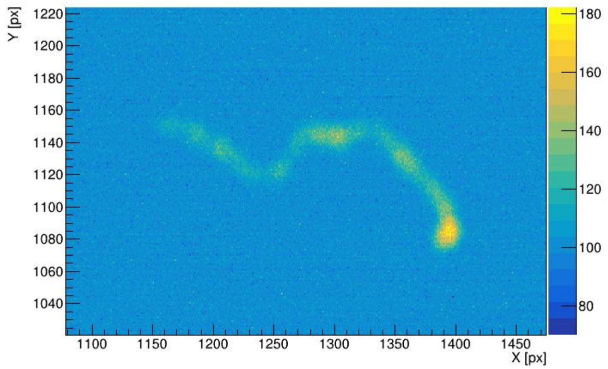


Sensor Noise

- Add a real CMOS image (pedestal) to the final track.
- This image is acquired when the GEM voltage is turned off.
- To address varying environmental conditions during different periods, the pedestal is extracted from the same dataset to be simulated.
- For simulating sensor noise variability, a distinct pedestal from the same dataset is used for each image.



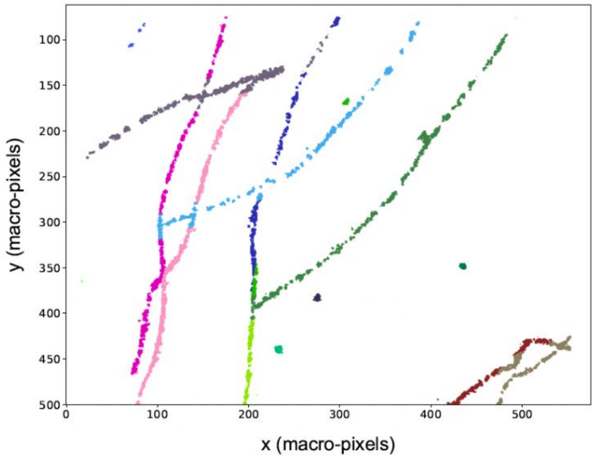
Apply noise

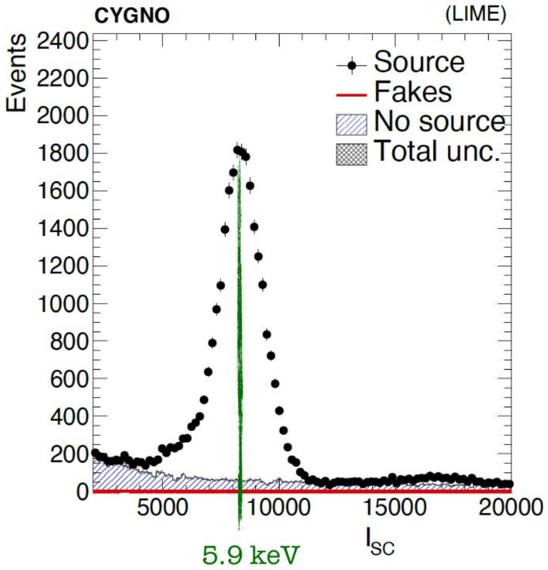


Parameter tuning with ^{55}Fe data

Data: X-ray source (^{55}Fe 6 keV) at different distance from GEM plane.

DBSCAN clustering



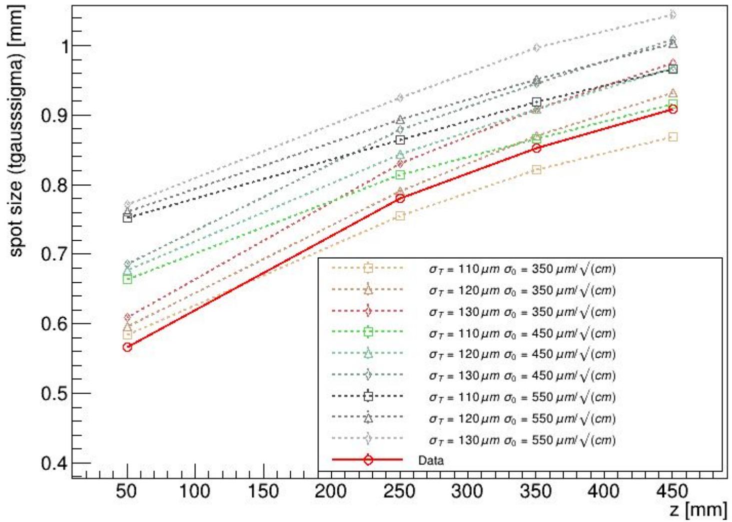


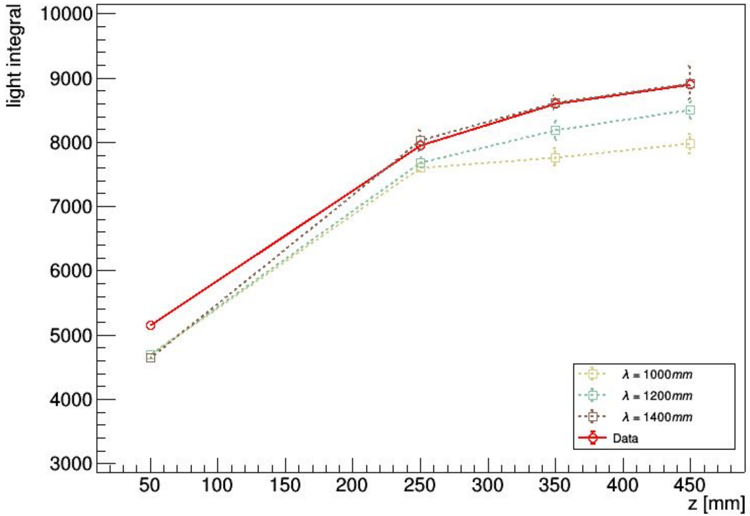
Simulation: electrons of (6 keV) generated at different distances from GEM plane.

We compared the following track properties: total light (integral), number of pixel on, gaussian spot profile amplitude and sigma.

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

	Initial value	Optimized value
λ	*1 m*	*1.4 m*





Data/MC comparison on multi-source data

Data: X-ray sources (energy from 3-44 keV)

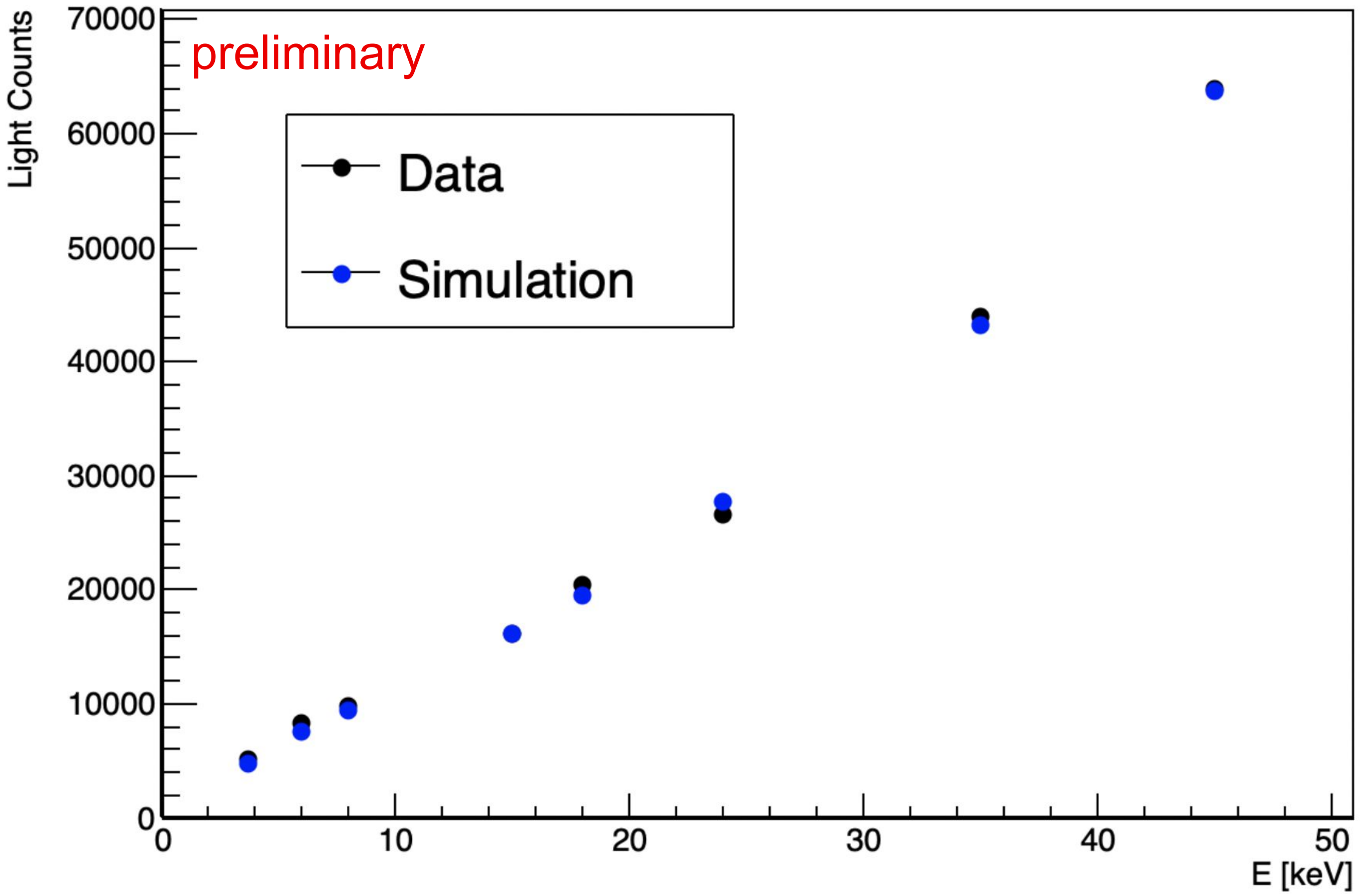
Simulation: electrons of 3-44 keV

X-ray emission

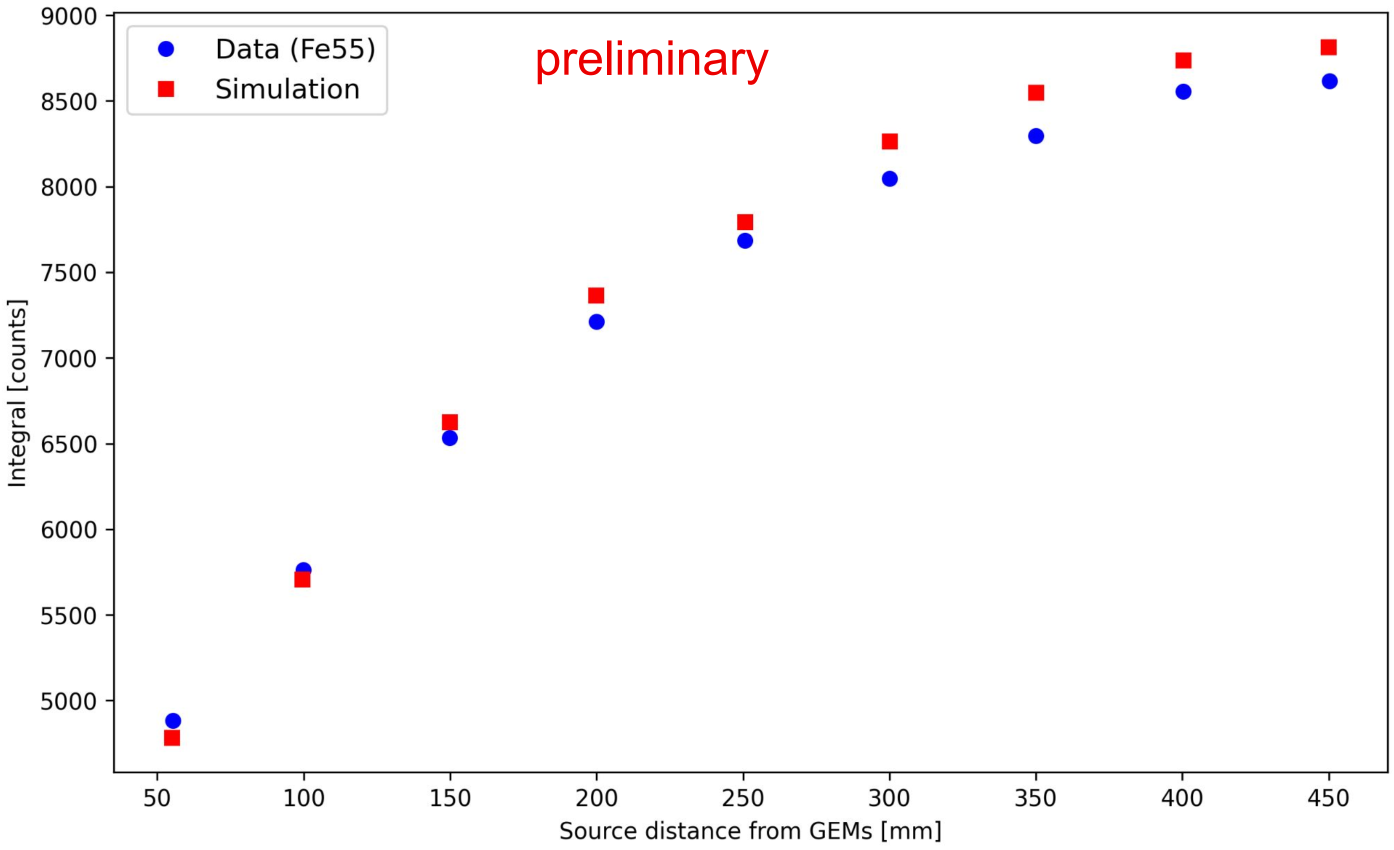
target selected	energy (keV)[1] Kα	Kβ	photon yield[2] (photons/sec per steradian)
Cu	8·04	8·91	$2{\cdot}5 \times 10^3$
Rb	13·37	14·97	$8{\cdot}8 \times 10^3$
Mo	17·44	19·63	$2{\cdot}43 \times 10^4$
Ag	22·10	24·99	$3{\cdot}85 \times 10^4$
Ba	32·06	36·55	$4{\cdot}65 \times 10^4$
Tb	44·23	50·65	$7{\cdot}6 \times 10^4$

We compared the following track properties: total light (integral), number of pixel on, length

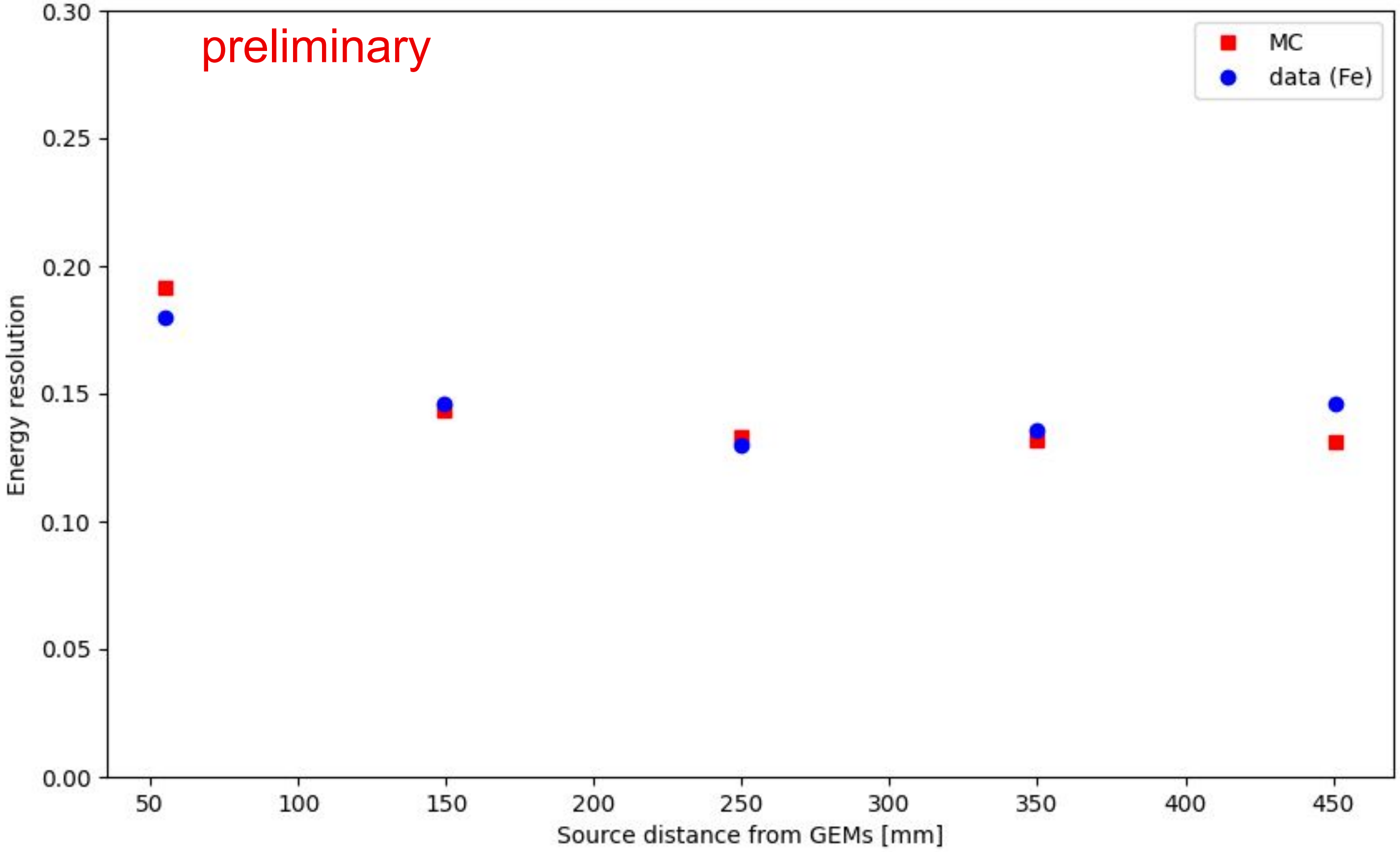
Detector response (track integral) at different energies



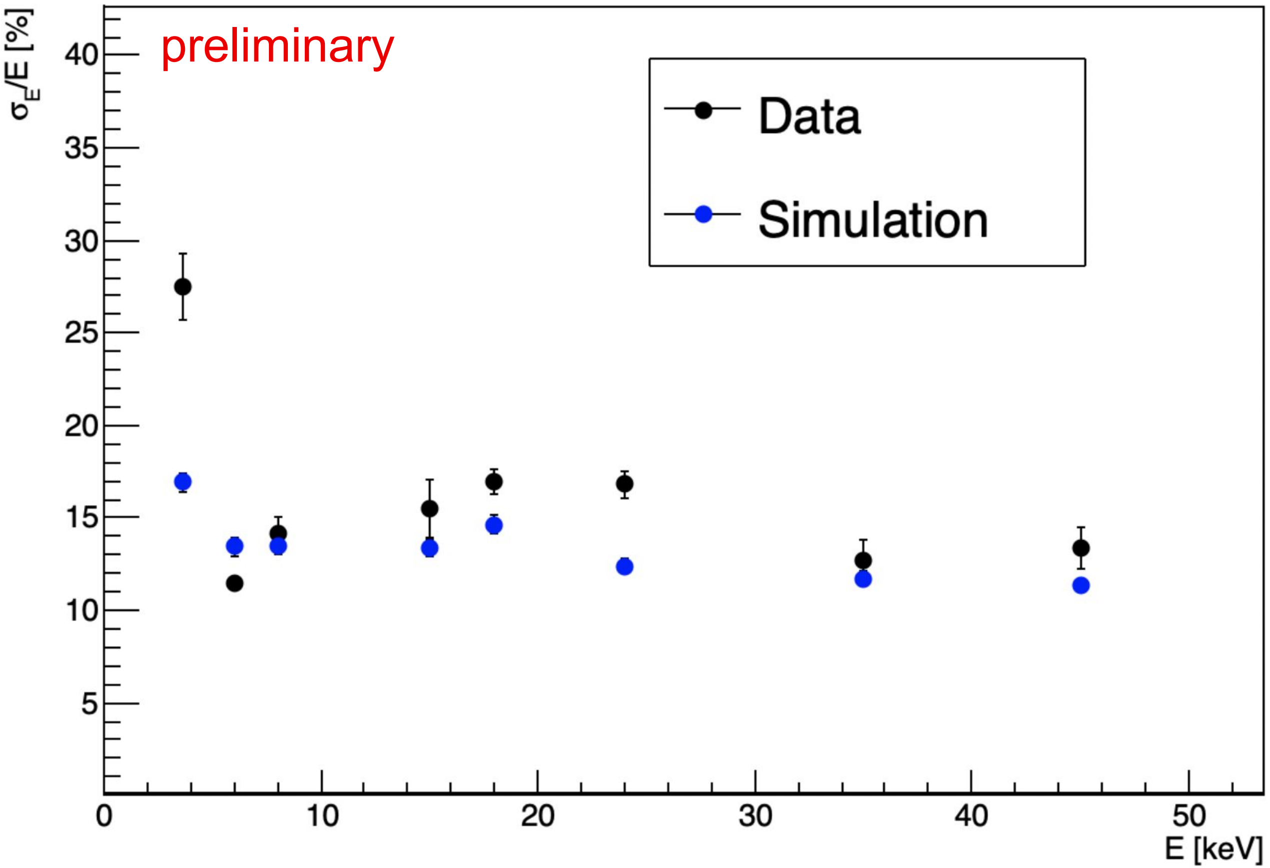
Detector response in different positions from the GEM plane (^{55}Fe)



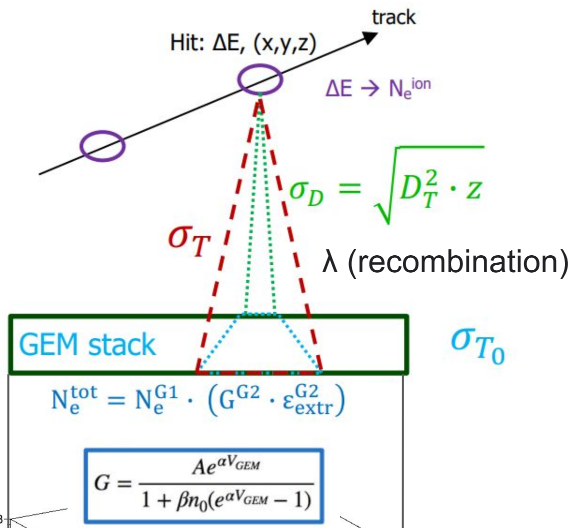
Energy resolution in different positions from the GEM plane (^{55}Fe)

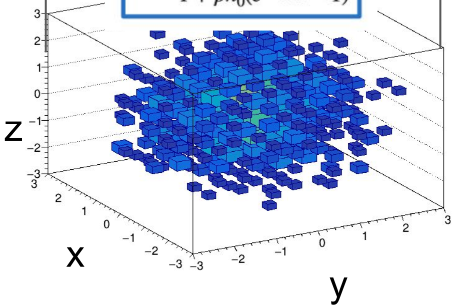


Energy resolution at different energies

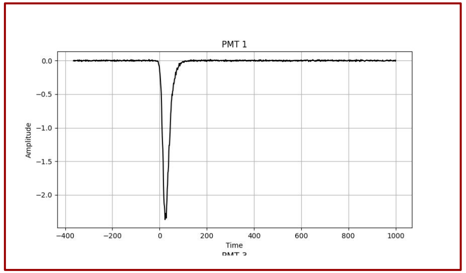


PMT Simulation

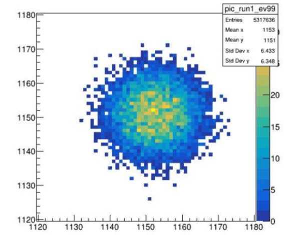




1. apply electron-photon factor
2. convert z into t (with drift velocity)
3. for each voxel (x,y,t, N) propagate each photon to each PMT
4. generate PMT waveforms according to number of hits at given times



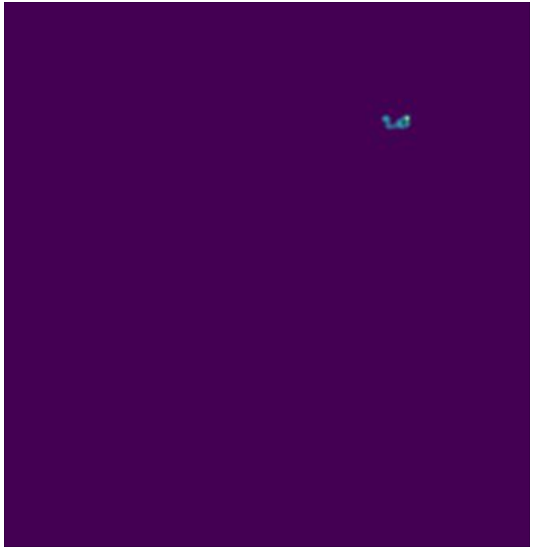
1. apply electron-photon factor
2. apply acceptance factor
3. apply photon-counts factor
4. project along z (drift direction)



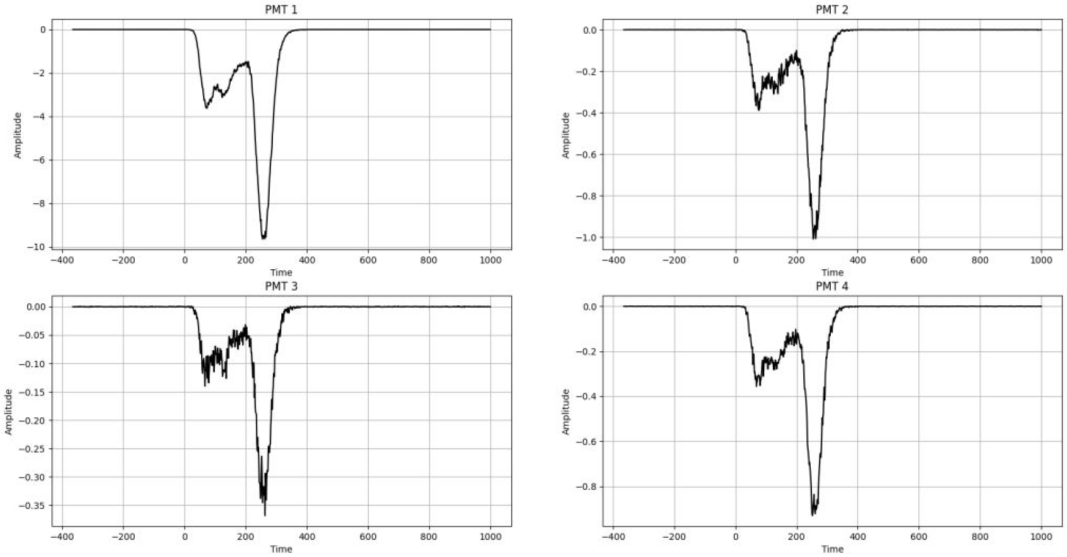
then
- apply vignetting
- add CMOS noise

Example of a simulated event:

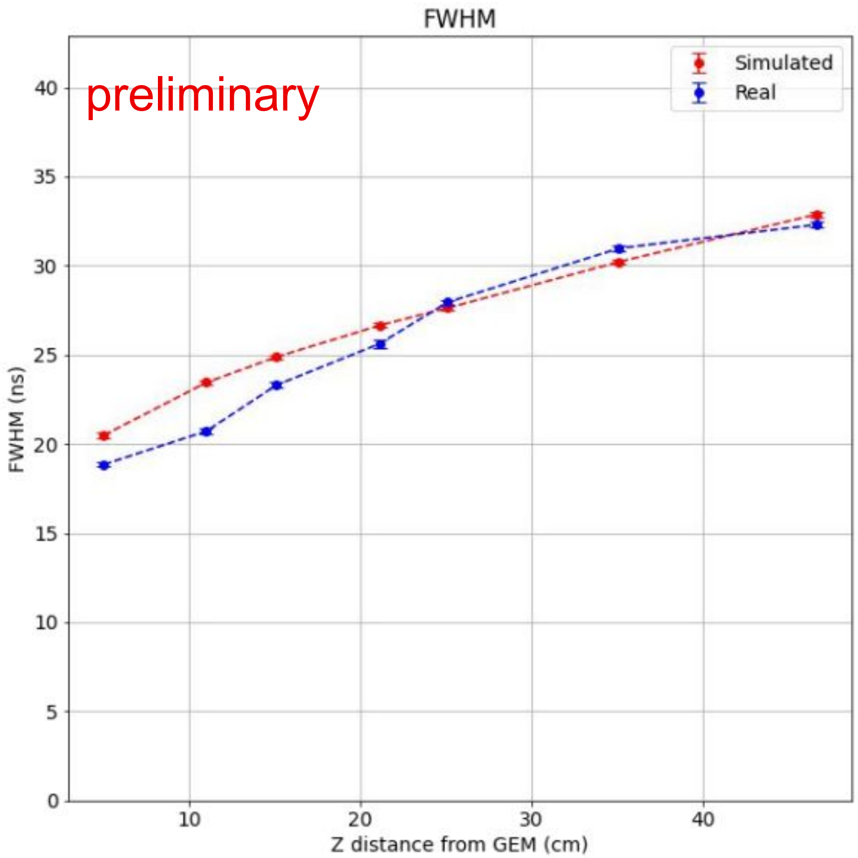
50 keV ER



50 keV ER



First Data/MC comparison for PMTs (^{55}Fe)



Conclusions

- Our modeling is able to reproduce detector response and energy resolution at different energies for ER.
- We're currently using our simulation to reproduce background at Gran Sasso Laboratory where LIME is taking data with the goal of measuring the environmental neutron flux.
- The preliminary implementation of the PMT simulation is also promising and confirms the reliability of the model.

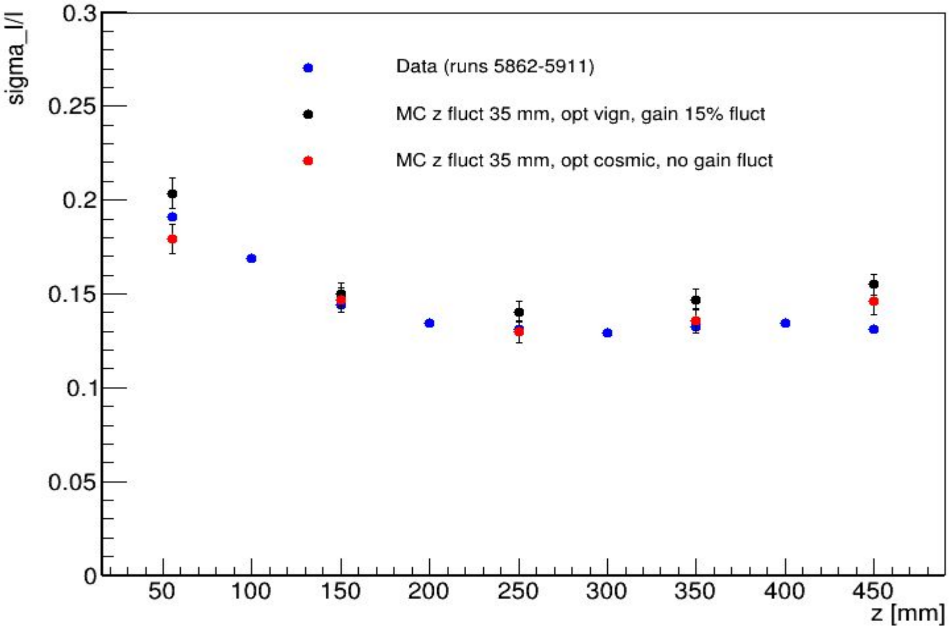
Thanks for the attention

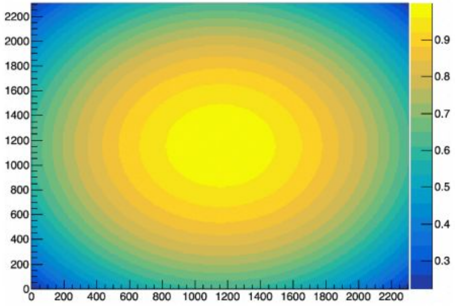
Backup

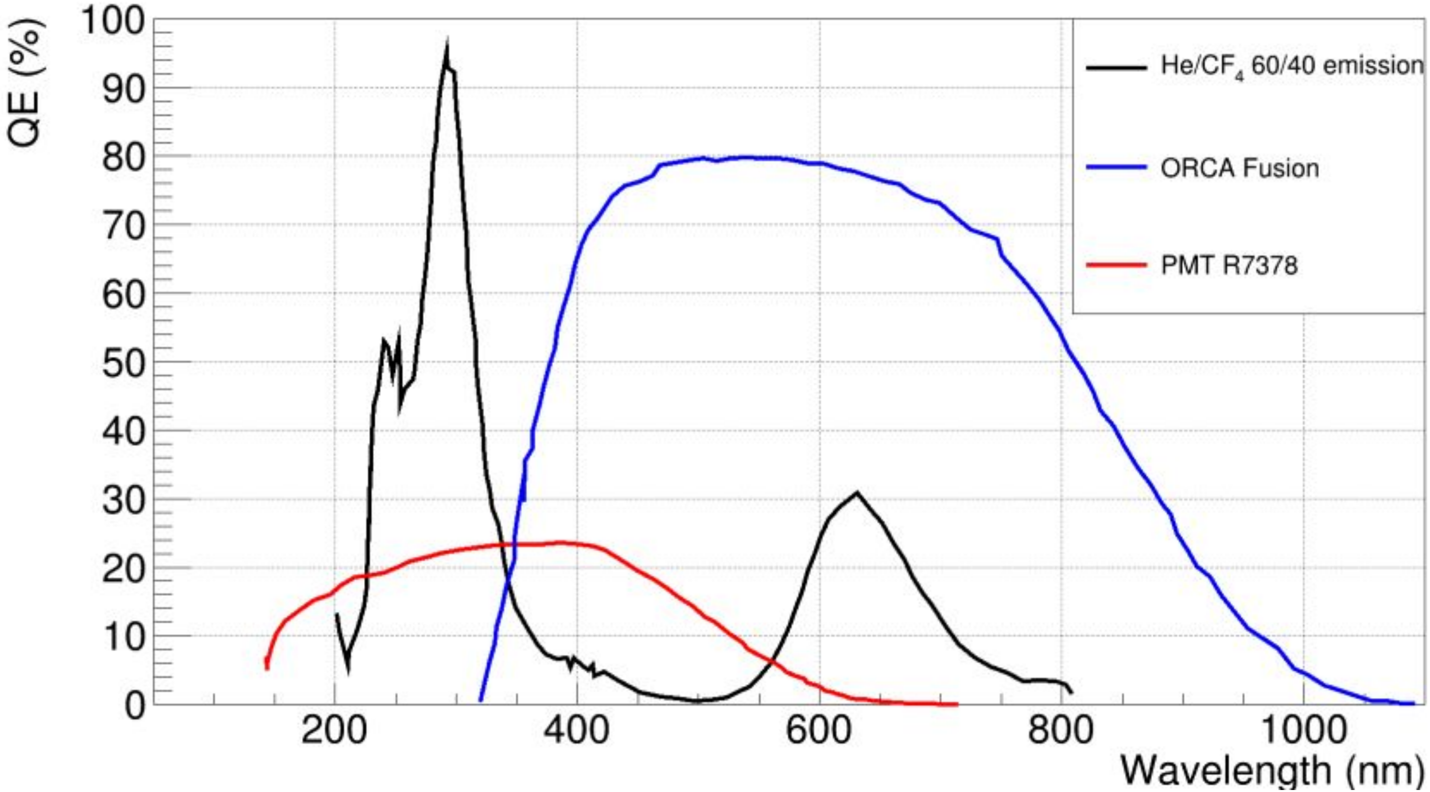
Gain non-uniformity

The use of the natural' radioactivity map is one possible way to simulate both vignetting ang gain non-uniformity.

We can also simulate gain non-uniformity by applying fluctuations to the GEM gain. And then simulate vignetting with a map produced by acquiring a uniformly illuminated wall (**optical map**)







QE (%)
100
90
80
70
60
50
40
30
20
10
0
200
400
600
800
1000
Wavelength (nm)
He/CF4 60/40 emission
ORCA Fusion
PMT R7378

LIME Underground Background Simulation