Status of data-MC comparison

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07/06/23
CYGNO analysis meeting, Coimbra

Simulation workflow

1. Interactions of ER/NR in the gas ➔ tracks (x,y,z,dE) — **Geant4 (ER) / SRIM (NR)**

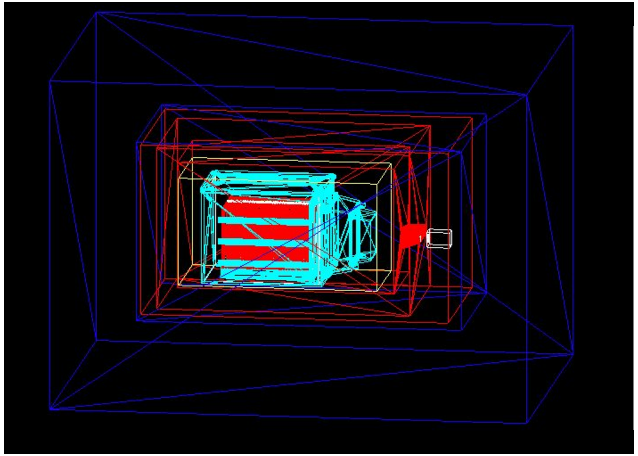
2. Calculate electron diffusion in CYGNO gas — **Garfield**

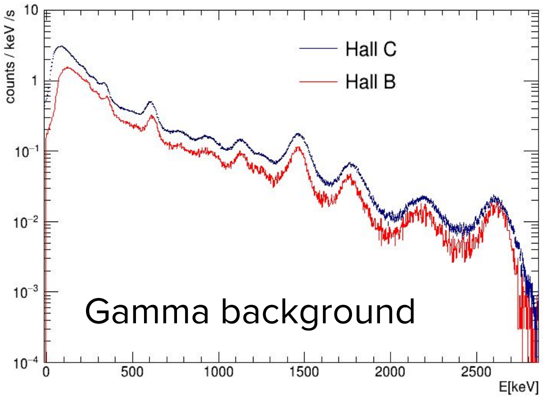
3. Simulation of primary electrons + transport to the GEMS
4. Simulation of GEM multiplication with saturation effect
5. Simulation of light production
6. Simulation of the camera / PMT — NEW

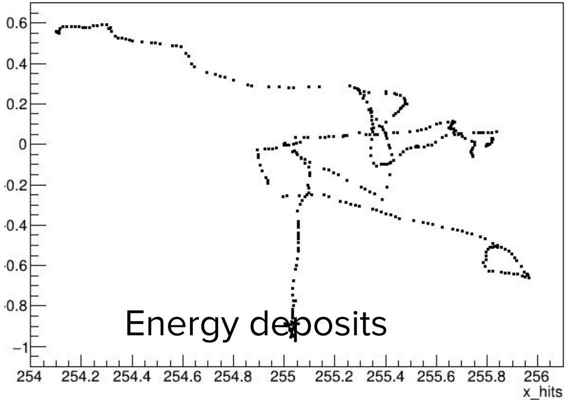
Steps 3–6: **detector simulation (digitization)**

Geant4 simulation

- Input:
  - geometry of the setup and materials
  - radioactivity of materials and surroundings
- Output:
  - energy deposits inside the gas (x,y,z, dE)



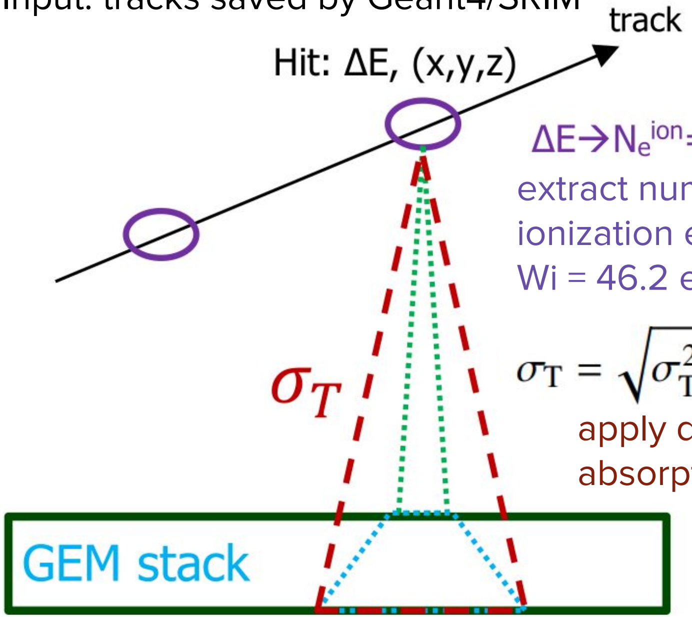




Electrons simulation

Github repository: https://github.com/CYGNUS-RD/digitization

Input: tracks saved by Geant4/SRIM



$\Delta E \rightarrow N_e^{ion} = \Delta E / W_i$

extract number of ionization electrons

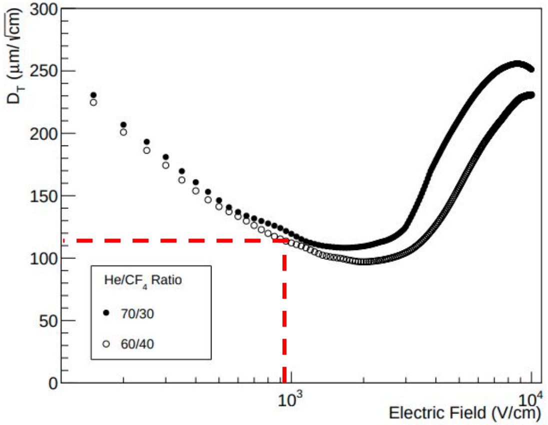
Wi = 46.2 eV

$$\sigma_T = \sqrt{\sigma_{T0}^2 \oplus D_T^2 \cdot z}$$

apply diffusion

absorption length = 1.4 m

Simulate electron multiplication & light production in GEM stack



$$D_T^{60/40} = 115 \frac{\mu m}{\sqrt{cm}}$$

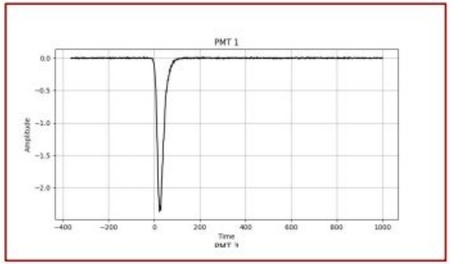
$$\sigma_{T0}^{60/40} = (280 \pm 60)\ \mu m$$

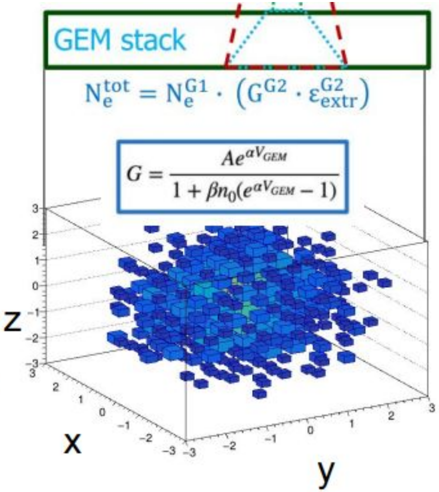
For 930V/cm drift field

Simulation of photodetectors

NEW

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**

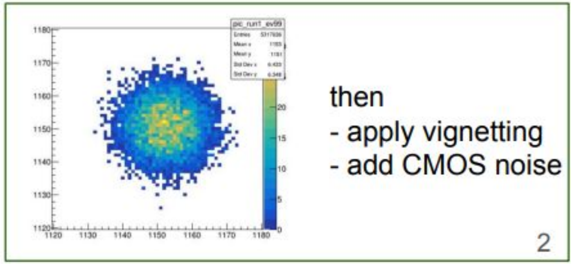




σ_{T_0}

G ➜ saturated gain as a function of V_{GEM}
Parameters A, beta optimized using ^{55}Fe scan vs V_{GEM} and z
n0 is the number of electrons in each voxel

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



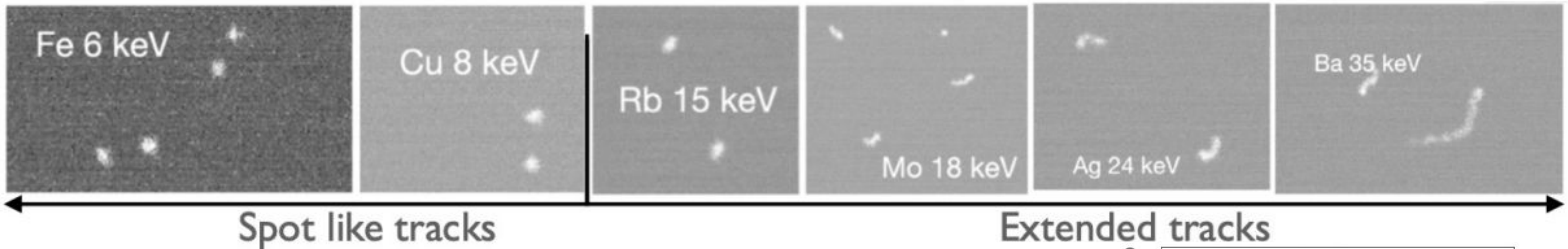
P. Meloni

After all these steps MC has the same exact format of data and can be processed with reconstruction code

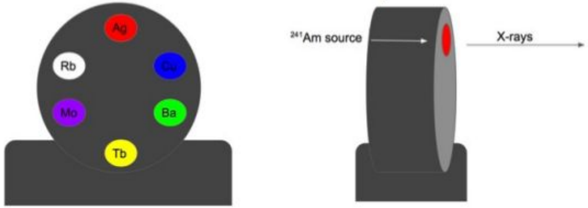
Data/MC comparisons using x-rays source

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

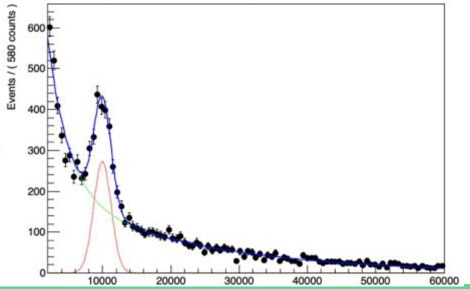
- 55Fe-source for 6 keV;
- Different materials (Cu, Rb, Mo, Ag, Ba, Tb) irradiated by a ^{241}Am-source for higher energies; 55Fe on a gypsum (Ca) target for 3.7 keV
- Simulation: ER in LIME at energies corresponding to the x-rays



Amersham AMC.2084 X-ray source

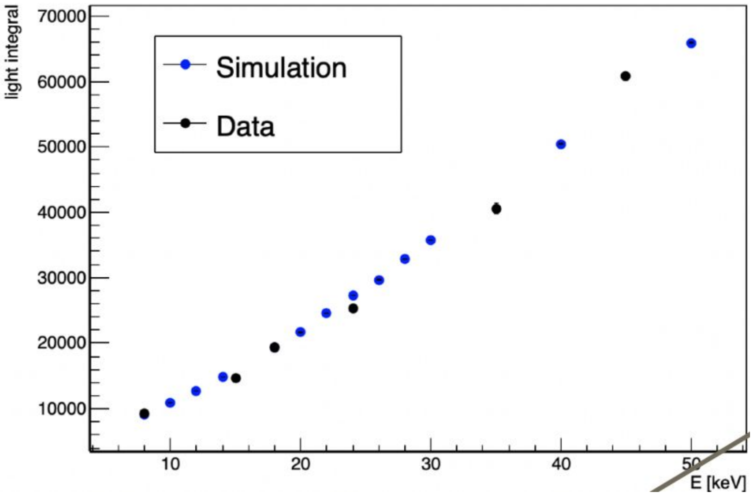


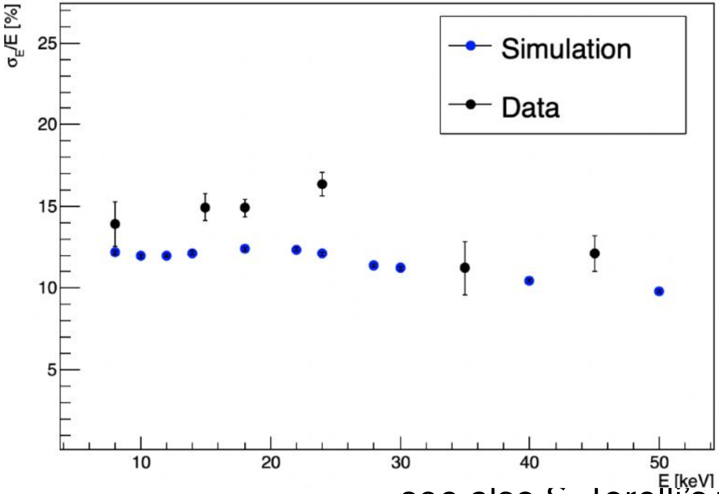
Combined fit of the source signal over the background



Energy response and resolution

- Parameters of the digitization, including saturation model tuned for ^{55}Fe (6 keV) and freezed
- Digitized MC is reconstructed with the same code used for the data
- Energy response is very well reproduced
- Energy resolution is reasonably reproduced
  - does not follow the expected ~1/sqrt(E) ➔ saturation, other effects?



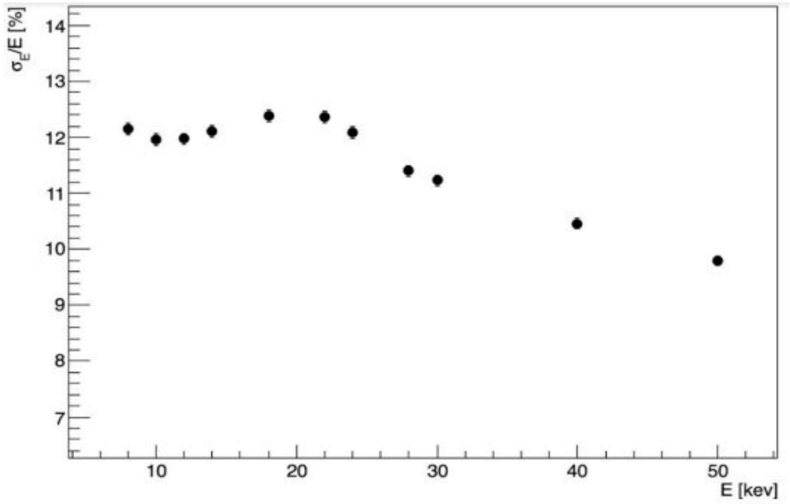


see also S. Torelli's talk

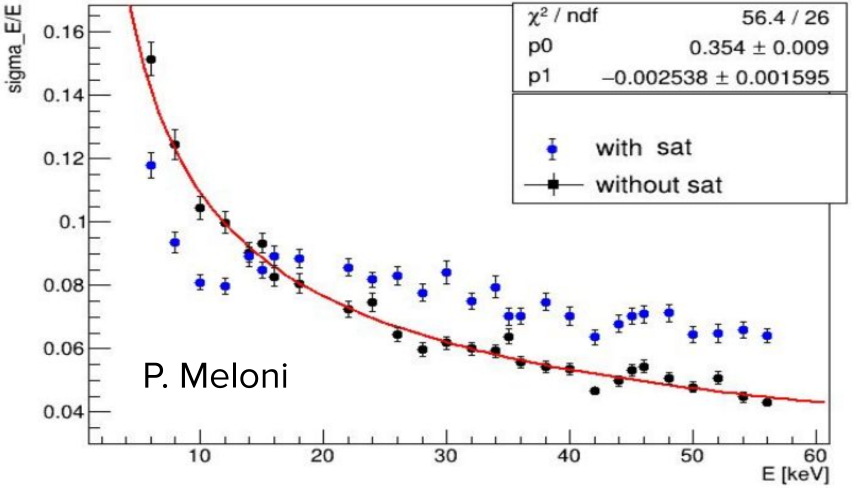
Energy resolution checks without noise

Same plot of previous slide (MC)

- 10000 MC events per energy point
- electronic noise included, reco applied



- 500 MC events per energy point
- NO electronic noise, NO reco, simplified analysis



- Shape qualitatively reproduced in simulation without noise (but **with saturation**)
- Noise probably contributes with an offset

Data/MC comparisons for LIME background

- External background: **flux of 0.56 gammas/cm^2/s**, spectrum from NaI measurements by SABRE
- Internal background: radioactivity of all materials (acrylic box, field cage, cathode, ecc...)
- Data taken with LIME underground (runs 1, 2 and 3)

Summary of LIME rates (ER) in MC(*) and data(**)

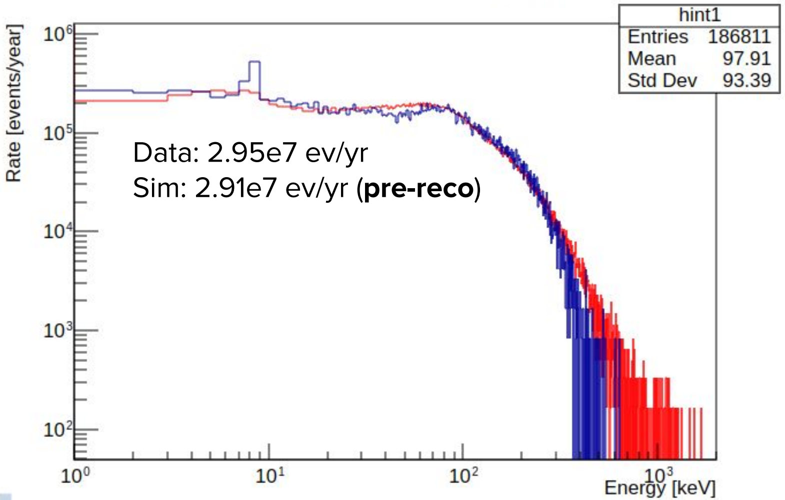
	External	**Internal**	**Shield**	**Tot MC**	**data**
	Rate Hz	**Rate Hz**	**Rate Hz**	**Rate Hz**	**Rate Hz**
No shield (run 1)	35.83	0.23	0.00	**36.15**	**35**
4 cm Cu (run 2)	0.84	0.23	0.02	**1.09**	**3.5**
10 cm Cu (run 3)	0.06	0.23	0.02	**0.31**	**1.3**
Full (water+Cu)	0.02	0.23	0.02	**0.26**	**-**

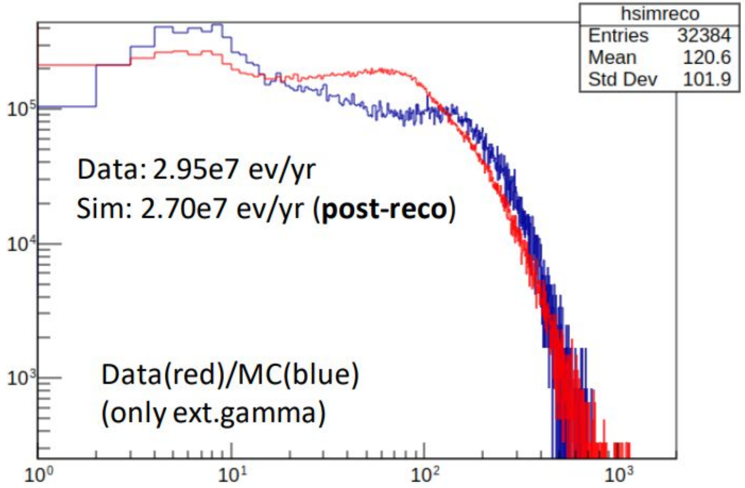
(*) Geant4 rates form this presentation. No digitization + reconstruction, only “MC truth”
(**) from this summary. Rates measured with PMTs, no dead time correction

Comparison of energy spectra (LIME run 2)

Comparison of energy spectra:

- Data of LIME run 2 are processed with official reconstruction code
- Left: MC truth (no digi+reco), Right: MC truth + digi + reco (same code as data)
- Rates for data are obtained counting reconstructed tracks and considering data taking time (no dead time correction)





see also F. Di Giambattista's talk

Data/MC comparisons using NaI detector

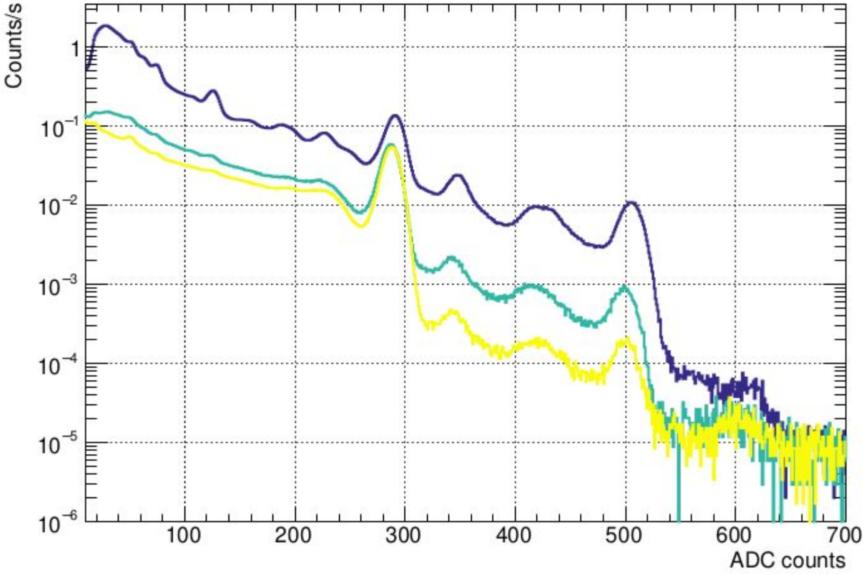
- To make a meaningful comparison of rates between data and MC:
  - take into account dead time in data
  - validate Monte Carlo

- MC validation
  - validate the “input” of the simulation
    ➙ previous measurements with NaI suggest difference of factor ~2 in gamma background between LNGS Halls
  - validate the simulation code

- NaI detector recently used for measurements in the experimental hall of LIME ➙ dedicated simulations

NaI data (3” crystal)

- Direct measurements with NaI in LIME experimental area
- Raw data without shield (blue), 4 cm Cu shield (green), and 10 cm Cu shield (yellow)

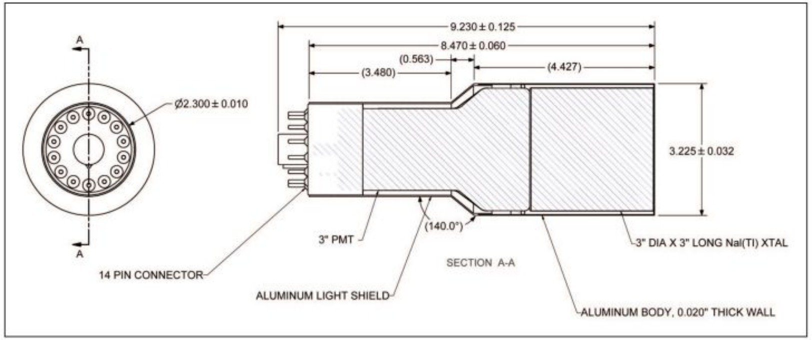


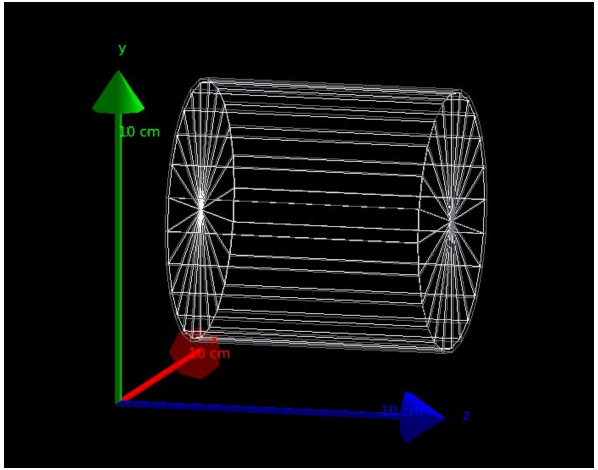
- Previous measurements by SABRE made with a NaI larger detector (4”x 4” x 16”)
- Difficult to compare directly these spectra (and rates) with previous NaI or LIME MC because:
  ➔ different detectors
  ➔ non-negligible internal background component, especially when we compare shielded spectra

➔ need a MC simulation of the NaI

Simulation of NaI crystal

- 3”x3”cylindrical crystal with 0.5 mm Aluminum case

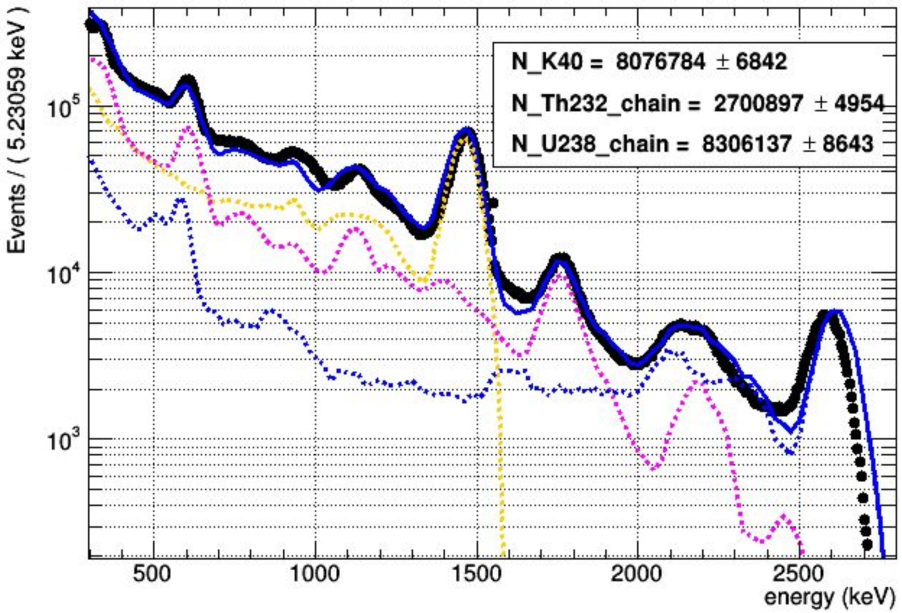




- Simulate decay of ^{40}K, ^{238}U chain and ^{232}Th chain (gamma emitters)

Fit data with simulated spectra (rock sphere)

- Use dataset outside shielding (in LIME control room), ~6 days livetime
- Fit range from 300 keV to 2800 keV




```
Floating Parameter    FinalValue +/-  Error
--------------------  --------------------------
               N_K40    8.0768e+06 +/-  6.84e+03
       N_Th232_chain    2.7009e+06 +/-  4.95e+03
        N_U238_chain    8.3061e+06 +/-  8.64e+03
```

Corresponding activities in the LNGS rocks

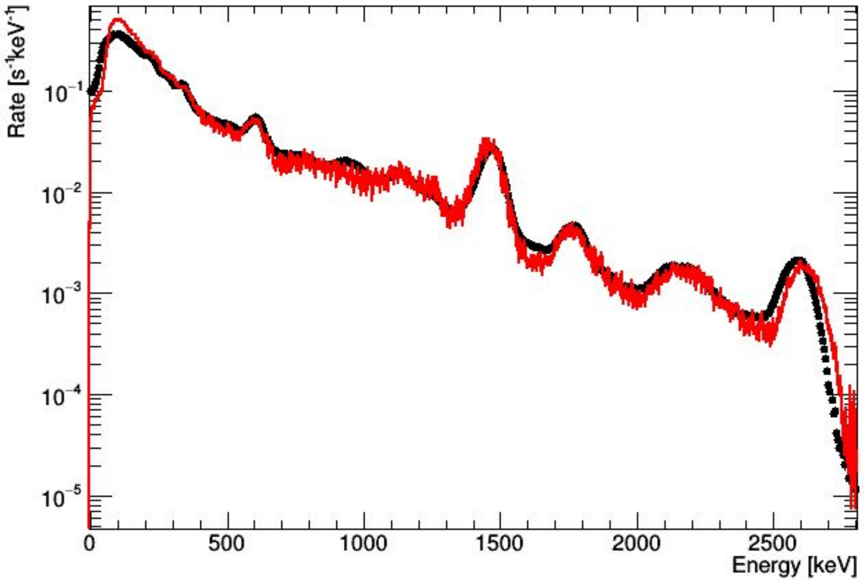
- ^{40}K → 93.5 Bq/kg
- ^{238}U → 7.9 Bq/kg
- ^{232}Th → 4.1 Bq/kg

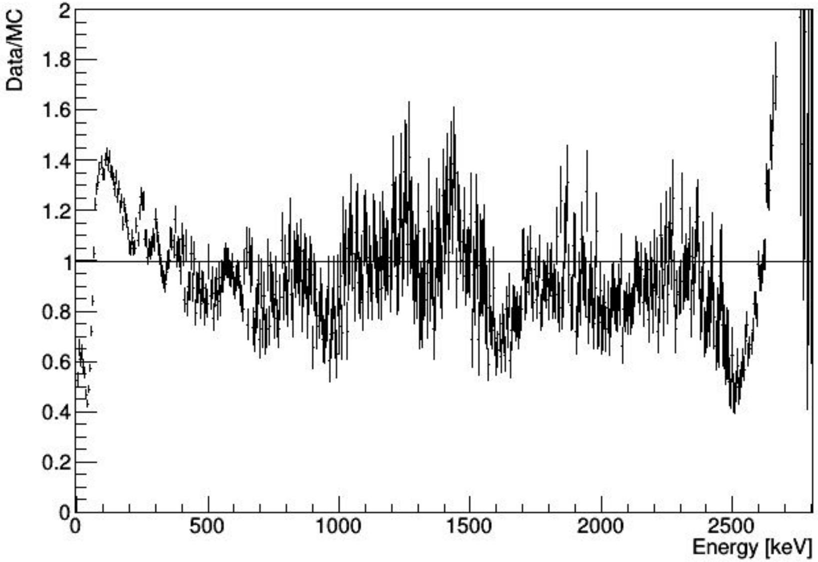
Counting gammas entering the hall

- ^{40}K → 0.21 gammas/cm^2/s
- ^{238}U → 0.25 gammas/cm2/s
- ^{232}Th → 0.12 gammas/cm^2/s
- **Total 0.58 gammas/cm^2/s**

Data/MC comparison

- Comparison on the full range (fit range [300-2800] keV)
- Agreement is quite good, considering statistics uncertainty of MC

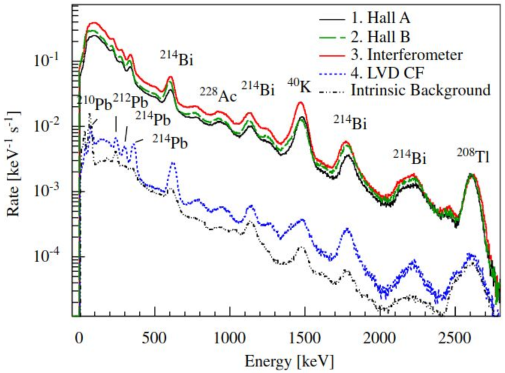




Comparison with literature

M. Haffke et al. / Nuclear Instruments and Methods in Physics Research A 643 (2011) 36–4138
https://doi.org/10.1016/j.nima.2011.04.027

NaI(Tl) cylindrical detector 3", very similar to our detector



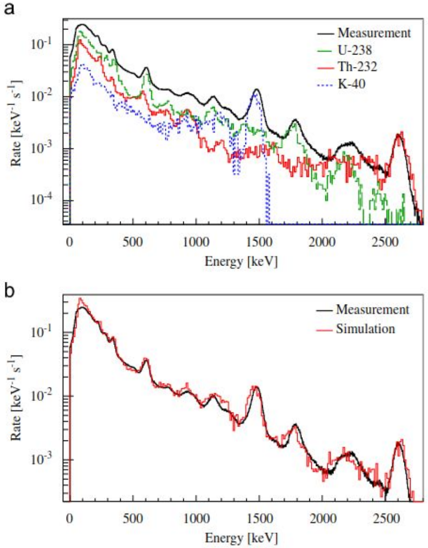


Fig. 3. Gamma spectrum of LNGS hall A (location 1). Top: measured data and the individual contributions of ^{238}U, ^{232}Th, and ^{40}K from of a Monte Carlo simulation of the setup. Bottom: measured data and Monte Carlo sum spectrum agree very well over a very large energy range.

Table 1
Gamma flux below 3000 keV, measured at several LNGS underground locations with a 3 in. NaI(Tl) detector.

Location	Time	Flux (s^{-1} cm^{-2})
1. Hall A	3 d	(0.28 ± 0.02)
2. Hall B	3 d	(0.33 ± 0.33)
3. Interferometer tunnel (XENON building)	2 d	(0.42 ± 0.06)
4. LVD Core Facility	10 d	(0.005 ± 0.001)

Table 2
Gamma activities of the primordial isotopes (in Bq/kg) as determined from measurements with a 3 in. NaI(Tl) detector.

Location	^{238}U	^{232}Th	^{40}K
1. Hall A	11.7 ± 3.9	14.8 ± 2.8	62 ± 14
2. Hall B	19.6 ± 4.9	13.2 ± 2.7	52 ± 10
3. Interferometer	37.8 ± 7.3	10.9 ± 2.8	206 ± 37
4. LVD CF	1.2 ± 0.4	0.34 ± 0.07	1.04 ± 0.32
Concrete (floor)[a]	26 ± 5	8 ± 2	170 ± 27
Concrete (wall)[a]	15 ± 2	3.8 ± 0.8	42 ± 6

[a] These concrete samples taken from the interferometer tunnel were screened in a HPGe detector in order to directly measure the radioactive contamination. They are to be compared to the NaI(Tl) results for location 3. *interferometer.*

Summary and conclusions

- **Simulation of ER** tracks and digitization of **images** (validated with x-rays data)
  - very **good agreement** in the **energy response**
  - **reasonable agreement** in the **energy resolution**
  - other shape variables (track length, density..) could be studied more systematically
  - recently **PMT simulations** has been integrated in the code ➔ to be validated

- **Simulation of NR** not covered in this summary because at the moment we have no data to make validation (AmBe data taking with LIME @LNGS foreseen this year)

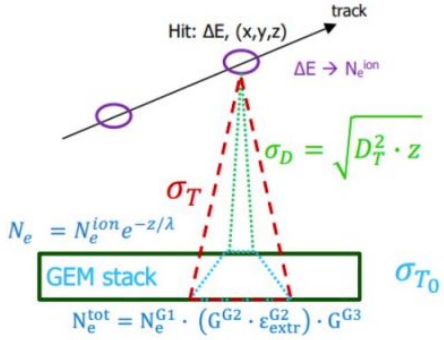
- **LIME background** simulations with Geant4 completed, now proceeding with full digitization + reconstruction
  - preliminary data/MC comparisons for LIME Run2 look promising
  - Run 3 data can be used to validate internal background

- **Simulations of the NaI detector** allow to deconvolve the gamma spectrum and give a more precise input for LIME simulations.

Extra slides

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	$\varepsilon = 0.873 \cdot e^{-0.002 \cdot HV}$	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	$\left(\frac{image\ size}{sensor\ size}\right) = \left(\frac{346\ mm}{14.976\ mm}\right)$	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}	$350\ \mu m$	Diffusion parameters
σ_{0L}	$260\ \mu m$	
σ_T	$110\ \mu m/\sqrt{cm}$	
σ_L	$100\ \mu m/\sqrt{cm}$	

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

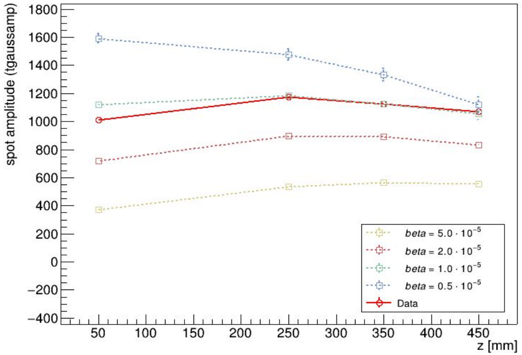
CYGNO 2nd Collaboration Meeting – 19-20 December 2022, Rome

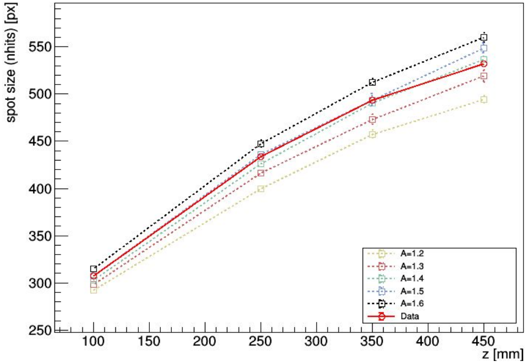
5

F.Petrucci – Summary of detector response simulation

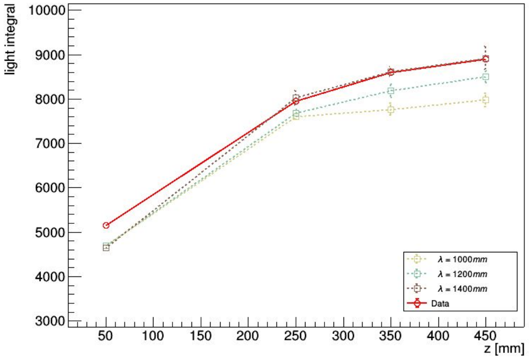
Optimization of digitization parameters

- Data from ^{55}Fe ➜ red solid line

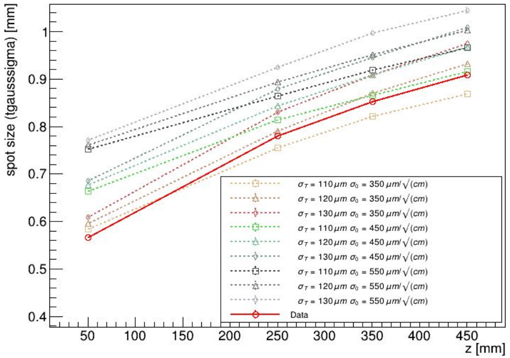




- beta and A parameters of **saturation**
- optimized variable: spot size and spot amplitude



- **attenuation length** of electrons in gas
- optimized variable: light integral



- **diffusion parameters**
- optimized variable: spot size

Closure test

- Generate gammas according to the true energy distribution
- Isotropic generation from a spherical surface of R=21 cm (10^7 events)
- Normalized to 0.58 gammas/cm^2/s, Nflu ➜ only gammas entering the sphere
  ➜ t_eq = Nflu/(Flux Area) = 1084 sec
  ➜ MC rate is in agreement with data within 15%