# Background simulation in LIME underground

CYGNO Collaboration Meeting – 21th December 2021

F. Di Giambattista, E. Baracchini

# LIME background underground at LNGS

Two main contributions were considered:

- **External** background: produced by natural gamma and neutron fluxes in underground LNGS
- **Internal** background: produced by radioactivity of the detector materials and surroundings (e.g. shield)

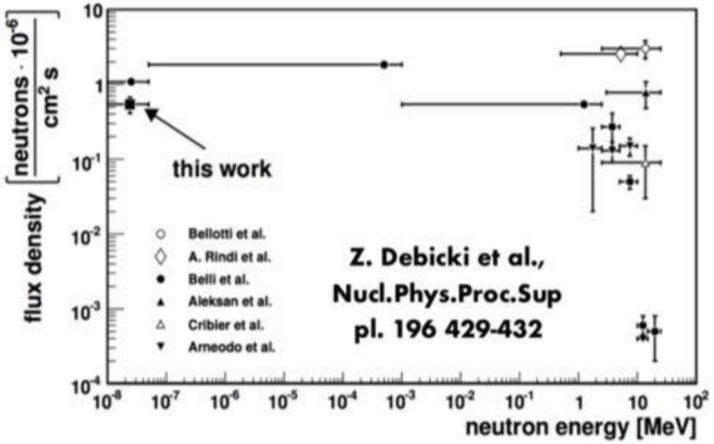
Data taking with LIME will go through 3 phases:

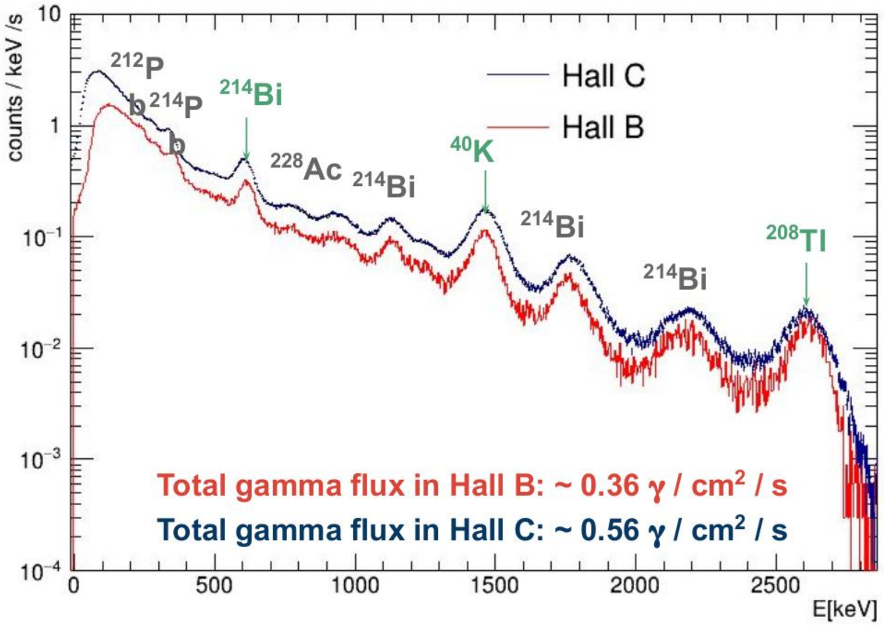
- **No shielding**: total background measurement
- **Gamma shielding**: measurement of the neutron flux underground – not only important to our experiment, but also provides a measurement for other underground operating experiments
- **Full shielding**: characterization of internal background, operation in typical conditions of a DM experiment – test the feasibility of the technique

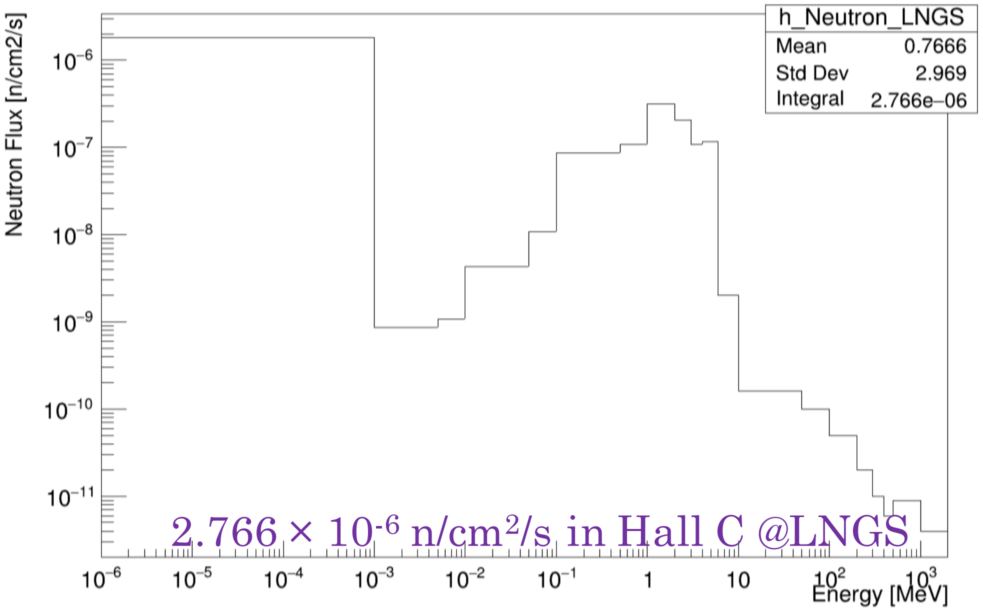
# External background

Gamma flux:
measurement by SABRE
Integrated flux:
0.56 cm$^{-2}$ s$^{-1}$

Neutron background:
many measurements
Integrated flux:
2.766×10$^{-6}$ cm$^{-2}$ s$^{-1}$



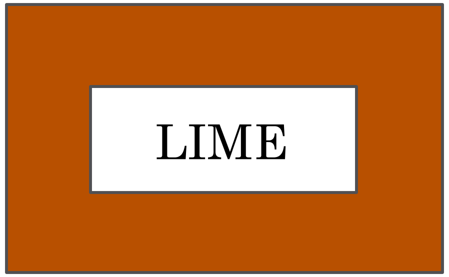
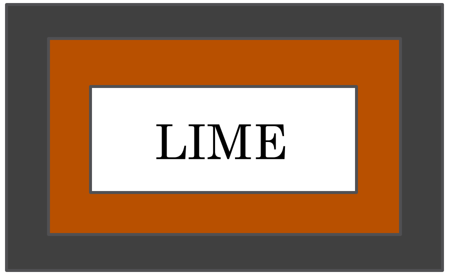

P. Belli et al., Il Nuovo Cimento A vol. 101, p. 959-966 (1989)

# External background - 1° phase

| | Energy range | ER+NR rate [events/year] | NR rate [events/year] |
|---|---|---|---|
| No shielding<br>LIME | 1-20 keV | $4.061(8)\times10^{8}$ | 340(2) |
| | 1-50 keV | $7.04(1)\times10^{8}$ | 556(2) |
| | total | $1.152(1)\times10^{9}$ | 1813(4) |
| 5 cm copper<br>LIME | 1-20 keV | $1.89(2)\times10^{7} + 1.377(7)\times10^{5}$* | 578(2) |
| | 1-50 keV | $2.99(2)\times10^{7} + 2.94(1)\times10^{5}$* | 866(3) |
| | total | $6.21(3)\times10^{7} + 5.34(1)\times10^{5}$* | 1576(4) |

*from copper radioactivity (210Bi and 207Bi)

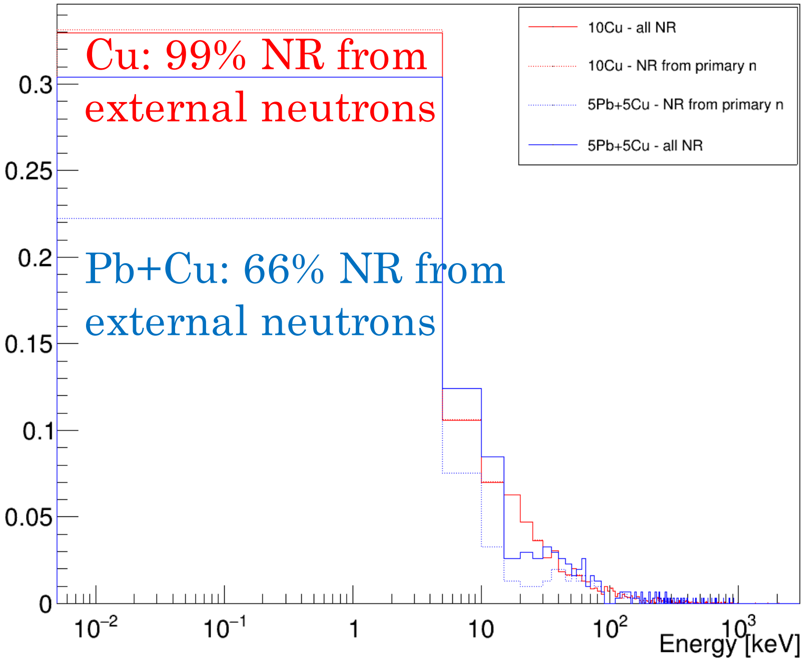
# External background - 2° phase

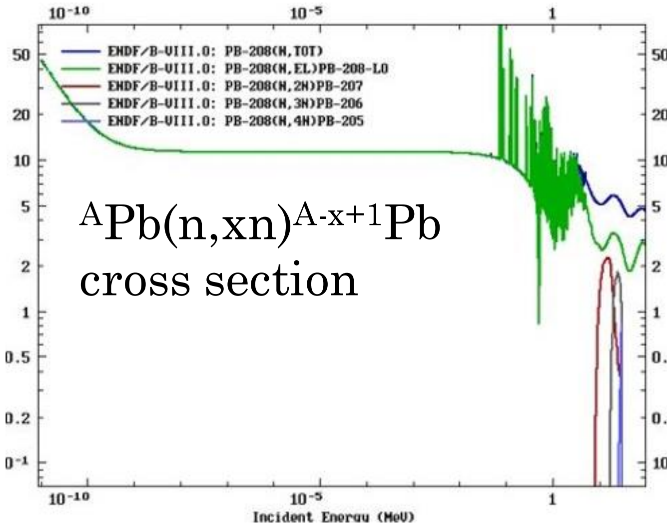
| | Energy range | ER+NR rate [events/year] | NR rate [events/year] |
|---|---|---|---|
| 10 cm copper   | 1-20 keV | $8.86(1)\times10^5 + 1.383(7)\times10^5$* | 447.2(6) |
| | 1-50 keV | $2.024(2)\times10^6 + 2.95(1)\times10^5$* | 638.2(7) |
| | total | $4.810(3)\times10^6 + 5.41(1)\times10^5$* | 1089(1) |
| 5 cm copper + 5 cm lead   | 1-20 keV | $2.301(9)\times10^5 + 1.59(8)\times10^5$** | 469(2) |
| | 1-50 keV | $4.94(1)\times10^5 + 3.34(1)\times10^5$** | 665(2) |
| | total | $1.299(2)\times10^6 + 6.10(1)\times10^5$** | 1176(3) |

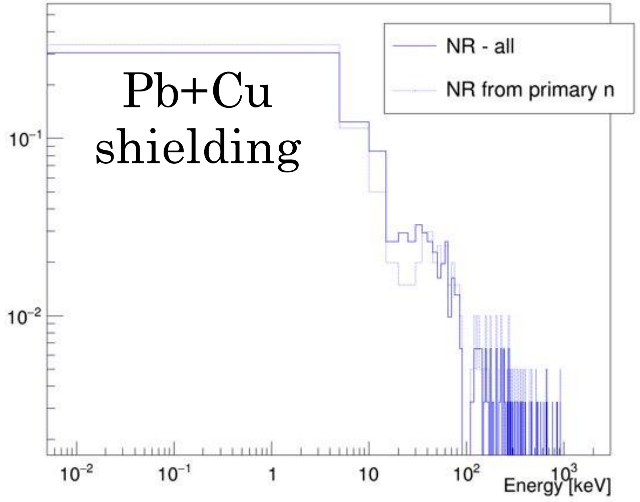
*from copper radioactivity (210Bi and 207Bi) **from copper and lead radioactivity (210Bi and 207Bi)

# Lead vs copper

- Lead is a more efficient gamma shielding material (by a factor ~4), but the simulation shows an increase in NR background



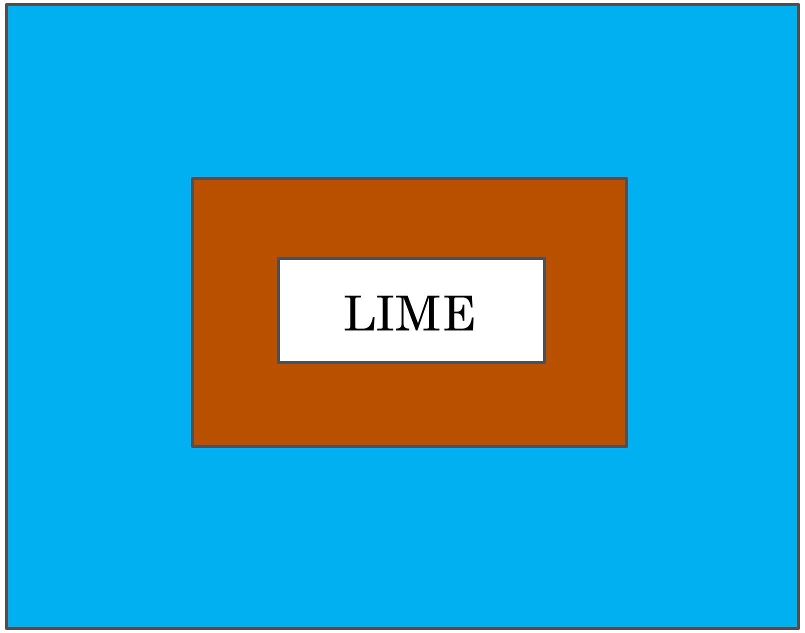




No peculiar feature in NR energy distribution - can not disentangle primary and secondary contribution

**Copper** is a better choice (despite its radioactive contamination) – cleaning the innermost layer of copper would reduce the radioactivity induced background to a negligible level

# External background - 3° phase

Final configuration
10 cm copper + 40 cm water

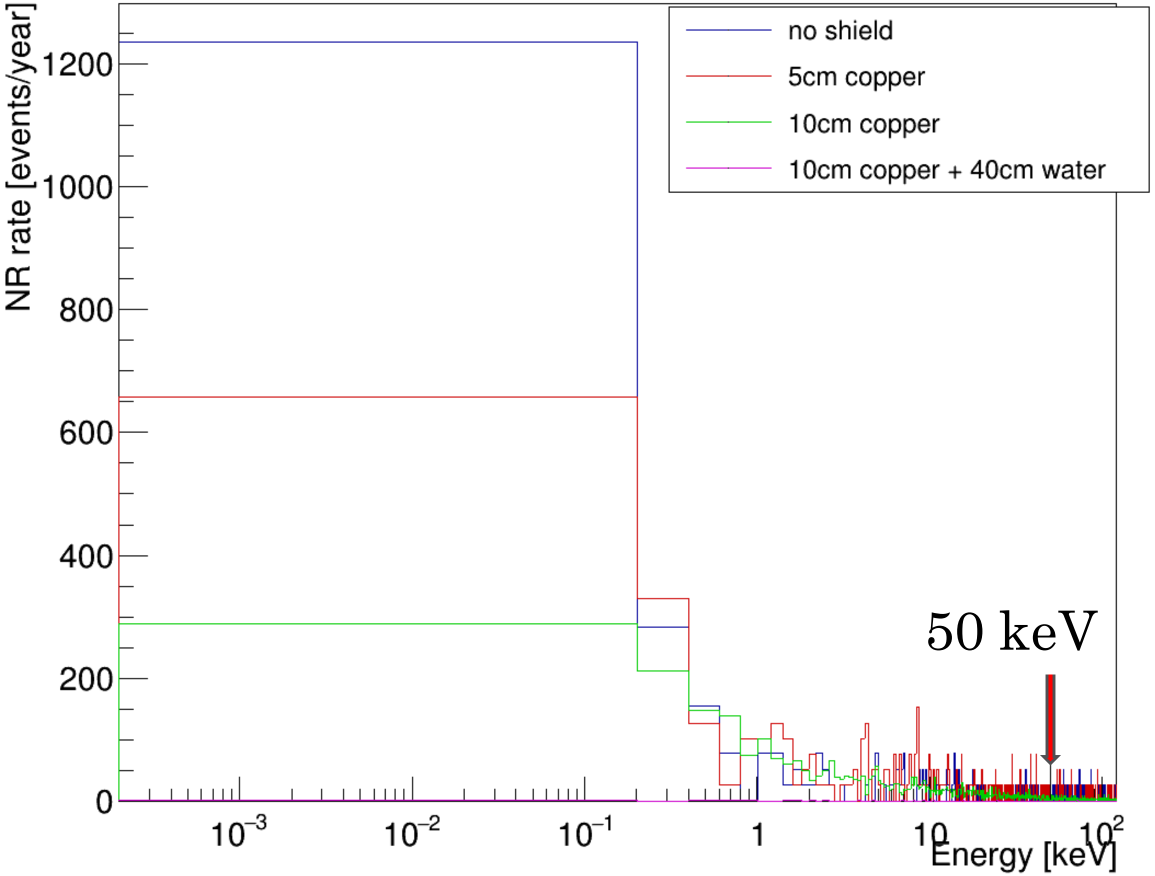



| Energy range | ER+NR rate [events/year] | NR rate [events/year] |
|---|---|---|
| 1-20 keV | $1.073(5)\times10^5 + 1.383(7)\times10^5$* | $9.57(5)\times10^{-1}$ |
| 1-50 keV | $2.366(7)\times10^5 + 2.95(1)\times10^5$* | 1.343(6) |
| total | $5.13(1)\times10^5 + 5.41(1)\times10^5$* | 2.337(8) |

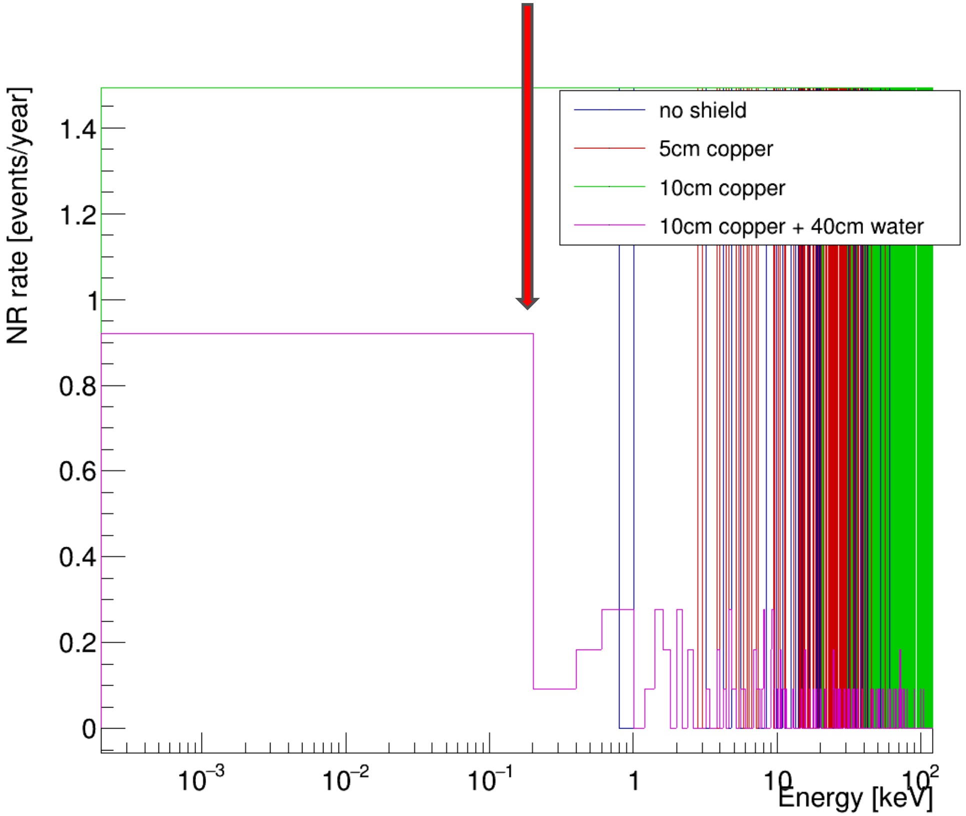
Maximum total space available for the whole shielding ~50 cm
Below 20keV we have practically no NR background

*from copper radioactivity (210Bi and 207Bi)

# NR spectra from external background

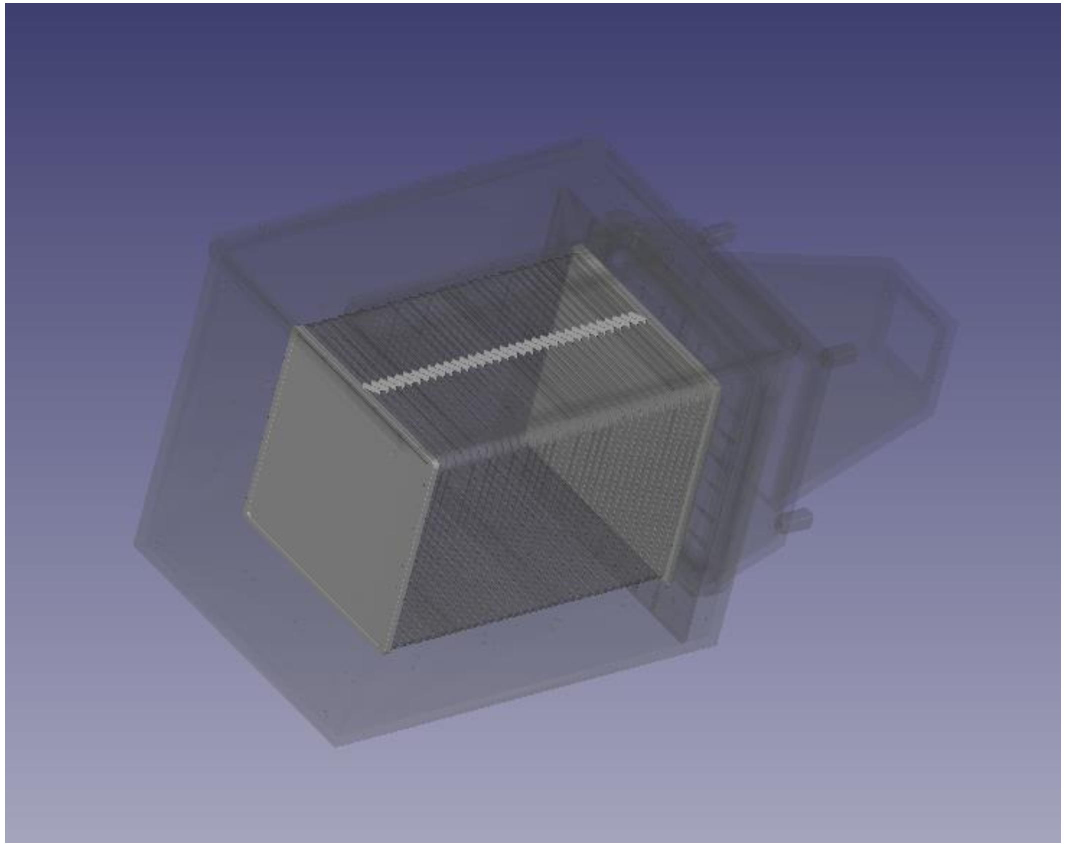



Most NR background is
below our threshold of 1 keV



# Internal background

- **Radioactivity** from natural radioactive decay chains $^{232}Th$, $^{238}U$, $^{235}U$ and other contaminants
- Activity of all main components of LIME were measured underground by M.Laubestein:
    - Acrylic box
    - Field rings
    - Cathode
    - Resistors
    - GEMs
    - Camera (body + lens)
- A secondary effect is the **radiogenic neutron** contribution, produced by (α,n) reactions and spontaneous fission (ongoing)
- Also the **cosmogenic neutron** contribution must be taken into account



# Radioactivity measurements

| | Radionuclide | FieldRings | Cathode | Resistors | GEM | Acrylic | Camera body | Camera lens |
|---|---|---|---|---|---|---|---|---|
| $^{238}$U chain | 234Th | <2,10E-01 | <2,10E-01 | 1,99E+01 | 1,63E-01 | - | 3,16E+00 | 4,22E+00 |
| | 234mPa | <7,70E-02 | <7,70E-02 | 2,19E+01 | - | - | - | - |
| | 226Ra | <1,30E-03 | <1,30E-03 | 2,16E+00 | 3,25E-02 | <3,50E-03 | 8,13E-01 | 1,92E+00 |
| | 210Pb | - | - | 5,94E+02 | - | - | - | - |
| $^{232}$Th chain | 228Ra | <1,10E-03 | <1,10E-03 | 3,50E+00 | <3,09E-02 | <5,00E-03 | 9,49E-01 | 3,61E-01 |
| | 228Th | <1,30E-03 | <1,30E-03 | 3,36E+00 | <1,56E-02 | <4,50E-03 | 9,49E-01 | 3,65E-01 |
| $^{235}$U chain | 235U | <1,60E-03 | <1,60E-03 | 3,37E-01 | <1,58E-02 | - | 1,81E-01 | 1,45E-01 |
| Other | 40K | <6,00E-03 | <6,00E-03 | <1,78E+00 | <3,58E-01 | <3,50E-02 | 8,59E-01 | 5,15E+01 |
| | 137Cs | <4,70E-04 | <4,70E-04 | <7,35E-02 | <8,13E-03 | - | 4,07E-02 | <2,67E-02 |
| | 60Co | <5,70E-04 | <5,70E-04 | <7,73E-03 | <7,48E-03 | - | <5,42E-03 | <4,64E-02 |
| | 58Co | 9,00E-04 | 9,00E-04 | <3,10E-03 | - | - | - | - |
| | Mn54 | <4,30E-04 | <4,30E-04 | <3,27E-03 | - | - | - | - |
| | La138 | - | - | - | - | - | - | 2,44E+00 |

Thanks to M.Laubestein

# Internal background rates

| Event rate [events/yr] | Field rings | Cathode | Resistors | GEMs | Acrylic box | Camera (body) | Camera (lens) | Total |
|---|---|---|---|---|---|---|---|---|
| ER+NR [$10^5$] (0-20keV) | 5.301(3) | 5.2817(5) | 3.944(3) | 0.6976(1) | 0.5283(4) | 0.0520(3) | 0.2777(9) | **16.082(8)** |
| ER+NR [$10^5$] (1-20keV) | 5.026(2) | 5.0586(5) | 3.802(3) | 0.6549(1) | 0.4947(4) | 0.0480(2) | 0.2603(9) | **15.344(7)** |
| ER+NR [$10^5$] (1-50keV) | 12.510(4) | 6.6179(6) | 8.183(4) | 1.4738(1) | 1.0134(6) | 0.1043(4) | 0.556(1) | **30.46(1)** |
| ER+NR [$10^5$] (all) | 35.846(5) | 11.0734(8) | 18.800(5) | 3.8426(2) | 2.7054(9) | 0.2455(6) | 1.521(2) | **74.03(1)** |
| NR only [0-20keV] | 770(6) | 126.2(8) | 148(2) | 321.4(4) | 0. | 0. | 0. | **1366(9)** |
| NR only [1-20keV] | 769(6) | 122.9(8) | 146(2) | 319.4(4) | 0. | 0. | 0. | **1357(9)** |
| NR only [1-50keV] | 1662(8) | 256(1) | 359(3) | 772.8(7) | 0. | 0. | 0. | **3050(13)** |
| NR only [all] | 22810(10) | 15235(9) | 5090(10) | 17953(3) | 0. | 0. | 0. | **61090(30)** |

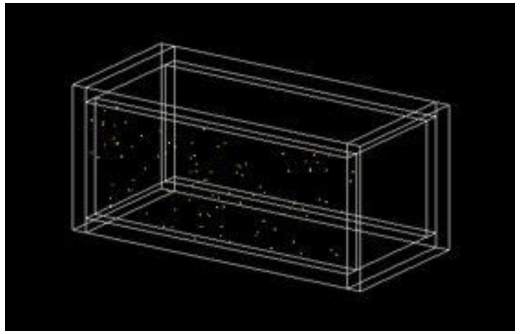
- A cut on the upper 5cm along y would reduce by 99.9% the NR from **resistors** and 33% of NR from the **rings**
- A cut of the first and last 5cm along the drift direction would reduce by 99% the NR coming from the **GEMs** and by 97% the ones from the **cathode**
- Overall reduction of sensitive volume of 33%

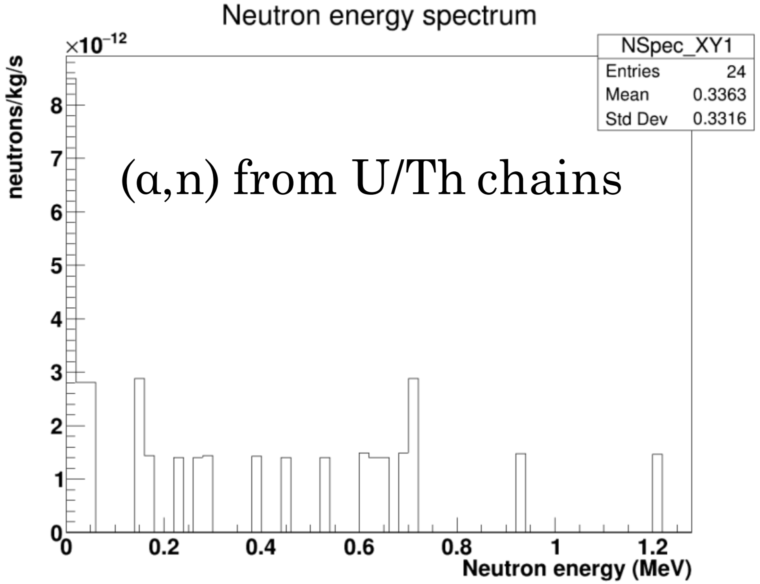
This is *unshielded;* Simulation with copper shield is ongoing

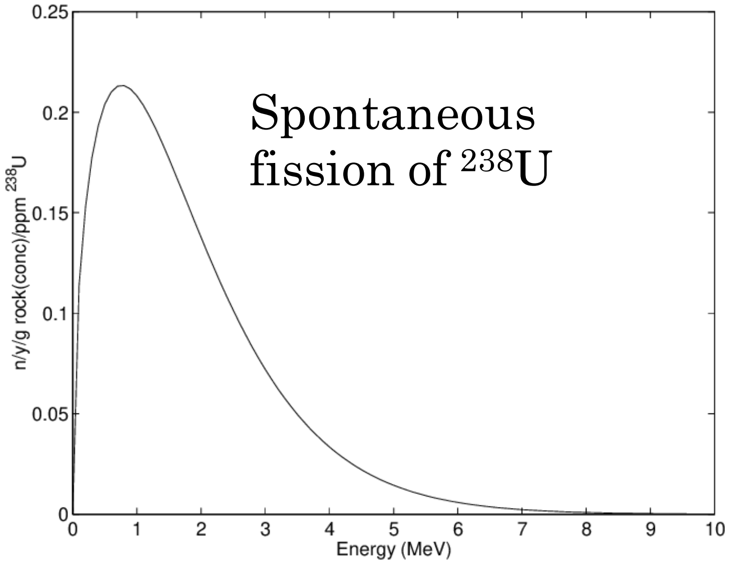
# Radiogenic neutron background

Radioactivity in the detector materials also produces an additional neutron background through (α,n) reactions and spontaneous fission (mainly from $^{238}U$)

- (α,n) yield: GEANT4 simulation (SaG4n http://win.ciemat.es/SaG4n/)
  - $R_{alpha,n} = 3.85\times10^{-11}$ n/kg/s → $\mathbf{4.13\times10^{-12}}$ **n/cm²/s**
- Fission neutron rate calculated as R = Activity × B.R. × yield
  - $R_{fission} = 2.14\times10^{-9}$ n/kg/s → $\mathbf{2.29\times10^{-10}}$ **n/cm²/s**



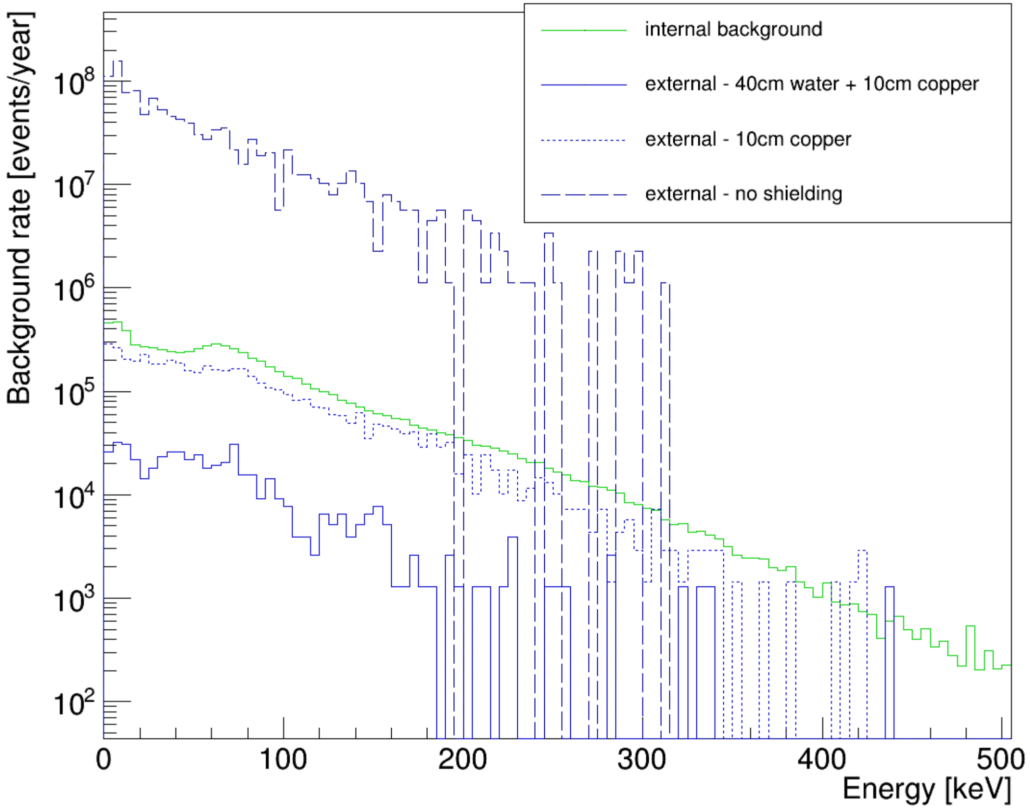



- Neutron flux is 4-6 orders of magnitude lower than the external one
- Cosmogenic contribution from muons to be assessed with MUSUN software

# Total background

| Shielding | Internal [ev/yr] (1-20 keV) | External* [ev/yr] (1-20 keV) |
|---|---|---|
| No shield | $1.5344(7)\times10^6$ | $4.061(8)\times10^8$ |
| 5cm copper | $1.5344(7)\times10^6$ | $1.90(2)\times10^7$ |
| 10cm copper | $1.5344(7)\times10^6$ | $1.024(2)\times10^6$ |
| 40cm water + 10cm copper | $1.5344(7)\times10^6$ | $2.46(1)\times10^5$ |




The data taking underground will start next year;

- We will measure the background and validate the Monte Carlo simulation
- We will measure the neutron flux underground
- Started the development of the analysis tools for NRs

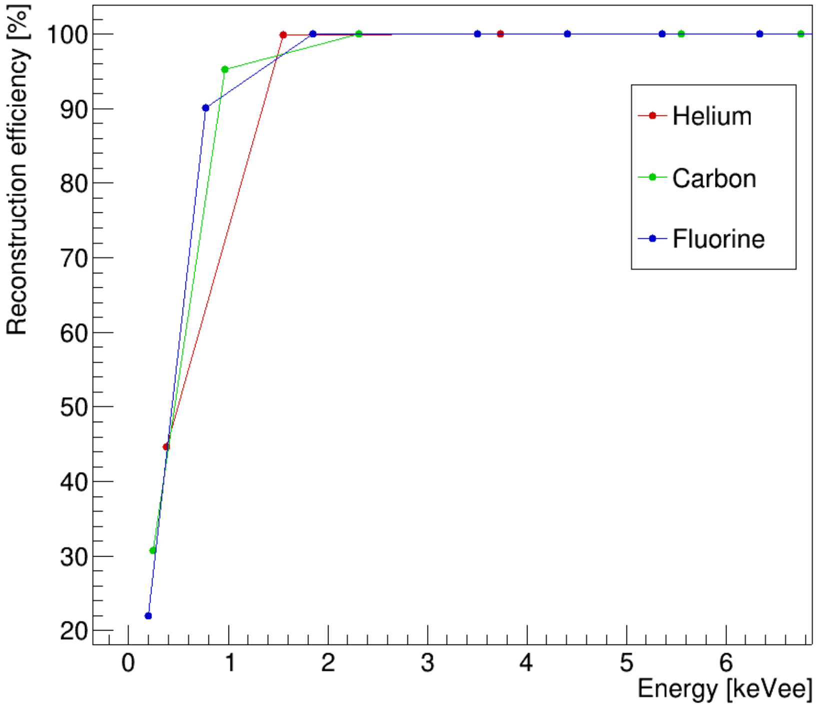
*includes the radioactivity of the shieldings

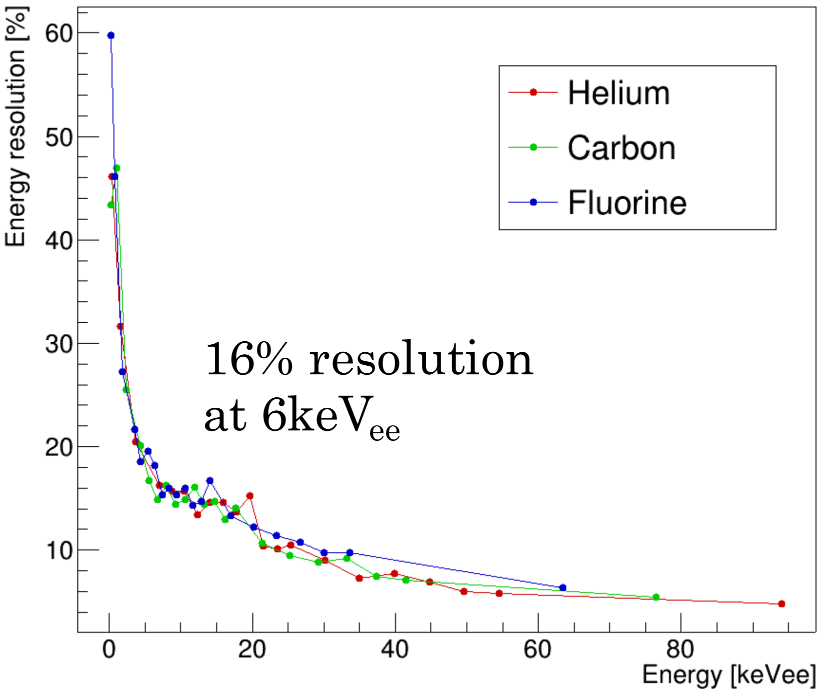
# Nuclear recoils track simulation

# NR sample production

- From **SRIM** simulations I produce the 3D ionization profile of the tracks in the gas mixture He:$CF_4$ 60/40
- Starting from the 3D profile, the tracks are **digitised** (without saturation) and then **reconstructed**
- He, C and F recoils of energy between 1 $keV_{nr}$ and 100 $keV_{nr}$, 1000 at each energy (63000 tracks in total)
- Digitized with random distance from the GEM plane (between 1cm and 50cm in LIME) and random direction

- Tracks were reconstructed with latest branch of the official reconstruction code (autumn21)
- High reconstruction efficiency even at low energy (but lowest energy tracks might be cut at the borders, must be optimized)

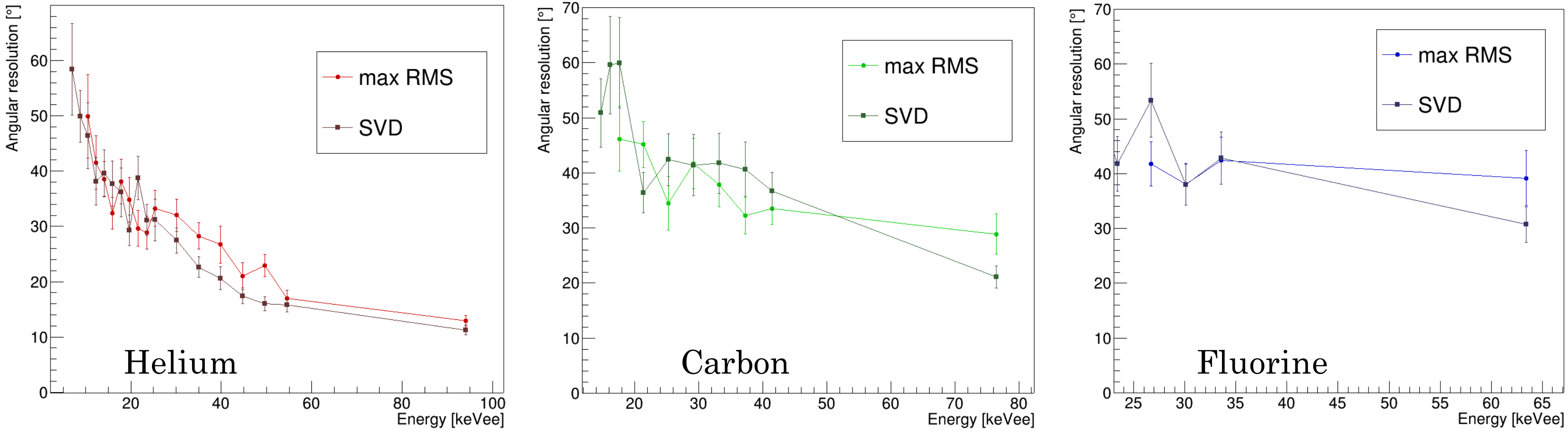


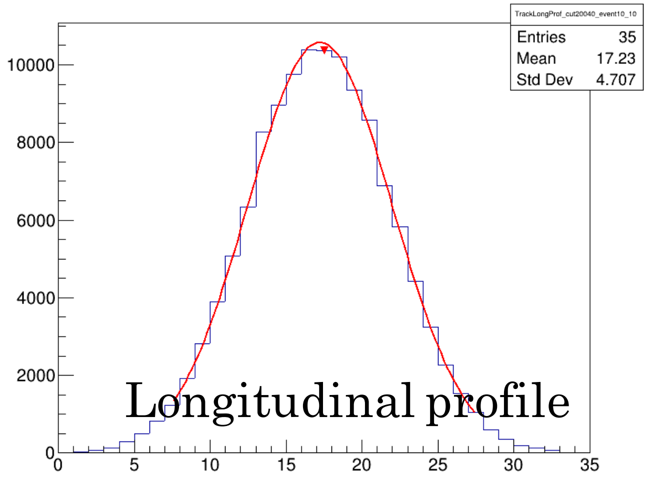
# Angular resolution

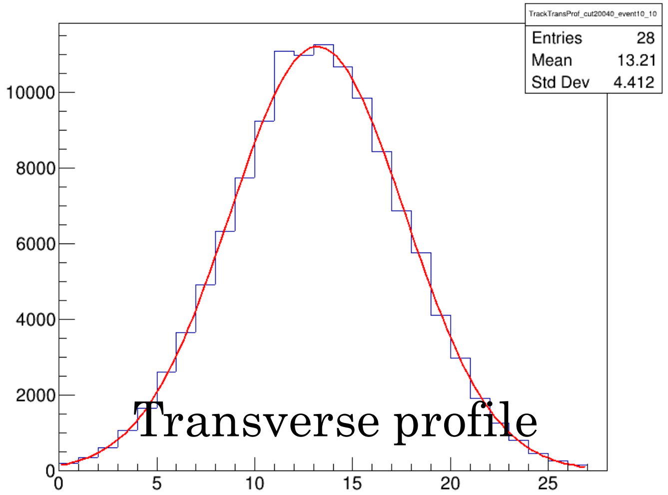
Two approaches were tested to determine the direction in the x-y plane (parallel to the GEMs):

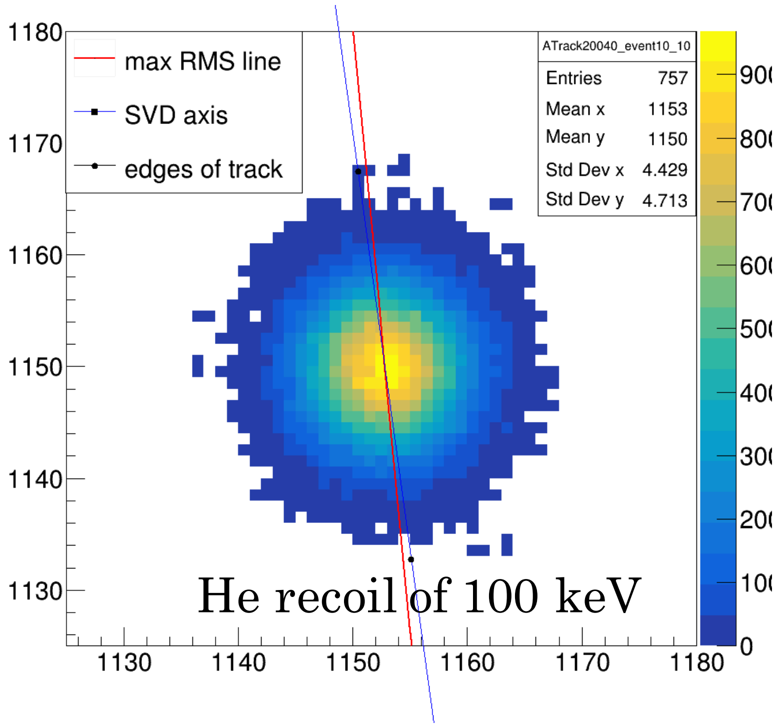
- The line along which the RMS of the weighted pixel distribution is maximum
- From the singular value decomposition of the covariance matrix, taking the major principal axis



# Track profile study




The profiles of the track are constructed by projecting the intensity-weighted pixels along the principal axes

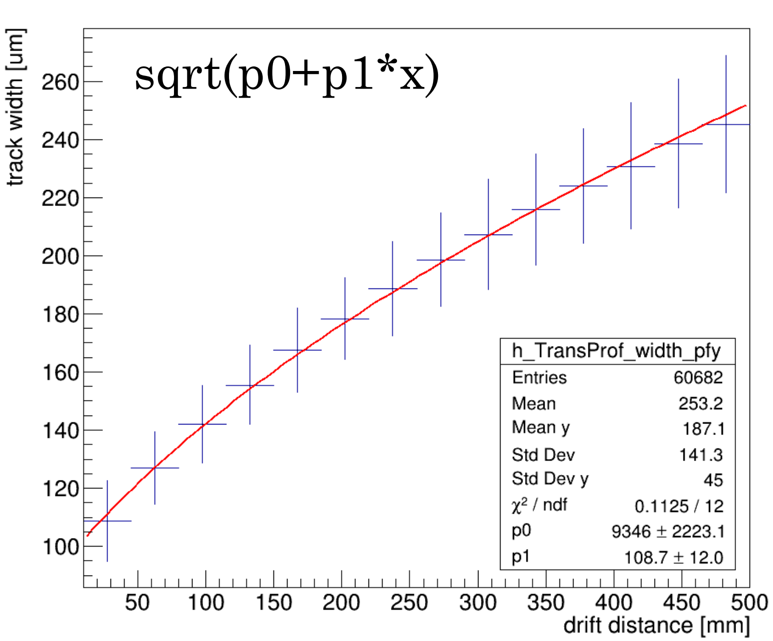
- From the *longitudinal* profile we can retrieve information on the asymmetry of the energy losses (head tail effect) and on the energy release profile (number of energy loss peaks can help discriminate between NR and ER)
- From the *transverse* profile we can retrieve information on the z coordinate – the sigma of the distribution depends on diffusion

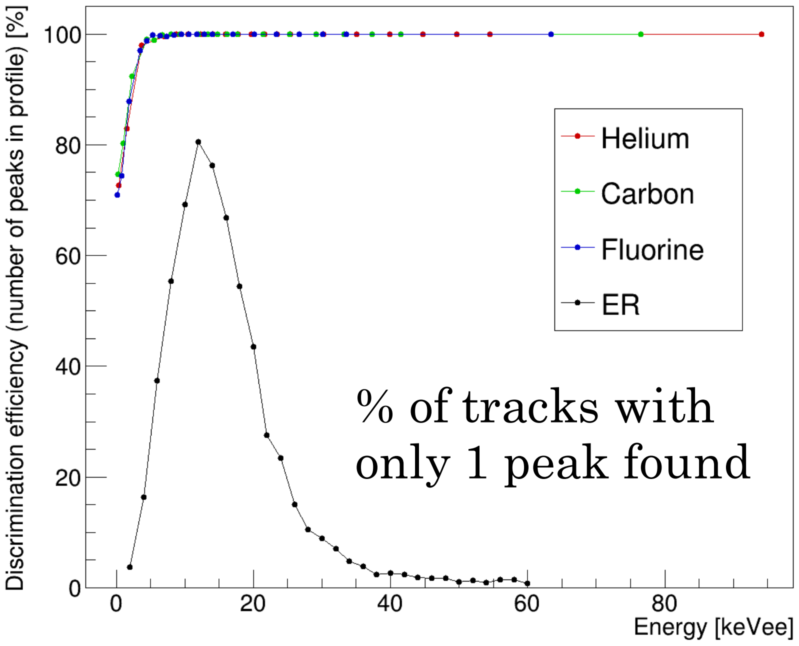
# Track profile study

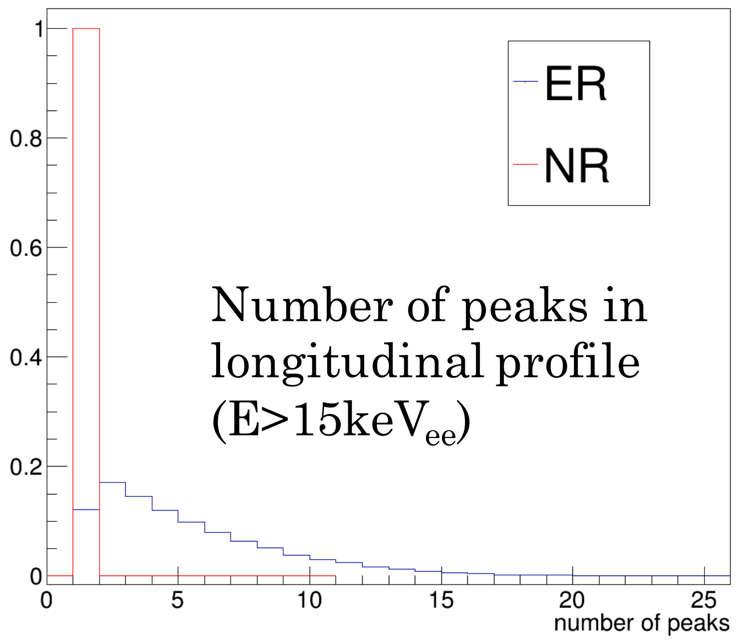
Sigma from gaussian fit of the *transverse profile* as a function of drift distance

**NRs** show one big peak in the *longitudinal profile*, **ERs** have a more sparse energy release

100% of NR identification efficiency
~88% of ER rejection efficiency
Above 15 $keV_{ee}$



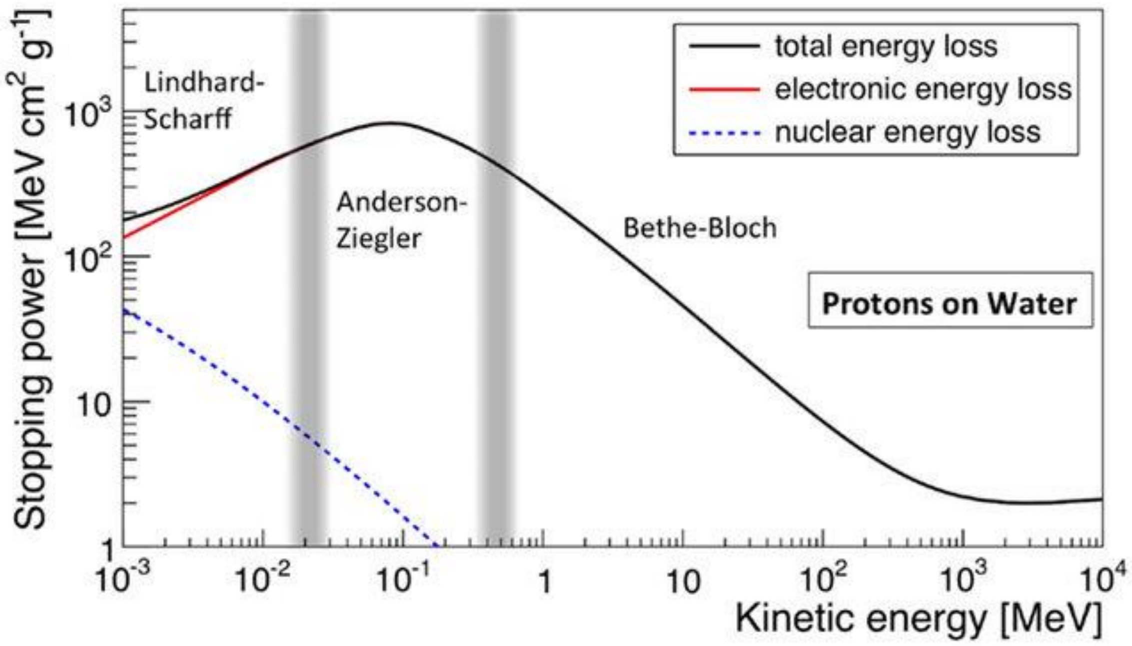
# Conclusions and future plans

- GEANT4 simulation of expected **background in LIME** underground is complete
- The copper from the field rings and the resistors are the main source of internal background
  - Might apply some cuts on fiducial volume to reduce the radioactivity induced background
- **Simulation of tracks** and analysis is ongoing, some preliminary results were presented
- The detector energy response must be precisely assessed in order to develop a method to **unfold** the NR spectrum, to retrieve the original neutron spectrum underground

# backup

# Low energy nuclear recoils

- NR from DM (or neutrons) are expected to be in the range 1-100 keV
- A significant fraction of the energy is lost to non-ionizing processes
- The stopping power decreases: ions lose the majority of their energy at the beginning of their path
- Key features to be studied:
  - Ionization quenching factor $QF(E) = \frac{E_{ionization}}{E}$
  - Ionization profile $\frac{dE_{ionization}}{ds}$
- Relevant for energy calibration, track analysis development, direction and head-tail study

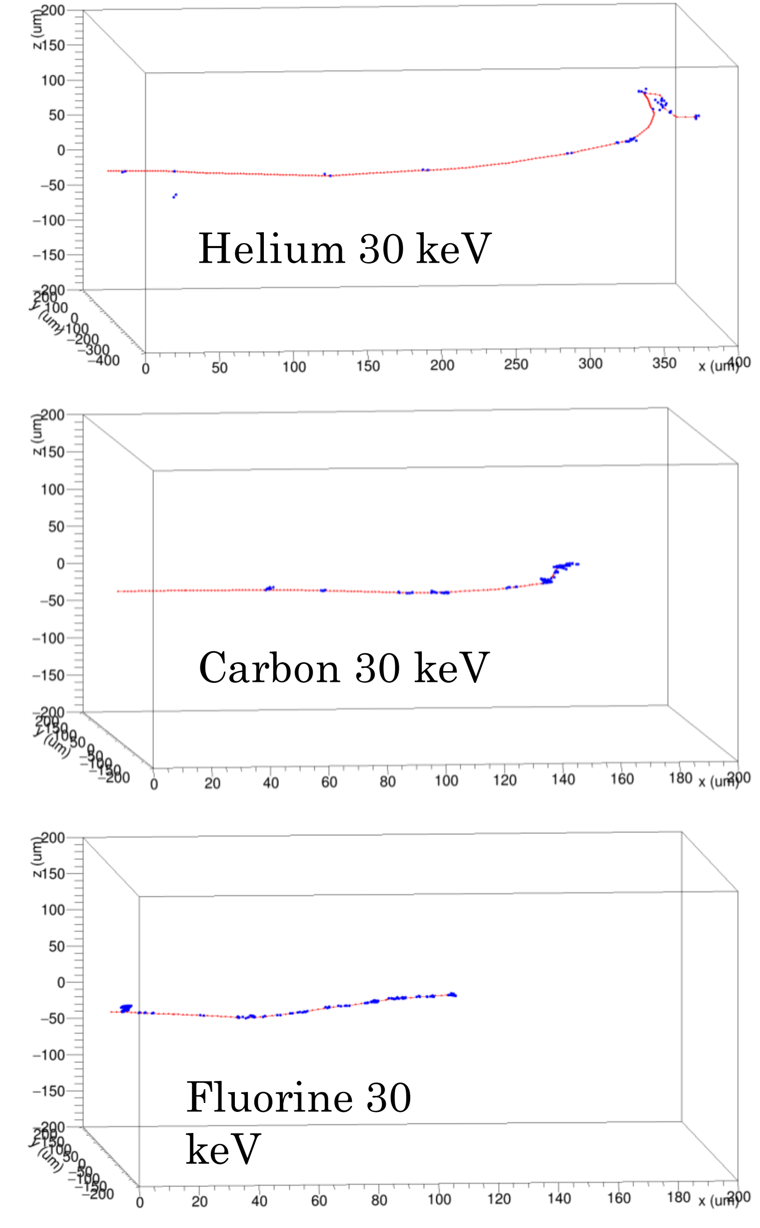


# SRIM simulation

- **SRIM** (Stopping and Range of Ions in Matter) - to simulate the passage of ions (NR) in He:$CF_4$ in 60/40 proportion for different energies and atoms (He, C and F)

- Post processing of SRIM simulations was necessary to retrieve the QF and the ionization profile (SRIM is not optimised for the study of the tracks)

- Main issues:
    - Nuclear energy losses (secondary recoils/cascades) are significant – but no explicit description is given by SRIM
    - No 3D ionization energy deposits: from the 3D *total* energy distribution I applied a **conversion factor** (dependent on the QF)

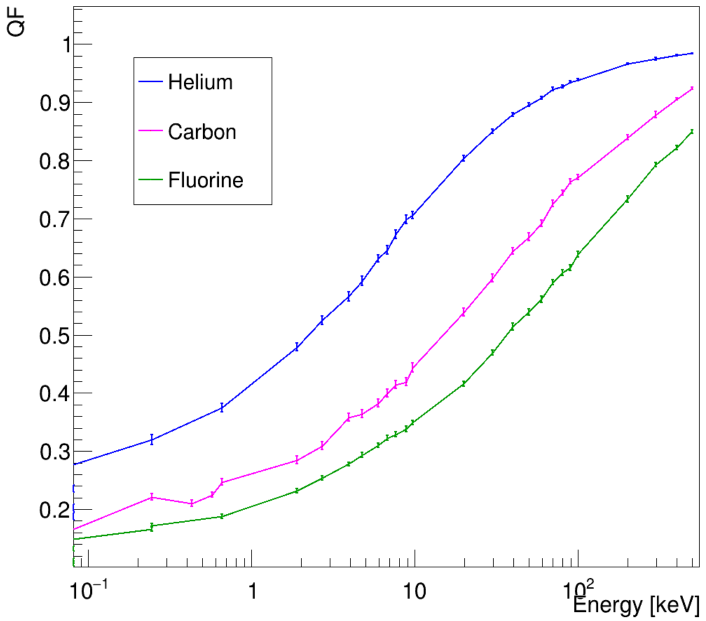


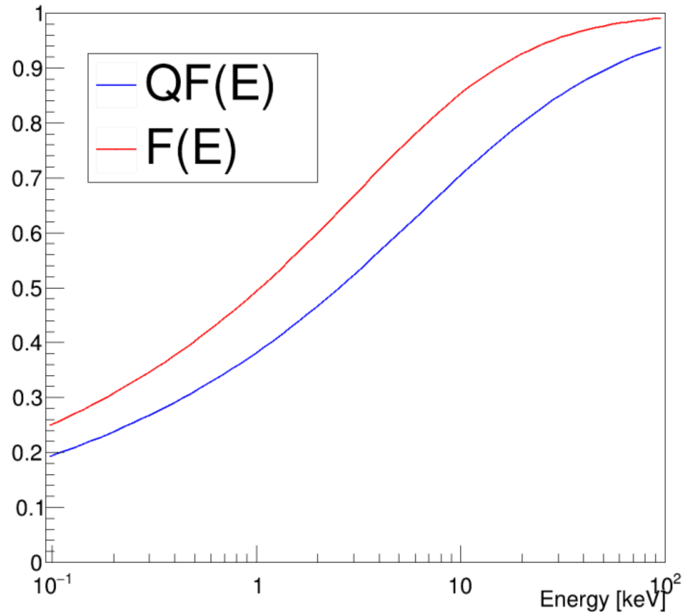

- Primary ionization
- Secondary ionization

# Quenching Factor

I computed the QF from the ionization profile along the shooting direction (x):

$$E_{ionization} = \int_0^{x_{max}} \left[ \left(\frac{dE}{dx}\right)_e + \left(\frac{dE}{dx}\right)_n \right] dx \longrightarrow \boxed{QF(E) = \frac{E_{ionization}}{E}}$$




A single ionization energy deposit is

$$E_{ionization} = \frac{d(E \times QF(E))}{dE} dE = F(E)dE$$

In each point in 3D space total energy deposit is **converted to ionization energy** through the F function

# Ionization profile

- The simulated ionization profile is fundamental for the study of **directionality and head-tail effect**
- I applied the conversion factor to the 3D energy distribution
- Whenever the energy of a secondary recoil is high enough, I **construct a cascade** based on expected stopping power of the hit atom (same for tertiary recoil, etc...)
- Results are consistent with SRIM results (both for energy deposit profile and spatial distribution)