35th cycle, PhD in Astroparticle Physics - 3rd year admission

Neutron flux measurement at LNGS with CYGNO/INITIUM

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Advisor: Prof. Elisabetta Baracchini

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Outline

- CYGNO experiment and the neutron background
- Nuclear recoils studies
- Underground background studies
- Conclusions and future perspectives

The CYGNO/INITIUM project and neutron background in underground experiments

The CYGNO/INITIUM project

- **CYGNO:** high resolution **Time Projection Chamber** with **optical readout** for **directional dark matter searches**
- He:CF_4 60/40 gas mixture at atmospheric pressure, triple GEM amplification, sCMOS cameras + PMT

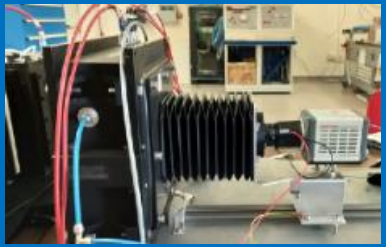
→ 3D tracking capability, ~ 1keV energy threshold

- In sinergy with **INITIUM** project on *negative ion drift* with the addition of SF_6
- R&D studies with different prototypes

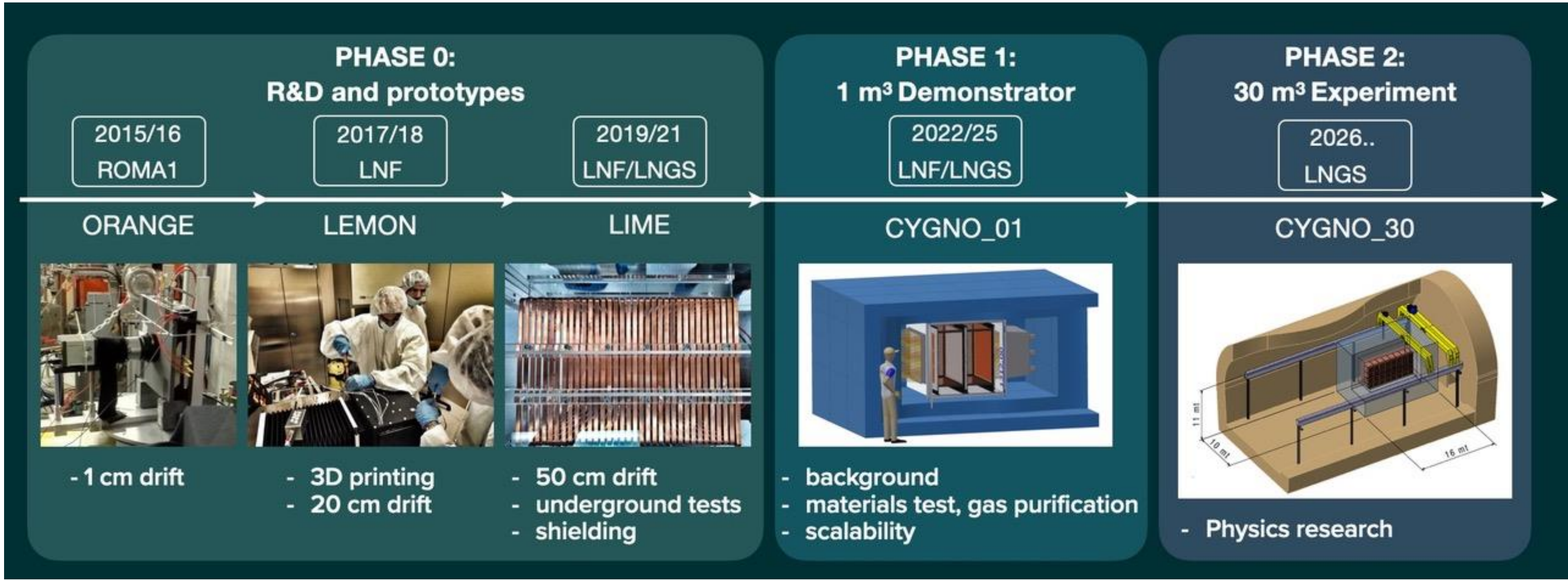
INITIUM

Currently
at LNGS (HdM)

MANGO

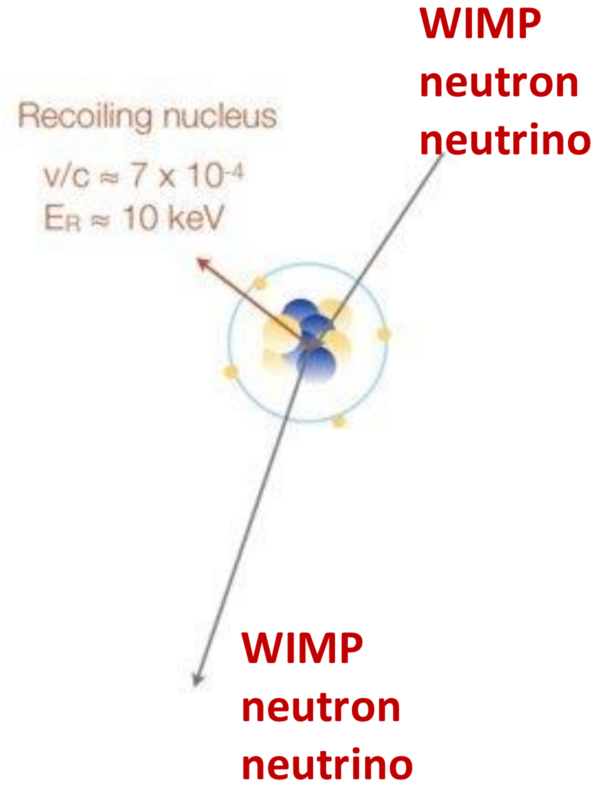


- Up to 5cm drift



Neutron background at LNGS

- Rare event searches experiments operate underground (reduction of cosmic ray background 10^{-6} muon, 10^{-3} neutron @LNGS)
- **Neutron background** is a major issue for many underground experiments (nuclear astrophysics, neutrinoless double beta decay, direct DM detection)
- Mainly produced by spontaneous fission, (α,n) reactions, radioactivity of the set up
- Neutral particles (neutrons, neutrinos) which interact with nuclei can mimic a WIMP-nucleus scattering
    - Neutrinos cannot be shielded – directionality is key
    - Neutrons can be shielded – knowledge of spectrum is paramount for the experiment design

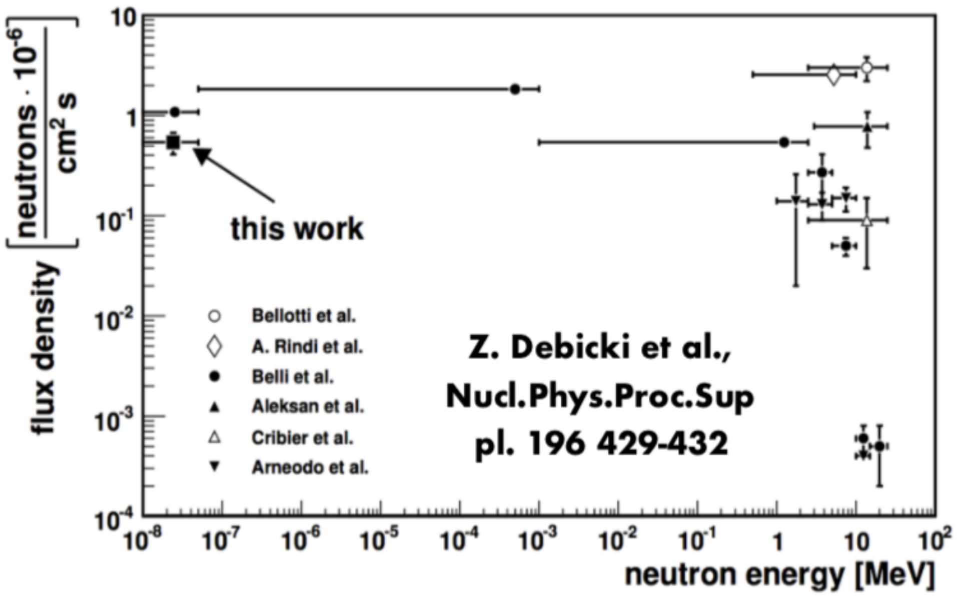


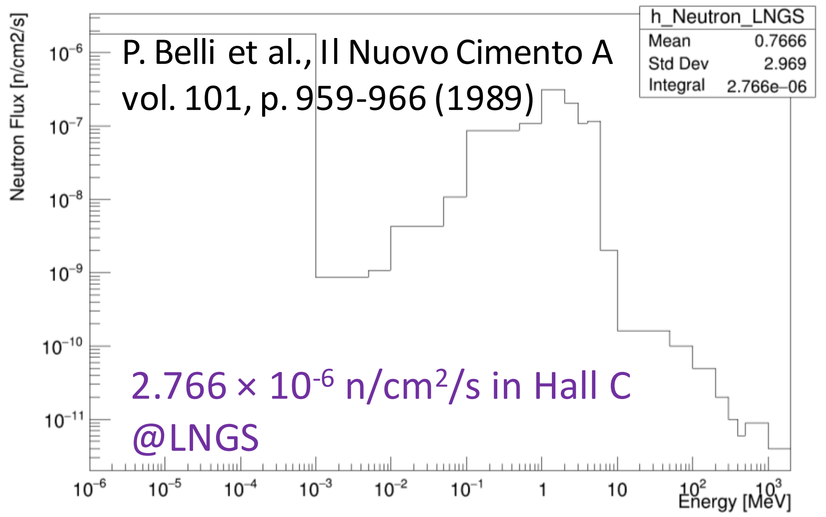
LIME can provide a spectral, directional measurement of the neutron flux underground at LNGS

Neutron background at LNGS

- The neutron flux measurements done so far:
    - Don't agree with each other
    - Have large binning/limited spectral sensitivity
    - Many tecnhiques based on thermal neutron absorption
- With the LIME gaseous TPC we can:
    - Directly measure the **fast** component through NR detection
    - Enhance sensitivity to **thermal** component with the addition of **^{3}He** (no change in gas mixture properties), through ^{3}He(n,p)^{3}H reactions
    - Directional measurement

- Moreover, the neutron measurement underground can show the **feasibility of the technique for DM detection**

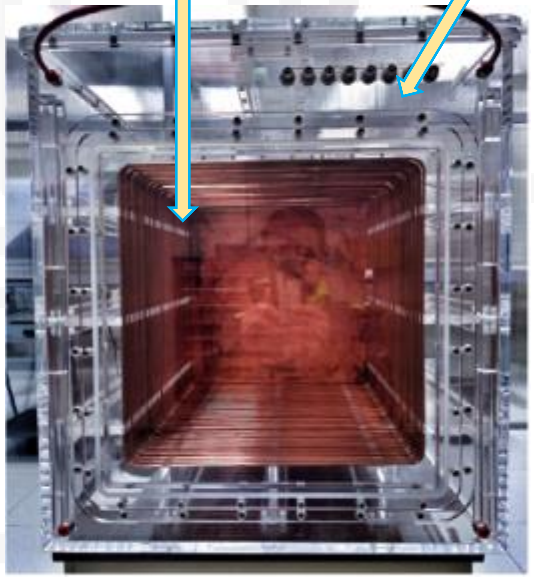


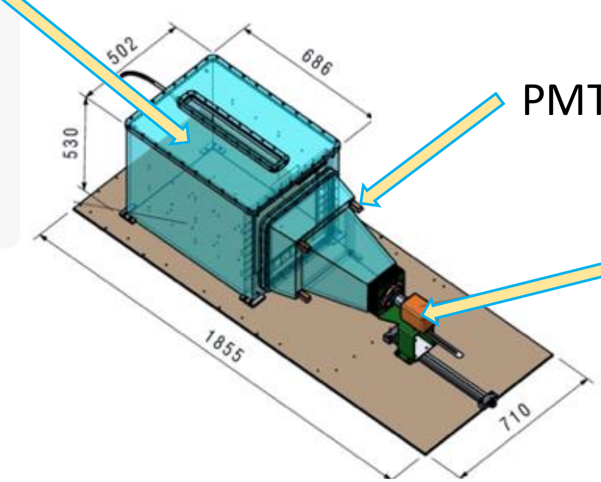


The LIME prototype

Drift field rings

Gas tight acrylic box

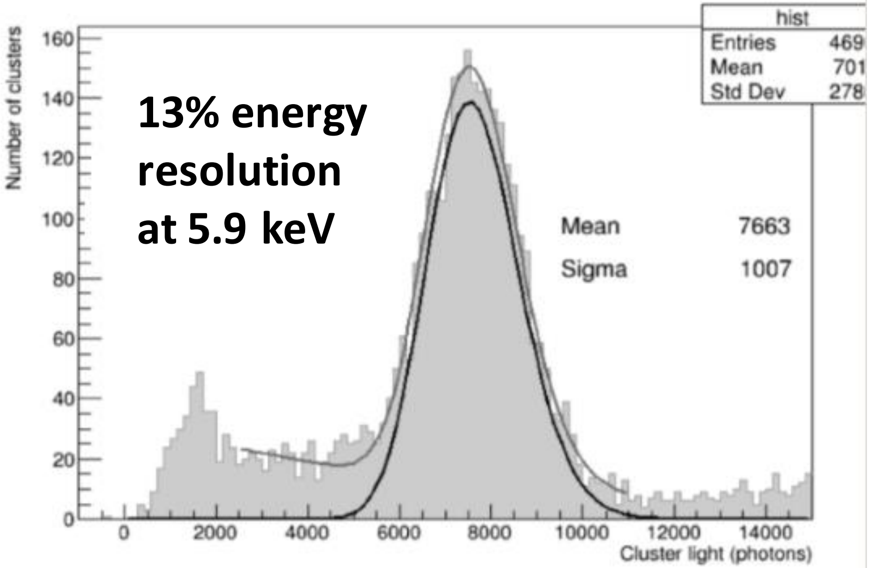




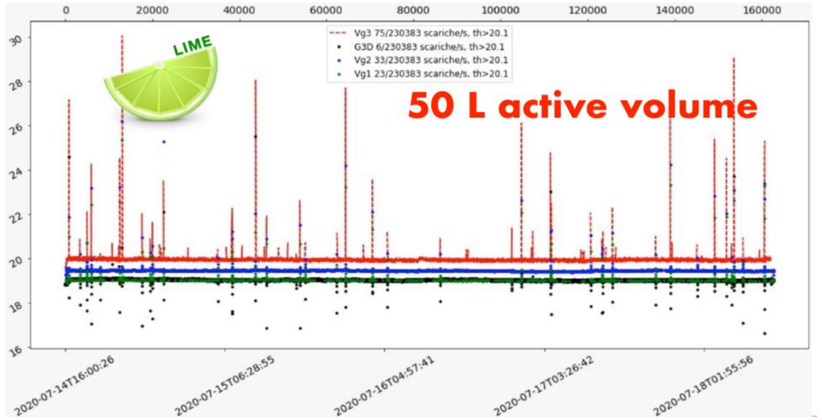
PMT (×4)

sCMOS camera ORCA fusion

- 50 liters sensitive volume
- He:CF_4 60/40 atm.pressure
- Triple GEM amplification
- 33x33 cm^2 readout area, 50cm drift
- 1sCMOS camera + 4 PMT



Stability over 1 month



- Already commisioned at LNF
- Tested operation stability,
- Energy resolution at 13% at 5.9keV (^{55}Fe) throughout the volume

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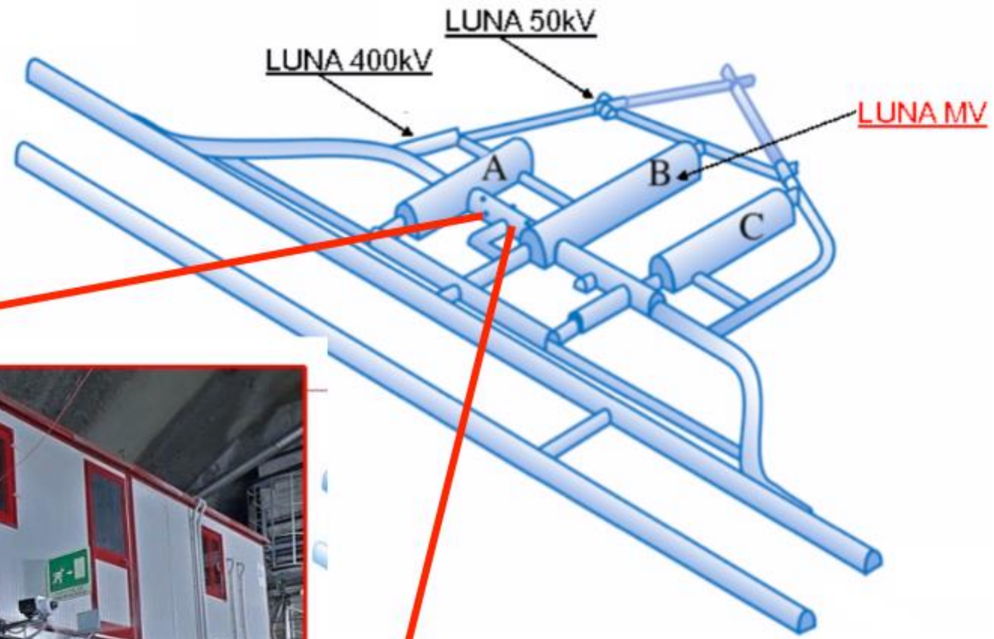
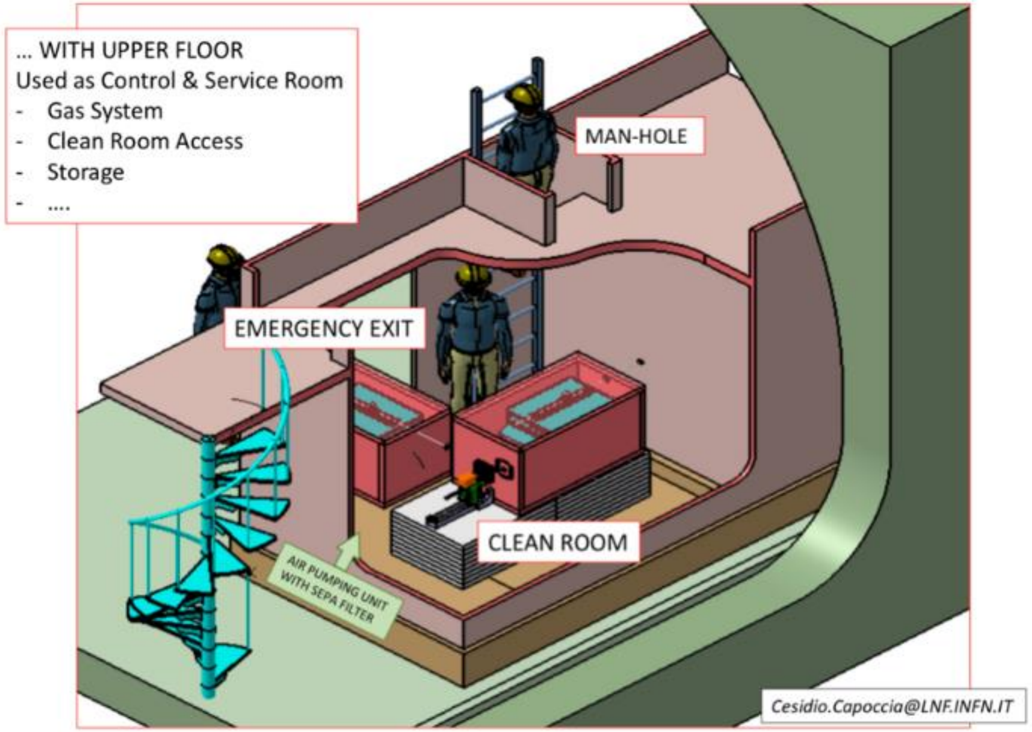
The LIME prototype



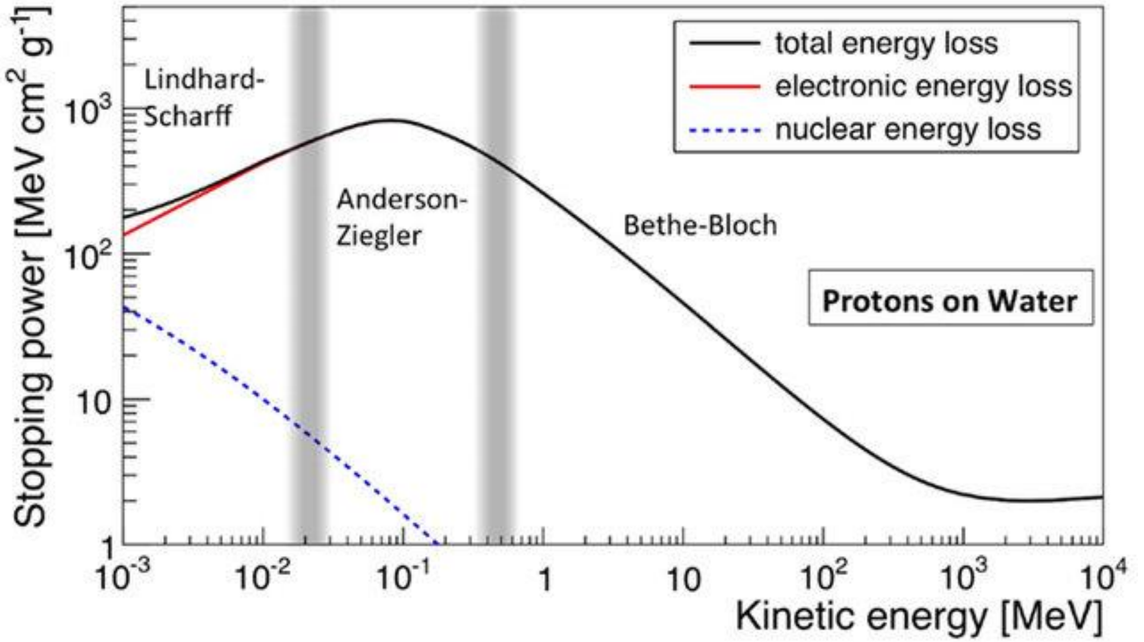


Installation underground at LNGS is foreseen by the end of November

Nuclear recoils:
tracks simulation and analysis

Low energy NR ionization

- 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



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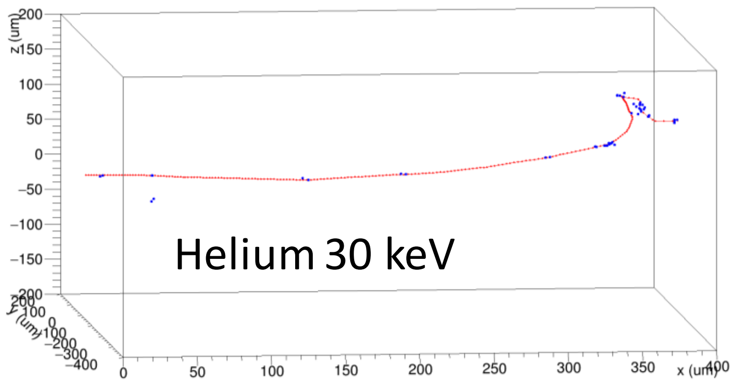

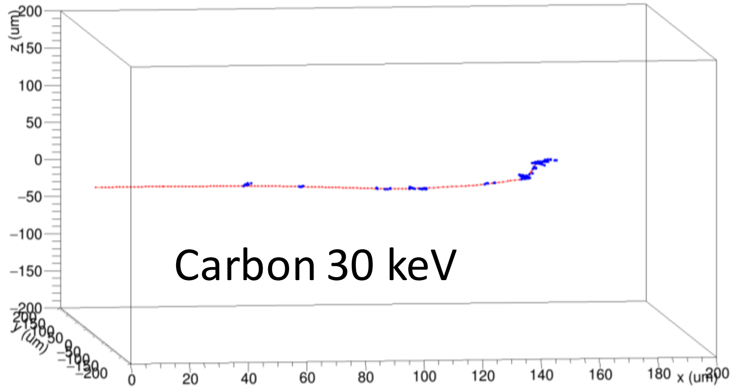

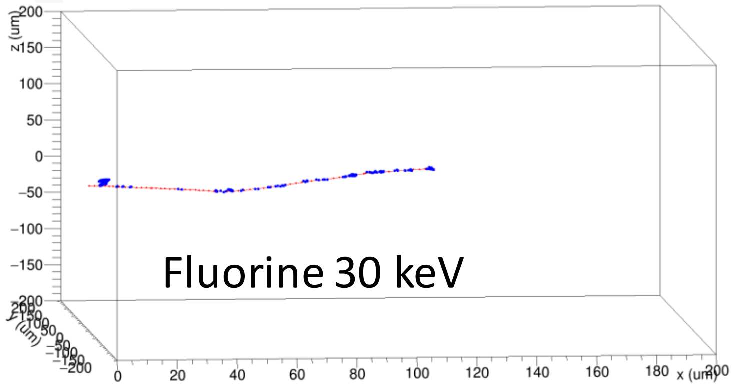

SRIM simulations

- **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

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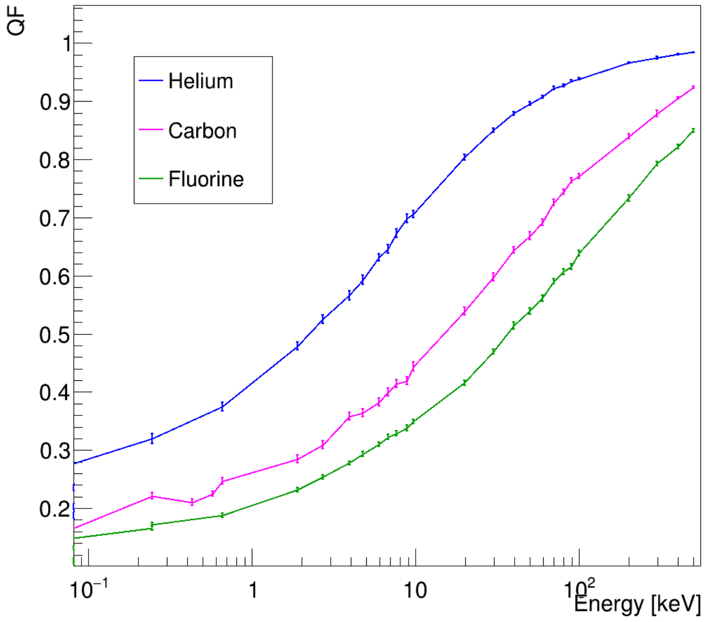
G S S I

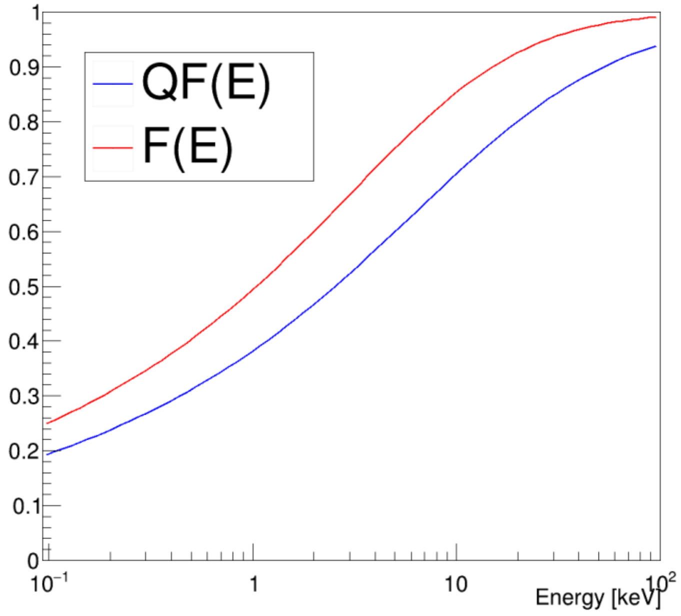
Quenching factor

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

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

The QF is a *global* feature of the track; but the ionization energy losses of the ion changes while it loses energy





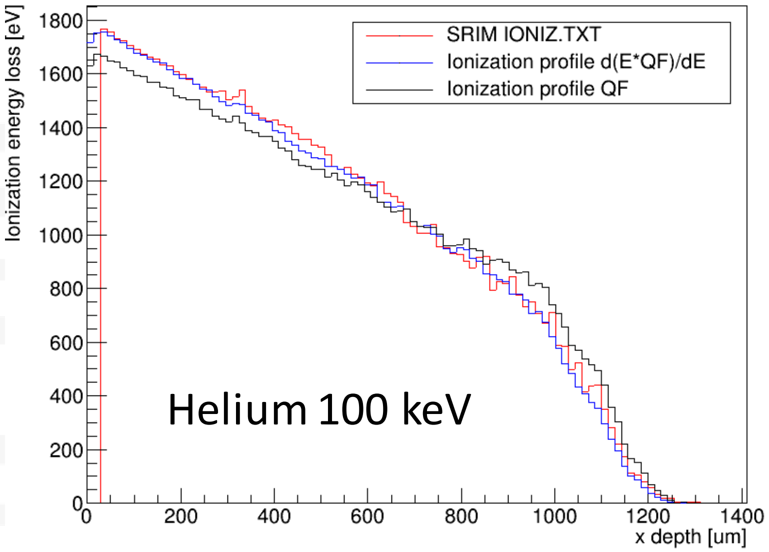
A single ionization energy deposit is

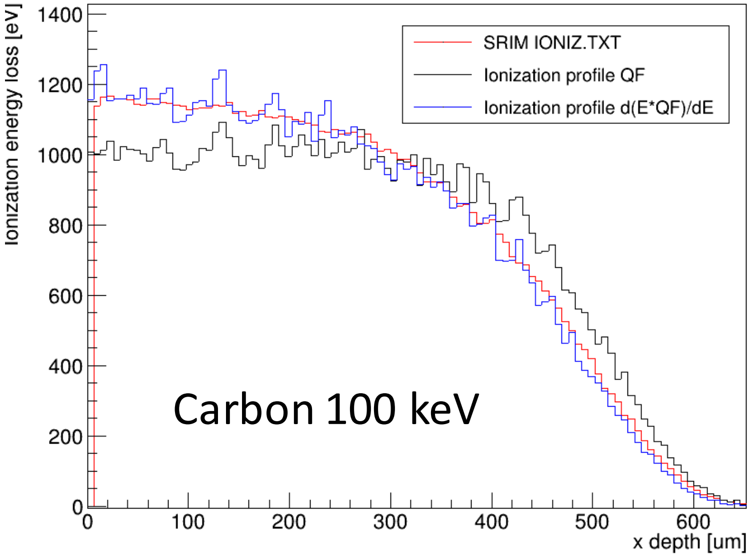
$$dE_{ionization} = \frac{d(E \times QF(E))}{dE} dE = F(E)dE$$

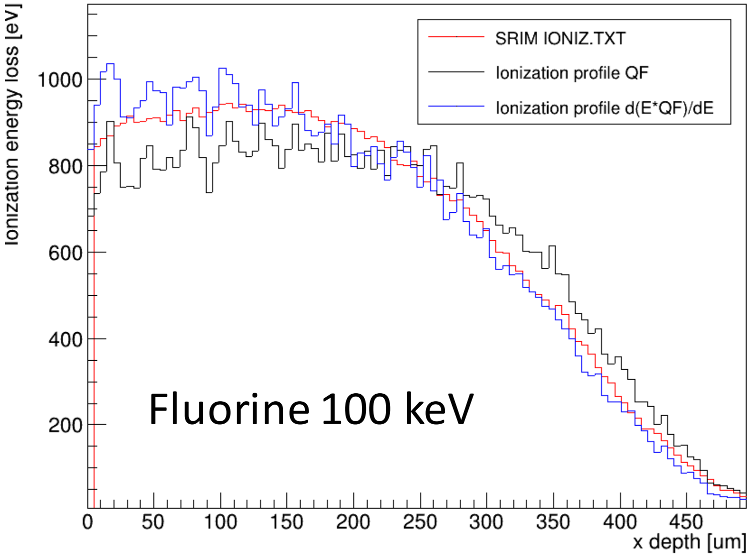
In each point in 3D space total energy deposit is **converted to ionization energy** through the F function

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)







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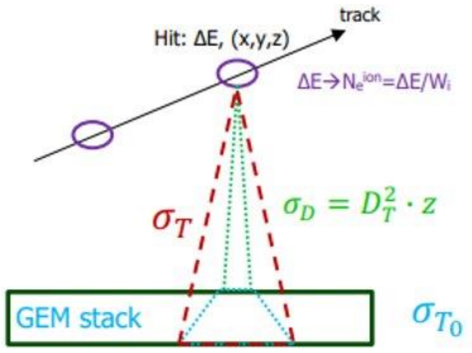
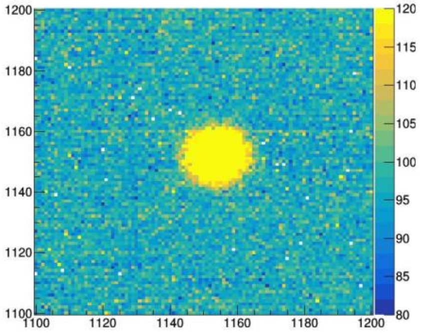
Simulation of images

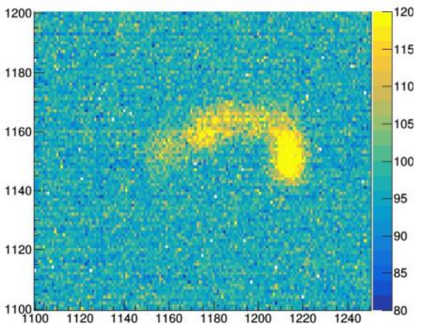
- The 3D ionization profile is the starting point to produce **simulated images** as seen from the sCMOS camera
- Ionization energy deposit → n° electrons (w-value) → multiplication in GEM avalanche → n° photons
- Positions of light determined by diffusion in drift region and GEM stack
- Light in the image depending of geometrical factors (dimension of detector and camera sensor)
- Sensor noise is added
- I produced a sample based on LIME parameters, I reconstructed the tracks with clustering algorithm* (GAC), and I analysed the results



He recoil 30 keV



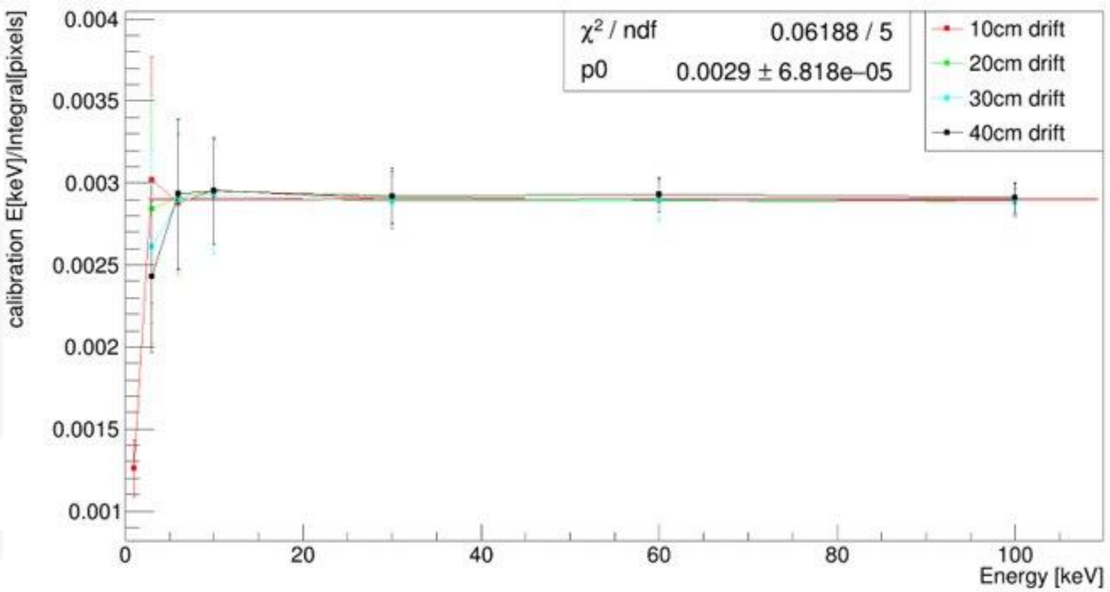
electron recoil 30 keV



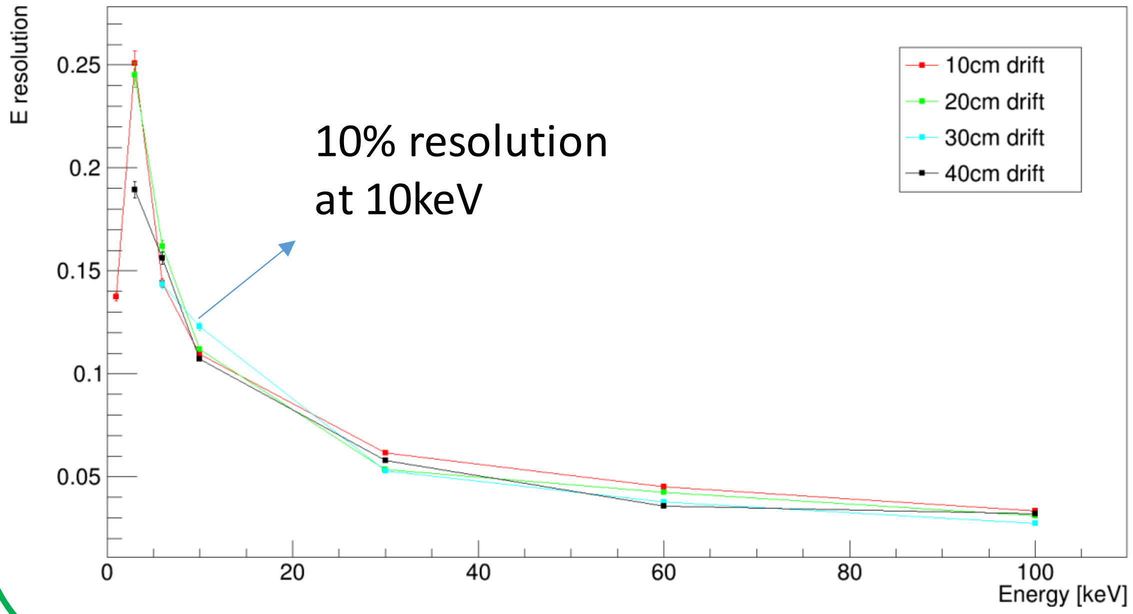
*E. Baracchini et al 2020 JINST 15 T12003

NR track analysis

Energy calibration: ratio between (visible) energy and track integral



Energy resolution: ratio between standard deviation and mean of the integral distribution



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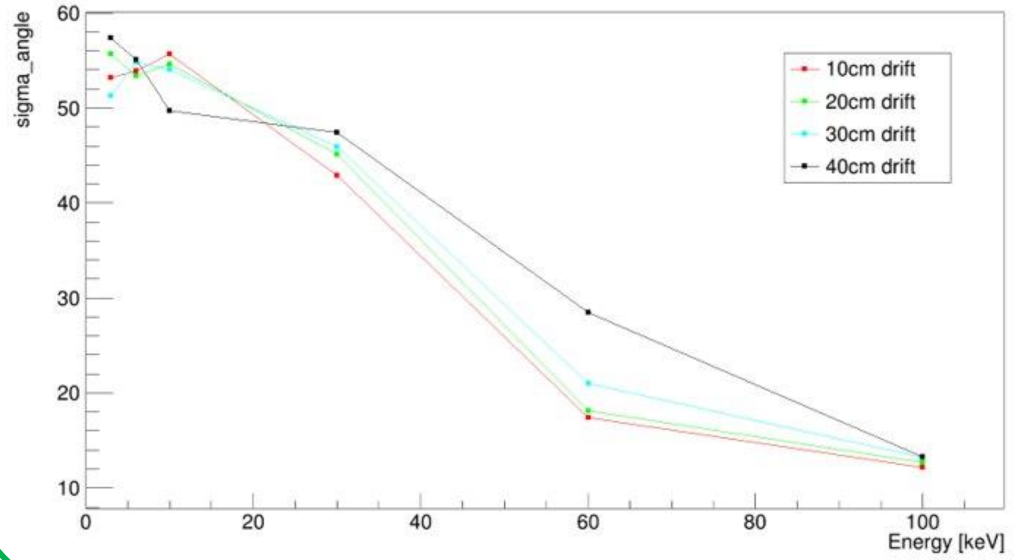
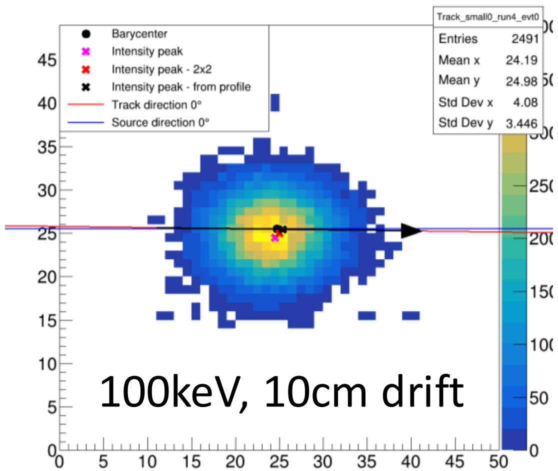
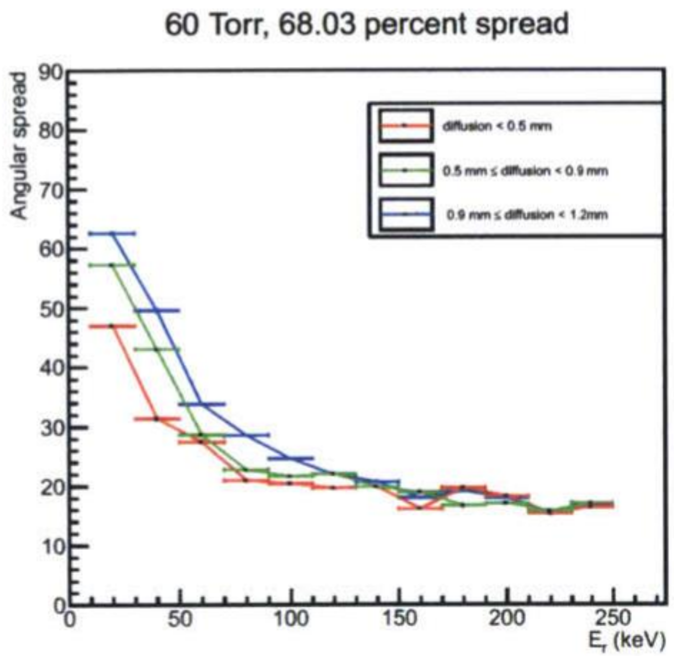
NR track analysis

Track direction: as a *preliminary* approach, it is the inclination of the line which maximizes the variance of the pixel distribution, weighted with their intensity. Further studies are needed





- DMTPC angular resolution:
  - Diffusion between 0.5 and 1.2 mm
  - F recoils (SRIM)

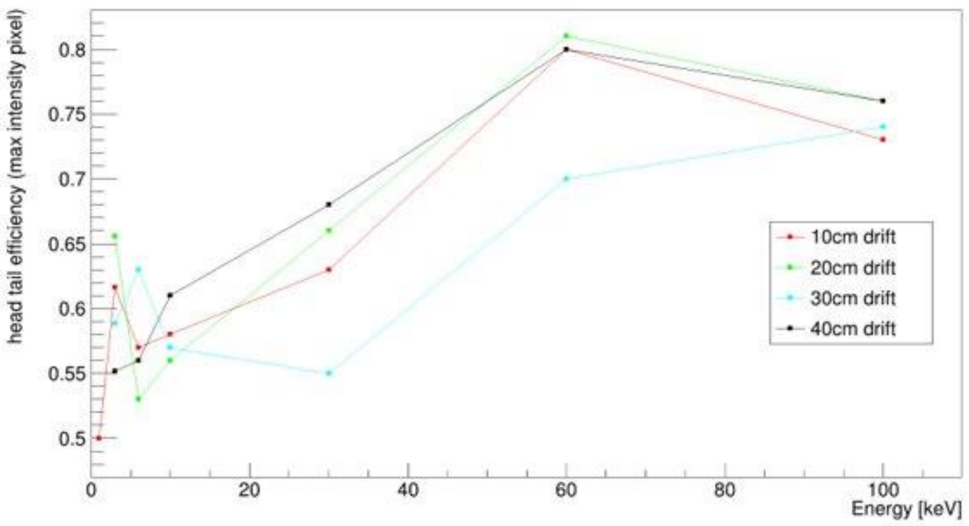


C.Deaconu, PhD Thesis, MIT (2009)

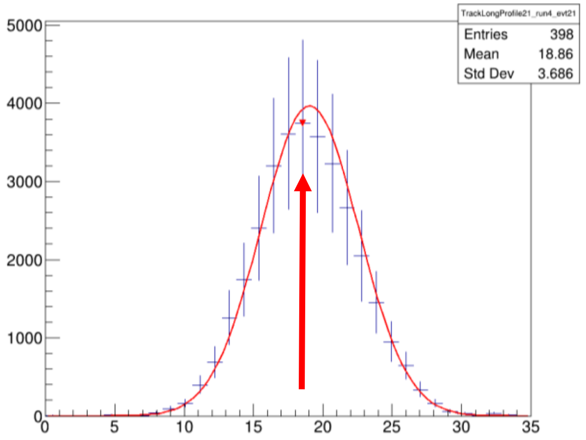
NR track analysis

Track sense: from head-tail effect identification.

- Asymmetry of the track (light integral difference in the two halves of the track)
- Relative position of intensity peak with respect to centre
  - Max intensity (macro)pixel / peak found in profile

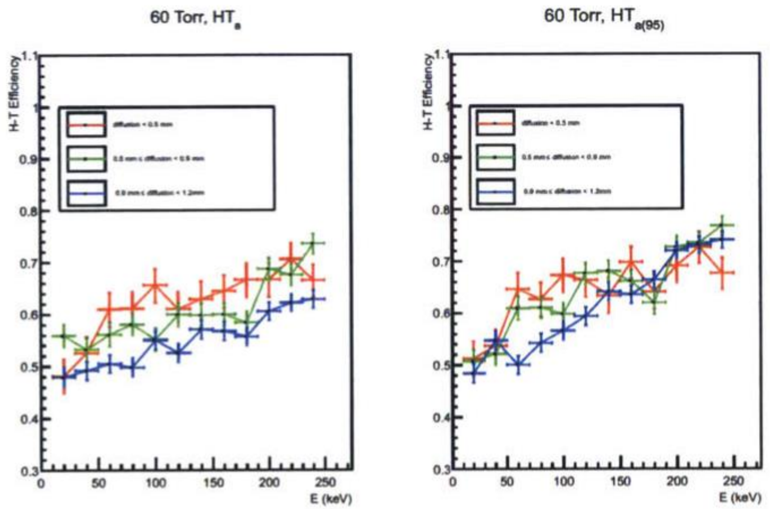


HT efficiency: percentage of tracks with direction correctly assigned to the range (–90°, 90°)



100keV, 10cm drift
Longitudinal profile

- DMTPC results:
  - Diffusion between 0.5 and 1.2 mm
  - F recoils (SRIM)



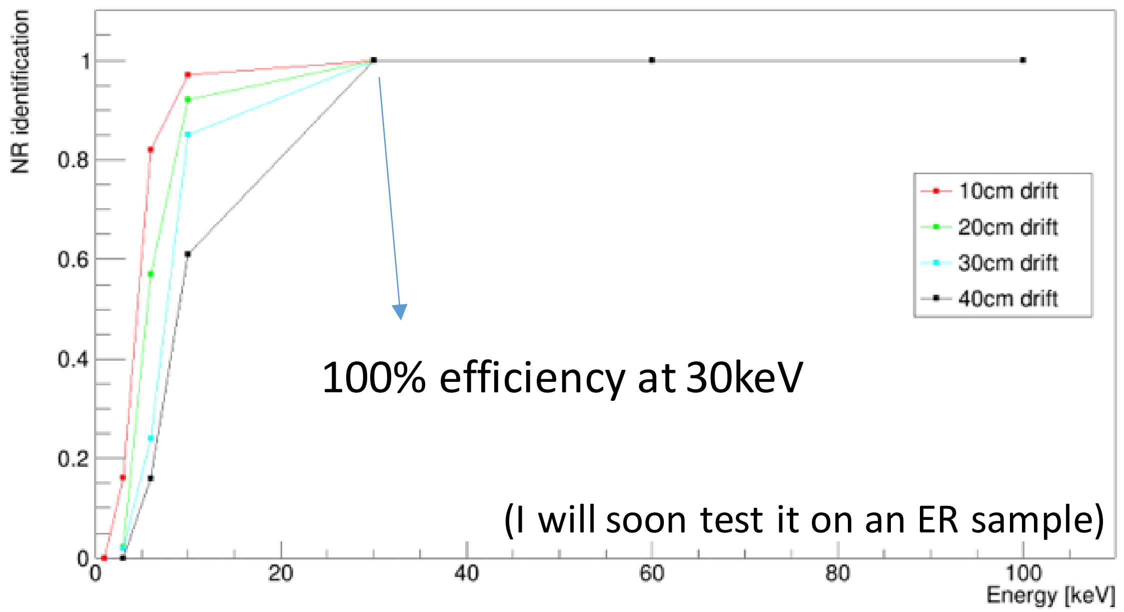
HT efficiency: percentage of tracks with more *electrons* in first half

C.Deaconu, PhD Thesis, MIT (2009)

NR track analysis

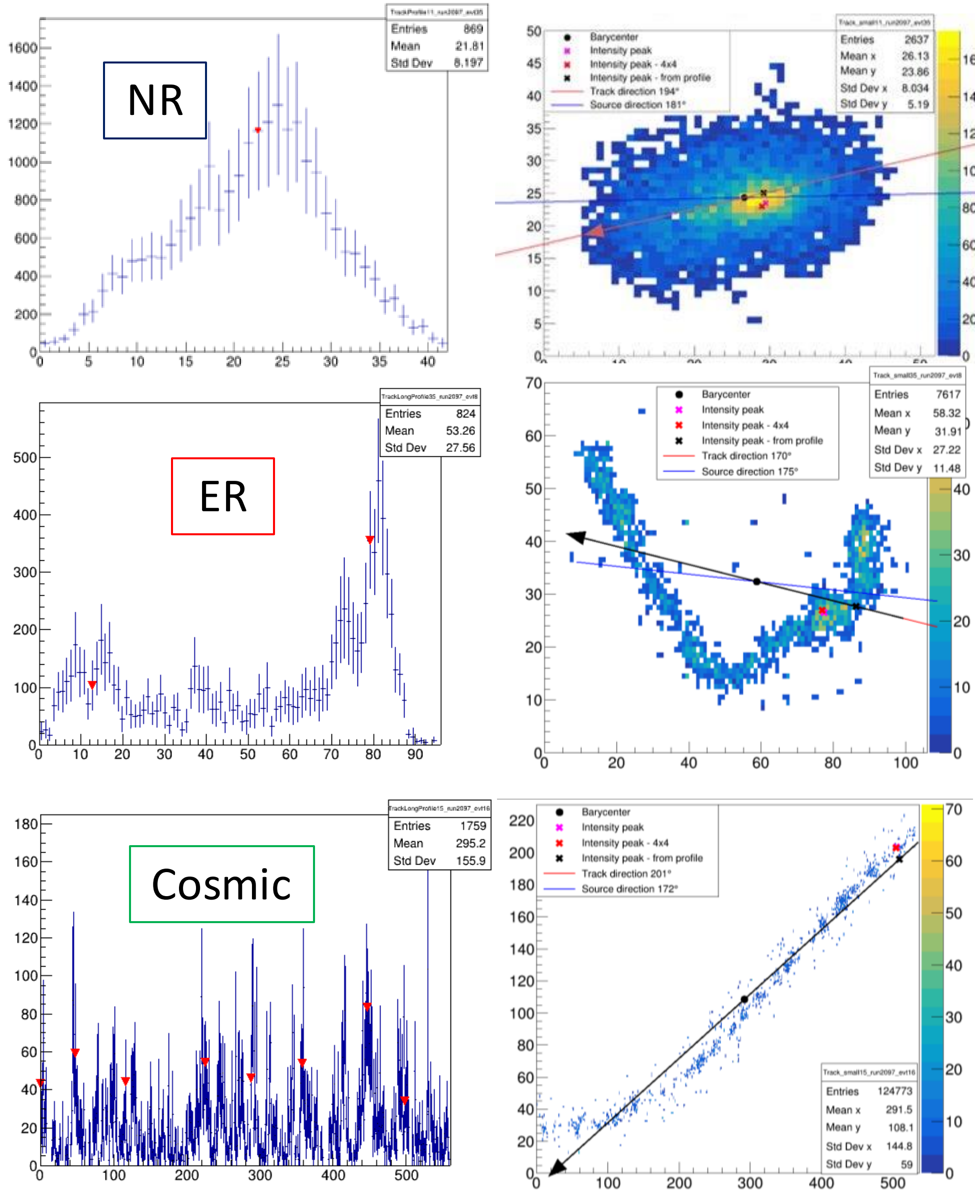
Tested on data taken with
AmBe neutron source with LEMON*:

NR identification: the number of peaks found in the profile could be used as a ER/NR discriminating variable
(in addition to Atul's work on ML)



100% efficiency at 30keV

(I will soon test it on an ER sample)



*E. Baracchiniet al., Meas. Sci. Technol. 32 025902 (2021)

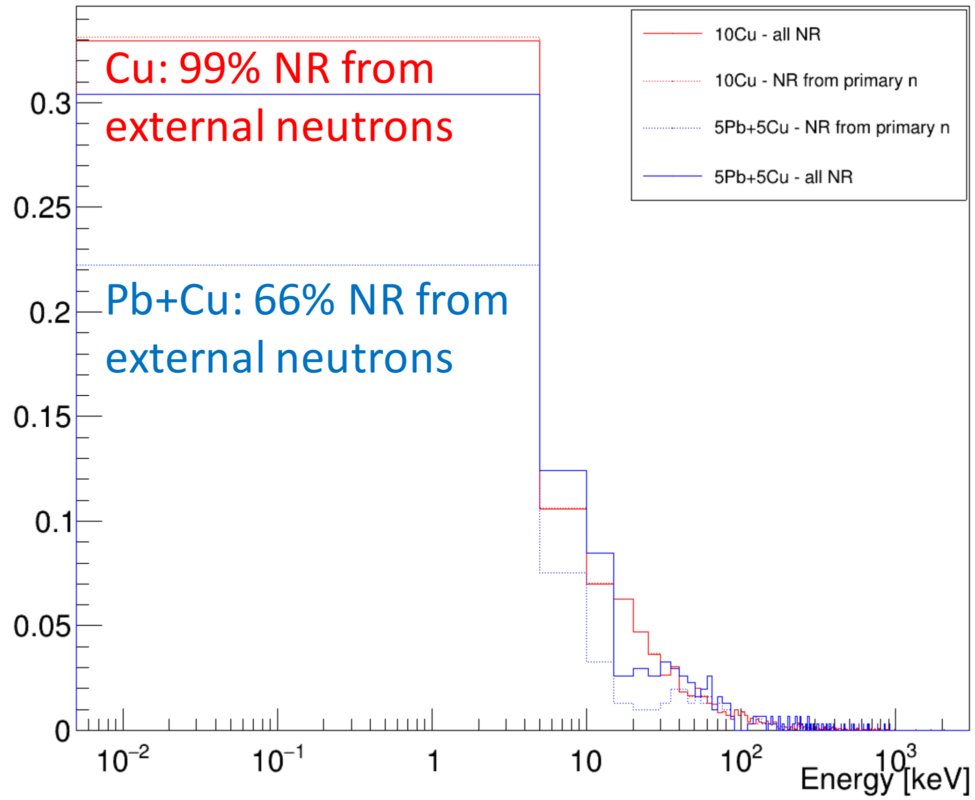
LIME background study for underground operation

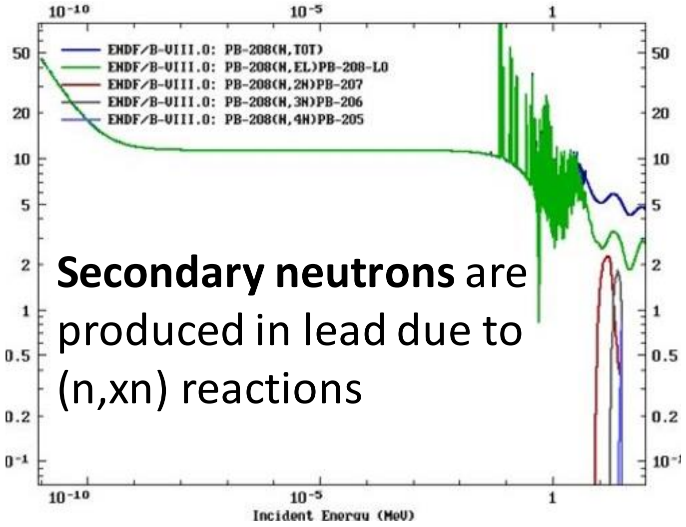
LIME background simulation

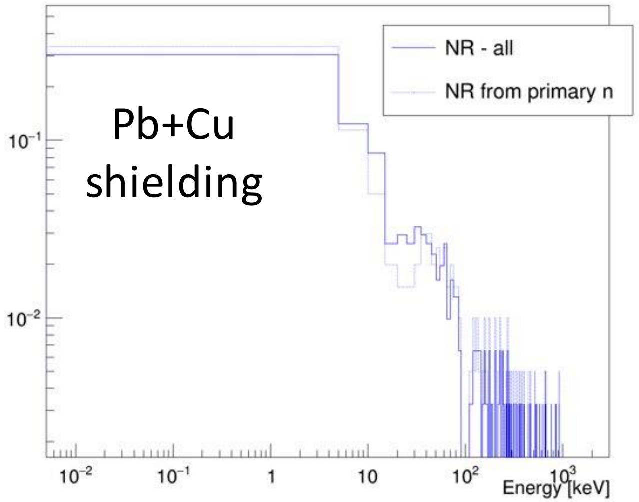
- **Background simulation** is fundamental for optimizing the shielding, choice of building materials, development and optimization of data analysis, DAQ set up, estimation of the duration of the data taking, study of the sensitivity reach...
- I simulated with GEANT4 the two background components:
  - Induced by **natural gamma and neutron fluxes** at LNGS
  - Induced by **radioactivity of materials**
- LIME will operate through 3 phases:
  - <u>1° phase</u>: external gamma background characterization
  - <u>2° phase</u>: neutron flux measurement
  - <u>3° phase</u>: MC validation and internal background characterization
- I optimized the shielding configurations for the 3 phases given the available space underground

Shielding optimization

I compared the performance of the use of **copper** or a combination of **copper and lead** as a gamma shielding







- NR from secondary neutrons don't show any characteristic behaviour in the energy or angular distribution

→ Impossible to disentangle the external neutron contribution

- <u>Copper was chosen as the shielding best option</u>

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External background simulation

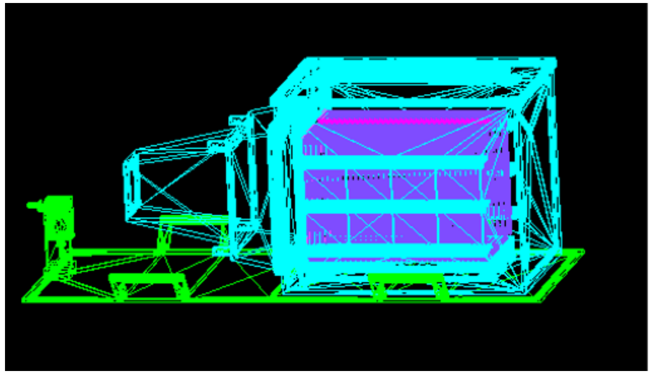
		Total NR	NR [0-20 keV]	Total ER	ER [0-20 keV]
1° phase	NO shield	**1810 NR/yr**	690 NR/yr	**1.15×10^{9} ER/yr**	4.27×10^{8} ER/yr
1° phase	5cm copper	**1570 NR/yr**	830 NR/yr	**6.21×10^{7} ER/yr**	1.89×10^{7} ER/yr
2° phase	10cm copper	**1090 NR/yr**	620 NR/yr	**4.81×10^{6} ER/yr**	9.5×10^{5} ER/yr
2° phase	5cm lead 5cm copper	**1180 NR/yr**	634 NR/yr	**1.30×10^{6} ER/yr**	2.43×10^{5} ER/yr
3° phase	40cm water 10cm copper	**2 NR/yr**	1 NR/yr	**5.13×10^{5} ER/yr**	1.11×10^{5} ER/yr

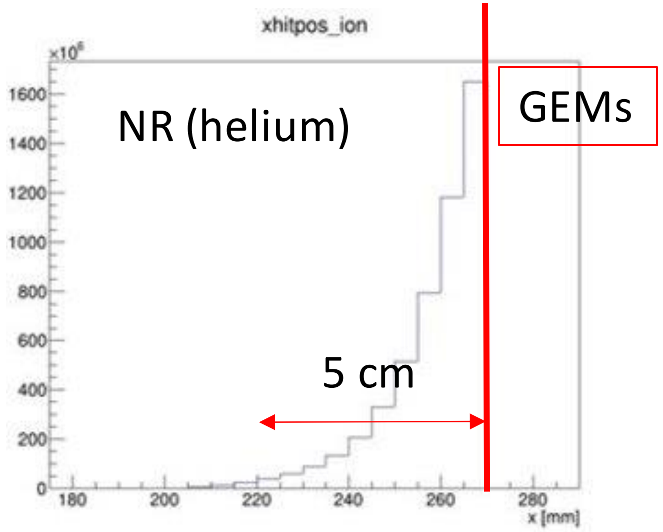
Internal background simulation

- Background simulation from radioactivity of the detector's components is ongoing - from preliminary results, the rate is O(10^5 events/yr)
- The only NR background comes from the GEMs – could be excluded by fiducialization
- Activity measured at LNGS by M.Laubestein (copper rings and resistors are being measured)

Component	^{238}U (^{234m}Pa)	^{238}U (^{226}Ra)	^{235}U	^{232}Th (^{228}Ra)	^{232}Th (^{228}Th)	^{40}K
Camera body [Bq/pc]	7	1.8	0.4	2.1	2.1	1.9
Camera lens [Bq/pc]	0.9	0.41	0.031	0.08	0.08	11
GEM foil [Bq/m^2]	< 0.104	0.004	< 0.002	< 0.004	< 0.002	< 0.045
Acrylic [Bq/kg]		0.003		0.005	0.004	0.035

- Single components of a broken BMI express sCMOS camera were measured, primary contribution from sensor and electronic board
  - We could use a custom non-radioactive sensor
  - Electronic board can be moved away from the detector





Spectrum deconvolution

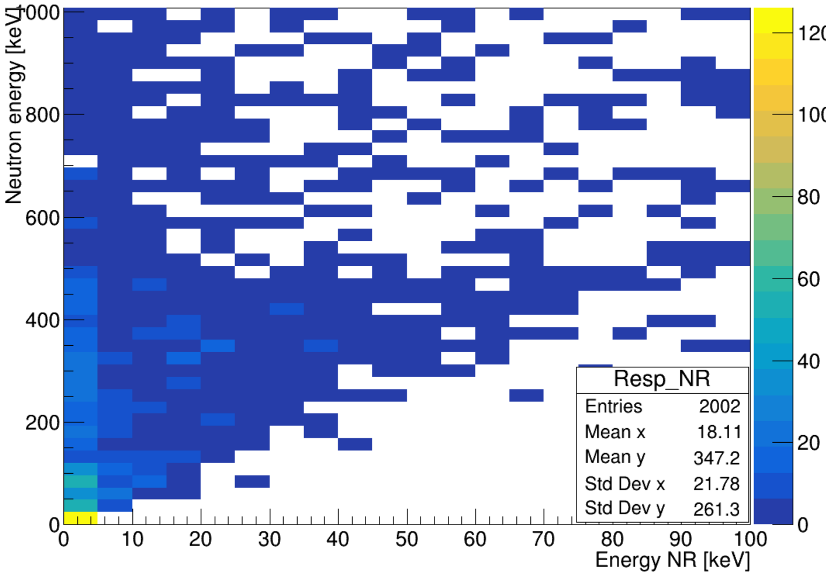
The measured NR spectrum will be the result of the convolution of the neutron spectrum with the detector response

$$N(E_{NR}) = \int R(E_{NR}, E_n)\Phi(E_n)dE_n$$

NR spectrum (measured)

Detector response (from MC simulations)

Neutron spectrum (true distribution)



I'm starting to study an iterative unfolding method based on the bayesian approach

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Future perspective and conclusions

Future perspectives

- **Analysis of simulated NR** will be improved and further developed with a larger and realistic sample
- **Comparison of simulated and measured tracks** will be done to validate the MC simulation and analysis
- A full simulation of the **internal background** will allow the optimization of LIME underground data taking and final choice of materials

- I will continue the R&D work on the MANGO prototype at overground LNGS – I will study the use of **^{3}He for thermal neutron detection**
- I will study the **unfolding method** to retrieve the neutron spectrum
- By the end on 2021 LIME will be installed and commissioned underground, next year the **data taking will start**

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Conferences/workshops:

- I presented a talk in the Early Career Plenary in CPAD Instrumentation Frontier Workshop 2021, online, 18/03/21 - 22/03/21. https://indico.fnal.gov/event/46746/contributions/210387/

Scientific publications:

- Directional Dark Matter Searches with CYGNO, CYGNO Collaboration, Particles 2021, 4,343-353. https://doi.org/10.3390/particles4030029

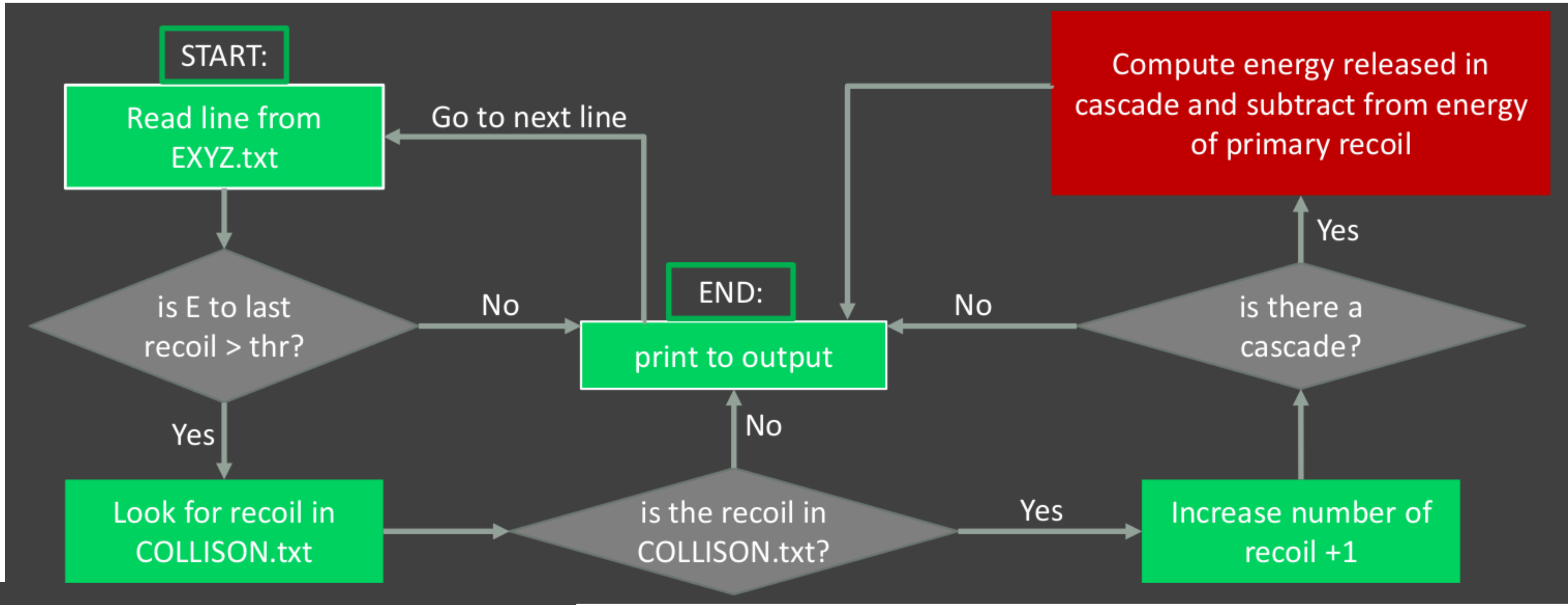
List of attended schools and courses:

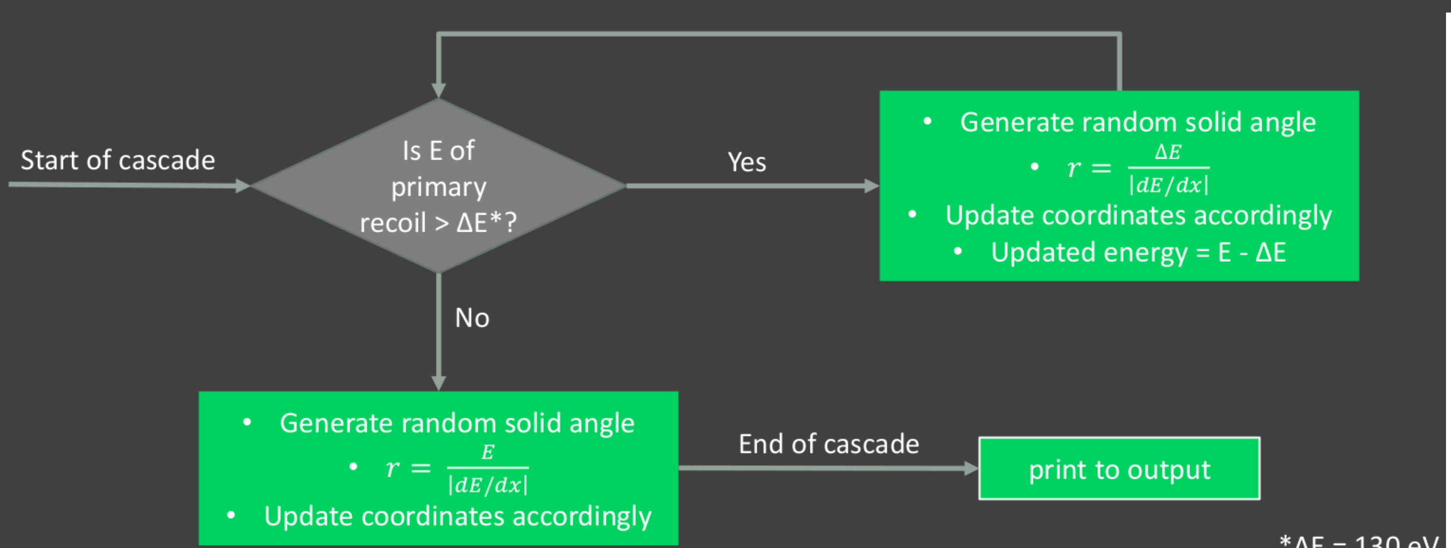
- INFN SOUP 2021 International School on Underground Physics, online, 28/06/21 - 02/07/21
- QSFP 2021 International School on Quantum Sensors for Fundamental Physics, online,06/09/21 - 17/09/21
- GSSI interdisciplinary course: Probabilistic reasoning in inference, forecasting and decision making, G. D'Agostini, 07/06/21 - 09/06/21, 14/06/21 and 16/06/21

backup

SRIM ionization profile

EXYZ = 3D energy deposition
COLLISON = info on when a cascade occurs





*ΔE = 130 eV

How the cascade is computed

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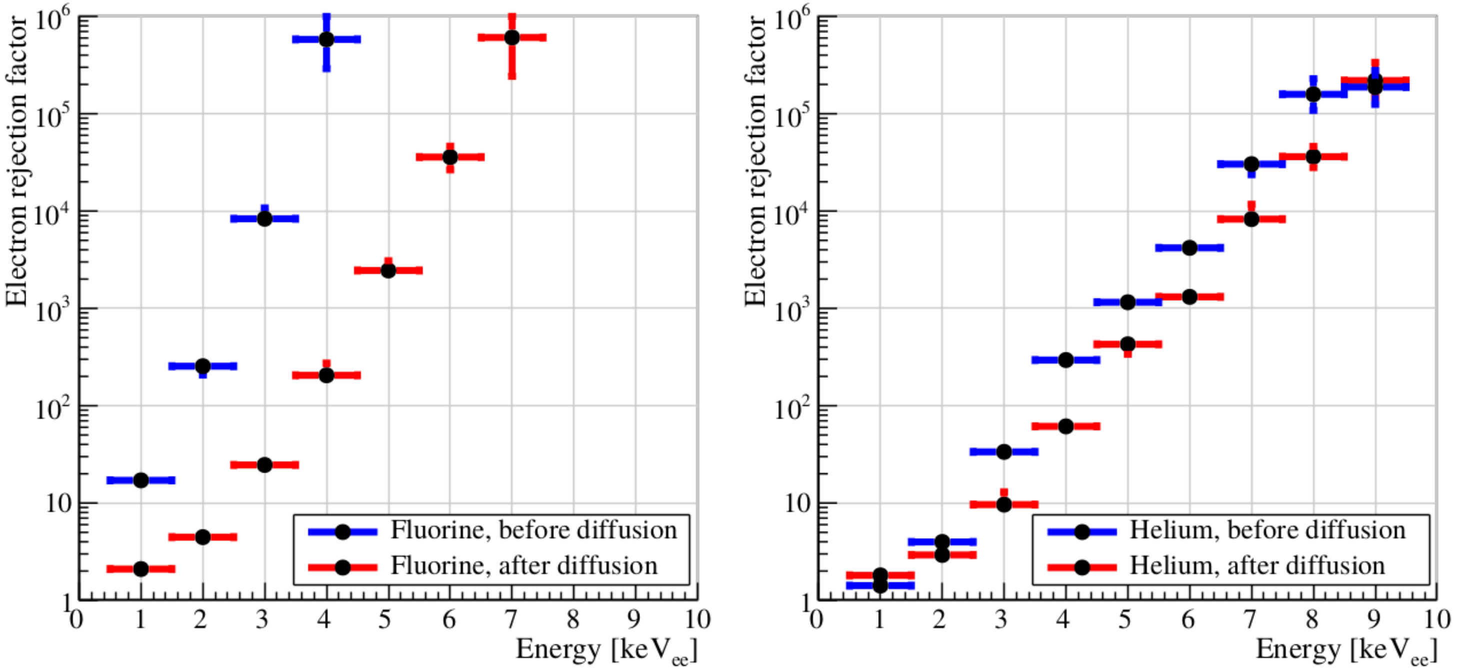
GSSI

ER rejection factor

- Simulation for 755:5 Torr of He:SF_6 – CYGNUS collaboration https://arxiv.org/abs/2008.12587
- R = expected electron recoil rejection factor based on track length selection, 50% efficiency for NR selection

$$R = N_{all}/N_{surv},$$

- If the rate is kept below 10^5 events/yr above 20keV, a zero background measurement is possible



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