Feasibility of solar neutrino measurement with the CYGNO/INITIUM experiment

Samuele Torelli on behalf of the CYGNO collaboration

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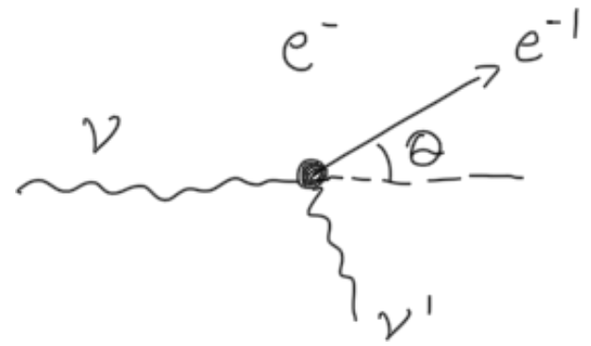
Magnificent CEvNS - 2023

Solar neutrino directional detection



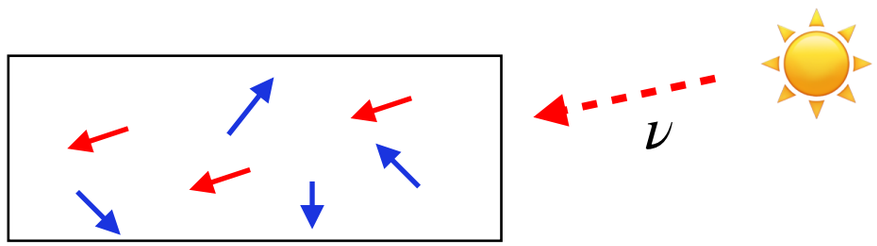
Neutrino from the Sun can be object of study with large TPC through $\nu - e^-$ elastic scattering as proposed in the '90:

Seguinot, Jacques & Ypsilantis, Thomas & Zichichi, Antonino. (1992). A high rate solar neutrino detector with energy determination.

In CYGNO gas mixture:
1 $ev/y/m^3$

Directional detection

Capability of discriminating signal from background from source direction

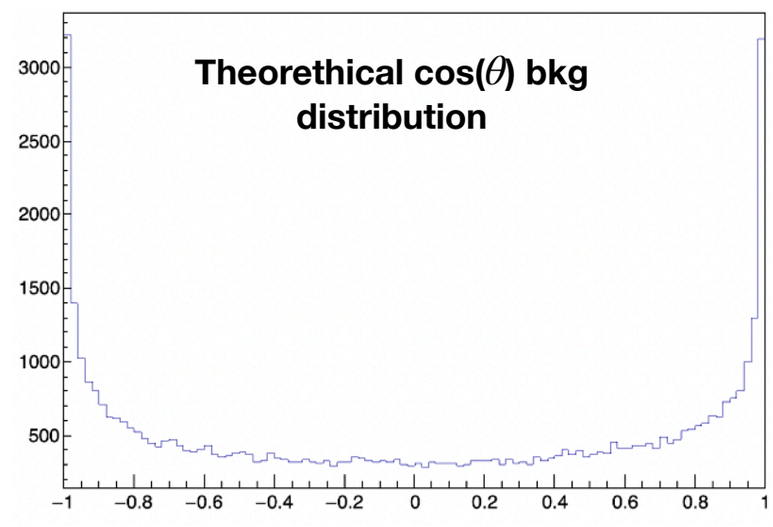


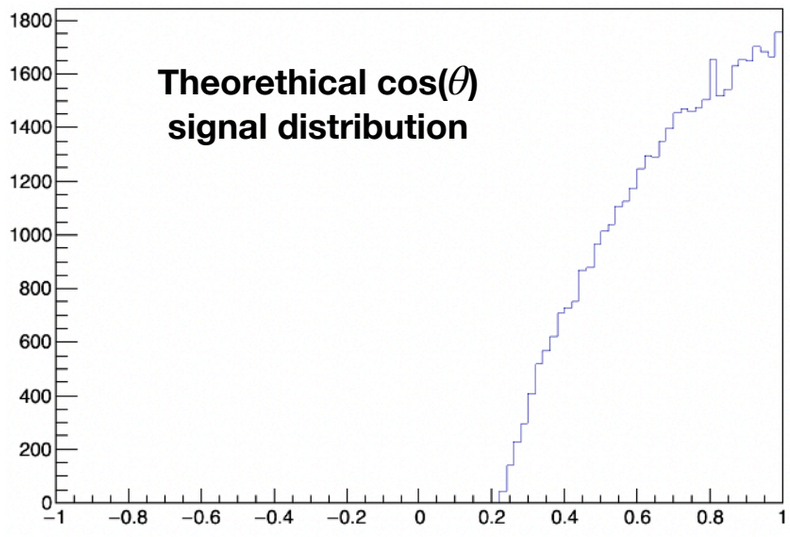
Possibility of event by event neutrino energy reconstruction (closed kinematic)

$$E_{\nu,Reco} = \frac{-m_e T_e - \sqrt{T_e^2 m_e^2 \cos(\theta)^2 + 2 T_e m_e^3 \cos(\theta)^2}}{(T_e - T_e \cos(\theta)^2 - 2 m_e \cos(\theta)^2)}$$

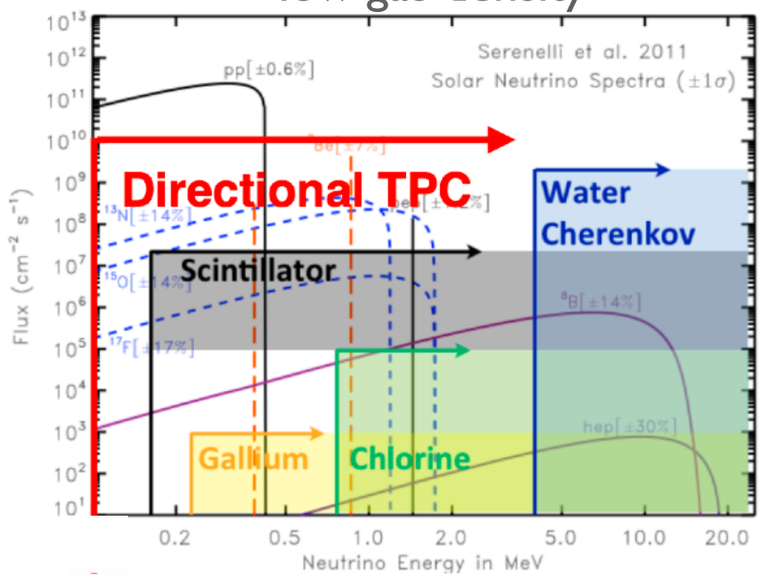
Much stronger signature than energy spectrum

Exponential Signal over exponential bkg	vs	Peaked distribution over flat bkg

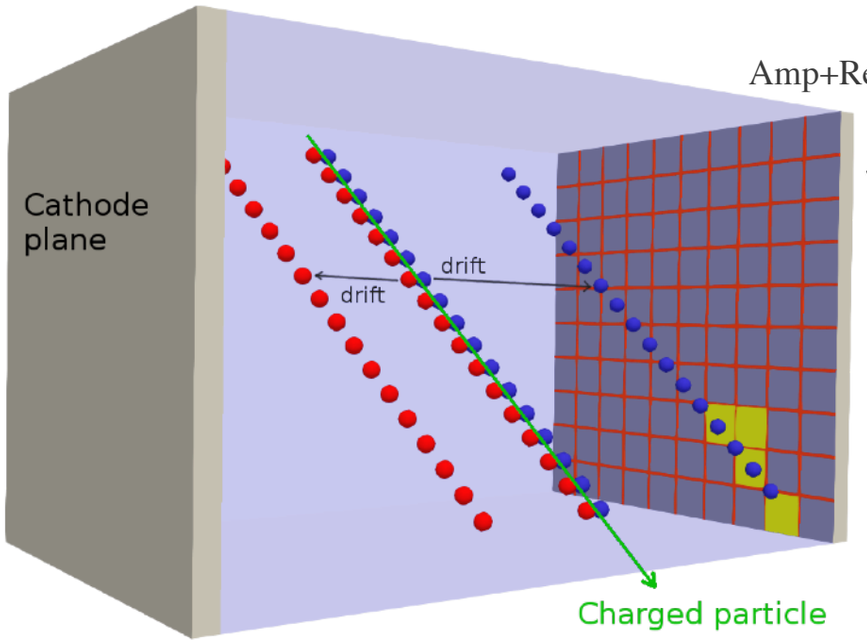




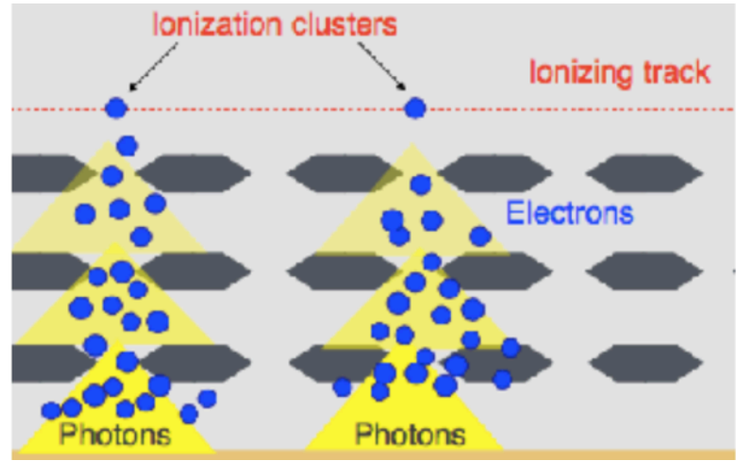
+ low gas density



The CYGNO technique



- Time projection chamber filled with He:CF_4 (60:40) at atmospheric pressure
- The trail of electrons produced in the TPC is transported to the readout
- Primary ionisation electrons are amplified by triple thin GEMs, where light is produced together with electron avalanches (0.07 photon/electron)
- Light is readout from a sCMOS and a PMT



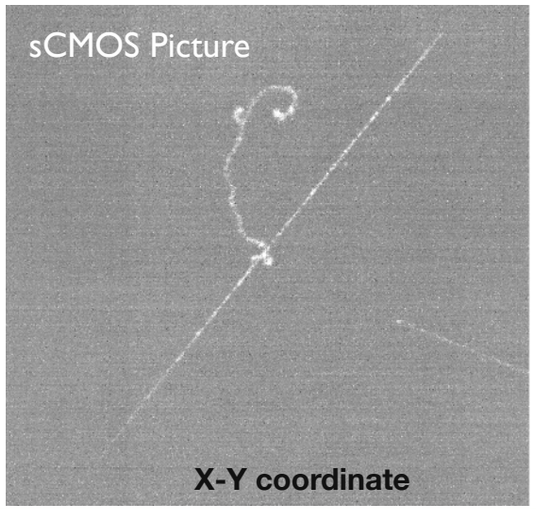
Triple GEM ampl. system

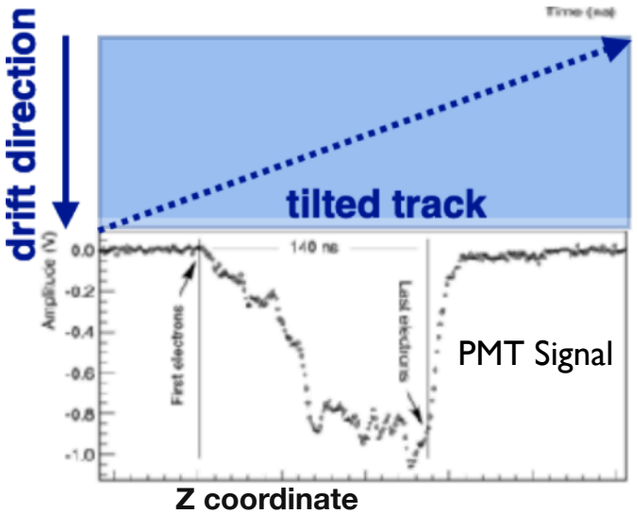
sCMOS camera

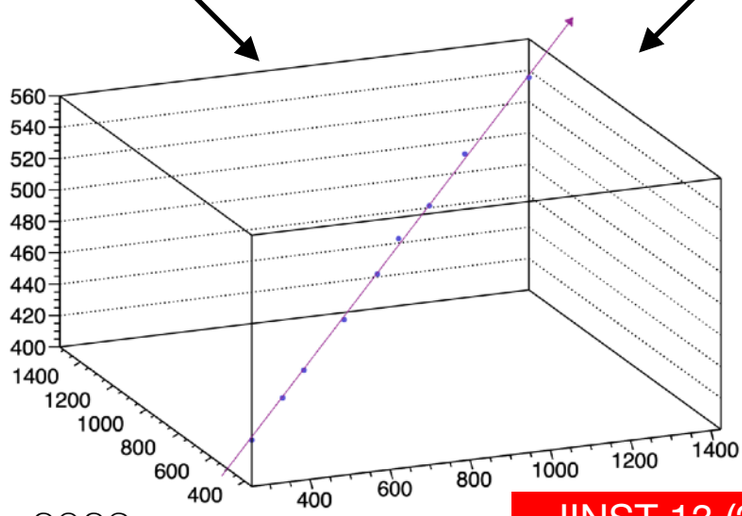
\+

PMT

Readout



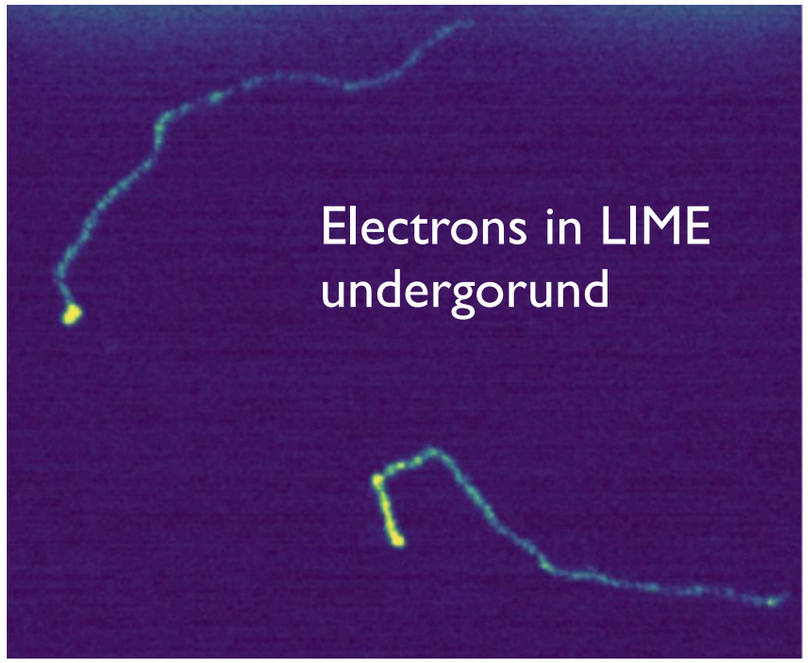


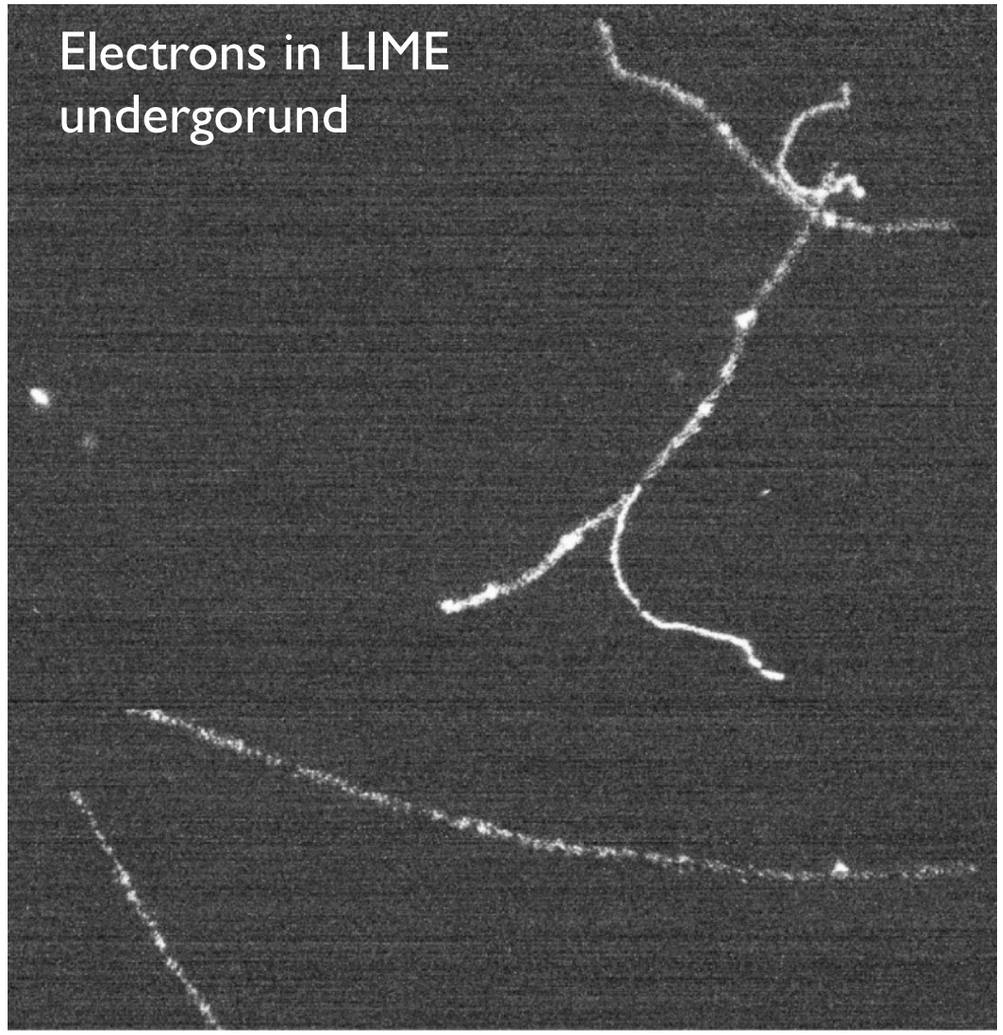


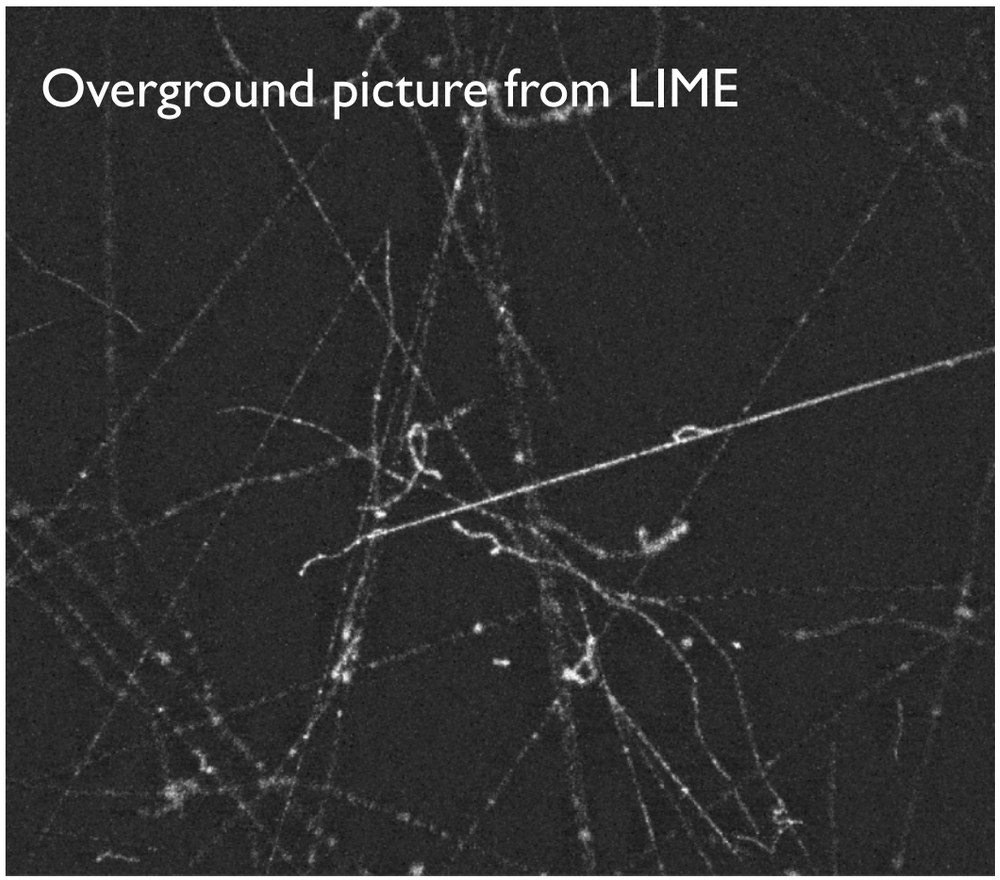
3D track reconstruction

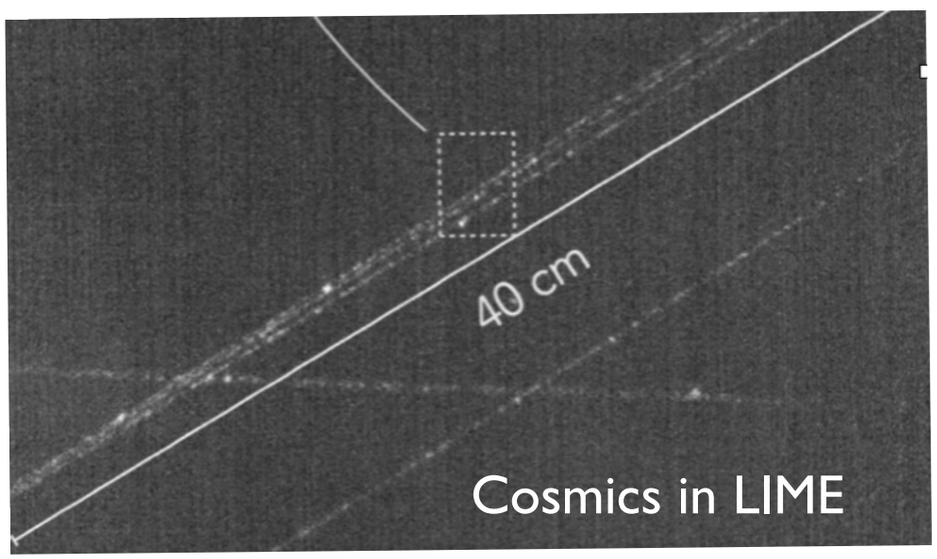
JINST 13 (2018) no.05, P05001

Particle tracks in CYGNO



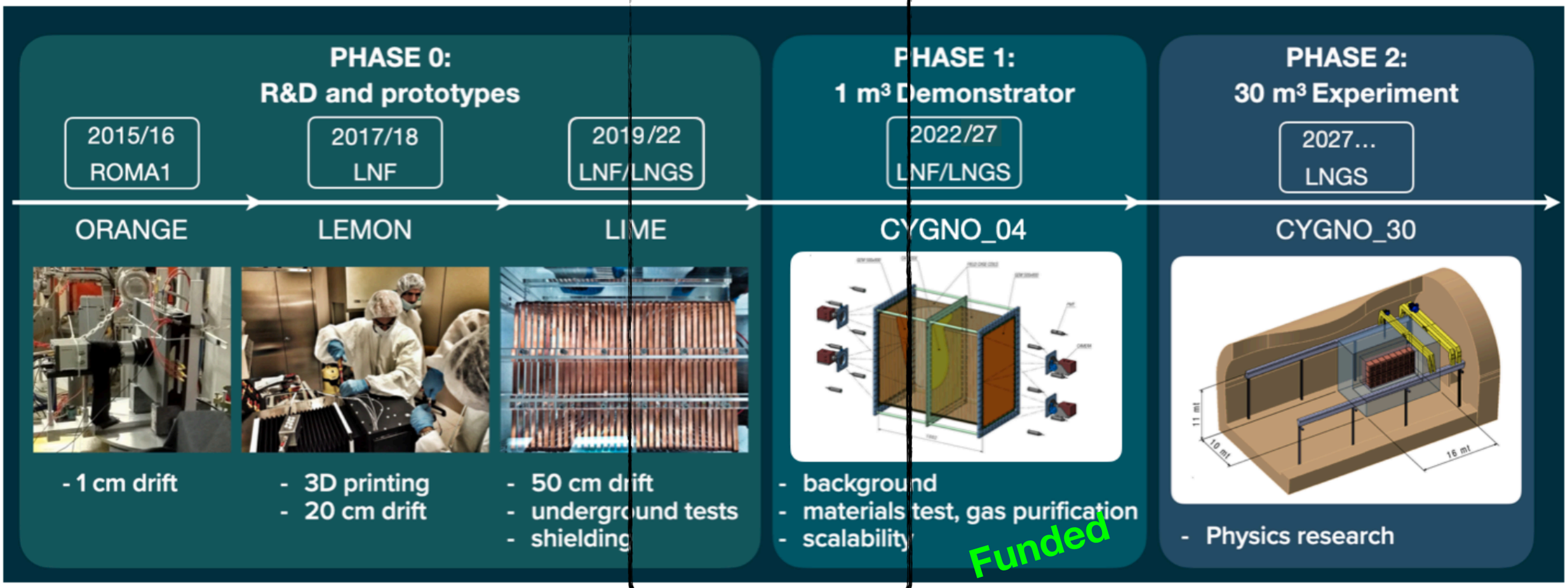






The CYGNO timeline

We are here



- Results in this presentations are from the LIME prototype
- CYGNO-04 will be employed to demonstrate the scalability
- CYGNO-30 used for physics research, composed by many CYGNO-04 modules

Multipurpose apparatus:
originally developed for DM searches

↓

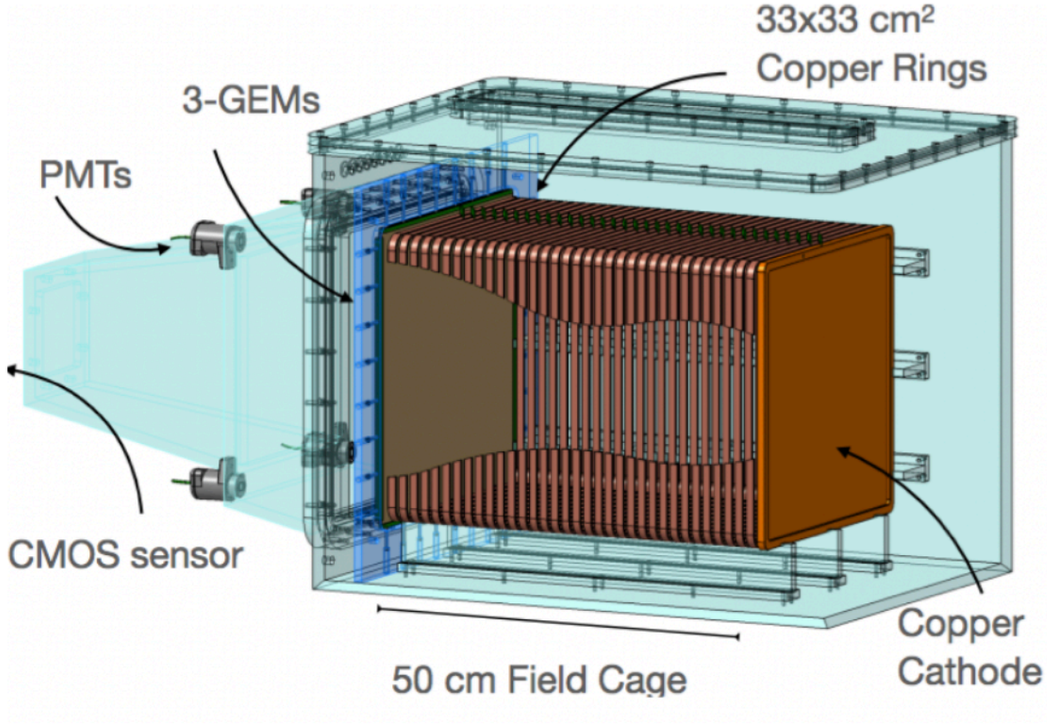
Can be employed for:
- Neutron flux measurement
- Solar neutrino

The LIME prototype: CYGNO Phase 0

- Directionality studies performed with LIME prototype
  - Basic module for larger detector

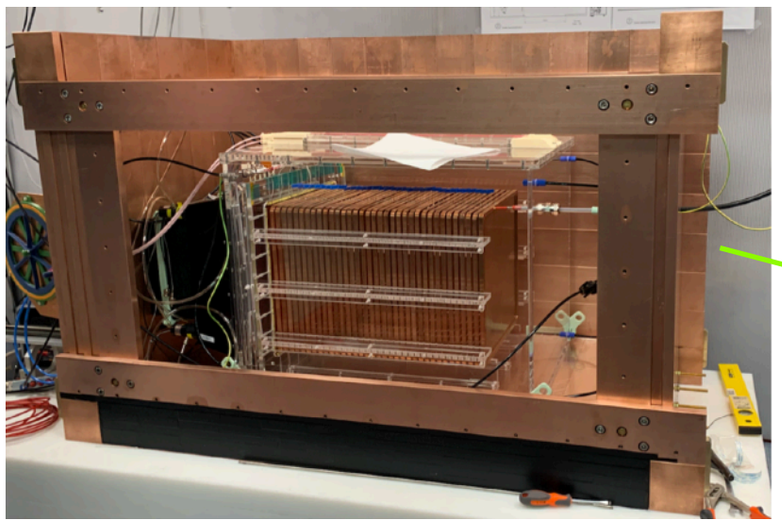
HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

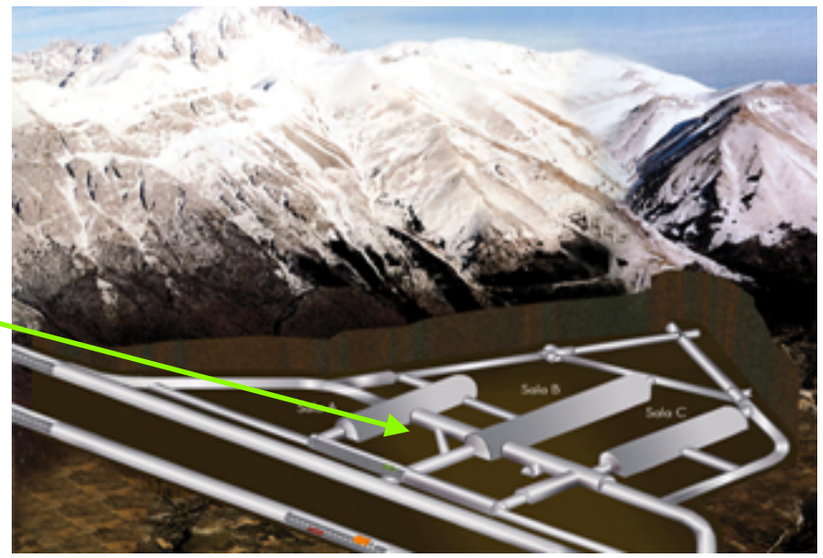
READOUT NOISE
0.7 electrons rms
Ultra-quiet Scan



- Last prototype developed:
  - 50 cm drift
  - 33 x 33 cm^2 GEMs
  - 50 litres sensitive volume (0.05 m^3)
  - 1 sCMOS camera (ORCA Fusion)
  - 4 PMTs

- Light response of 650 ph/keV
- Full detection efficiency in the whole 50 l
- <1 keV_{ee} threshold with the new camera





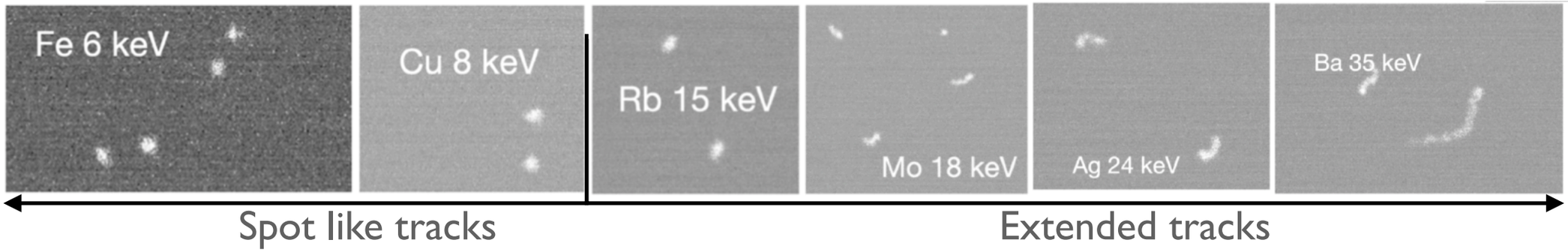
- LIME is currently taking data underground at LNGS

Amaro, F.D. et. al The CYGNO Experiment. Instruments 2022, 6, 6.

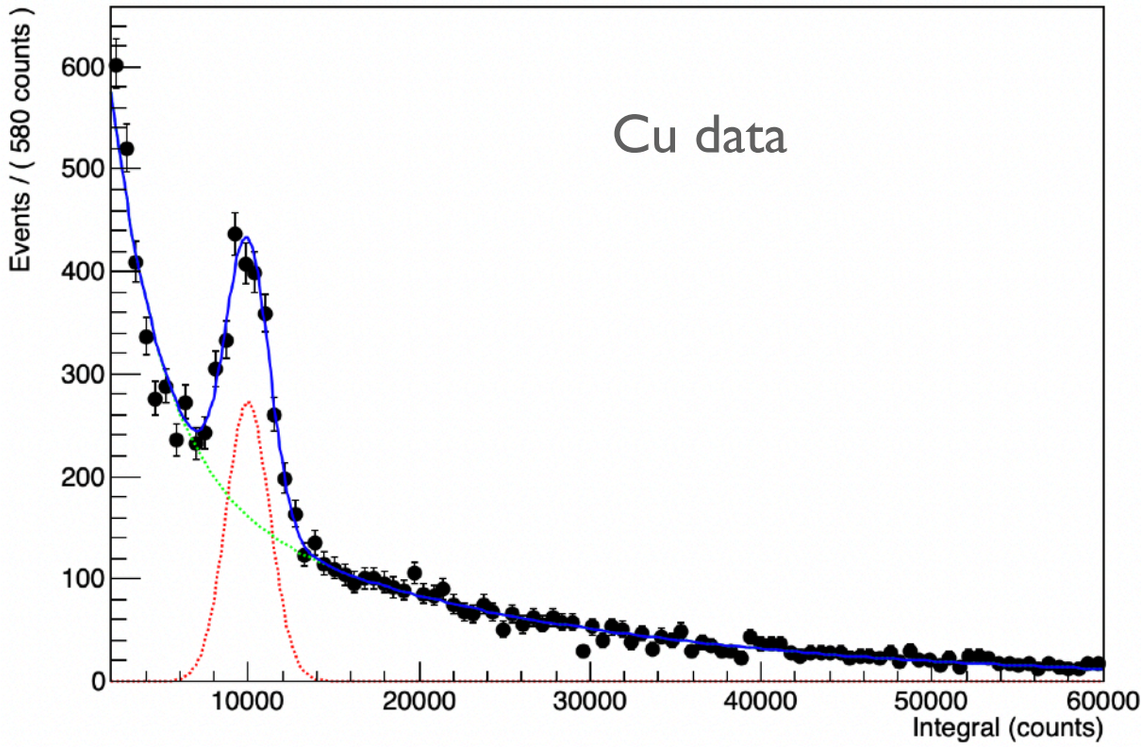
Energy response and resolution on data

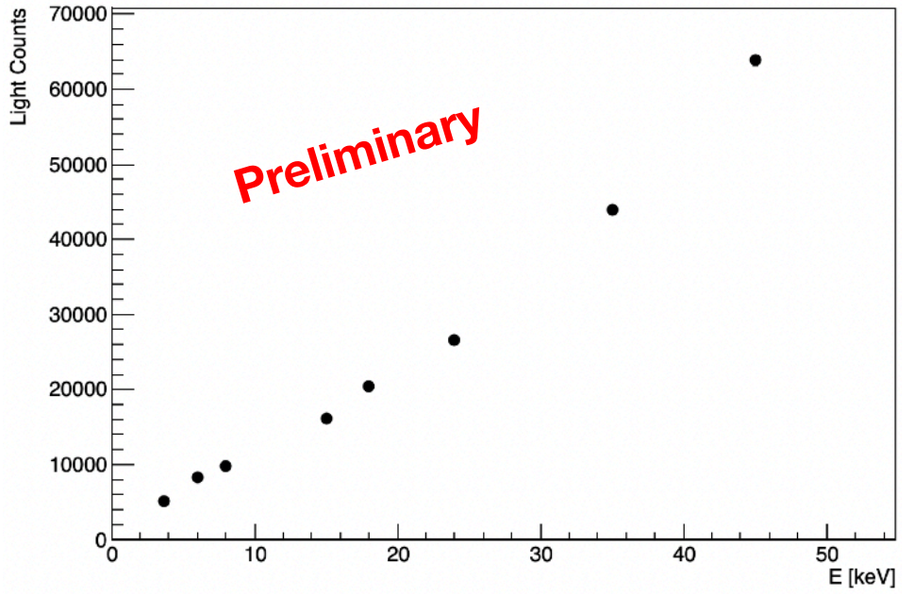
Paper out soon

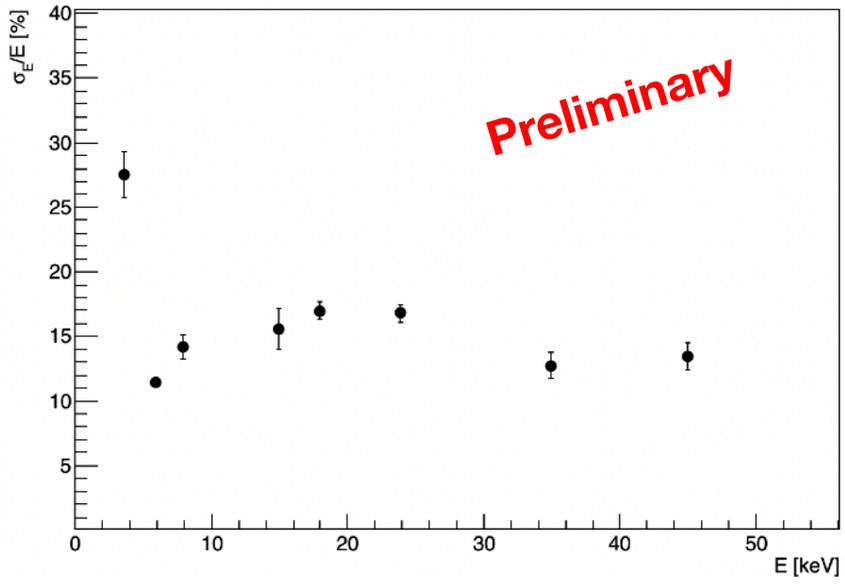
- Study of linearity and energy resolution performed overground with low energy electron recoils from X-Rays
- How tracks appear:



- Fit with 2 exponential + 1 gaussian





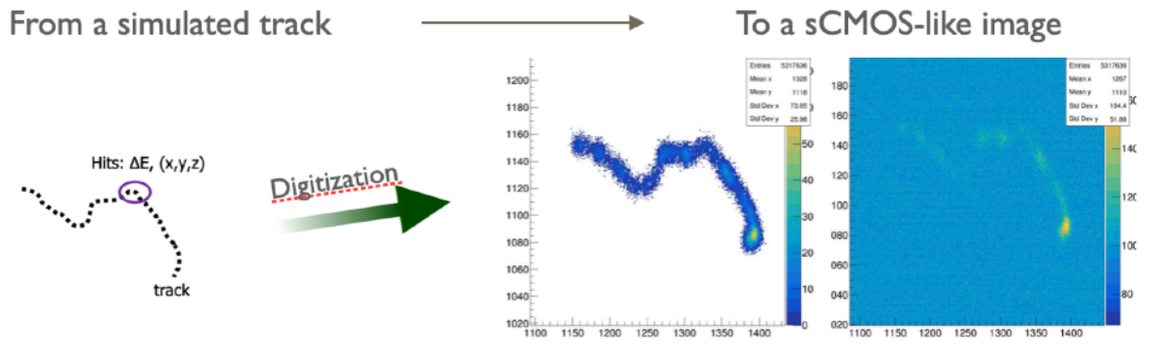


- Data shows good linearity in [6-35] keV
- Energy resolution ~ constant at 13% in same range

Same kind of tracks expected from ν scattering

Data-Simulation Comparison

- Digitization of simulated tracks into sCMOS pictures

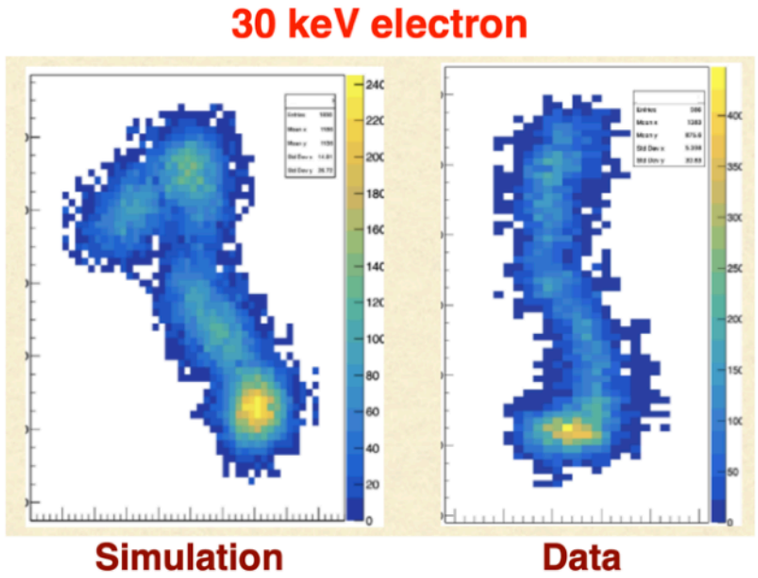


Developed taking into account detector effect:

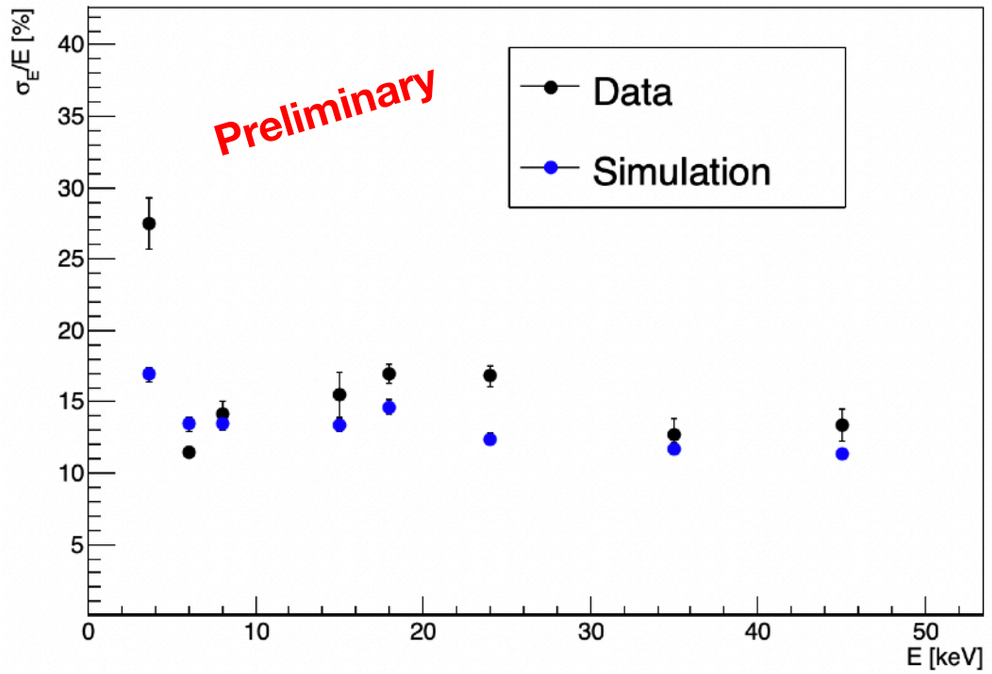
- Fluctuation in primary electrons production (poiss.)
- GEM gain fluctuation (expo.)
- Gain dependence on electron density
- Electron diffusion from measured coefficients
- Fluctuation in photon production (poiss.)
- Light collection efficiency
- Vignetting effect with track produced in different x-y
- Addition of noise from a real sCMOS picture

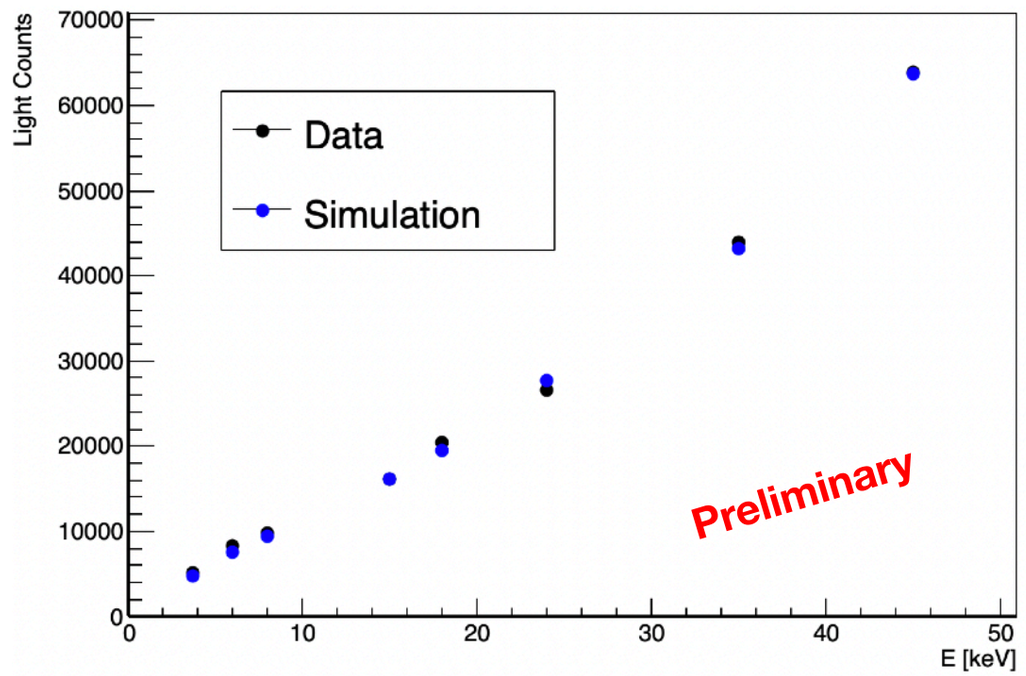
Paper out soon

- Simulation in agreement with data in response, E resolution, and other 9 track shape variables:



- Simulated tracks will be used to study 2D electron directionality
- Work in progress for the third coordinate



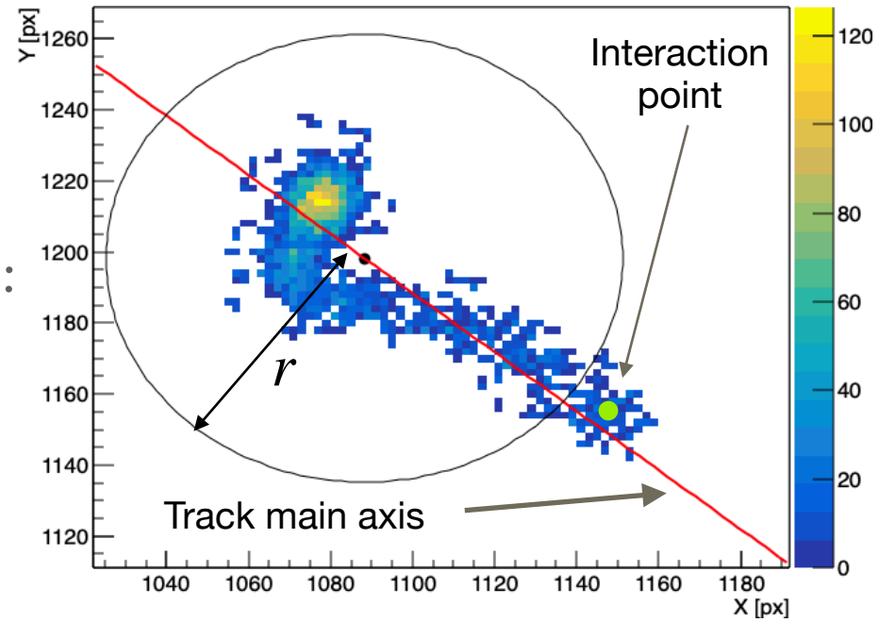


Directionality algorithm in a nutshell

- Algorithm adapted from X-ray polarimetry:

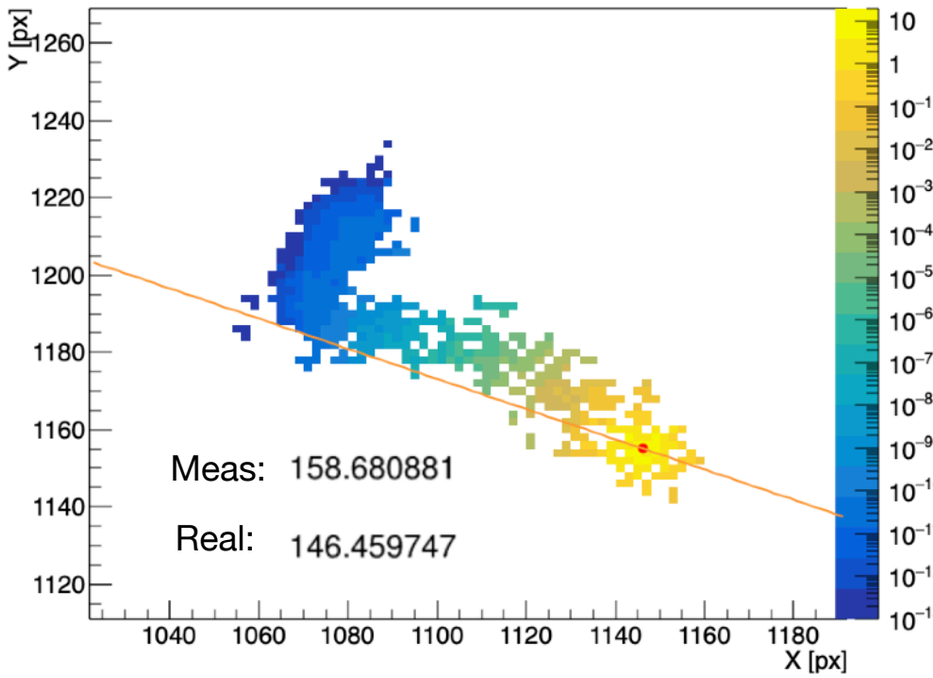
"Measurement of the position resolution of the Gas Pixel Detector"
Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105

- First part of the algorithm: searching for the beginning of the track with:
  - Skewness
  - Distance of pixels from barycenter (furthest pixels)
  - Selection of a region with fixed number of points N_{pt}



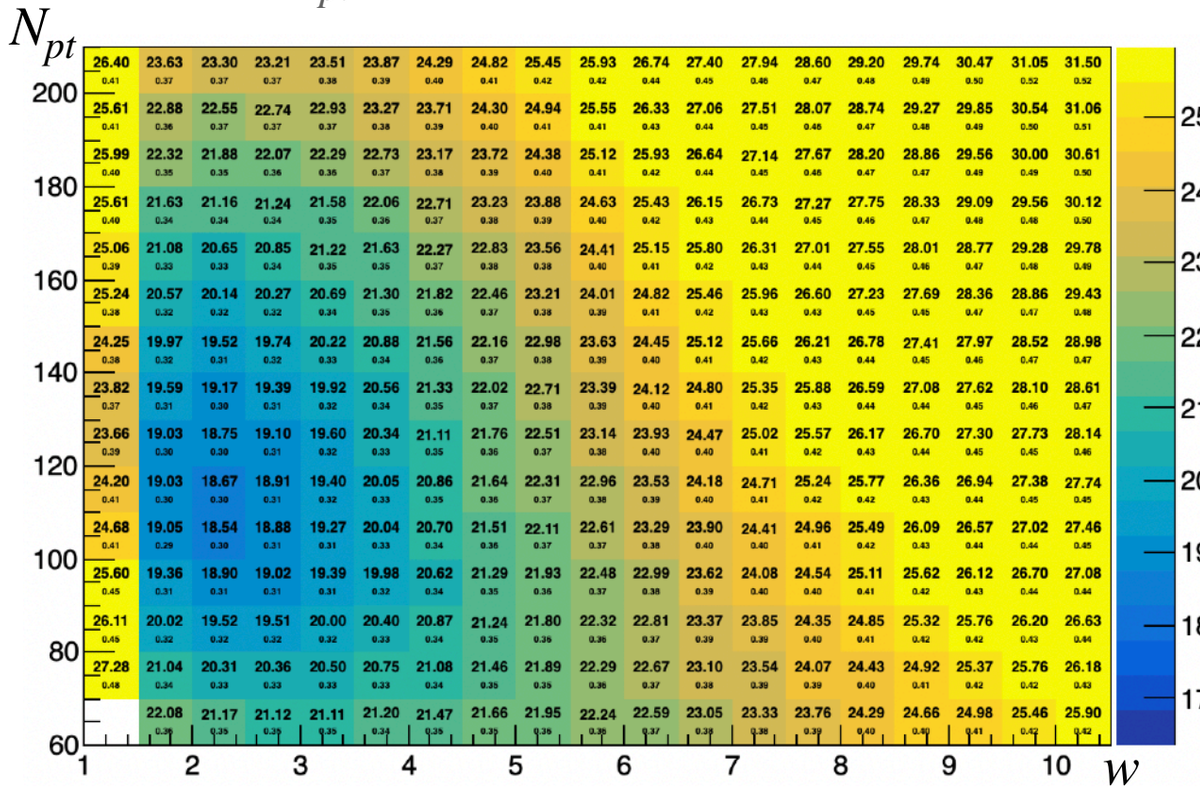
- Second part of the algorithm aims to find the direction:
  - Track point intensity rescaled with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the main axis of the rescaled track passing from the interaction point
  - Orientation given following the light in the pixels

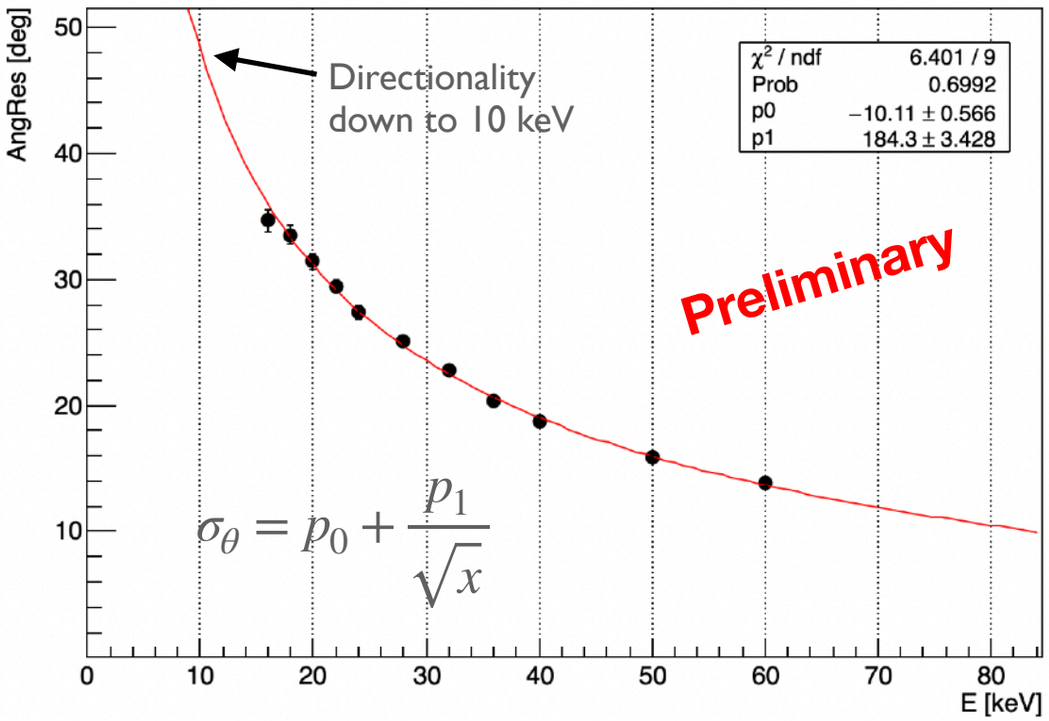
- Two parameters of the algorithm: N_{pt} and w

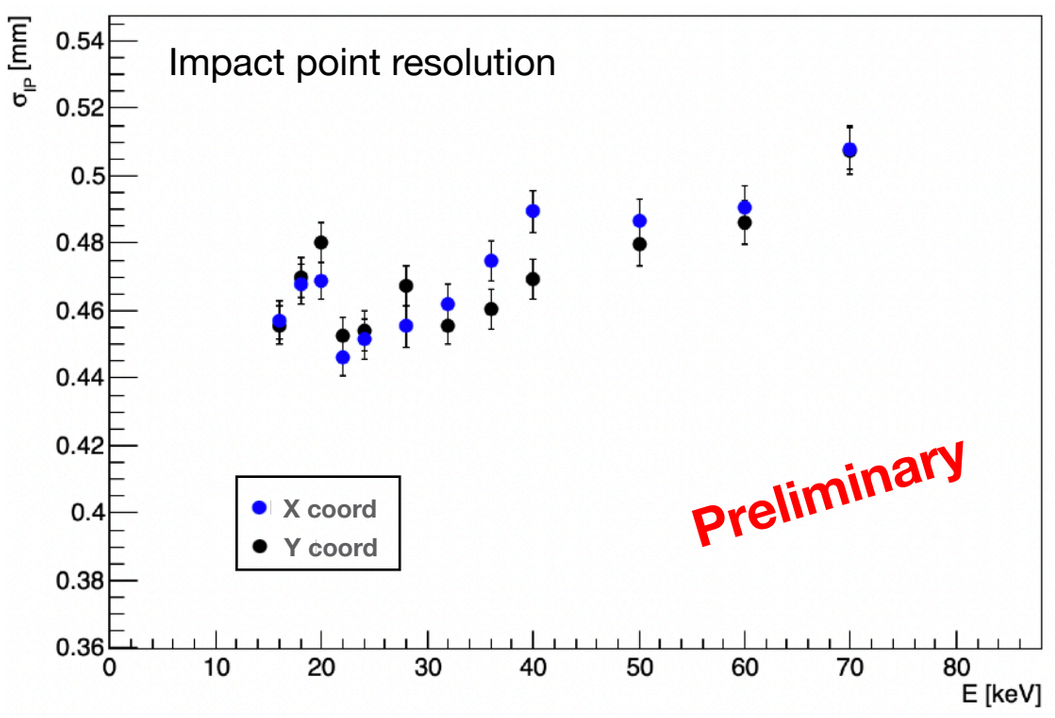


Parameters optimization and results

- Optimization of the parameters from a scan of angular resolution vs N_{pt} and w
- Values which provide the best angular resolution chosen
- Preliminary results of directionality resolution on low energy electron recoils
- Tracks simulated isotropically in angle and in the whole detector volume
- Resolution as the sigma of $\theta_{meas} - \theta_{true}$ distrib.







Sensitivity studies

- Sensitivity studies on solar neutrino detection performed with a Bayesian framework:

Posterior probability

Likelihood

Prior probabilities

$$p(\mu_s, \mu_b \,|\, D) = \frac{p(D \,|\, \mu_s, \mu_b) \cdot \pi(\mu_s) \cdot \pi(\mu_b)}{p(D)}$$

Normalization

$$L = \prod_{i,j} \frac{\lambda_{i,j}^{n_{i,j}} e^{-\lambda_{i,j}}}{n_{i,j}!}$$

- Assumptions:
  - Same resolution in both theta (on the GEM plane) and phi (respect to the perpendicular to the GEM plane) given the PMT time resolution.
  - Isotropic gamma background
  - Energy and angular resolution taken from data and MC respectively
  - Threshold on electron energy of 10 keV

- Made using on toy-MC realised starting from the theoretical distribution and including the detector response

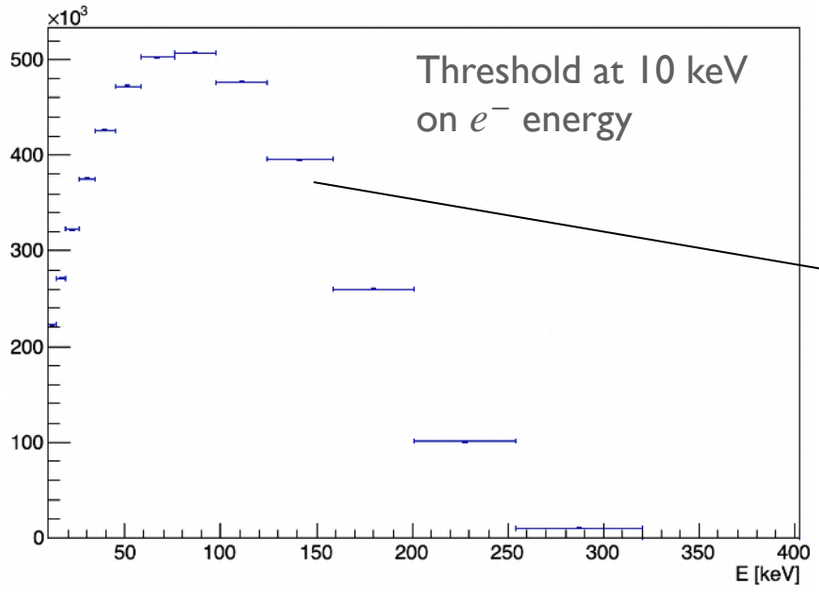
- Aim: find the exposure for 3/5σ sensitivity under different bkg hypotheses

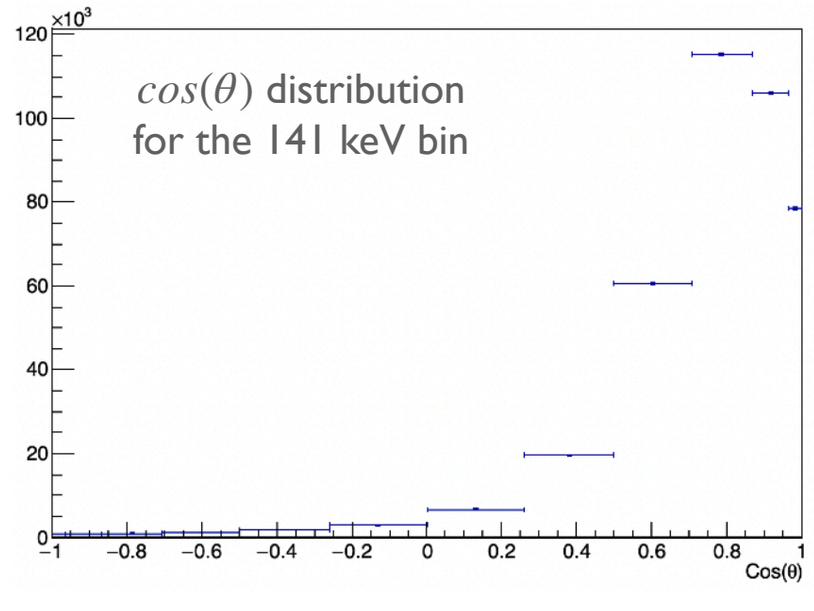
Template production

- Template produced starting from the expected distribution adding the detector resolution
  - For each energy bin the cos(θ) distribution is produced

- Signal

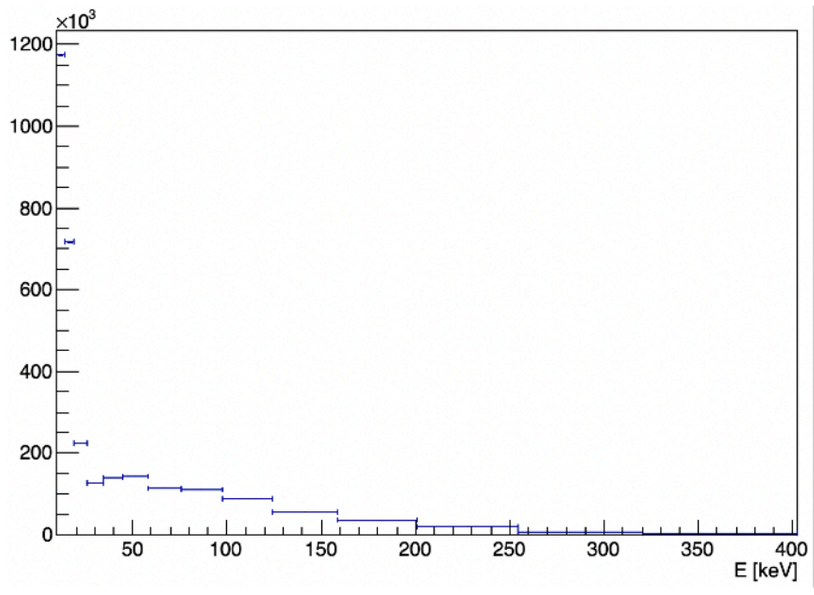
Produced starting from the pp cycle neutrino, simulating the interaction and adding the detector resolution

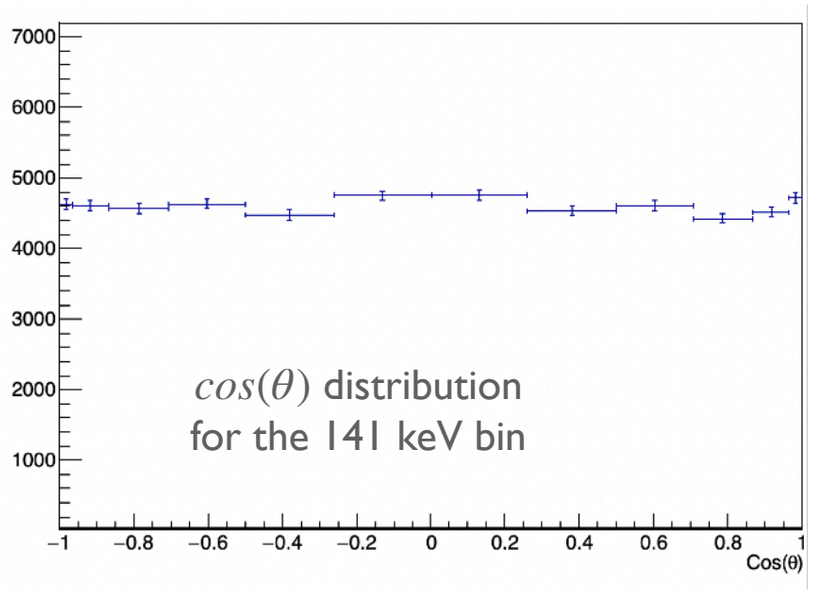




- Background

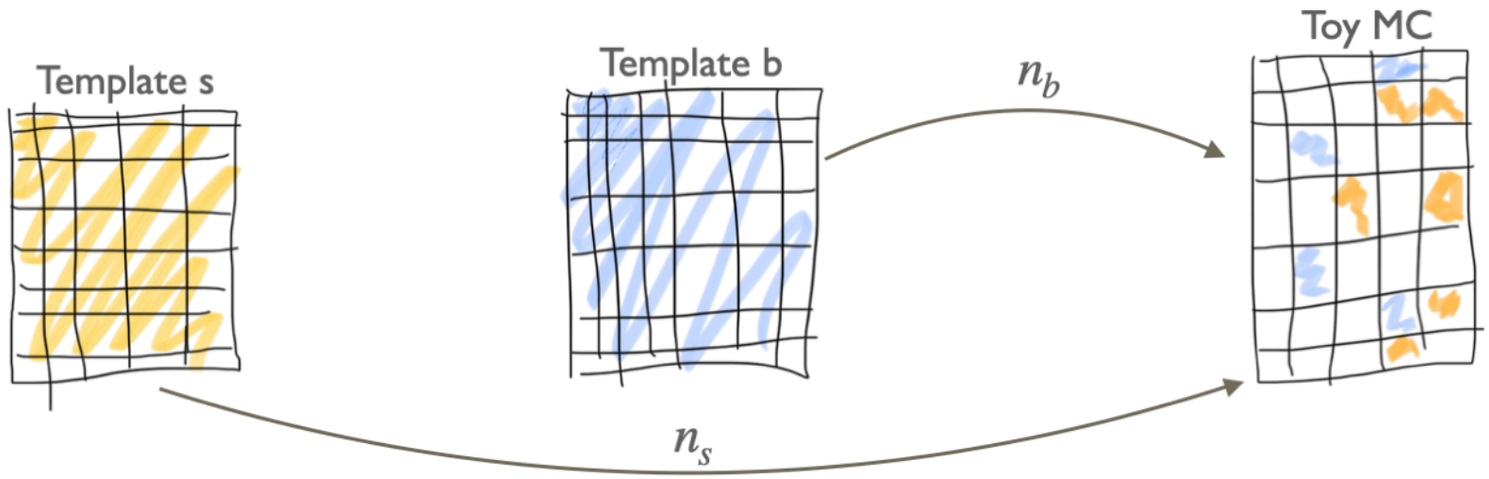
Produced starting from the simulated bkg spectra of LIME





Toy-MC

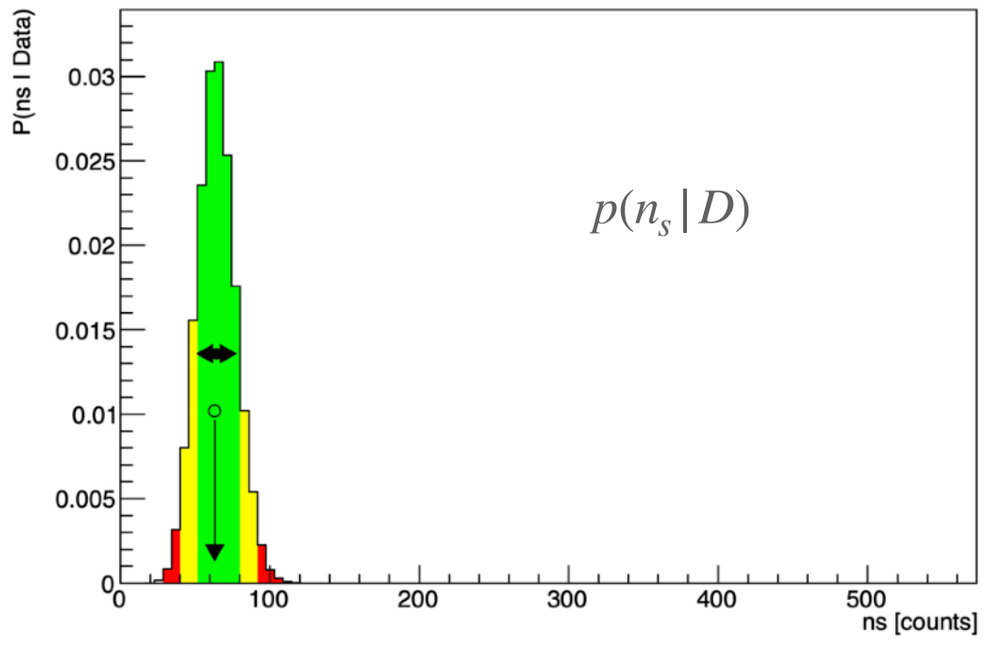
- Toy-MC generated by a hypothesis on of $\bar{N}_s$ and $\bar{N}_b$, extracting poissonianly the values of n_s and n_b, and filling an E-cos(θ) histogram with the extracted events from the templates



- 100 toy MC produced for every combination of $\bar{N}_s$ and $\bar{N}_b$ have been generated:
  - $\bar{N}_b$ = 10,100,500,1000,5000,10000,
  - $\bar{N}_s$ = 5, 10, 20, 40, 60, 100, 200, 400, 600, 1000

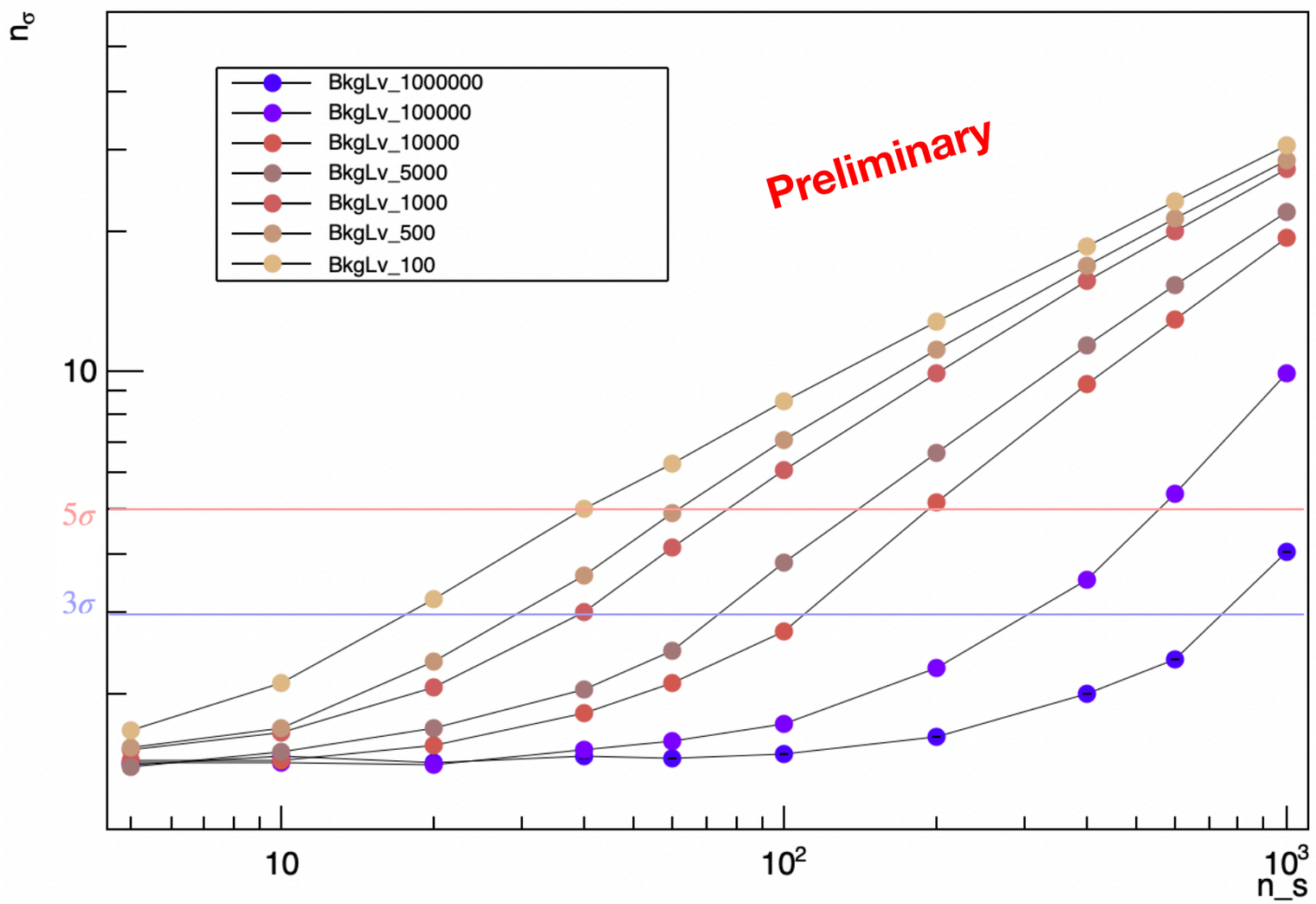
- For each dataset the posterior is calculated, and normalized with the Monte Carlo Markov Chain algorithm Metropolis-Hastings

- The posterior for the signal $p(n_s \mid D)$ is obtained from marginalisation



Sensitivity results

- Plot of the significance vs n_s under different hypotheses of background during the total exposure
- Each point is the average of the 100 toy-MC analyzed



- With a 30 m^3 detector ~30 ev/y are expected with 10 keV directional threshold.
- Feasible in a reasonable amount of time if bkg is constrained to ~10^4 ev/y

Conclusions

- Solar neutrino can be object of study with directional TPC approach

- Directionality can increase the bkg toleration and can lead to a spectroscopic measurement of the solar pp flux

- The energy response and resolution of the 50L prototype have been studied and a simulation able to reproduce the data has been developed

- In this context an algorithm to measure directionality of low energy electrons based on polarimetry studies has been developed, showing the feasibility of this measurement

- CYGNO-30 can perform this measurement provided that the background can be constrained down to ~10^4 events (same for DM)

Thank you for you attention… and follow us for future results

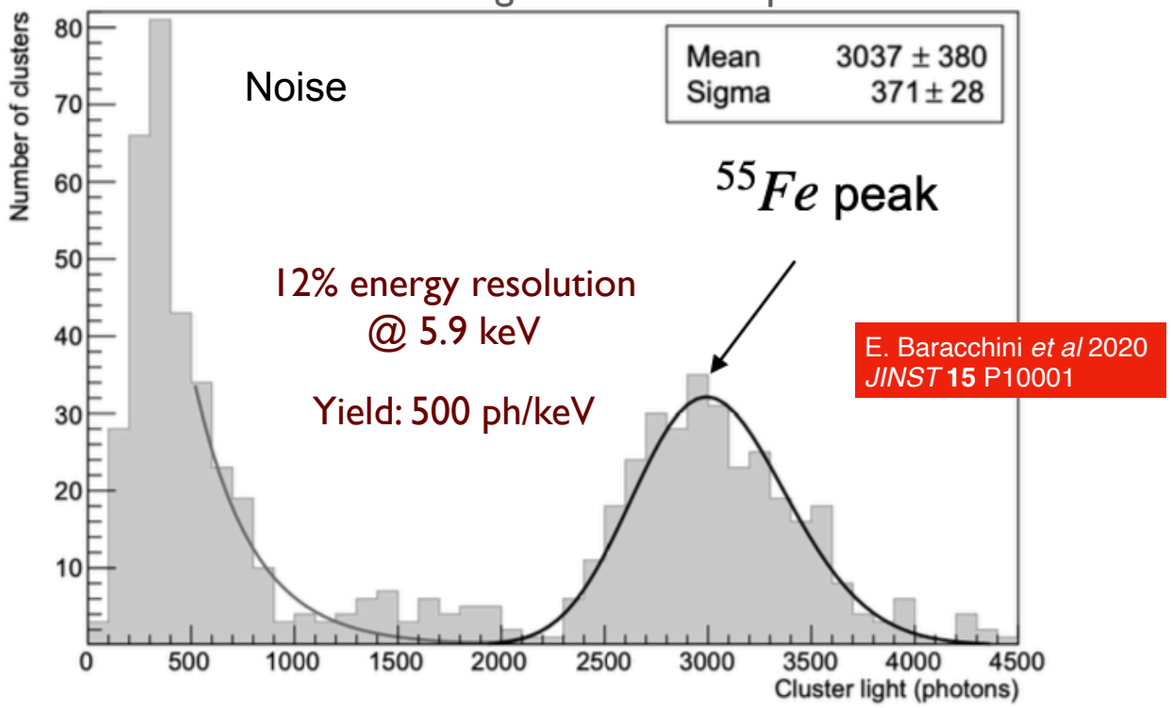
Acknowledgements:

This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the European Research Council (ERC) grant agreement No 818744 and from the Italian Ministry of Education, University and Research through the project PRIN: Progetti di Ricerca di Rilevante Interesse Nazionale "Zero Radioactivity in Future experiment" (Prot. 2017T54J9J)

Backup

LEMON results

Distribution of light content in spots



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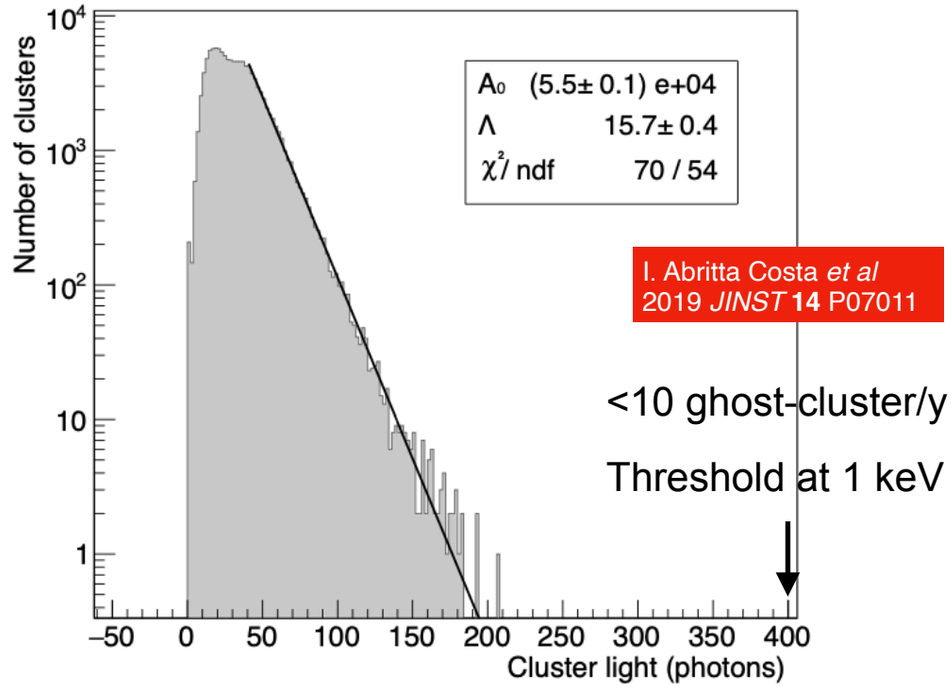
Number of photons in a light cluster with blind sensor



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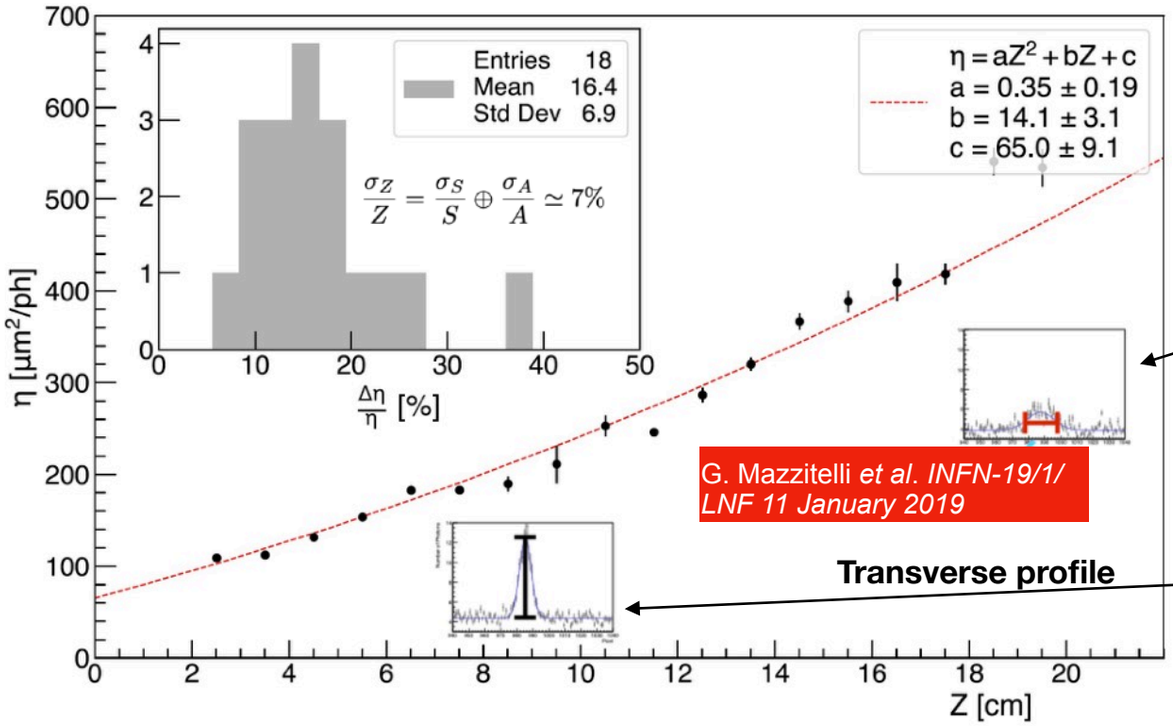
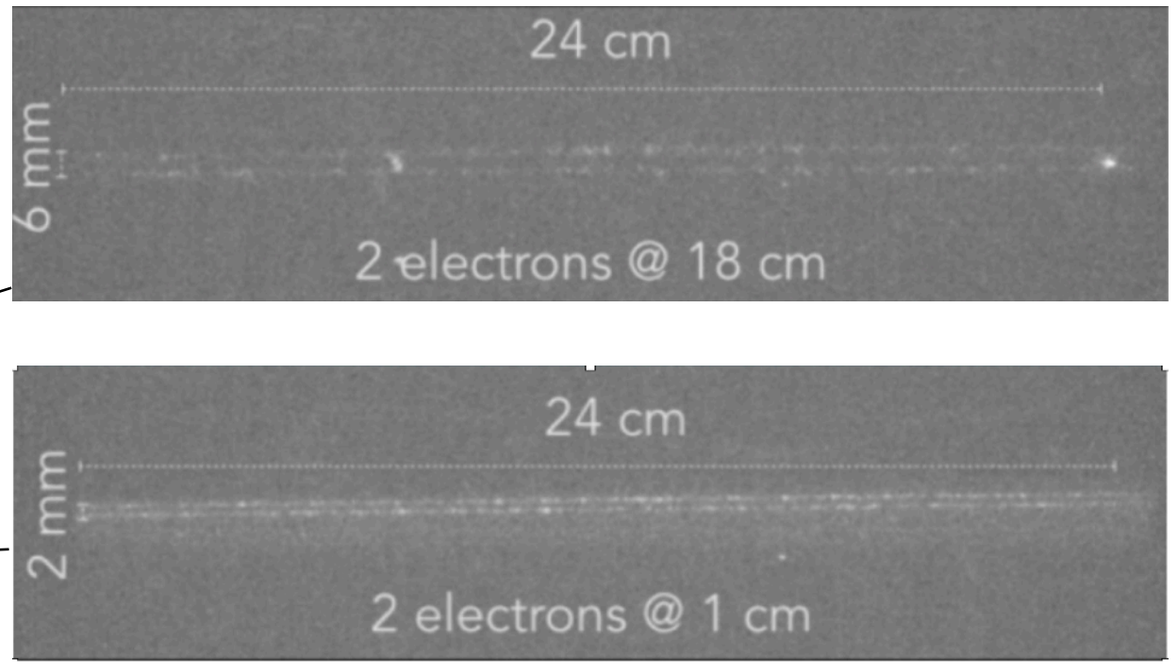
Fiducialization exploiting the track transverse diffusion



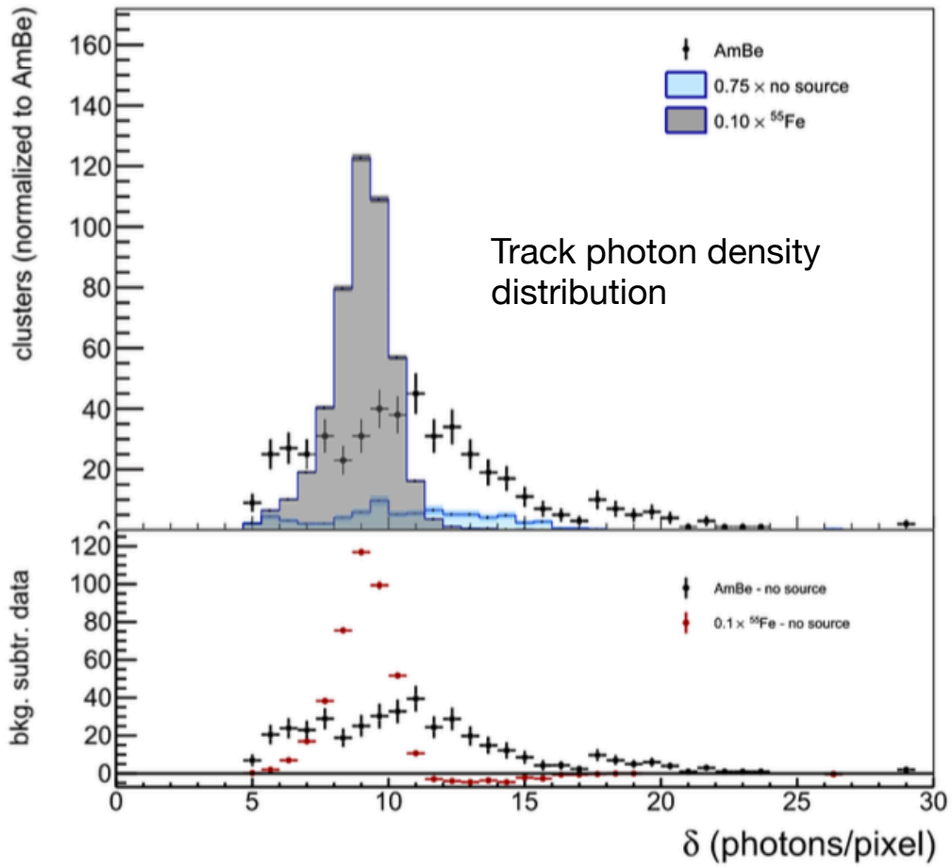
G. Mazzitelli *et al*. *INFN-19/1/ LNF 11 January 2019*

Transverse profile

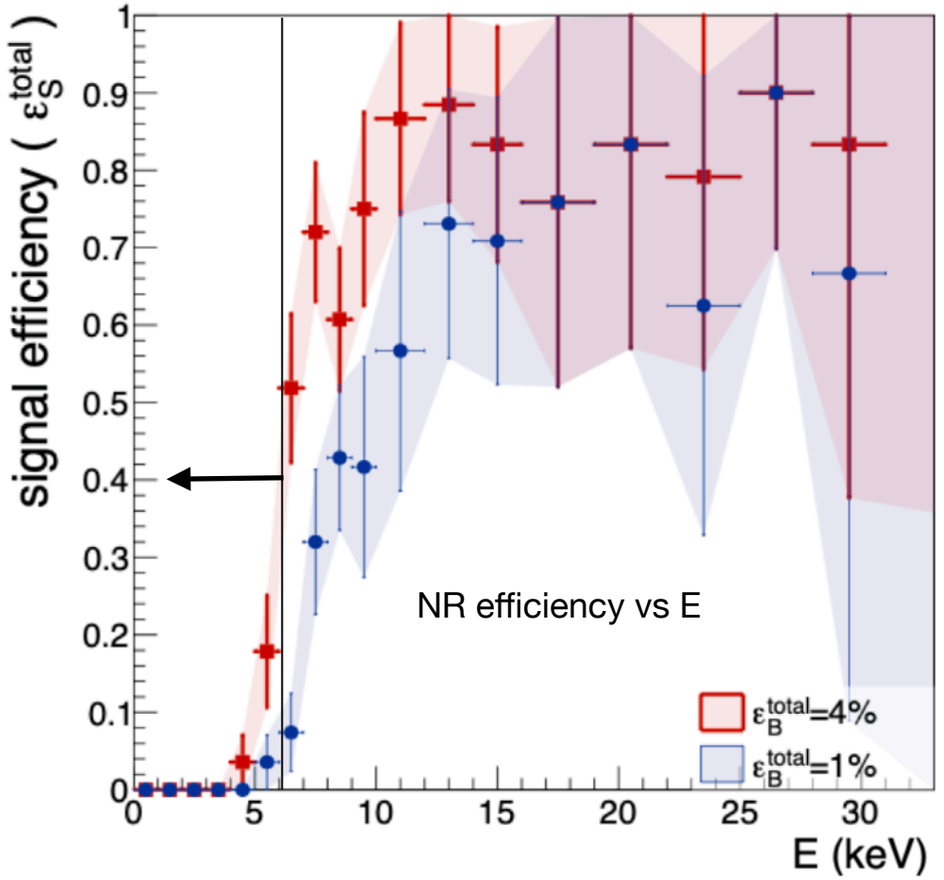


ER/NR discrimination

- Data taken with ^{55}Fe and Am-Be neutron source to study ER/NR discrimination



- Main discriminating variable is the energy density ($\delta = N_{ph}/N_{px}$)



- 40%(50%) efficiency on signal @ 6keV with 96.5% (99.2%) bkg rejection with cuts on δ>10 (δ>11)

- Work in progress on multivariate approach to improve ER/NR discrimination in progress (even with the use of neural network)

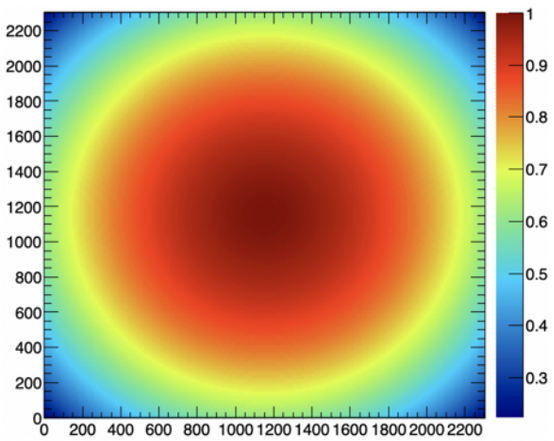
Track reconstruction code

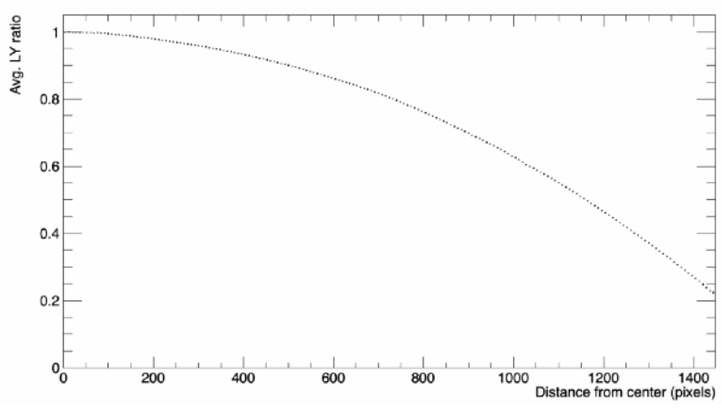
- High quantity of tracks with overlapping due to sensitive volume

- First iteration of directional iDBSCAN to reconstruct long and straight tracks

- Remaining tracks reconstructed with iDBSCAN

+ Vignetting correction:

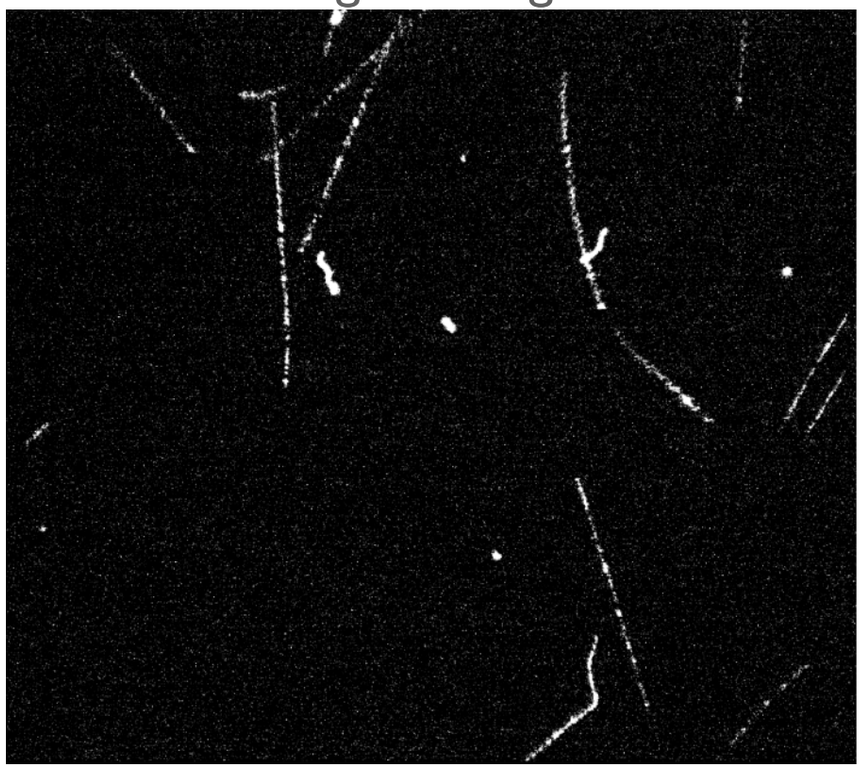




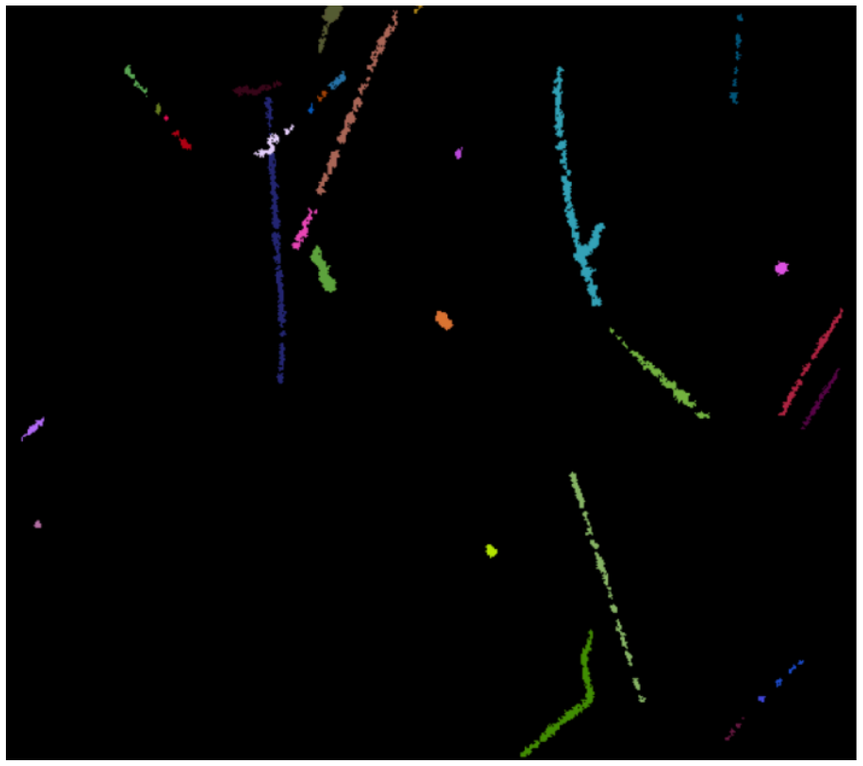
- Light Collection down up to 20% on the border of the images

- Saved information: pixels, light content, lenght, width, transverse and longitudinal rms …

Original image

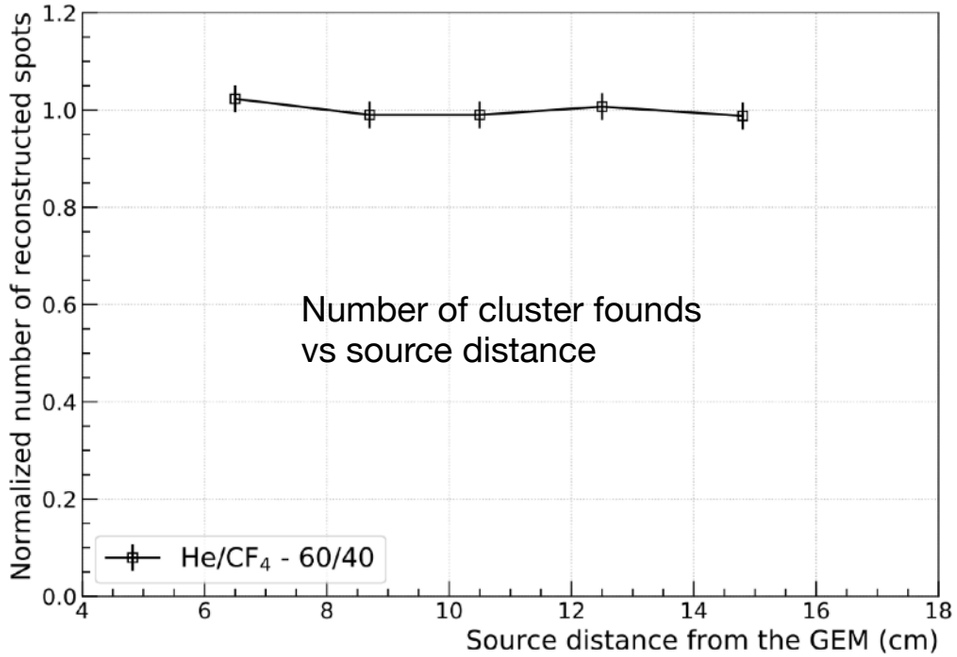


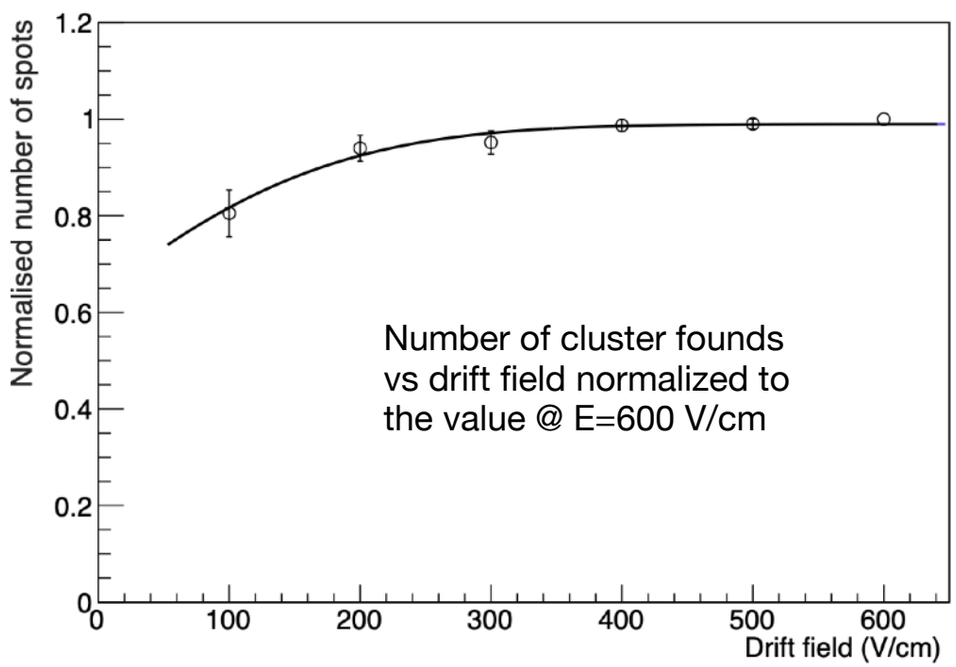
Tracks reconstructed

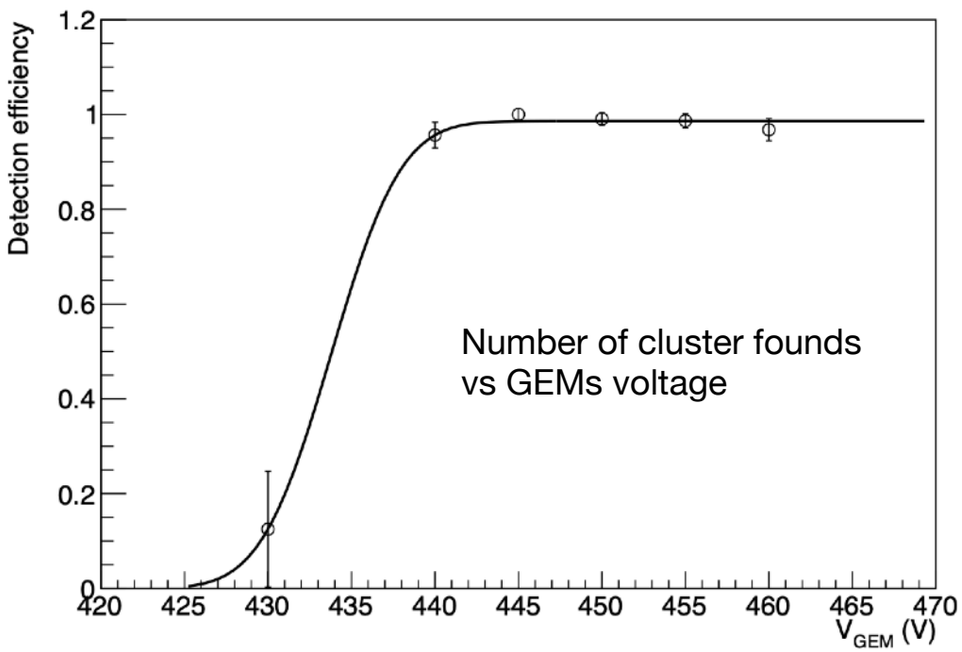


Detection efficiency

- Detection efficiency studied in the whole 7 liters volume of the detector for different fields
- Studies done using a source of ^{55}Fe (5.9 keV γ)
- 5.9 keV electrons produce light spot in the detector

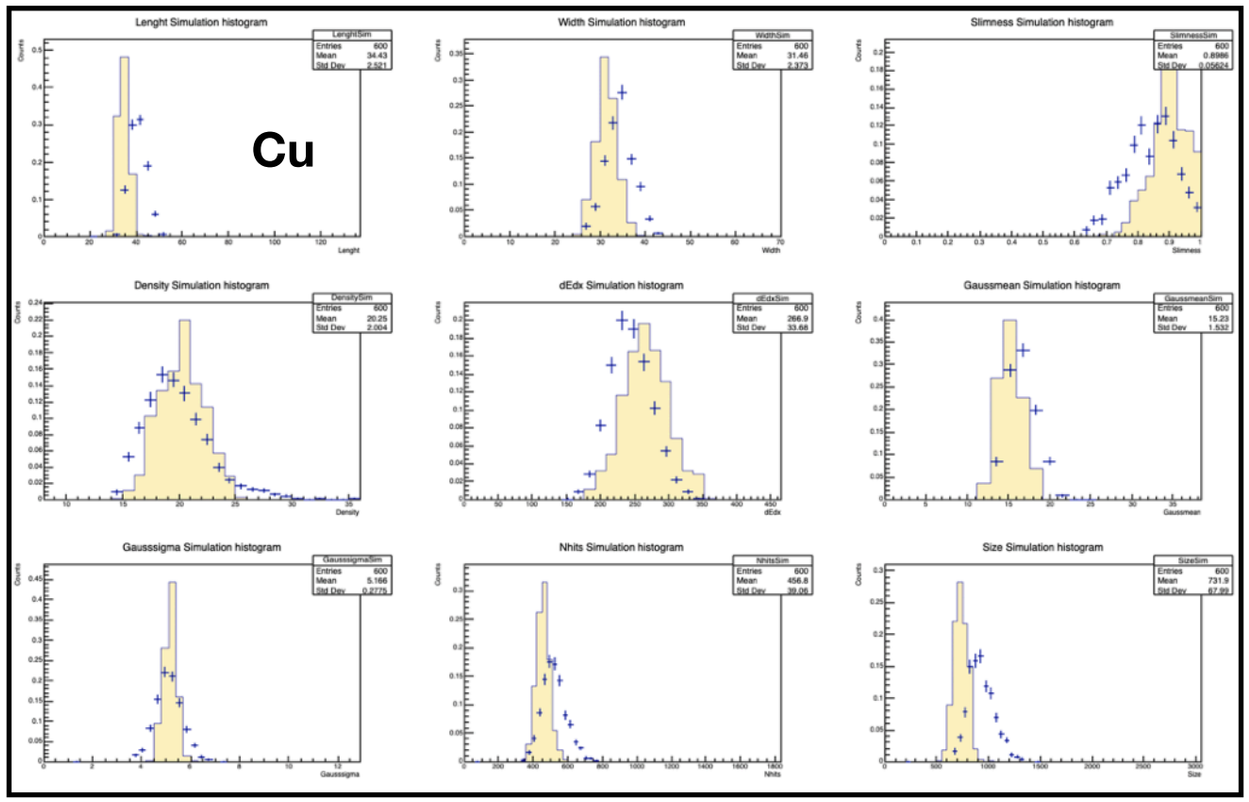


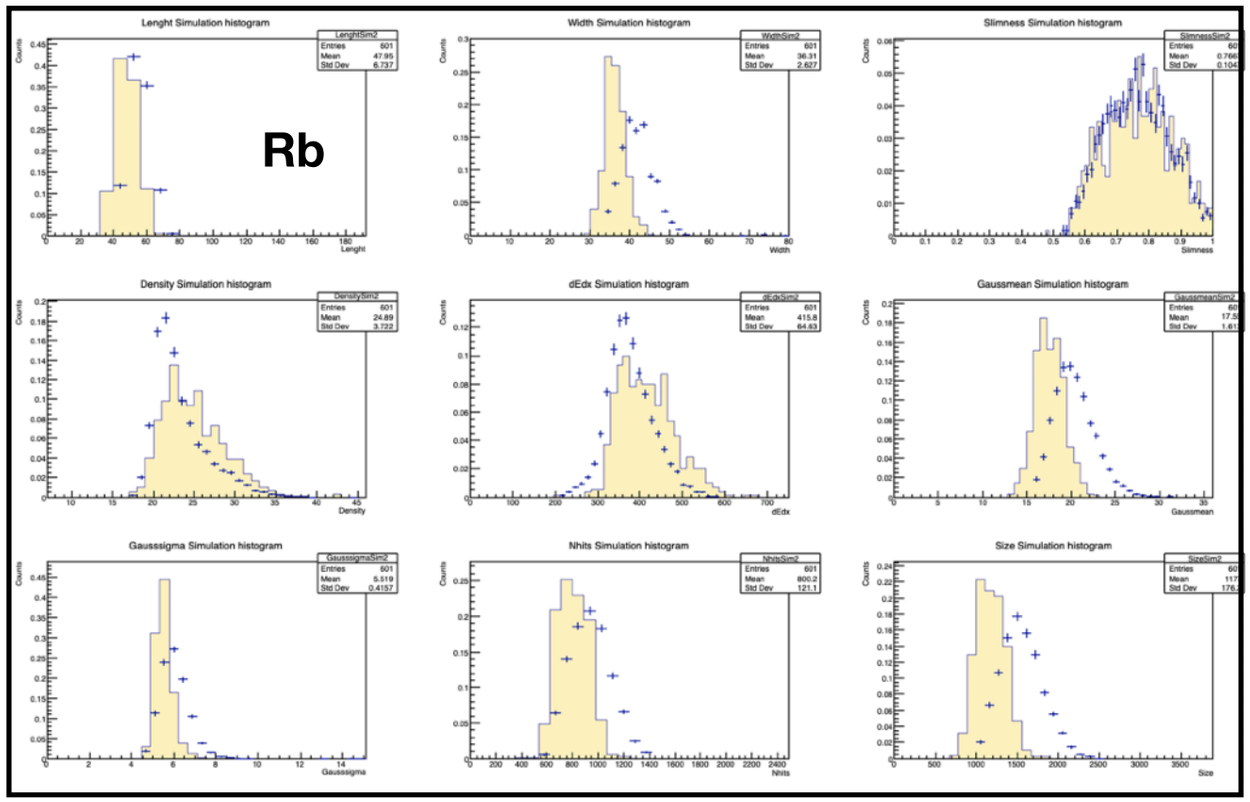


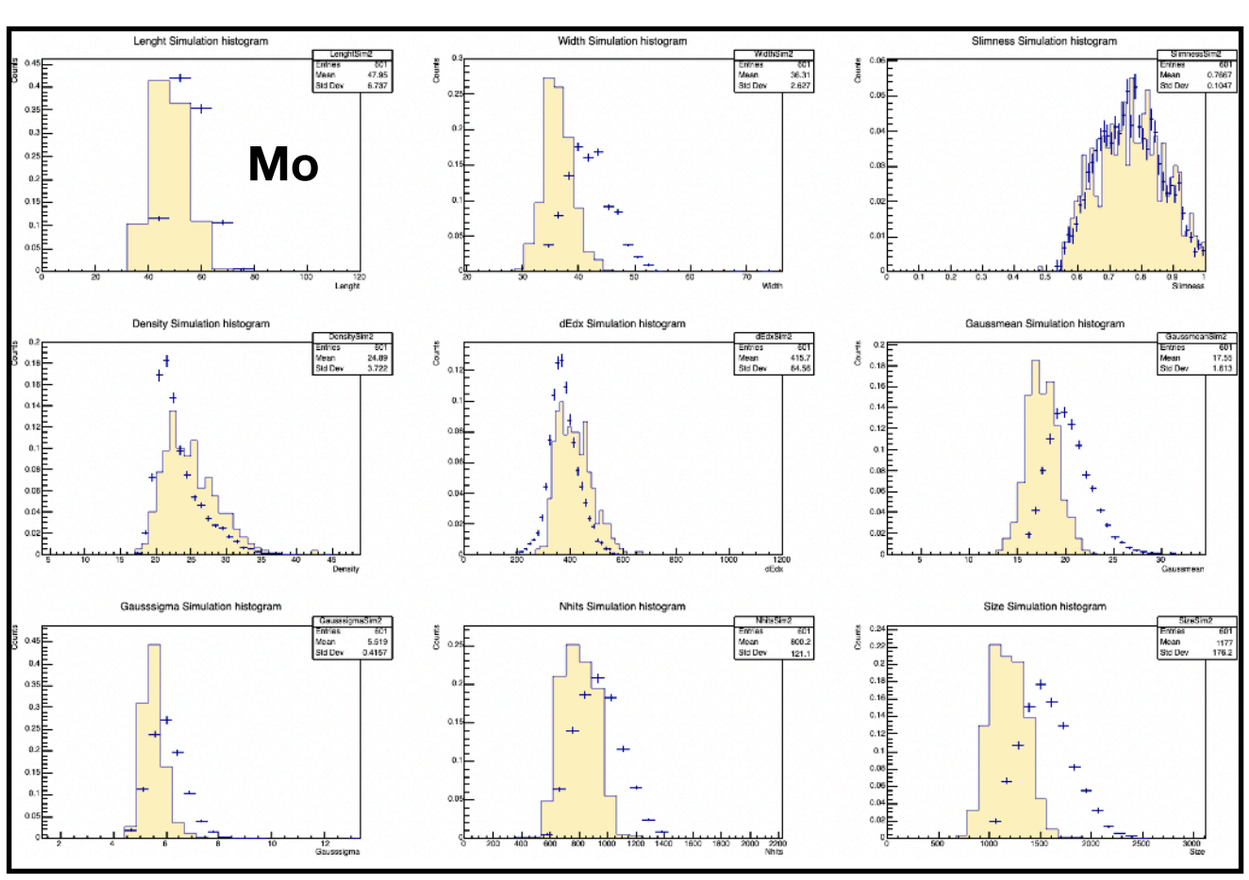


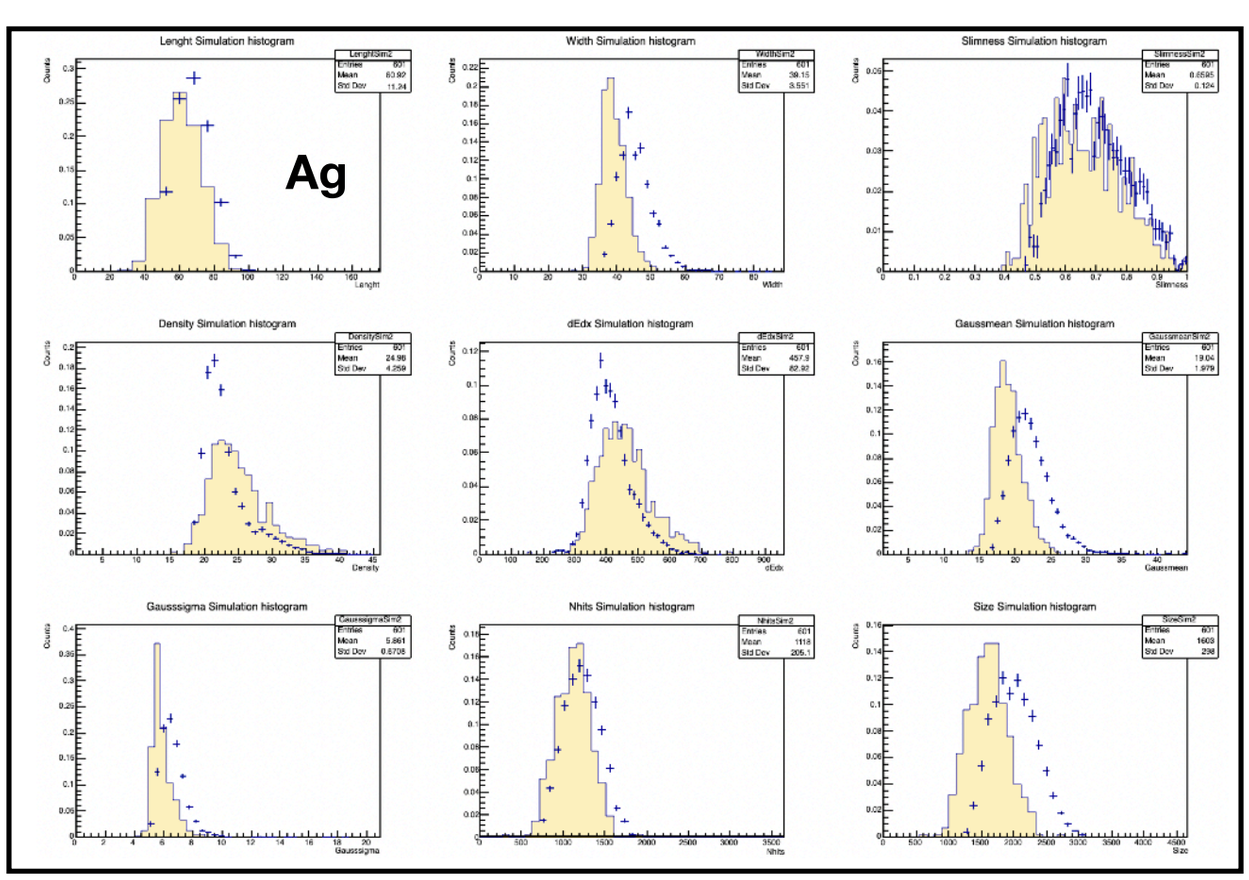
Track shape parameters comparison

Simulation Data



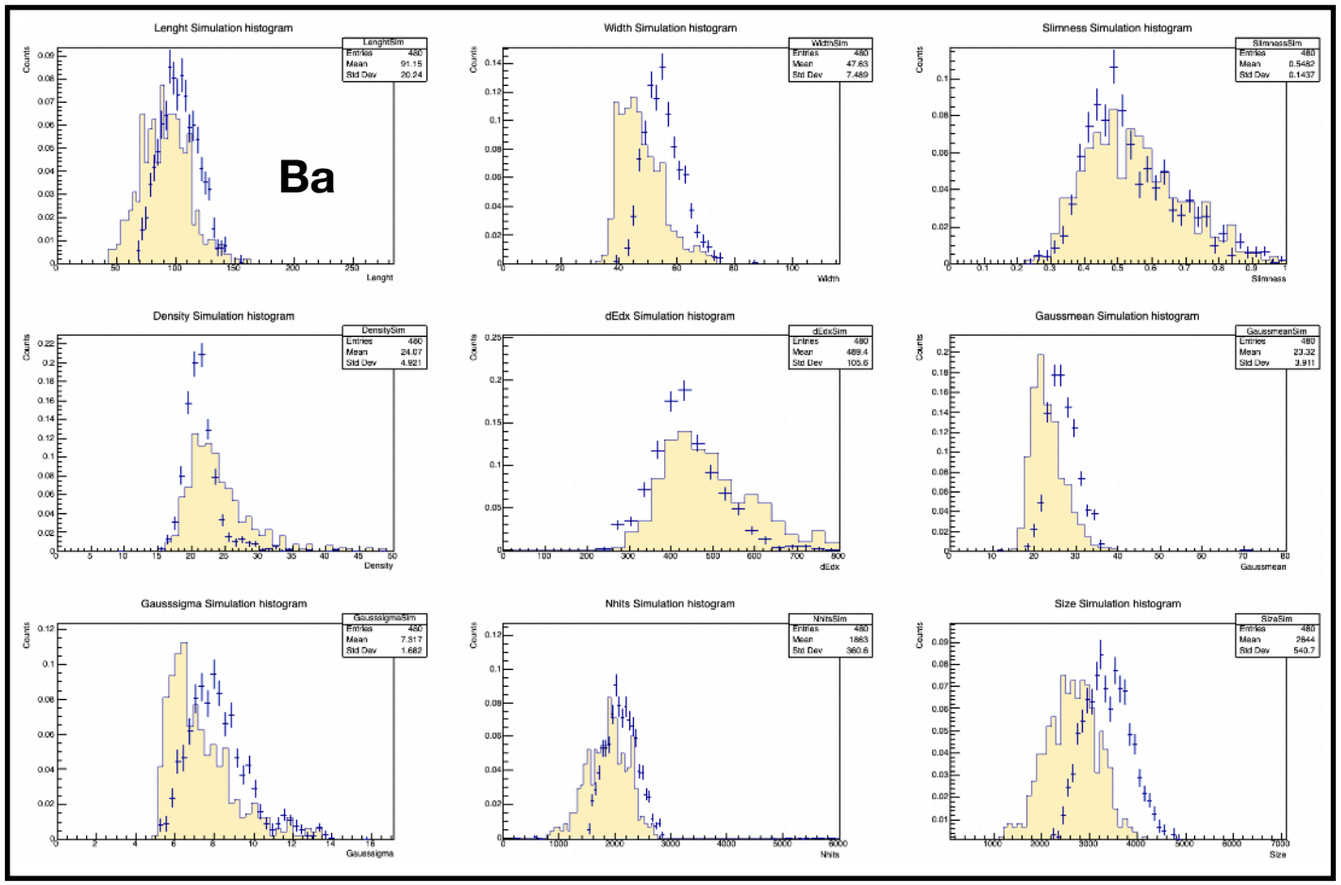


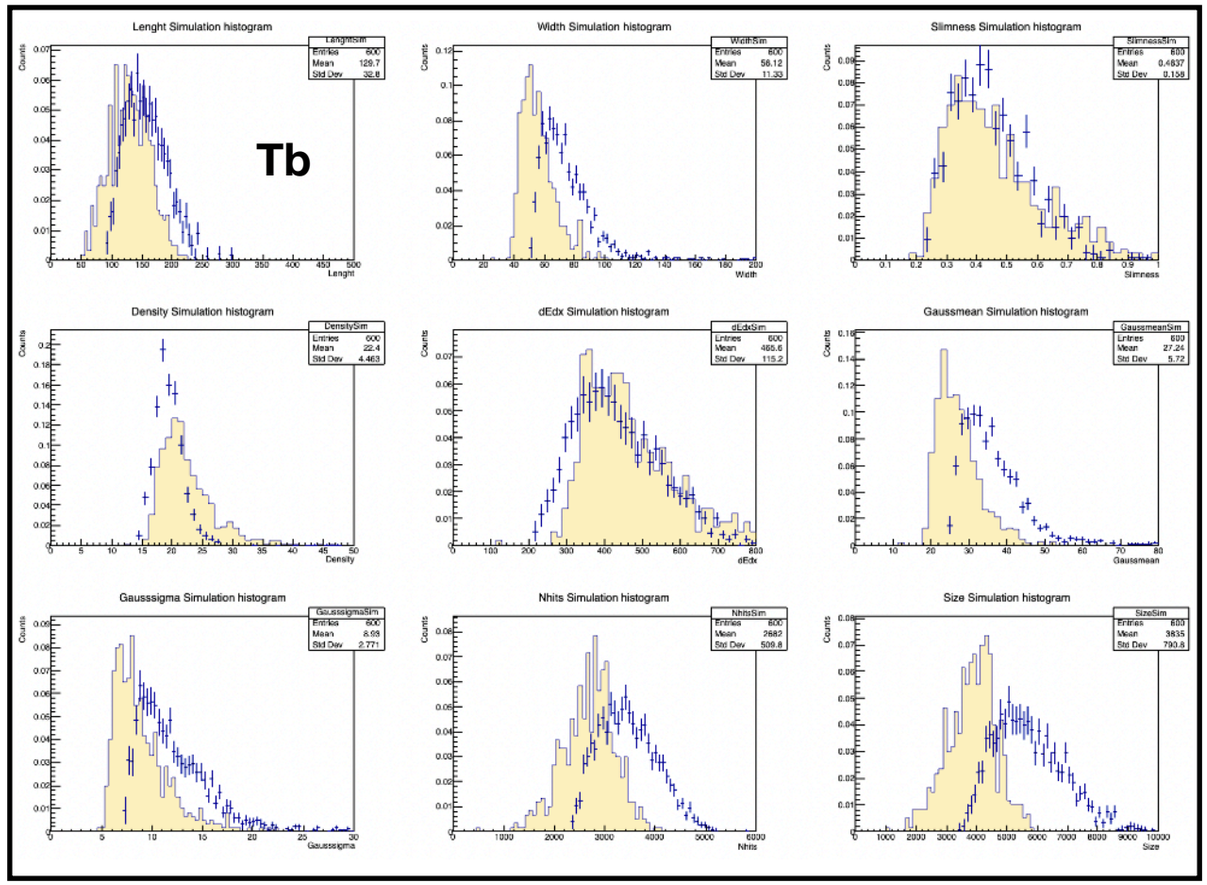




Track shape parameters comparison

Simulation Data





- Nice agreement in the distributions, some fine tuning of the parameters needed

LIME underground program

- Detailed studies performed on internal bkg expected in LIME
- Radioactivity measured for acrilic vessel, field cage (ring + resistors), GEM, cathode, all camera components
- Main contributions from resistors, GEMs and camera (lens and sensor)
- Spectra produced by MC simulation of LIME

Data taking program:

- Unshielded:
  - Detector characterization with ^{55}Fe and AmBe
  - External bkg studies with periodic ^{55}Fe calibration
- 6 cm Cu shield:
  - External bkg studies with periodic ^{55}Fe calibration
- 10 cm Cu shield:
  - Total bkg studies with periodic ^{55}Fe calibration
  - Spectral measurement of neutron flux (200 NR in 20-100 keV expected in 4 months)
- 10 cm Cu + 40 cm H_2O:
  - Study of internal background and validation of the MC (reduction of the residual bkg at a level less than the internal one)