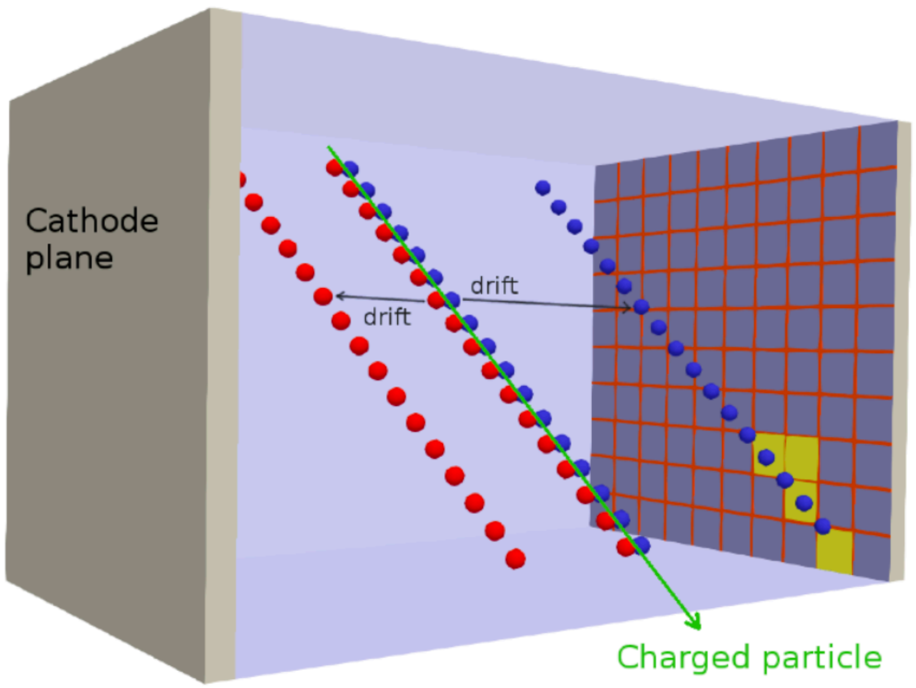
Feasibility of a directional solar neutrino measurement with the CYGNO/INITIUM experiment

S.Torelli on behalf of the CYGNO collaboration

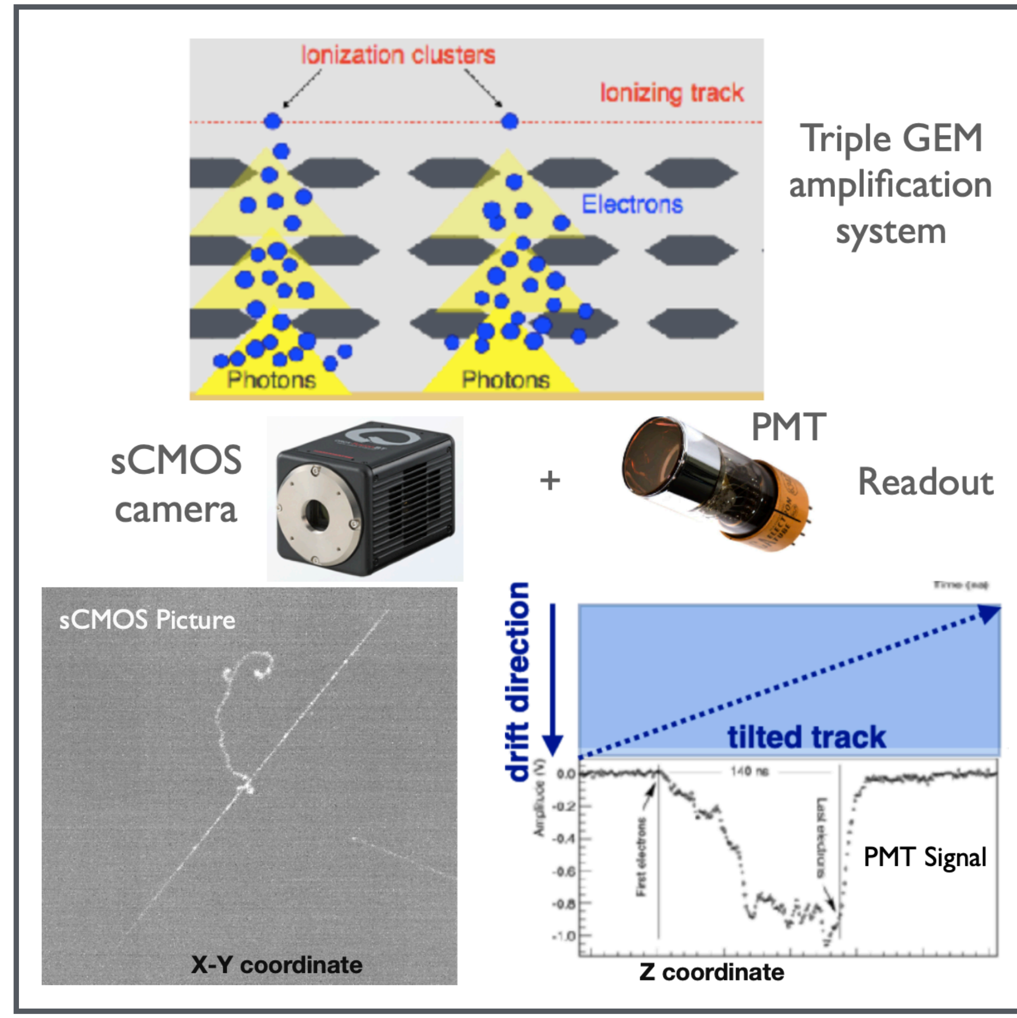
The CYGNO-Experiment in a nutshell

See D.Fiorina talk!

- Time projection chamber filled with He:CF_4 60:40 (low density gas → low diffusion)



Amplification and readout



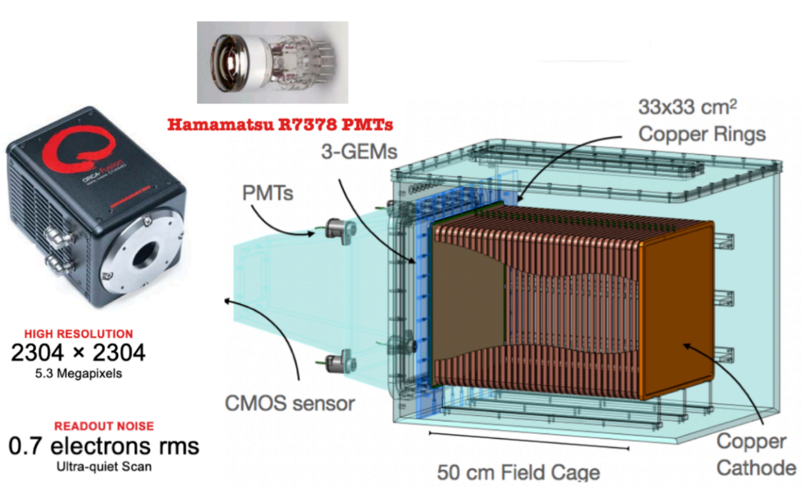
50-L prototype LIME - in operation since 2019

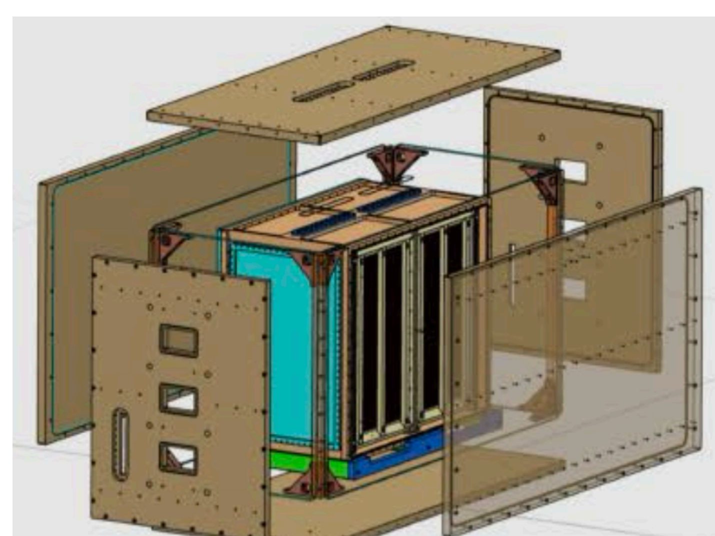
In a while →

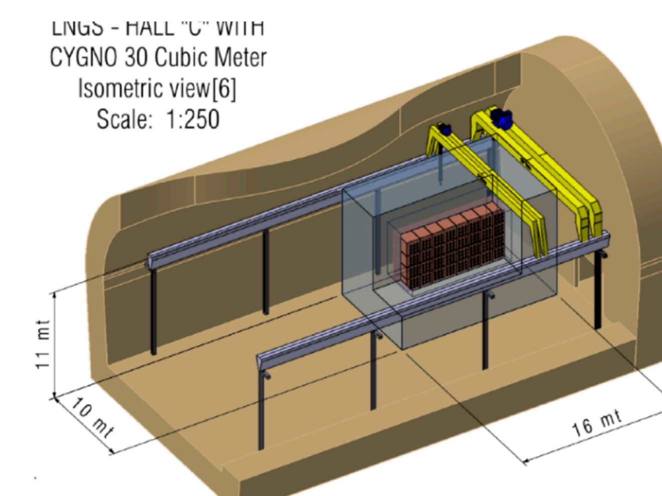
0.4m^3 - performances similar to LIME - in construction

In the future →

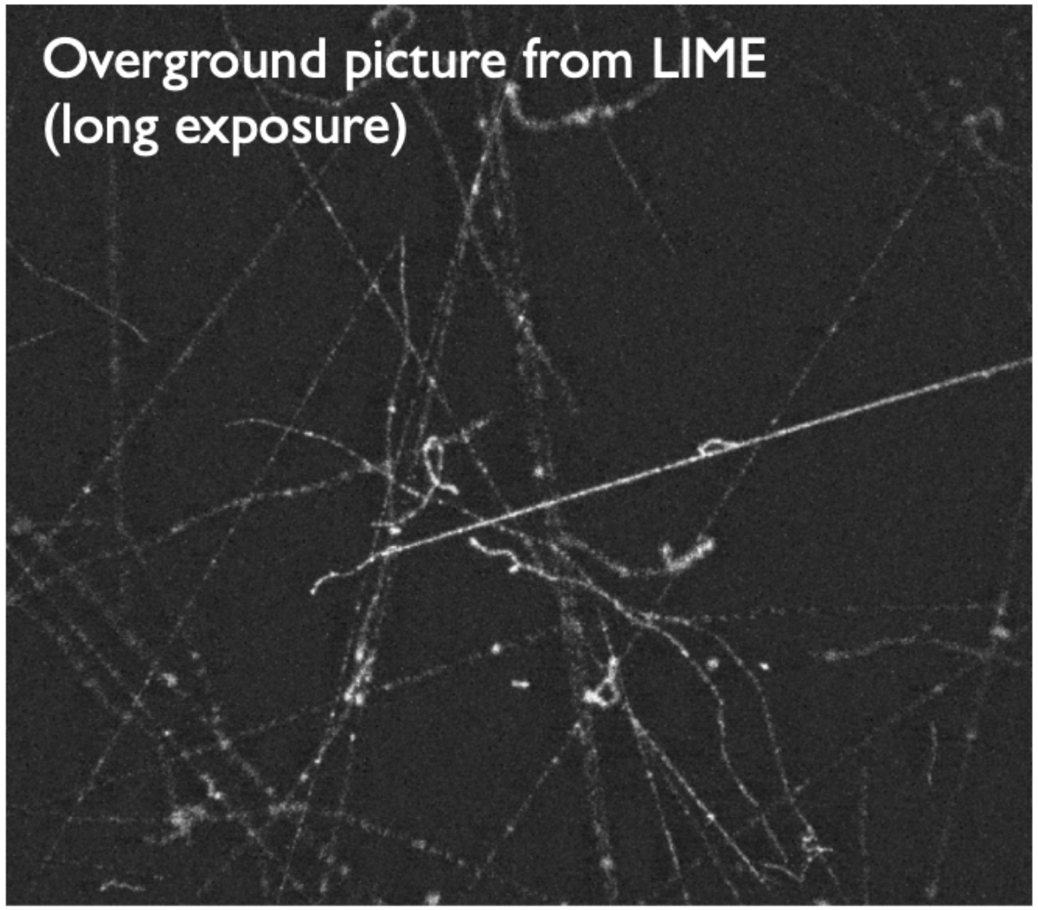
30 m^3 detector - made by 0.4m^3 modules

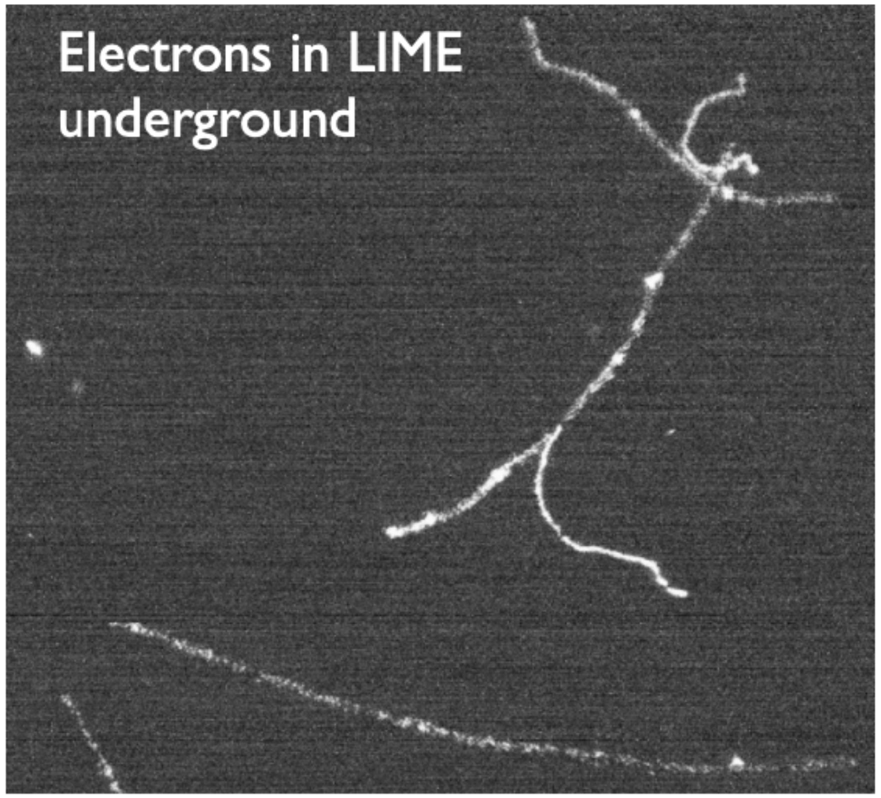


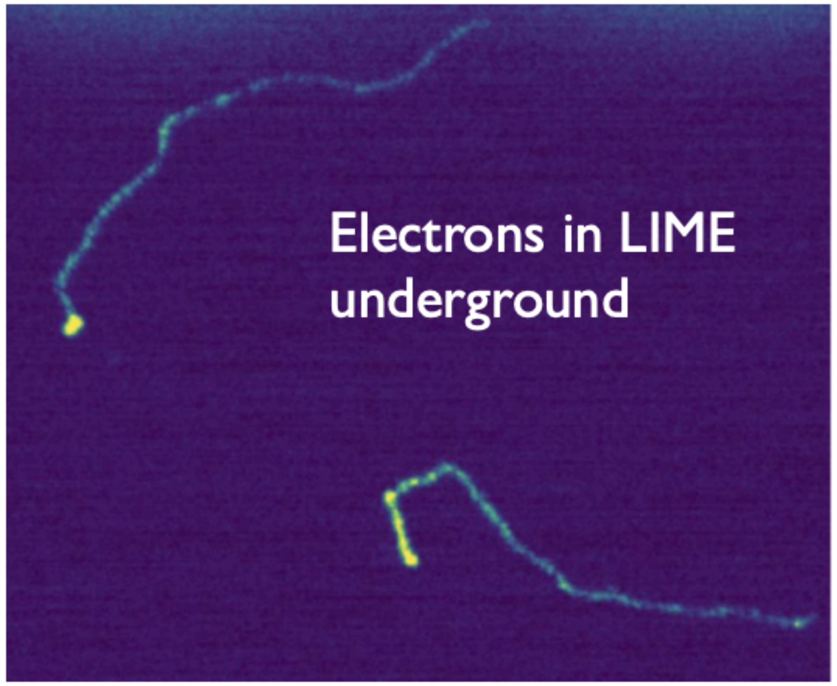


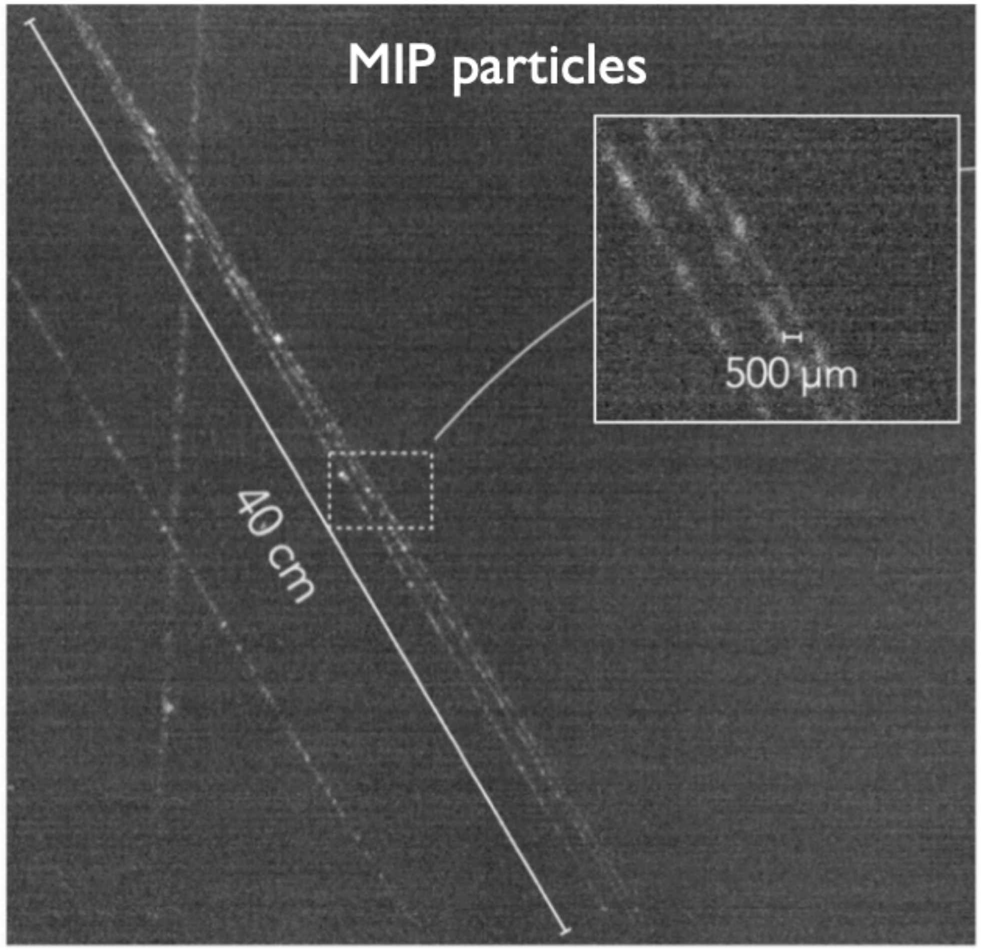


Particle tracks in CYGNO



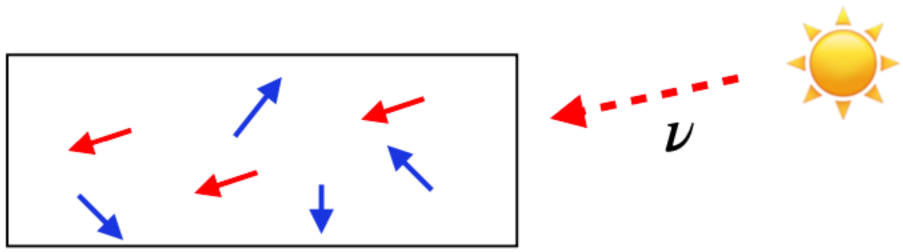






Why a directional measurement of solar neutrino

- Capability of discriminating signal from background from source direction



Introduction of a much stronger signature than the only energy spectrum

Signal peaked distribution over flat bkg in angle

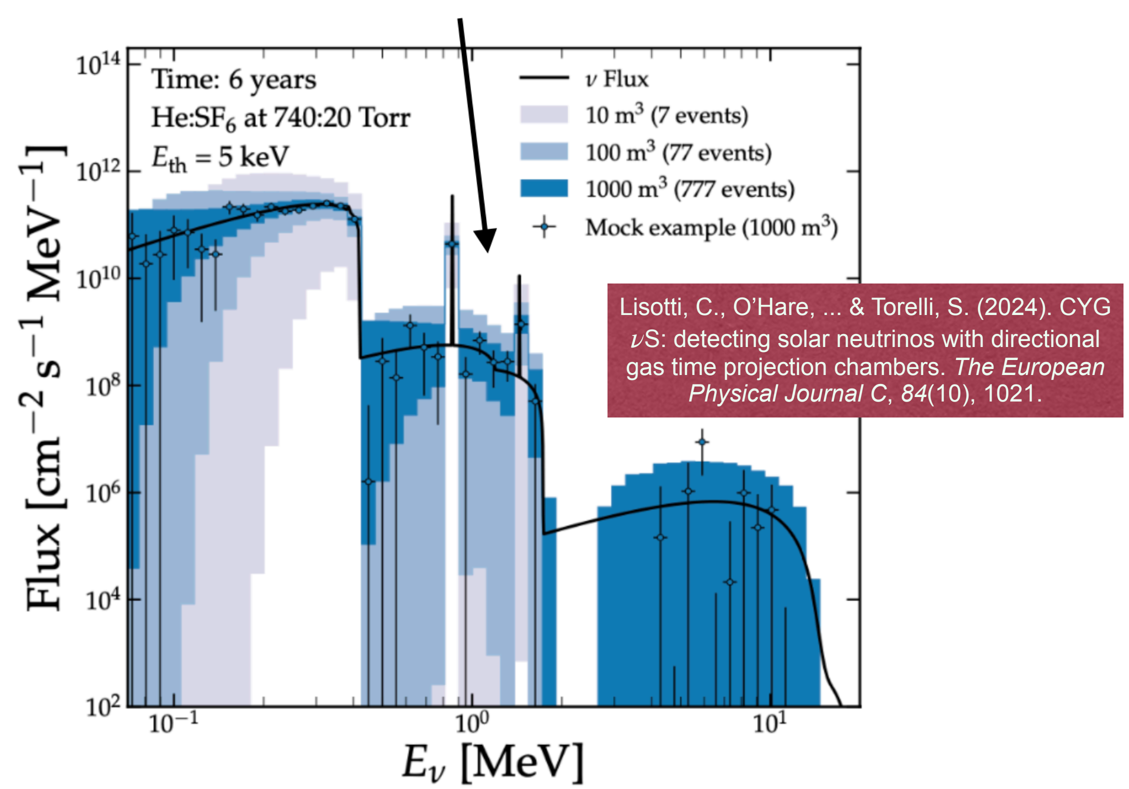
- Interests in:
  - Improve precision on the pp flux (Solar luminosity constraints)
  - Improve precision in CNO flux measurement (Metallicity problem)

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

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

Reconstruction of the original neutrino energy spectrum

Remove the spectral degeneracy of pep, ^{7}Be and CNO

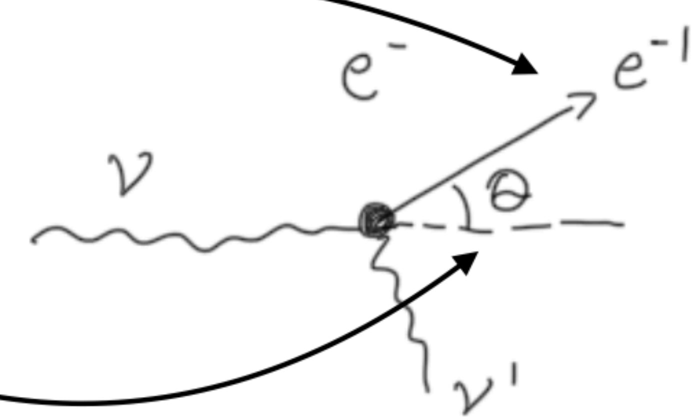


Feasibility study of a directional neutrino measurement

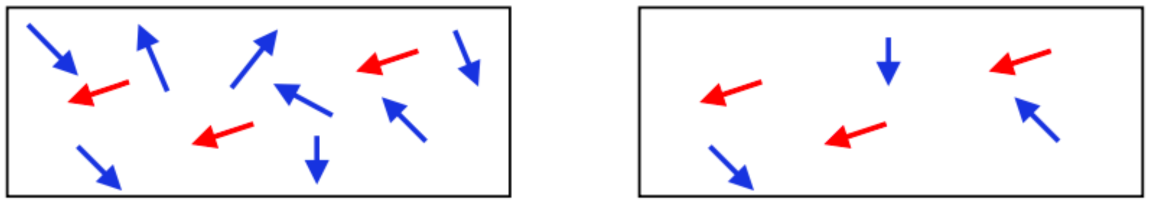
For this study 2 key elements critical to asses:

See D. Fiorina's presentation

1. Detector performances (energy and angular resolution)
   - CYGNO-30 will be composed by many CYGNO-04 modules, similar to LIME
   - Detector performances assessed on LIME
     - Energy resolution on X-Ray data in LIME
     - Angular resolution studies on LIME simulated tracks



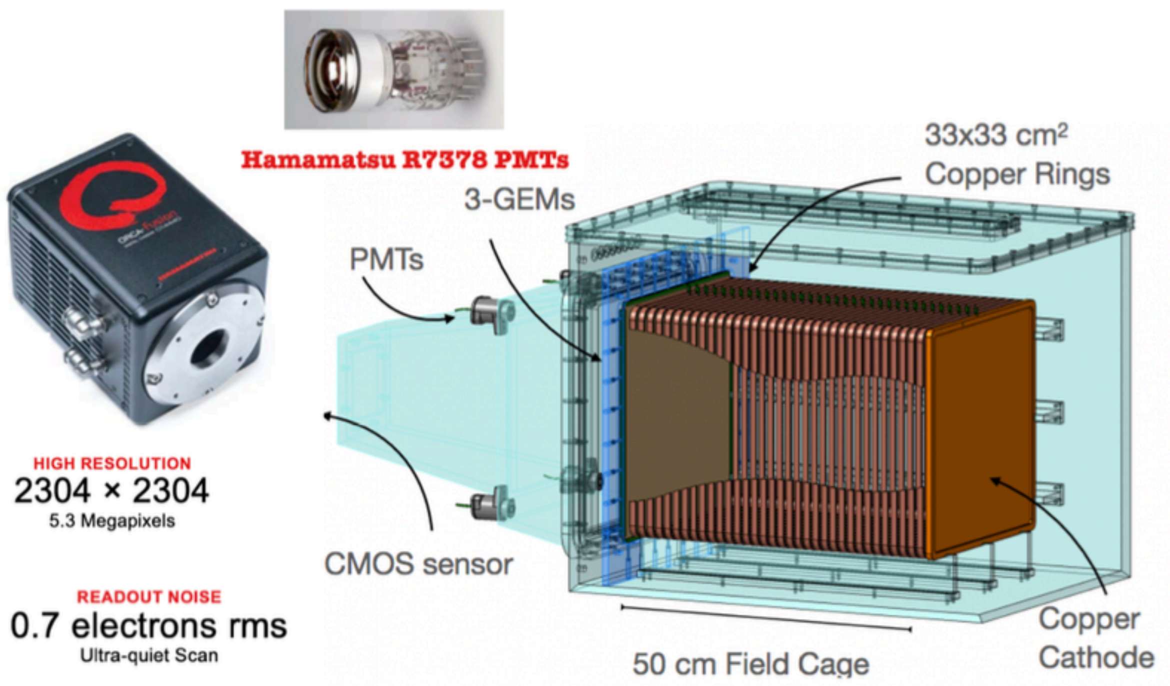
2. Electromagnetic background expected in the detector
   - CYGNO-30 conceptual design
   - Material and geometry "optimization"
   - GEANT4 simulation



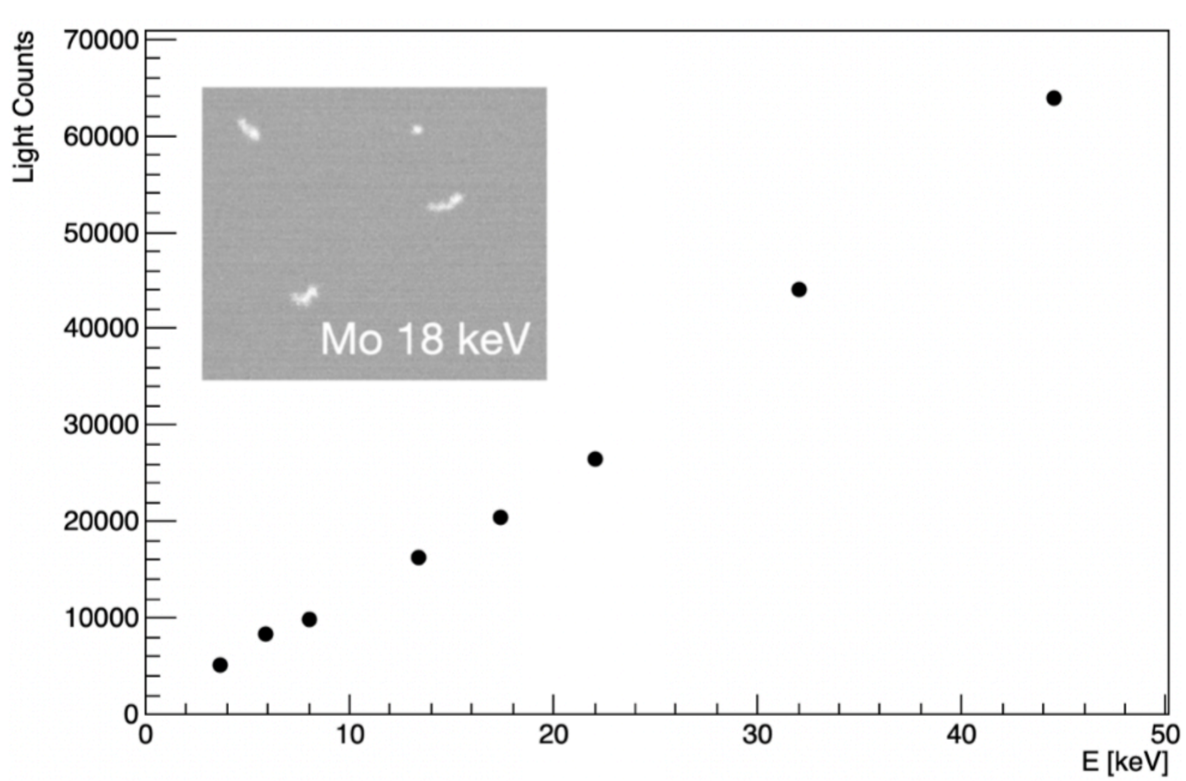
Step 1: Characterization of the detector response to low energy electron recoil

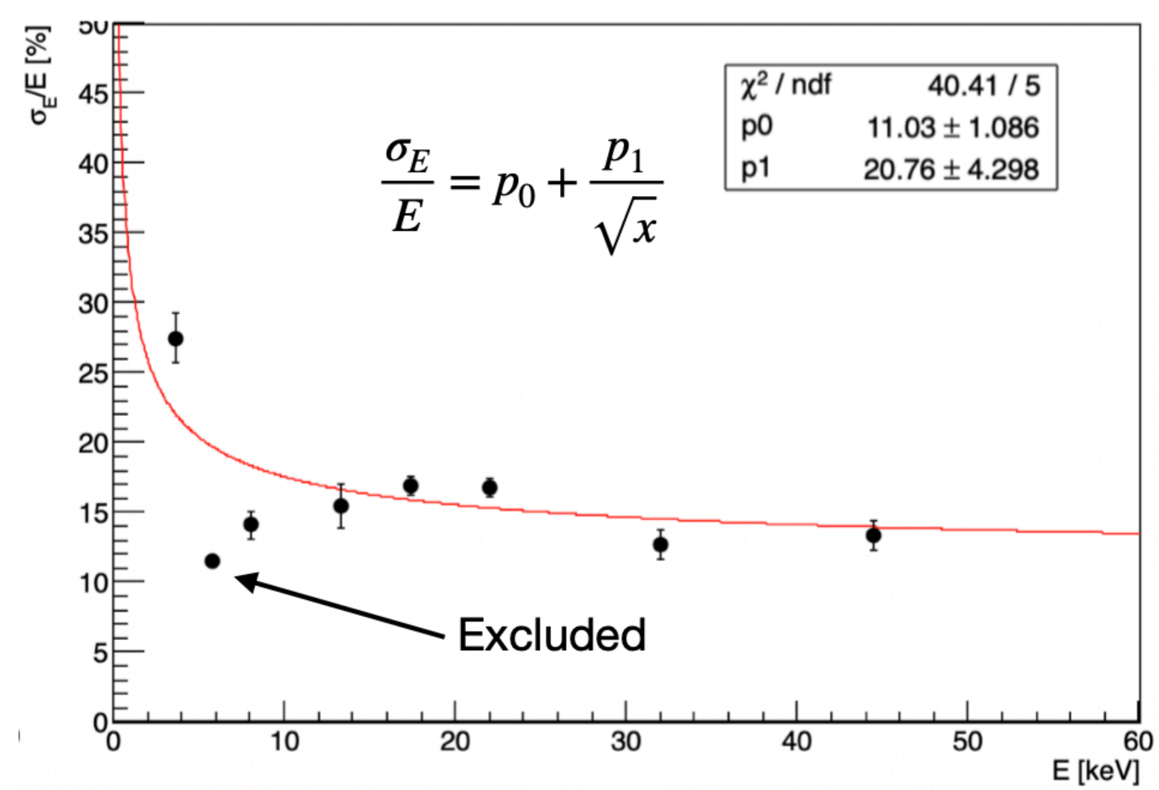
Multi-energy X-Ray analysis

- Study of response and energy resolution performed with LIME using different X-Ray sources



- LIME
  - 50 cm drift
  - Triple 33 x 33 cm 50 m GEMs
  - 50 liters sensitive volume (0.05 m)
  - 1 sCMOS camera (ORCA Fusion)
  - Camera images: 151 μm/pixel
  - 4 PMTs

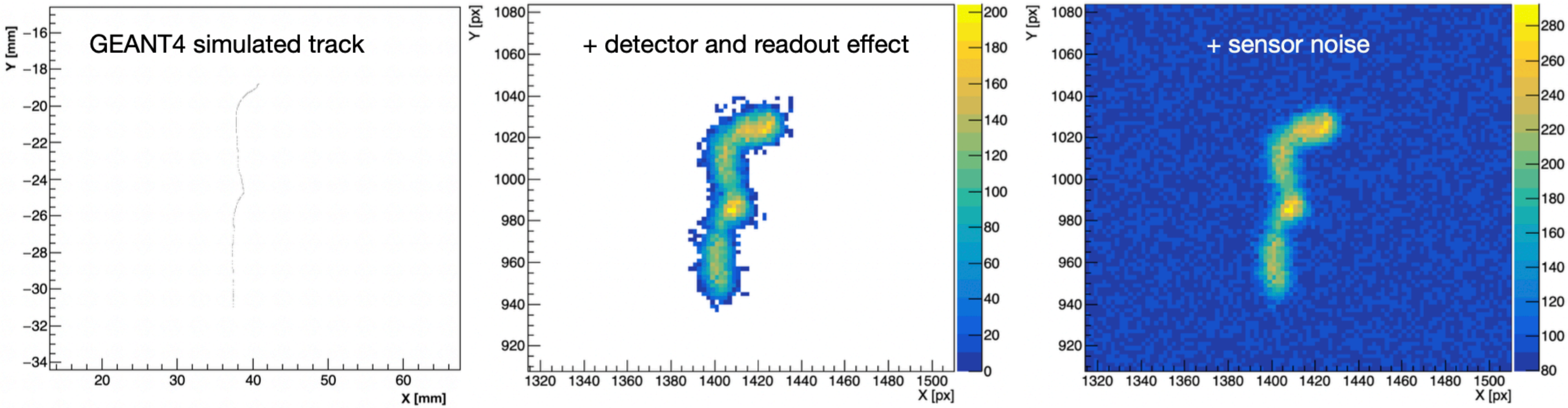




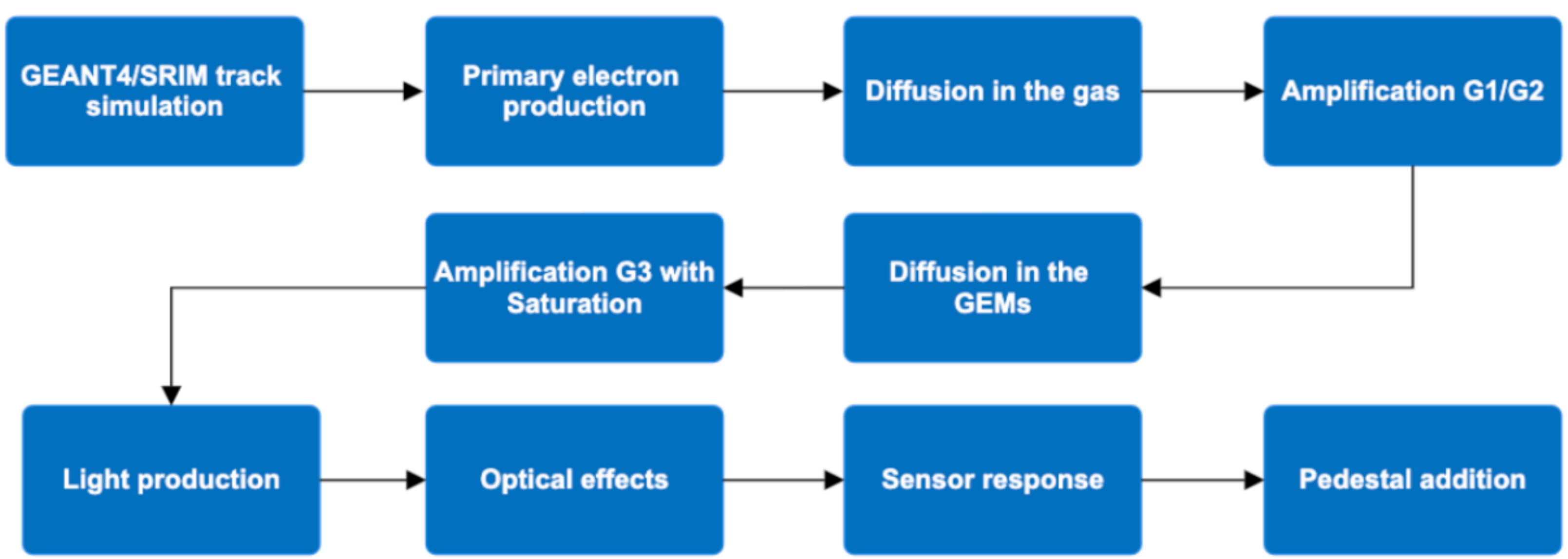
Step 2: Development of a simulation to produce low energy electron recoil sCMOS images

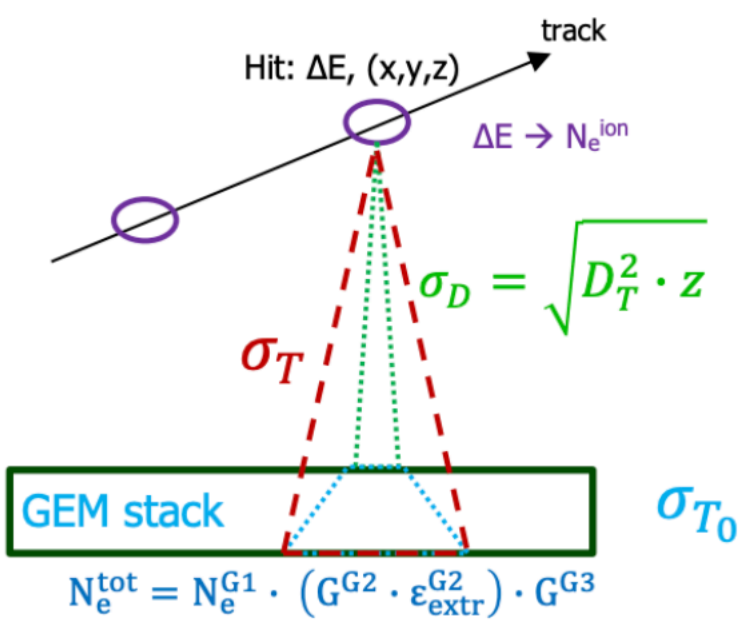
ER sCMOS images simulation

From a GEANT4 track — Detector response → To a sCMOS-like image



Workflow of the simulation (statistical effects included)

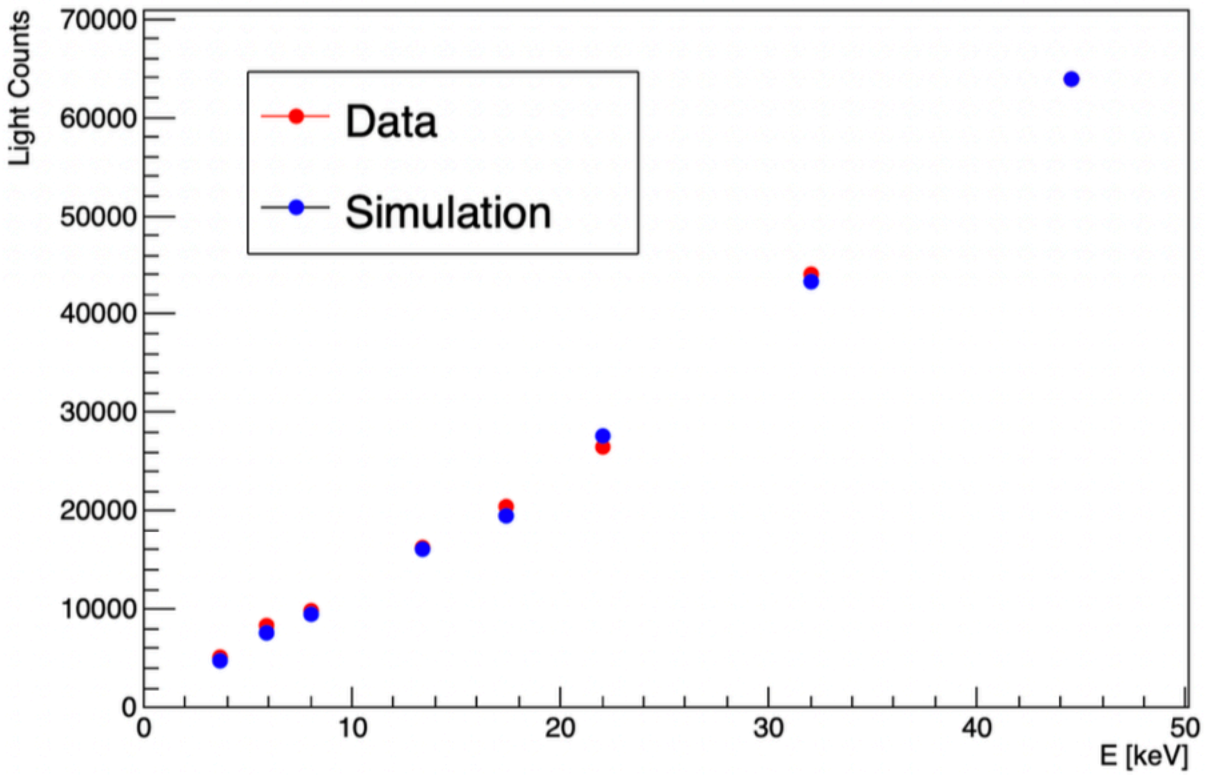


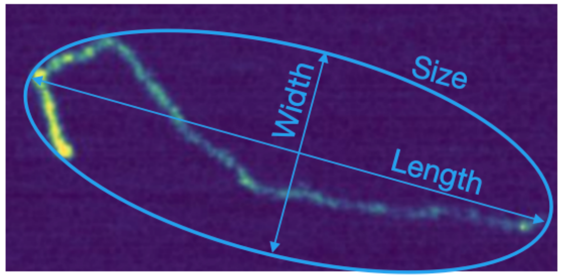


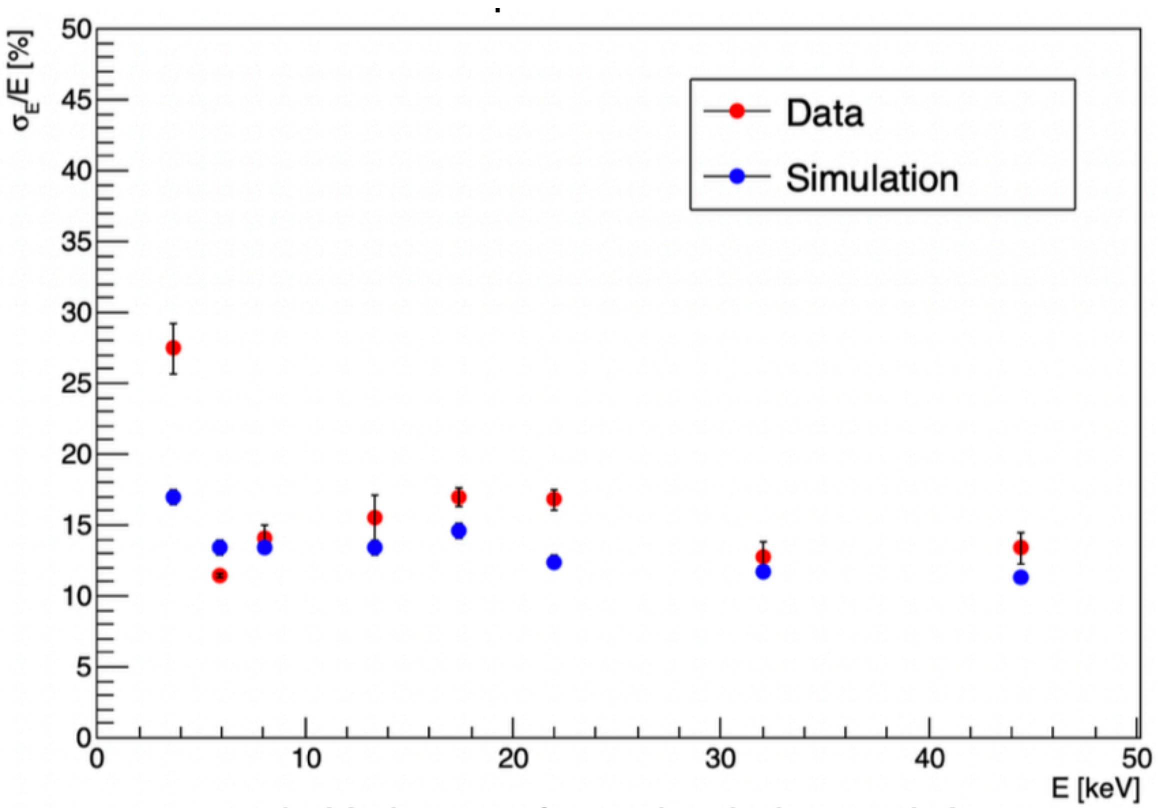
- Simulation parameters optimized on ^{55}Fe data

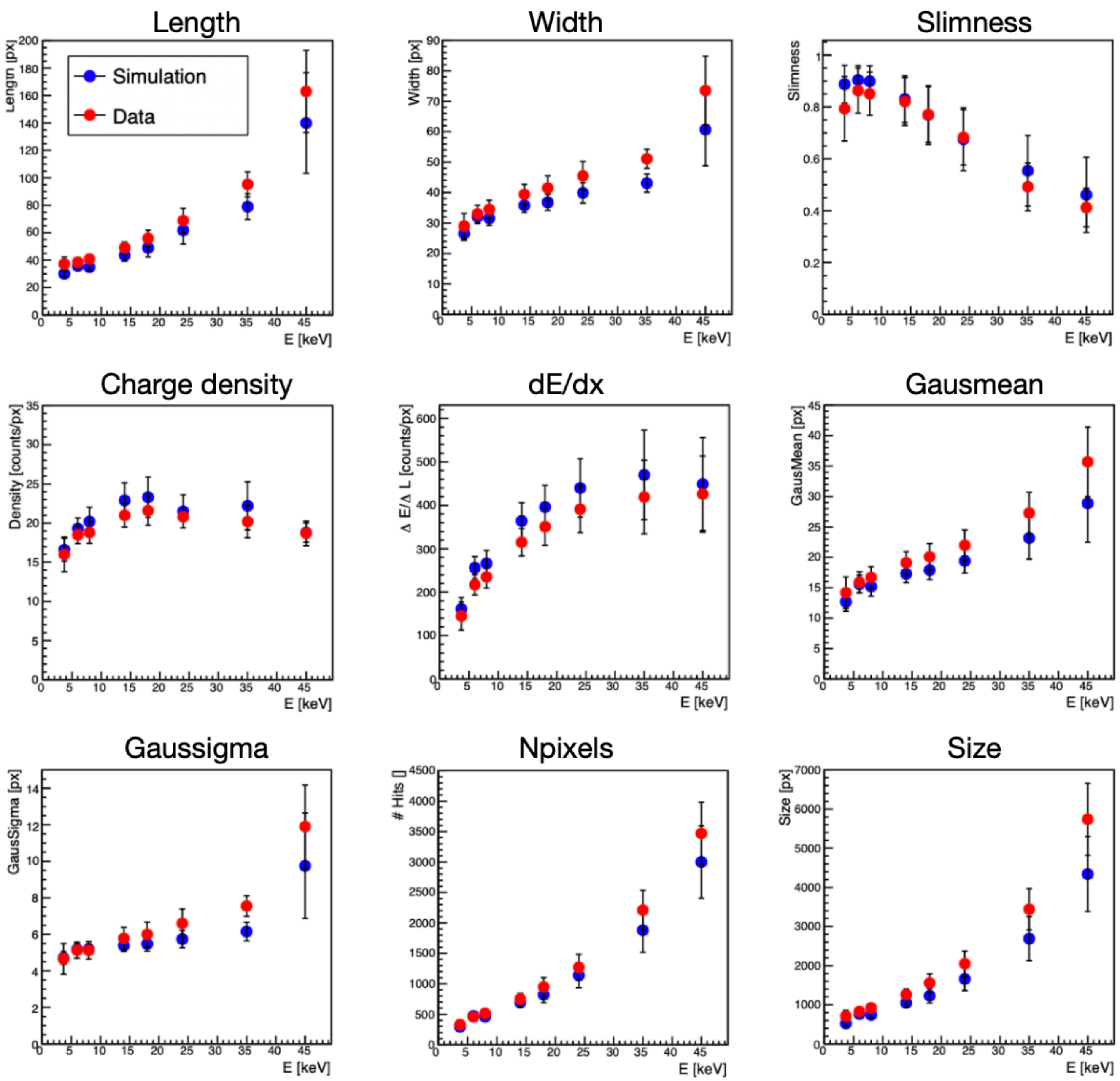
Data MC comparison

- Data-MC agreement in response, energy resolution, and a set of 9 shape variables







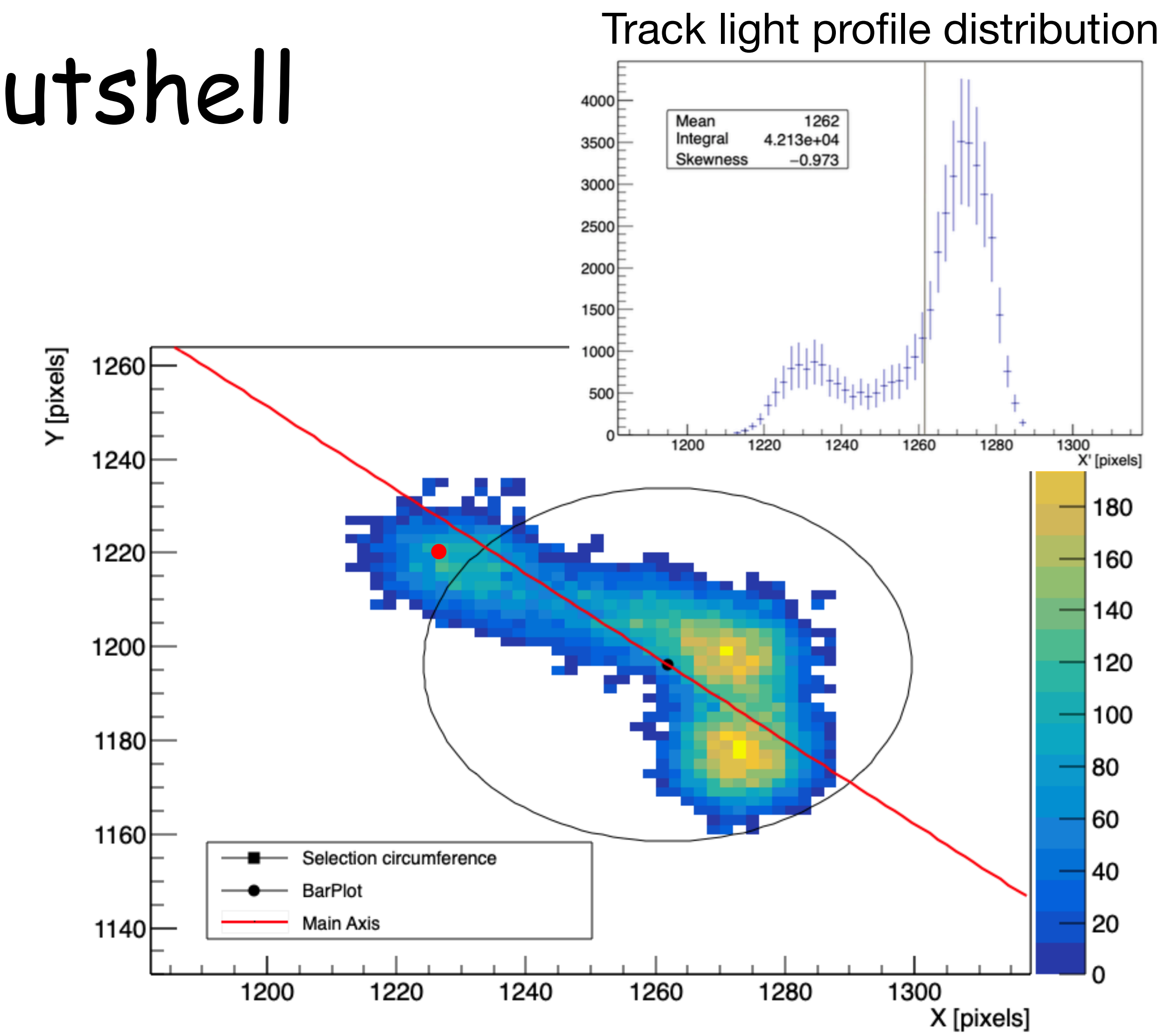


Step 3: Study the 2D angular resolution performances on electron recoils

Directionality algorithm in a nutshell

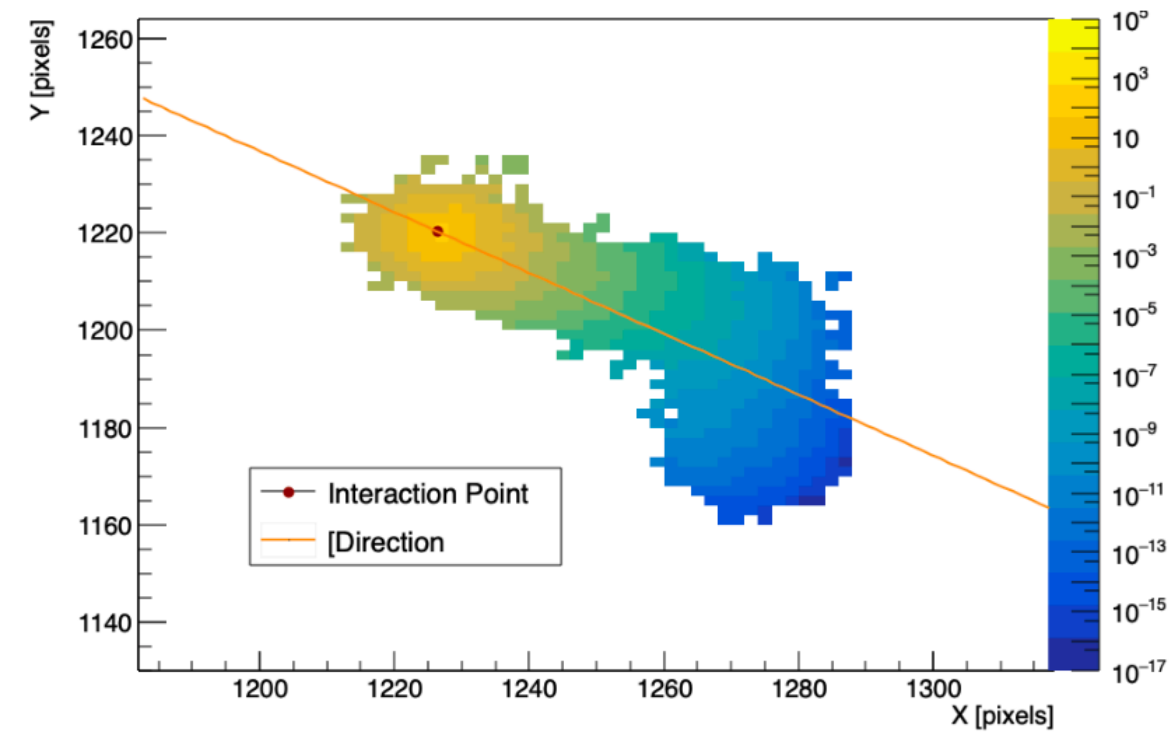
- Algorithm adapted from X-ray polarimetry:

Soffitta, Paolo, et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 700 (2013): 99-105.



1. Searching for the beginning of the track with:
   - Skewness
   - Distance of pixels from barycenter (farthest pixels)
   - Selection of a region with fixed number of points N_{pt}

2. Find the track 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

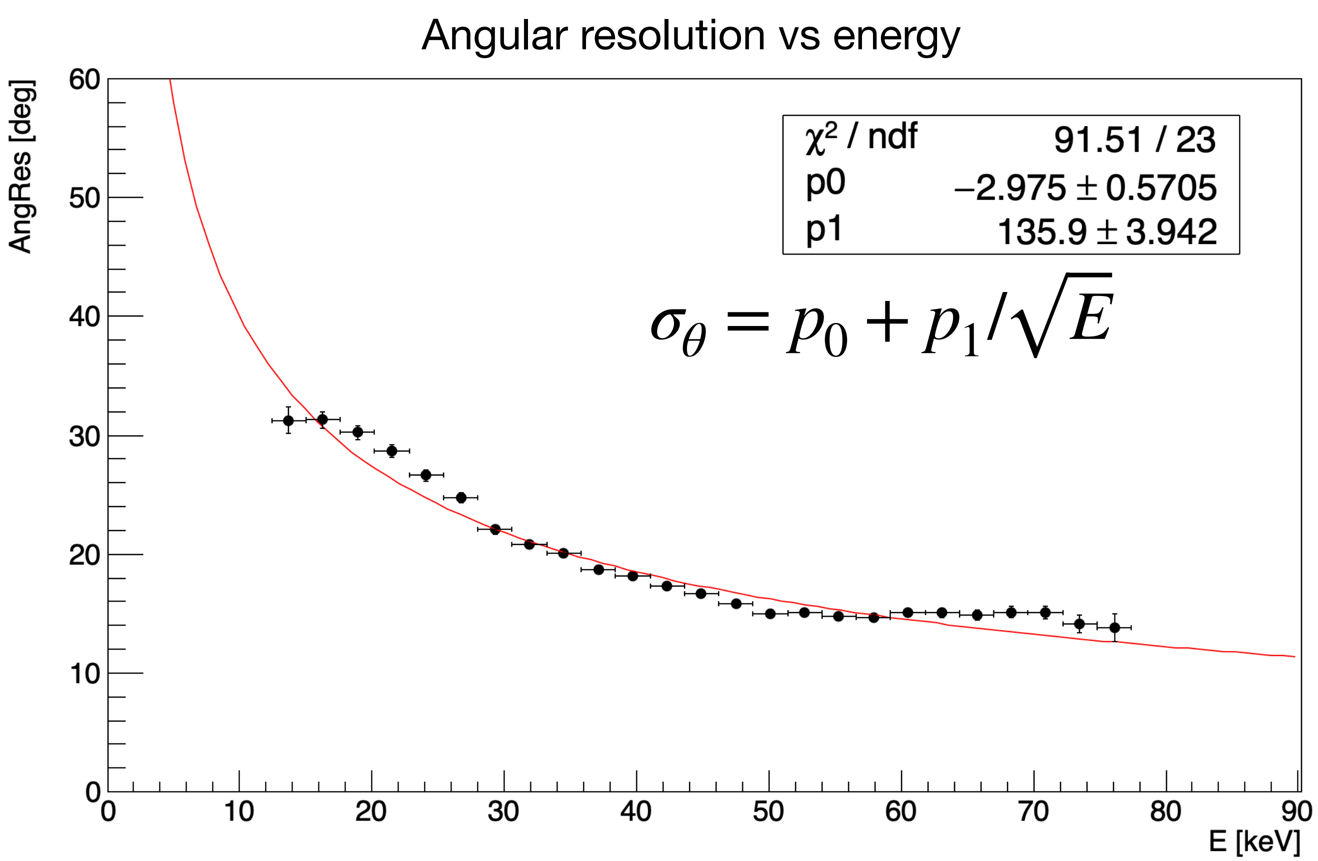


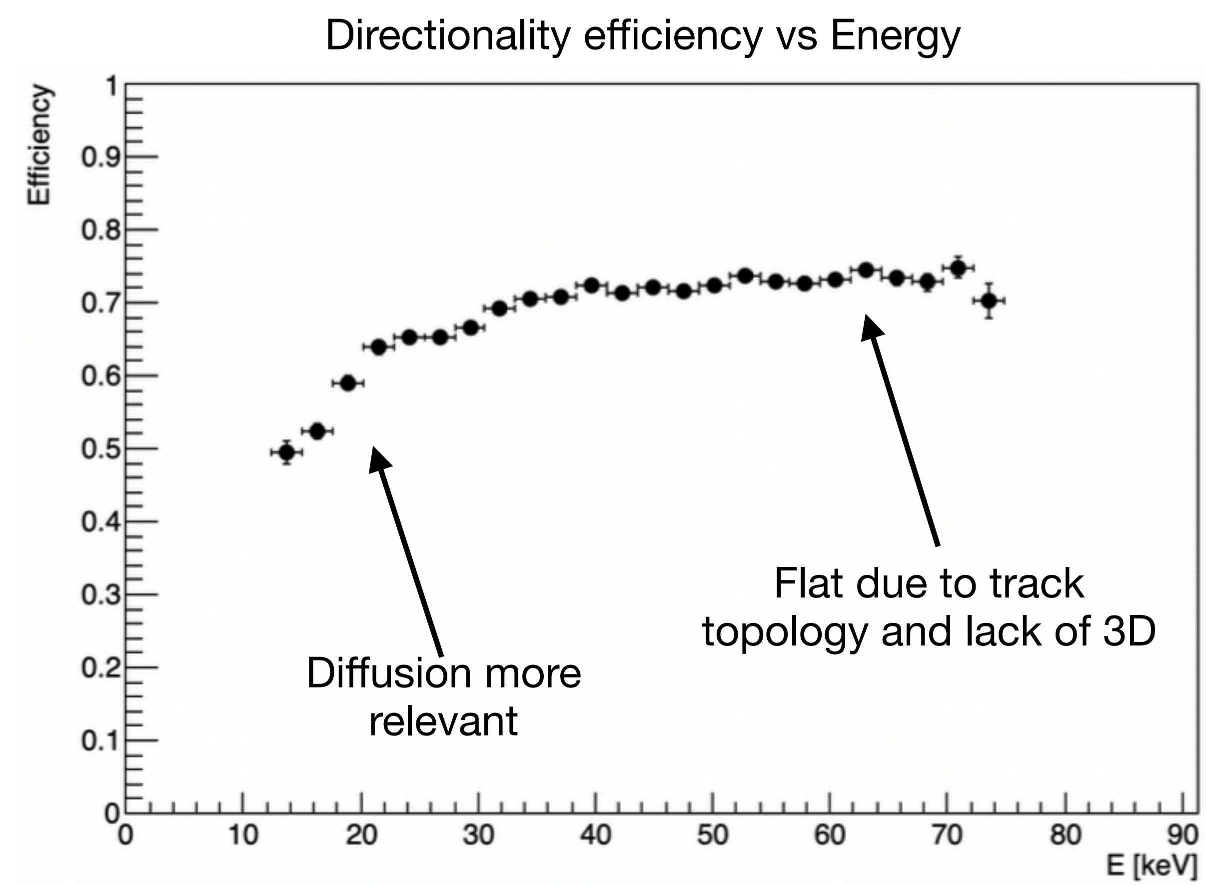
- Two parameters of the algorithm: N_{pt} and w

Results on angular resolution

Paper in preparation

- Angular resolution performances evaluated on a dataset with uniform energy tracks [16-70] keV
- For each track the parameters were set qual to ones of the closest energy





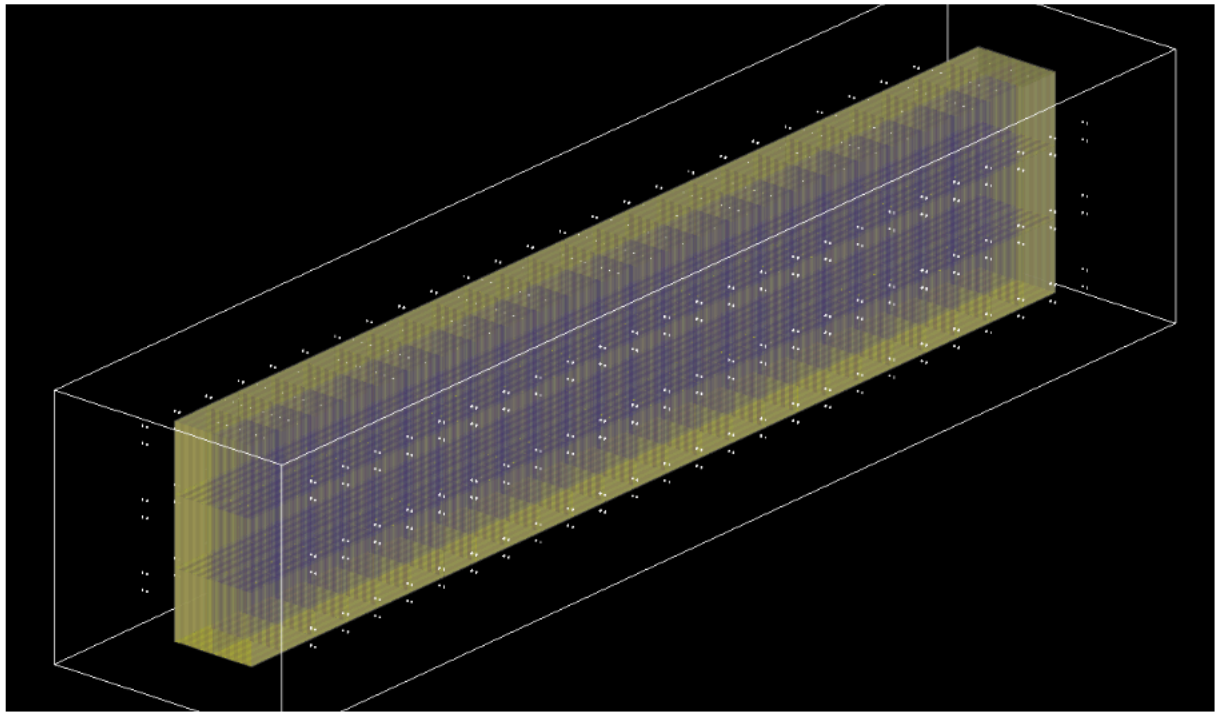
- First angular resolution result in this energy range
- Negative coefficient p_0 but it is expected to saturate at a value $\neq 0$ at higher energy

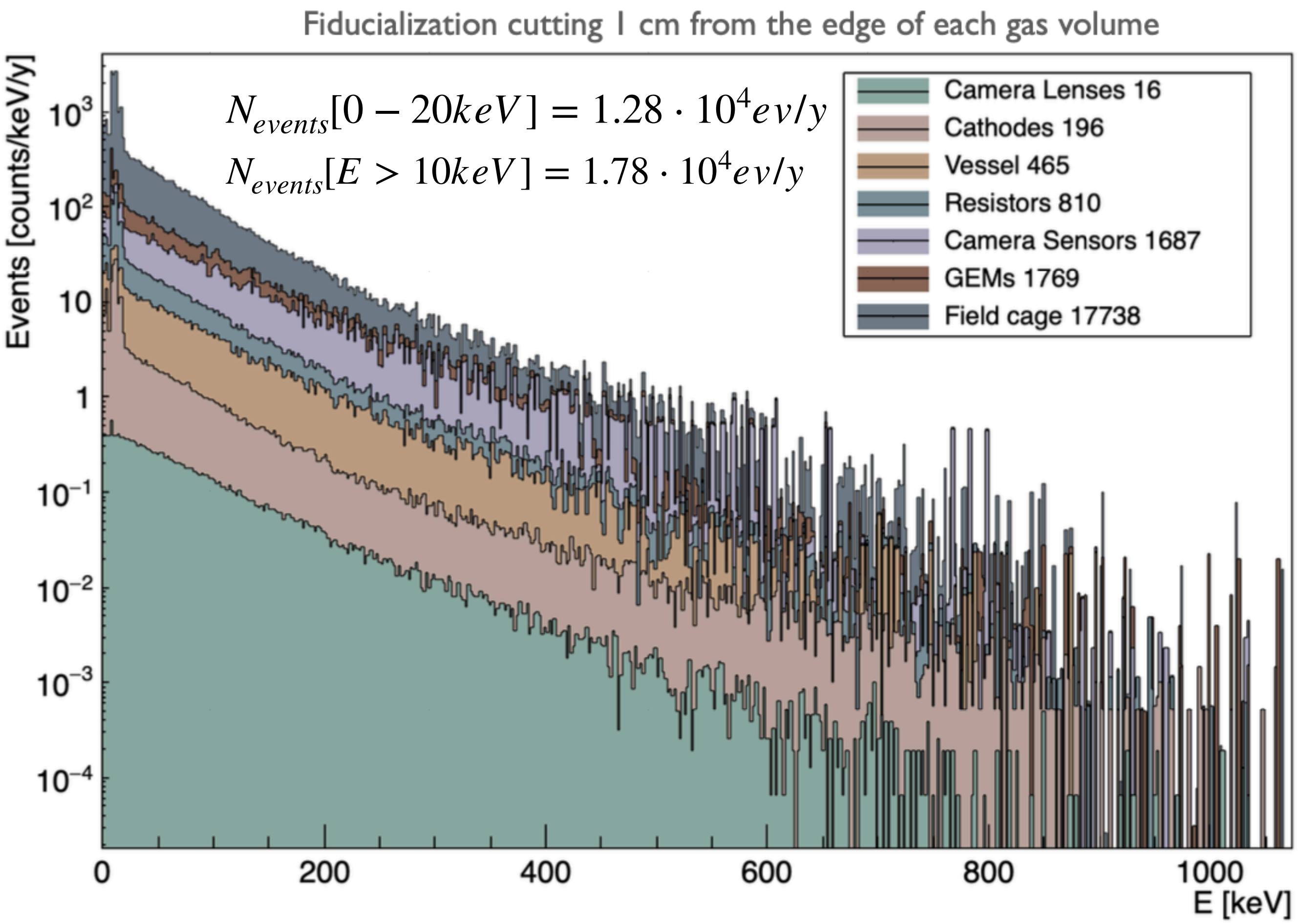
Step 4: Sensitivity studies for solar pp neutrinos with CYGNO 30 m^3

Background studies

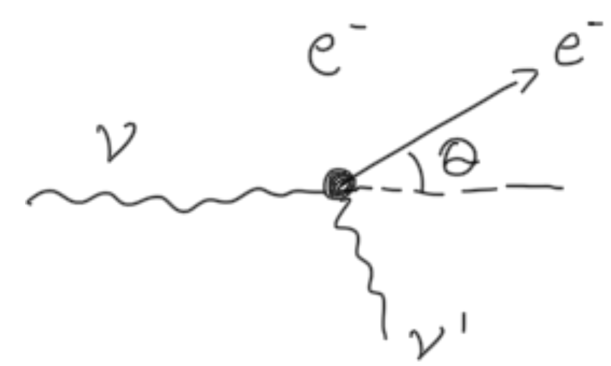
- Bkg simulation of the full detector geometry
- Three rows stack on each other with 25 CYGNO-04 modules
- Simulated all the components that have been observed to contribute the most in LIME
- Simulation done with most ultrapure materials available
- Field cage acrylic is the dominant contribution (x10)
- Recently found a new one x10 less radioactive

Arnquist, Isaac J., et al. "Ultra-low radioactivity Kapton and copper-Kapton laminates." *Nuclear Instruments and Methods*





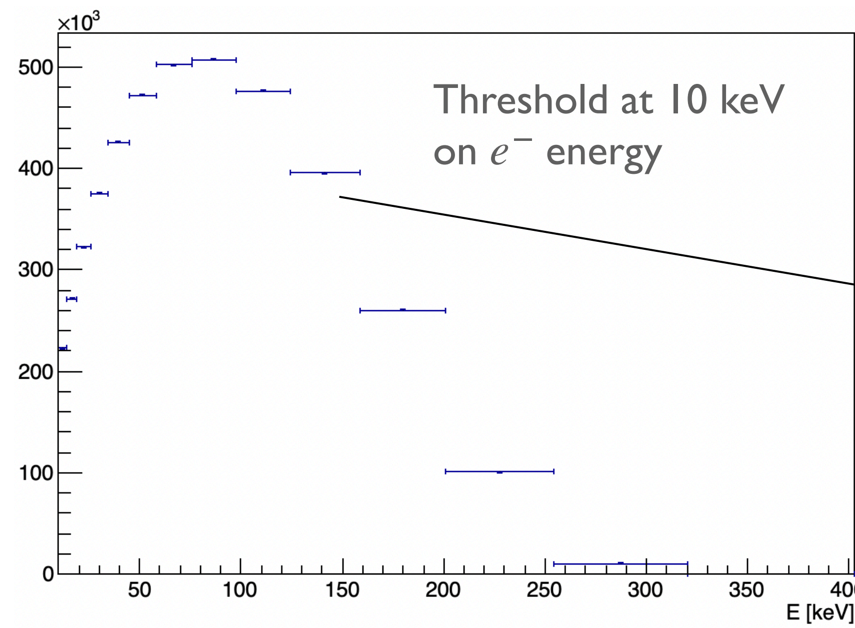
Template for bayesian analysis

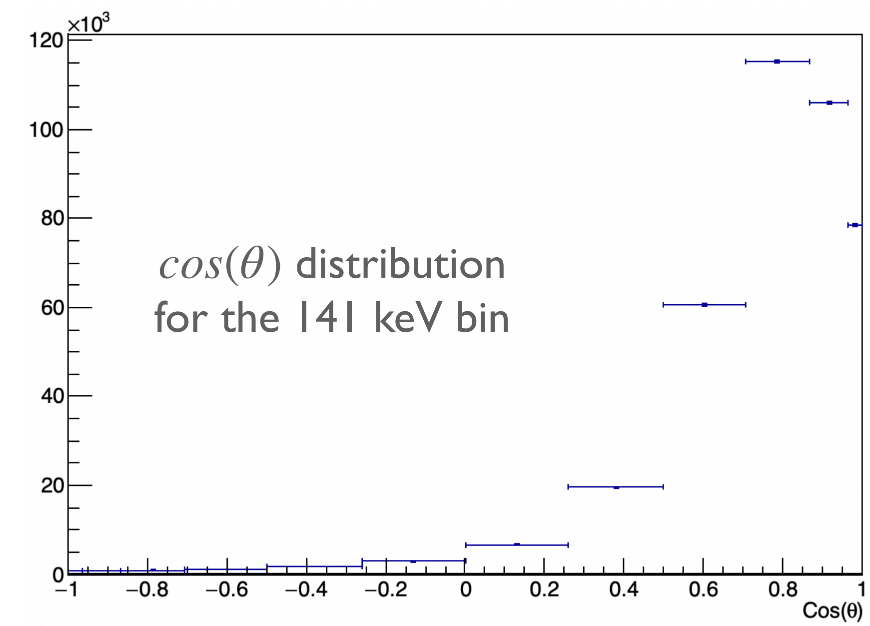


- Template produced starting from the expected distribution adding the detector resolution
  - Both the energy and angular spectrum in the Sun's reference frame are considered
  - For each energy bin the cos(θ) distribution is produced

- Signal

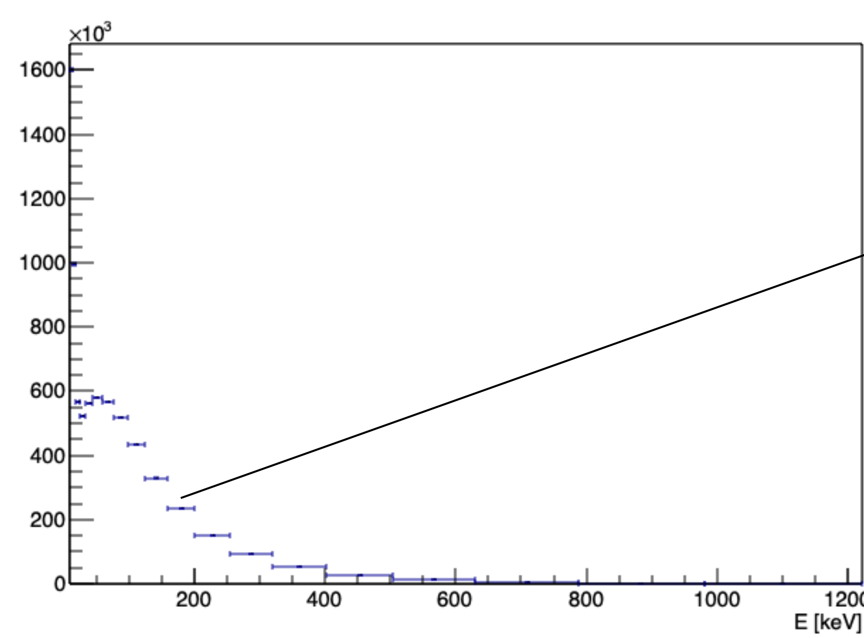
Produced starting from the pp chain neutrino spectrum, simulating the interaction and adding the detector resolution

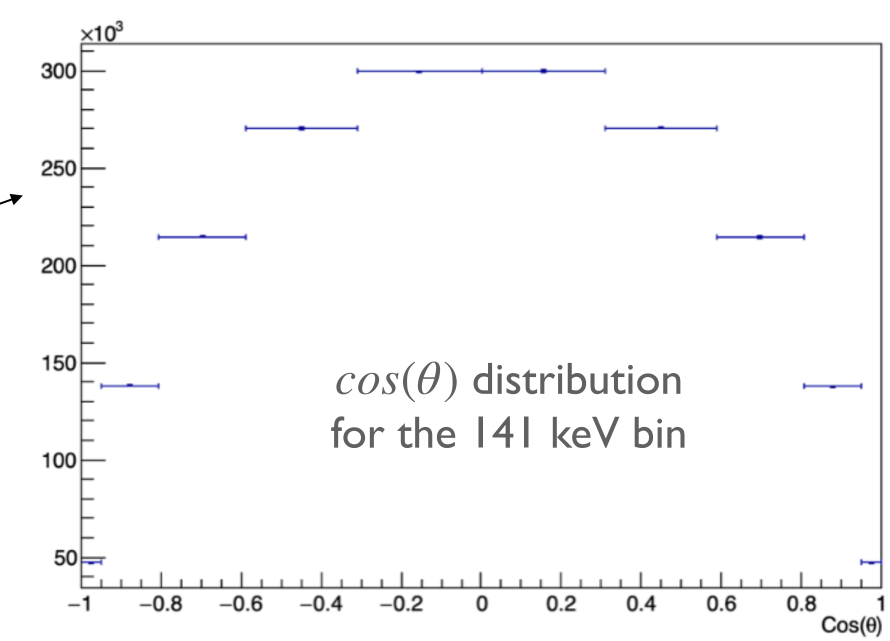




- Background

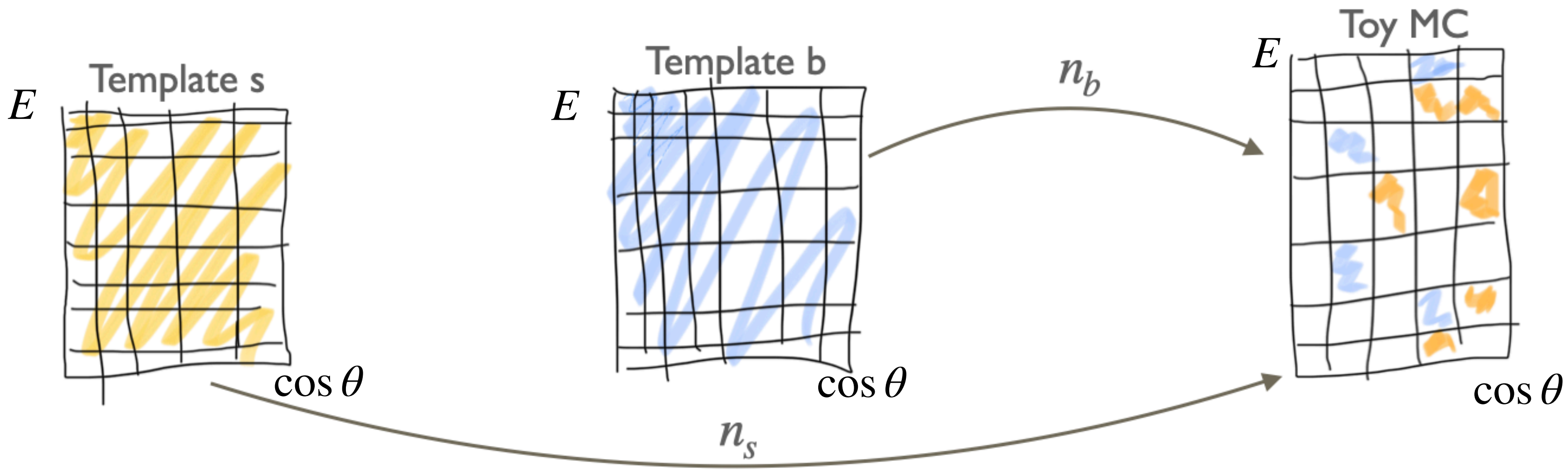
From CYGNO_30 background simulation, assuming an isotropic angular distribution





Toy-MC analysis

- Toy-MC generated by a hypothesis of expected number of events, extracting poissonianly the values of n_s and n_b, and filling an E-cos(θ) histogram with the extracted events from the templates



$$\bar{N}_s = 30ev/y \cdot exp$$

$$\bar{N}_b = 1.78 \cdot 10^4 ev/y \cdot exp \;/\; R_f$$

- Each toyMC fit with B (H_0) model and S+B (H_1) model

- Calculation of the Bayes factor: $$\frac{p(H_1|D)}{p(H_0|D)} = \frac{\int \mathscr{L}(D|\mu_b, \mu_s, H_1)\pi(\mu_b)\pi(\mu_s)d\mu_b d\mu_s}{\int \mathscr{L}(D|\mu_b, H_0)\pi(\mu_b)d\mu_b} \cdot \frac{\pi(H_1)}{\pi(H_0)} = B_f \frac{\pi(H_1)}{\pi(H_0)}$$
  0.5/0.5

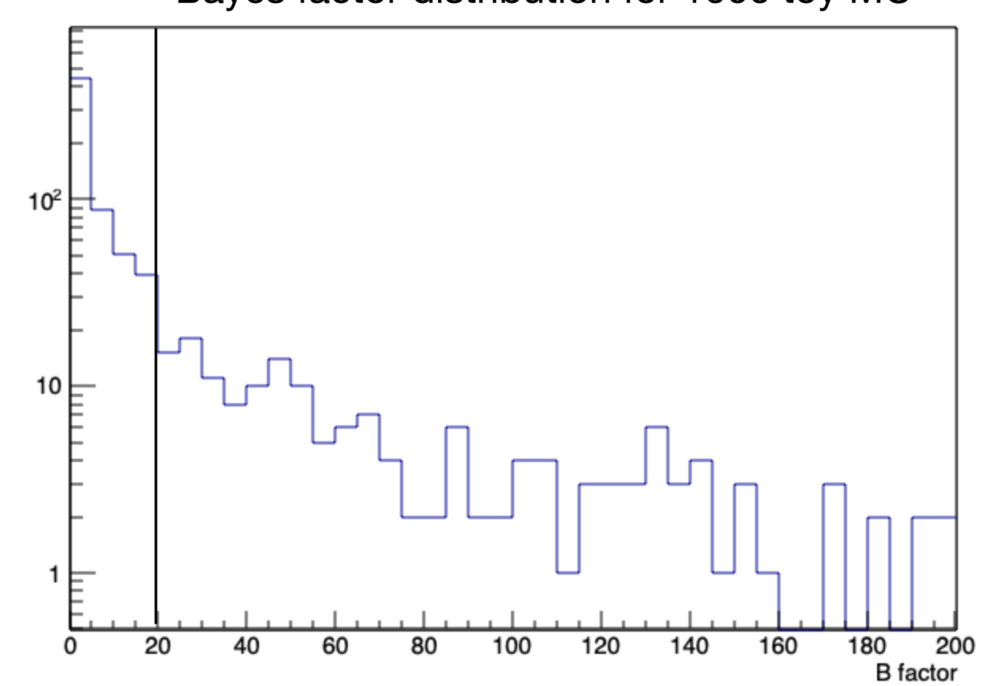
- Discovery probability with a BF>20 (=3σ confidence level): $$DP(exp, R_f) = \frac{N_{toy}(BF > 20)}{N_{toy}}$$

- Sensitivity studied as a function of detector exposure from 0.5 to 10 years.

- Given possible future reduction of materials radiopurity, not possible to predict today, sensitivity evaluated in various background reduction scenario

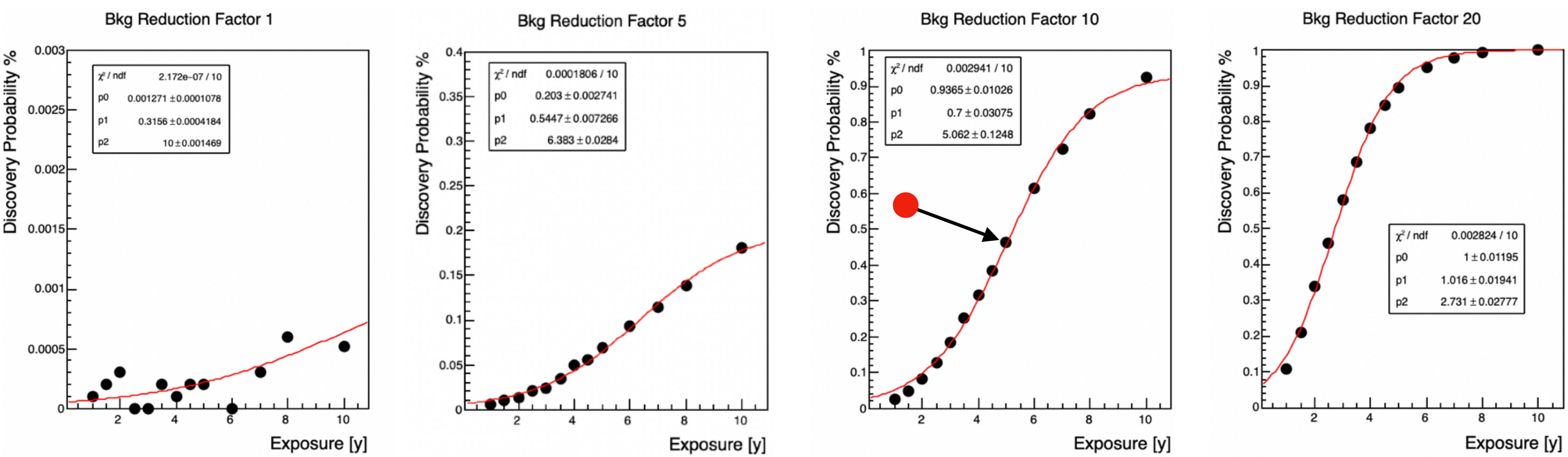
- 10000 Toy MC produced for each configuration

Bayes factor distribution for 1000 toy MC



Sensitivity results

- Plot of the discovery probability with BF>20 as a function of the exposure for different further background reduction



- With a further bkg reduction of a factor 10, in 5.5 y there is a 50% probability of collecting data for which the S+B model is at least 20 times (3σ) more probable than the only B model

$\overline{B}_{10}$	$\ln \overline{B}_{10}$	sigma	category
2.5	0.9	2.0	
2.9	1.0	2.1	'weak' at best
8.0	2.1	2.6	
12	2.5	2.7	'moderate' at best
21	3.0	3.0	
53	4.0	3.3	
150	5.0	3.6	'strong' at best
43000	11	5.0	

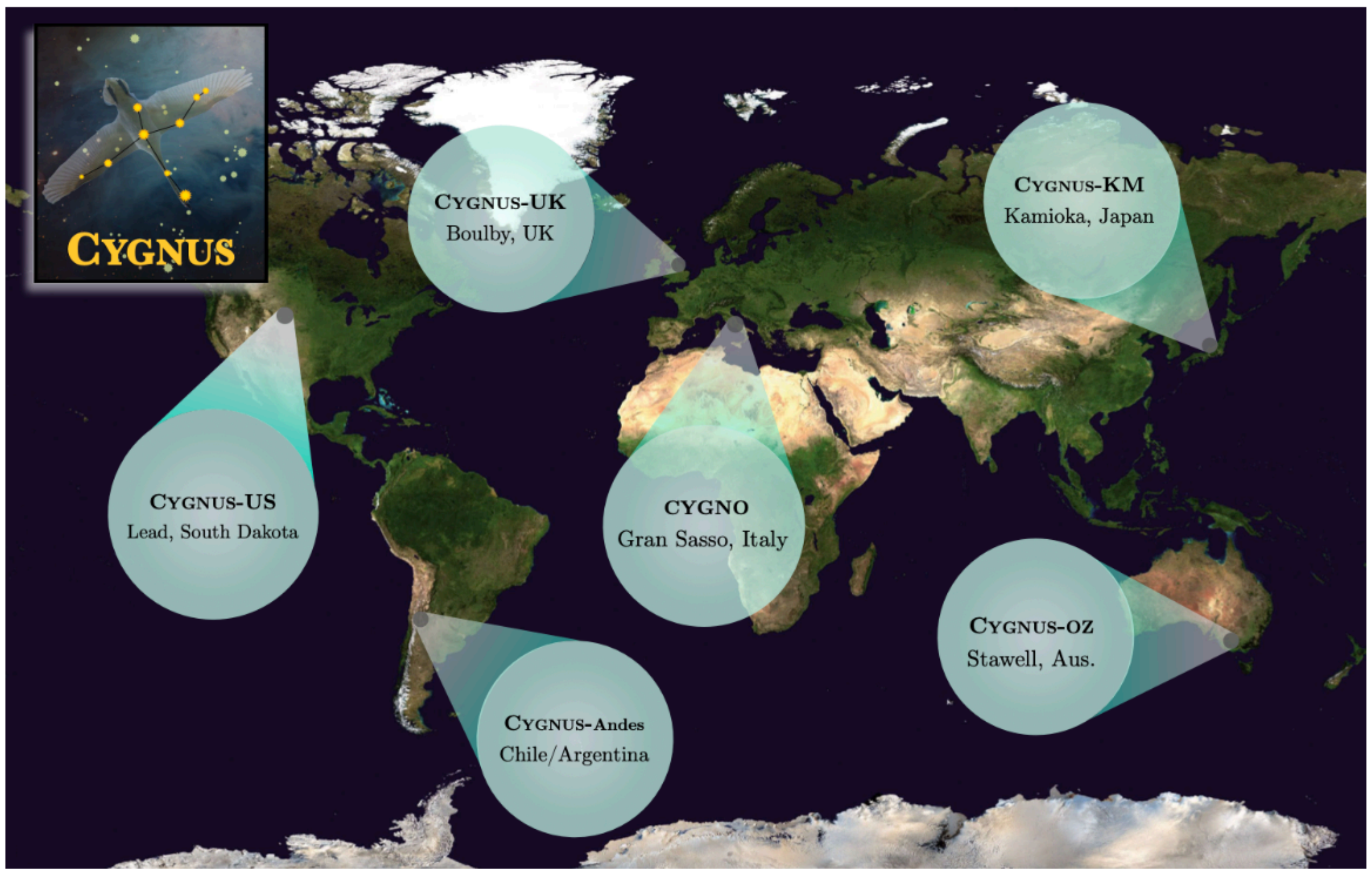
Trotta, Roberto. "Bayes in the sky: Bayesian inference and model selection in cosmology." *Contemporary Physics* 49 (2008): 104 - 71.

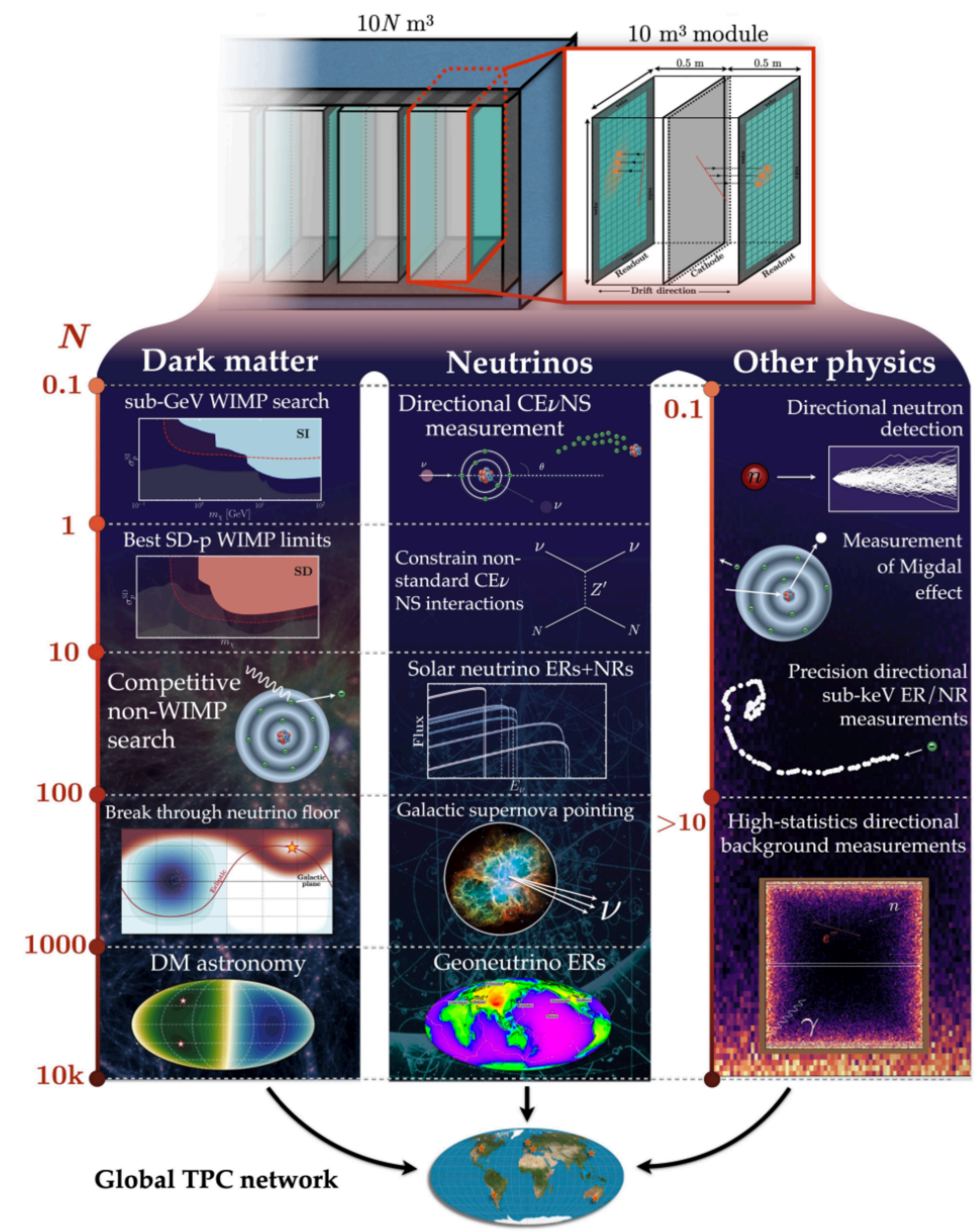
- Exposure corresponding to165 neutrino signal over 9790 ev. of background
- Equivalent to a rate Bgk/Signal $\simeq$ 60, very strong background toleration
- Borexino in the pp measurement had a ratio Bgk/Signal $\simeq$ 2.3

Future in the CYGNUS protocollaboration

O'Hare, C. A. J., et al.
arXiv:2203.05914

- The CYGNUS protocollaboration could point on this idea for the future alongside with DM





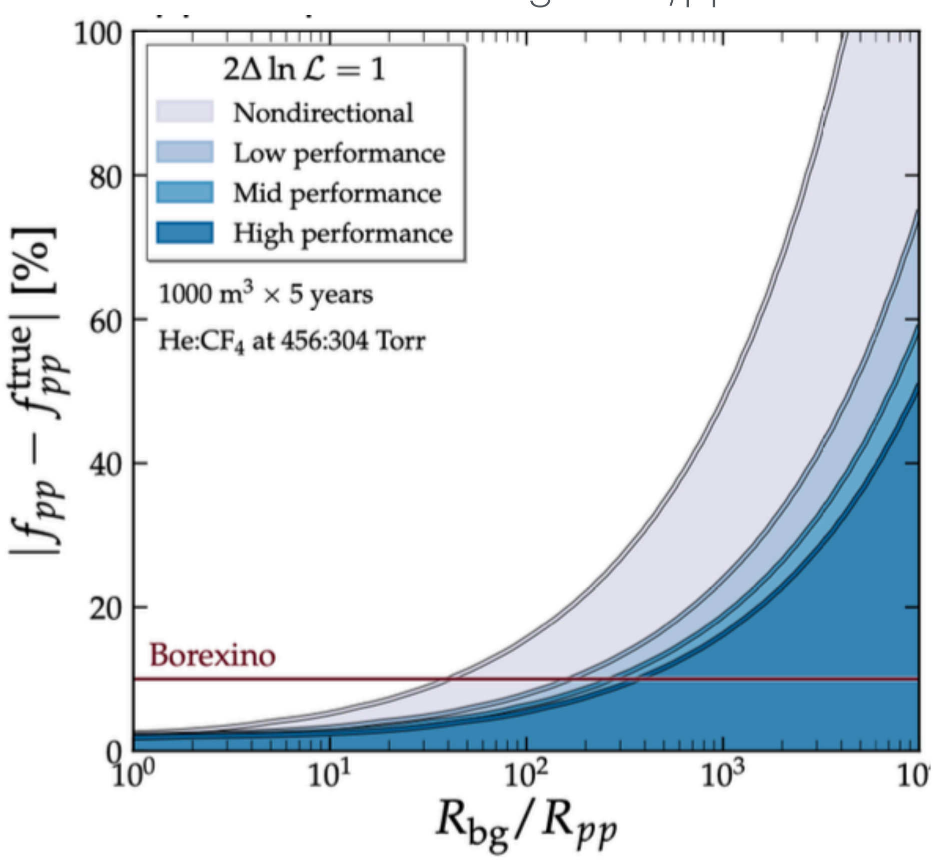
- After a CYGNO 30 m^3, within the context of CYGNUS, this physics case can be pursued at larger exposures

- With modularity and multisite distribution the goal of a $\mathcal{O}(1000\ m^3)$ TPC network can be feasible

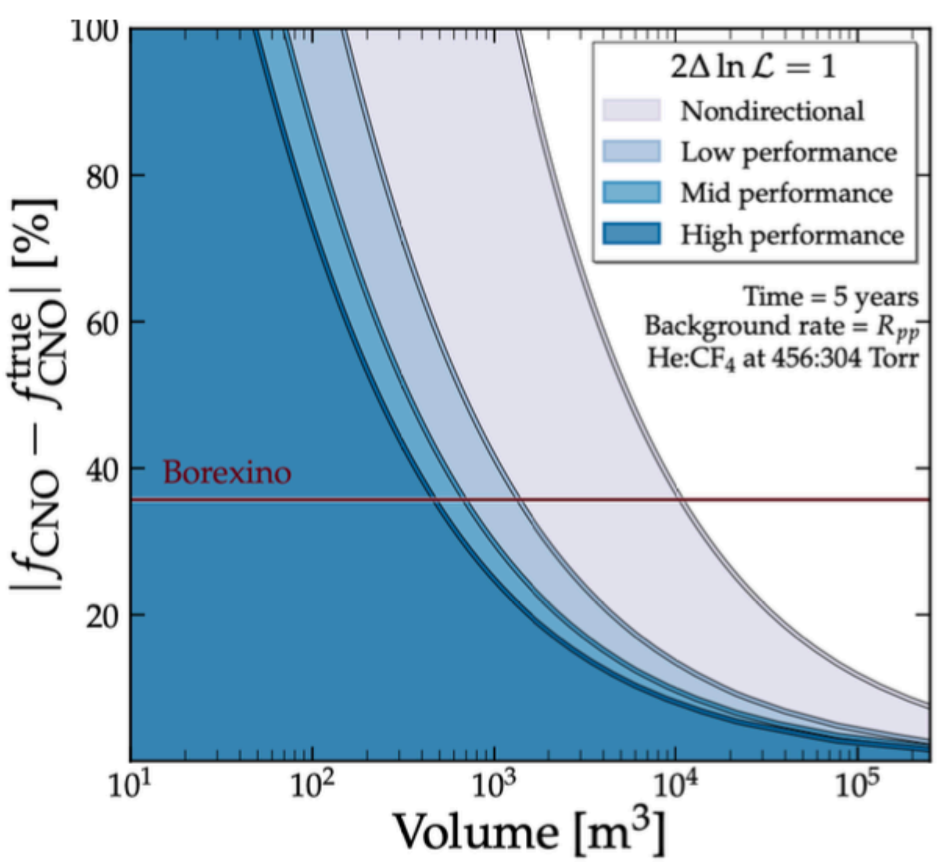
Prospects of higher volume detectors

- Projection for the precision of a pp and CNO flux measurement in CYGNUS:

Precision vs background/pprate



Precision vs detector volume



Lisotti, C., O'Hare, ... & Torelli, S. (2024). CYGνS: detecting solar neutrinos with directional gas time projection chambers. *The European Physical Journal C*, *84*(10), 1021.

- CYGNO already within high and mid performance in angular resolution and low to mid in E resolution

- Future experiments with higher volumes and lower background levels can be competitive

Conclusions on the feasibility of a directional solar neutrino measurement

- Solar neutrinos has been proposed as object of study with directional TPC approach trough $\nu - eES$
- Directionality can increase the bkg toleration and can allow for spectroscopic measurement of solar neutrinos

In this work the feasibility of an observation of solar neutrino from the pp cycle with the CYGNO 30 m^3 detector has been investigated

- The energy response and resolution of the 50L prototype have been studied and a simulation able to reproduce electron tracks has been developed
- In this context an algorithm to measure directionality of low energy electrons has been developed and optimised for CYGNO, and the angular resolution performances have been studied
- A simulation of the background expected in a CYGNO-30 detector has been performed and together withe the detector performances will serve as benchmark for the whole CYGNUS collaboration
- As a result of this thesis work a CYGNO-30 experiment can perform an observation with 3σ sensitivity at 10 keV threshold in 5.5y if the background can be constrained to ~10^3 events/y
- This highlight the high discriminating power of the directionality capable of distinguishing 165 signal events over 9680 background events tolerating $R_{B/S} \sim 60$ (Borexino had 2.3 on the pp)
- This is a feasibility study with the status of art of the detector - NO optimization has been made specifically

Thank you for you attention

Everything in detail in: https://www.arxiv.org/abs/2408.03760

Acknowledgements:

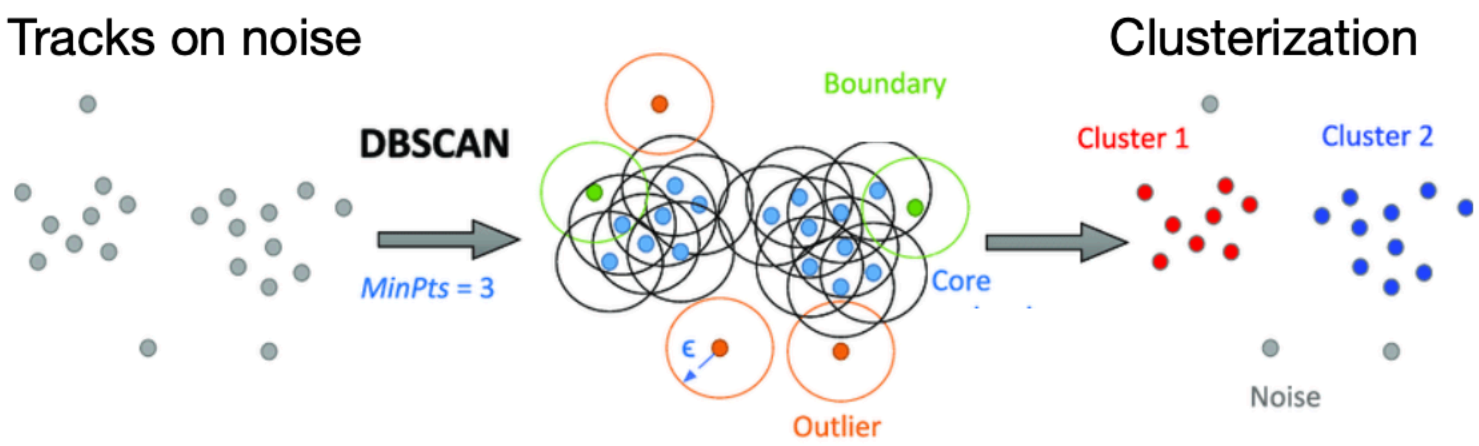
This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the European Research Council (ERC) grant agreement No 818744 and from the Italian Ministry of Education, University and Research through the project PRIN: Progetti di Ricerca di Rilevante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

Backup

Track reconstruction code

F D Amaro,..., S. Torelli,..., et al 2023 Meas. Sci. Technol. 34 125024

- Reconstruction algorithm based on the Density-Based Spatial Clustering of Applications with Noise (DBSCAN)



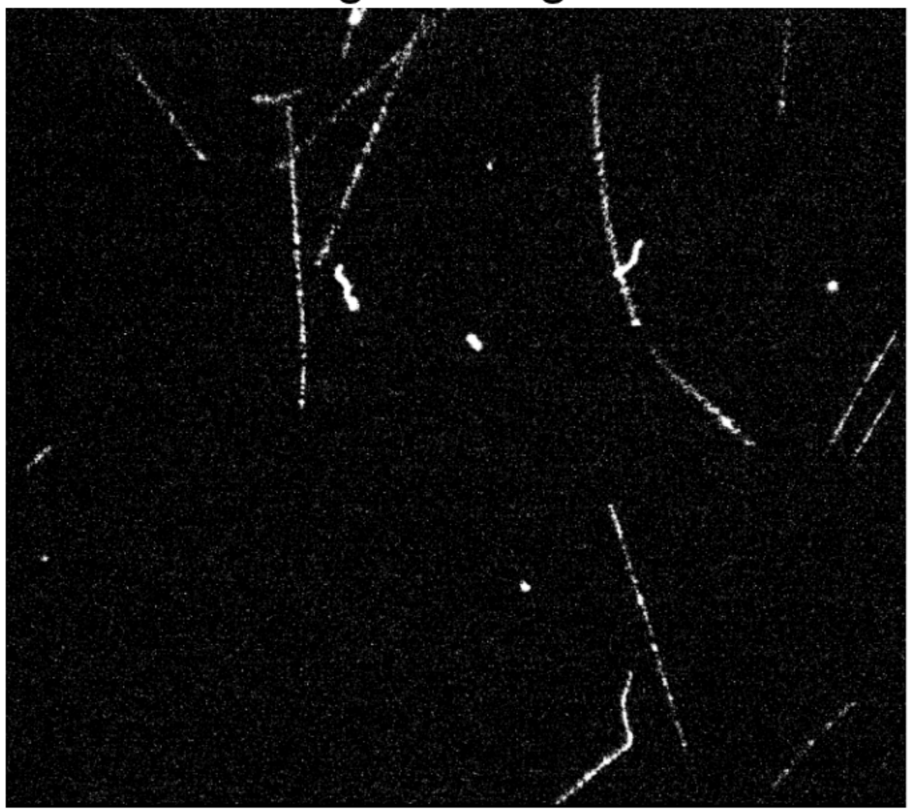
- A pixel-intensity based version of DBSCAN is used

- First iteration of directional iDBSCAN to reconstruct long and straight tracks 1st and 3rd degree polynomial

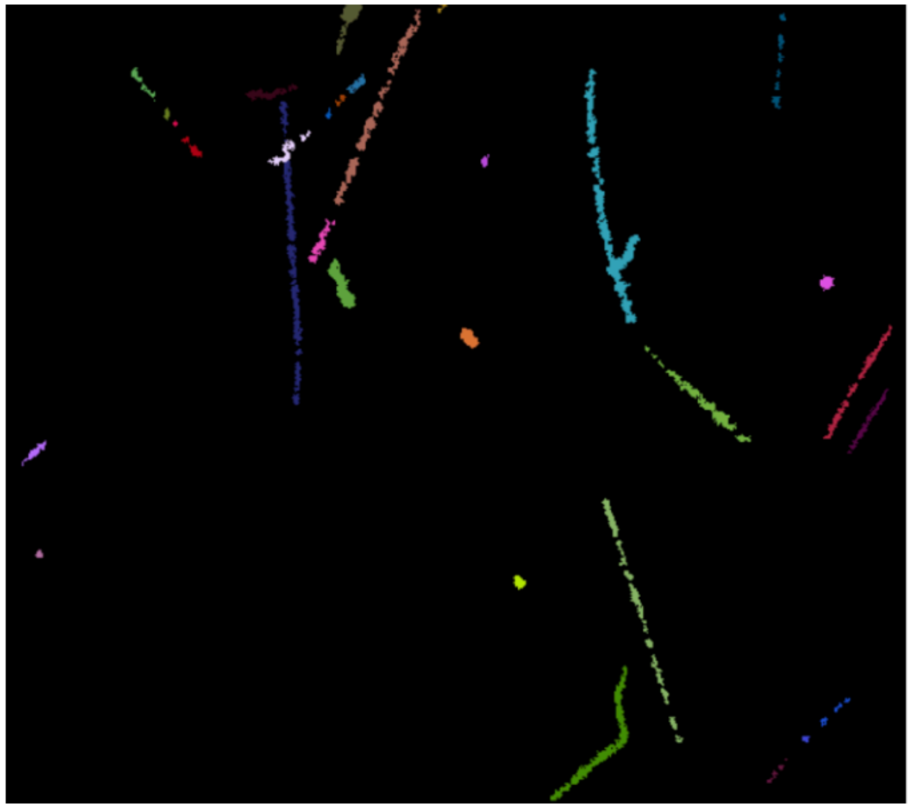
- Remaining tracks reconstructed with iDBSCAN

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

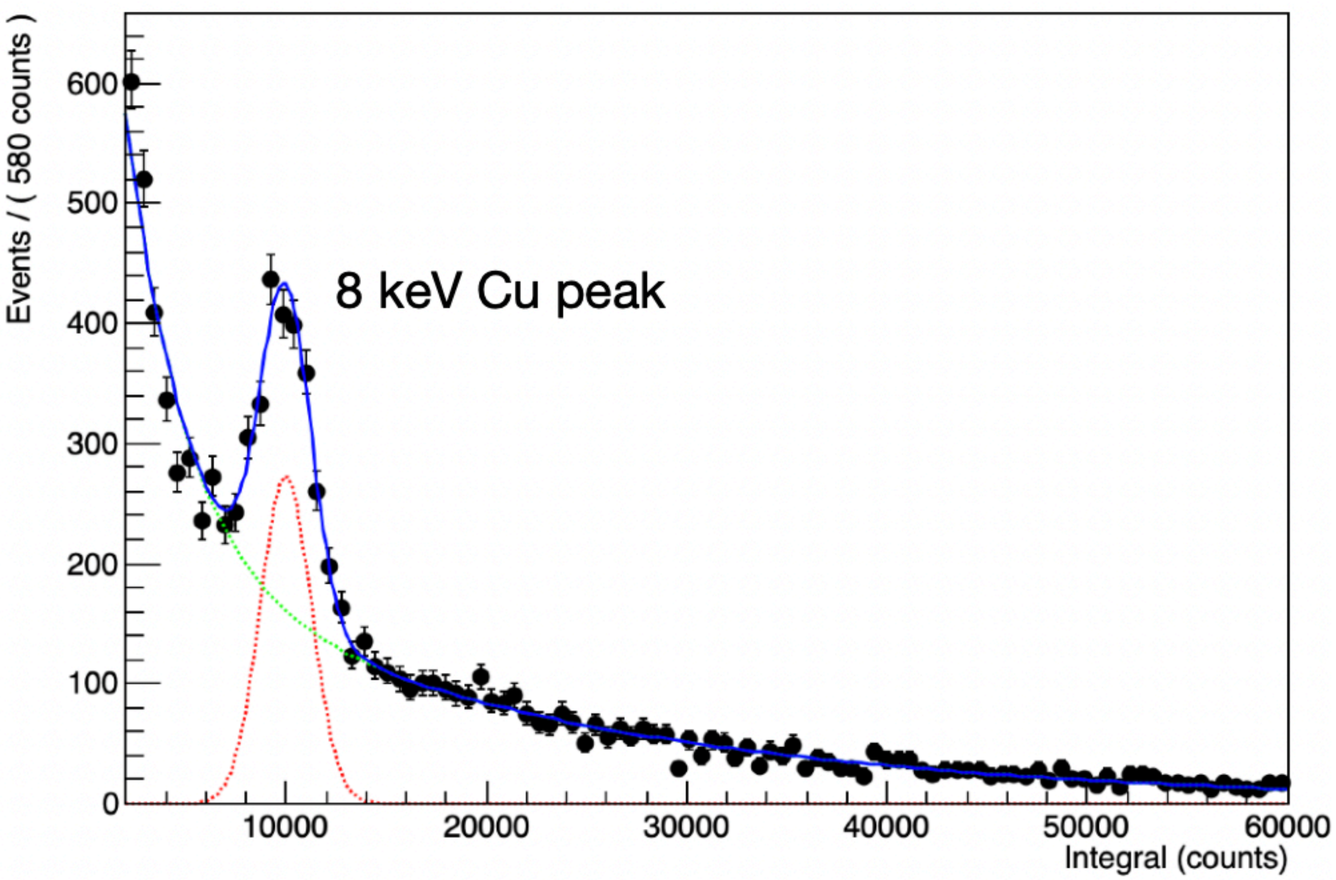
Original image



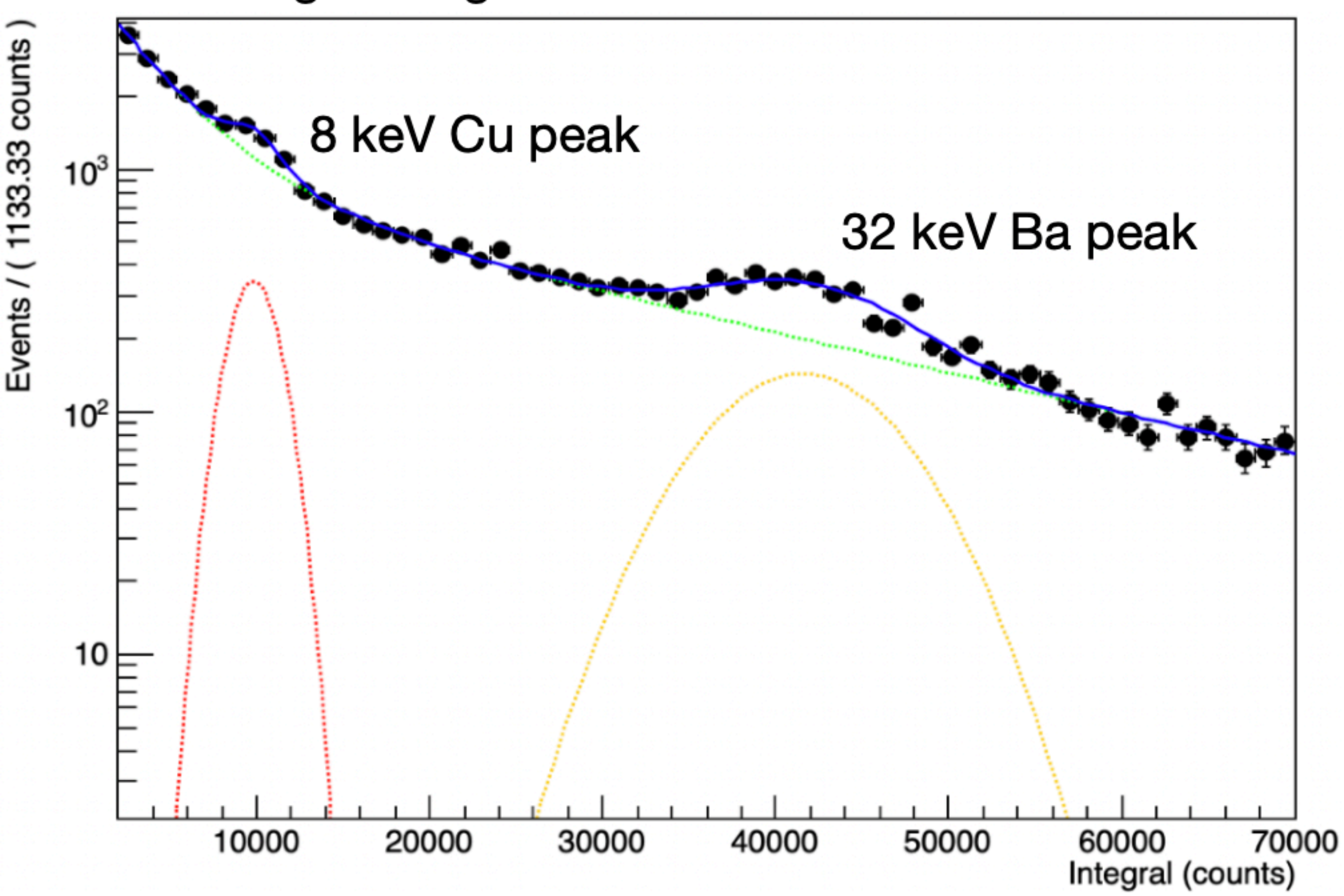
Tracks reconstructed



Light integral distribution Cu dataset



Light integral distribution Ba dataset

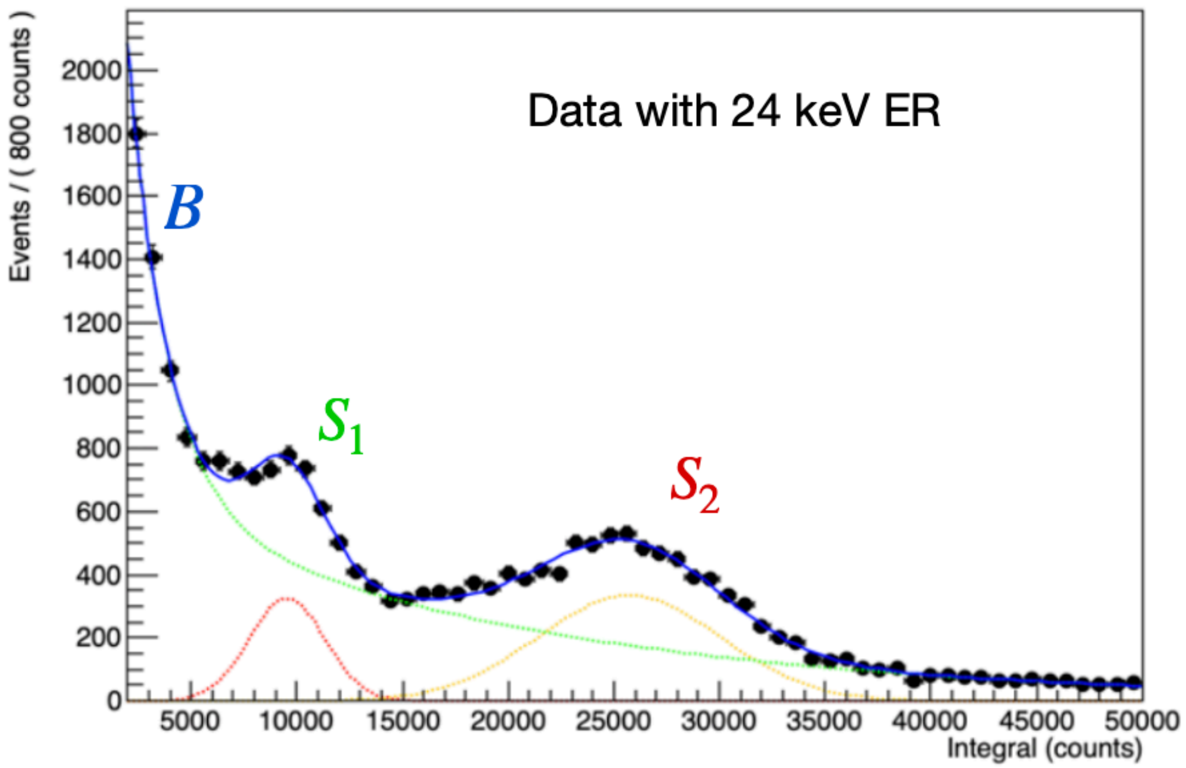


- Cu peak present in dataset with E>8 keV due to stimulated emission from Copper field cage

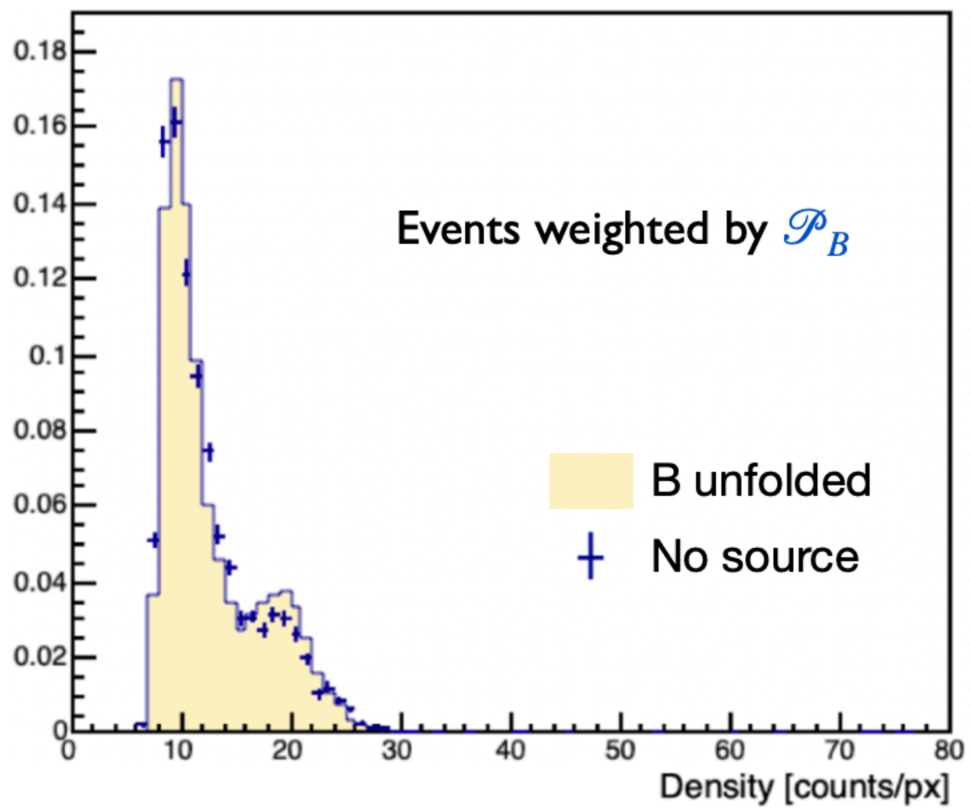
sPlots: practical explanation

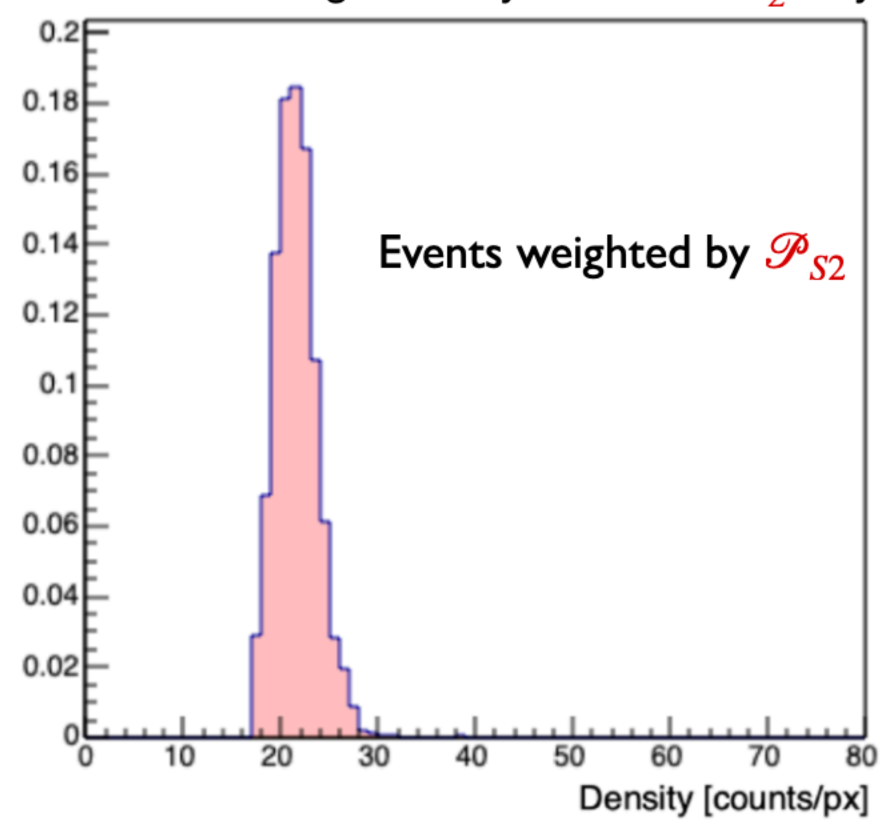
- Fit light integral with known model containing background and two signals $B + S_1 + S_2$
- With the unbinned likelihood fit three weights are assigned to each event

  $\mathscr{P}_B$ $\mathscr{P}_{S1}$ $\mathscr{P}_{S2}$



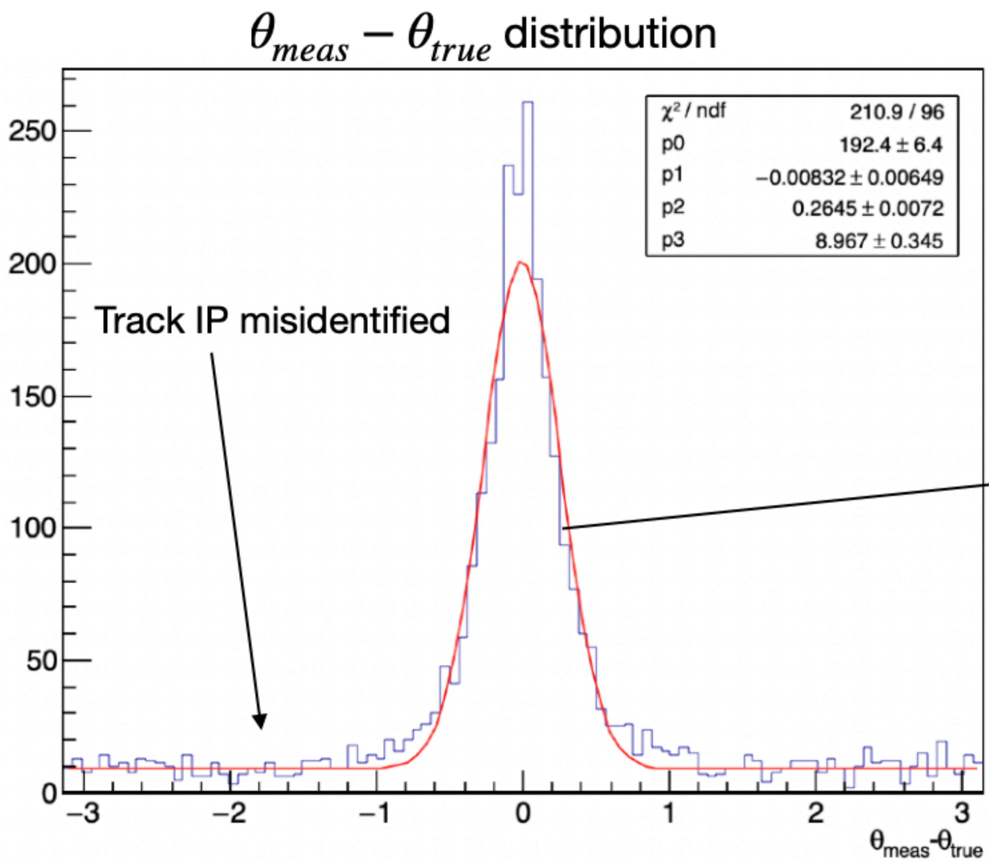
- Building a distribution weighting events by $\mathscr{P}_X$ the unfolded distribution for the specie X is obtained

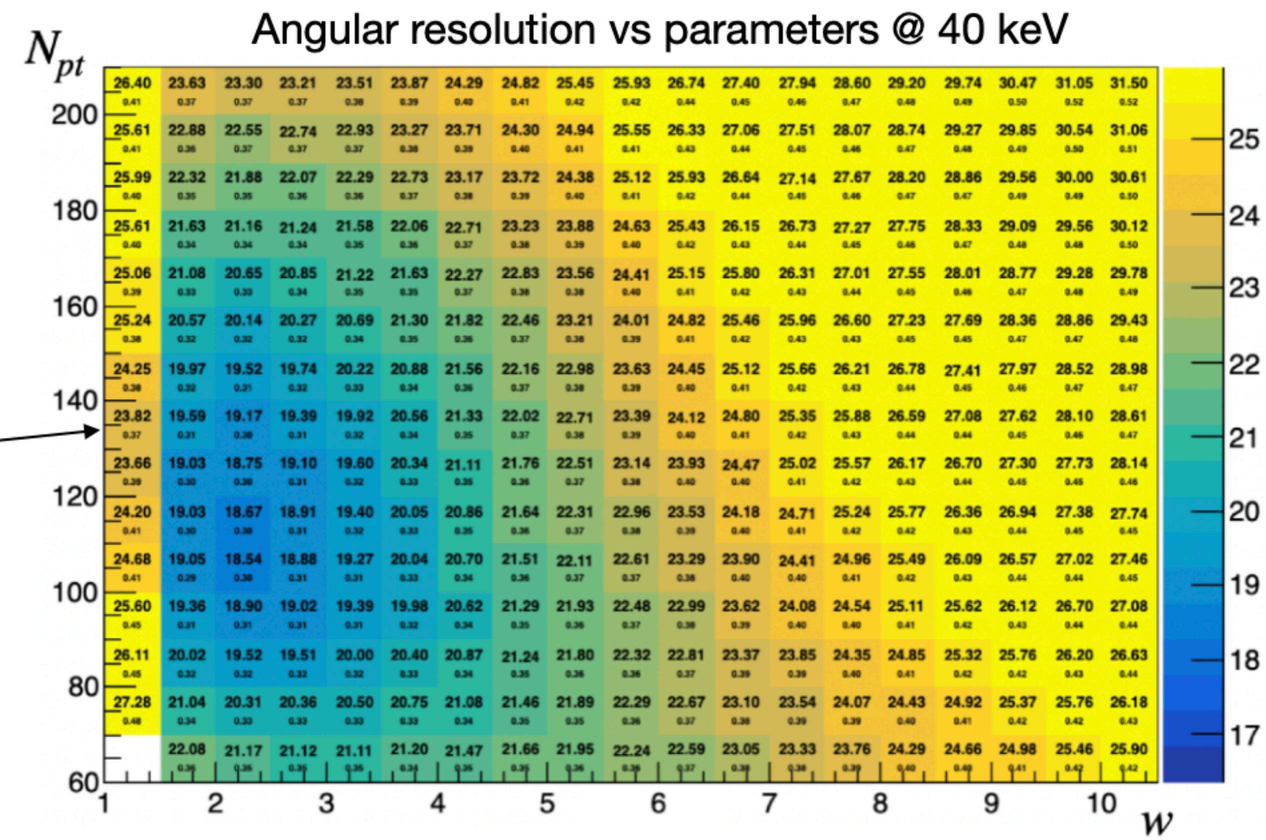




Parameters optimization

- Since the parameters are not known a priori, these have been optimized with a scan:
  - Datasets of digitised tracks at different energies
- Angular resolution evaluated as the sigma of the $\theta_{meas} - \theta_{true}$ distribution



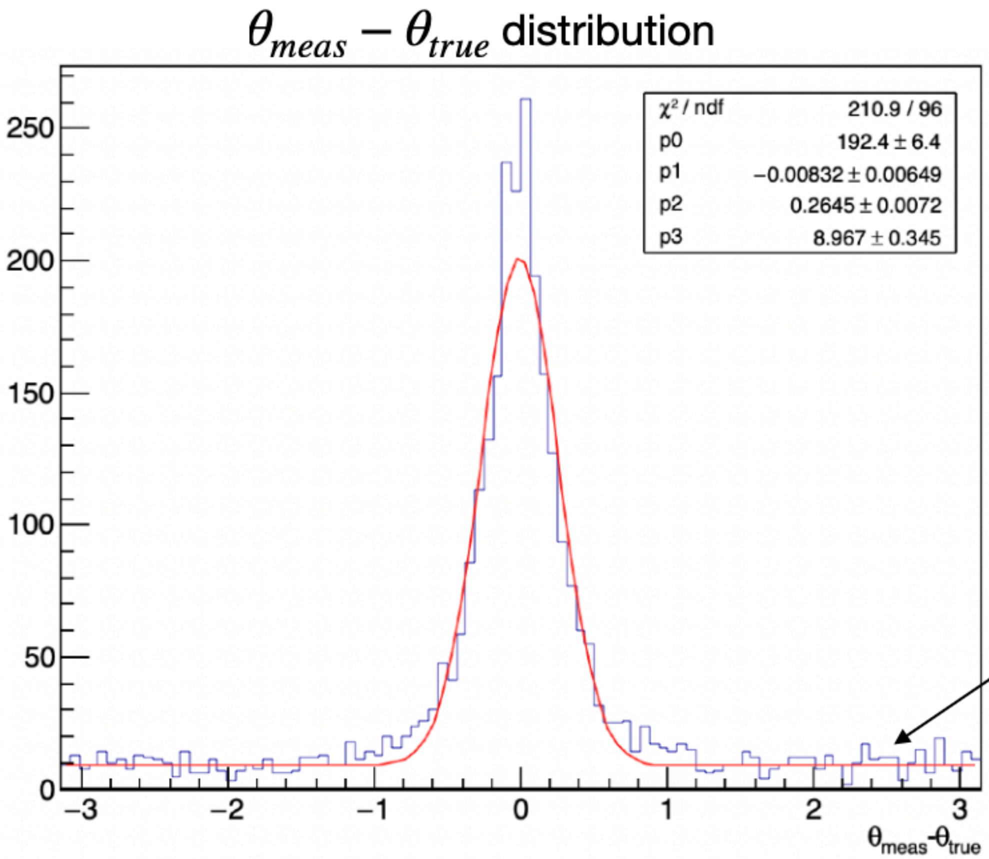


- Optimal parameters found for different datasets at fixed energy:

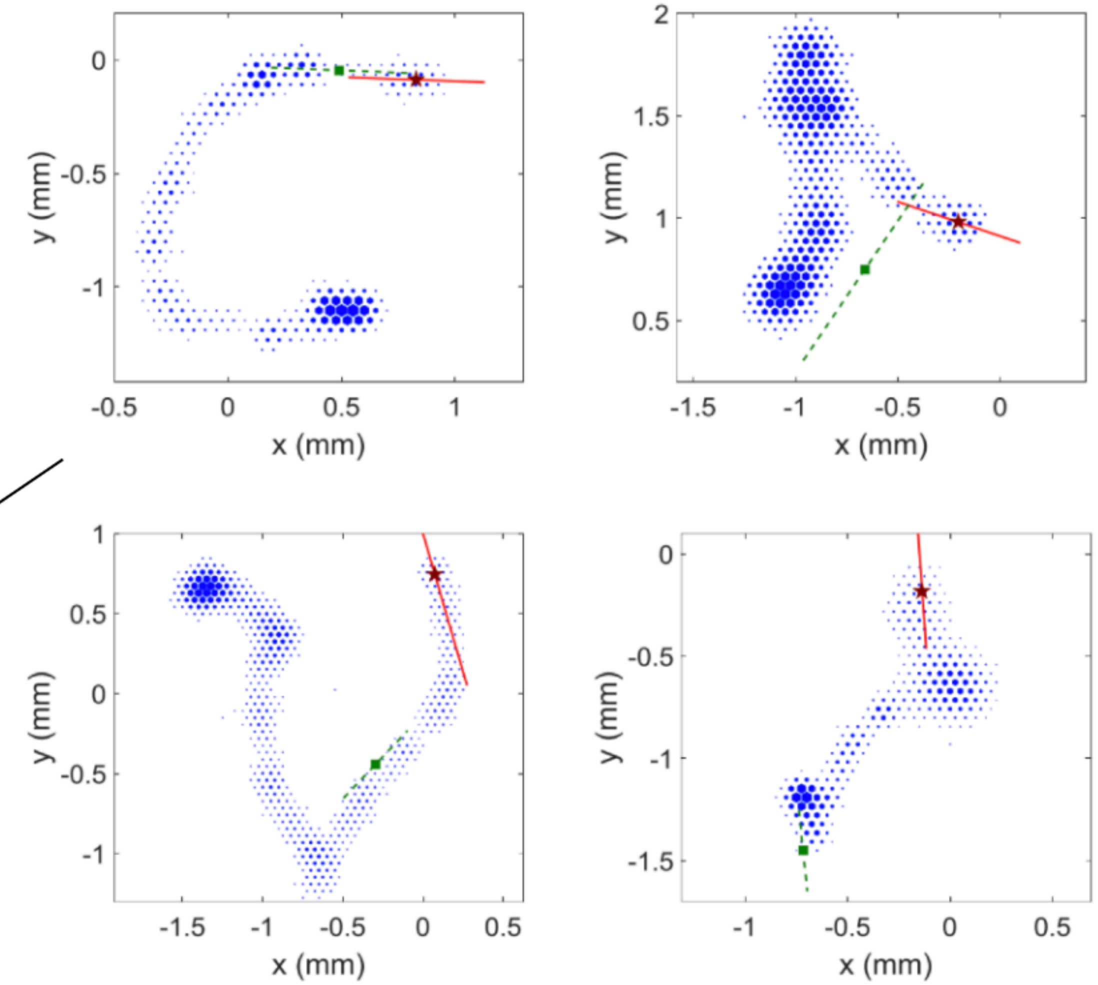
E [keV]	16	18	20	22	24	28	32	36	40	50	60	70
N_{pt}	100	100	100	100	110	110	110	120	120	120	120	120
w	1.5	1.5	1.5	1.5	1.5	1.5	2	2	2	2.5	2.5	2.5

Algorithm efficiency

- Algorithm has an efficiency different from 1



- Incorrect handling of the track topology



+ Lack of 3rd coordinate

- Efficiency as the number of event falling in the gaussian divided by the total number of events

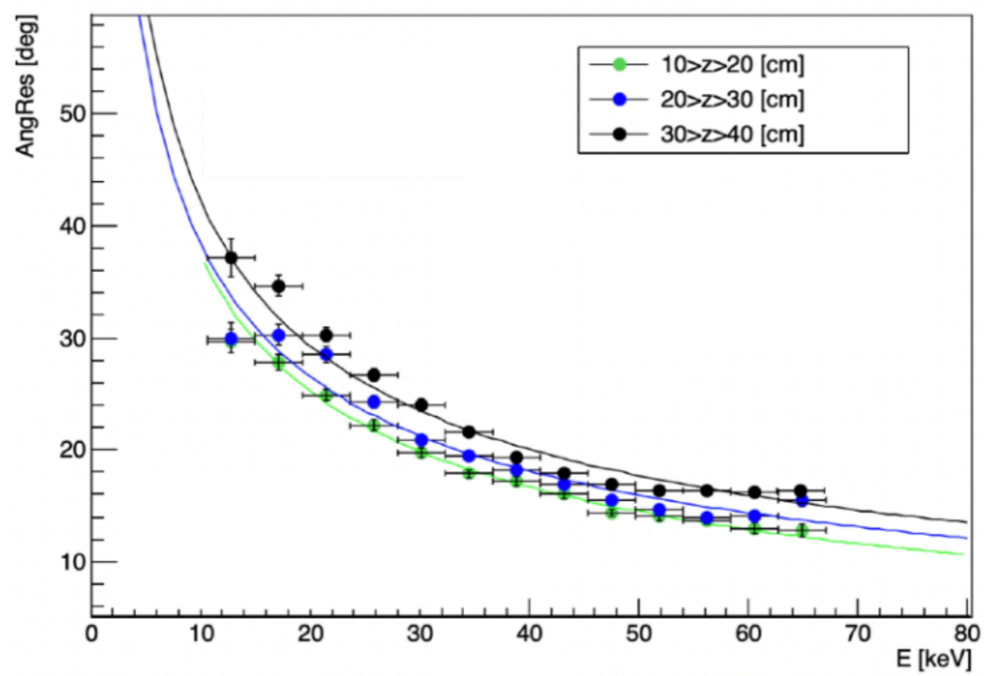
- New algorithm to better handle the track topology under development

- PMT information addition could solve the remaining cases (work in progress…)

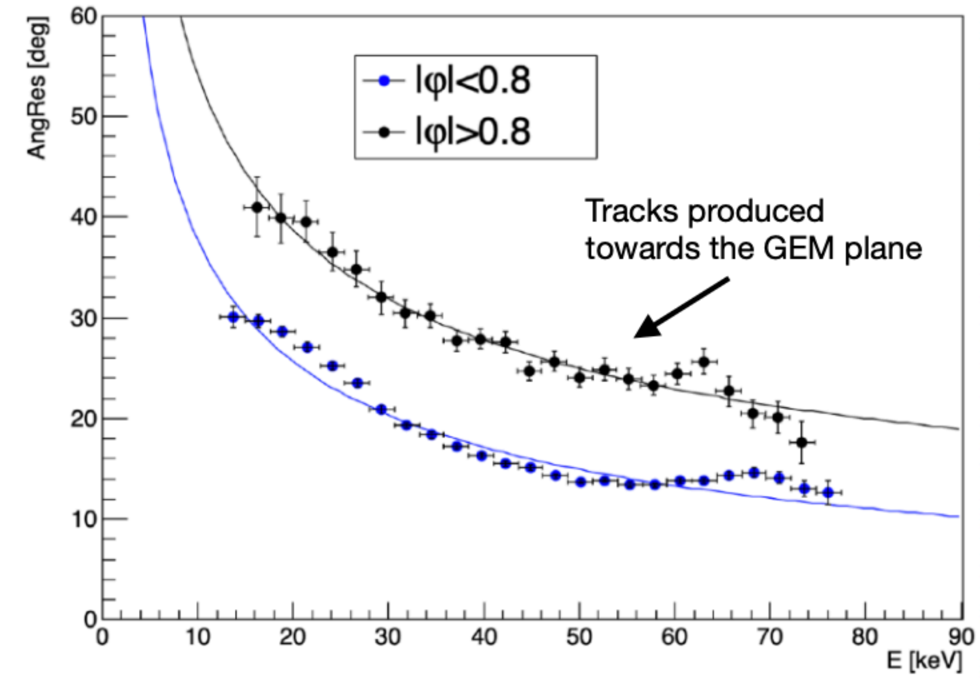
Further considerations

- Ang Res performances vs E for different drift distances and different angles with respect to the GEM plane

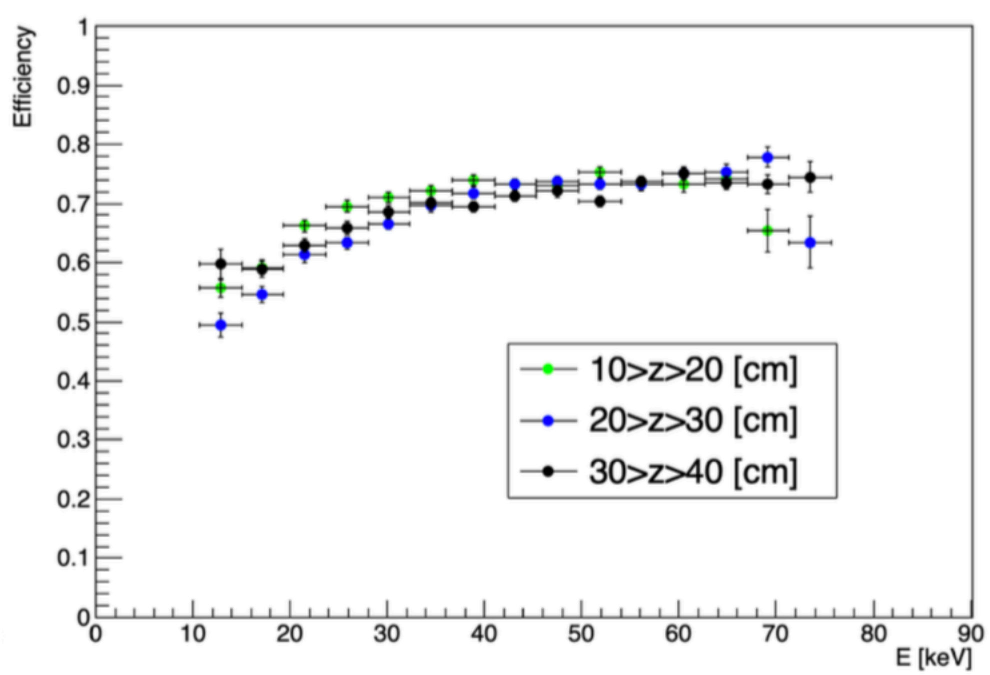
Angular resolution vs energy for different drift length



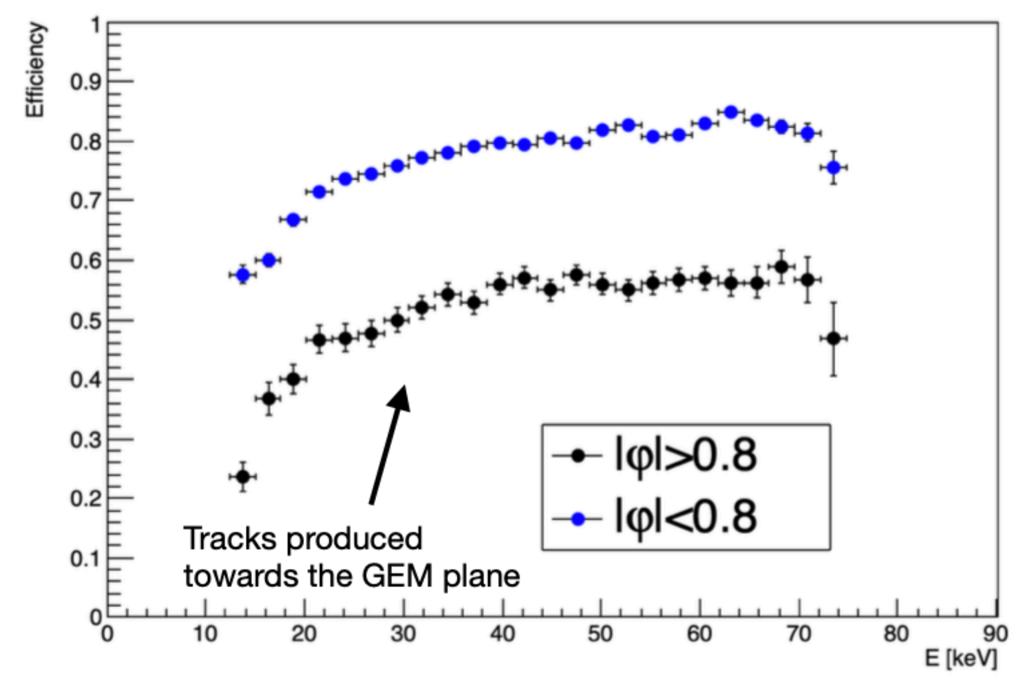
Angular resolution vs energy for different φ



Efficiency vs energy for different drift length



Efficiency vs energy for different φ



- Worsening in angular perfromances when tracks are produced perpendicular to the GEM plane (lack of 3D)

Material choice

Reference:

- Electroformed copper by Majorana Collaboration:

MAJORANA Collaboration • N. Abgrall (LBNL, NSD and Shanghai Jiao Tong U.) et al. Nucl.Instrum.Meth.A 828 (2016), 22-36

- Acrylic insulator from SNO:

Systematic study of trace radioactive impurities in candidate construction materials for EXO-200 D.S. Leonard (Alabama U.), et al. Nucl.Instrum.Meth.A 591 (2008), 490-509

- SMD Resistors from XENON-1T:

Material radioassay and selection for the XENON1T dark matter experiment. XENON Collaboration • E. Aprile (Columbia U.) et al. Eur.Phys.J.C 77 (2017) 12, 890

- Suprasil lenses and camera sensor:

Measurement performed @ LNGS - low radioactivity lab.

Detector element	Material	^{238}U	^{232}Th	^{40}K	^{235}U	^{226}Ra	^{228}Th
GEM core	Acrylic	$< 296.0\ \mu$Bq/Kg	$< 56.9\ \mu$Bq/Kg	$< 71.2\ \mu$Bq/Kg	x	eq	eq
GEM armor	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Field cage support	Acrylic	$< 296.0\ \mu$Bq/Kg	$< 56.9\ \mu$Bq/Kg	$< 71.2\ \mu$Bq/Kg	x	eq	eq
Field cage strip	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Cathode	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Vessel	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Camera sensor	Silicon	2 mBq/Kg	2.8 mBq/Kg	9 mBq/Kg	x	eq	eq
Camera lenses	Suprasil	123 μBq/Kg	40.7 μBq/Kg	0.3 mBq/Kg	x	eq	eq
Resistors	Al_2O_3	1 μBq/pc	0.14 μBq/pc	1.2 μ Bq/pc	0.04 μ Bq/pc	0.18 μ Bq/pc	0.13 μ Bq/pc

- GEMs with acrylic core from:

S.E. Vahsen(Hawaii U.), et. Al. ADS Abstract Service - arXiv:2008.12587

- Purest material available employed for detector realization