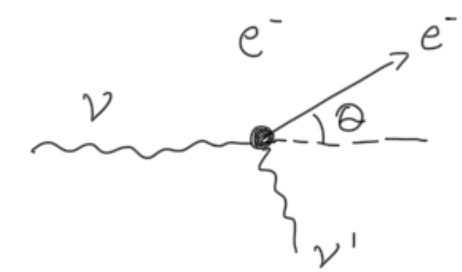
Feasibility of a directional solar neutrino measurement with the CYGNO/INITIUM experiment

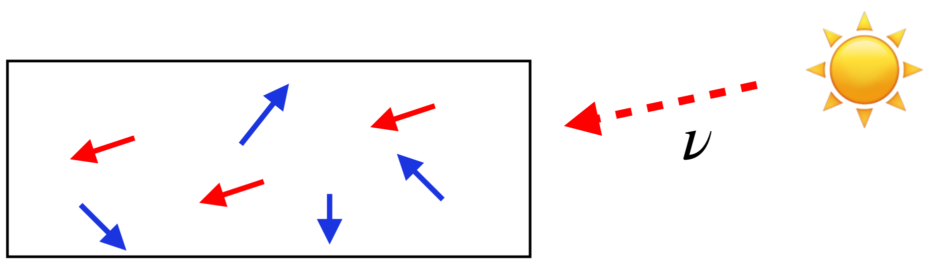
Samuele Torelli

Prof. Elisabetta Baracchini

Why a directional measurement



- 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

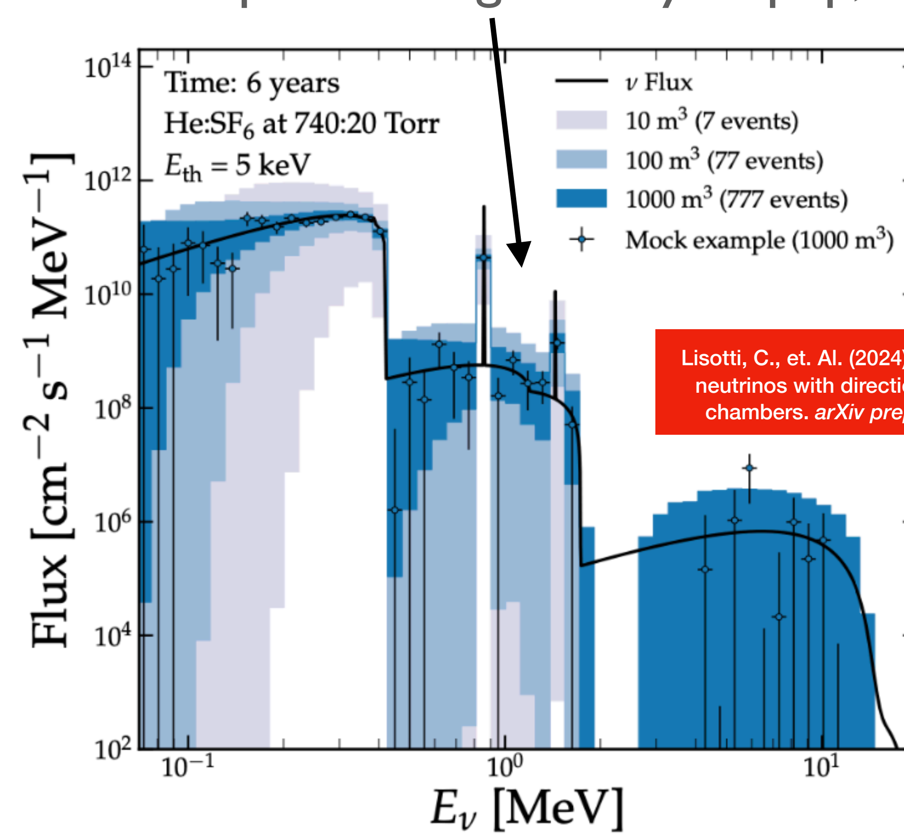
- Interests in:
  - Improve precision on the pp flux (Solar luminosity constraints)
  - Improve precision in CNO flux measurement (Metallicity problem)

- 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

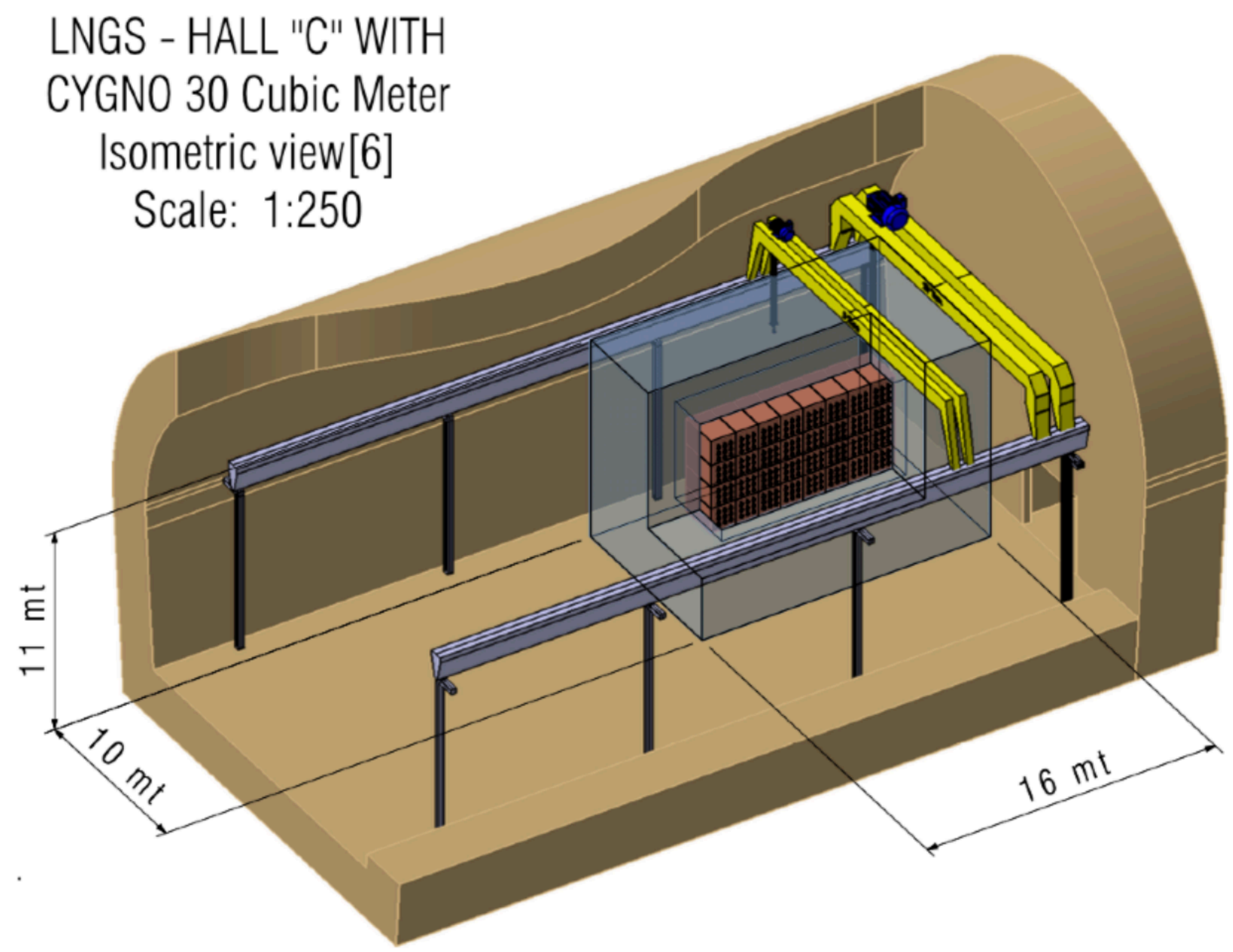
Remove the spectral degeneracy of pep, ^{7}Be and CNO



Lisotti, C., et. Al. (2024). CYGνS: Detecting solar neutrinos with directional gas time projection chambers. *arXiv preprint arXiv:2404.03690.*

With a CYGNO 30 detector

- CYGNO 30 m^3 detector proposed to be suitable for this measurement
- Modular approach: at the moment composed by 75 CYGNO_04 modules



- Significant contribution in DM searches for SI and SD couplings
- Proposed additionally to be suitable for a directional measurement of solar neutrino from pp chain

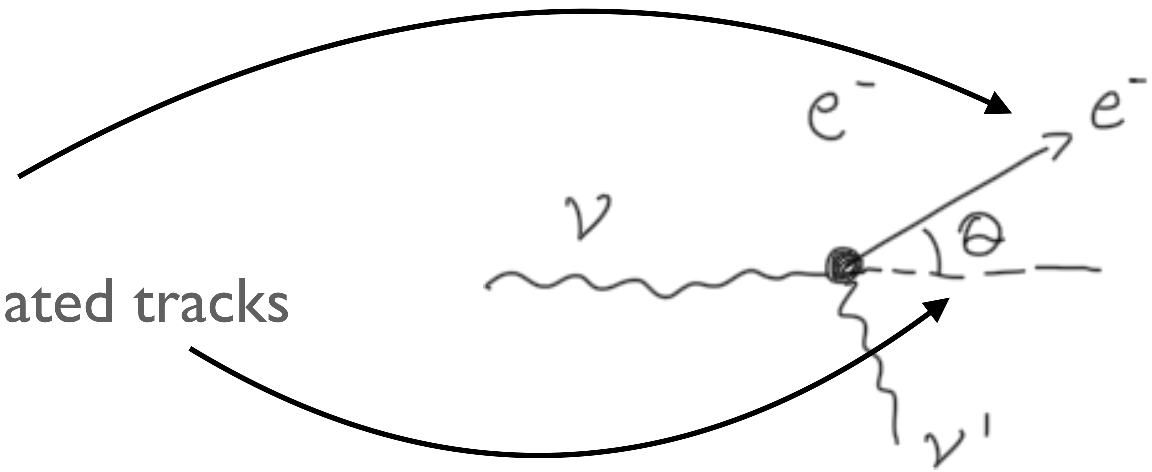
Feasibility study of a directional neutrino measurement

The purpose of my PhD thesis has been to evaluate the feasibility of a directional measurement of solar neutrino produced in the pp chain with a 30 m^3 CYGNO detector

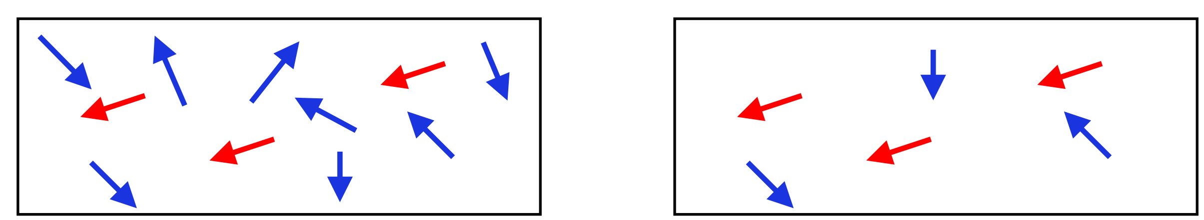
For this study 2 key elements critical to asses:

O'Hare, C. A. J.,… S.Torelli…, et al. *arXiv:2203.05914*

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

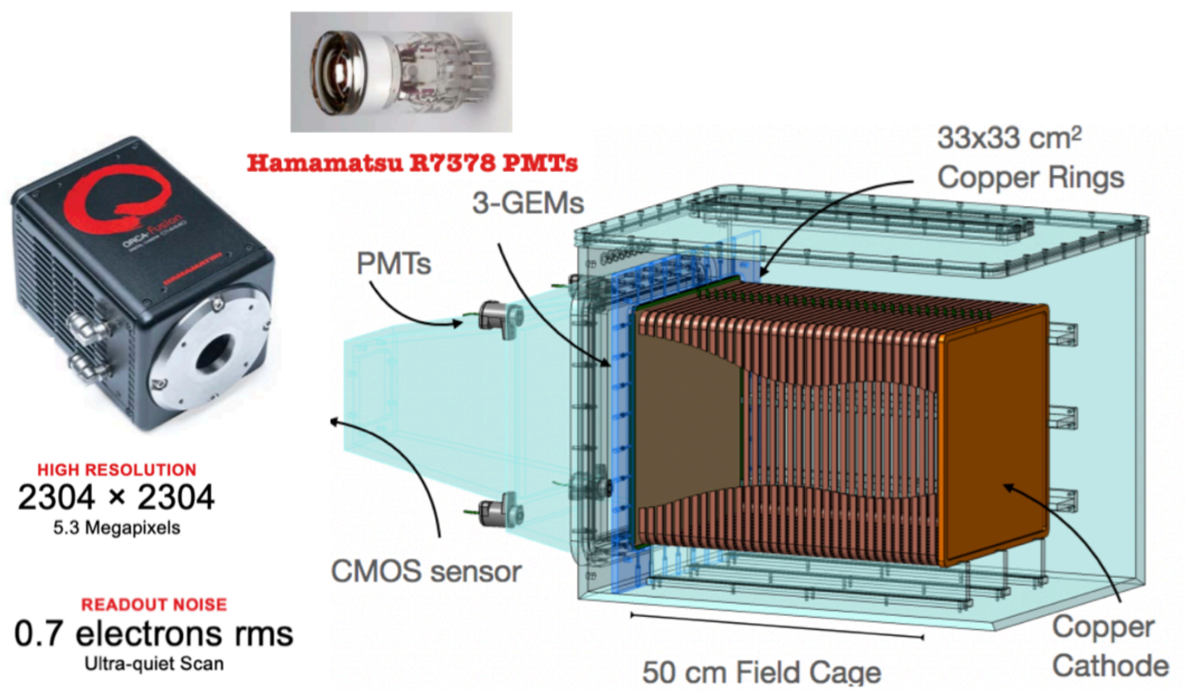


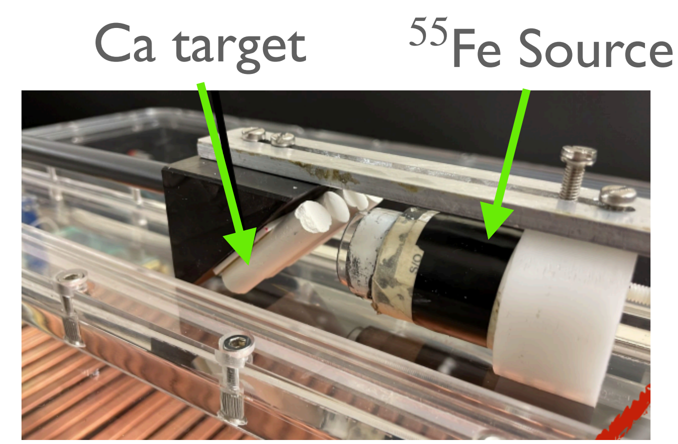
Step 1: Characterization of the detector response to low energy electron recoil

Multi-energy X-Ray data

Data taken overground at LNF: High pileup

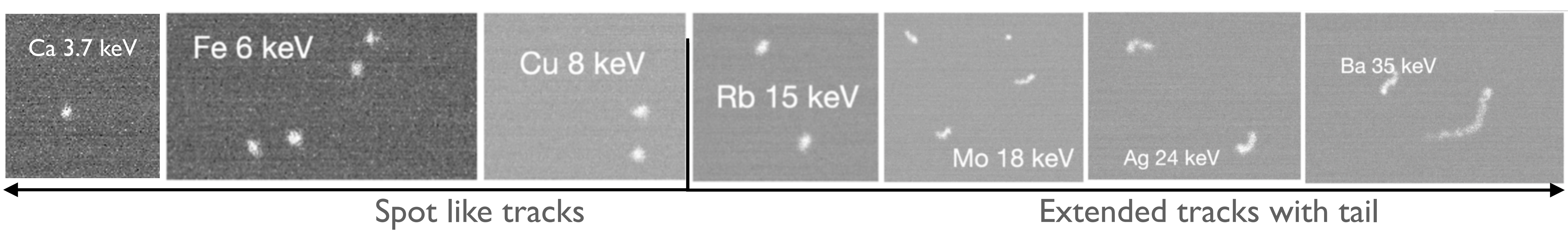
- Study of linearity and energy resolution performed overground with different X-Ray sources
- LIME detector used 33×33 cm^2 with 50 cm drift





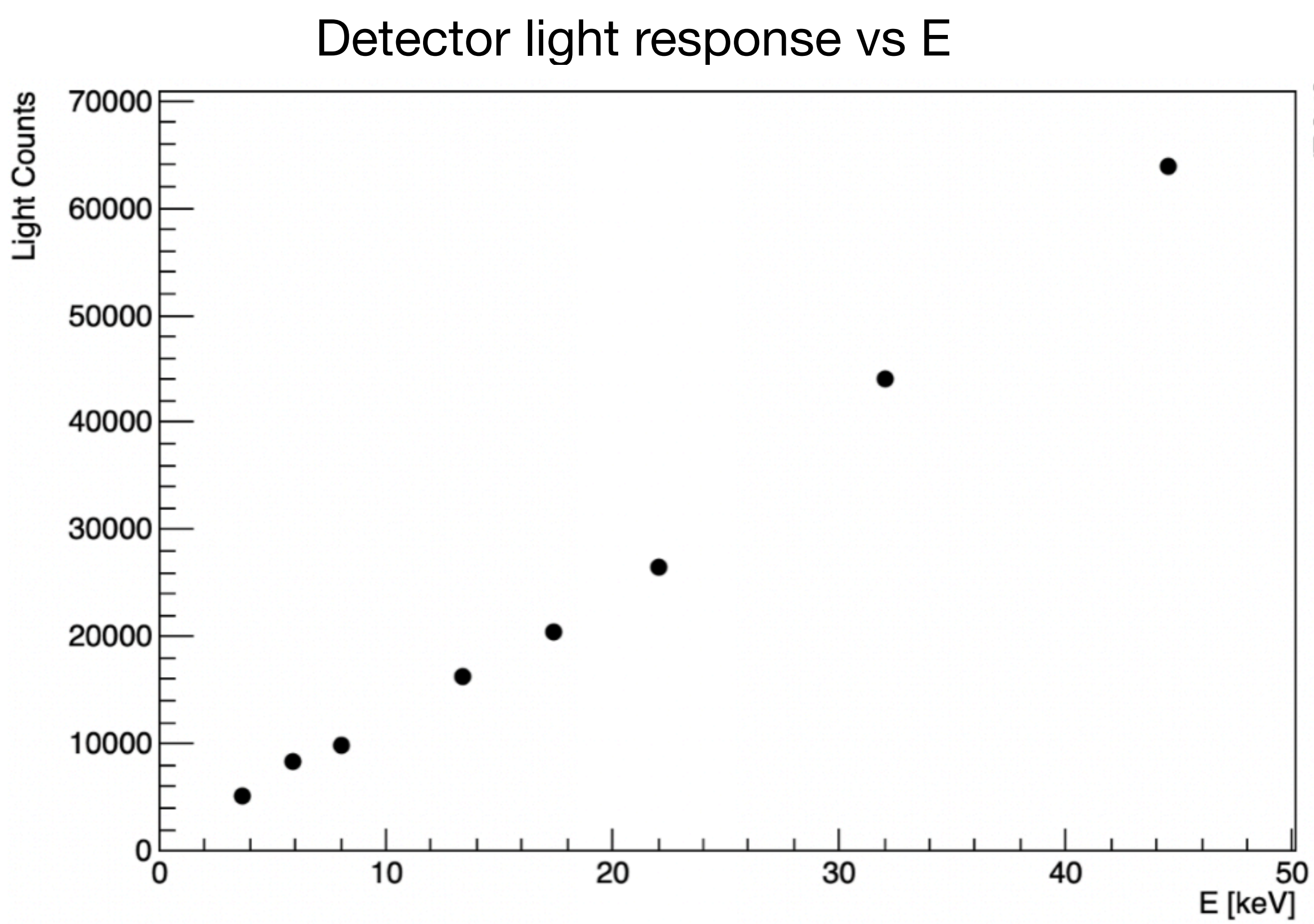
Target Selected	Energy (keV) K_alpha	K_beta	Photon Yield (#/sec/steradian)
Cu	8.04	8.91	2,500
Rb	13.37	14.97	8,800
Mo	17.44	19.63	24,000
Ag	22.10	24.99	38,000
Ba	32.06	36.55	46,000
Tb	44.23	50.65	76,000

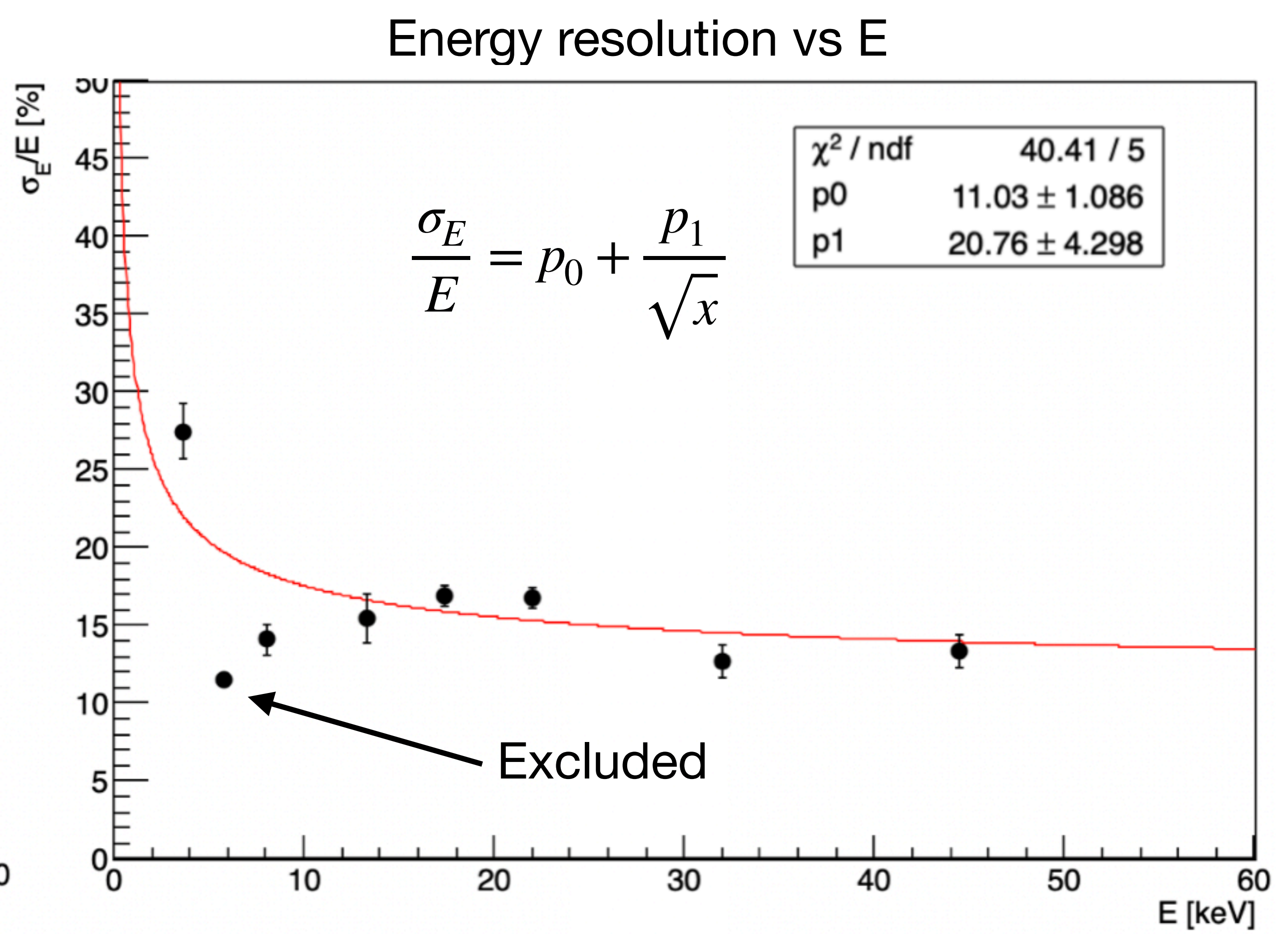
- How tracks appear:



Light response and energy resolution

- From the data analysis the detector response and the energy resolution:





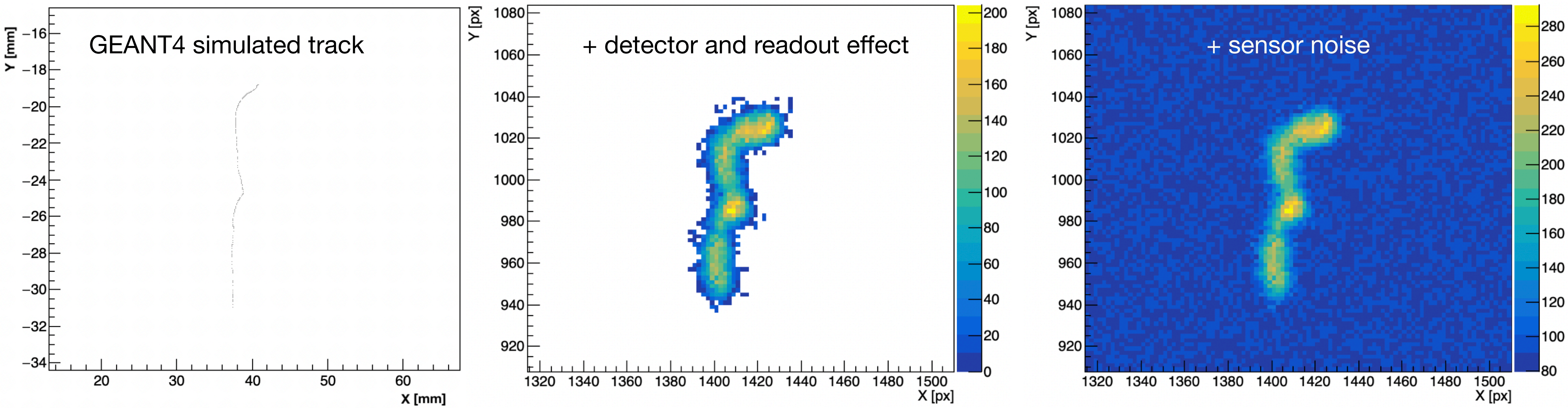
- Response expected to be subject to saturation at very low E and less saturated at high E

- Energy resolution behaviour compatible with typical resolution of a gas detector

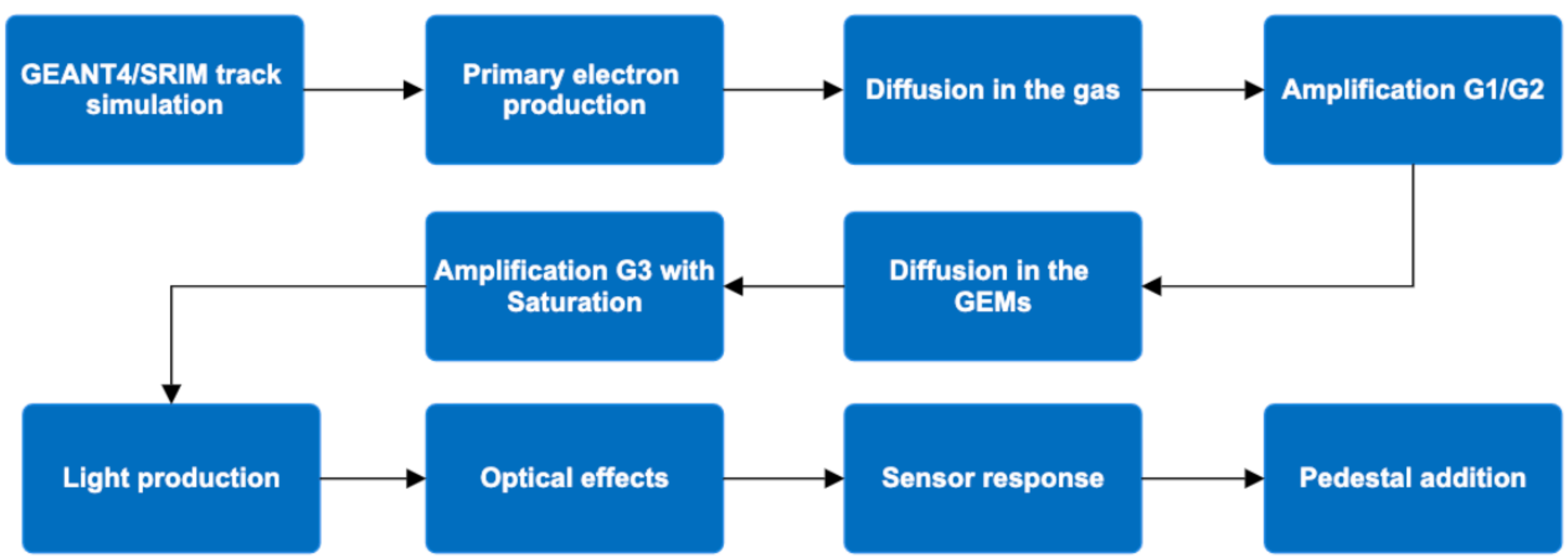
Step 2: Development of a simulation to produce low energy electron recoil sCMOS images

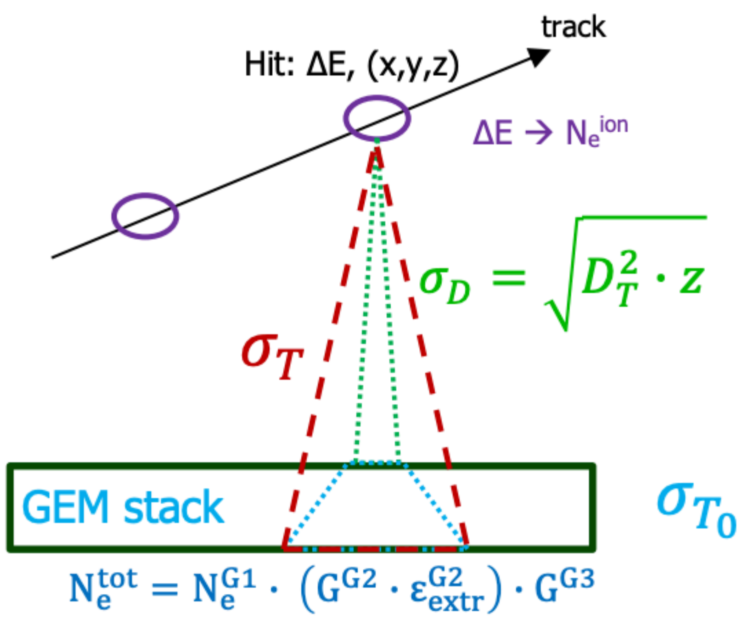
ER sCMOS images simulation

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



Working flow of the simulation (statistical effects are considered)

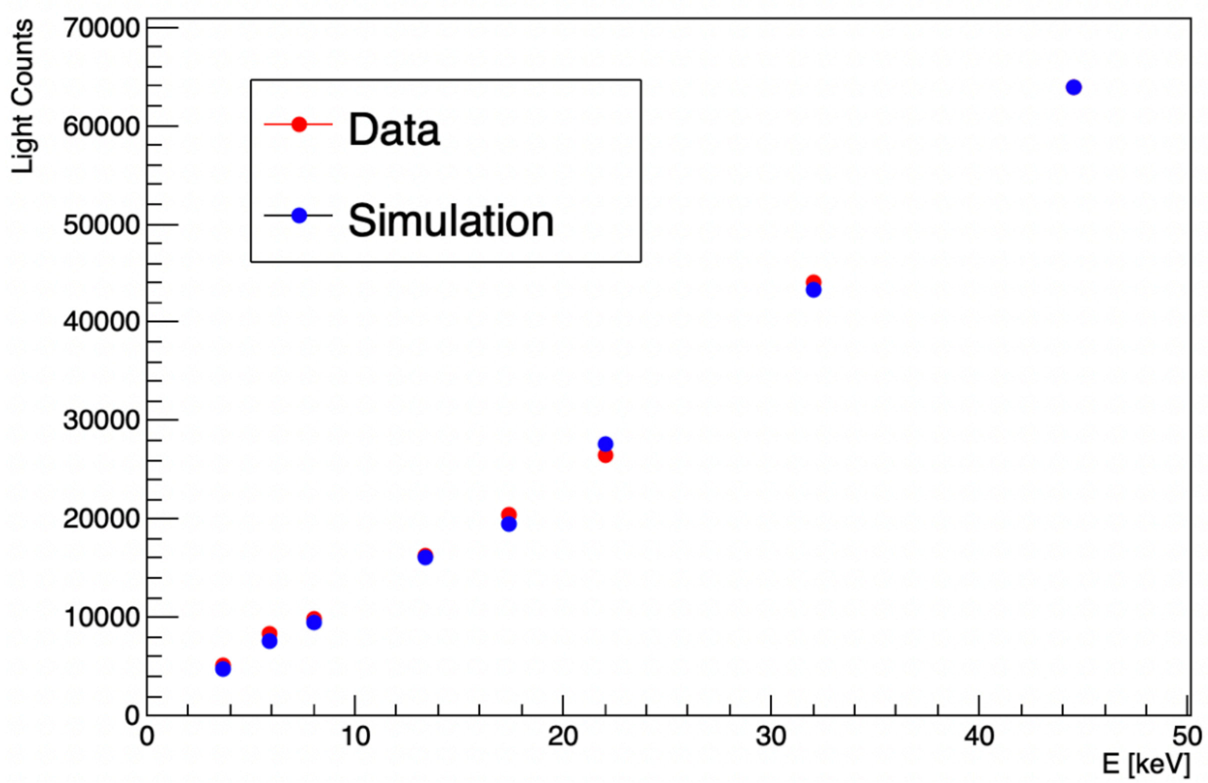


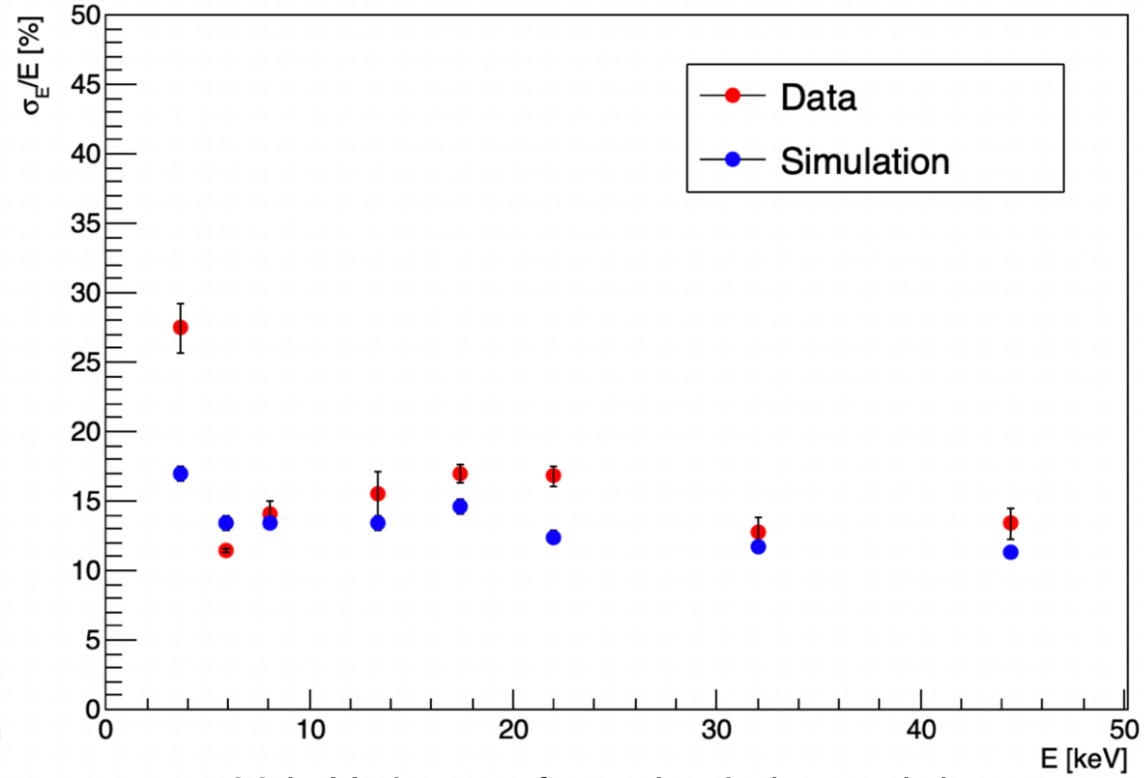


- Simulation parameters optimized on ^{55}Fe data

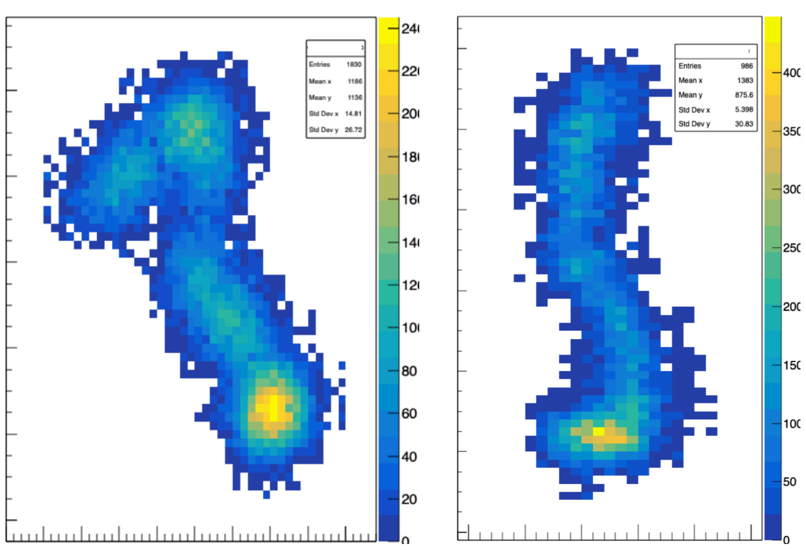
Data MC comparison

- Set of data produced at the same energies of the multi-energy X-ray data
- Parameters at the operative condition on LIME





30 keV electron from simulation and data

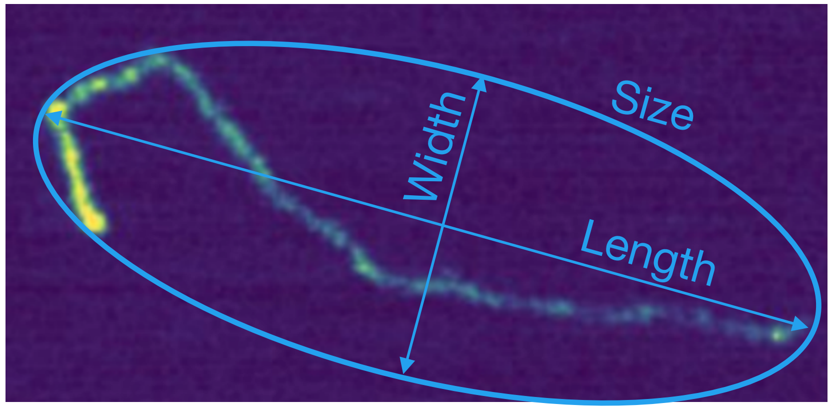


- Satisfactory level of agreement in light response and energy resolution
- Additionally a set of 9 topological track shape variables has been compared in Data and MC

↓

Signal/Background separation done with ${}_s\mathcal{P}lot$ technique

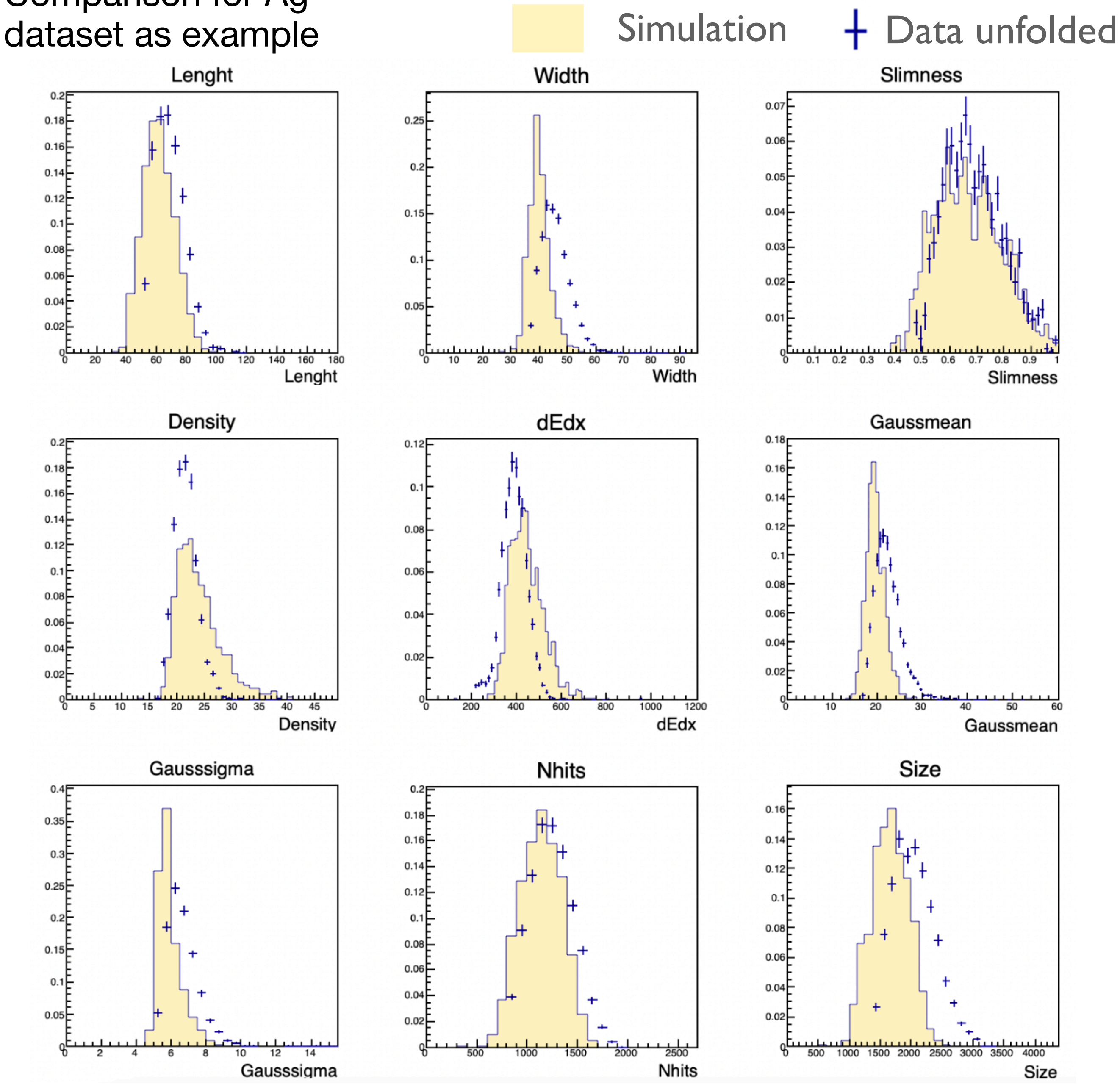
Track shape parameters comparison



- Shape variables compared for every energy dataset:

- Track length
- Track width
- Ratio width/length (slimness)
- Ratio light/npixels (density)
- Ratio light/length
- Mean transversal projection of the light distribution
- Sigma transversal projection of the light distribution
- Number of pixels
- Size of the cluster

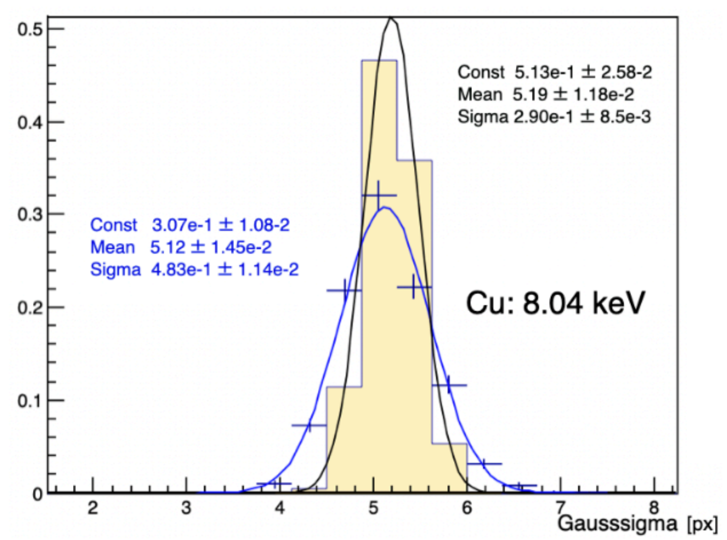
Comparison for Ag dataset as example

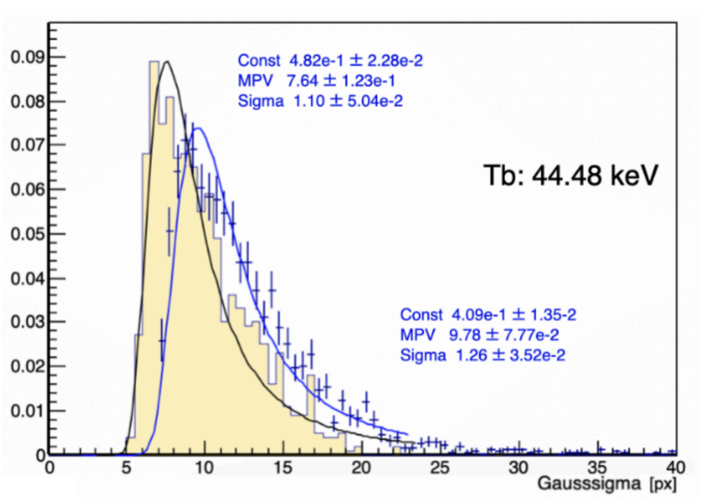


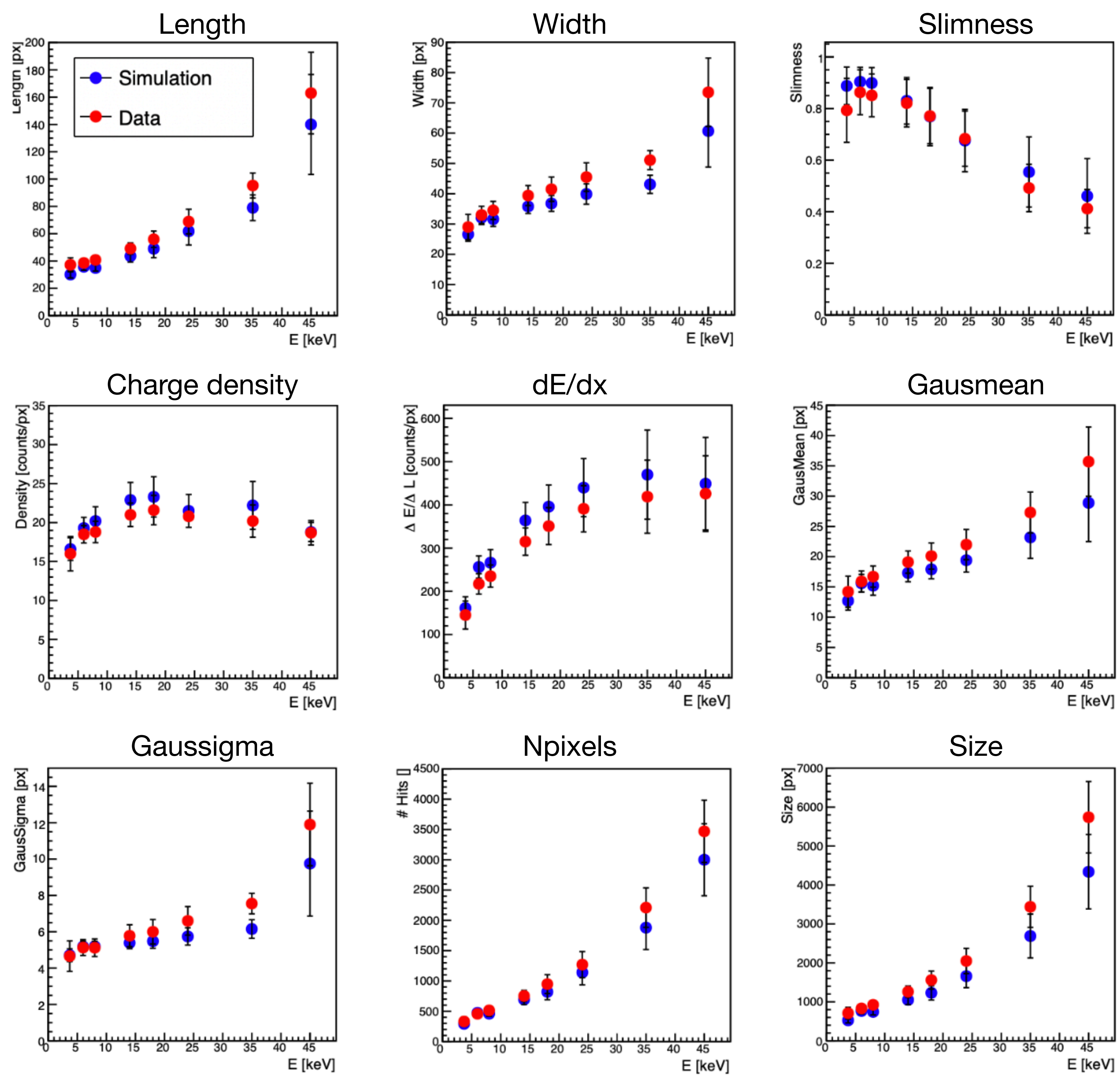
Track shape parameters comparison

Paper in preparation

- Mean and Sigma of the variable reported as a function of the energy for the different variables





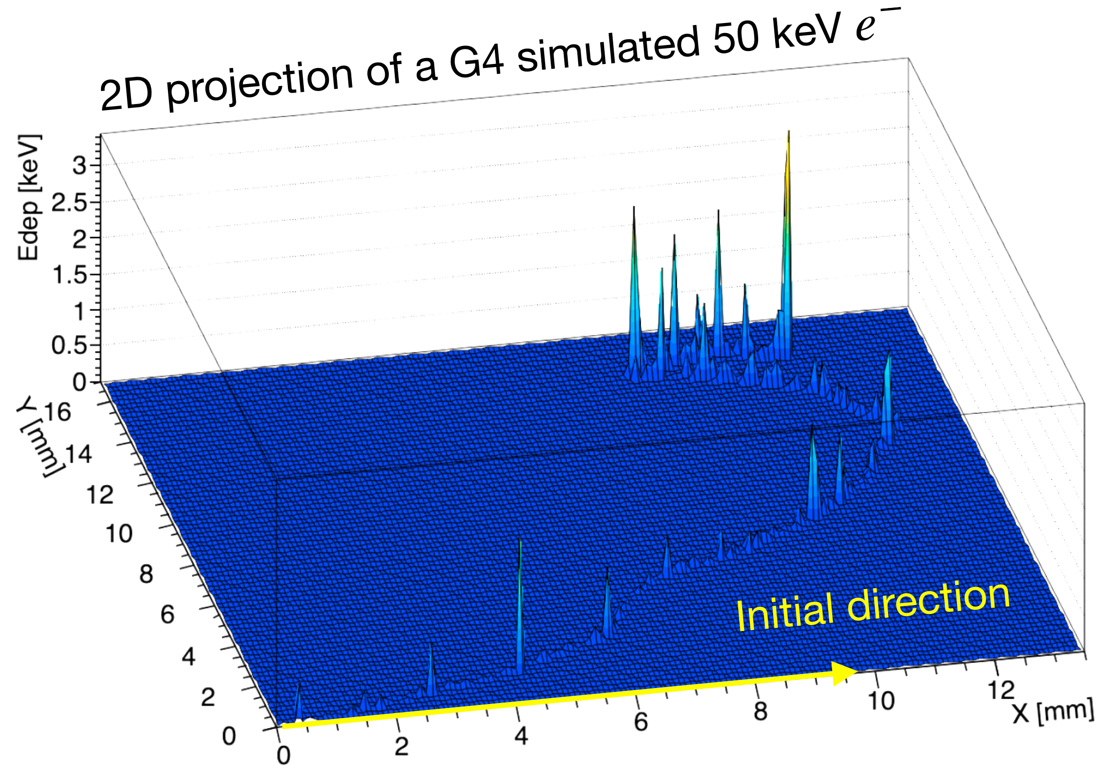


- Satisfactory agreement reached given the complexity of the simulation

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

Directionality of low energy electron recoil

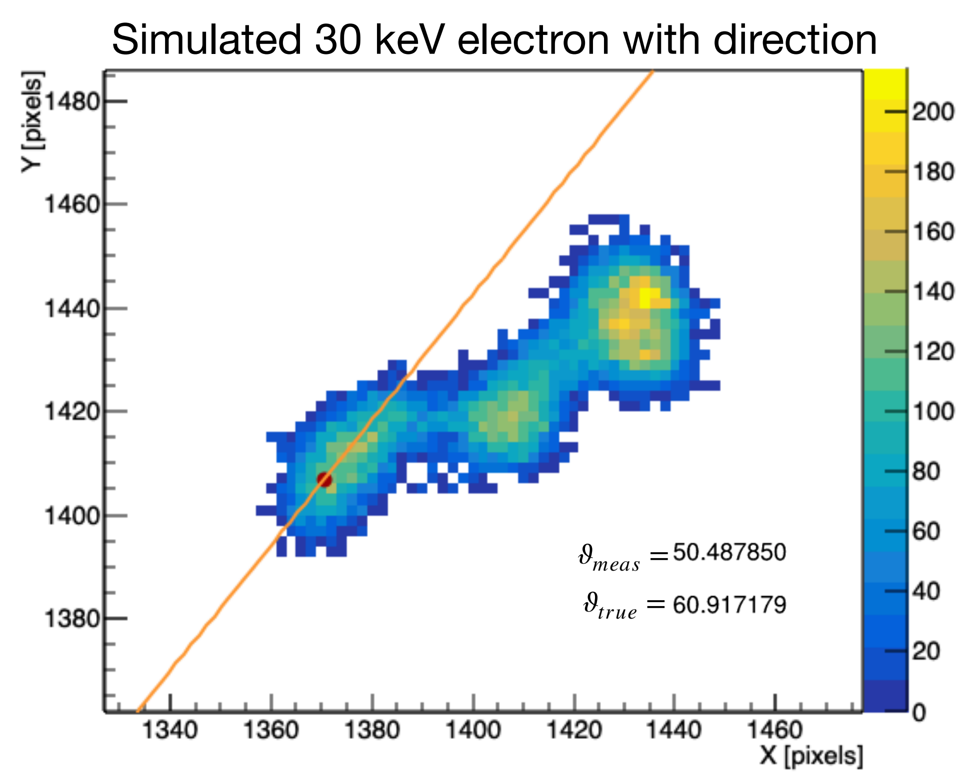
- Measuring the electron recoil direction is one of the key points to study the feasibility of this measurement



- Electrons in gas undergo multiple scattering, thus the directional information is rapidly lost

- Only connecting the beginning of the track with the end is not enough to determine the diffusion

  →Dedicated algorithm needed



- Given the absence of ER with known direction the algorithm has been optimized end testes on simulated tracks

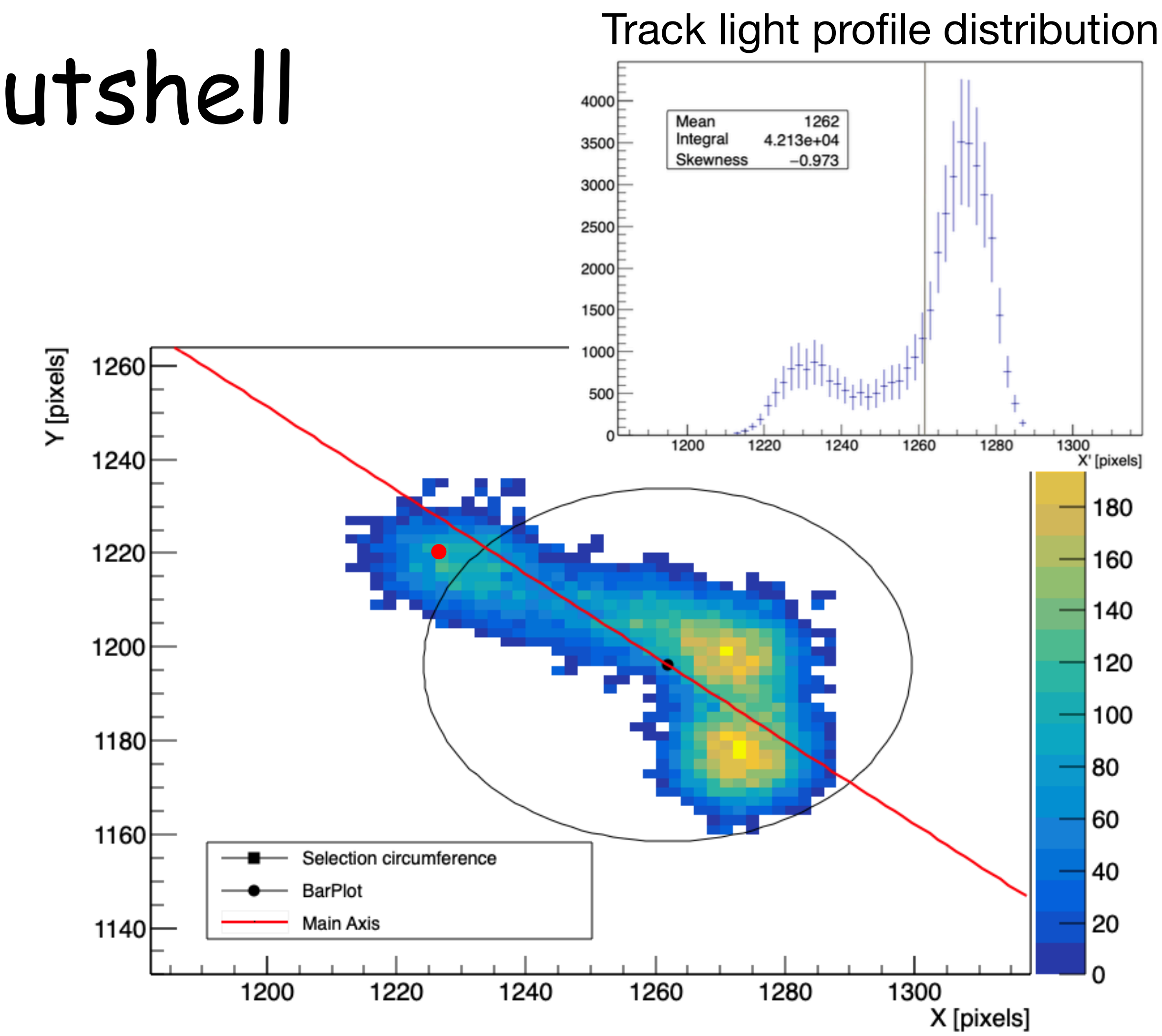
- Studied on 2D tracks projection, PMT for 3rd coordinate will be introduced in the future

Directionality algorithm in a nutshell

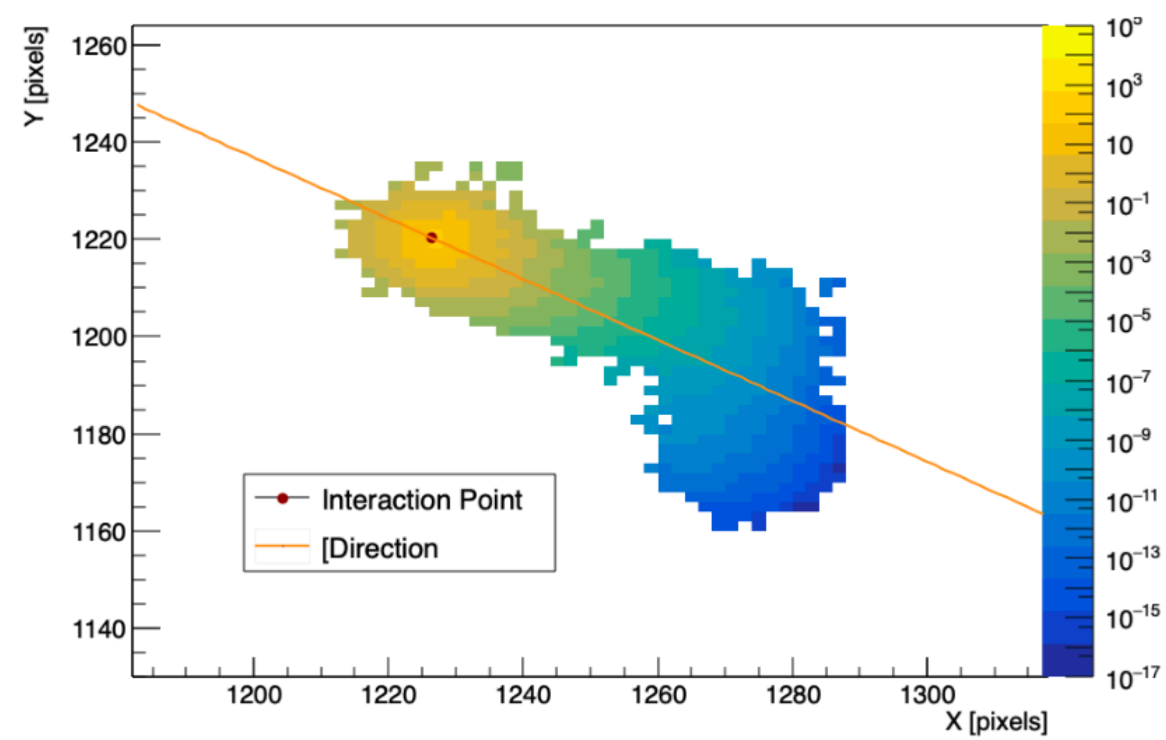
- Algorithm adapted from X-ray polarimetry:

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

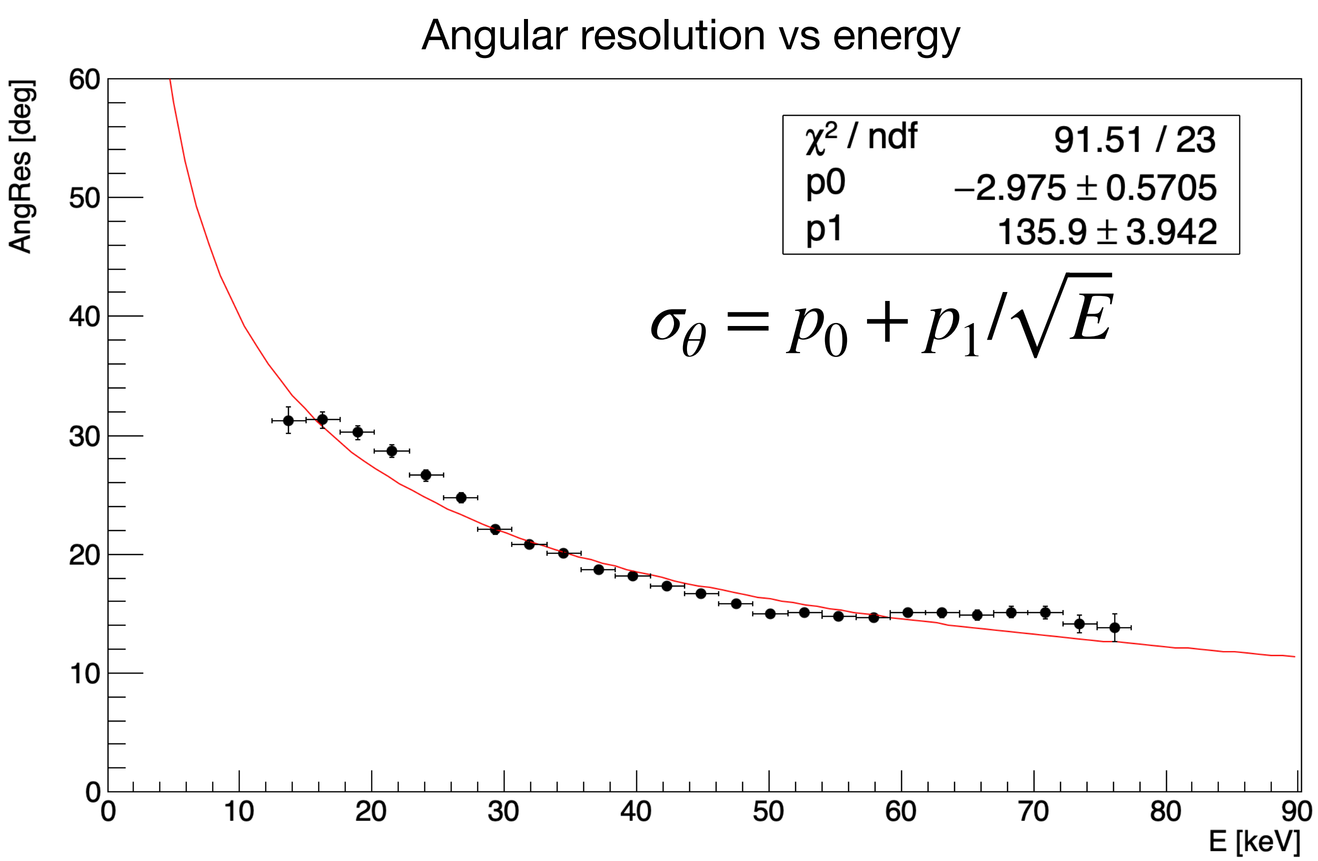


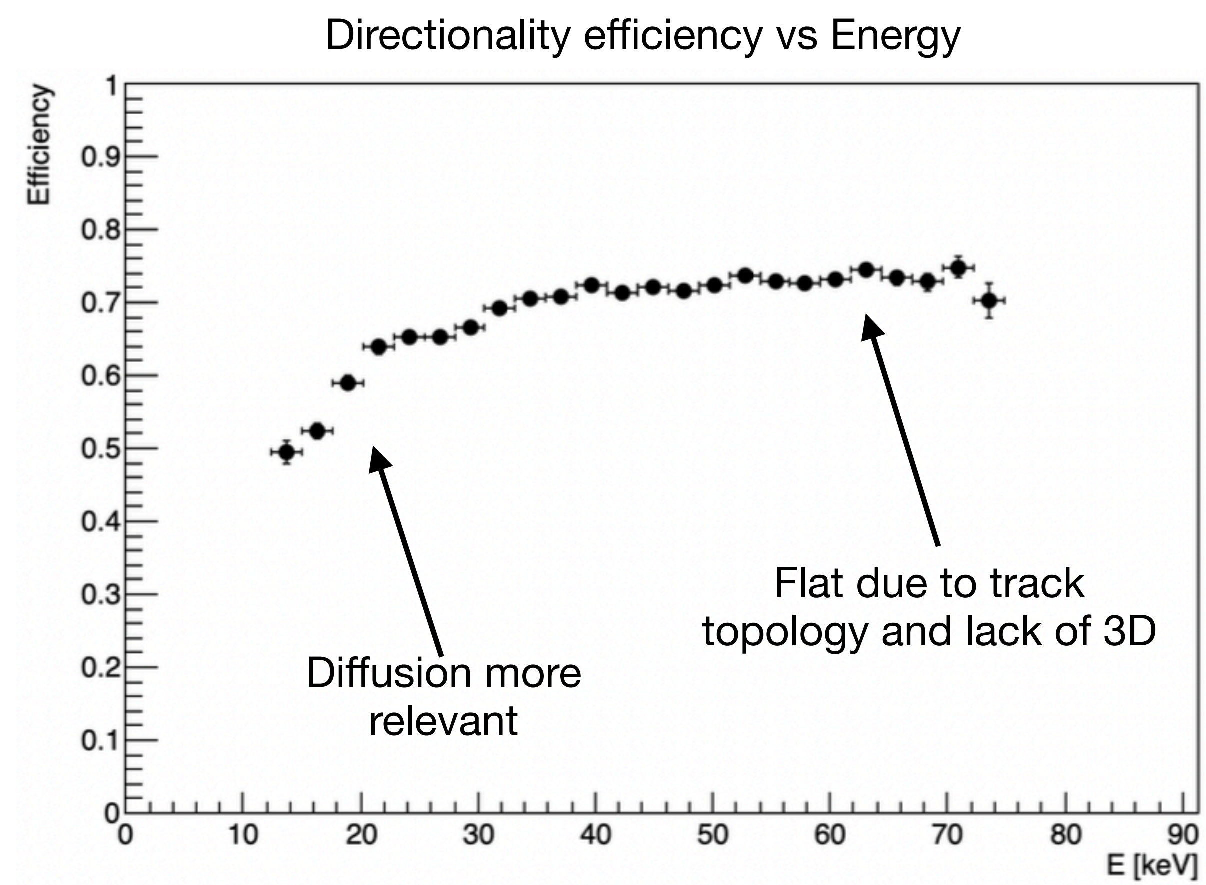
- Two parameters of the algorithm: N_{pt} and w

Results on angular resolution

Paper in preparation

- Angular resolution performances evaluated on a dataset with uniform energy tracks [16-70] keV





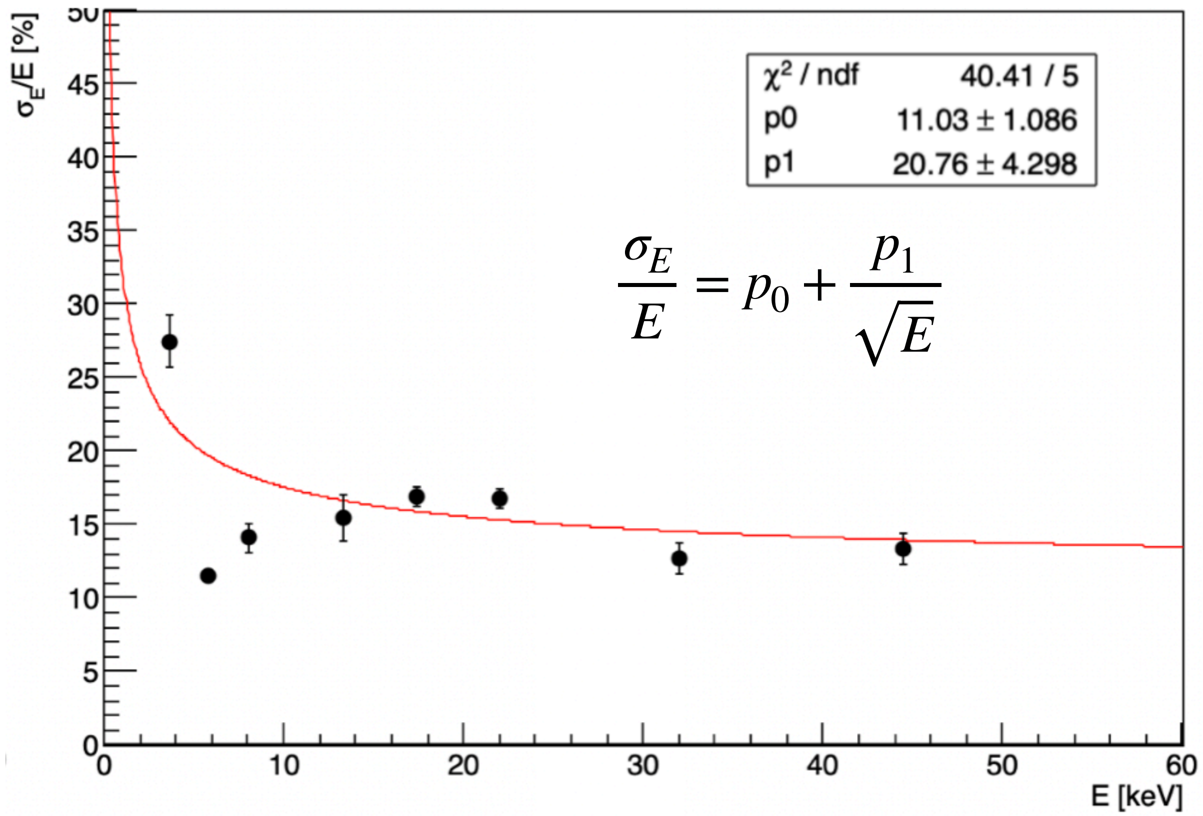
- First angular resolution result in this energy range

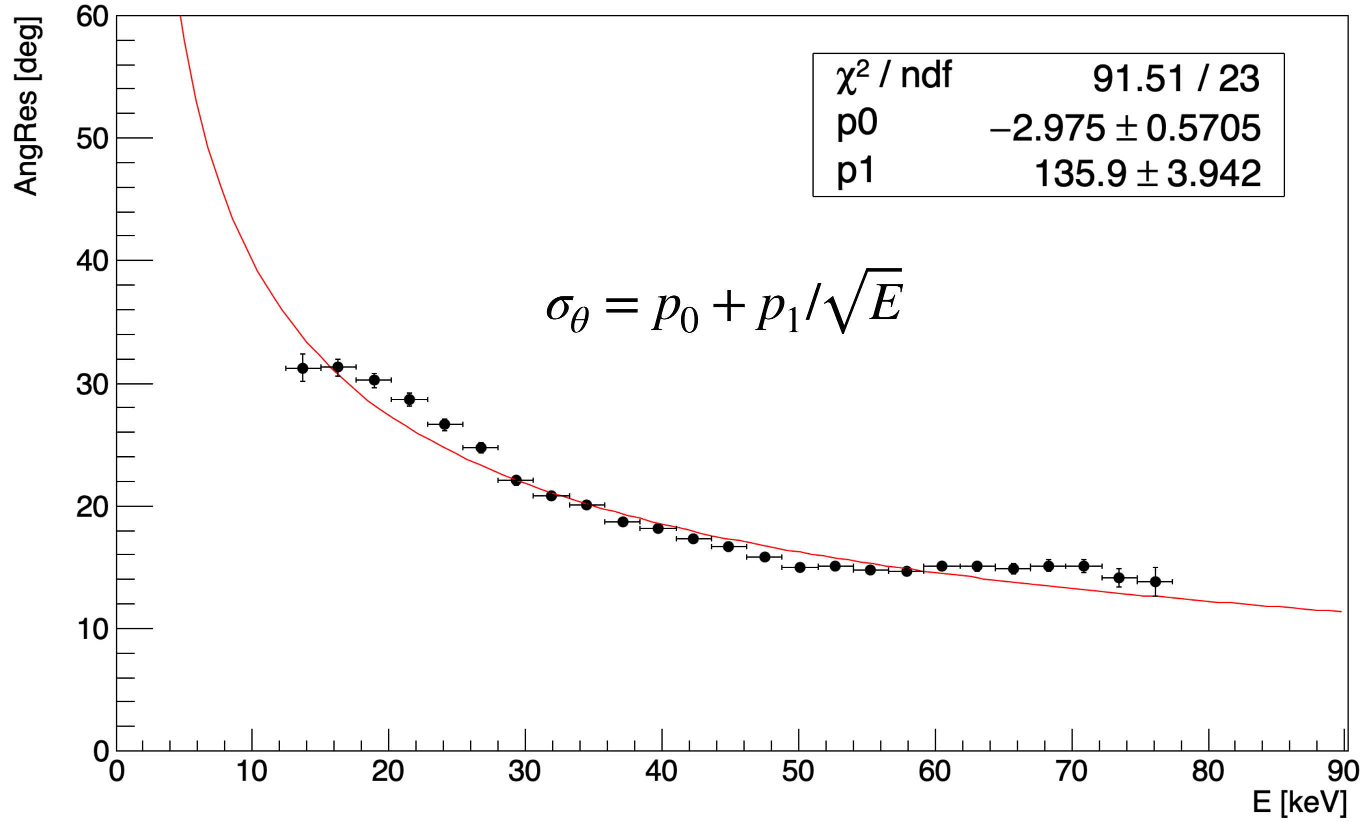
- Negative coefficient p_0 but it is expected to saturate at a value $\neq 0$ at higher energy

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

Resolutions and assumptions

- LIME resolutions will be assumed for the analysis





- Assumptions:
  - Same resolution in both theta (on the GEM plane) and phi (with respect to the perpendicular to the GEM plane) given the PMT time resolution.
  - Linear detector response
  - Threshold on electron energy of 10 keV (55 keV on ν energy)

In CYGNO gas mixture: expected 1 $ev/y/m^3$ (Oscillation included)

Bayesian approach for sensitivity studies

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

Posterior probability; Likelihood; Prior probabilities; Normalization

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

Binned likelihood

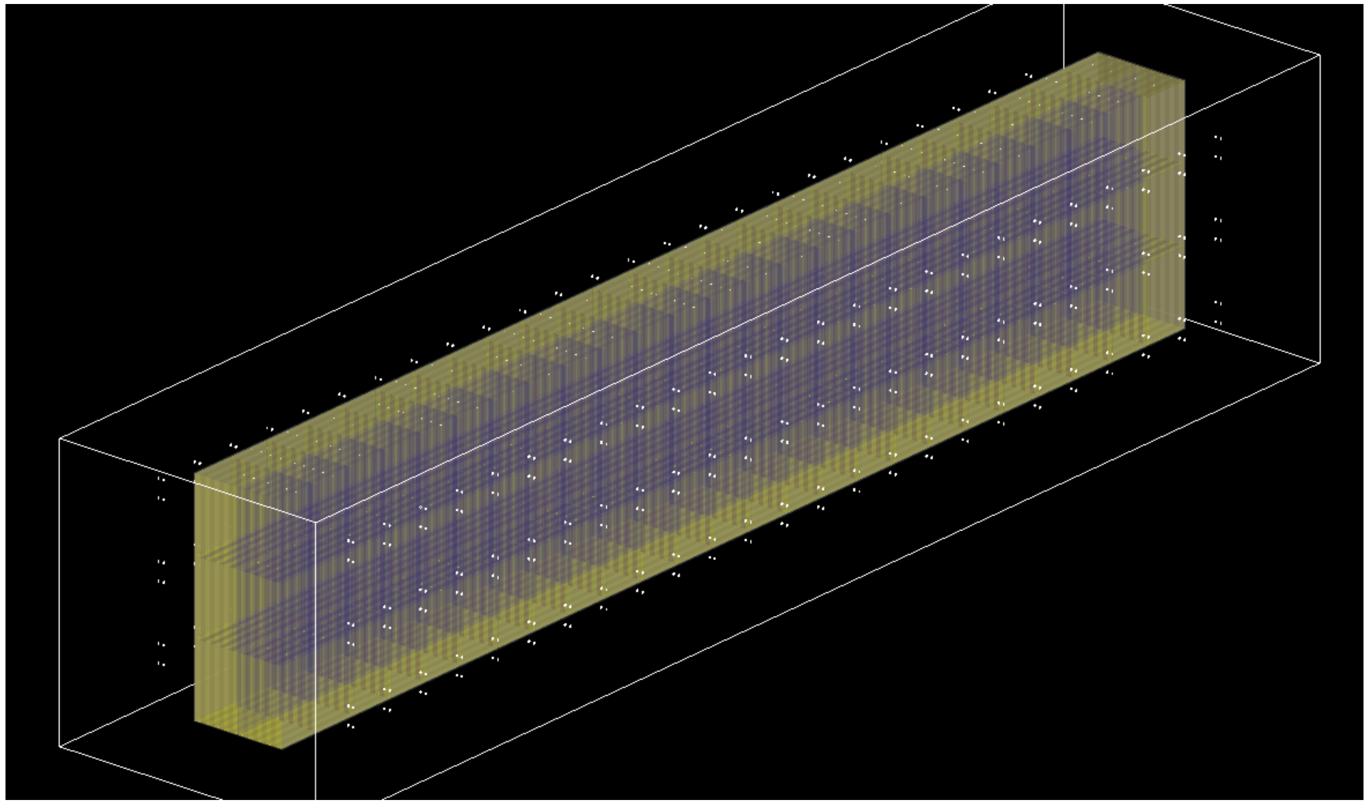
$$\mathcal{L} = \prod_{i,j} \frac{\lambda_{i,j}^{n_{i,j}} e^{-\lambda_{i,j}}}{n_{i,j}!}$$

$$p(H_1|D) = \frac{\mathcal{L}(D|H_1) \cdot \pi(H_1)}{p(D)} \qquad p(H_0|D) = \frac{\mathcal{L}(D|H_0) \cdot \pi(H_0)}{p(D)}$$

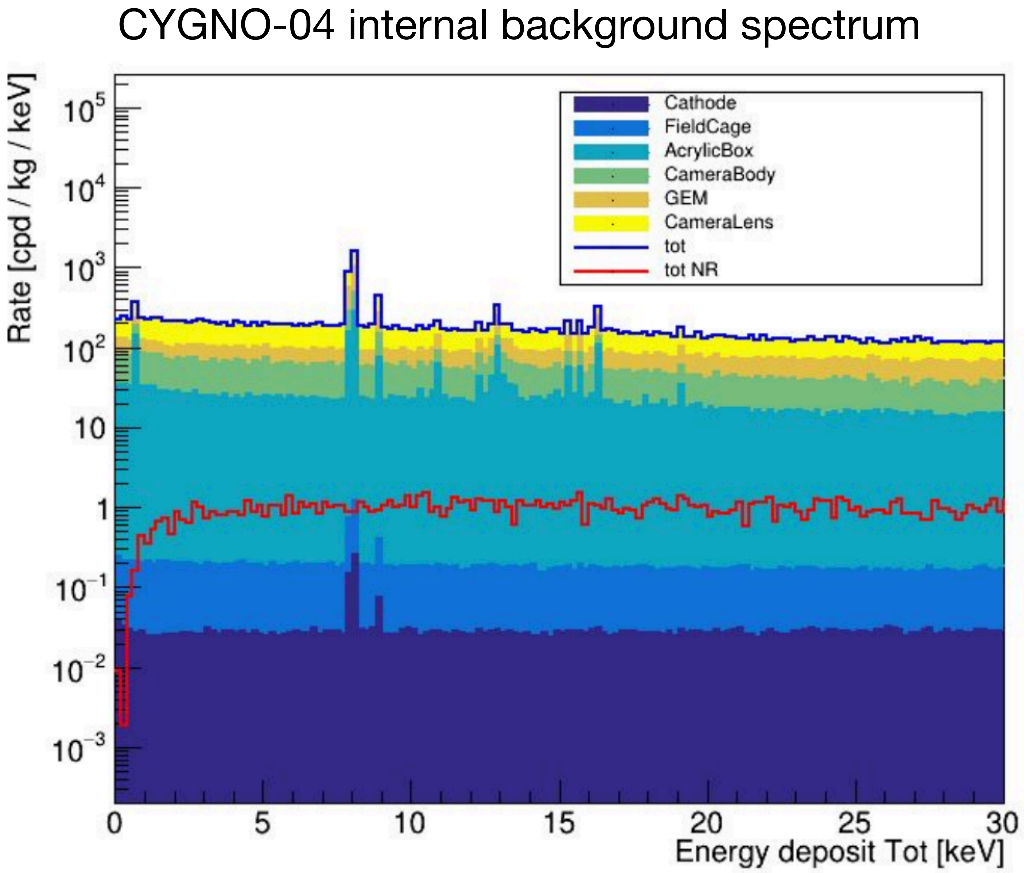
- Strategy:
  - Theoretical model for signal and background with the detector resolution included
  - ToyMC production
  - Likelihood fit for S+B model (H_1) and only B model (H_0)
  - Calculation of the Bayes factor and discovery probability vs exposure

$$\frac{p(H_1|D)}{p(H_0|D)} = \frac{\mathcal{L}(D|H_1) \cdot \pi(H_1)}{\mathcal{L}(D|H_0) \cdot \pi(H_0)} = B_f \frac{\pi(H_1)}{\pi(H_0)}$$

Background studies



- Bkg simulation of the full detector geometry
- Three rows stack on each other with 25 CYGNO-04 modules
- All 75 modules enclosed in a common vessel
- Most critical detector element from CYGNO-04 background studies included in the simulation:
  - Field cage
  - Cathode
  - GEMs
  - Detector body (Vessel)
  - Resistors
  - Camera lenses
  - Camera sensor
- Simulation done with most ultrapure materials available now → detector to be realized in ~ 6y
- Shielding thick and pure enough such that the level of the external background is less than the internal one



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.

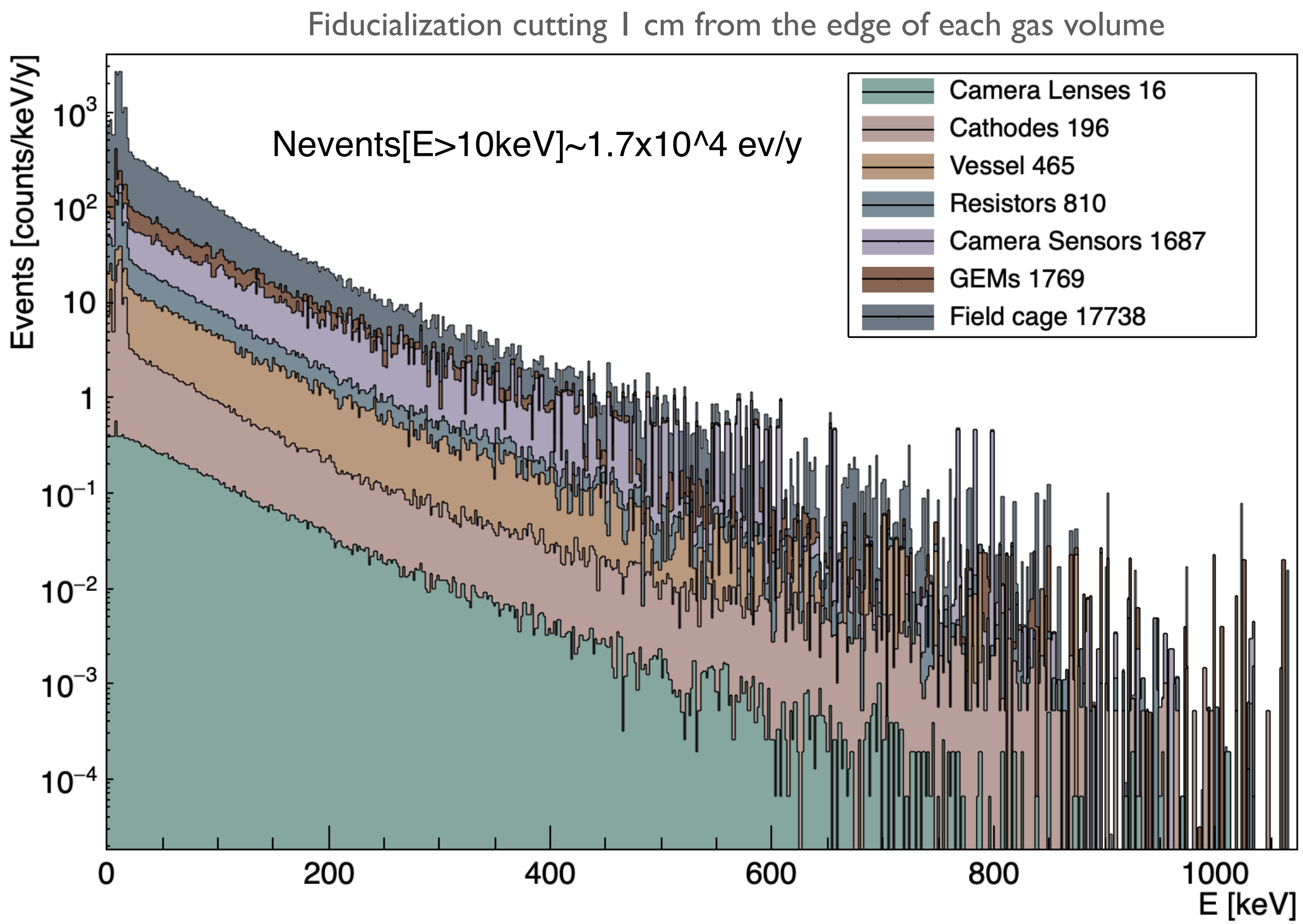
Detector element	Material	^{238}U	^{232}Th	^{40}K	^{235}U	^{226}Ra	^{228}Th
GEM core	Acrylic	$< 296.0\ \mu$Bq/Kg	$< 56.9\ \mu$Bq/Kg	$< 71.2\ \mu$Bq/Kg	x	eq	eq
GEM armor	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Field cage support	Acrylic	$< 296.0\ \mu$Bq/Kg	$< 56.9\ \mu$Bq/Kg	$< 71.2\ \mu$Bq/Kg	x	eq	eq
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

Final background spectrum



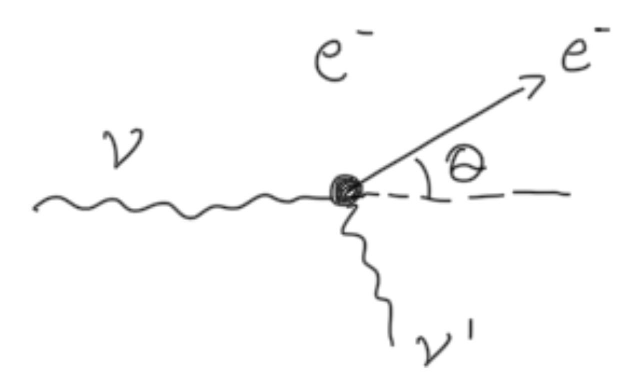
- Field cage acrylic is the dominant contribution (x10)
- Very recently we found a more suitable insulator

Material	^{238}U	^{232}Th	^{40}K
Acrylic	< 296.0 μBq/Kg	< 56.9 μBq/Kg	< 71.2 μBq/Kg
Kapton	~ 10 μBq/Kg	~ 10 μBq/Kg	X

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

- x10 less radioactive than the SNO acrylic

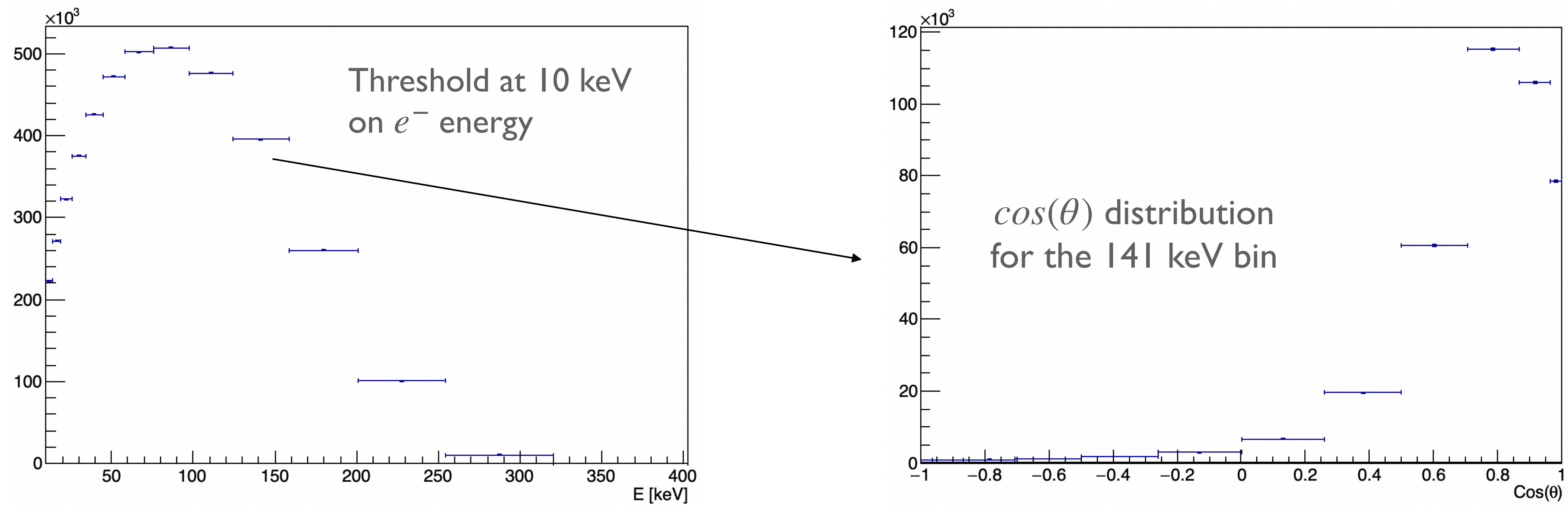
Template for bayesian analysis



- 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

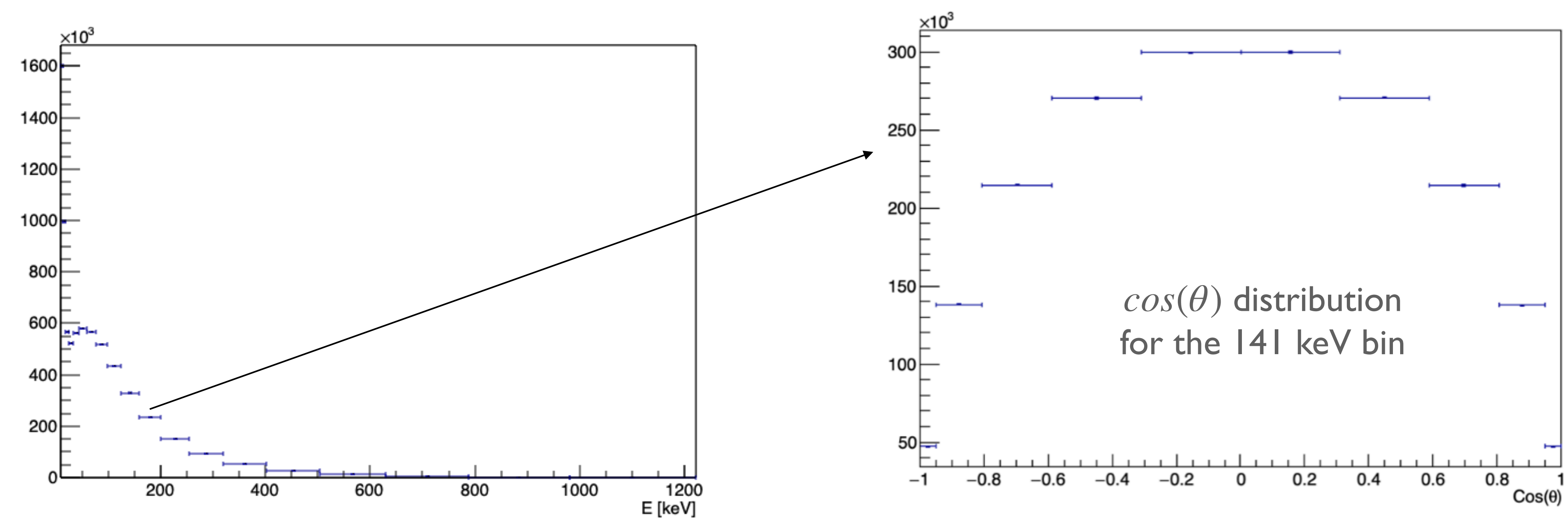
- Signal

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



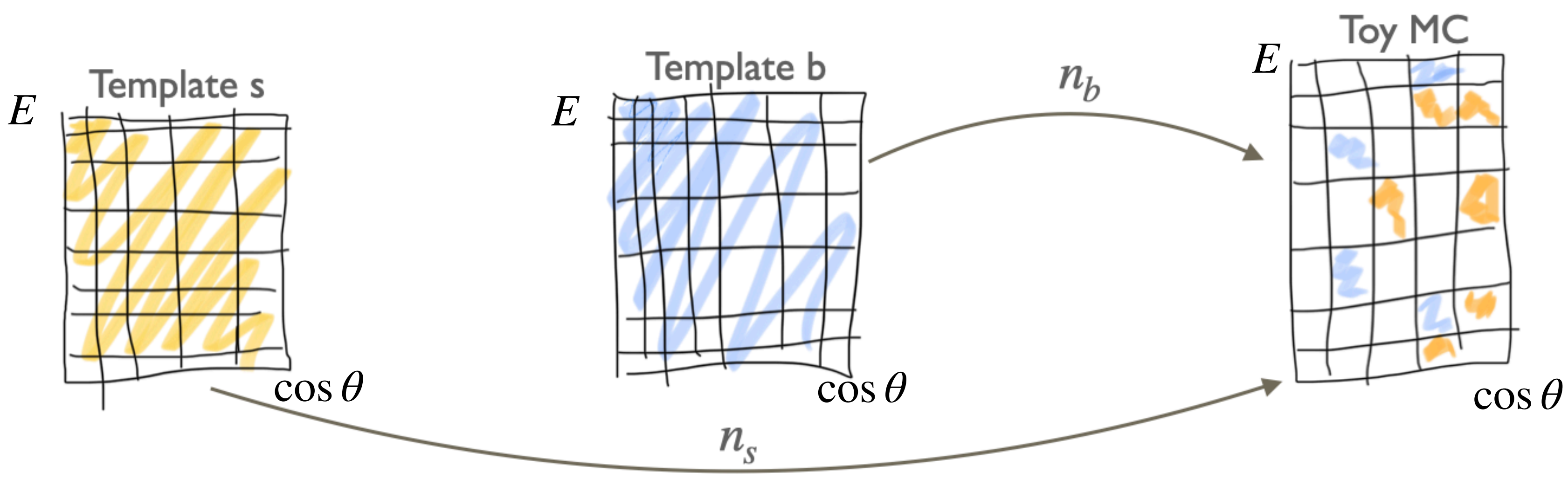
- Background

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



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

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

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

- Calculation of the Bayes factor:

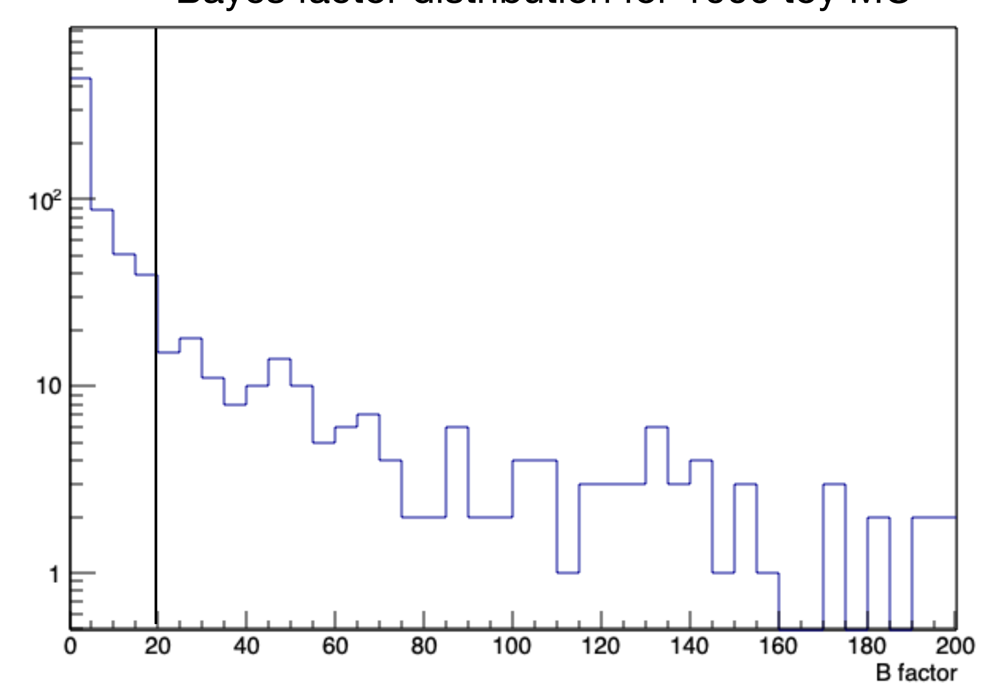
0.5/0.5

$$\frac{p(H_1|D)}{p(H_0|D)} = \frac{\int \mathscr{L}(D|\mu_b, \mu_s, H_1)\pi(\mu_b)\pi(\mu_s)d\mu_b d\mu_s}{\int \mathscr{L}(D|\mu_b, H_0)\pi(\mu_b)d\mu_b} \cdot \frac{\pi(H_1)}{\pi(H_0)} = B_f \frac{\pi(H_1)}{\pi(H_0)}$$

- Discovery probability with a BF>20 (=3σ confidence level):

$$DP(exp, R_f) = \frac{N_{toy}(BF > 20)}{N_{toy}}$$

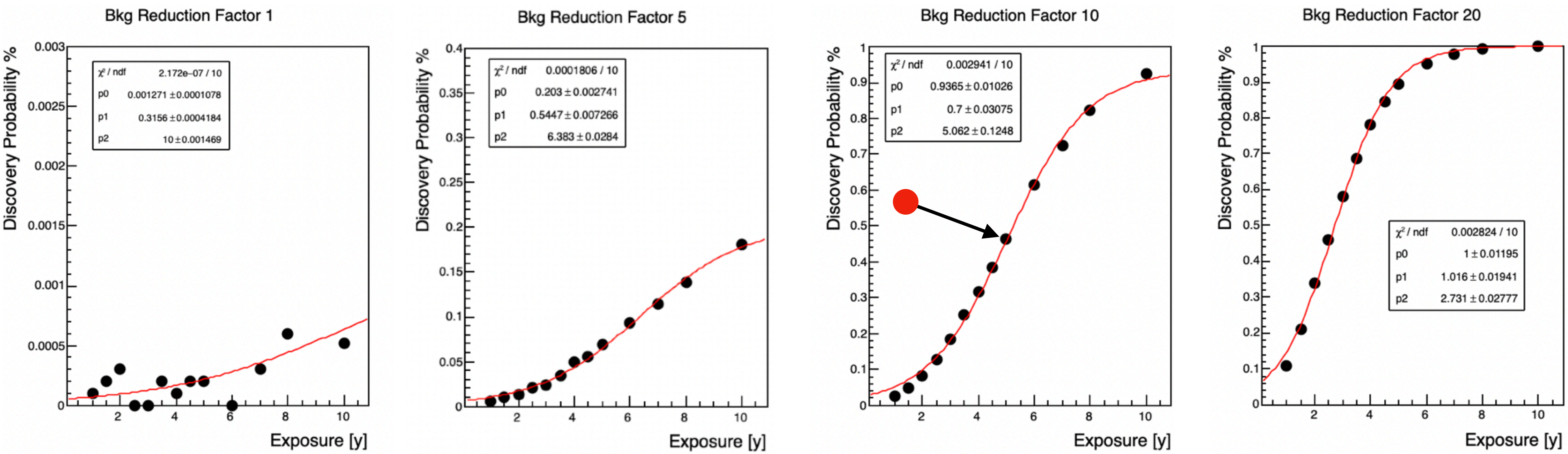
Bayes factor distribution for 1000 toy MC



- 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

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

- Exposure corresponding to165 neutrino signal over 9790 ev. of background

- Equivalent to a rate Bgk/Signal $\simeq$ 60, very strong background toleration

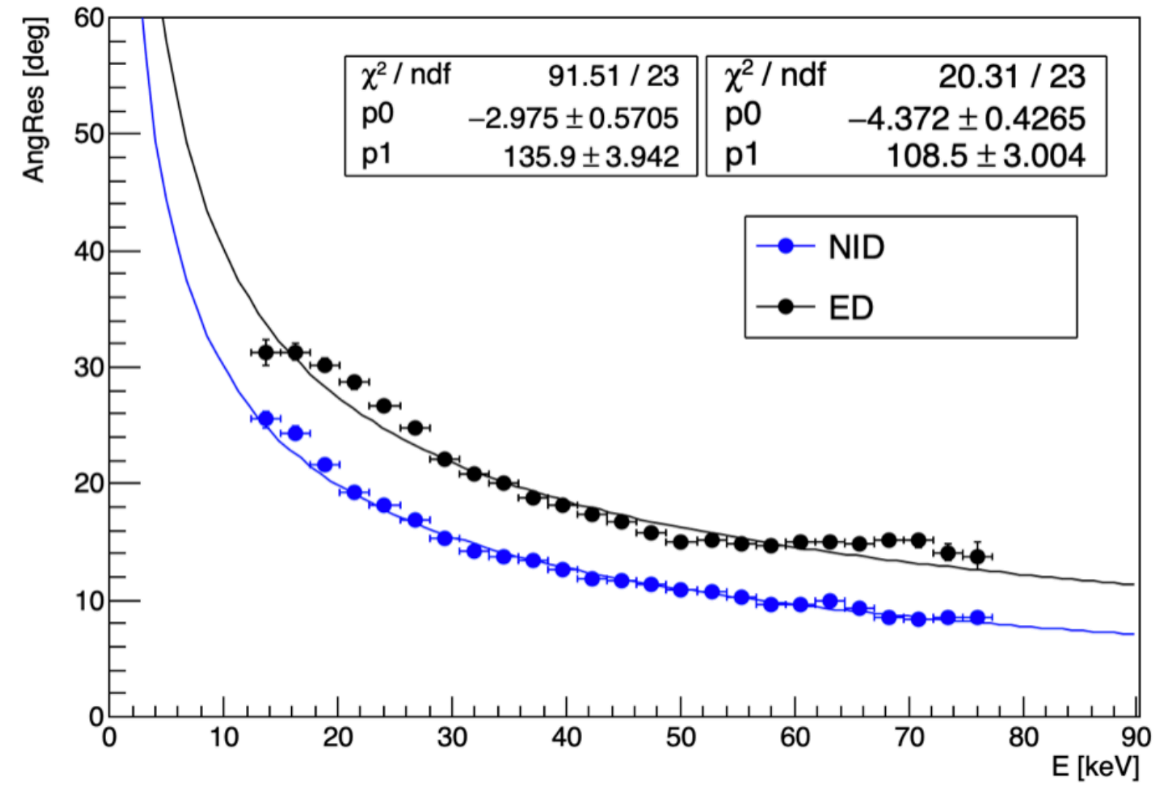
- Borexino in the pp measurement had a ratio Bgk/Signal $\simeq$ 2.3

$\overline{B}_{10}$	$\ln \overline{B}_{10}$	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.

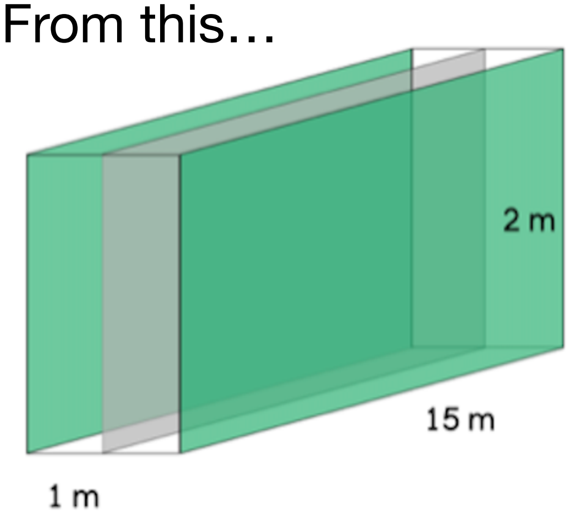
Sensitivity results with NID angular resolution

- Same study repeated with NID angular resolution assuming the same energy resolution
- No significant improvement obtained with only reduced diffusion:
    1. Sensitivity dominated by the energy resolution (improvement in both needed)
    2. Angular distribution of the scattered ER dominates

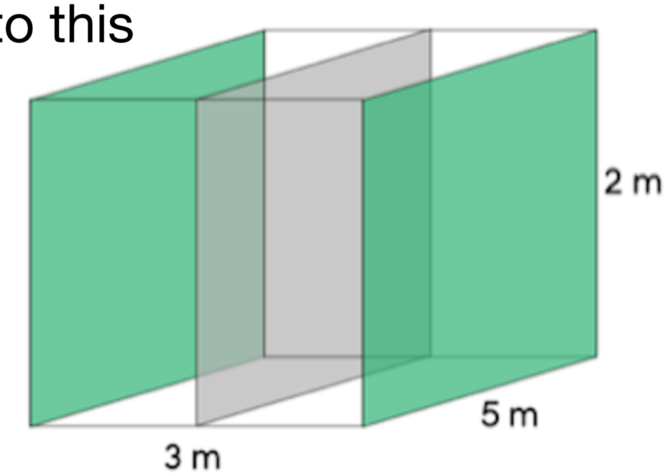


- However NID would allow to build a detector with 1.5 m drift length with still better performances than ED operation →
    - More compact detector
    - 1/3 of GEMs, cathodes, cameras…
    - Less background
    - Less shield required
    - Much cheaper realization costs

From this…

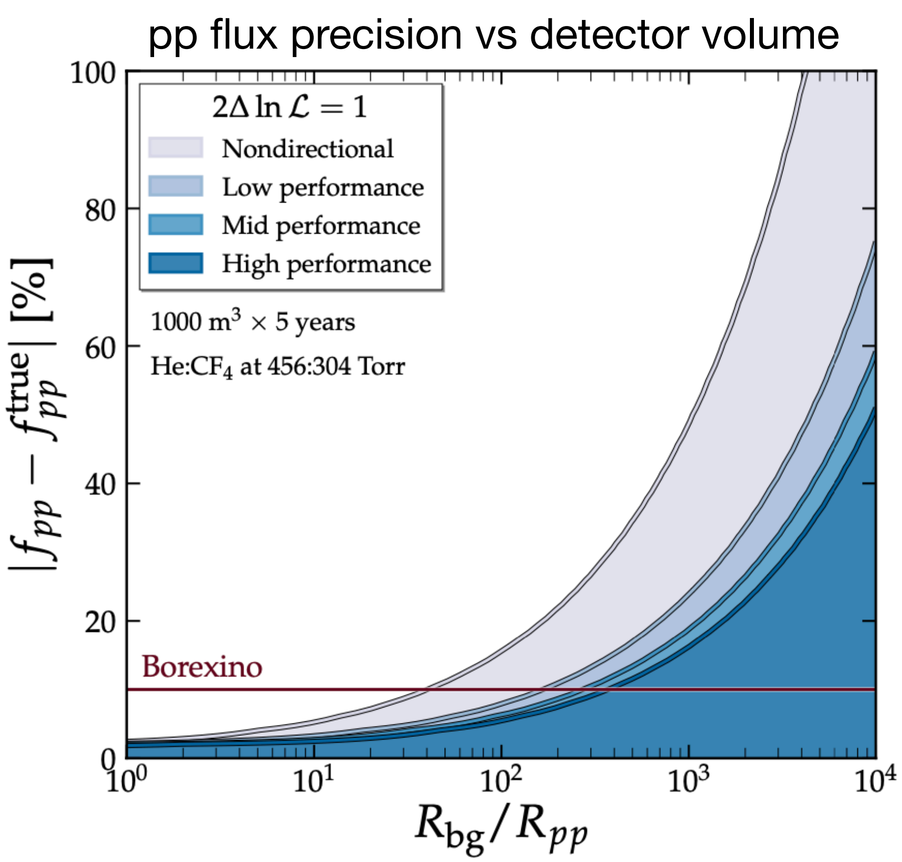


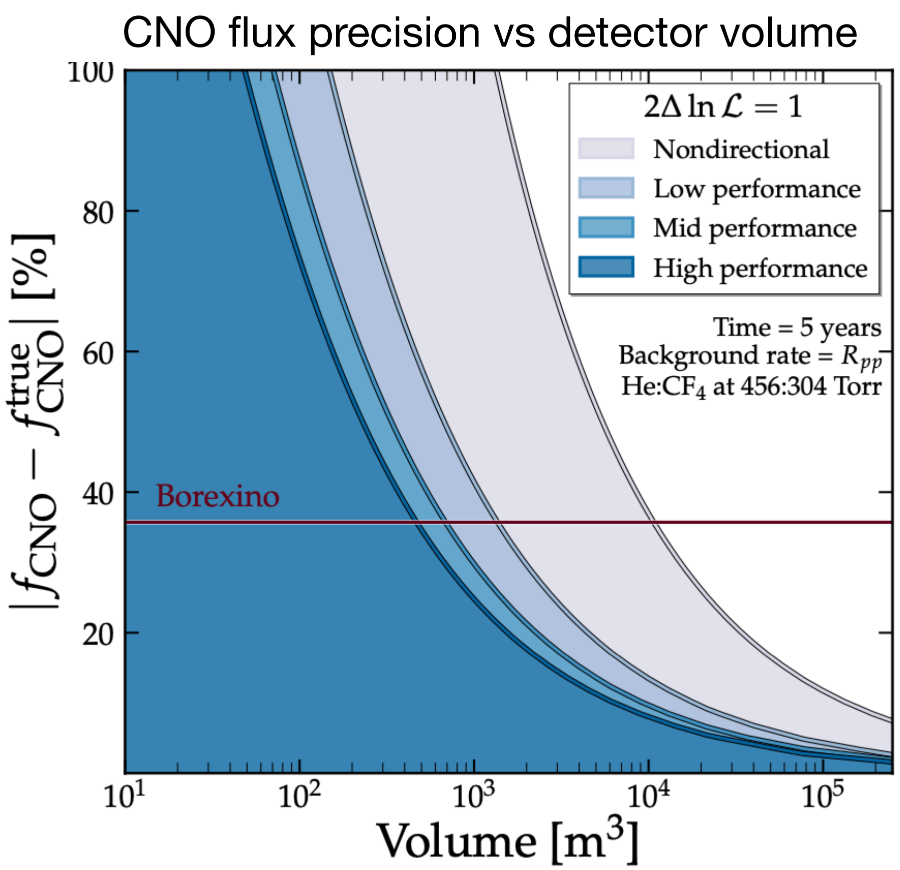
… to this



Future development in solar neutrino measurement

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





Lisotti, C., O'Hare, C. A., Baracchini,... & Torelli, S. (2024). CYGνS: Detecting solar neutrinos with directional gas time projection chambers. *arXiv preprint arXiv:2404.03690*.

- In the future no other experiments are expressly designed to measure pp and CNO neutrinos:
- JUNO's capability for a CNO measurement will strongly depend on the background expected (developed for reactor's neutrinos, might take 10s of years to reach the Borexino bgk level)
- DARWIN could precisely measure the pp but the Xe 2β decay might prevent CNO measurement
- It could be worth to invest on the gas TPC technology to study solar neutrino alongside with DM

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 my PhD thesis 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)