Feasibility of solar neutrino measurement with the CYGNO/INITIUM experiment

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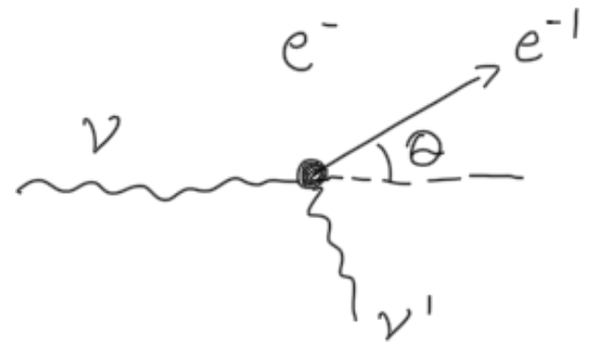
CYGNO Collaboration meeting - Dec 2023

Solar neutrino directional detection



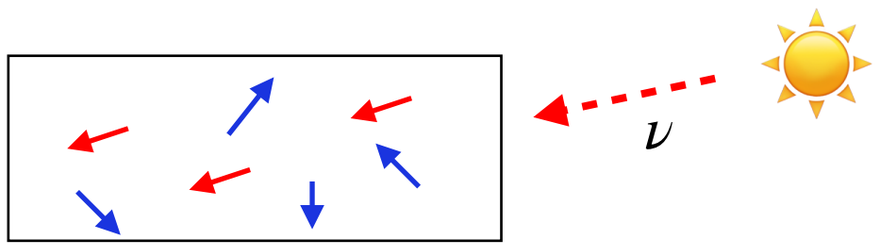
Neutrino from the Sun can be object of study with large TPC through $\nu - e^-$ elastic scattering as proposed in the '90:

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

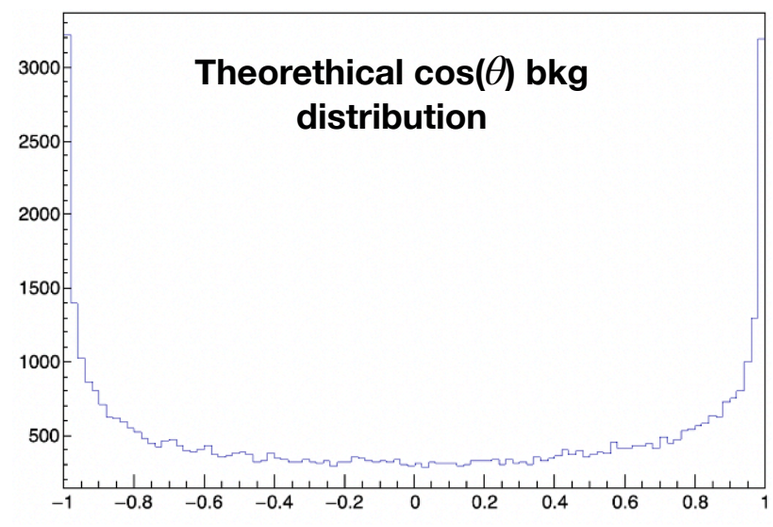


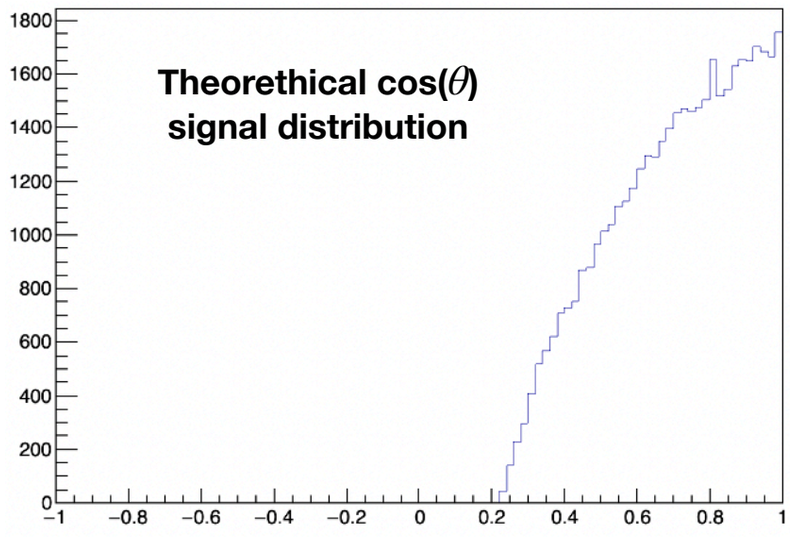
Possibility of event by event neutrino energy reconstruction (closed kinematic)

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

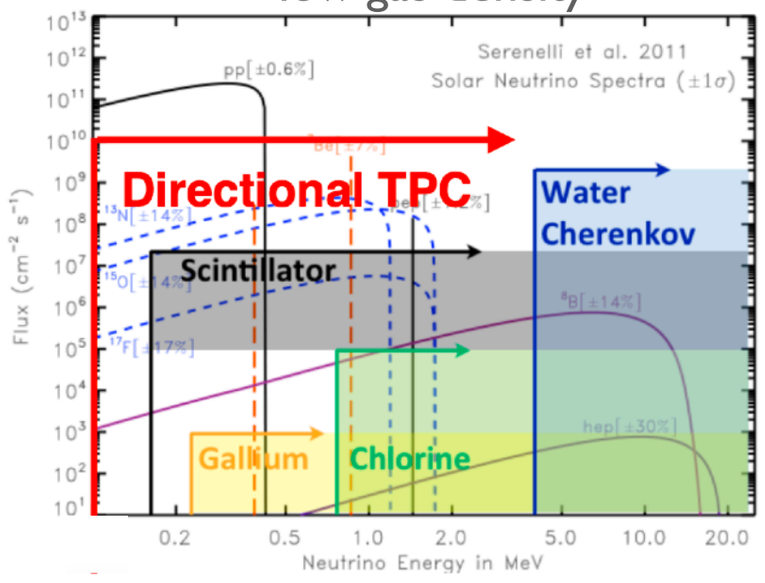
Much stronger signature than energy spectrum

Exponential Signal over exponential bkg	vs	Peaked distribution over flat bkg



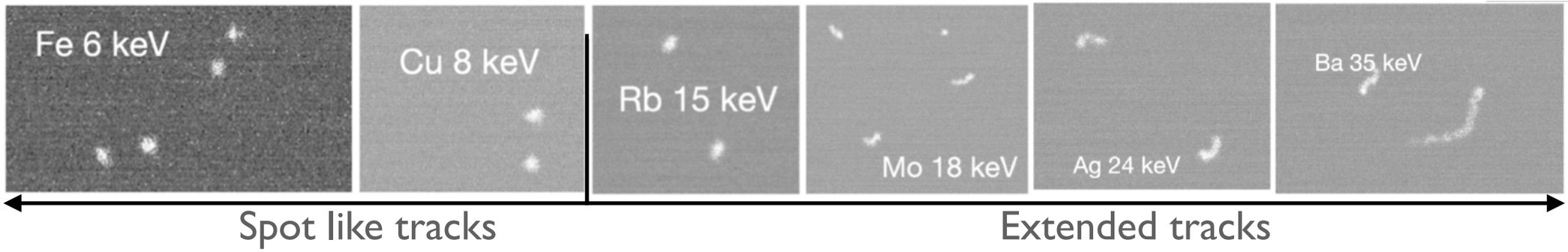


+ low gas density

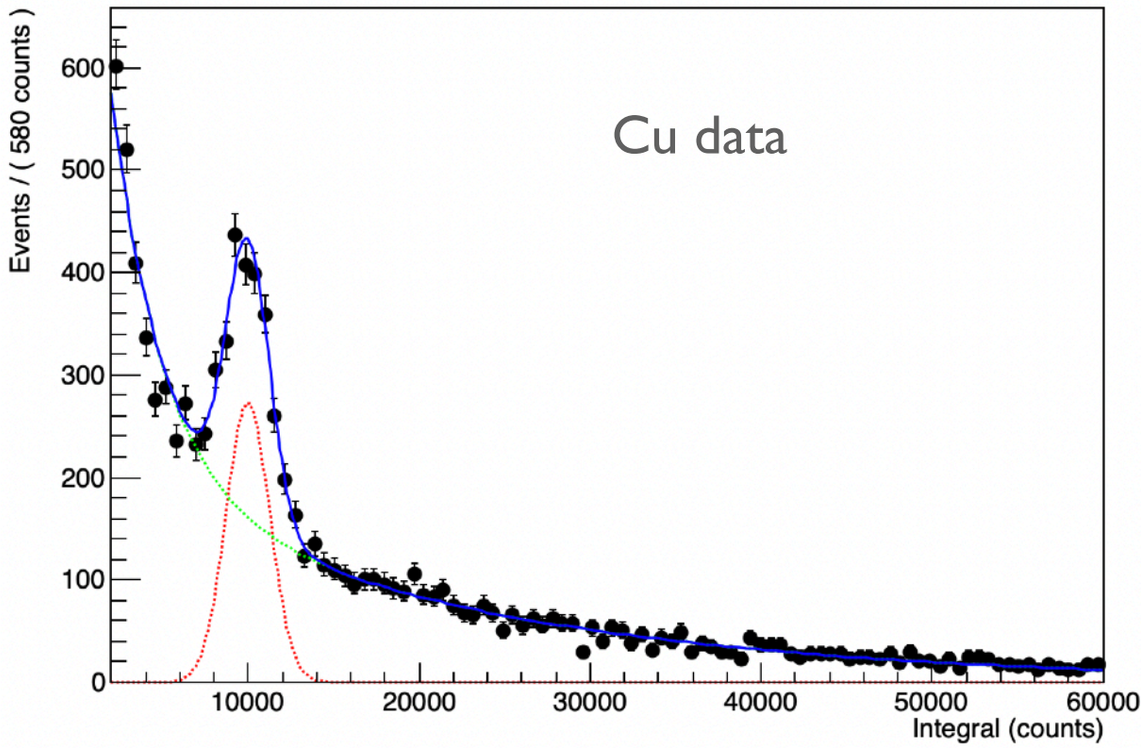


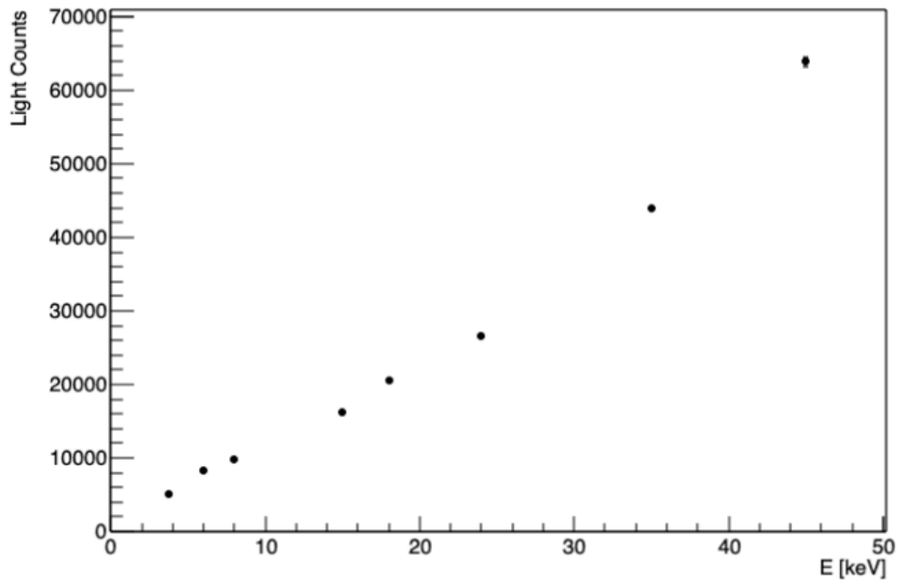
Energy response and resolution on data

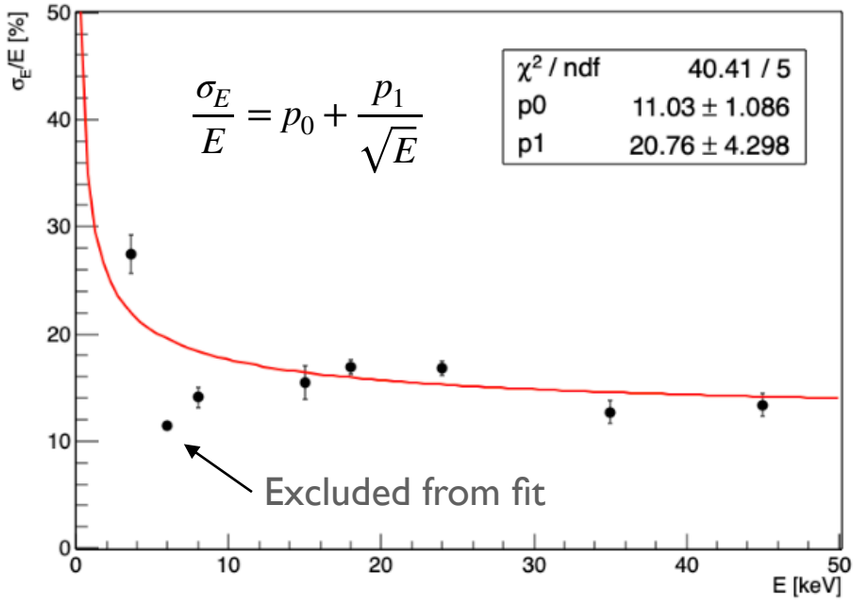
- Study of linearity and energy resolution performed overground with low energy electron recoils from X-Rays
- How tracks appear:



- Fit with 2 exponential + 1 gaussian





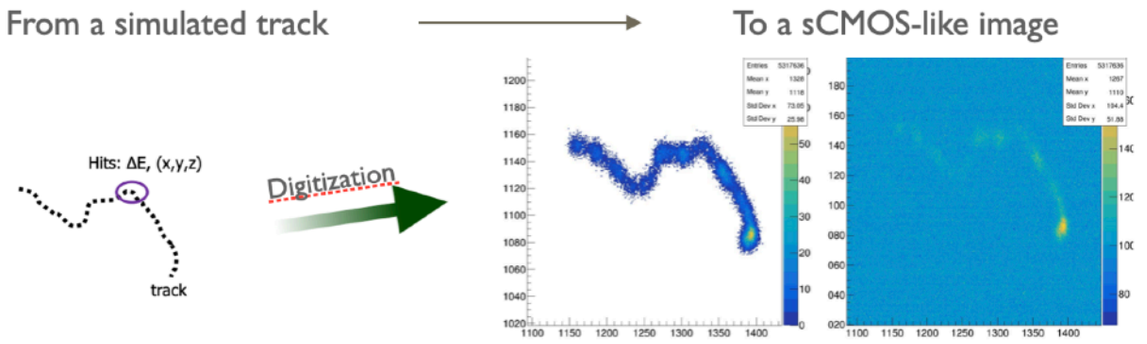


- Data shows good linearity in [6-35] keV
- Energy resolution ~ constant at 13% in same range

Same kind of tracks expected from ν scattering

Data-Simulation Comparison

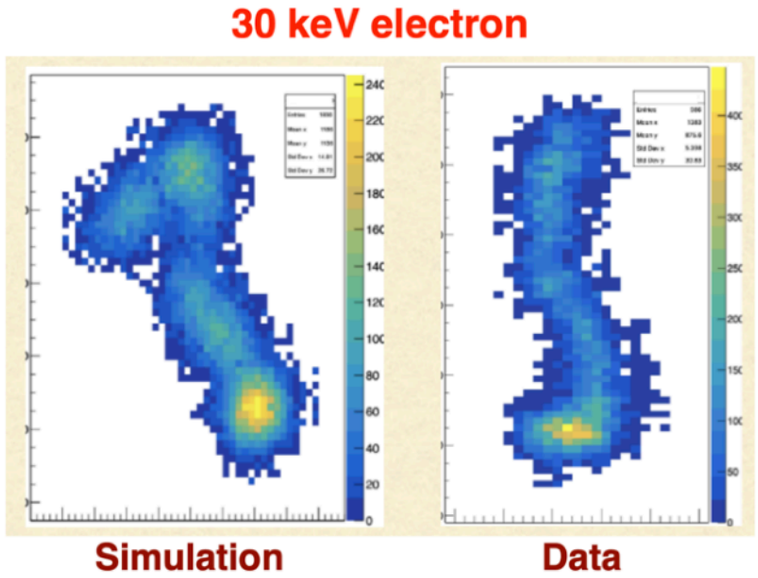
- Digitization of simulated tracks into sCMOS pictures



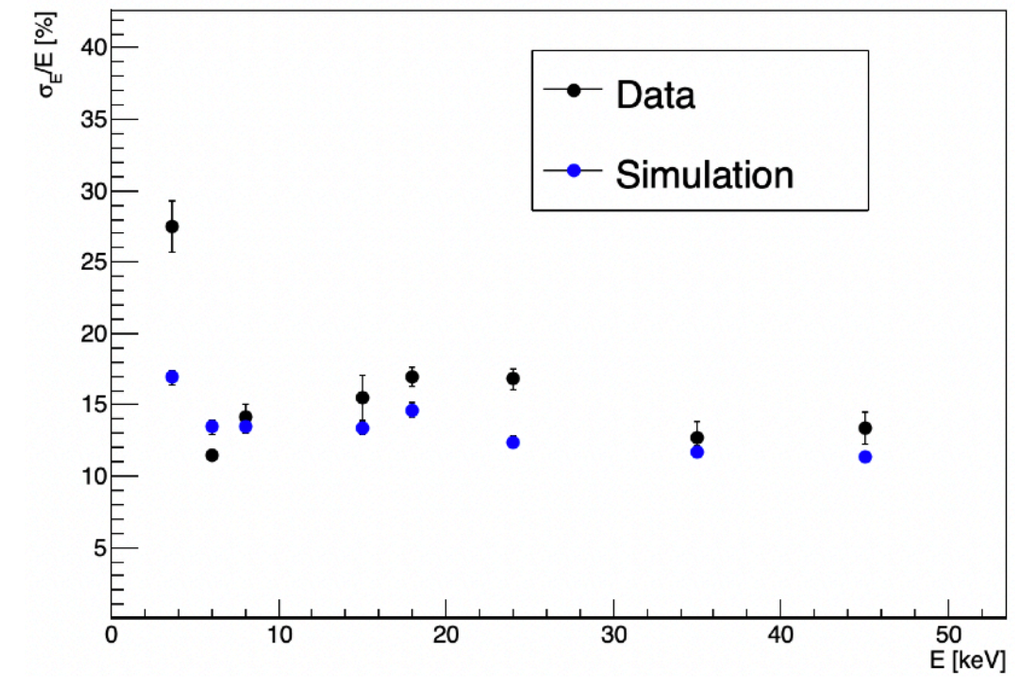
Developed taking into account detector effect:

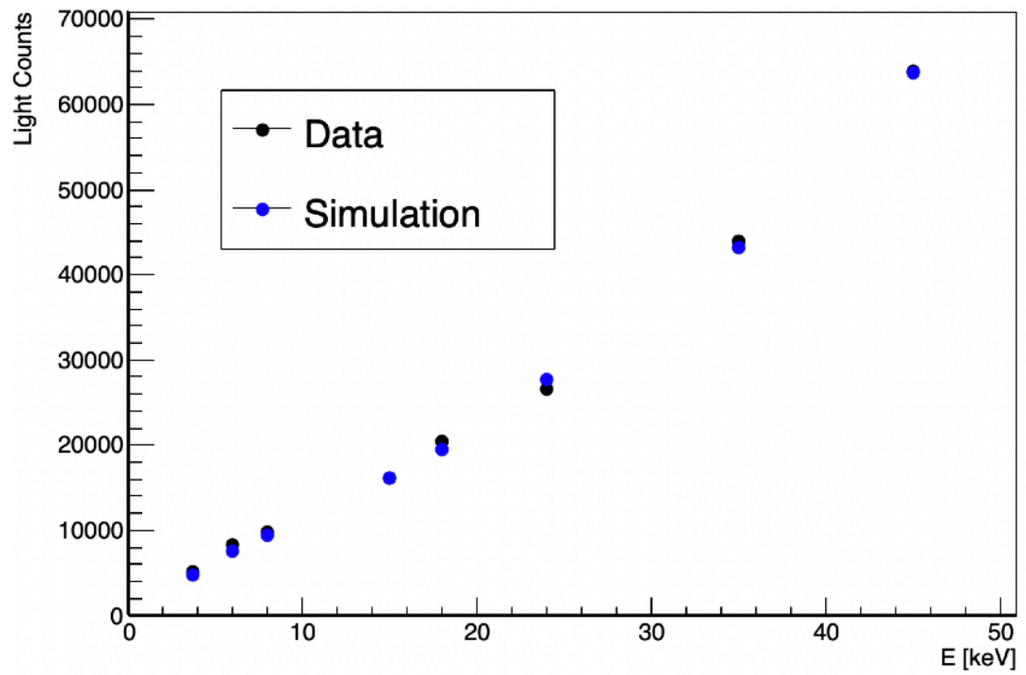
- Fluctuation in primary electrons production (poiss.)
- GEM gain fluctuation (expo.)
- Gain dependence on electron density
- Electron diffusion from measured coefficients
- Fluctuation in photon production (poiss.)
- Light collection efficiency
- Vignetting effect with track produced in different x-y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

- 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



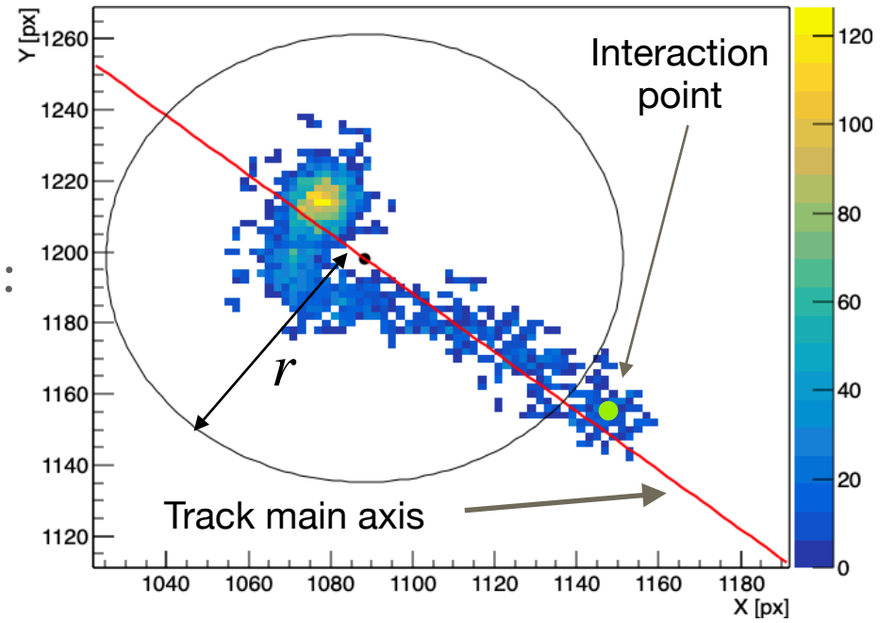


Directionality algorithm in a nutshell

- Algorithm adapted from X-ray polarimetry:

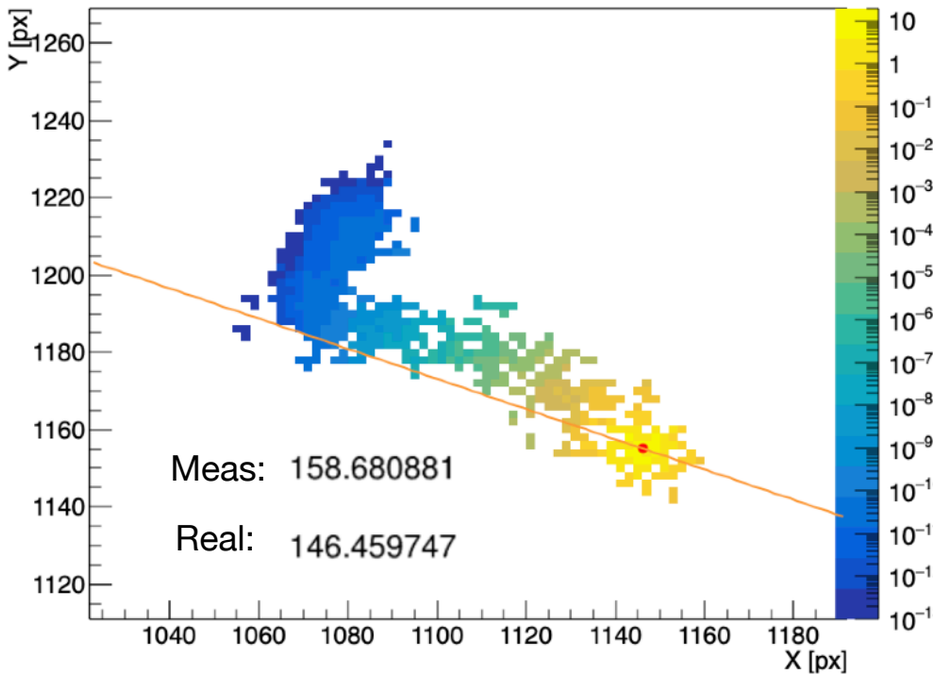
"Measurement of the position resolution of the Gas Pixel Detector"
Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105

- 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}



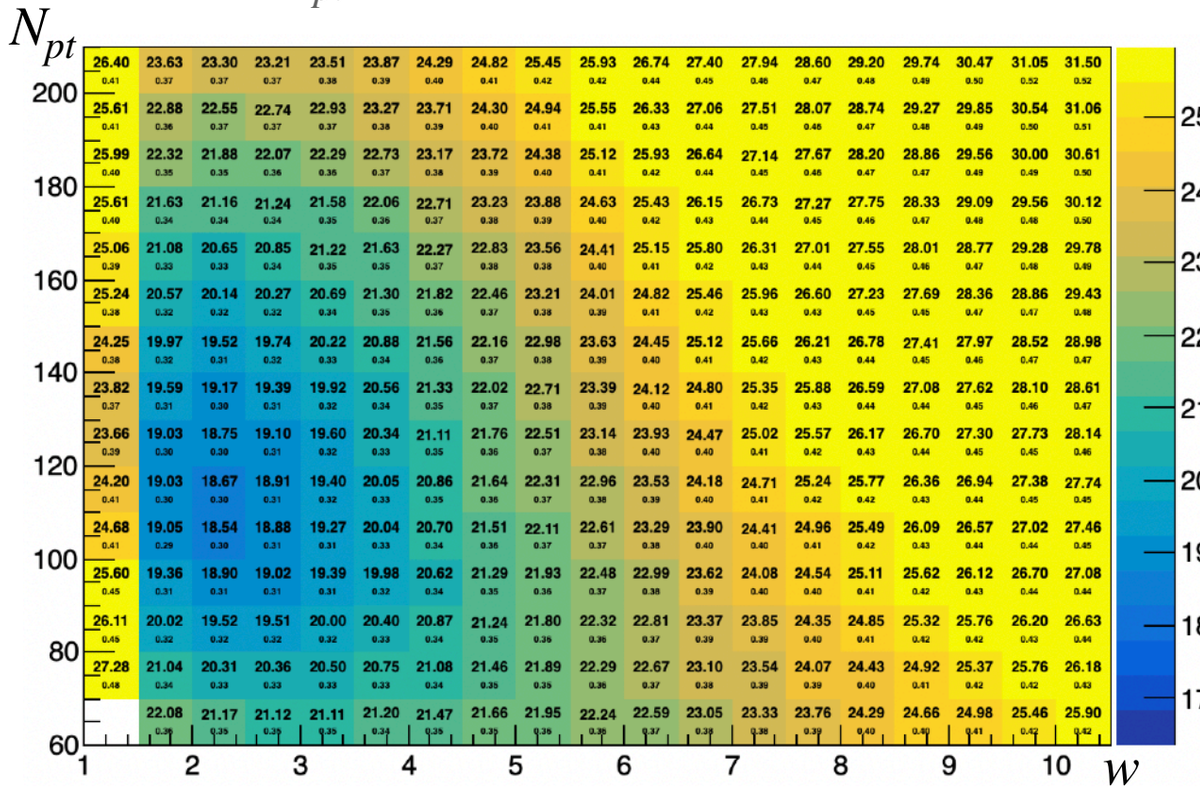
- Second part of the algorithm aims to find the direction:
  - Track point intensity rescaled with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the main axis of the rescaled track passing from the interaction point
  - Orientation given following the light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

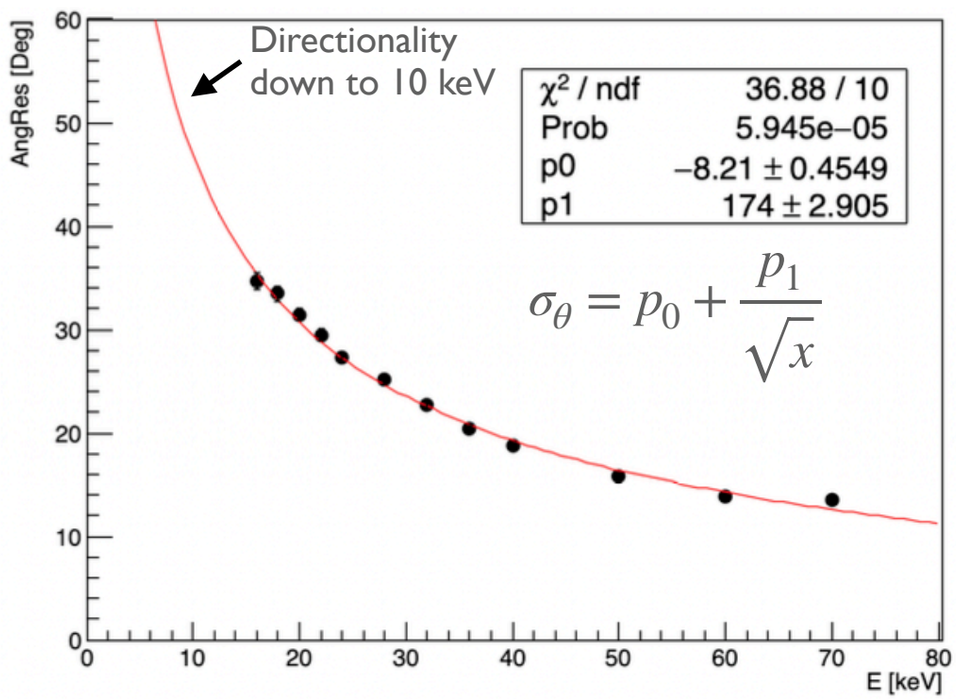
- Two parameters of the algorithm: N_{pt} and w

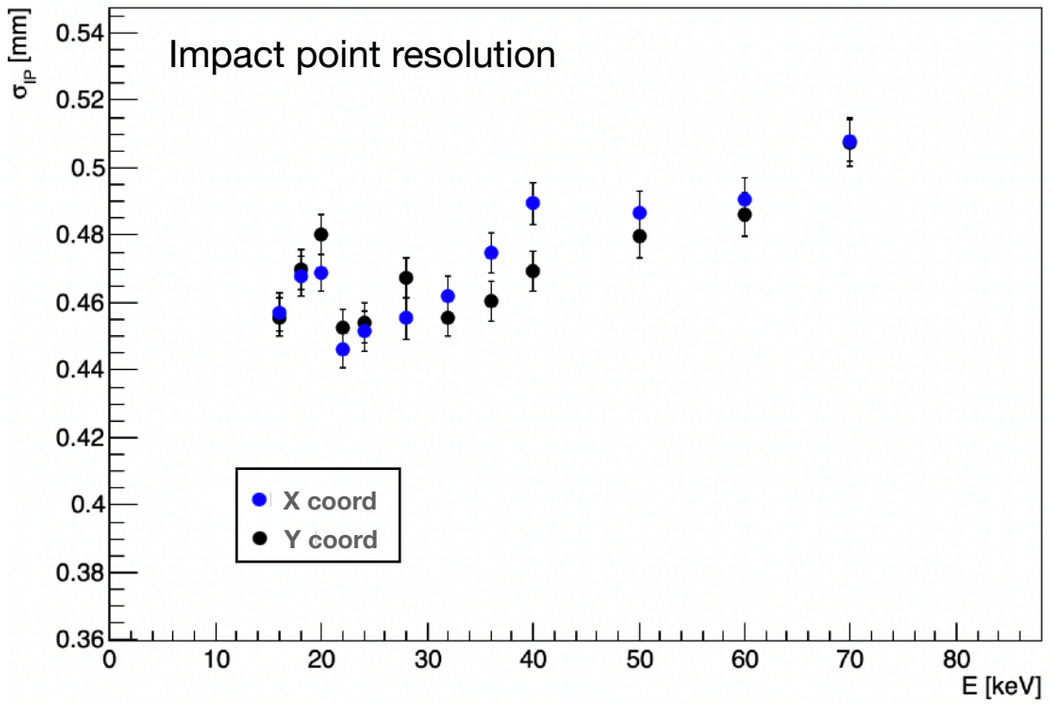


Parameters optimization and results

- 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

Binned likelihood

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

- 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 (55 keV on ν energy)

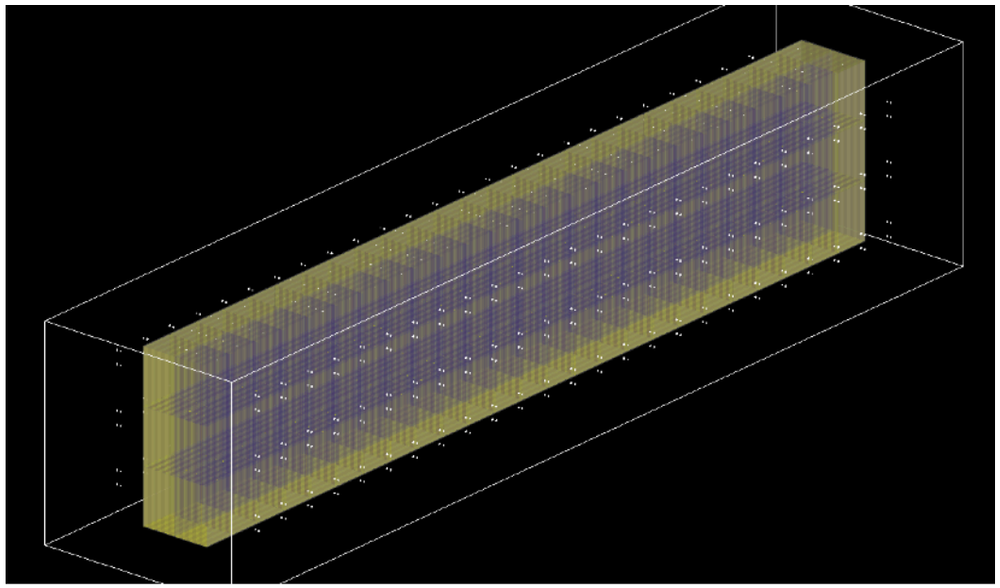
- Strategy:
  - Model for signal and background
  - ToyMC production
  - Likelihood fit for S+B model (H_1) and only B model (H_0)
  - Calculation of the Bayes factor and discovery probability vs exposure

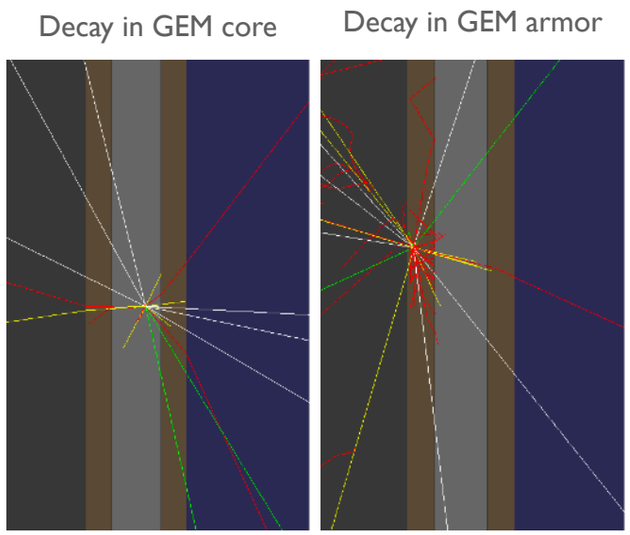
$$p(H_1 \,|\, D) = \frac{\mathscr{L}(D \,|\, H_1) \cdot \pi(H_1)}{p(D)} \qquad p(H_0 \,|\, D) = \frac{\mathscr{L}(D \,|\, H_0) \cdot \pi(H_0)}{p(D)}$$

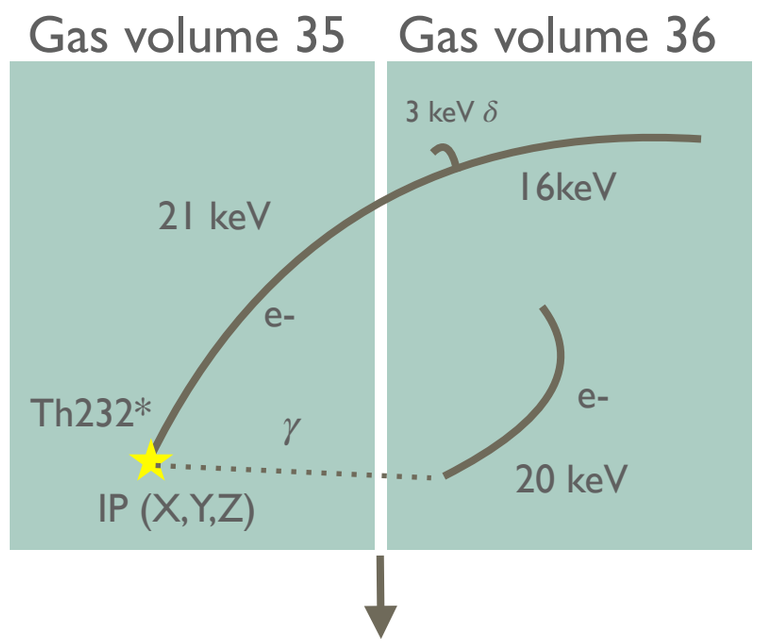
$$\frac{p(H_1 \,|\, D)}{p(H_0 \,|\, D)} = \frac{\mathscr{L}(D \,|\, H_1) \cdot \pi(H_1)}{\mathscr{L}(D \,|\, H_0) \cdot \pi(H_0)} = B_f \frac{\pi(H_1)}{\pi(H_0)}$$

Background studies

- Bkg simulation of the full detector geometry → 3x25 CYGNO-04 modules



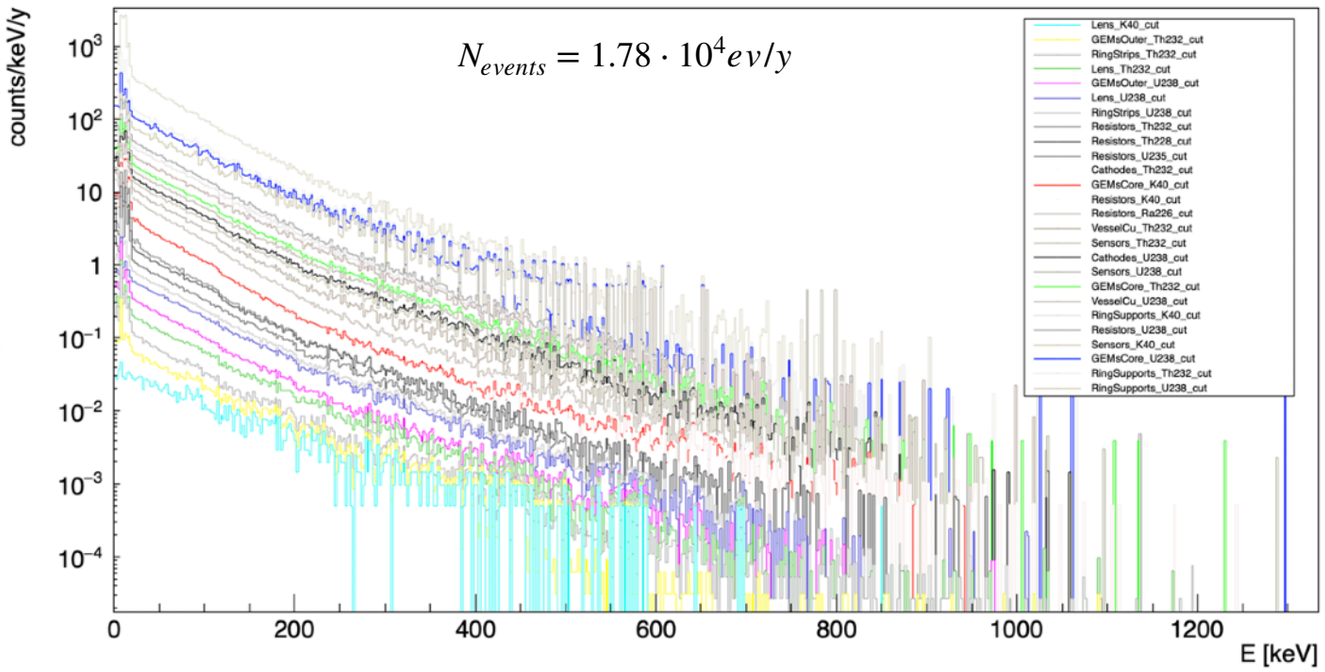




40 keV electron +20 keV electron in the final spectrum

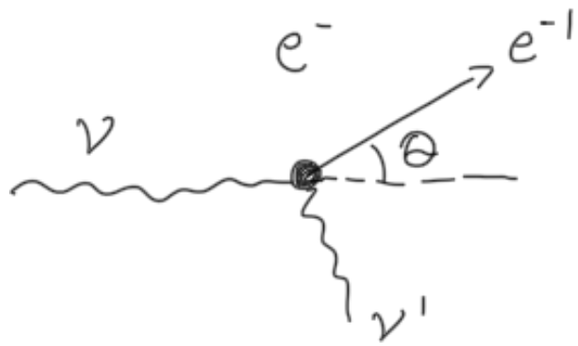
- Simulation done with ultrapure materials

- Simulation included:
  - 50 μm GEMs made by EFCu and acrylic
  - Fied cage made by 75μm acrilic with EFCu strip on top
  - Cathode made by 1 mm EFCu
  - Vessel made by 1cm EFCu
  - Lens made by suprasil
  - Sensors made by Silicon
  - SMD resistors from Xenon



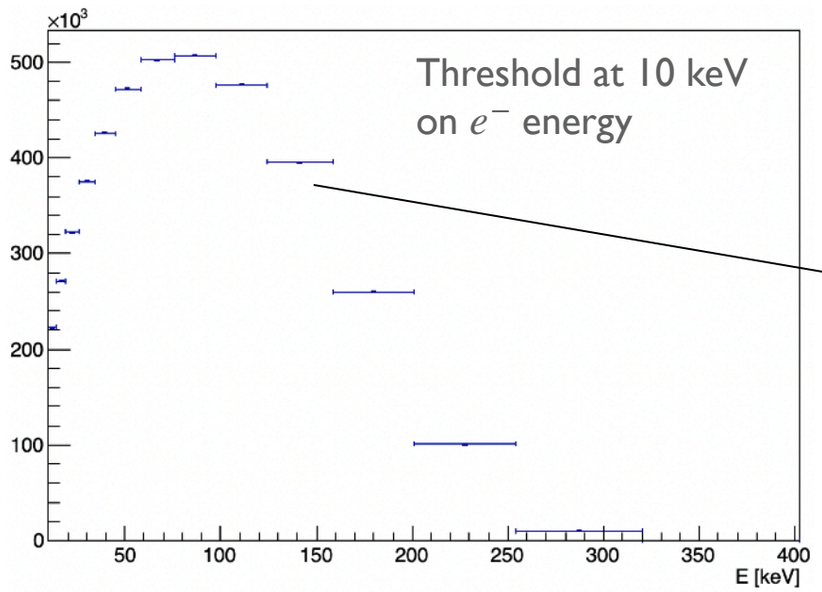
Template production

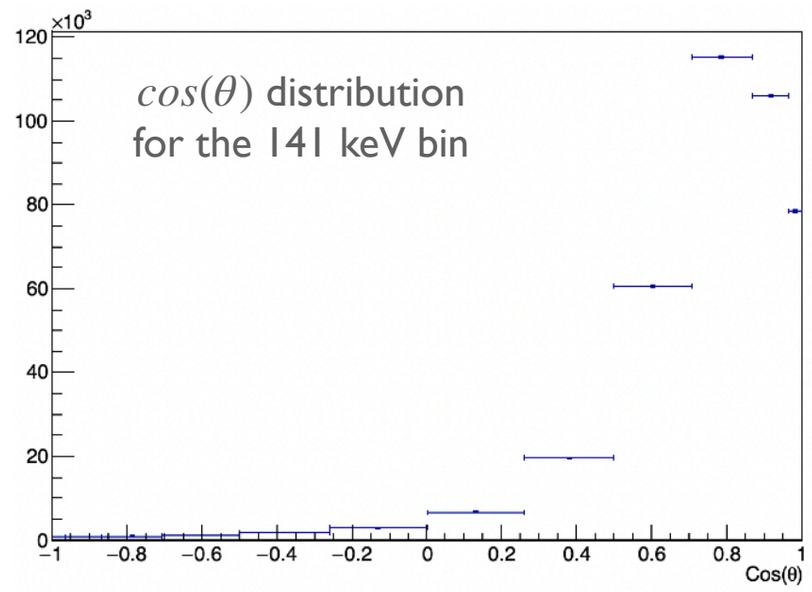
- Template produced starting from the expected distribution adding the detector resolution
  - For each energy bin the cos(θ) distribution is produced



- Signal

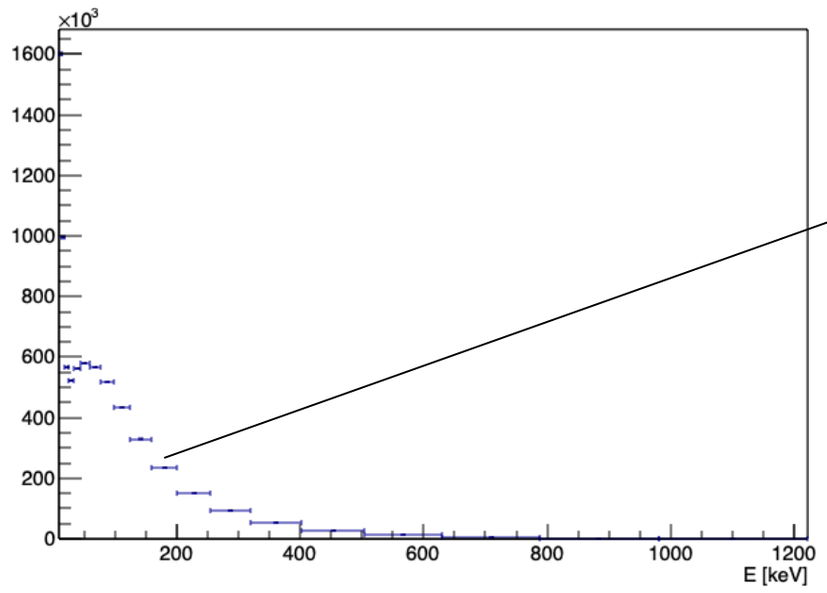
Produced starting from the pp cycle neutrino, simulating the interaction and adding the detector resolution

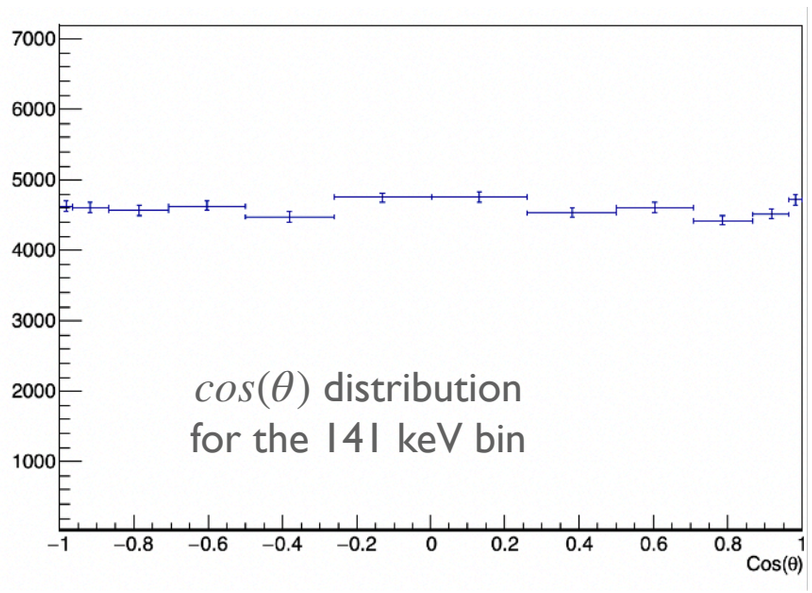




- Background

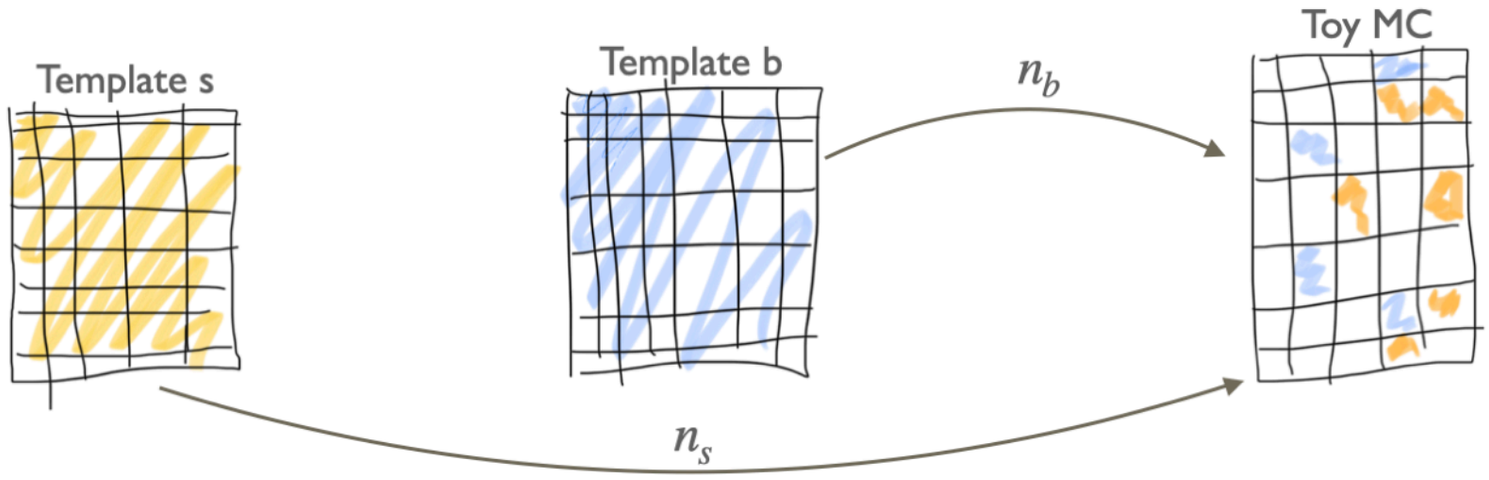
From CYGNO_30 background simulation



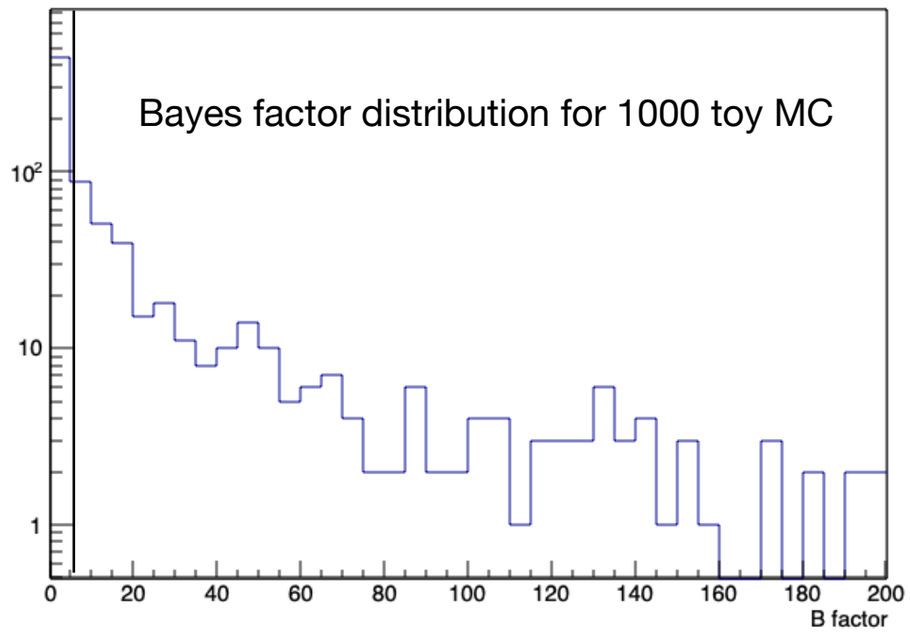


Toy-MC

- 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

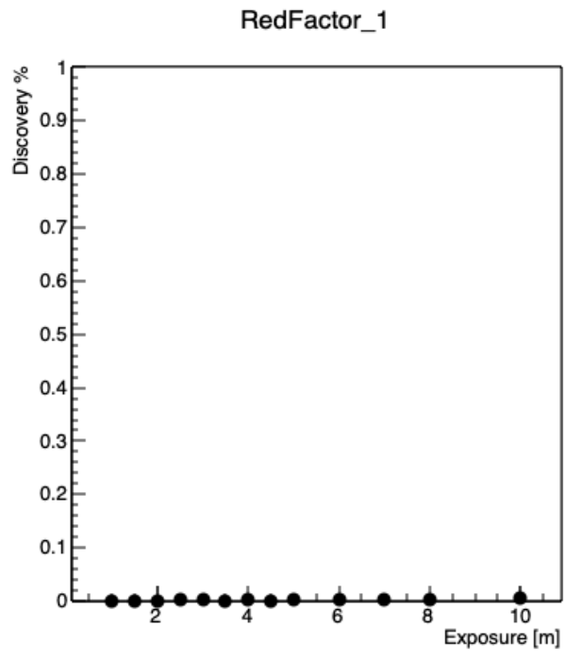


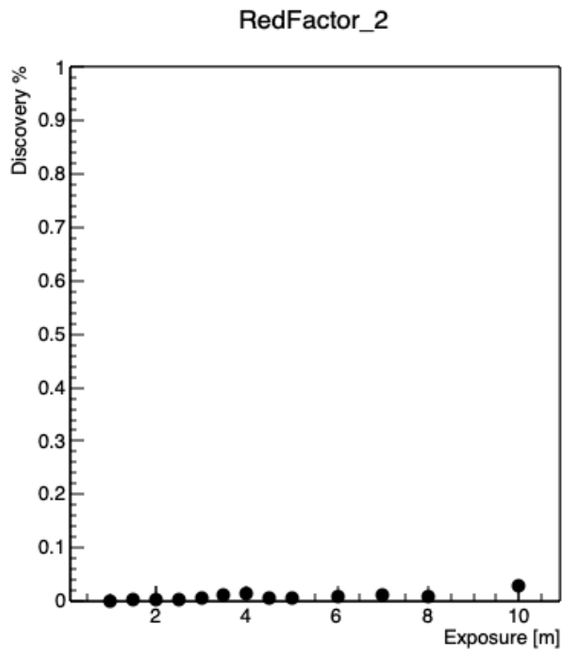
- 1000 toy MC produced for different exposure have been produced: from 6 to 120 months in step of 6 months
  - $\bar{N}_s = 30 ev/y \cdot exp$ $\bar{N}_b = 1.78 \cdot 10^4 ev/y \cdot exp$
- Fit with B (H_0) model and S+B (H_1) model
- Calculation of the Bayes factor $\frac{p(H_1|D)}{p(H_0|D)} = \frac{\mathscr{L}(D|H_1)\cdot\pi(H_1)}{\mathscr{L}(D|H_0)\cdot\pi(H_0)} = B_f \frac{\pi(H_1)}{\pi(H_0)}$
- Discovery probability with a BF>5 as the fraction of cases in which the BF>5 over the total number of toy

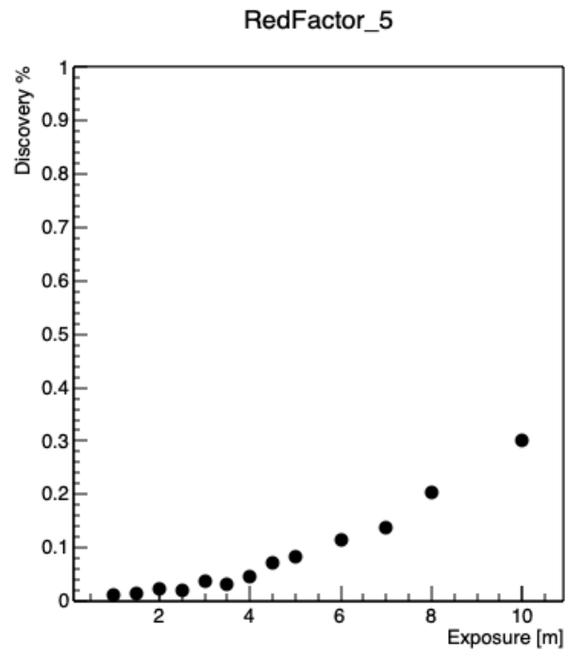


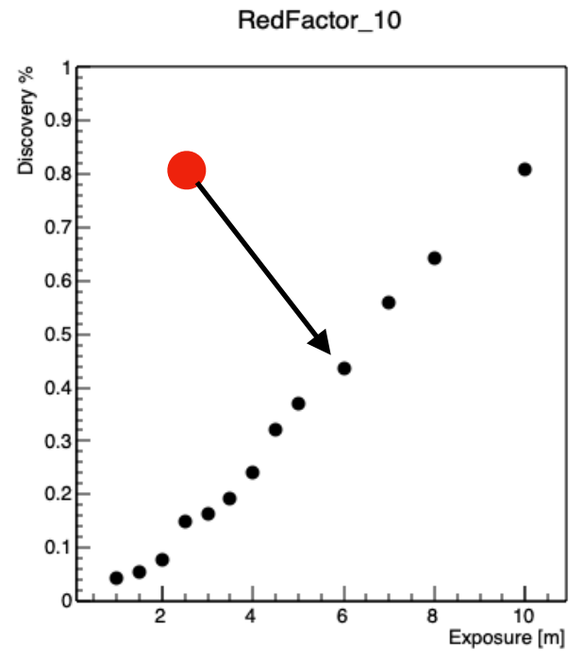
Sensitivity results

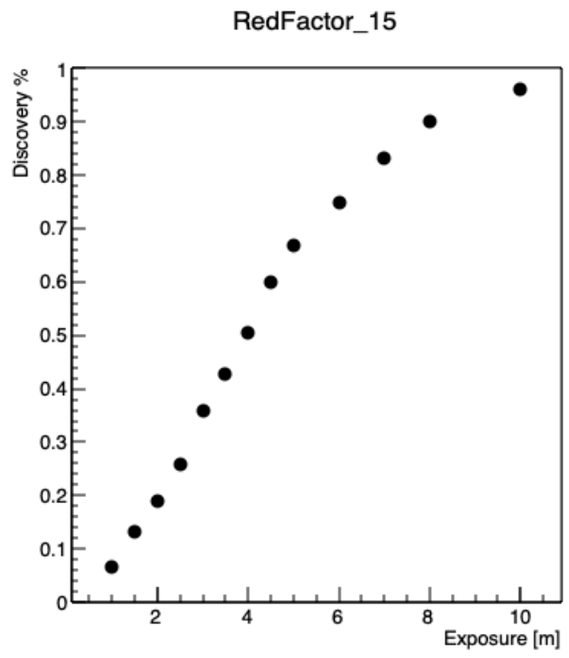
- Plot of the discovery probability with BF>5 as a function of the exposure

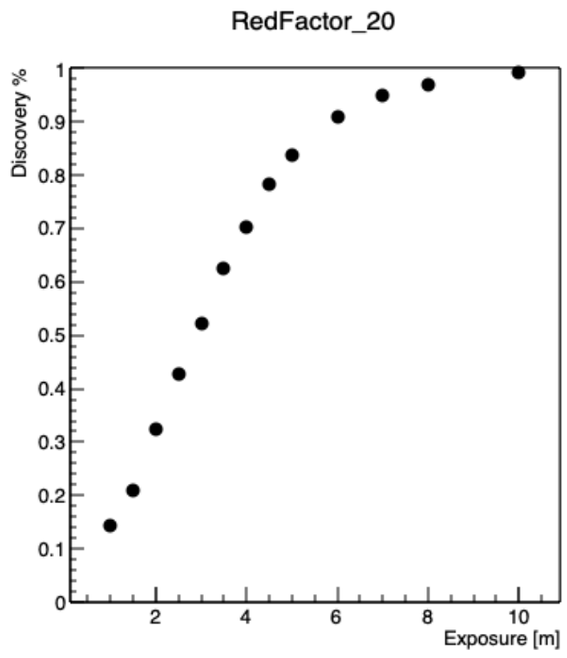


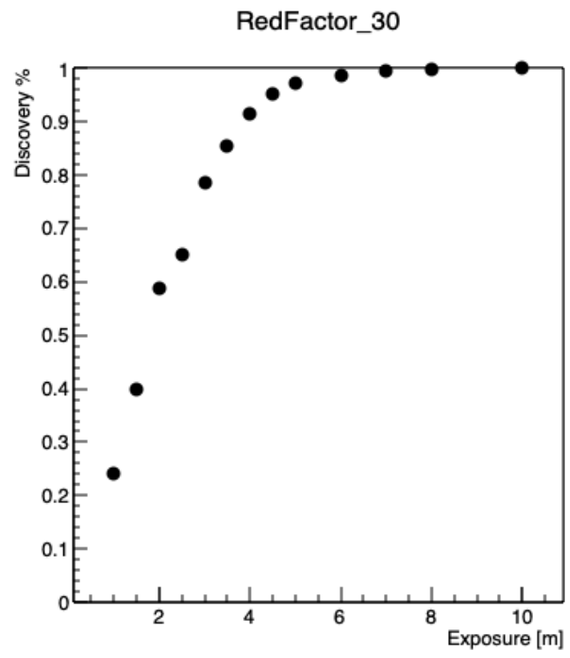


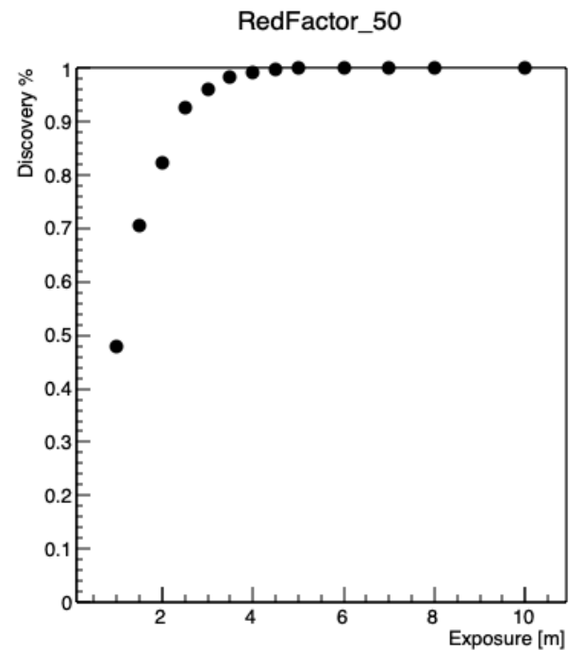












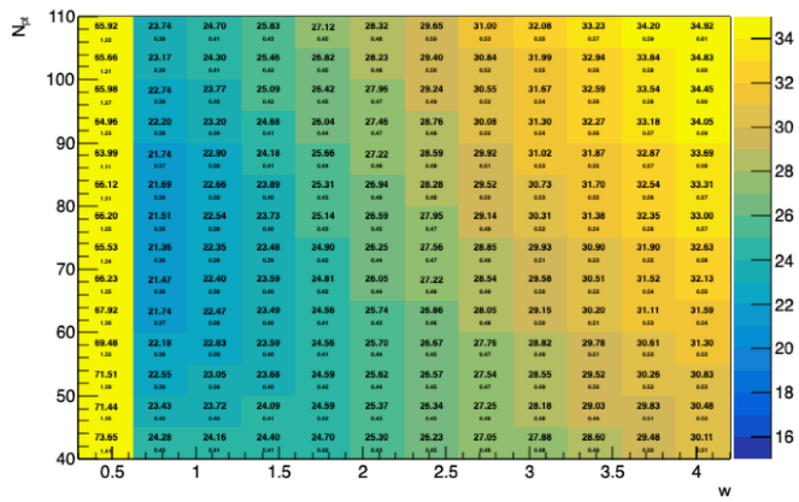
- With a bkg reduction of a factor 10 there are 45% probability of collecting data for which the S+B model is at least 5 times more probable than the only B model → 180 neutrino signal over 10680 ev. of background

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

To do…

- Study the angular resolution for NID diffusion
- Repeat the sensitivity study with the new resolution found



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

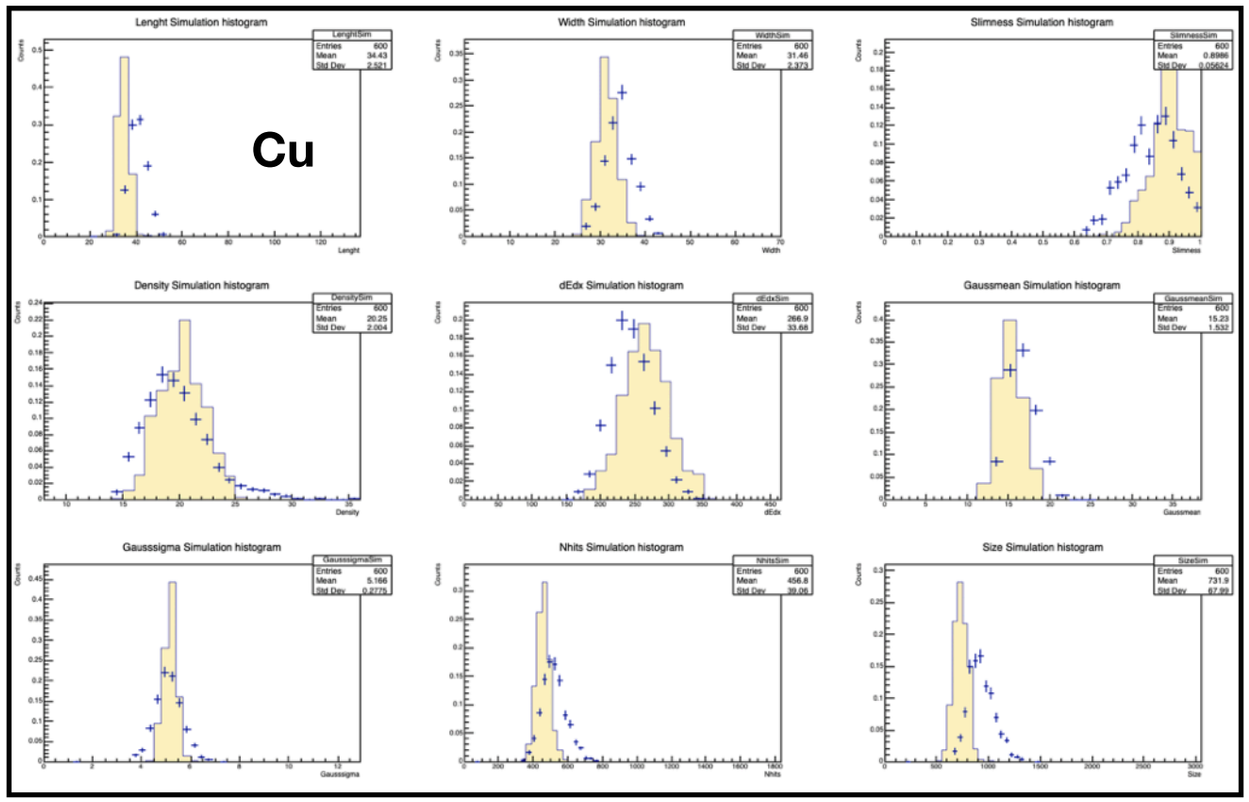
Acknowledgements:

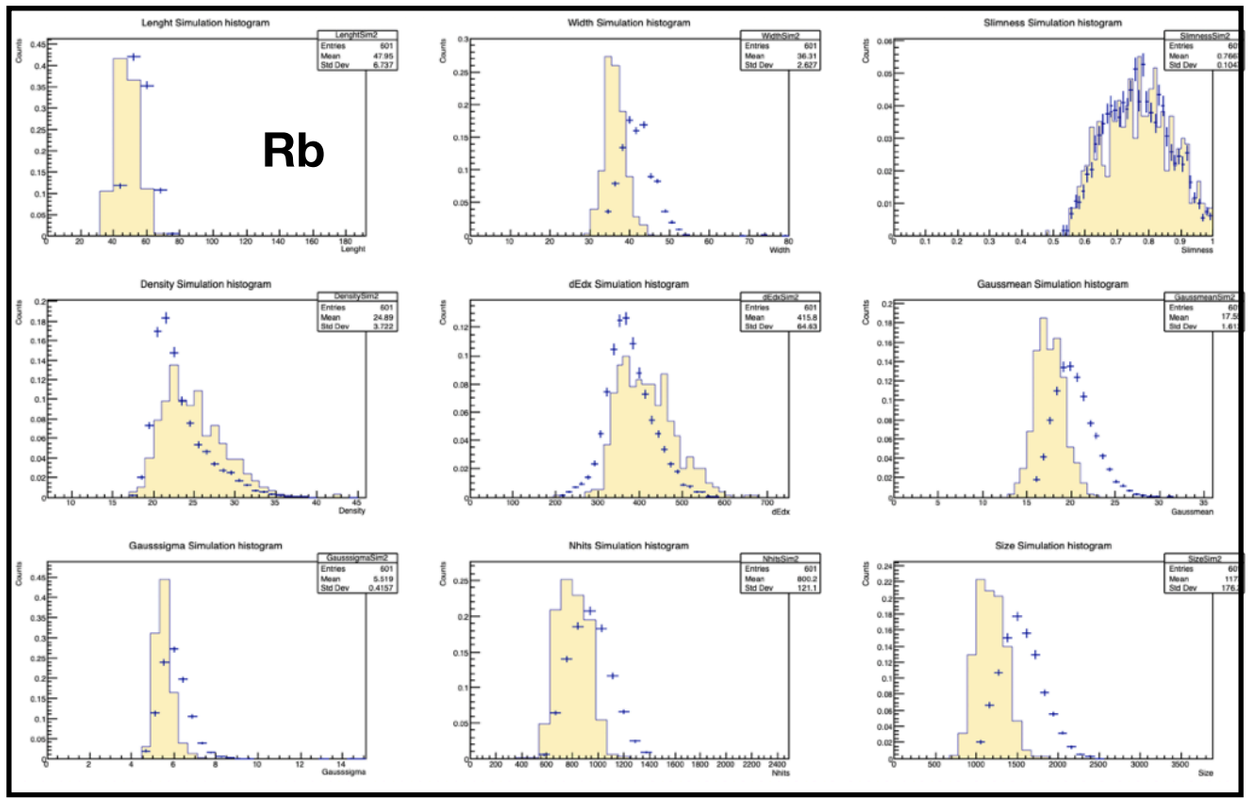
This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the European Research Council (ERC) grant agreement No 818744 and from the Italian Ministry of Education, University and Research through the project PRIN: Progetti di Ricerca di Rilevante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

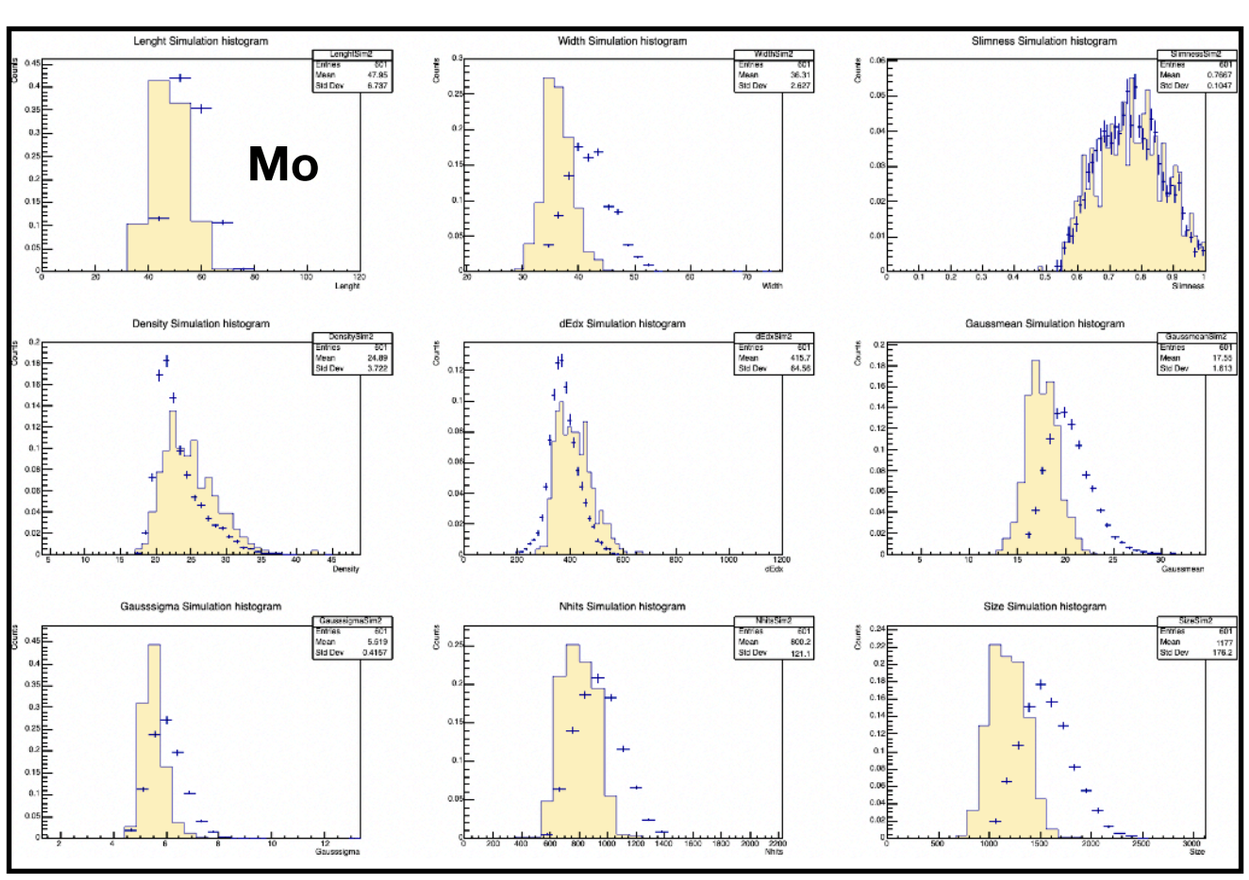
Backup

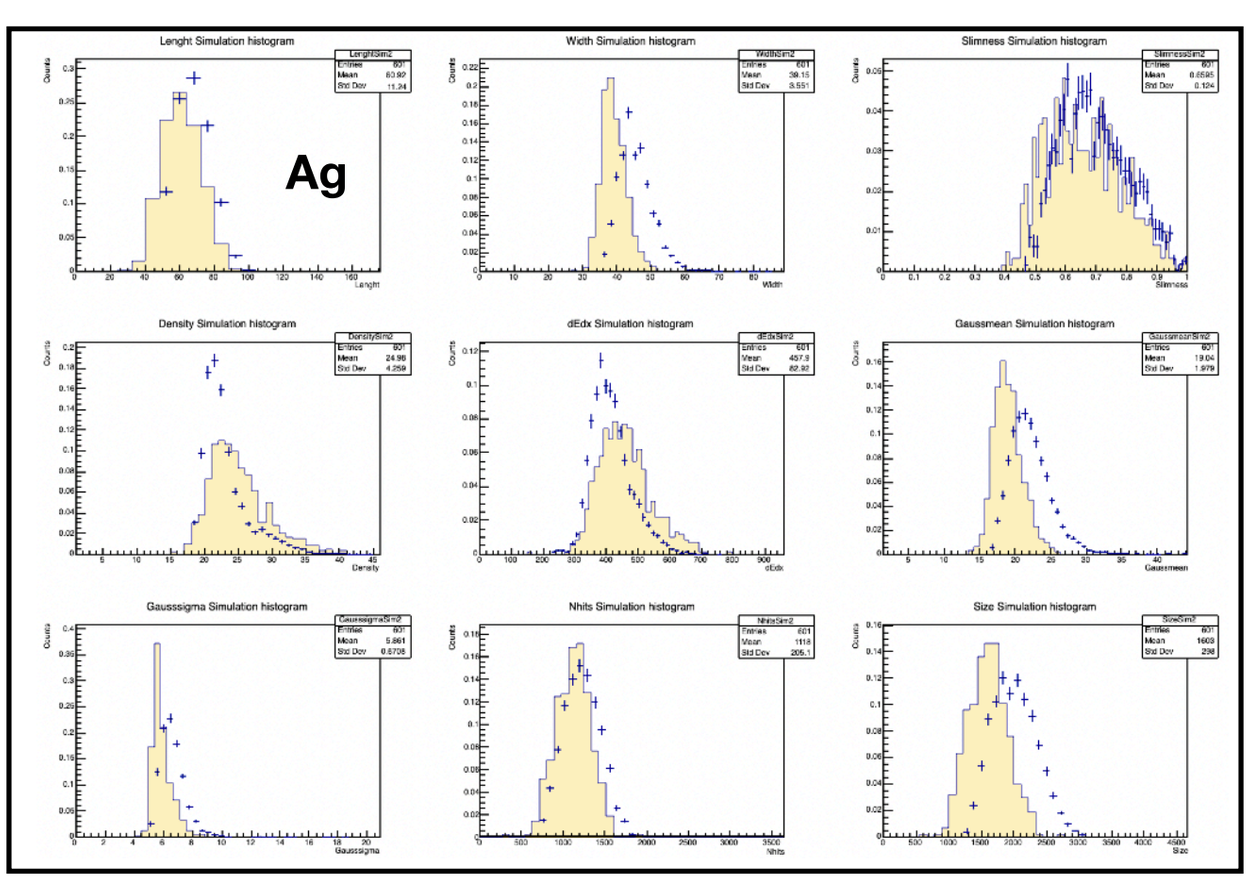
Track shape parameters comparison

Simulation Data



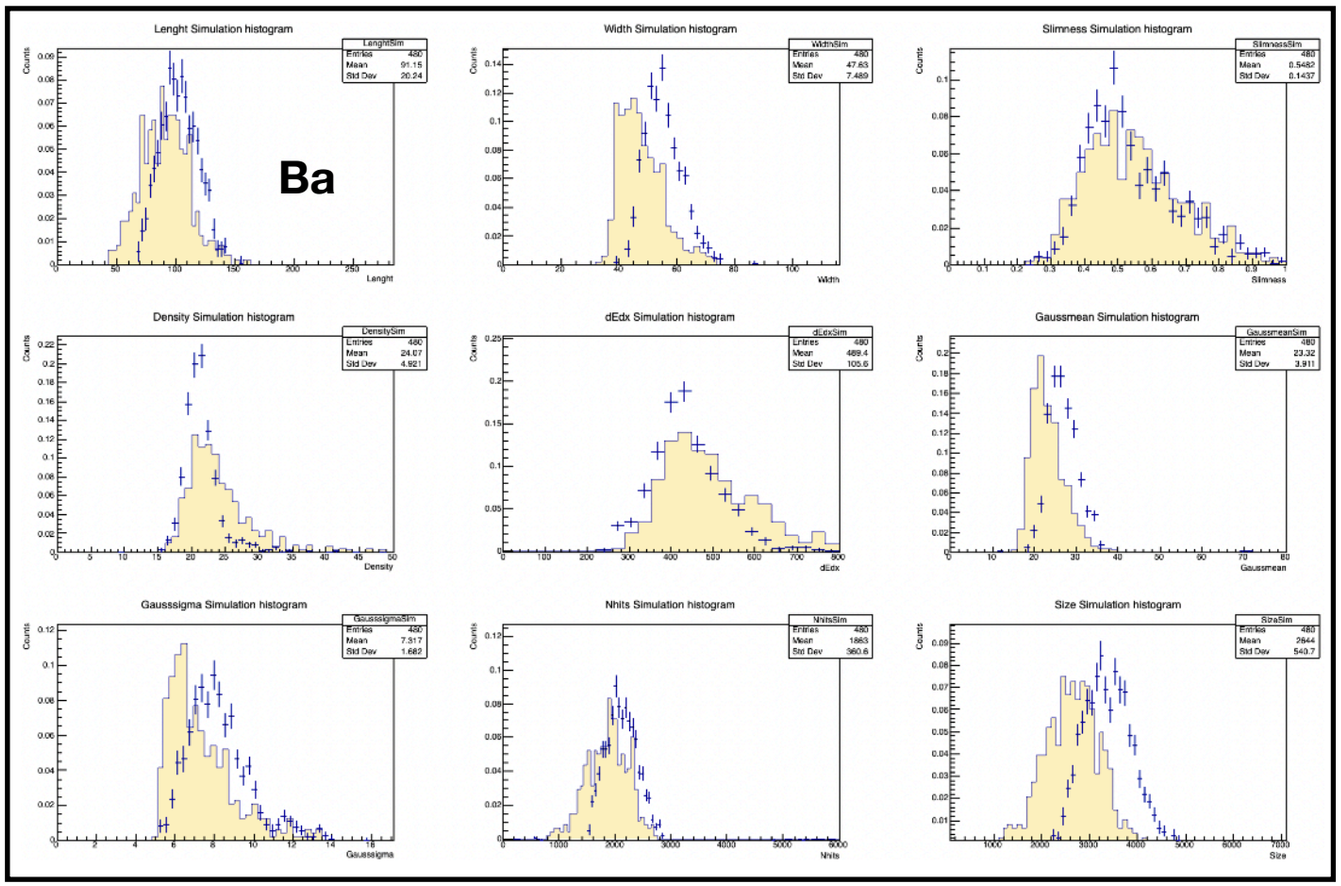


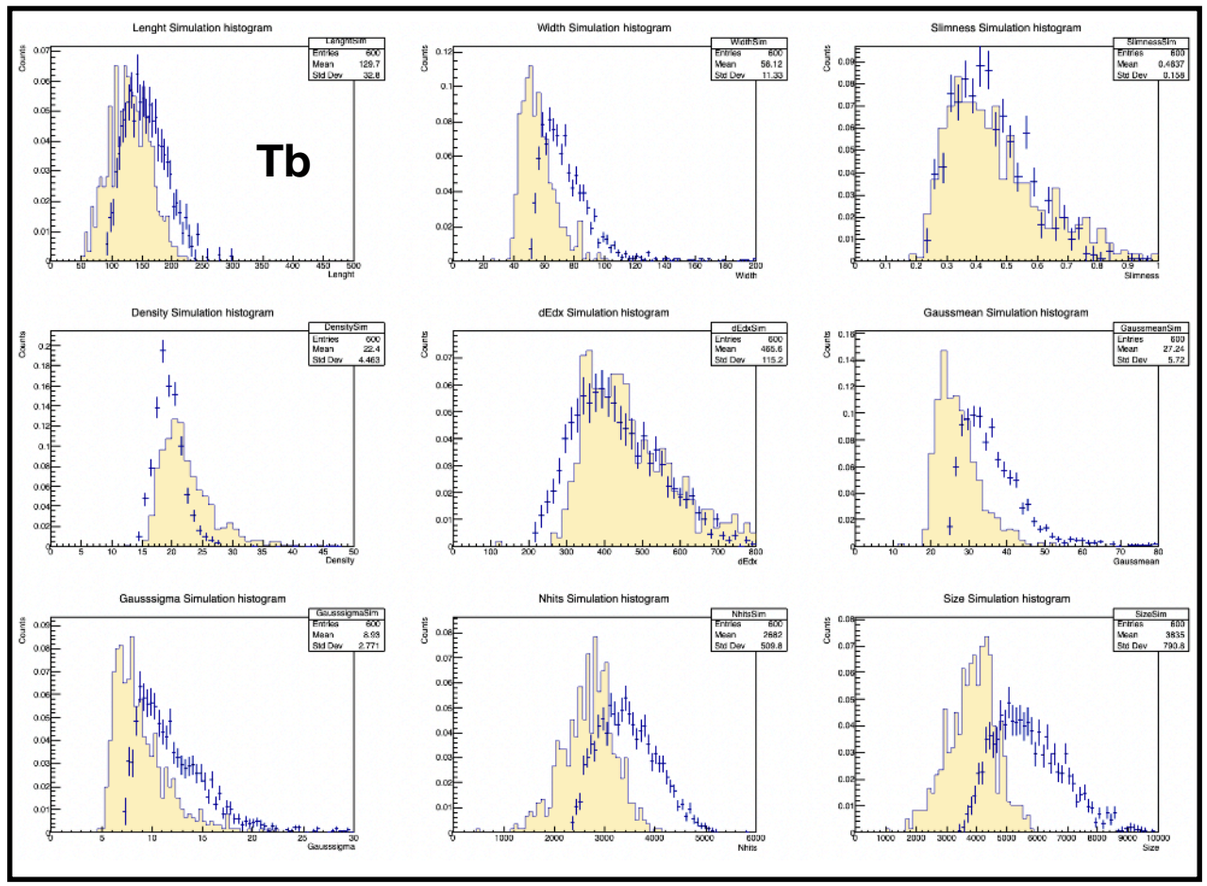




Track shape parameters comparison

Simulation Data





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