# WP2

Giorgio Dho

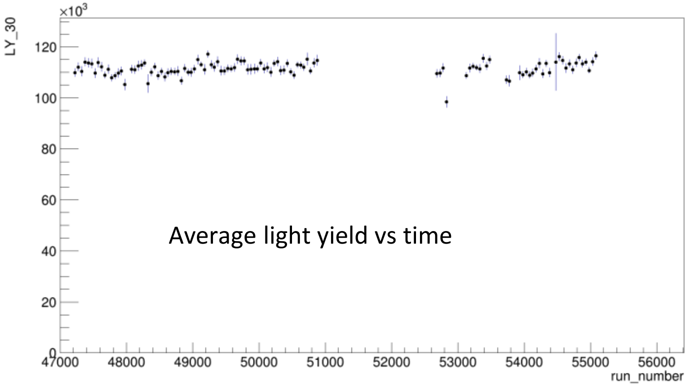
*Istituto Nazionale di Fisica Nucleare (INFN-LNF), Frascati (RM), Italy*

# Where were we

- Data Analysis on Run4 data ( copper and water shielding) was begun.

  Highlighed stability of data taking

  (>90% duty cycle)

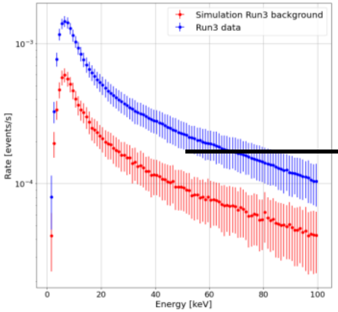




- Data-MC comparison hinted internal contamination (Radon?)

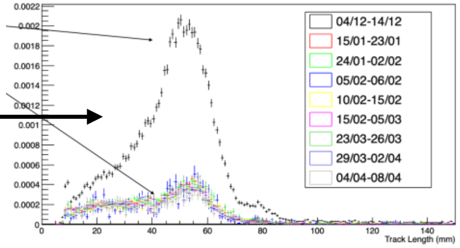
**Run3**

Data and MC

energy spectra




Length of high energy particles




- This half year we focused a lot on development of software and tools to more efficiently and better analyse data

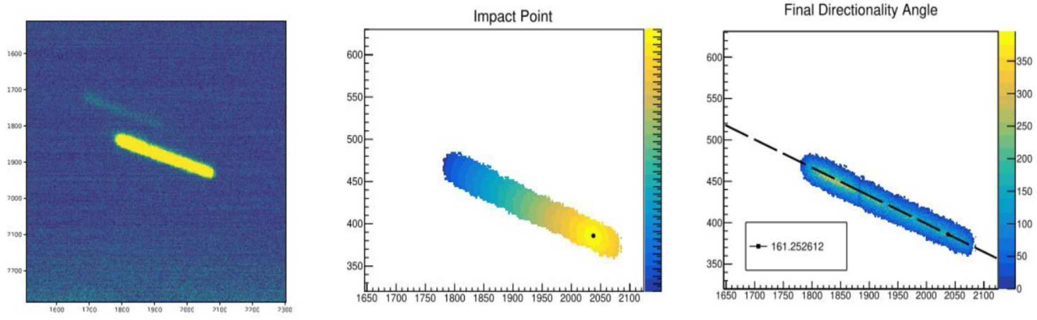
Reconstruction | 3D association | Digitisation (simulation) | Directionality | Physics fit

# 3D Reco

**WP2.1 and 2.2**

- To develop the 3D reconstruction algoritm we started simple ⟶ long, straight, not-so-rare tracks: **alphas**
- 2 detector type:

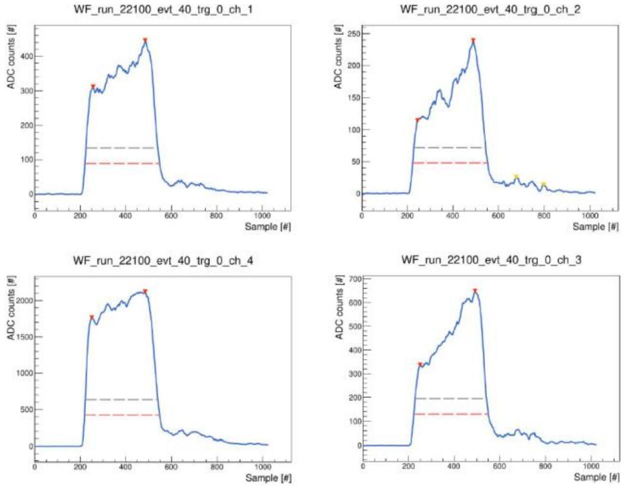
**Camera**




From X-Y pixel distribution and intensity we can obtain:

- bidimensional angle of direction (Φ)
- sense of direction in 2D
- Projected length in 2D

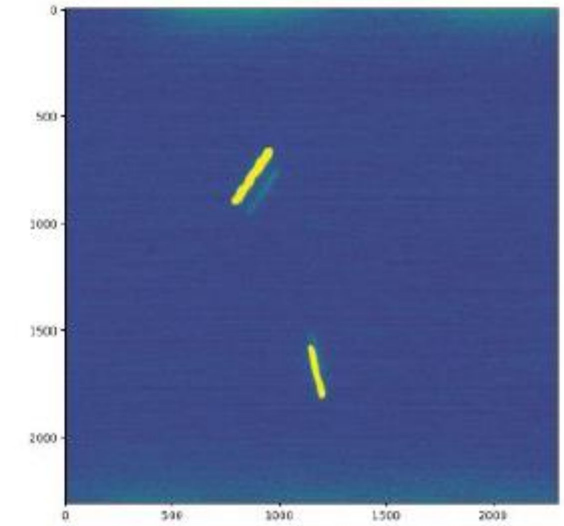
**PMT**

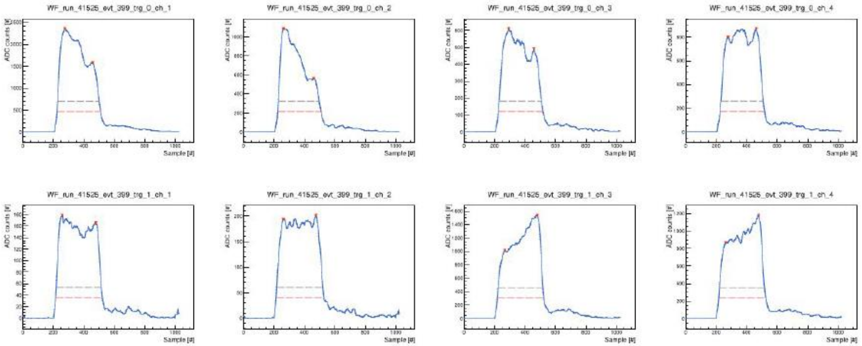



From relative intensity of PMT signals, Time over threshold and waveform shape we can obtain:

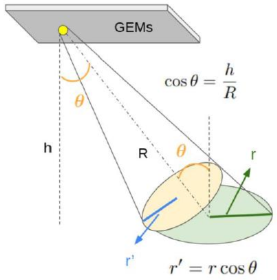
- sense of direction in Z
- Projected length in Z

# 3D Reco II





- Different response of the 4 PMTs in LIME

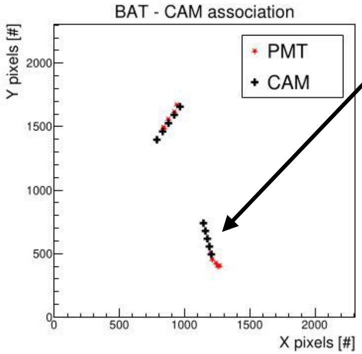


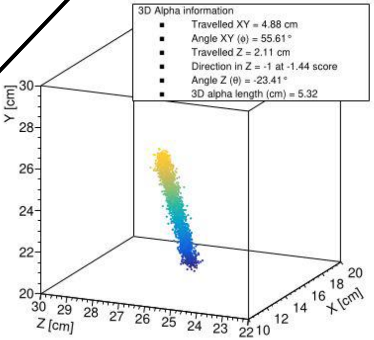

- Multivariate Bayesian fit procedure

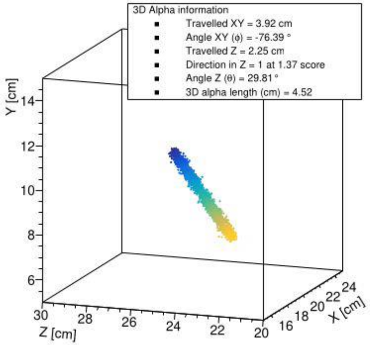
$$p(\{x_{ij}\}\,|\,\theta) = \prod_{j=1}^{N_{points}} \prod_{i=1}^{4} \mathcal{N}(\{x_{ij}\}\,|\,L'_{ij}(\theta))$$

- Calibrated on $^{55}$Fe source
- **Precision of ~1 cm**

(e)

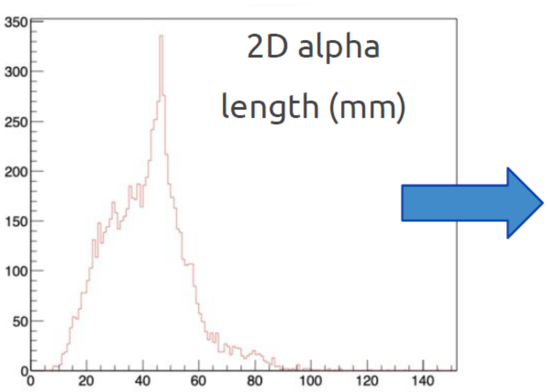


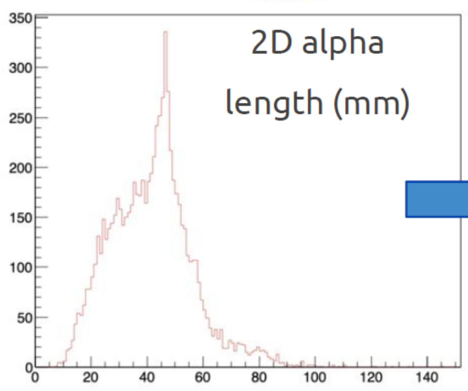
# 3D Reco III

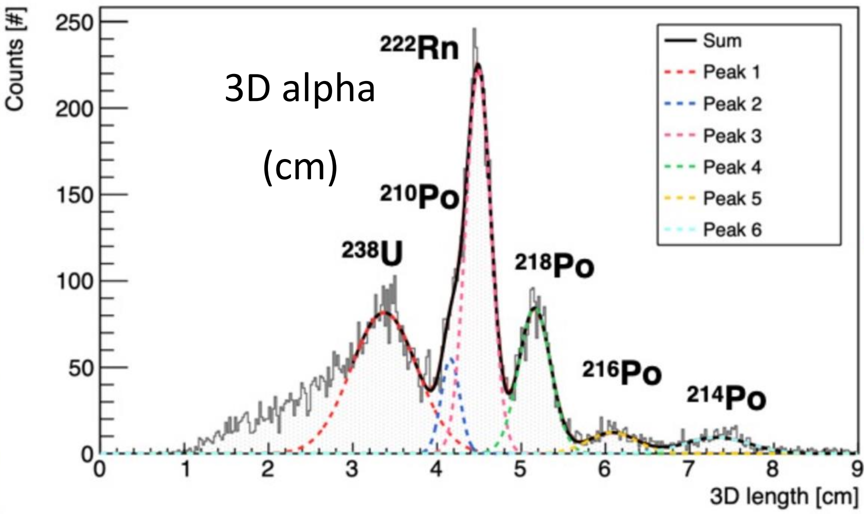
- With 3D recoed tracks we can look at lengths



# 3D Reco III

- With 3D recoed tracks we can look at lengths




Theory + *detector effect* (7% error)

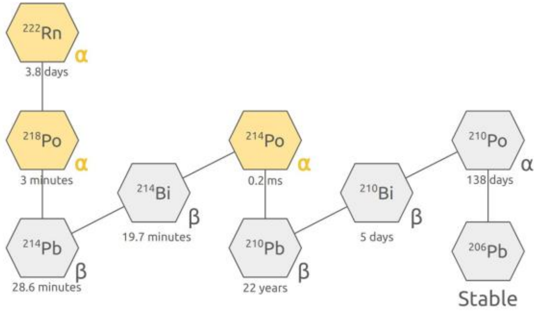
- $^{238}$U -> 4.17 MeV -> 33.7 mm
- $^{216}$Po -> 6.78 MeV -> 61.6 mm
- $^{210}$Po -> 5.30 MeV -> 43.1 mm

Measured (5% error)

- 33 mm
- 61 mm
- 41.6 mm

**Contamination from border and GEM**

- Expecting Radon contamination:




Theory + *detector effect* (7% error)

- $^{222}$Rn -> 5.50 MeV -> 45.7 mm
- $^{218}$Po -> 6.00 MeV -> 51 mm
- $^{214}$Po -> 7.69 MeV -> 71 mm

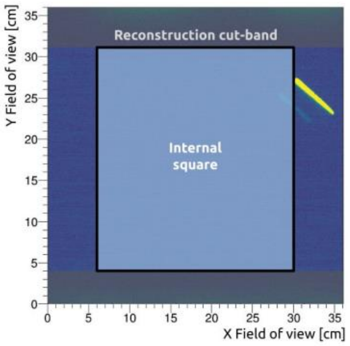
Measured (1% error)

- 44.3 mm
- 51.2 mm
- 72.9 mm

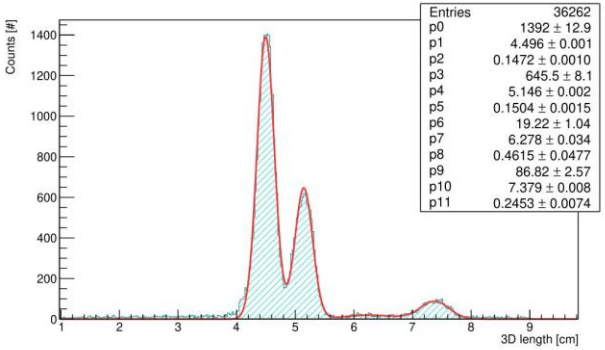
**Radon contamination confirmed**

# 3D Reco IV

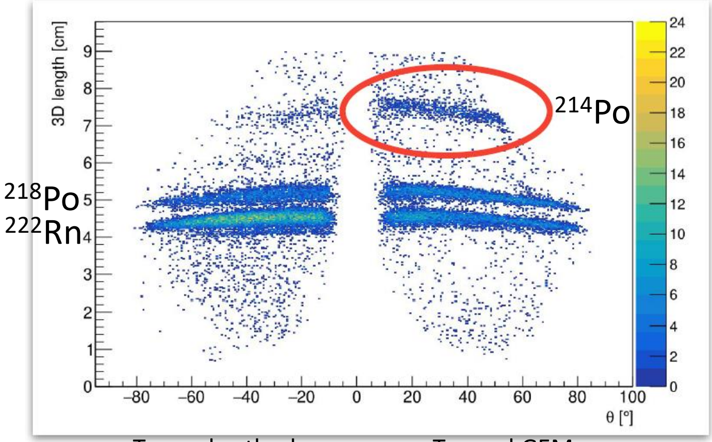
- What about orientation of these Rn daughter alphas?
- Selection in the centre to include cathode, GEM and detector gas (no borders with resistors and field rings)
- Inclination angle and rough estimation of absolute z coordinate support Radon daughter behaviour

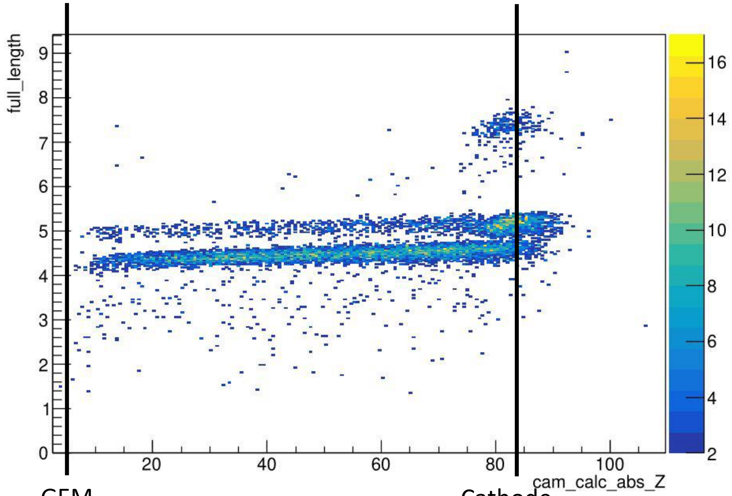



(a) Geometrical cut - central square




(b) 3D length of alphas




Daughters, generated positively charged, will move to the cathode:

- Higher Z (closer to cathode)
- Emission mostly toward GEM

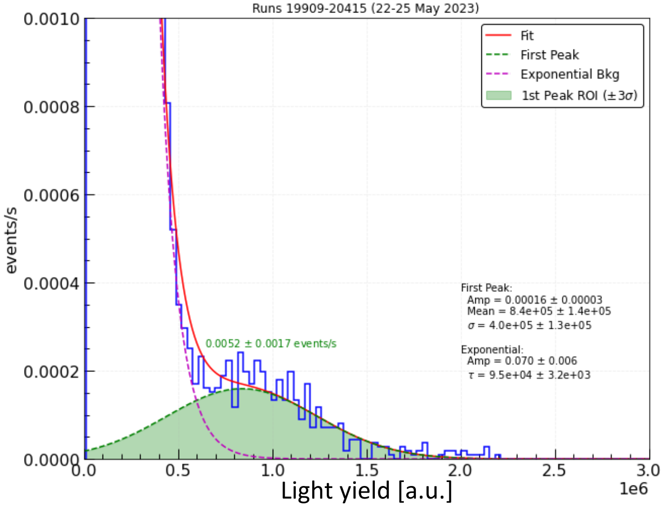
**Potential of 3D just starts unveiling!**

**Paper in preparation**

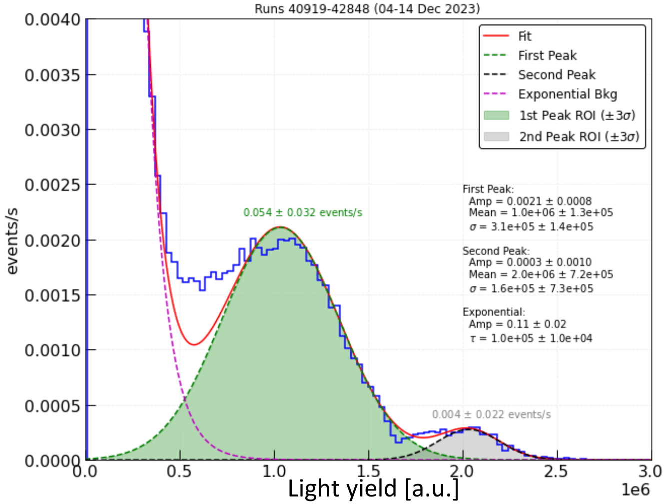
# Run4: High energy

- Normalisation of spectra based on time duration of runs
- Different periods of data of Run4 taken into consideration
- Data normalised in light intensity: $10^4$ about 5.9 keV (non-linear response in z not considered yet)

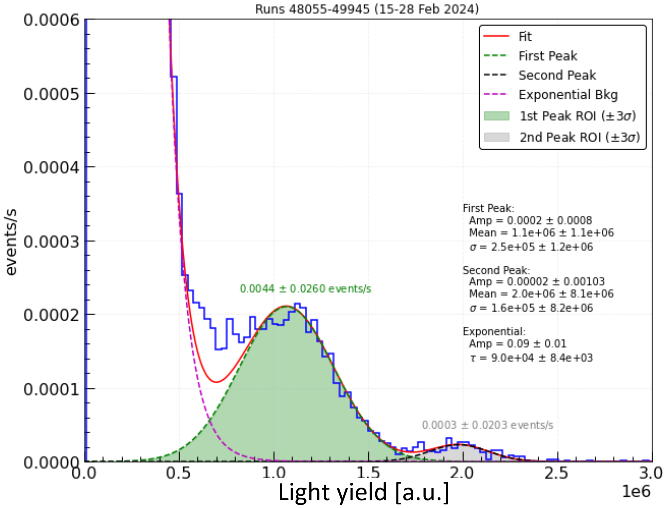
**Run3 no ricirculation**
low Rn




**Run4 unfiltered**
high Rn




**Run4 filtered**
low Rn



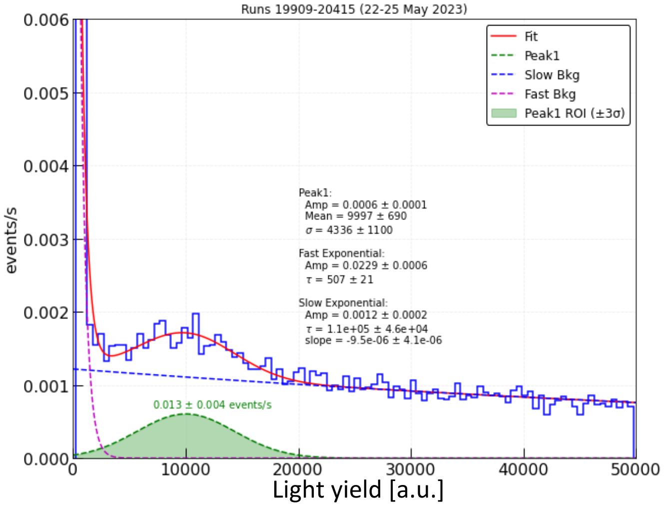

**Energy range of alphas**

# Run4: Low energy

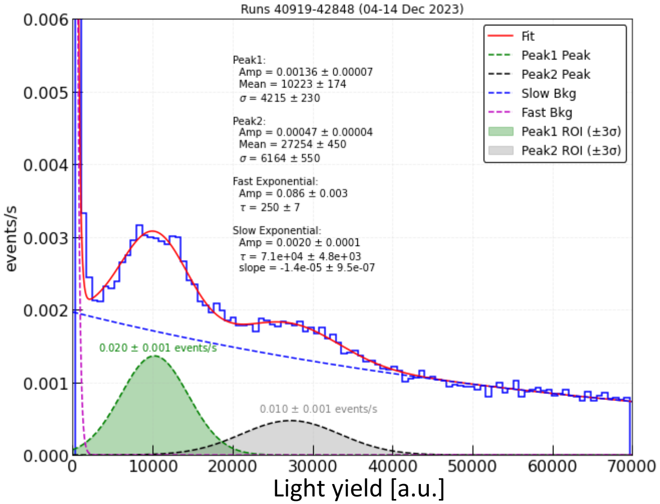


- Different periods of data of Run4 taken into consideration
- Data normalised in light intensity: 10000 about 5.9 keV (non-linear response in z not considered yet)
- How is the low energy range behaving?

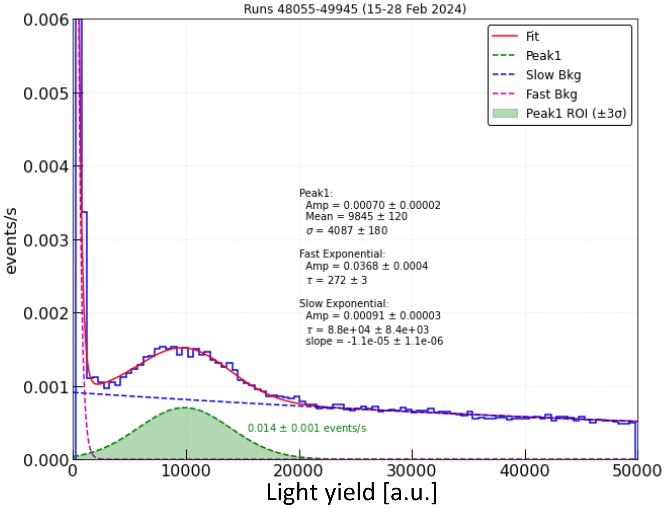
**Run3 no ricirculation**
low Rn




**Run4 unfiltered**
high Rn




**Run4 filtered**
low Rn

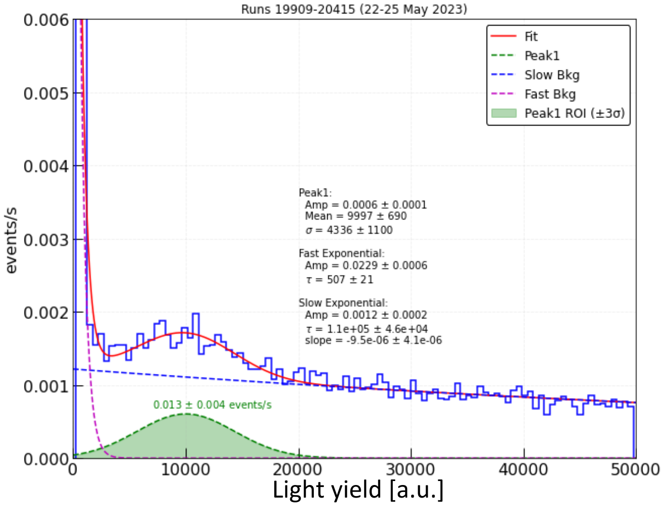


# RUN4: LOW ENERGY

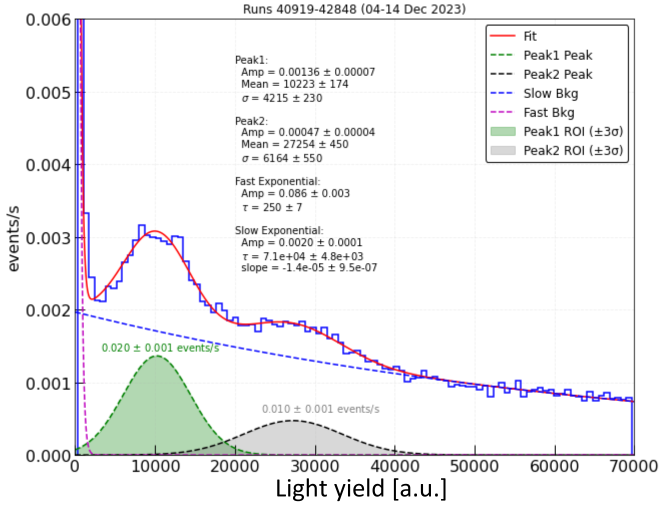
PRELIMINARY

- Different periods of data of Run4 taken into consideration
- Data normalised in light intensity: 10000 about 5.9 keV (non-linear response in z not considered yet)
- How is the low energy range behaving?

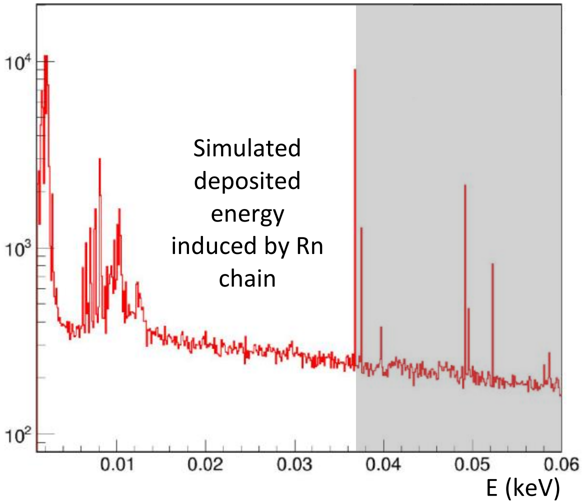
**Run3 no ricirculation**
low Rn




**Run4 unfiltered**
high Rn




**GEANT4 Simulation Rn energy deposits**




- MC comparison will give further insight

**We are studying the impact of Rn chain on low energy region**

**Simulation code improved to speed up MC comparison: Now 10 times faster and more efficient**

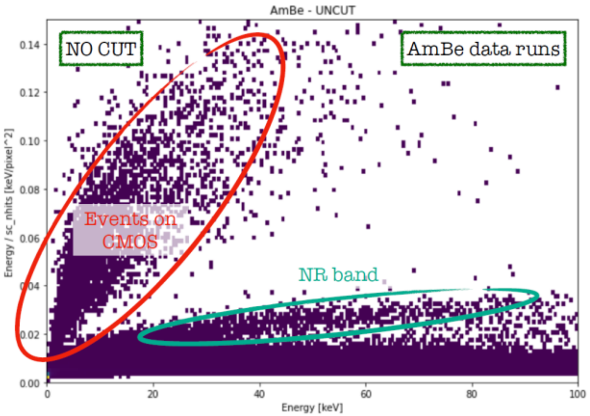
# Run4: New Variables

- New reconstructed variables exploiting pixel distribution and intensity

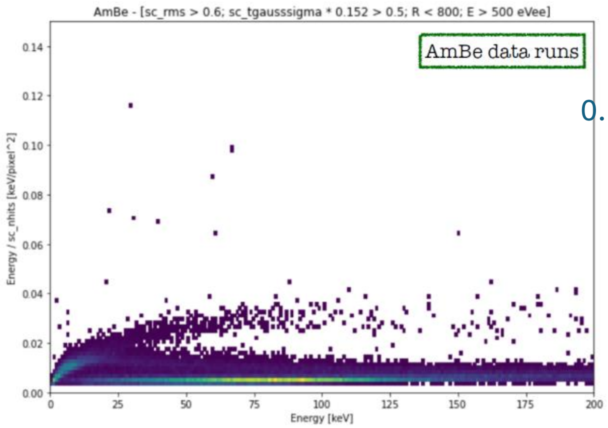
$$\rho \equiv \frac{sc\_rms}{sc\_nhits}$$

RMS of distribution of pixel intensity

Number of pixel above threshold

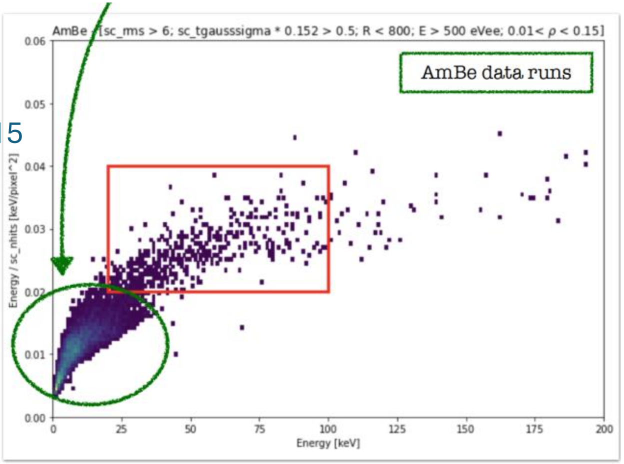



$\rho < 0.15$




$0.01 < \rho < 0.15$

Still ER contamination

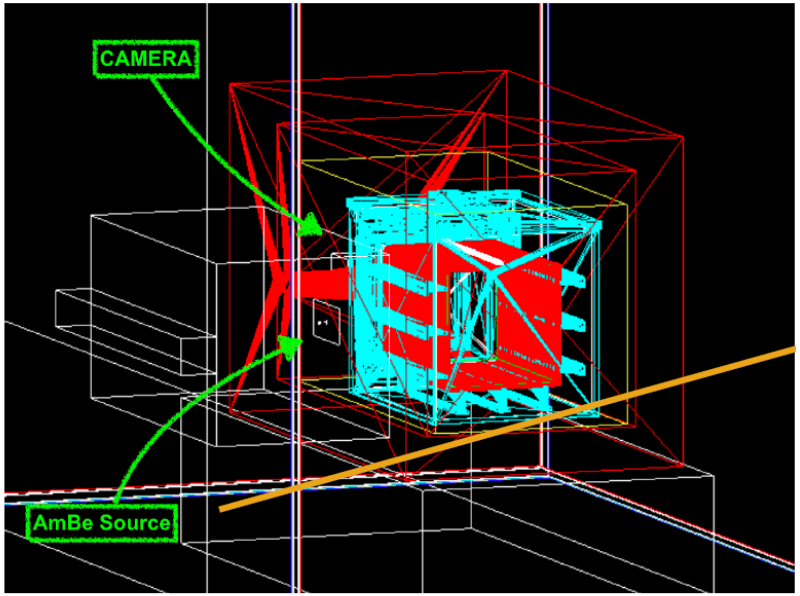


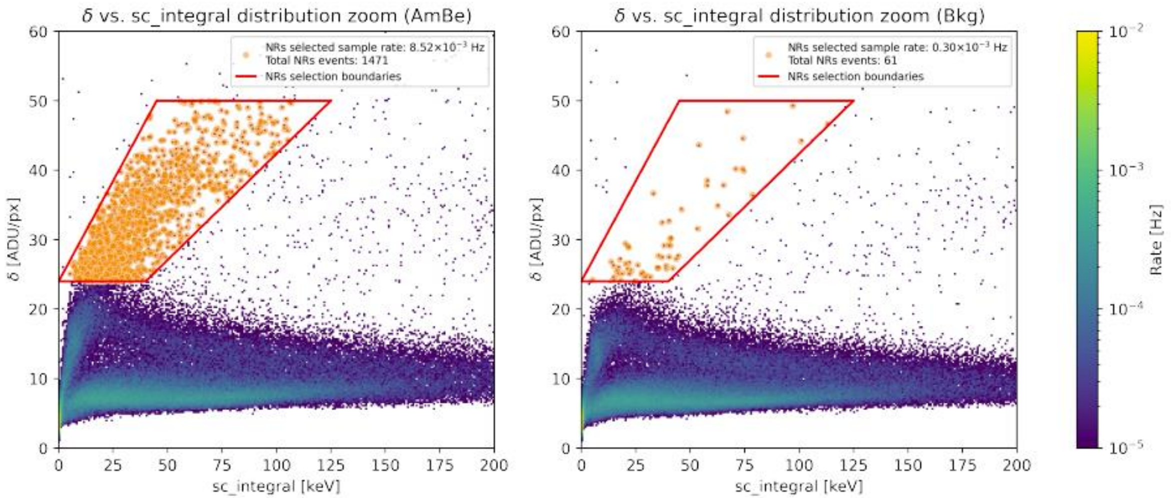

- This variable appears to be a good method to remove ER
- It will be included in ER/NR rejection studies →

Recent interest received from a Trieste group expert on machine learning (prof. Trotta)

# NUCLEAR RECOIL ANGULAR RESOLUTION

- AmBe neutron source was exploited to induce large amount of NR in LIME detector
- This data set is a key test bench for NR angular resolution measurements, ER/NR discrimination



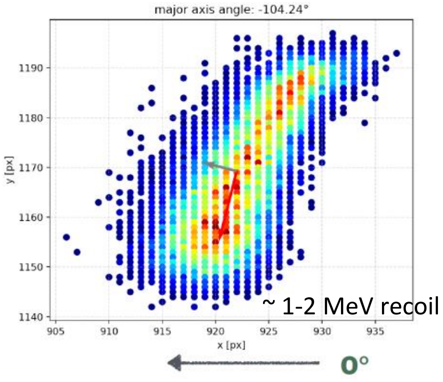

- From the camera point of view, the neutrons emitted horizontally are aligned so that their angle is 0˚

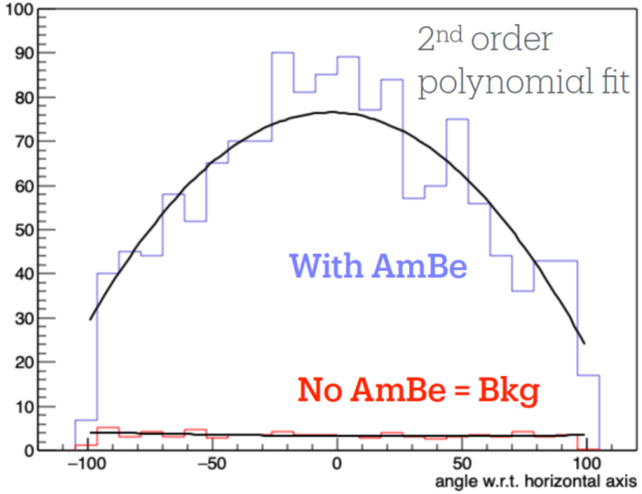
**Machine learning work on ER/NR discrimination will help improve selection and select in lower energy range**

# Nuclear Recoil Angular Resolution III

PRELIMINARY

- Direction estimated by simple principal component decomposition




Background is flat

Source peaked at 0 deg

- Kinematic simulation of the recoil distribution is convoluted with gaussian angular resolution and tested with data

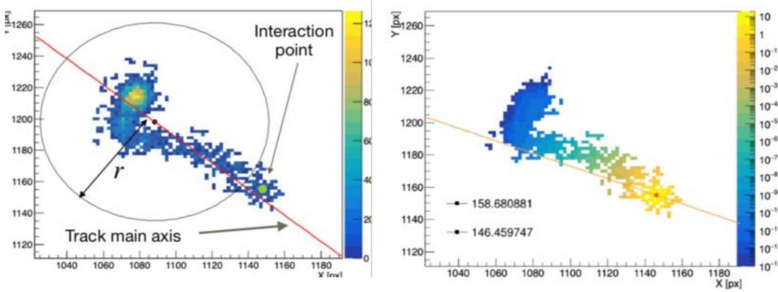
**Data suggests 45° 2D angular resolution above 100 $keV_{ee}$ at atmospheric pressure**

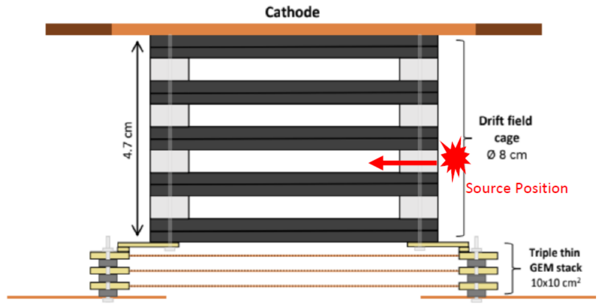
Convolution with source distribution to be removed

- 3D reconstruction can help improving the direction and the determination of the energy (by length)
- New simulation will improve the MC comparison

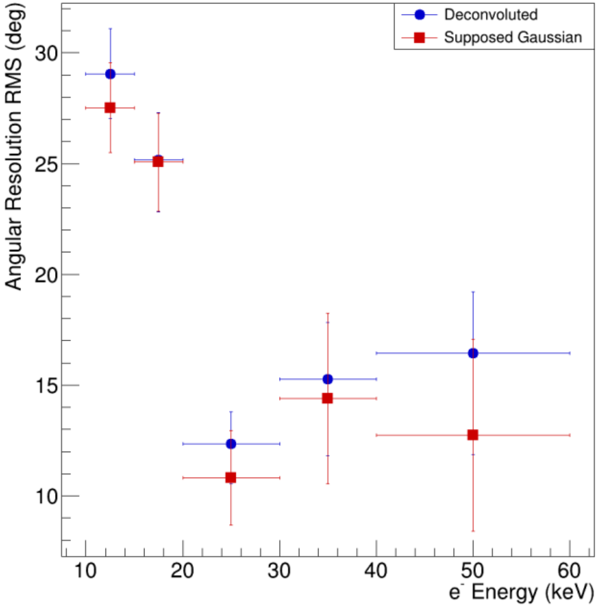
# Directional Reconstruction

- Code for directional reconstruction was developed in the past
- Recently the code was improved and applied to real data taken with a prototype
- Beta$^-$ emitter $^{90}$Sr source




Confronting MC and data, the angular resolution was measured




- Excellent result on data for ER angular resolution
- HT 100% at all energies
- **Can be adapted to NR and applied to AmBe data**

**Paper in published in the context of the PRIN project HypeX**

*Interesting for neutrinos too!!*

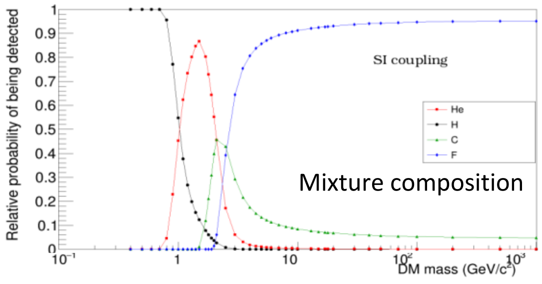
# SENSITIVITY LIME

- Strong effort to put into a single code the calculation of the spectra of expected DM signal and the Bayesian fit procedure to estimate Credible interval limit (BAT toolkit used)

$$p(\vec{\mu},\vec{\theta}|\vec{x},H) = \frac{p(\vec{x}|\vec{\mu},\vec{\theta},H)\pi(\vec{\mu},\vec{\theta}|H)}{\int_\Omega \int_D p(\vec{x}|\vec{\mu},\vec{\theta},H)\pi(\vec{\mu},\vec{\theta}|H)d\vec{\mu}d\vec{\theta}}$$

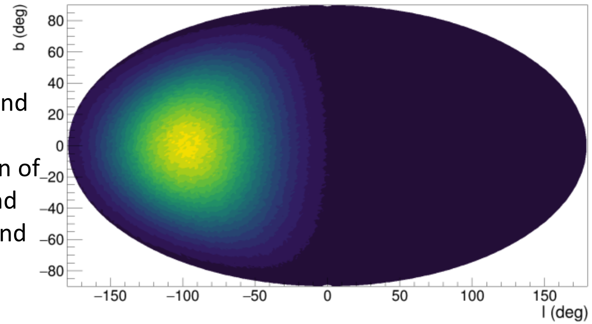
$$\mathcal{L}(\vec{x}|\mu_s,\mu_b,H_1) = (\mu_b+\mu_s)^{N_{evt}} e^{-(\mu_b+\mu_s)} \prod_{i=1}^{N_{\text{bins}}} \left[ \left( \frac{\mu_b}{\mu_b+\mu_s} P_{i,b} + \frac{\mu_s}{\mu_b+\mu_s} P_{i,s} \right)^{n_i} \frac{1}{n_i!} \right]$$

- Detector effects can be included




Mixture composition

Angular and energy distribution of signal and background




- LIME is not able to provide limits yet: unknown contamination -> no background model (LIME was not meant for this!!)
- However, we can use it to estimate where the exposure of the detector can lead us
- As a first test no measurable variables were included in the study:

As if LIME was a simple counting experiment →

Large background
Counting experiment:
**Worst possible scenario**

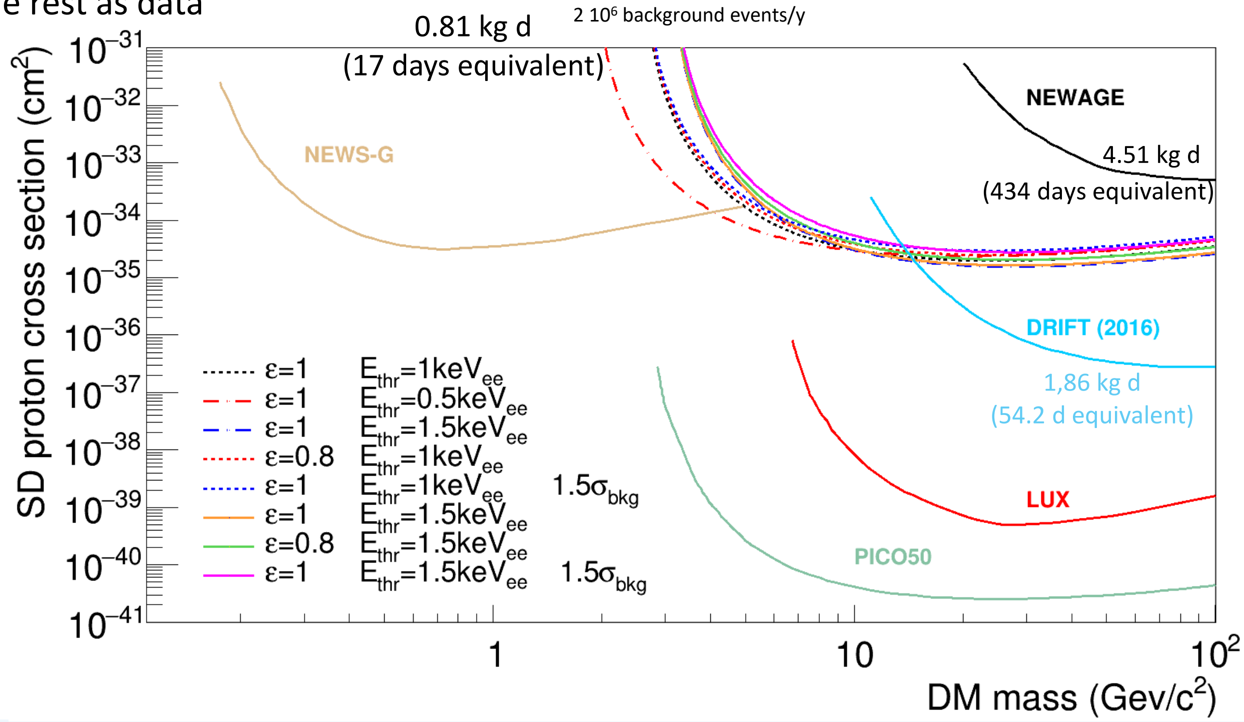
# SENSITIVITY LIME II

PRELIMINARY

- Simple cuts on geometry to exclude borders (33 L active volume)
- Loose cut on rho variable to remove many ER (Machine learning technique will strongly improve this)
- Different thresholds and NR efficiency analysed
- 20% of Run4 data used as background model and the rest as data

**We are quite close to DRIFT**
(with a detector not thought for DM search)

**Great improvement in energy threshold** (with respect to other directional detectors)

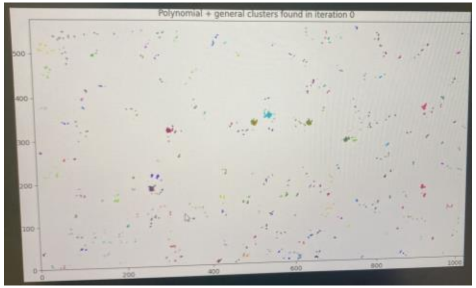


WP2.2

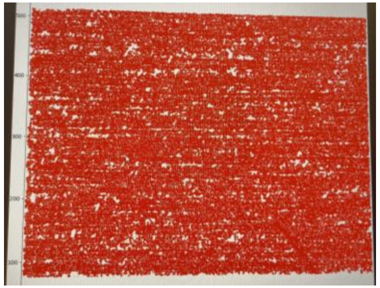
# Analysis code and Data Reduction

- CYGNO-04 will use ORCA QUEST camera as sCMOS detector (different shape, noise, performance) and new lens
- Analysis and simulation code integrated the new camera and lens interface
- Example of data clusterised with same reconstruction parameters

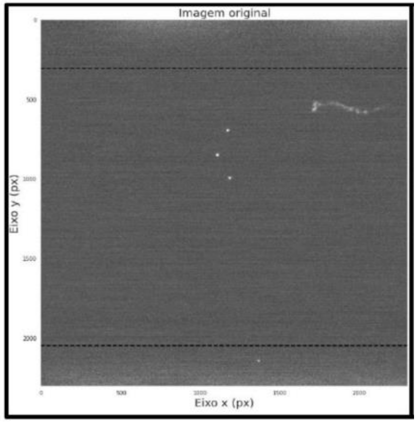
QUEST

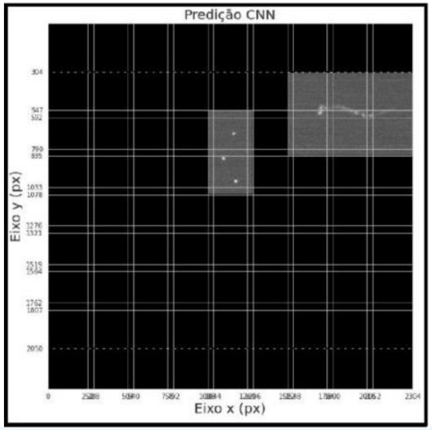



Fusion



- Machine learning technique (and not) study to be applied at frontend level to reduce the raw data output for CYGNO-04 (we will use 6 cameras!)



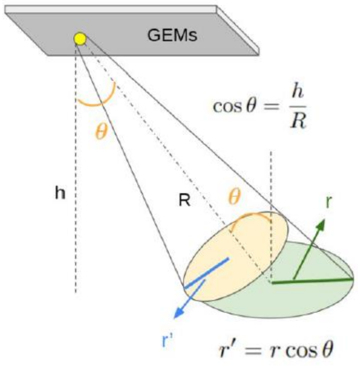

Data reduction expected to be of a factor **150**

Efficiency at low energy under study (already outperforming current reconstruction algorithm)

# CONCLUSIONS

- During these months a lot of effort was spent in improvement of software in order to carry out more complex analysis
- 3D reconstruction algorithm is currently working for long NR tracks with extremely interesting results
- AmBe campaigns are paramount to determine operative parameters of the CYGNO detector and will soon exploit the software improvements
- A conservative angular resolution of 45 deg on NR above 100 $keV_{ee}$ was found
- An angular resolution on electrons was measured of 30 deg at 10 keV and below 20 deg above 20 keV
- Extremely conservative estimation of exposure of LIME puts it within range of DRIFT results
- Work on analysis tools and data reduction for CYGNO-04 has already started

# BACKUP I: 3D RECO II




- Merging the two detector allows 3D reconstruction
- LIME has 4 PMTs whose distance from the event changes their intensity
- Important to match the signals of the detectors: multivariate Bayesian fit

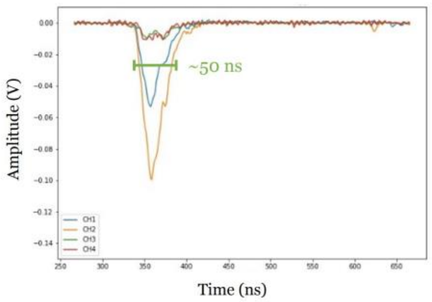
- $L'_{ji} = c_i \frac{L_j}{R_{ij}^{\alpha}}$
- $R_{ji} = \sqrt{x_{ji}^2 + y_{ji}^2 + z^2}$

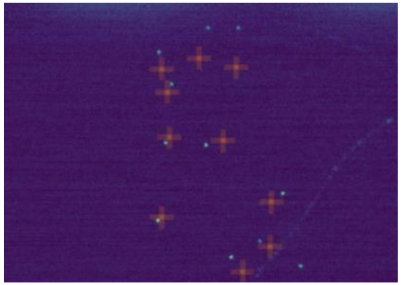
$$p(\{x_{ij}\}\,|\,\theta) = \prod_{j=1}^{N_{points}} \prod_{i=1}^{4} \mathcal{N}(\{x_{ij}\}\,|\,L'_{ij}(\theta))$$

One can retrieve from PMT signals x,y coordinate and L (light yield at GEM)

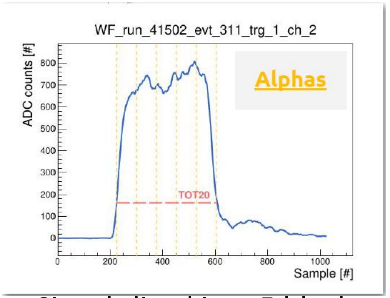
1. Calibrated with iron signal with known x,y position from camera

2. Applied to alpha signal



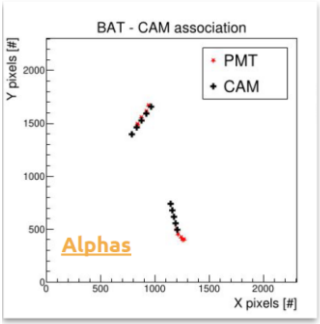



**Resolution of about 1 cm**




Signal sliced into 5 blocks

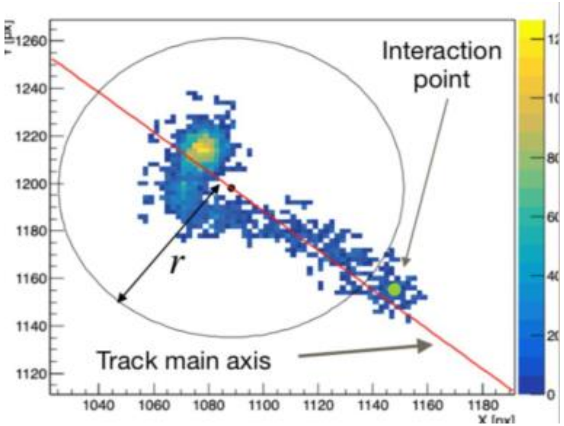
**Accuracy within 2 cm**

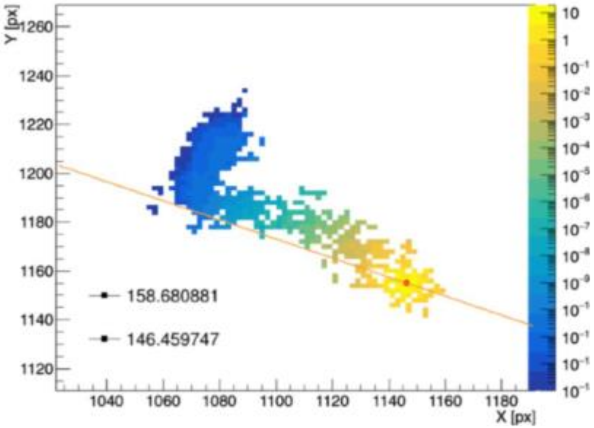



Enough for association purposes

# BACKUP II: DIRECTIONALITY

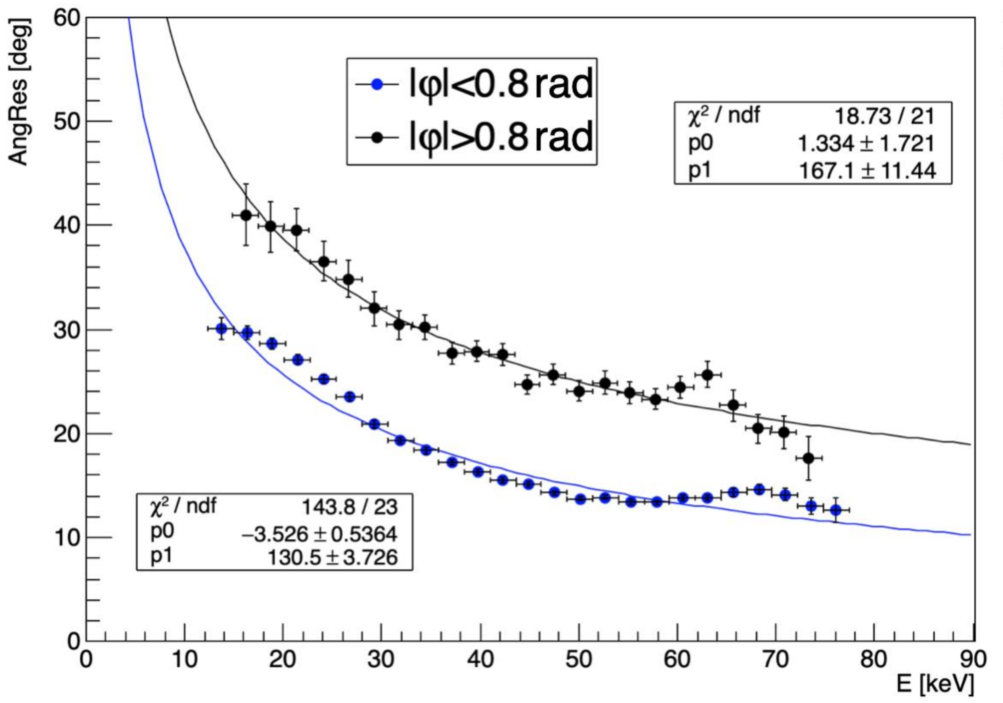
- Track reconstructed by analysis code
- Noise and below threshold pixel pruned
- Principal axis component and barycenter calculated
- Radius r opened around the barycenter and new barycenter calculated on the pixels outside the radius in the region with low skewness
- After finding the Impact Point (IP), the track is weighted in intensity as a function of the distance from IP
- Linear fit of the weighted points



# BACKUP III: ANGULAR RESOLUTION SIMULATION

- Directionality algorithm was applied in the past to simulation of ER, yielding:




In the data tracks were mostly parallel to the GEM -> like blue points

Measurement has finer granularity than simulation and results in **better results** than simulation

# BACKUP IV: SENSITIVITY LIME

- The limit estimation and fit procedure of the data is a key element for dark matter physics
- Strong effort to put into a single code the calculation of the spectra of expected DM signal and the Bayesian fit procedure to estimate limit (BAT toolkit used)
- Limit evaluation based on Credible Interval calculated by exploiting Bayesian technique.

$$p(\vec{\mu}, \vec{\theta}|\vec{x}, H) = \frac{p(\vec{x}|\vec{\mu}, \vec{\theta}, H)\pi(\vec{\mu}, \vec{\theta}|H)}{\int_\Omega \int_D p(\vec{x}|\vec{\mu}, \vec{\theta}, H)\pi(\vec{\mu}, \vec{\theta}|H) d\vec{\mu} d\vec{\theta}}$$

$$\mu_1(90\%CI) : \int_0^{\mu_1(90\%CI)} p(\mu_1|\vec{x}, H) d\mu_1 = 0.9$$

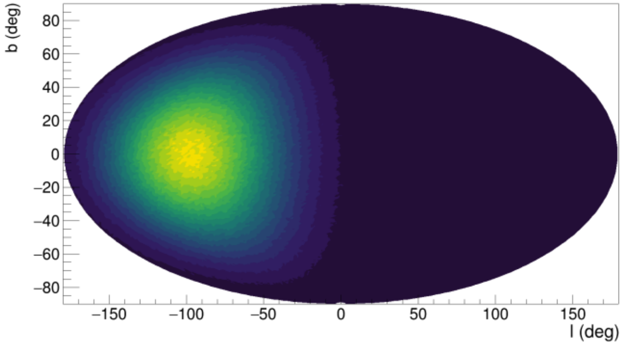
- In general based on a Likelihood profiled on measurable variables as direction and energy

$$\mathcal{L}(\vec{x}|\mu_s, \mu_b, H_1) = (\mu_b + \mu_s)^{N_{evt}} e^{-(\mu_b+\mu_s)} \prod_{i=1}^{N_{\rm bins}} \left[ \left( \frac{\mu_b}{\mu_b + \mu_s} P_{i,b} + \frac{\mu_s}{\mu_b + \mu_s} P_{i,s} \right)^{n_i} \frac{1}{n_i!} \right]$$

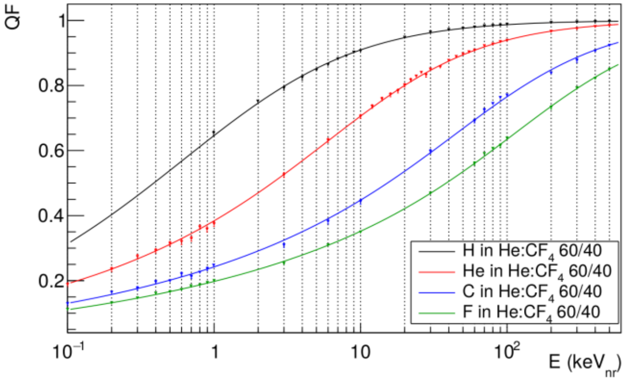
# SENSITIVITY LIME II

- Detector effects which can be included are

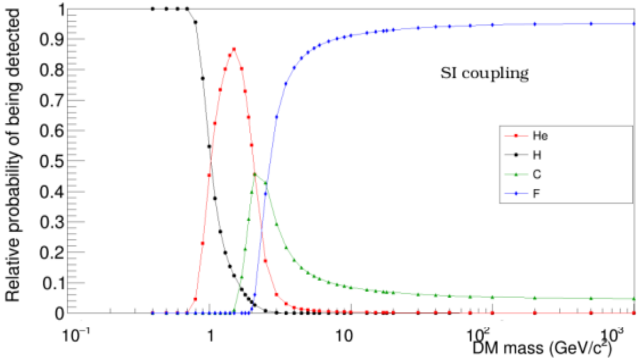
Angular and energy distribution of signal and background




Quenching factor of elements in gas




Mixture composition




- LIME is not able to provide limits yet: unknown contamination -> no background model (LIME was not meant for this!!)
- However, we can use it to estimate where the exposure of the detector can lead us
- As a first test no measurable variables were included in the study:

As if LIME was a simple counting experiment → Large background Counting experiment: **Worst possible scenario**