PMT Analysis for 3D reconstruction & Negative Ion Drift

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Part of this project has been funded by the European Union's Horizon 2020 research and innovation programme under the ERC Consolidator Grant Agreement No 818744

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CYGNO in The DM paradigm

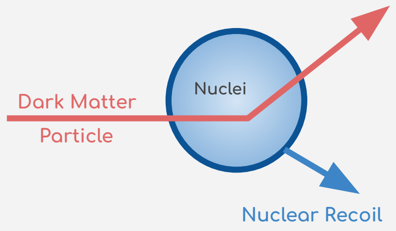
In the WIMP model, DM forms a halo within our galaxy

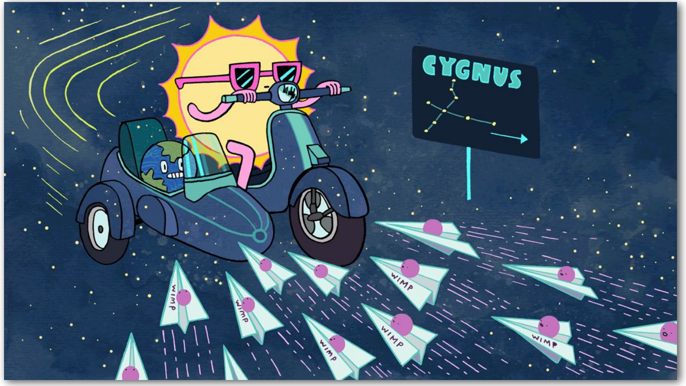
+

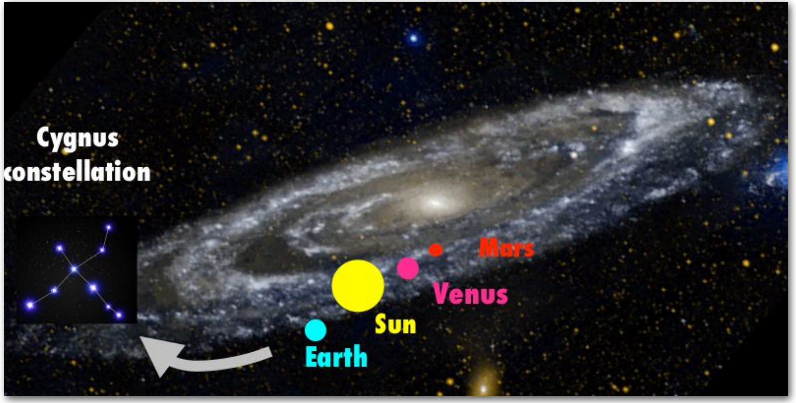
Solar system rotates around galaxy towards Cygnus constellation

Earth susceptible to an apparent WIMP wind from Cygnus direction! CYGNO wants to observe it through direct detection of nuclear recoils

- SM + $\chi \rightarrow$ SM + χ
- **<u>Direct detection</u>** of nuclear recoil







CYGNO in The DM paradigm

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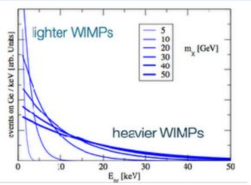
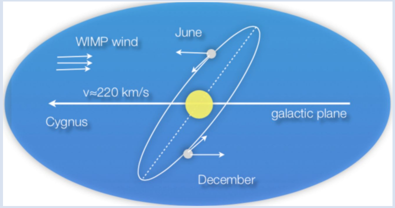
- **ENERGY ⇒** Excess would result in **falling exponentials**.

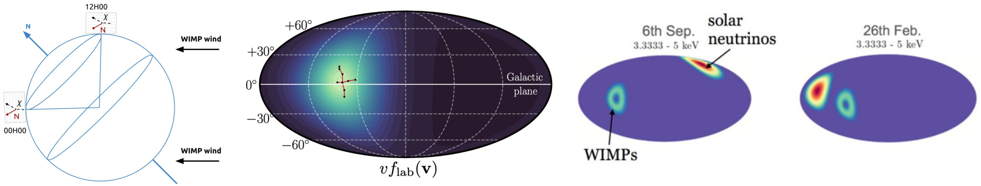


- **TIME ⇒** Results in a **few % annual modulation.**



★ **DIRECTION ⇒** Results in a characteristic **anisotropy** in the **angular distribution** of nuclear recoils ⇒ **No background can mimic!**

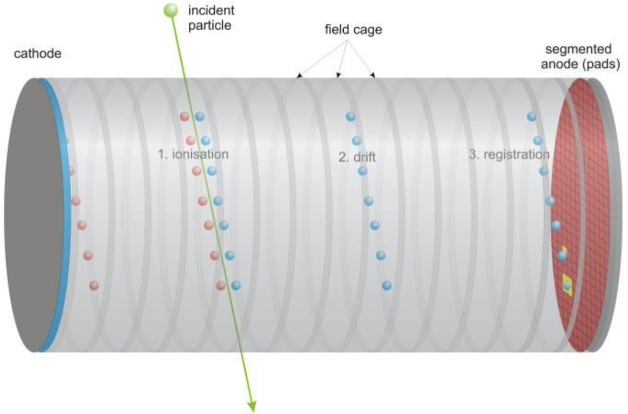
Directional discrimination is a striking feature to positively identify Dark Matter!

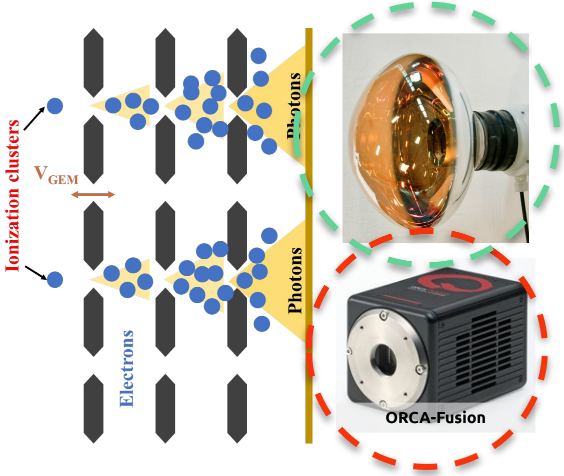


CE*ν*NS produces NRs identical to the DM-induced ones, but, below 10 GeV/c^2, we have mostly Solar neutrinos ⇒ **with directionality***, these **never superimpose with Cygnus**, allowing us to **venture into the neutrino fog.**

CYGNO - What's the setup?

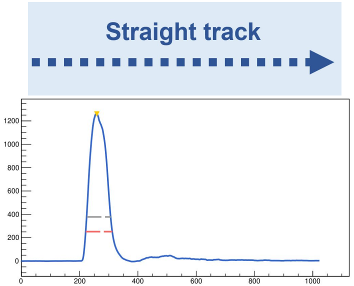
TPC → **Triple GEM**
Charge multiplication → **Camera + PMT**
Light from **gas scintillation** during electron avalanche

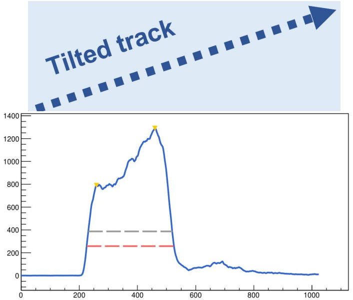




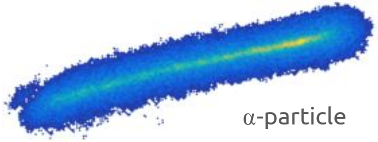
1. Independent **energy** measurement.

2. Electrons **times of arrival** ⇒ **dZ coordinate** (track's tilt)



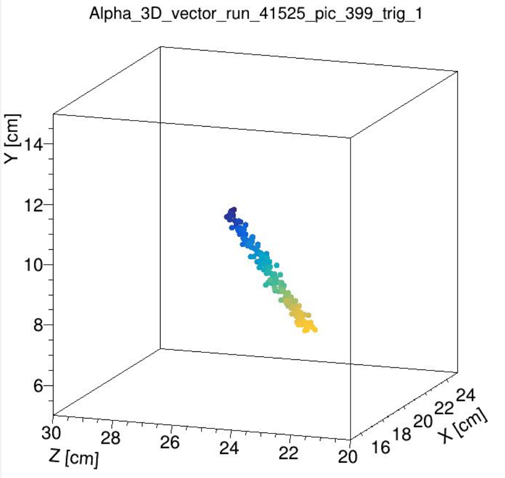


With the high granularity of the camera, we measure **energy** + **X & Y coordinates**



CYGNO - What's the setup?

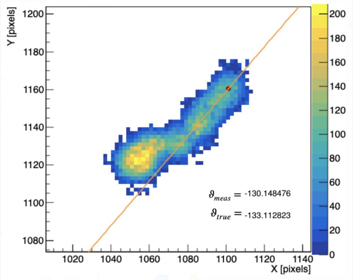
X + Y + dZ =
3D reconstructed track

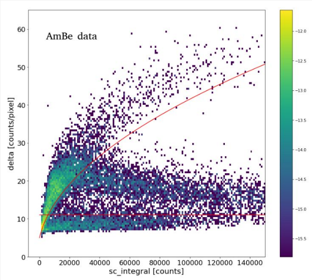


Track's deposited energy topology (dE/dx)

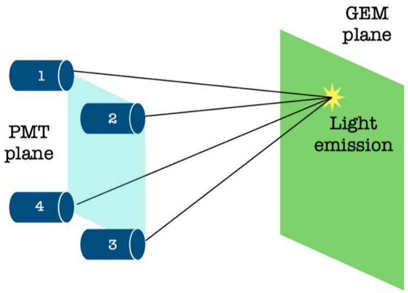
Head-tail asymmetry
+ recoil direction
↓
Directionality

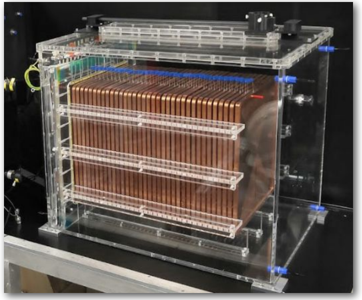
Particle
↓
BG rejection





LIME - Detector and Data





- ➔ **50 L** & **50 cm** drift gaseous **TPC**
- ➔ **He:CF4**, 60:40, **1 Atm** (910 mbar), 293 K
- ➔ 4 PMTs + 1 sCMOS camera

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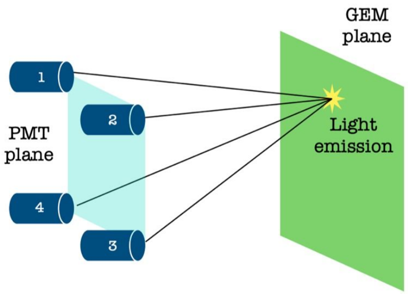

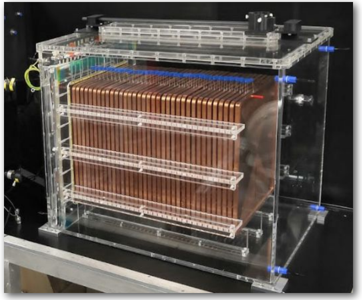

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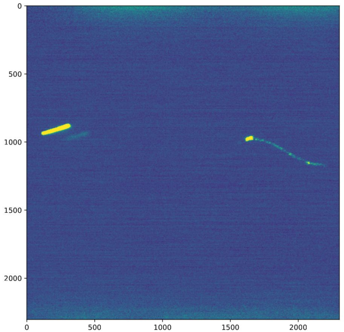
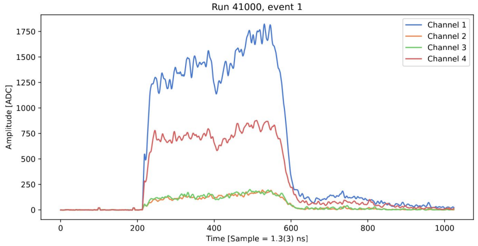
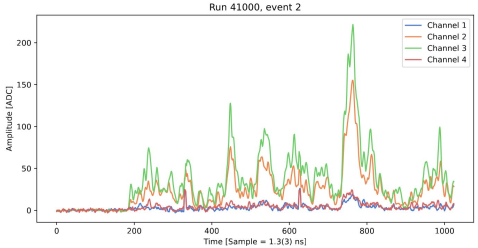
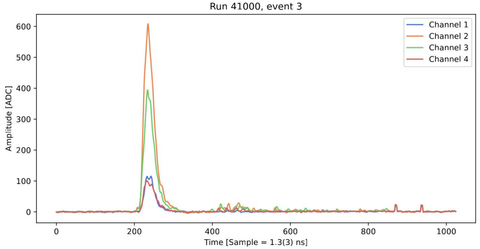
- ➔ **He:CF4**, 60:40, **1 Atm** (910 mbar), 293 K
- ➔ 4 PMTs + 1 sCMOS camera
- ➔ **One event =**
  - ◆ **1 CMOS pic:** $R_{\Delta t}$ = 500 ms
  - ◆ **X PMT WFs** = $N_{triggers} * N_{PMTs} * N_{digitiz}$
    - $R_{\Delta t}$ = **1.3 ns** & **4 ns**









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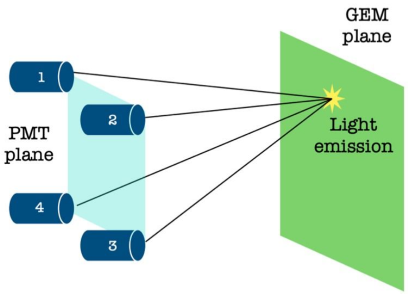

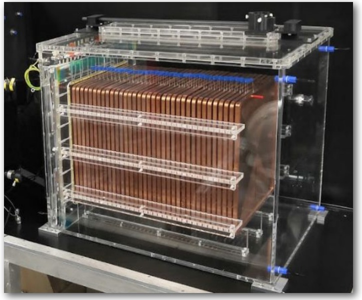

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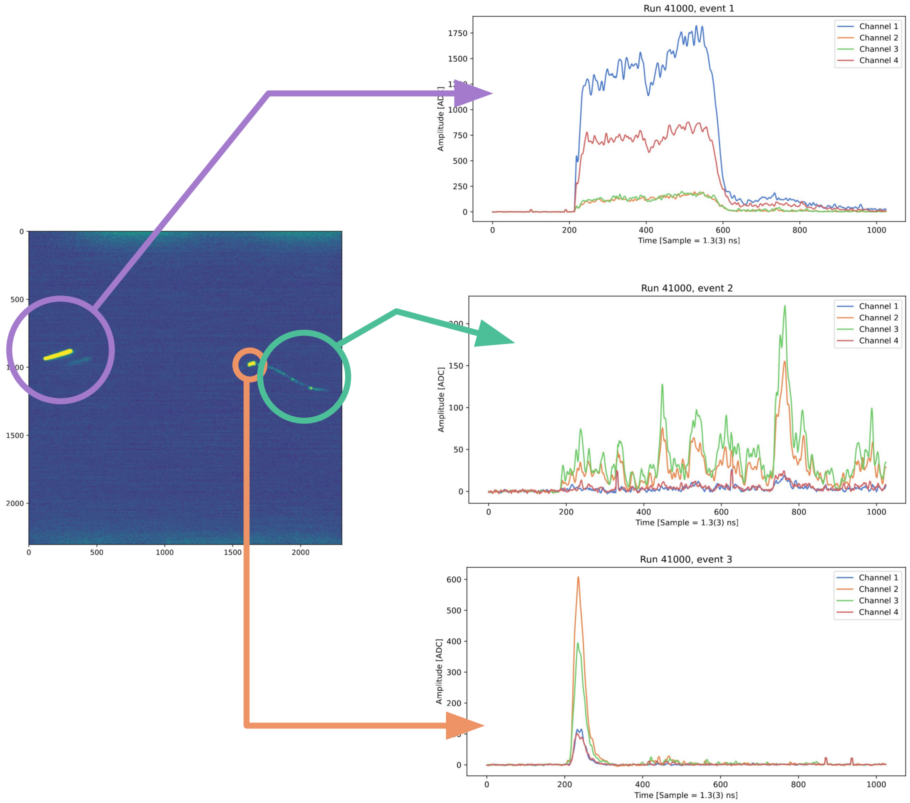
    - $R_{\Delta t}$ = **1.3 ns** & **4 ns**
- ➔ **The information needs to be matched!**



3D Event Reconstruction

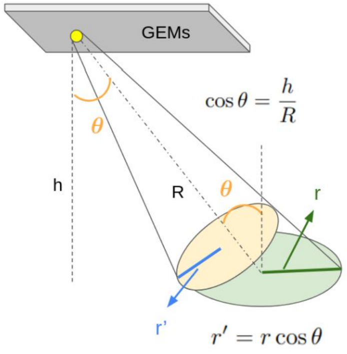
One-to-One association

3D Events - One-to-One association

➔ To **fully reconstruct** the information of **one event** we need to merge the **CMOS** and **PMTs** information.

- We developed a **1-to-1 association** to merge the ***CMOS clusters*** to ***PMT triggers***.

1. **Light** seen by each PMT depends on their **relative positions**.



$$L_{PMT} = \frac{L_{spot}}{4\pi R_i^2}\frac{\pi r^2 h}{R_i}$$

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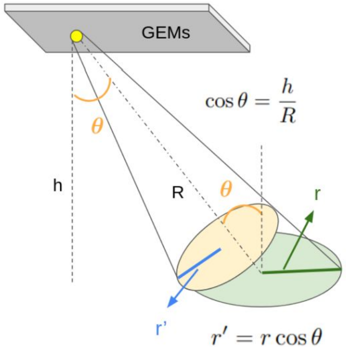
1. **Light** seen by each PMT depends on their **relative positions**.

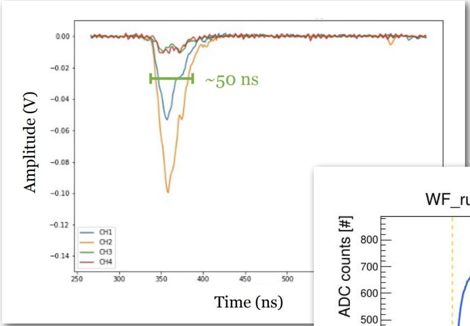
2. By **integrating the charge** in a time window, it's possible to retrieve the **(x, y, L) information** by performing a **multi-variable Bayesian fit**.

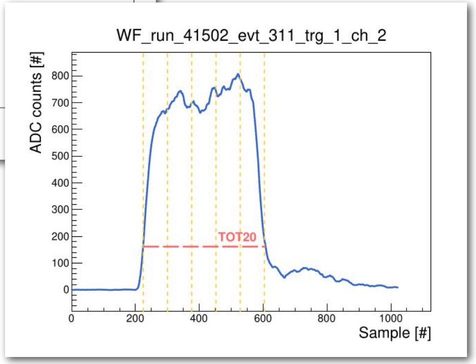


$$\cos\theta = \frac{h}{R}$$

$$r' = r\cos\theta$$

$$L_{PMT} = \frac{L_{spot}}{4\pi R_i^2}\frac{\pi r^2 h}{R_i}$$





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

With:

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

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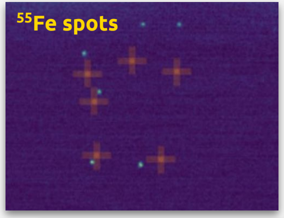
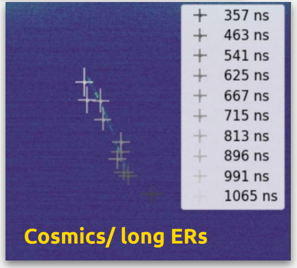
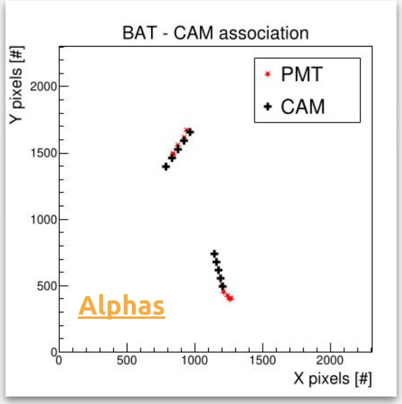
3. With (x, y, L) retrieved, we compare with CMOS clusters and assign them through the closest neighbor.







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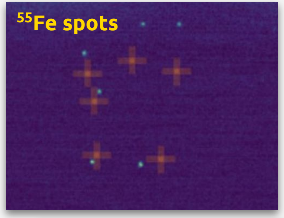
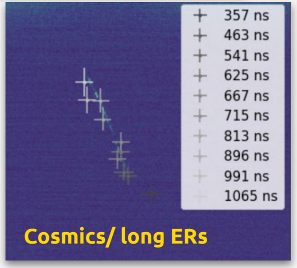
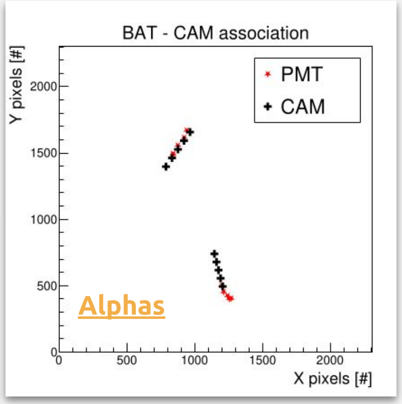
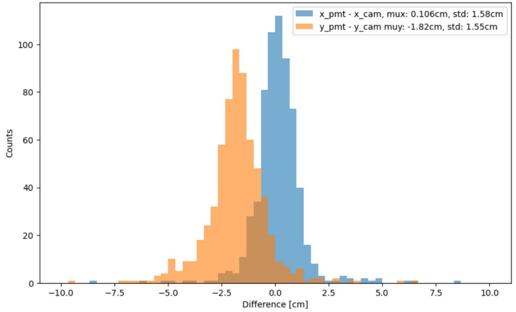






4. The **final goal** is to implement this technique at the detector **front-end level**. The **efficiencies** are promising! (The reference is the 33x33cm^2 GEM plane)



Performances for

- ^{55}**Fe** (spot-like) events:
  - X_{std}/Y_{std} **~ 1.6 cm**
- **Alphas**:
  - X_{std}/Y_{std} **~ 2,3 cm**

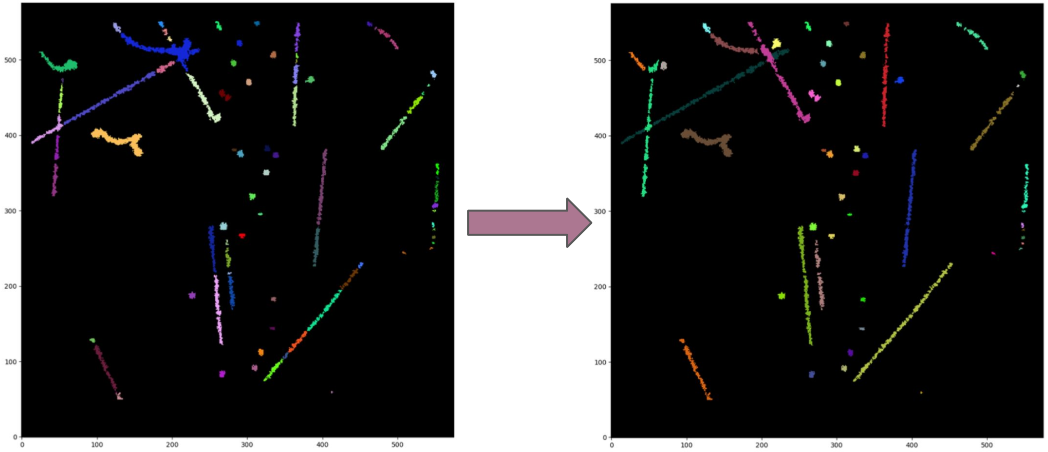
➔ ***Optimization undergoing*** concerning effects like saturation, lens barreling, gain inter-calibration, etc.

3D Event Reconstruction

CMOS analysis

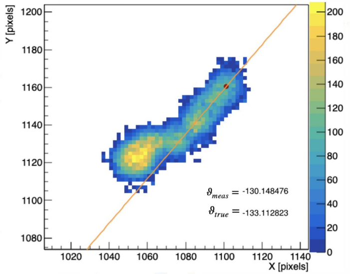
3D Events - CMOS analysis

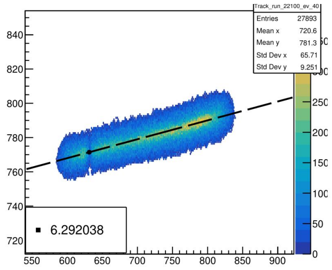
1. The **analysis of the CMOS images** starts with a directional iDBSCAN algorithm which clusters groups of pixels belonging to the same ionization event.
   a. For PID, each cluster can be selected through its: ***light integral, length, slimness, photon density, dE/dx, etc.***



Directional iDBSCAN to detect cosmic-ray tracks for the CYGNO experiment - IOPscience

2. A second layer analysis is used to determine other more dedicated variables such as 2D direction





Reconstructed info here:

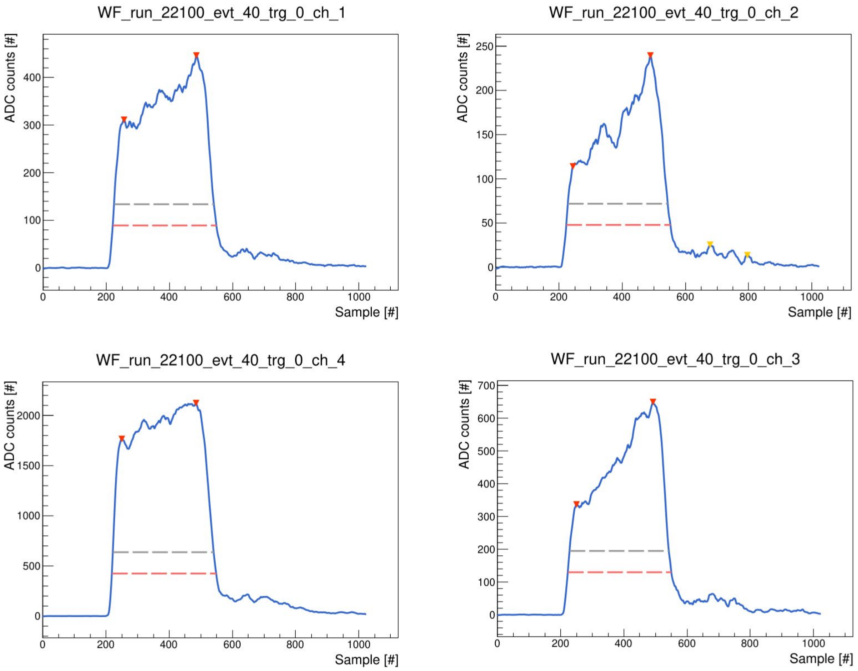
- **ΔXY**
- **X-Y angle (ϕ)**
- **2D direction**

3D Event Reconstruction

PMT analysis

3D Events - PMT analysis

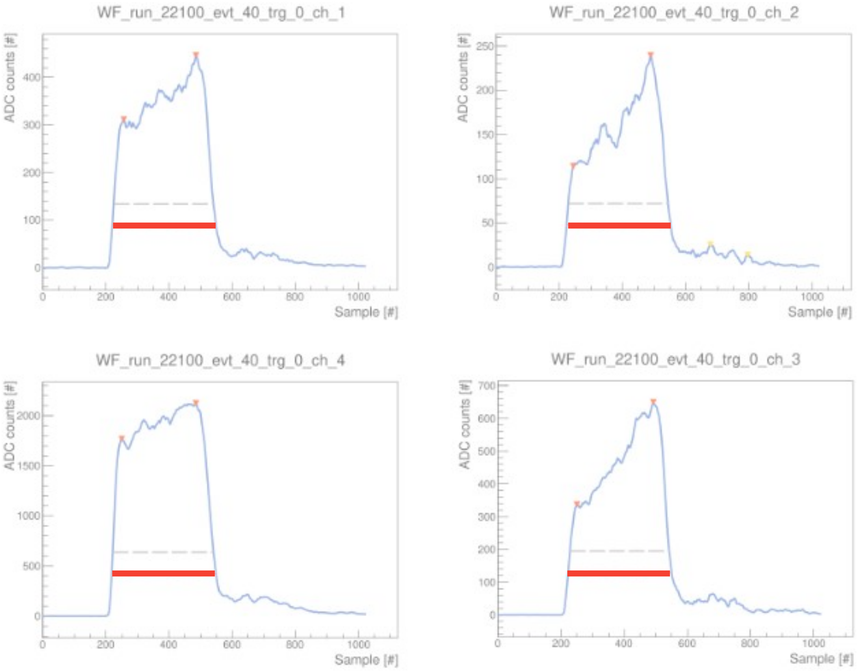
➔ The **PMTs** gives us information regarding the **longitudinal coordinate Z**, and allows us to close the **3D geometry**



3D Events - PMT analysis

➔ The **PMTs** gives us information regarding the **longitudinal coordinate Z**, and allows us to close the **3D geometry**

1. **Time-over-Threshold ⇒ Traveled Z**



3D Events - PMT analysis

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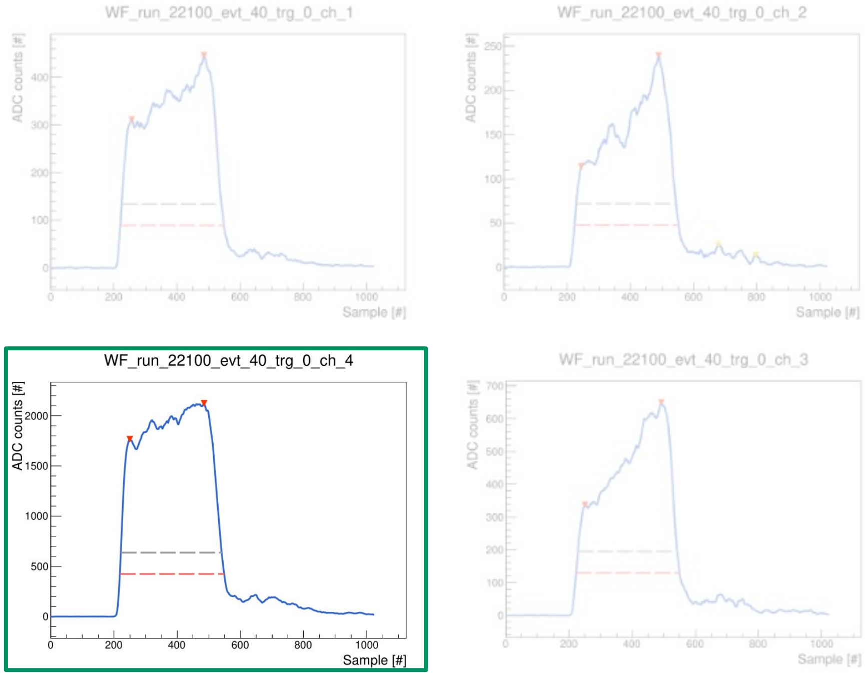
1. Time-over-Threshold ⇒ Traveled Z
2. **Highest integral ⇒ XY Quadrant**



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1. Time-over-Threshold ⇒ Traveled Z
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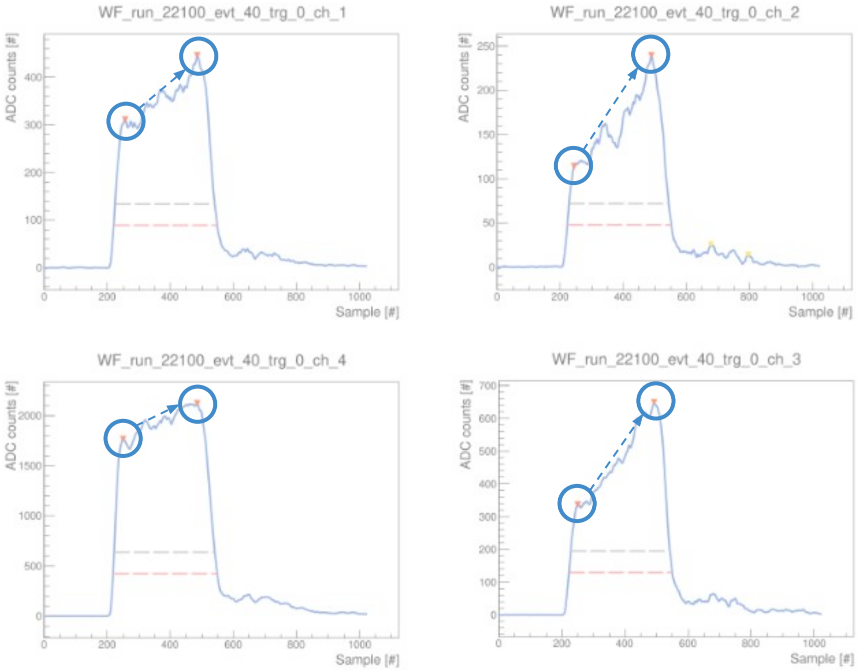
3. **Bragg peak position ⇒ Moving towards GEMs or cathode**



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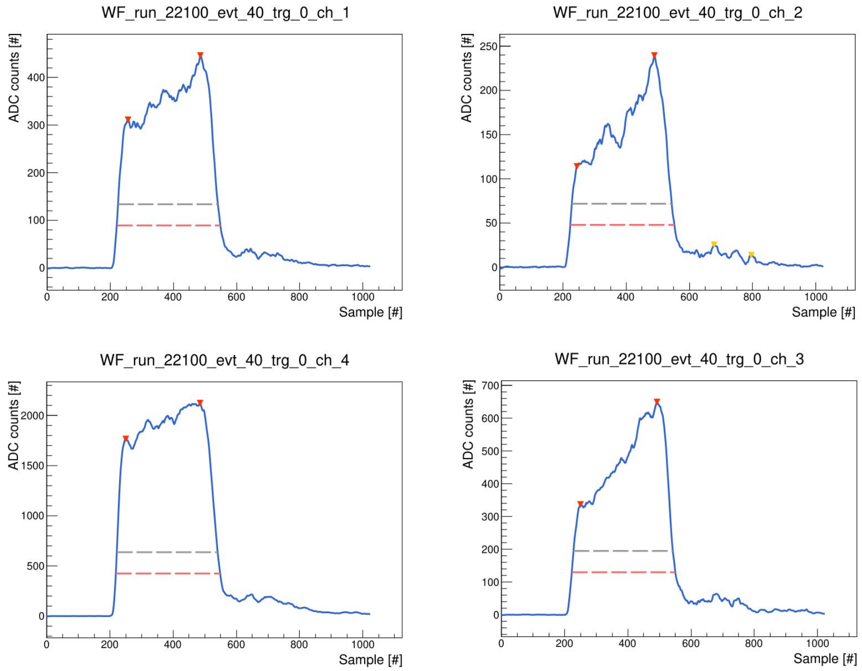
Additional reconstructed info:

- **ΔZ**
- **Sign of θ**



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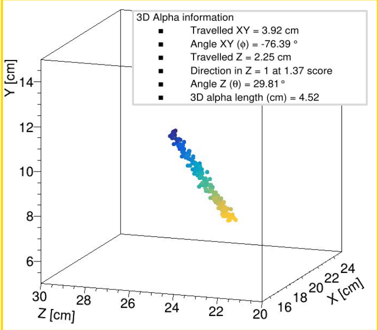
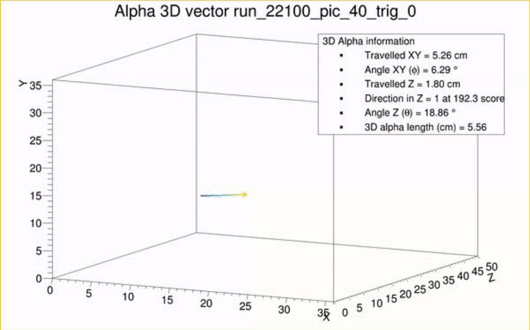
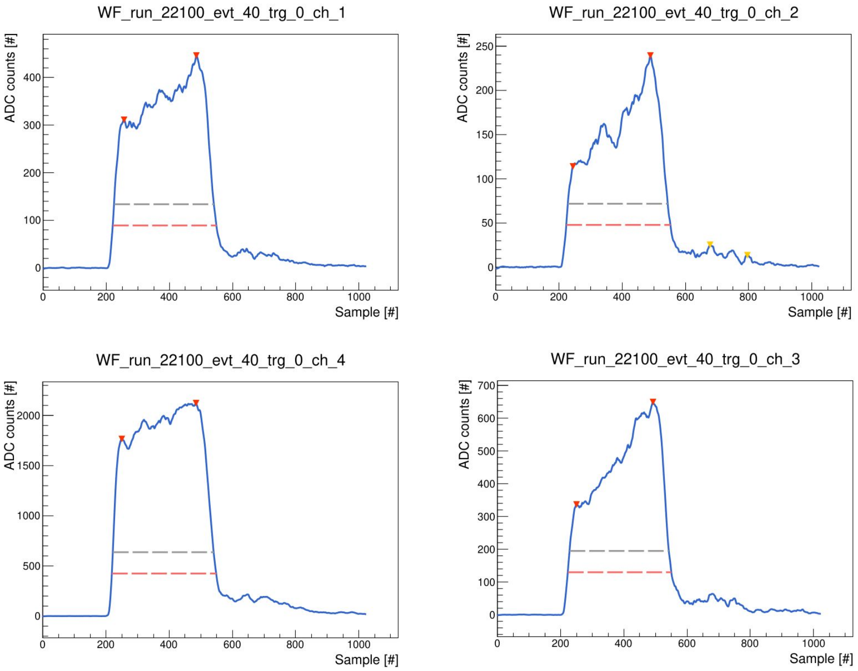
2. Highest integral ⇒ XY Quadrant
3. Bragg peak position ⇒ Moving towards GEMs or cathode

Additional reconstructed info:

- **ΔZ + ΔXY = Z angle (theta)**
- **Sign of θ + sign of ϕ = Head-tail**







3D Event Reconstruction

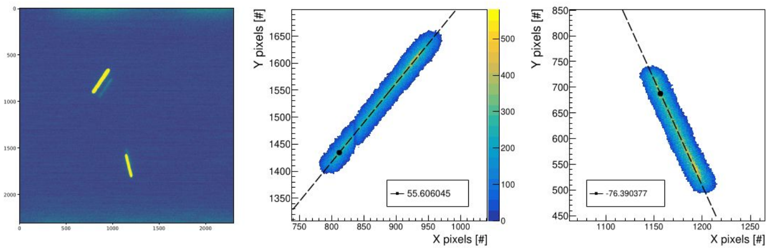
Dual sensor 3D analysis

3D Events - 3D analysis

➔ With the sensors' individual and merged information, we can now fully analyze the events and perform **particle ID**, **reject backgrounds** from known sources, and fully **characterize the 3D direction** ⇒ ***Directionality***

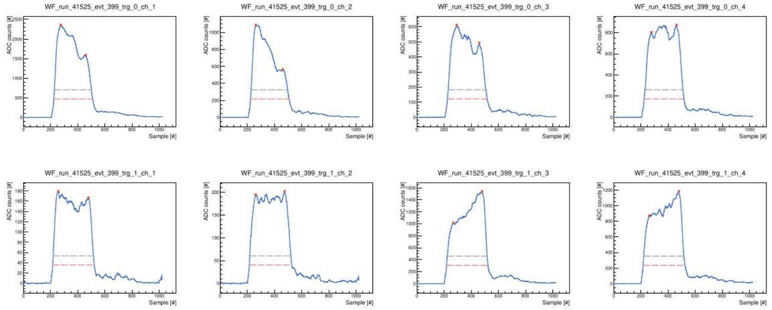
◆ The first studies were focused on **Alpha Particles**

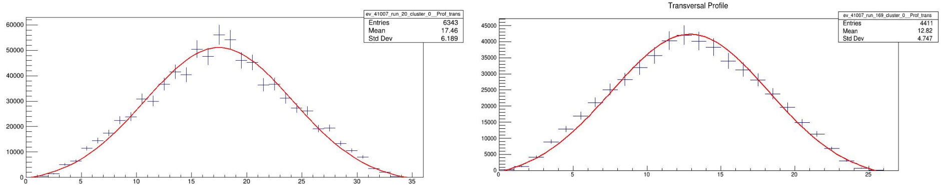
(a)



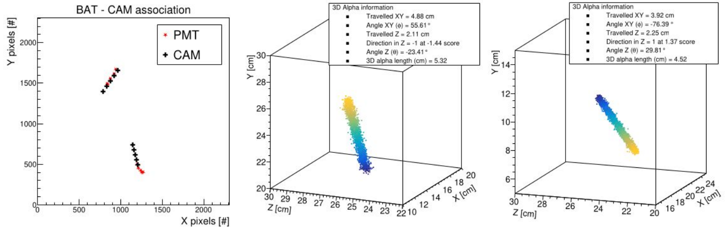
(c)

(d)



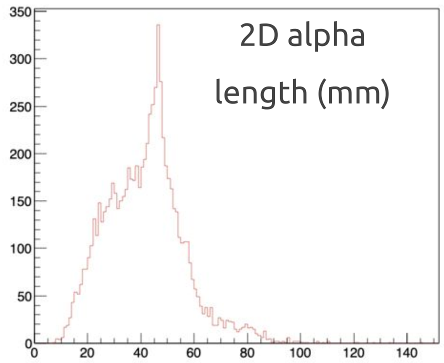


(e)



3D Events - The Rn study

➔ When comparing our data vs. simulation, we found discrepancies, ***possibility attributed to ^{222}Rn***.



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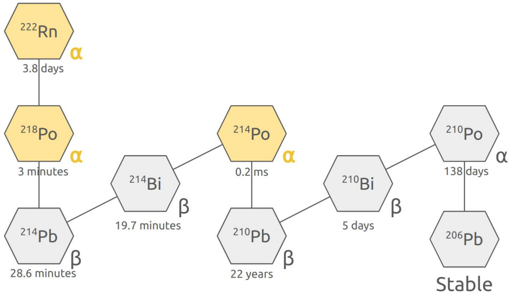

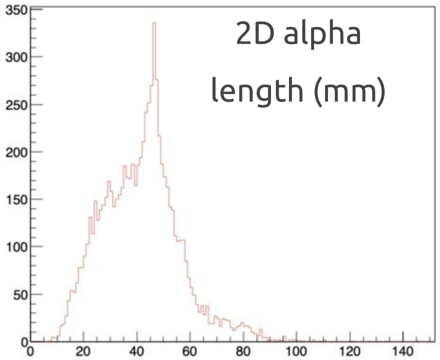

★ ^{222}Rn ⇒ 5.59 MeV ⇒ **4.3 cm**

★ ^{218}Po ⇒ 6.12 MeV ⇒ **5.0 cm**

★ ^{214}Po ⇒ 7.83 MeV ⇒ **7.3 cm**

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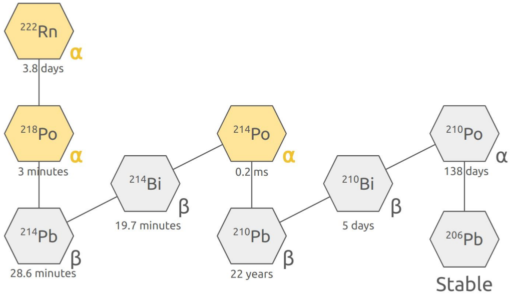

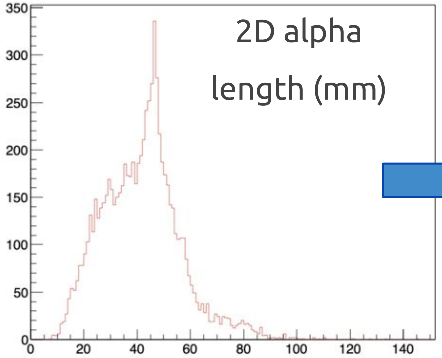

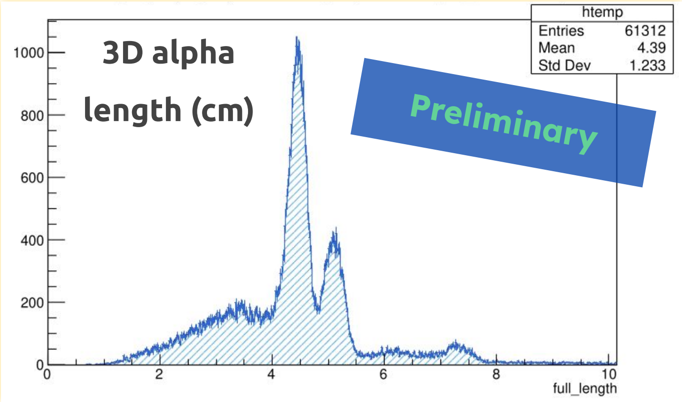

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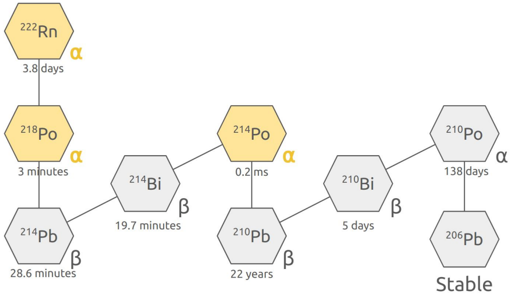

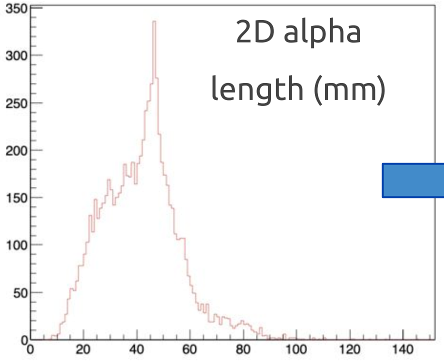

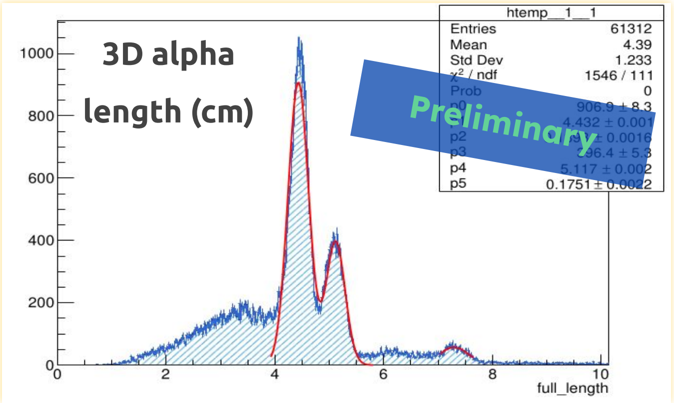

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- ★ **^{214}Po** ⇒ 7.83 MeV ⇒ **7.3 cm**

Very similar!

Additional resolution reassure us of the presence of Rn in the gas.

Fitted peaks:

- **4.43 cm**
- **5.12 cm**
- **7.29 cm**

3D Events - The Rn study

➔ When studying the distribution of the supposedly Rn alphas, we focused on their **absolute Z position** and **angular distribution**.

3D Events - The Rn study

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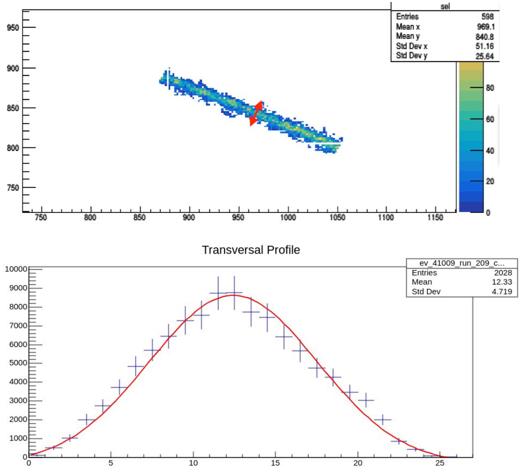
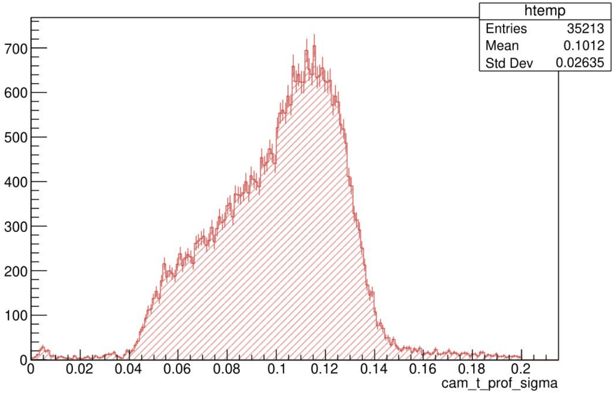
- The absolute Z position, or ***fiducialization***, is determined by fitting the **distribution of light** (pixel intensity) in the **orthogonal direction** of the alpha track ⇒ **"Transverse profile"**





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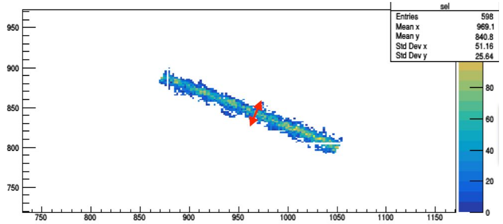

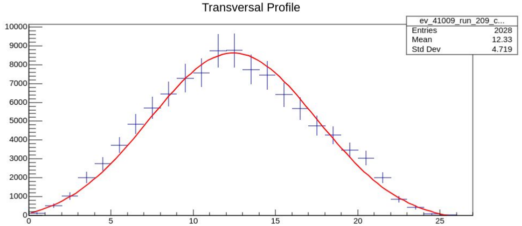

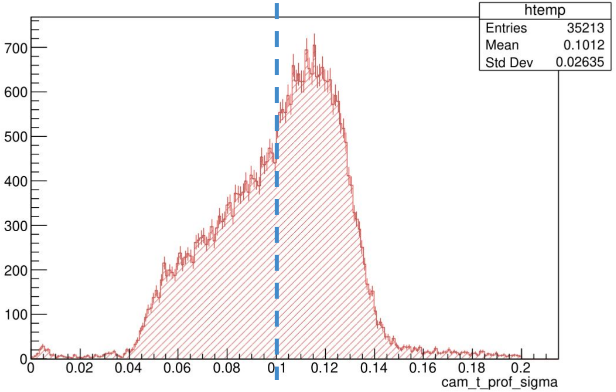

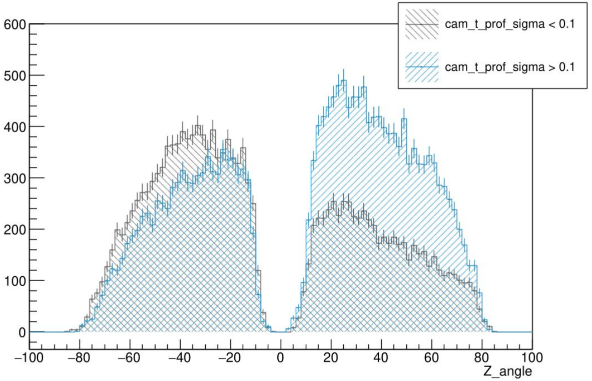

The angular distribution shows more particles moving towards the GEMs at higher diffusion (~ higher Z), presumably from the cathode, and vice versa.

3D Events - The Rn study

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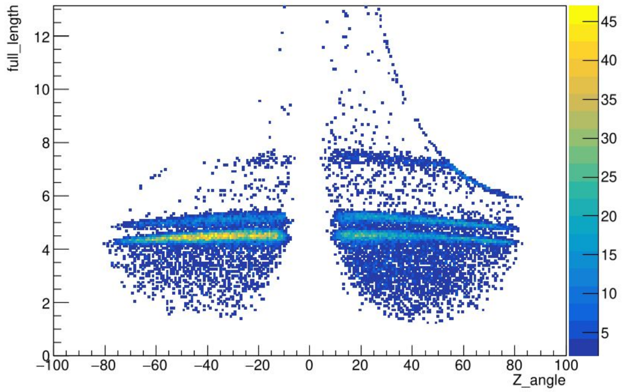

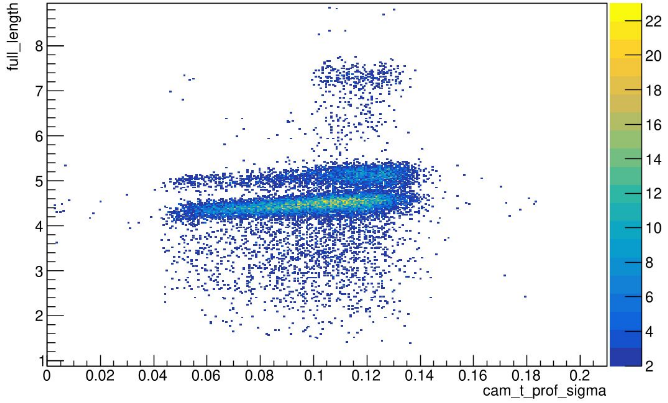

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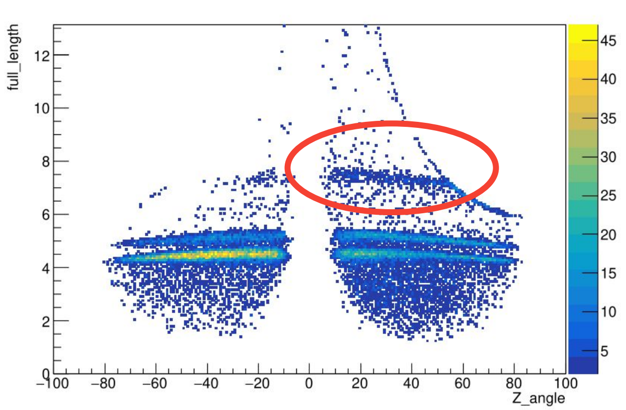

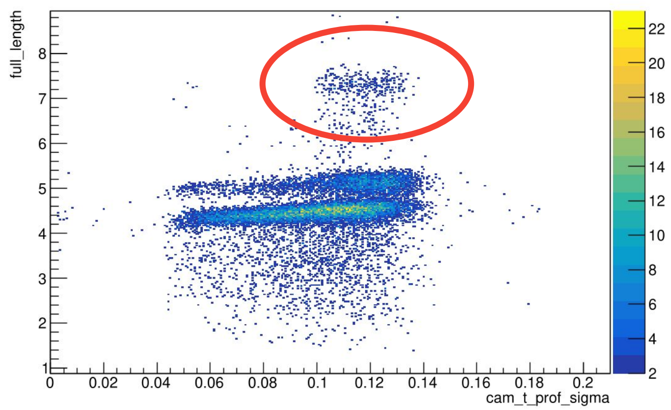

➔ Alphas at ~7 cm length (^{214}Po) preferentially towards GEM and at high Z. Is it thought that the positively charged ^{214}Po daughters drift towards the cathode and decay there, originating this effect.

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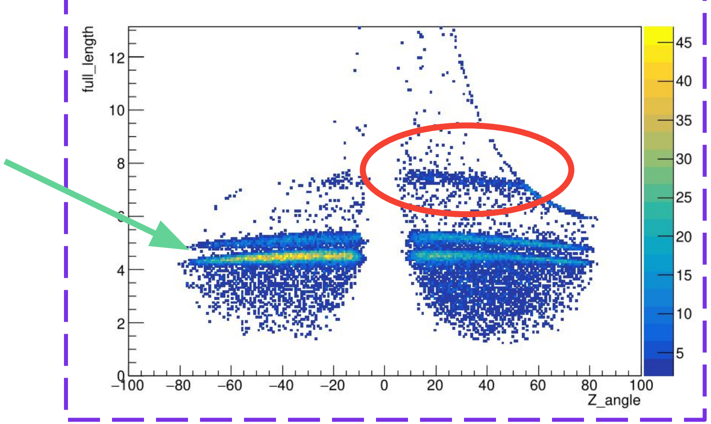

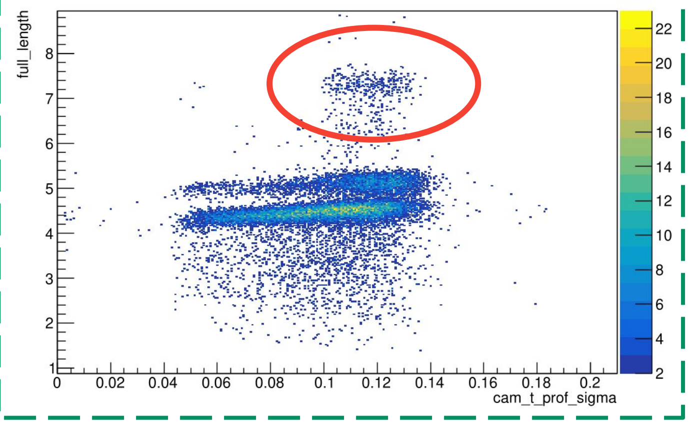

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- ➔ Alphas at ~4 cm length (^{222}Rn) see a preferential emission towards the cathode instead, although their origin is still being investigated.

3D Events - The Rn study

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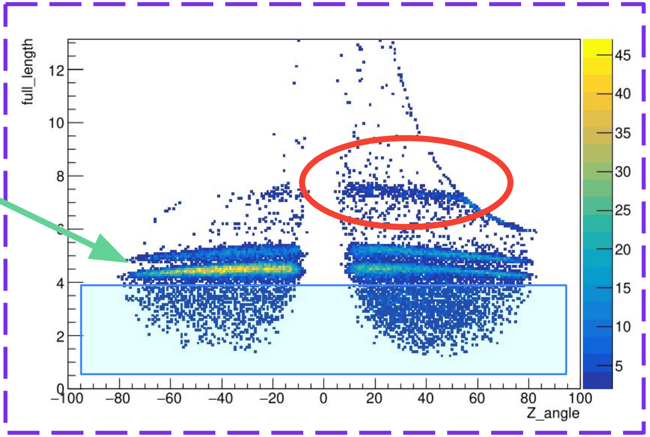
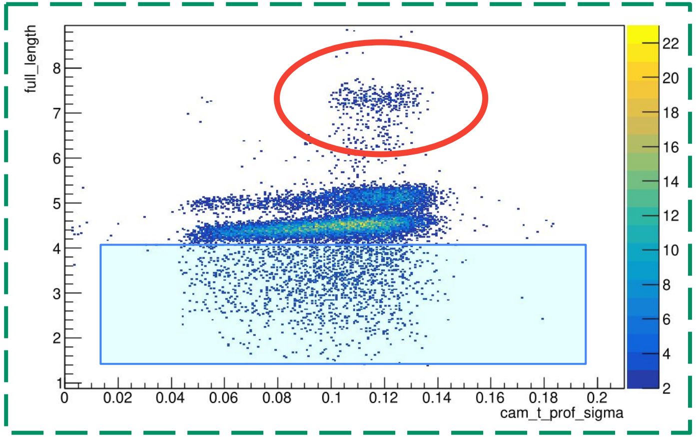
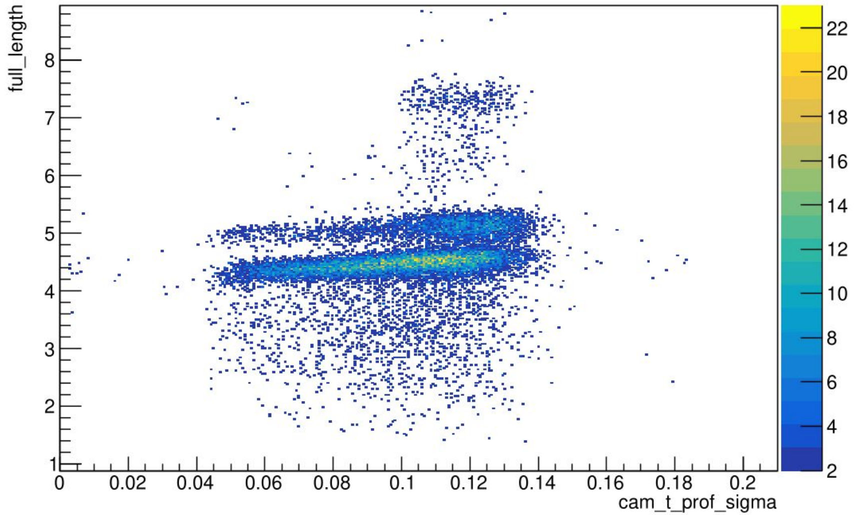




- ➔ Alphas at ~7 cm length (^{214}Po) preferentially towards GEM and at high Z. Is it thought that the positively charged ^{214}Po daughters drift towards the cathode and decay there, originating this effect.
- ➔ Alphas at ~4 cm length (^{222}Rn) see a preferential emission towards the cathode instead, although their origin is still being investigated.
- ➔ Remaining alphas at lower (< 4 cm) length (see α-lengths) are thought to come from the U/Th chains, and emitted uniformly in angle and Z.

3D Events - The Rn study

➔ The transverse diffusion allows us to have some idea about the distribution of absolute Z of these alphas, but this methodology could be improved…



We could use

Negative Ions!

Negative Ions - Concept

[an Innovative Negative Ion TIme projection chamber for Underground dark Matter searches | INITIUM | Project | Fact sheet | H2020 | CORDIS | European Commission]

Advantages:

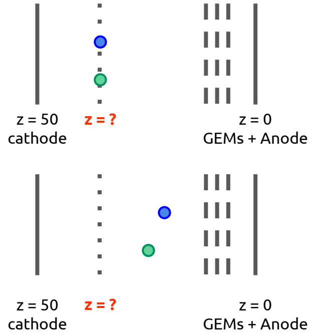
Reduced diffusion

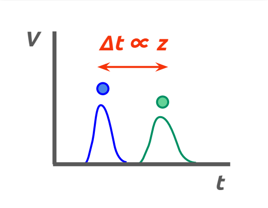
Longitudinal and transverse **diffusion reduced to thermal limit**

$$\sigma_D = \sqrt{\frac{4\varepsilon L}{eE}}$$

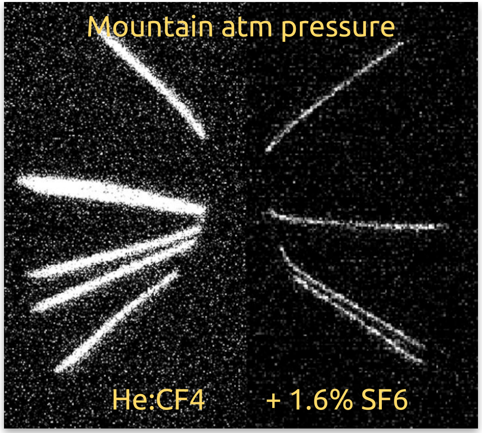
Better **spatial resolution!**

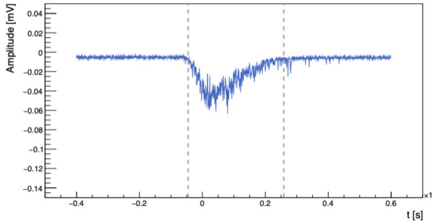
Multiple charge carriers





Absolute Z from **Δt** between minority charge carriers





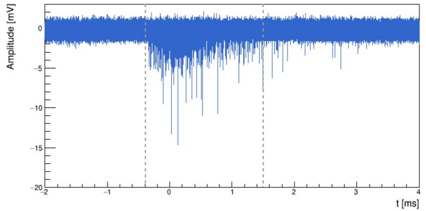
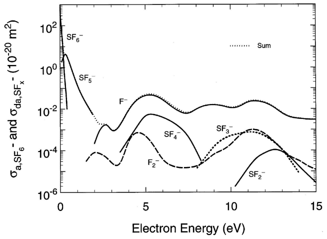


Table 2
Collisional processes that originate the SF_6 ion species of interest for this work. Adapted from Ref. [46].

Reaction	Process	Energy
$e^- + SF_6 \rightarrow SF_6^{-*}$	Electron attachment	<1 meV
$SF_6^{-*} \rightarrow SF_6 + e^-$	Autodetachment	(Metastable: > 1 μs)
$SF_6^{-*} + SF_6 \rightarrow SF_6^- + SF_6$	Collisional stabilization	
$e^- + SF_6 \rightarrow SF_5^- + F$	Dissociative electron attachment	0–2 eV
$e^- + SF_6 \rightarrow SF_4^- + 2F$		3–8 eV
$e^- + SF_6 \rightarrow F^- + SF_5$		1–14 eV
$e^- + SF_6 \rightarrow F_2^- + SF_4$		1–14 eV
$SF_{5/6}^- + SF_6 \rightarrow SF_{5/6} + SF_6 + e^-$	Collisional detachment	>90 eV
$SF_6^- + SF_6 \rightarrow SF_6 + SF_6^-$	Charge transfer	
$SF_6^- + SF_6 \rightarrow SF_5^- + F + SF_6$	Dissociative charge transfer	>1 eV



https://doi.org/10.1016/j.nima.2022.1661416

Negative Ions - Analysis

ED: He:CF_4 60:40

NID: He:CF_4:SF_6 59:39.6:1.6

< CMOS >

< PMT >

Negative Ions - Analysis

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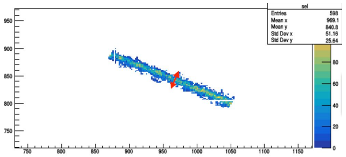
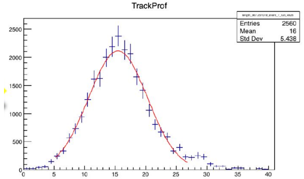
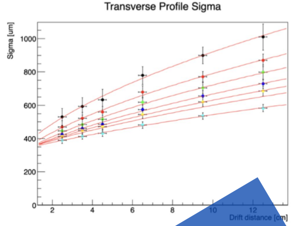
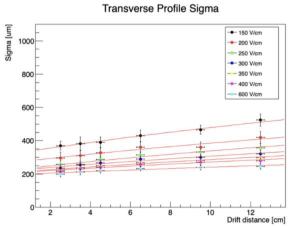
Transverse profile of track studied and fitted with Gaussian to estimate diffusion









$$\sigma_{meas} = \sqrt{\sigma_0^2 + \sigma_T^2 L}$$

Drift field [V/cm]	σ_0^{ED}	σ_T^{ED}	σ_0^{NID}	σ_T^{NID}
150	300 ± 100	280 ± 20	320 ± 30	110 ± 10
200	290 ± 60	230 ± 10	260 ± 30	88 ± 20
250	284 ± 60	210 ± 10	220 ± 20	81 ± 10
300	300 ± 40	190 ± 10	220 ± 20	68 ± 10
350	300 ± 40	170 ± 10	210 ± 20	62 ± 10
400	310 ± 30	160 ± 10	210 ± 20	56 ± 9
600	320 ± 22	140 ± 10	200 ± 20	45 ± 10

Negative Ions - Analysis

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< CMOS >

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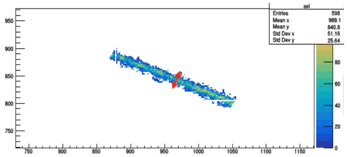

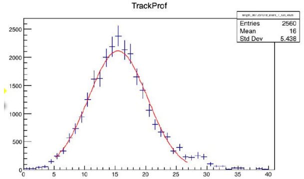

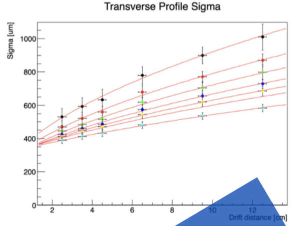

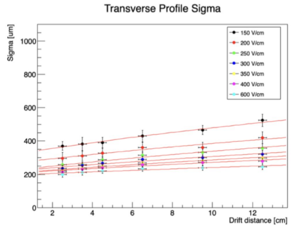

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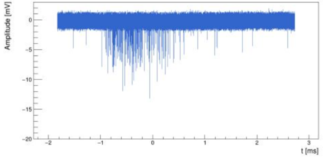
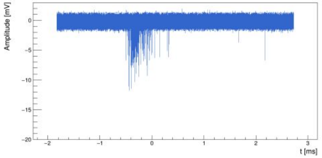
< PMT >

★★ First ever PMT analysis for optical NID signals ★★



(a) 300 V/cm.



(b) 700 V/cm.

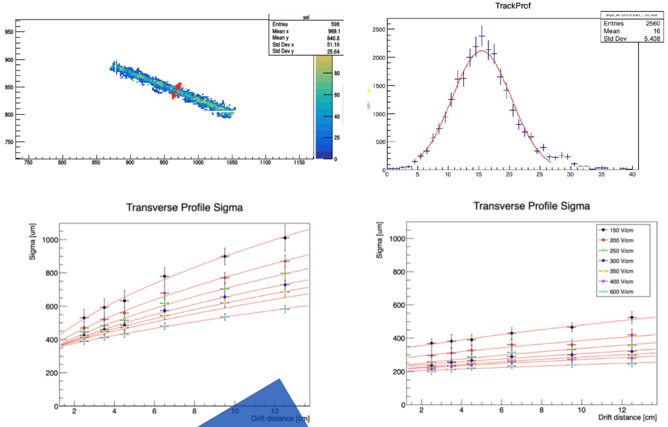
Negative Ions - Analysis

ED: $He:CF_4$ 60:40

NID: $He:CF_4:SF_6$ 59:39.6:1.6

< CMOS >

Transverse profile of track studied and fitted with Gaussian to estimate diffusion



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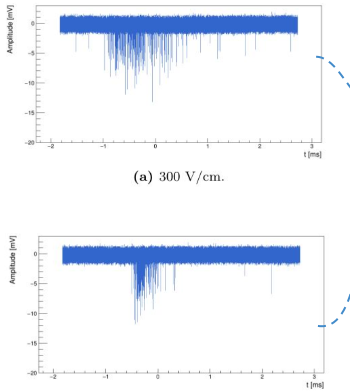
< PMT >

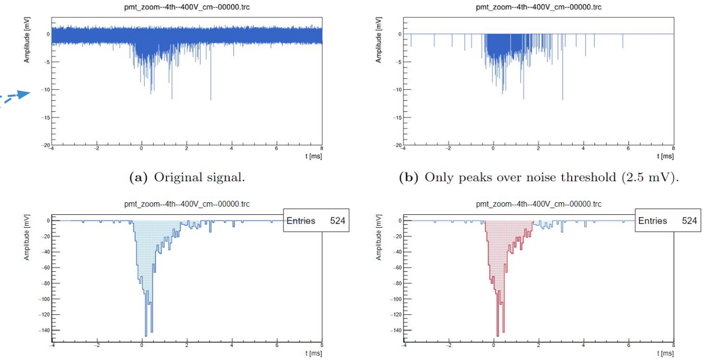
★★ First ever PMT analysis for optical NID signals ★★

1. **Threshold** ➡ Only individual peaks above 6*RMS
2. **Rebin** ➡ Selected peaks put into histogram
3. **Delimitation** ➡ Start (end) when 2 bins are above (below) 10 mV



(a) 300 V/cm.

(b) 700 V/cm.



(a) Original signal.

(b) Only peaks over noise threshold (2.5 mV).

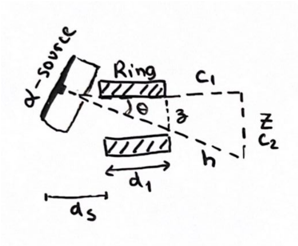
(c) Rebinned waveform.

(d) Reconstructed signal in red.

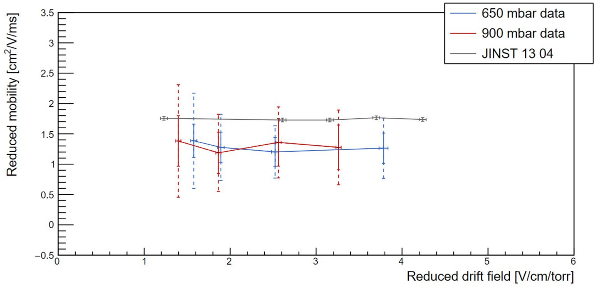
Negative Ions - Ion mobility

Final measurement: Ion Mobility

1. Tilted ED alpha tracks
   a. Distribution ➡ Get mean value (Δt)
   b. Knowing electrons' velocity in gas (v)
      i. Z travelled by track ➡ 1.5 cm



2. Tilted NID alpha tracks
   a. Average time window (Δt)
      i. Z / Δt = *v_ion*



- Data ***self-consistent*** with at 650 and 900 mbar
- Charge carriers' ***mobility*** consistent with ***SF6-*** in literature

Negative Ions - Ion mobility

Final measurement: Ion Mobility

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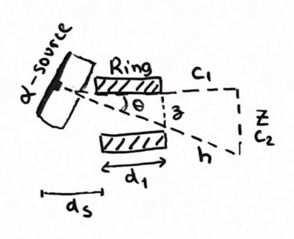

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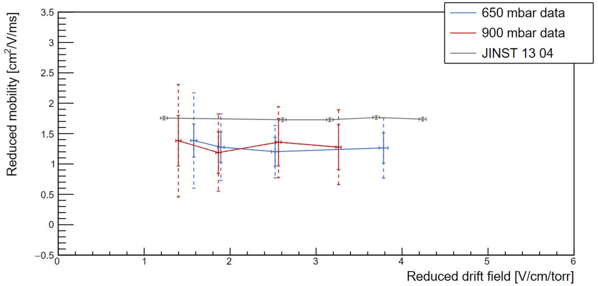
      i. Z / Δt = *v_ion*



- Data ***self-consistent*** with at 650 and 900 mbar
- Charge carriers' ***mobility*** consistent with ***SF6-*** in literature

Achievements:

- CMOS shows a **transverse diffusion** ~3 times **smaller**!
- PMT undoubtedly proves NID regime with **optical readout!**

Next steps:

- *Longitudinal diffusion*
- *Fiducialization with SFX-*
- *Primary ionization cluster counting*
- ***CMOS + PMT NID 3D analysis***

Conclusions

- ➔ The CYGNO collaboration is developing a high-precision gaseous TPC at atmospheric pressure with optical readout.
- ➔ The main focus is the directional direct search of DM WIMP-like particles in the low mass range (0.5-10 GeV).
- ➔ Through nuclear recoil direction, backgrounds can be rejected and unambiguous confirmation of DM is possible.

- ➔ The merging of CMOS (X-Y) with PMT (Z) information is performed with a Bayesian fit.
  - ◆ The ability of reconstructing ionization events in 3 dimensions greatly improves our spatial resolution and our PID capabilities.
  - ◆ From the suspicion of the **presence of Rn**, the 3D analysis allows us to almost confirm its presence and, through its emission direction, its origin became more clear.

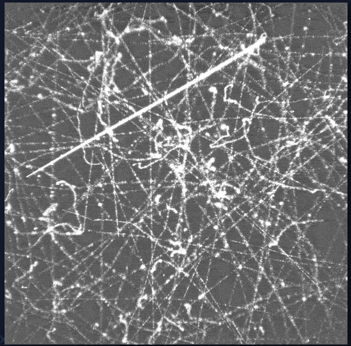
- ➔ The addition of SF6 in the mixture would put the detector in the Negative Ion Drift (NID) regime.
  - ◆ Preliminary studies prove its plausibility at atmospheric pressure.
  - ◆ Upcoming studies will show how the diffusion can be improved with NID and how minority carriers could become a technique for detector Z-fiducialization.

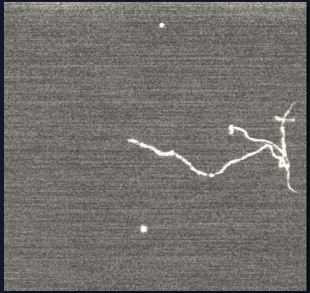
…check out our white paper!
The CYGNO Experiment - Instruments

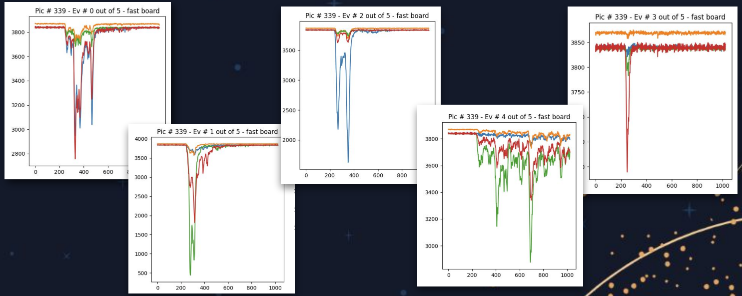
Thank you for your attention!

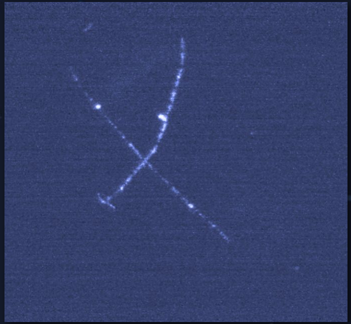
The CYGNO Project counts with the collaboration of several international researchers, coming from:

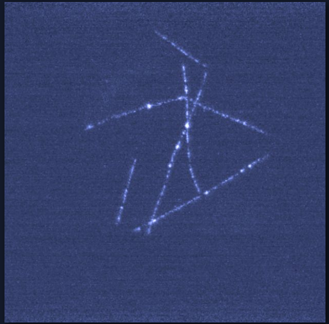
Some cool pictures

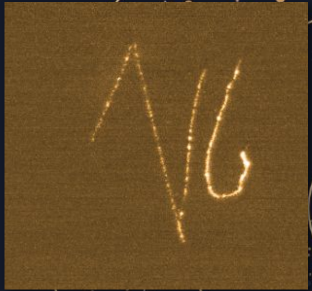


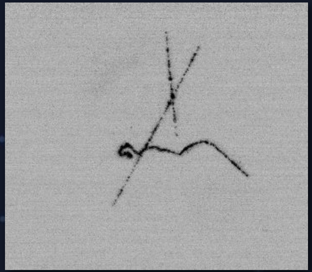


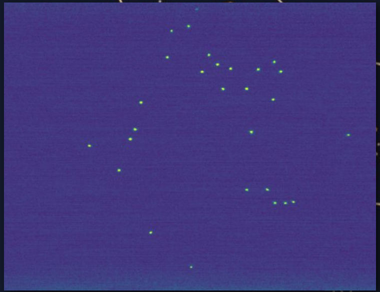










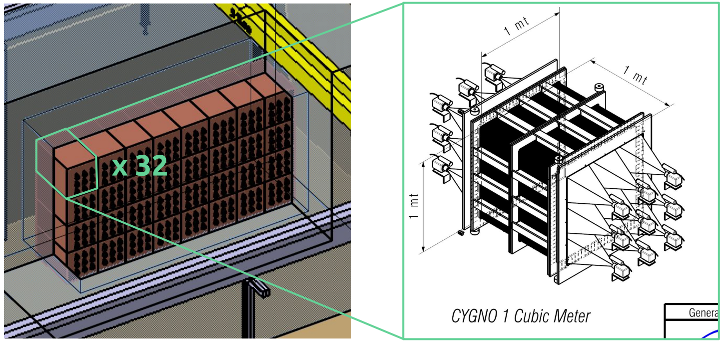


Backup

& more details

CYGNO-30 - Prospects

- ➔ **Low mass (0.5 - 10 GeV) directional DM searches**
- ➔ > 2027
- ➔ **30 - 100 m3** detector
- ➔ **0.5 - 1 keV$_{ee}$** energy threshold
- ➔ **30°** angular resolution

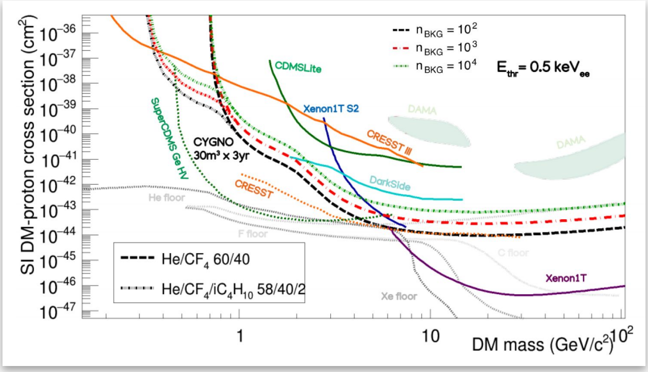


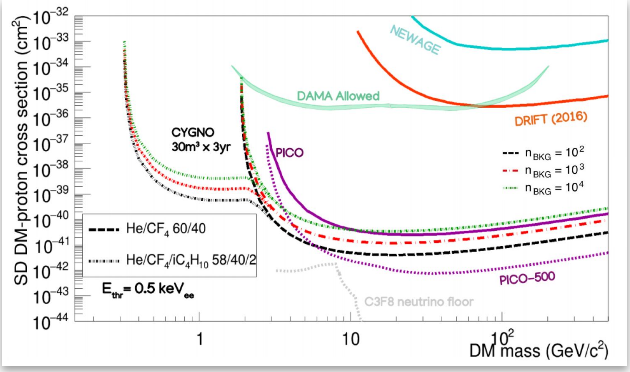
Expected **SI** and **SD** (90% CL)

interaction cross-section exclusion

Quenching factor simulated with **SRIM** ⟶ Direct measurement incoming!

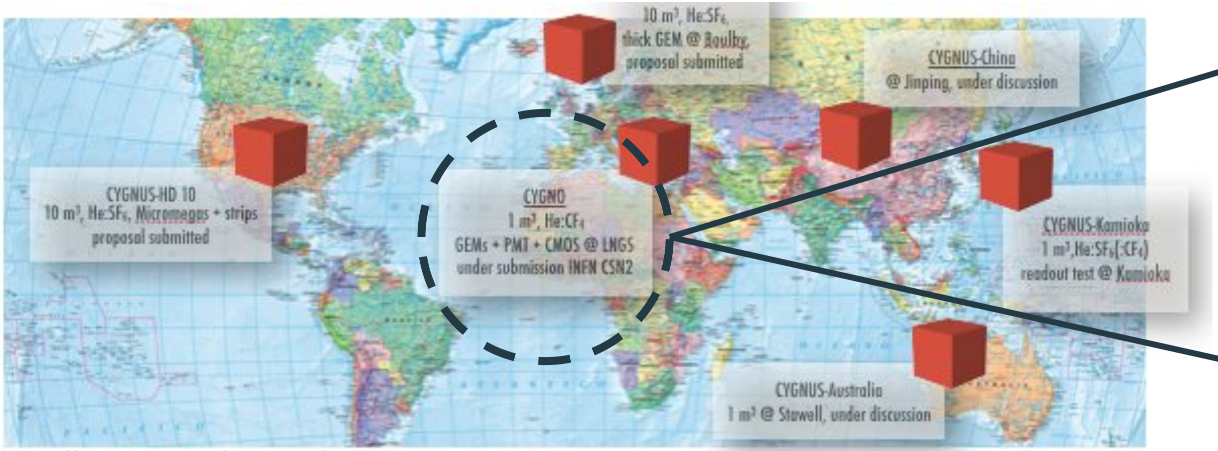
He / (eventually H) allows us to explore very low DM masses!



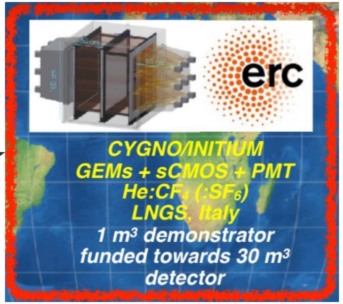


The CYGNUS project

CYGNO is part of a proto-collaboration, **CYGNUS,** focused on establishing a **Galactic Directional Recoil Observatory** that could test and study DM hypothesis beyond the neutrino floor.



https://inspirehep.net/literature/1813839



Within the CYGNUS collaboration, several approaches are being studied.

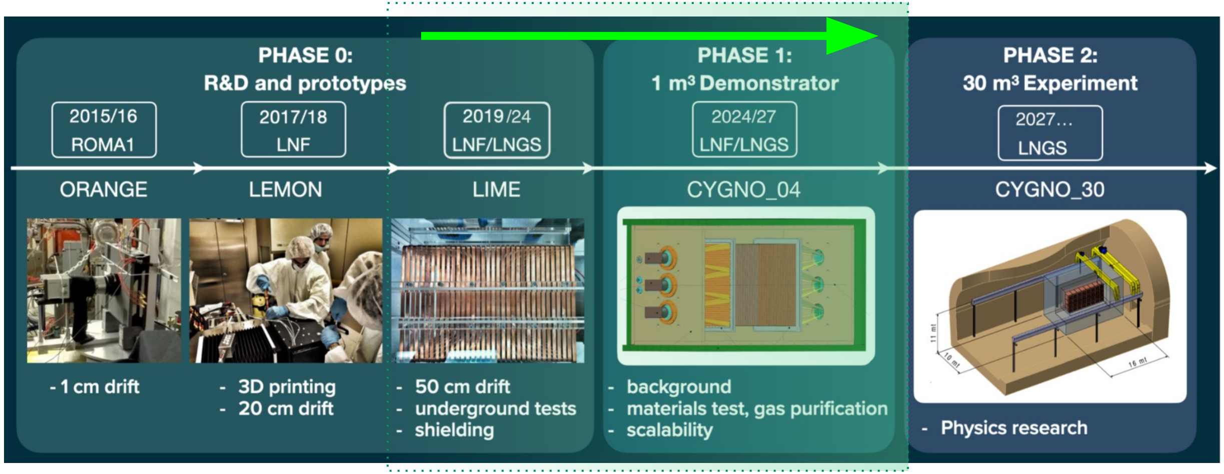
The Italian group, CYGNO, is developing a **gaseous TPC** based on the setup:

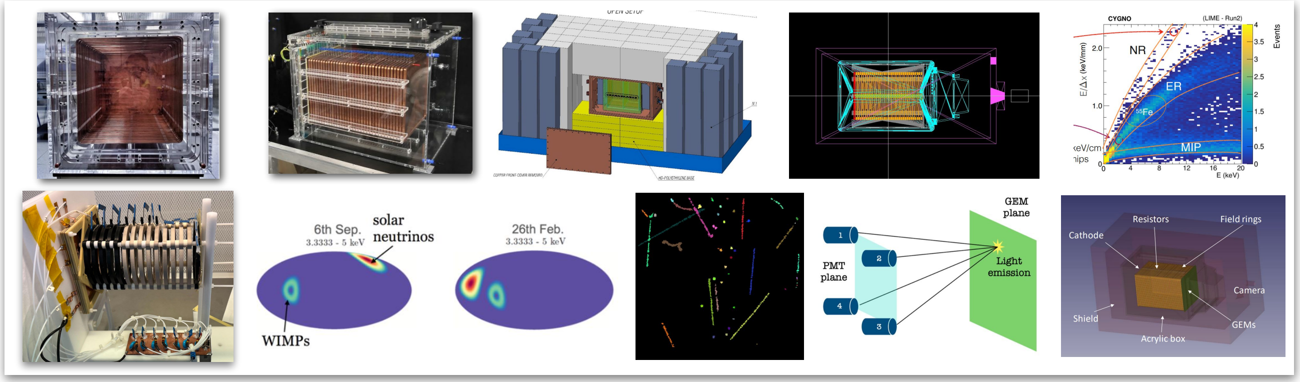
GEMs + sCMOS + PMT to test **Optical Readout**

CYGNO - Roadmap

Several ongoing efforts in different fronts:

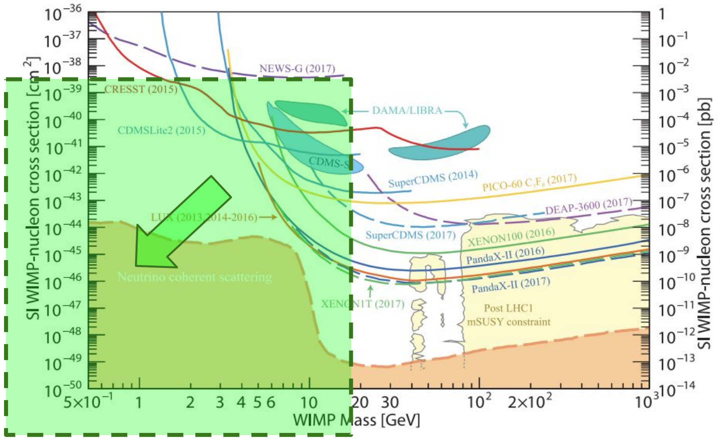
- 3D reconstruction
- Directionality
- ER vs. NR (+ML)
- Shielding optimization
- Background data vs. MC
- DM Sensitivity
- Design and Commissioning of CYGNO_04
- Enhancement of the light yield
- Negative Ion drift





CYGNO - Dark Matter paradigm

CYGNO Dark Matter exploration region



Low Density @ atm pressure

➔ Allows tracks of up to **millimetres** at **few keV** without compromising exposure.

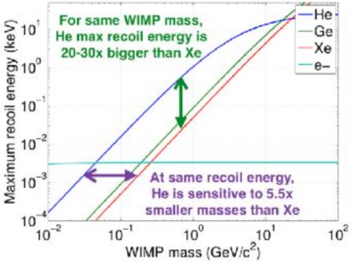
< 10 GeV/c²

➔ To observe lower WIMP masses:

- **Low thresholds** are necessary, since lower mχ originate lower energy recoils.
- **Light nuclei** used to maximize energy transfer.

Helium (He)

➔ Light target for SI in low mass range.



Fluorine (F)

➔ Heavier target to intermediate WIMP masses.

➔ One of the highest sensitivity to SD coupling.