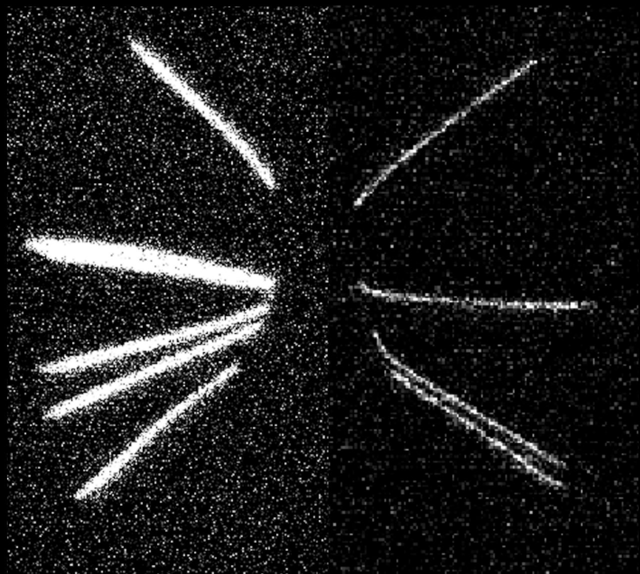
Elisabetta Baracchini

Gran Sasso Science Institute & Istituto Nazionale Fisica Nucleare

Negative ion drift with optical readout at atmospheric pressure



Fernando Domingues Amaro [1], Elisabetta Baracchini [2,3], Luigi Benussi [4], Stefano Bianco [4], Cesidio Capoccia [4], Michele Caponero [4,5], Danilo Santos Cardoso [6], Gianluca Cavoto [7,8], André Cortez [2,3], Igor Abritta Costa [9], Rita Joanna da Cruz Roque [1], Emiliano Dané [4], Giorgio Dho [2,3], Flaminia Di Giambattista [2,3], Emanuele Di Marco [7], Giovanni Grilli di Cortona [4], Giulia D'Imperio [7], Francesco Iacoangeli [7], Herman Pessoa Lima Júnior [6], Guilherme Sebastiao Pinheiro Lopes [9], Amaro da Silva Lopes Júnior [9], Giovanni Maccarrone [4], Rui Daniel Passos Mano [1], Michela Marafini [10], Robert Renz Marcelo Gregorio [11], David José Gaspar Marques [2,3], Giovanni Mazzitelli [4], Alasdair Gregor McLean [11], Andrea Messina [7,8], Cristina Maria Bernardes Monteiro [1], Rafael Antunes Nobrega [9], Igor Fonseca Pains [9], Emiliano Paoletti [4], Luciano Passamonti [4], Sandro Pelosi [7], Fabrizio Petrucci [12,13], Stefano Piacentini [7,8], Davide Piccolo [4], Daniele Pierluigi [4], Davide Pinci [7,*], Atul Prajapati [2,3], Francesco Renga [7], Filippo Rosatelli [4], Alessandro Russo [4], Joaquim Marques Ferreira dos Santos [1], Giovanna Saviano [4,14], Neil John Curwen Spooner [11], Roberto Tesauro [4], Sandro Tomassini [4] and Samuele Torelli [2,3]

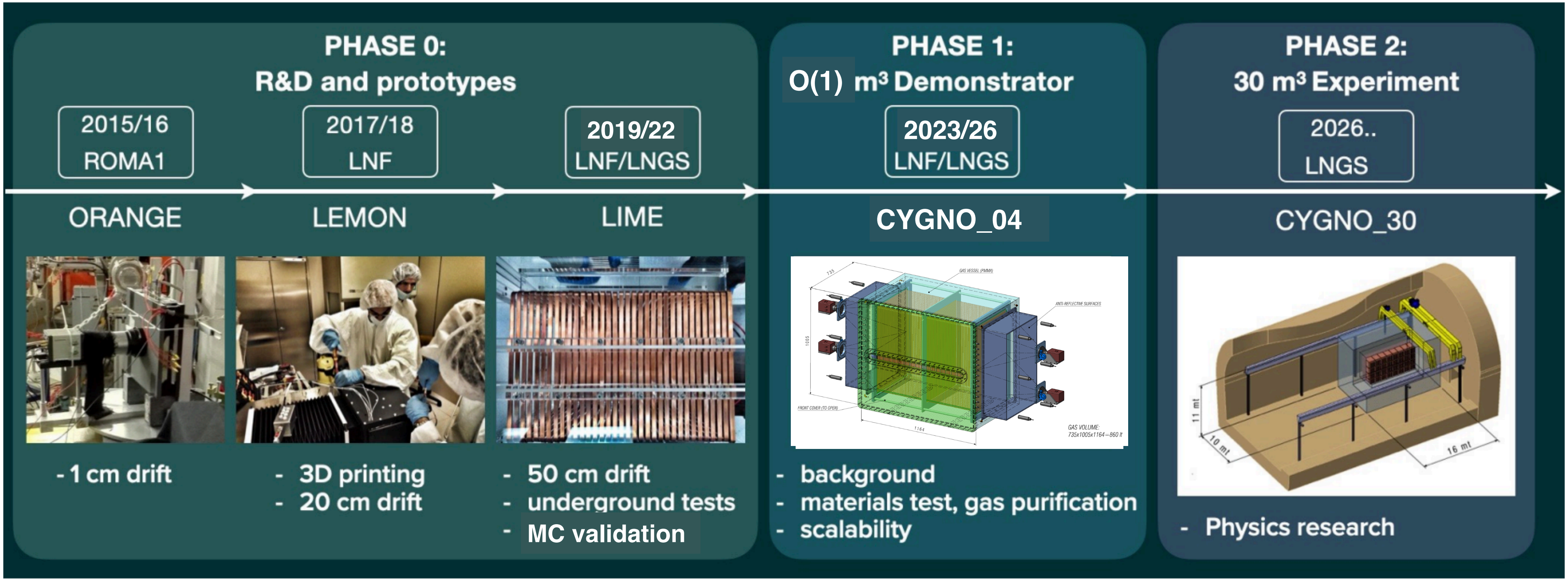
The 7th International Confefence on Micro Patter Gaseous Detectors 2022

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

See F. Petrucci talk @ 16.40

CYGNO experiment

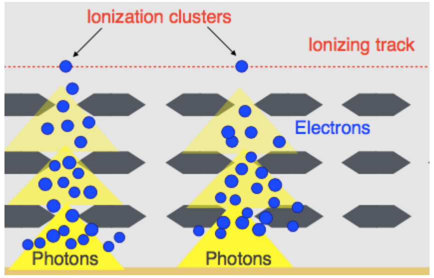
F. D. Amaro et al [CYGNO Collaboration], Instruments, Volume 6, Issue 1



High precision 3D optical TPC for directional Dark Matter searches and solar neutrino spectroscopy

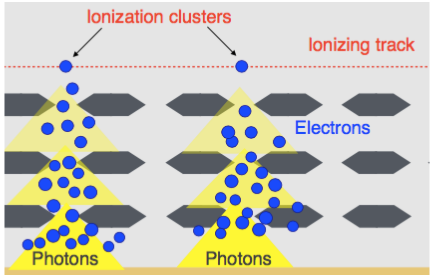
https://web.infn.it/cygnus/

JINST 13 (2018) no.05, P05001



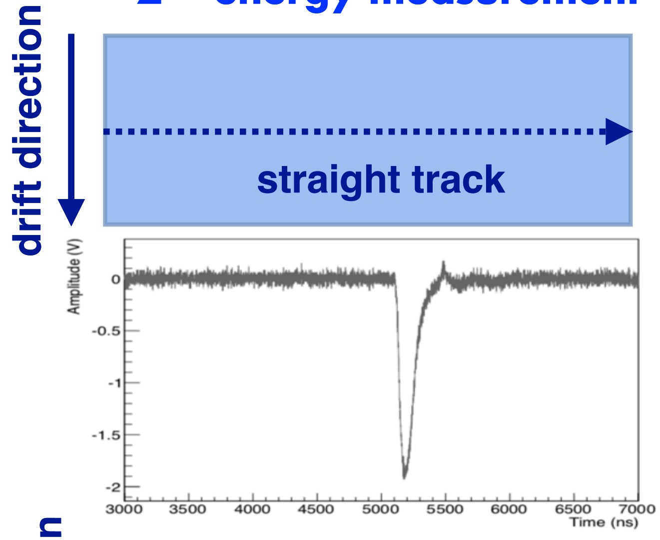
CYGNO :3D TPC with optical readout via PMT + sCMOS

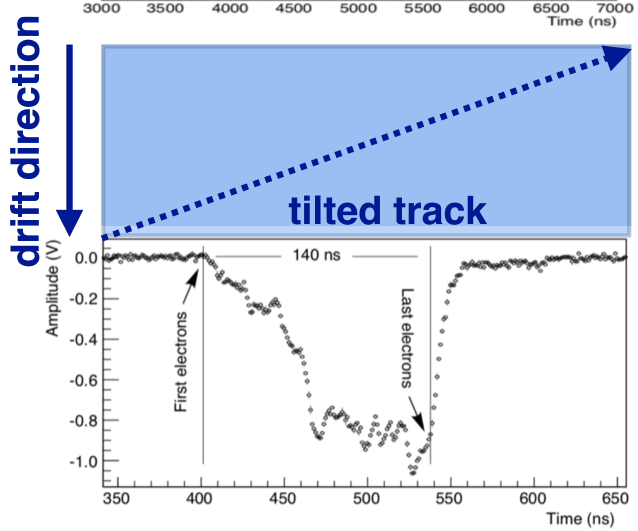
JINST 13 (2018) no.05, P05001



PMT:

integrated
Z + energy measurement



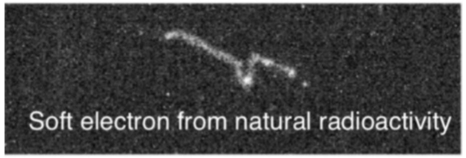


CYGNO :3D TPC with optical readout via PMT + sCMOS

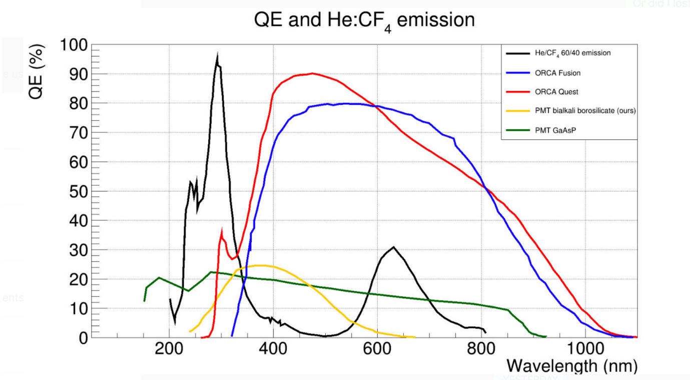
JINST 13 (2018) no.05, P05001

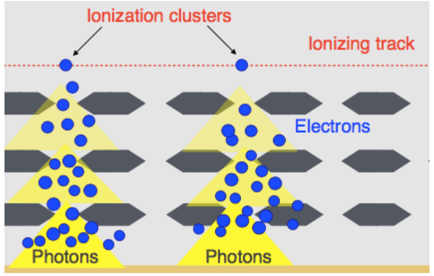
sCMOS:

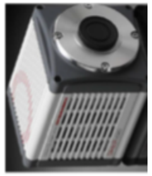
high granularity
X-Y + energy measurements



- **1/3 noise w.r.t. CCDs**
- Market pulled
- Single photon sensitivity
- Decoupled from target
- Large areas with proper optics







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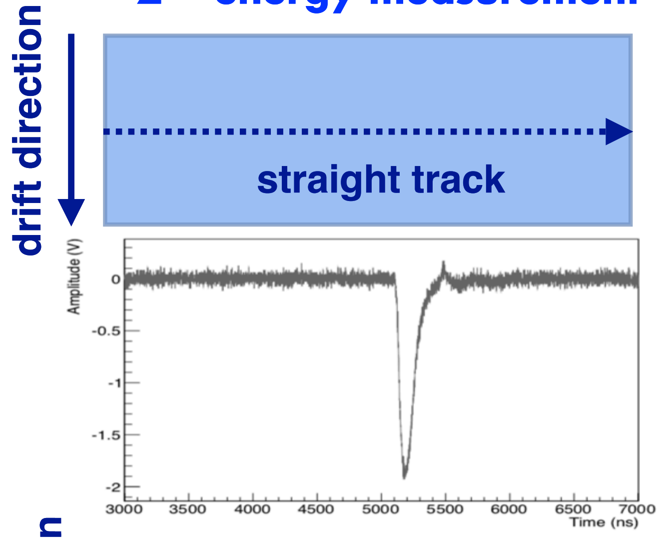
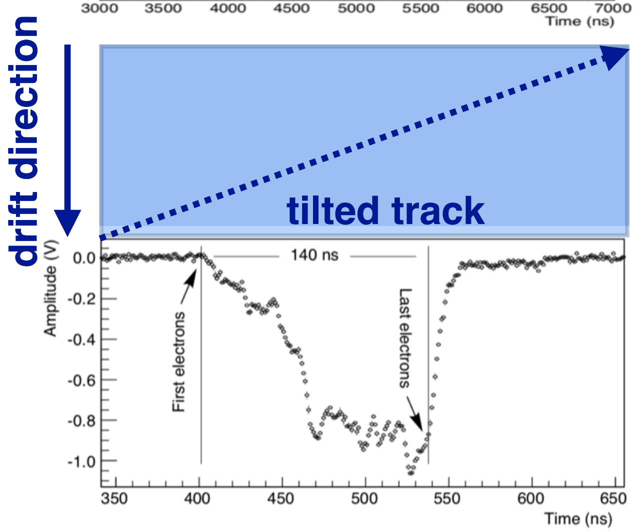




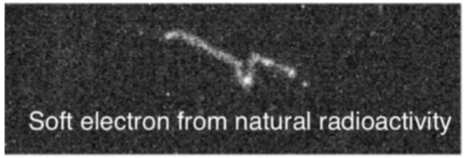
CYGNO :3D TPC with optical readout via PMT + sCMOS

JINST 13 (2018) no.05, P05001

sCMOS:

high granularity

X-Y + energy measurements



- **1/3 noise w.r.t. CCDs**
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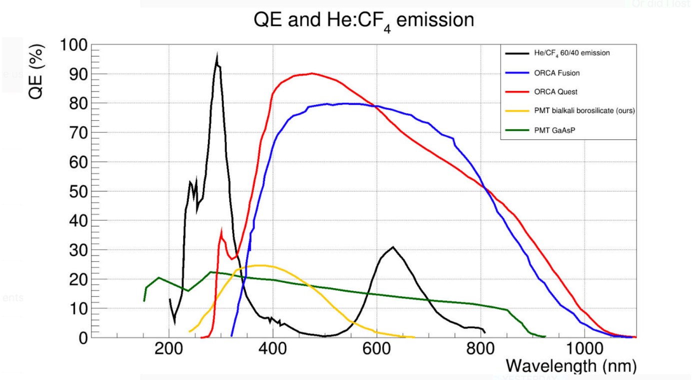
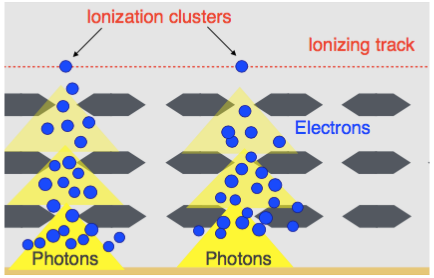
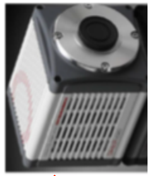
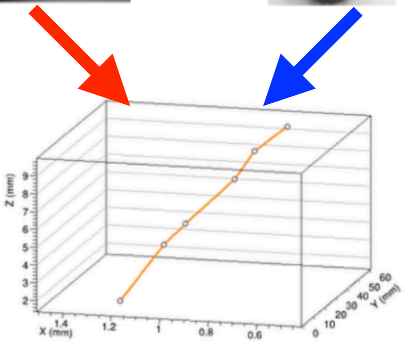
- Single photon sensitivity
- Decoupled from target
- Large areas with proper optics

QE and He:CF_4 emission





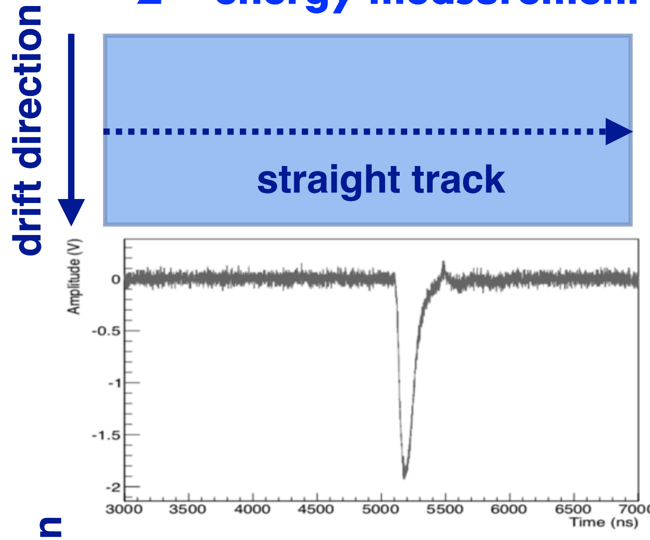


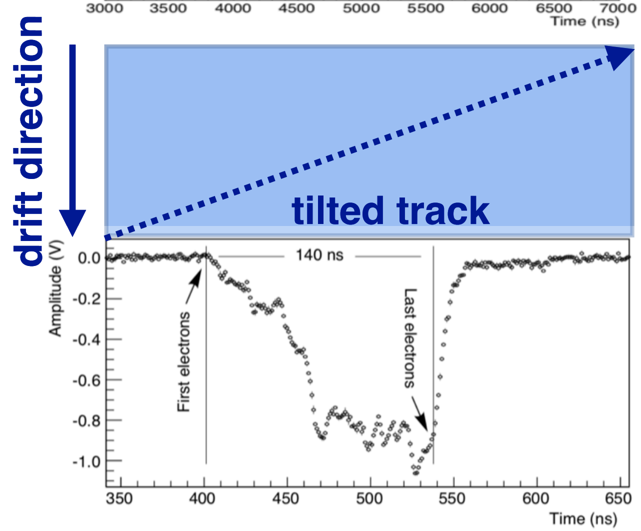


PMT:

integrated

Z + energy measurement





He:CF_4 @ 1 atm

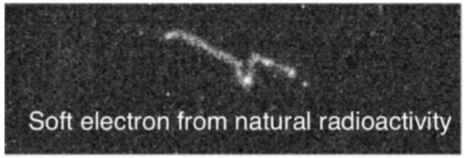
CYGNO :3D TPC with optical readout via PMT + sCMOS

JINST 13 (2018) no.05, P05001

sCMOS:

high granularity

X-Y + energy measurements



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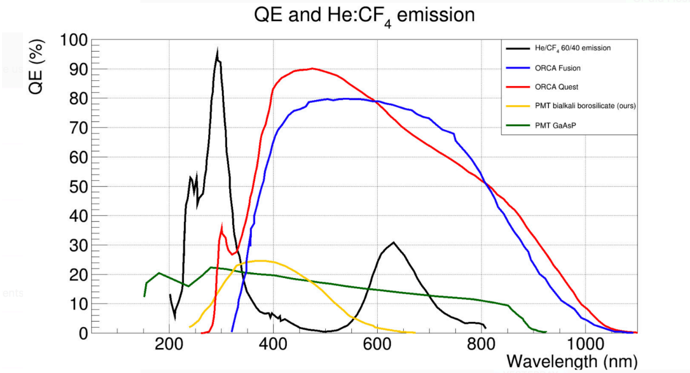
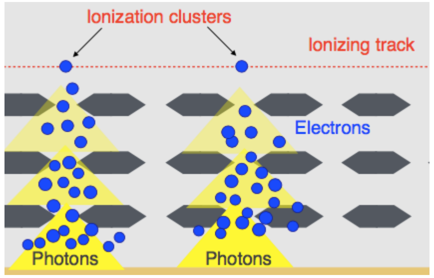
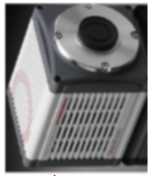
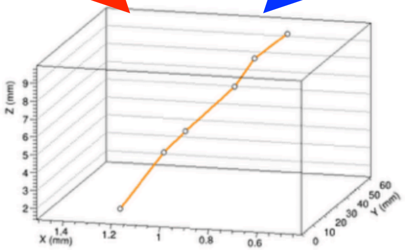








+ SF_6 for negative ion drift

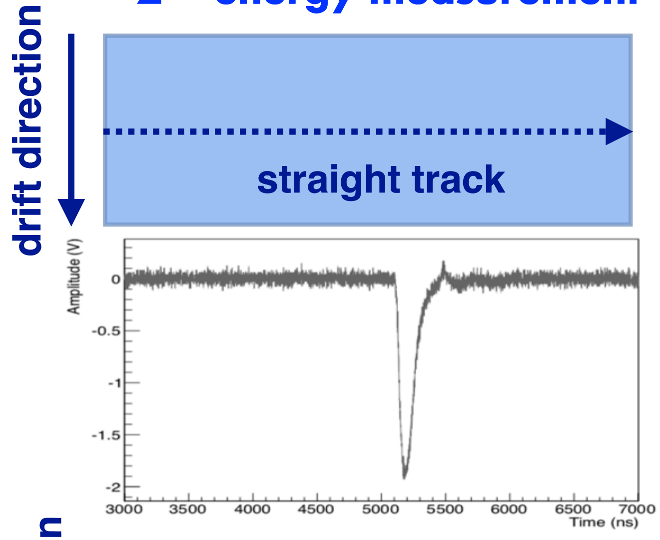
European Research Council

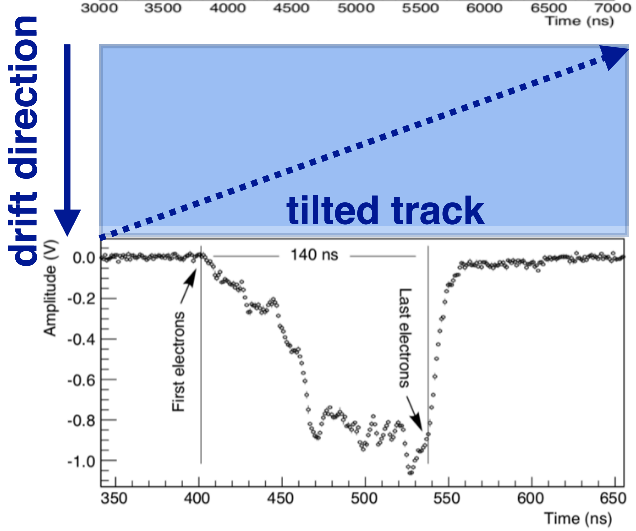
INITIUM

PMT:

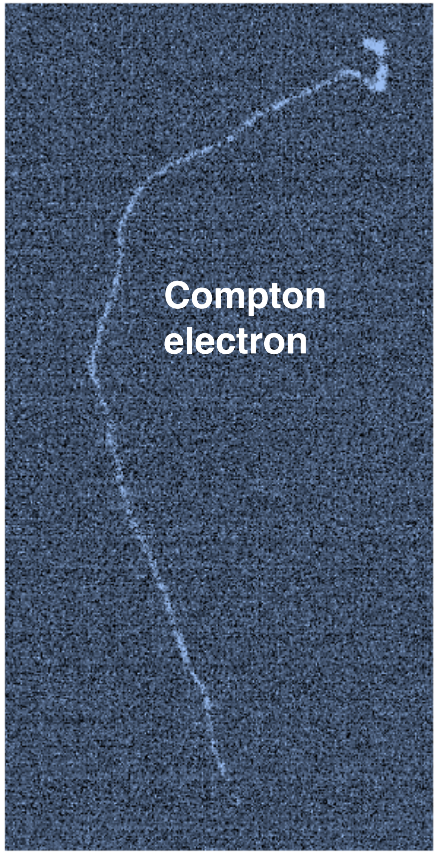
integrated

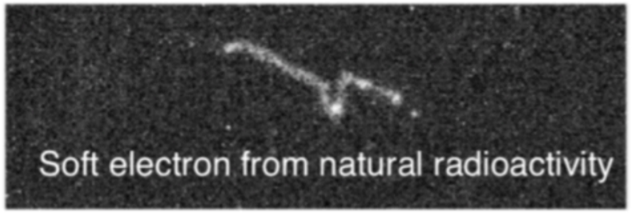
Z + energy measurement

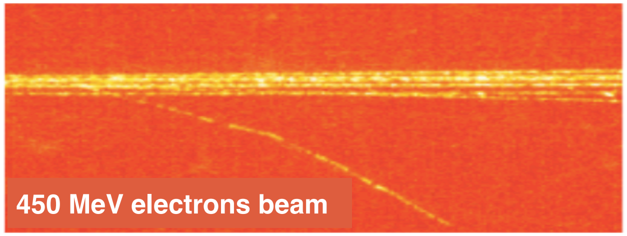


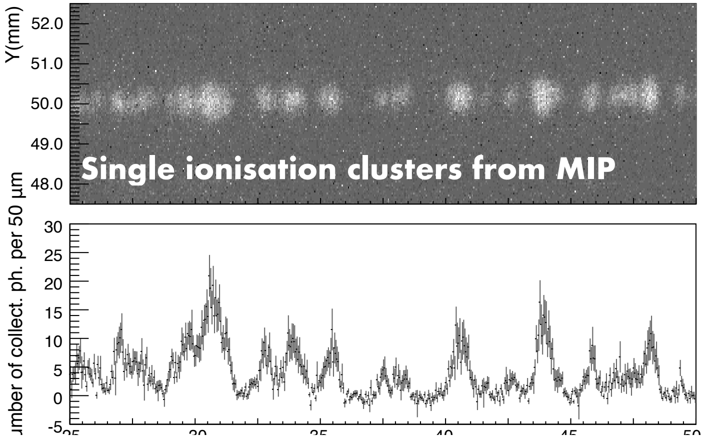


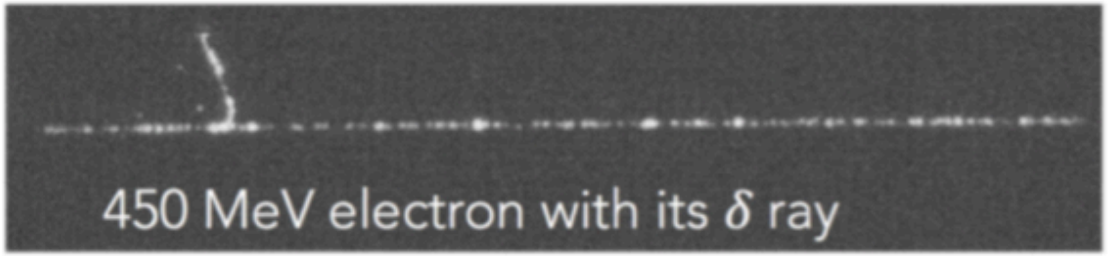
Imaging tracks with CYGNO

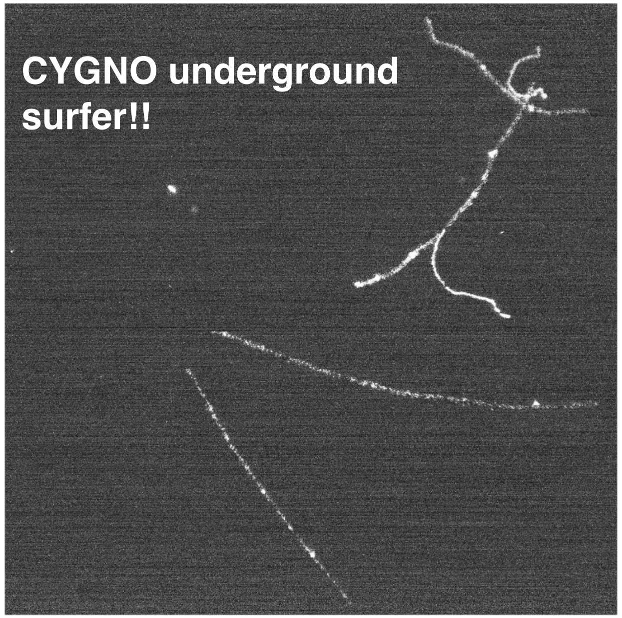


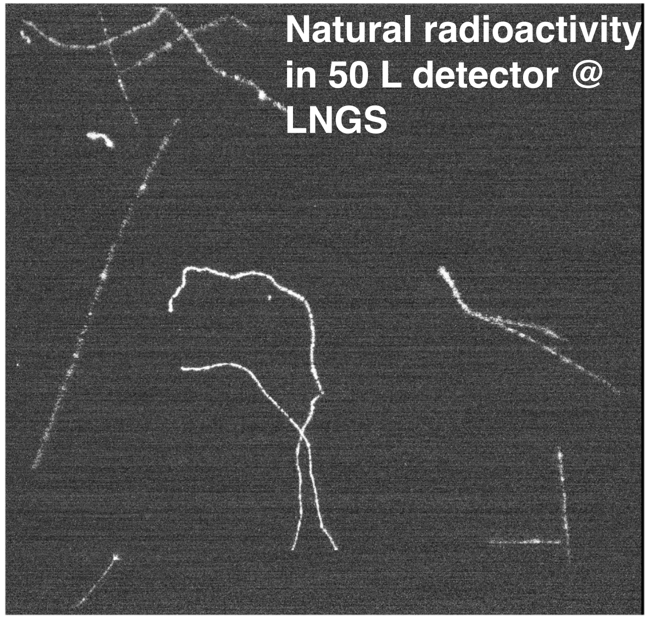




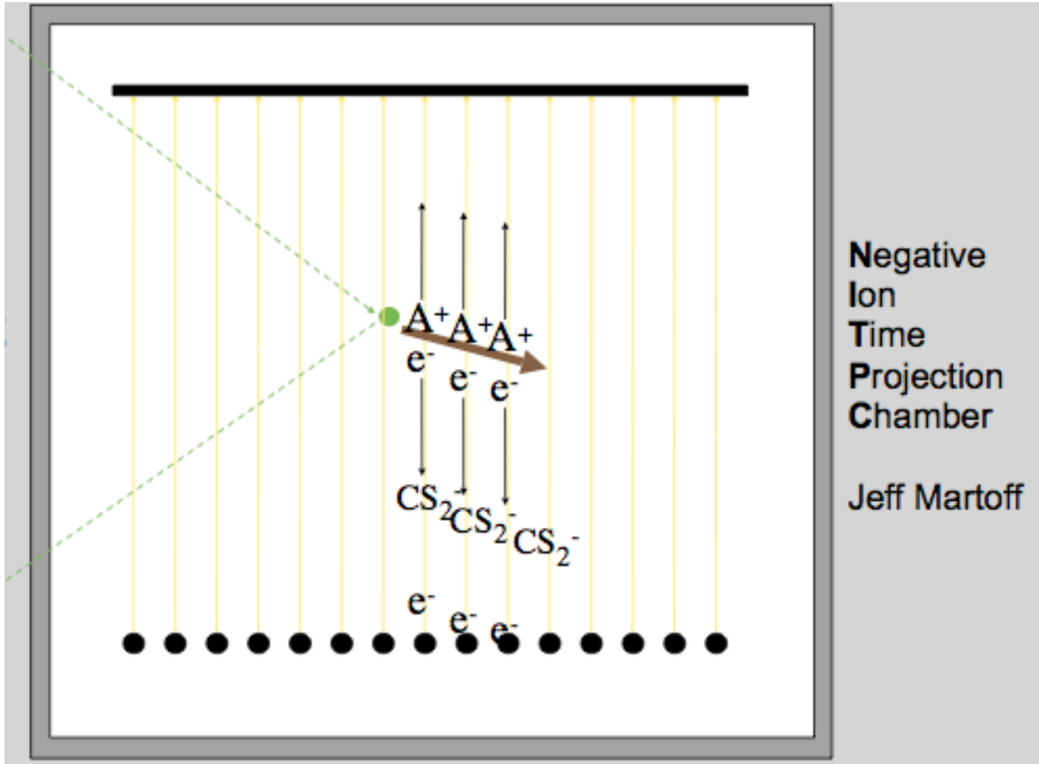








Negative ion drift: reduced diffusion & improved tracking



- Electronegative dopant in the gas mixture (CS_2, CH_3NO_2, ...)
- Primary ionization electrons captured by electronegative gas molecules at O(100) um
- Anions drift to the anode acting as the effective image carrier instead of the electrons
- Longitudinal and transverse diffusion reduced to thermal limit thanks to the large mass of the charge carrier
  - Allow for realisation of larger TPC volume with same (or improved) tracking performance
- Negative ion drift velocity is O(cm/ms), compared to O(cm/us) electon drift velocity because of larger mass
  - Significant improvement of resolution along drift direction thanks to slower image carriers for low rate applications

T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

$$\sigma = \sqrt{\frac{2kTL}{eE}} = 0.7\,\mathrm{mm}\left(\frac{T}{300\,\mathrm{K}}\right)^{1/2}\left(\frac{580\,\mathrm{V/cm}}{E}\right)^{1/2}\left(\frac{L}{50\,\mathrm{cm}}\right)^{1/2}$$

The classical “thermal limit” formula you have always seen……

Which thermal limit?

Diffusion coefficient as from Eq. 2.61 of the Rolandi - Blum - Riegler book

$$\sigma_{tot}^2 = 2Dt$$

$$D = \frac{2}{3}\frac{\varepsilon}{m}\tau.$$

ε energy of the drifting particle

m mass of the drifting particle

τ average time between collisions

Which thermal limit?

Diffusion coefficient as from Eq. 2.61 of the Rolandi - Blum - Riegler book

$$\sigma_{tot}^2 = 2Dt = \frac{2DL}{\mu E}$$

$$D = \frac{2}{3}\frac{\varepsilon}{m}\tau.$$

ε energy of the drifting particle

m mass of the drifting particle

τ average time between collisions

By rewriting this in terms of the electron mobility, Rolandi-Blum obtain the well-know thermal limit for electrons

$$\sigma_{tot}^2 = \frac{2kTL}{eE}$$

Which thermal limit?

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$$\sigma_{tot}^2 = \frac{2kTL}{eE}$$

....but electrons and ions mobility differ due to the larger mass and the more efficient energy exchange during collisions of the second:

electron mobility

$$\mu_e = \frac{e}{m_e}\tau$$

electron mass

$$\mu_i = e\tau\left(\frac{1}{m_i} + \frac{1}{m_g}\right)$$

ion mobility

ion mass

gas molecule mass

Which thermal limit?

Diffusion coefficient as from Eq. 2.61 of the Rolandi - Blum - Riegler book

$$\sigma_{tot}^2 = 2Dt = \frac{2DL}{\mu E}$$

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By rewriting this in terms of the electron mobility, Rolandi-Blum obtain the well-know thermal limit for electrons

$$\sigma_{tot}^2 = \frac{2kTL}{eE}$$

IONS THERMAL LIMIT IS DIFFERENT FROM ELECTRONS THERMAL LIMIT!

....but electrons and ions mobility differ due to the larger mass and the more efficient energy exchange during collisions of the second:

electron mobility

$$\mu_e = \frac{e}{m_e}\tau$$

electron mass

$$\mu_i = e\tau\left(\frac{1}{m_i} + \frac{1}{m_g}\right)$$

ion mobility

ion mass

gas molecule mass

Generalization of thermal limit

$$y = \frac{m_p}{m_t}$$

mass of the drifting particle

mass of the gas molecule

$$y \rightarrow 0$$

for electrons

Generalized drift velocity

$$u = \frac{eE}{m_p}\tau(1 + \frac{m_p}{m_t}) = \frac{eE}{m_p}\tau(1+y)$$

Generalized mobility

$$\mu_p = \frac{e}{m_p}\tau(1+y)$$

Generalization of thermal limit

$$y = \frac{m_p}{m_t}$$

mass of the drifting particle

mass of the gas molecule

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Generalized drift velocity

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Generalized mobility

$$\mu_p = \frac{e}{m_p}\tau(1+y)$$

Generalized diffusion for monoatomic gases

$$\sigma_{tot}^2 = \frac{2kTL}{eE}\frac{1}{1+y}$$

Generalization of thermal limit

$y = \frac{m_p}{m_t}$ mass of the drifting particle / mass of the gas molecule

$y \to 0$ for electrons

Generalized drift velocity

$$u = \frac{eE}{m_p}\tau(1 + \frac{m_p}{m_t}) = \frac{eE}{m_p}\tau(1 + y)$$

Generalized mobility

$$\mu_p = \frac{e}{m_p}\tau(1 + y)$$

Generalized diffusion for monoatomic gases

$$\sigma^2_{tot} = \frac{2kTL}{eE}\frac{1}{1 + y}$$

Generalized diffusion for gas mixtures

$$\sigma^2_{tot} = \frac{2kTL}{eE}\frac{\sum_t^{gas} \kappa_t \frac{\rho_t}{A_t} k_t (R_t + R_p)^2}{\sum_t^{gas} \frac{\rho_t}{A_t} k_t (R_t + R_p)^2}$$

Fractional momentum loss between the drifting particle *p* and the gas species *t*

$$\kappa_t = \frac{1}{1 + y_t} = \frac{1}{1 + \frac{m_p}{m_t}}$$

with R_t and R_p being the radius of the gas specie t and the travelling particle p respectively, ρ_t is the relative density and A_t the molar mass of the specie t, and k_t its percentage in the gas mixture.

Ionic and electronic thermal limits

NID thermal limit differs from electron thermal limit and depends on the gas mixture

$$\sigma^2_{tot} = \sigma^2_T L = \begin{cases} \frac{2kTL}{eE} & \text{for electrons} \\ \frac{2kTL}{eE}\frac{1}{2} & \text{for ions in mono} - \text{specie gases} \\ \frac{2kTL}{eE} * 0.25244 & \end{cases}$$

i.e. pure SF_6

For the gas mixture used in this study

the larger the ratio between the drifting ion and the gas mixture molecules, the smaller the thermal limit

….not all NID are the same ;)

Negative ion drift: history and status

Charge Readout | **Optical Readout**

Low pressure

- Concept demonstratred in 2000 at 40 Torr CS_2 with MWPC [1]
- Pioneered in a actual experiment by DRIFT with $CS_2:CF_4:O_2$ at 40 Torr with MWPC [2]
- 20-40 Torr pure SF_6 in 2017 with THGEM [3]
- 20 Torr pure SF_6 with THGEM-multiwire [4] and muPIC in 2020 [5] *See also S. Hishino talk @ 12.30*

Optical readout:

- 50-150 Torr $CF_4:CS_2$ with glass GEM and CMOS [D. Loomba, talk at RD51 June 2022 meeting]

(nearly) Atm pressure

- Demonstrated in 2010's in $He:CS_2$[6] and $CO_2:Ne:CH_3NO_2$[7] with GEMs and MWPC
- In 2017 at 610 Torr of $He:CF_4:SF_6$ with GEMs and TimePix2 [8]
- In 2021 in $Ar:iC_4H_{10}:CS_2$ with GridPix (Ingrid + Timepix3) [9] *See also J. Kaminsky talk on Tue*

Optical readout:

THIS TALK

[1] C. J. Martoff et al. NIM A 440 335
[2] G. J. Alner et al., NIM A 535
[3] N. S. Phan et al, *JINST* 12 (2017) 02, 02
[4] A. C. Ezeribe NIM A 987
[5] T. Ikeda et al, *JINST* 15 07, P07015
[6] C. J. Martoff et al, NIM A 555
[7] C. J. Martoff et al, NIM A 598
[8] E. Baracchini et al, *JINST* 13 04, P04022
[9]C. Ligtenberg et al, NIM A 1014 165706

*Detector operated at LNGS (1100 m): atm pressure is 900 mbar

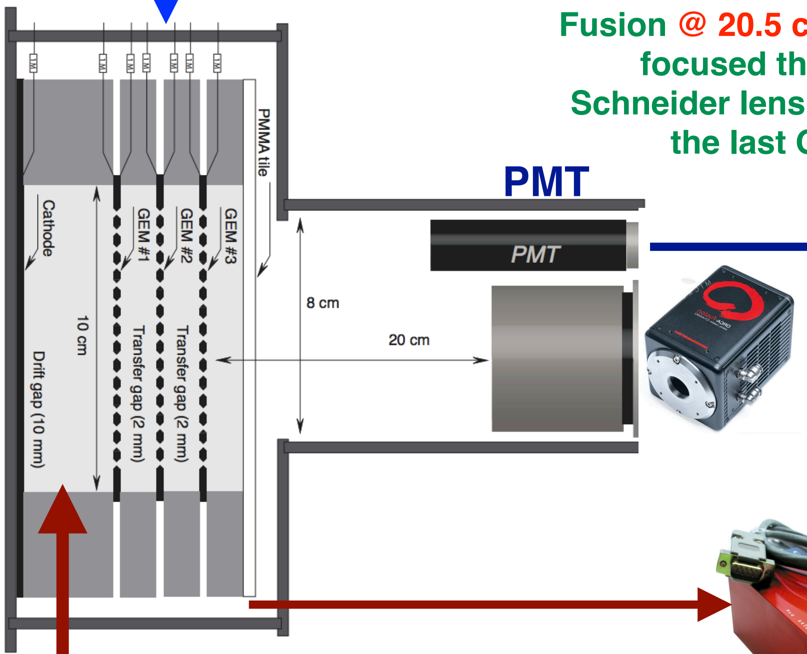
The MANGO detector

Triple thin 50 um GEM stack 10 x 10 cm^2

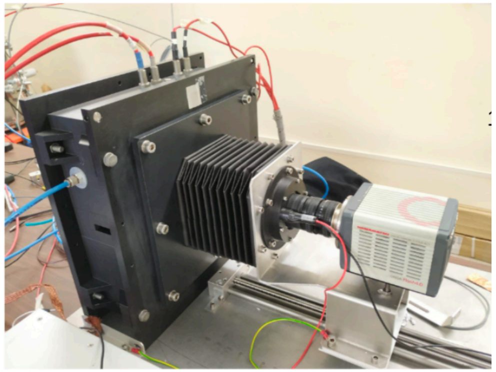
Acquired with Hokawo 3.0 software

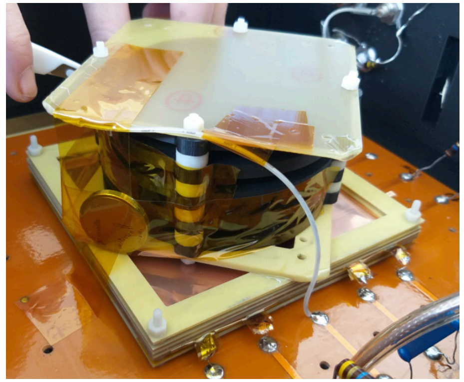
sCMOS camera Orca Fusion @ 20.5 cm distance focused through Schneider lens (f/0.95) on the last GEM

PMT

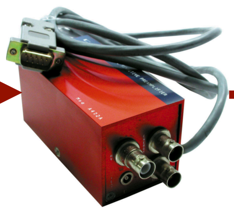


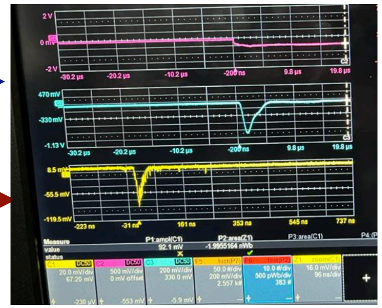
5 cm drift gap setup inside plastic gas-tight box





Acquire sCMOS images, PMT & GEM waveforms with ^{241}Am source



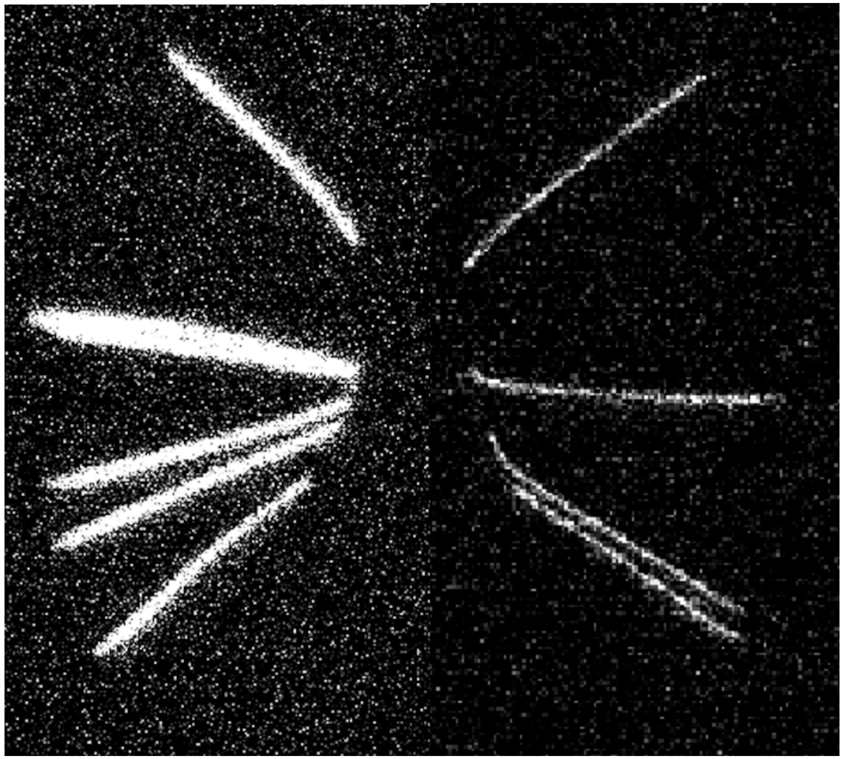


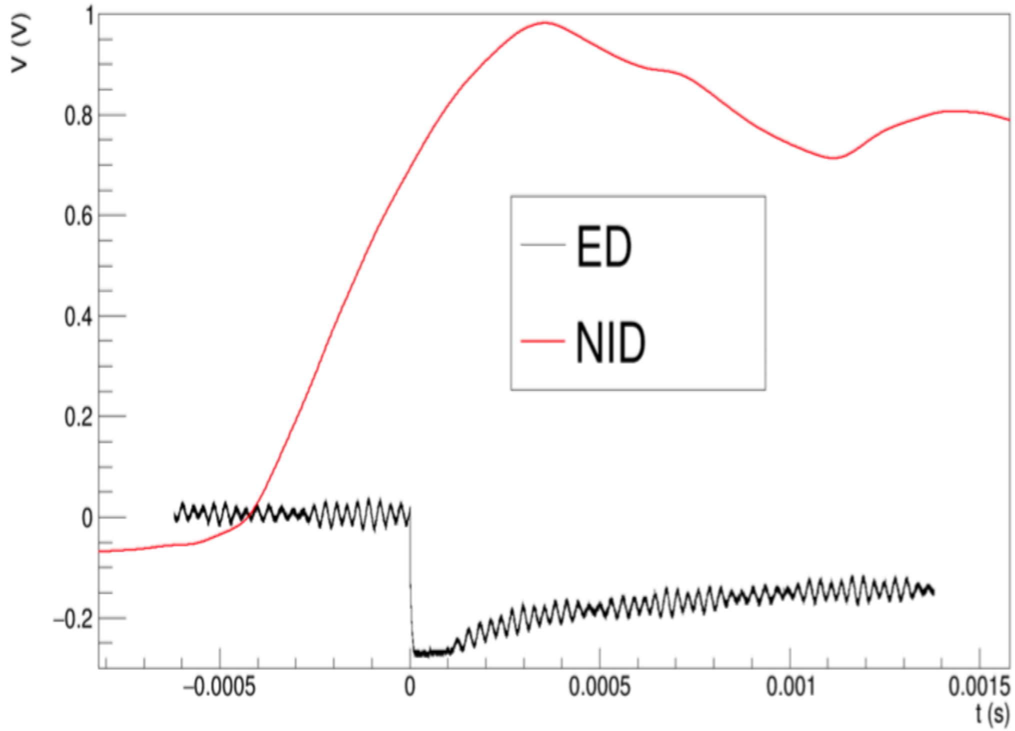
Drift gap (variable from 5 to 15 cm)

Charge sensitive preamplifier
300 us decay time
0.113 mV/fC

Oscilloscope

Eyes (and waveforms) can't lie





He:CF_4
60:40
1 kV/cm
(ED)

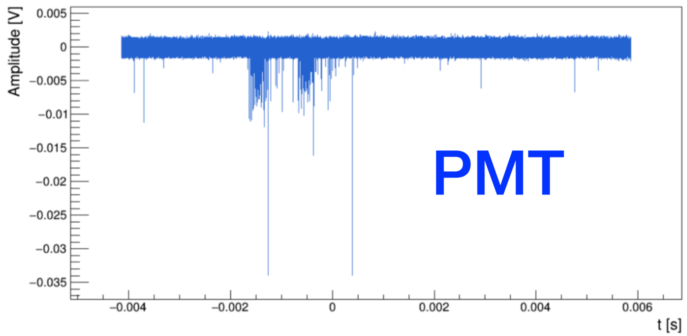
He:CF_4:SF_6
59:39.4:1.6
0.4 kV/cm
(NID)

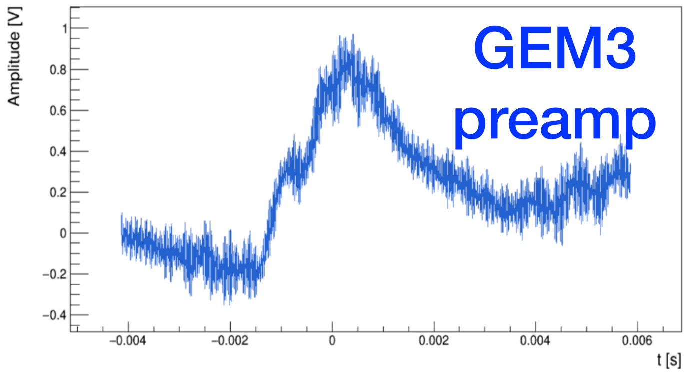
GEM preamp output
O(us) rise for ED
O(ms) rise for NID

0.90 atm
(LNGS atmospheric pressure)

*First time NID are observed with PMTs!

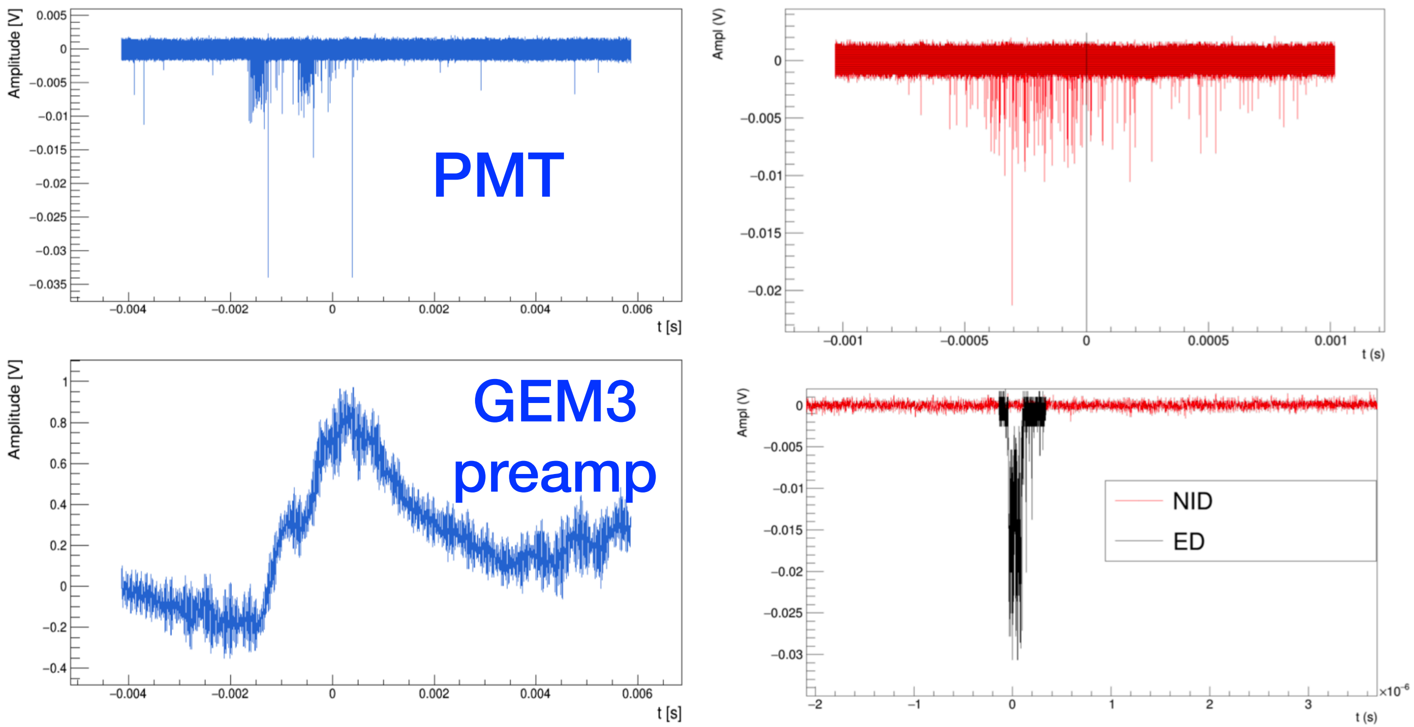
PMT waveforms: how peculiar!





*First time NID are observed with PMTs!

PMT waveforms: how peculiar!



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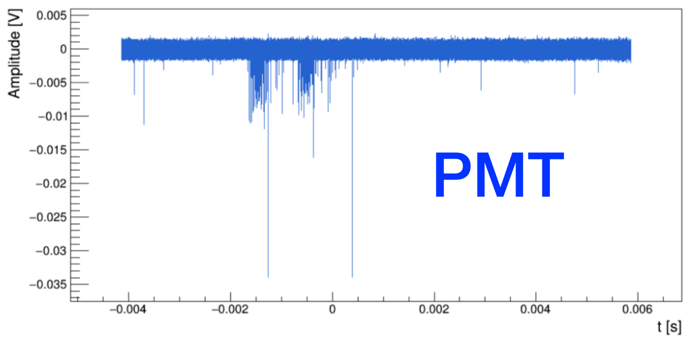

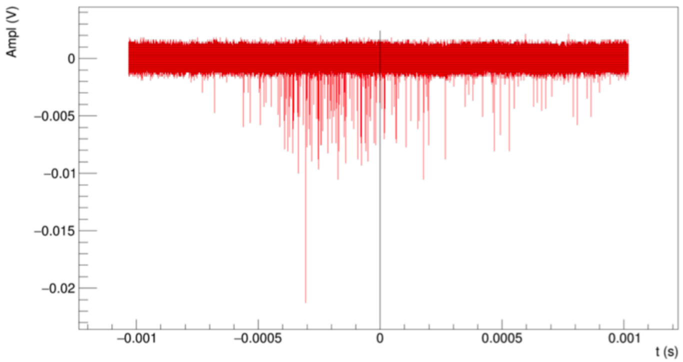

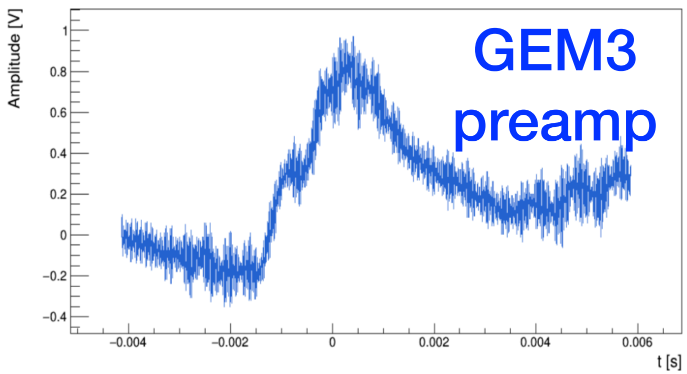

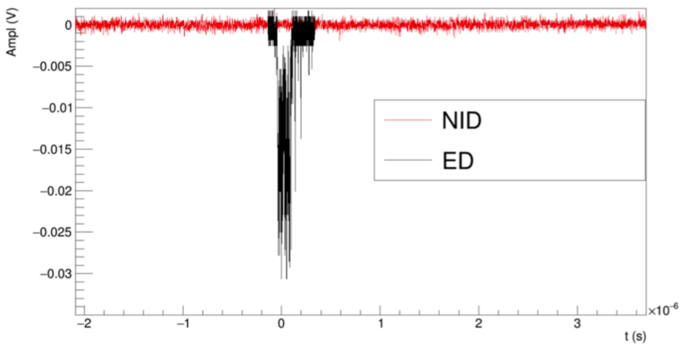

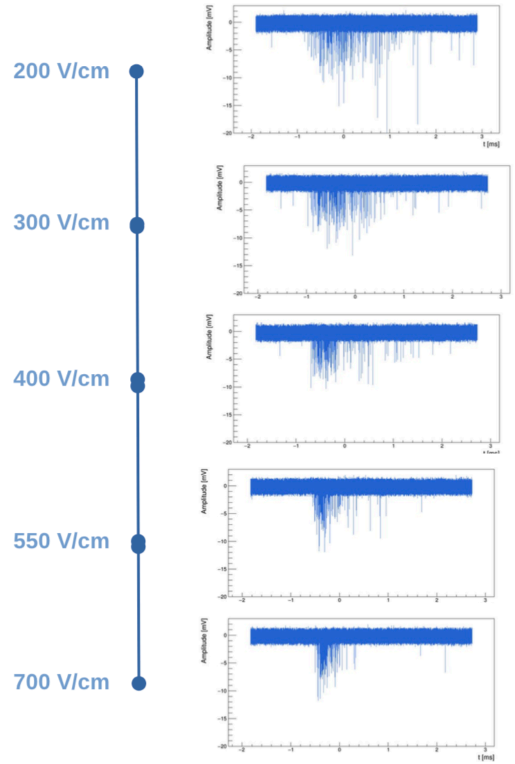

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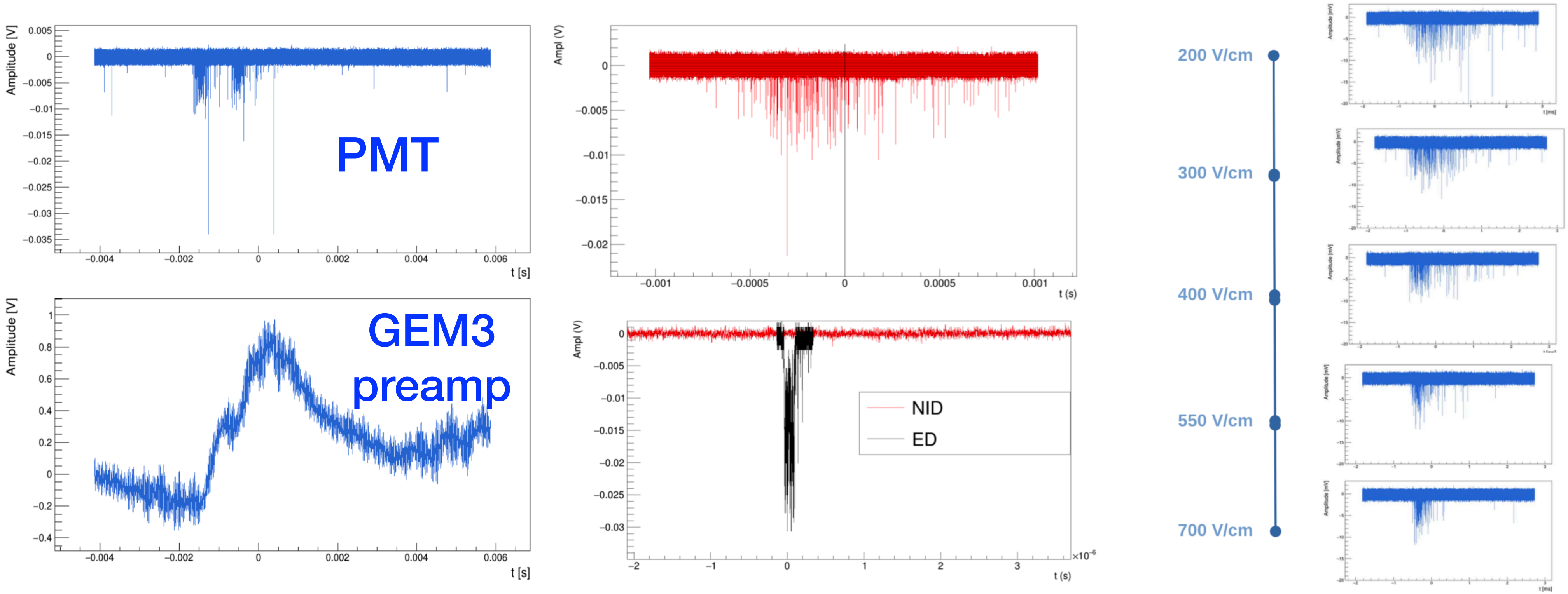
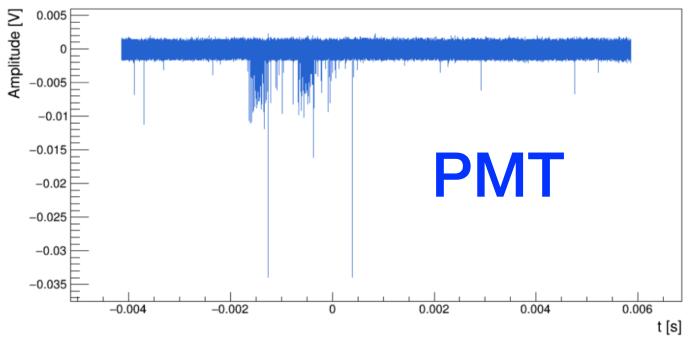
PMT waveforms: how peculiar!

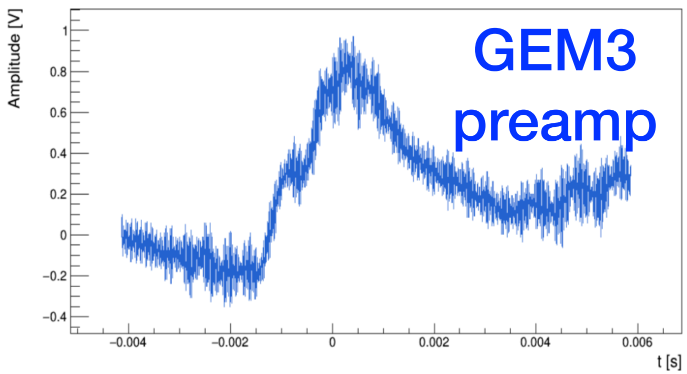


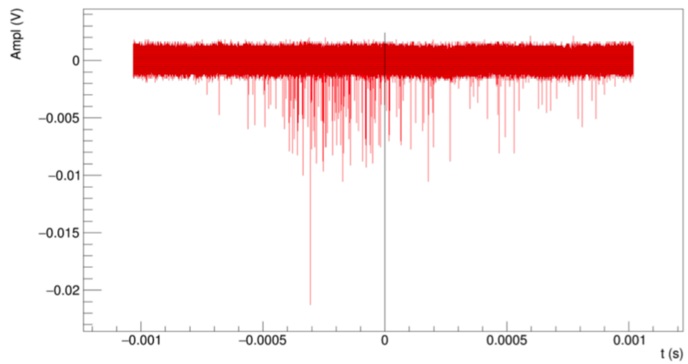
Given the PMT bandwidth and the "slow" arrival of charge carriers, individual clusters are visible in the PMT signal --> WF analysis requires proper rebinning (not trivial)

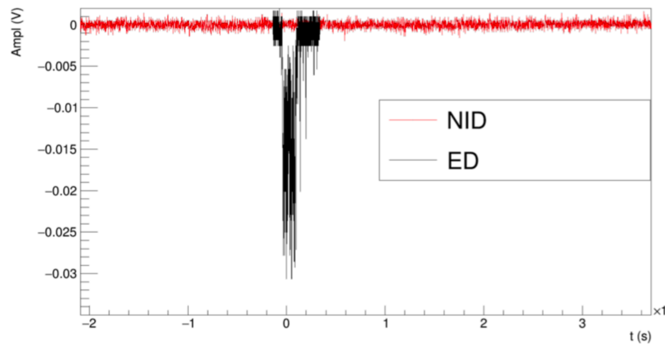
*First time NID are observed with PMTs!

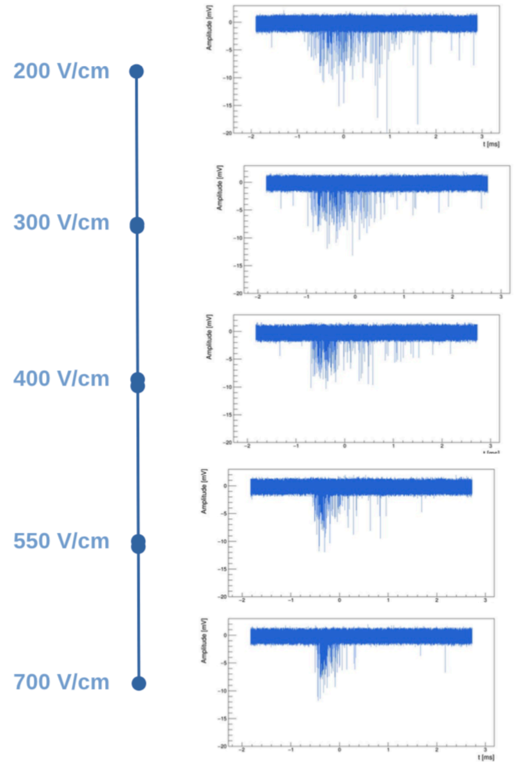
PMT waveforms: how peculiar!



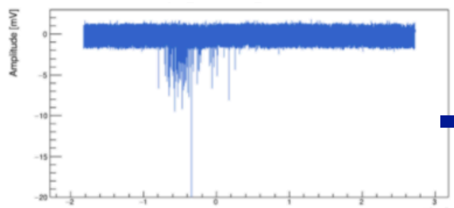




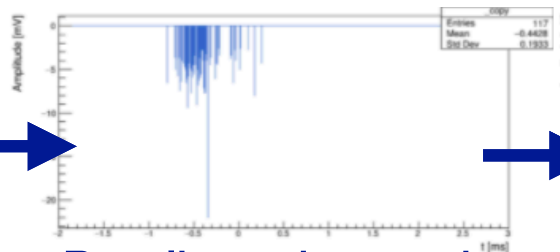




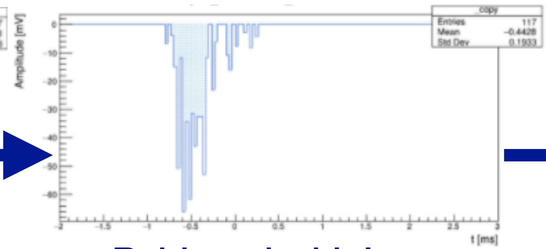
Given the PMT bandwidth and the "slow" arrival of charge carriers, individual clusters are visible in the PMT signal --> WF analysis requires proper rebinning (not trivial)



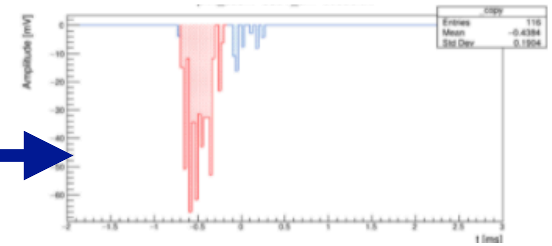
Raw WF



Baseline subtracted

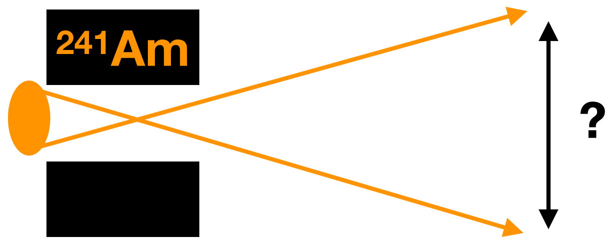


Rebinned with loose constraints



Rebinned with only over threshold peaks considered

NID drift velocity and mobility from WF analysis

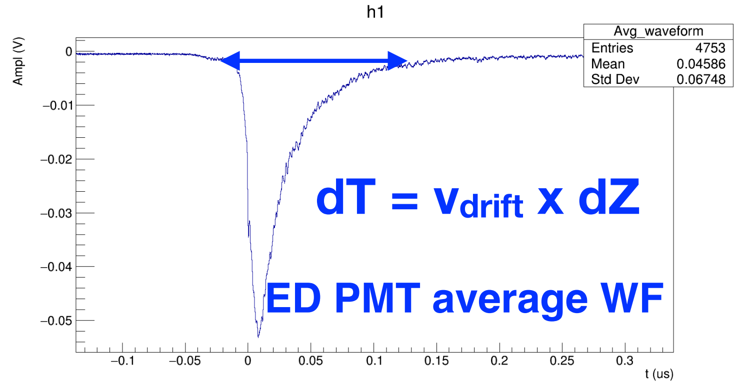


Field cage rings

From ED PMT signal, given the known drift velocity, we estimate the alpha dZ spread (? == 7 mm)

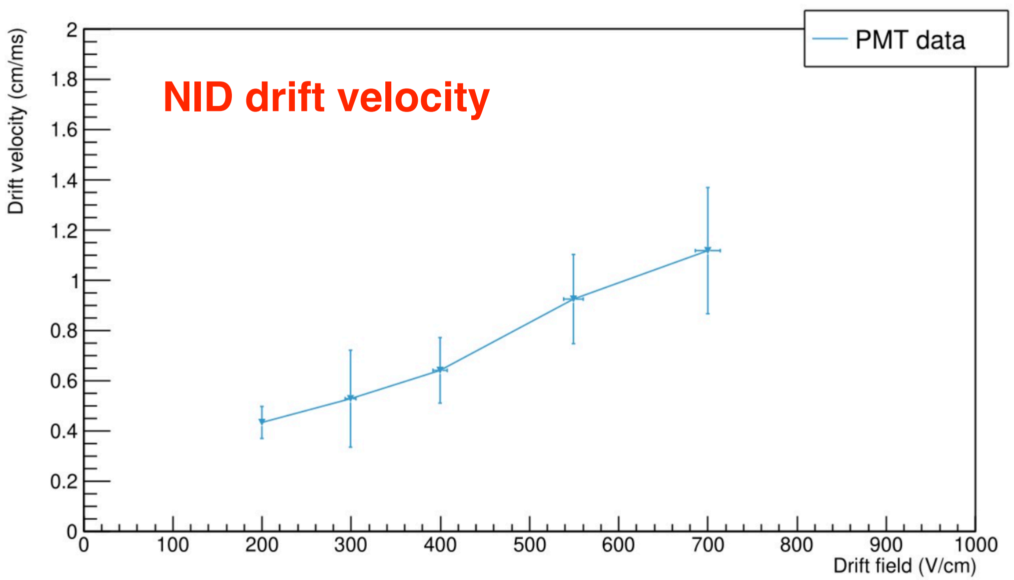
0.90 atm

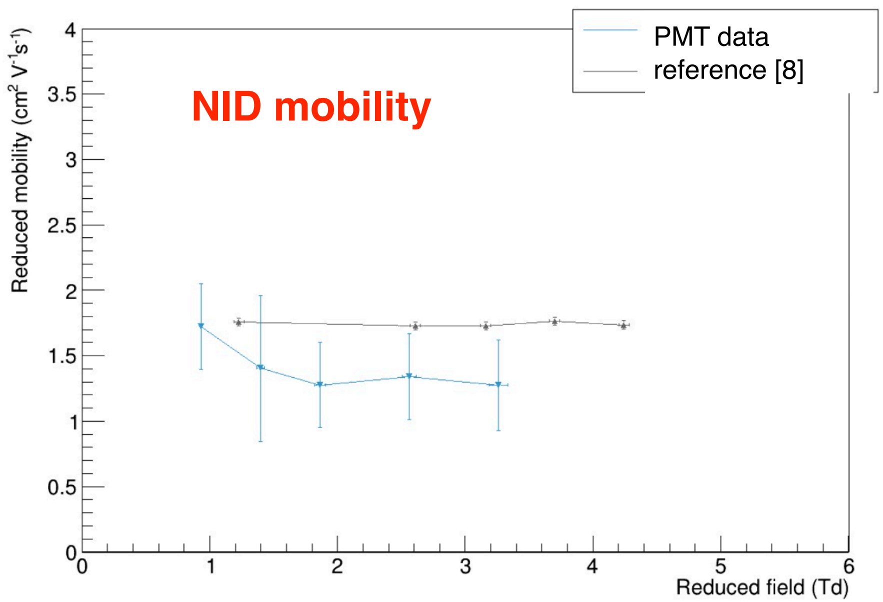
(LNGS atm pressure)



Given the alpha dZ spread estimated from ED (7 mm), estimate NID drift velocity:

- From GEM preamp output rise time
- From PMT waveforms time window extension, after proper WF rebinning

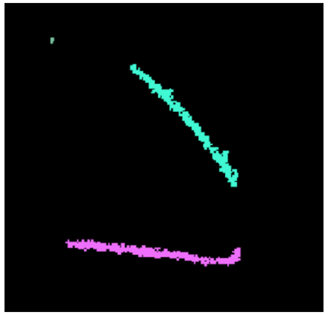


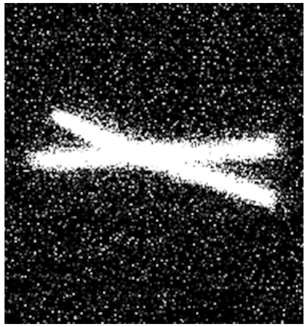


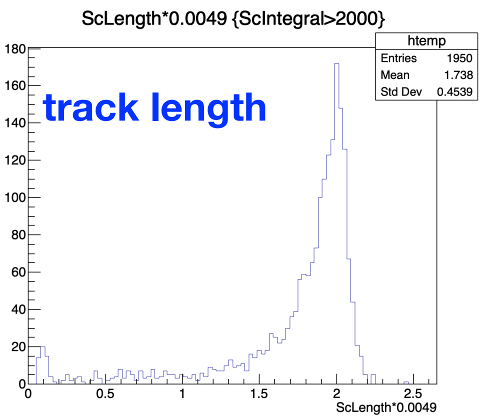
Black points from published data with charge readout and same mixture at 610 Torr [8]

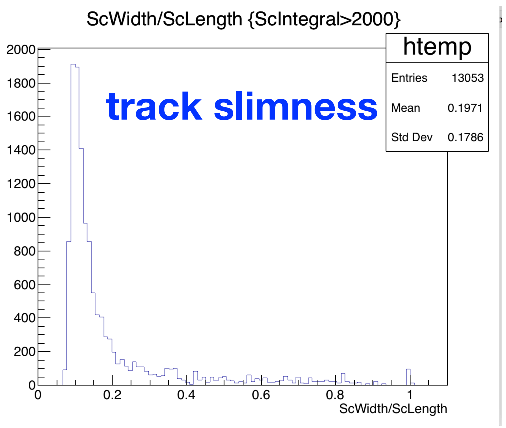
sCMOS images analysis

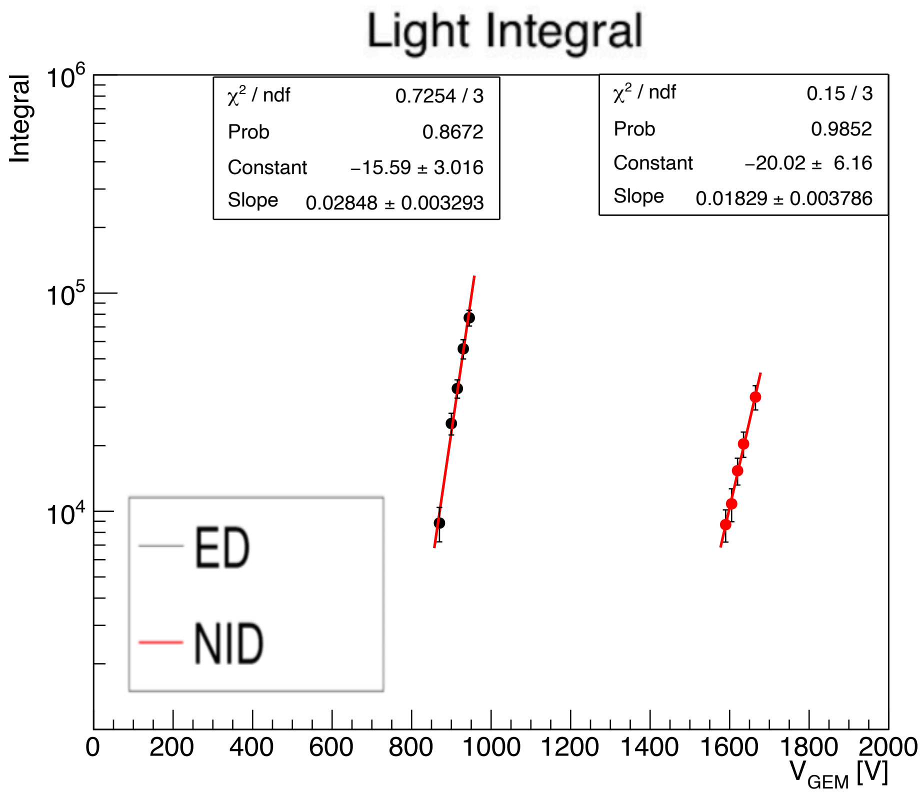
- Alphas selection:
  - tracks reconstructed with iterative DBSCAN algorithm [10]
  - track length > 1.47 cm
  - track slimness < 0.3
- Sum of pixel content is light integral











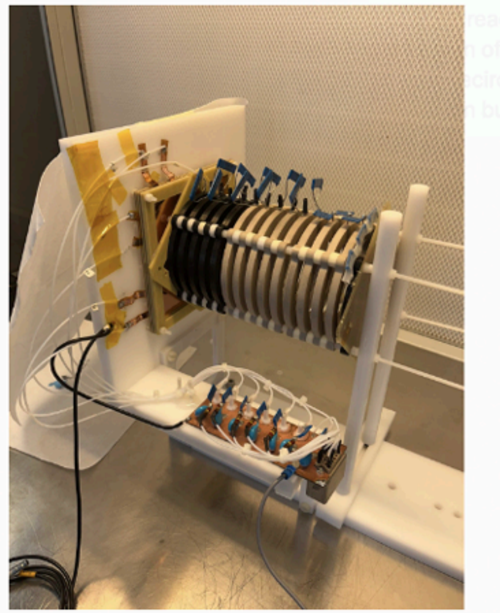
Assuming SF_6 does not absorb light and that light production mechanism stays the same with NID, extrapolating from previous CYGNO measurement ED & NID gain is ~1-3 10^4

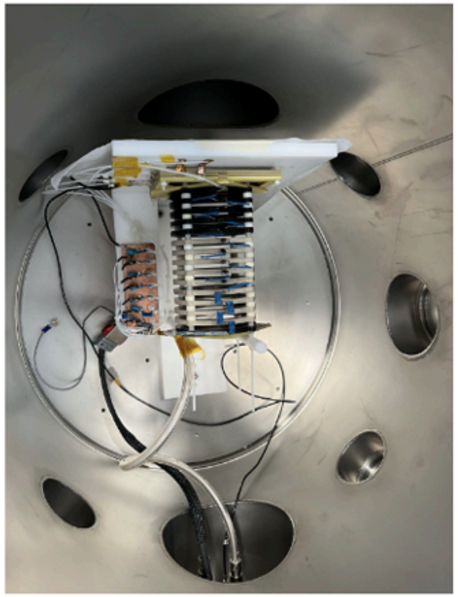
(rough evaluation)

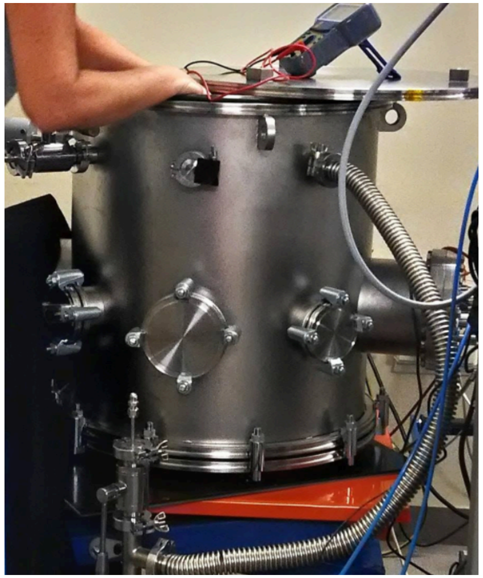
[10] E. Baracchini et al, JINST 15 (2020) 12 T12003

A MANGO "in the keg"

Longer drift distance is necessary to measure diffusion: MANGO was installed in a vacuum vessel that could host a longer field cage



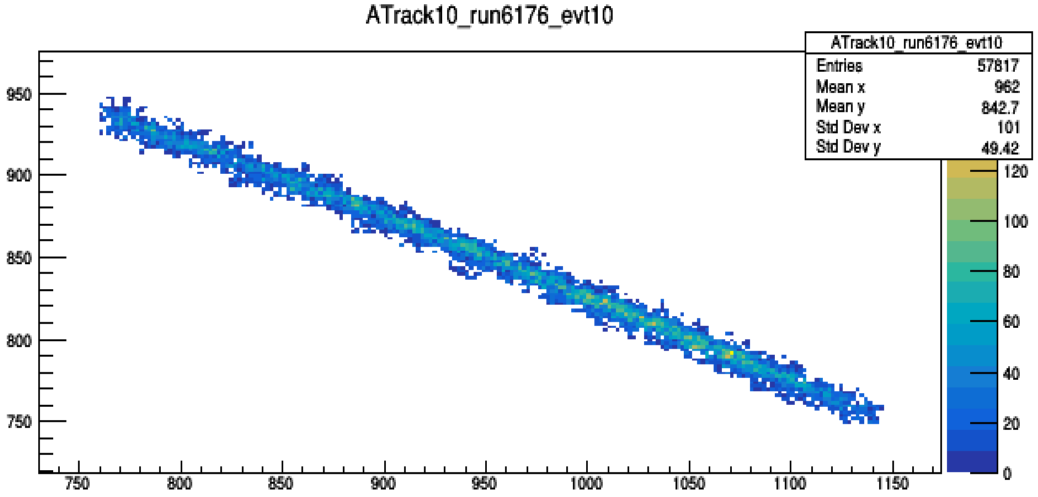


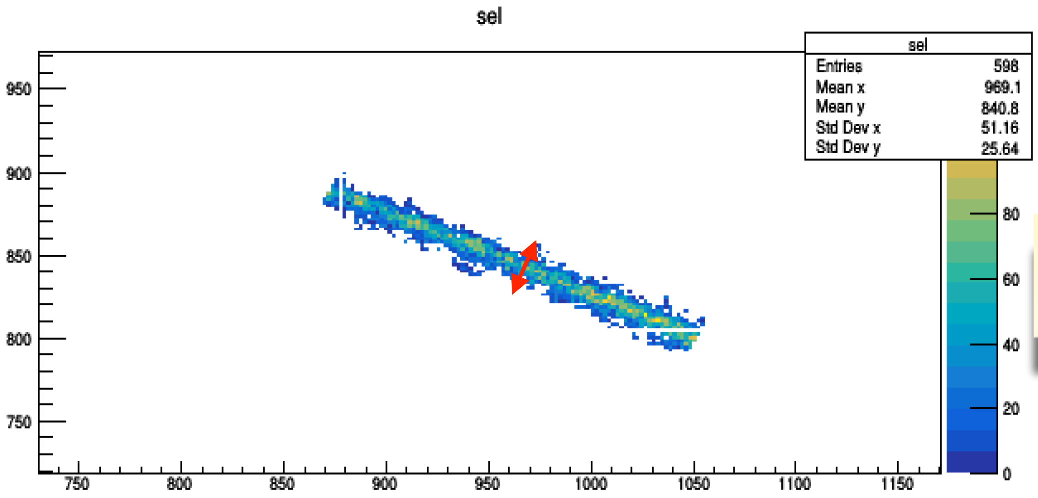


Because of geometry constraints, the camera is now at 26.6 cm distance (w.r.t. 20.5 cm of the previous setup): the light yield reaching the camera sensor is reduced of 2/3 with respect to previous configuration

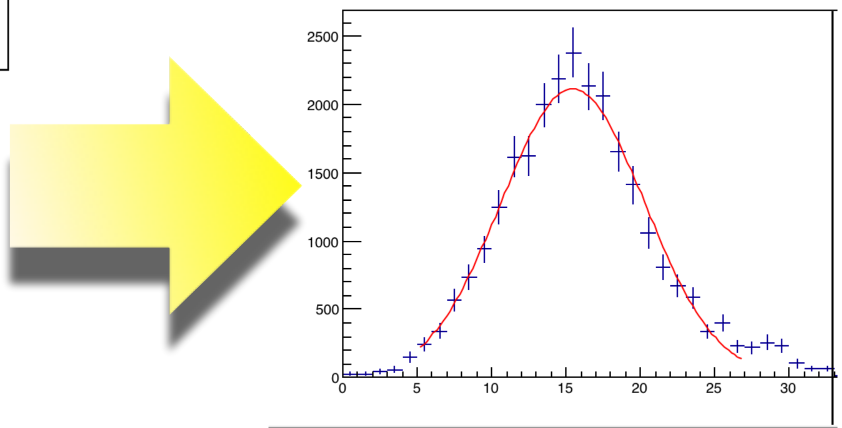
For this reason and in order to be able to measure the diffusion at ~15 cm drift length and low ~150 V/cm drift fields, we reduced the pressure to 650 mbar in the diffusion measurements

sCMOS images analysis for diffusion measurement





- Track selection
  - tracks reconstructed with iterative DBSCAN algorithm [10]
  - track length > 1.47 cm
  - track slimness < 0.3
  - # of peaks in the transverse profile == 1 (select single tracks)
  - Chi2/nDOF of transverse fit profile < 5 (remove additional multiple tracks)

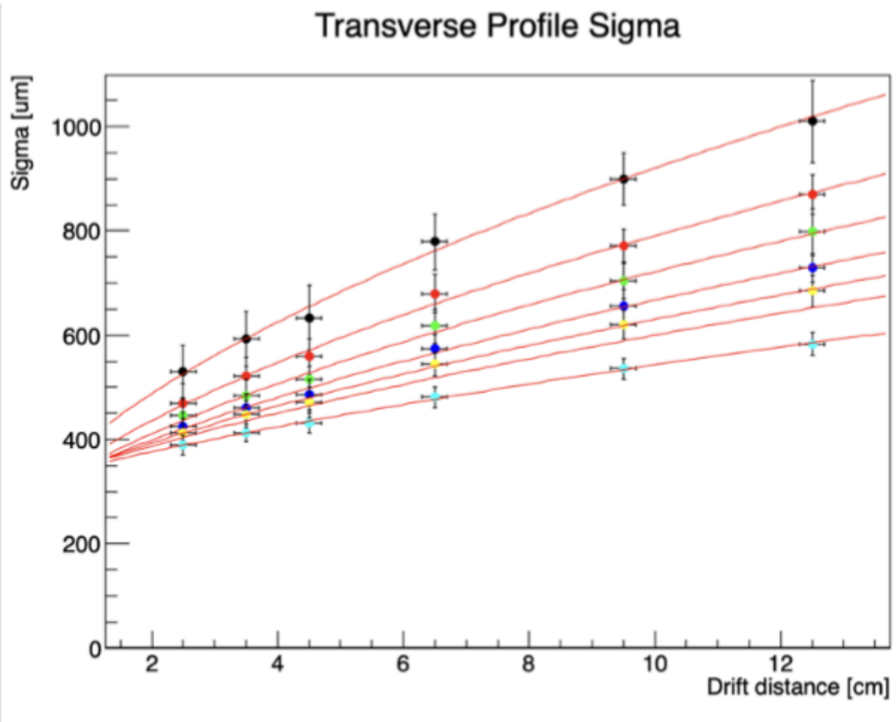


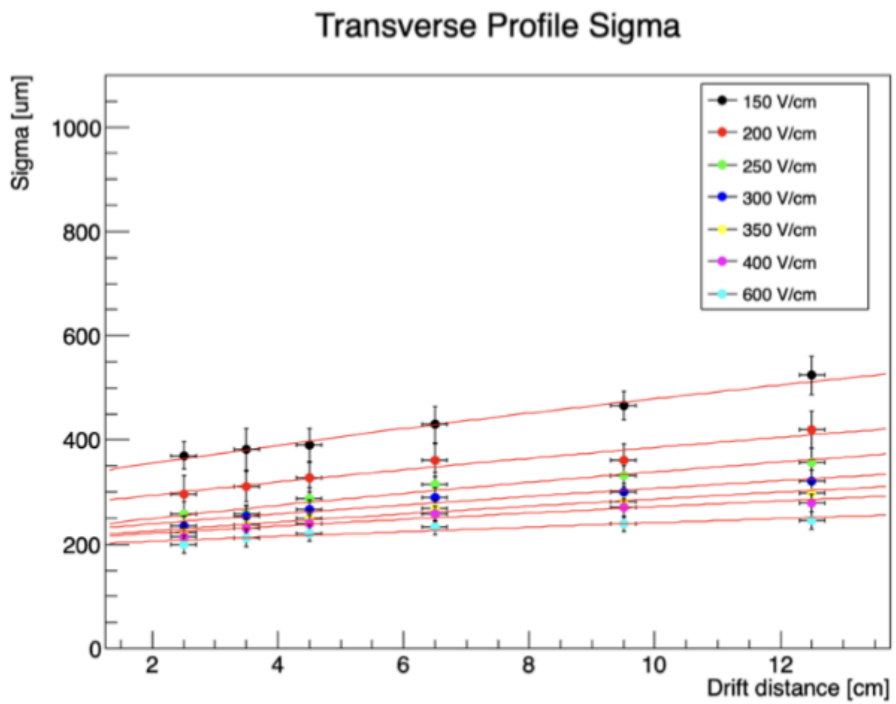
Sigma of track profile and track integral fitted with Gaussian to estimate diffusion and light yield

ED & NID diffusion

$He:CF_4$ 60:40 (ED)

$He:CF_4:SF_6$ 59:39.4:1.6 (NID)

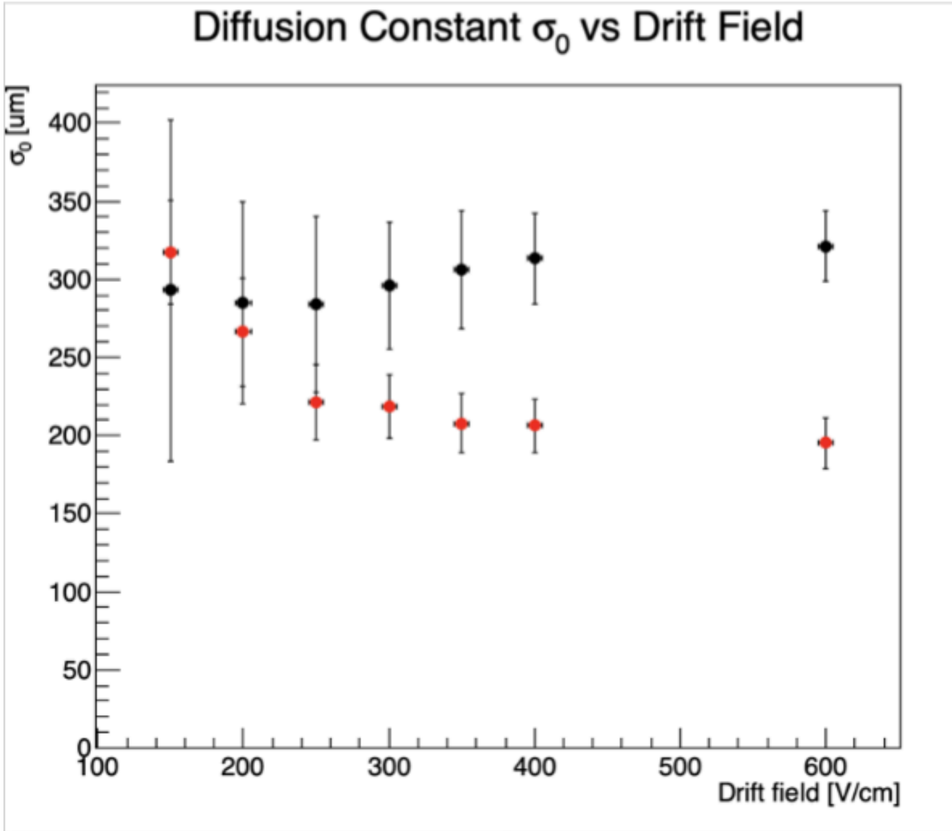


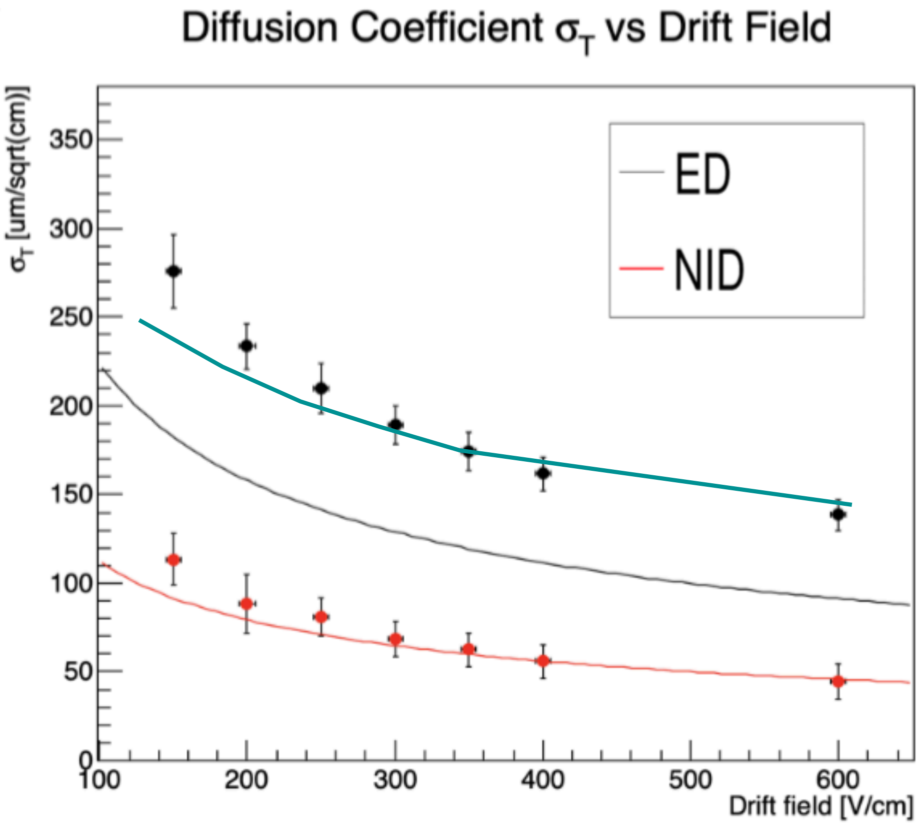


$$\sigma_{meas} = \sqrt{\sigma_0^2 + \sigma_T^2 L}$$

Drift field [V/cm]	σ_0^{ED} [um]	σ_T^{ED} [um/$\sqrt{cm}$]	σ_0^{NID} [um]	σ_T^{NID} [um/$\sqrt{cm}$]
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

Diffusion constant & coefficient vs drift field





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

Garfield simulation of He:CF$_4$ 60:40 @ 650 mbar

Electron thermal limit $\sigma_T^2 L = \frac{2kTL}{eE}$

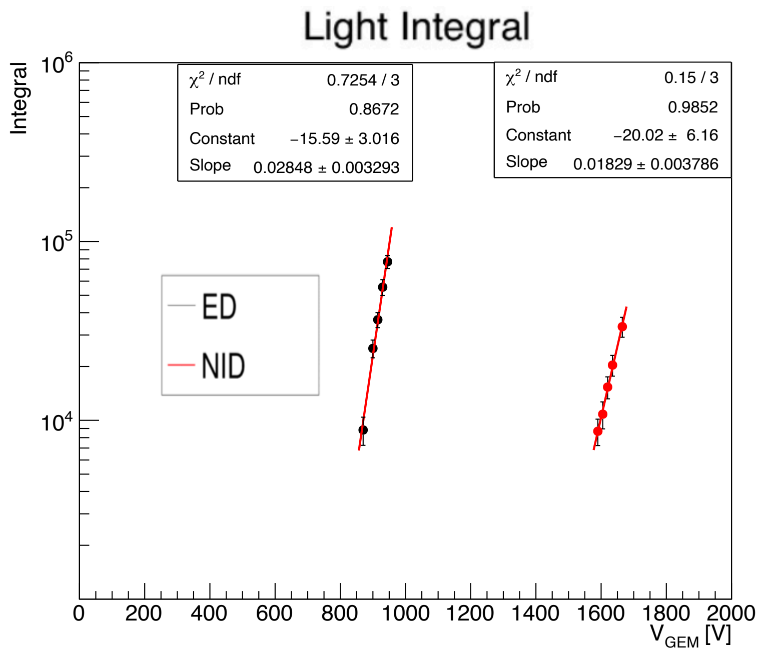
NID mixture thermal limit $\sigma_T^2 L = \frac{2kTL}{eE} * 0.25244$

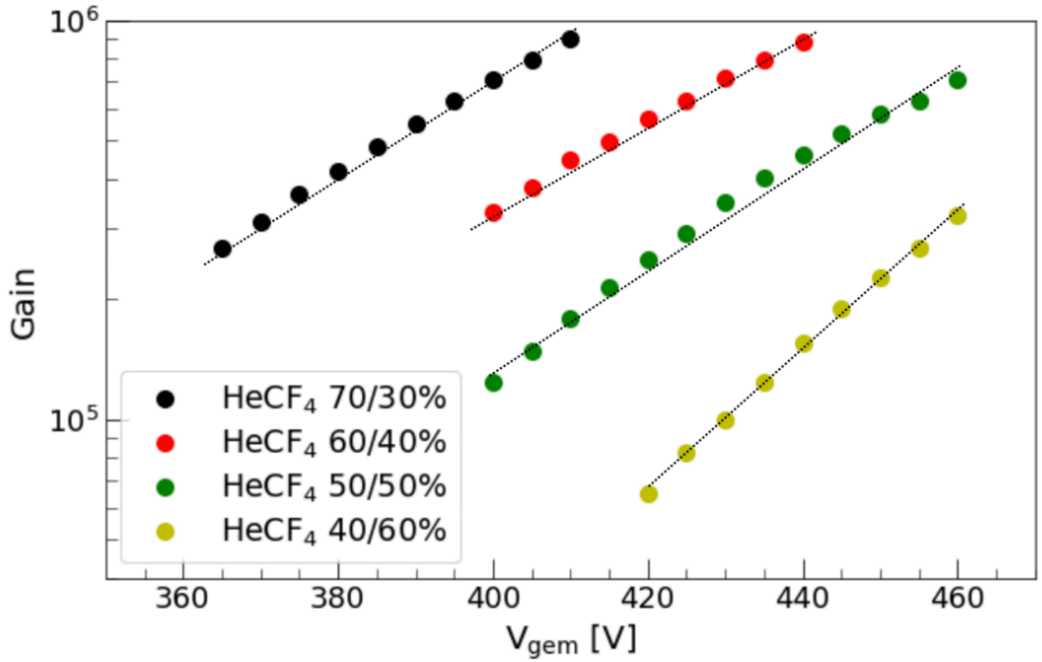
Conclusions & outlook

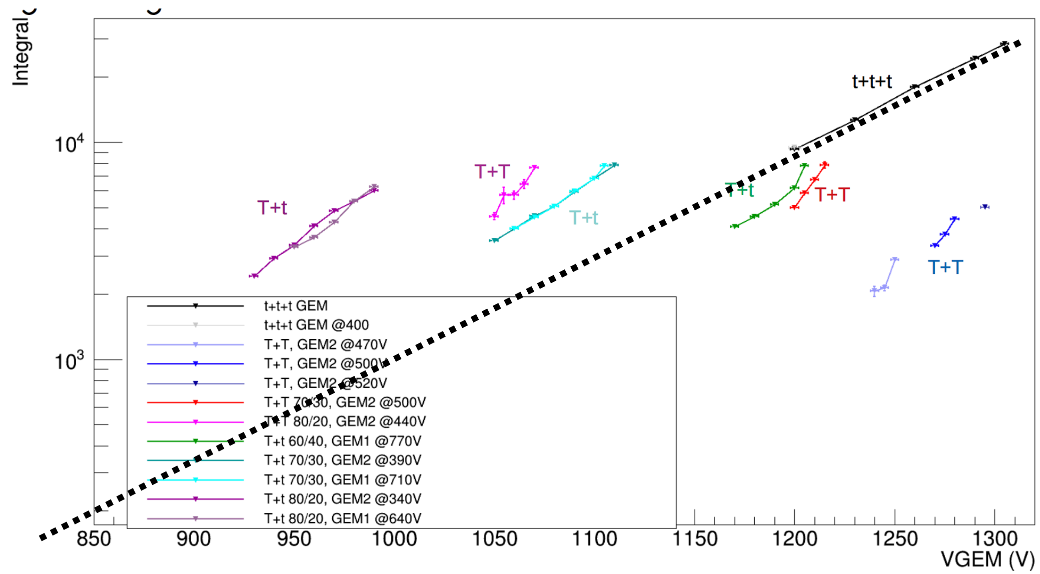
- We revised out diffusion expressions and demonstrated electron thermal limit IS NOT NID thermal limit
  - NID thermal limit depends on the ratio of the mass of the drifting ion w.r.t. the gas mixture masses
- We obtained Negative Ion Drift operation at LNGS atmospheric pressure with optical readout with both PMT and sCMOS
  - Drift velocity and mobility consistent with previous measurement with charge readout
  - First time NID are observed with a PMT!
    - Possibility of cluster counting and improved energy resolution and PID?
  - O(10^4) charge gain achieved
- We measured ED and NID diffusion at 650 mbar
  - ED consistent with Garfield simulation and significantly above electron thermal limit
  - Huge reduction (factor 3) of NID mixture diffusion compared to ED
  - NID diffusion consistent with expected ionic thermal limit for the mixture under study
  - Since NID diffusion is thermal, expected to be the same at full atmospheric pressure
- Only the first step towards a systematic investigation of He:CF_4:SF_6 NID mixture potentialities at atmospheric pressure (with either optical or charge readout)

Backup slides

Light Integral & gas gain

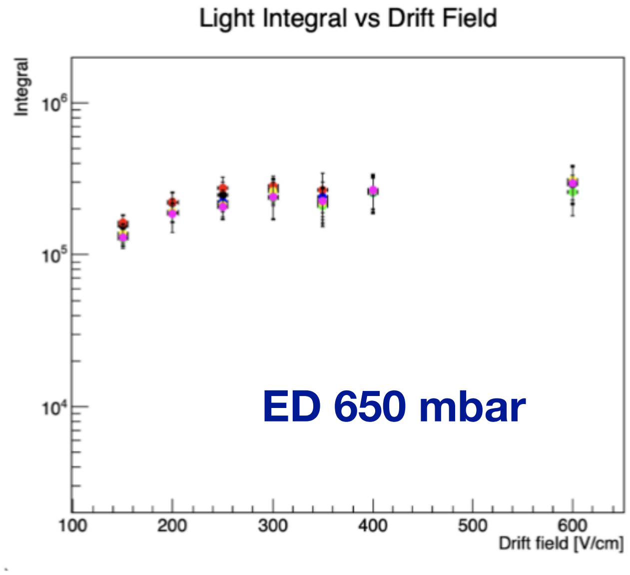


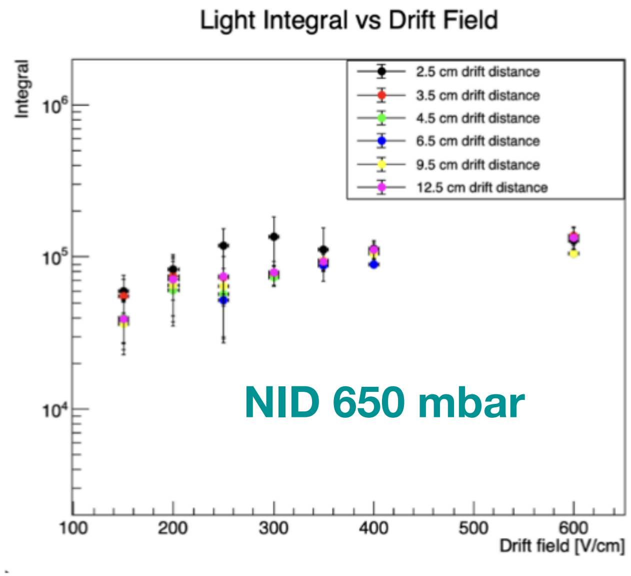


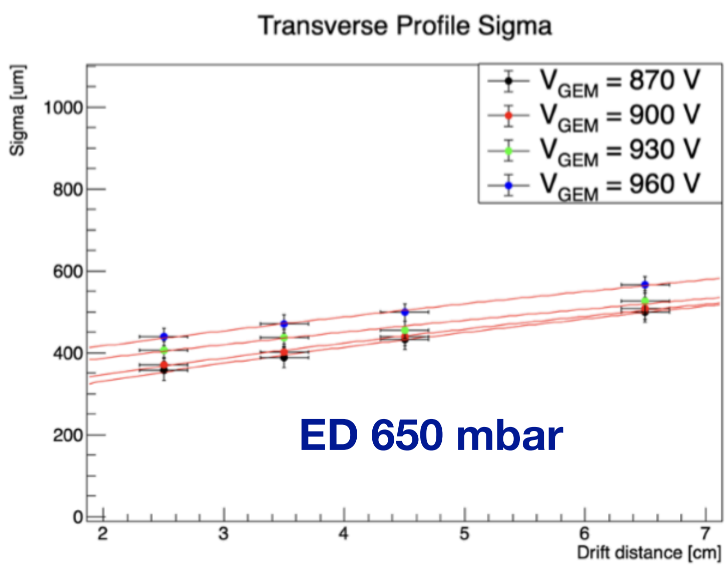


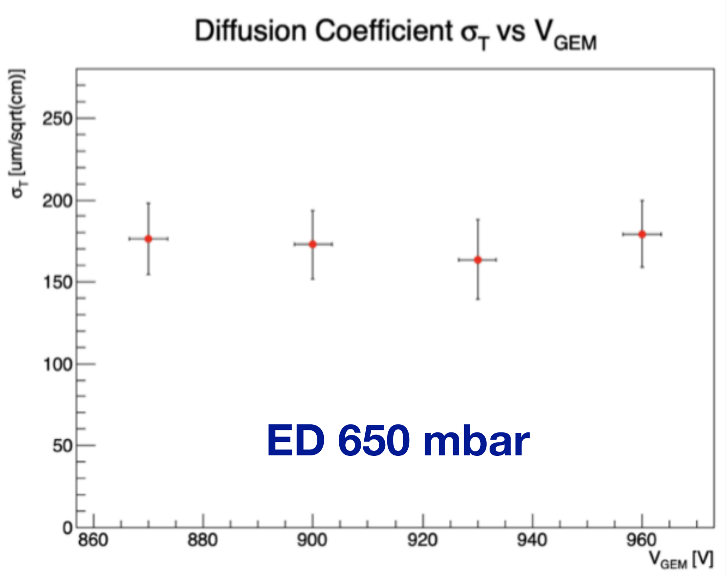
- **Light yield in MANGO is 10^4 for GEMs at 1200 V for ^{55}Fe, corresponding to a 3 x 10^5 charge gain**
- **Light yield at 1000 V on the GEMs is reduced of a factor 10 w.r.t. 1200 V**
- **Hence, charge gain for 1000 V on GEMs is about 10^4**

Further crosschecks



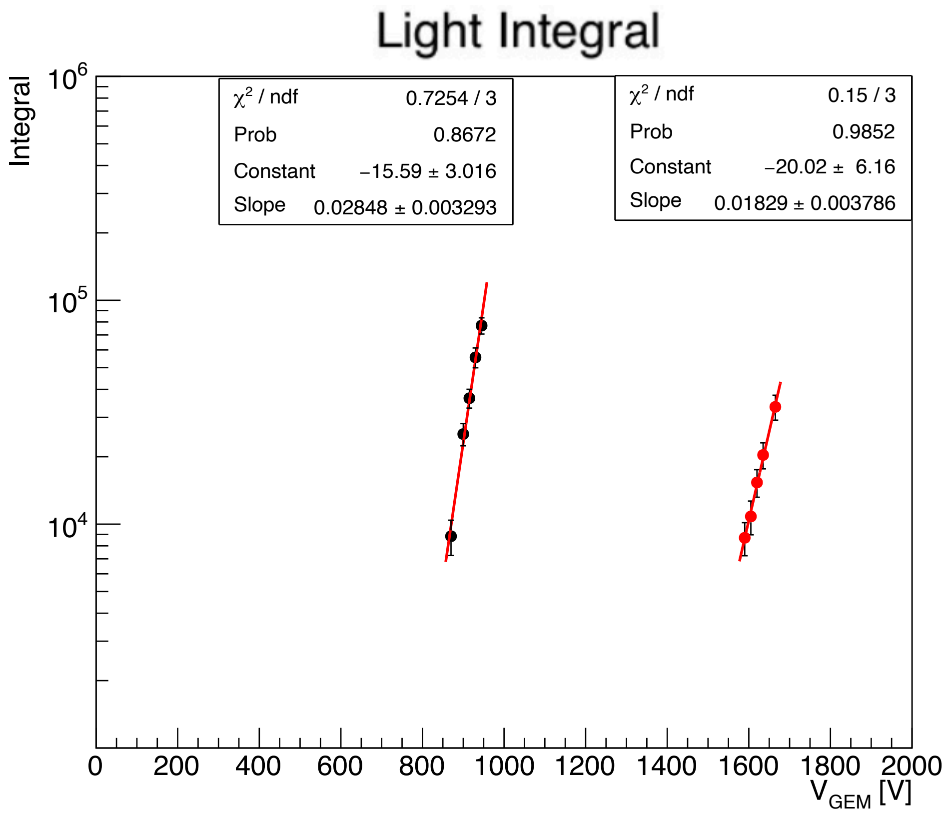




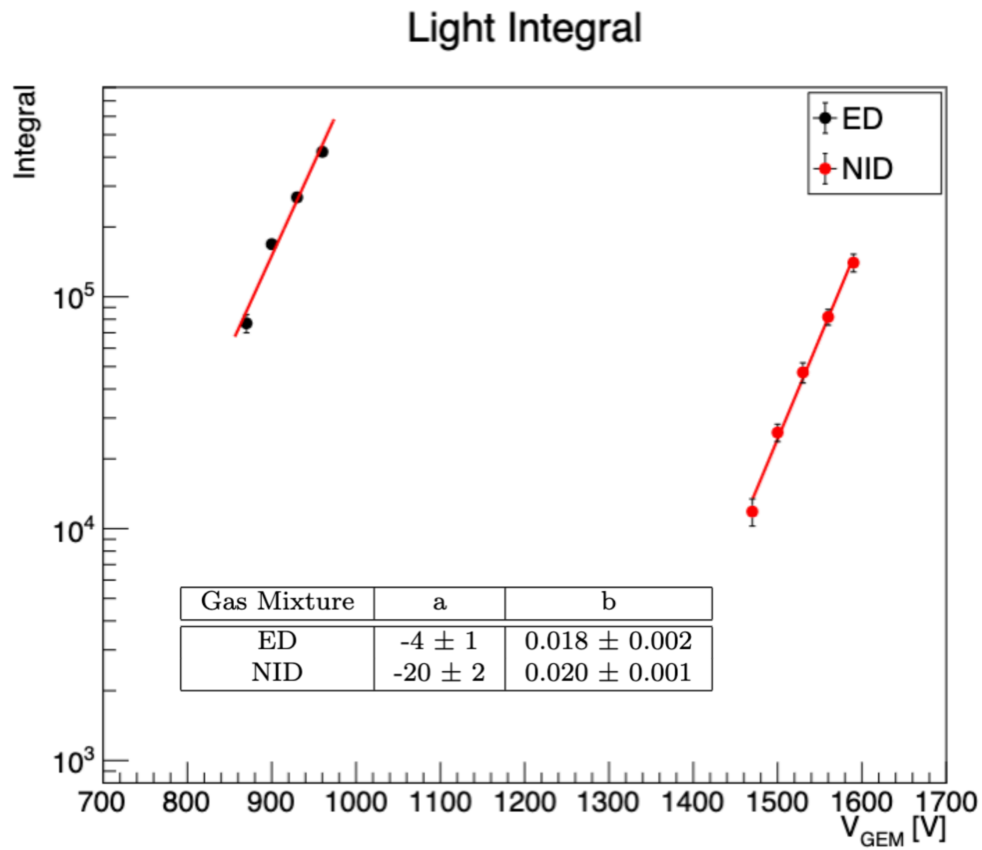


Light integral vs pressure vs V_{GEM}

900 mbar



650 mbar



Gas Mixture	a	b
ED	-4 ± 1	0.018 ± 0.002
NID	-20 ± 2	0.020 ± 0.001