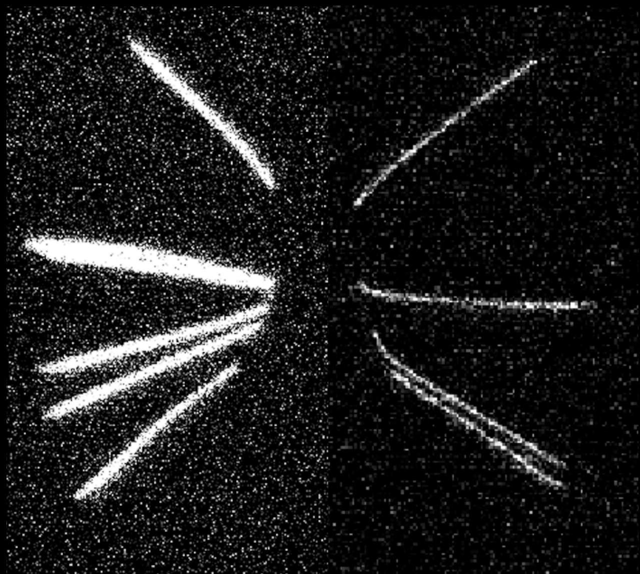
Elisabetta Baracchini

Gran Sasso Science Institute & Istituto Nazionale Fisica Nucleare

Negative ion drift with optical readout at atmospheric pressure

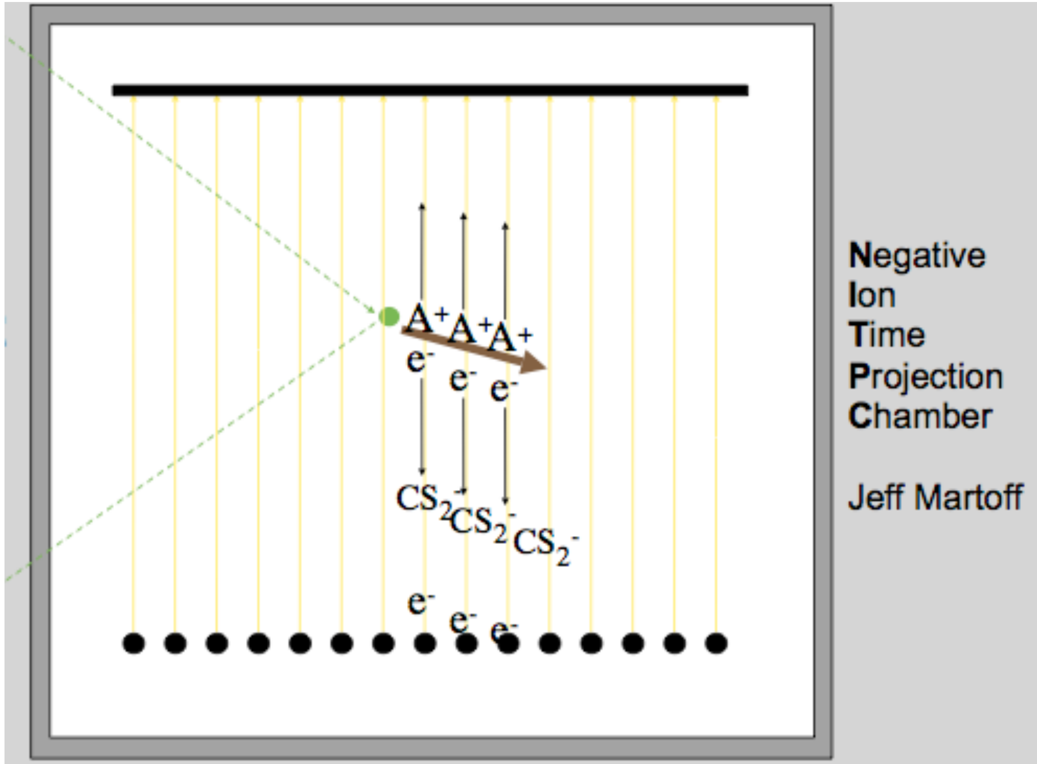


Fernando Domingues Amaro [1], Elisabetta Baracchini [2,3], Luigi Benussi [4], Stefano Bianco [4], Cesidio Capoccia [4], Michele Caponero [4,5], Danilo Santos Cardoso [6], Gianluca Cavoto [7,8], André Cortez [2,3], Igor Abritta Costa [9], Rita Joanna da Cruz Roque [1], Emiliano Dané [4], Giorgio Dho [2,3], 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]

CYGNO Collaboration Meeting 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

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?

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

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

....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

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

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

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

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

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

$y \to 0$ 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

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

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

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

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

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

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

Low pressure

- Concept demonstrated 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]

(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]

Optical Readout

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

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

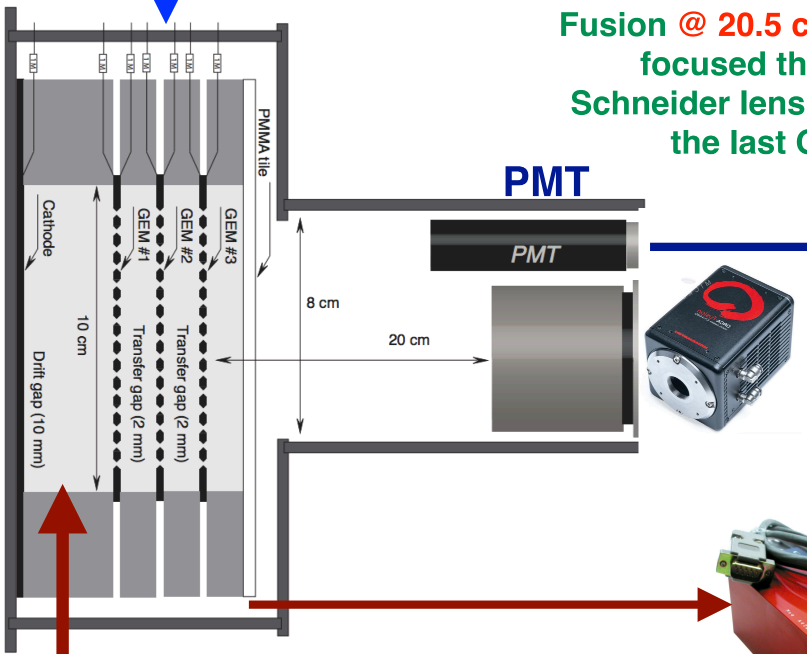
The MANGO detector

Triple thin 50 um GEM stack 10 x 10 cm²

Acquired with Hokawo 3.0 software

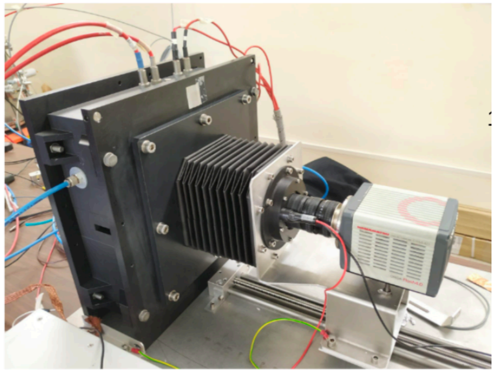
sCMOS camera Orca Fusion @ 20.5 cm distance focused through Schneider lens (f/0.95) on the last GEM

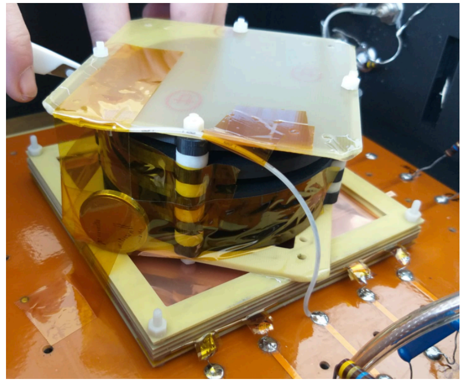
PMT



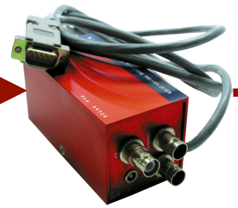
Drift gap (variable from 5 to 15 cm)

5 cm drift gap setup inside plastic gas-tight box





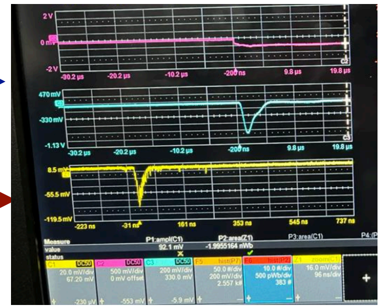
Acquire sCMOS images, PMT & GEM waveforms with ^{241}Am source



Charge sensitive preamplifier

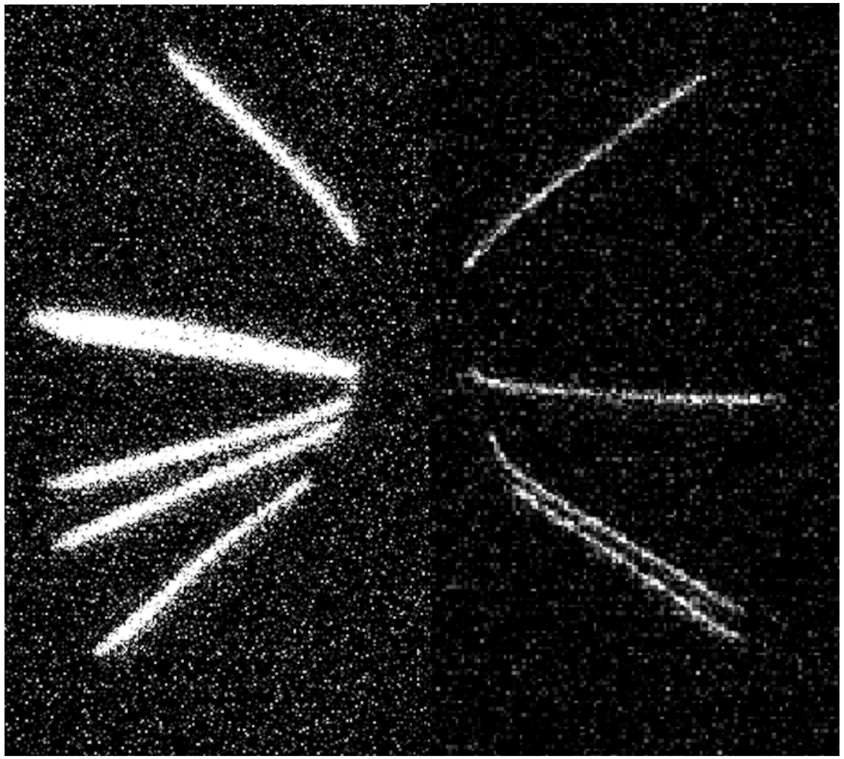
300 us decay time

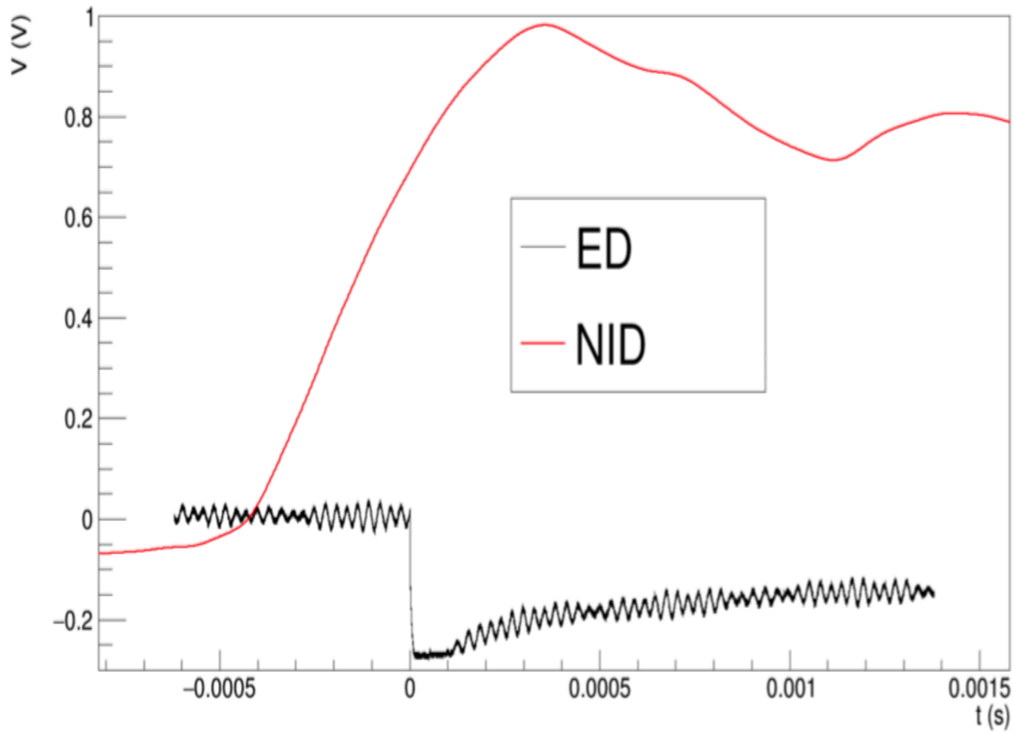
0.113 mV/fC



Oscilloscope

Eyes (and waveforms) can't lie





He:CF_4	He:CF_4:SF_6
60:40	59:39.4:1.6
1 kV/cm	0.4 kV/cm
(ED)	(NID)

GEM preamp output

O(us) rise for ED

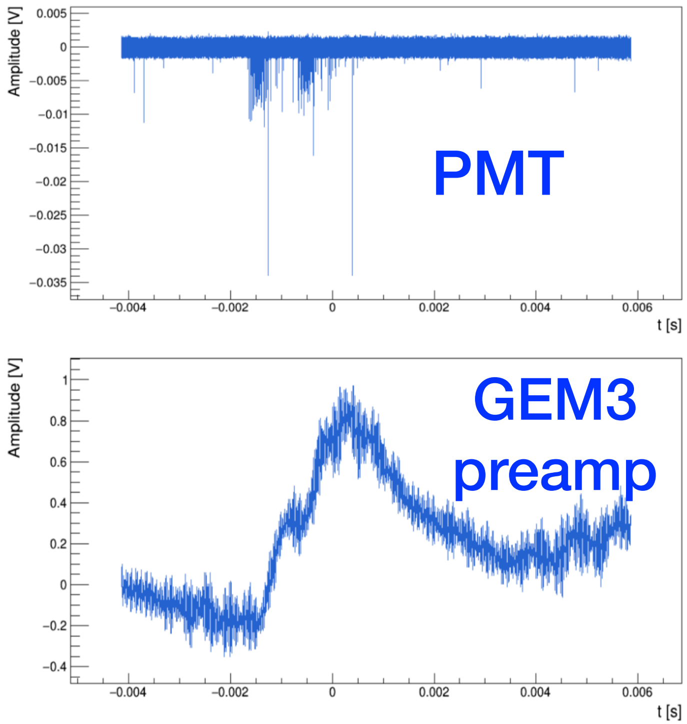
O(ms) rise for NID

0.90 atm

(LNGS atmospheric pressure)

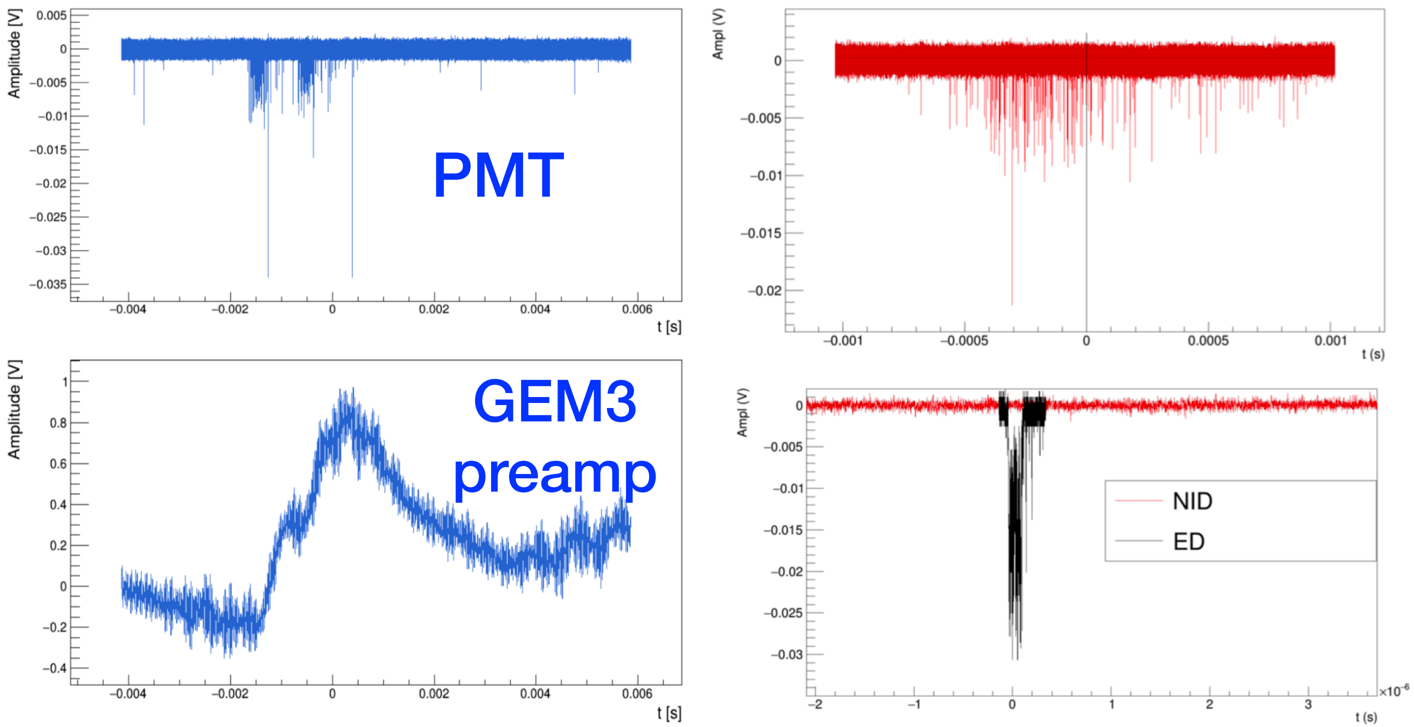
*First time NID are observed with PMTs!

PMT waveforms: how peculiar!

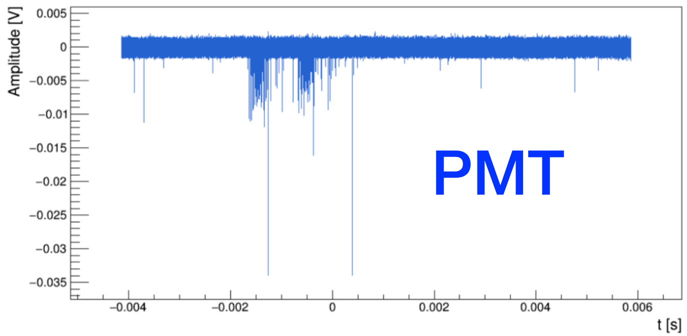


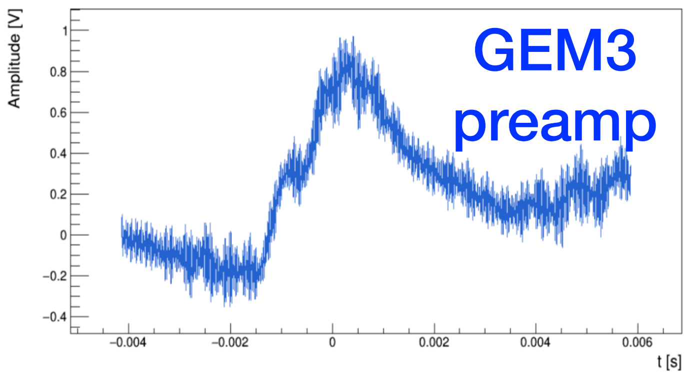
*First time NID are observed with PMTs!

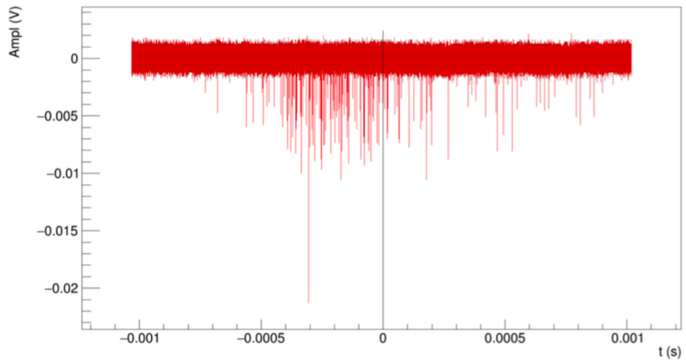
PMT waveforms: how peculiar!

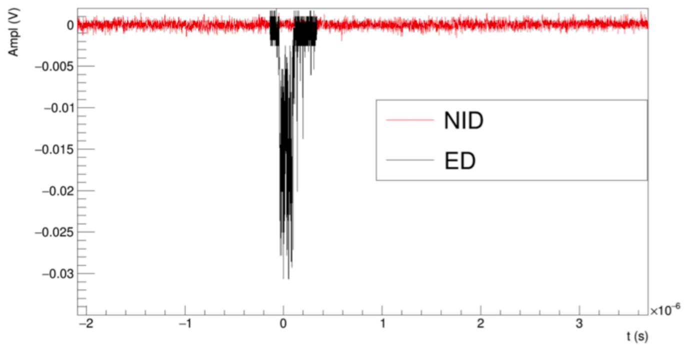


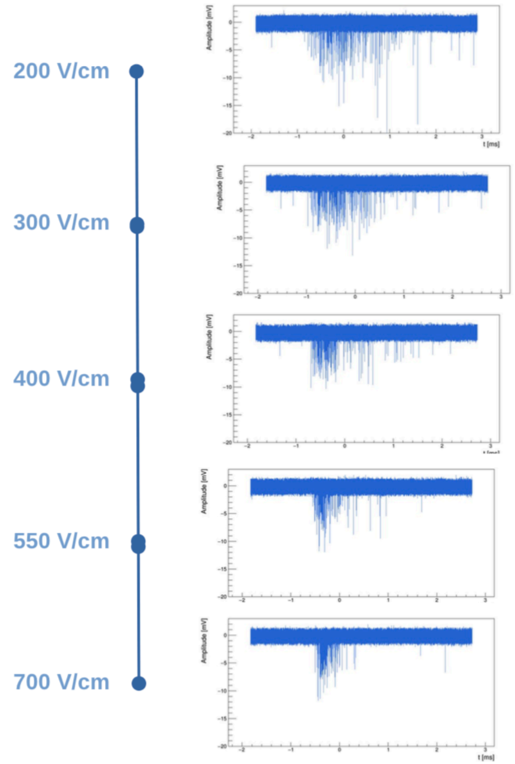
PMT waveforms: how peculiar!



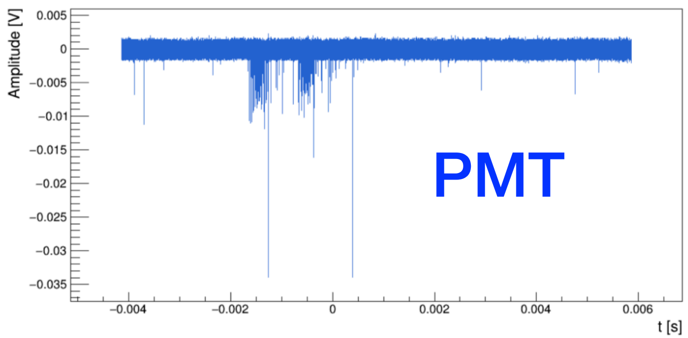


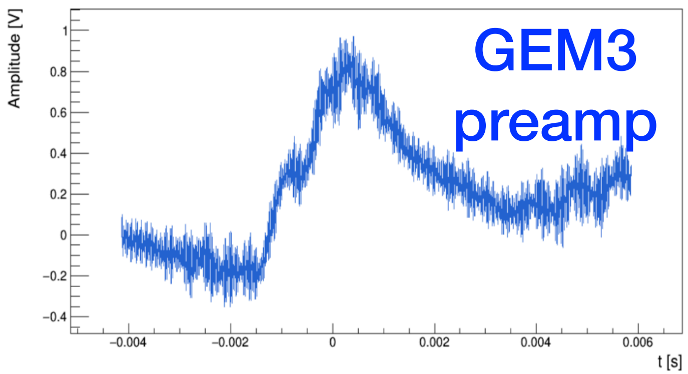


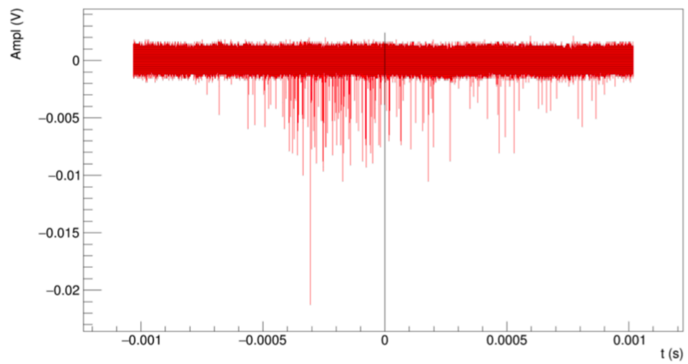


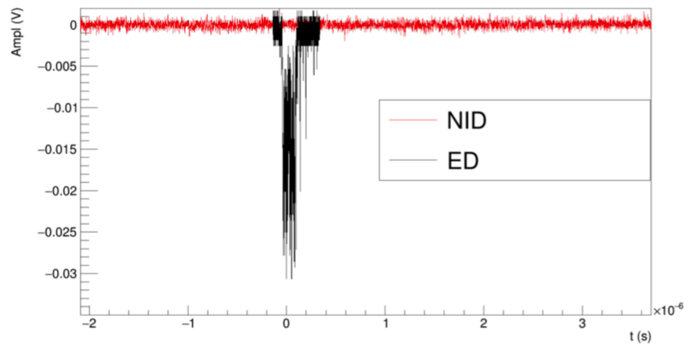


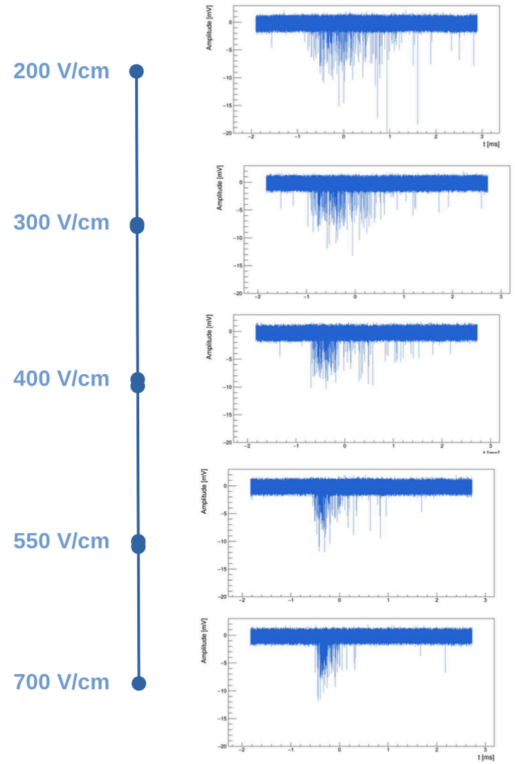
PMT waveforms: how peculiar!







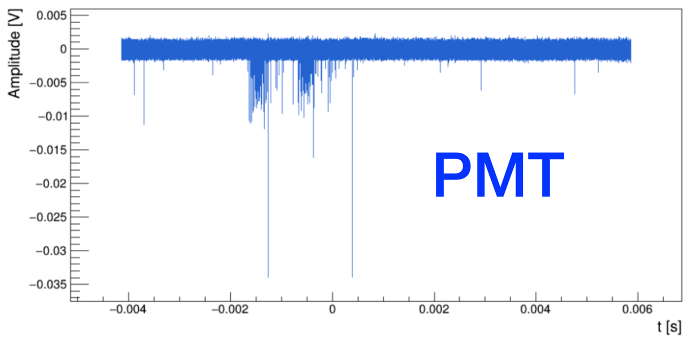


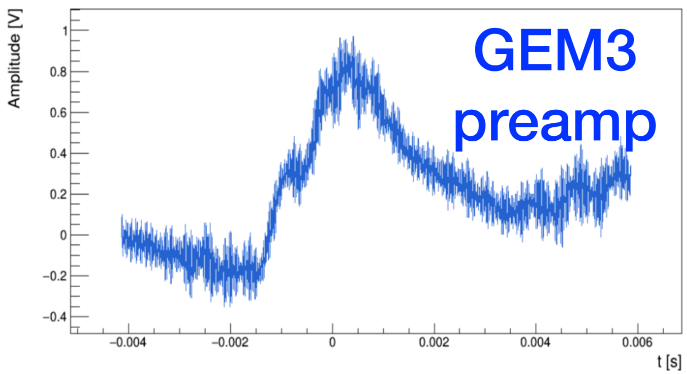


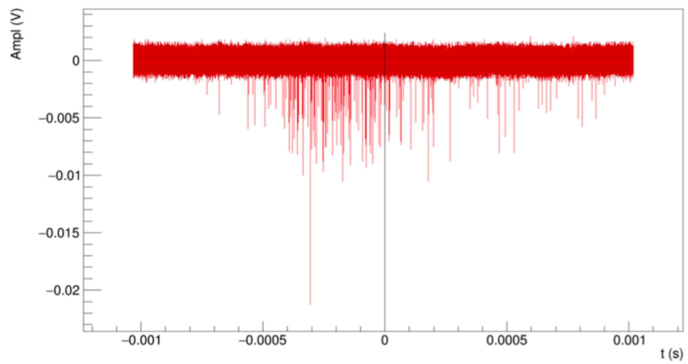
Given the PMT bandwidth and the "slow" arrival of charge carriers, individual clusters are visible in the PMT signal --> WF analysis requires proper rebinning (not trivial)

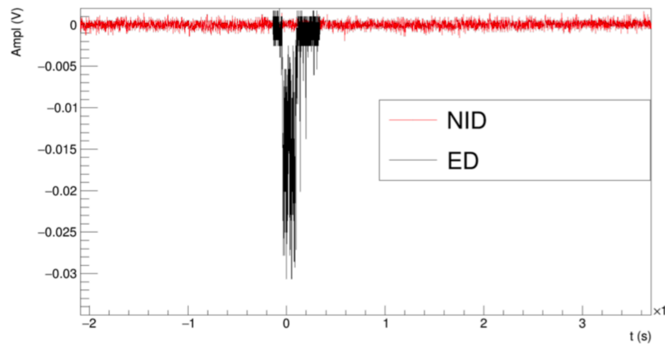
*First time NID are observed with PMTs!

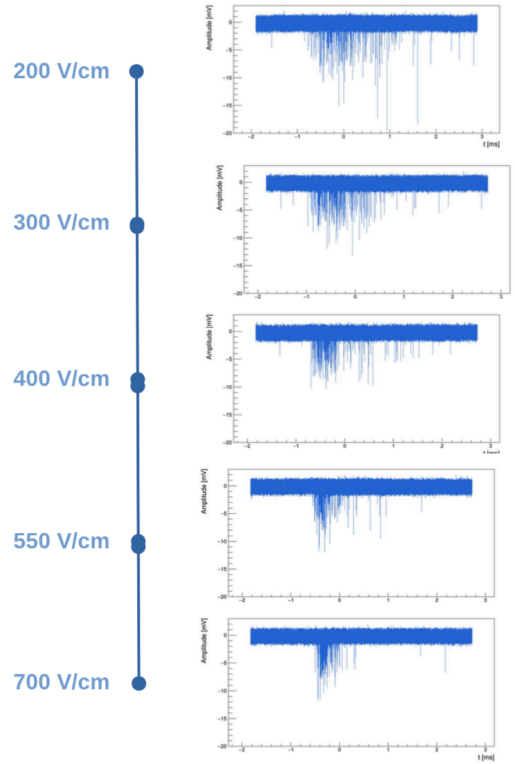
PMT waveforms: how peculiar!



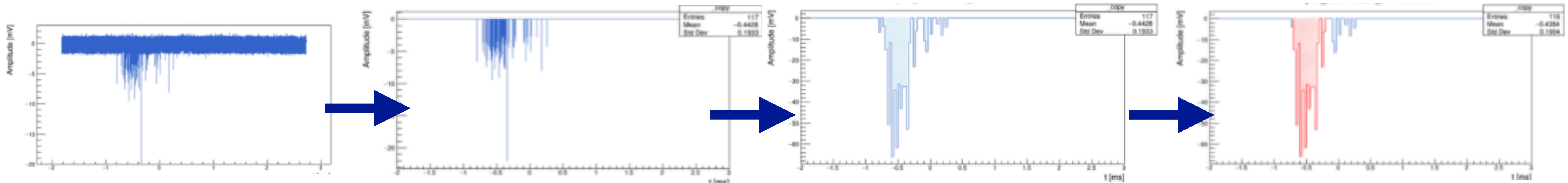




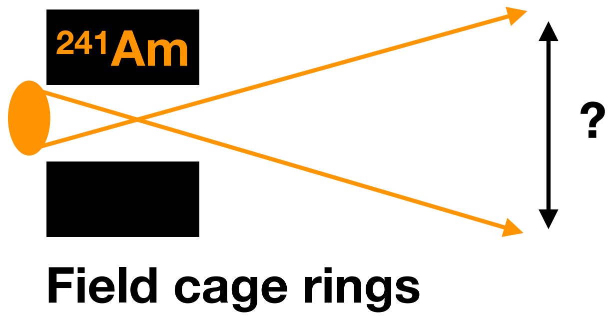




Given the PMT bandwidth and the "slow" arrival of charge carriers, individual clusters are visible in the PMT signal --> WF analysis requires proper rebinning (not trivial)

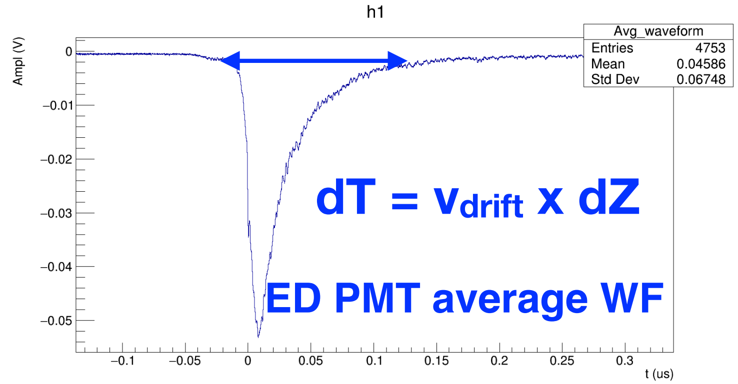


NID drift velocity and mobility from WF analysis



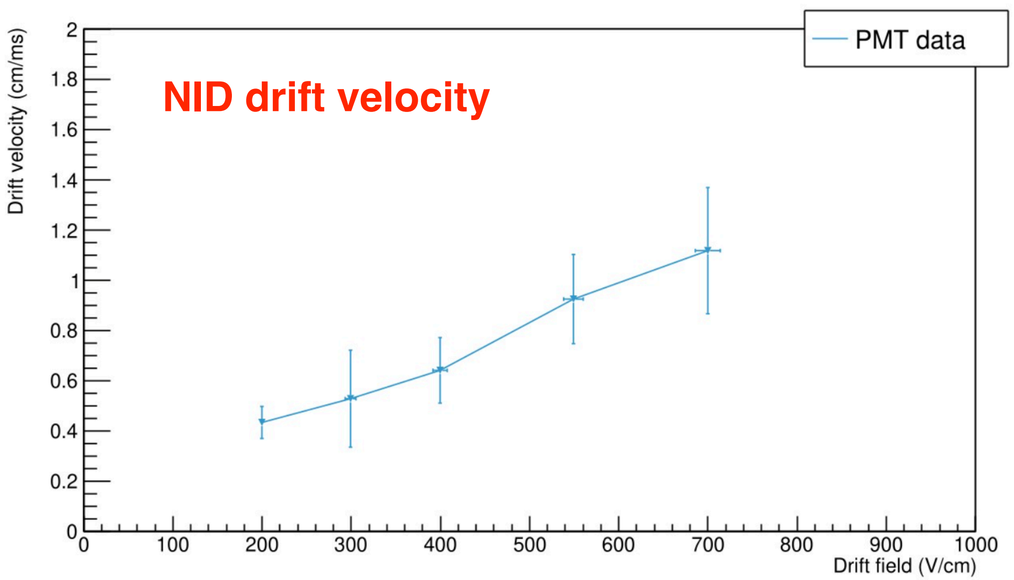
From ED PMT signal, given the known drift velocity, we estimate the alpha dZ spread (? == 7 mm)

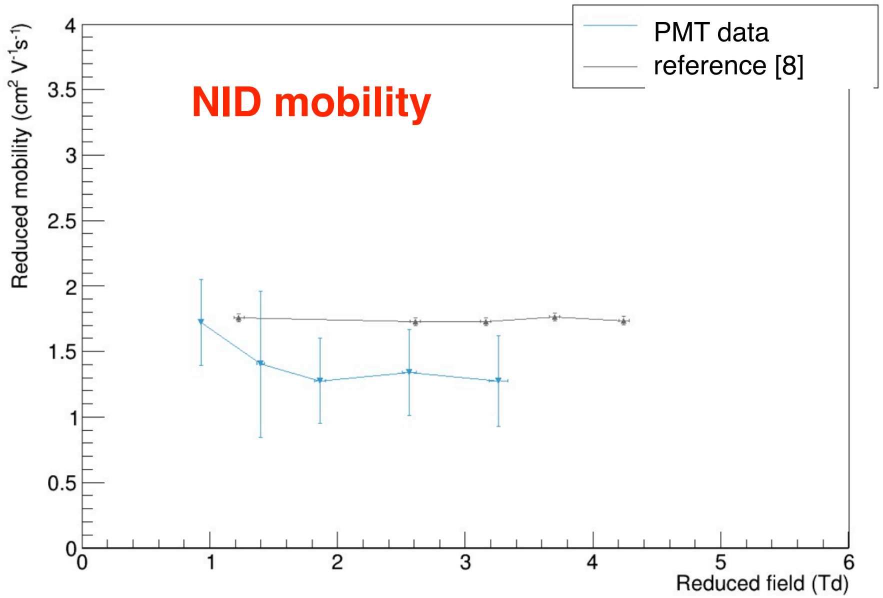
0.90 atm
(LNGS atm pressure)



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

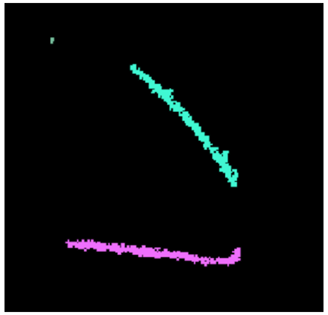


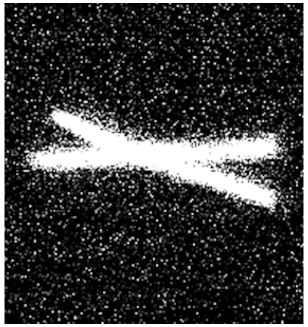


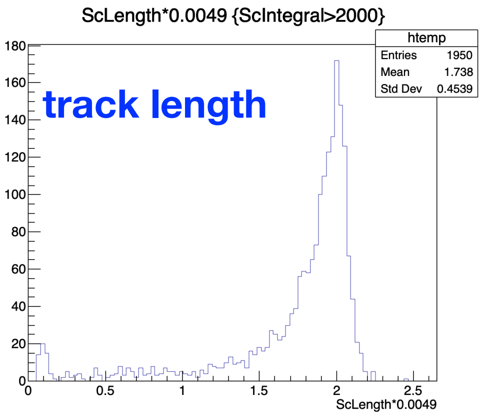
Black points from published data with charge readout and same mixture at 610 Torr [8]

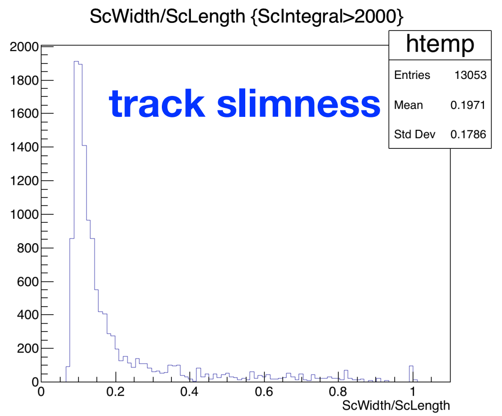
sCMOS images analysis

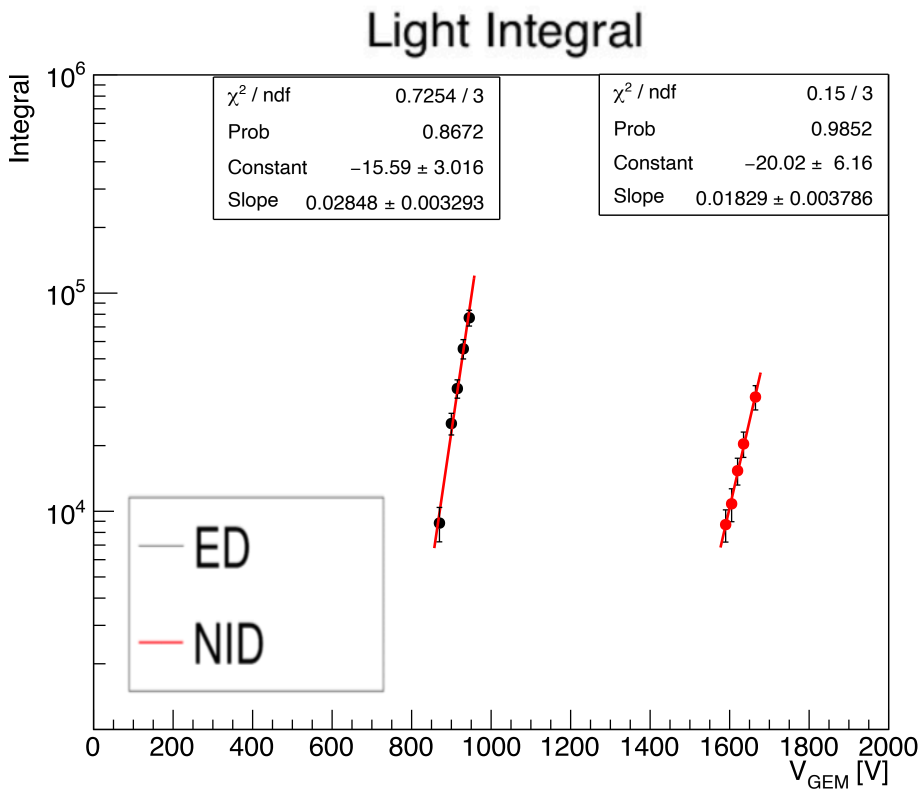
- Alphas selection:
  - tracks reconstructed with iterative DBSCAN algorithm [10]
  - track length > 1.47 cm
  - track slimness < 0.3
- Sum of pixel content is light integral









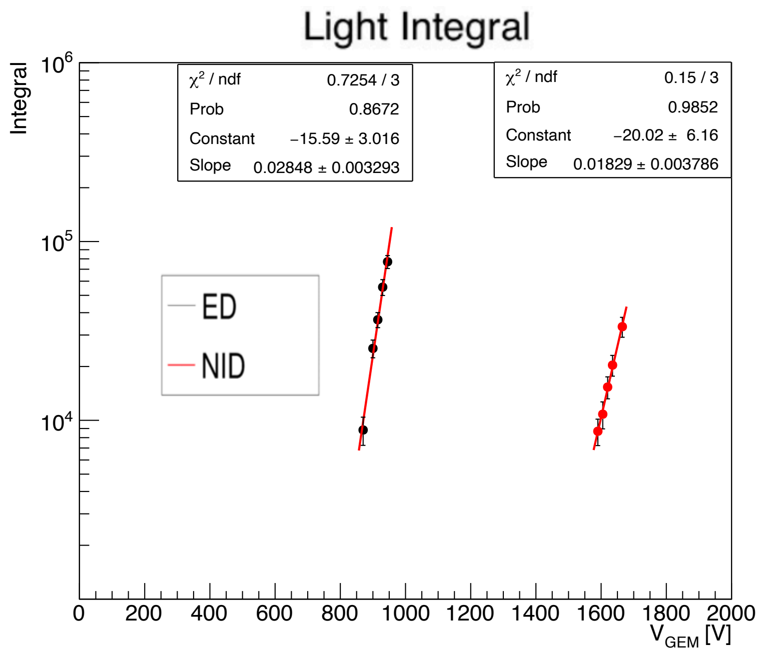


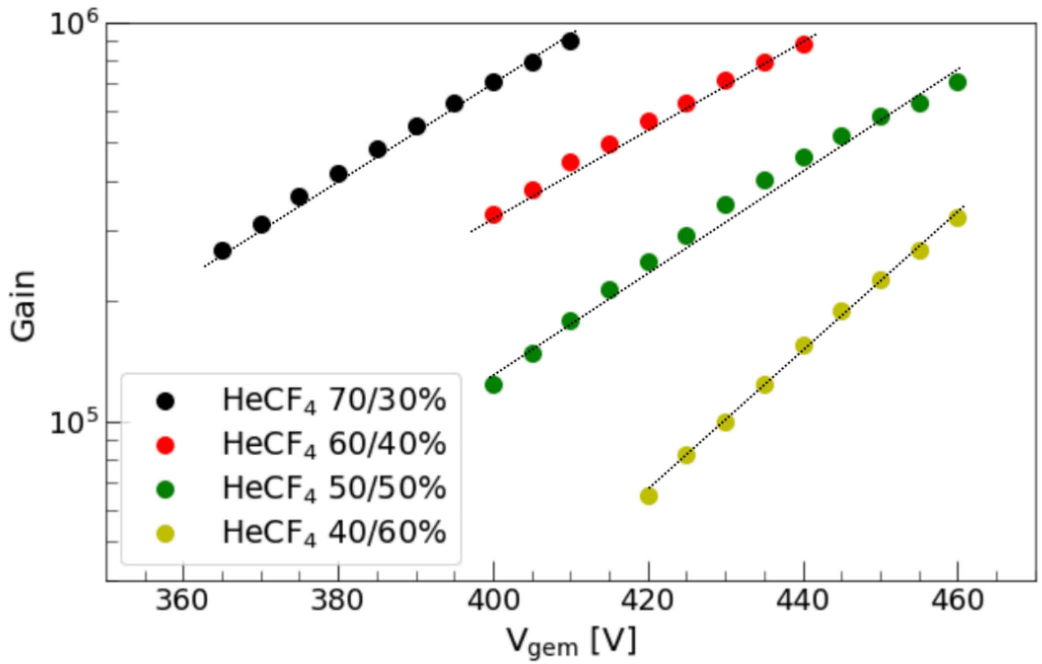
[10] E. Baracchini et al, JINST 15 (2020) 12 T12003

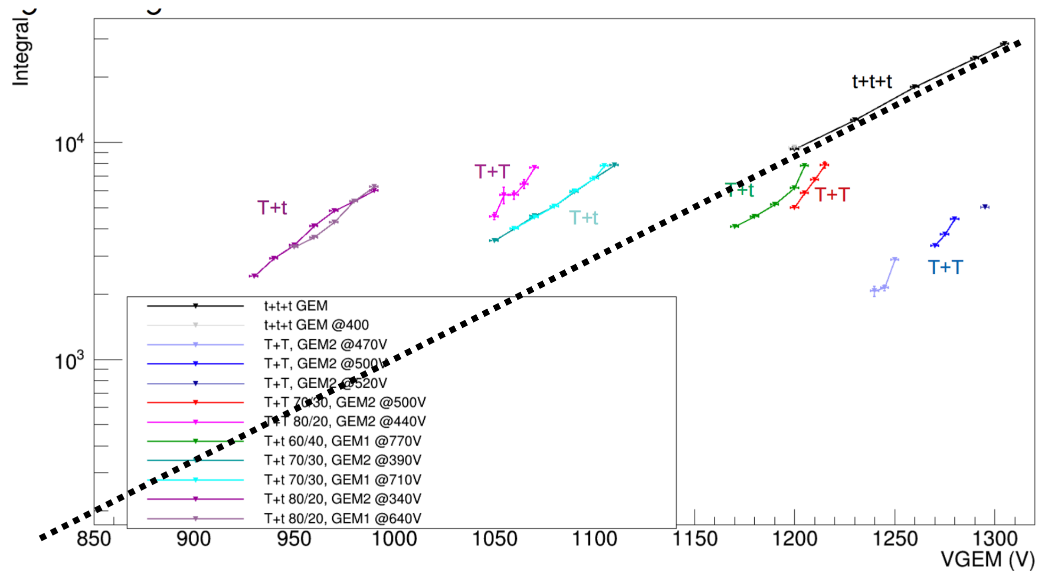
Assuming SF_6 does not absorb light and that light production mechanism stays the same with NID, extrapolating from previous CYGNO measurement ED & NID gain is ~1-3 10^4

(rough evaluation, see next slide)

Gas gain rough evaluation



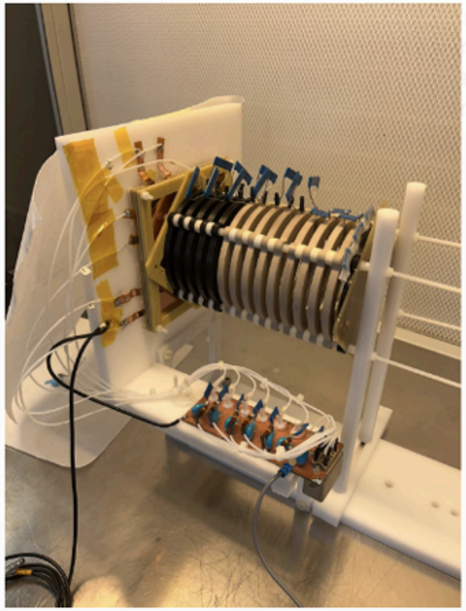


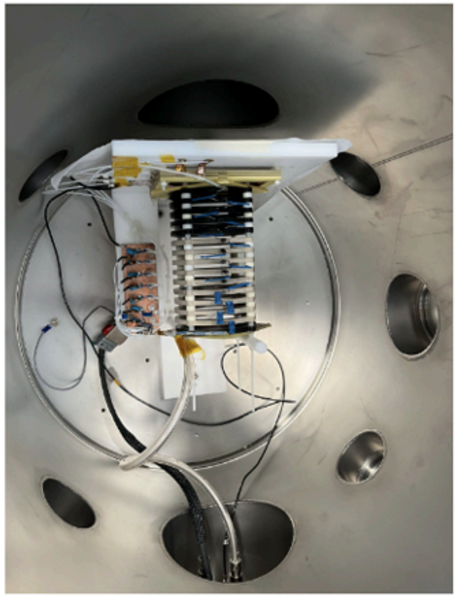


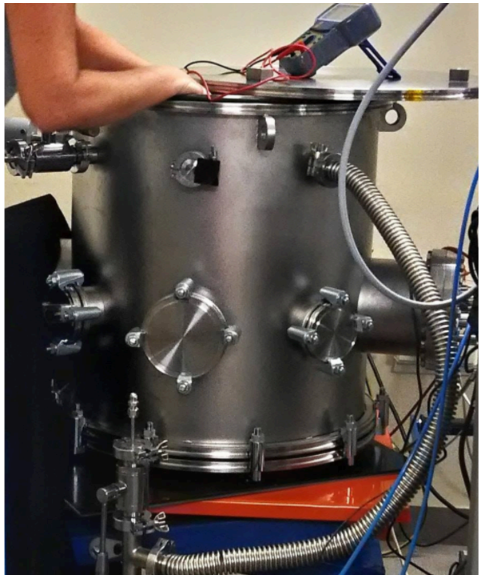
- **Light yield in MANGO is 10^4 for GEMs at 1200 V for ^{55}Fe, corresponding to a 3 x 10^5 charge gain**
- **Light yield at 1000 V on the GEMs is reduced of a factor 10 w.r.t. 1200 V**
- **Hence, charge gain for 1000 V on GEMs is about 10^4**

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



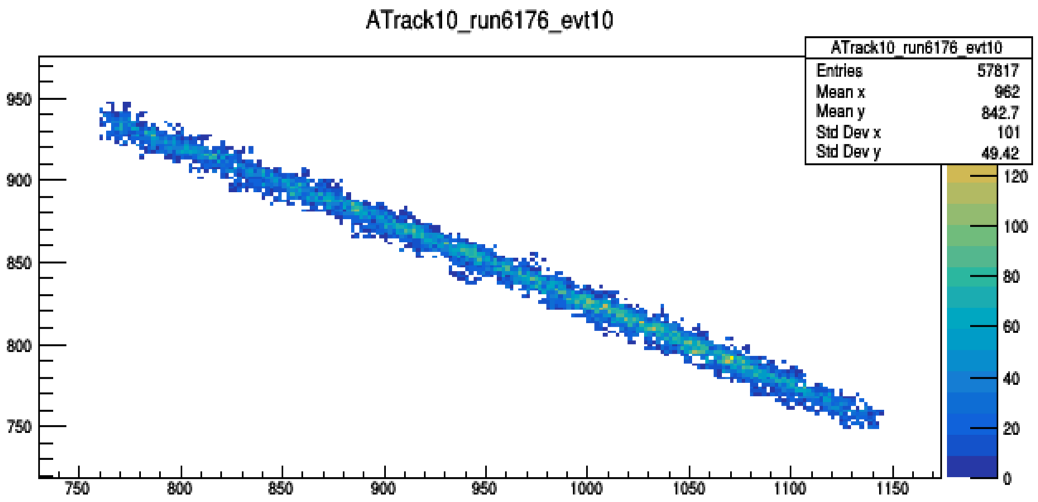


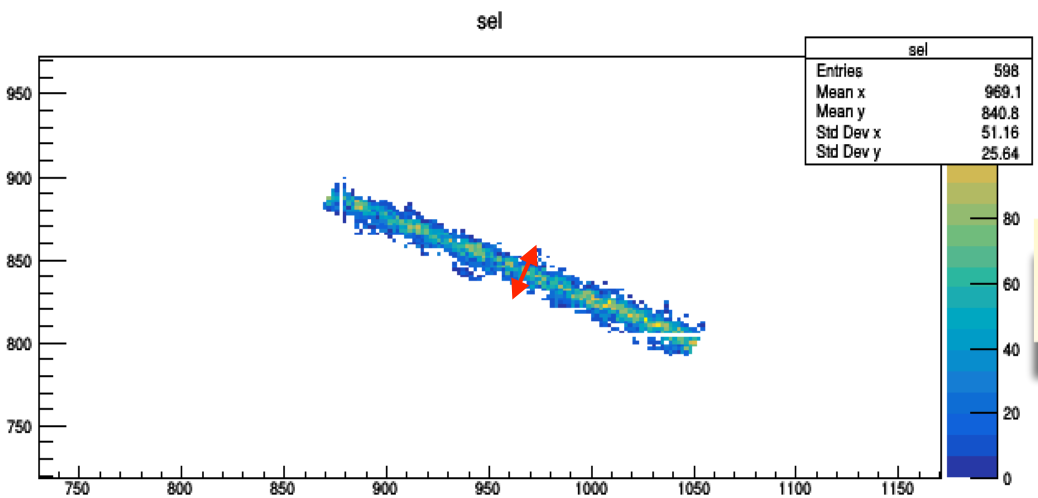


Because of geometry constraints, the camera is now at 26.6 cm distance (w.r.t. 20.5 cm of the previous setup): the light yield reaching the camera sensor is reduced of 2/3 with respect to previous configuration

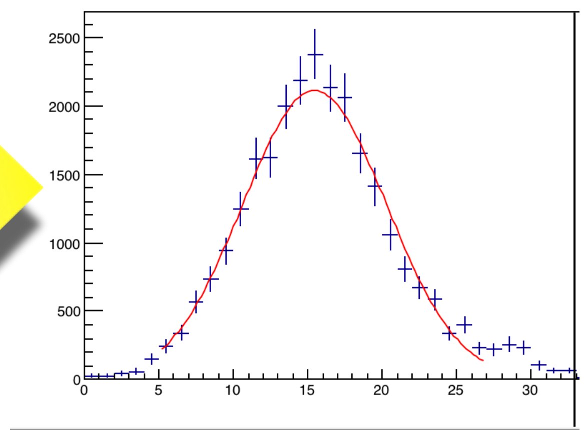
For this reason and in order to be able to measure the diffusion at ~15 cm drift length and low ~150 V/cm drift fields, we reduced the pressure to 650 mbar in the diffusion measurements

sCMOS images analysis for diffusion measurement





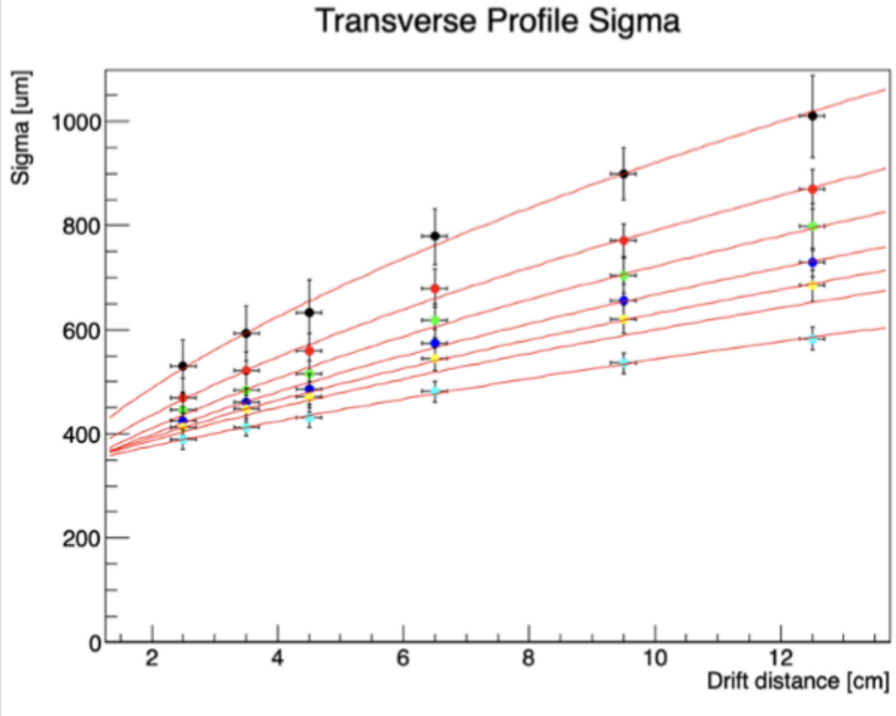
- Track selection
  - tracks reconstructed with iterative DBSCAN algorithm [10]
  - track length > 1.47 cm
  - track slimness < 0.3
  - # of peaks in the transverse profile == 1 (select single tracks)
  - Chi2/nDOF of transverse fit profile < 5 (remove additional multiple tracks)



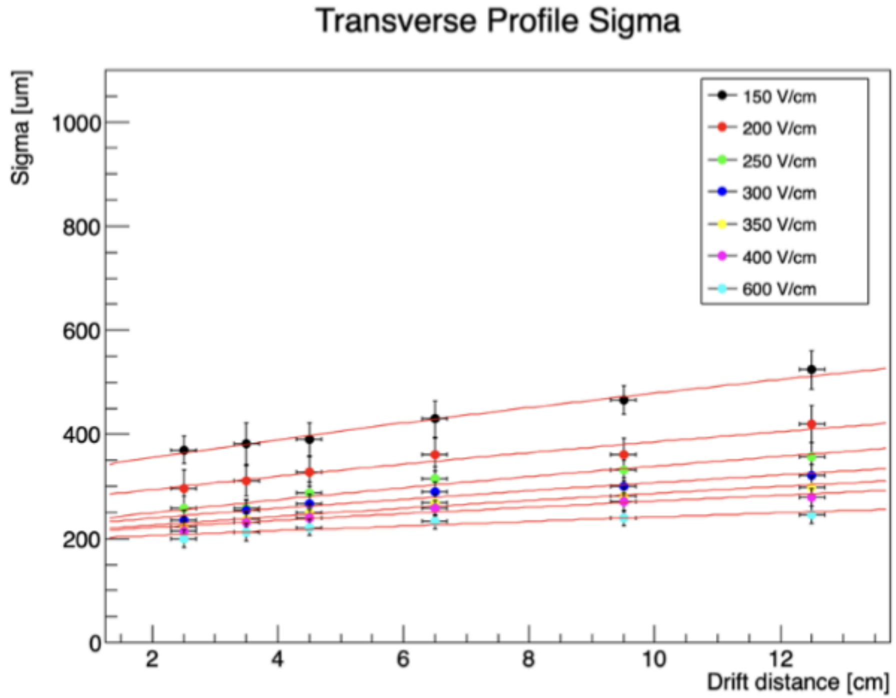
Sigma of track profile and track integral fitted with Gaussian to estimate diffusion and light yield

ED & NID diffusion

$He:CF_4$ 60:40 (ED)



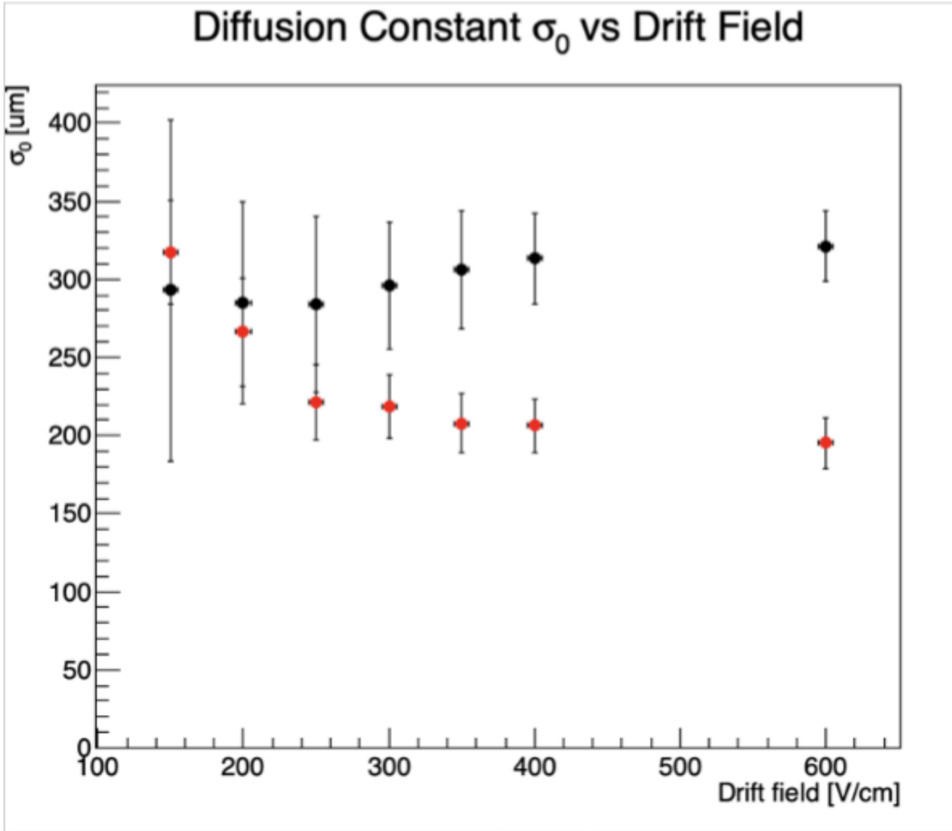
$He:CF_4:SF_6$ 59:39.4:1.6 (NID)

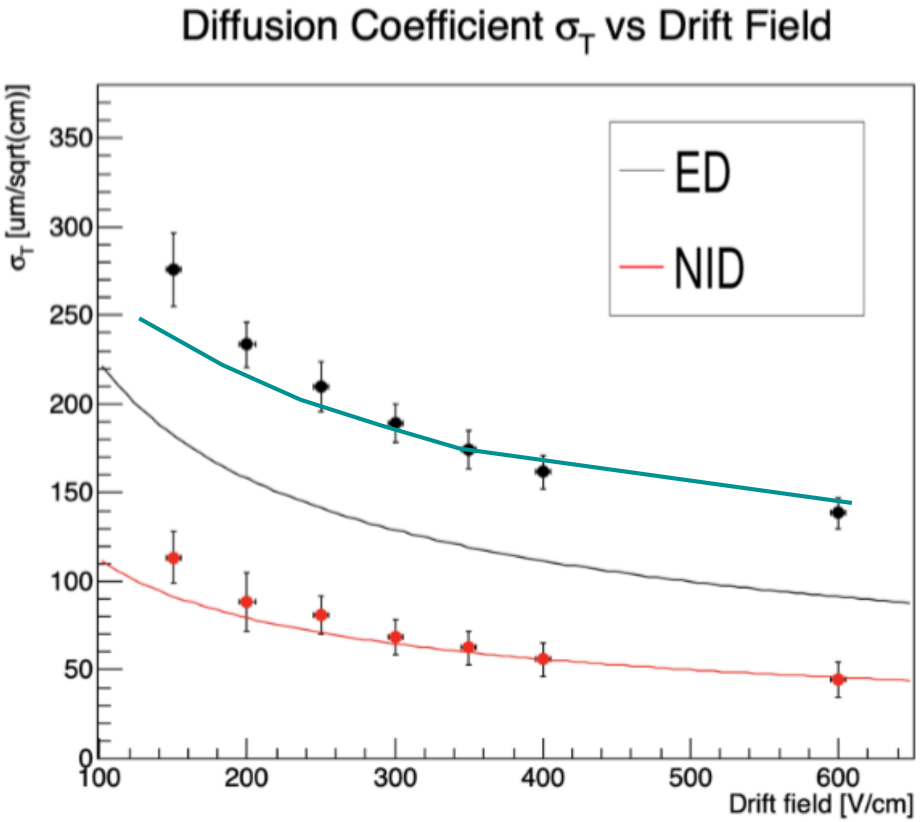


$$\sigma_{meas} = \sqrt{\sigma_0^2 + \sigma_T^2 L}$$

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





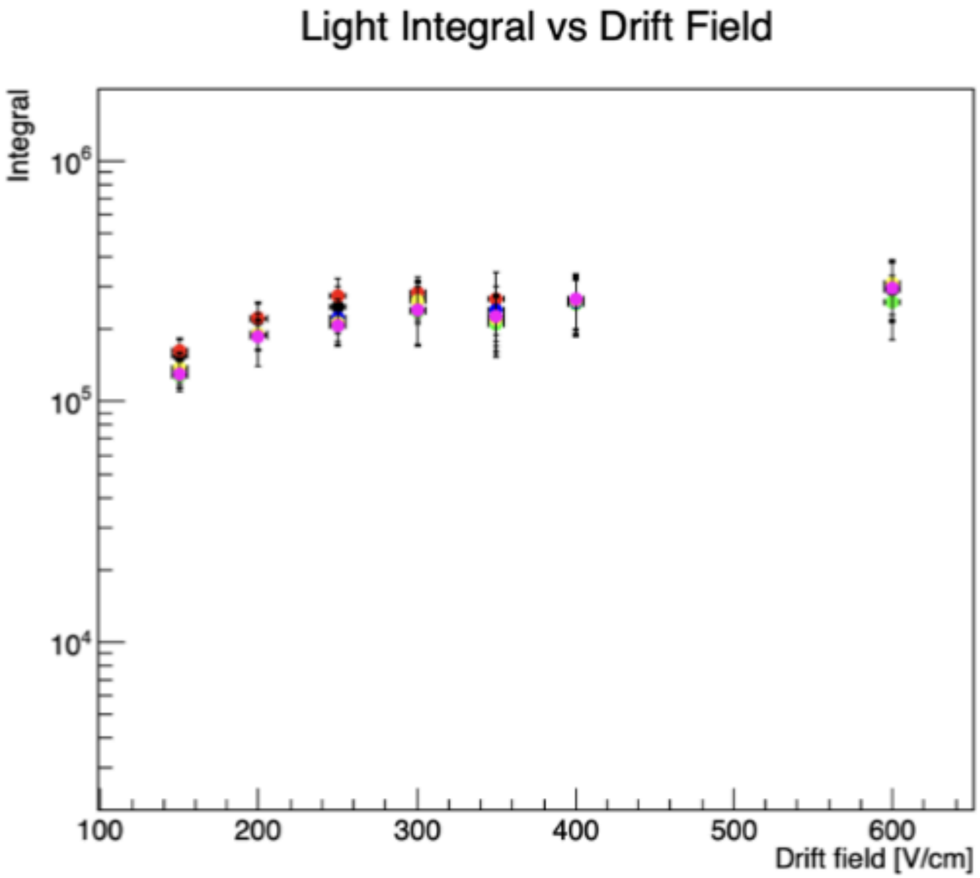
$$\sigma_{meas} = \sqrt{\sigma_0^2 + \sigma_T^2 L}$$

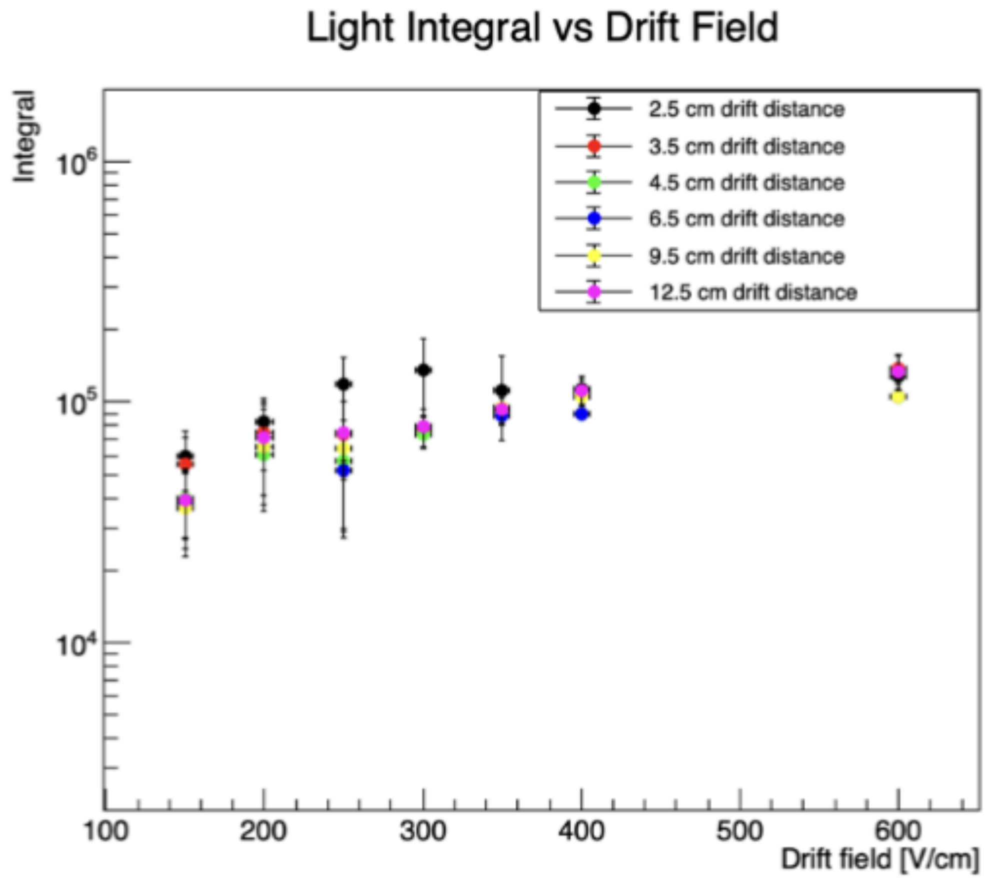
Garfield simulation of He:CF_4 60:40 @ 650 mbar

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

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

Further crosschecks: light yield vs drift field vs drift distance

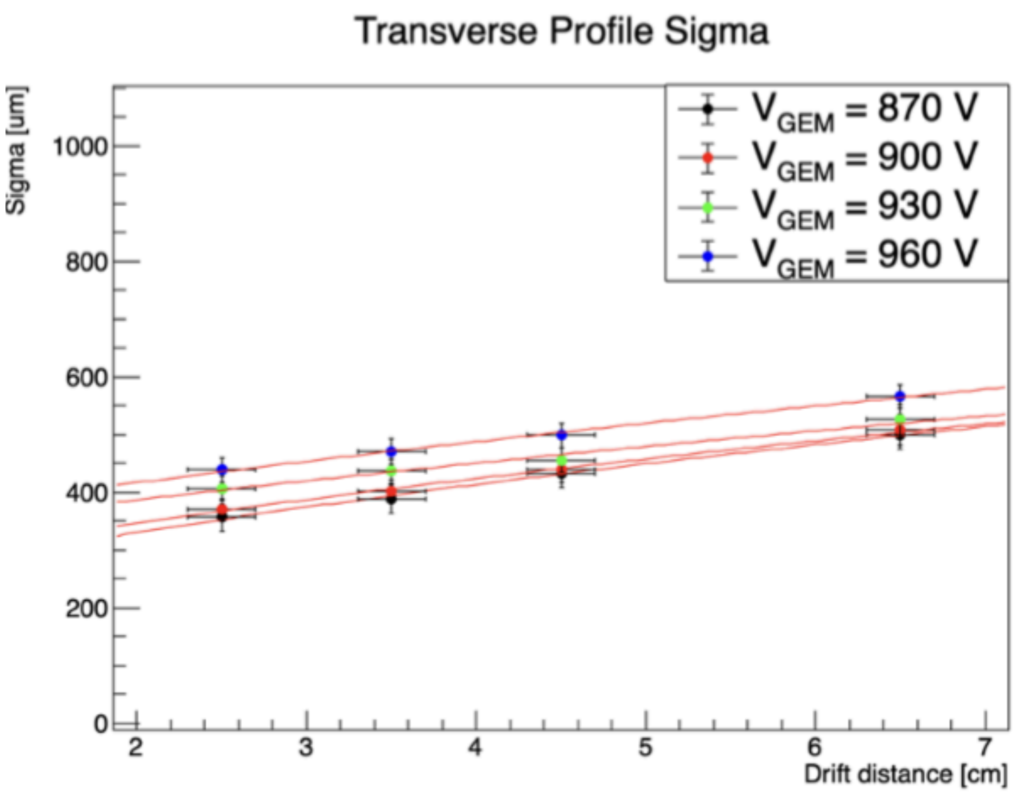




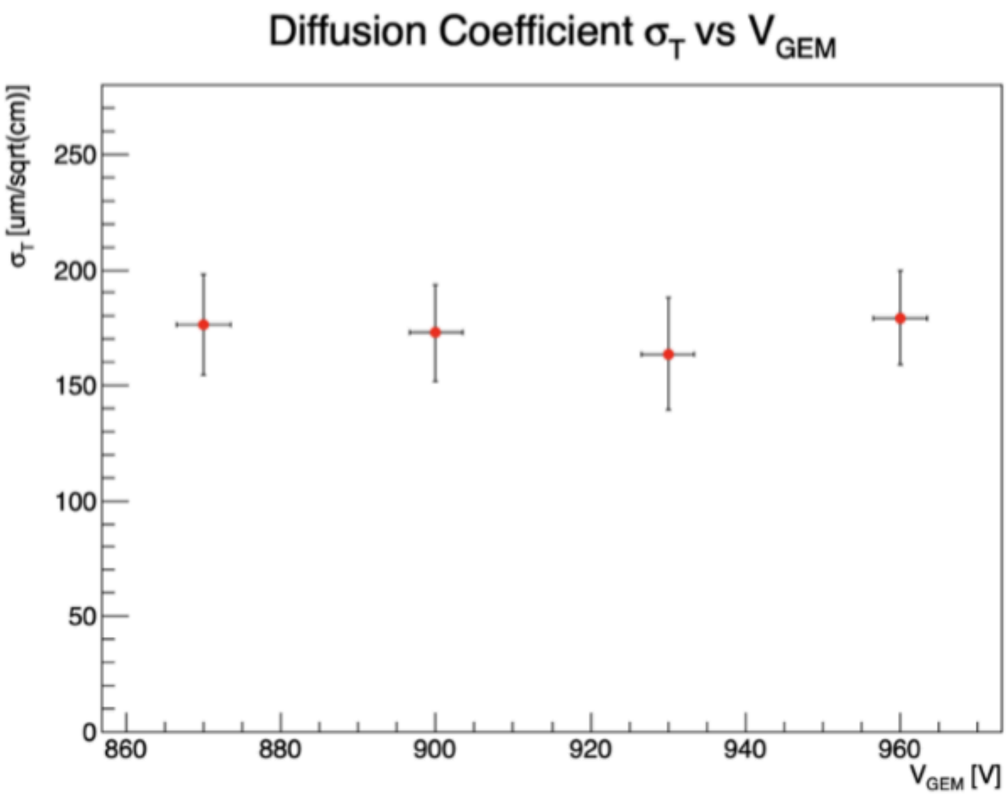
ED 650 mbar

NID 650 mbar

Further crosschecks: diffusion vs V_{GEM}



ED 650 mbar



ED 650 mbar

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

Detailed calculations

In this low momenta approximation, the general collision between an ion and a gas molecule can be expressed in the centre of mass frame reference. Here, the scattering is isotropic and the momentum loss in the direction of motion is

$$p_{CM}(1-\cos\theta_{CM})$$

with the subscript CM linking the quantities to their value in the centre of mass frame of reference. p_{CM} is the modulus of the momentum in the centre of mass which is equivalent to $m_t v_{CM}$, with v_{CM} the velocity needed to transform the velocities from the laboratory frame to the centre of mass one, and is equal to

$$v_{CM} = \frac{P_0}{m_p + m_t} \tag{A10}$$

The momentum loss is an invariant quantity for Galilean transformations, valid when non relativistic motion is considered, and can be averaged on the possible angles which results in p_{CM}. As a result, the average fractional momentum loss can be estimated as

$$\kappa = \frac{p_{CM}}{P_0} = \frac{m_t}{m_p + m_t} = \frac{1}{1+y} \tag{A11}$$

In the laboratory frame, the previous derivation implies that while the average momentum loss is constant, each scattering is not isotropic. Therefore, the drift velocity can be expressed as:

$$w = v + c_d = \frac{eE}{m_p}\tau + c_d \tag{A12}$$

- E electric field,
- m_p mass of the drifting gas (projectile),
- τ average time between two collisions,
- c_d velocity in the direction of the drift as a result of the collision with molecules.

c_d is given by the average momentum loss in the direction of the drift and it is estimated by [?] as $c_d = v(1-\kappa)/\kappa$. Thus,

$$w = v + c_d = \frac{v}{\kappa} = \frac{eE}{m_p\kappa}\tau, \tag{A13}$$

which allows to find a generic expression for the mobility as:

$$\mu = \frac{w}{E} = \frac{e\tau}{m_p\kappa} = \frac{e\tau}{m_p}(1+y) \tag{A14}$$

Detailed calculation

A.2.2 Diffusion

As electrons and ions are drifted within the gas, the numerous scatters they are subjected to modify the actual velocity and direction of motion between two subsequent collisions. The continuity equation applied to the conserved current can be written as

$$\frac{\partial n_c}{\partial t} + n_c \nabla \cdot \vec{w} - D\nabla^2 n_c = 0 \tag{A15}$$

with n_c the number density of charge carriers, and D the diffusion coefficient. In the assumption that there is a symmetry in the system, a possible solution of the equation is

$$n_c = \left(\frac{1}{\sqrt{4\pi D t}}\right) e^{-\frac{r^2}{4Dt}}, \tag{A16}$$

with r the distance from the centre of the charge position. This means that a point-like cloud of charge carriers at time $t = 0$ expands with a Gaussian shape in time and its standard deviation is defined as

$$\sigma_D^2 = 2Dt = 2\frac{D}{w}L = 2\frac{D}{\mu}\frac{L}{E} \equiv \xi^2 L \tag{A17}$$

with ξ the diffusion parameter.

Microscopically, the diffusion can be evaluated by estimating the mean square displacement in one direction $\hat{u}$ (orthogonal to the drift direction for example) as:

$$\sum_i^{n_u} \int (l_i \cos\phi_i)^2 \frac{1}{\lambda} e^{-\frac{l_i}{\lambda}} f(\cos\phi_i) dl_i d\cos\phi_i \tag{A18}$$

- l_i distance l travelled in the between the ith and ith-1 collision
- $\cos\phi_i$ angle between the ion direction and $\hat{u}$ after the ith collision
- λ mean free path
- $f(\cos\phi)$ probability distribution of the $\cos\phi$ due to the ion to gas molecule collision
- n_u number of collision after a time t (large number of collisions)

Following the arguments of [?], the distribution of the angles $f(\cos\phi)$ can be considered isotropic for low momenta collisions, and thus the integral results in a 1/3 term. It is not excluded that the peculiar type of interaction between gas species would modify the value of this integral, but the approximation is considered valid enough for the studied case. Recalling the definition of mobility found above and that $n_u = t/\tau$:

$$\sigma_D^2 = \frac{2}{3}\lambda^2\frac{t}{\tau} = \frac{2}{3}\bar{v}\lambda t = \frac{2}{3}\bar{v}^2\tau t = 2\frac{2\epsilon}{3m_p}\tau t \tag{A20}$$

with ϵ, the energy of the drifting particle and $\bar{v}$ its average velocity. Comparing the final result of Equation A20 with the second block of Equation A17, it is possible to deduce that

$$D = \frac{2\epsilon}{3m_p}\tau \tag{A21}$$

Akin to the mobility, it depends on τ a term quite rough to evaluate.
In the approximation of the thermal limit, when the dominant term of the kinetic energy of the drifting particle is indeed the thermal one, the average energy can be reduced to $\epsilon = \frac{3}{2}k_B T$. Moreover, expressing the drift time t in terms of distance L travelled in the drift direction:

$$\sigma_D^2 = 2\frac{k_B T}{m_p}\tau t = \frac{2k_B T\tau}{m_p \mu}\frac{L}{E} \tag{A22}$$

Now, the expression for the mobility derived above can be inserted, so that:

$$\sigma_D^2 = \frac{2k_B T\tau L m_p \kappa}{m_p E e \tau} = \frac{2k_B T L}{eE}\kappa = \frac{2k_B T L}{eE}\frac{1}{1+y} \tag{A23}$$

This estimation of the Gaussian spread of a point-like cloud of charge is independent of the term τ at first order of approximation, which allows to avoid complex calculations on the cross section between gas species. Similarly to the mobility, in case of electron drift in thermal regime, $y \to 0$ and the famous formula of thermal limit, found for example in [?], is obtained.

the drift. Therefore, the total spread σ_{tot} can be expressed as a quadrature sum of a constant flat term σ_0, which depends on the experimental conditions of the measurement, with σ_D:

$$\sigma_{tot}^2 = \sigma_0^2 + \sigma_D^2 = \sigma_0^2 + \xi^2 L, \tag{A24}$$

Detailed calculation

Gas Mixture

Equation A23 can be further generalised for a generic gas mixture with g different gas components. Following Equation 2.39 of [?] the diffusion spread can be estimated as

$$\sigma^2_{D,gas} = \frac{2k_B TL}{eE}\bar{\kappa} \tag{A25}$$

where $\bar{\kappa}$ is the fractional momentum loss averaged on the various gas components as a weighted average on the mean free path of the drifting particle in each gas.

$$\bar{\kappa} = \frac{\sum_t^g \frac{\kappa_t}{\lambda_t}}{\sum_t^g \frac{1}{\lambda_t}} = \frac{\sum_t^g \kappa_t n_t \sigma_t}{\sum_t^g n_t \sigma_t} \tag{A26}$$

with the subscript t indicating the tth component of the gas. The number density of each gas component can be evaluated as:

$$n_t = \frac{\rho_t \frac{P}{P_0}\frac{T_0}{T} k_t N_A}{A_t}, \tag{A27}$$

with

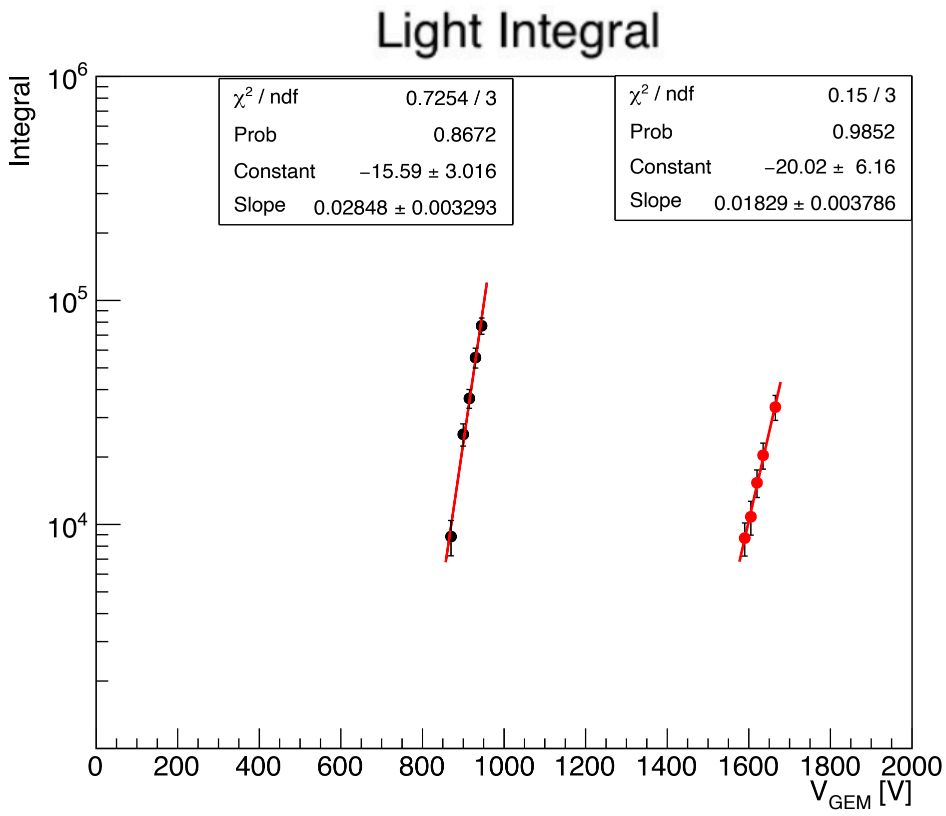
- ρ_t density of the gas at atmospheric pressure and room temperature
- P_0 is the atmospheric pressure and P the working pressure
- T_0 is the room temperature and T the working temperature
- k_t percentage of gas in the mixture
- N_A Avogadro number
- A_t molar mass of the molecule

Regarding the cross section, a simple but effective approximation is to use the impact parameter of the two colliding particles in the assumption they are spherical. Thus, the diffusion parameter in a gas mixture can be computed as:

$$\sigma^2_{D,gas} = \frac{2k_B TL}{eE}\frac{\sum_t^g \kappa_t \frac{\rho_t}{A_t} k_t (R_t + R_p)^2}{\sum_t^g \frac{\rho_t}{A_t} k_t (R_t + R_p)^2} \tag{A28}$$

Light integral vs pressure vs V_{GEM}

900 mbar



650 mbar