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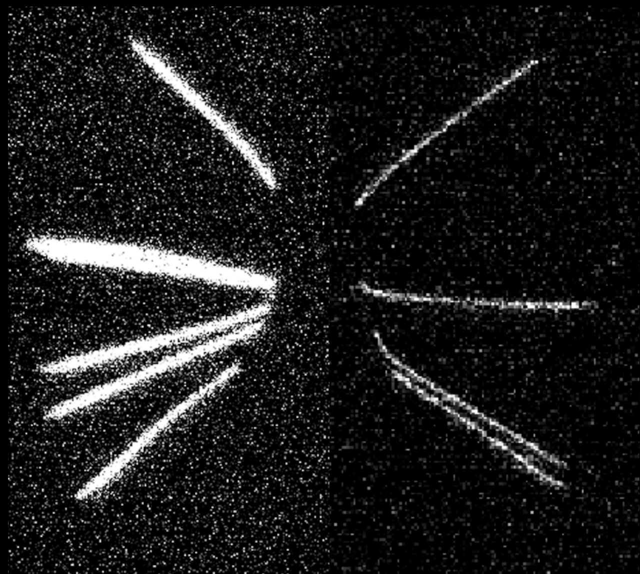
Gran Sasso Science Institute & Istituto Nazionale Fisica Nucleare

Optical negative ion drift operation 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]

IN TIUM

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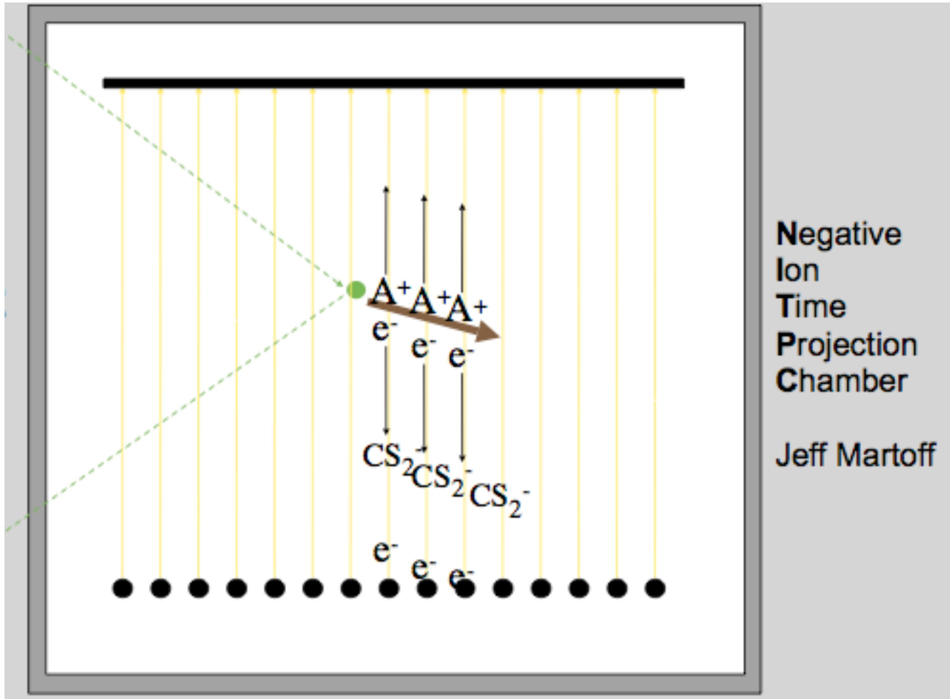
Outline

- **Negative ion drift operation with MANGO**
  - **Mobility and drift velocity measurements at LNGS atmospheric pressure (900 mbar)**
  - **Charge gain evaluation at 900 mbar (by exploiting data at 650 mbar and other CYGNO measurements)**
  - **Diffusion measurements at 650 mbar**
- **Discussion & comparison with other published results**
- **Conclusions & outlooks**

Negative ion drift operation: a recap



T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

- 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 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
- Presence of minority carriers allows fiducialization with O(mm) precision!

Negative ion drift: history and status

	Charge Readout	Optical Readout
Low pressure	Concept demonstratred in 2000 at 40 Torr Ar/Xe: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]	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]	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

MANGO at LNGS atmospheric pressure (900 mbar)

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

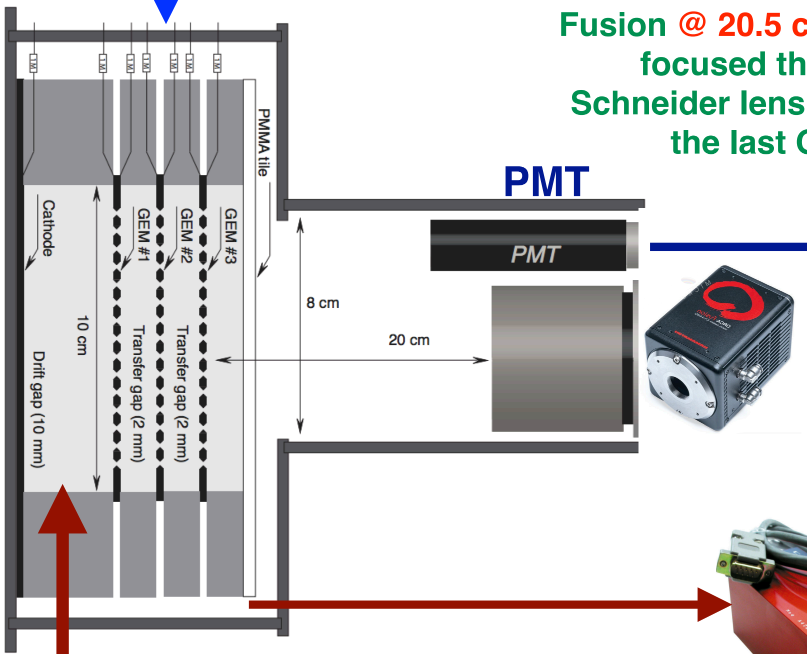
Experimental setup: the MANGO detector

Triple thin 50 um GEM stack
10 x 10 cm²

Acquired with
Hokawo 3.0 software

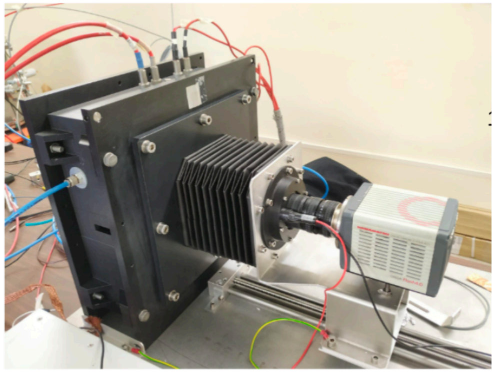
sCMOS camera Orca Fusion @ 20.5 cm distance focused through Schneider lens (f/0.95) on the last GEM

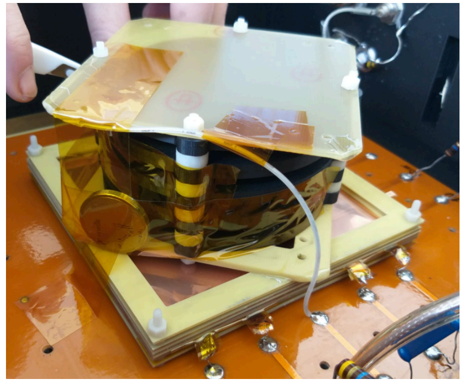
PMT



Drift gap (variable from 5 to 15 cm)

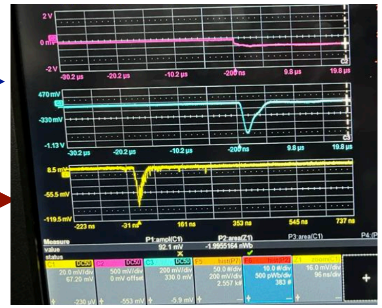
5 cm drift gap setup inside plastic gas-tight box





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

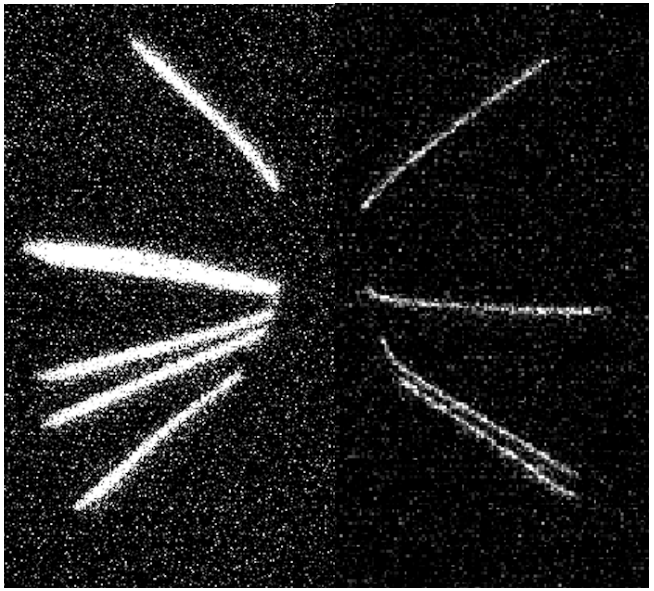
Charge sensitive preamplifier reading bottom of last GEM
300 us decay time
0.113 mV/fC

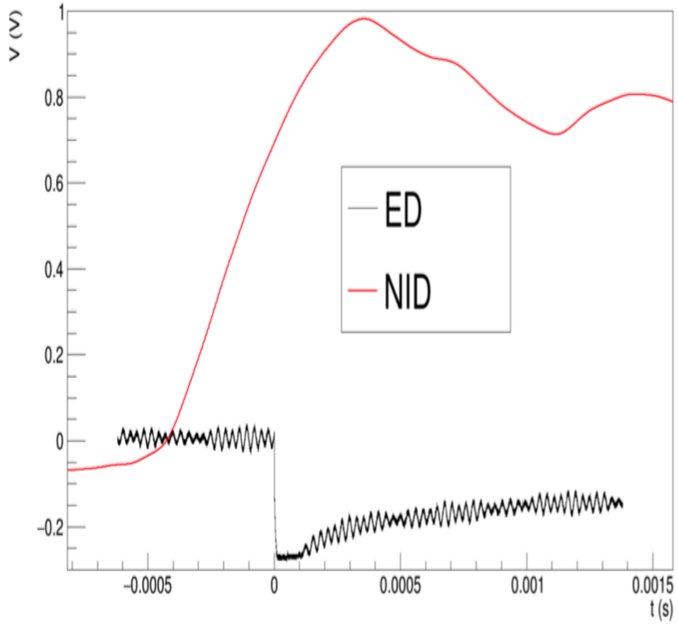


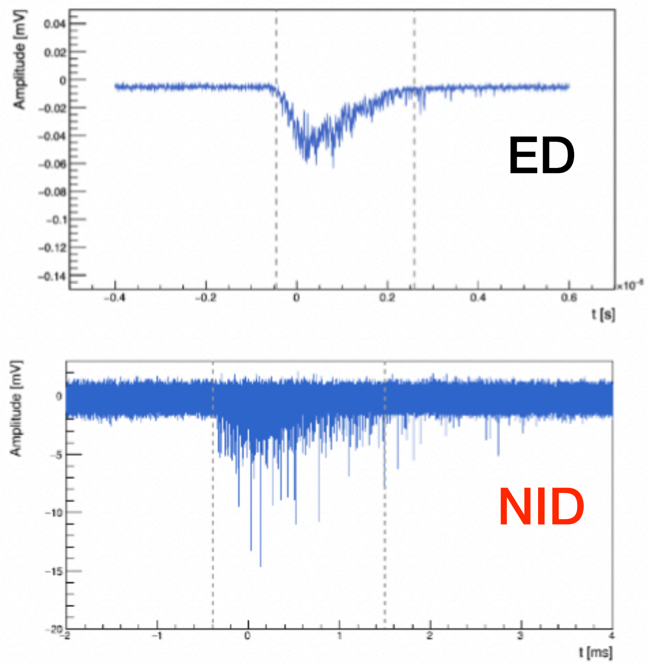
Oscilloscope

Eyes (and waveforms) can't lie

sCMOS image | **GEM preamp output** | **PMT waveforms**







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

Total GEM voltage O(1000 V)

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

Total GEM voltage O(1700 V)

O(us) rise for ED
O(ms) rise for NID

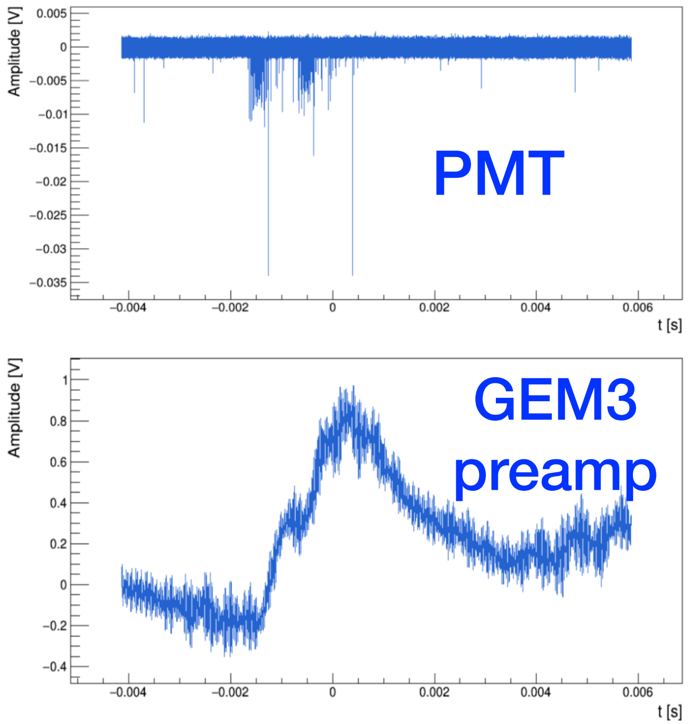
O(0.1 us) time extent for ED
O(10 ms) time extent for NID

0.90 atm

(LNGS atmospheric pressure)

*First time ever NID are observed with PMTs!

NID PMT waveforms: how peculiar!



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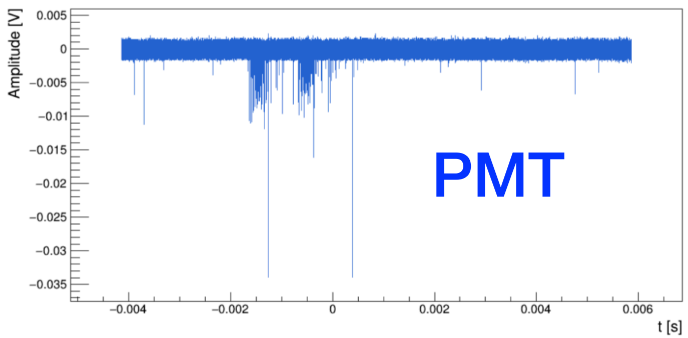

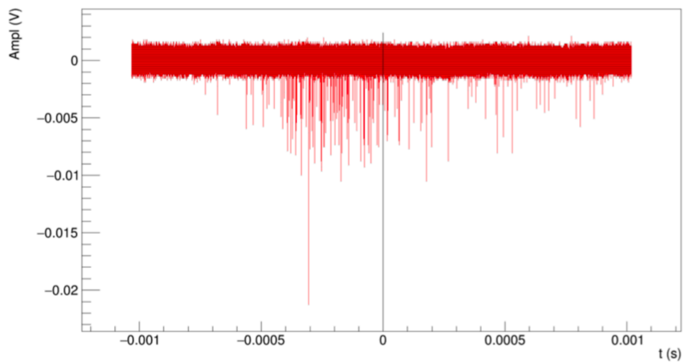

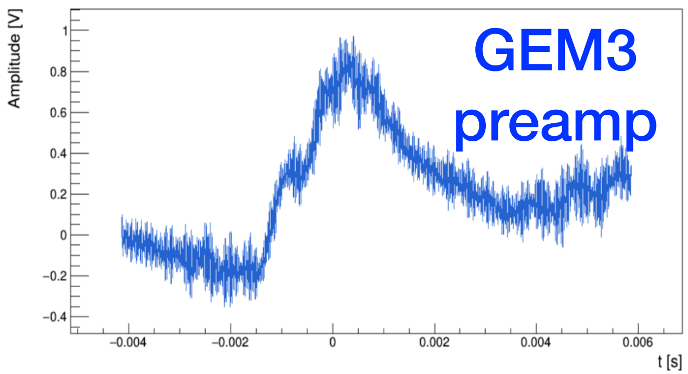

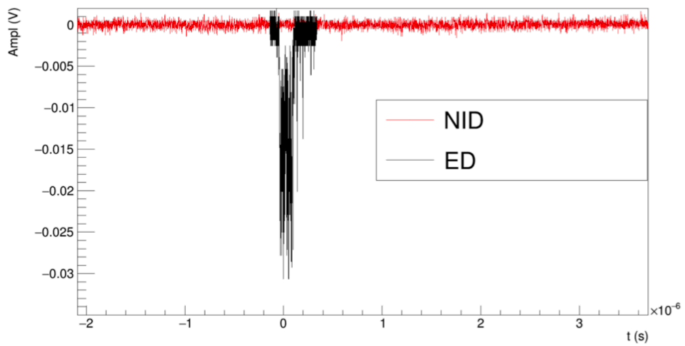

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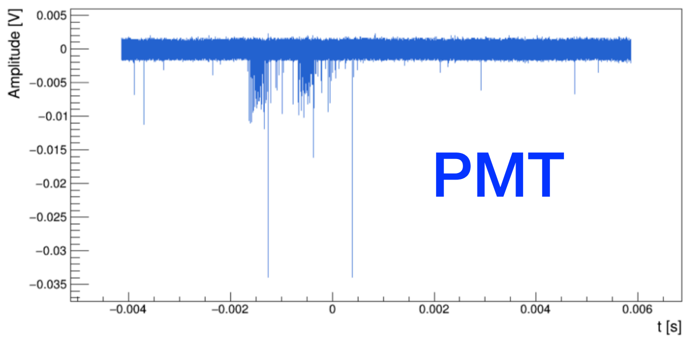
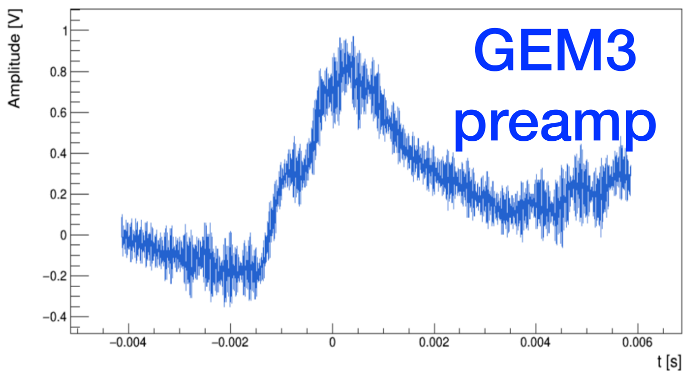
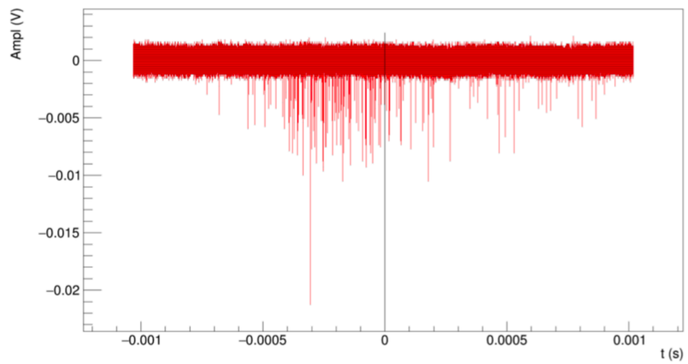
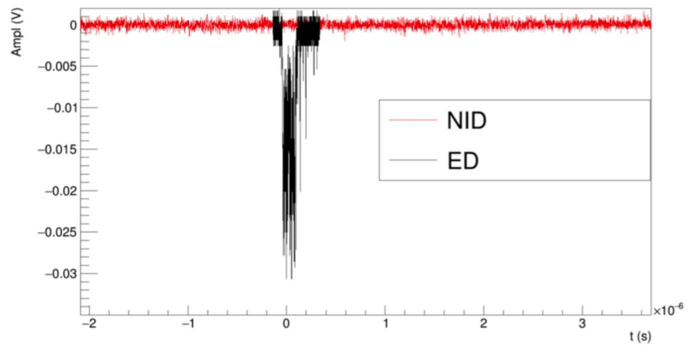
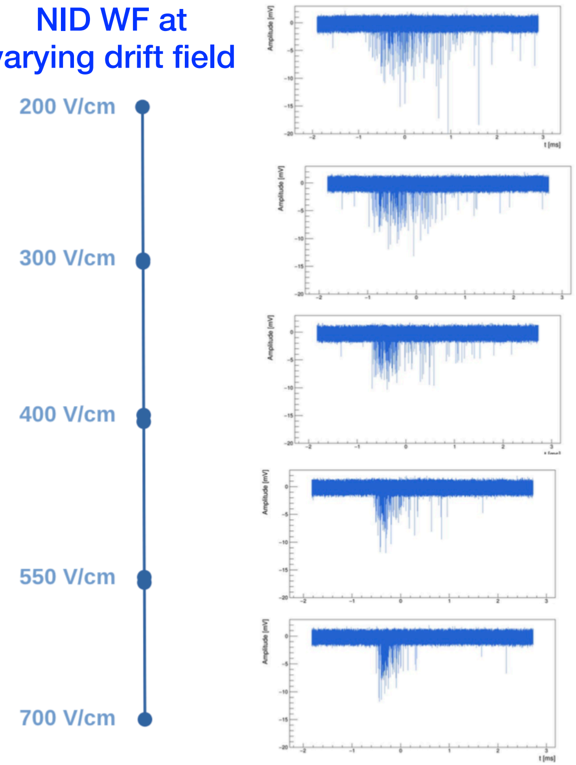








NID WF at varying drift field



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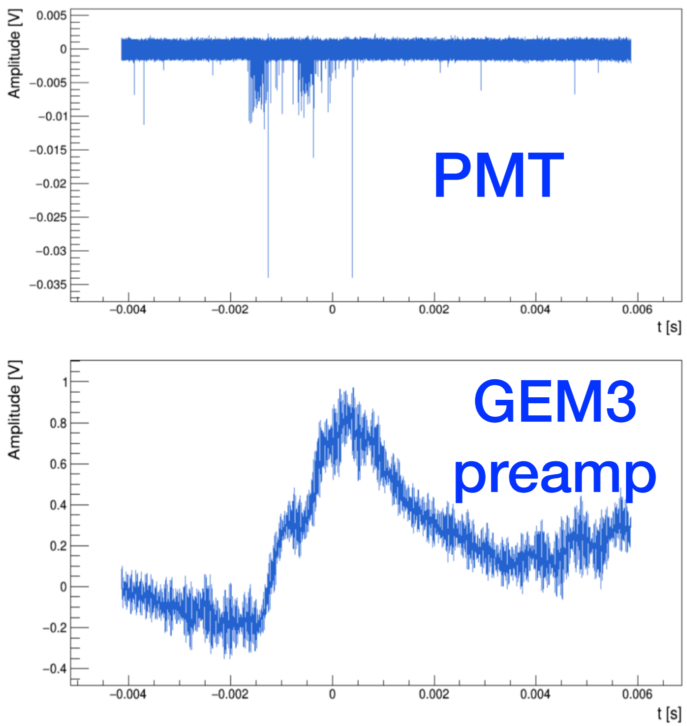
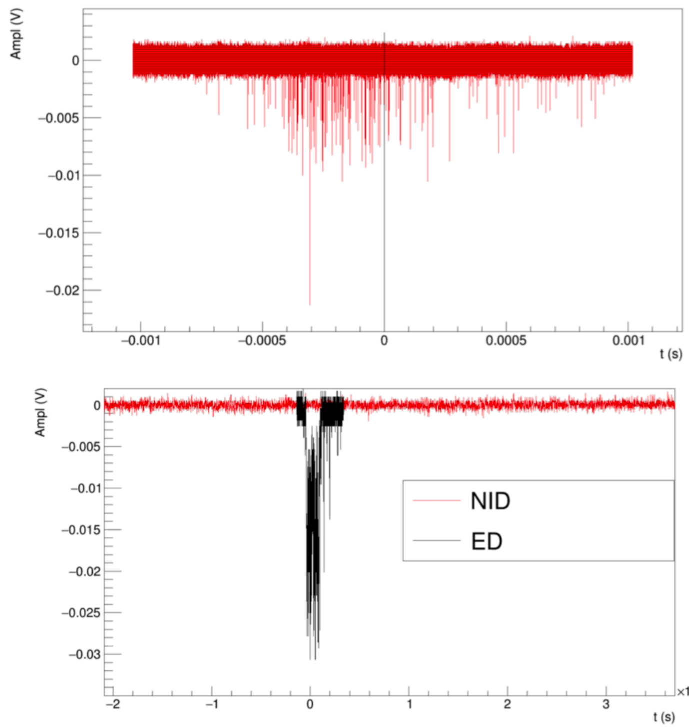
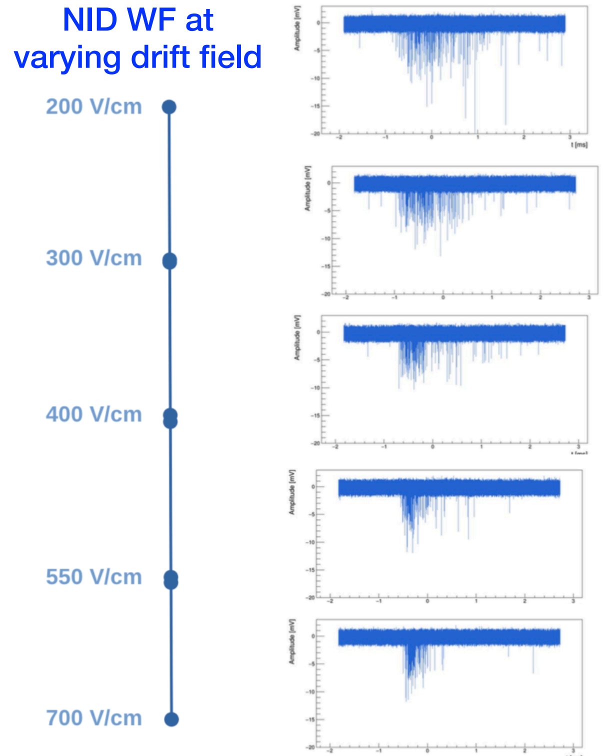






Given the PMT bandwidth and the "slow" arrival of charge carriers, individual clusters are visible in the PMT signal --> ideally, this could allow cluster counting technique for superior energy resolution

H. Fischle et al., NIM A 301, 202 (1991)

G. Cataldi et al., NIM A 386, 458 (1997)

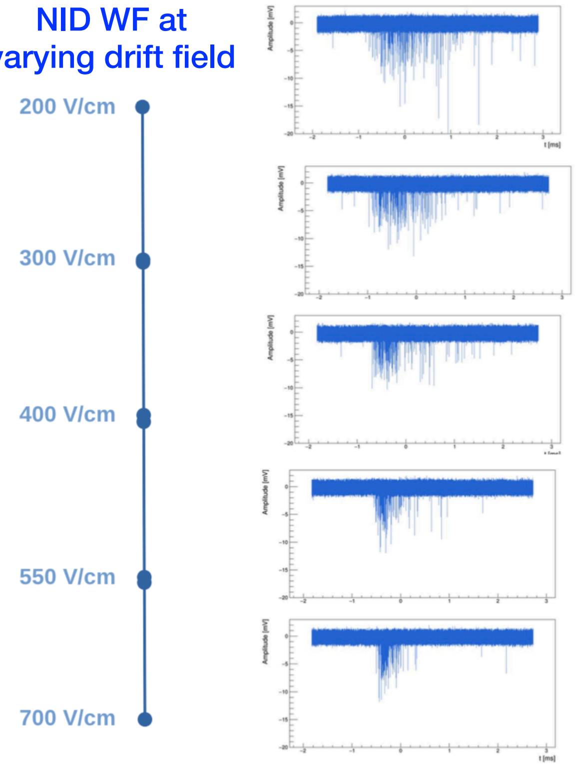
G. Chiarello et al., JINST 12 (07) C07021

Not a topic of this talk, but ongoing work along this line

*First time ever NID are observed with PMTs!

NID PMT waveforms analysis

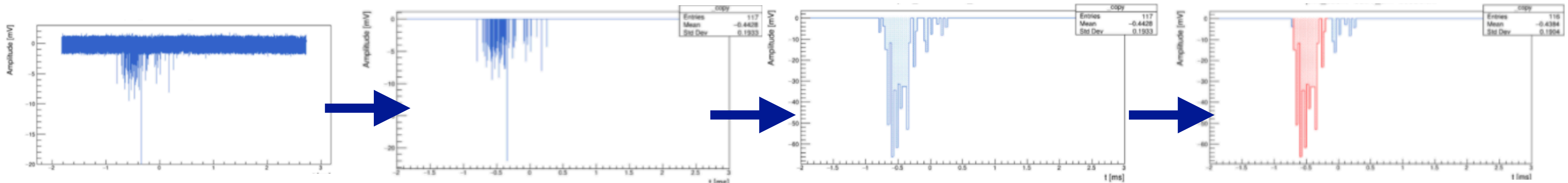
NID WF at varying drift field



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

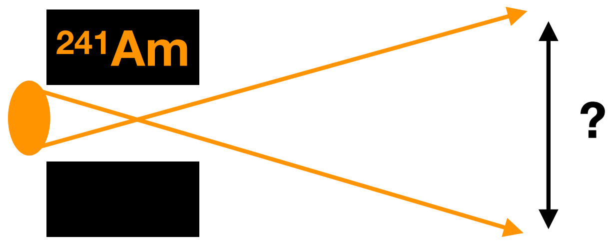
- Initial approach ⇒ Time rebinning
  a. **Threshold** ➡ Only peaks above 6*RMS are taken into account
  b. **Rebin** ➡ Selected points are put into histogram
  c. **Delimitation** ➡ Start (end) when 2 bins are above(below) 10 mV
  d. **Systematics** ➡ Varying #bins & threshold voltage **(reworked analysis)**

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

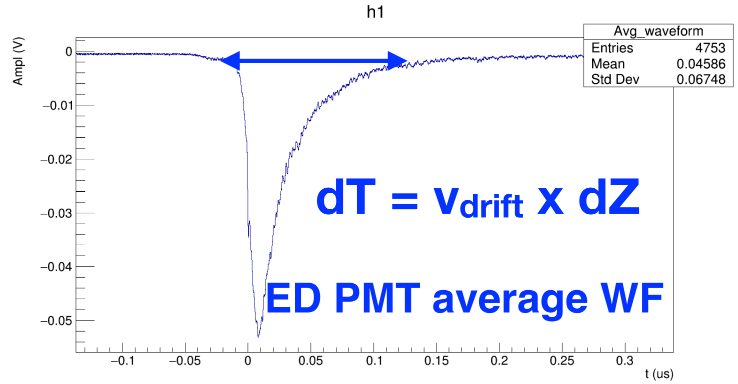
NID drift velocity and mobility from PMT WF analysis



Field cage rings

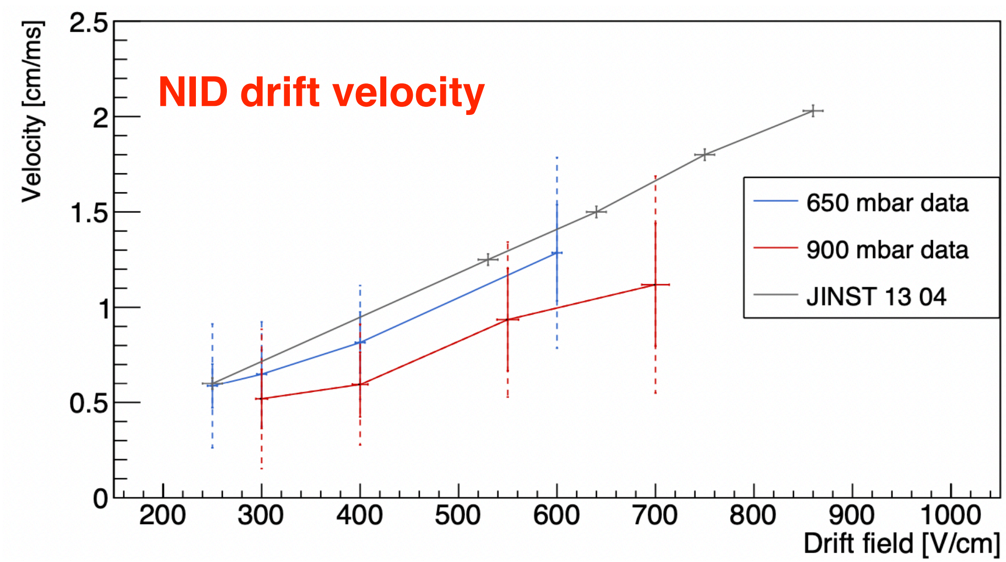
From ED PMT signal, given the known drift velocity, we estimate the alpha dZ spread

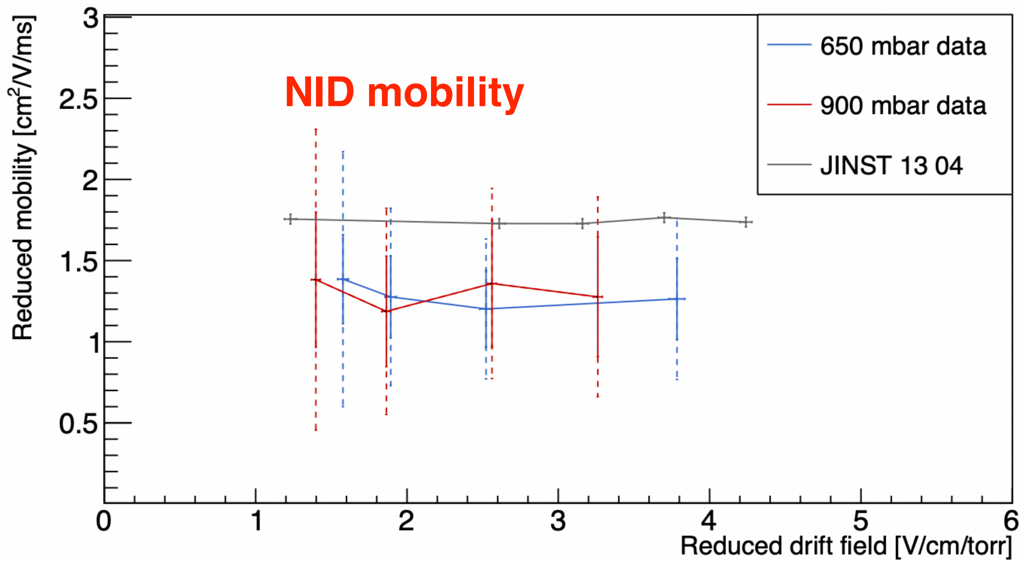
dZ = 7 mm @ 900 mbar
dZ = 15 mm @ 650 mbar



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**



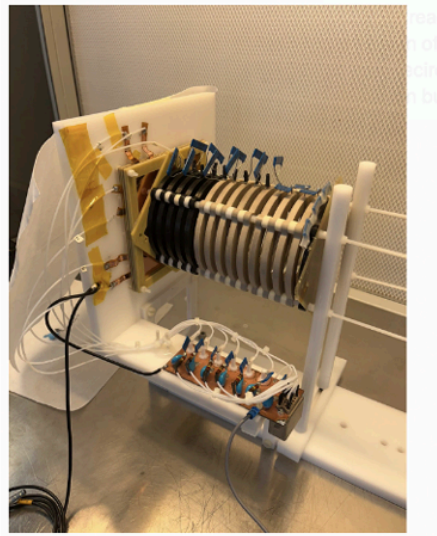


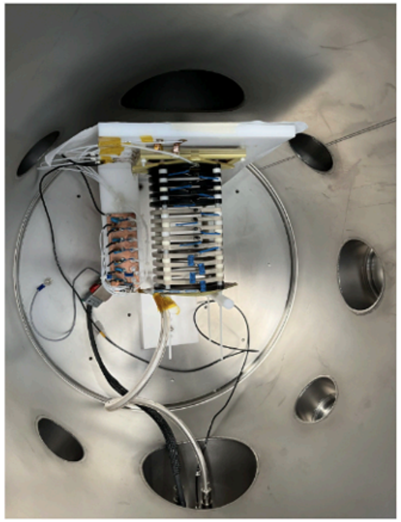
Black points from published data with pixel charge readout and same mixture at 610 Torr [8]

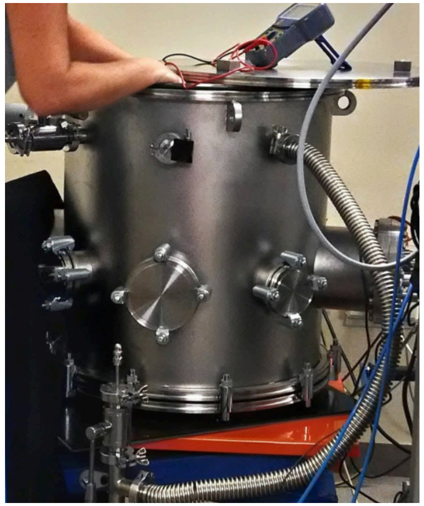
MANGO experimental setup for below atmospheric pressure measurements

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





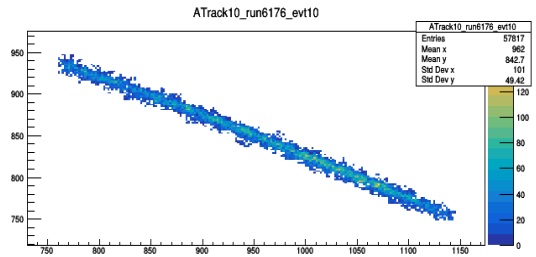


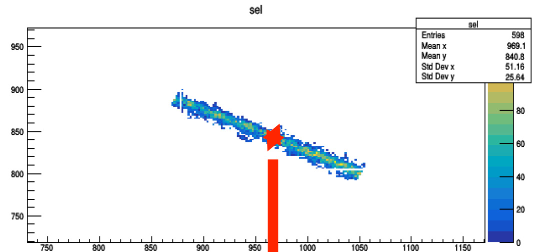
NOTE: diffusion is expected to be independent of pressure

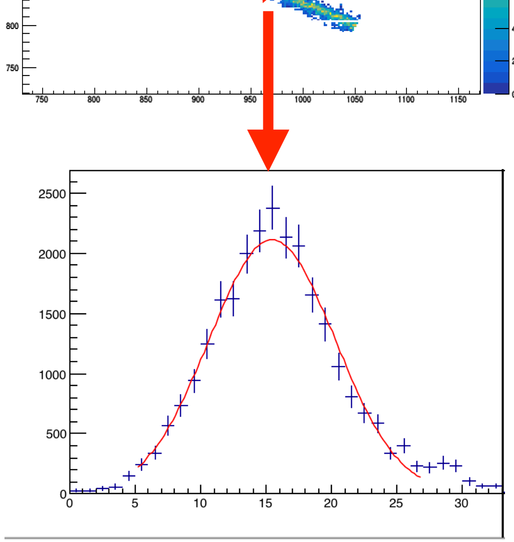
- Because of geometry constraints, the light yield reaching the camera sensor in this configuration is reduced of 2/3
- For this reason, we acquired diffusion measurement data for He:CF_4 60:40 and He:CF_4:SF_6 60:38.4:1.6 at 650 mbar
- In addition, combining light yield measurement at 900 mbar and 650 mbar allows us to provide an estimate of the gain achieved
- We further extended our measurement to a second NID mixture where we copletely remove the Helium: CF_4:SF_6 98.4:1.6
- In order to have long enough alpha tracks and enough gain, CF_4:SF_6 98.4:1.6 data taken at 305 mbar

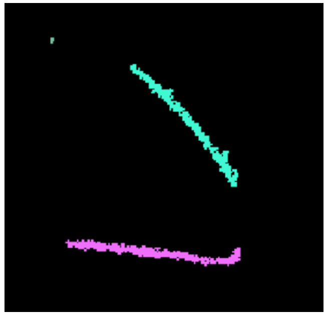
sCMOS images analysis for gain & diffusion measurements

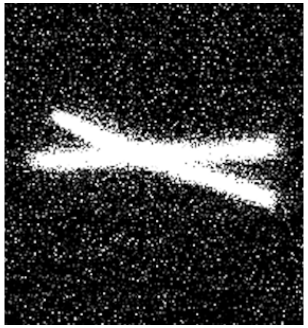
- Alphas selection:
  - tracks reconstructed with iterative DBSCAN algorithm [10]
  - track length > 1.47 cm
  - track slimness < 0.3
  - # of peaks in the cutted transverse profile == 1 (select single tracks)
  - Chi2/nDOF of transverse fit of cutted profile < 5 (remove additional multiple tracks)



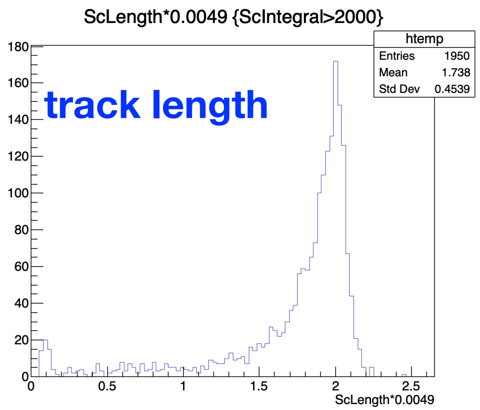


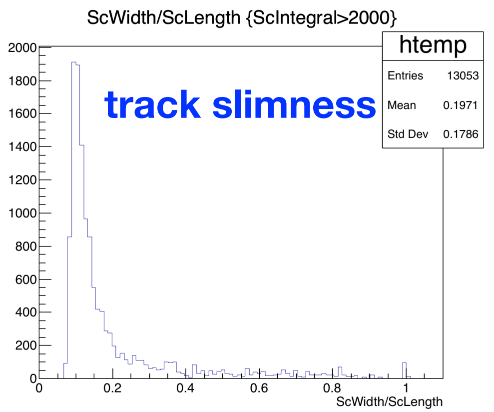






NOTE: same <u>identical analysis & cuts</u> applied to all the ED and NID data





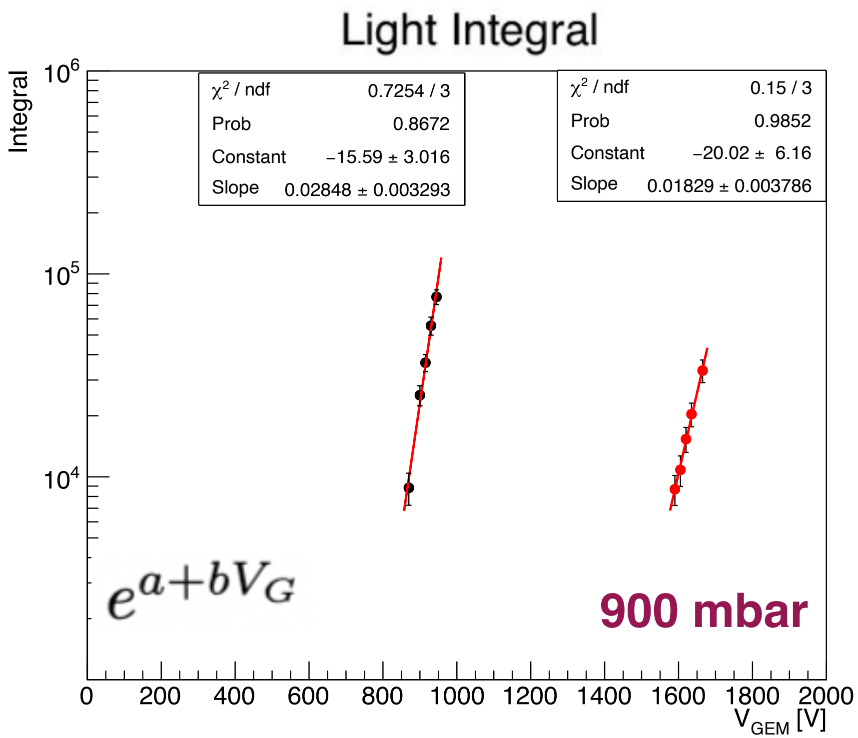
- Full track **integral** used to estimate **light yield**
- **Sigma** of cutted track profile used to estimate **diffusion**

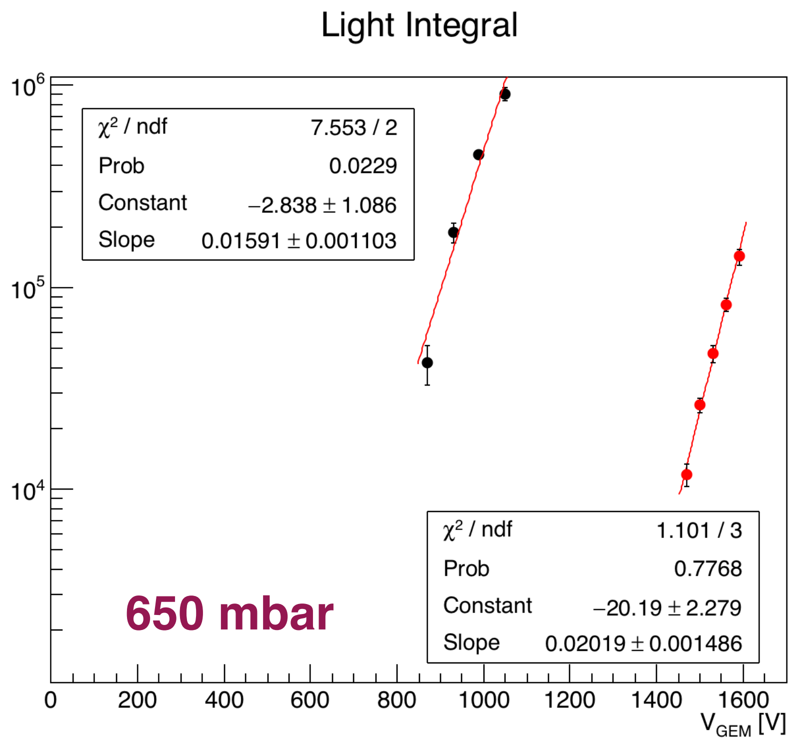
[10] E. Baracchini et al, JINST 15 (2020) 12 T12003

Light yield at 900 mbar and 650 mbar and NID gain evaluation

Gain measurements @ 900 mbar and 650 mbar

Alpha track light Integral measurements





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

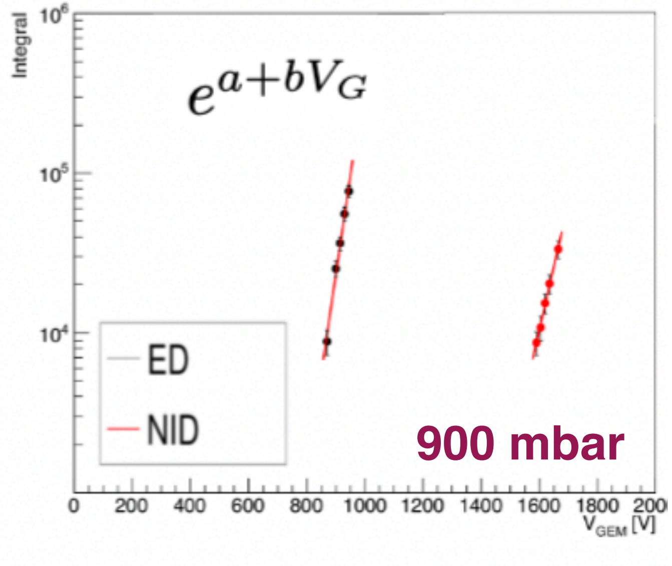
He:CF_4:SF_6
59:39.4:1.6
0.4 kV/cm
(NID)

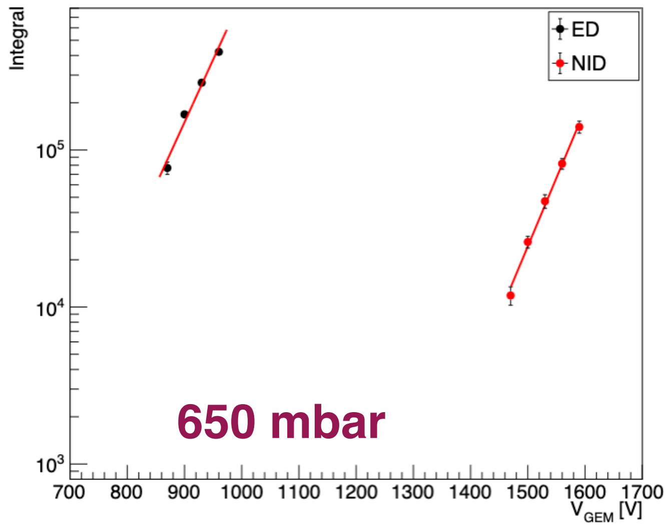
Nice exponential behaviour observed also for He:CF_4:SF_6 NID mixture

By assuming same light to charge ratio production in ED and NID

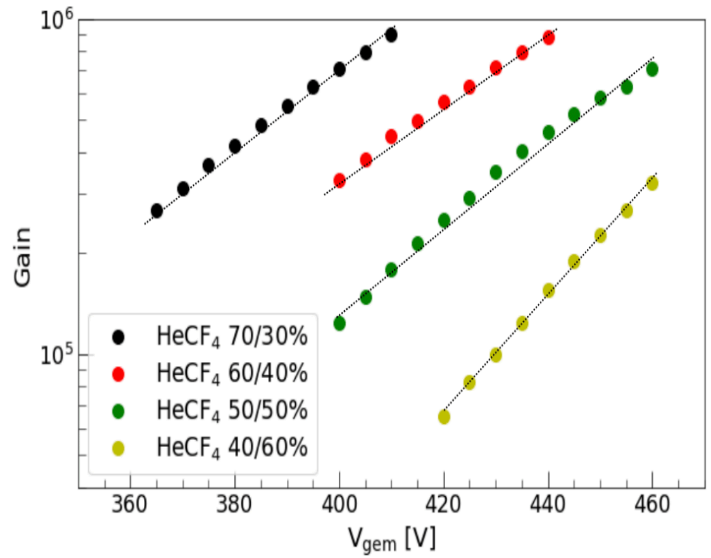
NID charge gain evaluation

Alpha track light Integral measurements





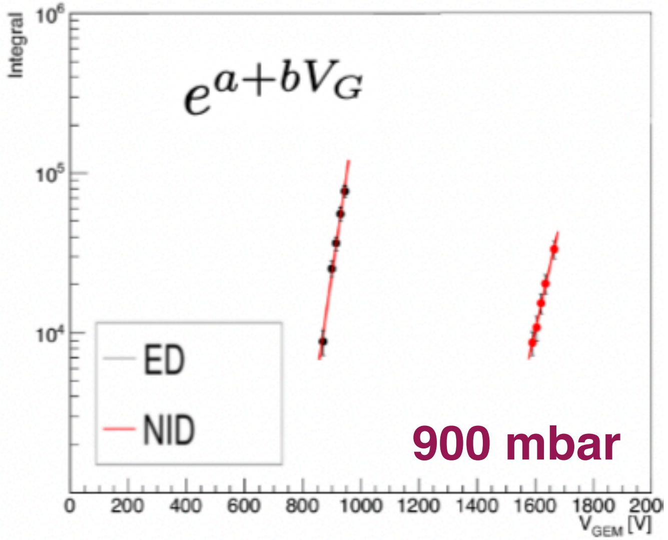
Absolute ED gain measurement at 1 bar

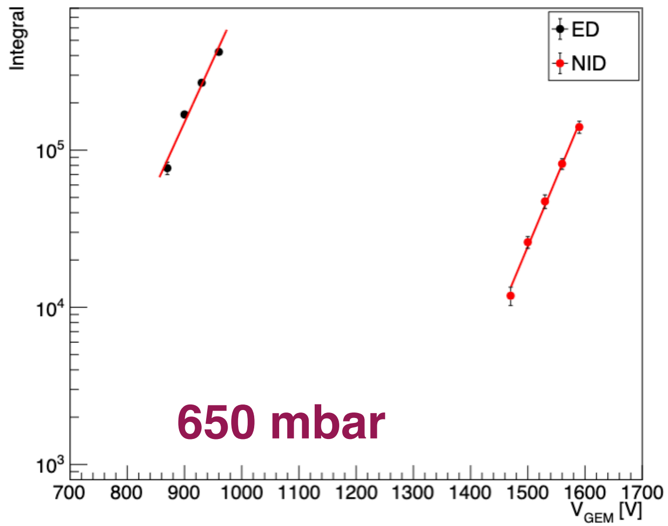


By assuming same light to charge ratio production in ED and NID

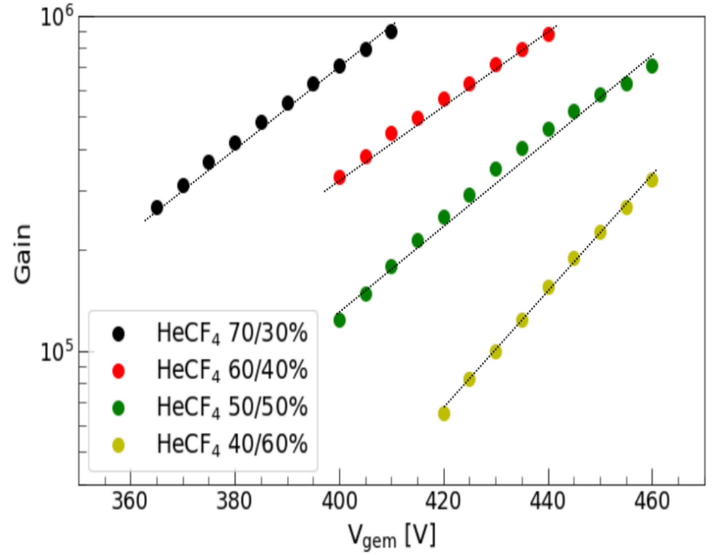
NID charge gain evaluation

Alpha track light Integral measurements





Absolute ED gain measurement at 1 bar



From T. Thorpe & S. Vahsen NIM A 1045 (2023) 167438

$$\frac{\ln(G)}{n_g pt} = A_0 \left(\frac{V_G}{n_g pt}\right)^m exp\left(-B_0\left(\frac{n_g pt}{V_G}\right)^{1-m}\right) + C_0$$

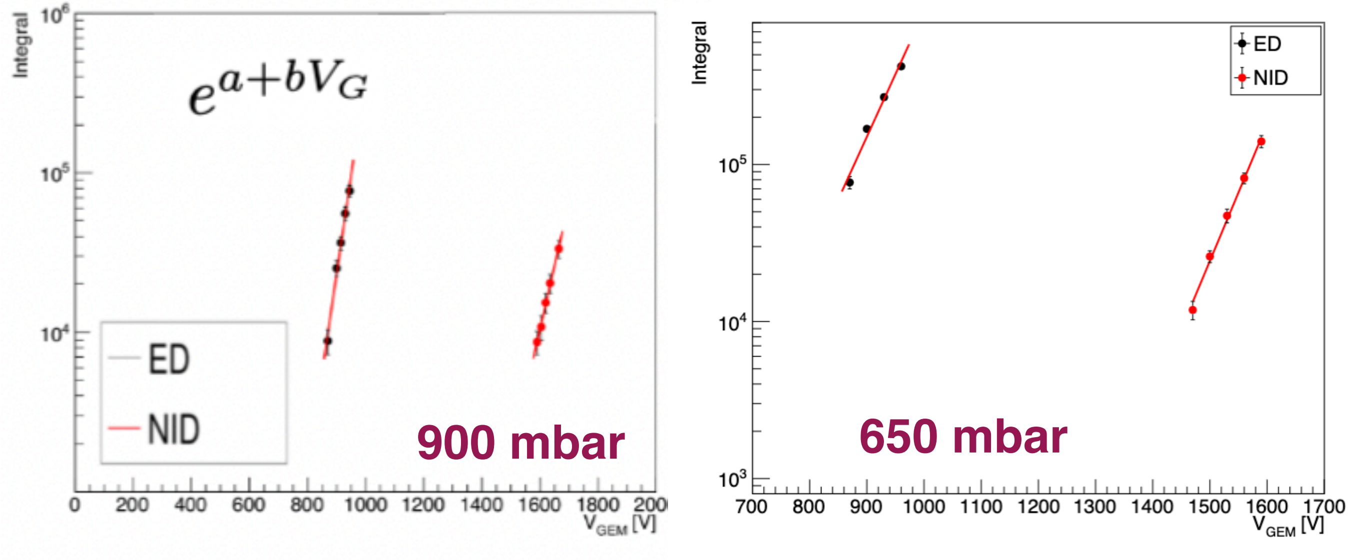
Need 5 experimental observation to determine 5 parameters

$$\ln(G) = Ap^q V_G^m \cdot e^{-Bp^q V_G^{m-1}} + C_0,$$

NOTE: q is introduced to account for Penning transfer

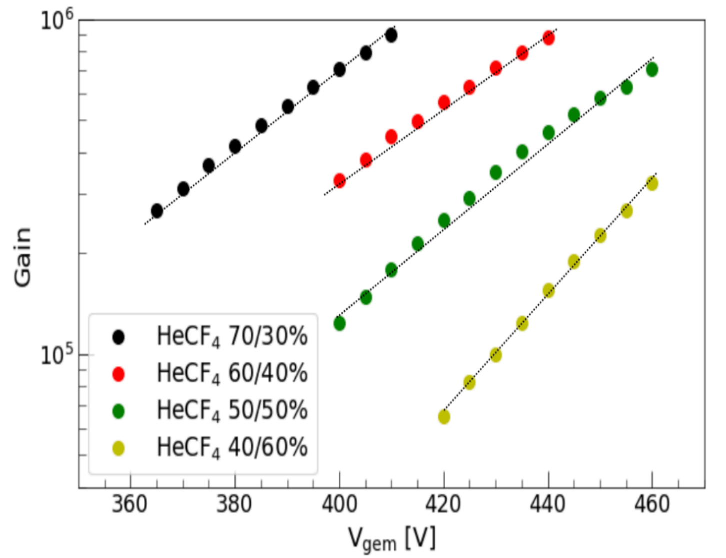
NID charge gain evaluation

Alpha track light Integral measurements



From T. Thorpe & S. Vahsen NIM A 1045 (2023) 167438

Absolute ED gain measurement at 1 bar



$$\frac{\ln(G)}{n_g pt} = A_0 \left(\frac{V_G}{n_g pt}\right)^m exp\left(-B_0\left(\frac{n_g pt}{V_G}\right)^{1-m}\right) + C_0$$

Need 5 experimental observation to determine 5 parameters

$$\ln(G) = Ap^q V_G^m \cdot e^{-Bp^q V_G^{m-1}} + C_0,$$

NOTE: q is introduced to account for Penning transfer

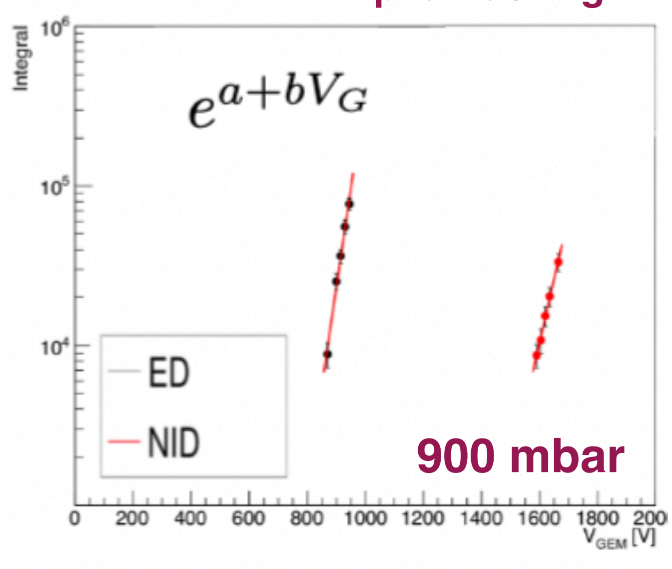
- ED dG/dV_{GEM} with alpha tracks @ 650 mbar
- ED dG/dV_{GEM} with ^{55}Fe events @ 900 mbar
- ED alpha tracks dG/dp (data @ 650 and 900 mbar)
- ED dG/dp from ^{55}Fe events @ 1000 mbar +/- 15mbar
- Absolute gain measurement at 1000 mbar

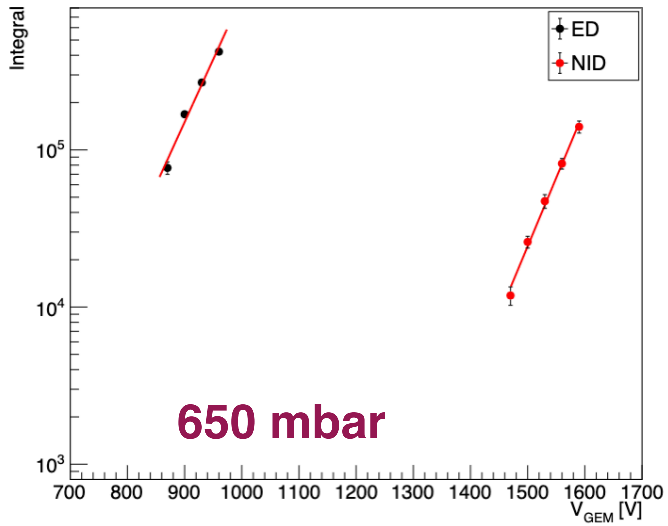
Last two from independent measurement within CYGNO

By assuming same light to charge ratio production in ED and NID

NID charge gain evaluation

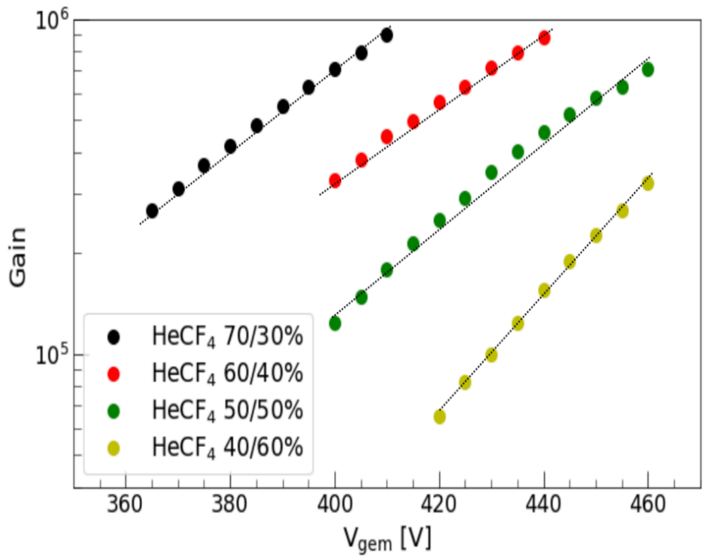
Alpha track light Integral measurements





From T. Thorpe & S. Vahsen NIM A 1045 (2023) 167438

Absolute ED gain measurement at 1 bar



$$\frac{\ln(G)}{n_g pt} = A_0 \left(\frac{V_G}{n_g pt}\right)^m exp\left(-B_0 \left(\frac{n_g pt}{V_G}\right)^{1-m}\right) + C_0$$

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- ED dG/dV$_{GEM}$ with alpha tracks @ 650 mbar
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- ED alpha tracks dG/dp (data @ 650 and 900 mbar)
- ED dG/dp from ^{55}Fe events @ 1000 mbar +/- 15mbar
- Absolute gain measurement at 1000 mbar

Last two from independent measurement within CYGNO

A	B	C_0	m	q
(-8.9 ± 1.9) 10^{-6}	-21.8 ± 1.2	42 ± 18	0.85 ± 0.01	0.023 ± 0.002

G^{ED} (Vgem = 930 V) = G^{NID} (Vgem = 1575 V)

> 5 x 10^3 @ 900 mbar

Allows O(keV) threshold for charge readout!

(more precise number under evaluation, but surely in this ballpark)

....last but DEFINITELY not least: diffusion measurements beyond expectations!

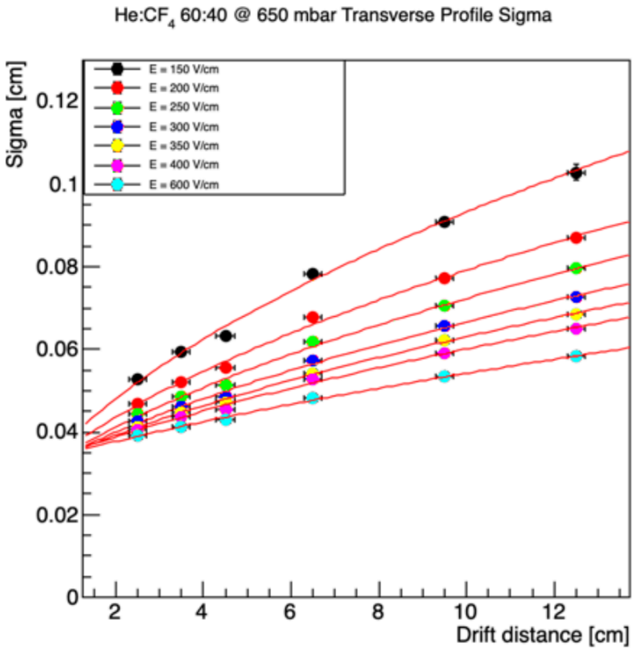
He:CF_4 (ED)
60:40 @ 650 mbar

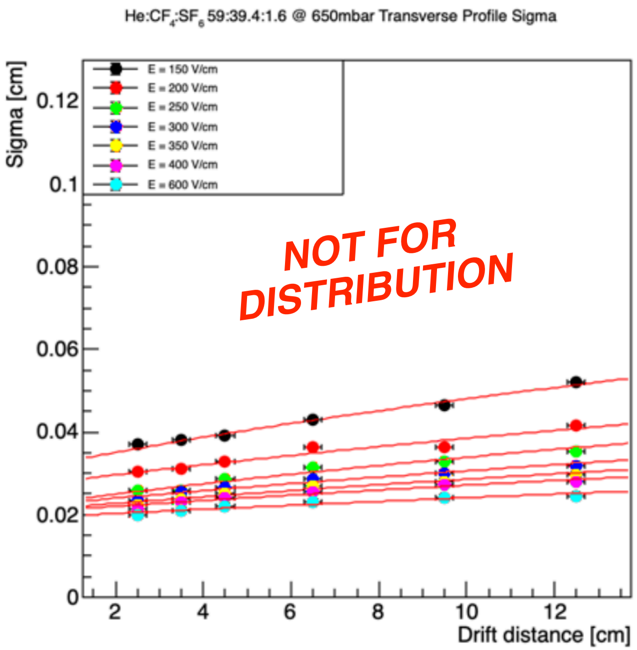
He:CF_4:SF_6 (NID1)
59:39.4:1.6 @ 650 mbar

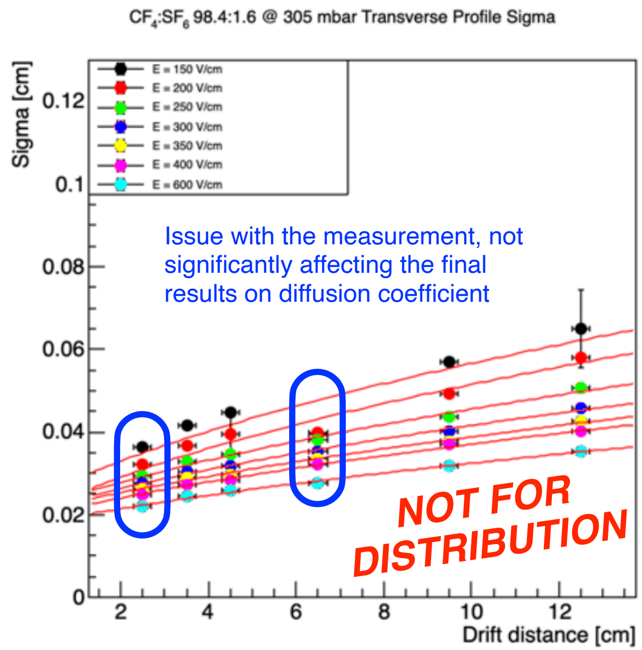
CF_4:SF_6 (NID2)
98.4:1.6 @ 305 mbar

Measured diffusion versus distance at varying drift fields

He:CF_4 (ED) 60:40 @ 650 mbar	He:CF_4:SF_6 (NID1) 59:39.4:1.6 @ 650 mbar	CF_4:SF_6 (NID2) 98.4:1.6 @ 305 mbar







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

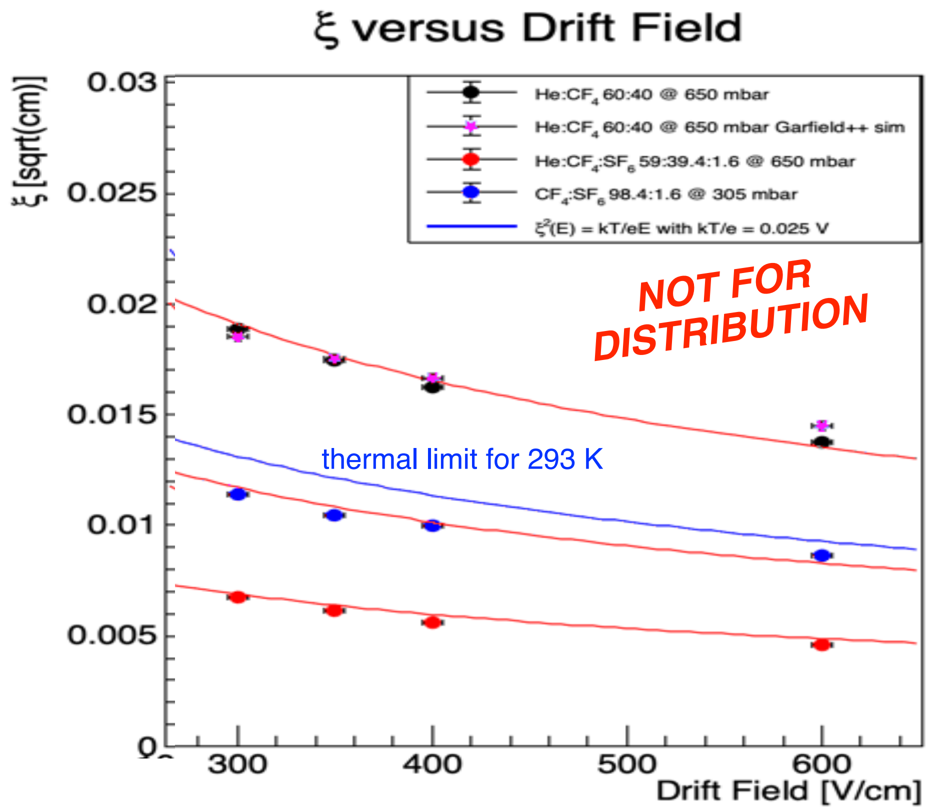
Low drift fields affected by additional systematics

E [V/cm]	σ_0^{ED} [μm]	ξ^{ED} [μm/$\sqrt{\text{cm}}$]	σ_0^{NID1} [μm]	ξ^{NID1} [μm/$\sqrt{\text{cm}}$]	σ_0^{NID1} [μm]	ξ^{NID1} [μm/$\sqrt{\text{cm}}$]
150	270 ± 30	280 ± 5	320 ± 30	110 ± 10	314 ± 10	110 ± 10
200	280 ± 20	230 ± 3	260 ± 30	90 ± 20	320 ± 30	110 ± 10
250	280 ± 20	210 ± 3	220 ± 20	81 ± 10	320 ± 30	110 ± 10
300	300 ± 10	190 ± 2	220 ± 20	68 ± 10	320 ± 30	110 ± 10
350	300 ± 10	170 ± 10	210 ± 20	60 ± 10	320 ± 30	110 ± 10
400	310 ± 10	160 ± 10	210 ± 20	56 ± 9	320 ± 30	110 ± 10
600	320 ± 5	140 ± 10	200 ± 20	45 ± 10	320 ± 30	110 ± 10

Diffusion coefficient versus drift field

We observed data at 150 V/cm, 200 V/cm and 250 V/cm suffers additional diffusion effects due to disuniformity of drift field close to the border, so these data are removed from this plots

$$\xi(E) = \sqrt{\frac{2kT_{eff}}{eE}}$$



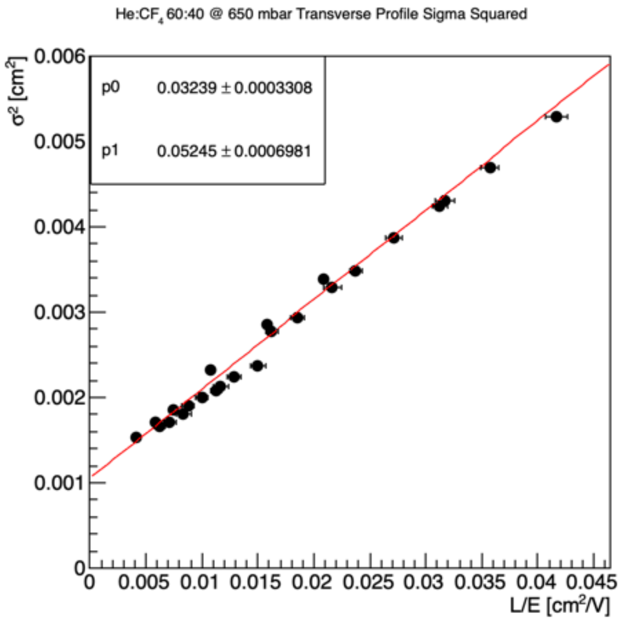
He:CF_4 60:40 ED data highly consistency with Garfield++ simulation @ 650 mbar strongly demontrate the robustness of the experimental method & analysis

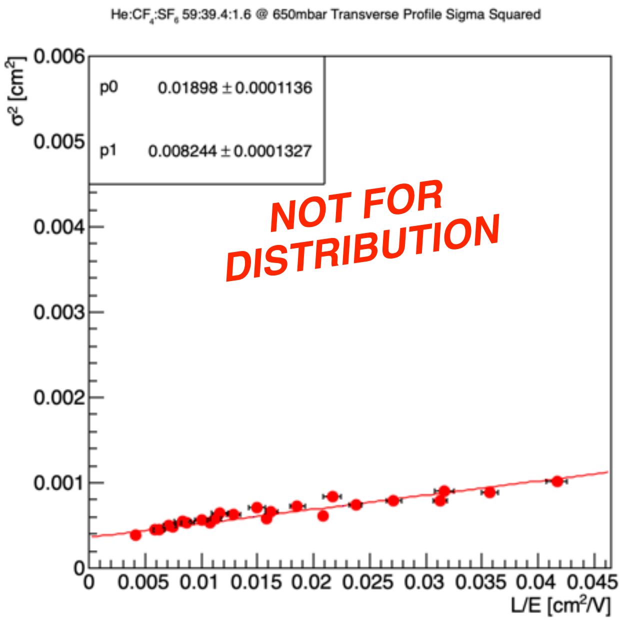
Diffusion coeffient behaviours following expected 1/sqrt(E)

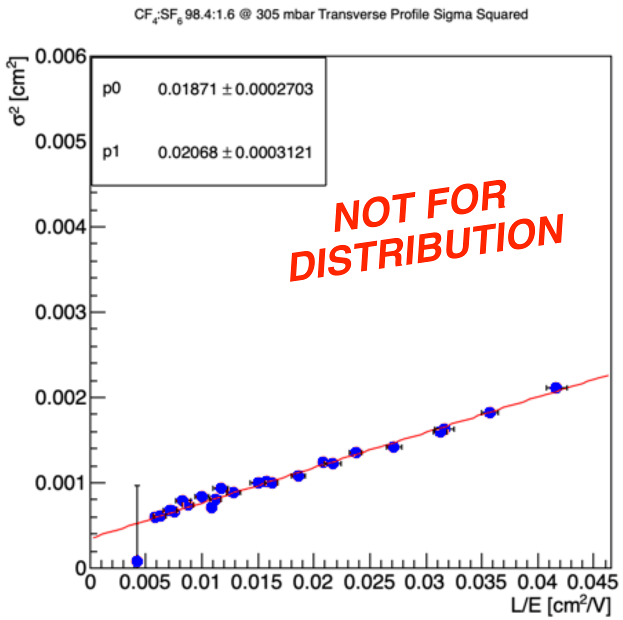
For a better estimation of the actual parameters see next slide

Measured diffusion versus L/E and parameters estimation

We observed data at 150 V/cm, 200 V/cm and 250 V/cm suffers additional diffusion effects due to disuniformity of drift field close to the border, so these data are removed from this plots







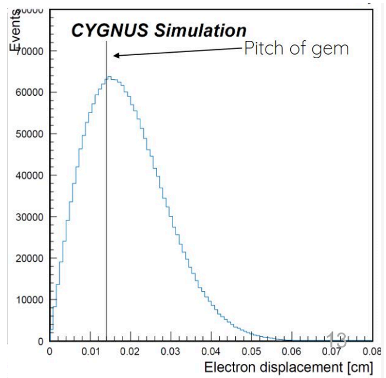
$$\sigma^2_{meas} = \sigma_0^2 + \frac{2kT_{eff}}{e}\frac{L}{E} = p_0^2 + 2p_1\frac{L}{E}$$

kT/e thermal = 0.0257 V

	$He:CF_4$ 60:40	$He:CF_4:SF_6$ 60:38.4:1.6	$CF_4:SF_6$ 98.4:1.6
σ_0 [um]	324 +/- 3	190 +/- 1	187 +/- 3
kT_{eff}/e [V]	0.0525 +/- 0.0007	0.00824 +/- 0.0001	0.0207 +/- 0.0003

Measured diffusion versus L/E and parameters: discussion

- **Constant diffusion term σ_0 significantly reduced with NID compared to ED**
- **Constant diffusion term σ_0 consistent between two NID mixtures with very different energy-dependent (i.e. kT_{eff}/e) terms**
- **We believe that ED σ_0 comes from charge build-up, that due to repulsion spreads out the avalanche electrons in between GEMs more than expected from pure diffusion**
- **With NID operation, the same charge reaches the GEM but much more separated in time due to the lower mobility, and therefore no charge build-up happens and NID σ_0 reduces to only the geometrical factor —> see Lindsey's slides!**



Most probable value around 200 um

$$\sigma^2_{meas} = \sigma_0^2 + \frac{2kT_{eff}}{e}\frac{L}{E} = p_0^2 + 2p_1\frac{L}{E}$$

kT/e thermal = 0.257 V

	He:CF_4 60:40	He:CF_4:SF_6 60:38.4:1.6	CF_4:SF_6 98.4:1.6
σ_0 [um]	324 +/- 3	190 +/- 1	187 +/- 3
kT_{eff}/e [V]	0.0525 +/- 0.0007	0.00824 +/- 0.0001	0.0207 +/- 0.0003

Measured diffusion versus L/E and parameters: discussion

- He:CF_4:SF_6 gas mixture diffusion is 3.6 times below the thermal limit (+/- 80 K)
- If Helium is removed from the mixture while keeping SF_6 content the same, diffusion increases to nearly the thermal limit (+/- 220 K)
- The difference between NID mixtures diffusion with and without Helium correspond to +/- the amount of CF_4 in the mixture
  - 0.0207 V*0.384 = 0.00795 V
- It appears that SF_6/He scattering during drift do not contribute to diffusion
- New diffusion measurement with varying He content under preparation to experimentally test and demonstrate this hypothesis
- If this proven true, an He:SF_6 99:1 gas mixture (for charge readout) could possibly display nearly no diffusion!

$$\sigma^2_{meas} = \sigma_0^2 + \frac{2kT_{eff}}{e}\frac{L}{E} = p_0^2 + 2p_1\frac{L}{E}$$

kT/e thermal = 0.0257 V

	He:CF_4 60:40	He:CF_4:SF_6 60:38.4:1.6	CF_4:SF_6 98.4:1.6
σ_0 [um]	324 +/- 3	190 +/- 1	187 +/- 3
kT_{eff}/e [V]	0.0525 +/- 0.0007	0.00824 +/- 0.0001	0.0207 +/- 0.0003

Comparison with other measurements

Nucl.Instrum.Meth.A 440 (2000) 355-359

16.5, 40 Torr
MWPC readout

Diffusion measured by moving a 300 µm wide collimator on top of the sensing wire

R.m.s. diffusion of negative ions measured in noble gas mixtures with CS_2. Drift length was 15 cm. The diffusion values reported are corrected for the finite sizes of apertures and for electric field mismatch between drift and proportional counter regions

Gas	Pressure (Torr)	E (kV/m)	Transverse diffusion (mm r.m.s.)
Ar mix	40	47.0	$0.12\ ^{+0.05}_{-0.1}$
Ar mix	40	35.3	$0.21\ ^{+0.02}_{-0.1}$
Ar mix	40	23.5	0.38 ± 0.02
Xe mix	40	47.0	$0.13\ ^{+0.05}_{-0.1}$
Xe mix	16.5	23.5	0.33 ± 0.03

Even though thermal behaviour is claimed in the text, working out the numbers factor 2-3 below thermal is found + falling faster than 1/sqrt(E) expected from thermal

Only transverse diffusion measurements can be compared among themselves due to electric anysotropy that induces larger longitudinal diffusion

(all other results on slide 9 are longitudinal diffusion measurements)

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Nucl.Instrum.Meth.A 555 (2005) 55-58

40 Torr
MWPC readout

Diffusion measured by moving the position where the photoelectrons where generated on the cathode by 40, 125 μm steps.

Gas Mixture	Slope	Temperature
$100\%CS_2$	0.16 ± 0.02 Vmm/Torr	360 ± 40 K
$90\%CS_2$-$10\%Ar$	0.13 ± 0.03 Vmm/Torr	300 ± 80 K
$50\%CS_2$-$50\%Ar$	0.11 ± 0.02 Vmm/Torr	260 ± 40 K
$25\%CS_2$-$75\%Ar$	0.10 ± 0.02 Vmm/Torr	240 ± 50 K

Effective diffusion temperature dependence on amount of Ar, going below the thermal limit

Only transverse diffusion measurements can be compared among themselves due to electric anysotropy that induces larger longitudinal diffusion

(all other results on slide 9 are longitudinal diffusion measurements)

Comparison with other measurements

Nucl.Instrum.Meth.A 440 (2000) 355-359	Nucl.Instrum.Meth.A 555 (2005) 55-58	Nucl.Instrum.Meth.A 1014 (2021) 165706

16.5, 40 Torr
MWPC readout

Diffusion measured by moving a 300 μm wide collimator on top of the sensing wire

R.m.s. diffusion of negative ions measured in noble gas mixtures with CS_2. Drift length was 15 cm. The diffusion values reported are corrected for the finite sizes of apertures and for electric field mismatch between drift and proportional counter regions

Gas	Pressure (Torr)	E (kV/m)	Transverse diffusion (mm r.m.s.)
Ar mix	40	47.0	$0.12\ ^{+0.05}_{-0.1}$
Ar mix	40	35.3	$0.21\ ^{+0.02}_{-0.1}$
Ar mix	40	23.5	0.38 ± 0.02
Xe mix	40	47.0	$0.13\ ^{+0.05}_{-0.1}$
Xe mix	16.5	23.5	0.33 ± 0.03

Even though thermal behaviour is claimed in the text, working out the numbers factor 2-3 below thermal is found + falling faster than 1/sqrt(E) expected from thermal

40 Torr
MWPC readout

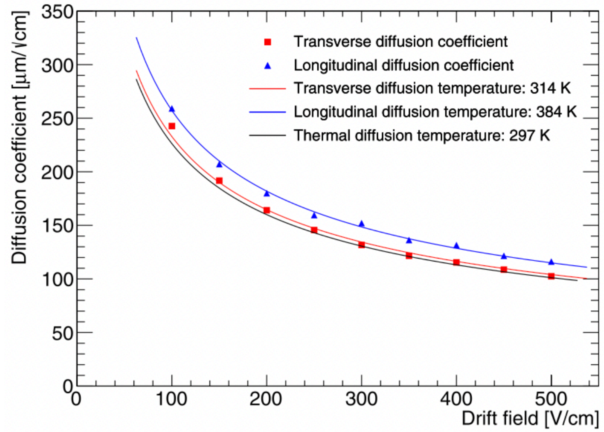
Diffusion measured by moving the position where the photoelectrons where generated on the cathode by 40, 125 μm steps.

Gas Mixture	Slope	Temperature
100%CS_2	0.16 ±0.02 Vmm/Torr	360 ±40 K
90%CS_2-10%Ar	0.13 ±0.03 Vmm/Torr	300 ±80 K
50%CS_2-50%Ar	0.11 ±0.02 Vmm/Torr	260 ±40 K
25%CS_2-75%Ar	0.10 ±0.02 Vmm/Torr	240 ±50 K

Effective diffusion temperature dependence on amount of Ar, going below the thermal limit

Atmospheric pressure
Pixel readout

Diffusion measured through the standard deviation of the hits position



Longitudinal and transversal diffusion slightly above the thermal limit, but peculiar mixture with idrocarbons $Ar:iC_4H_{10}:CS_2$ 93.6:5.0:1.4

Only transverse diffusion measurements can be compared among themselves due to electric anysotropy that induces larger longitudinal diffusion

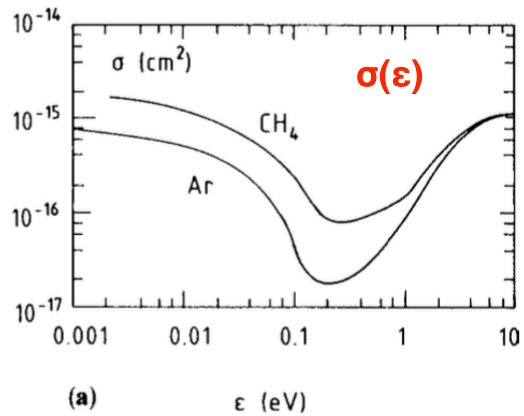
(all other results on slide 9 are longitudinal diffusion measurements)

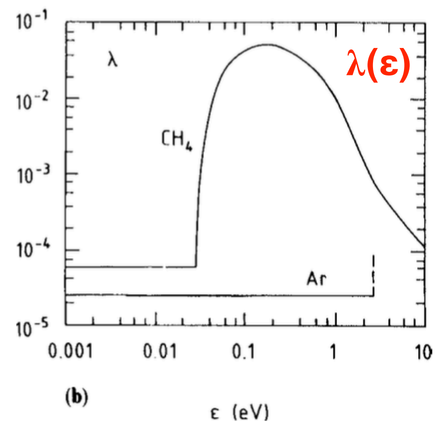
Comparison with other measurements: comments & discussion

Nucl.Instrum.Meth.A 440 (2000) 355-359	Nucl.Instrum.Meth.A 555 (2005) 55-58	Nucl.Instrum.Meth.A 1014 (2021) 165706
16.5, 40 Torr MWPC readout	**40 Torr MWPC readout**	**Atmospheric pressure Pixel readout**
Diffusion measured by moving a 300 μm wide collimator on top of the sensing wire	Diffusion measured by moving the position where the photoelectrons where generated on the cathode by 40, 125 μm steps.	Diffusion measured through the standard deviation of the hits position

- None of these measurements use He with SF_6
- He is the smaller and most symmetric atom you can imagine (H has an empty s shell), often considered electron-like in ions physics
- SF_6 is a large and complex molecule, with many roto-vibrational modes to dissipate energy in inelastic channels
- The statement that the thermal limit can not be breached is based on the assumption that ALL interactions between the drifting charges (either ions or electrons) and the gas molecule is ELASTIC: if inelasticity comes into play it can reduce the effective temperature
- IN FACT, drifting electrons through quantum effects display Ramsauer minima in the diffusion in some gases
- Possibly, SF_6 is experiencing a Ramsauer-like effect when scattering against Helium
- While understading of the origin of the effect goes beyond the scope of these measurements, relentless :D study of chemistry/atomic physics on-going in our collaboration, soon with contribution from theoriticians

Ramsauer minima





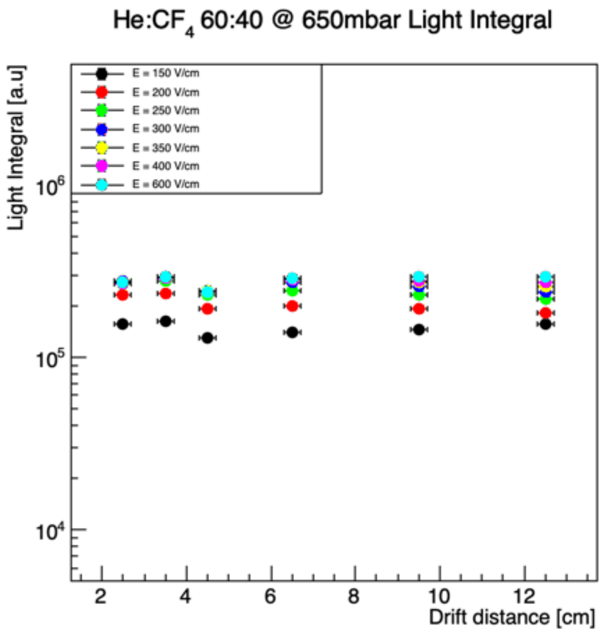
Experimental crosscheck performed on diffusion measurements

Want to be 100% sure to claim below thermal diffusion!

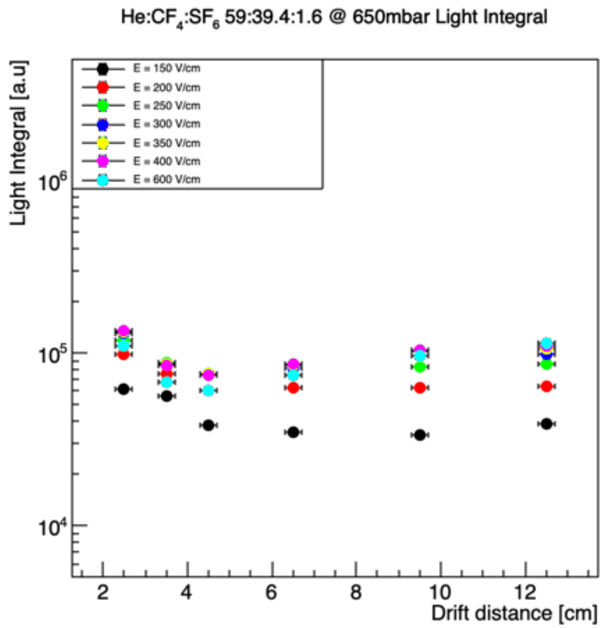
- **Many track variables checked for track passing selection and used for the diffusion estimation**
  - Integral, track width/track lenght, variance of diffusion RMS, tgausssigma, tgaussampl, track lenght, track width, reconstruction efficiency: all nicely Gaussian and following expected behaviour as a function of distance/drift field
- **Repeated the analysis using an alternative (more rough) estimation of diffusion**
  - All results (ED, NID1 and NID2) consistent with standard analysis
- **Checked the sCMOS images noise integral, RMS and mean**
  - ED and NID1 consistent, NID2 slightly lower values: depends on the data taking campains and do not affect the results
- **Is the light yield affecting the diffusion measurement?**
  - I will demonstrate how this is not the case in the next slides, anyway we plan to retake all the measurements (ED, NID1 and NID2) improving the consistency among them and lower the ED light yield to make it equal to NID1

Light yield vs distance vs drift field

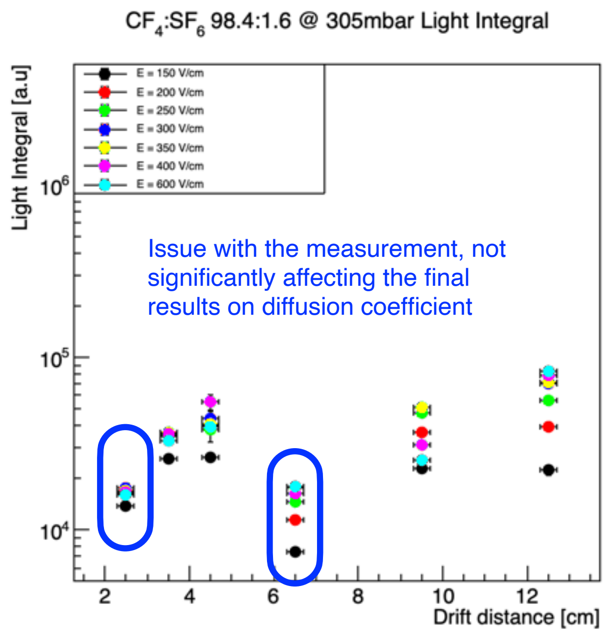
He:CF_4 (ED)
60:40 @ 650 mbar



He:CF_4:SF_6 (NID1)
59:39.4:1.6 @ 650 mbar



CF_4:SF_6 (NID2)
98.4:1.6 @ 305 mbar

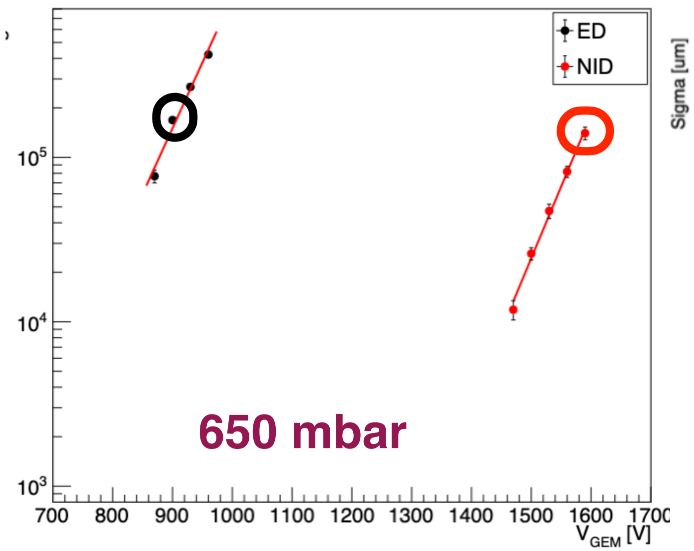


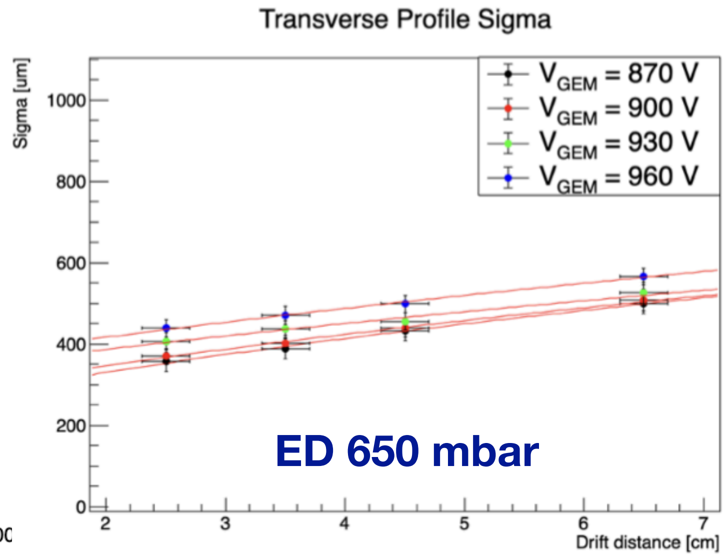
Light yield is within a factor 2 between ED and NID1

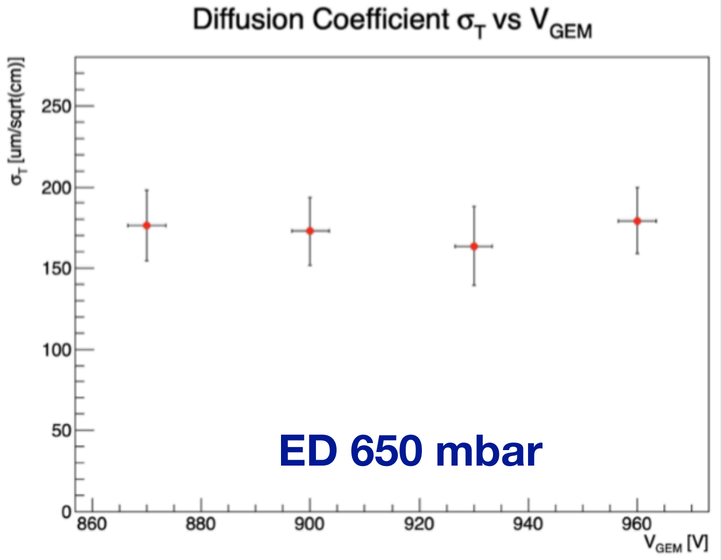
NID1 has larger light yield than NID2, but show significantly smaller diffusion

ED measured diffusion independent of light yield

Diffusion measurement gain







Same diffusion coefficient measured for ED within nearly one order of magnitude light yield variation

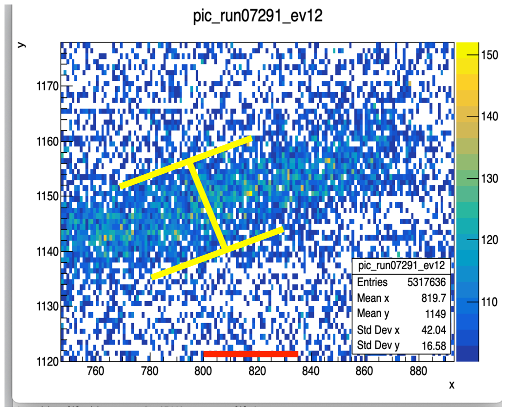
Check track image "by eye"

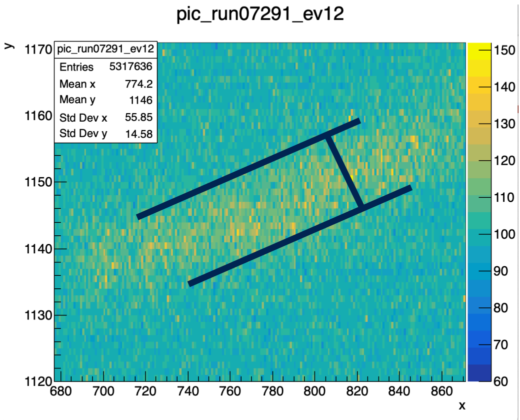
(...big systematics from myopia... :D)

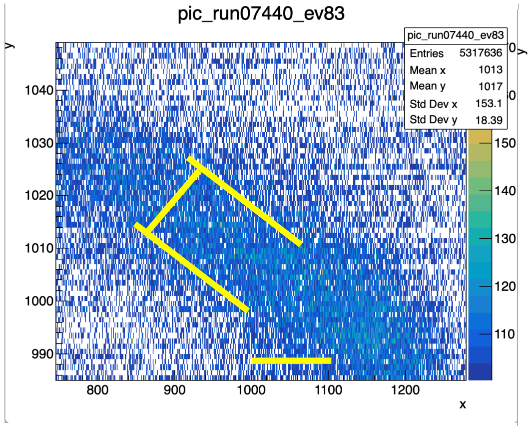
even though large systematic associated, track dimension by eye seems consistent with analysis results

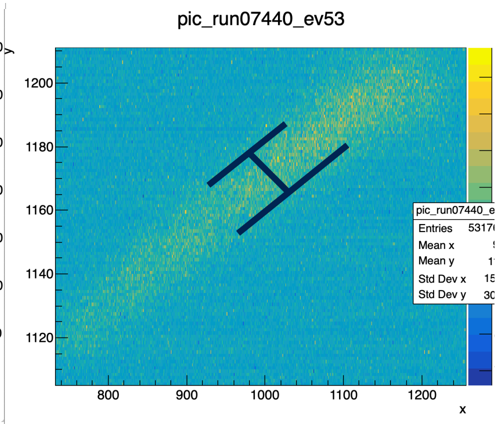
He:CF_4:SF_6 (NID1)

He:CF_4 (ED)

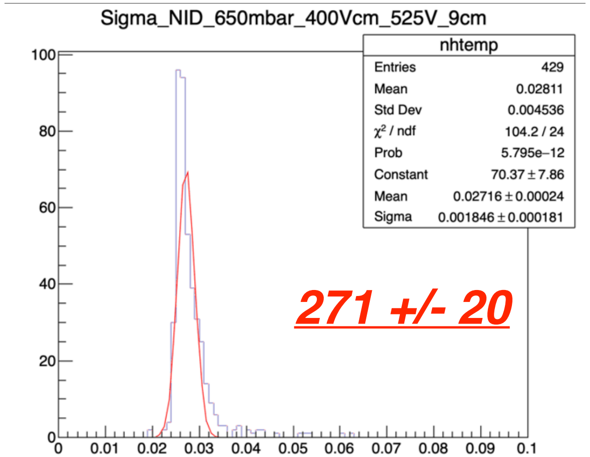


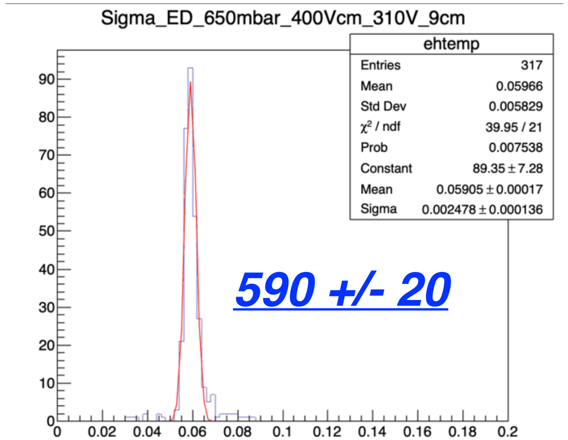






244 um | **213 um** | **427 um** | **600 um**





Conclusions & outlook

- **Negative ion drift operation demonstrated with full optical readout (sCMOS + PMT) at LNGS atmospheric pressure**

- **Impressive reduction of transveral diffusion measured with He:CF_4:SF_6 60:38.4:1.6 gas mixture, 3.6 times below the thermal limit**
  - **The combination of He and SF_6 seems to be the winning strategy**
  - **If this confirmed, an He:SF_6 mixture (for charge readout) with very small SF_6 content could display a super-low transversal diffusion, beyond our wildest immagination!**
  - **In addition, the estimated 10^4 charge gain at 900 mbar would allow a charge readout to easily reach O(keV) threshold**
    - **Enabling a super-performing CYGNUS 1 Ton!!!**
    - **NOTE that we assumed 78.6 um/sqrt(cm) in arXiv:2008:12587 for He:SF_6 755:5 Torr**

- **Next steps within CYGNO/INITIUM:**
  - **Validation of the He-SF_6 peculiar scattering interactions assumption by measuring diffusion at varying He concentration**
    - **Further validation requested by the collaboration by testing Ar:CF_4:SF_6 mixture**
  - **Test of alternative amplification structures (i.e. MMThickGEMs, COBRA-GEM) to increase gain towards reaching O(keV) with optical readout**


PULP FICTION
THANKS!