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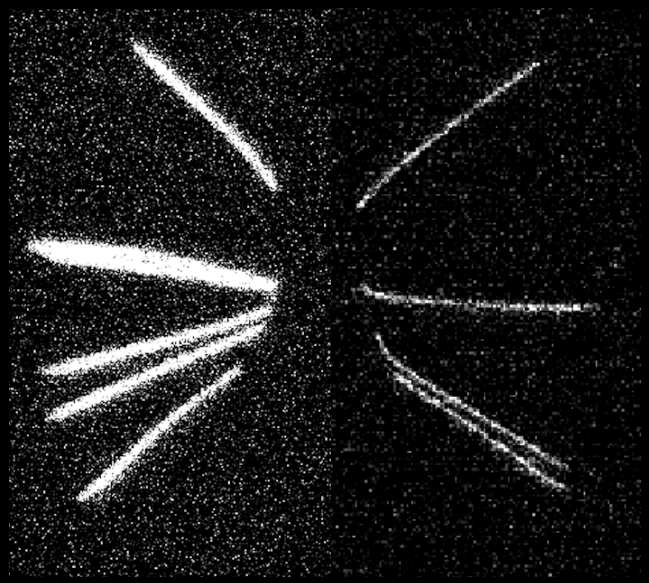
Negative ion drift operation below the thermal limit



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 December 2023

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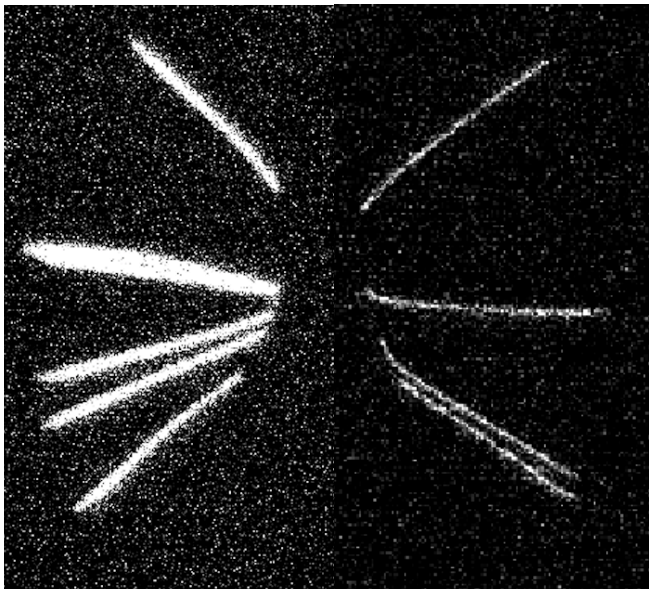
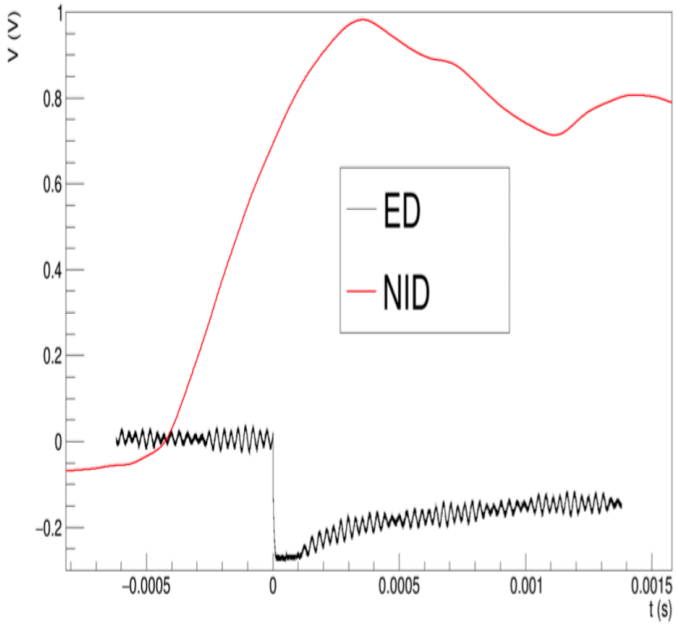
NID observation

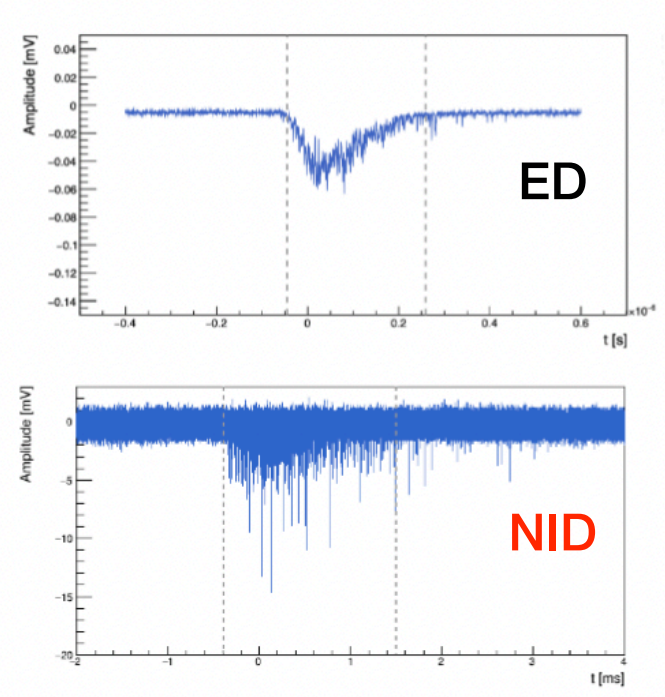
sCMOS image



GEM preamp output



PMT waveforms



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

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

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

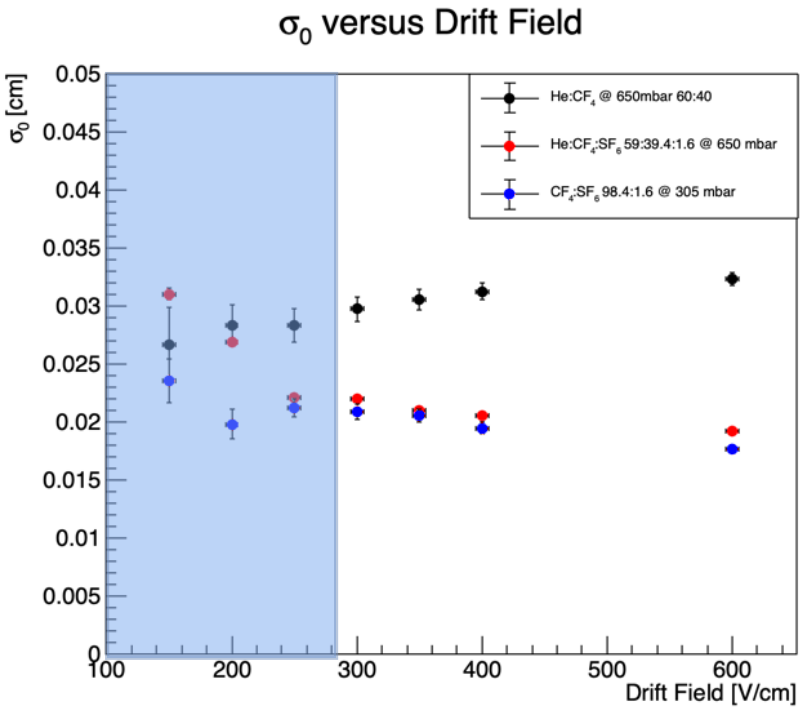
0.90 atm
(LNGS atmospheric pressure)

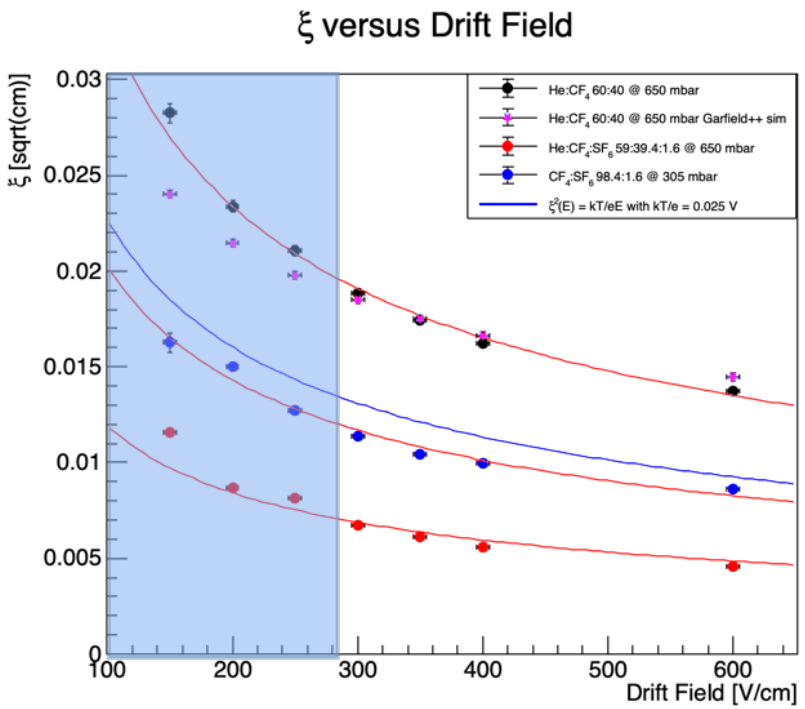
Recap of measurements & observation

- **Drift velocity and diffusion measurements with He:CF_4SF_6**
  - Demonstration of NID operation at LNGS atmospheric pressure (900 mbar)
  - Measured drift velocity and mobility consistent with literature
- **Diffusion measurements with He:CF_4 / He:CF_4SF_6 / CF_4SF_6**
  - He:CF_4 consistent with literature and Garfield++ simulation
  - He:CF_4:SF_6 factor 3.6 below the thermal limit
  - CF_4:SF_6 nearly at the thermal limit (slightly below, but uncertainty on the actual temperature of the gas during measurement)
  - Results point towards Helium as the component inducing the lower than thermal diffusion
- **Diffusion measurements He:CF_4SF_6 result so innovative and such beyond current expectation that we would like to aim at a very high impact journal (Nature/Science)**
  - For this reason, extensive review focused on diffusion measurement only for the moment

Diffusion constant & coefficient vs drift field

Drift field below 300 V/cm introduce additional smearing from effects not depending on diffusion (i.e. disuniformities in the drift field): to not be considered for the final publication





$$\sigma_{meas}(E,L) = \sqrt{\sigma_0^2(E) + \frac{2kT_{eff}L}{eE}} = \sqrt{\sigma_0^2(E) + \xi^2(E)L} = \sqrt{\sigma_0^2(E) + 2\delta(E)L}$$

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

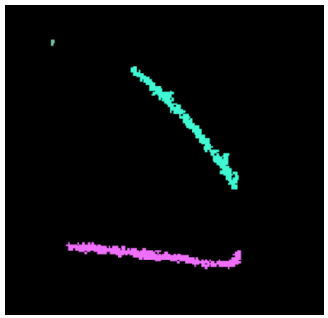
thermal limit
$kT_{eff}/e = 0.0257$ V

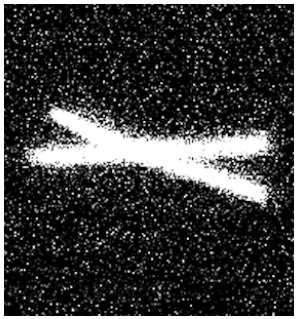
- **$He:CF_4$ $kT_{eff}/e = 0.0546 +/- 0.0006$ V**
- **$CF_4:SF_6$ $kT_{eff}/e = 0.0204 +/- 0.0003$ V**
- **$He:CF_4:SF_6$ $kT_{eff}/e = 0.0070 +/- 0.0001$ V**

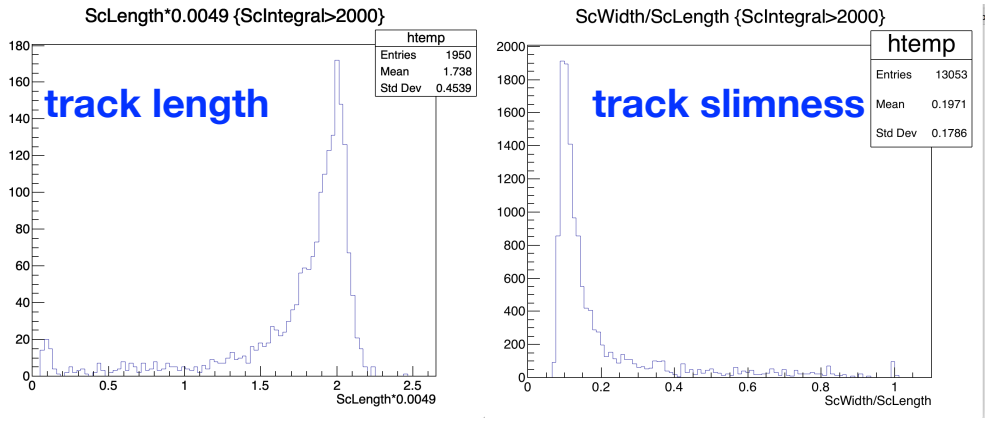
removing He, diffusion increases

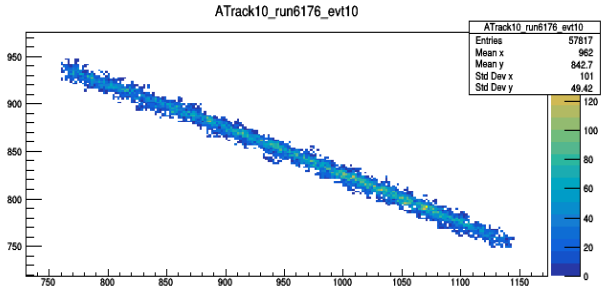
sCMOS images analysis

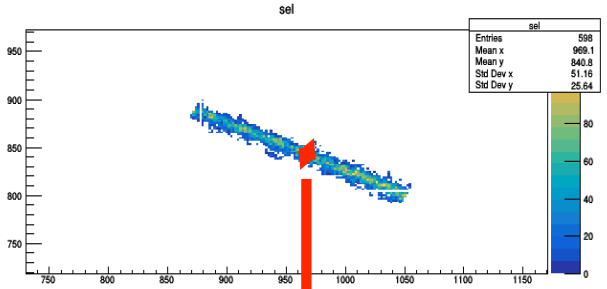
- Alphas selection:
  - tracks reconstructed with iterative DBSCAN algorithm [10]
  - track length > 1.47 cm
  - track slimness < 0.3
  - # of peaks in the transverse profile == 1 (select single tracks)
  - Chi2/nDOF of transverse fit profile < 5 (remove additional multiple tracks)

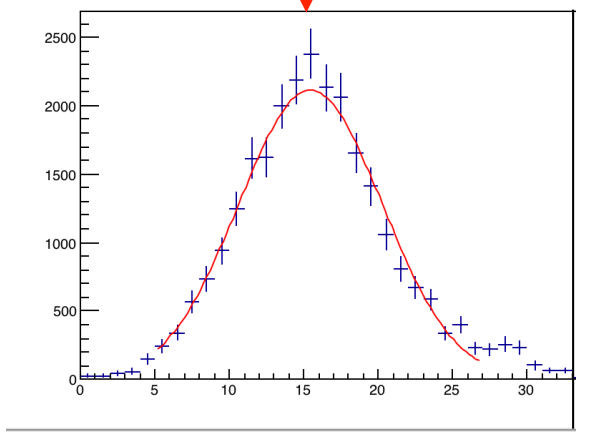












Sigma of track profile and track integral fitted with Gaussian to estimate diffusion and light yield

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

Crosscheck performed

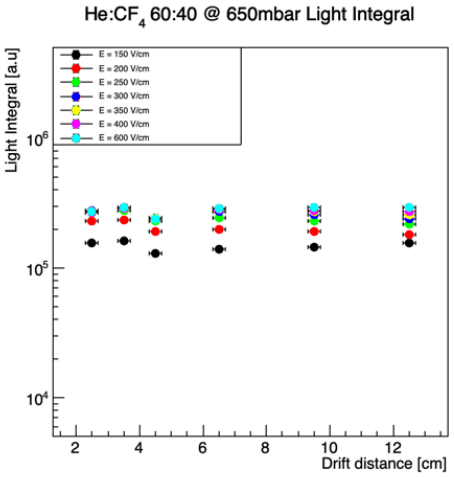
- Variables checked for track passing selection and used for the diffusion estimation
  - Integral, slimness, variance of diffusion RMS, tgausssigma, tgaussampl, lenght, width, alphas rate: all nicely Gaussian and following expected behaviour as a function of distance/drift field
  - Verified that tgausssigma*tgaussampl = integral
- Repeated the analysis using tgaussigma as estimate of diffusion
  - All results (ED, NID1 and NID2) consistent with standard analysis
- Checked the pedestal integral, RMS and mean for ED, NID1 and NID2
  - ED and NID1 consistent, NID2 slightly lower values
- Check effect of DBSCAN reconstruction on final results
  - We are re-running a set of ED and NID1 data with larger and smaller sigma noise parameters of DBSCAN, stay tuned

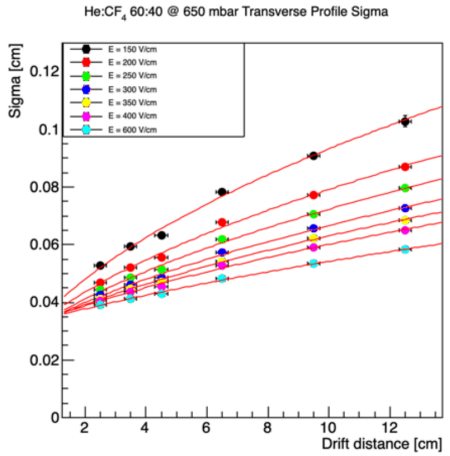
Is the light yield affecting the diffusion measurements?

No, will show in multiple ways and also repeat measurements

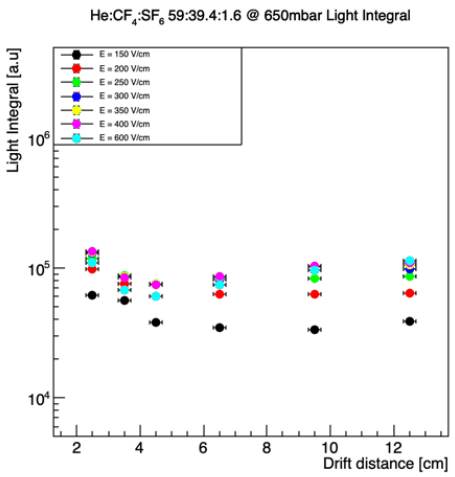
Light yield vs distance vs drift field

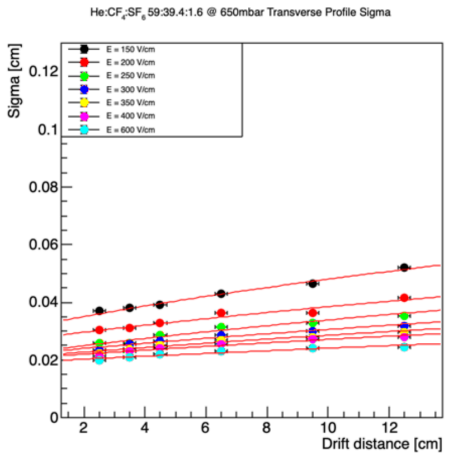
$He:CF_4$ (ED)



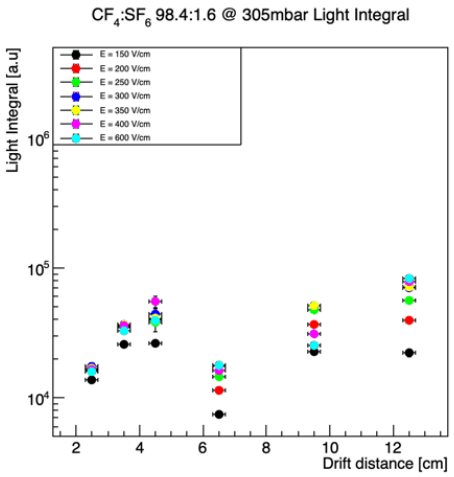


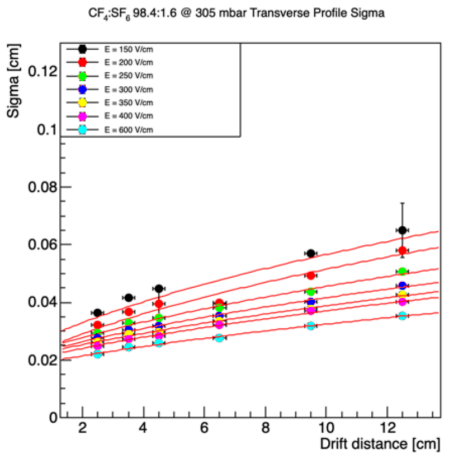
$He:CF_4:SF_6$ (NID1)





$CF_4:SF_6$ (NID2)



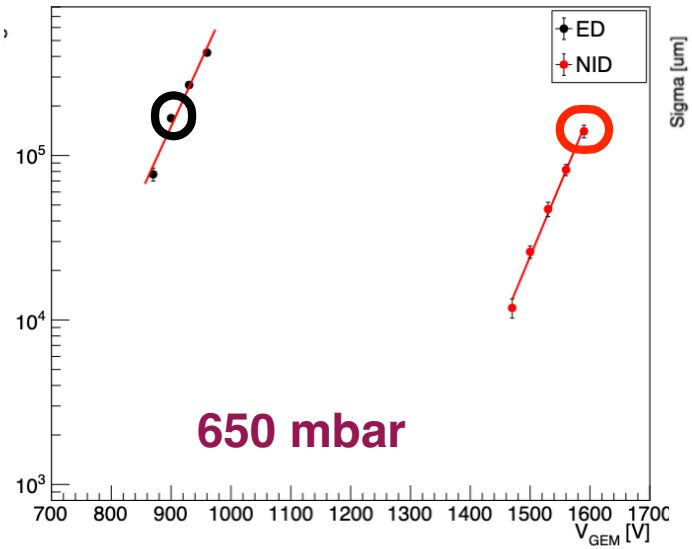


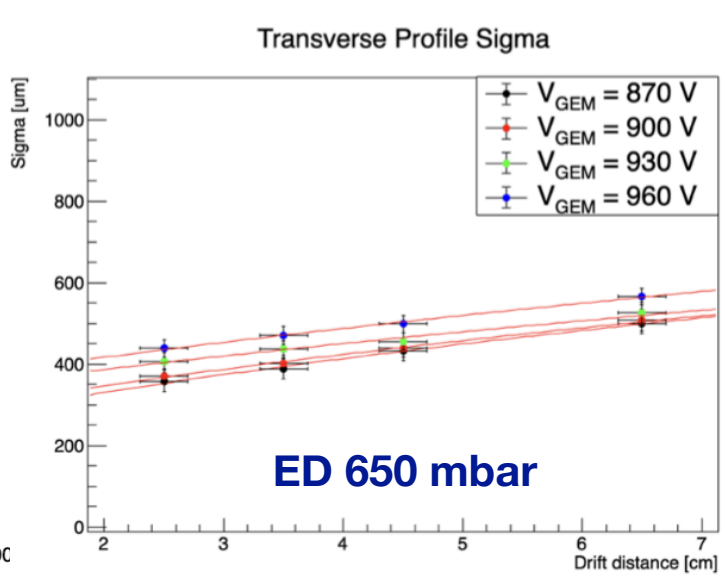
Light yield is within a factor 2 between ED and NID1

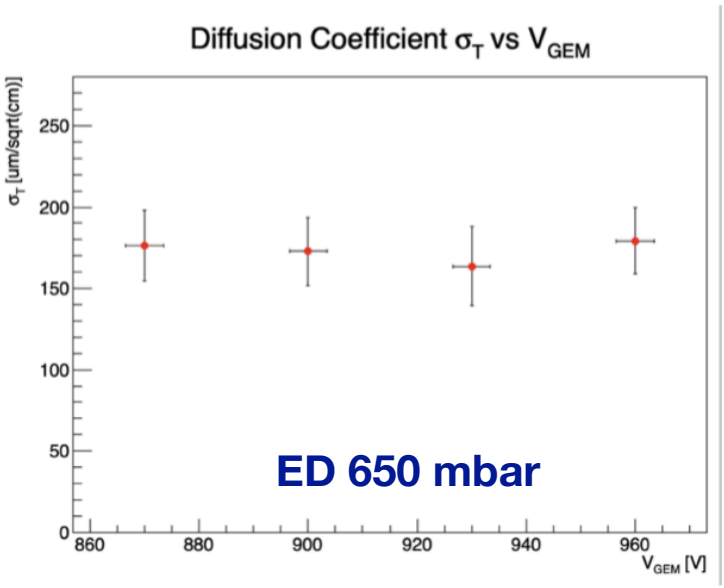
NID1 has larger light yield than NID2, but show significantly smaller diffusion

ED measured diffusion independent of light yield

Diffusion measurement gain







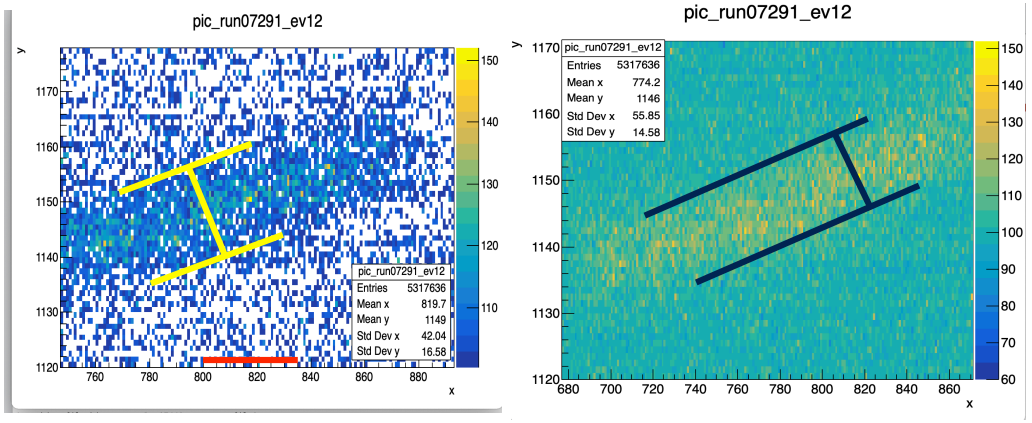
Same diffusion coefficient measured for ED within nearly one order of magnitude light yield variation

Check track image "by eye"

(…big systematics from myopia… :D)

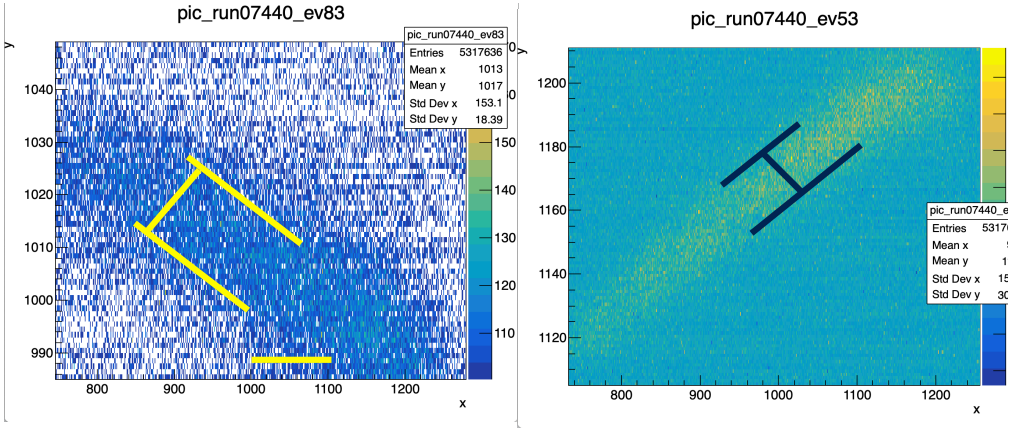
even though large systematic associated, track dimension by eye seems consistent with analysis results

$He:CF_4:SF_6$ (NID1)

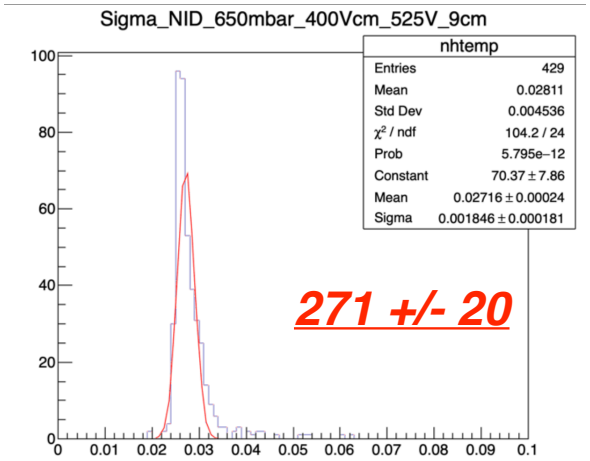


244 um ***213 um***

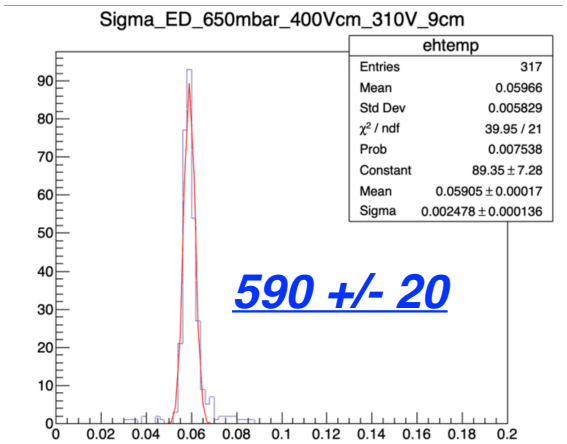
$He:CF_4$ (ED)



427 um ***600 um***



271 +/- 20



590 +/- 20

To convince without any possible doubt everybody we will:

1) repeat all the measurement again in a more consistent way and with 2 different light yield also for NID1(and NID2?)

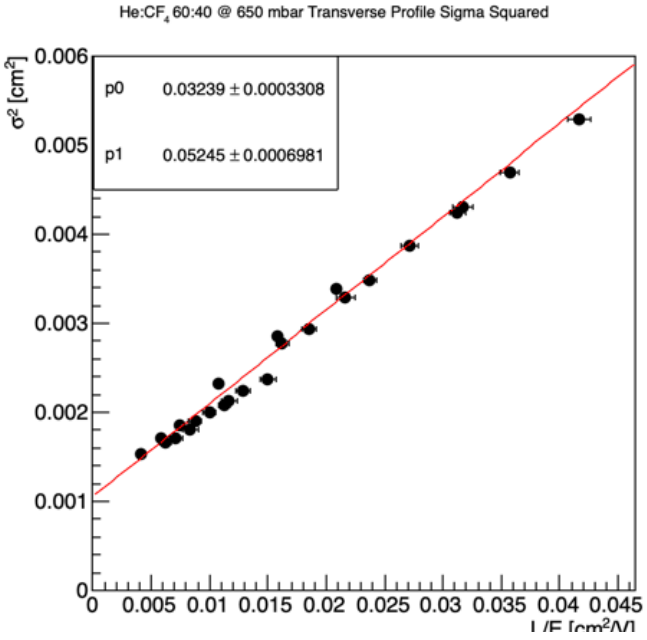
2) perform diffusion measurement with varying concentration of Helium

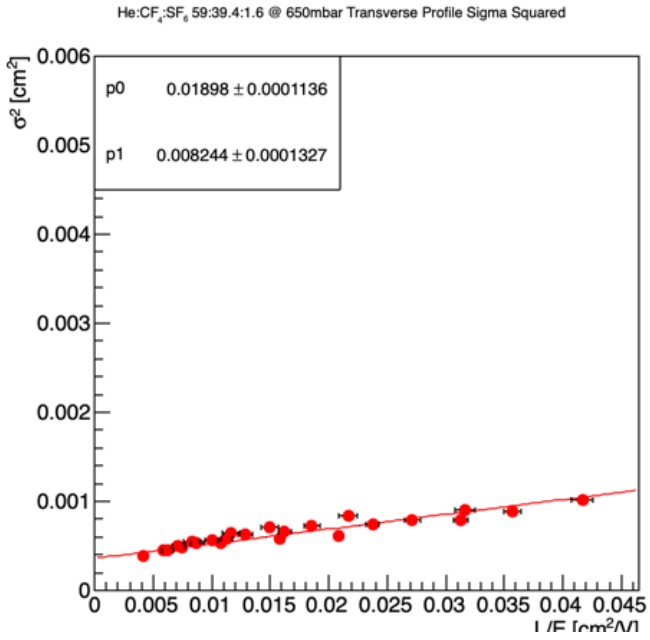
Big uncertainty in the estimate of the constant σ_0 term: can you improve it it?

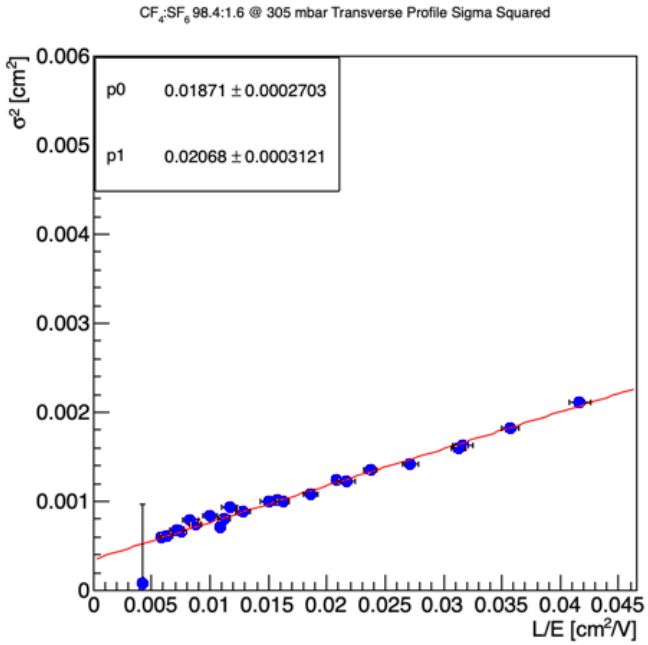
YES

Fitting as a function of L/E

Note: all the data plotted together, i.e. 300 V/cm, 350 V/cm, 400 V/cm, 600 V/cm for 2, 3, 4, 6, 9 and 12 cm, i.e. 24 points per plot







$$\sigma^2_{meas} = \sigma^2_0 + \frac{2kT}{e}\frac{L}{E} = p_0^2 + p_1\frac{L}{E}$$

Consistency of all data when plotted together further strenghten our measurement and improves the estimate of all paramters

- **He:CF_4 kT_{eff}/e = 0.0525 +/- 0.0007 V**
- **CF_4:SF_6 kT_{eff}/e = 0.0207 +/- 0.0003 V**
- **He:CF_4:SF_6 kT_{eff}/e = 0.00824 +/- 0.0001 V**

Conclusions & outlook

- Many experimental and analysis aspects verified
- All of them results consistent with expectations and further strenghten the robustness of the measurements
- Final crosschecks under way
- New measurements foreseen in next 2 weeks to
  - show reproducibility
  - demonstrate once and for all diffusion measurement independence on light yield
  - improve consistency among different data taking point
  - test the performances with varying Helium concentration

A question I would like to have answered:

Do we all agree in pushing for a very high impact journal and writing that our measurements are poses challenges to the current knowledge of ions transport properties in gases or do we want to aim at JINST and just publish the numbers?

Backup slides

Electrons diffusion during drift

$$\sigma^2 = 2Dt = \frac{2DL}{v_d} = \frac{2L}{E}\frac{D}{\mu}$$

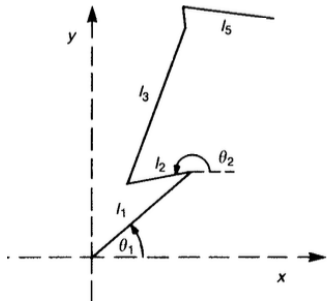
$$v_d = \mu E$$

Macroscopic quantities

- σ r.m.s. normal distance at time t
- D diffusion coefficient
- v_d constant drift velocity <<< c
- μ mobility
- L = v_dt distance travelled after time t

Microscopic quantities

- c instantaneous velocity between collisions
- l_0 mean free path of the drifting particle
- τ average time between collisions
- N number density
- σ_{int} interaction cross section



$$\sigma^2 = 2Dt = \int \left(\sum_1^n l_i \cos\theta_i\right)^2 \prod_1^n g(l_k)\mathrm{d}l_k \frac{\mathrm{d}\cos\theta_k}{2} = n\frac{2}{3}l_0^2 = \frac{2}{3}\frac{l_0^2}{\tau}t.$$

$$D = \frac{l_0^2}{3\tau} = \frac{c^2\tau}{3}$$

kinematic

$$\epsilon_e = \frac{1}{2}m_e c_e^2 = \epsilon_K + \frac{3}{2}kT$$

mobility

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

interaction

$$\frac{1}{\tau} = N\sigma_{int}c$$

$$l_0 = c\tau$$

diffusion

$$\sigma^2 = \frac{2L}{E}\frac{m_e}{e\tau}\frac{c^2\tau}{3} = \frac{2}{3}\frac{L}{eE}mc_e^2 = \frac{2}{3}\frac{L}{eE}(2\epsilon_E + 3kT) \xrightarrow[\epsilon_E \to 0]{=} \frac{2kTL}{eE}$$

Ions diffusion during drift

$$\sigma^2 = 2Dt = \frac{2DL}{v_d} = \frac{2L}{E}\frac{D}{\mu}$$

$$v_d = \mu E$$

Macroscopic quantities

- σ r.m.s. normal distance at time t
- D diffusion coefficient
- v_d constant drift velocity <<< c
- μ mobility
- L = v_dt distance travelled after time t

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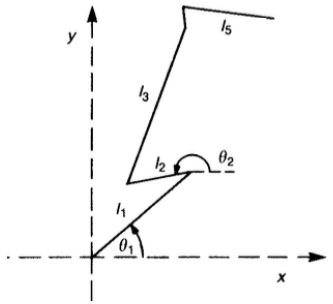


$$\sigma^2 = 2Dt = \int \left(\sum_1^n l_i \cos\theta_i\right)^2 \prod_1^n g(l_k)\mathrm{d}l_k \frac{\mathrm{d}\cos\theta_k}{2} = n\frac{2}{3}l_0^2 = \frac{2}{3}\frac{l_0^2}{\tau}t.$$

$$D = \frac{l_0^2}{3\tau} = \frac{c_{rel}^2\tau}{3}$$

kinematic

$$\epsilon_n = \frac{1}{2}m^* c_{rel}^2 = \epsilon_K + \frac{3}{2}kT \cong \frac{3}{2}kT$$

$$\frac{1}{m^*} = \frac{1}{m_n} + \frac{1}{M_{gas}}$$

$$c_{rel}^2 = c_n^2 + c_{gas}^2 = 3kT\left(\frac{1}{m_n} + \frac{1}{M_{gas}}\right)$$

mobility
(low field approximation)

$$\mu_n = \left(\frac{1}{m_{ni}} + \frac{1}{M_{gas}}\right)^{1/2}\left(\frac{1}{3kT}\right)^{1/2}\frac{e}{N\sigma_{int}} = \frac{c_{rel}}{3kT}\frac{e}{N\sigma_{int}}$$

interaction

$$\frac{1}{\tau} = N\sigma_{int}c_{rel}$$

$$l_0 = c_{rel}\tau$$

diffusion

$$\sigma^2 = \frac{2L}{E}\frac{c_{rel}^2\tau}{3}\frac{3kT}{c_{rel}}\frac{N\sigma_{int}}{e} = \frac{2kTL}{eE}c_{rel}\tau\frac{1}{c_{rel}\tau} = \frac{2kTL}{eE}$$

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

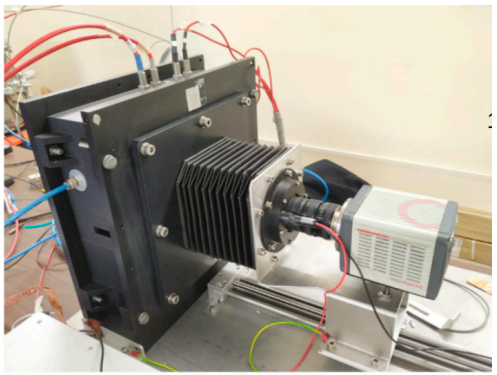
Experimental setup: the MANGO detector

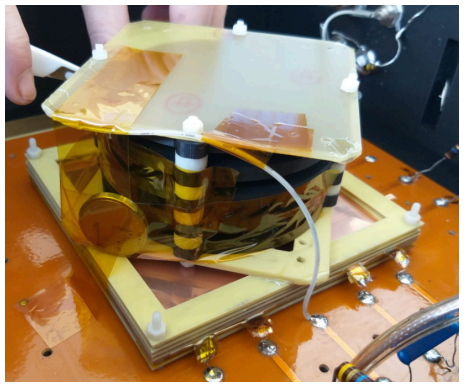
Triple thin 50 um GEM stack 10 x 10 cm²

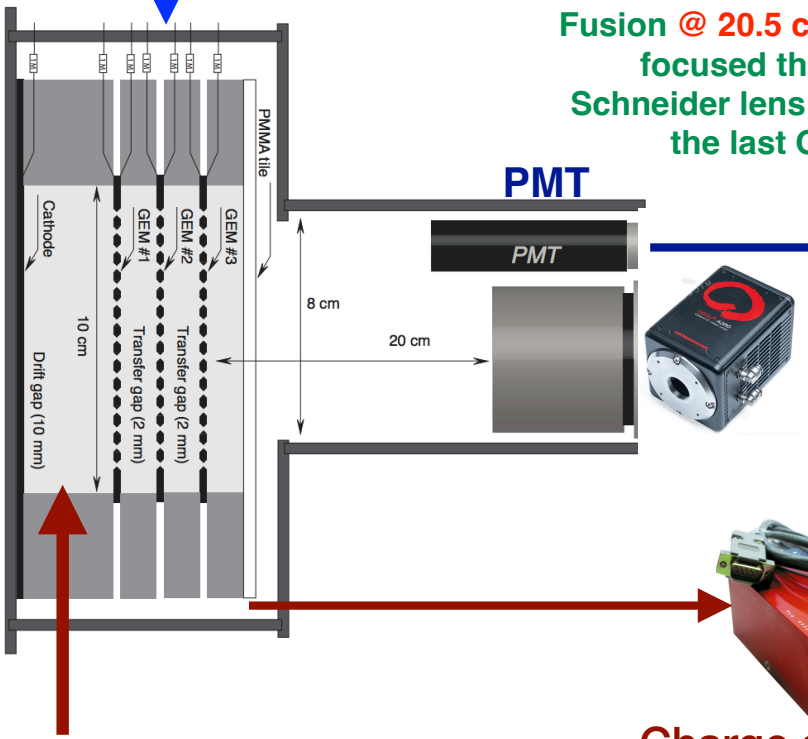
Acquired with Hokawo 3.0 software

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

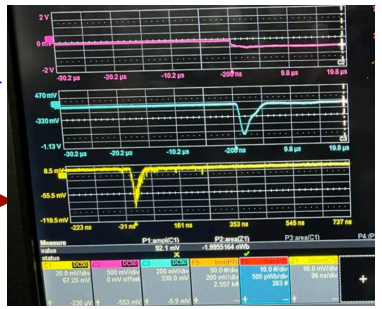
5 cm drift gap setup inside plastic gas-tight box







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



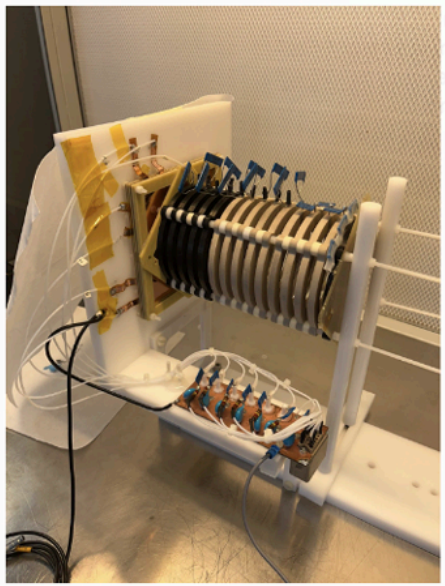
Drift gap (variable from 5 to 15 cm)

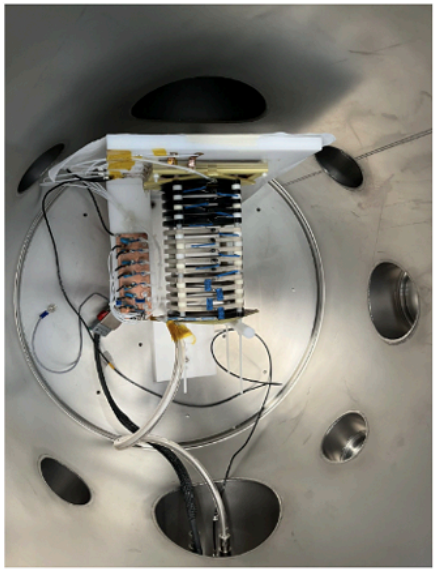
Charge sensitive preamplifier
300 us decay time
0.113 mV/fC

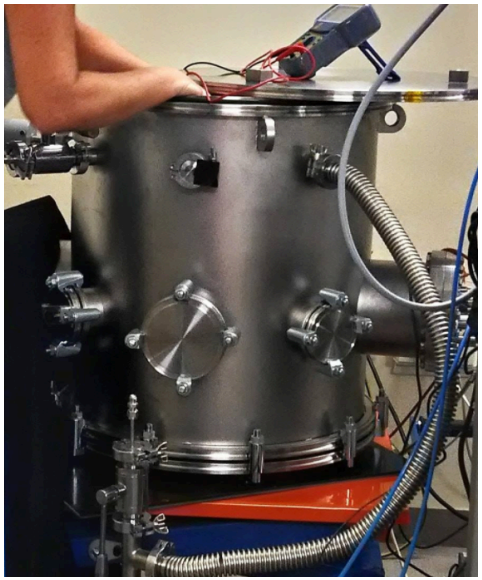
Teledyne LeCroy oscilloscope

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





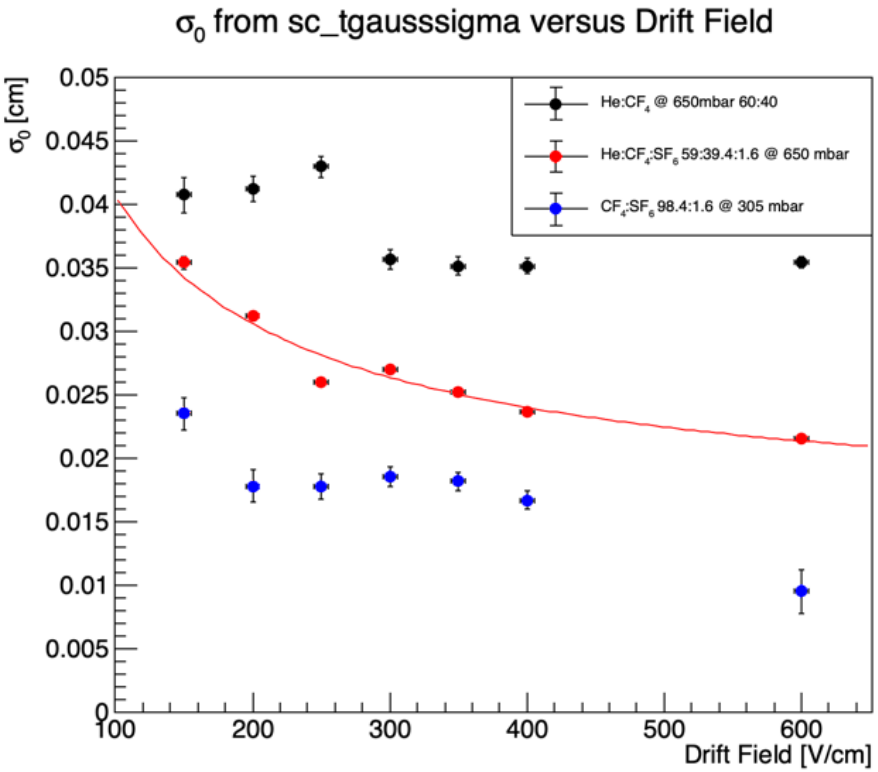


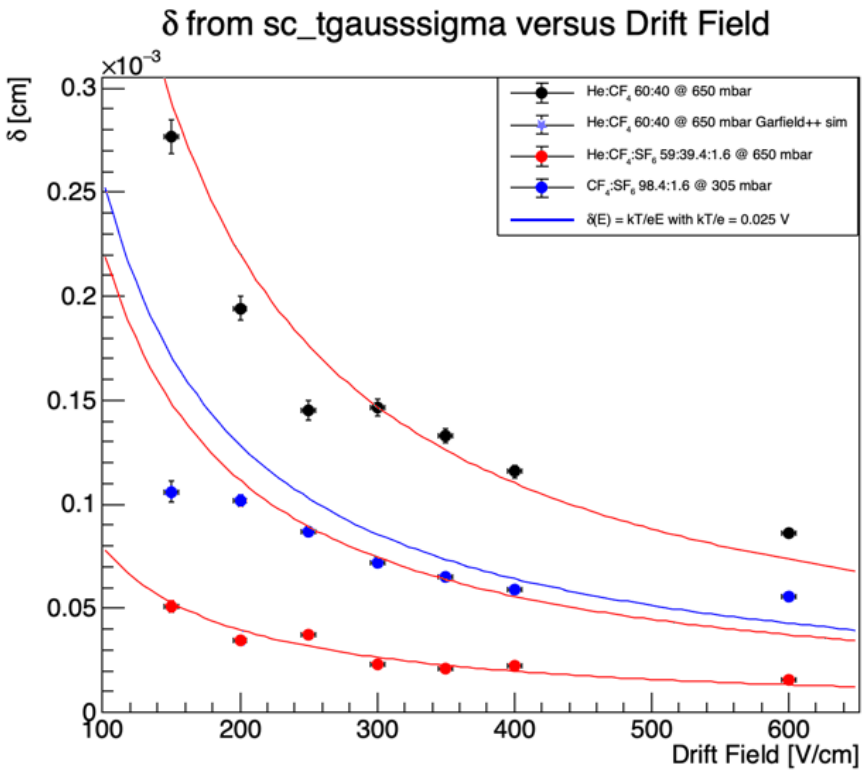
Because of geometry constraints, the camera is now at 26.6 cm distance (w.r.t. 20.5 cm of the previous setup): the light yield reaching the camera sensor is reduced of 2/3 with respect to previous configuration

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

NOTE: diffusion is expected to be independent of pressure

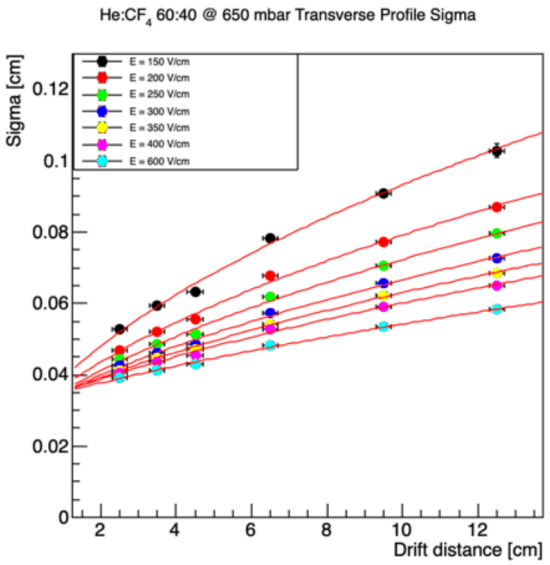
fatto con tgaussigma

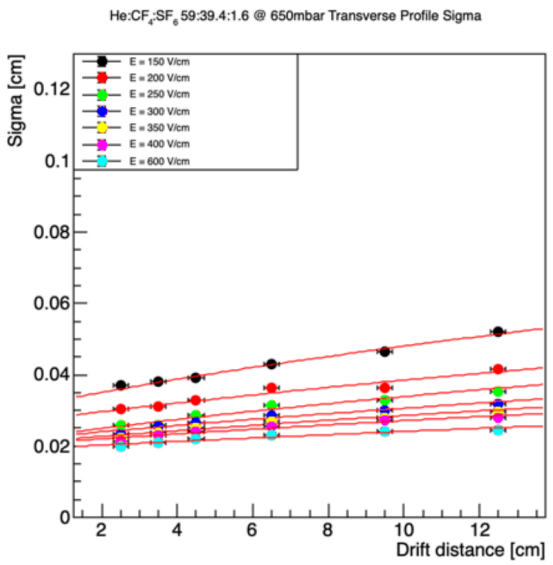


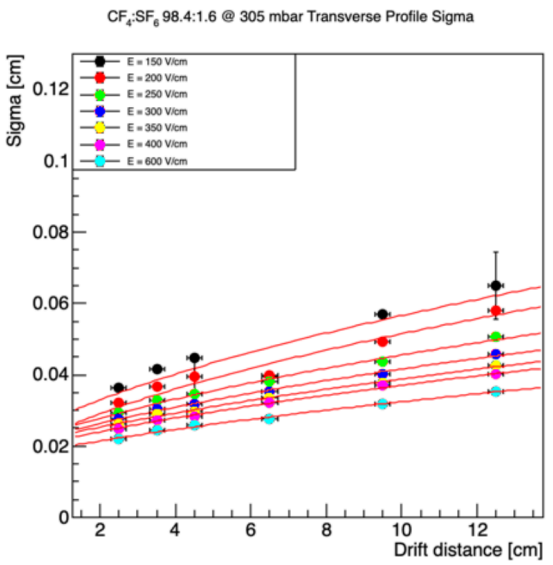


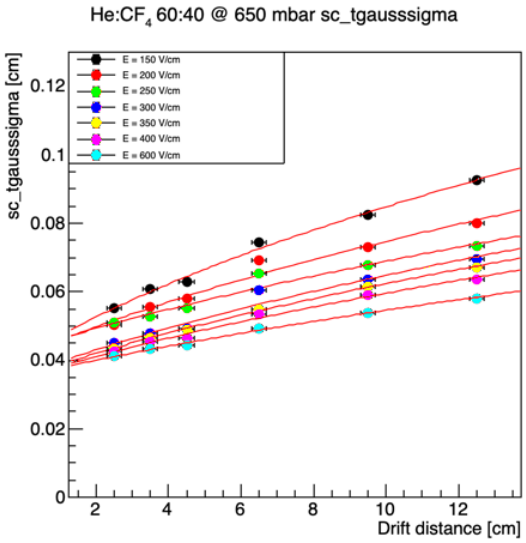
- **$He:CF_4$ kT_{eff}/e = 0.0441 +/- 0.0006 V**
- **$CF_4:SF_6$ kT_{eff}/e = 0.0223 +/- 0.0003 V**
- **$He:CF_4:SF_6$ kT_{eff}/e = 0.0079 +/- 0.0002 V**

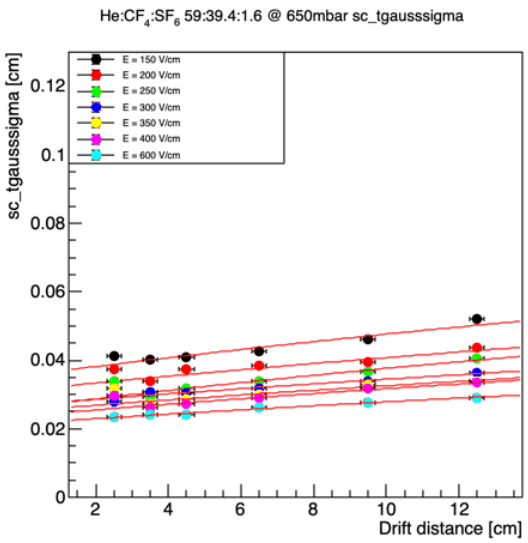
$$\sigma_{meas}(E,L) = \sqrt{\sigma_0^2(E) + \frac{2kT_{eff}L}{eE}} = \sqrt{\sigma_0^2(E) + \xi^2(E)L} = \sqrt{\sigma_0^2(E) + 2\delta(E)L}$$

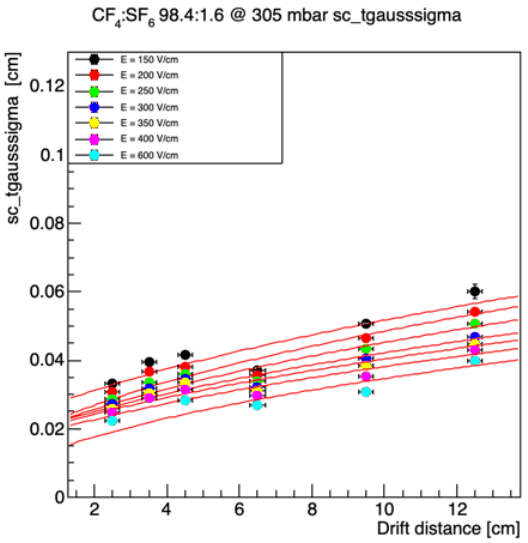








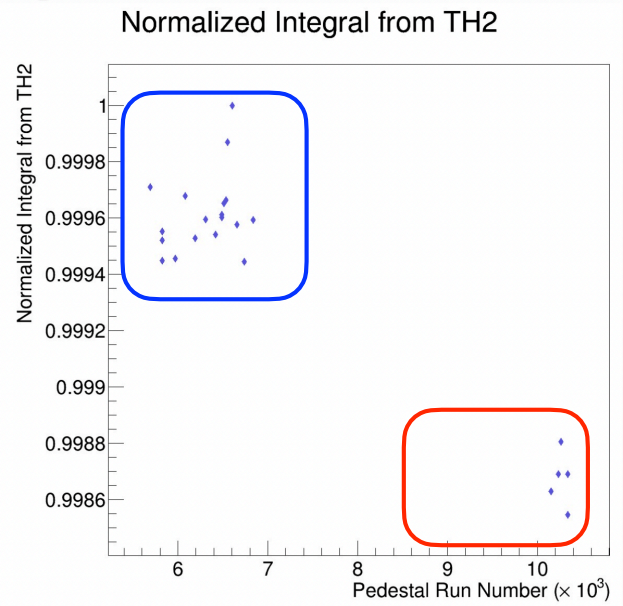


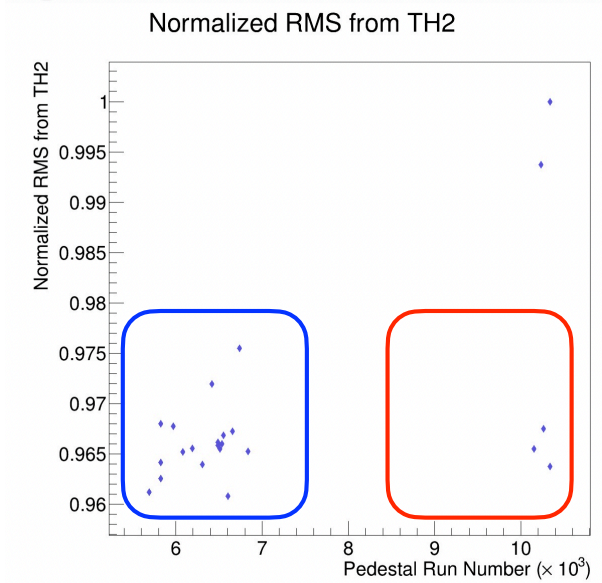


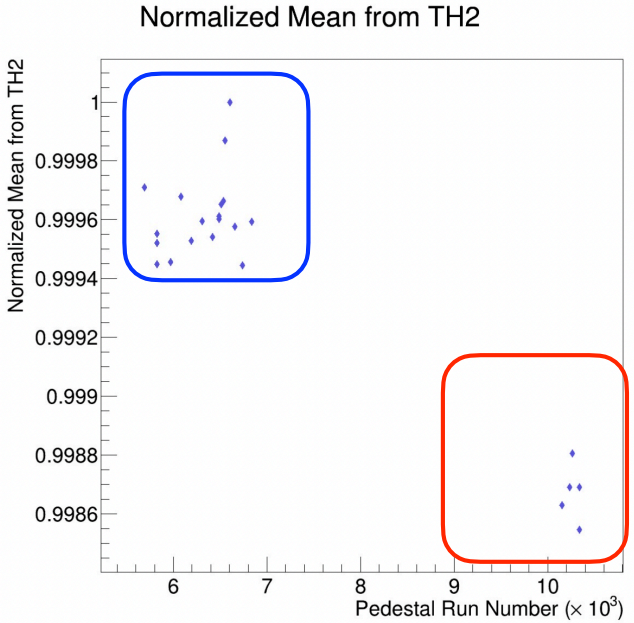
He:CF4 & He:CF4:SF6 data

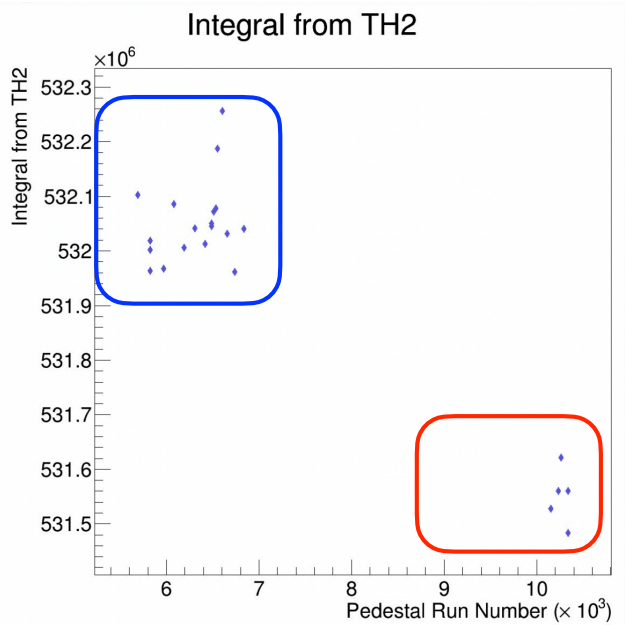
Pedestal study

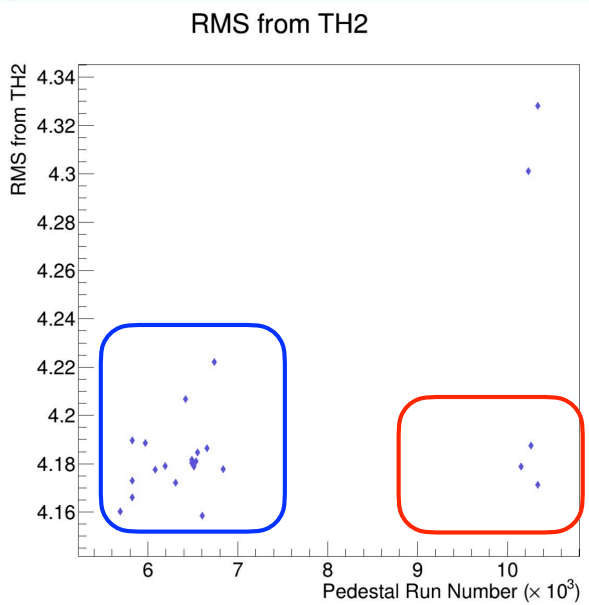
CF4:SF6 data

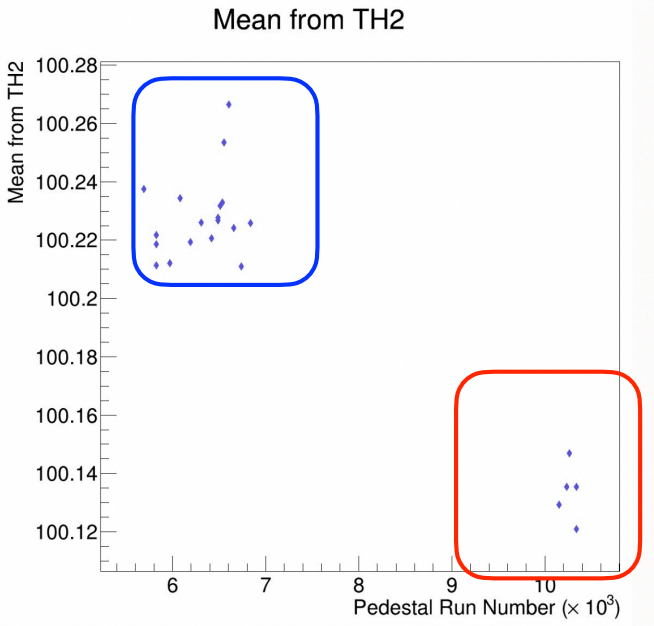












Data to be rerun with different DBSCAN parameters

- NID1 2 cm 400 vcm 5803-5812
- NID1 12 cm 400 vcm 5941-5955
- NID1 6 cm 400 vcm 6273-6288
- ED 12 cm 400 vcm 6585-6594
- ED 2 cm 400 vcm 6921-6930
- ED 6 cm 400 vcm 7535-7544

dalla tesi di rita dipendenza Drift field

could not be detected.

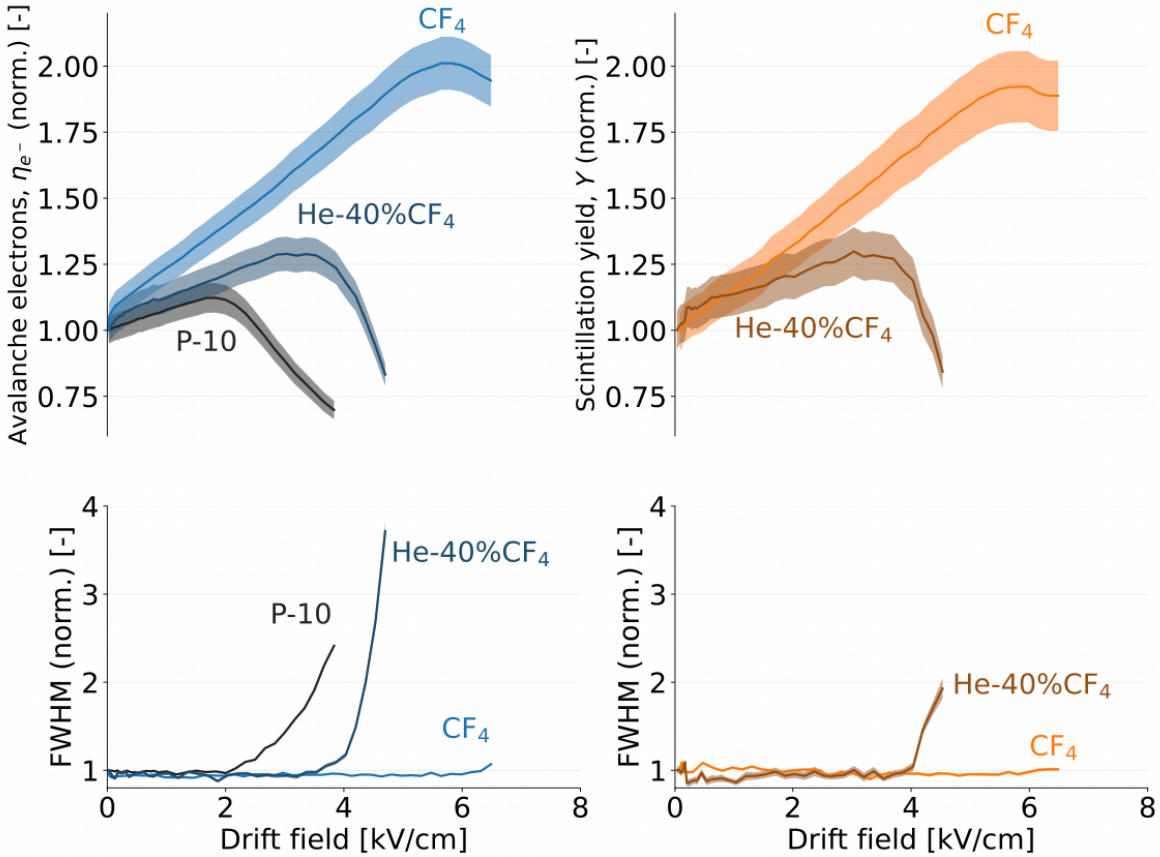


Figure 4.1: **Drift field optimisation for CF_4, He-40%CF_4, and P-10:** the normalised charge gain (left), scintillation yield (right), and corresponding energy resolution (bottom) are presented as a function of drift field. The curves are normalised to the first measurement, taken at the lowest drift field. Although these are experimental results, solid lines and coloured areas (3-σ confidence interval) are used to improve the plot legibility.

dalla tesi di rita dipendenza da Vgem

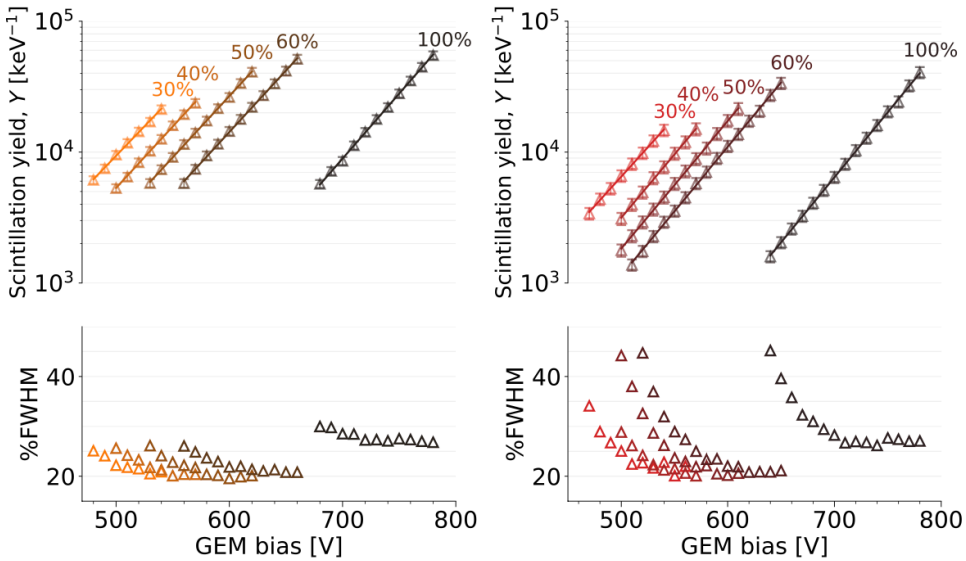
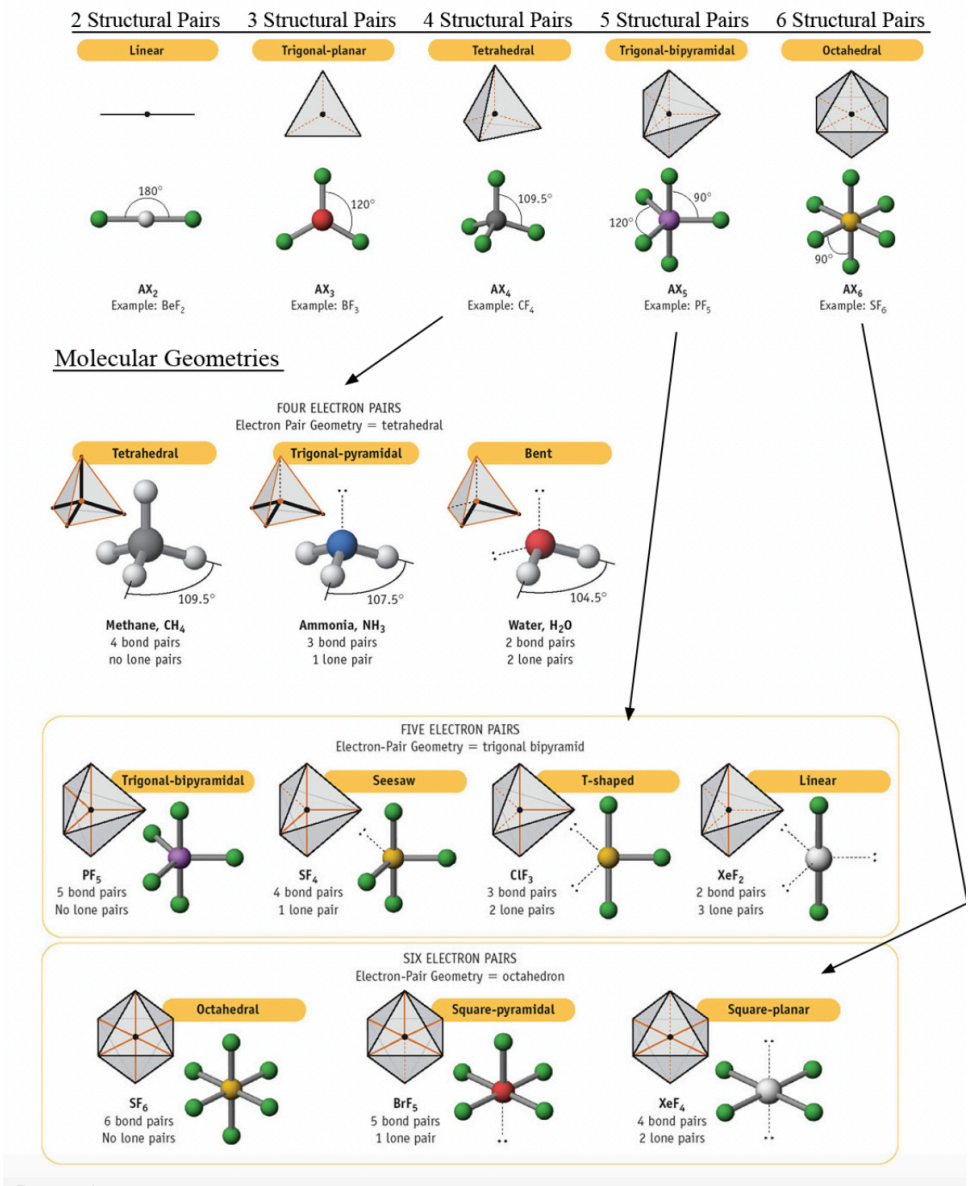
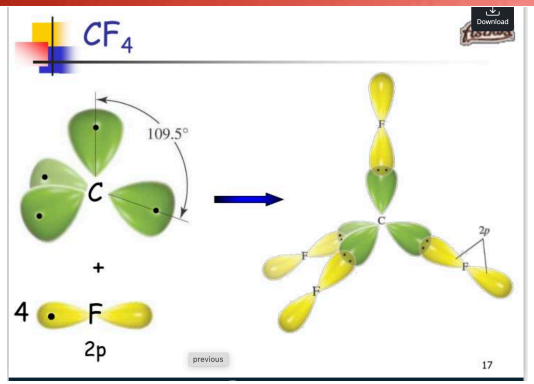


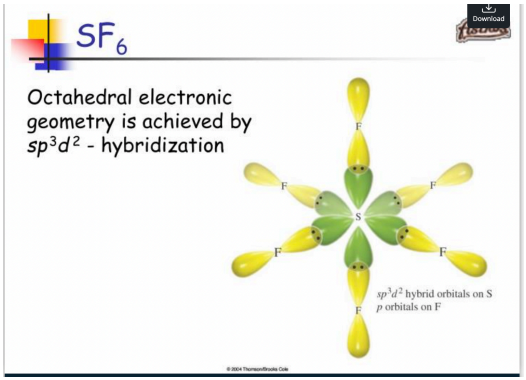
Figure 4.4: **GEM-induced scintillation yield in He-CF_4 mixtures:** the total emission (left) and visible component of the scintillation (right) are presented as a function of GEM bias. The measurements are depicted by the open triangles, whereas the solid lines illustrate the exponential trendlines fitted to each He-CF_4 mixture.

	He-30%CF_4	**He-40%CF_4**	**He-50%CF_4**	**He-60%CF_4**	**CF_4**
Avalanche electrons					
β	0.0209(10)	0.0217(8)	0.0219(5)	0.0220(5)	0.0230(5)
$\eta_{e^-}^{max}$ ($\times 10^6$)	1.26(6)	1.27(6)	2.04(10)	2.50(12)	1.93(10)
FWHM^{min} [%]	13.47(16)	13.48(19)	14.50(14)	15.83(23)	21.79(23)
Total scintillation					
β	0.0207(13)	0.0216(11)	0.0216(8)	0.0216(7)	0.0229(7)
Y^{max} ($\times 10^4$)	2.13(14)	2.37(17)	4.10(30)	5.2(4)	5.5(4)
FWHM^{min} [%]	20.5(5)	20.1(4)	19.55(27)	20.8(4)	26.81(29)
Visible scintillation					
β	0.0207(10)	0.0228(11)	0.0224(8)	0.0226(5)	0.0229(5)
Y^{max} ($\times 10^4$)	1.47(21)	1.50(15)	2.14(21)	3.36(31)	4.1(4)
FWHM^{min} [%]	20.10(32)	20.09(31)	20.20(27)	20.82(30)	26.17(26)

Molecular structures







VB vs. VSEPR Theories

Regions of High Electron Density	Electronic Geometry	Hybridization
2	Linear	sp
3	Trigonal planar	sp^2
4	Tetrahedral	sp^3
5	Trigonal bipyramidal	sp^3d
6	Octahedral	sp^3d^2

26

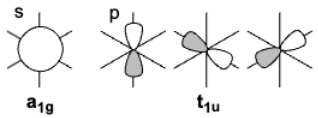
SF_6 Molecular orbital structures

Molecular Orbitals in SF_6

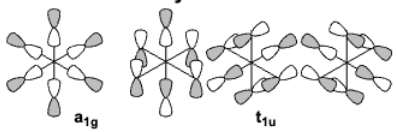
The Lewis structure of SF_6 describes six pairs of electrons as bond pairs, despite the availability of only four valence orbitals on sulphur. The valence bond description of this hypervalent complex must therefore invoke d-orbitals. However, high-level theoretical calculations suggest that the electronic structure involves not d-orbitals and six bonds, but instead only *four* bonds, each delocalized over all seven atoms.

O_h	E	$8C_3$	$6C_2$	$6C_4$	$3C_2$	i	$6S_4$	$8S_6$	$3\sigma_h$	$6\sigma_d$	
A_{1g}	1	1	1	1	1	1	1	1	1	1	$x^2+y^2+z^2$
A_{2g}	1	1	−1	−1	1	1	−1	1	1	−1	
E_g	2	−1	0	0	2	2	0	−1	2	0	(z^2,x^2-y^2)
T_{1g}	3	0	−1	1	−1	−1	1	0	−1	−1	
T_{2g}	3	0	1	−1	−1	−1	−1	0	−1	1	(xy,xz,yz)
A_{1u}	1	1	1	1	1	1	−1	1	−1	−1	
A_{2u}	1	1	−1	−1	1	1	1	1	−1	1	
E_u	2	−1	0	0	2	2	0	−1	−2	0	
T_{1u}	3	0	−1	1	−1	−1	−1	0	1	1	(x,y,z)
T_{2u}	3	0	1	−1	−1	−1	1	0	1	−1	

Four S AOs:

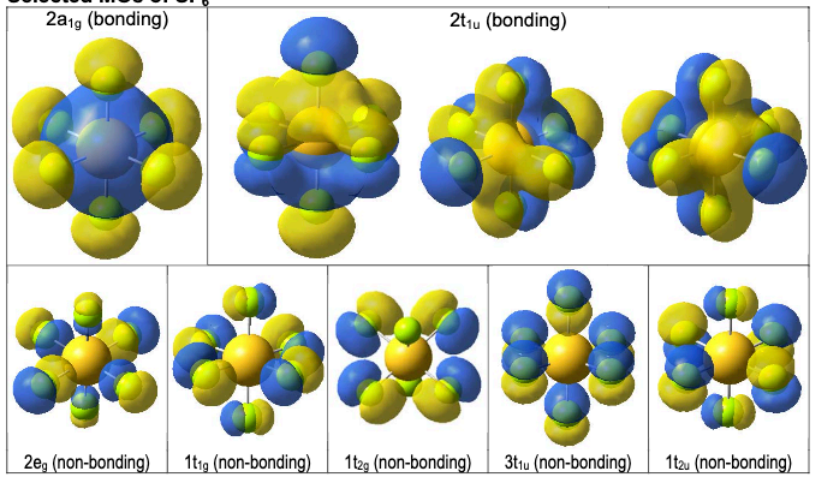


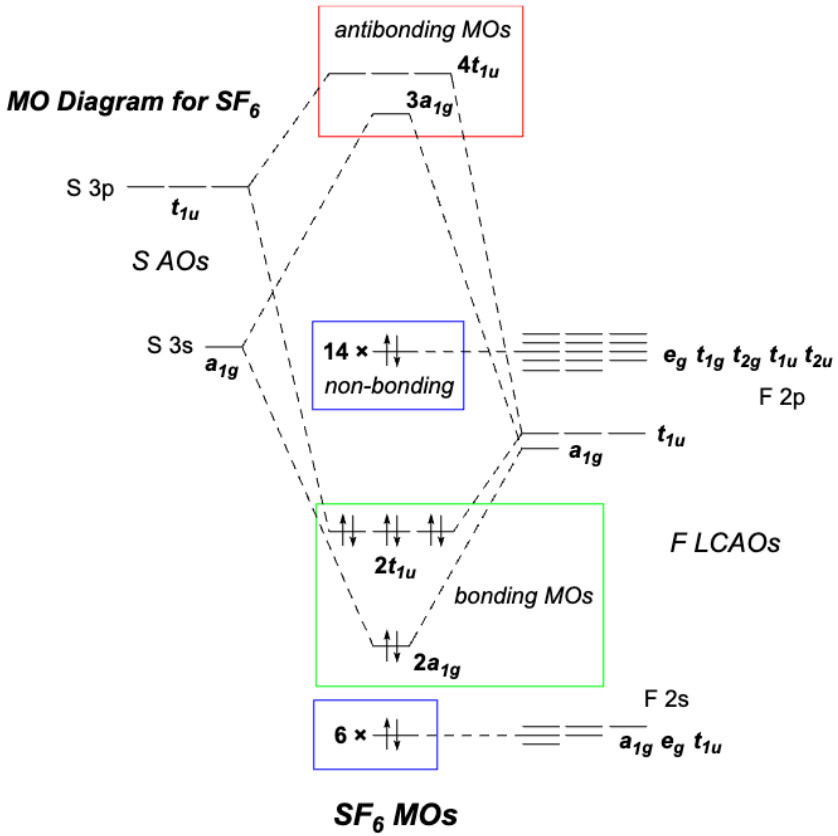
Four of the twenty-four F SALCAOs:



The six F 2s orbitals give linear combinations that transform as a_{1g} e_g and t_{1u}, but they are very low in energy and remain effectively non-bonding. The eighteen F 2p orbitals give linear combinations transforming as a_{1g} e_g t_{1g} t_{2g} $2\times t_{1u}$ and t_{2u}. Most of these remain non-bonding, but four combinations, a_{1g} and one of the t_{1u} sets, can overlap with the S AOs to give four bonding and four anti-bonding MOs. Shown below are all four bonding MOs and one of each symmetry of the F 2p non-bonding MOs.

Selected MOs of SF_6



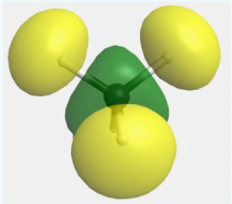
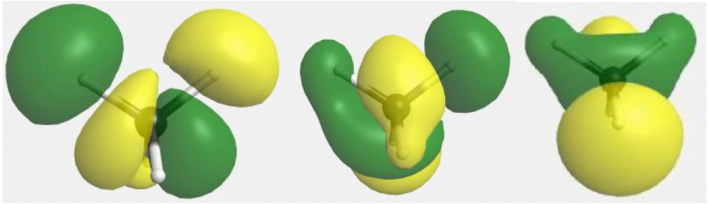
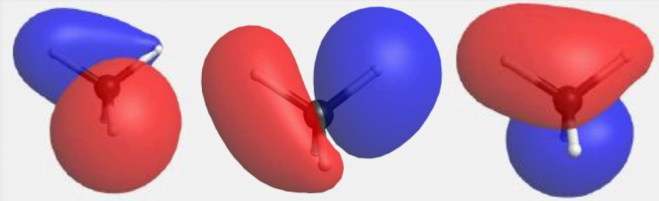
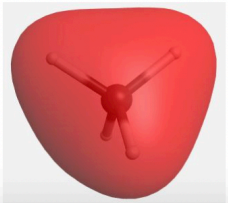


The resulting MO diagram contains:

- 6 non-bonding MOs derived from F 2s AOs
- 4 bonding and 4 anti-bonding MOs of a_{1g} and t_{1u} symmetry, derived from F 2p AOs
- 14 non-bonding MOs, also derived from F 2p AOs

The 48 valence electrons of SF_6 fill the first 24 available MOs: 20 non-bonding and 4 bonding MOs. This leads to an interpretation that is different than that of the Lewis structure: not 18 LPs and 6 BPs, but 20 F-based lone pairs and only 4 bond pairs! The total bond order equals 4, or an "average" of only 2/3 bond per S-F interaction. In MOT, hypervalency manifests as electron-deficient bonding, with fewer than 2 bonding electrons per formal bonding interaction. Weird. Eerie.

CF_4 Molecular orbital structures

Symmetry Label	Orbital(s)	Energy (eV)
a_1*		26.479
t_2*		3.649
t_2		-15.334
a_1		-24.545