Paper Presentation: Enhancing the light yield of He:CF_4 based gaseous Detector

G. Dho

What Why Who

- **What:** Paper on the studies of the different amplification structures and addition of a strong electric field below the last GEM plane

- **Why:** Optimisation of the amplification studies for larger light yield

- **Who:** Giorgio Dho, Elisabetta Baracchini with help and support from Davide Pinci

- **Where:** Different journals under consiration, taking into account OA policies.

JINST Meas. Sci. Tech. (pending OA policy) EPJC Astro. Phys Elsevier

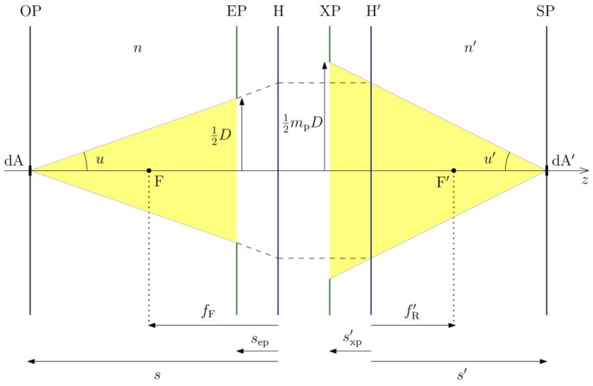
To be decided

Summary

Contents

- Contextualise CYGNO in the dark matter search
- The optical readout allows to image large areas, but the solid angle covered can be as small as 10^{-4}

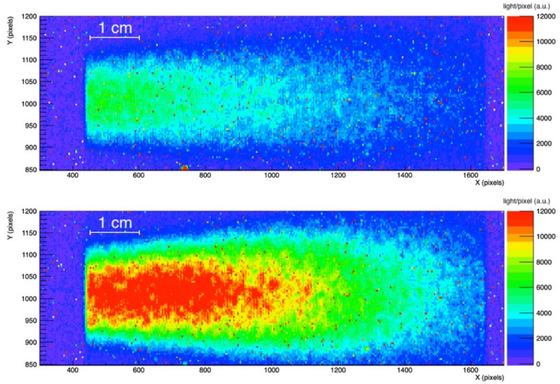
$$\Omega_f = \frac{1}{\left(4N^2\left(\frac{1}{I}+1\right)\right)}$$



Rowalds., book, IOP Publishing (2017)

- **Maximising the light production** is key for low threshold
- Measurement of light enhancement with strong electric field below last GEM

High field turned on



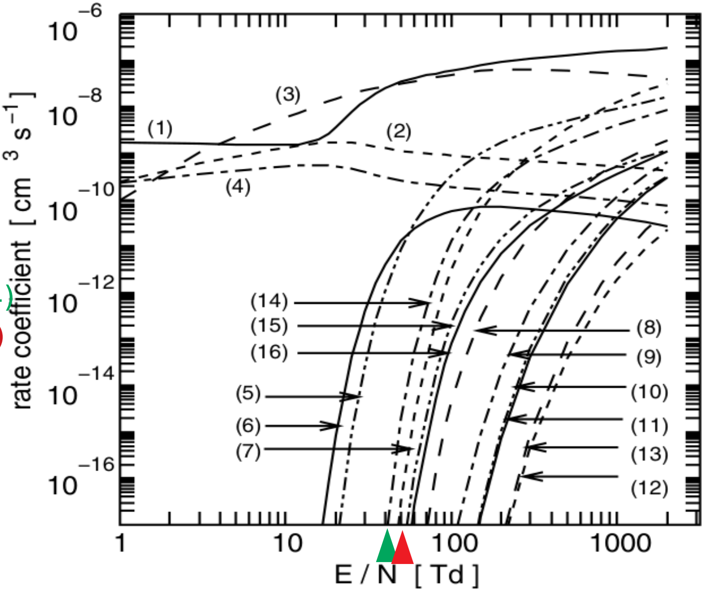
Baracchini et al., JINST, 15 (08) (2020)

- The general features of the scintillating spectrum of He:CF_4 are briefly introduced

- In CF_4, light produced by neutral fragmentation, charge from ionising fragmentation

Process	Threshold (eV)	Energy loss (eV)
Direct vibrational excitation ν_4 ν_3	0.078 0.159	0.078 0.159
Indirect vibrational excitation	4.0	0.4
Electron attachment	4.3	4.3
Electronic excitation (dissociation into neutral fragments)†	12.5 (10)	12.5 (10)
Dissociative ionization†	15.9	15.9

Neutral Fragmentation (14)
First ionisation (7)

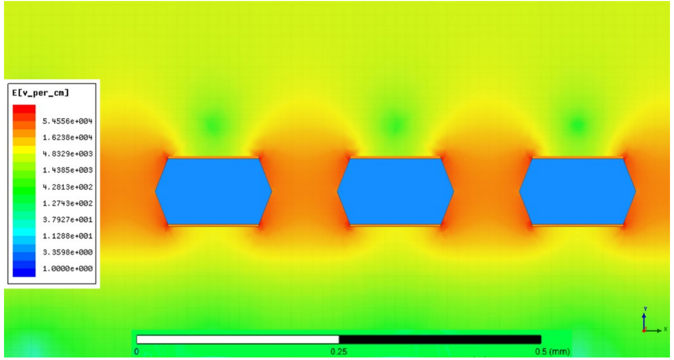


Kurihara et al, JPD, 33 (17) (2000)

- **Cross section of pure CF_4**
- **It may change with He**
- **Large difference in energy threshold among CF_4 and He**

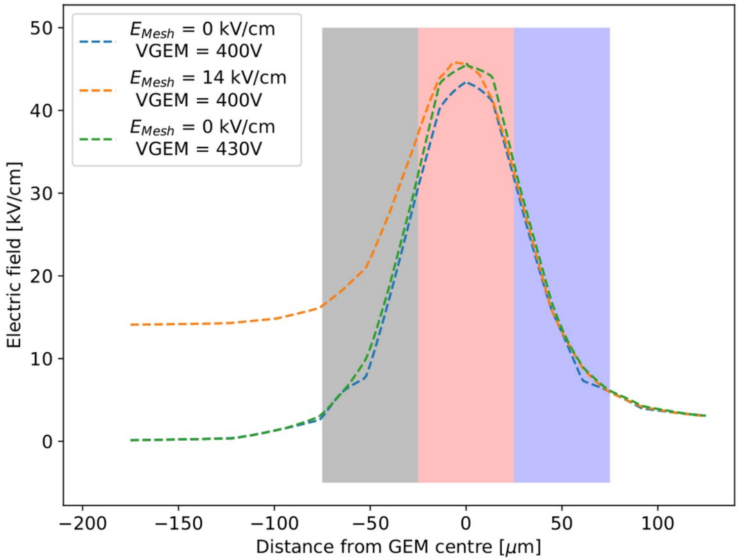
- Passing from 0 to high field, light is first produced → low degradation of energy res can be expected

- Ansys Maxwell program used to simulate the electric field of the experimental setup (TPC) and GEMs
- The uniformity of the field in the induction gap was confirmed (the gap between the last GEM and a new induction electrode)
- However, a hundred of micrometer away from GEM holes the fields are far from constant

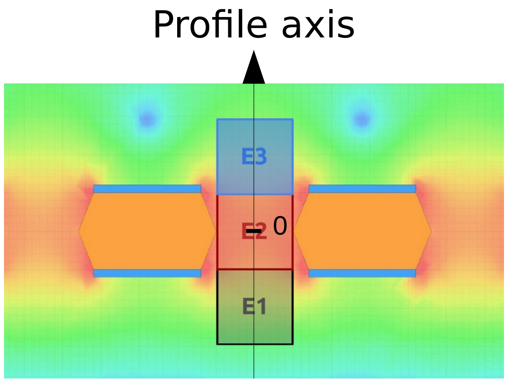


- The profile of the electric field is studied on an axis perpendicular to the GEM plane in three conditions
    - Low V_g, no induction field
    - High V_g, no induction field
    - Low V_g, high induction field

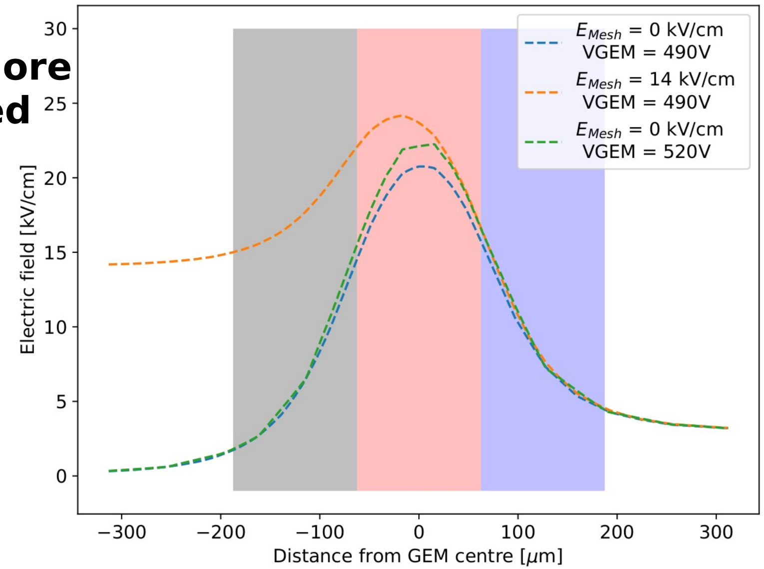
t (50 μm thick, 70 μm hole diameter, 140 μm pitch)



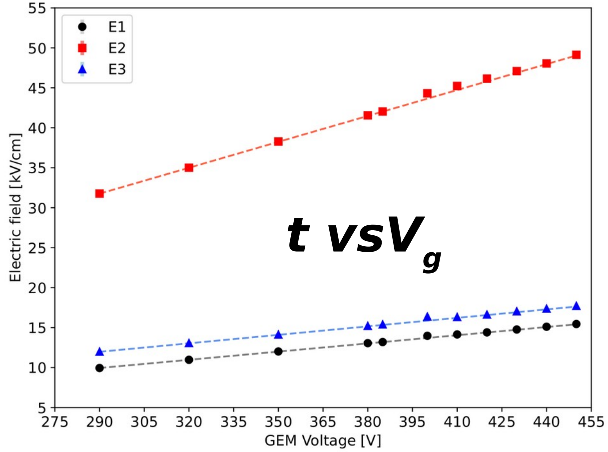
T GEM more affected

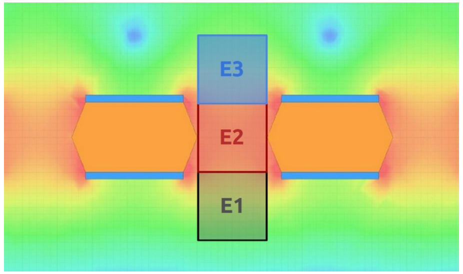


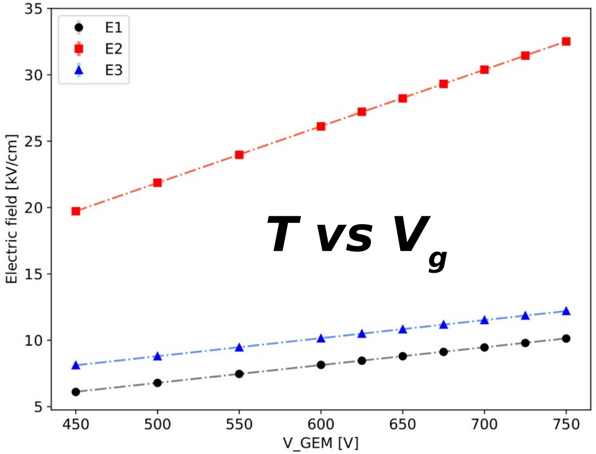
T (125 μm thick, 175 μm hole diameter, 350 μm pitch)



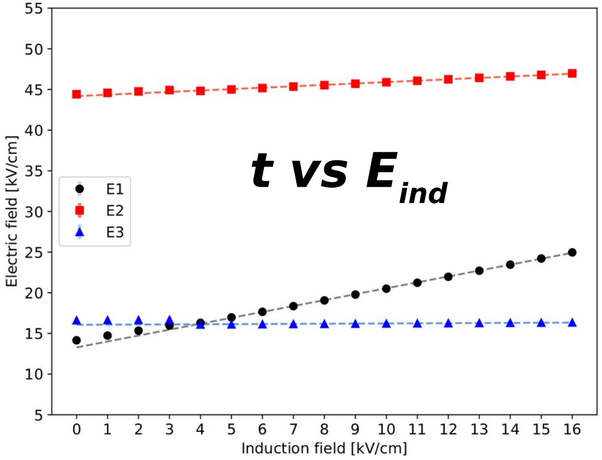
- Increasing V_g enhances the field strength without changing the structure
- A strong E_{mesh} modifies the shape of the profile generating a region below the GEM where light production and amplification can take place
- To quantify the electric field intensity, the value is averaged in 3 regions

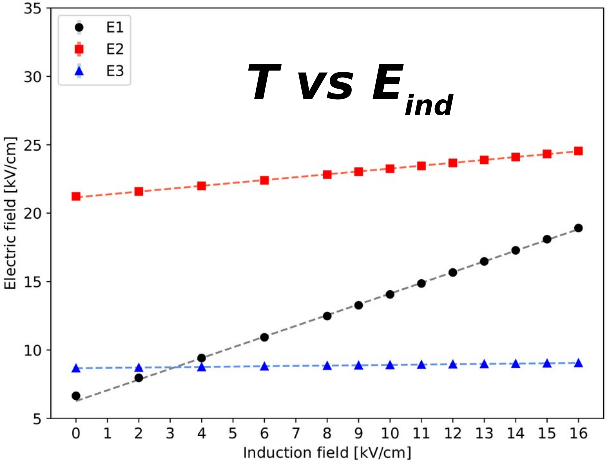




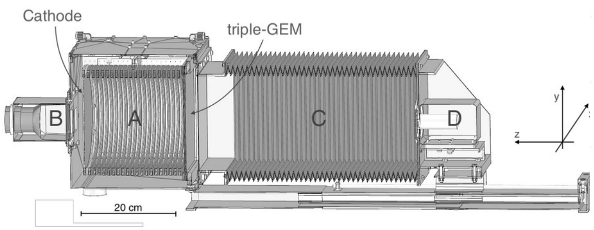


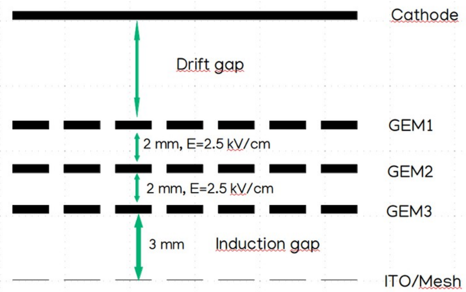
- The induction field does not affect the field above the GEM
- The induction field increses the field inside the GEM hole, but less than V_g
- The field below the GEM is strongly enhanced up to values where amplification is achievable
- *T* GEM has intrinsically lower fields, so the induction field is relatively larger

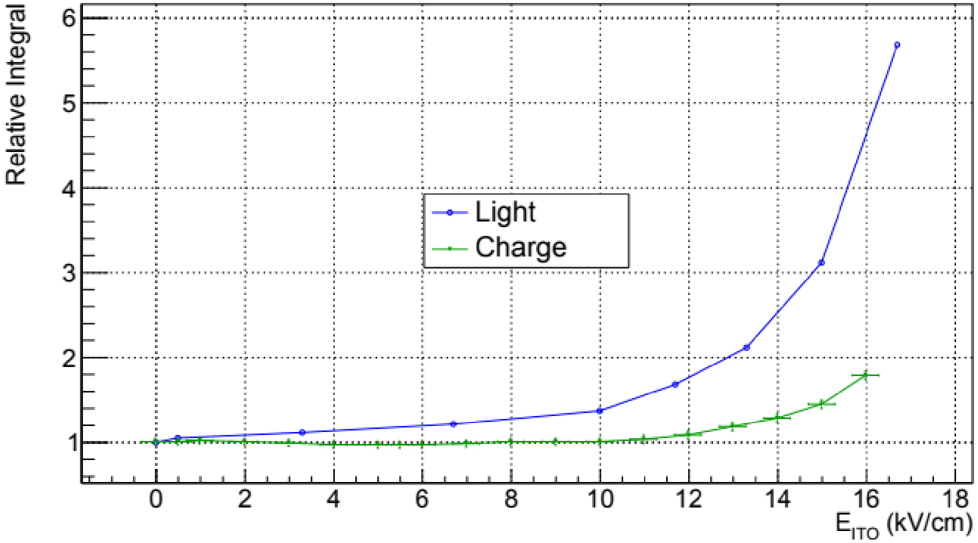




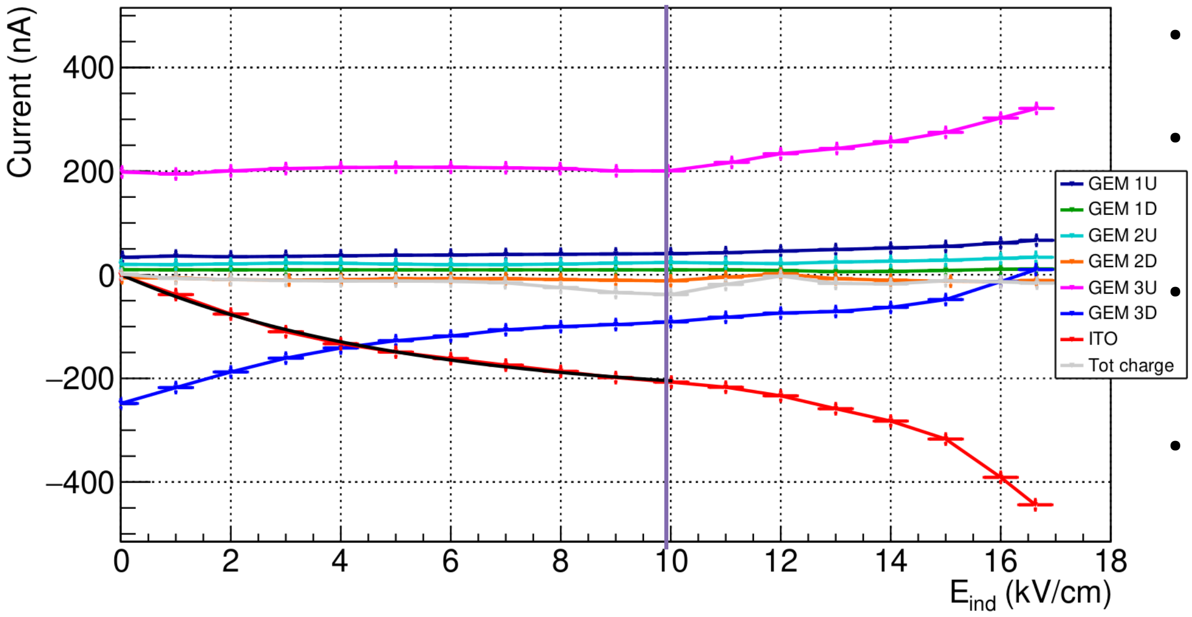
- LEMOn detector: 20x24 cm^2 readout area and 20 cm drift, effective granularity 125 x 125 μm^2)
- Studies on the light amplification induce\d by electric field below the last GEM extended with LEMOn prototype and an ITO glass (T=0.9)
- ^{55}Fe source (5.9 keV X-ray) of 115 MBq produces current signals well above the sensitivity of the LEMOn current reader (10 nA)
- The light measurements used 1 s exposure and average light output on different areas (after noise pedestal subtraction)





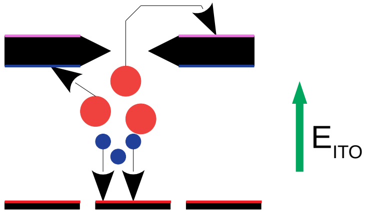


Light increment far exceeds the extra charge produced

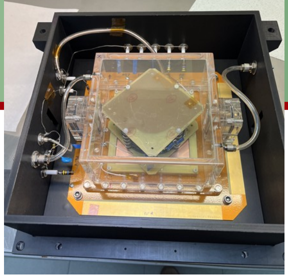


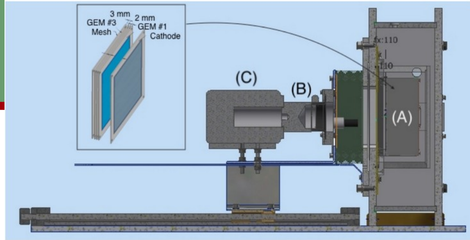
- Below 10 kV/cm 3U is constant
- Above 10 there is a rise in charge → **Charge is produced**
- The amount of charge created can be evaluated from the ITO after taking into account for the sharing of electrons between 3D and ITO

- Total sum of the charge is zero (gray)
- 3U collects ions from 3rd stage of amplification (magenta)
- ITO (red) and 3D (blue) share the electrons generated by the amplification
- If any new charge is generated in the induction:
  - 3D and 3U collect the ions
  - ITO only collects electrons



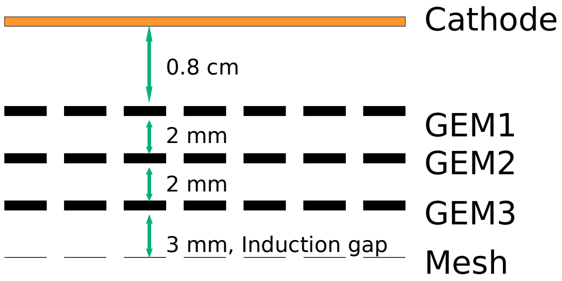
Section V: MANGO



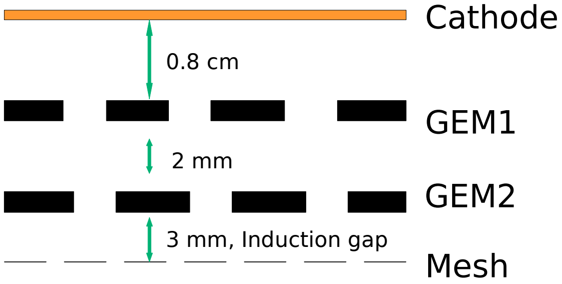


- MANGO detector used to extend the induction field study to other GEM configurations and He concentrations (60% or 70%)
- MANGO is 10x10 cm^2 readout area with variable drift gap (0.8 cm here)
- Metallic mesh employed as induction electrode (T=0.55)
- ***ttt:*** Stack of 3 thin GEMs (50 μm thick, 70 μm hole diameter, 140 μm pitch)
- ***TT:*** Stack of 2 thicker GEMs (125 μm thick, 175 μm hole diameter, 350 μm pitch)
- ***Tt:*** Stack of 1 *T* GEM and a *t* one

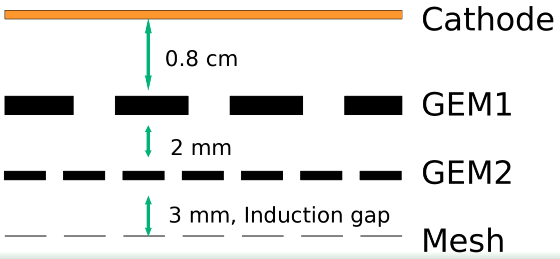
ttt



TT



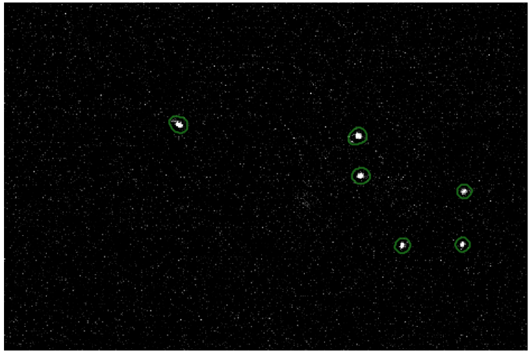
Tt



- ^{55}Fe source of 48 kBq allows an event by event analysis of the images

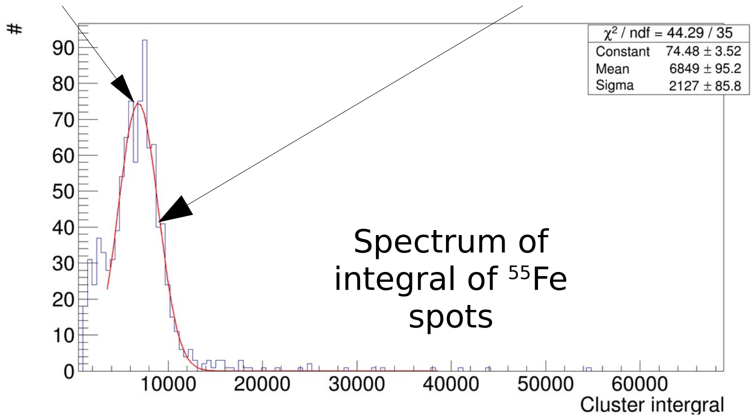
- Camera exposure 0.5 s exposure

- Optimisation of the amplification structure based on the analysis of **light yield**, **energy resolution** and **intrinsic diffusion**

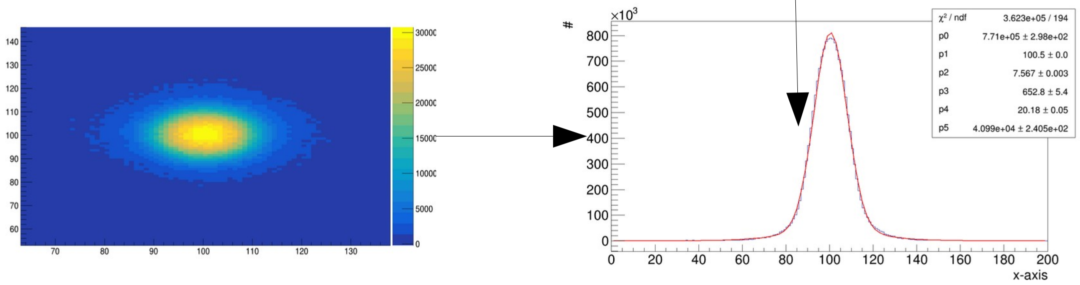


Light yield

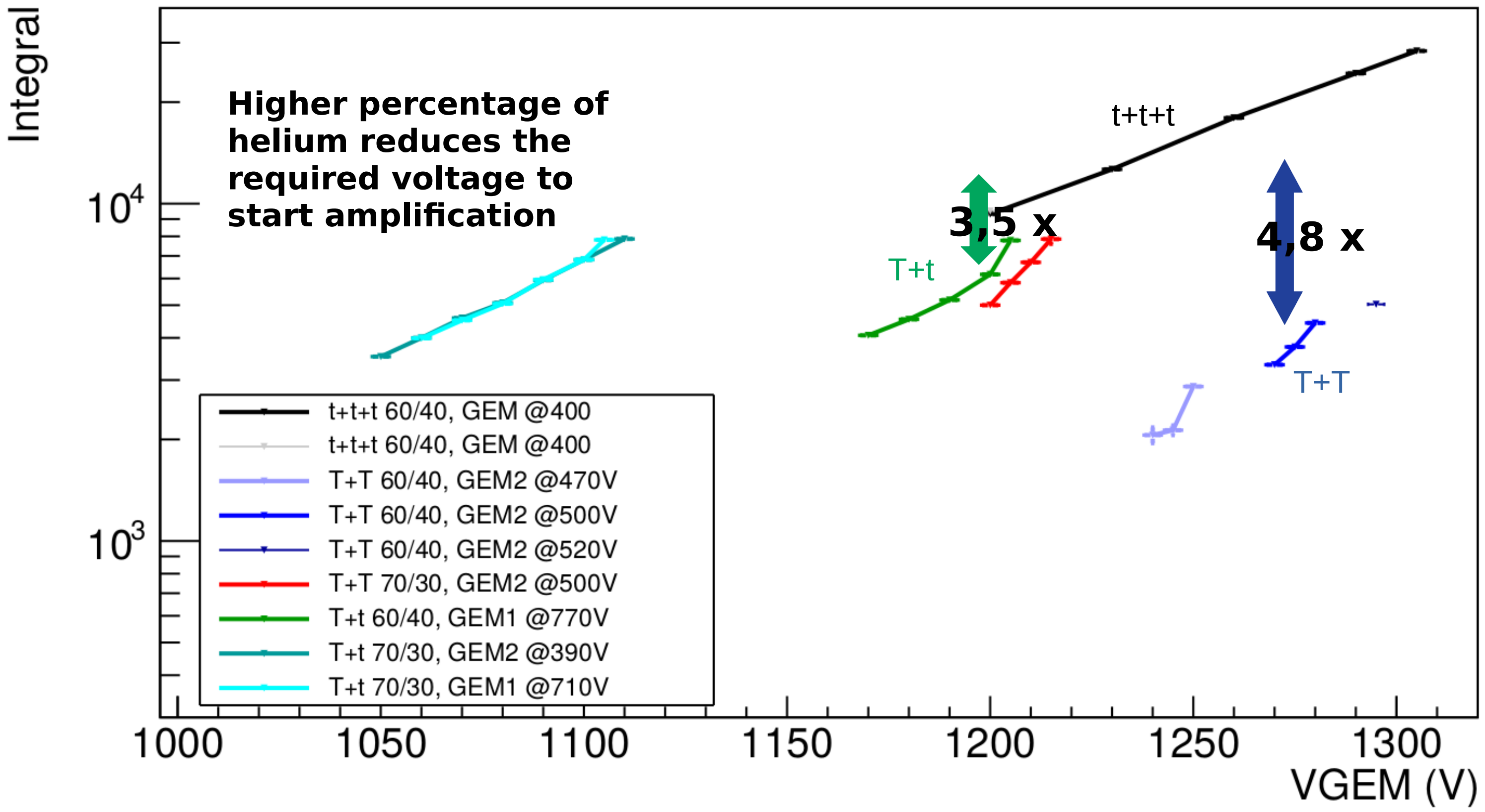
Energy resolution $\frac{\sigma}{Mean}$



Intrinsic diffusion



- Characterisation of the setups with regular operation



- The gain can be parametrised as a function of a *reduced field* (Σ) inside the GEM holes as (T.N. Thorpe, S.E. Vahsen, 10.1016/j.nima.2022.167438)

$$\Gamma = \frac{ln(G)}{n_g pt} = A_0 + B_0\Sigma = A_0 + \frac{B_0}{pn_g t}V_g$$

$$\Sigma = \frac{V_g}{n_g pt}$$

- (Γ) reduced gain
- **p** pressure
- $\mathbf{n_g}$ number of GEMs
- $\mathbf{A_0}$, $\mathbf{B_0}$ free parameters
- **t** thickness of GEM
- $\mathbf{V_g}$ sum of voltage across GEMs

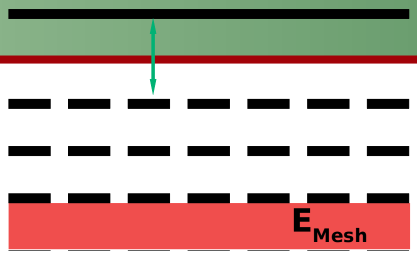
- Table obtained by fitting the data of previous slide
- The consistency of the parameters suggests the parametrisation is correct within the uncertainties
- Good understanding of the multiplication process

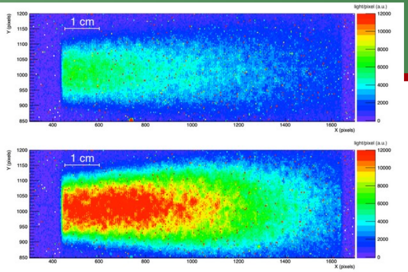
Config	Colour	[0] $\frac{1}{torr \cdot cm}$	$\sigma_{[0]}$ $\frac{1}{torr \cdot cm}$	[1] $\frac{1}{torr \cdot cm \cdot V}$	$\sigma_{[1]}$ $\frac{1}{torr \cdot cm \cdot V}$
ttt 60/40	Black	-0.36	0.14	0.00106	0.00011
Tt 60/40	Green	-0.7	0.2	0.0012	0.0004
Tt 70/30	Cyan	-0.6	0.2	0.0012	0.0003
Tt 70/30	Dark Green	-0.49	0.19	0.0011	0.0002
TT 60/40	Blue	-1.6	0.9	0.0017	0.0007
TT 70/30	Red	-1.6	1.0	0.0018	0.0006

Section VI: Image Analysis (E_{IND})

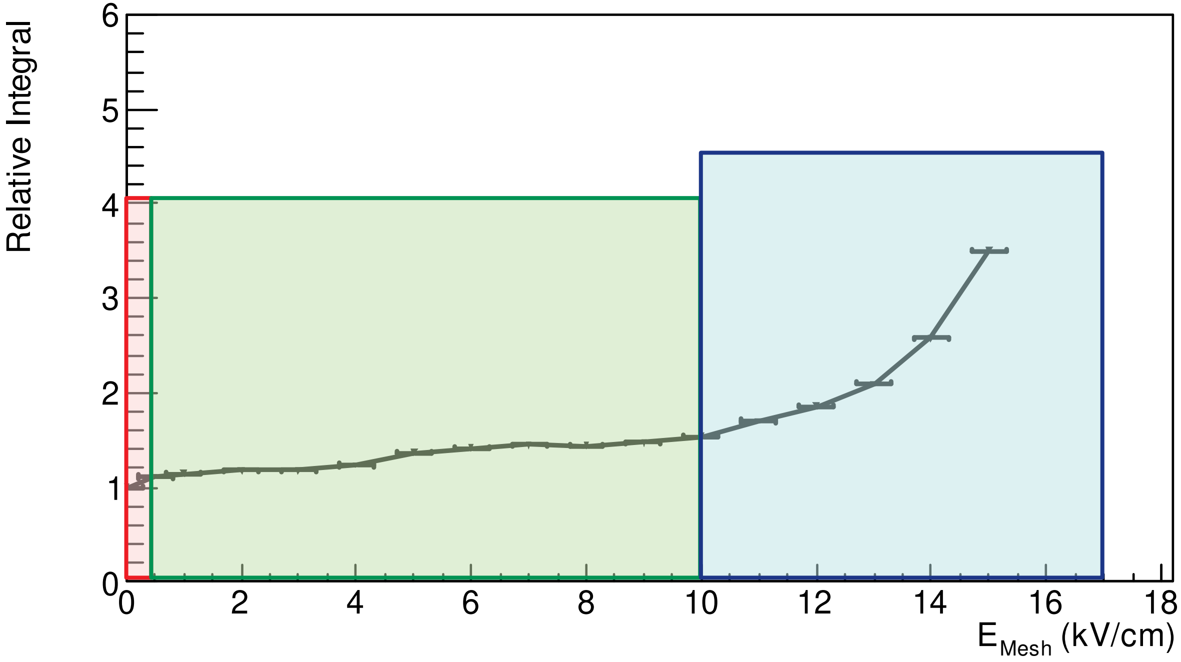
- Fixing the V_g and increasing the induction field (E_{Mesh})

Last GEM





ttt case



- **Immediate increase**, due to better defined field lines below the last GEM (Maxwell simulations)
- Linear increase
- Exponential growth

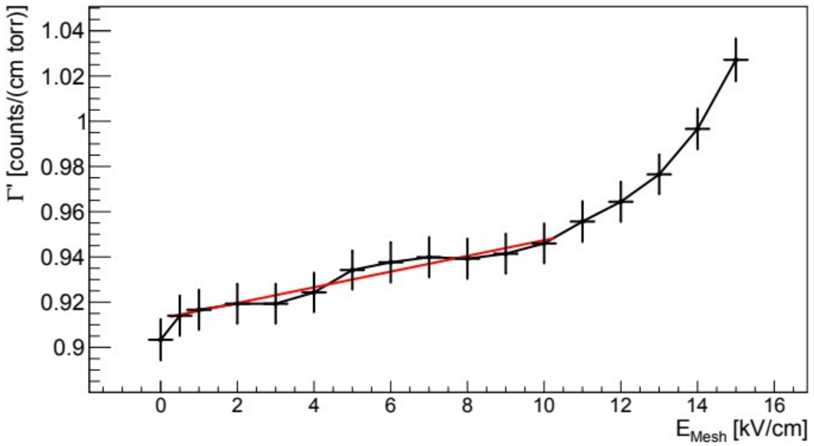
- Employing the parametrisation of the gain, the reduced field can be expanded with a term to include the influence of E_{mesh}, as suggested by Maxwell simulations

$$\Sigma = \frac{1}{p}\left(\frac{V_g}{n_g t} + \alpha E_{mesh}\right)$$

Once V_g is fixed this is a constant term ([0]) which should match the terms fitted with the gain (**Condition C**)

$$\Gamma = A_0 + \frac{B_0}{p n_g t} V_g + \frac{B_0 \alpha}{p} E_{mesh}$$

[1]: Term proportional to E_{Mesh}

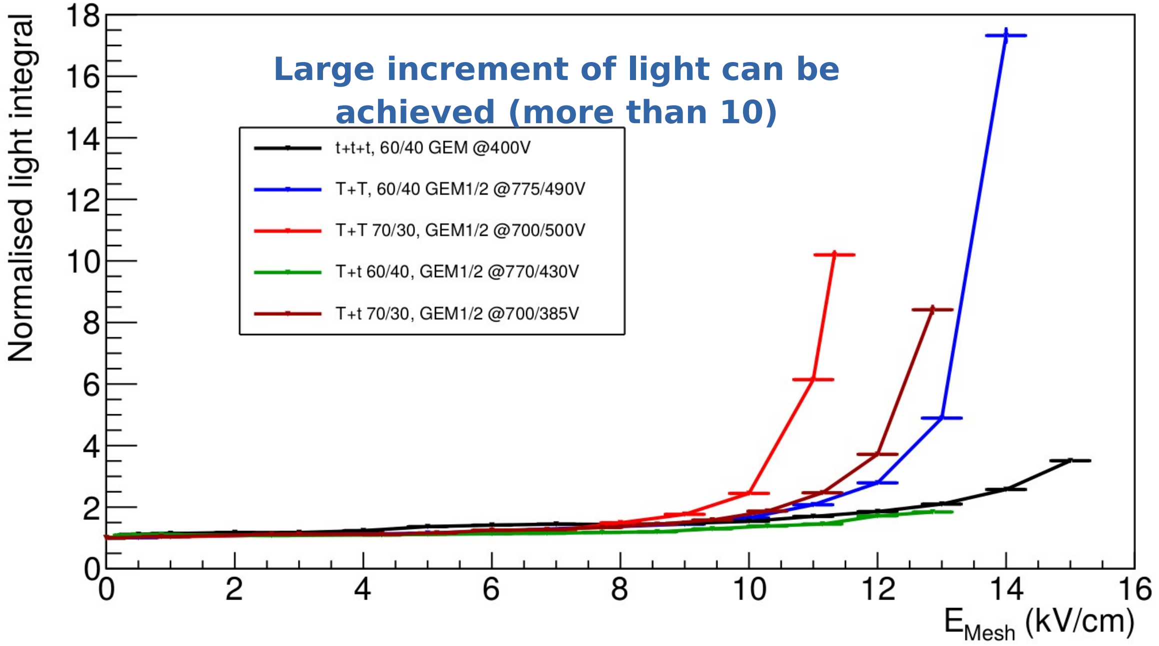


Conf	$[0]\ \frac{1}{torr \cdot cm}$	$\sigma_{[0]}\ \frac{1}{torr \cdot cm}$	$[1]\ \frac{1}{torr \cdot kV}$	$\sigma_{[1]}\ \frac{1}{torr \cdot kV}$	Cond. C
ttt 60/40	0.912	0.005	0.0036	0.0010	✓
Tt 60/40	0.747	0.009	0.0010	0.0009	✓
Tt 70/30	0.704	0.007	0.0029	0.0015	✓
TT 60/40	0.48	0.01	0.0025	0.0013	✓
TT 70/30	0.505	0.004	0.0016	0.0010	✓

- Above 10 kV/cm the linear fit fails to represent the data
- New phenomenon must be happening at larger fields

Section VI: Image Analysis (E_{IND} III)

- The exponential part is studied after removing the linear contribution



As suggested by simulations, structures with T last GEM generate larger light enhancement

- The **intensity** of the light increase depends on the last GEM
- The data are fitted in order to find the breaking point of the exponential growth

$$a + b \cdot e^{cE_M - d}$$

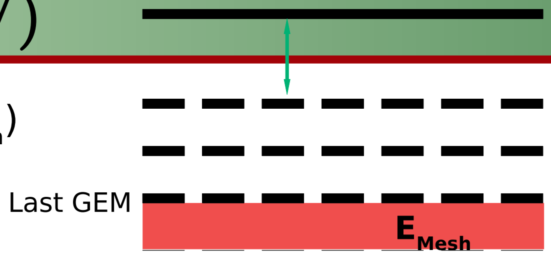
- The helium content modifies the breaking point

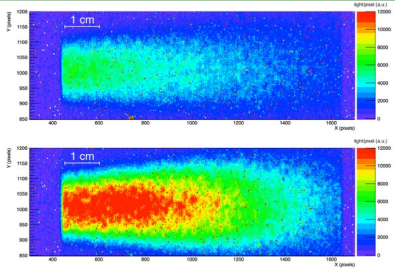
$E_{break,60/40} = (9.7 \pm 0.8)$ kV/cm

$E_{break,70/30} = (8.7 \pm 0.7)$ kV/cm

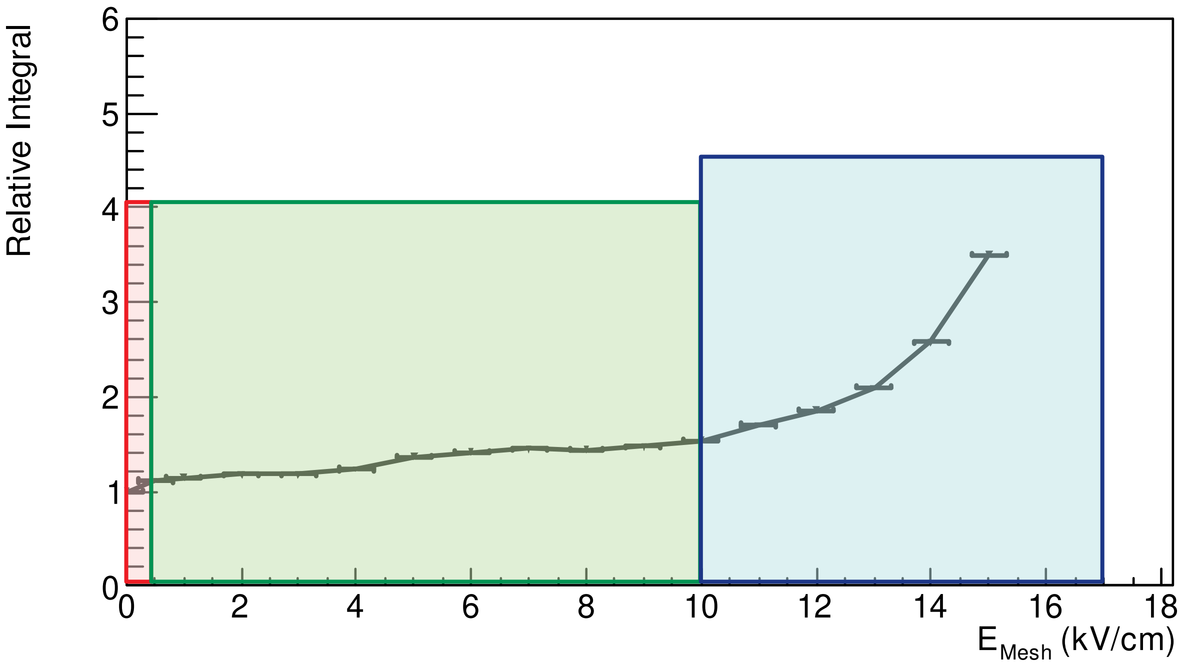
As for the gain scan, more helium requires lower field for the phenomenon to begin

- Fixing the V_g and increasing the induction field (E_{Mesh})



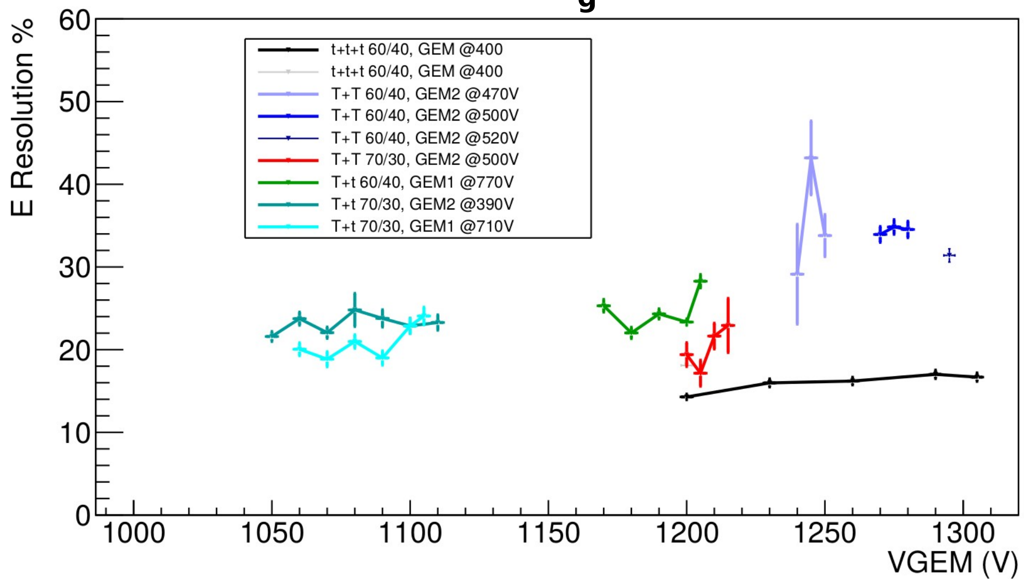


ttt case

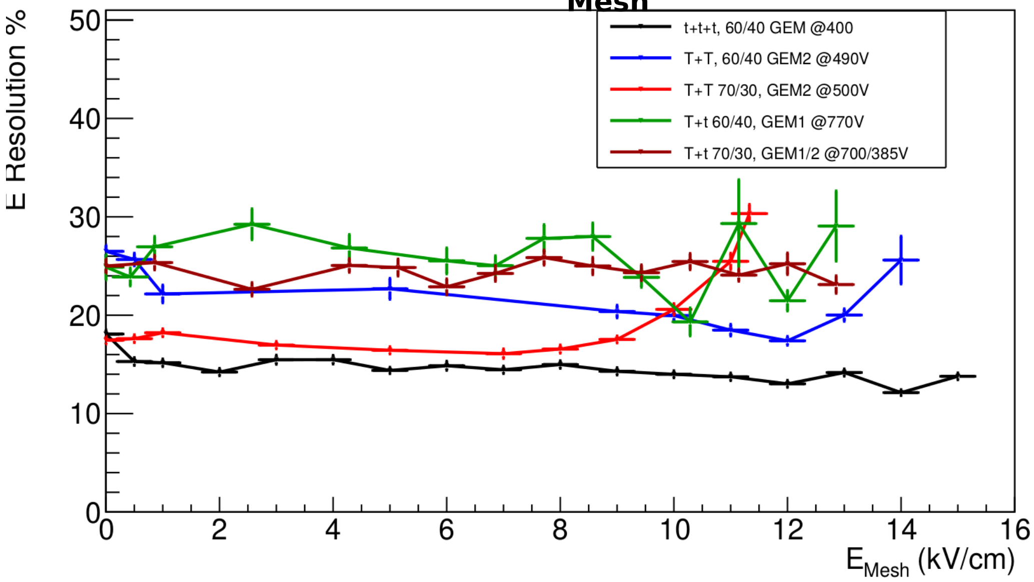


- Increase due to better defined field lines below the last GEM (Maxwell simulations)
- Linear increase due to the induction field affecting the field inside GEM
- Exponential growth due to the large electric field generated in the small region below the last GEM

vs V_g



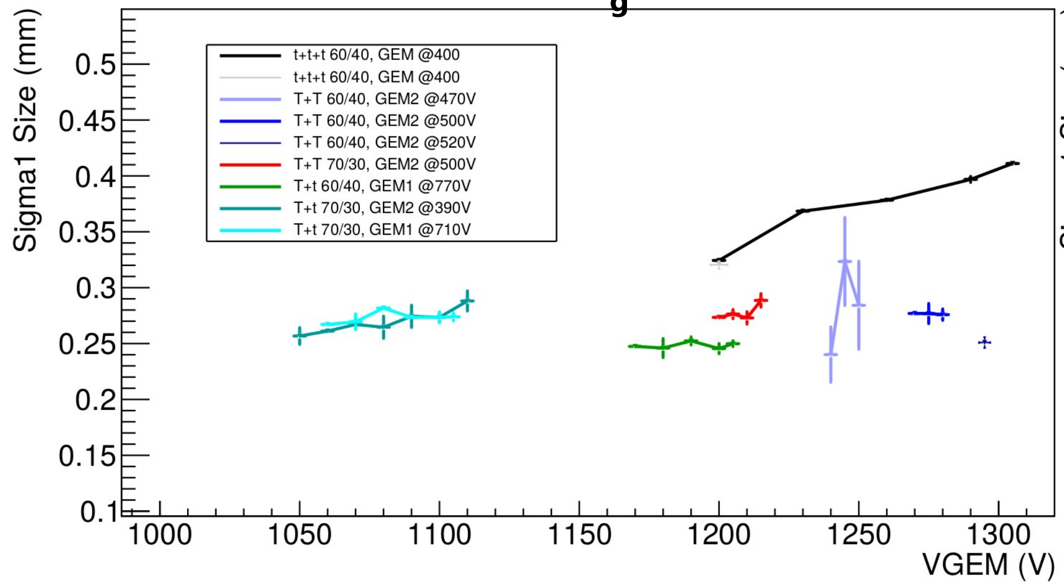
vs E_{Mesh}



- Best energy resolution obtained with stronger fields and higher gain (*ttt*)
- Energy resolution roughly constant with V_g

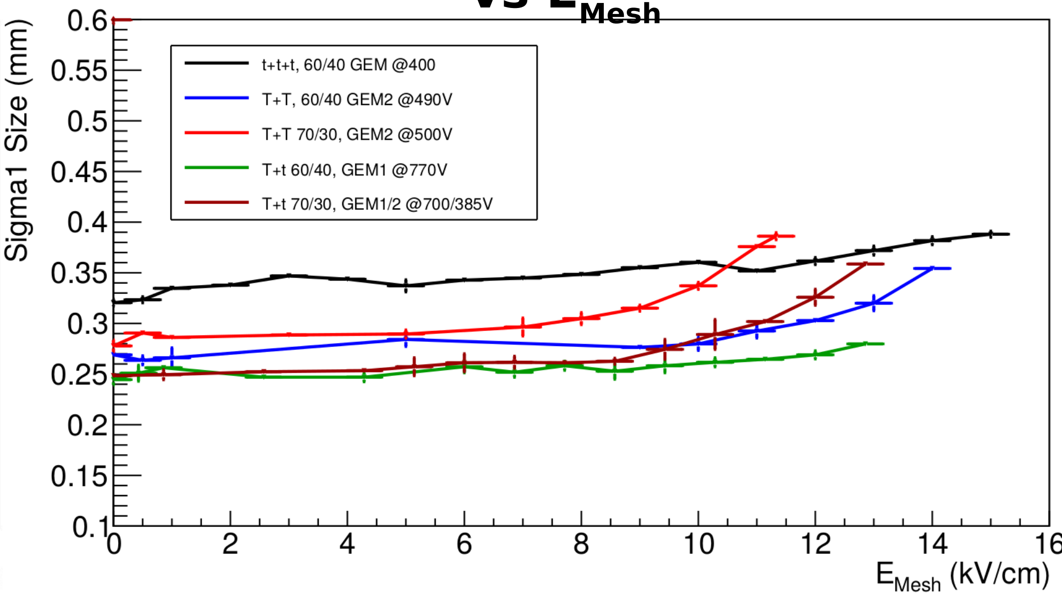
- Energy resolution is constant or improves with field if the last GEM is thin
- At the breaking point the *TT* GEMs have a clear worsening of the resolution

vs V_g



- Diffusion is in general independent of the V_g
- *ttt* clearly worsens with the applied voltage
- *Tt* has the lowest diffusion among all (only two GEMs and the granularity copes with the GEM pitch)

vs E_{Mesh}



- From the breaking point the spot size increases
- Expected as extra light is generated out of the focus

Section VII: Discussion

- Innovative way to enhance light yield with He:CF_4 mixture

- The induction field allows any structure to reach larger light yield

		Integral	E res (%)	Diff [μm]
ttt	min	9510 ± 40	16.0 ± 0.3	320 ± 4
	max V_{GEM}	28400 ± 110	16.6 ± 0.3	412 ± 5
	max E_{Mesh}	33500 ± 140	13.8 ± 0.3	388 ± 5
TT	min	3410 ± 20	28.0 ± 1.5	260 ± 3
	max V_{GEM}	5090 ± 30	31.0 ± 0.6	255 ± 3
	max E_{Mesh}	58800 ± 300	25.7 ± 0.5	356 ± 5
Tt	min	4600 ± 30	25.2 ± 0.5	245 ± 3
	max V_{GEM}	7700 ± 40	27.8 ± 0.5	245 ± 3
	max E_{Mesh}	11800 ± 50	26.8 ± 0.5	280 ± 4

Section VII: Discussion (II)

		Integral	E res (%)	Diff [μm]
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	max E_{Mesh}	11800 ± 50	26.8 ± 0.5	280 ± 4

- Innovative way to enhance light yield with He:CF_4 mixture
- The induction field allows any structure to reach larger light yield
- Each structure excels in a particular feature

Max E_{Mesh}

	E_{Mesh} [kV/cm]	Integral	E res (%)	Diff [μm]
ttt	15 ± 0.3	33500 ± 140	13.8 ± 0.3	388 ± 5
TT	14 ± 0.3	58800 ± 300	25.7 ± 0.5	356 ± 5
Tt	12.8 ± 0.2	11830 ± 50	26.8 ± 0.5	280 ± 4

- *ttt* Energy resolution
- *TT* light yield
- *Tt* intrinsic diffusion

- Application to many fields depending optimisable depending on need

Section VIII: Conclusion

- Conclusion with cyclical style to adhere to the introduction
- Highlight on the improvements possible with the strong induction field introduction for a He:CF_4 gas mixture
- Presenting the agreement of the simulation estimation with the experimental results
- Focus on the versatility of the different amplification structures depending on the experimental needs

BACKUP

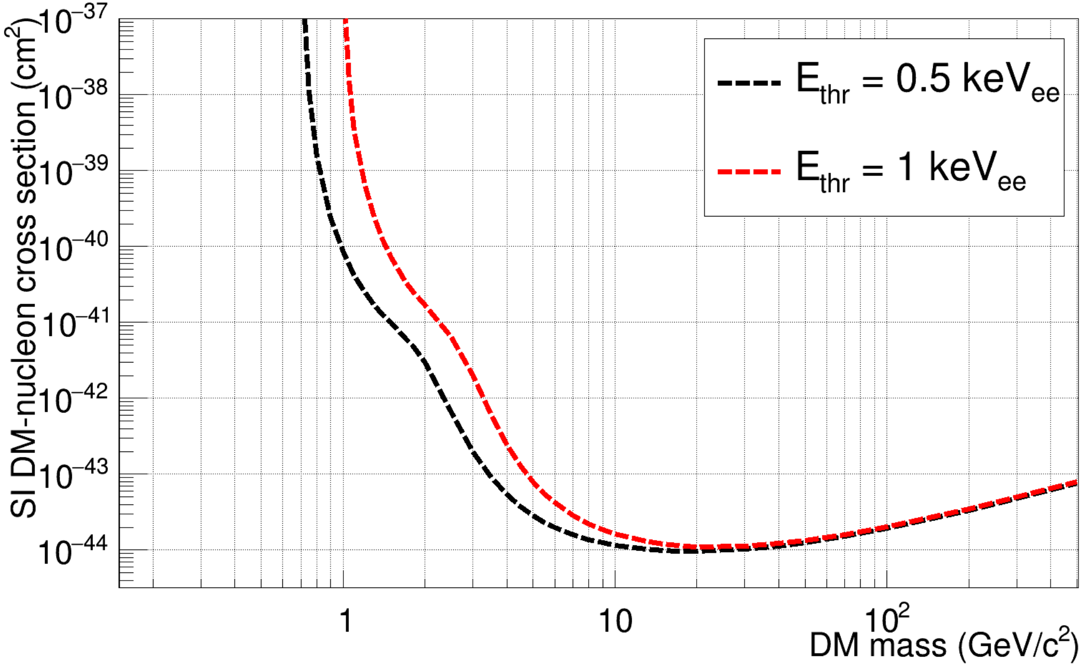
Threshold 1 or 0.5 keV$_{ee}$

- The WIMP masses which can induce detectable recoils depend on the E_{thr}

$$E_{max} = \frac{1}{2} m_\chi r (v_{lab} \cos\gamma + v_{esc})^2$$

	1 keV$_{ee}$		0.5 keV$_{ee}$	
	$E_{thr,nr}$ (keV$_{nr}$)	Min DM mass (GeV/c^2)	$E_{thr,nr}$ (keV$_{nr}$)	Min DM mass (GeV/c^2)
H	1.4	0.5	0.8	0.3
He	2.1	1.0	1.2	0.7
C	3.1	1.9	1.8	1.4
F	3.8	2.5	2.2	1.9

- Also it modifies the part of the velocity distribution which can cause a recoil

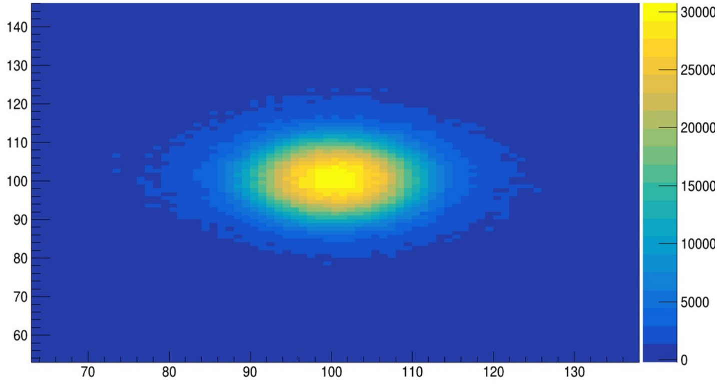


He:CF_4 gas in CYGNO-like 30 m^3

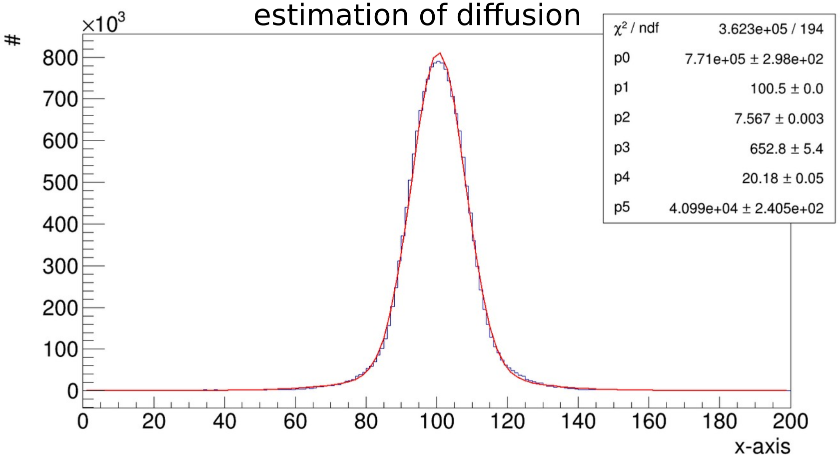
DIFFUSION MEASUREMENT

- ^{55}Fe emits X-rays of 5.9 keV which induce ERs travelling for O(100) μm in the gas
- The diffusion contribution prevails over the topology of the original track → Round spots on camera images
- Given the extremely small drift gap, the intrinsic diffusion of the **amplification stage dominates**
- A double Gaussian fit is applied to the spatial distribution of the overlap of all the ^{55}Fe signal once their barycentres are aligned
- Method independent of the light intensity

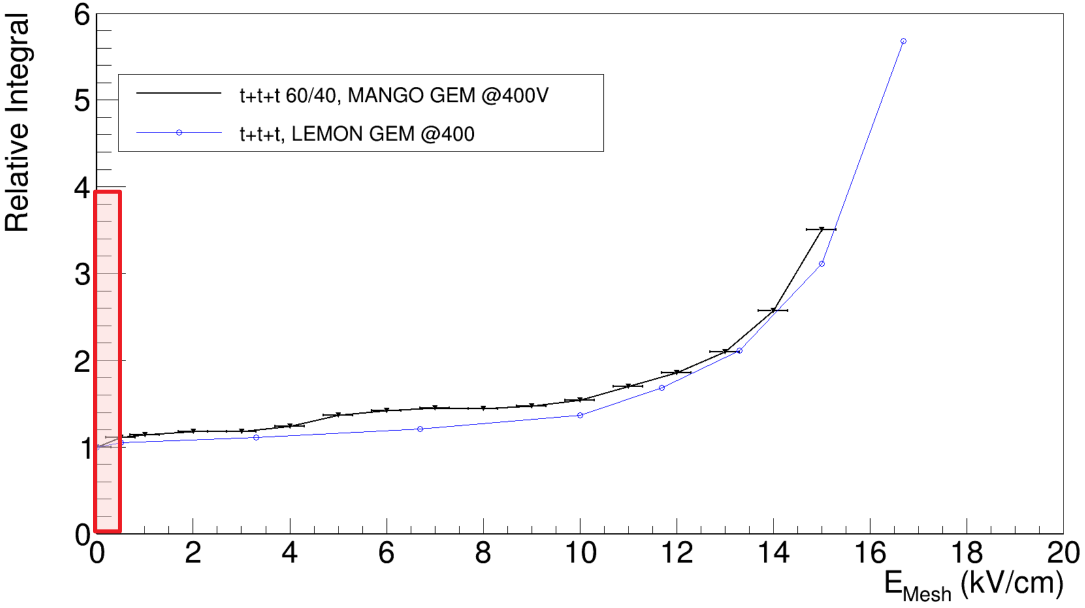
Average spatial projection of the superimposed ^{55}Fe spots



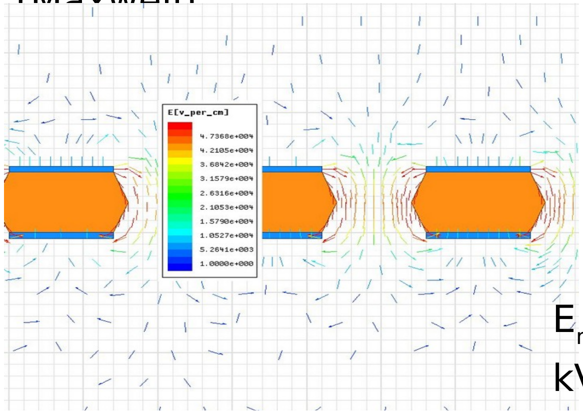
Primary sigma taken as the estimation of diffusion



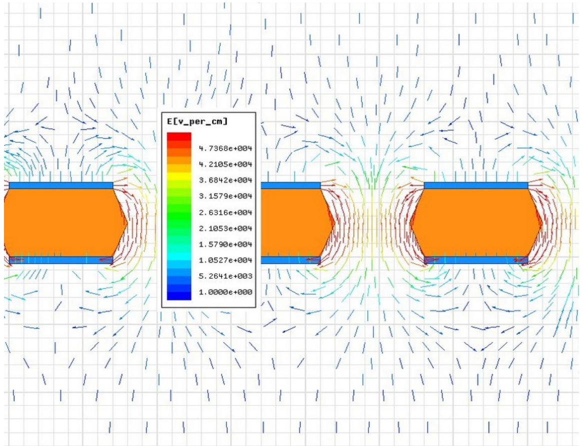
Increase at Low Field



Increase due to better defined field lines below the last GEM (Maxwell)

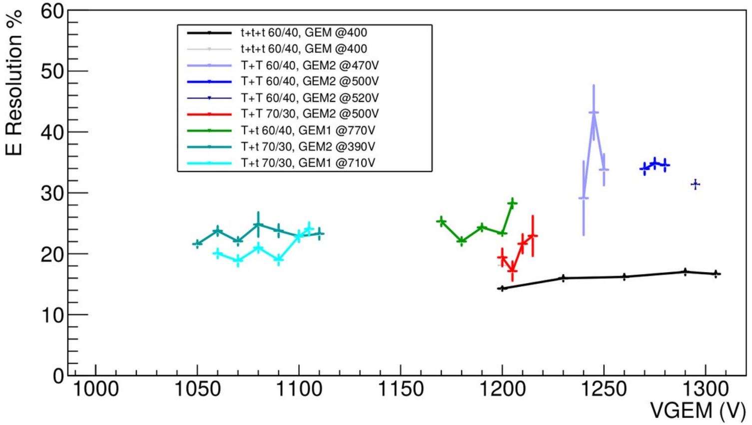


E_{mesh} = 0 kV/cm



E_{mesh} = 1 kV/cm

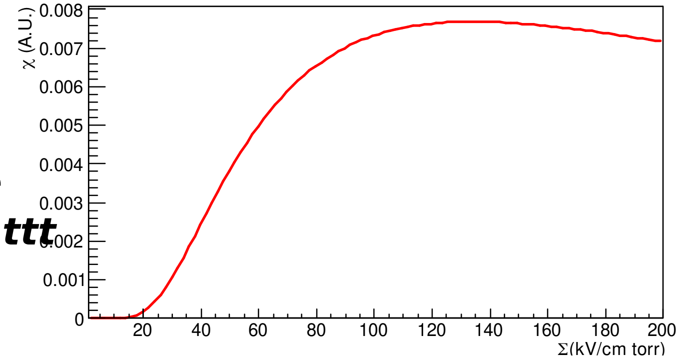
Energy Resolution



$$\sigma_E^2 = \left(\frac{\sigma_{n_0}}{n_0}\right)^2 + \frac{1}{n_0}\left(\frac{\sigma_A}{\bar{A}}\right)^2 = \left(\frac{F}{n_0}\right) + \frac{1}{n_0}\left(\frac{\sigma_A}{\bar{A}}\right)^2$$

Depends on a function χ: Alkhazov, NIM, 89 (1970)

the larger χ, the smaller σ_A



Favours large reduced fields: *ttt*