GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

CYGNO Experiment

Latest Updates on the Luminescence Studies with the Strong Field Below the Last GEM

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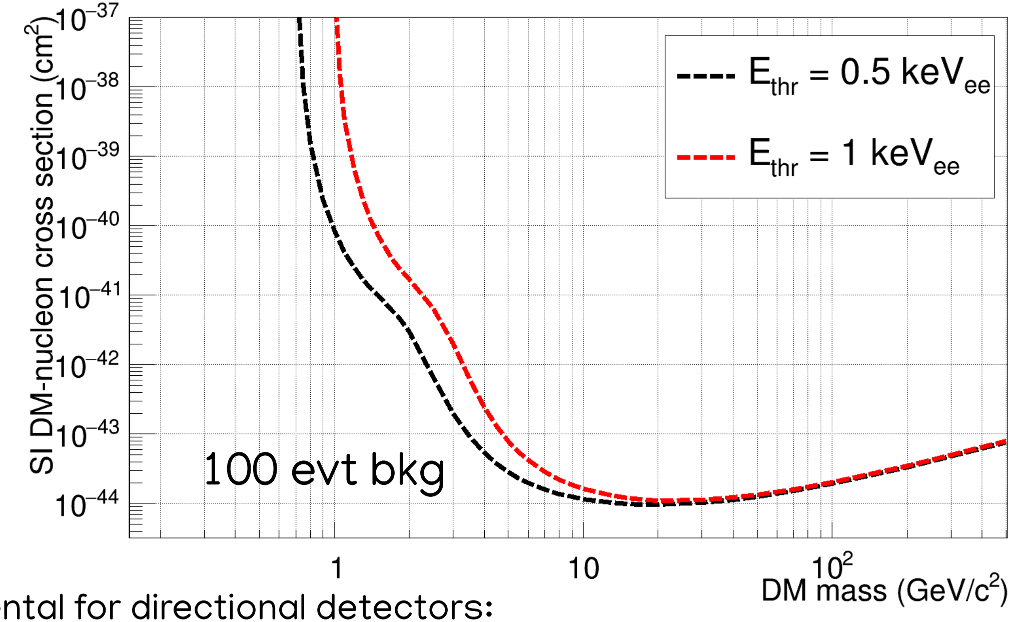
CYGNO Meeting

Roma 19/12/2022

Why More Light and Less Diffusion

- Maximising the light yield is very important as it directly affects the energy threshold of detection

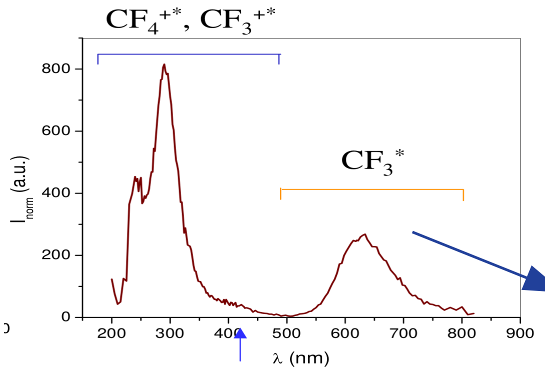


- Half a keV gained can improve orders of magnitude the sensitivity at low energy

- At the same time reducing the diffusion is fundamental for directional detectors:
    - Improves the angular resolution
    - Allows for larger drift length → more exposure
    - Reduces the directionality threshold

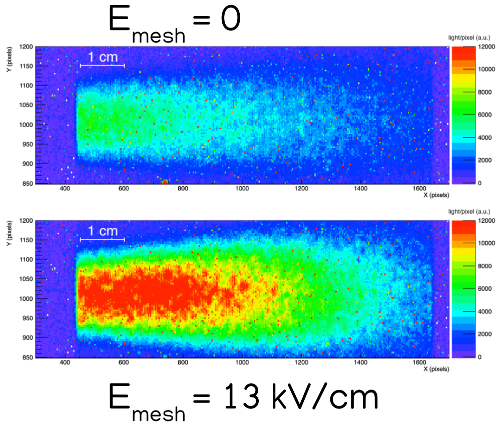
Luminescence Adding Electric Field Below the Last GEM

- The addition of a strong electric field below the last GEM to accelerate electrons to generate extra light is possible and has been investigated in the past

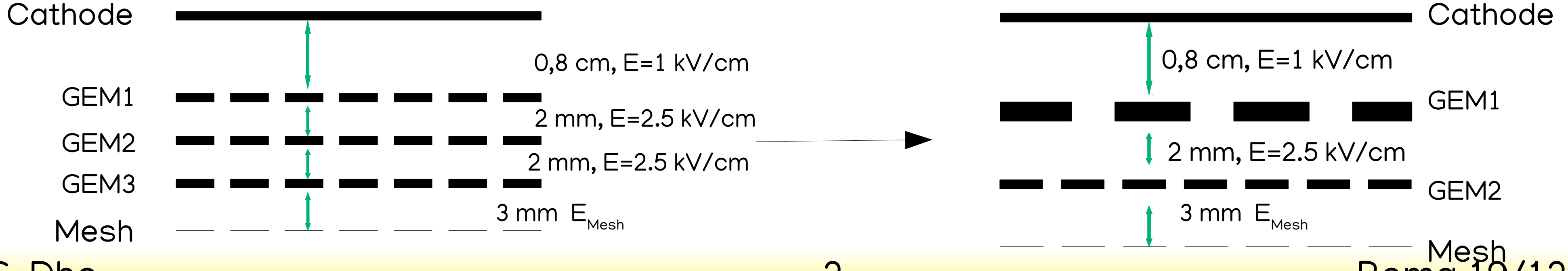


Fraga presentation

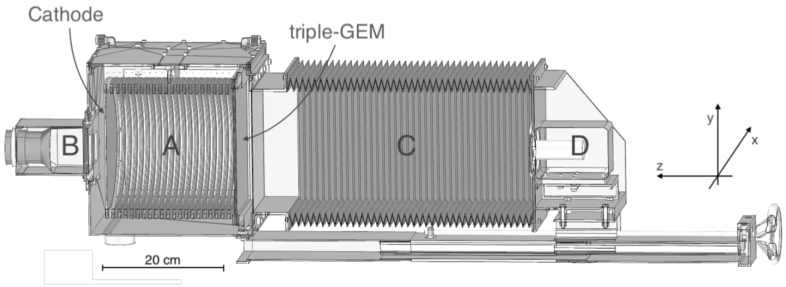
Process	Threshold (eV)	Energy loss (eV)
Direct vibrational excitation ν_4 ν_3	0.078 0.159	0.078 0.159
Indirect vibrational excitation	4.0	0.4
Electron attachment	4.3	4.3
Electronic excitation (dissociation into neutral fragments)†	12.5 (10)	12.5 (10)
Dissociative ionization†	15.9	15.9



- Combining the extra electrode with a different structure of amplification (thickness and number of GEMs) could possibly reduce diffusion while keeping high light yields

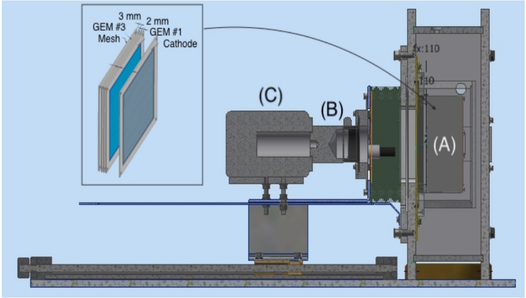


LEMOn



- Large volume and readout area
- ITO glass as extra electrode (T=0.9)
- Very intense ^{55}Fe source which allows to measure
  - average light output
  - Integrated charge from the power supply

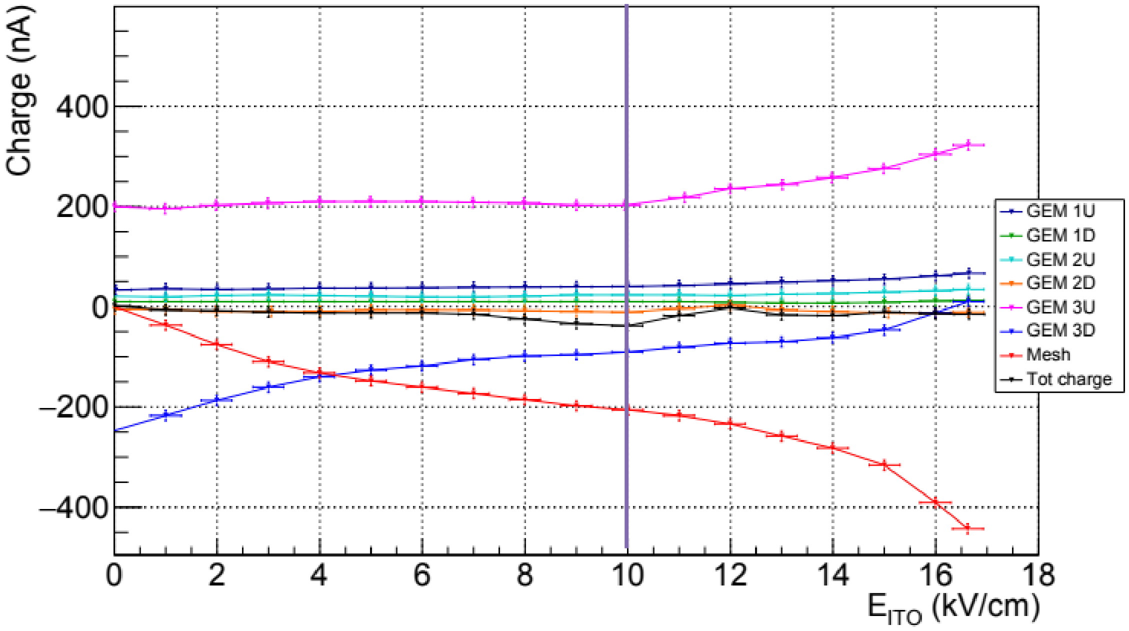
MANGO



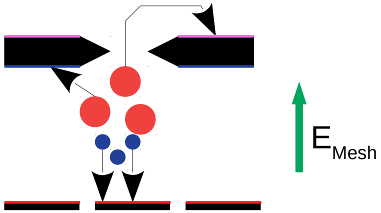
- Small 10 X 10 cm^2 readout area and 0,8 cm drift
- Metallic mesh as extra electrode (T=0.55)
- Low activity ^{55}Fe source which allows to measure event by event the light from the ^{55}Fe interactions

LEMON

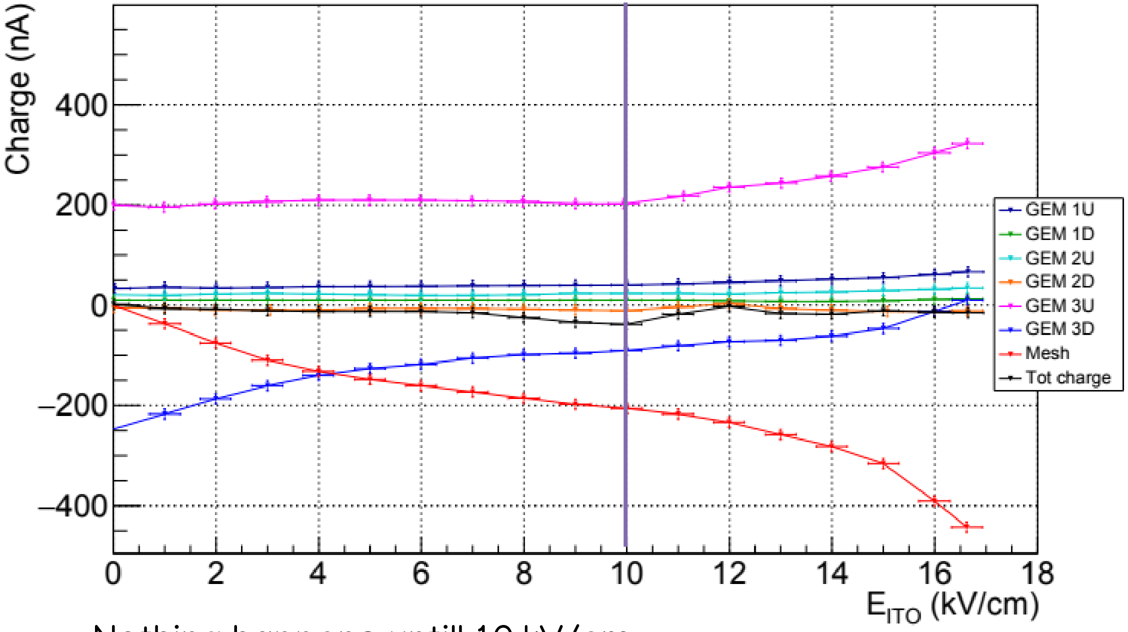
Charge Measurements



- Total sum of the charge is zero (black)
- 3U collects ions from 3rd stage of amplification (magenta)
- Mesh (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
  - Mesh only collects electrons



Charge Measurements



- Nothing happens untill 10 kV/cm
- Above 10 there is a rise in charge → **Charge is produced**
- The amount of charge created can be evaluated from the mesh after taking into account for the sharing of electrons between 3D and mesh

- Total sum of the charge is zero (black)
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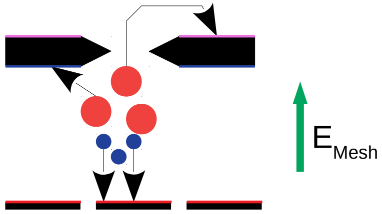
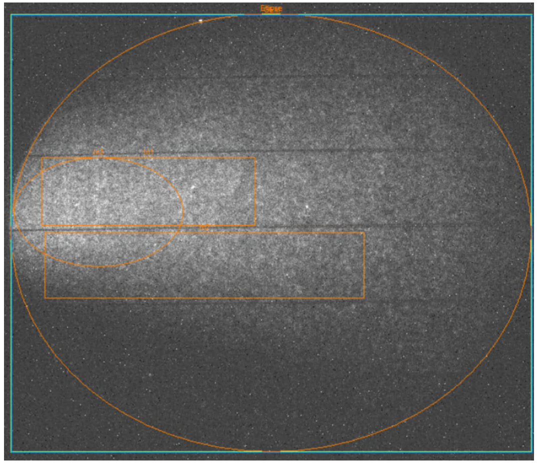
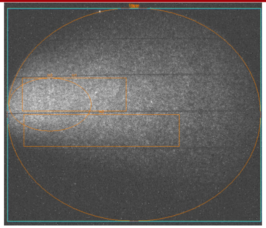


Light Measurements



- Long exposure (1s) pictures taken with the camera
- Different regions are selected on the images and the average light measured after pedestal evaluation

Light Measurements



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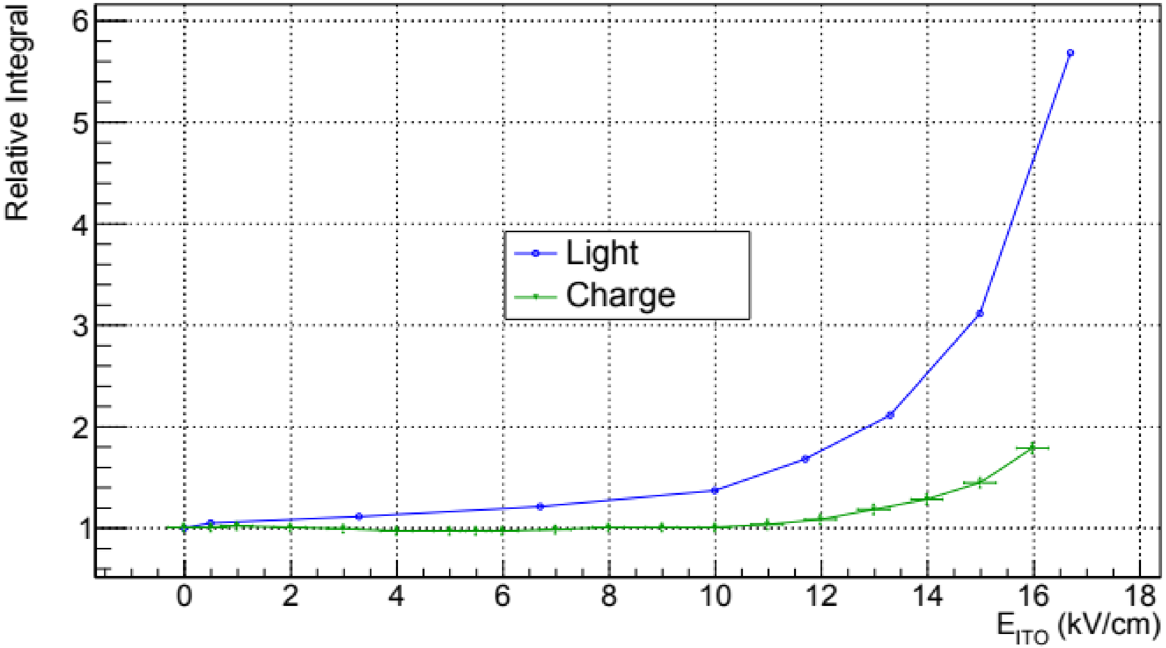


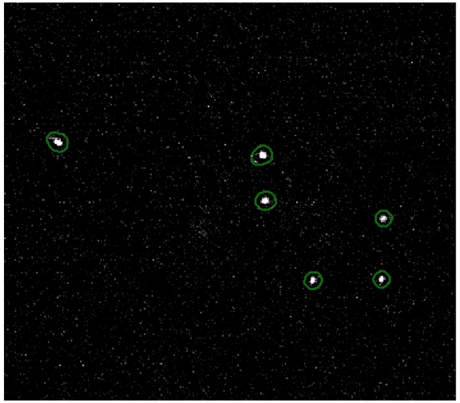
- Clear increase in light yield
- Since 10 kV/cm charge is produced but it is considerably less than the light

Light increment far exceeds the extra charge produced

MANGO

Light Measurements: Analysis

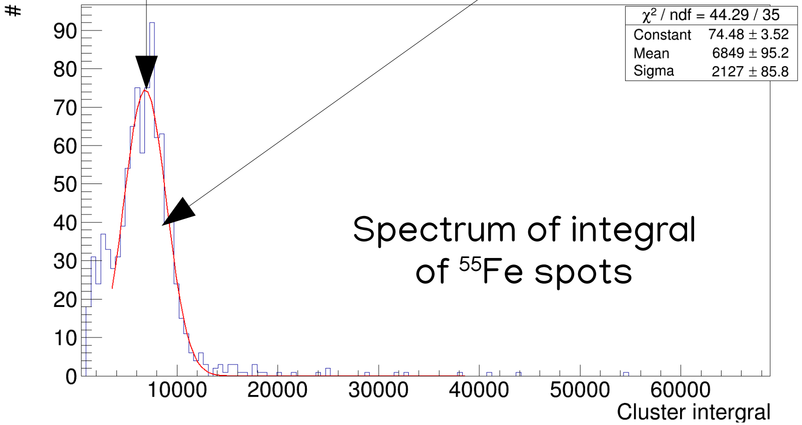
- The lower activity of the radioactive source induce a low occupancy on the camera pictures
- This allows an event by event analysis



Light yield

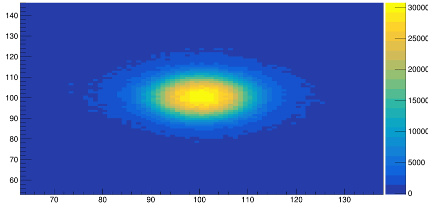
Energy resolution

$$\frac{\sigma}{Mean}$$

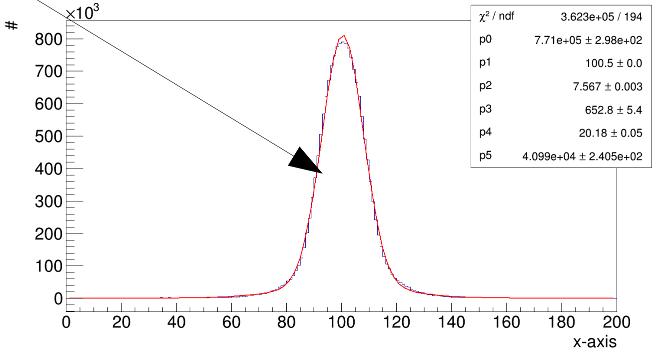


Spectrum of integral of ^{55}Fe spots

Intrinsic diffusion



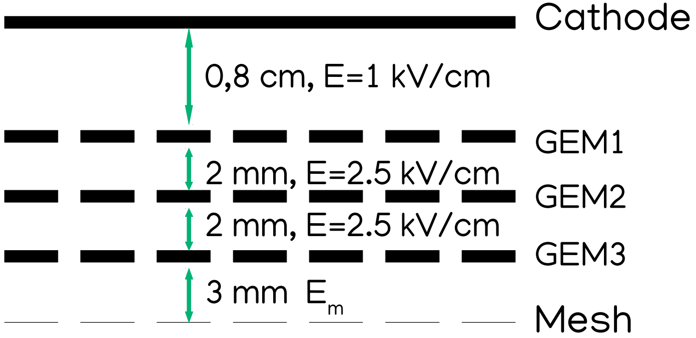
Average spatial projection of the superimposed ^{55}Fe spots



Different GEM stack configurations

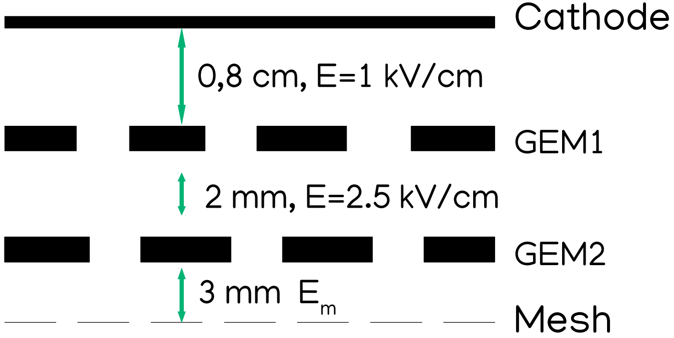
- Different combinations of GEM thicknesses and number of GEMs were implemented in MANGO.
- Also helium content was increased from 60 up to 80 %

50um GEM , 70um holes 140um pitch

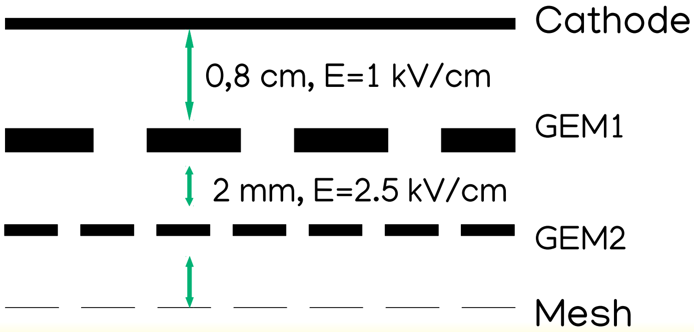


ttt

125um GEM , 175 um holes 350 um pitch



TT

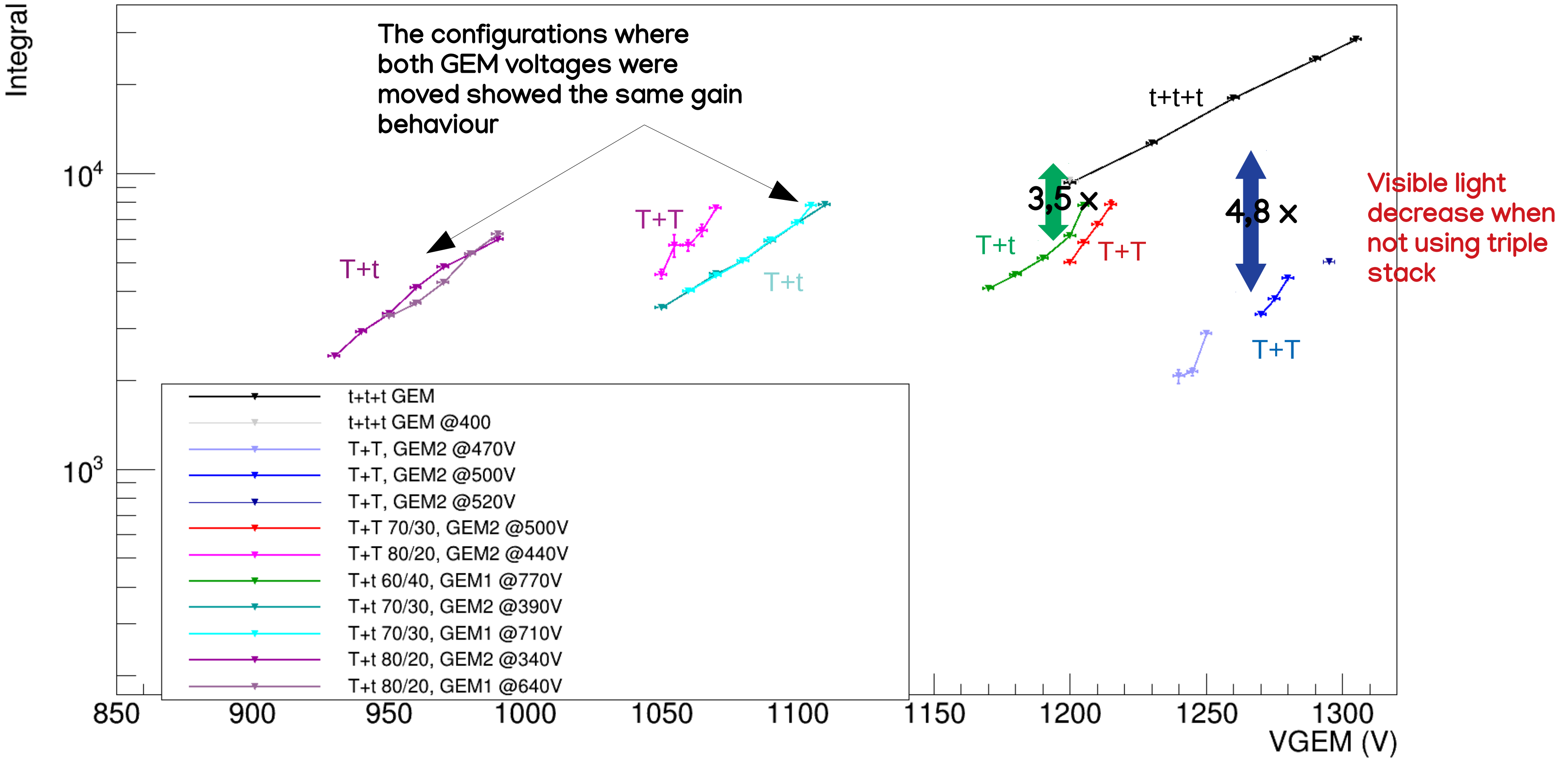


Tt

MANGO

Light Yield

GAIN: VOLTAGE SCAN



Gain: Parametrisation

- A parametrisation of the gain can be performed in terms of reduced gain (Γ) and reduced field (Σ) (T.N. Thorpe, S.E. Vahsen, 10.1016/j.nima.2022.167438)

$$\Gamma = \frac{ln(G)}{n_g pt} = A\left(\frac{V_G}{n_g pt}\right)^m exp\left(-B\left(\frac{n_g pt}{V_g}\right)^{1-m}\right)$$

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

– **A, B** free parameters
–**m** parameter of the gas between 0 and 1
– **n$_g$** number of GEMs
– **G** light yield
– **p** pressure
– **t** thickness of GEM
–**V$_g$** sum of voltage across GEMs

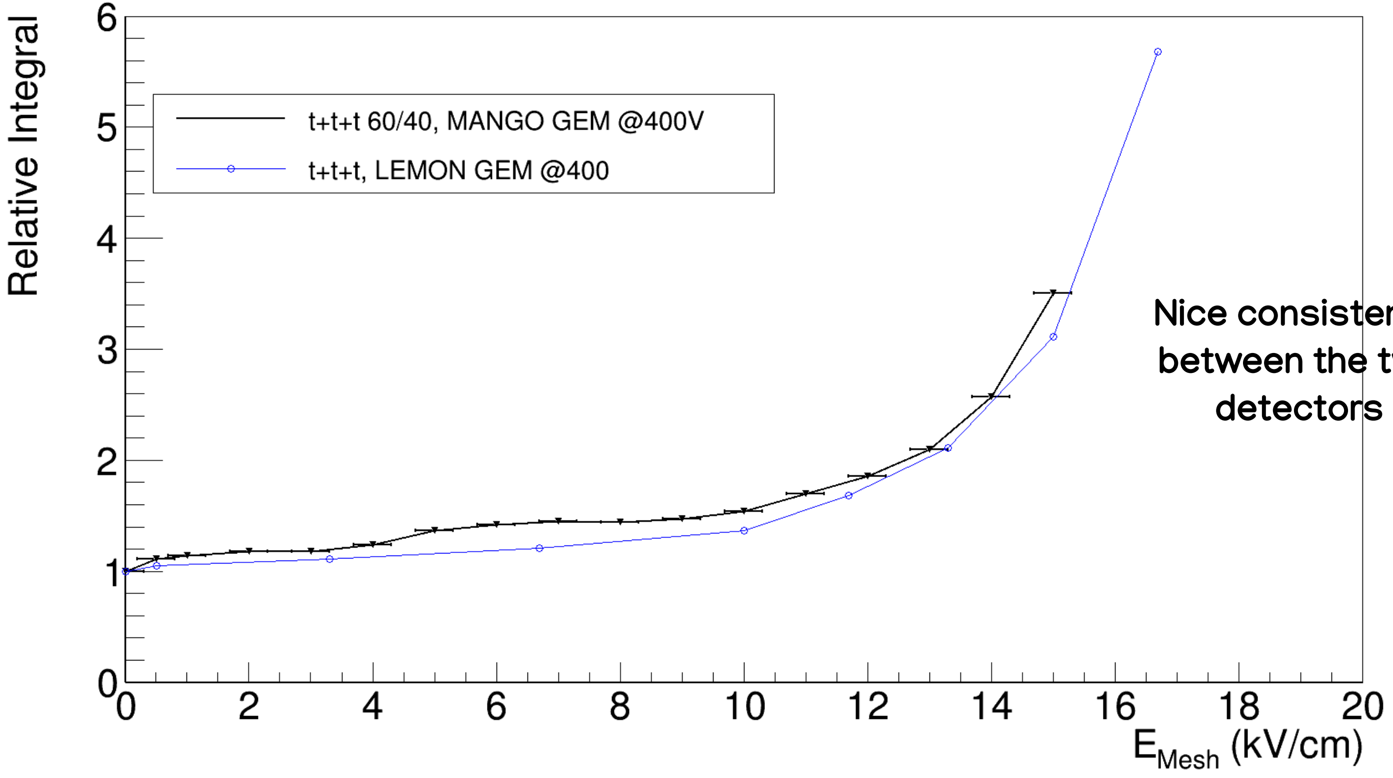
- In the voltage scan performed, the reduced field scanned is small so the approximation m=1 can be performed

$$\Gamma = A_0 + B_0\Sigma = A_0 + \frac{B_0}{pn_g t}V_g$$

- Fitting the data of previous slide the table is obtained
- The parameters are consistent with each other
- Good understanding of the amplification parametrisation

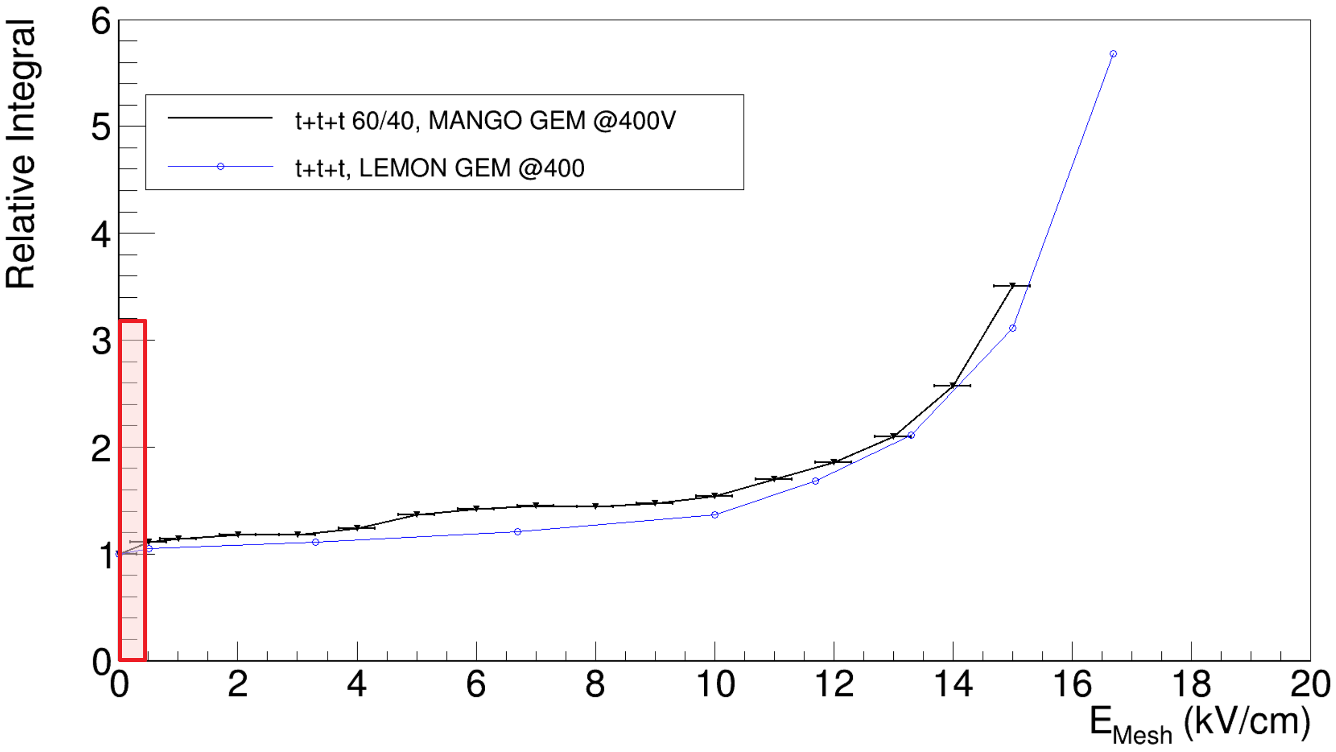
Conf	Colour	[0] $\frac{1}{torr \cdot cm}$	$\sigma_{[0]}$ $\frac{1}{torr \cdot cm}$	[1] $\frac{1}{torr \cdot cm \cdot V}$	$\sigma_{[1]}$ $\frac{1}{torr \cdot cm \cdot V}$
ttt 60/40	Black	-0.36	0.14	0.00106	0.00011
Tt 60/40	Green	-0.7	0.2	0.0012	0.0004
Tt 70/30	Cyan	-0.6	0.2	0.0012	0.0003
Tt 70/30	Dark Green	-0.49	0.19	0.0011	0.0002
Tt 80/20	Purple Gray	-0.6	0.3	0.0014	0.0004
Tt 80/20	Dark Purple	-0.6	0.2	0.0013	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
TT 80/20	Magenta	-1.1	1.5	0.0015	0.0010

Induction Field: Light Yield

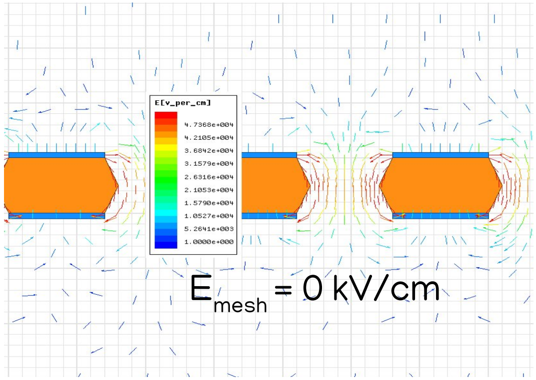


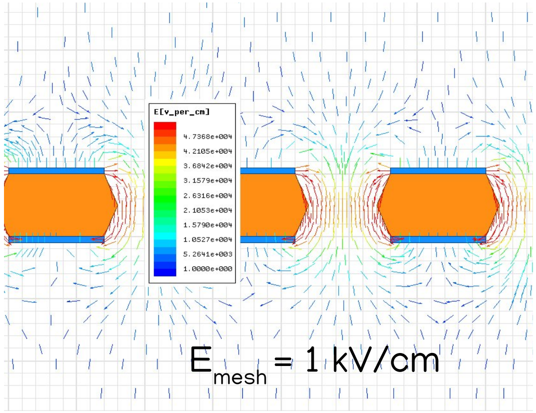
Nice consistency between the two detectors

INDUCTION FIELD: LIGHT YIELD

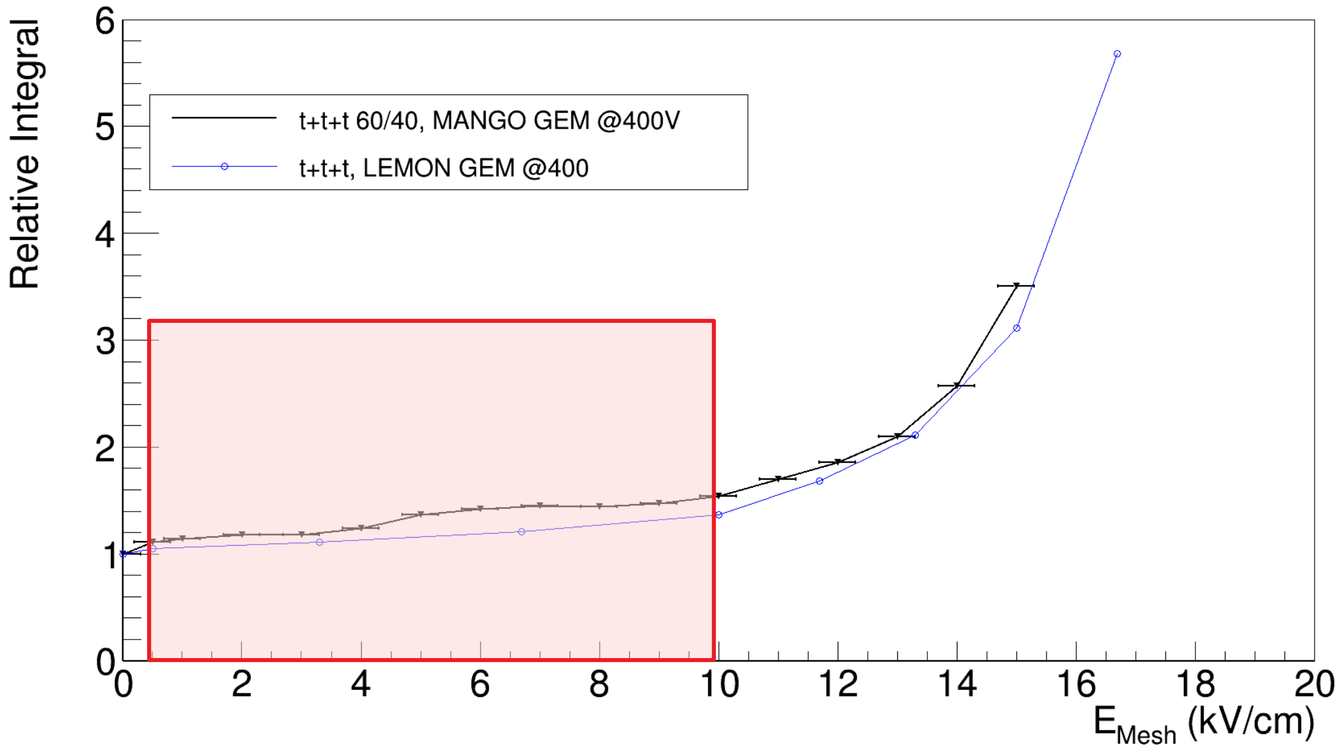


Increase due to better defined field lines below the last GEM (Maxwell)

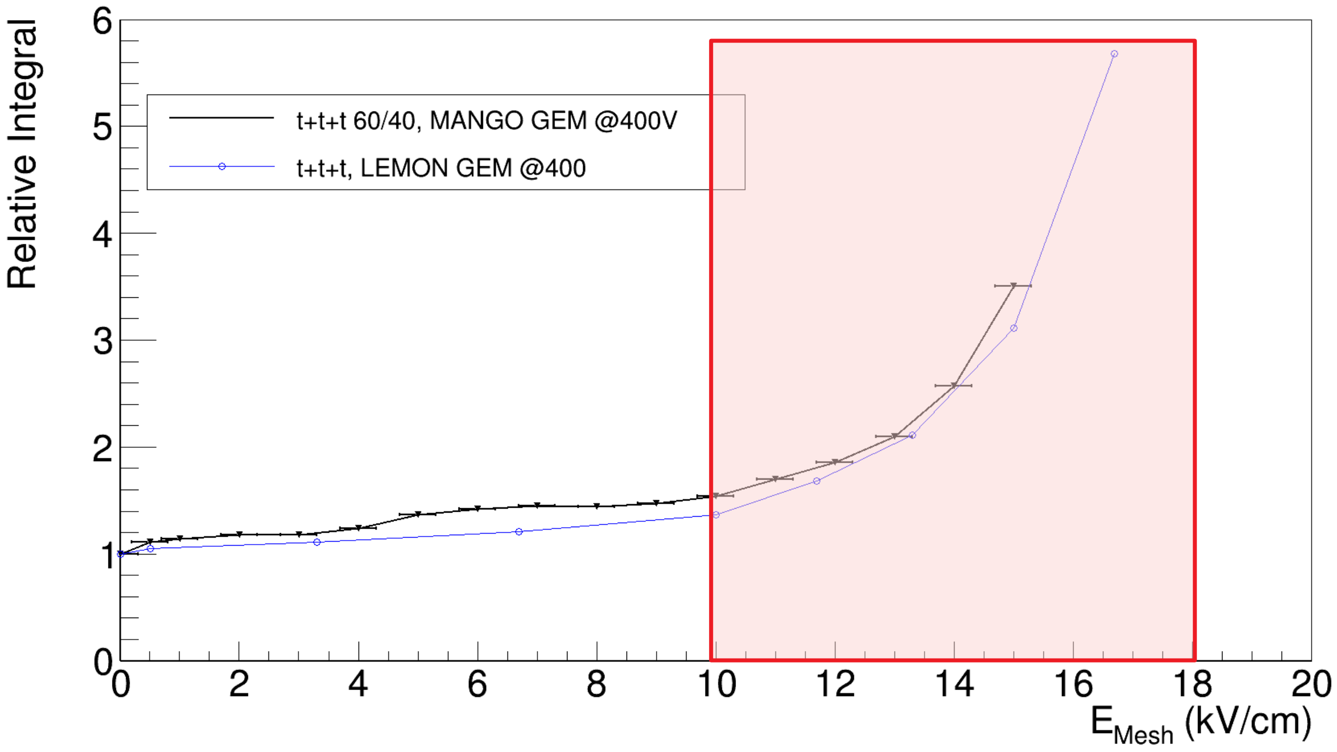




Induction Field: Light Yield



Linear increase due to the induction field affecting the field inside GEM



Exponential growth due to a different phenomenon happening inside the induction gap

Induction Field: Linear Rise

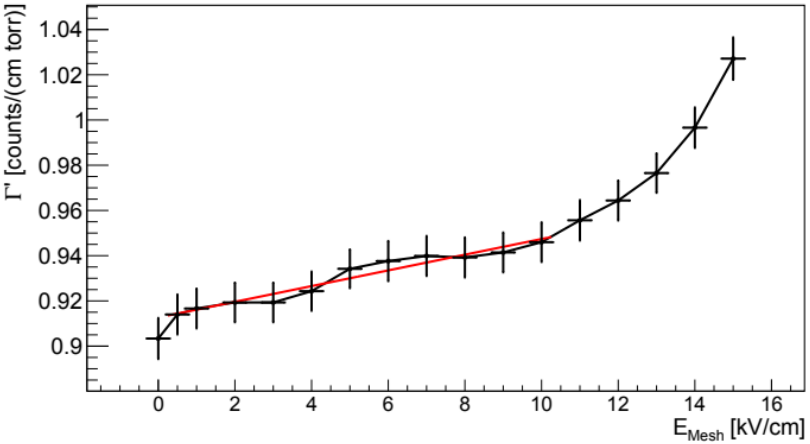
- Employing the parametrisation of the gain, the reduced field can be expanded with a term to include the influence of E_{Mesh}

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

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

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

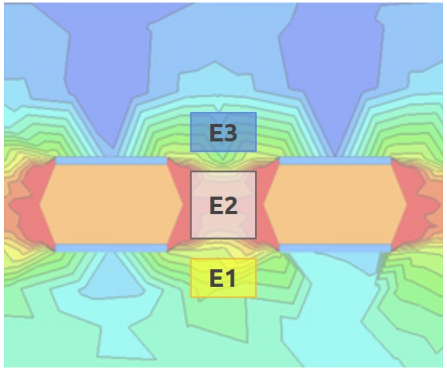
[1]:
Term proportional to E_{Mesh}

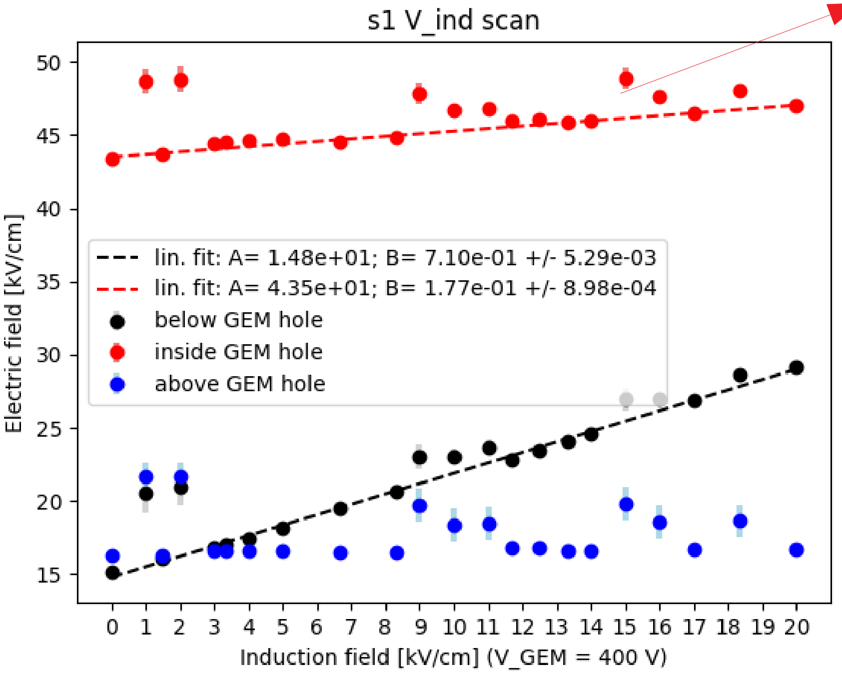


Conf	[0] $\frac{1}{torr\cdot cm}$	$\sigma_{[0]}$ $\frac{1}{torr\cdot cm}$	[1] $\frac{1}{torr\cdot V}$	$\sigma_{[1]}$ $\frac{1}{torr\cdot V}$	Cond. C
ttt 60/40	0.912	0.005	0.0036	0.0010	✓
Tt 60/40	0.747	0.009	0.0010	0.0009	✓
Tt 70/30	0.704	0.007	0.0029	0.0015	✓
Tt 80/20	0.700	0.009	0.0031	0.0019	✓
TT 60/40	0.48	0.01	0.0025	0.0013	✓
TT 70/30	0.505	0.004	0.0016	0.0010	✓

Induction Field: Linear Rise

- Maxwell simulations presented at the previous meeting also confirm that the field inside the GEM hole is modified





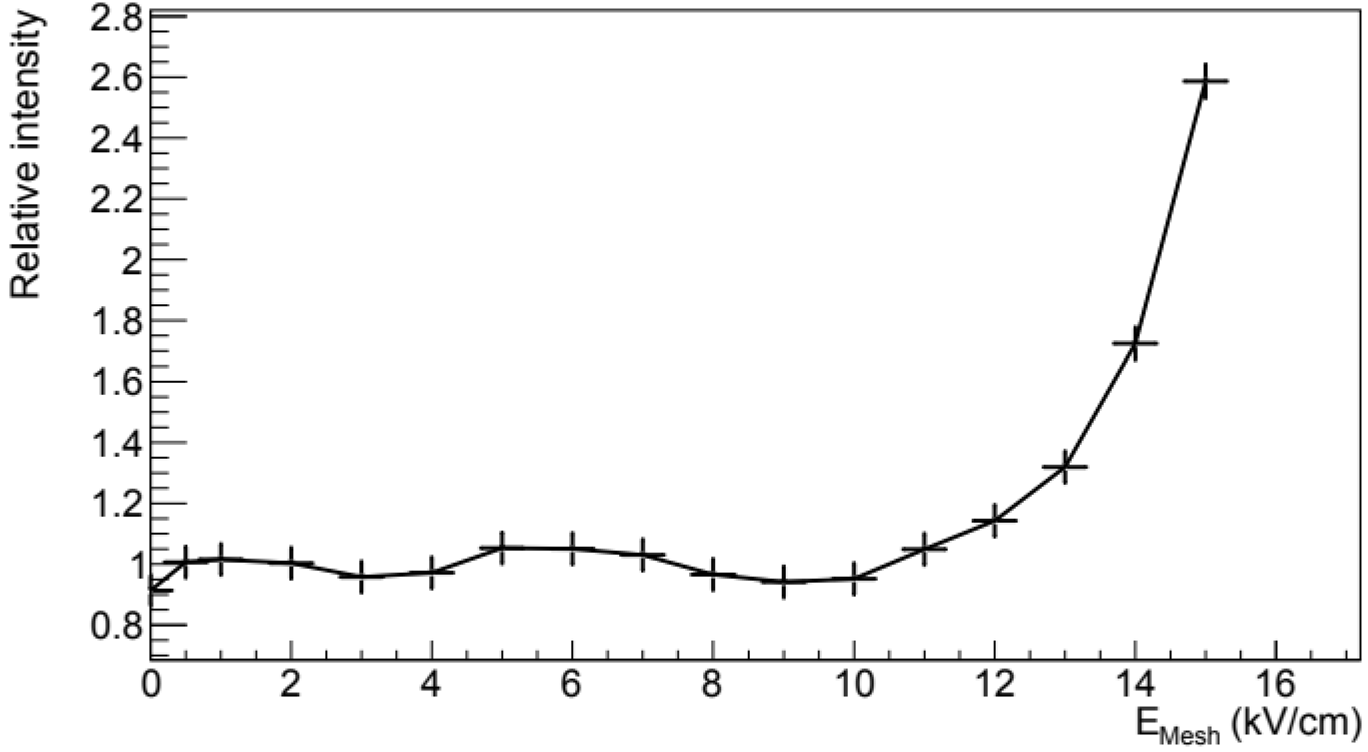
The linear increase is due to the influence of the E_{mesh} on the field inside the GEM hole

It does not explain the change in behaviour of the light yield

The exponential growth is induced by another phenomenon

Induction Field: Linear Rise

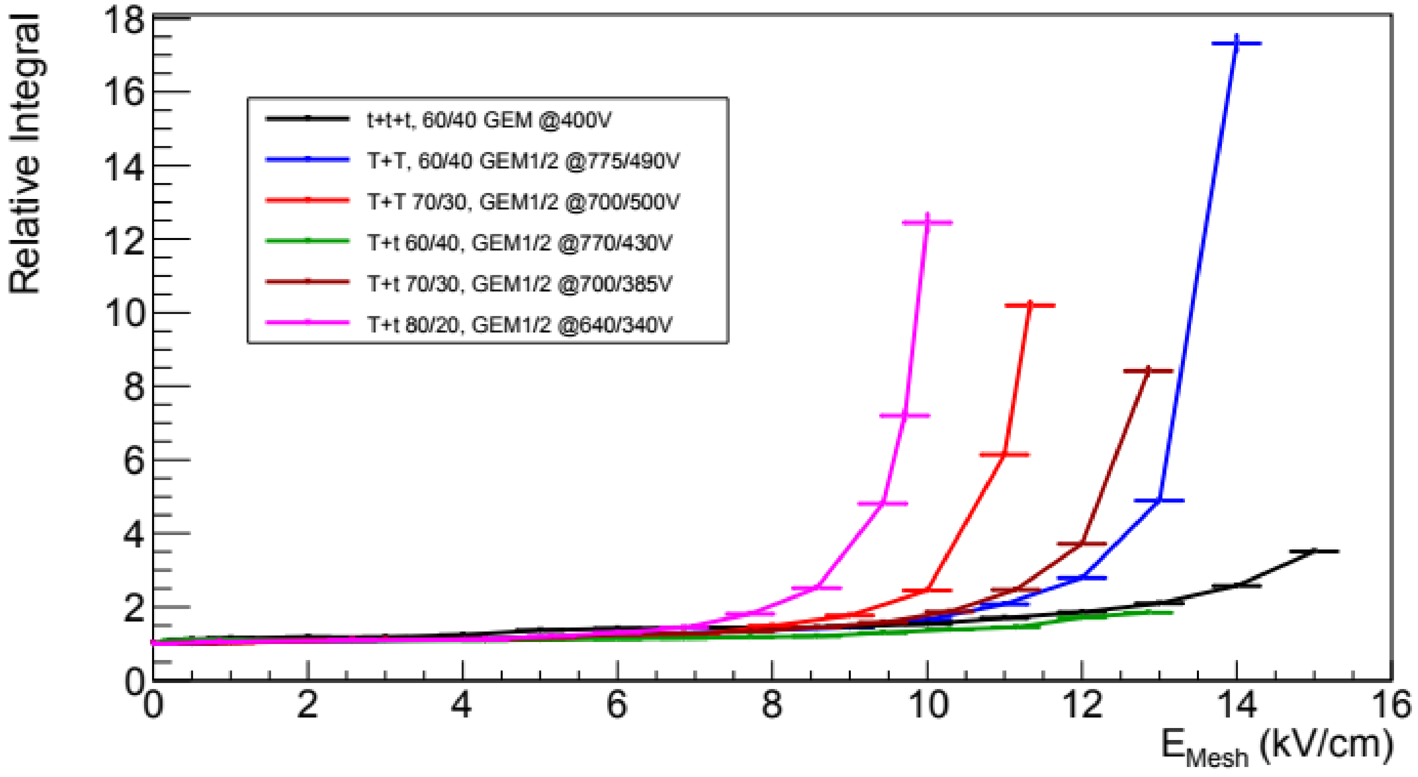
- As we want to study the exponential growth phenomenon we can remove this linear growth



Flat until 10, then it changes behaviour

Induction Field: Break Point

- The reduction is applied to all the dataset

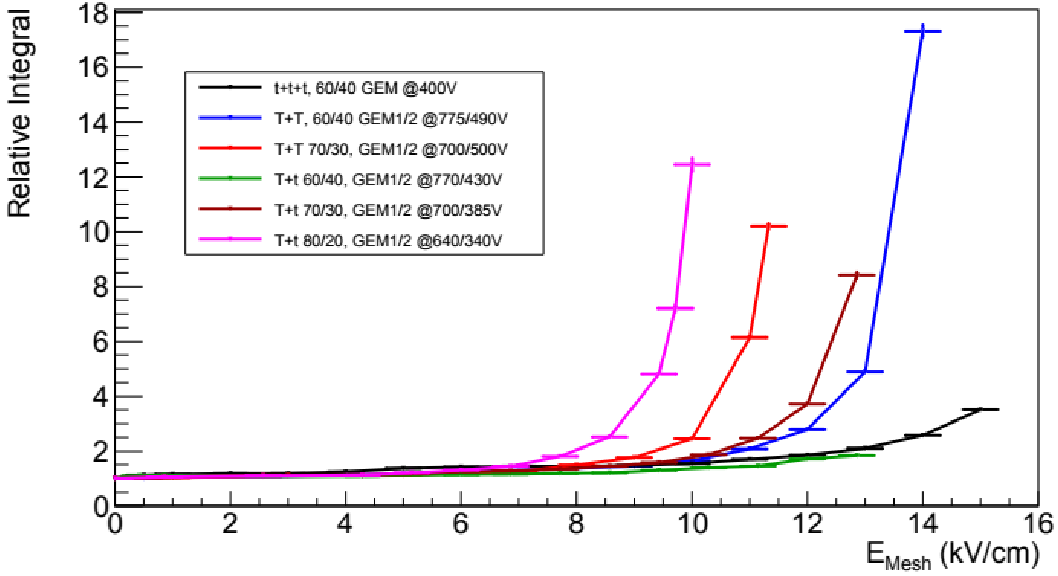


The intensity of the light increase seems to depend on the last GEM

The gas affects the E_{mesh} needed to initiate the phenomenon

INDUCTION FIELD: BREAK POINT

- The gas affects the E_{mesh} needed to initiate the phenomenon



- The data are fitted in order to find the breaking point of the exponential growth

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

- Consistency is found with the same helium content

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

$E_{break,60/40} = (8.7 \pm 0.7)$ kV/cm

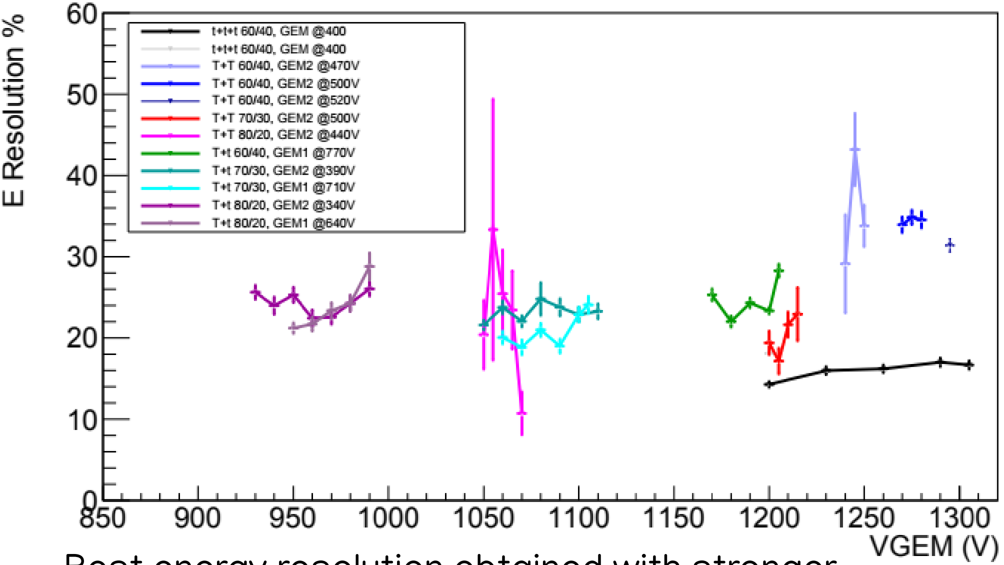
$E_{break,80/20} = (7.1 \pm 1.1)$ kV/cm

As for the gain scan, more helium requires less voltage for the phenomenon to begin

MANGO

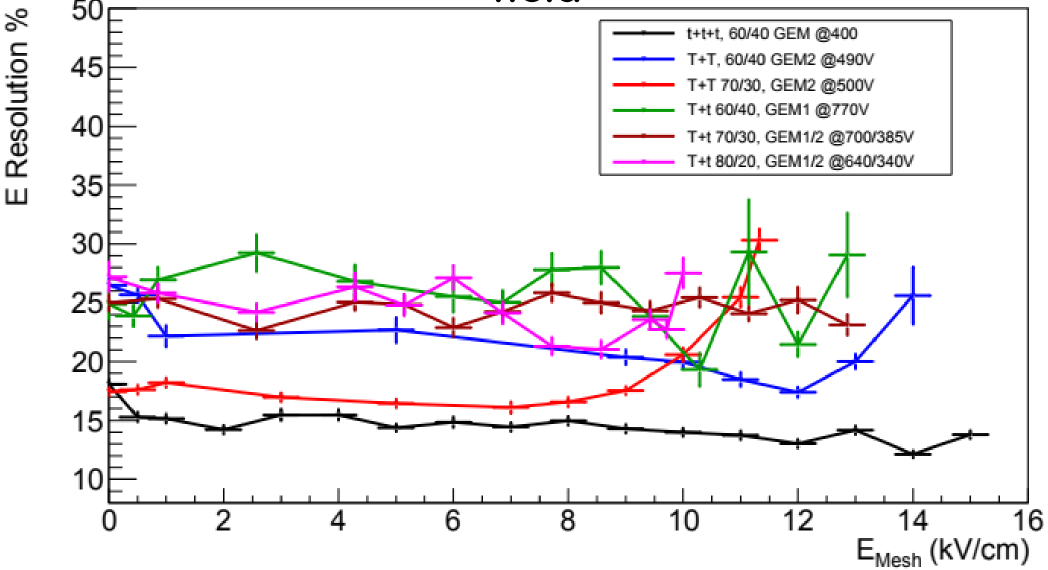
Energy Resolution

Gain



- Best energy resolution obtained with stronger fields and higher gain (*ttt*)
- 80/20 mixtures suffer from camera noise and lots of sparks
- Energy resolution roughly constant with V_g

Induction field

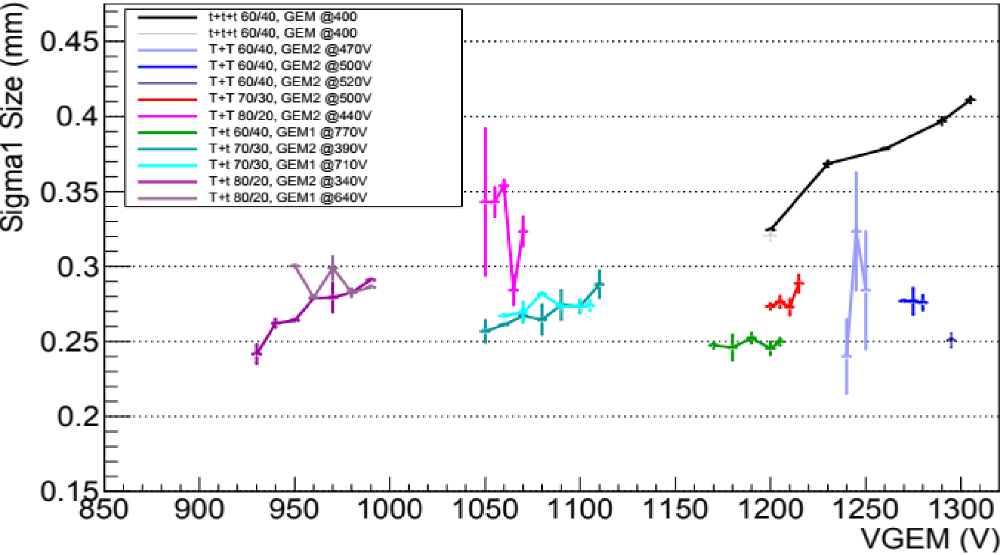


- Energy resolution is constant with field if the last GEM is thin
- At the breaking point the thick GEMs have a clear worsening of the resolution

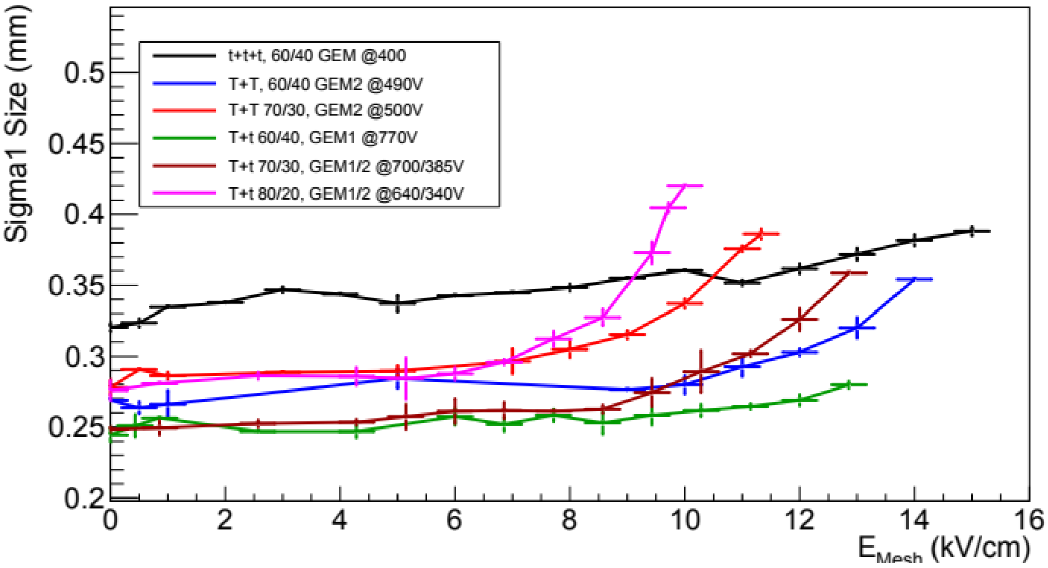
MANGO

DIFFUSION

Gain



Induction field



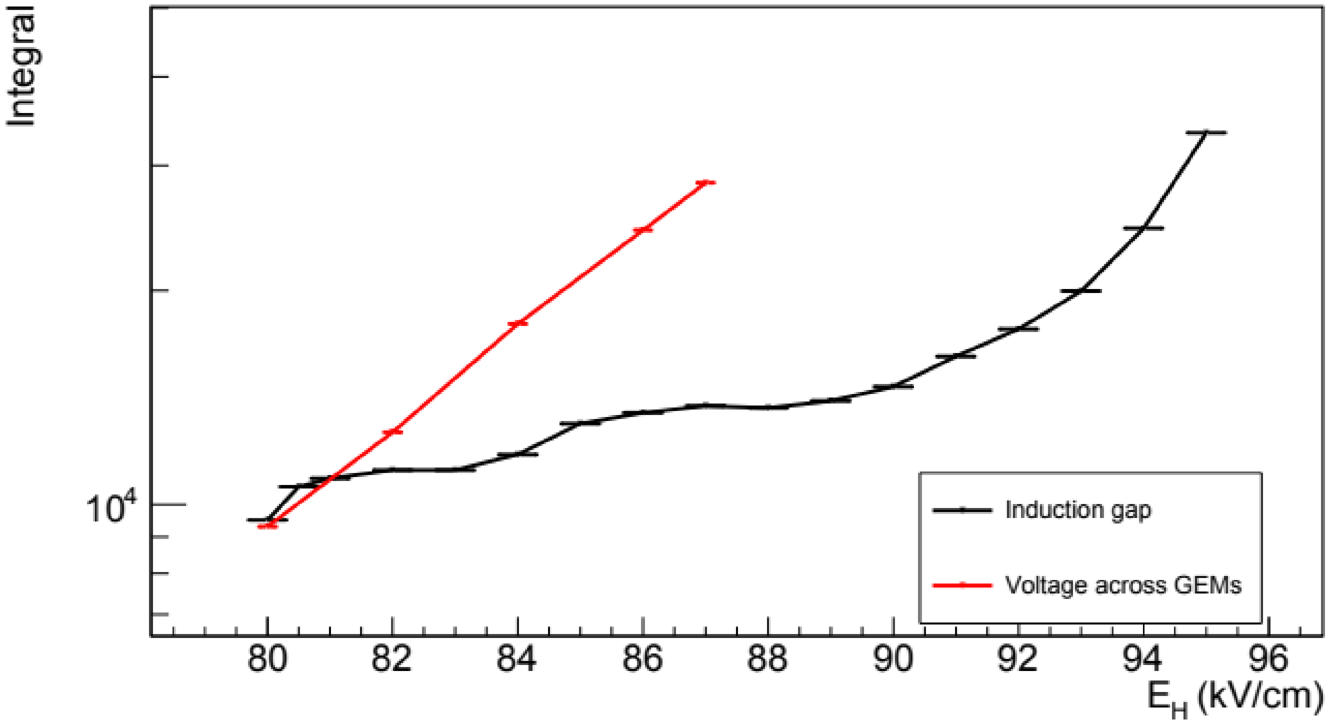
- Diffusion is in general independent of the V_g
- *ttt* clearly worsens with the applied voltage
- *Tt* has the lowest diffusion among all (only two GEMs and the granularity copes with the GEM pitch)

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

Advantages

Light Optimisation with Diffusion

- How much light can be recovered with the large induction field?



Fictional variable to express the two data sets on the same plot

- With the *ttt* 14 kV/cm can revover almost all the light obtained at the higher gain

- At the same light output the diffusion of the amplification stage is

σ_{gain}= (396 $\pm$ 2) um

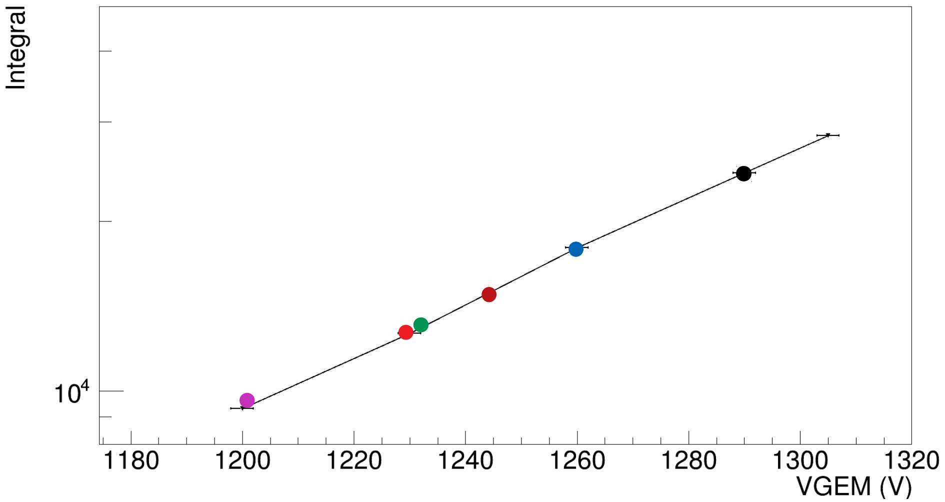
σ_{EL}= (382 $\pm$ 4) um

The value has worsened of 19% with respect to when no field was applied

Slower than the voltage scan

Light Optimisation with Diffusion

- Assuming we can accept a worsening of the diffusion of 19% for the increase of the induction field how much light the various configuration can recover



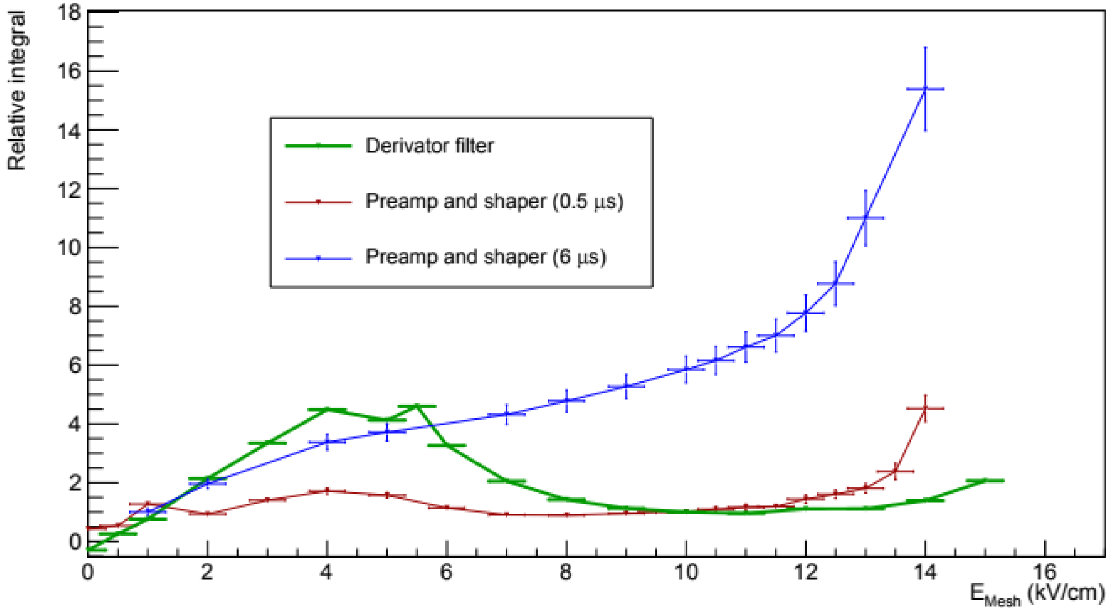
ttt 60/40	σ_{EL} = (382 ± 4) um
TT 60/40	σ_{EL} = (320 ± 7) um
TT 70/30	σ_{EL} = (337 ± 3) um
Tt 60/40	σ_{EL} = (280 ± 2) um
Tt 70/30	σ_{EL} = (326 ± 8) um
Tt 80/20	σ_{EL} = (328 ± 6) um

- Mixture with more helium are in general more unstable and do not give in return better performances but only similar
- Extremely interesting the *Tt* as recovers a nice amount of the light yield of *ttt* but offers 100 um advantage in diffusion
- Could it recover also saturation? (under study after article and thesis)

What is Happening with the Induction Field?

MANGO Charge Measurements

- MANGO could also measure the charge with two different readout chains:
  - RC filter to directly look at the waveform (total charge is distorted, but the measurements are only relative)
  - Preamplifier (CAEN A422A, 300 us decay time) and shaper (CAEN N968 Spectroscopy amplifier, shape time 0,5–6 us)



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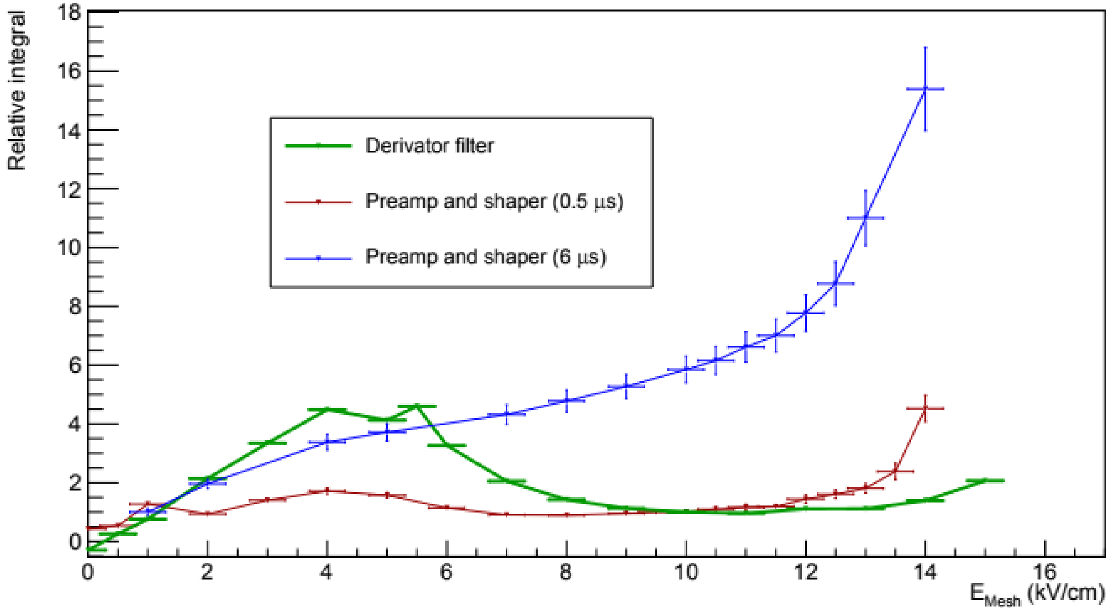


Shockley-Ramo

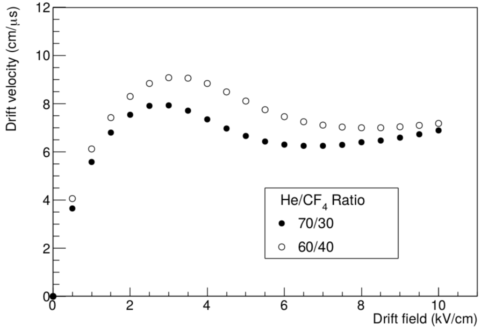
- The Shockley–Ramo theorem describes the istantaneous current induced on an electrode

$$i = q\, v\, E_v$$

i : istantaneous current induced on an electrode
q : charge of the particle in motion
v : instantaneous velocity
E_v : electric field component parallel to the instantaneuos velocity calculated with charges removed and only the electrode under analysis with voltage 1 (the rest with zero)

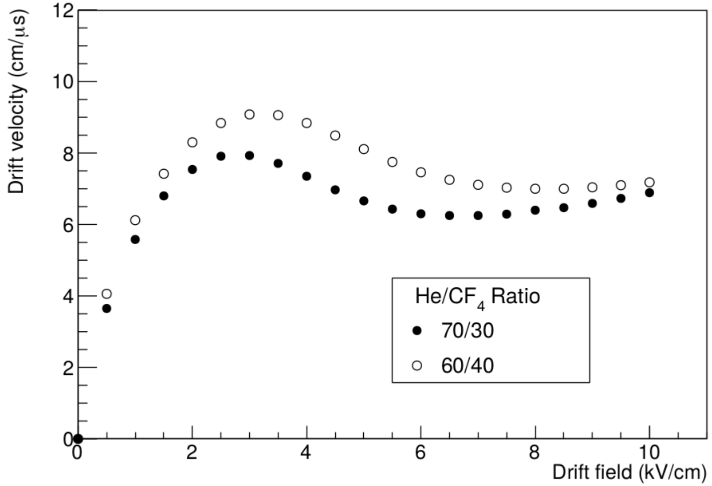
The best way to calculate the charge is to integrate infinitely long to integrate all the contributions: as done in LEMOn

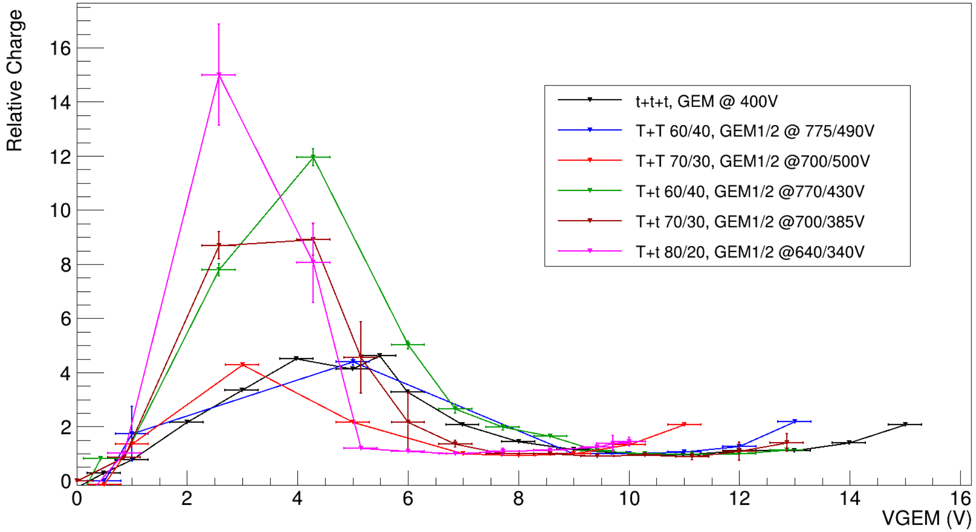
- The bump at around 4 kV/cm seen by the derivator and the preamp can be due to the drift velocity properties of the gas mixture



Bump at Low Field

- Also the dependence on the helium content seems somewhat followed

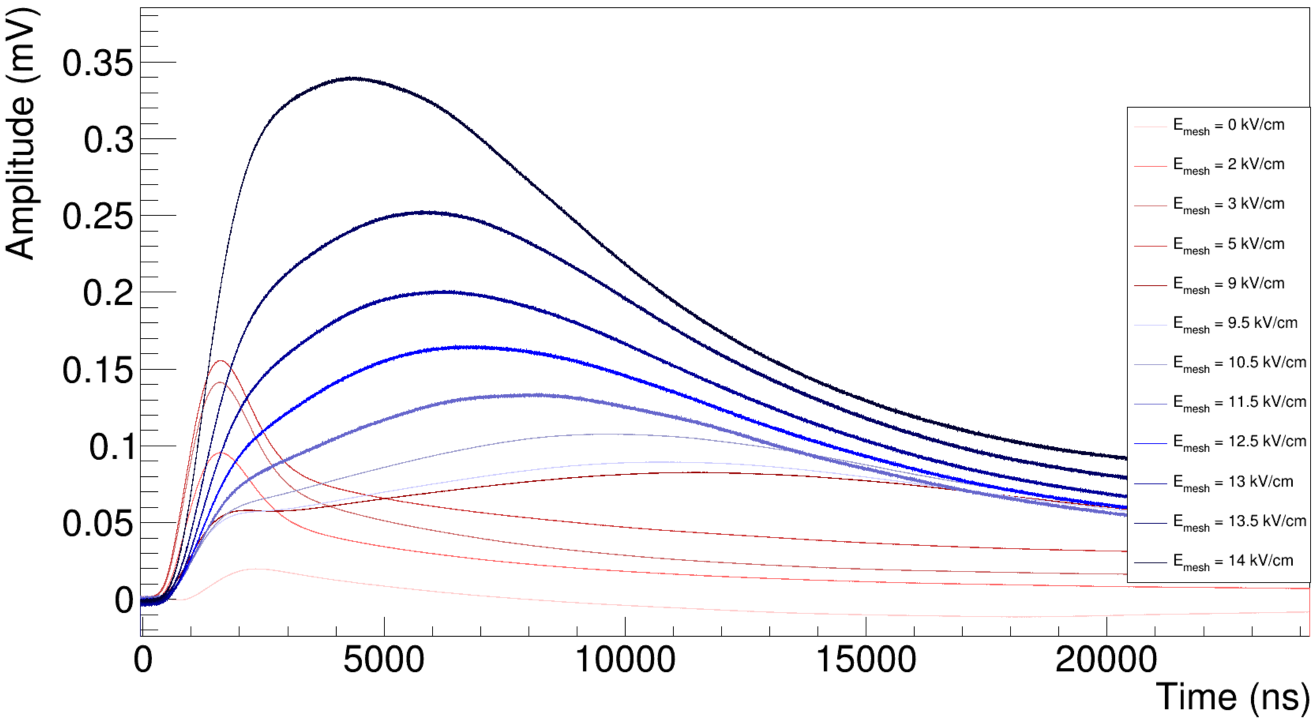




- The higher the helium content the earlier the peak in the bump is
- But what about the increase of charge at high fields?

Shaper Waveforms

- *ttt* 60/40 shaper waveforms of the GEM with 0,5 us shaping time

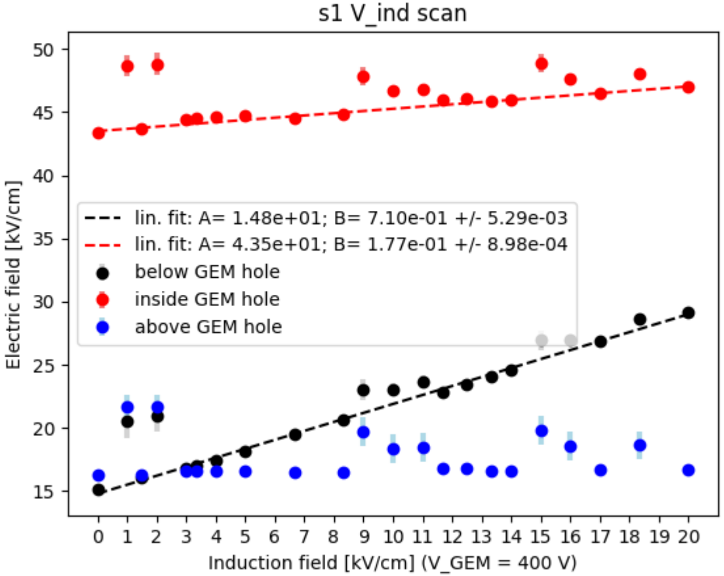


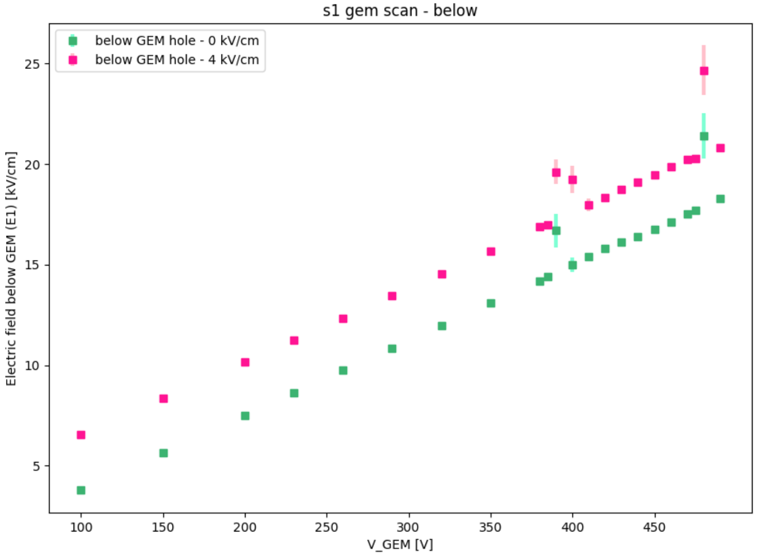
A larger shaping time includes more of this signal, changing the increment of charge at high fields. Also the derivator is affected

- Already shown that the increase in light and charge happen together
- A new slow signal is appearing at 9.5 kV/cm
- The time length indicates it is induced by ions
- The ionic signal is induced as soon as they move but is detectable only if it gets close to the GEM
- By the time distance it can be generated few tens of um away from the GEM
- The higher the field the faster they are and induce strong signals

Maxwell Simulations

- Maxwell simulations were performed also on the intensity of the electric field below the GEM



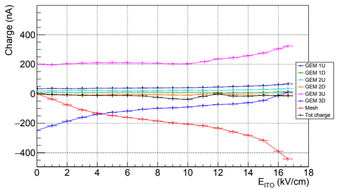


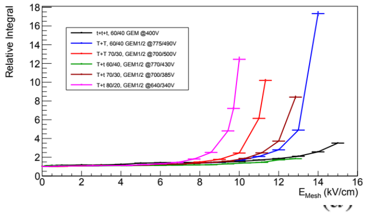
- Very strong electric fields are generated below the GEM holes (few tens of um away) which can induce amplification
- These are not normally present
- The effect is relatively stronger on thick GEMs

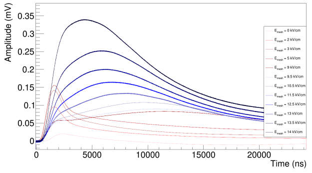
Charge Produced Very Close to the GEMs

- The hypothesis: the induction field is generating a region few tens of micrometers were the field becomes extremely strong and charge an light are produced

- It explains







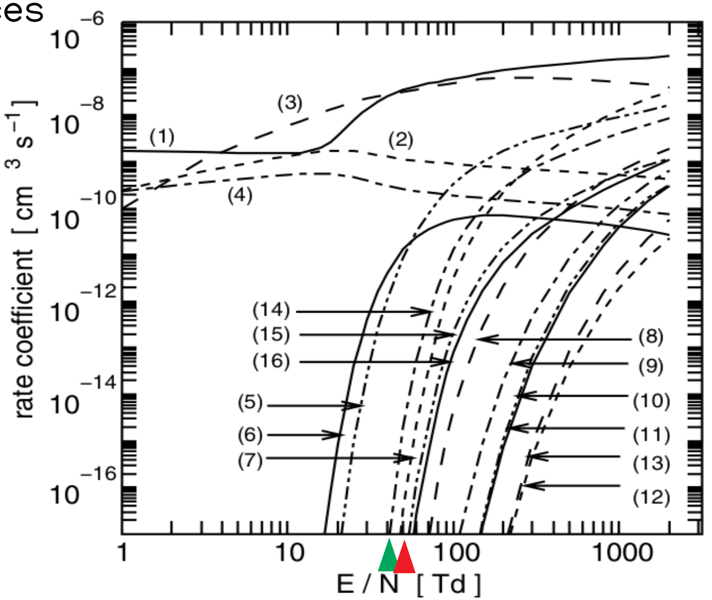
  - Why so many ions are collected on 3U
  - Why thick GEMs have higher light production but poorer performances
  - The waveforms behaviour
  - Why there is more light than charge

The field induces just enough energy to start the fragmentation processes

The lower threshold allows to produce more light than charge

Neutral Fragmentation (14)

First ionisation (7)



Kurihara, J. Phys. Appl. **33,** 2146 (2000)

Conclusions

- In the CYGNO context, it is important to otimise the amplification stage to maximise the light output, while minimising the diffusion.
- With LEMOn and MANGO detector, the possibility of enhancing the light yield with the addition of a strong field below the last GEM withdifferent configurations of GEMs was tested
- With a mixture of 60/40, above 10 kV/cm on the induction gap both charge and light are produced, but light far exceeds the charge production
- With the induction field it is possble to recover large part of the light emitted in the brightest configuration (*ttt*), but it is possible to do so with a lower diffusion induced by the amplification stage
- The generation of a small region below the GEM hole of few tens of micrometres with a very strong electric field which can produce the light and the charge observed is a possible explanation of the phenomenon