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Mesh Transparency of Electrons in a MMThGEM Gain Stage Device for Directional Dark Matter Searches

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The CYGNUS Collaboration

- CYGNUS proposes a modular and multi site nuclear recoil observatory
- Time Projection Chambers (TPCs) filled with a low pressure negative ion gas like SF_6
- Capable of directional sensitivity to dark matter and neutrinos.

CYGNUS detector with a 755:5 He:SF_6 mixture at atmospheric pressure with a 6 year exposure predicts:

1. 10-40 solar neutrinos
2. unexplored sub-10 GeV/c^2

Proposed sites for network:

- Boulby, UK
- Gran Sasso, Italy
- Kamioka, Japan
- Stawell, Australia

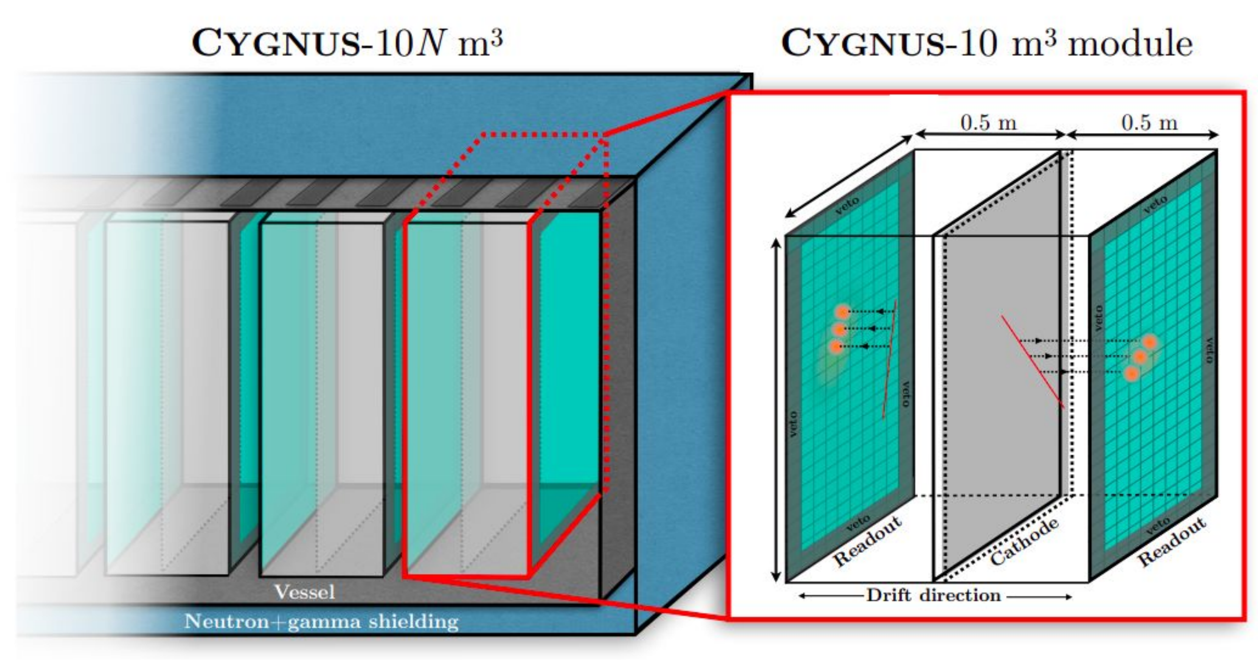

Figure 1: Modular N x 10 m^3 CYGNUS detector diagram (modular read out area of 1 m x 1 m)

Multi-Mesh ThGEM (MMTHGEM) Device

Similar to a ThGEM but it has additional mesh layers.

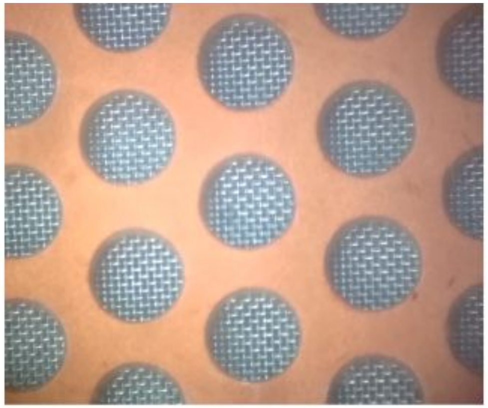

Figure 2: Close up image of MMThGEM holes from above [2].

- Made by MPGD group (CERN)
- Multiple amplification stages are beneficial for use with SF_6
- Mesh layers make the amplification fields uniform
- Potential to improve the avalanche characteristics
- Reduction in +ve Ion Back Flow (IBF)
- Potential to hinder the passage of desirable -ve charge
- Can we optimise the Mesh transparency for -ve charge?

Detector can be divided into six regions:

1. drift field
2. collection field
3. first amplification field
4. first transfer field
5. second amplification field
6. second transfer field

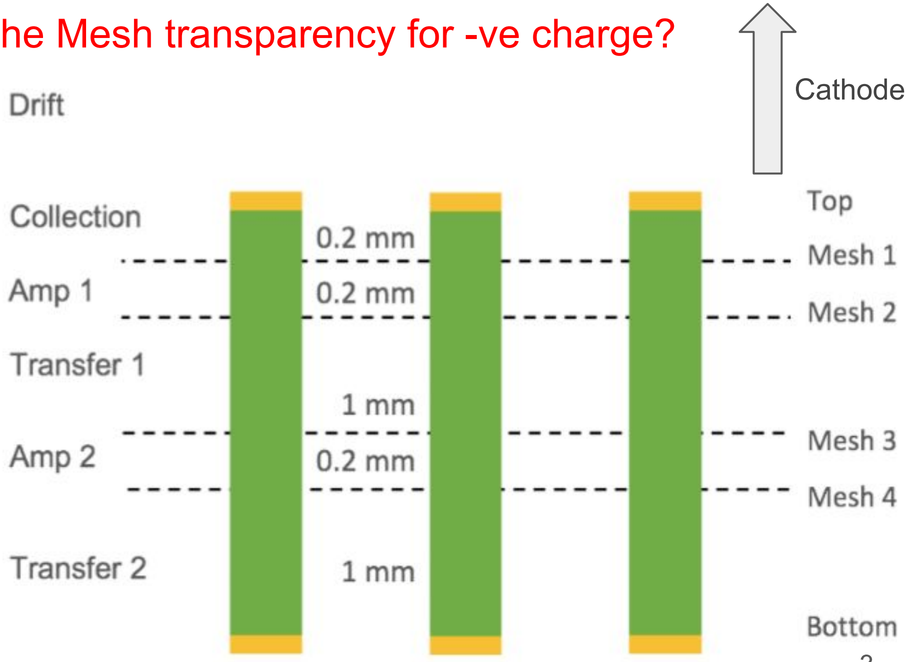

Figure 3: Cross sectional diagram of the MMThGEM structure [2].

Experiment 1: Setup/Method for M2

It is **easier** to test the mesh transparency for a **high to low field strength** ratio than low to high. This is because a gain of 1 can be assumed in the Transfer 1/2 regions. Here the transparency of mesh 2 is being measured.

Setup

- **Cathode** with 3cm drift region
- **MMThGEM** with top grounded and meshes 1, 2, and 3 biased individually
- **Iron-55** source collimated towards centre of drift region
- **Cremat preamps** and **shapers** connected to **meshes 2 and 3**
- **Ortec ADC** for collecting iron-55 spectra from mesh 2 and 3
- **40 Torr CF_4** gas

Bias scheme

Cathode: -300 V

M1: 320 V, 240 V

Amp 1: 22000 V/cm, 26000 V/cm respectively

Transfer 1: Field strengths used in simulation (high to low)

M2 ⇨ $M_t = 1 - (F_e^{M2} / I_e)$, M3 ⇨ $M_t = F_e^{M3} / I_e$

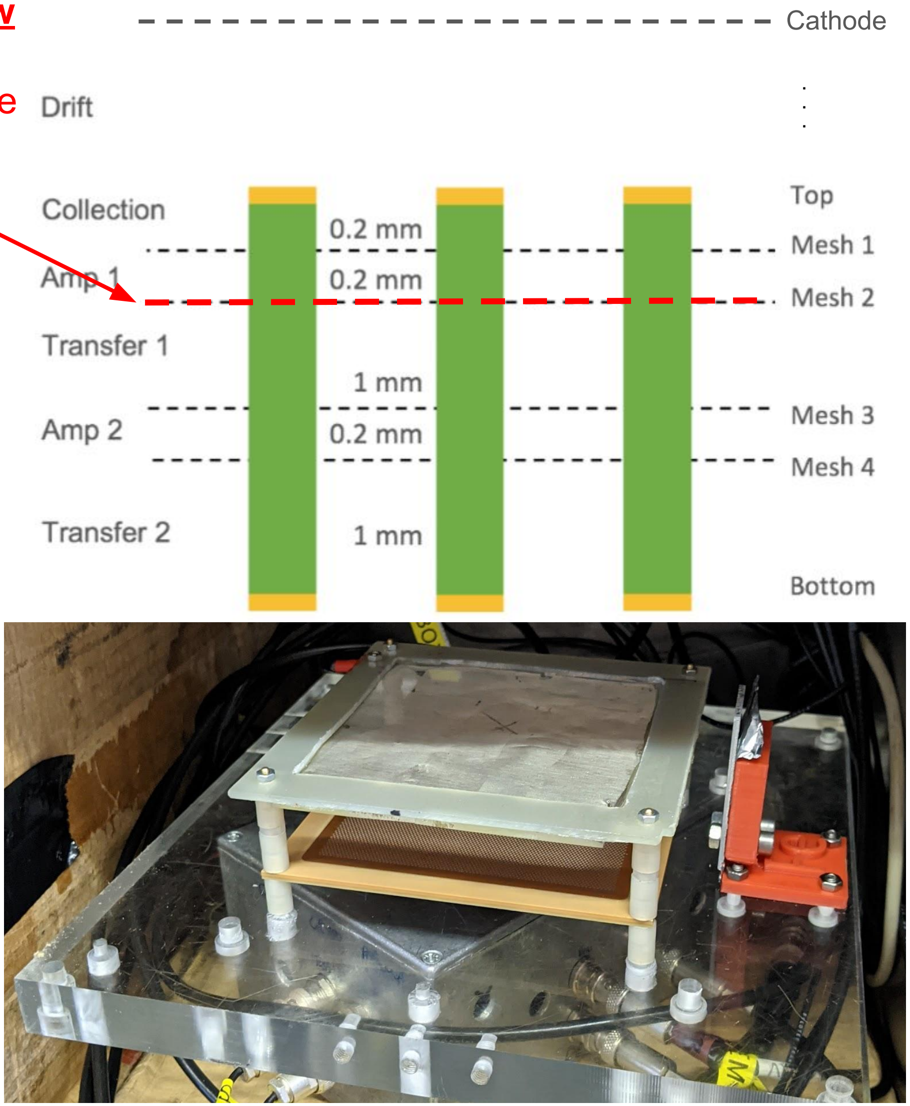

Figure 4: Cross sectional diagram of the MMThGEM structure (top) [2], picture of experimental setup showing the cathode, MMTHGEM and ^{55}Fe source holder (bottom).

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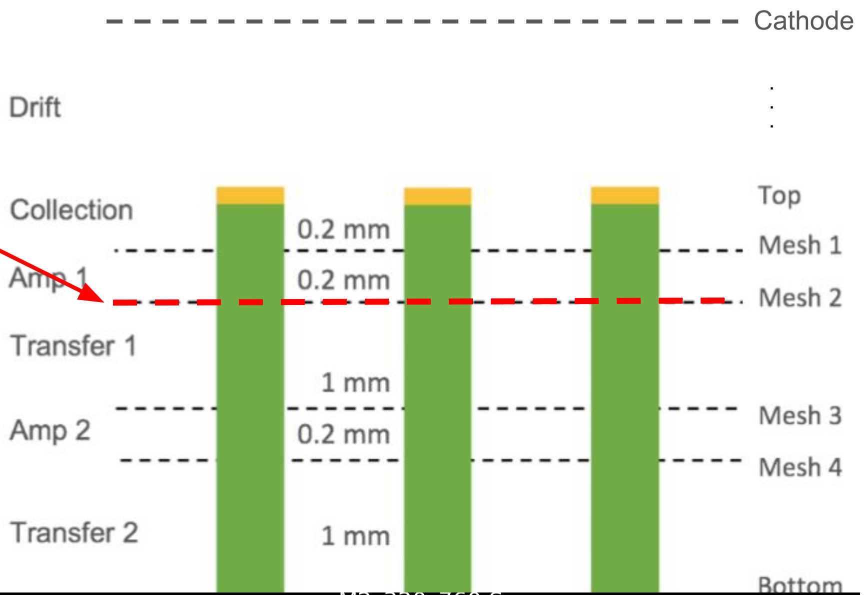

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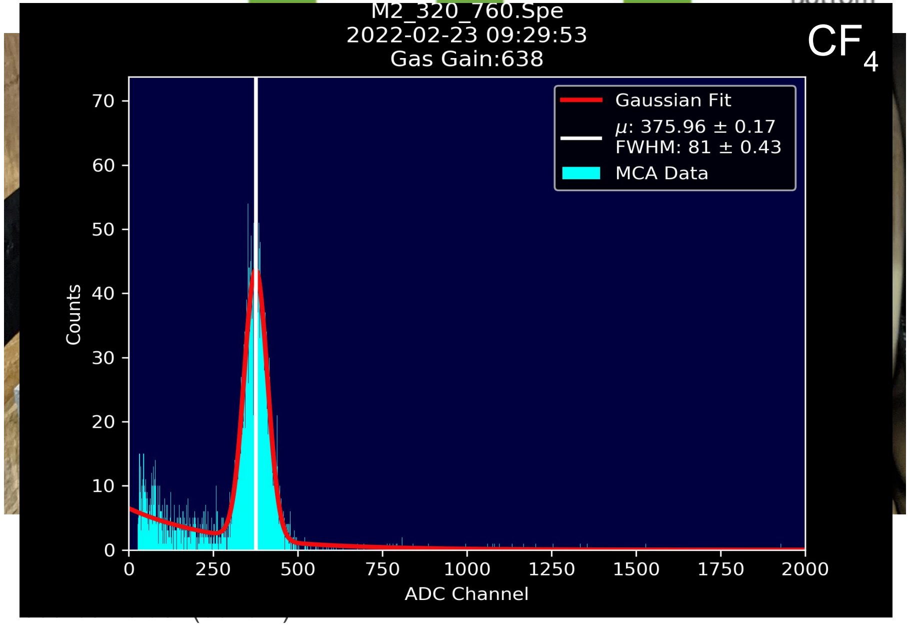

Experiment 2: M3 Setup/Method

It is **more difficult** to test the mesh transparency for a **low to high field strength** ratio due to the coupling of mesh transparency and gain in the following amplification region. Here the transparency of mesh 3 is being measured.

Setup

- **Cathode** with 3cm drift region
- **MMThGEM** with top grounded and meshes 1, 2, and 3 biased individually
- **Iron-55** source collimated towards centre of drift region
- **Cremat preamps** and **shapers** connected to **meshes 3 and 4**
- **Ortec ADC** for collecting iron-55 spectra from mesh 3 and 4
- **40 Torr of CF_4** gas

Bias scheme

Cathode: -300 V

M1: 320 V

M2: 710 V

Transfer 1: Varied between 50 and 1350 V/cm

Amp 2: 12500 V/cm, i.e. the gain between M3 and M4 is constant - **only a relative mesh transparency can be calculated**

$M^{rel}_{t} = F_{e}^{M4} / I^{M3}_{e}$ →normalise to simulated data

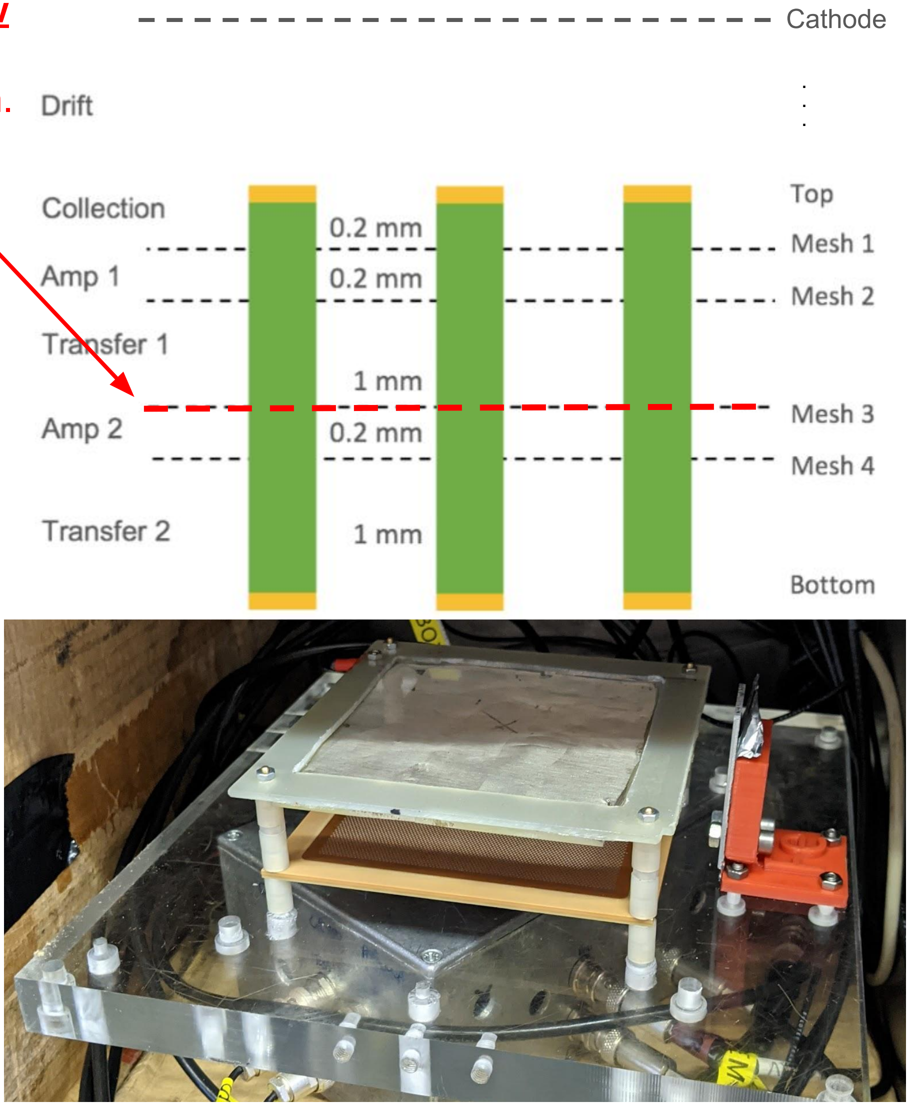

Figure 4: Cross sectional diagram of the MMThGEM structure (top) [2], picture of experimental setup showing the cathode, MMTHGEM and ^{55}Fe source holder (bottom).

Experiment 2: Supplementary Garfield++ Simulation of M3

Simulation

- Single infinite mesh plane between 2 parallel plates
- Gas used: CF_4 at 40 Torr
- Transfer 1 field was varied
- Amp 2 field held constant
- Mesh Transparency measured as the number of electrons that pass through the mesh divided by the total number of simulated electrons
- 10000 electrons simulated
- Avalanche electrons were ignored

ANSYS Model

- Single mesh generated using partial Torus shapes
- Mesh mirrored in x and z dimensions to form infinite mesh plane

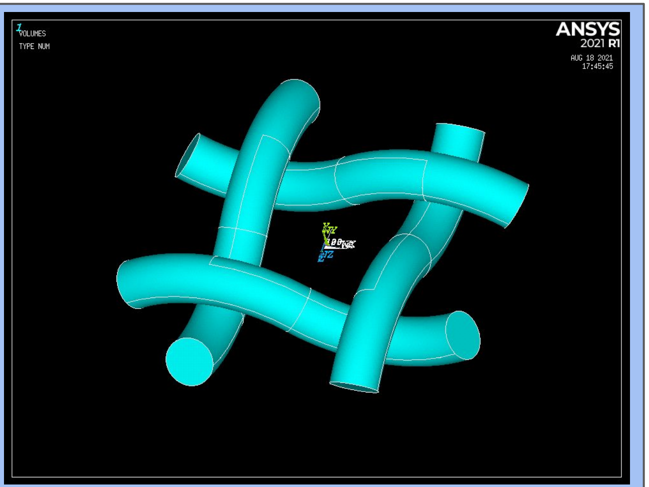

Figure 5: ANSYS model of single mesh.

Electron End Points

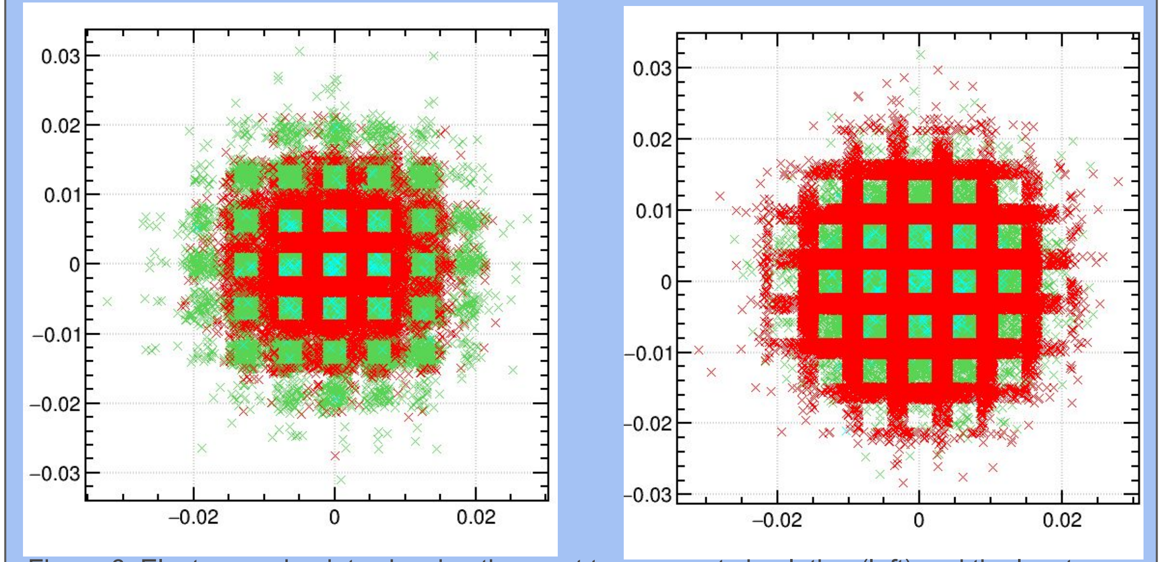

Figure 6: Electron end points showing the most transparent simulation (left) and the least transparent simulation (right)

Experiment 1: Results of Mesh Transparency for M2

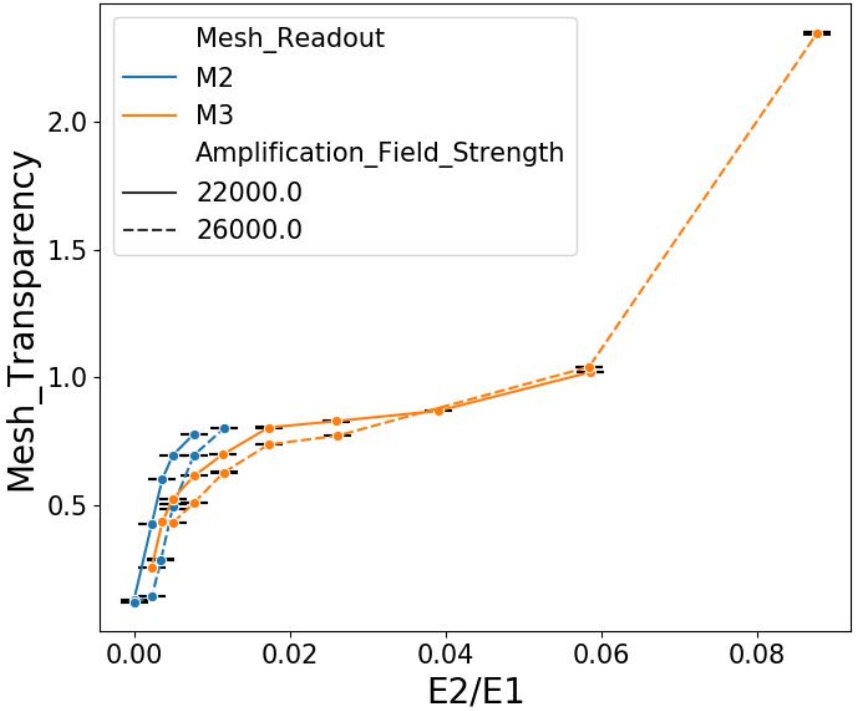

Figure 7: Experimental mesh transparency results for mesh 2.

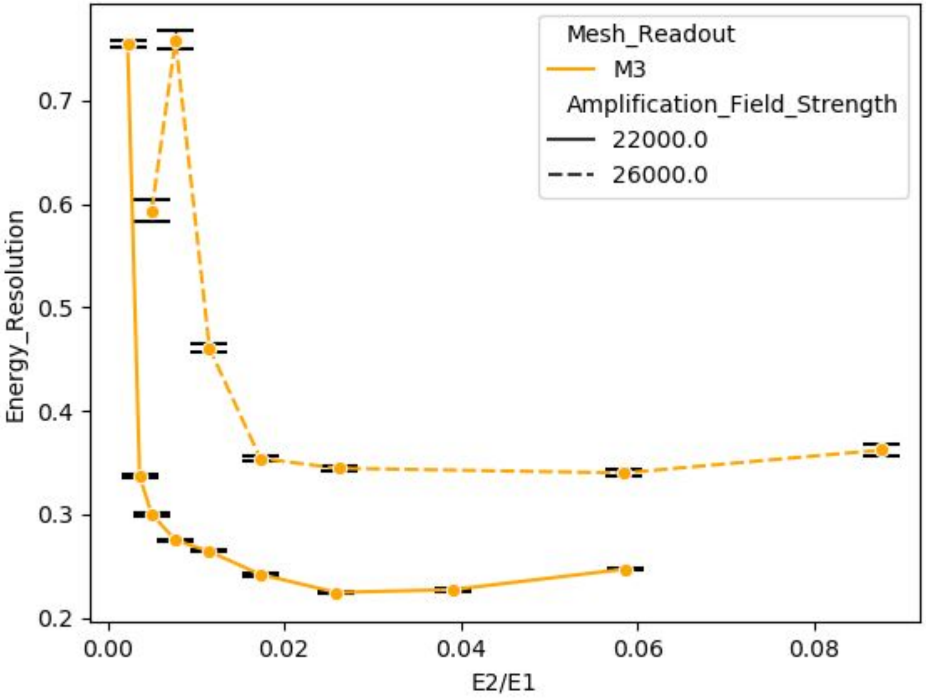

Figure 8: Experimental energy resolution as measured on mesh 3.

- As voltage on M3 increases the transparency increases until it plateaus around 80%
- Transparencies measured on M2 are higher than M3 likely due to additional induced signal/some losses in the transfer 1 region
- Above E2/E1 = 0.04 electron avalanche is evident

- Energy resolution decreases and plateaus around E2/E1 ~ 0.02
- Observed minima (~0.025) offers possibility for optimisation of the transfer region

Experiment 2: Results of Mesh Transparency for M3

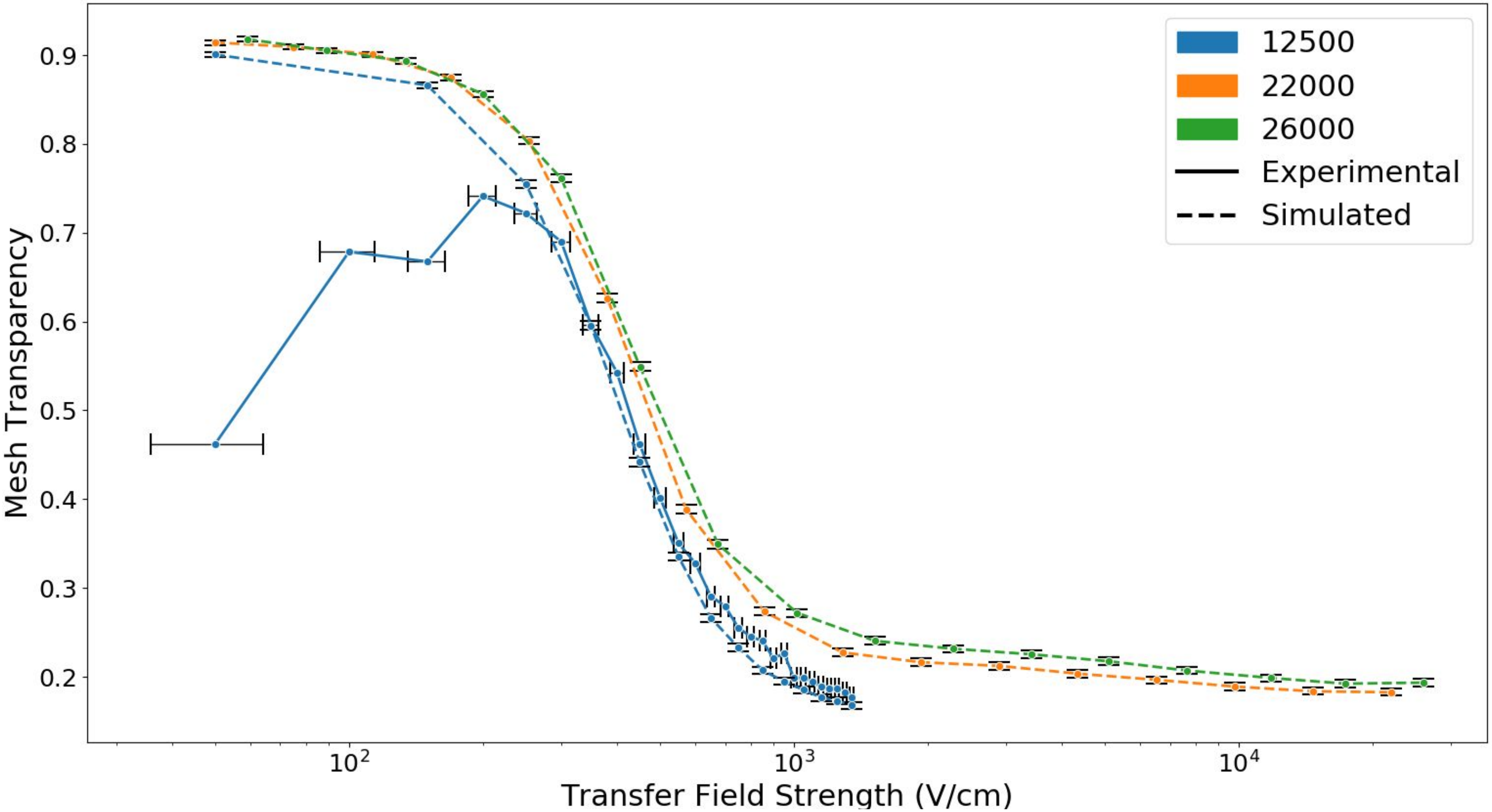

Figure 9: Experimental mesh transparency results for mesh 3 showing simulated data and experimental data that has been normalised against the simulation.

- As transfer field increases, mesh transparency decreases
- Decrease depends strongly on field strength rather than field ratio
- Simulated data shows smooth transition from high transparency to low transparency
- Experimental data shows large discrepancy with simulated trend at low field strengths
- Transparency peaks around ~200 V/cm
- Only experimental data for field strengths of 12500 V/cm as sparking occurred at larger field strengths
- Under normal operation field strengths of 22000 V/cm are more common

Discussion and Conclusion

- MMThGEM is can help improve gas gain in NID gases
- The mesh structures can prevent the flow of negative charge - hindering gain
- Investigated the effect of field ratio going from a high to low field strength (M2) experimentally
- Field strength ratio of 0.025 was found to be optimum for this transition based on transparency and energy resolution
- Investigated the effect of field strength ratio in the transition from a low to a high field strength by utilising a combination of experimentation and simulation
- Transfer field strength of 200 V/cm was found to be the optimum based on mesh transparency
- Study is currently limited to CF_4 by the electronegative nature of SF_6 - it is difficult to measure signals on earlier meshes in the device with SF_6

Future Work - SF_6

- Although it is more difficult achieve sufficient gas gain on earlier meshes in SF_6, it might not be impossible
- Preliminary results with MMThGEM show some of the highest gas gains ever achieved in SF_6 (>60000) comparable to CF_4 when the amplification fields are taken to much larger amplification field strengths
- Preliminary optimisation of the Transfer 1 region in SF_6 shows a similar trend to the transparency of M2
- NID modification of Garfield++ code developed by Kobe University

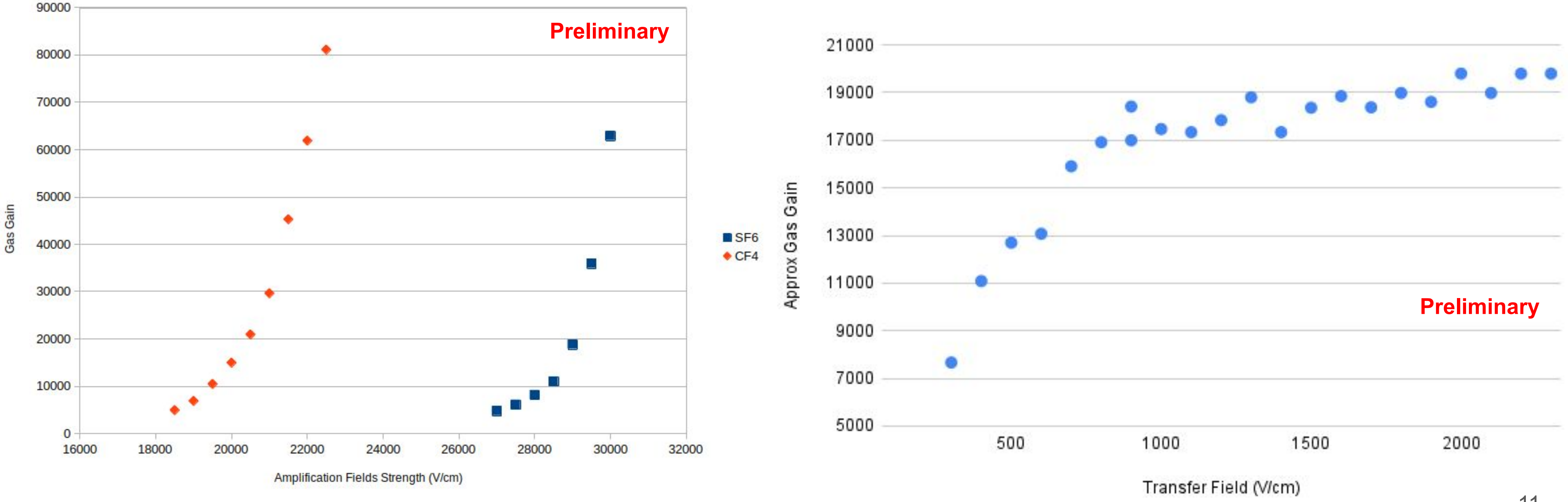

Figure 10: Gas gain of CF_4 compared to SF_6 (with optimised collection and transfer field strengths) as a function of amplification field strength (left). Gas Gain as measured on M4 as a function of transfer 1 field strength (right).Transfer field varied while drift field, M1 voltage, and amplification fields kept constant - 500 V/cm, 30 V, and 29000 V/cm respectively.

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- AWE

Supervision and guidance provided by:

- Neil Spooner
- Tom Crane

Lab assistance provided by:

- Robert Renz Marcelo Gregorio
- Anthony Chigbo Ezeribe

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Thank You for Listening!

Any Questions?

References

[1] S. E. Vahsen, C. A. J. O’Hare, W. A. Lynch, et al., Cygnus: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos, 2020. arXiv:2008.12587 [physics.ins-det].

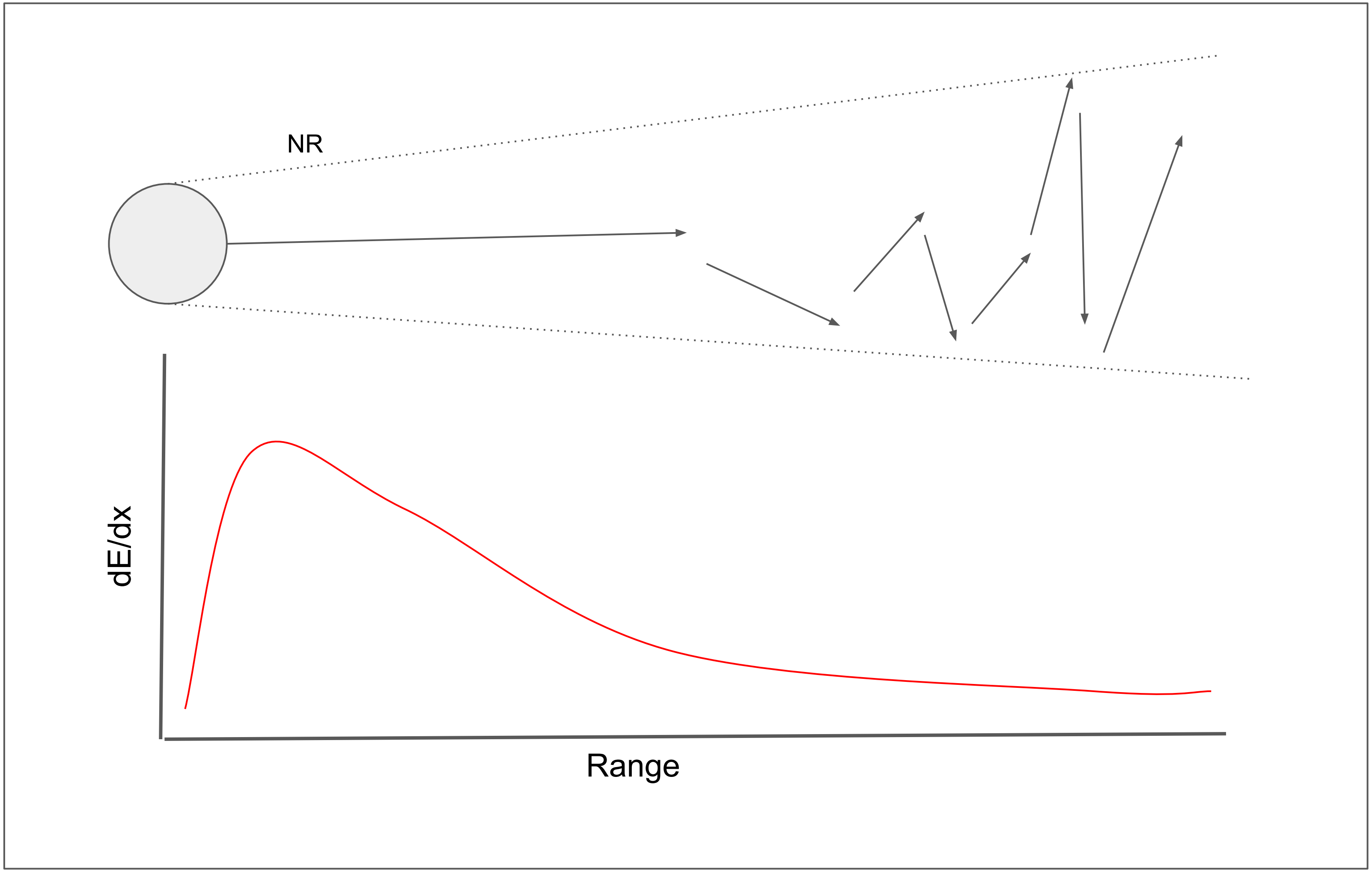
[2] C. Eldridge, New Negative Ion Time Projection Chamber Technology for Directional Detection of Dark Matter, Neutrinos and Fast Neutrons. PhD thesis, University of Sheffield, 2021. https://etheses.whiterose.ac.uk/29645/

Bonus Slide Reference

[3] K. Nikolopoulos, P. Bhattacharya, V. Chernyatin, and R. Veenhof, “Electron transparency of a Micromegas mesh,” Journal of Instrumentation, vol. 6, no. 6, pp. P06011–P06011, Jun. 2011, doi: 10.1088/1748-0221/6/06/p06011.

Bonus Slides

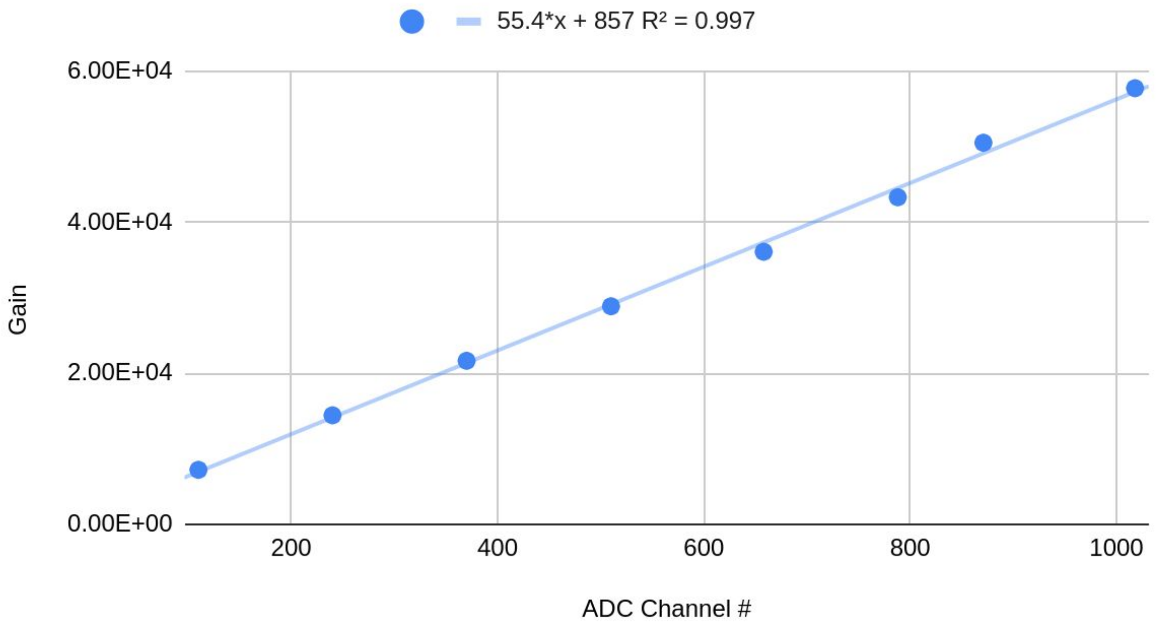
Head-tail effect



- Straggling increases along track
- Charge collection profile changes along track

Electronics Calibration

Test Pulse Amplitude (mV)	Initial # of Electrons	Final # of Electrons	Gas Gain
200	1.73E+02	1.25E+06	7.22E+03
400	1.73E+02	2.50E+06	1.44E+04
600	1.73E+02	3.75E+06	2.16E+04
800	1.73E+02	5.00E+06	2.89E+04
1000	1.73E+02	6.25E+06	3.61E+04
1200	1.73E+02	7.50E+06	4.33E+04
1400	1.73E+02	8.75E+06	5.05E+04
1600	1.73E+02	1.00E+07	5.77E+04



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Experiment 2: M2 Method Cont.

Spectra collected on **meshes 2 and 3**…

Calculate gain on **mesh 2** via ADC with mesh 3 floating to establish **total # of electrons on mesh 2 (I_e)**

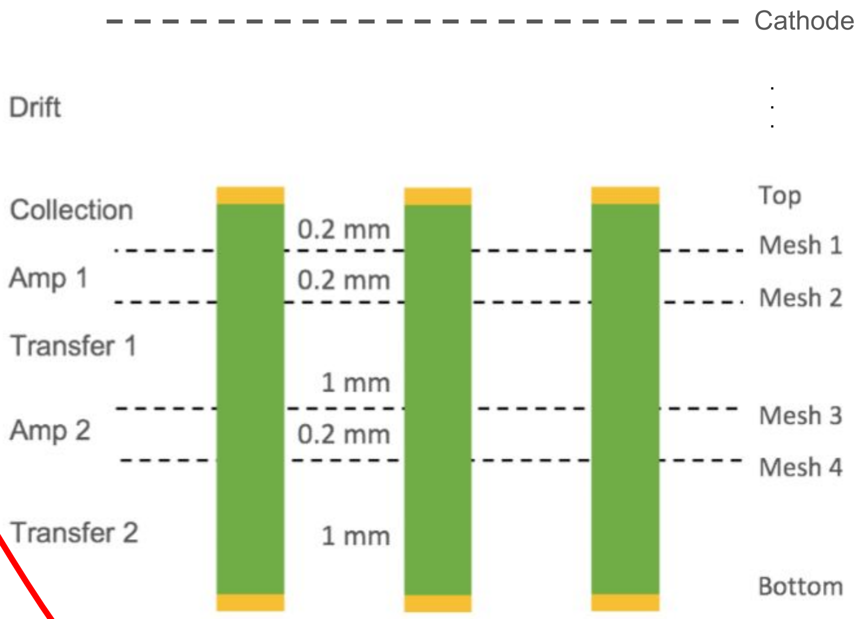
Turn on **mesh 3** and slowly increase until signal can be seen on **mesh 3**

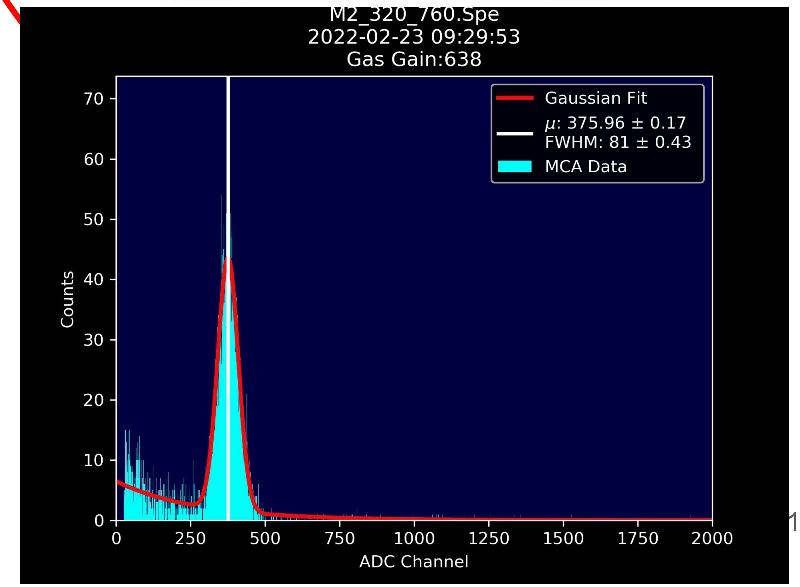
After mesh 3 is turned on the measured **gain on mesh 2 decreases (F_e^{M2})** and **mesh transparency (M_t)** can be determined via:

M2 ⇨ $M_t = 1 - (F_e^{M2} / I_e)$

Can also determine **# of electrons on mesh 3 (F_e^{M3})** and hence how many electrons have passed through mesh 2 via:

M3 ⇨ $M_t = F_e^{M3} / I_e$





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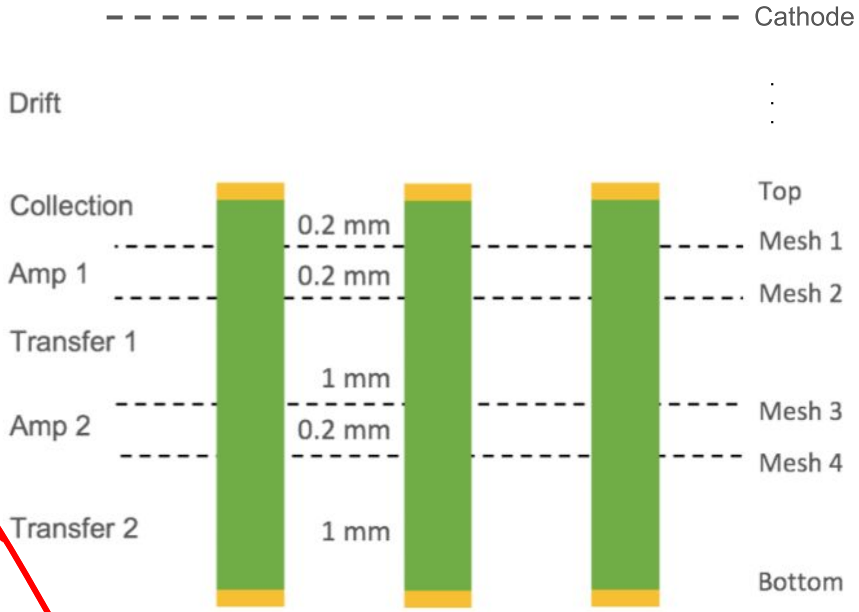
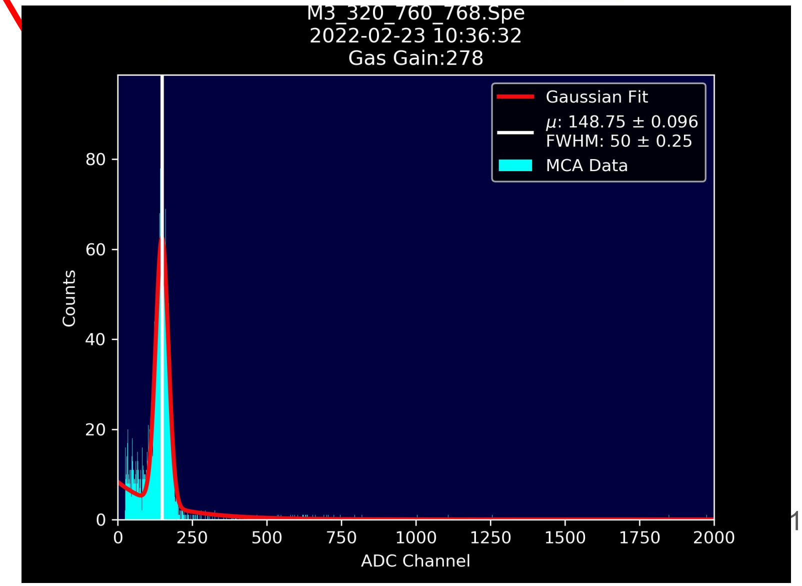




Experiment 2: M3 Method Cont.

Spectra collected on **meshes 3 and 4**…

Calculate gain on **mesh 3** via ADC with mesh 4 held 2 V below mesh 3 voltage to establish a slight reverse bias

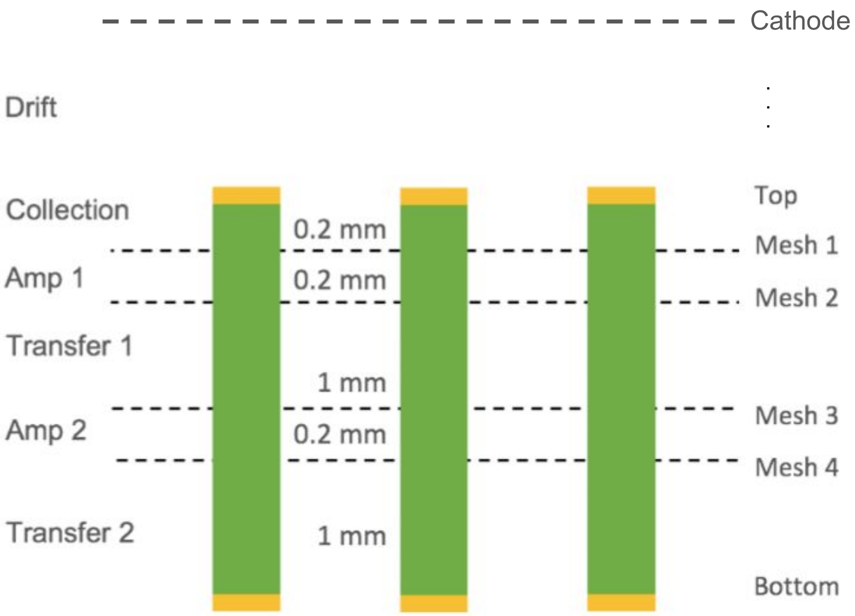
This allows us to establish **total # of electrons on mesh 3 (I^{M3}_{e})**

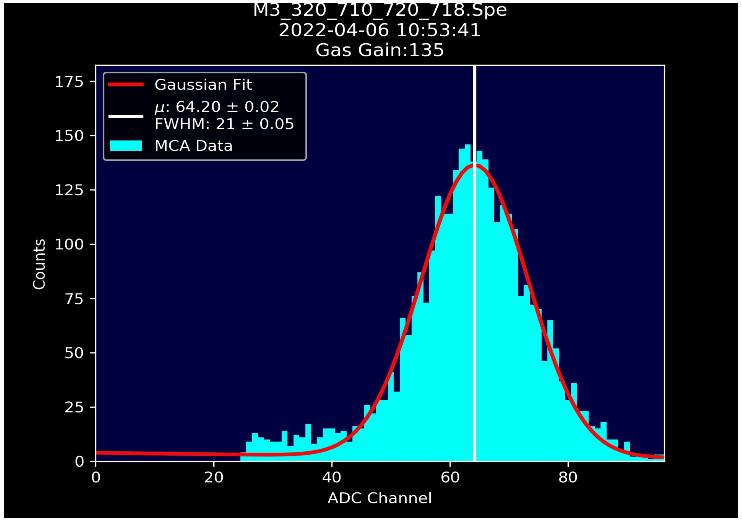
Then **increase the mesh 4 voltage** to set up an amplification field of **12500 V/cm**

Calculate gain on **mesh 4** via ADC to find (F_{e}^{M4})

Taking the ratio of these two measurements give us a **relative mesh transparency** because **gain and mesh transparency are coupled** together

Because the gain is constant we can **normalise to simulated data** to **estimate the absolute transparency**





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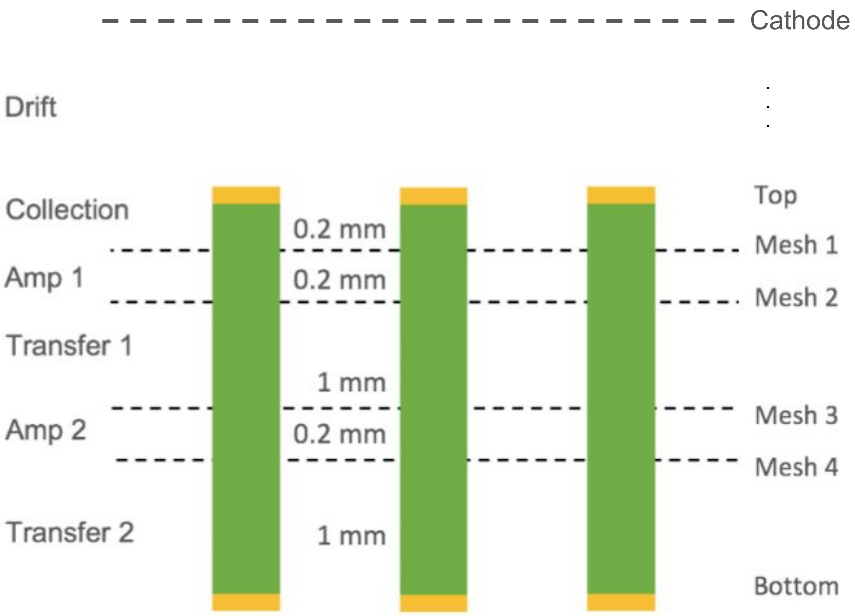
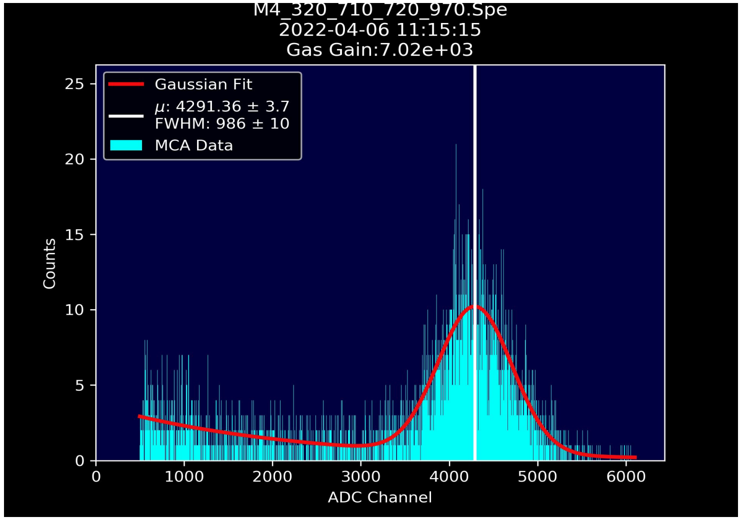
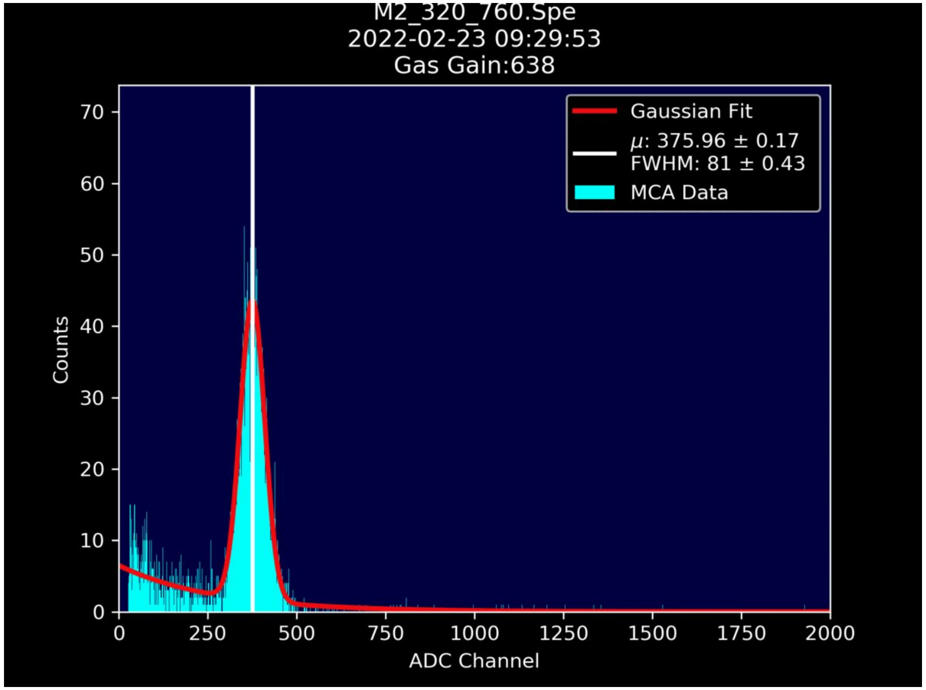
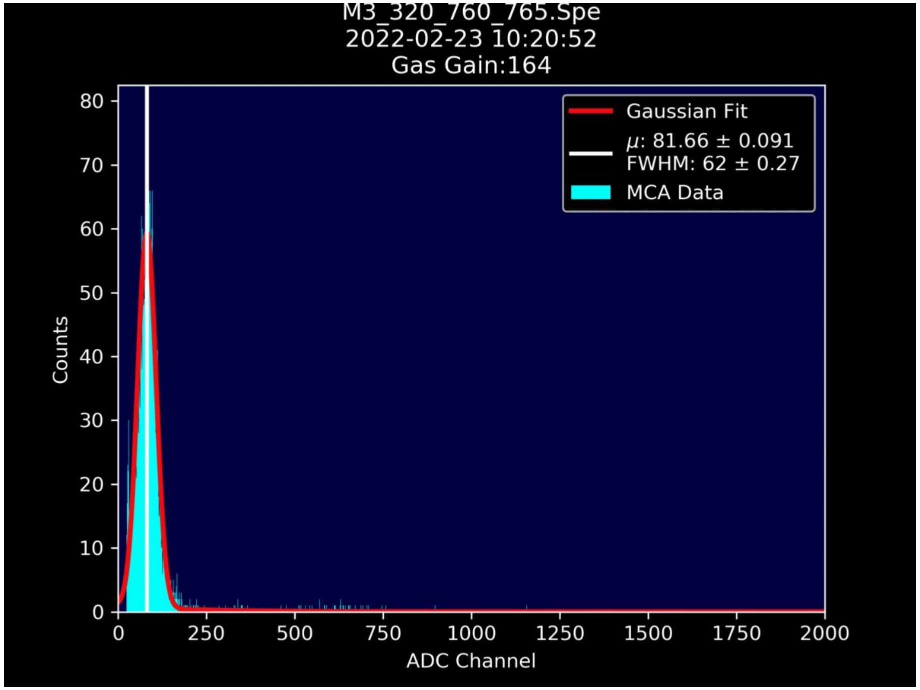




Visualising Mesh Transparency of M2

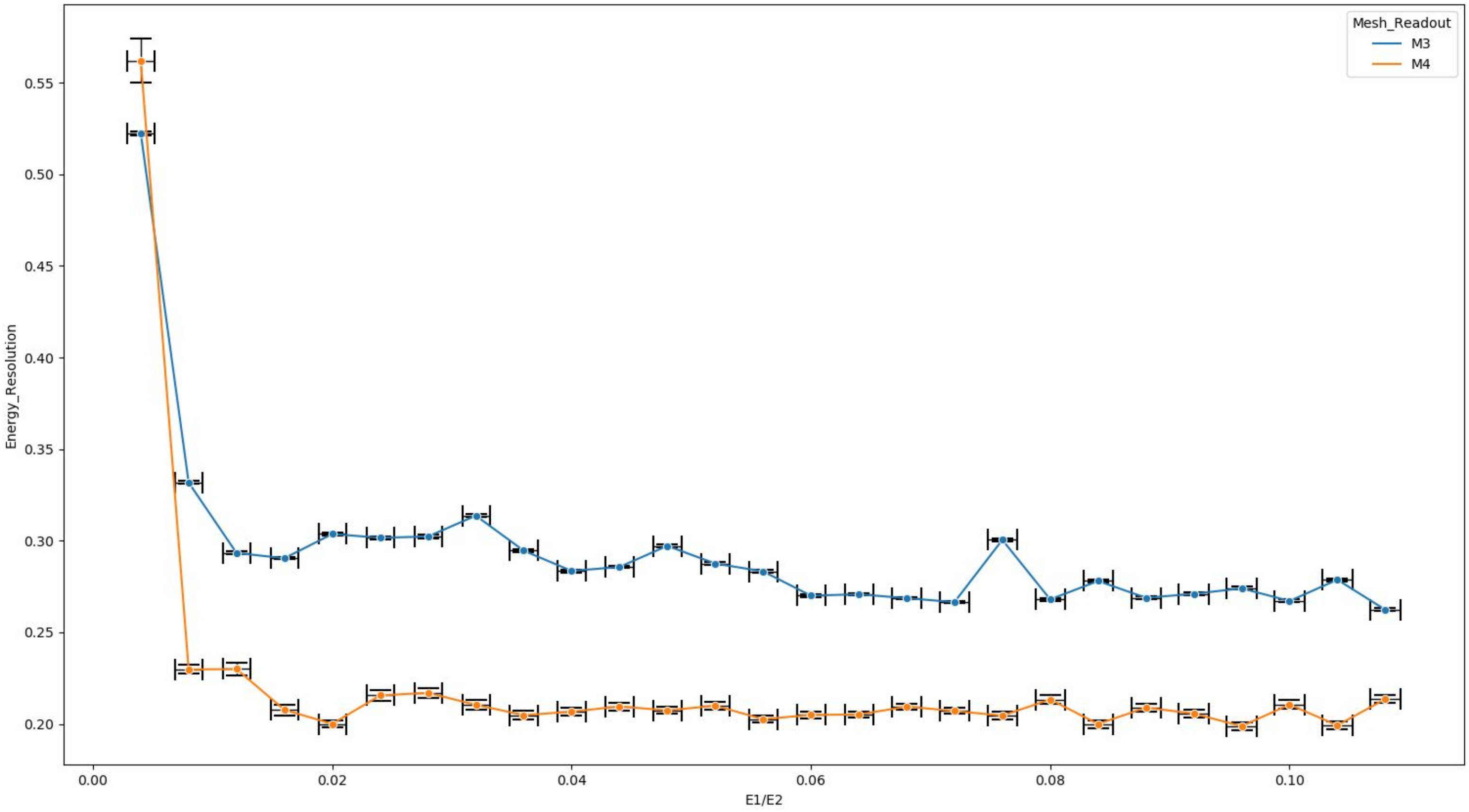




GIF shows:

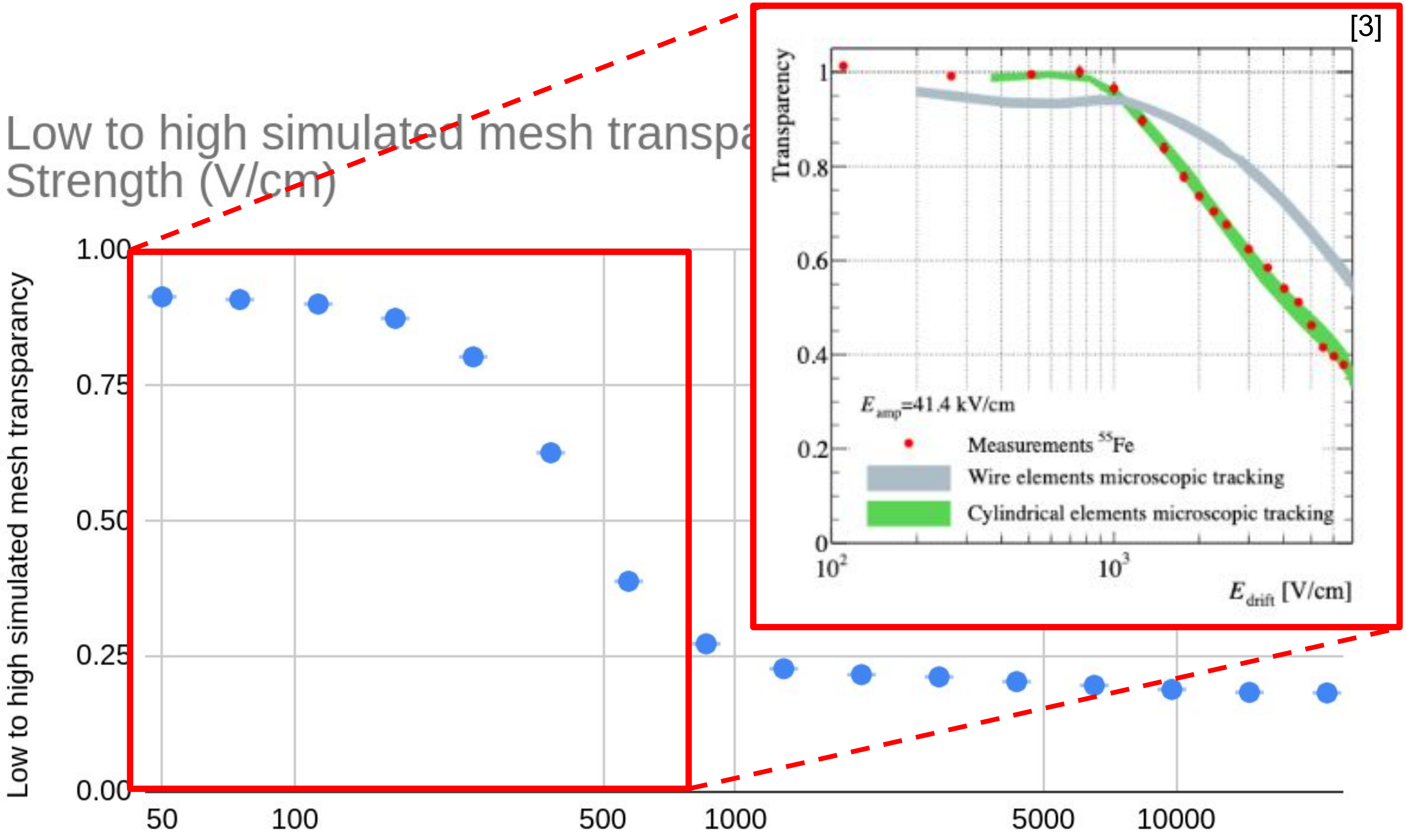
- Number of Electrons on M2 (left) decreases as the voltage on M3 increases
- Number of electrons on M3 (right) increases as voltage on M3 increases

Energy Resolution M3 - Results

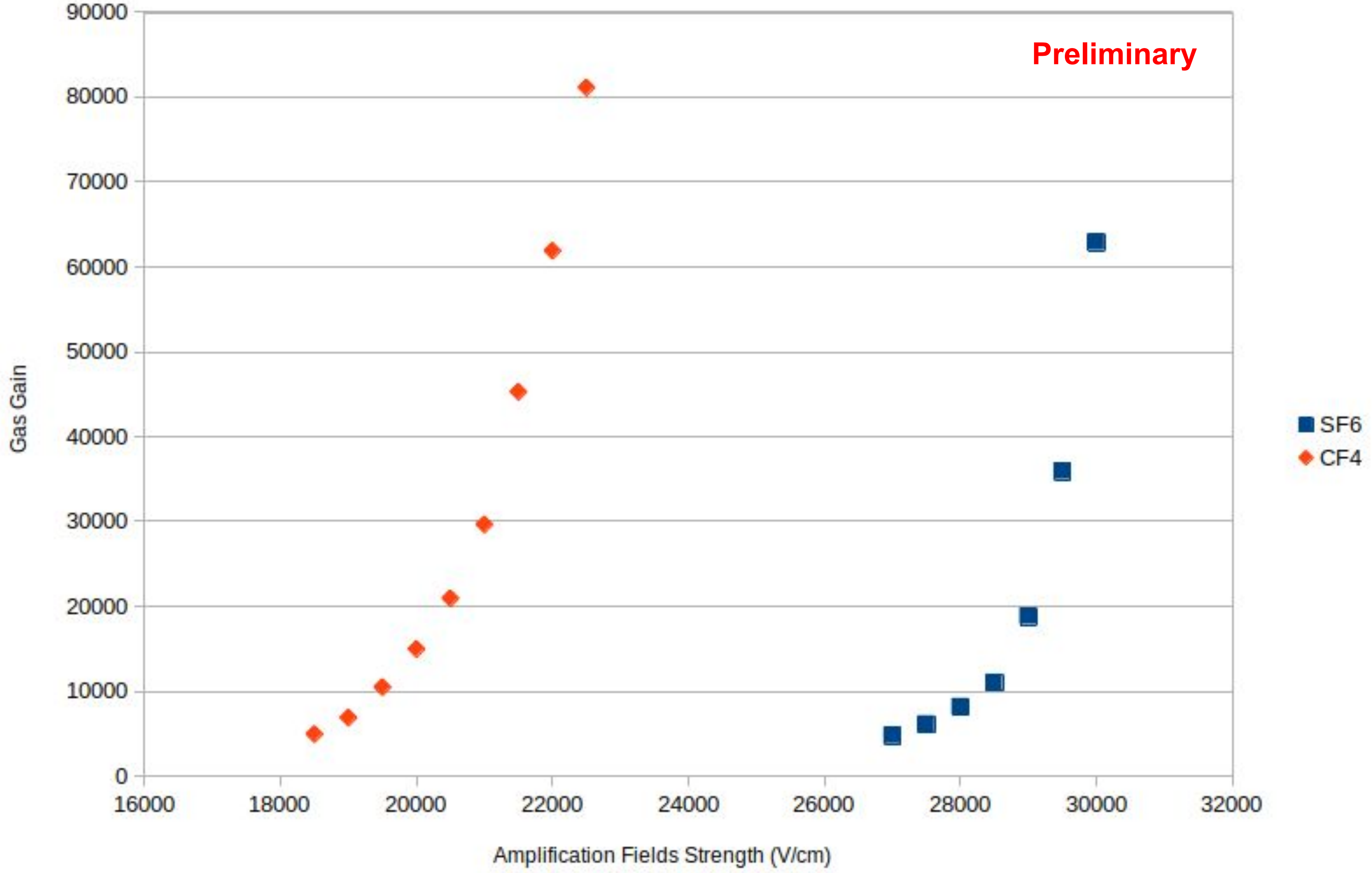


- Plateau above 100 V/cm
- More significantly influenced by M2 transition

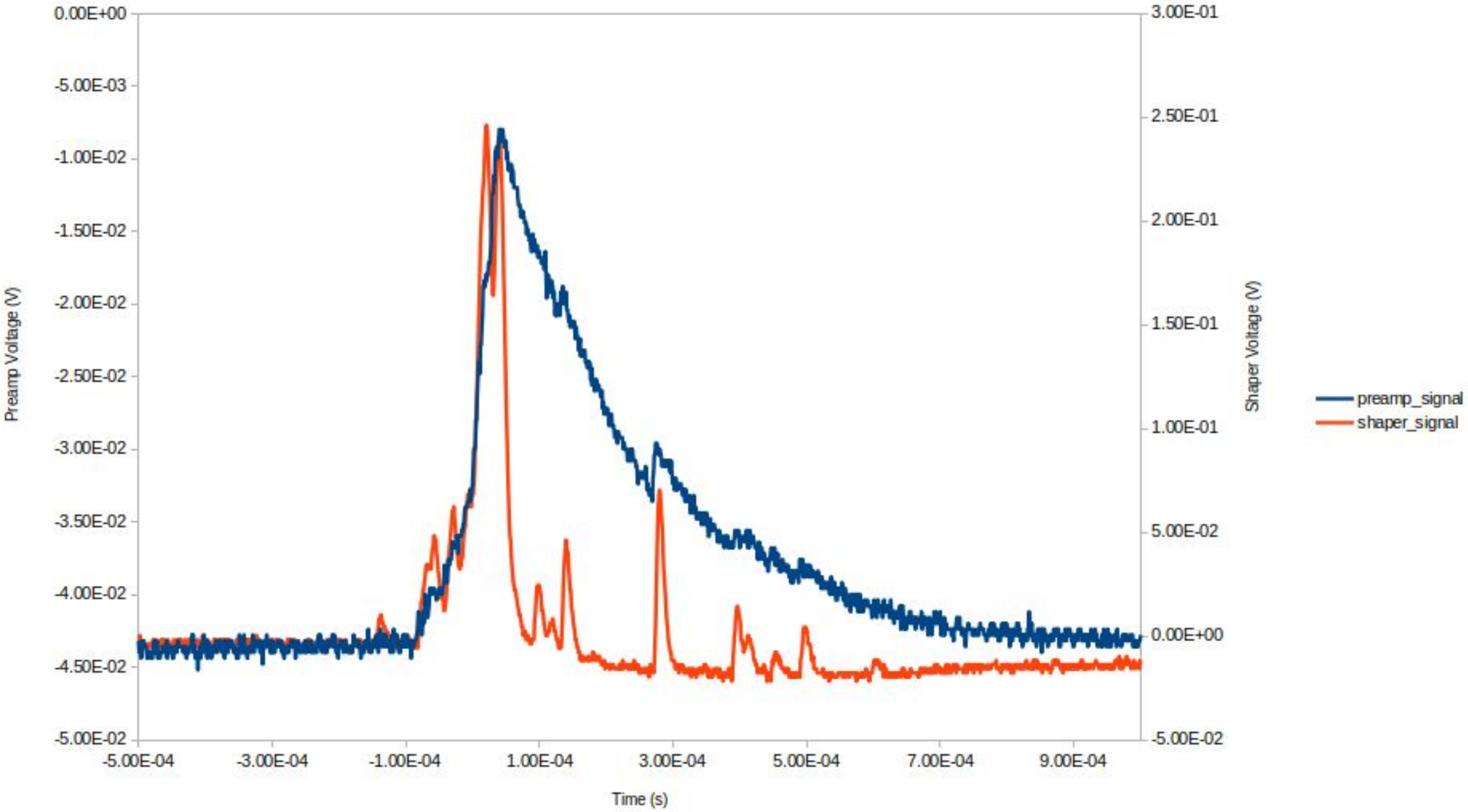
Similar Mesh transparency Studies with Micromegas Mesh



Optimised SF_6 compared to CF_4

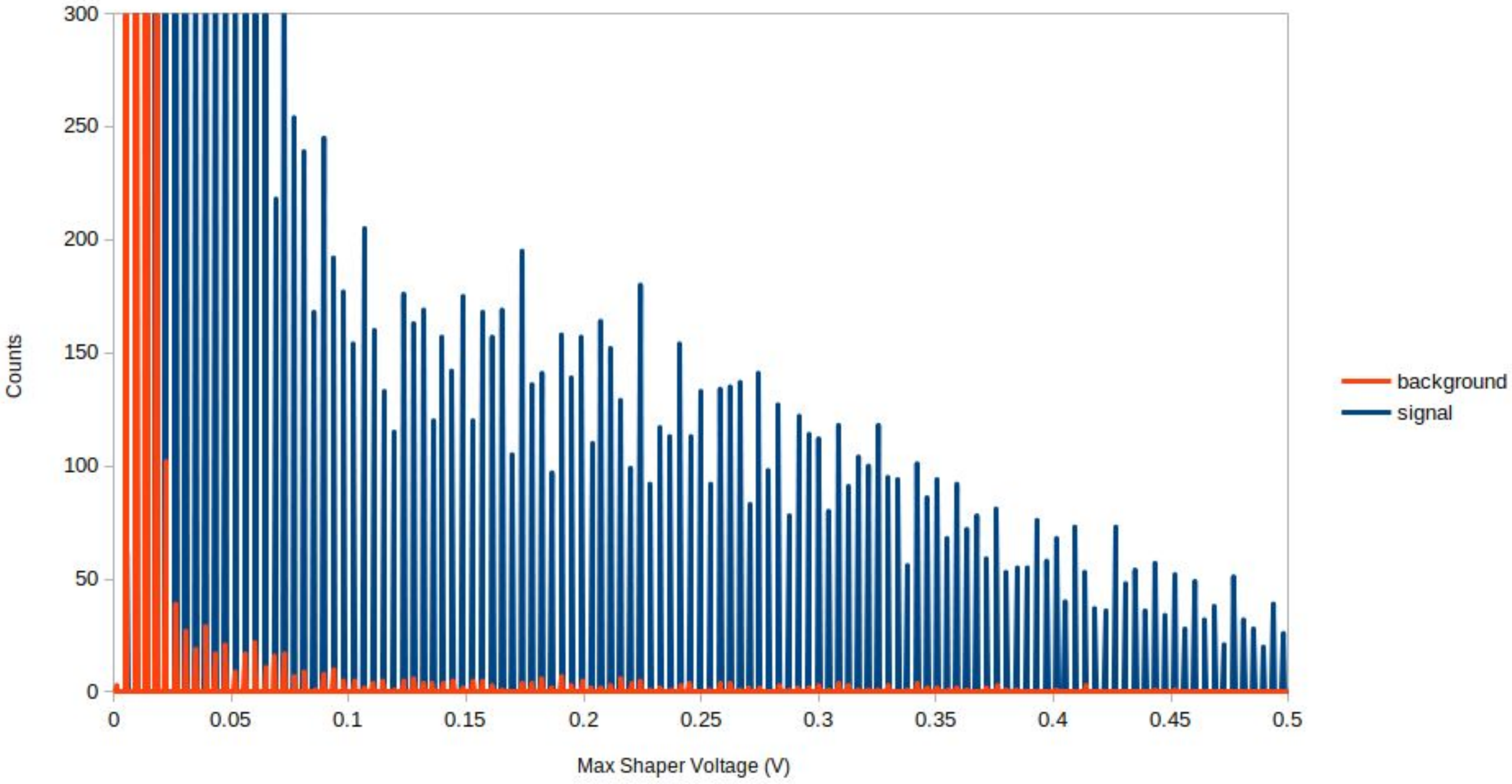


Typical signals in SF$_6$



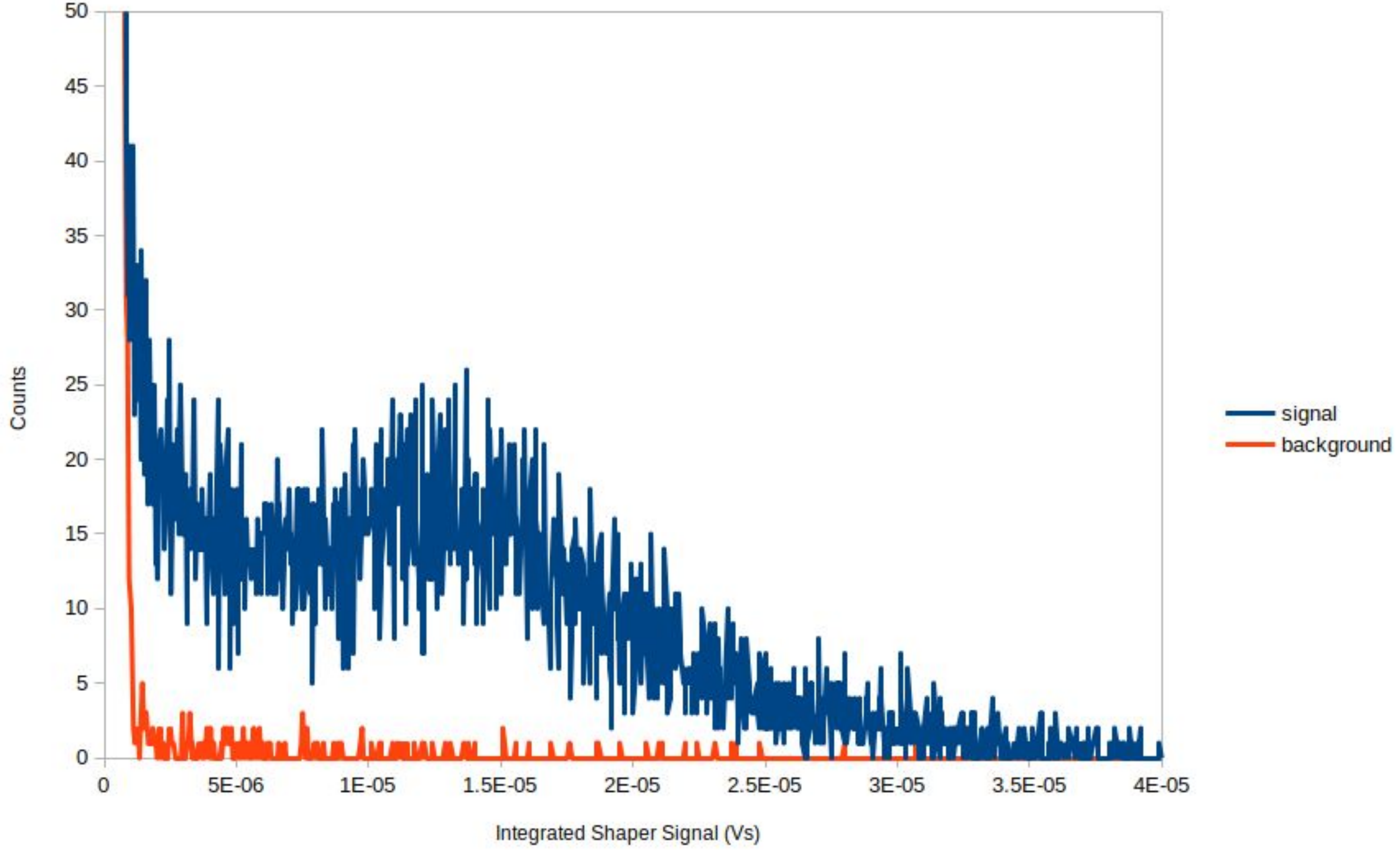
Biasing scheme -> c = -500 V, M1 = 30 V, M2 = 610 V, M3 = 700, M4 = 1280

Fe55 Spectrum using Max Voltage in SF$_6$



Biasing scheme -> c = -500 V, M1 = 30 V, M2 = 620 V, M3 = 680, M4 = 1270

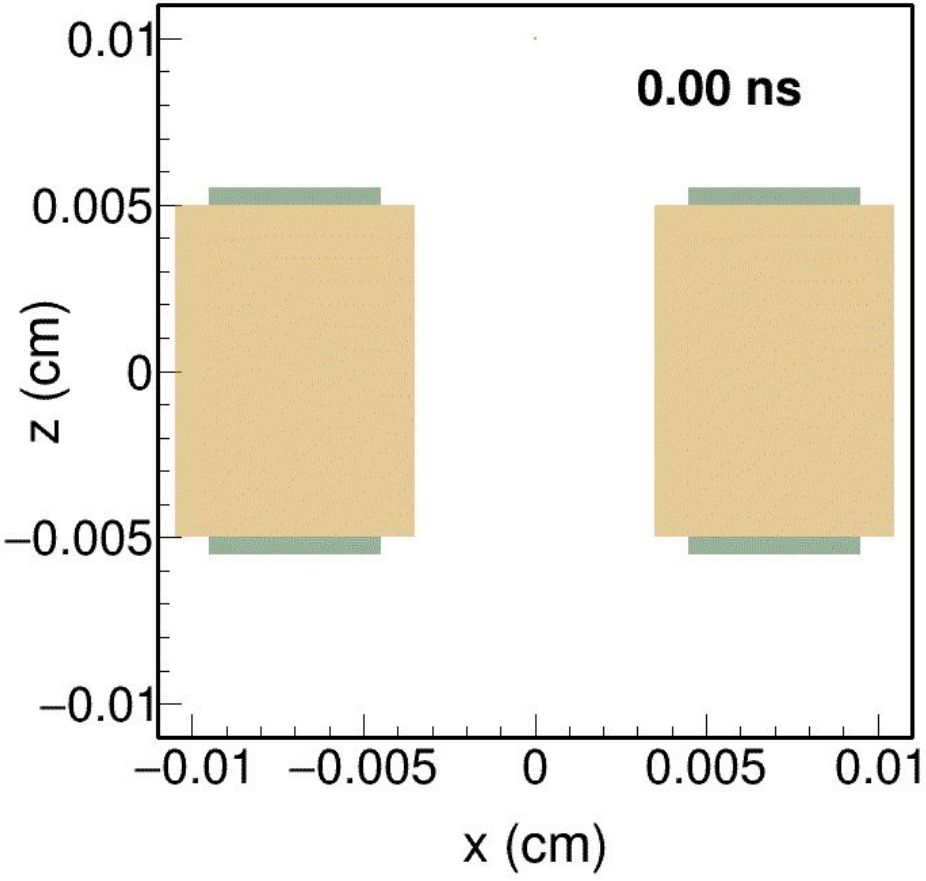
Fe55 Spectrum using Integrated Signal i SF$_6$



Biasing scheme -> c = -500 V, M1 = 30 V, M2 = 620 V, M3 = 680, M4 = 1270

Negative Ion Garfield++

- Negative Ion Garfield mod has been developed by colleagues at the University of Kobe
- Mesh transparency has not been investigated in NID gases
- The mesh transparency simulations will be repeated with this modified code
- Gif shows NI (blue) approaching GEM before electrons (orange) detach from the NI and proceed to avalanche before attaching to the NI gas again



Courtesy of Hirohisa Ishiura (Kobe Univ.)