University of Sheffield

First Results from a CYGNUS-10 scale SF_6 TPC Vessel with a Coupled MMThGEM-Micromegas

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The University of Sheffield[1], Kobe University[2], Queen Mary University of London[3]

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- *Directional dark matter detection with the CYGNUS collaboration*
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- *Demonstration in a 1 m^3 vessel*
- *Ongoing efforts to scale the readout*

IDM 2024 - L'Aquila

11/07/2024

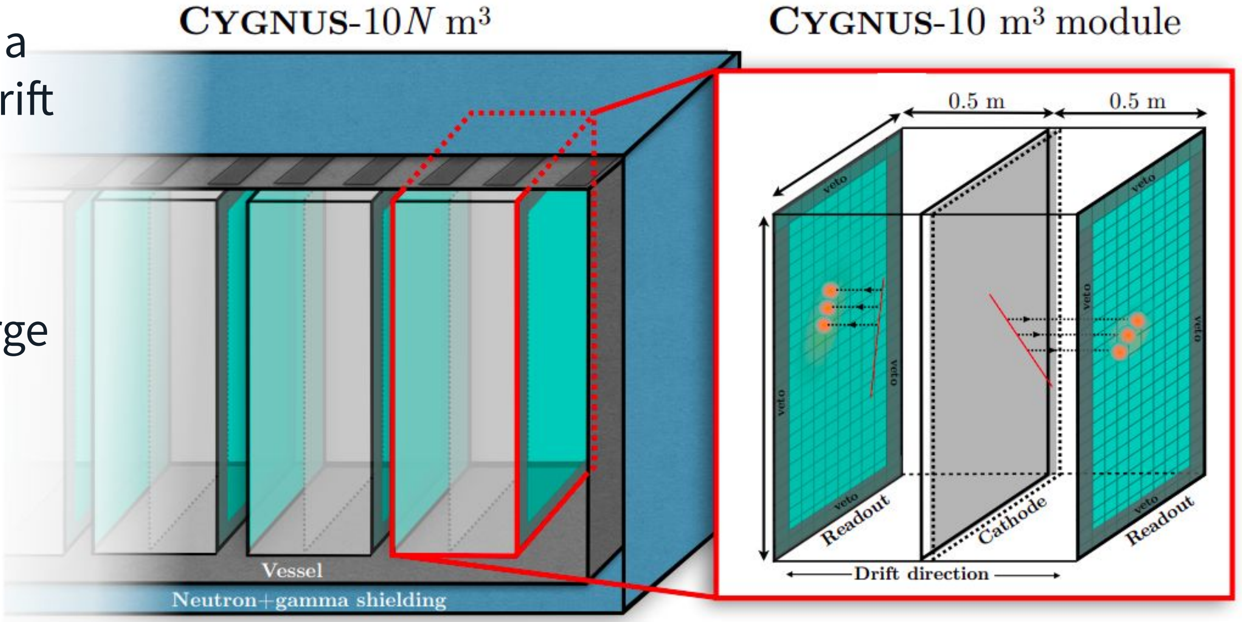
Directional Dark Matter Detection and the CYGNUS Collaboration

- CYGNUS proposes a modular and multi site nuclear recoil observatory
- Time Projection Chambers (TPCs) capable of reconstructing recoils
- Capable of directional sensitivity to dark matter and neutrinos

CYGNUS modules will likely use a gas mixture with Negative Ion Drift (NID) gas component like SF_6

NID gases require special techniques to achieve high charge amplification

Recent work with a MMThGEM demonstrates strong avalanche capability in SF_6



The Multi-stage MMThGEM for Charge Amplification in Negative Ion Gases

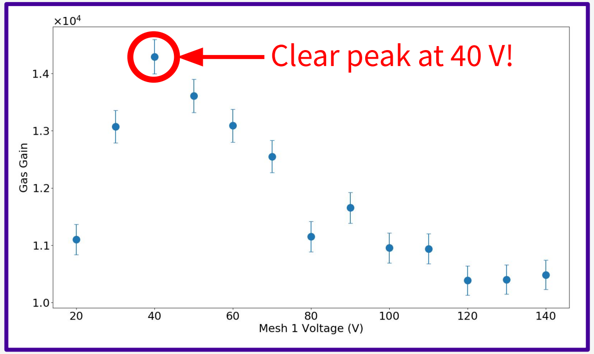
The Multi-stage Multi-Mesh ThGEM for Charge Amplification in Negative Ion Gases

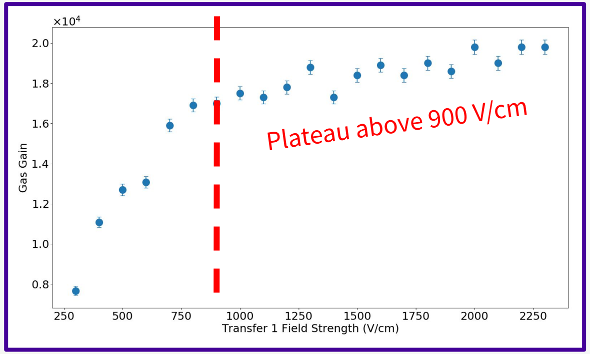
SF_6 - 40 Torr

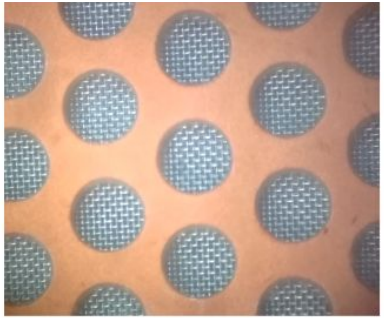
MMThGEM

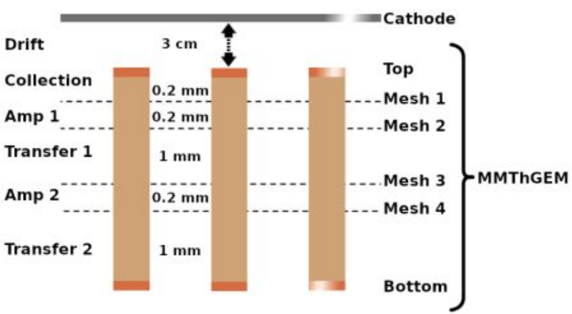
- Multiple amplification stages are beneficial for use with SF_6
- Mesh layers make the amplification fields uniform
- Improved avalanche characteristics
- Reduction in +ve Ion Back Flow (IBF)

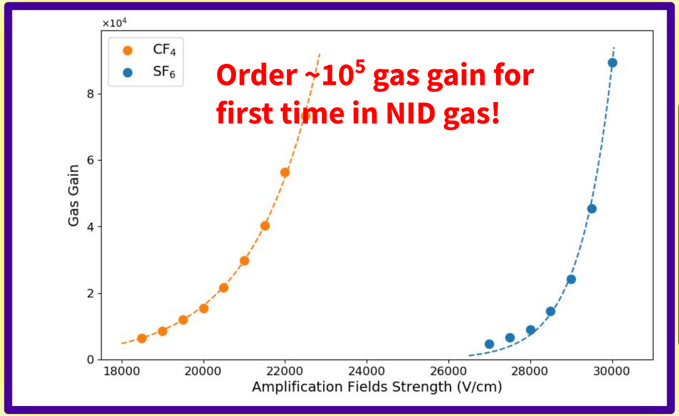
Recent success in low pressure SF_6











SCAN ME

See publication for more information

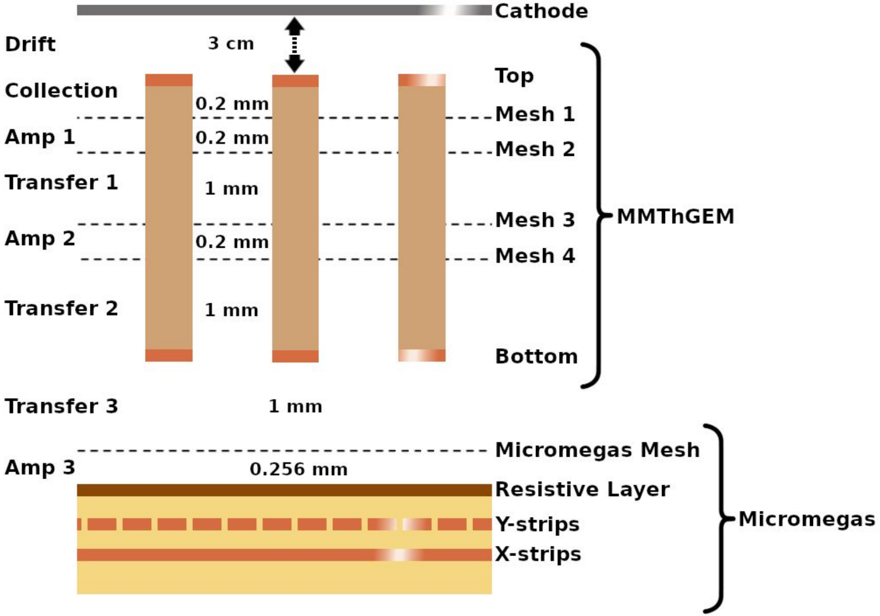
MMThGEM-Micromegas Experimental Setup - Kobe Test Vessel

Coupled MMThGEM-Micromegas - Kobe Test Vessel

Micromegas Device -

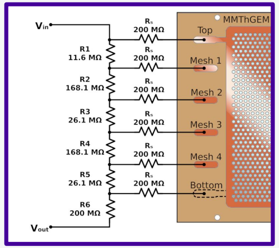
(MMThGEM is used as a gain stage device)

- Perpendicular x-y strip readout plane
- Resolution/strip pitch: 250 µm
- Strip width: 100 µm (y) and 220 µm (x)
- Active area: 10 x 10 cm
- Amplification gap: 256 µm
- Diamond Like Carbon (DLC) layer: 50 MΩ/□

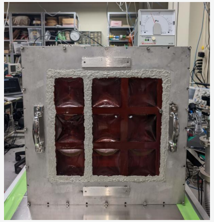


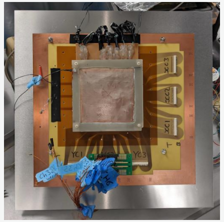
Biasing Scheme for MMThGEM

- Resistor chain soldered to electrode contacts
- Resistor values dictated by previous optimisation
- Reduces the number of HV feedthroughs required for operation



Starting in the Kobe test vessel



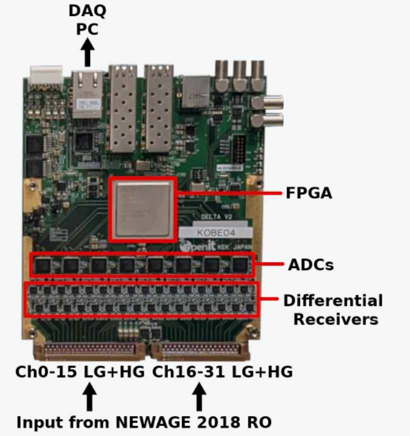


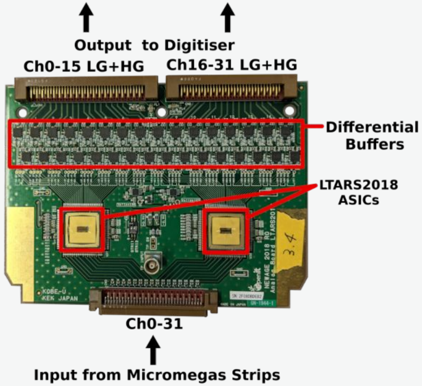
LTARS2018 - “NEWAGE 2018 RO” Boards

The Low Temperature Analog Readout System (LTARS) designed specifically for NID gases

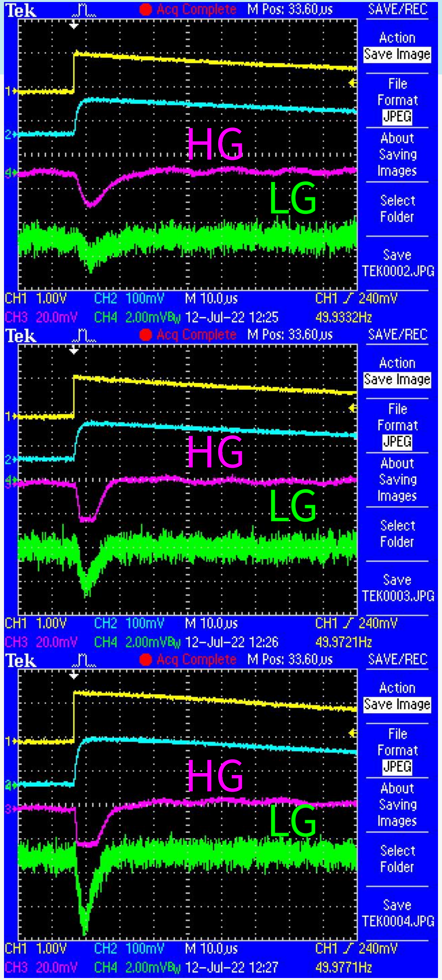
- Designed by researchers at Kobe University and KEK
- LTARS2018 chips (x2) mounted on the NEWAGE 2018 RO board
- Board provides the charge sensitive readout electronics for 32 channels
- Each channel is split into low electronic gain and high electronic gain for large dynamic range

32 y-strips on the Micromegas were instrumented with LTARS2018 charge sensitive electronics...



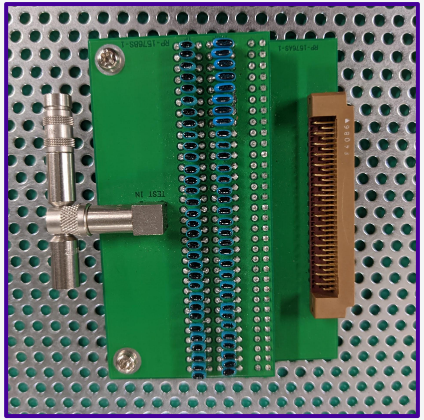


Low gain and high gain channels provide large dynamic range



Charge Calibration

Charge calibration was performed by injecting charge into LTARS ASIC via 32 parallel test capacitors on a custom PCB

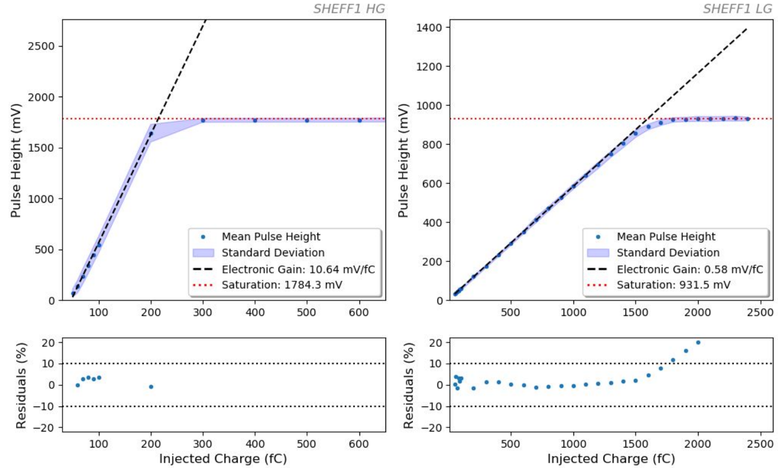


Two methods of charge calibration were employed:

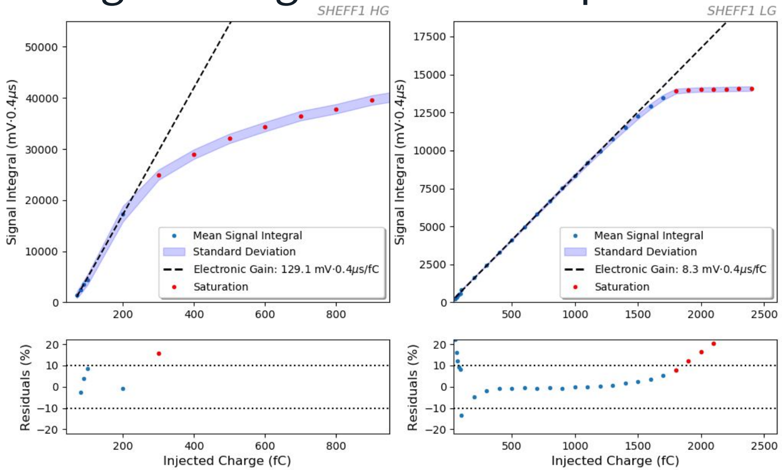
1. **Signal Amplitude** - standard

2. **Signal Integration** - used to compensate for slow arrival of negative ions

Signal Amplitude : standard…

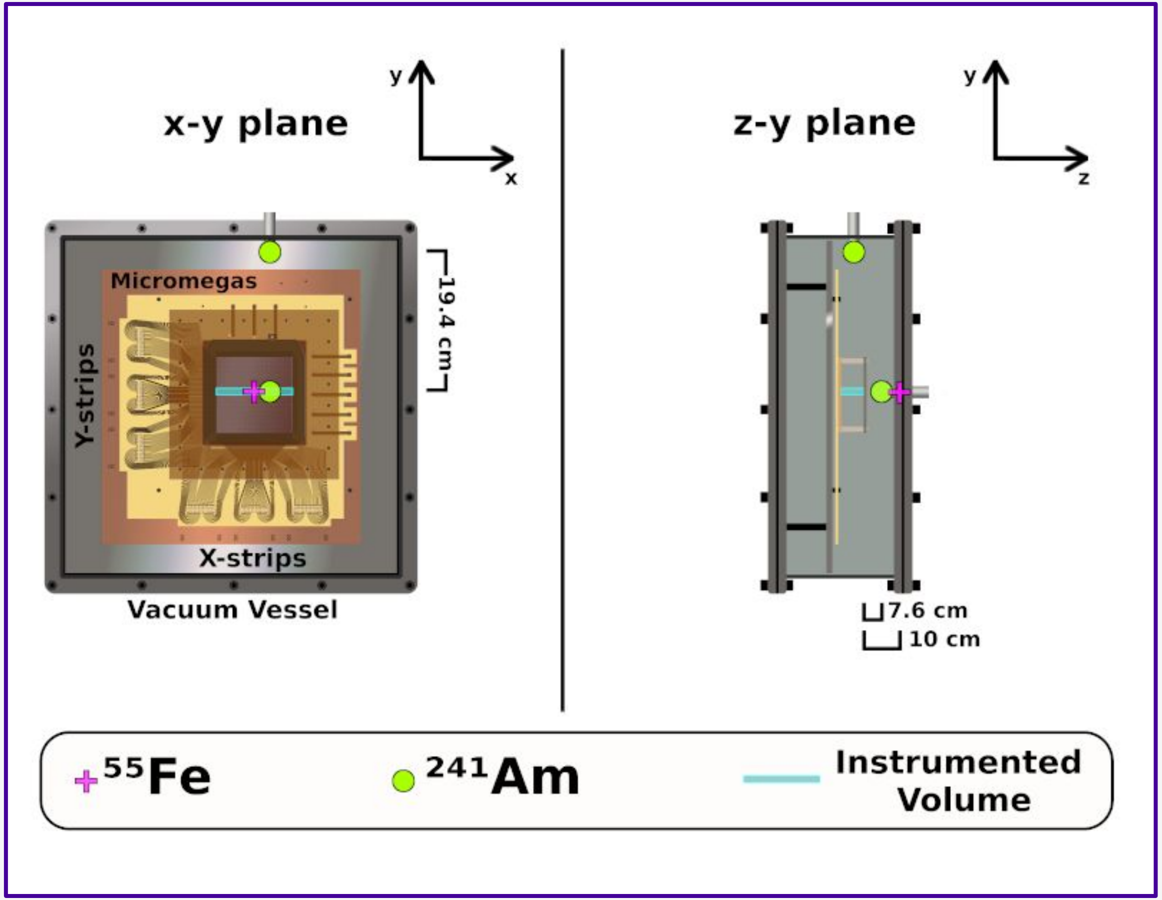


Signal Integration: NI compensation



Measurements in Kobe Test Vessel

Source Positioning Around Test Vessel



^{55}Fe x-ray source

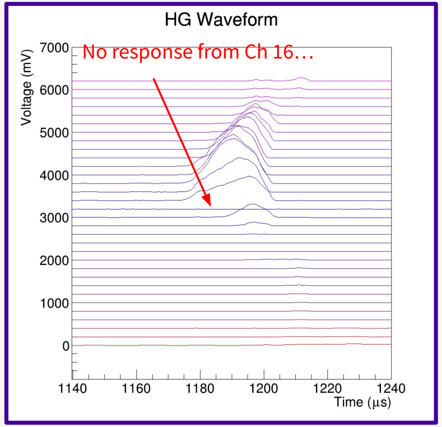
- ~10 cm above instrumented strips (z-axis exposure)

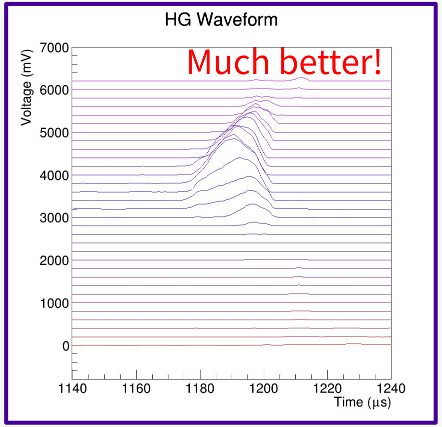
^{241}Am alpha source

1. ~8 cm above instrumented strips (z-axis exposure)
2. A distance of ~20cm perpendicular to y-strips (y-axis exposure)

^{55}Fe X-ray Exposure - Signal Preprocessing

SF_6 - 40 Torr





Channel Interpolation

97% of channels were fully operational

Ch #16 was found to have a loose connection during measurements

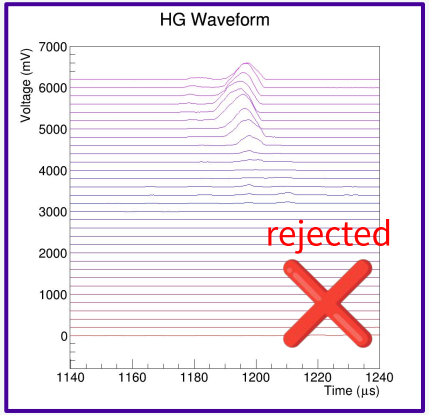
Instantaneous voltage of Ch 16 was determined via the linear interpolation of Ch 15 and 17

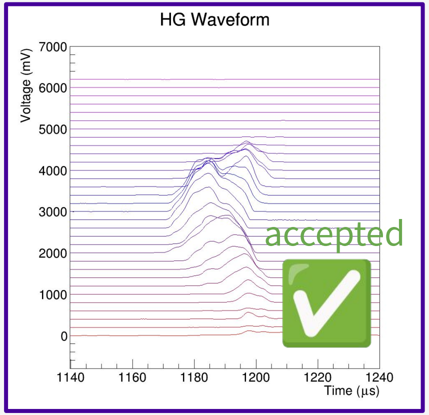
Edge Event Cut

Due to charge spreading in resistive layer, many channels are found to be above threshold per event…

Edge event threshold cut applied:

13 < Centre Ch# < 17





^{55}Fe X-ray Exposure - Gain Measurements

Biasing settings: -2900 V, -1900 V, 100 V, and -530 V for the cathode, V_{in} , V_{out} and Micromegas mesh respectively

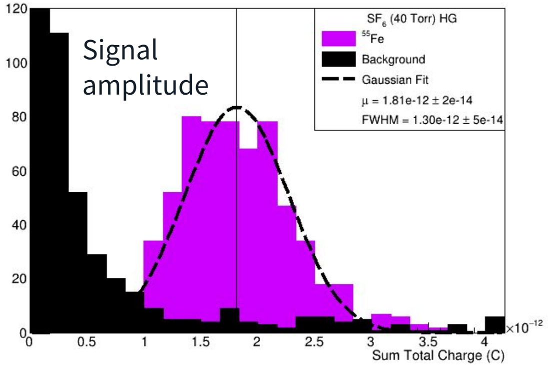
A photopeak can be observed in both the signal amplitude and signal integral spectrum

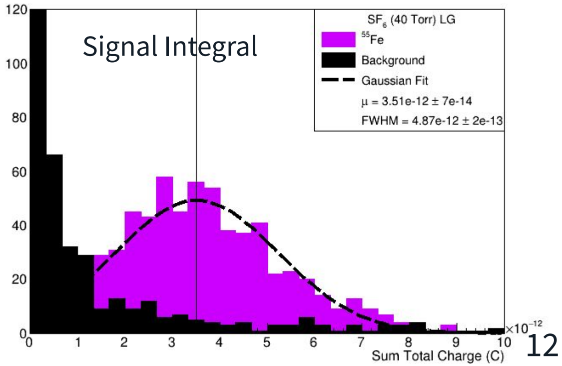
A gaussian distribution was fitted to the spectrum and the amount of charge was determined via the charge calibration

The gas gain was determined via the w-value of SF_6 (34 eV)

Gas gain was found to be as high as 1.24 x10^5!
with an energy resolution of 1.28

Effective gas gain in 40 Torr of SF_6 - **charge on strips**



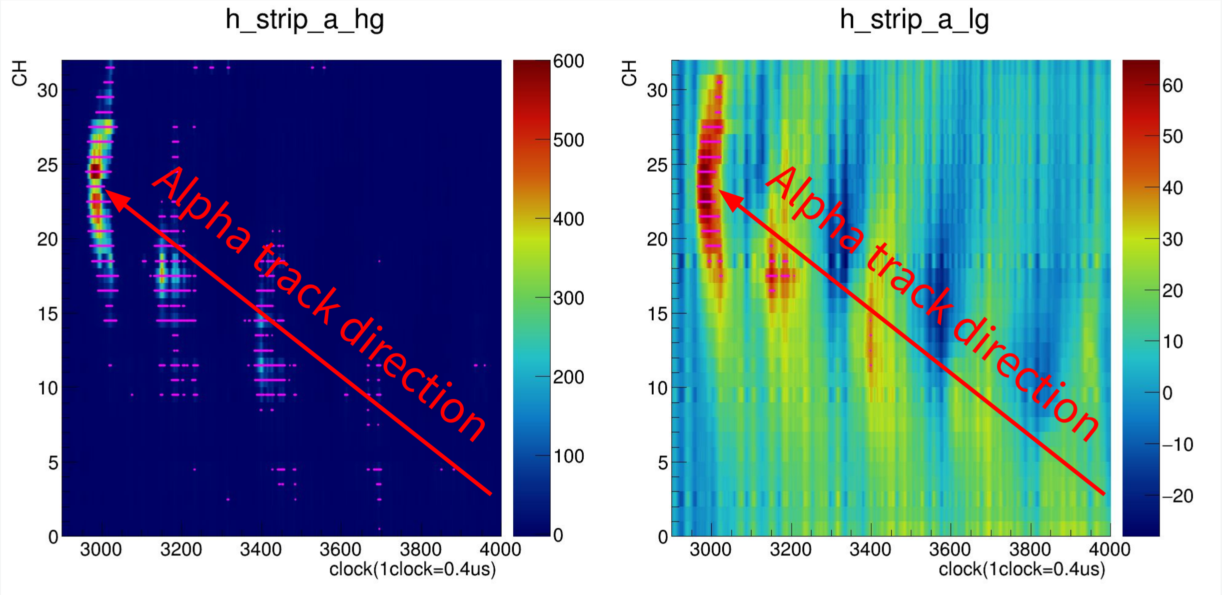


^{241}Am Alpha Exposure - Event Structure

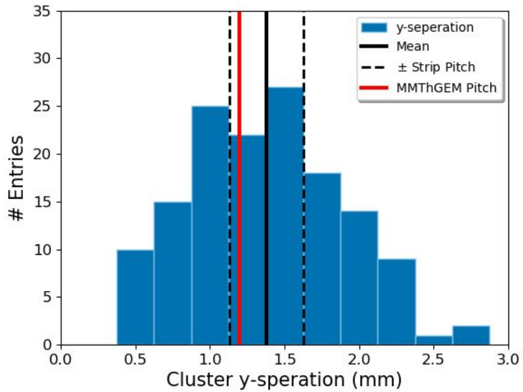
The voltages applied to the cathode, V_{in} , V_{out} , and the Micromegas mesh were -2800 V, -1800 V, 100 V, and -500 V respectively.

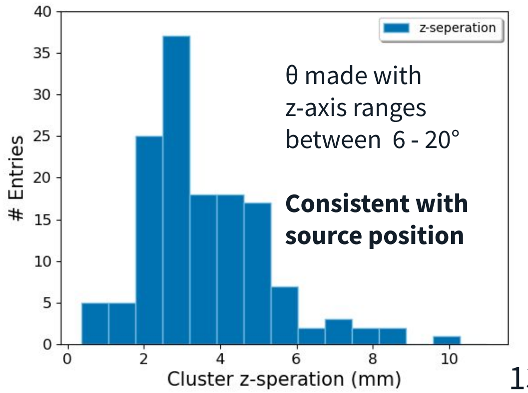
Example alpha particle track shows a structure caused by the MMThGEM hole pitch

MMThGEM hole pitch: 1.2 mm



Inspection of 100 typical events





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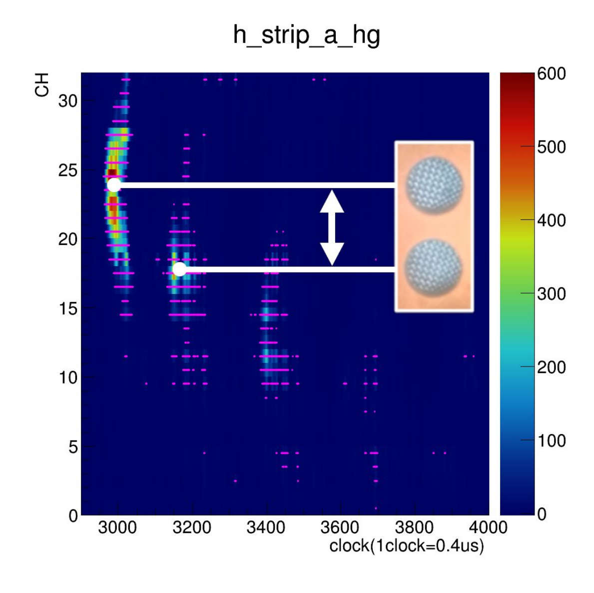

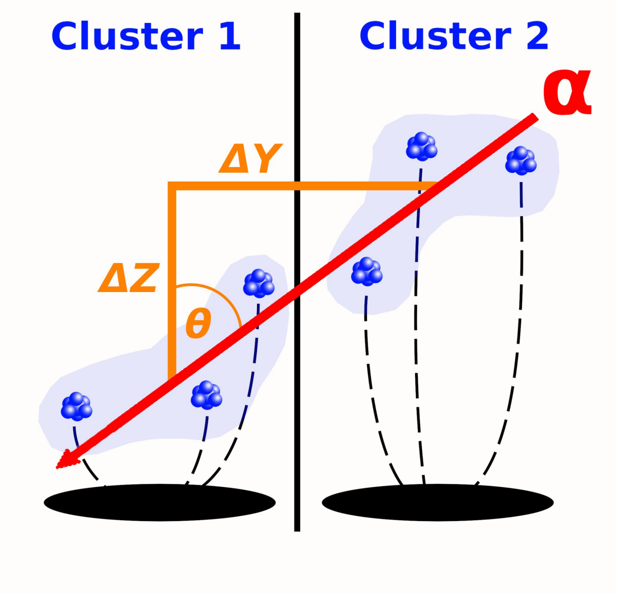

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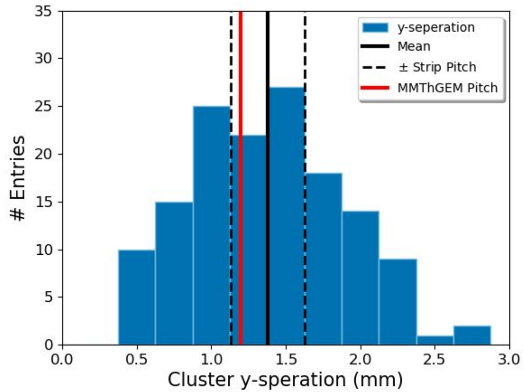
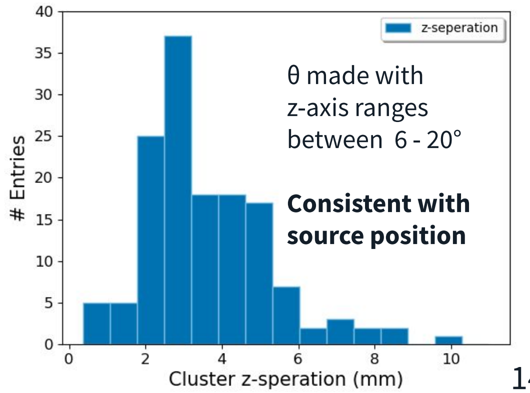


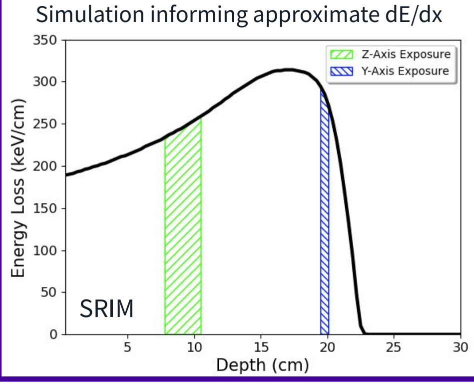


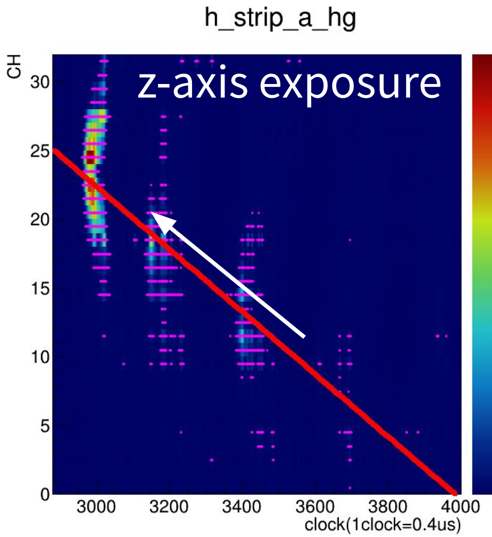
^{241}Am Alpha Exposure - Track Reconstruction

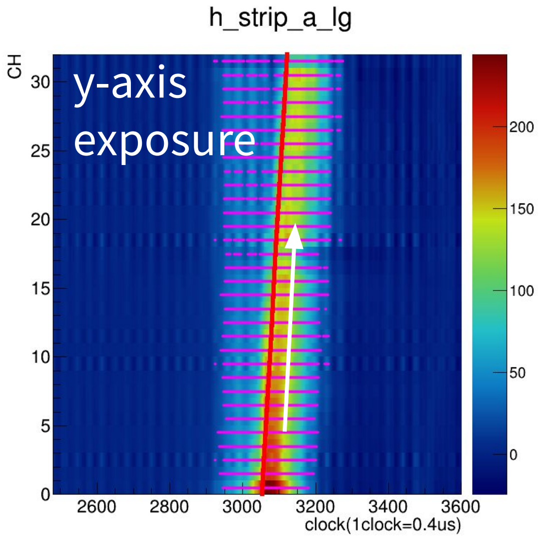
SF$_6$ - 40 Torr

Total linear regression algorithm applied for track reconstruction:

1. Isolate points above threshold
2. Convert both axes into spatial units via strip pitch and drift velocity
3. Perform total linear regression - minimisation of residual on both axes







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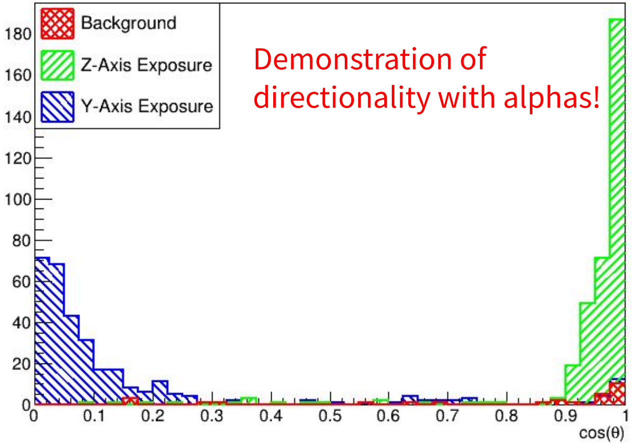
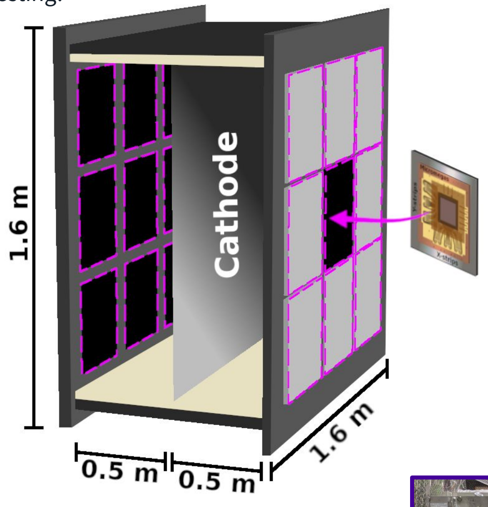


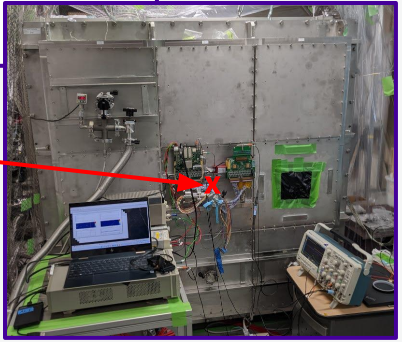
Kobe “BENTO” Vessel

CYGNUS-10 Scale Kobe “BENTO” Vessel

Kentaro and Satoshi welcome your detector modules for testing!



^{252}Cf source positioned externally 10 cm behind micromegas plane



The “BENTO” vessel at Kobe University

Large CYGNUS-10 scale vessel - 50 cm drift length

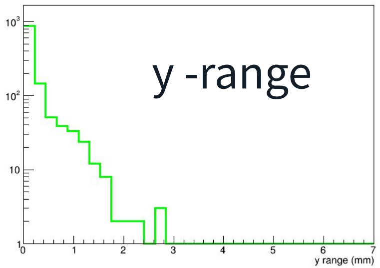
Modular design which can support up to 18 readout detector planes

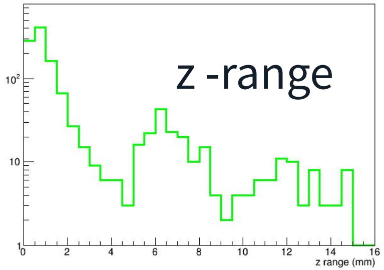
MMThGEM-Micromegas was transferred to the central panel on the BENTO vessel

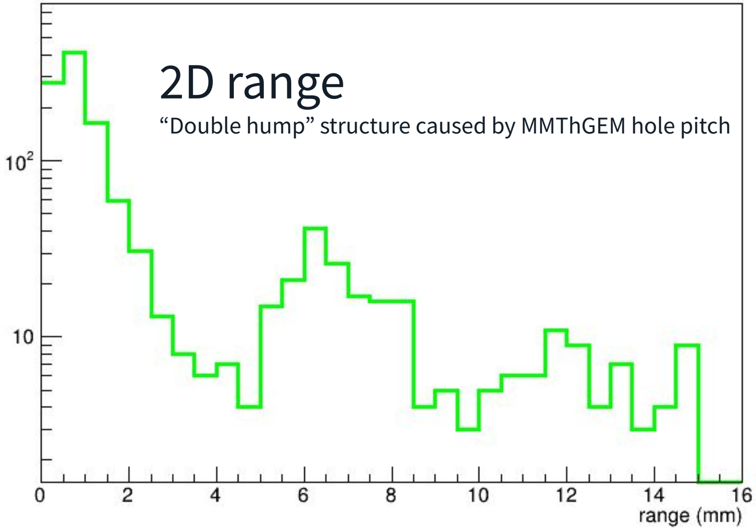
Detector mounting conveniently fits test vessel dimensions

^{252}Cf Induced Nuclear Recoil Range Measurements

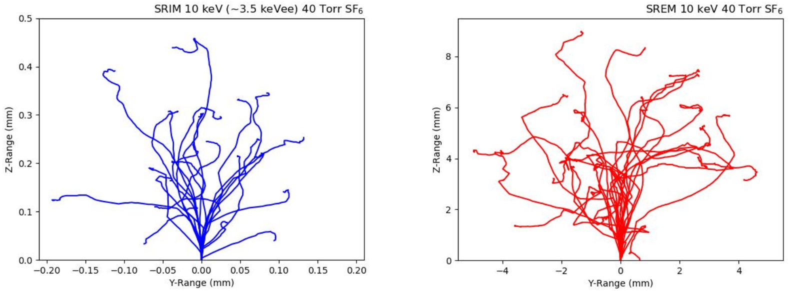
SF_6 - 40 Torr



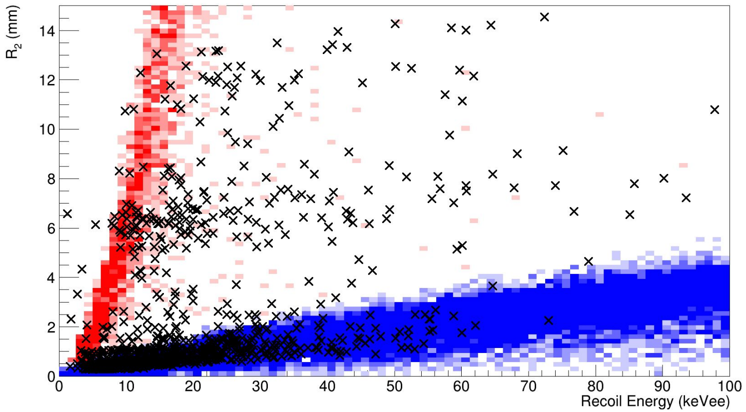




Comparison to SRIM/SREM recoil simulations



With trigger threshold = 40 mV (LG), the effective recoil threshold ~ 1.8 keVee



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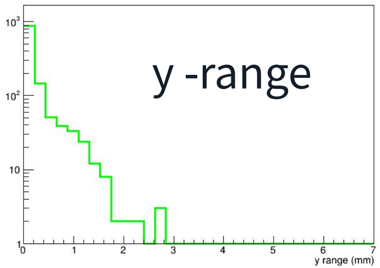

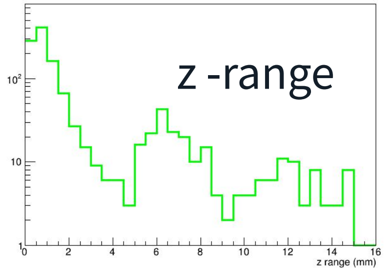

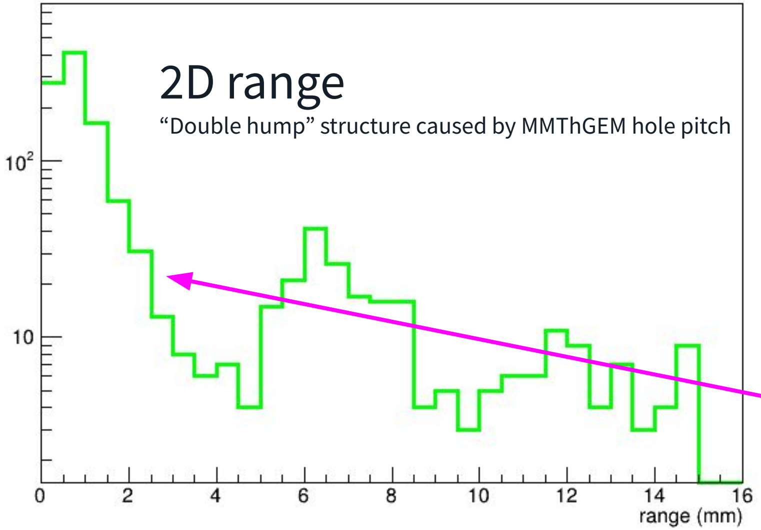

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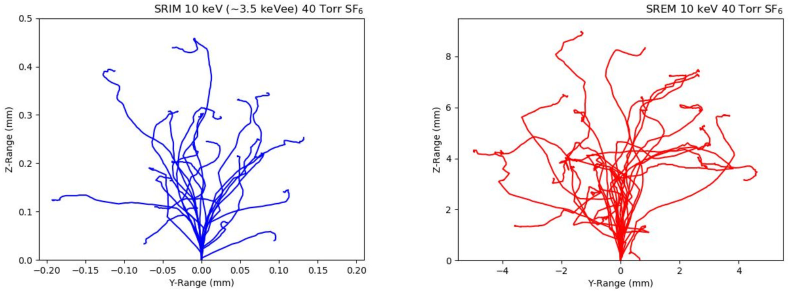

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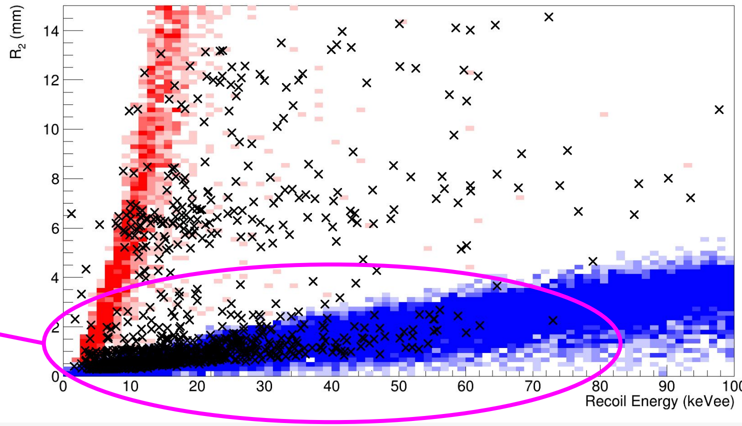

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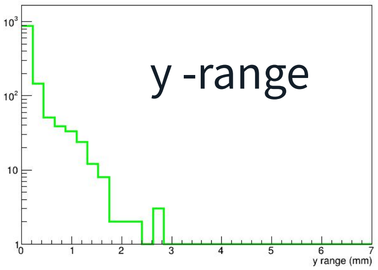

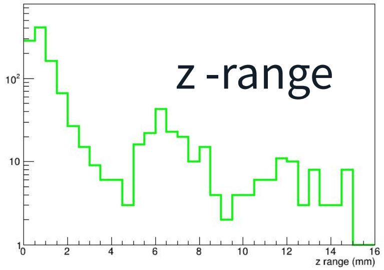

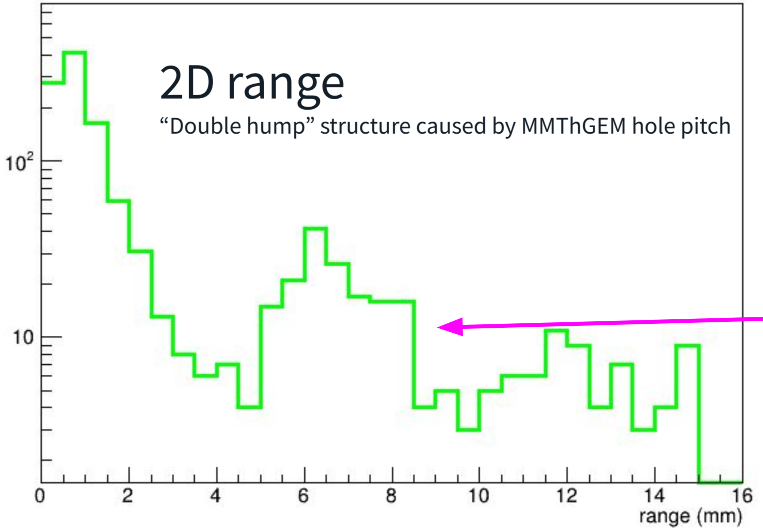

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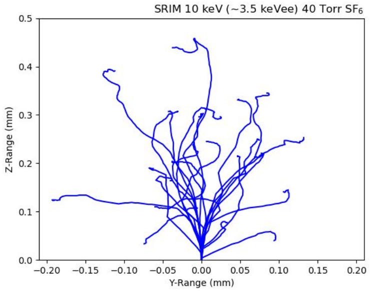

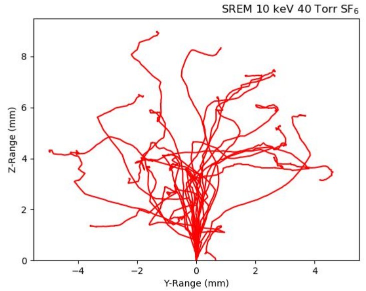

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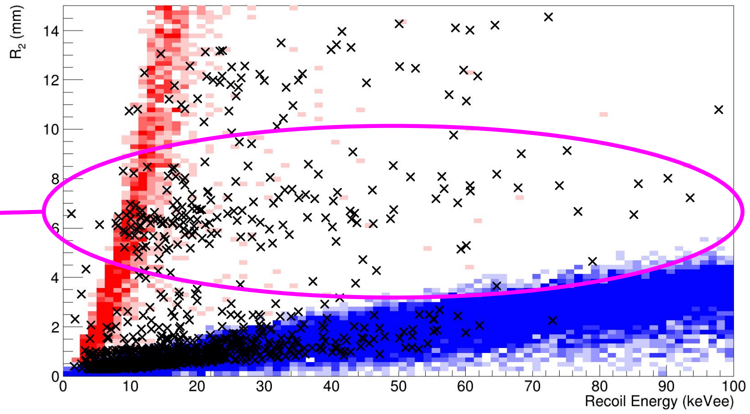

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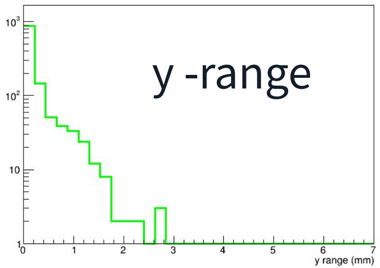

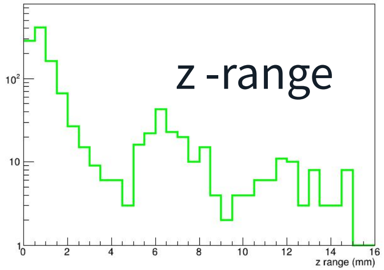

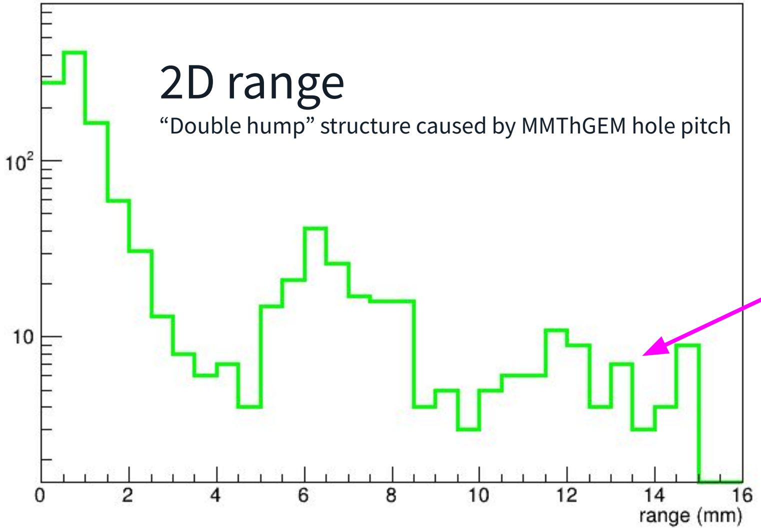

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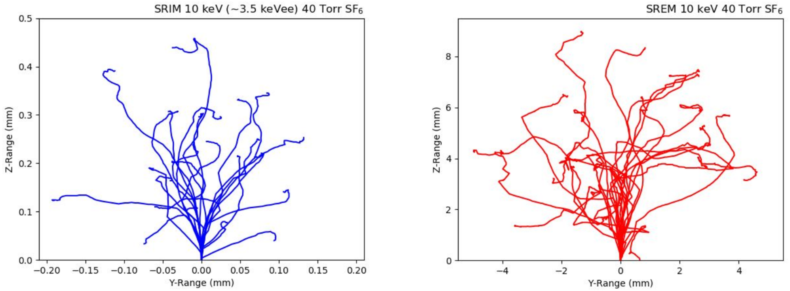

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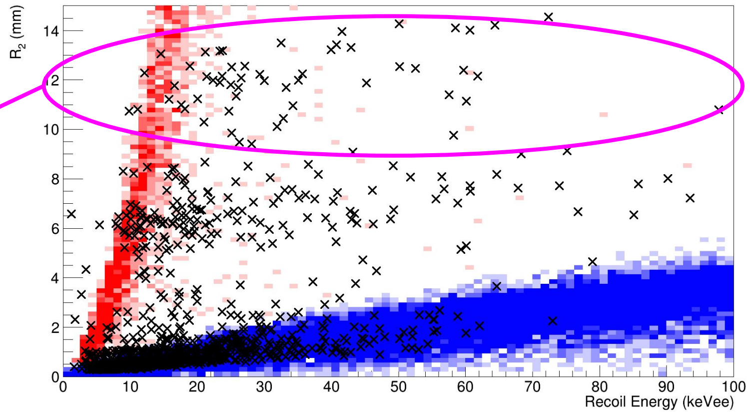

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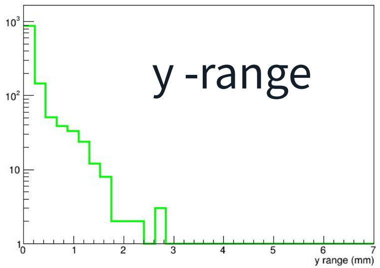
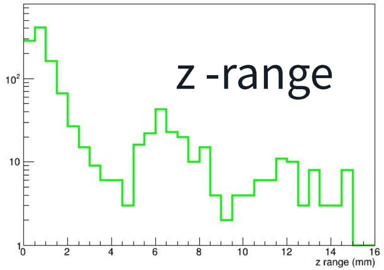
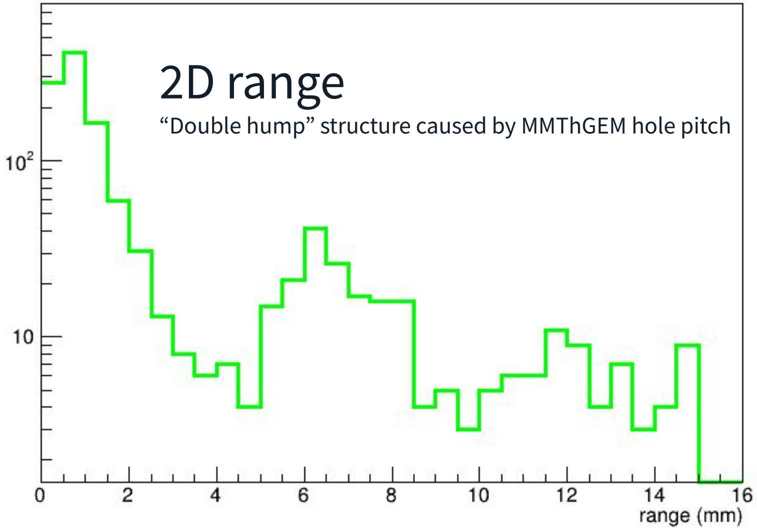
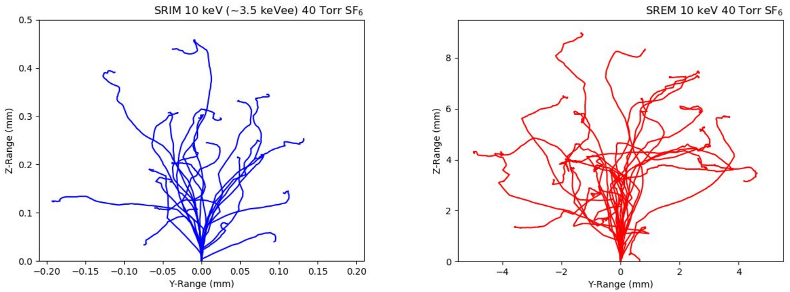


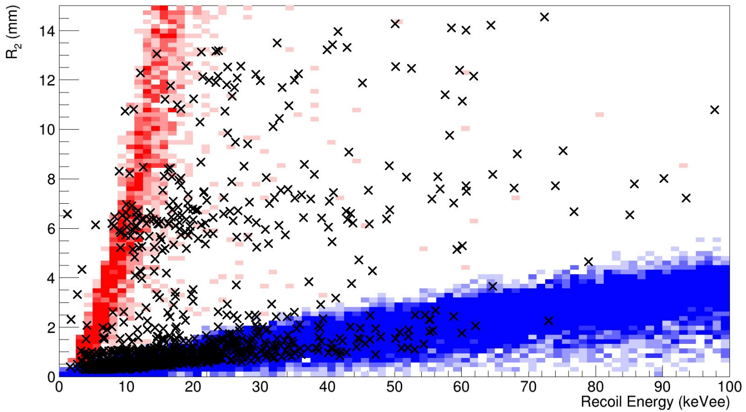




Comparison to SRIM/SREM recoil simulations

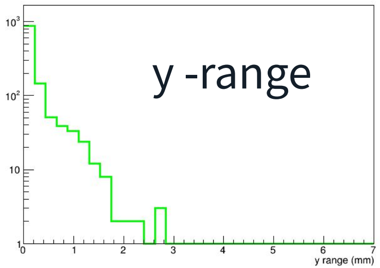


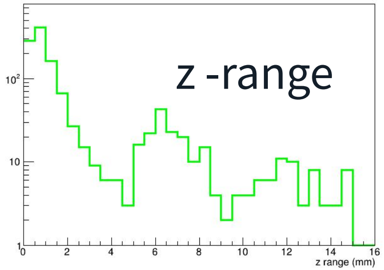
With trigger threshold = 40 mV (LG), the effective recoil threshold ~ 1.8 keVee

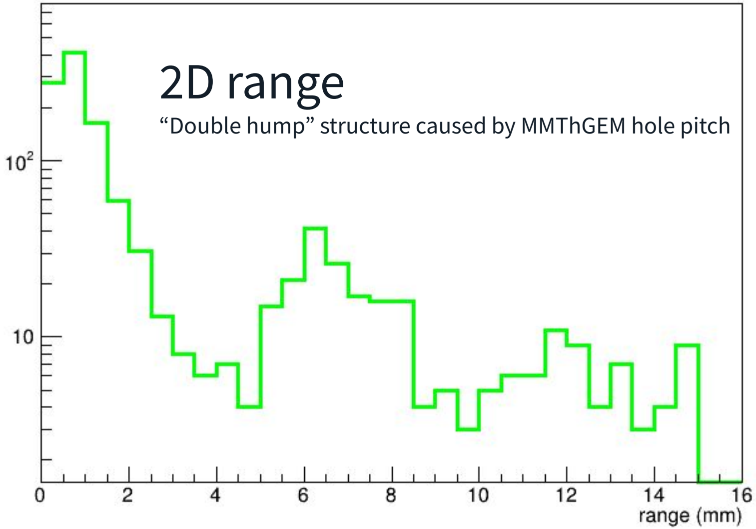


^{252}Cf Induced Nuclear Recoil Range Measurements

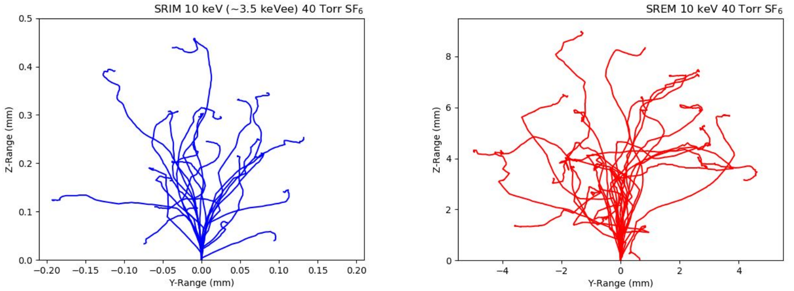
SF_6 - 40 Torr



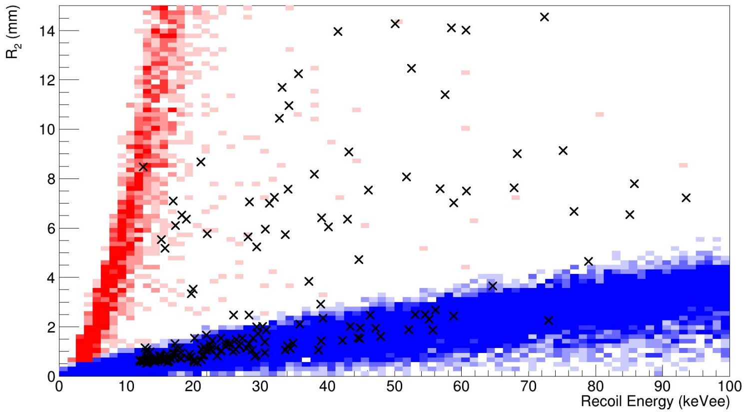




Comparison to SRIM/SREM recoil simulations

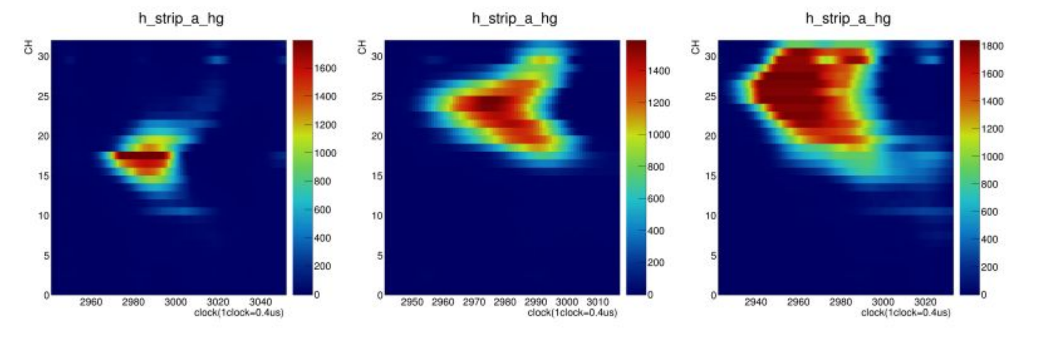


With trigger threshold = 200 mV (LG), the effective recoil threshold ~ 12 keVee



Inspection of Individual Events

SF_6 - 40 Torr



Events inside NR band:

Symmetrical - charge amplification likely confined to single MMThGEM hole

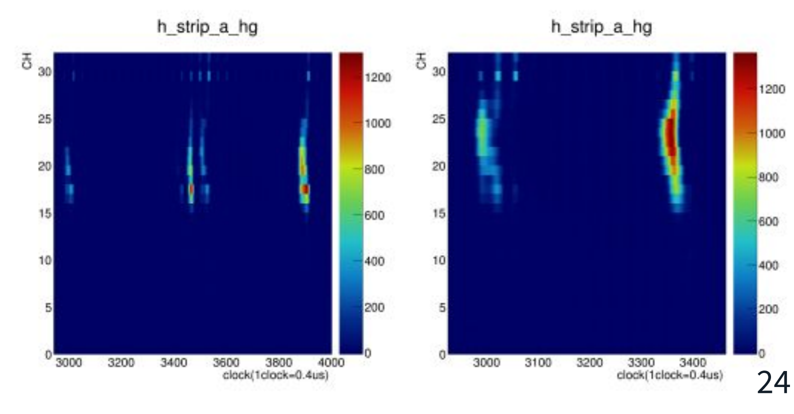
Classic "V" shape caused by the charge dissipation in DLC layer

Events outside NR band:

Possible evidence of SF_5^- minority peaks

Further work required:

- Relatively short exposure time so far
- Gamma exposure for ER/NR

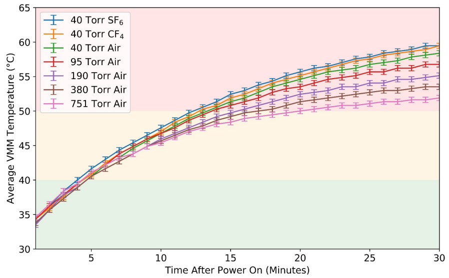


Ongoing and Future Work…

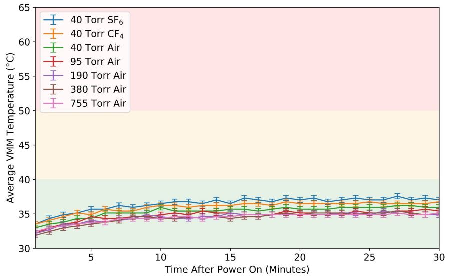
Strip Instrumentation with CERN SRS Electronics

CF_4 - 40 Torr

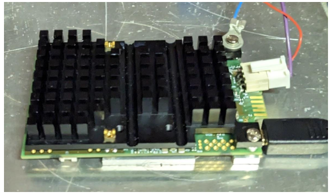
Thermal Management of VMM Hybrids at Low Pressure - crucial for long term operation



No mitigation



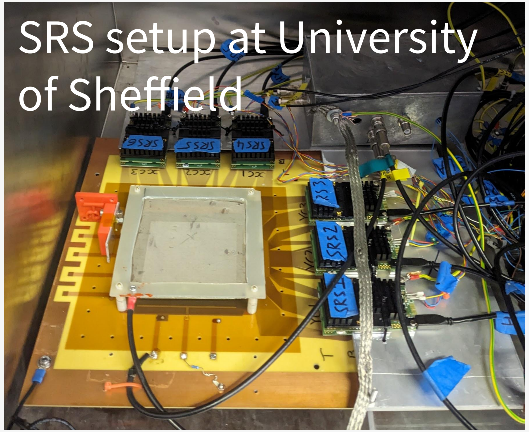
Thermal coupling to vessel with heat sink compound

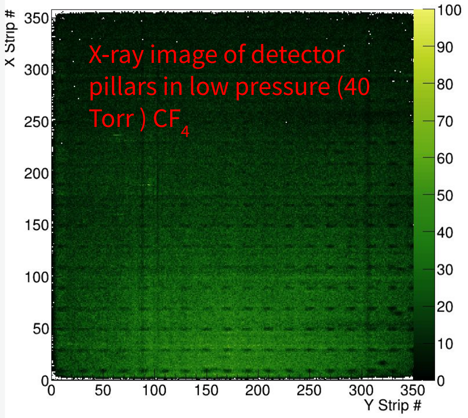


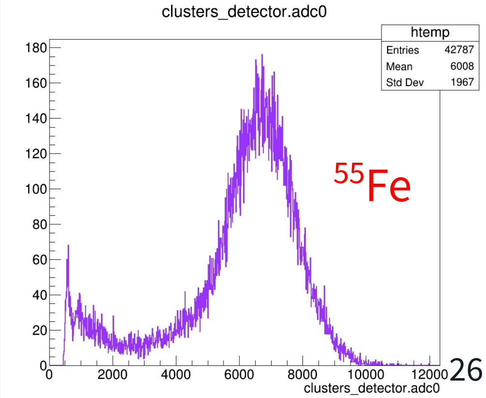
First time SRS has been used at low pressure!

Some preliminary results in 40 Torr of CF_4!

Evidence of response to x-ray source







Conclusions

Conclusions

1. Next generation directional dark matter searches will likely utilise a NID gas like SF_6 - MMThGEM is a promising amplification stage design

2. Coupled MMThGEM-Micromegas detector has been demonstrated with 32 channels in low pressure SF_6

3. Exposure to various radioactive sources has highlighted successes (10^5 gas amplification) and room for improvement (coarse hole pitch and charge spreading)

4. First exposure of the detector in a large CYGNUS-10 scale vessel has provided first look at potential nuclear recoil events and evidence of possible SF_5^- minority peaks

5. Ongoing and future work is expanding to full scale strip instrumentation - first light operation of CERN SRS electronics at low pressure has been achieved!

Thank you for your attention

Discussion and questions are welcomed!

Please email me if you have further queries:
ali.mclean@sheffield.ac.uk

A huge thank you to:

Kentaro Miuchi for your kind invitation and hospitality both in and outside the lab which made this work possible

Satoshi Higashino for your assistance during the data collection and analysis

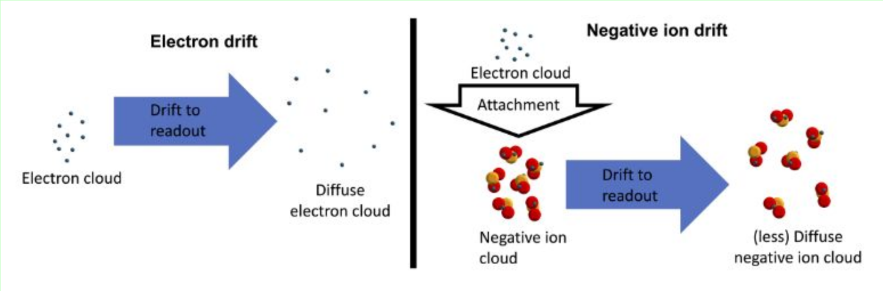
We would like to acknowledge the funding provided by a DDP scholarship awarded to A.G.McLean

Additional Slides

Why use SF_6 gas?

Pros!

- Electronegative/Negative Ion Drift (NID) gas - high fidelity
- Fluorine content - possible improvement in WIMP cross section
- Not toxic! - previously CS_2 was used as a NID gas but it is toxic



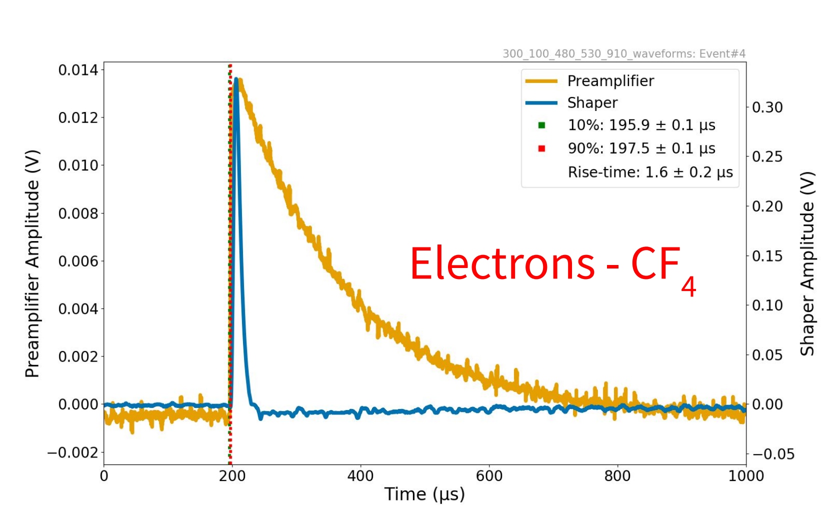
Con...

Very difficult to produce significant gas gains with...

Electron must first be stripped from the NI before amplification can occur

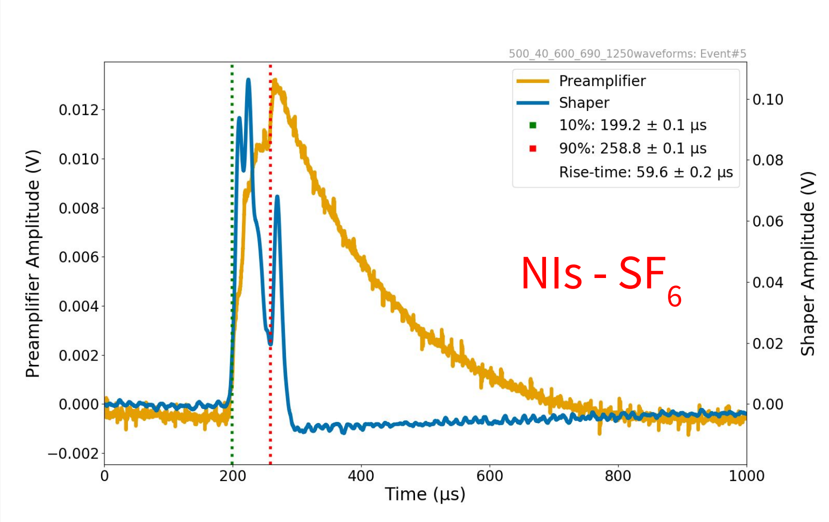
Limits sensitivity of detector to low energy recoils

Electron vs Negative Ion Pulse Shapes - MMThGEM



Typical ^{55}Fe x-ray induced event in 40 Torr CF_4 with the MMThGEM

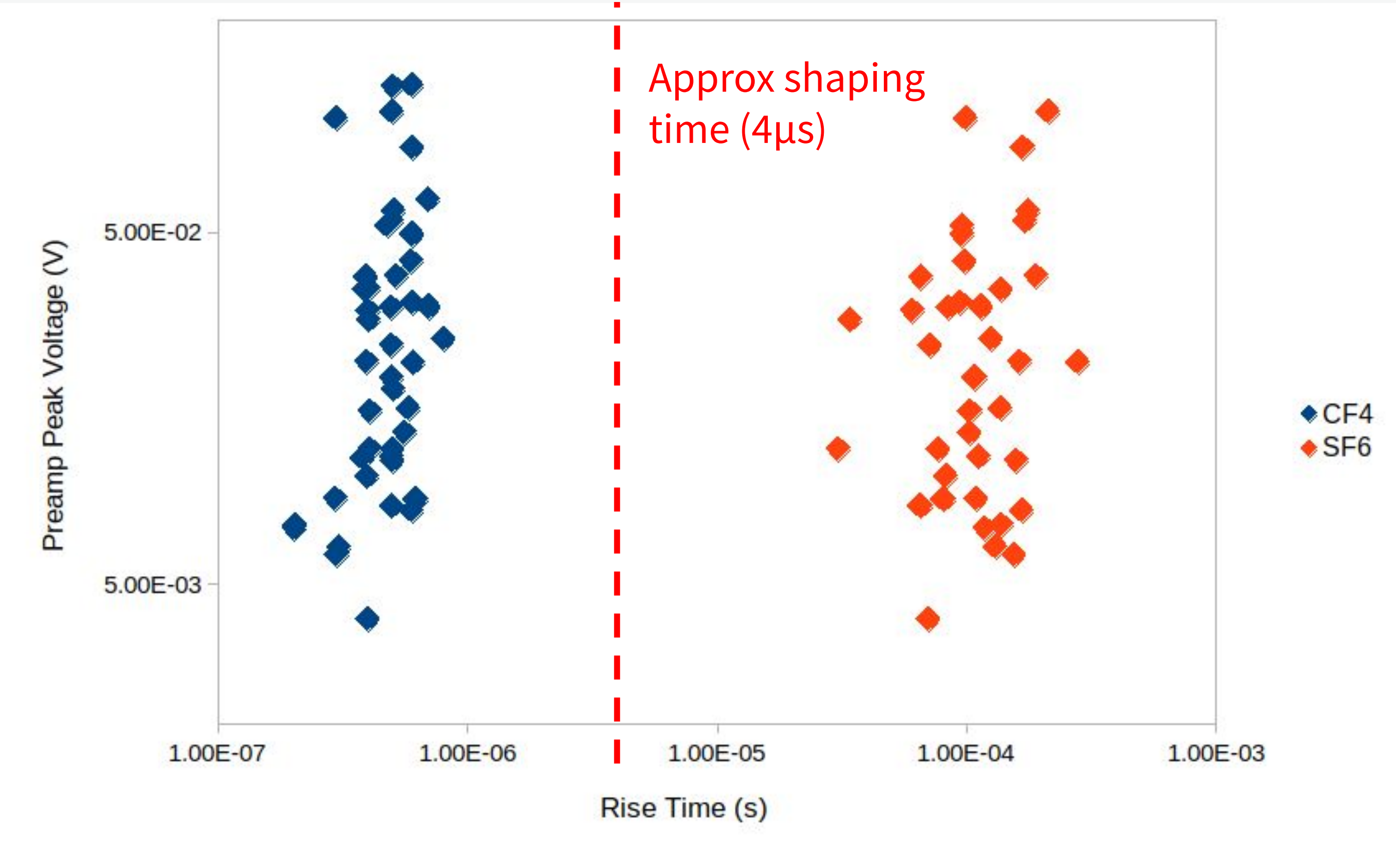
Charge arrives at electrode within shaping time of electronics



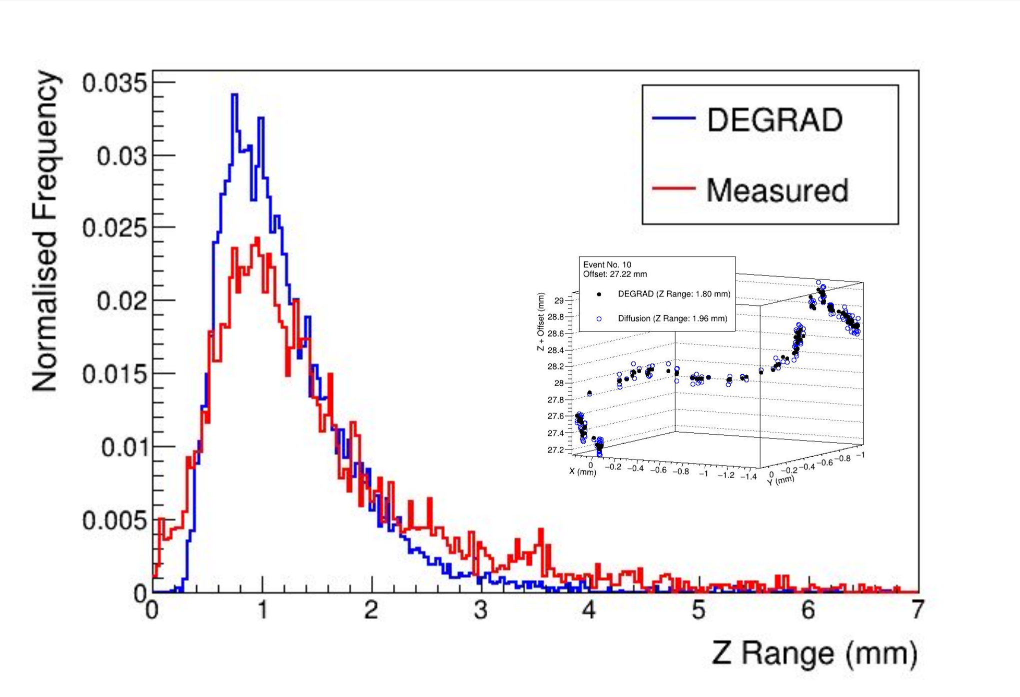
Typical ^{55}Fe x-ray induced event in 40 Torr SF_6 with the MMThGEM

Charge arrives at electrode slower than the shaping time of electronics

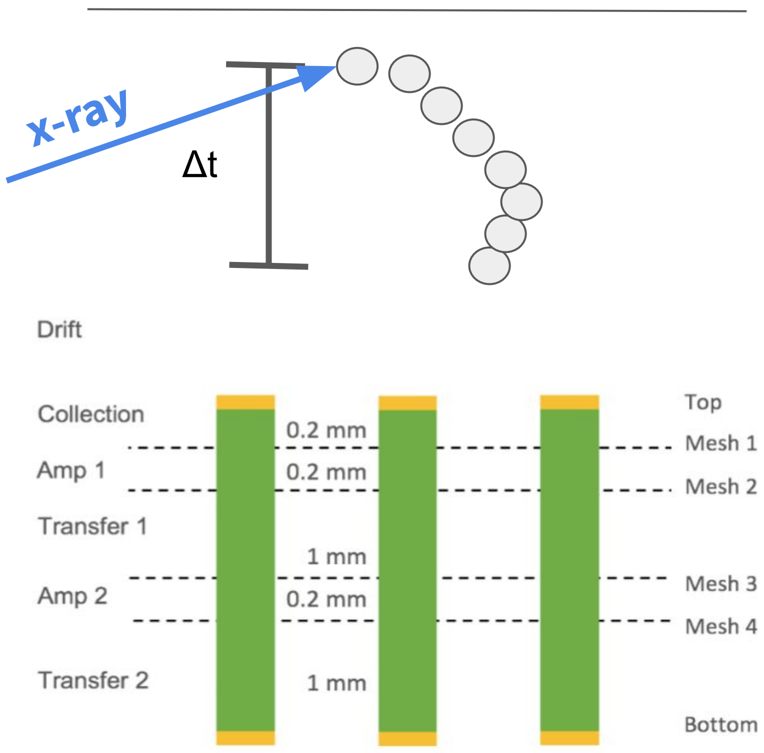
Difference in Preamp Rise Time



Rise Time (z-range calculations/simulations)

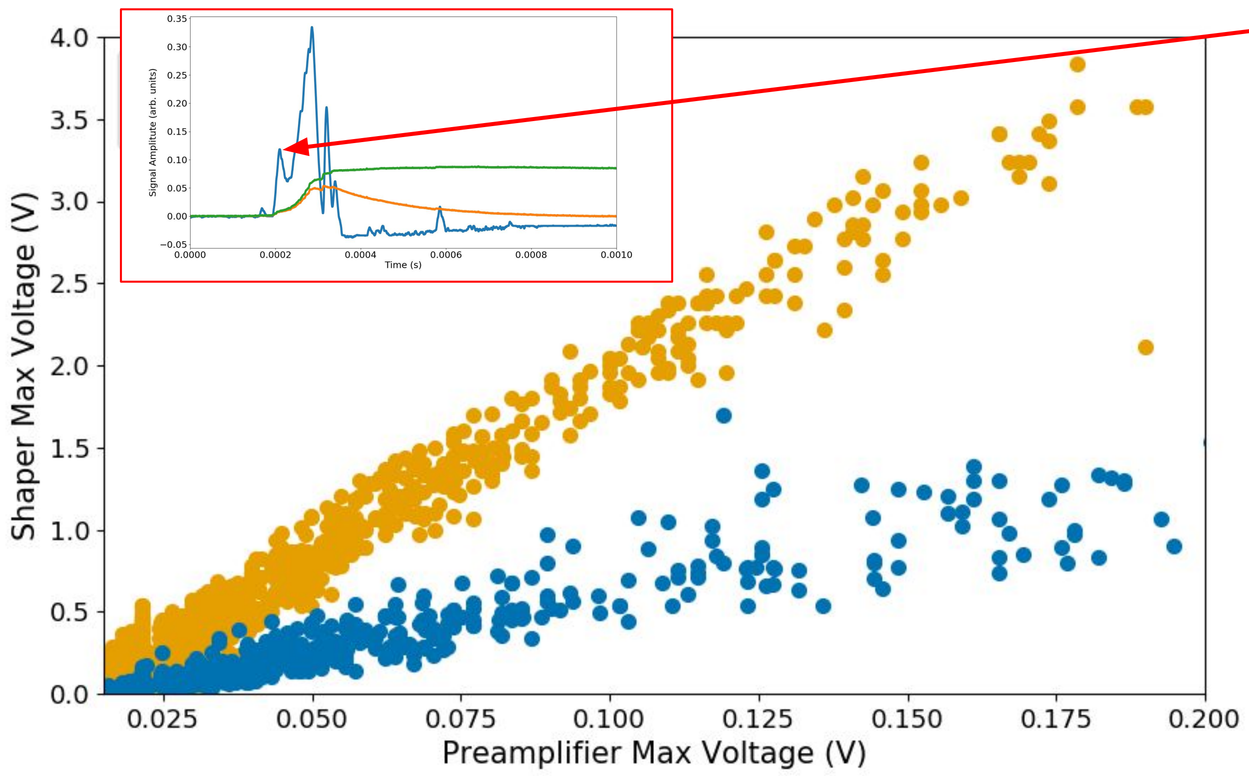


Simulations (adjusted for diffusion) agree with measured z-range



Δt = rise time of preamp (10-90%)

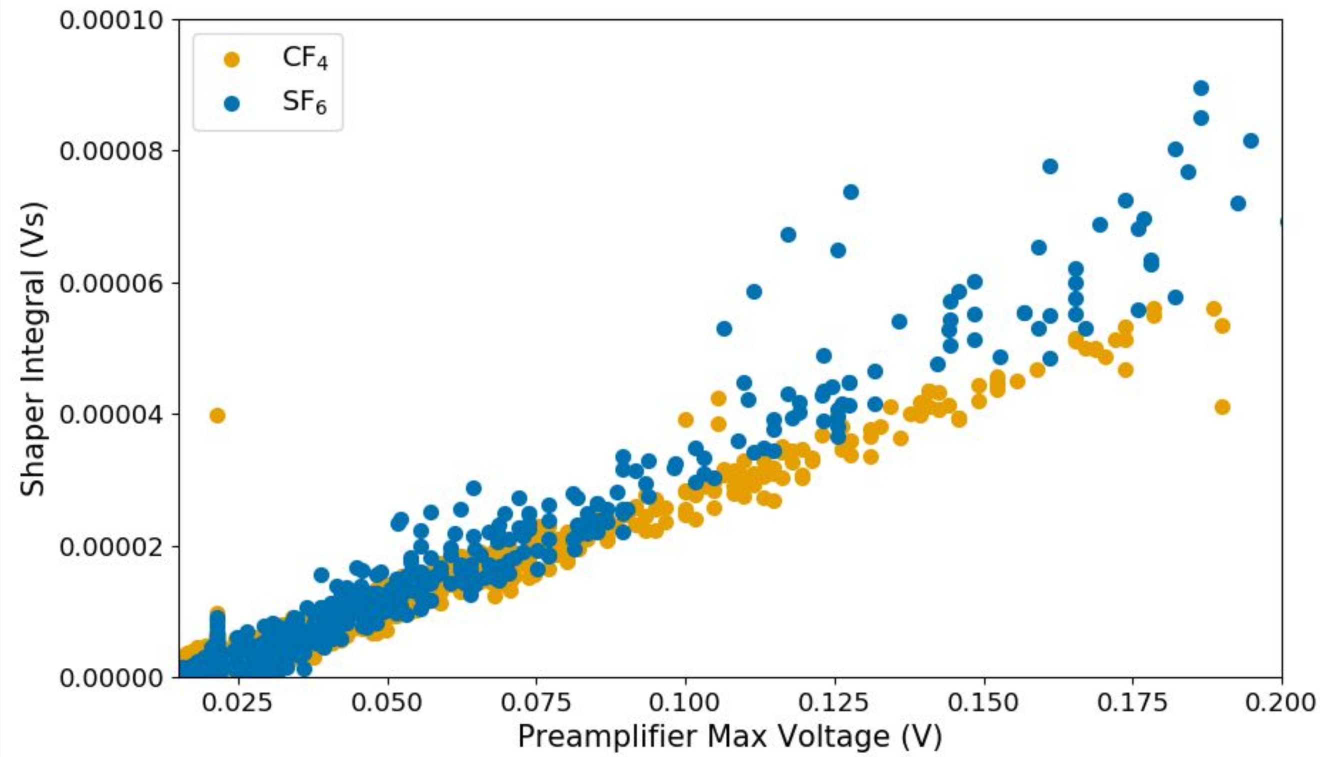
Electronic Gain - Max Voltage of Shaper Signal



<u>We see this here!</u> The shaper begins integrating the signal before the preamp stops rising!

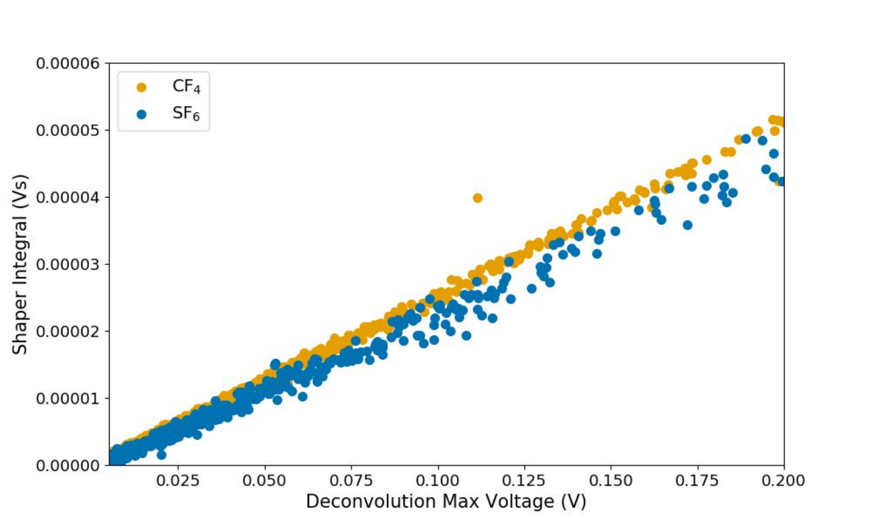
- The electronic gain (amplitude of shaper/amplitude of preamplifier) is not the same for both gasses.
- Smaller for SF_6 but still approximately linear.
- Gradient for CF_4 is 20.95 and 4.69 for SF_6.
- This is because the rise time is longer than the shaper time.

Electronic Gain - Integrated Shaper Signal



- Using the integral method - the electronic gain between the two gases is much more comparable
- Linear regression gives a gradient of 0.0003 s and 0.0004 s - much better agreement
- Still a bit of a discrepancy and larger spread at higher preamp voltages
- Likely an artifact of the decay time of the preamp

Integrated Shaper Signal vs Preamp Deconvolution Signal



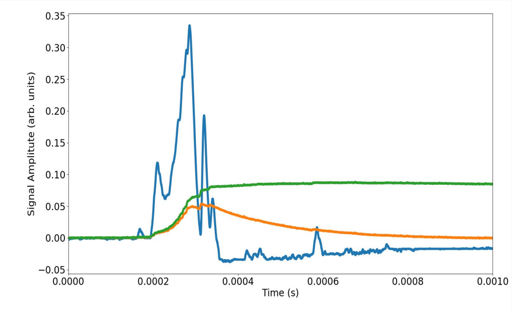
Deconvolution Algorithm

$$V_i^{rec} = \begin{cases} V_i^{av}, & i = 1, \\ V_{i-1}^{rec} + V_i^{av} - V_{i-1}^{av} \times \exp(-\Delta t/\tau), & i > 1. \end{cases}$$

https://arxiv.org/pdf/1508.04295.pdf

The deconvolution algorithm calculates cumulative charge from the preamp signal.

It essentially removes the losses due to the decay time of the preamp.



By accounting for the decay time of the preamplifier the agreement at larger preamp signals improves.

Gradient CF_4 = 0.00025

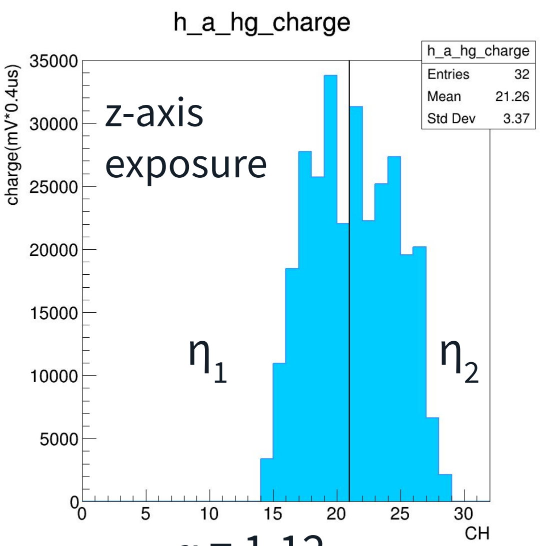
Gradient SF_6 = 0.00023

^{252}Cf Directed Neutron Runs

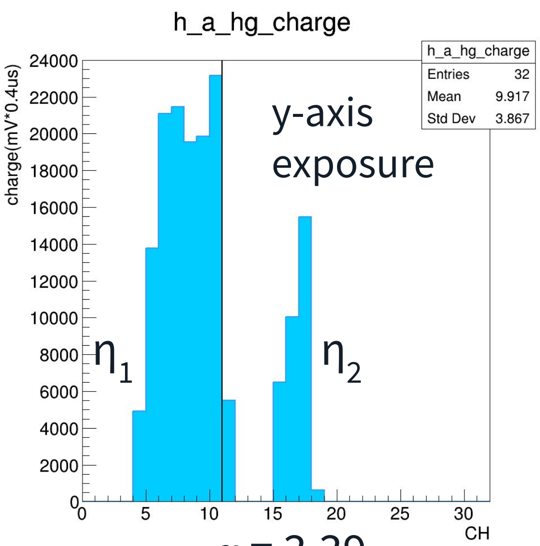
SF_6 - 40 Torr

Preliminary evidence for possible nuclear recoil head-tail asymmetries

The HV detector settings were set to be -2900 V, -1900 V, 100 V, and -530 V for the cathode, V in , V out and Micromegas mesh respectively - identical to ^{55}Fe measurements



$\alpha = 1.12$



$\alpha = 3.39$

Head-tail determination is important for directional dark matter searches

This can significantly reduce the number of events required for the identification of a galactic signature

Head-tail α parameter defined as:

$$\alpha = \eta_1/\eta_2$$

A value close to 1 indicates no asymmetries

Full study is ongoing…

^{55}Fe X-ray Exposure - Gain Measurements

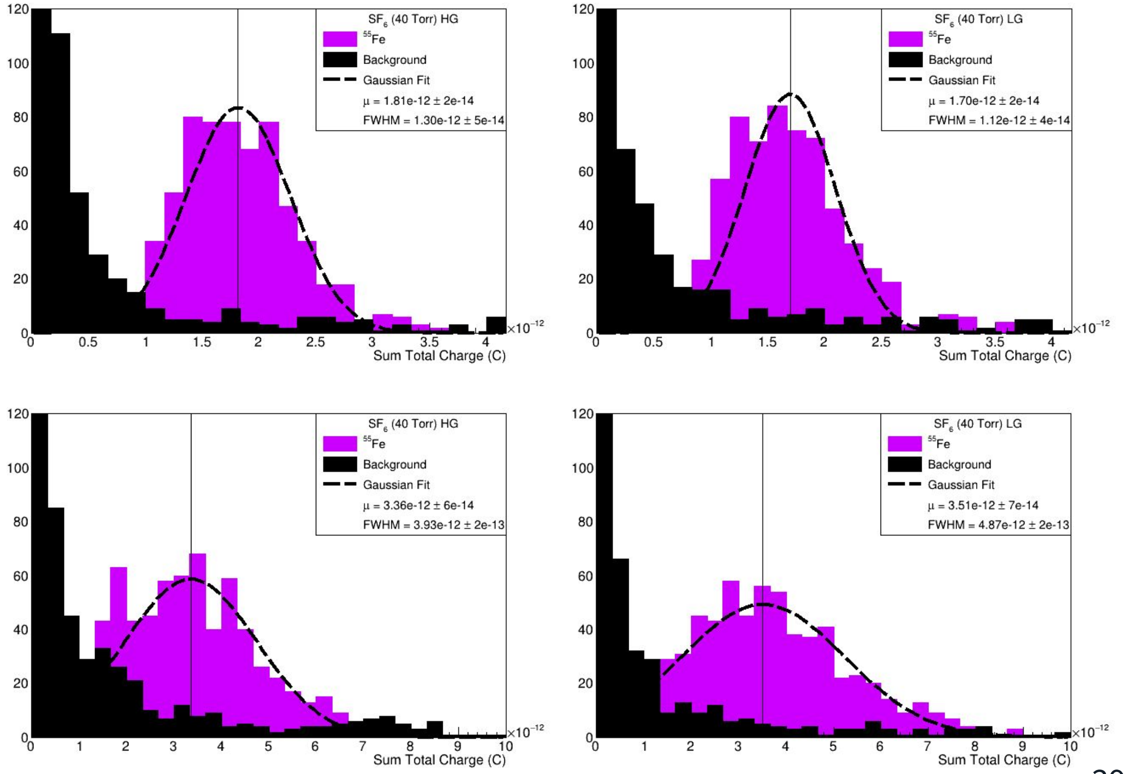
A photopeak can be observed in both the signal amplitude and signal integral spectrum

A gaussian distribution was fitted to the spectrum and the amount of charge was determined via the charge calibration

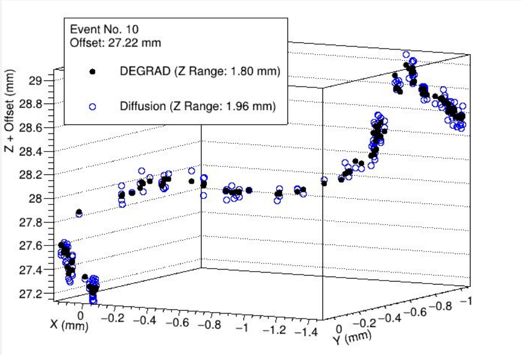
The gas gain was determined via the w-value of SF_6 (34 eV)

Gas gain was found to be as high as 1.24 x10^5!

Effective gas gain in 40 Torr of SF_6 - **charge on strips**



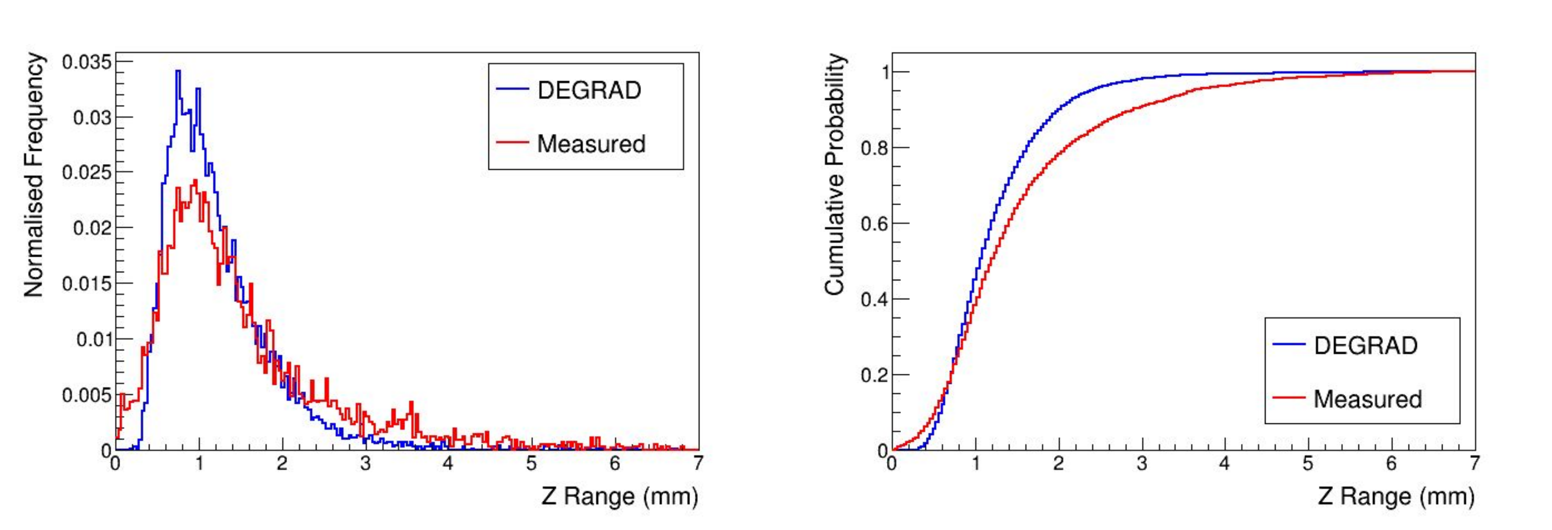
MMThGEM + NID Preamp Rise Times vs Simulations



^{55}Fe x-rays simulated in DEGRAD

Z-axis range from simulations is consistent with preamplifier rise times

Preamp rise time converted to spatial coordinated via SF_6^- drift velocity



Integral Method for Slow NI Compensation