Glass-GEM Simulations for the MIGDAL Experiment

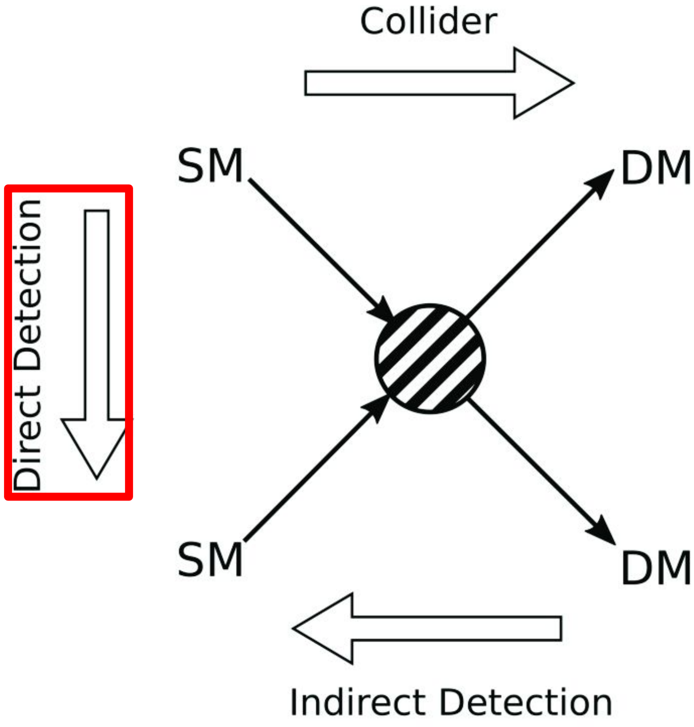
Ruize Li
PPD Summer Student
University of Cambridge
20 Aug 2025

UKRI Science and Technology Facilities Council

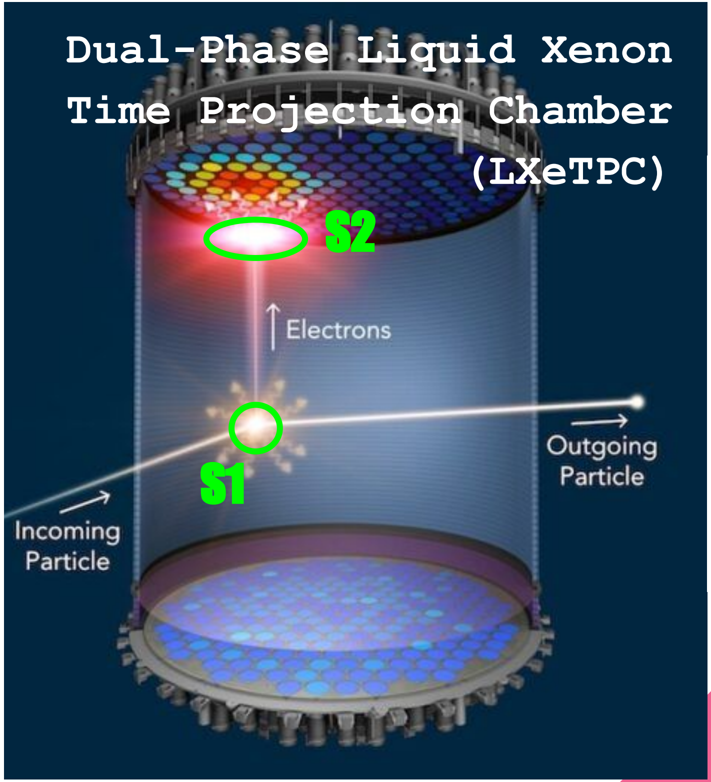
MIGDAL
Migdal In Galactic Dark mAtter expLoration

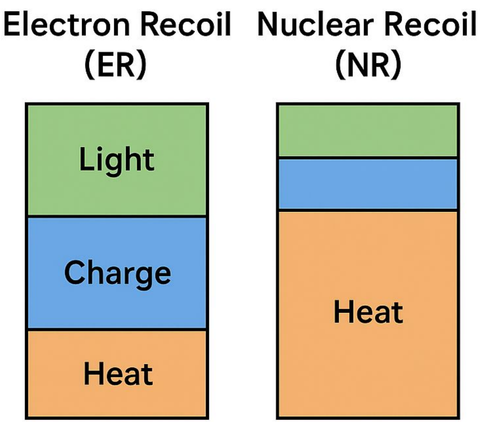
Dark matter

Science and Technology Facilities Council
Particle Physics



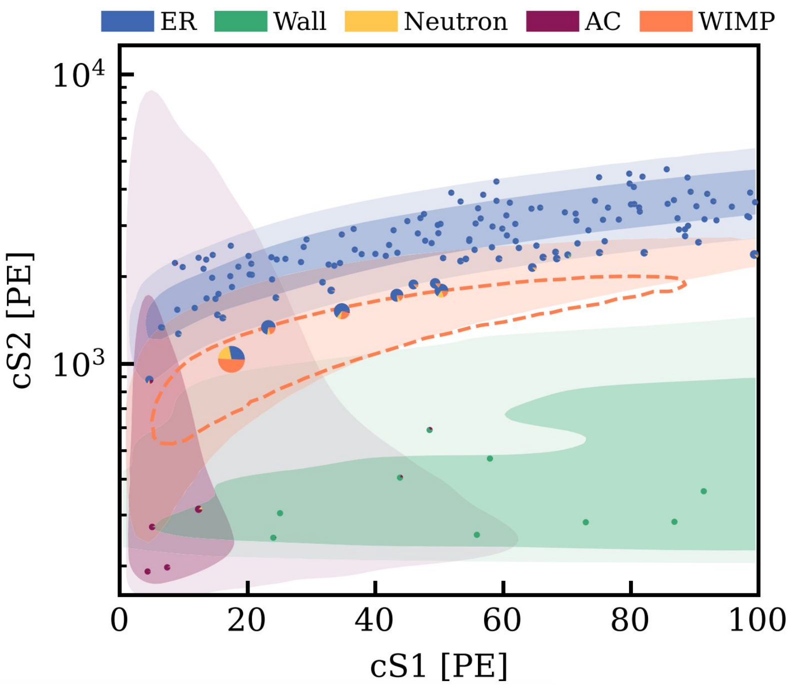
10.3389/fphy.2019.00075





DM direct search

Science and Technology Facilities Council
Particle Physics



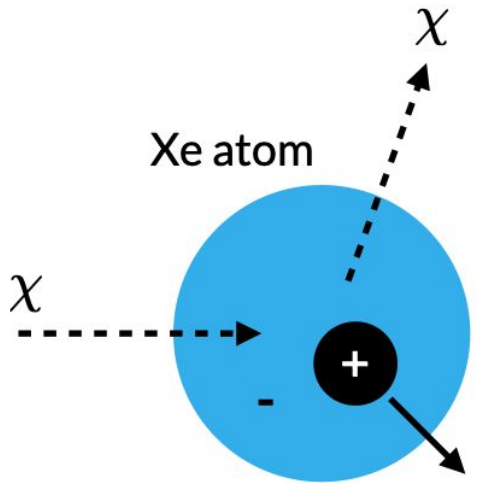
10.1103/PhysRevLett.131.041003

- Electrons/Gammas/Muons: Electron recoils;
- Neutrons/WIMPs: Nuclear recoils.

Identify particles using a S2 vs S1 plot.

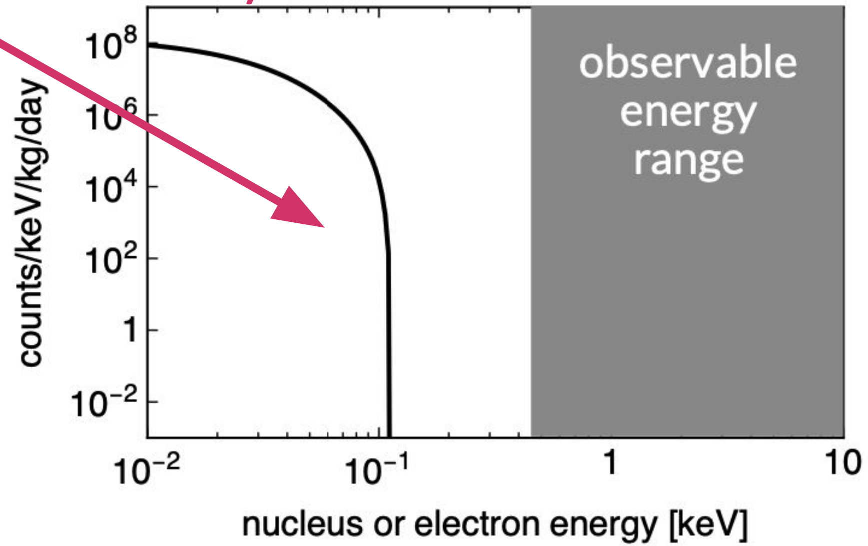
- Sensible only to WIMPs with high mass:
  - Threshold at ~keV NR,
  - approx. ~GeV DM mass.
- Light WIMPs, axions, ALPs?
  - **The Migdal effect!**

Typical nuclear recoil for low-mass DM

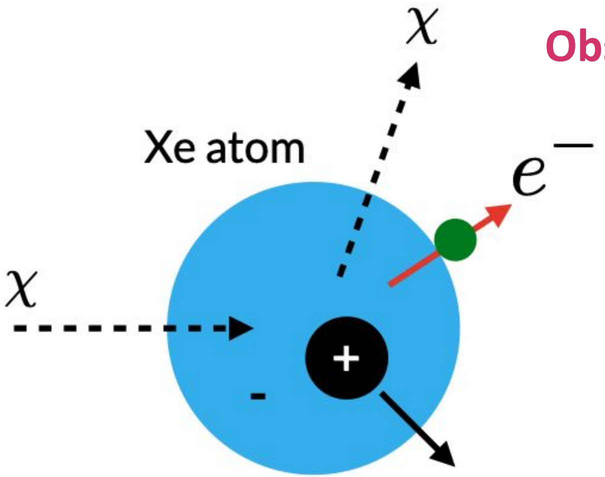


m_{DM} = 1 GeV
'Normal' nuclear scattering

Invisible (below threshold)

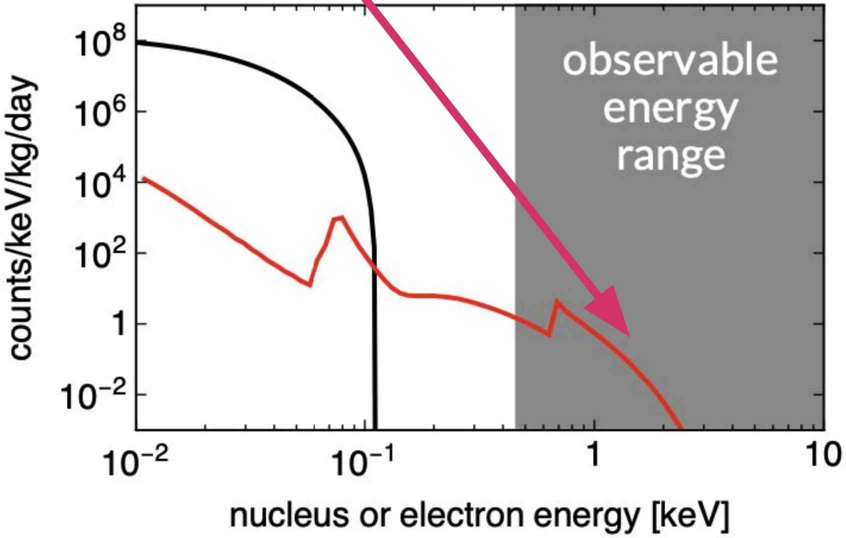


Migdal effect: electron “left behind”



m_{DM} = 1 GeV
‘Normal’ nuclear scattering
+ Migdal effect (ionisation of 1 electron)

Observable (above threshold)

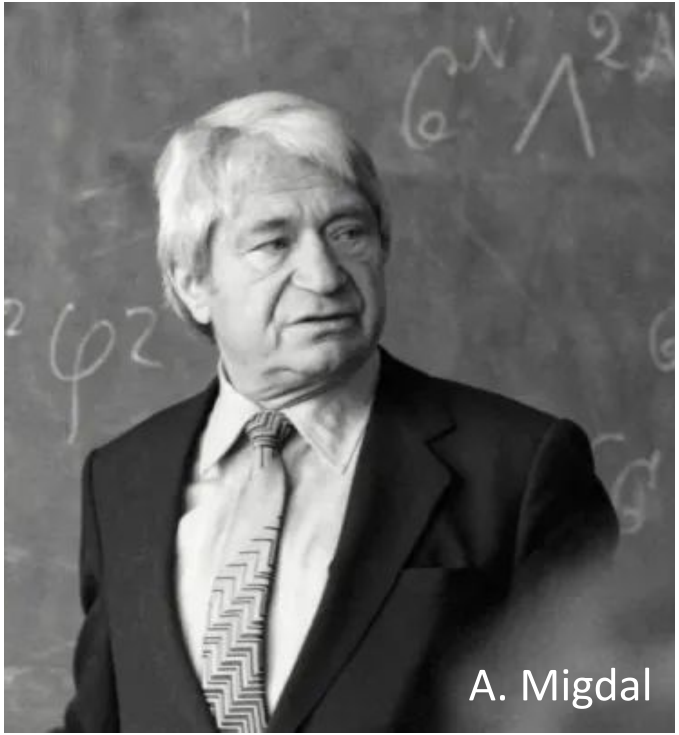


NEVER directly measured!

Migdal effect: theory and experiments

Science and Technology Facilities Council

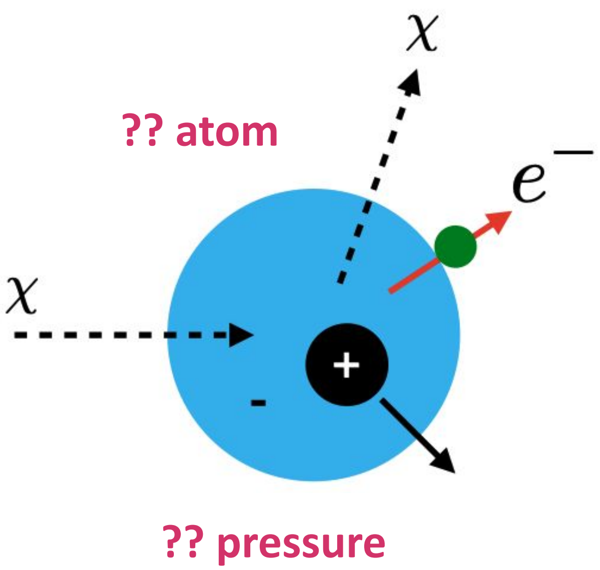
Particle Physics



- A. Migdal *ZhETF, 9, 1163-1165 (1939)* (in nuclear reactions) then 1941 paper in radioactive decays.
- Directly measured in
  - Alpha (1975) and Beta (2012) decays
  - Positron decay (2018)
- Theory for NR and DM direct search
  - Ibe, et. al. *JHEP03(2018)194*
  - Cox, et. al. *PhysRevD.107.035032*

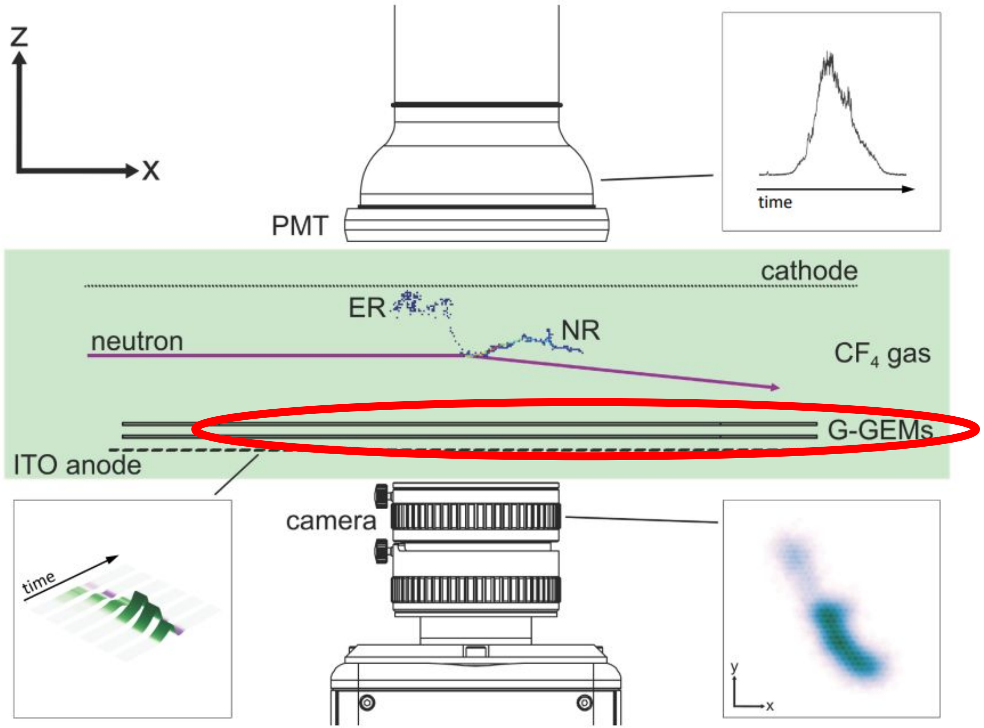
Measuring Migdal effect in NR

Science and Technology Facilities Council
Particle Physics



- D-T (higher energy) or D-D (lower energy) neutron beams;
- Time projection chamber;
- A suitable medium:
  - LXe (*arXiv:2112.08514*)
  - **CF4 or CF4/noble gas mixture**
    - High pressure (*arXiv:2009.05939*)
    - **Low pressure** (**MIGDAL**, *arXiv:2207.08284*)

Gas Electron Multipliers in MIGDAL OTPC

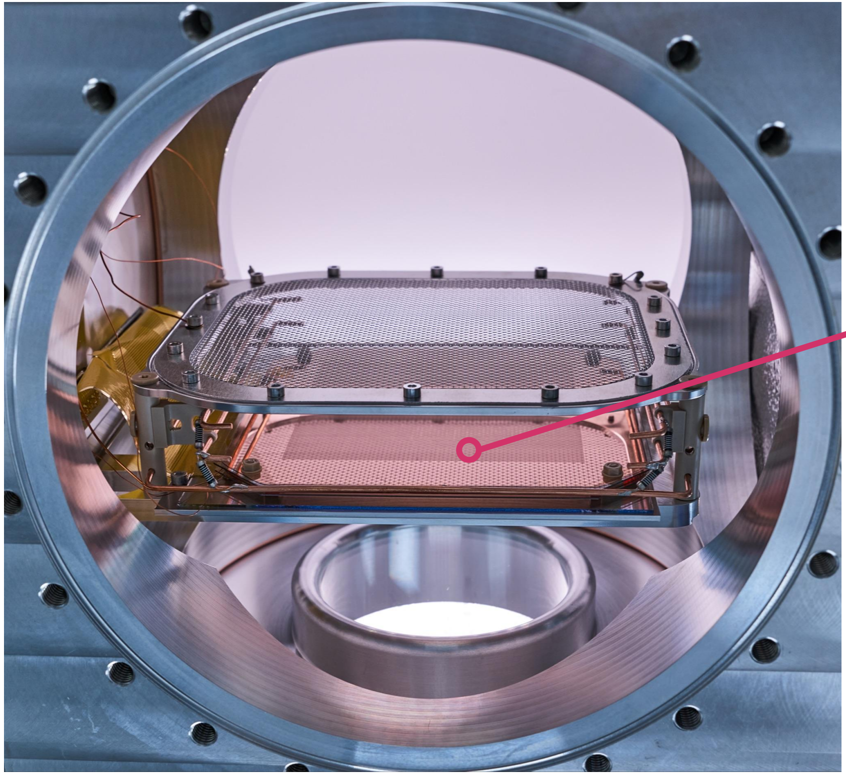


Electrical and optical readouts:

- Photomultiplier tube (array): energy reconstruction & as external trigger.
- **Glass-GEMs**: amplify electric signal for ITO & produce light for camera.
- ITO mesh: Collect electrons.
- Camera: Imaging

MIGDAL 2207.08284

GEM Configuration



Drift region

570 µm

1st GEM

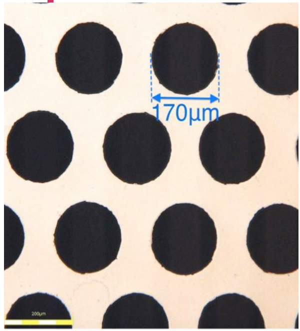
Transfer region

280 µm

2nd GEM

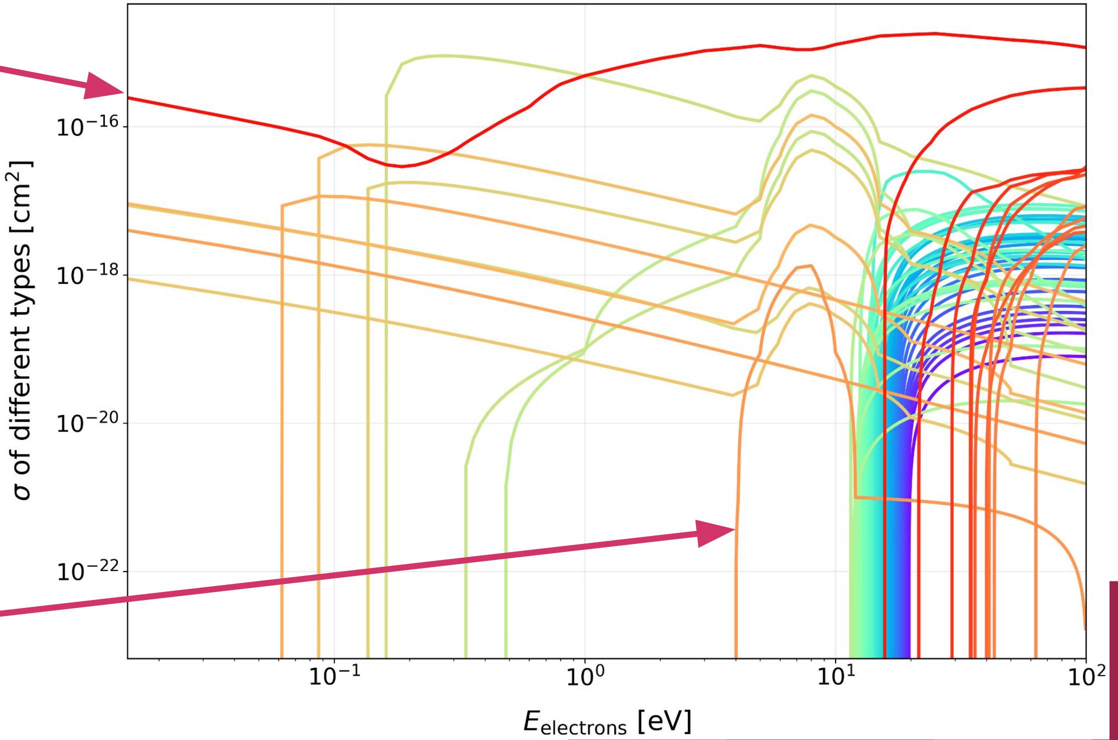
Induction region

ITO mesh & camera below

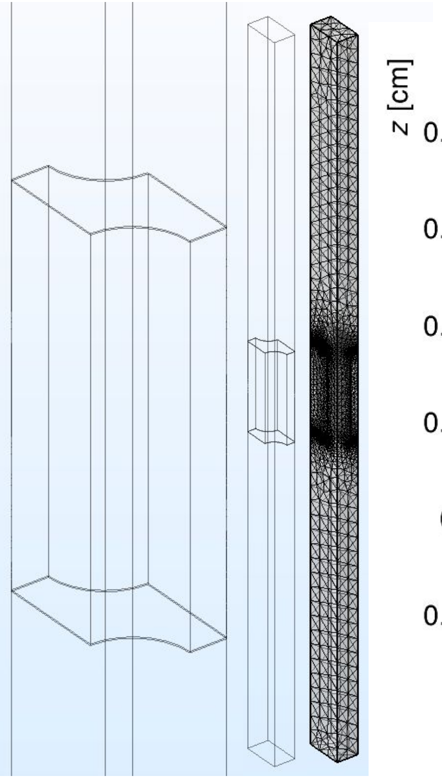


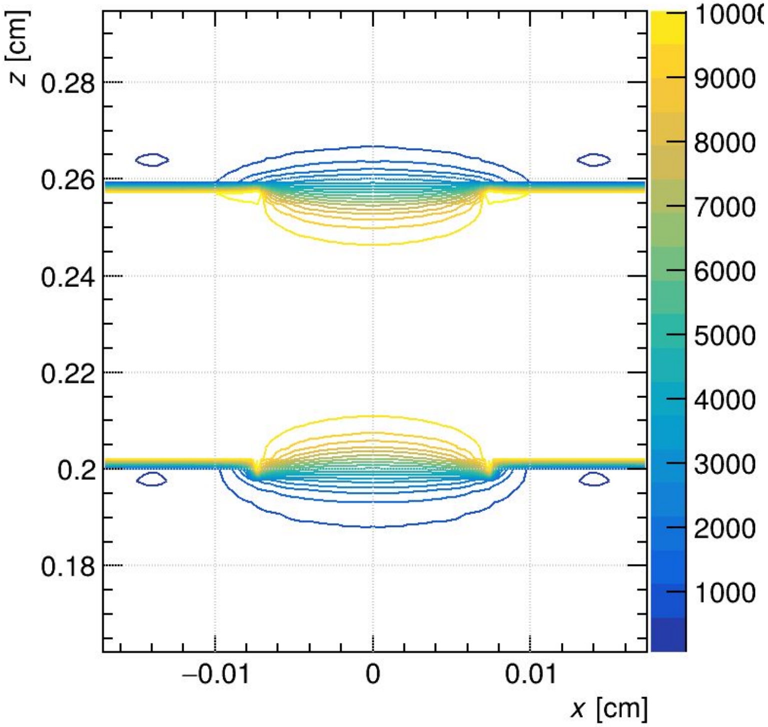
Electrons in low-pressure CF4

description	ELOSS
ELASTIC ANISOTROPIC CF4	0
ION CF3 +	15.7
ION CF2 +	21.47
ION CF +	29.14
ION F +	34.5
ION C +	34.77
DOUBLE ION CF3 + , F +	36
DOUBLE ION CF2 + , F +	40
IONS CF3 ++ OR CF2 ++	41
DOUBLE ION CF + , F +	43
DOUBLE ION C + , F +	63
ATTACHMENT	0
VIB V2 ANISOTROPIC	-0.0539
VIB V2 ANISOTROPIC	0.0539



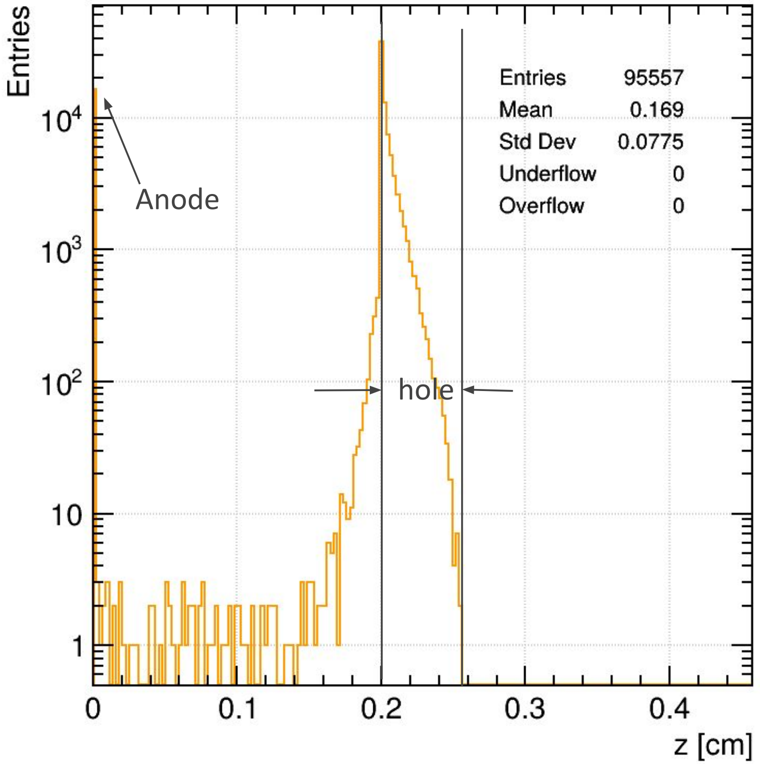
Geometry and fieldmap

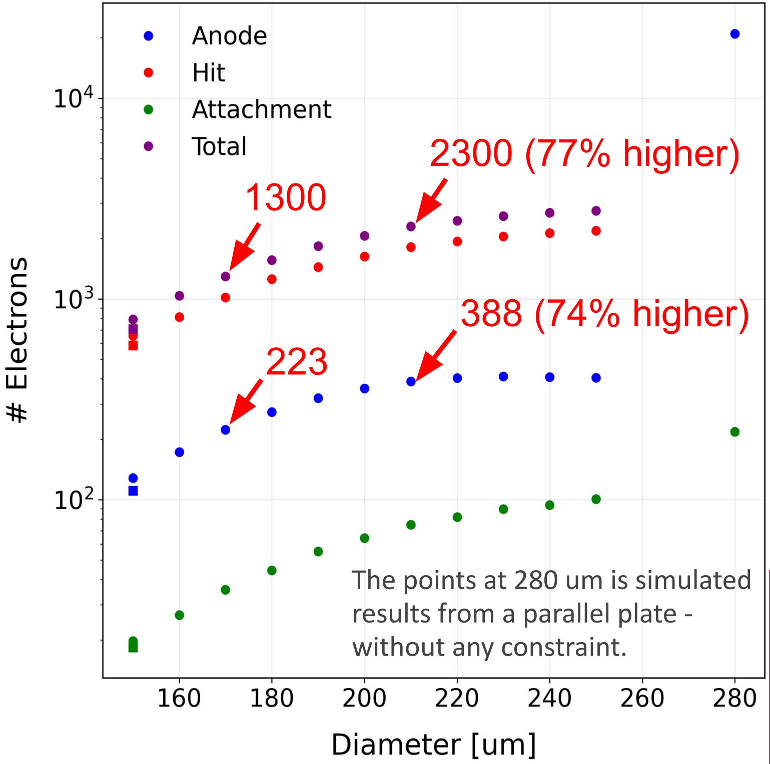




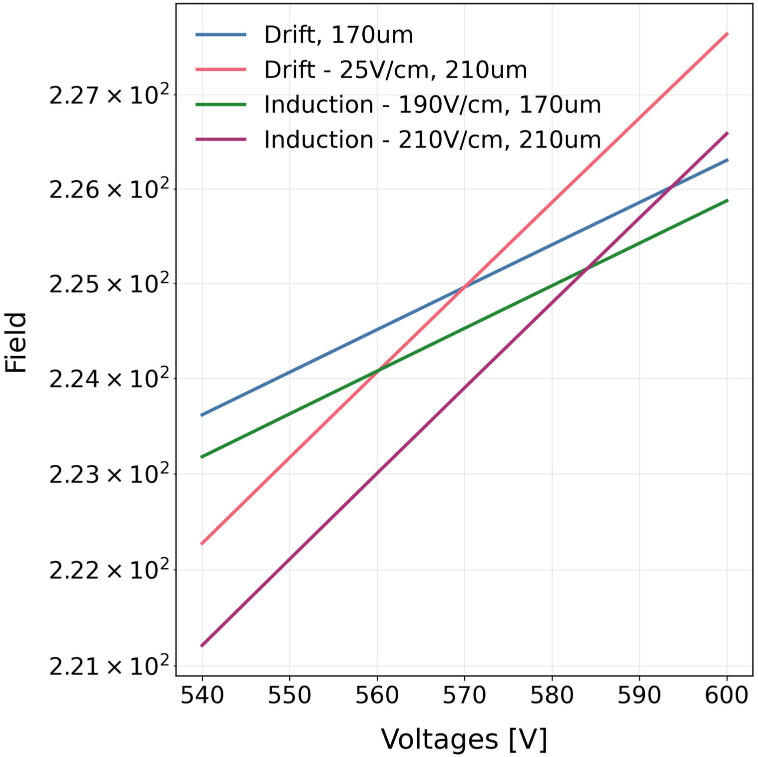
- COMSOL: a multiphysics simulation software.
- Generates E-field using Finite Element Method.
- Only two ¼ holes needed due to mirror symmetry.

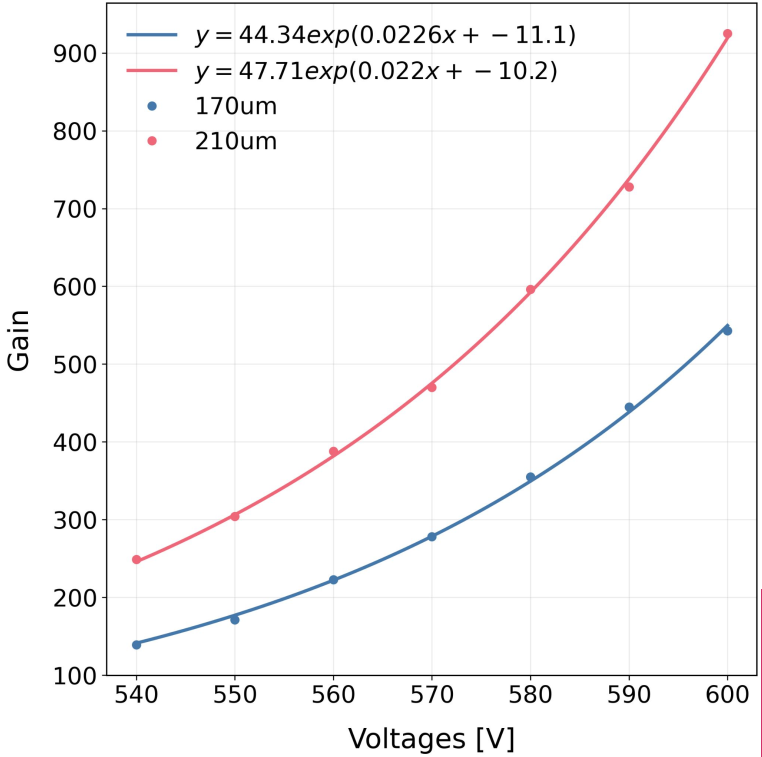
Single G-GEM with varying diameter



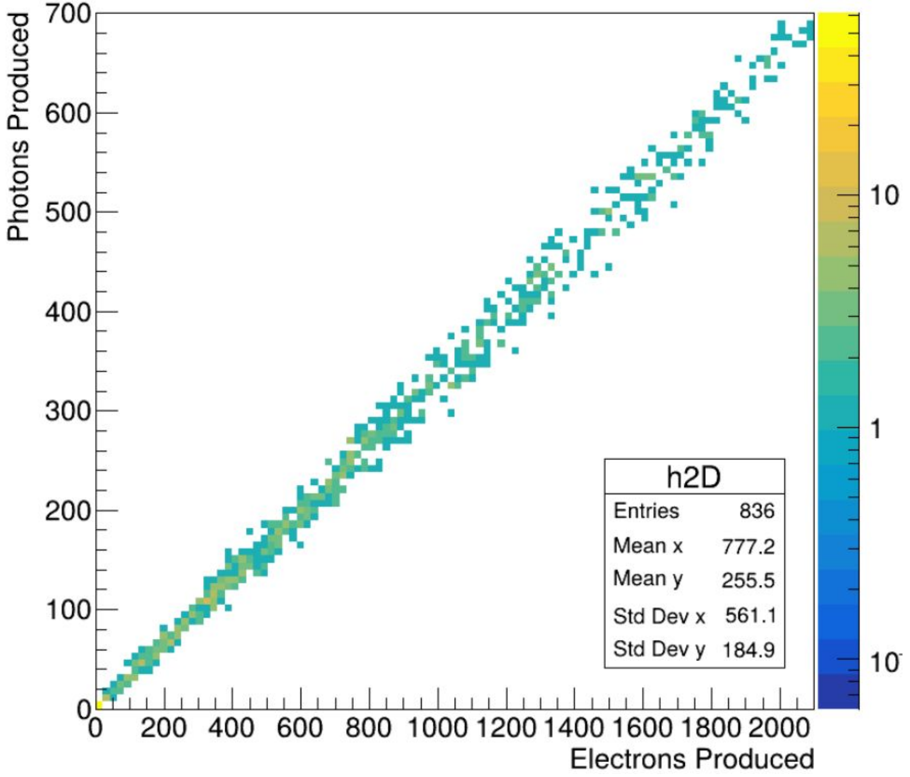


Field corrections





Scintillation in pure CF4

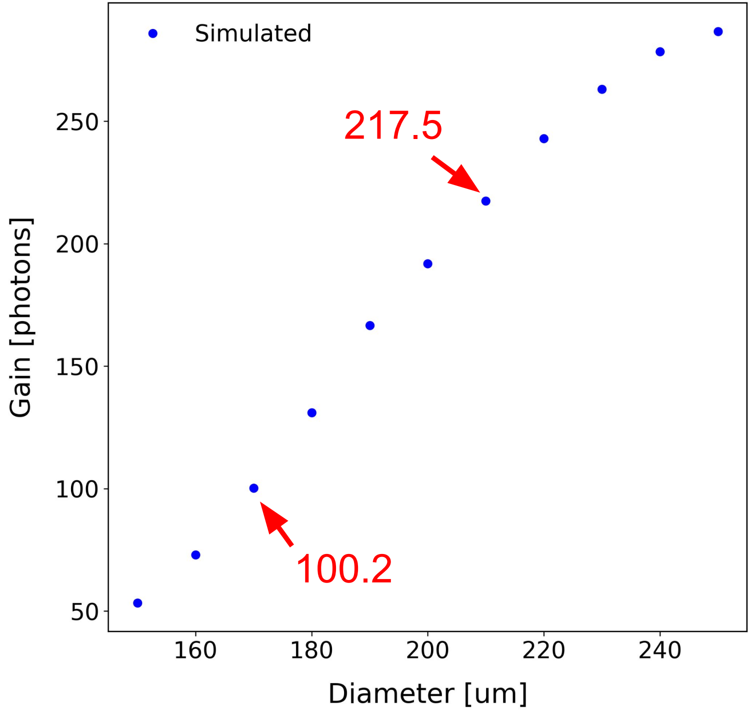


- Choose ionisations with ELOSS > 14 eV and scintillation probability 33%;

=> Nγ/Ne=34%, at any pressure, any field. [0803.2195]

- Difficult to apply to CF4/Ar mixtures as excitation/transfer mechanism not understood.

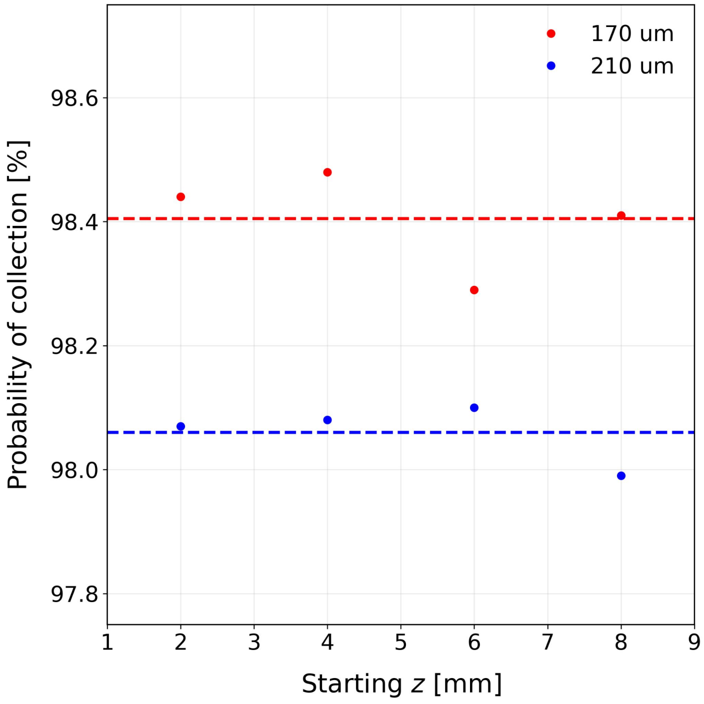
Photons reaching anode plane



- We can access the position of emission, (x,y,z), for **every** photon.
- Assumed a random direction of emission (θ,ϕ).
- Position on anode plane easily calculated.
- A position distribution with std of x and y:
  - 0.95 mm for 170 um
  - 1 mm for 210 um

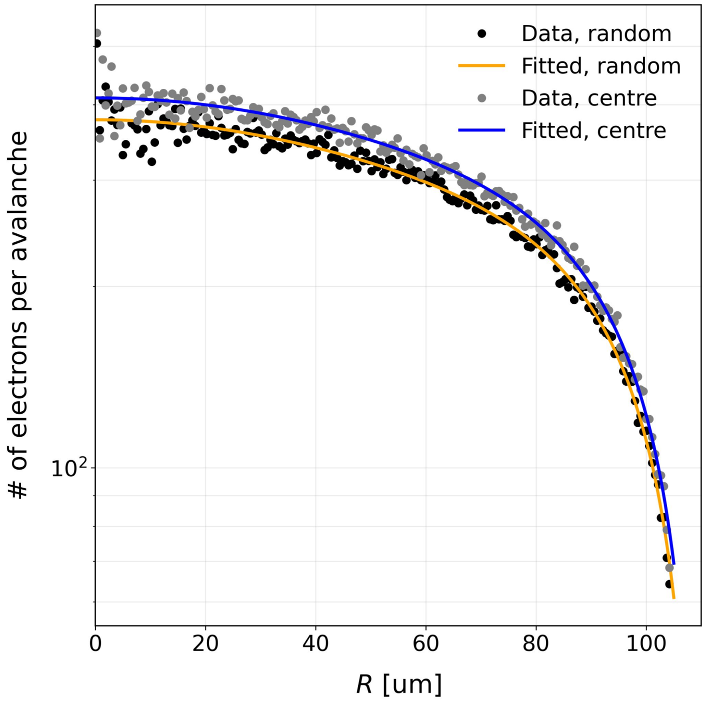
Three GEMs with corrected voltage

Science and Technology Facilities Council
Particle Physics



- **210 um, 510 V**
- A full avalanche takes >10h
- Break into parts:
  a. Drift to the first GEM
  b. Avalanche in a hole
  c. Drift between GEMs
  d. (repeat b and c)
  e. Drift to the ITO
- Distribution at the end of every step???

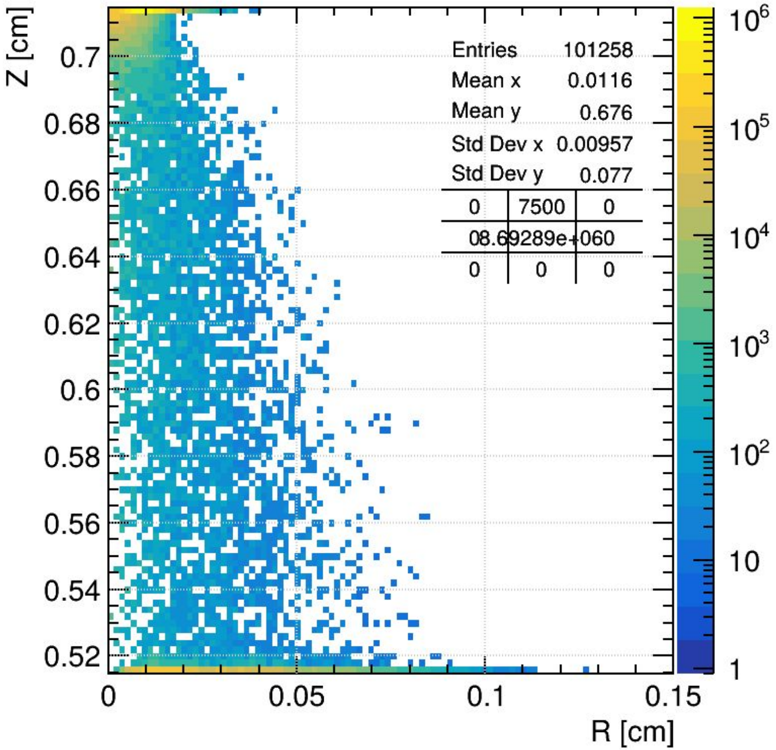
Three GEMs: avalanche in a GEM hole



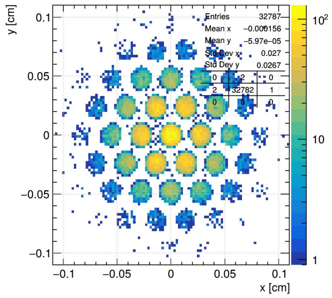
- Different distributions of starting points:
  - Random position at the top
  - All starting at top-centre
- Distribution was fitted to a six-order polynomial (normalised)
- Difference within 8%.
- **Additional check on asymmetry: any asymmetry will be washed out by avalanche**

Three GEMs: drift to the next GEM

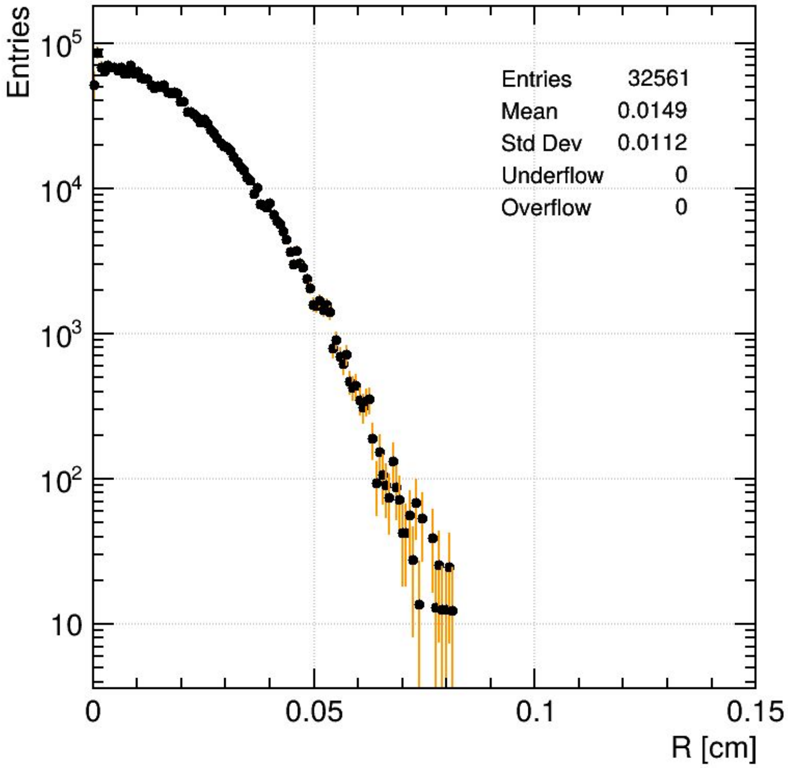
Science and Technology Facilities Council
Particle Physics



- Aligned and misaligned (shifted by ½ pitch to the *x*-direction)
- Consider all holes <= 4*pitch.
- From endpoint histogram, it's clear that we have more attachment closer to GEM.
- 36% electrons enter the next GEM.

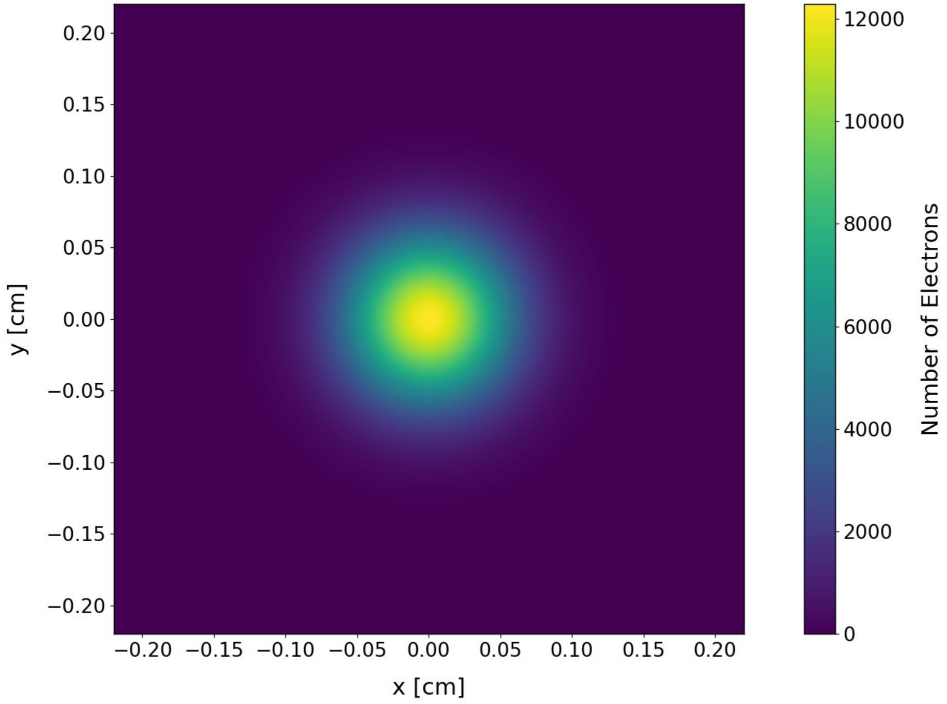


Three GEMs: induction



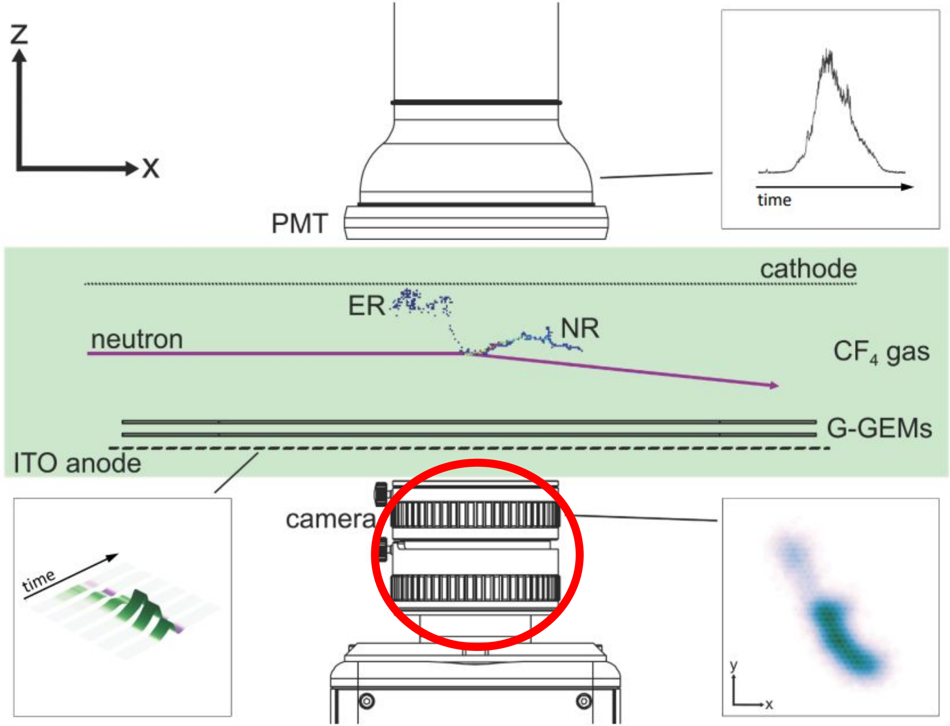
- 32.6% electrons exiting the last GEM survive to the ITO.
- FWHM from MC: 0.044 cm
- FWHM from diffusion constant: 0.037 cm (starting at only one point)

Three GEMs: results



- Aligned: 6-fold symmetry,
- appears to be fully symmetric due to transverse diffusion.
- Gain:
  - Aligned: 9.06e5 (2%)
  - Misaligned: 8.95e5 (2%)
- Std of x and y:
  - Aligned: 0.413 mm
  - Misaligned: 0.397 mm

Next steps:



- Photon collection map for the camera.
- Simulations for CF4-Ar mixture (combine with Thomas's work).

MIGDAL 2207.08284

Summary

Science and Technology Facilities Council
Particle Physics

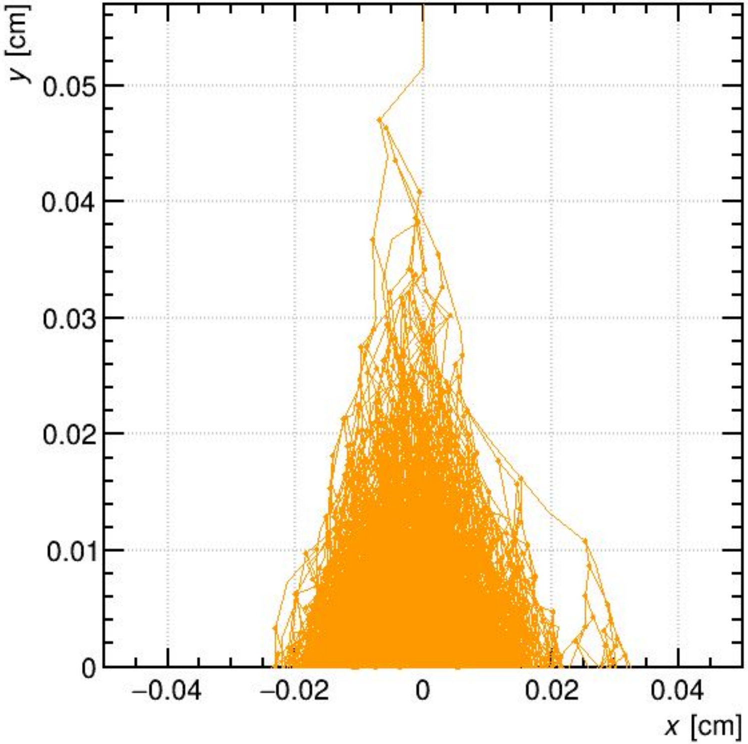
- MIGDAL experiment aims to perform an unambiguous observation of the Migdal effect in nuclear recoil.
- Low-pressure CF4 - clear track for the Migdal electron.
- Glass-GEM to amplify both electrical and optical signals.
- Corrections on fields.
- Scintillation in pure CF4: $N\gamma/Ne=34\%$.
- A stack of Glass-GEMs with larger holes, aligned / misaligned.
- Gain of three GEMs: ~1e6.

Thank you!

Science and
Technology
Facilities Council

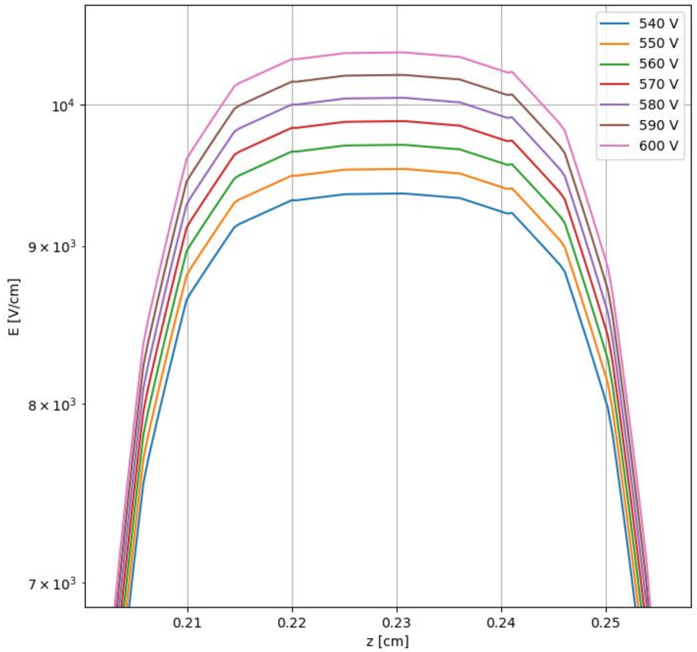
MIGDAL
Migdal In Galactic Dark mAtter expLoration

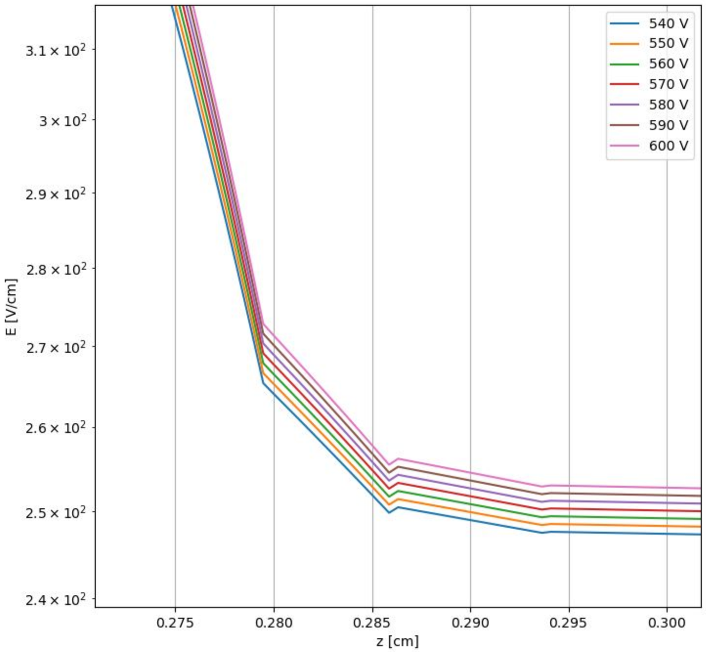
Back-up: full avalanche



- 9825 V/cm between parallel plates.

Back-up: E field





Back-up: E field

Science and Technology Facilities Council
Particle Physics