Experimental comparison of strip micromegas readouts in gaseous TPCs for directional recoil detection

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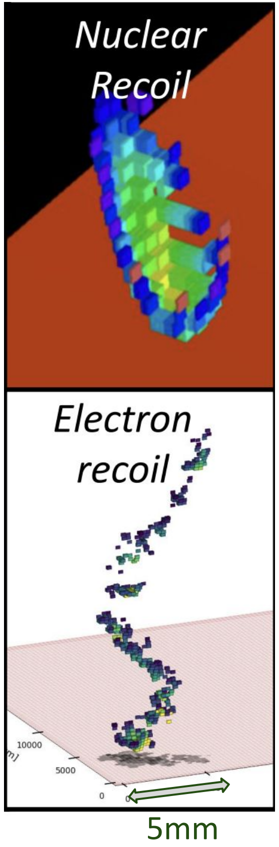
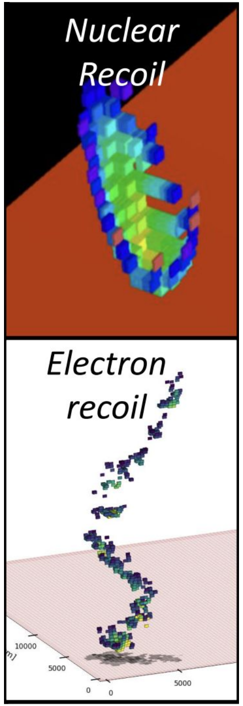
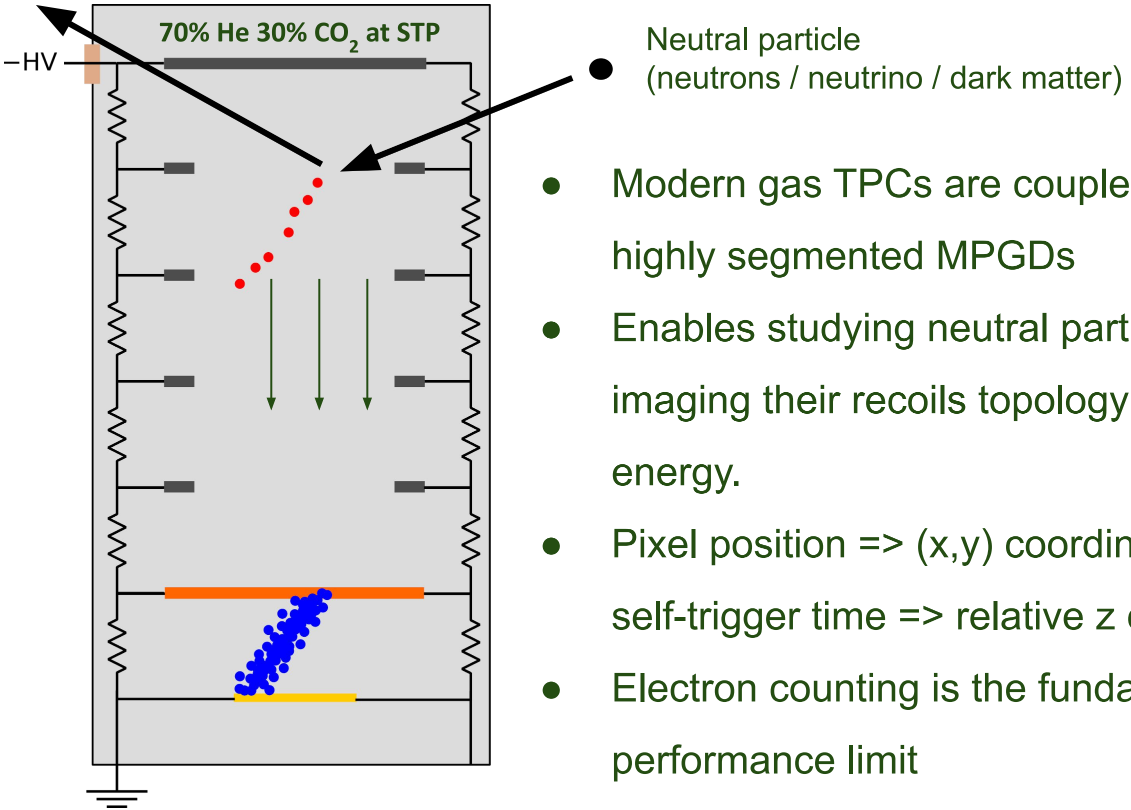
Preprint Available here: https://arxiv.org/abs/2410.00048



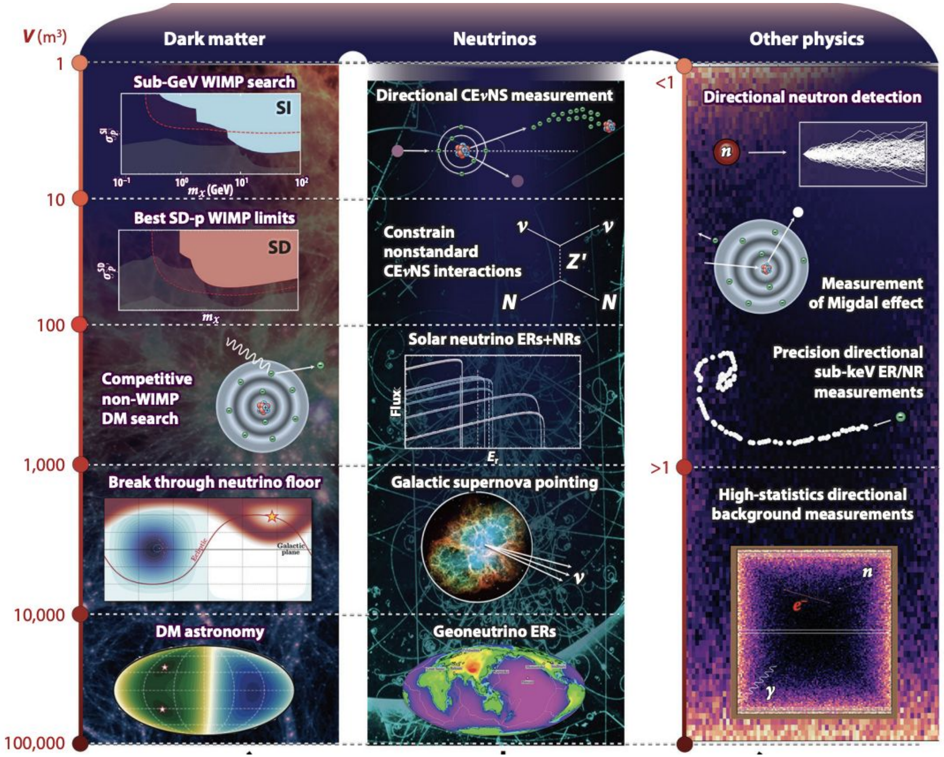
3D charge reconstruction in gaseous TPCs

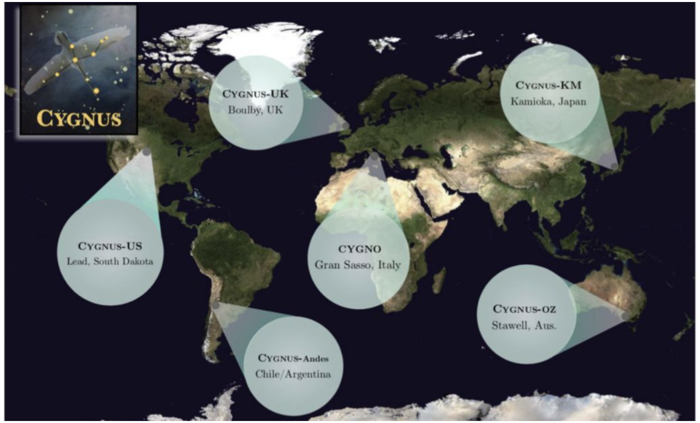




- Modern gas TPCs are coupled with highly segmented MPGDs
- Enables studying neutral particles by imaging their recoils topology and energy.
- Pixel position => (x,y) coordinate, self-trigger time => relative z coordinate
- Electron counting is the fundamental performance limit

CYGNUS vision for a directional recoil observatory



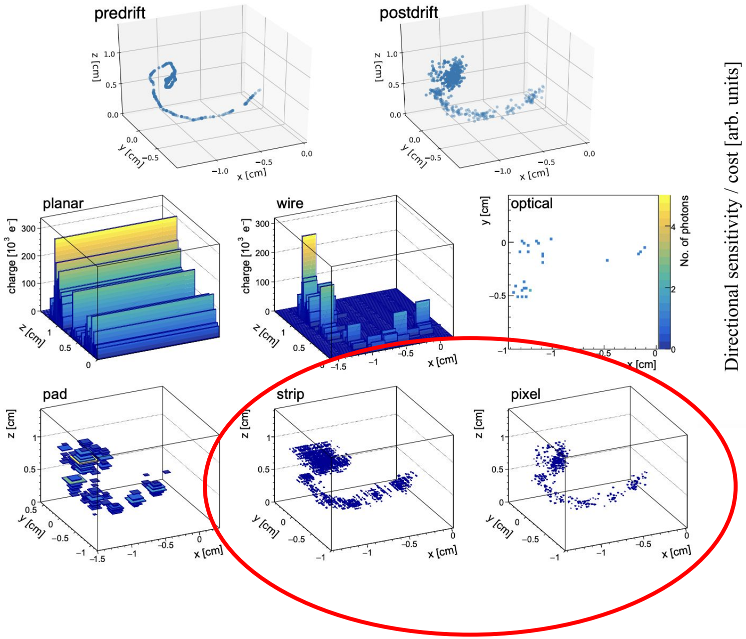


- Multi-site Galactic Recoil Observatory with directional sensitivity to WIMPS and neutrinos
- https://arxiv.org/abs/2008.12587 Vahsen et. al. [2]
  - Technical feasibility
  - Detailed simulation of readout options
  - Background discrimination studies
- https://arxiv.org/abs/2404.03690 Lisotti et. al. [3]
  - Utility as solar neutrino observatory

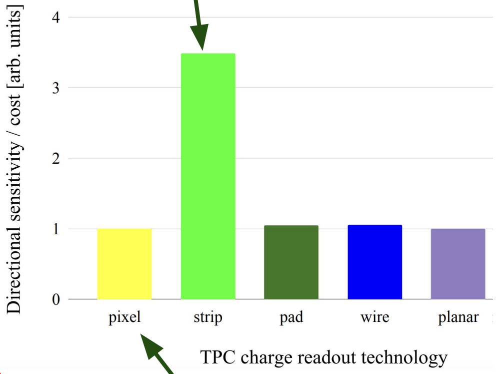
https://www.annualreviews.org/content/journals/10.1146/annurev-nucl-020821-035016 [4]

Scaling up in Vahsen Lab at U. Hawaii

Detailed simulation of readout technologies [2]

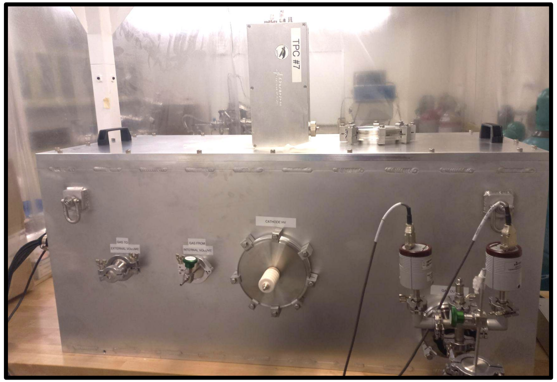


Best directional WIMP sensitivity / unit cost



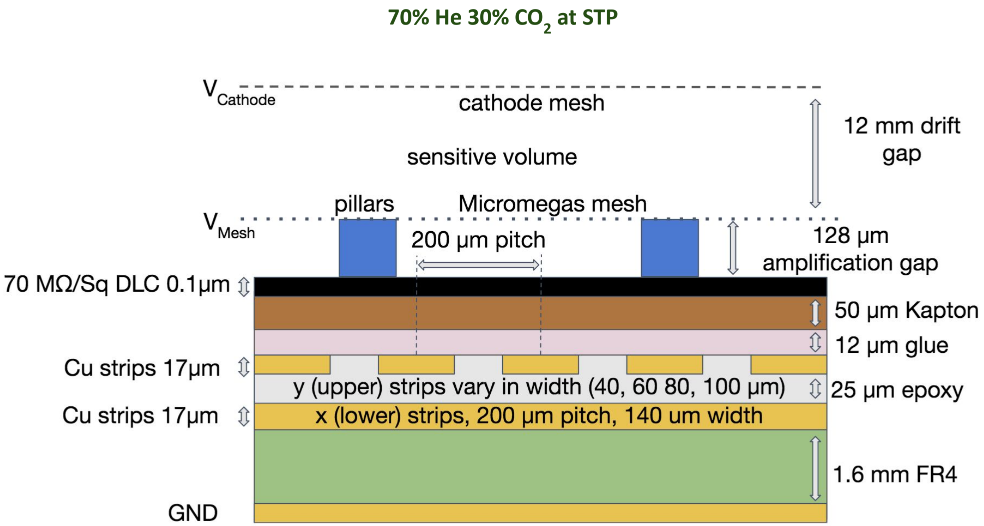
Best Raw Performance

We are scaling up by an order of 10^3!



An Experimental Comparison of x/y strips readouts

- Scaling up our detectors entails transitioning to an x/y strip readout
- We experimentally compare several x/y strip readouts to inform the design choices of our larger detector
- We go over highlights from this study



Preprint Available here:

https://arxiv.org/abs/2410.00048 [5]

An Experimental Comparison of x/y strips readouts

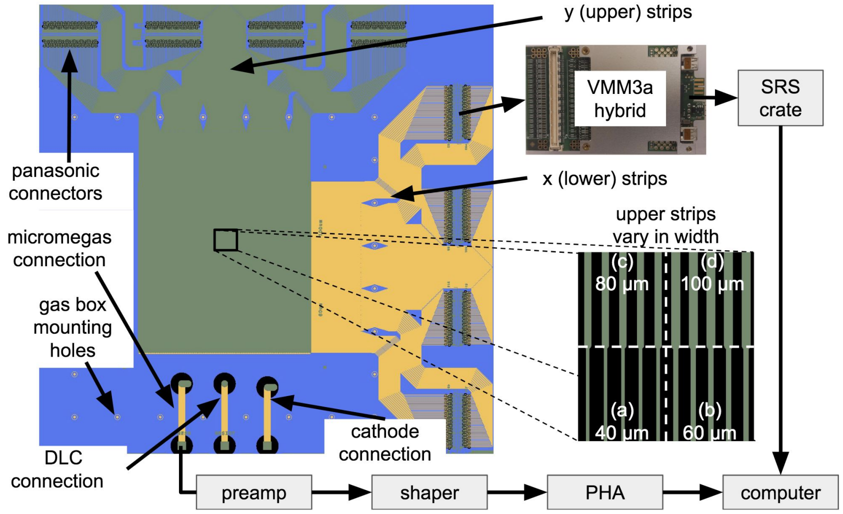
Nine different 2D strip configurations:

- DLC: Diamond like carbon (with / without)
- Strip geometry (upper strip width)
- Amplification Gap

Two instrumentation methods:

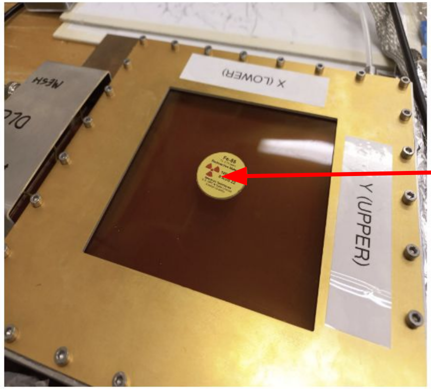
- Pulse height analyzer (PHA) to read the Micromegas mesh
- VMM / SRS to readout [6]

*BULK Micromegas readouts produced at CERN



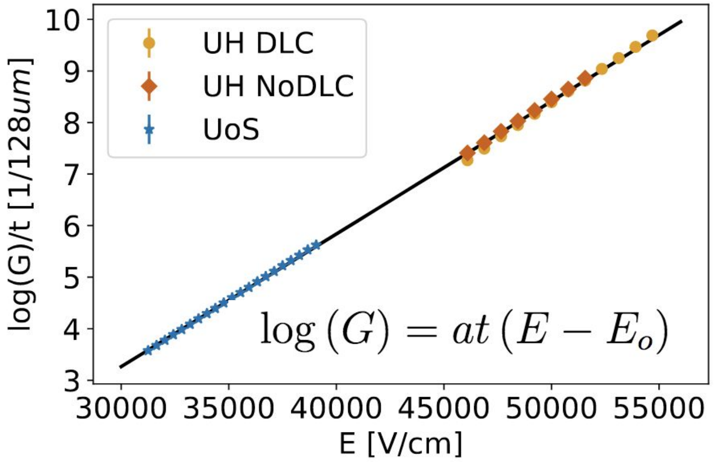
Detector Name	UH DLC	UH NoDLC	UoS
Amplification gap [µm]	128	128	256
DLC Resistivity [MΩ/sq]	70	N/A	50
Pitch [µm]	200	200	250
Quadrant Names	a,b,c,d	a,b,c,d	N/A
y (upper) strip width [µm]	40, 60, 80, 100	40, 60, 80, 100	100
x (lower) strip width [µm]	140	140	220

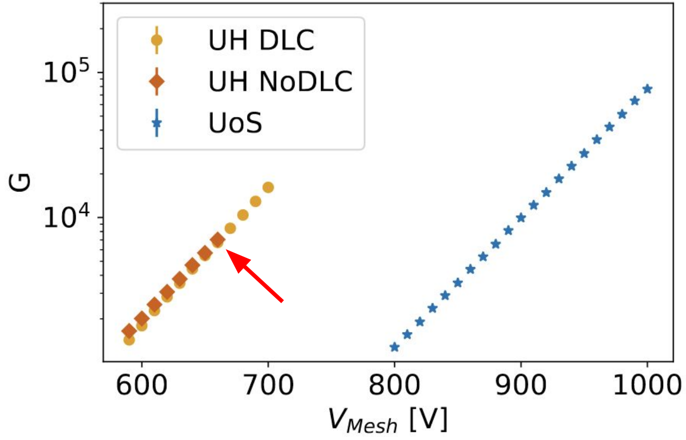
Avalanche Gain (PHA)



70% He 30% CO_2 at STP

Fe55 source to calibrate gain

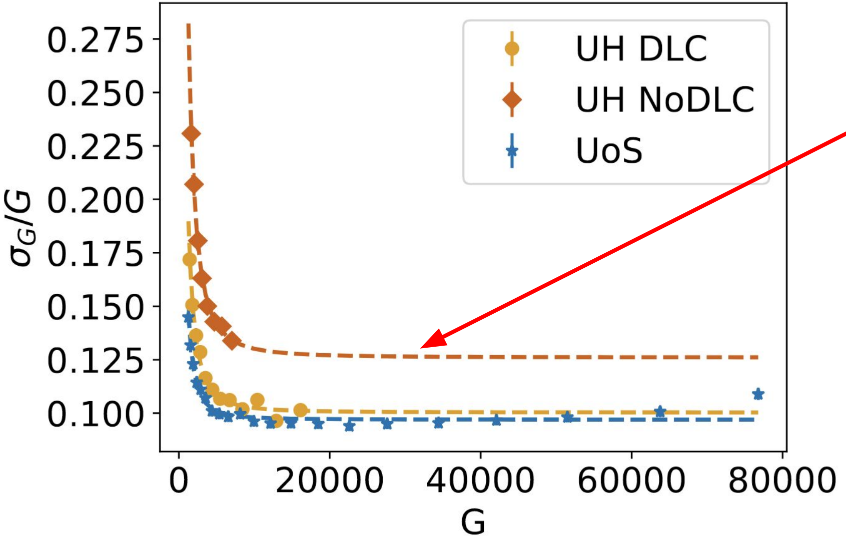




Takeaways:

- DLC layer => larger E => larger G
- Larger amplification gap => larger G
- General expression for G(t,E) in our gas mixture

Fractional Gain Resolution (PHA)

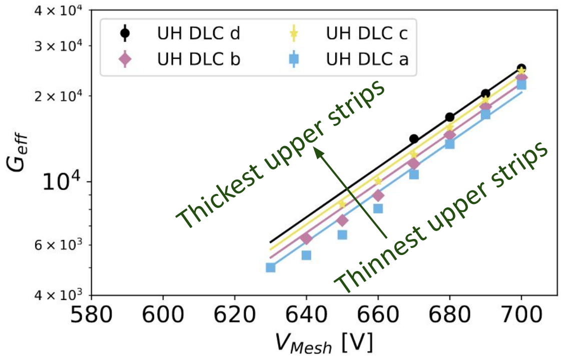


$$\sigma_G/G = \sqrt{\left(\frac{\beta}{G}\right)^2 + \gamma^2}$$

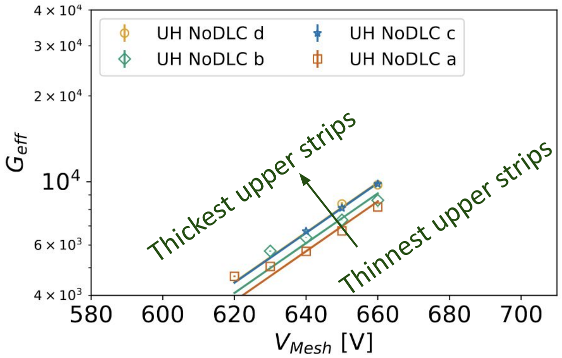
Takeaways:

- Asymptotic fractional gain resolution:
  - 0.097 (UoS)
  - 0.100 (UH DLC)
  - 0.126 (UH NoDLC)
- The only detector without a DLC layer has the worst fractional gain resolution

Effective Gain (VMM)



(a)

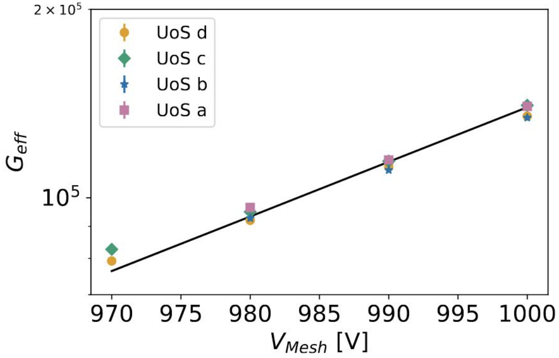


(b)

Multiplicative factor

$$G_{\text{eff}} = M \exp\left[at\left(E - E_o\right)\right]$$

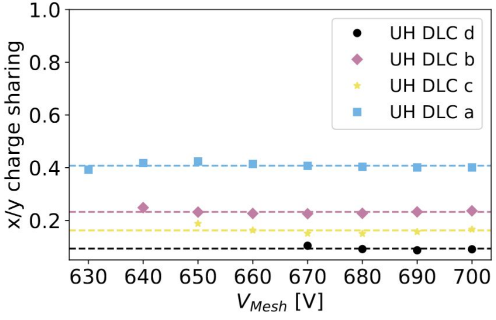
PHA result



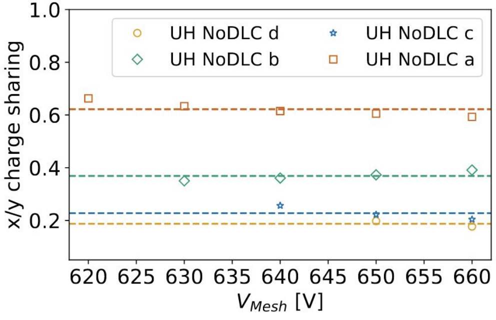
Takeaways:

- Configurations with wider upper strips see a slightly larger effective gain
- This effect is slightly smaller in UH NoDLC

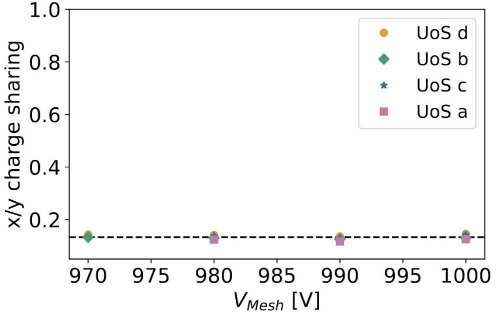
x/y charge sharing (VMM)



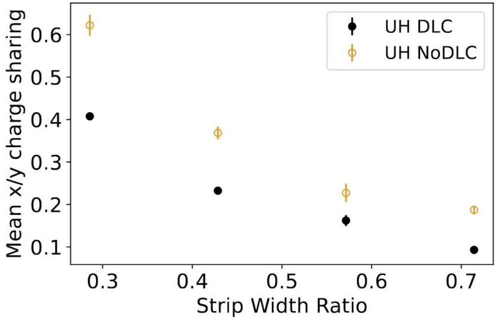
(a)



(b)



(c)



(d)

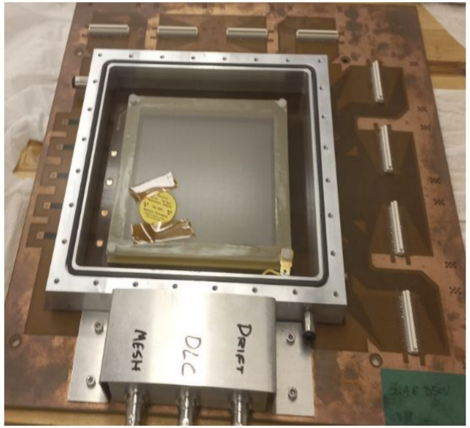
x/y charge sharing:

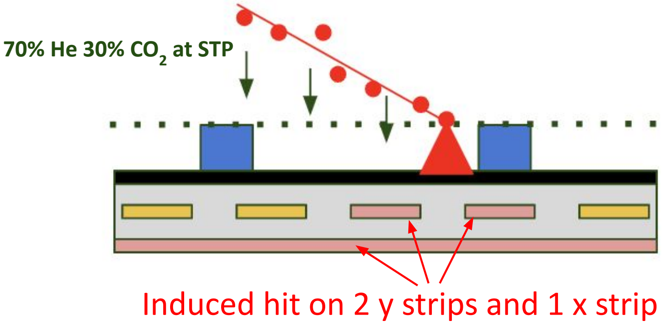
Fraction of charge detected on the lower versus upper strips

Takeaways:

- DLC layer reduces the x/y charge sharing
- Thinner upper strips => much better charge sharing

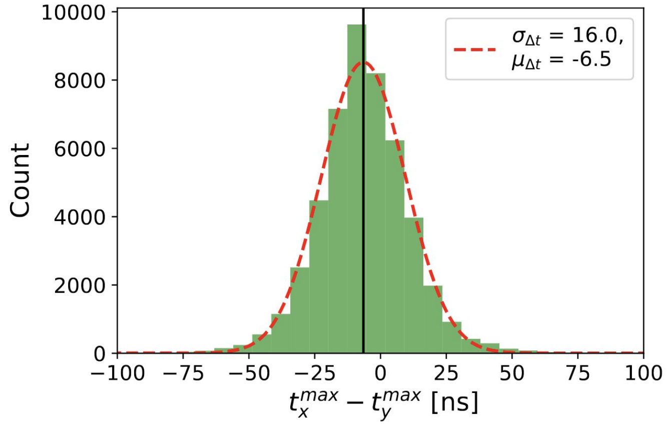
3D Reconstruction of alpha tracks

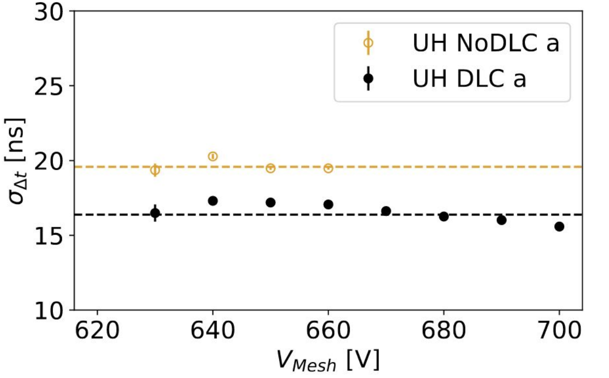




- 3D reconstruction of alpha tracks from Po210 source
- Line of ionization used to assess point resolution
- The x and y channels independently self-trigger
- 3D reconstruction requires matching x and y hits
- Must understand the expected timestamp difference between x and y hits corresponding to the same primary ionization

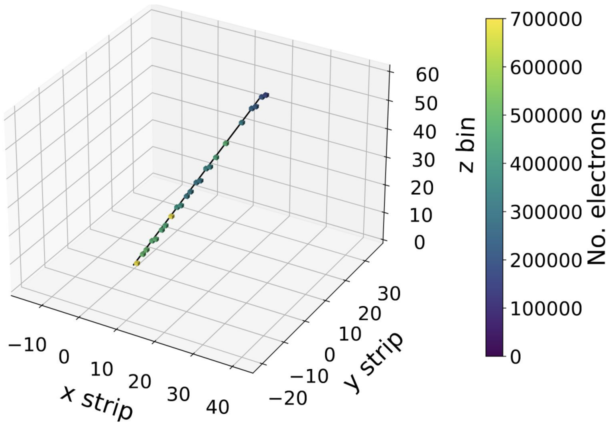
3D Reconstruction of alpha particles



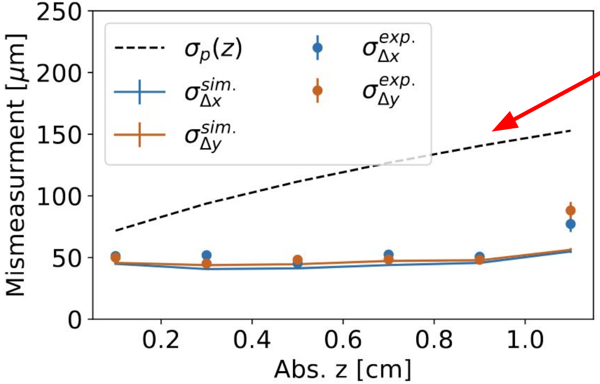


- The Fe55 data is used to get the timestamp difference distribution
- For each event we find $t_x^{max\ ADC} - t_y^{max\ ADC}$
- The distributions are fit to a Gaussian to determine σ and μ
- This quantity doesn't seem to depend on V_{Mesh}
- With this info 3D reconstruction is possible

Point Resolution



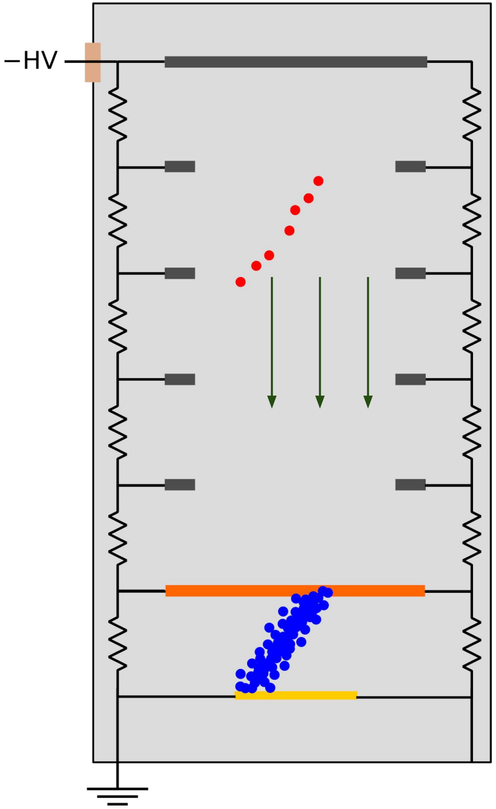
- Events are binned in z and mismeasurements for each z bin are fit to a Gaussian
- Experimental results agree with a simple simulation
- Both experiment and simulation differ from a naive expectation



$$\sigma_x(z) = \sigma_y(z) = \sqrt{(200\,\mu\mathrm{m}/\sqrt{12})^2 + (\sigma_T\sqrt{z})^2}$$

Outlook: Electron Counting

- Instead of integrating charge, pulses corresponding to individual electrons are resolved and counted [7]
- Will either require NID or faster electronics
- Several benefits:
    - Energy resolution is pushed to the fundamental limit
    - NID suppresses diffusion => improved point resolution
    - Ambiguities related to x/y strip readouts are resolved
- Our noise measurements (not shown here) suggest gain of ~60k in a NID gas mixture is required for electron counting with x/y strip readouts
- Similar gains have been demonstrated with the Multi-Mesh THGEM [8,9], however finer segmentation is required.



Conclusion

- Experimental comparison of 9 x/y strip configurations
- Results have informed the design of our upcoming 40L detector
- Must re-assess expected directional performance with diffusion suppression
- Electron counting with x/y strip readout could be within reach but will likely require an improved amplification device
- For more details, please see the preprint: https://arxiv.org/abs/2410.00048

References

[1] Jaegle, Igal, et al., (2019) Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging, NIMA 2019. https://doi.org/10.1016/j.nima.2019.06.037.

[2] Vahsen, Sven E. ... Ghrear, Majd, et al. (2020). Cygnus: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos. https://arxiv.org/abs/2008.12587.

[3] Lisotti, Chiara, et al. "CYG $\nu $ S: Detecting solar neutrinos with directional gas time projection chambers." arXiv preprint arXiv:2404.03690 (2024).

[4] Vahsen, Sven E., Ciaran AJ O'Hare, and Dinesh Loomba. "Directional recoil detection." Annual Review of Nuclear and Particle Science 71 (2021): 189-224.

[5] Ghrear, Majd, et al. "A Comparison of Micromegas with x/y Strip Charge Readouts for Directional Recoil Detection." arXiv preprint arXiv:2410.00048 (2024).

[6] L. Scharenberg et al., *Development of a high-rate scalable readout system for gaseous detectors*, Journal of Instrumentation **17** (2022) C12014. https://doi.org/10.1088/1748-0221/17/12/C12014

[7] Sorensen, Peter, et al. "Towards energy resolution at the statistical limit from a negative ion time projection chamber." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 686 (2012): 106-111.

[8] de Olivera, Rui, and Marco Cortesi. "First performance evaluation of a Multi-layer Thick Gaseous Electron Multiplier with in-built electrode meshes—MM-THGEM." *Journal of Instrumentation* 13.06 (2018): P06019.

[9] McLean, A. G., et al. "Gas gains over 104 and optimisation using 55Fe X-rays in low pressure SF6 with a novel Multi-Mesh ThGEM for directional dark matter searches." *Journal of Instrumentation* 19.03 (2024): P03001.

Thank you!
Questions?

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Backup slides

3D reconstruction Algorithm

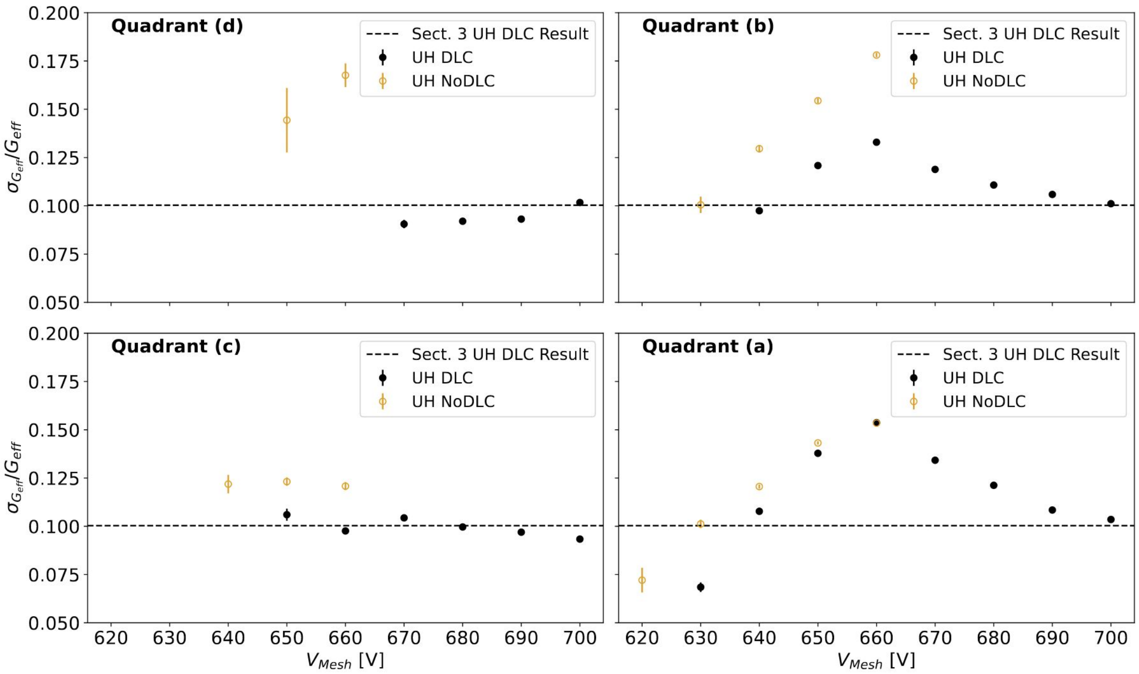
Our 3D reconstruction algorithm uses $\bar{\mu}_{\Delta t}$ and $\bar{\sigma}_{\Delta t}$ to reconstruct clustered events, as follows:

1. Find all i, j pairs such that $(t_i^x - t_j^y - \bar{\mu}_{\Delta t})/\bar{\sigma}_{\Delta t} < 3$. These paired x/y hits are referred to as vertices.
2. Define N_i^x and N_j^y as the number of vertices in which the ith x hit and jth y hit appear, respectively. Assign a charge $e_{ij} = e_i^x/N_i^x + e_j^y/N_j^y$ to each vertex. Doing so, each hit's charge is equally shared between the vertices in which it appears.
3. Assign a timestamp to each vertex calculated by $t_{ij} = (t_i^x + t_j^y)/2$, the average of the paired hits.
4. Assign 3D coordinates to the vertices as (x_i, y_j, z_{ij}), where $z_{ij} = v_{\text{drift}} t_{ij}$ and v_{drift} is the drift speed. These coordinates establish the event geometry with absolute (x, y)-coordinates and relative z-coordinates.
5. Adjust the timestamps of unmatched hits by subtracting (adding) $\bar{\mu}_{\Delta t}/2$ to the timestamp of the x (y) hits.
6. Distribute the charge detected on unmatched hits across all vertices. This distribution is weighted by the inverse of the difference between t_{ij} and the adjusted hit time.

The simulations

- The simulation assumes that alpha particles travel in a straight trajectory.
- SRIM is used to determine dE/dx, which is used to simulate energy deposition along the tracks.
- The alpha-particle direction is drawn isotropically.
- Diffusion along the 12\,mm drift length is simulated using the transverse and longitudinal diffusion coefficients, σ_T=135 um/sqrt(cm) and σ_L= 129 um/sqrt(cm) , as obtained from Magboltz.
- The drift speed is also obtained from Magbolts as 8 um/ns.
- The simulated gain is obtained by substituting V_{mesh} = 540 V into our PHA gain fit, which results in a gain of 604.
- After amplification, the avalanche charge is read out by the simulated upper and lower strips independently. The pitch of the strips is 200 um. The charge is shared between the upper and lower strips according to the measure x/y charge sharing for each configuration.
- Each strip is assumed to integrate the charge above it for a duration of 200 ns, equal to the VMM peaking time setting.
- If the integrated charge exceeds the threshold, as measured, a hit is formed.
- The timestamp of each hit is determined as the charge-weighted mean time of the integrated charge.
- For consistency with experimental data, each strip is only allowed to form one hit per event, channels 296, 306, 307, and 326 are masked, and hits with a gap of equal to or greater than 2 strips to their nearest neighbor are identified as noise and removed.

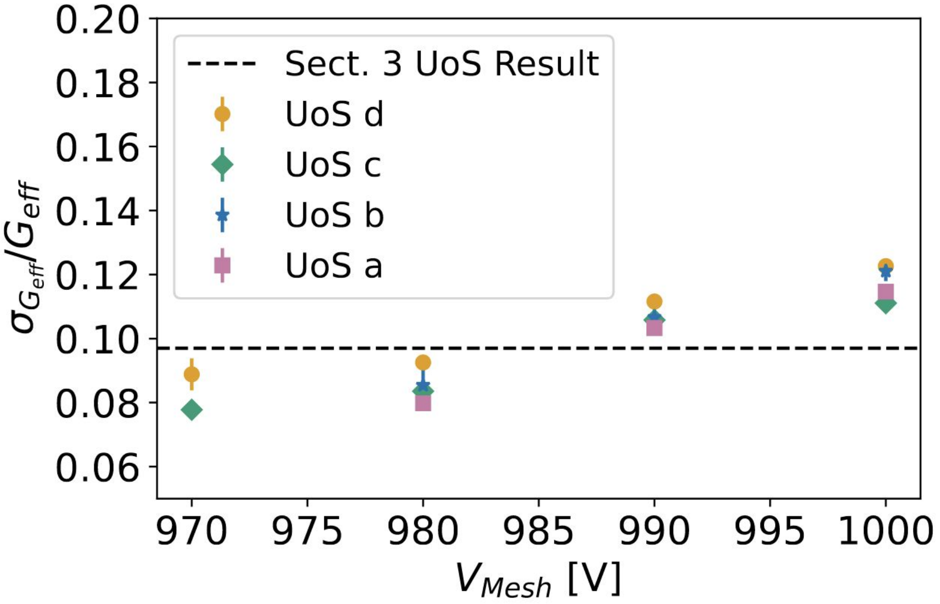
Effective Fractional Gain Resolution (VMM)



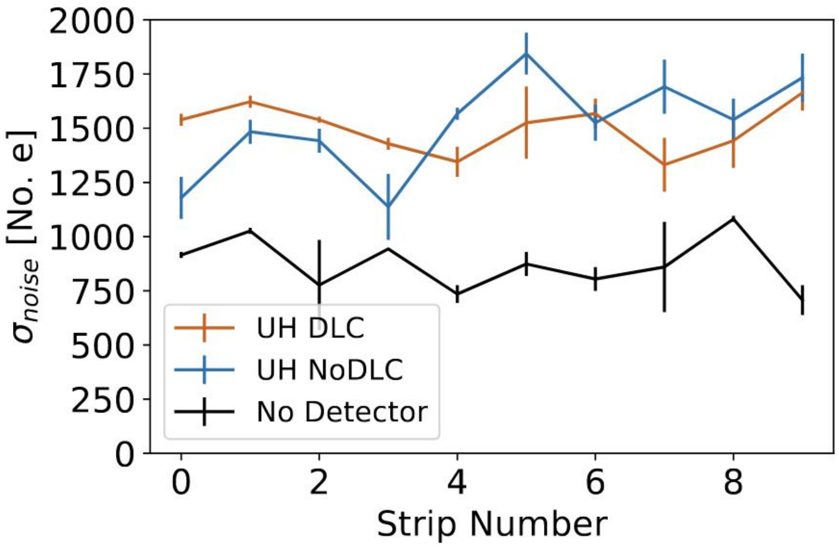
Takeaways:

- Charge below threshold artificially reduces the fractional gain resolution at low V_{Mesh}
- The VMM readout contribution to the fractional gain resolution is small

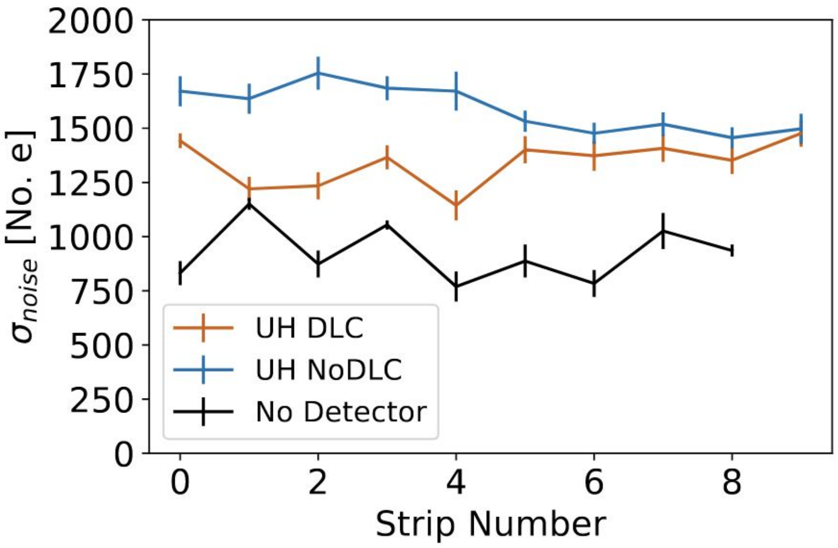
VMM fractional gain resolution UoS



Noise measurements



Upper strips



Lower strips

Justify gain required for electron counting

In Section 4.2, the noise level of the UH detectors is measured as $\sigma_{\text{noise}} \approx$ 1500 electrons. For a well-grounded and shielded detector, we anticipate that threshold can be set $6\,\sigma_{\text{noise}}$ above pedestal, so that 9000 electrons are needed to trigger a hit. We assume that the avalanche for a single primary electron is contained above a single 200 µm strip in x and y. The mean x/y charge sharing of the UH DLC detector quadrant a is 0.41, meaning that the lower (upper) strips observe 29% (71%) of the amplified charge. With this x/y charge sharing, 31000 (12700) avalanche electrons would be required to produce an above threshold signal on the lower (upper) strips. We further assume that the avalanche gain for a single primary electron is drawn from an exponential distribution

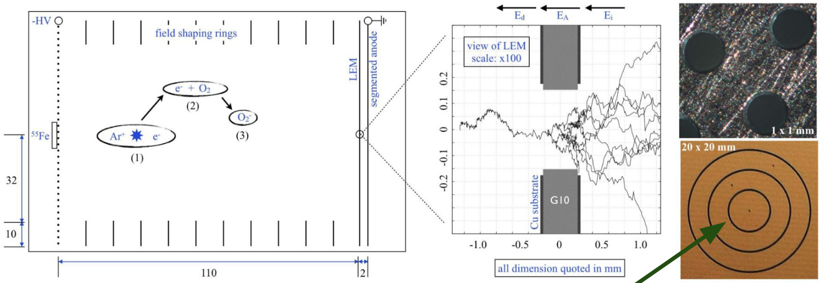
$$f_{exp}(x) = \begin{cases} 0, & \text{for } x < 0 \\ \frac{1}{\mu_e} \exp\left[\frac{-x}{\mu_e}\right], & \text{for } x \geq 0 \end{cases}, \tag{7}$$

where μ_e is the mean value of the gain. Let us define electron counting as the point were 80% of the primary electrons are detected and counted. The expected fractional energy resolution 5.2% [54], a substantial improvement over the asymptotic fractional gain resolution measured is sections 3 and 4. With this definition, in order to achieve electron counting in the lower strips, the required (mean) gain is given by solving

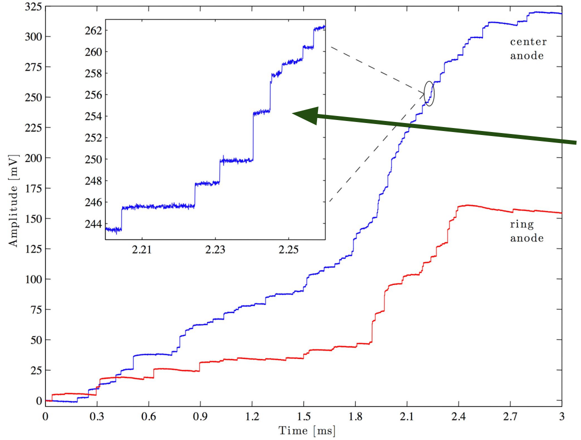
$$0.20 = \int_0^{31000} \frac{1}{\mu_e} \exp\left[\frac{-x}{\mu_e}\right] dx,$$

to obtain $\mu_e = 1.39 \times 10^5$. If electron counting is only desired on the upper strips, then $\mu_e = 5.68 \times 10^4$. In Section 3, the maximum gain of 7.73×10^4 was achieved by the UoS detector which has a 256 µm amplification gap. Although these gains were attained with an electron drift gas mixture, similar gains have been demonstrated using a novel multi-mesh ThGEM amplification structure in NID gas mixtures as detailed in Ref. [25]. While the

Towards Electron Counting



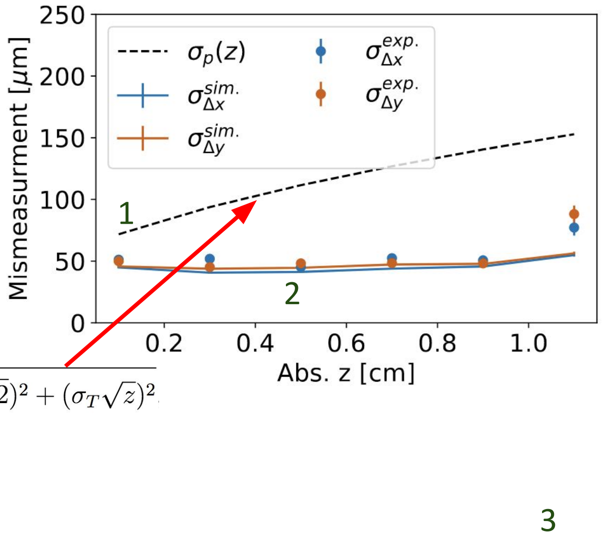
Four concentric rings of radius 3, 6, 9 and 40 mm



Single electron pulses

- Ref. [6] presents most successful attempt
  - $Ar{:}CO_2$ gas at 0.2 bar, doped with O_2 for NID
  - Large electron multiplier
  - 22 μs subsequent arrival times
  - 20 MHz acquisition sufficient for most ions to generate distinct signals. (res. n_s / f_{ADC} = 1 μs)
- **Achieved an electron counting efficiency of 0.78**
- Lack of segmentation thought to be main problem in past work
- Will be addressed by highly segmented x/y strip micromegas readout

Point Resolution



$$\sigma_x(z) = \sigma_y(z) = \sqrt{(200\,\mu\mathrm{m}/\sqrt{12})^2 + (\sigma_T\sqrt{z})^2}$$

- Varying parameters in simulation reveals 3 effects:
  1. The VMM threshold reduces mismeasurements in lowest bin
  2. Digitization time suppresses diffusion in the following bins
  3. Integration time can influence sim / exp agreement in final bin

Explaining the point resolution of Po210 with x/y strips

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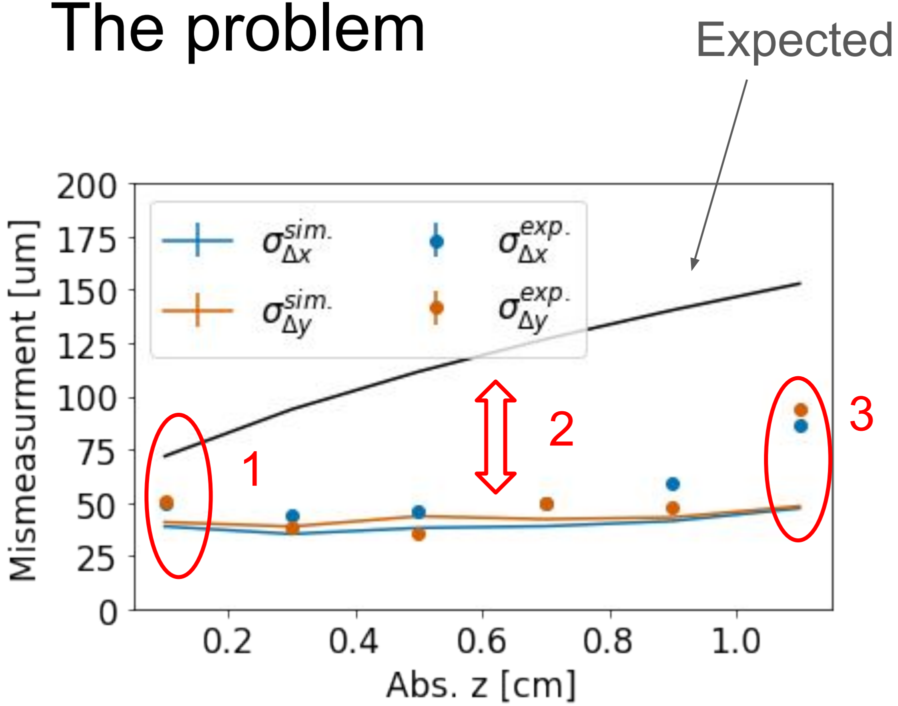
The problem



Method

- Po210 tracks recorded with a x/y strip readout, reconstructed in 3D, and fit to a line using SVD
- The transverse mismeasurements along the x and y dimensions are recorded versus z
- The point resolution is assessed by fitting the mismeasurements to a Gaussian for each slice in z

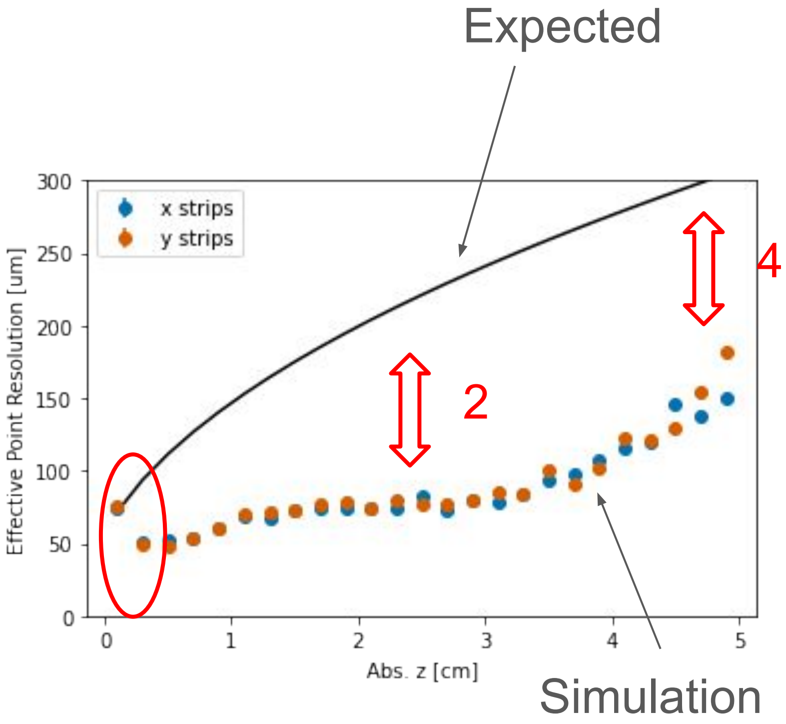
The problem:

- The observed point resolution is lower than expected
- This is observed in both experimental and simulation data

There are 3 main observations:

1. At the lowest z bin, the point resolution is less than what is expected from readout segmentation
2. The diffusion versus absolute z is not captured
3. At high absolute z, there is a stronger disagreement between simulation and experiment

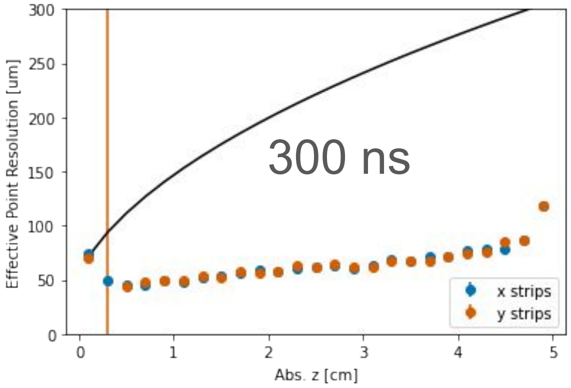
Test 1: remove threshold and repeat simulations with a 5 cm drift length

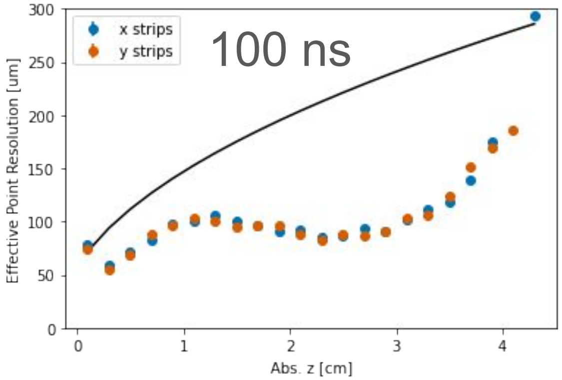


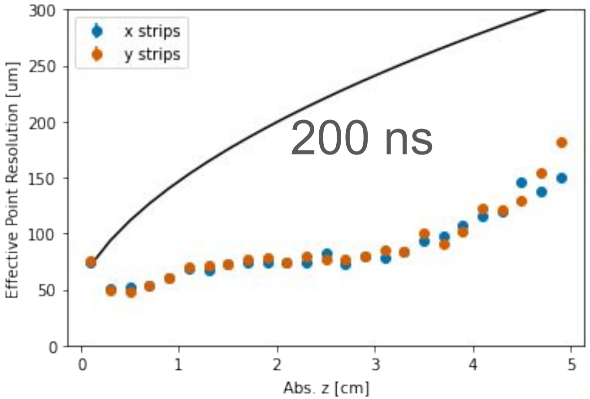
- With the threshold removed, observation 1 is resolved, the lowest z bin agrees with what is expected
- Observation 3 could be due to interactions of the alpha with the cathode. CYGNO has seen similar effects
- Observation 2 remains
- Observation 4: Now, the resolution appears to increase sharply at larger absolute z, why is that?

Test 1: remove threshold and repeat simulations with a 5 cm drift length

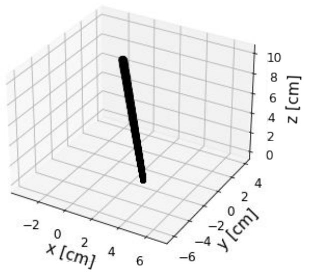
Observation 4 is related to the peaking time. In simulation, each strip integrates charge for the duration of the peaking time. At high absolute z, the integration can be cut off by the drift length, making mismeasurements larger. This explains observation 4.

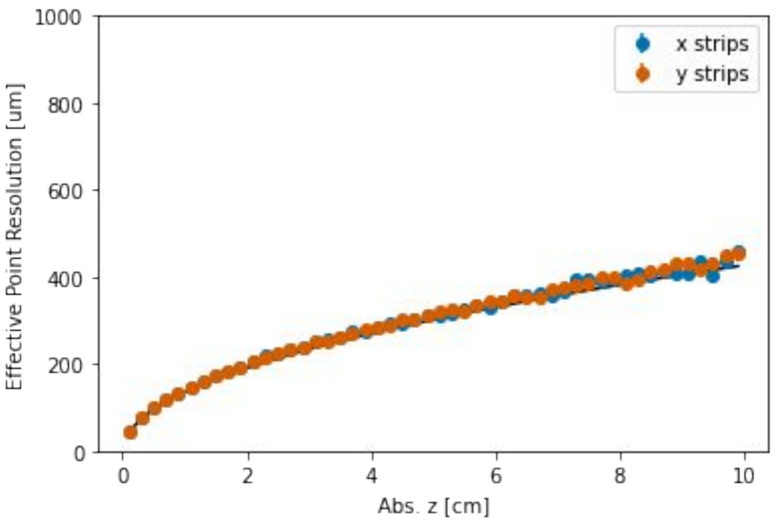






Start from Scratch: Raw tracks

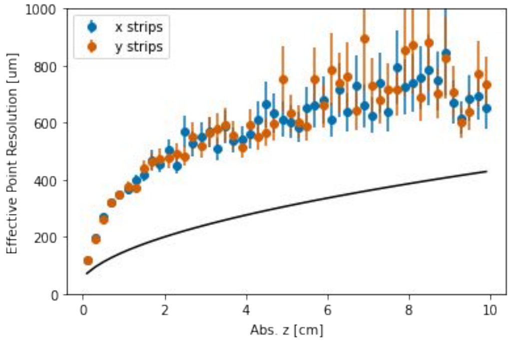


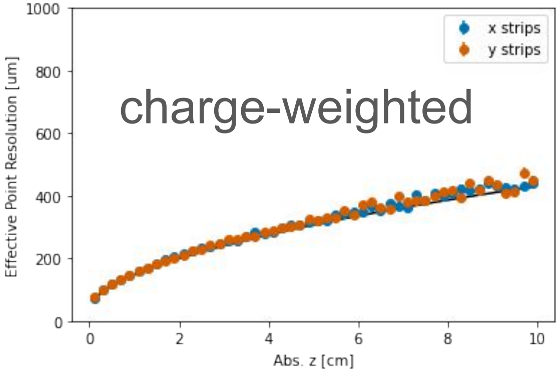


- Instead of alpha tracks we simulate charge uniformly spread on a line and apply the same diffusion versus z
- The drift length is increased to 10 cm
- We asses the point resolution of the raw tracks
- The results match our expectation

Start from Scratch: perfect pixel chip

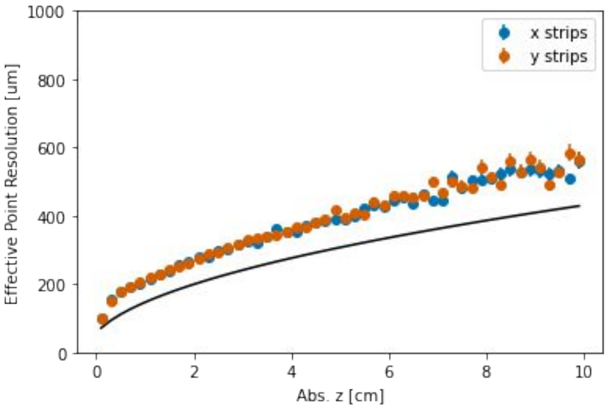
Not charge-weighted

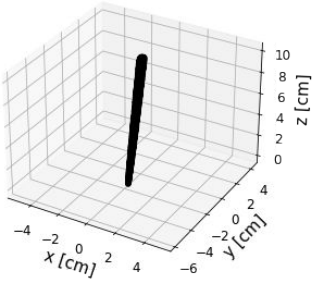


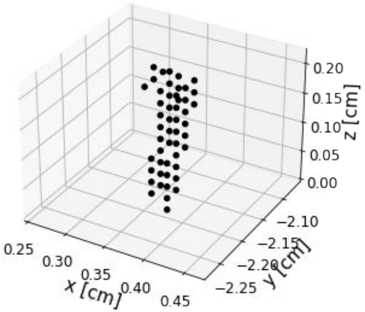


- Now the tracks are binned into (200um)^3 pixels to simulate a perfect pixel readout
- The results do not match our expectation immediately
- With pixels chips and no threshold, the mismeasurements must be charge-weighted
- **The entire Po-210 analysis has been updated to include charge-weighted mismeasurements**

Start from Scratch: perfect strip readout







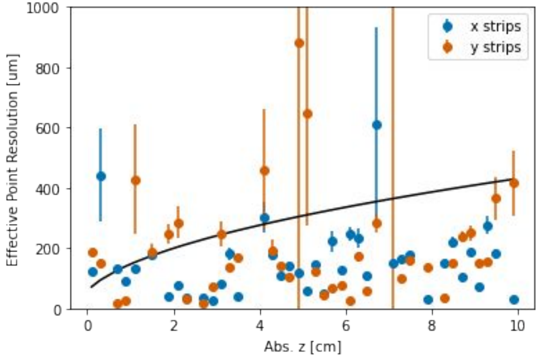
- The tracks are binned into (200um)^3 pixels
- The tensor for each track is summed along the x (y) axis to simulate the x (y) hits of a perfect strip readout
- We find a point resolution that is better than the unweighted perfect pixel chip but worse than the weighted perfect pixel chip

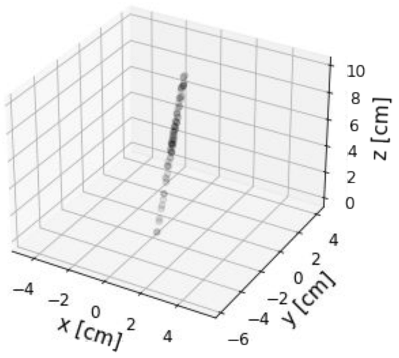
This does a little worse for two reasons:

1. The charge distribution is not captured as well for each slice in z, therefore the charge weighting is not as effective

2. Because for each slice in z, every y hit is matched to every x hit, the reconstruction is in the for of rectangles stacked in z (see below)

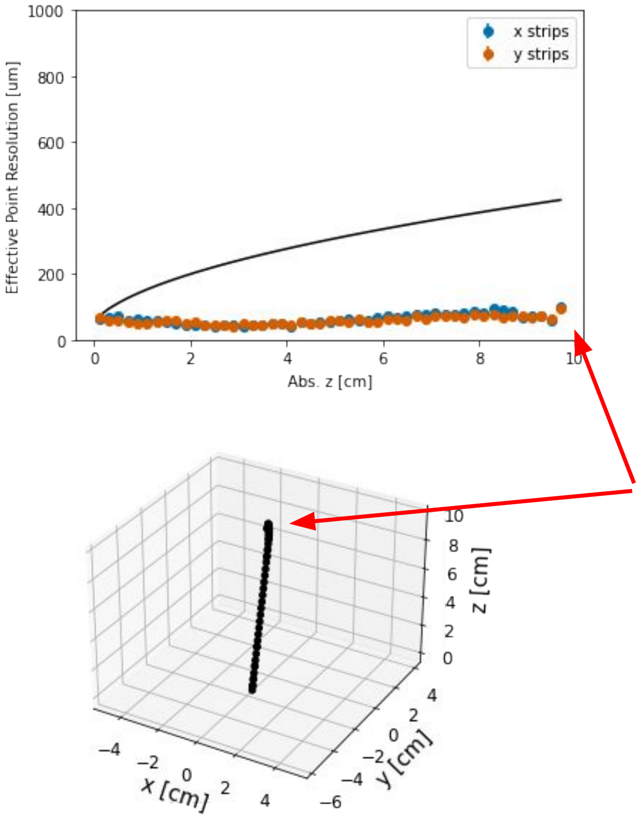
Start from Scratch: strip readout with digitization time





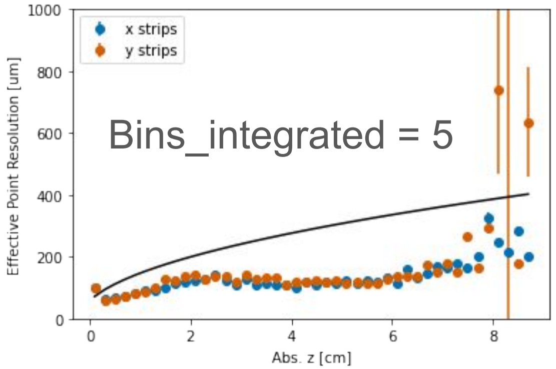
- The simulations of the perfect strip readout are modified to include a digitization time
- After a strip fires, it will not create another hit for [n] bins in z, this charge is ignored
- Now we see the tracks appear more slim and the point resolution decreases
- But the strips are not segmented in z, they find the z coordinate by integrating charge

Start from Scratch: strip readout with full charge integration

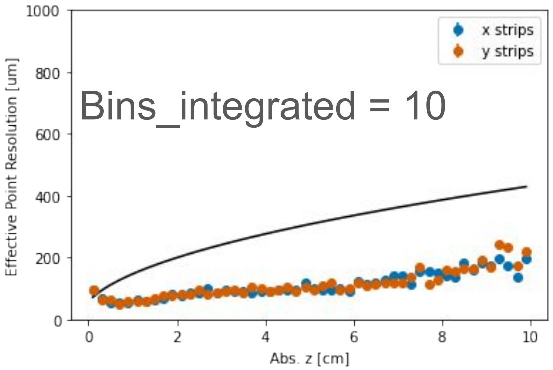


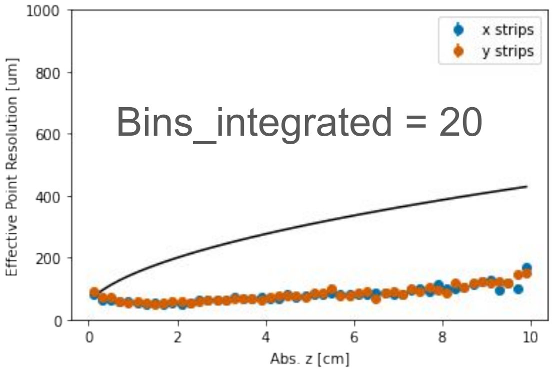
- The simulations of the perfect strip readout are modified so that each strip integrate all of the charge above it
- The absolute z position is the mean position of the charge above each strip
- Now we see very similar performance to our previous simulations
- The increase at the end can be explained by the drift length cutting off the charge integration

Start from Scratch: strip readout with peaking time



- The simulations of the perfect strip readout are modified so that each strip integrate all of the charge in the [bins_integrated] bins above it
- The absolute z position is the mean position of the charge integrated
- We see the expected behaviour with peaking time (bins_integrated)





Summary

- Observation 1: At the lowest z bin, the point resolution is less than what is expected from readout segmentation
    - This is due to the threshold. If the threshold is 0 then x/y strip readouts produce the expected point resolution at the lowest slice in z
- Observation 2: The diffusion versus absolute z is not captured
    - This is an artifact of have charge integrating strips. This makes sense because as a track is imaged for higher z, only the portion of charge that is above strips that have not fired before can be imaged
- Observation 3: At high absolute z, there is a stronger disagreement between simulation and experiment
    - This could be due to the alpha tracks interacting with the cathode, or because the peaking time is smaller than expected in experiment (or that the peaking time is not simulated very carefully)
- Observation 4: For large drift lengths and no thresholds, the resolution appears to increase sharply at larger absolute z
    - This is caused by the peaking time, or the time span for which a strip integrates charge

Adjusting our full simulation

- By setting the threshold to 0 we should get the expected point resolution
- By decreasing the integration time from 200 ns to 100 ns we get better agreement between simulation and experiment