Towards Three Dimensional Electron Counting in Gaseous Detectors

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GIRA Honorable Mention
CPAD Workshop 2023
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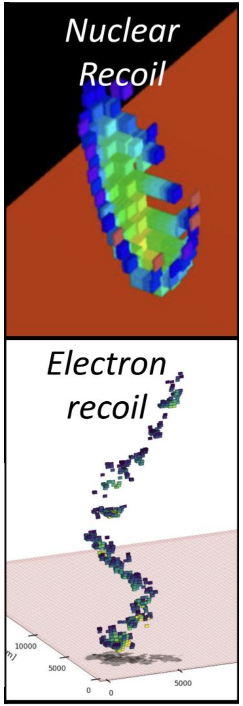
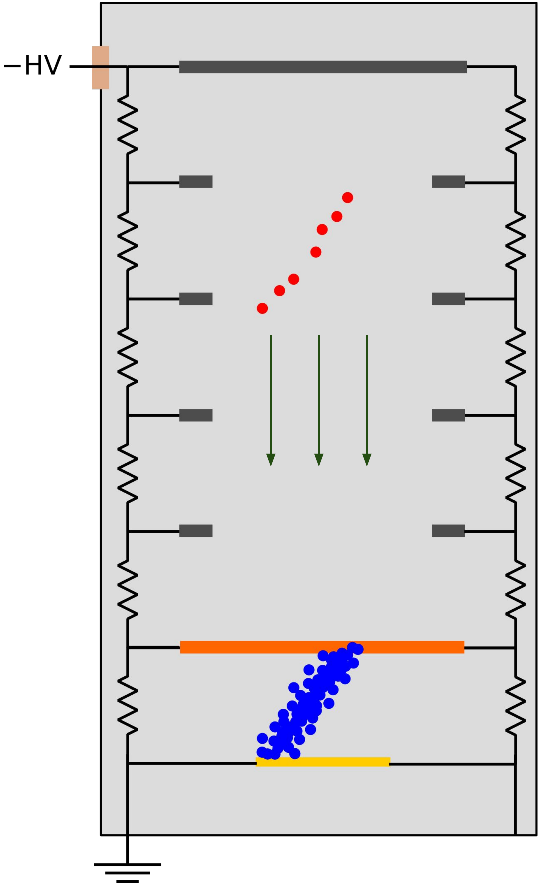
Gas TPCs with highly-segmented MPGDs

Highlights [1]

- Gains up to O(50,000)
- (250 x 50) μm^2 pixels
- Noise floor ~100 electrons
- Single electron efficiency at ~20k gain

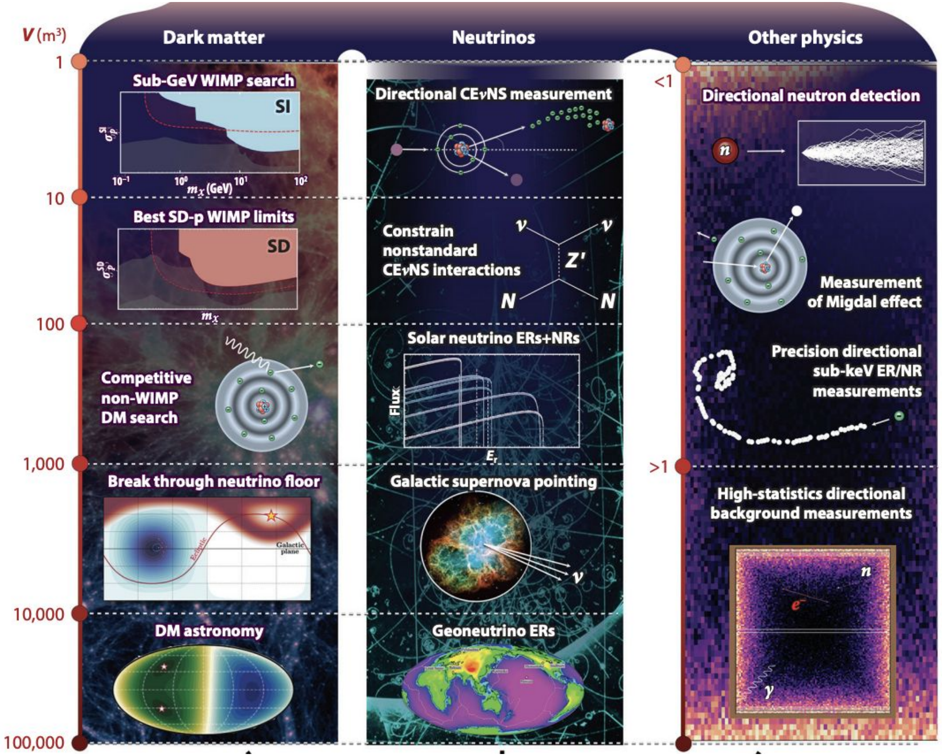


$$\frac{\sigma_E}{E} = \sqrt{n \times (F + f)}$$



- 3D event topology and energy
- Hit contains many primary electrons
- **Counting primary electrons counting is a fundamental performance limit**
- Negative ion drift [2] slows drift so readouts can resolve pulses from individual electrons
  1. Energy resolution only determined by fluctuations in primary ionization
  2. Full event topology is reconstructed
  3. NID suppresses diffusion

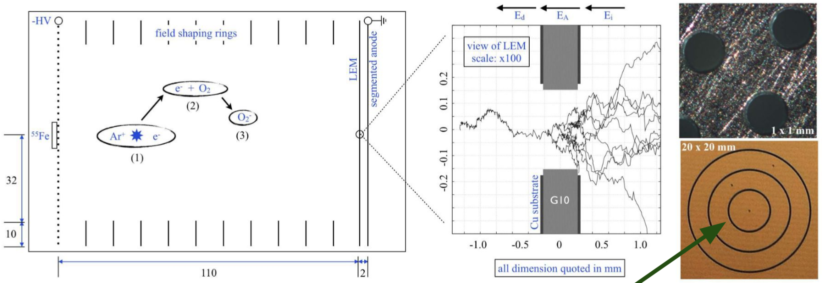
Directional Recoil Detection



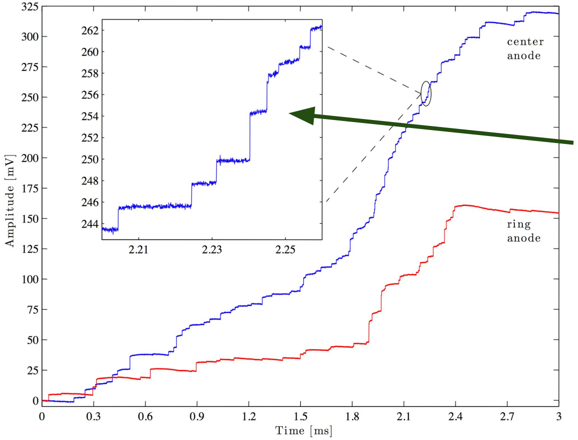
See talks by J. Schueler, E. Tilly, and S. Vahsen, this conference (RDC6 on Thursday)

- Directional recoil detection
  - A powerful way to search for dark matter in the neutrino fog
  - Can confirm the galactic origin
  - Unique abilities to probe DM properties
- **Electron counting with NID - a breakthrough!**
  - Top priorities for the field [3]
  - Feasibility paper [4] assumes operation with NID
- Best energy resolution, improved particle ID and angular resolution
- **Highly-segmented strip readouts provide the best directional sensitivity per unit cost**

Towards Electron Counting



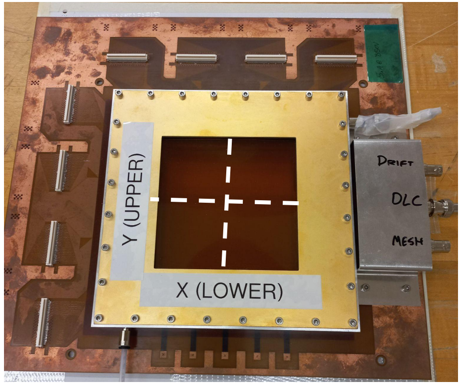
Four concentric rings of radius 3, 6, 9 and 40 mm

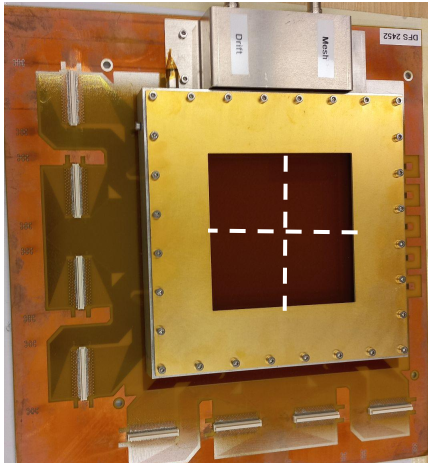


Single electron pulses

- Ref. [5] 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

Readout Optimization



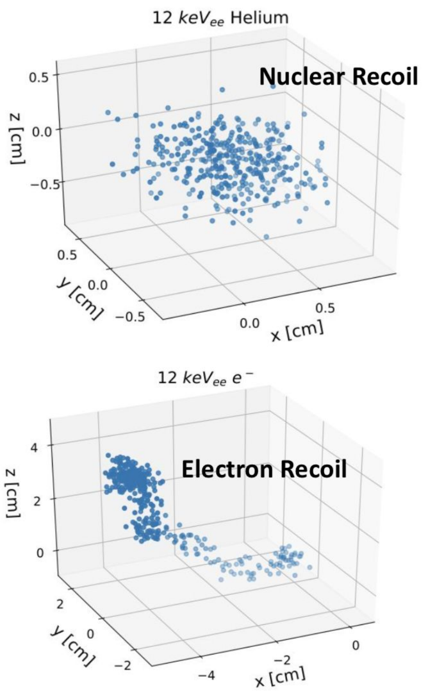


Comparing

- Gain
- Gain Resolution
- Charge sharing
- Point resolution

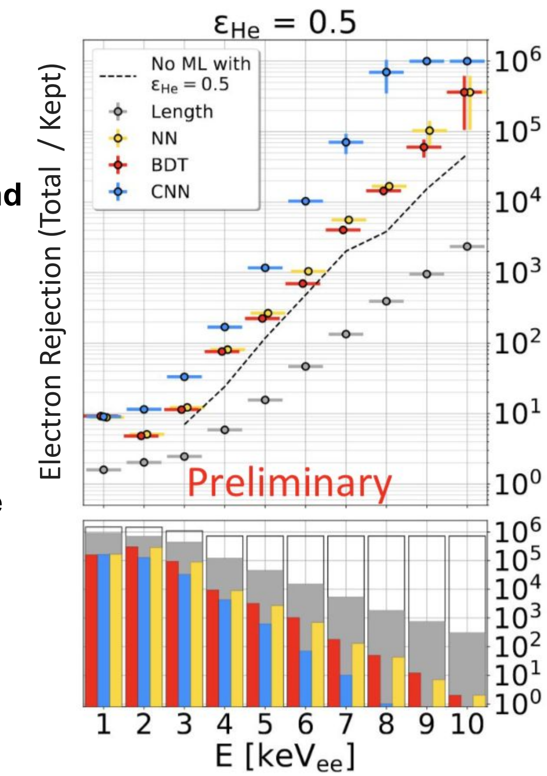
- Highly segmented 2D strip MICROMEGAS appear optimal
- We are optimizing this type of readout for a 40L directional gas TPC
  - 200um segmentation
  - VMM3a frontend chips [6] inside the RD51 scalable readout system
  - Noise of a few thousand electrons [7]
- MICROMEGAS gain structure
  - single electron gain shower triggers 1-2 channels
  - gains of 10-20k to amplify single electron above noise
- Time resolution
  - BCID resolution of 25ns
  - **0.25us to digitize a hit < 22us average subsequent arrival times [5]**

Improved Particle ID



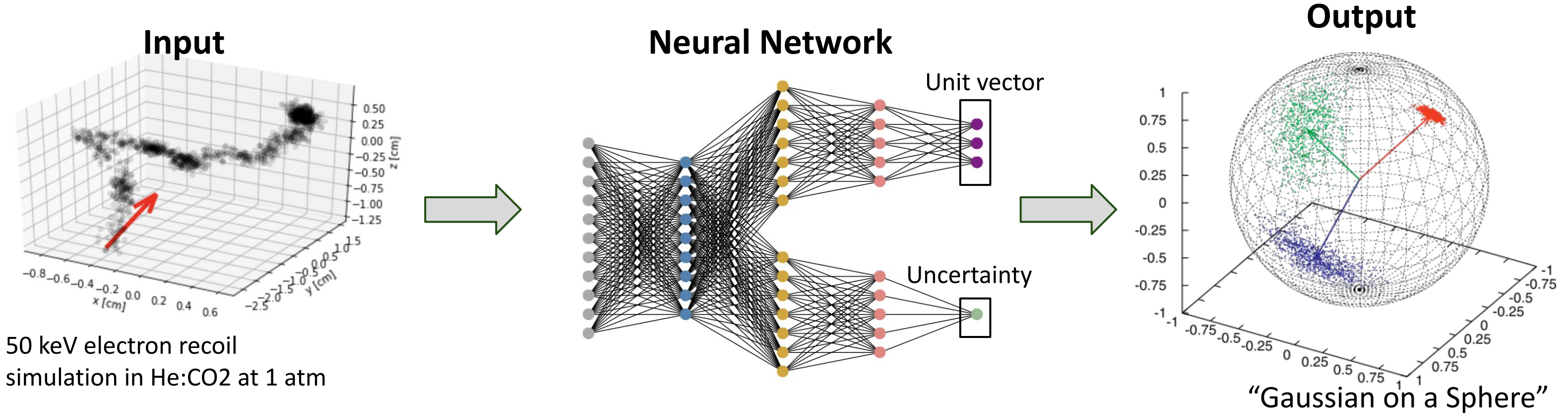
In $He:CF_4:CHF_3$ at 40 Torr

- Electron counting: **easier to distinguish electron and nuclear recoils**
- By combining physical observables we can improve electron rejection by 2 orders of magnitude [8]
- Further improvements expected via ML, see "Machine Learning for Improved Analyses of High Resolution Gaseous Detector Data", J. Schueler, this conference



J. Schueler

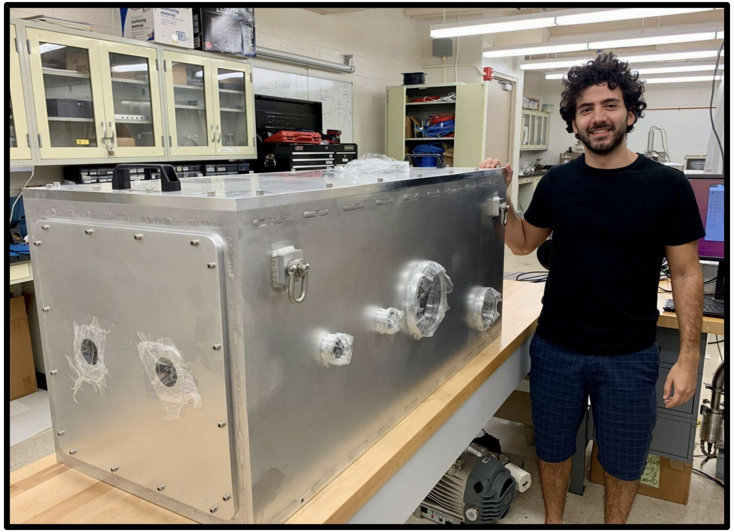
Improved Angular Resolution



- With all electrons reconstructed it is **easier to determine the initial direction of recoils**
- New deep learning techniques can not only improve angular resolution, but also model uncertainty in predicted directions
- This leads to significant improvements in directional performance [9]

Summary

- A definitive demonstration of electron counting is within reach but has yet to be demonstrated
- Electron counting with NID and highly-segmented charge readout
    - Improve energy resolution to the statistical limit
    - Allow us to reconstruct the full event topology
    - Lower diffusion allows us to resolve low-energy tracks over longer drift lengths
- For directional recoil detection this means
    - Best energy resolution
    - Improved particle ID
    - Improved angular resolution



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] Martoff, C. Jeff, et al. "Suppressing drift chamber diffusion without magnetic field." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 440.2 (2000): 355-359.

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

[4] 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

[5] 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.

[6] Iakovidis, George. "VMM3a, an ASIC for tracking detectors." Journal of Physics: Conference Series. Vol. 1498. No. 1. IOP Publishing, 2020

[7] Lupberger, Michael. “VMM and the SRS update.” RD51 mini-week. https://indico.cern.ch/event/702782/contributions/2900689/attachments/1602661/25457 00/RD51_MiniWeek_Feb2018_CERN.pdf

[8] Ghrear, Majd, Vahsen, Sven E., and Cosmin Deaconu. "Observables for recoil identification in high-definition Gas Time Projection Chambers." Journal of Cosmology and Astroparticle Physics 2021.10 (2021): 005.

[9] Ghrear, Majd, et al., “Deep probabilistic 3D angular regression for directional dark matter detectors”, under review

Thank you!
Questions?

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