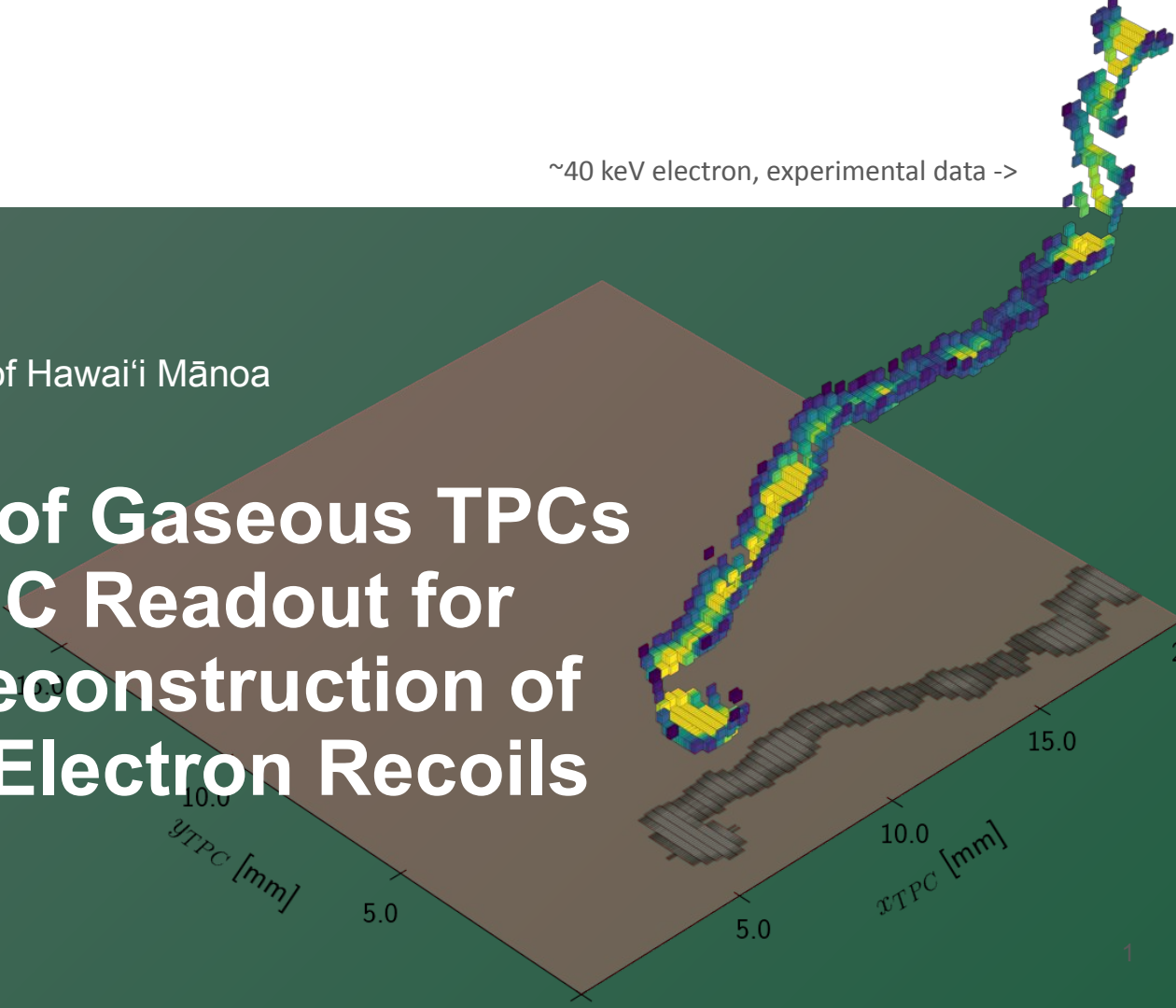
Haiqi (Sola) Long, University of Hawai‘i Mānoa

Performance of Gaseous TPCs with Pixel ASIC Readout for Directional Reconstruction of 10-keV-scale Electron Recoils

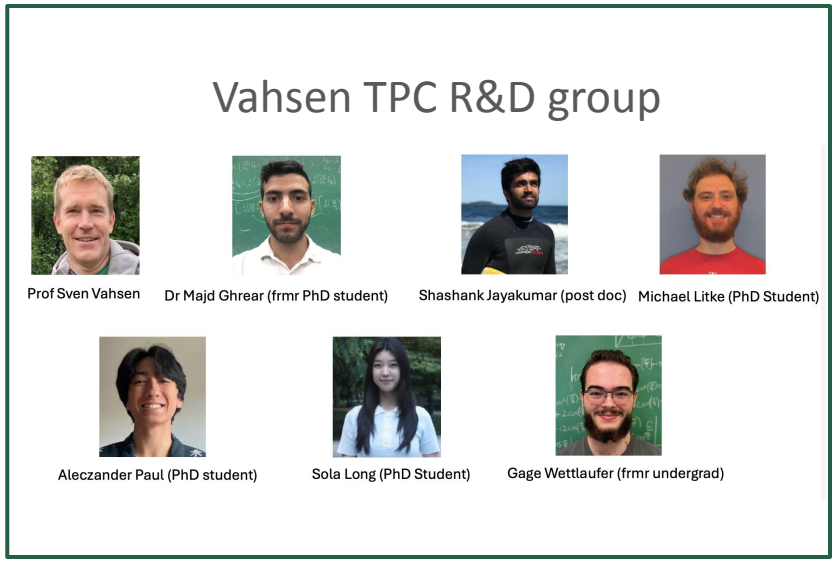
CPAD 2026 at Seattle

~40 keV electron, experimental data ->



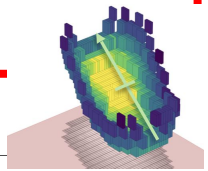
Overview

- Physics Cases for Directional Detectors
- Neutral Particle Detection via Recoils in Gas TPCs
  - BEAST TPCs at U. Hawaii
  - Detector effects
- Experiment on characterizing detector resolution
  - Electron multiple scattering
  - Gain resolution and fiducialization
  - Preliminary results
- Outlook: towards 3D electron counting with NID
  - 1000x scale up being commissioned



Motivation for Directional Recoil Detection

New paper published last week! Expect ~ 37 CEνNS / m^3 / year, started neutron background measurement at ORNL SNS



PHYSICAL REVIEW D **114,** 072006 (2026)

Directional recoil detection for CEνNS measurements with light nuclei at the Spallation Neutron Source

Ciaran A. J. O'Hare,[1,*] Anirudh Chandra Shekar,[2] Chiara Lisotti,[1] Michael Litke,[3] Nityasa Mishra,[2] Jayden L. Newstead,[4] Louis E. Strigari,[2] and Sven E. Vahsen[3]

[1]*ARC Centre of Excellence for Dark Matter Particle Physics, The University of Sydney, School of Physics, NSW 2006, Australia*

[2]*Department of Physics and Astronomy, Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*

[3]*Department of Physics and Astronomy, University of Hawaii, 2505 Correa Road, Honolulu, Hawaii, 96822, USA*

[4]*ARC Centre of Excellence for Dark Matter Particle Physics, School of Physics, The University of Melbourne, Victoria 3010, Australia*

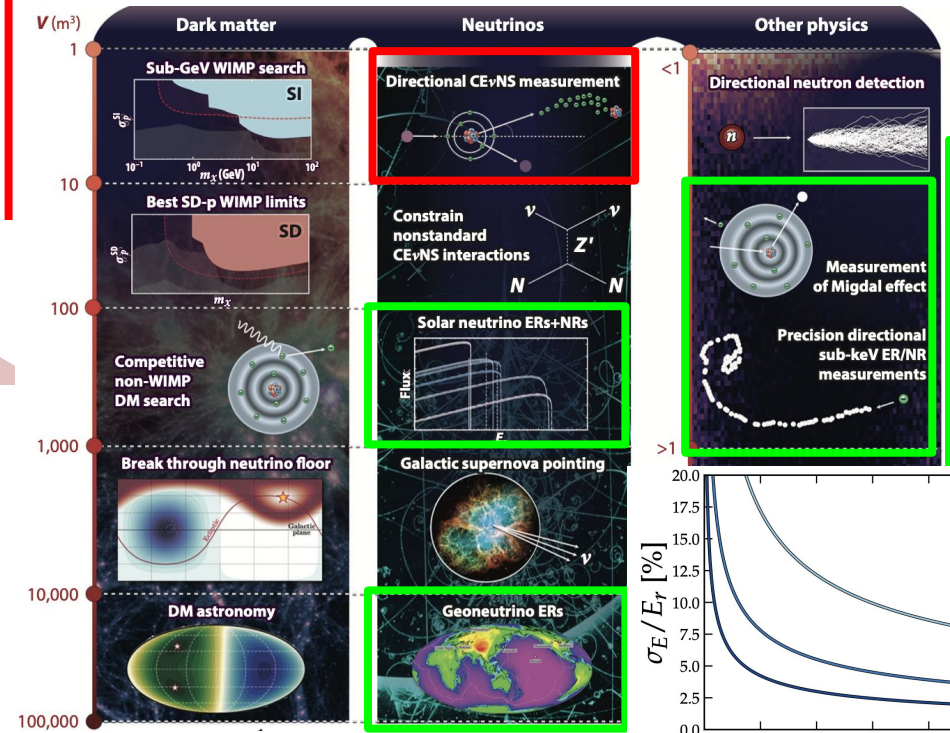
(Received 2 April 2026; accepted 30 September 2026; published 16 October 2026)

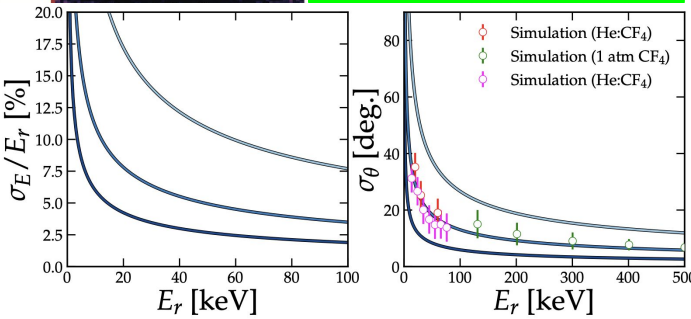
The coherent elastic scattering of neutrinos on nuclei, also known as CEνNS, has been studied for several years by the COHERENT program of experiments using neutrinos from stopped-pion decays produced at the Oak Ridge Spallation Neutron Source (SNS). We propose a new approach for CEνNS measurements at the SNS that aims to complement the COHERENT experiments in two main ways: by reconstructing the *angular* distribution of CEνNS -induced recoils, and by measuring CEνNS on much lighter target nuclei such as helium, carbon, and fluorine. The proposed detector would employ a gaseous time-projection chamber with a highly segmented charge readout to enable the spatial reconstruction of ~10–500 keV ionization tracks created by CEνNS -induced recoils. This would enable the simultaneous measurement of the CEνNS recoil energy and scattering angle, thereby allowing event-by-event reconstruction of the neutrino energy. We estimate that a 60:40 He:CF_4 gas mixture at atmospheric pressure offers a good trade-off between total target mass and good directionality and could deliver a detection of the angular distribution of CEνNS, even under pessimistic background conditions. We project the sensitivity of 1 and 10 m^3-scale detectors in the context of several physics cases, including: the measurement of the Standard Model CEνNS cross section, reconstruction of the flavor-dependent neutrino fluxes, observing the neutrino-induced Migdal effect, constraints on beyond-Standard-Model neutrino interactions, and probing 10-eV-scale sterile neutrinos.

DOI: 10.1103/kj5m-y2g7

O'Hare et al.https://doi.org/10.1103/kj5m-y2g7 (2026)

Vahsen et al., https://doi.org/10.1146/annurev-nucl-020821-035016 (2021)

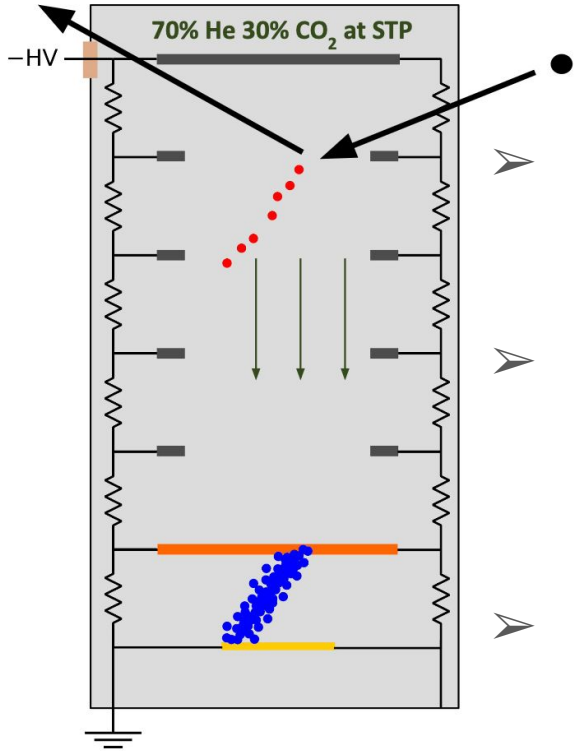




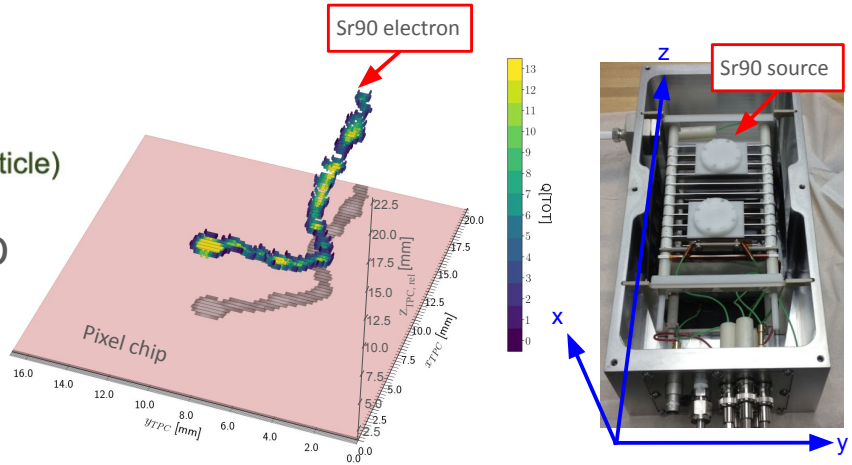
Unexplored signature: only simulation studies done on electron recoils

Lisotti et al., https://doi.org/10.1140/epjc/s10052-024-13392-3 (2024)

Neutral Particle Detection via Recoils in Gas TPCs



- Highly segmented MPGD amplification and detection
- 3D recoil ionization reconstruction with (x, y) from pixel position, z from trigger time
- Provides recoil direction, particle ID, and energy



Jaegle et al., https://doi.org/10.1016/j.nima.2019.06.037 (2019)

BEAST TPCs at U. Hawaii

Mini size: 40 cm³ gas volume

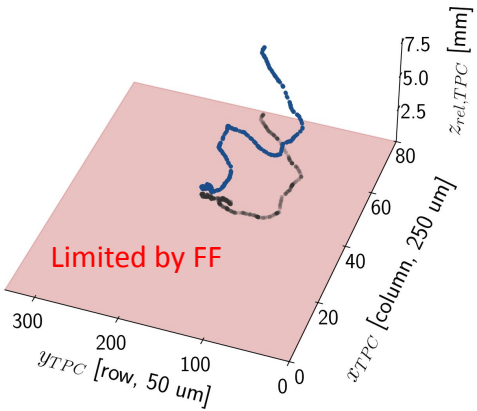
Amplification: double GEMs, ~20k gain

Charge readout: ATLAS FE-I4B Pixel ASIC

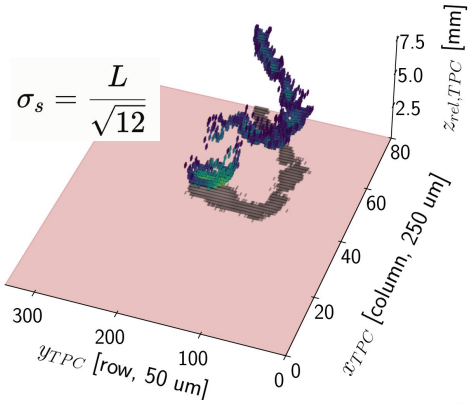
~100 e- noise

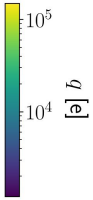
Simulating Detector Effects

2-4 are modeled as detector PR: $\sigma^2_{x,y,z} = \sigma^2_d + \sigma^2_s$

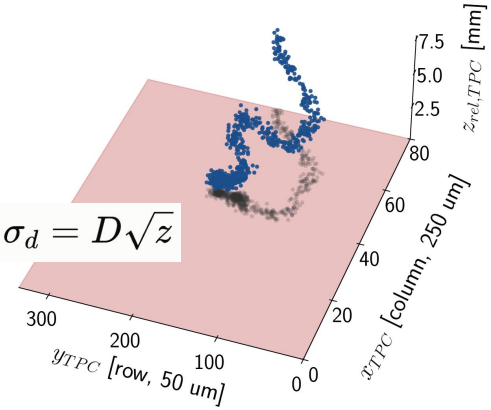


1. Ionization:
25 keV Degrad electron's primary ionization in atm 70:30 $He:CO_2$

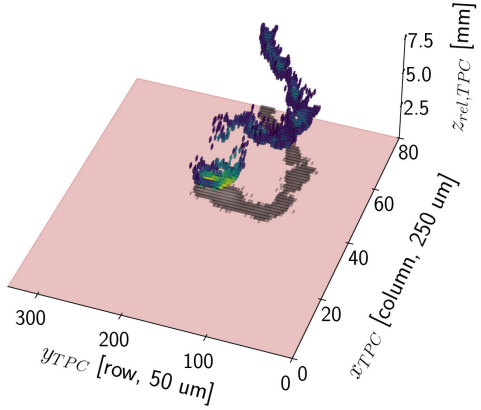


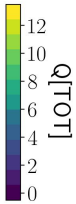


3. Segmentation:
Amplification and readout segmentation



2. Diffusion:
Ionized electrons drift through BEAST TPC, track smearing





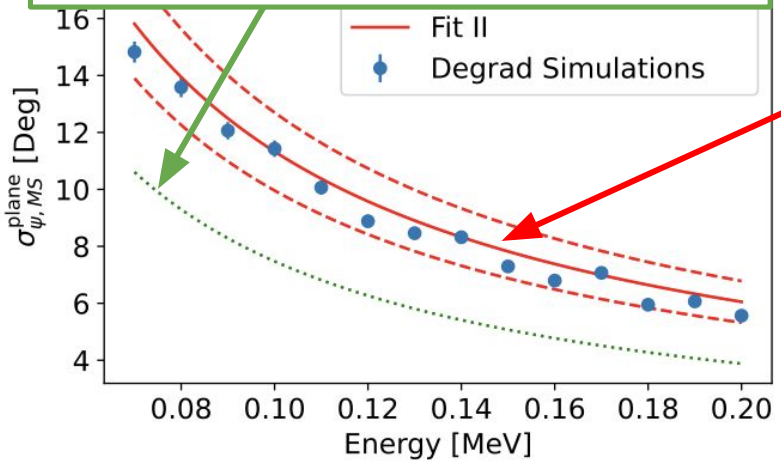
4. Digitization:
Hit threshold, quantize charge into "Time over Threshold", 4-bit ToT resolution

Ghrear & Vahsen, https://arxiv.org/abs/2502.12387 (2025)

Electron Multiple Scattering: Modified PDG Approx.

PDG approx. only fitted for heavy particles, does not consider detector resolution

$$\sigma_{\psi}^{\text{plane}} = \frac{z}{\sqrt{3}} \frac{13.6\,\text{MeV}}{\beta cp} \sqrt{\frac{x}{X_o}} \left[1 + 0.038 ln(\frac{xz^2}{X_o \beta^2})\right]$$



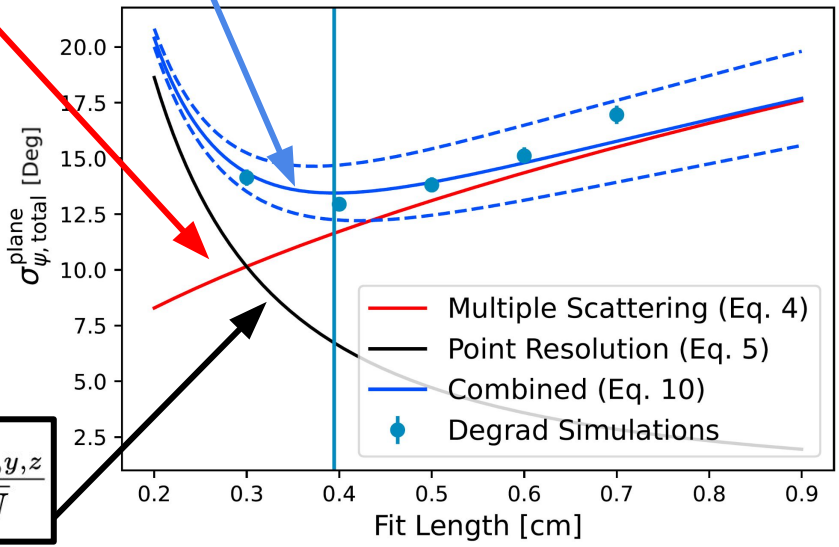
$$\sigma_{\psi,\text{MS}}^{\text{plane}} = \frac{1}{\sqrt{3}} \frac{13.2 \pm 1.59\,\text{MeV}}{\beta cp} \sqrt{\frac{x}{X_o}}$$

Ghrear et al. simulated electron recoils to approx. MS in He:CF_4

Added detector PR contribution

$$\sigma_{\psi,\text{PR}}^{\text{plane}} = \frac{\sqrt{12}\sigma_{x,y,z}}{x\sqrt{N}}$$

$$\sigma_{\psi,\text{total}}^{\text{plane}} = \sqrt{(\sigma_{\psi,\text{MS}}^{\text{plane}})^2 + (\sigma_{\psi,\text{PR}}^{\text{plane}})^2}$$



But is Degrad accurate?

Experiment

We aim to experimentally quantify two performance measures for electron recoils:

- **Angular resolution**
- **Energy resolution**

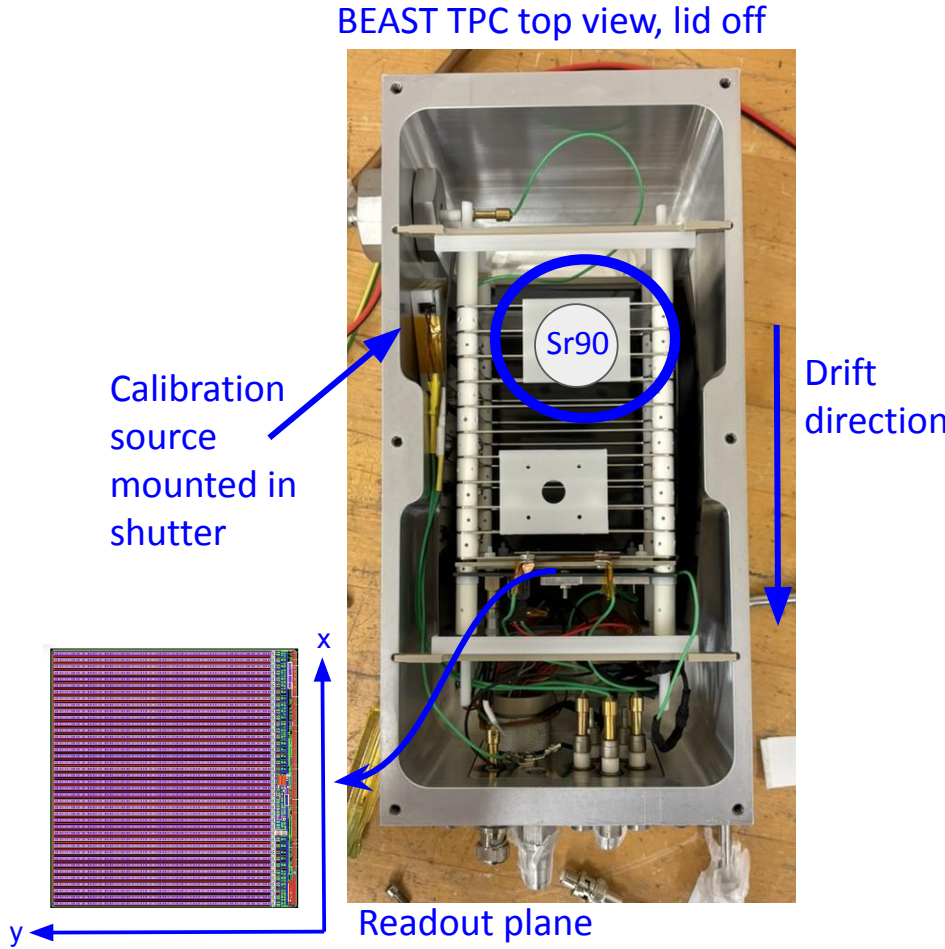
We used 1 atm 70:30 $He:CO_2$

^{55}Fe (calibration, 5.9keV) and ^{90}Sr (signal)

Pixel threshold ~1200 e-

Varied double GEM HV

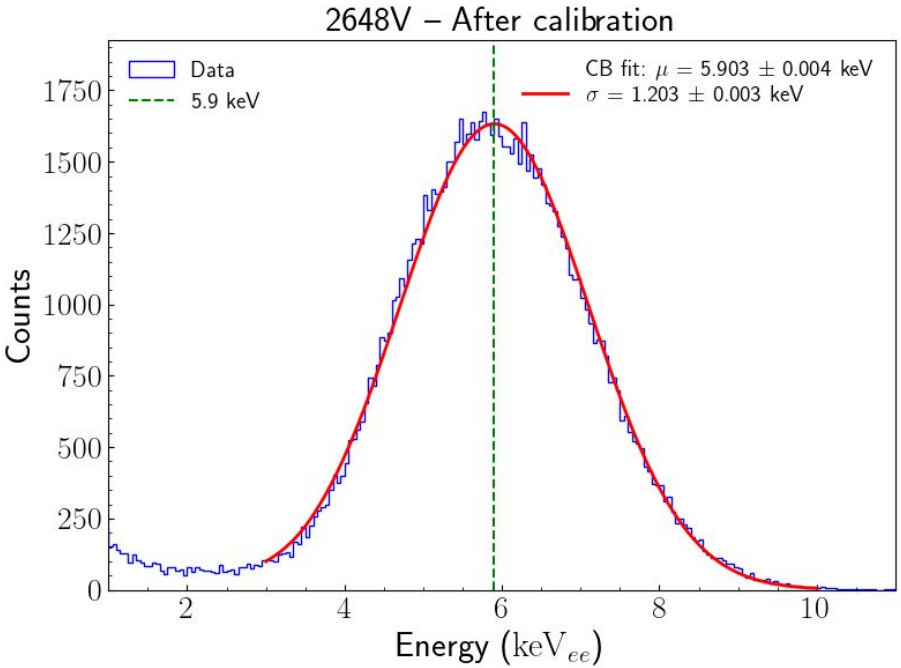
2548 V, 2598 V, 2648 V

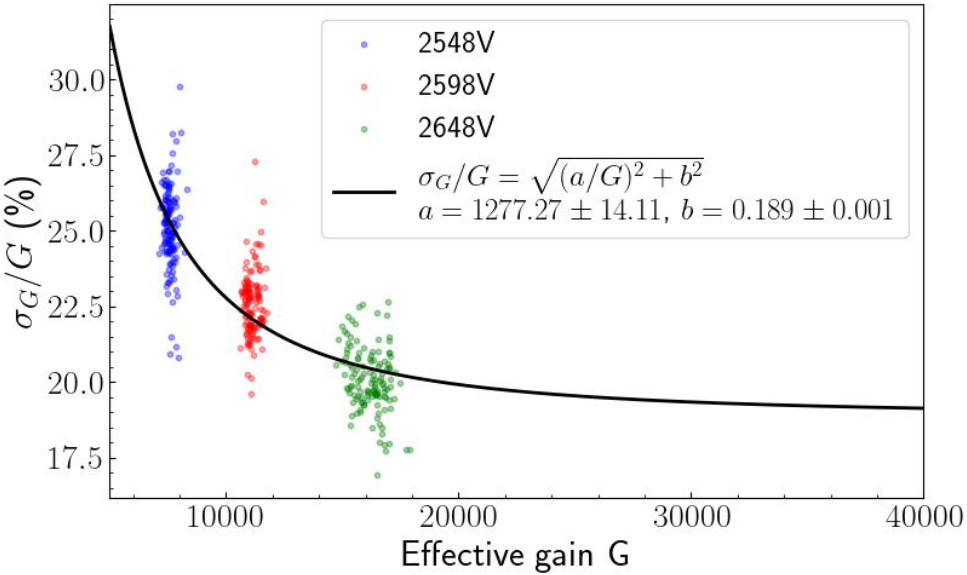


GEM gain resolution and energy calibration

Used known Fe-55 X-ray energy to calibrate the beta energy scale

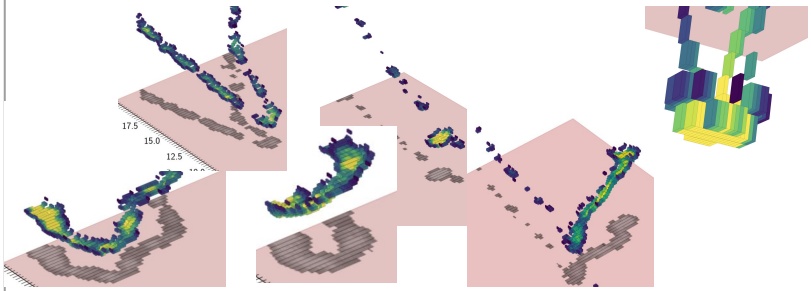
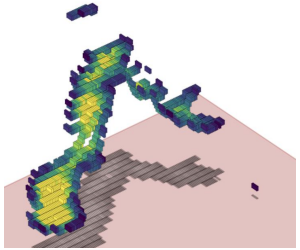
Shutter pattern: 1 min Fe55+Sr90 exposure followed by 10 min Sr90 only

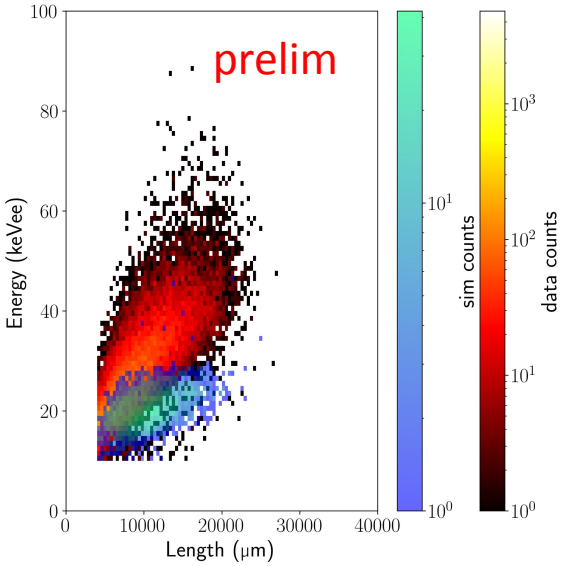




Gain resolution approaches 20% at high gain

Fiducialization and Sr90 track quality selection

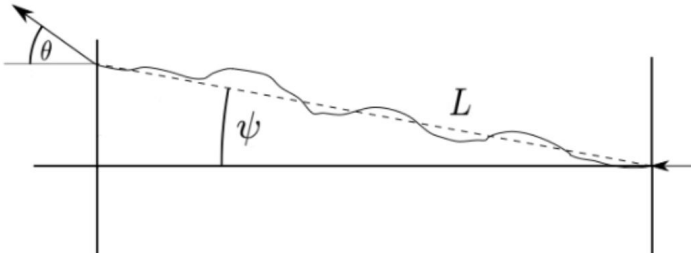
	Fiducialization	Quality cut
Selection criteria	-Require source-side contact only -Edge hits (cols 78–79): keep if y-spread ≤ 2.5 mm, else veto -Δz ≤ 30 mm: reject tracks that fill the drift volume -Earliest BCID cluster ≤ 60% the transverse size of the next	≥ 5 hits, L > 4 mm, E > 10 keV, No gaps ≥ 0.2 mm along the track axis
Rejected event sample		
% of events remaining	57% (9,291,907/16,383,068)	0.4% (66,232/16,383,068)



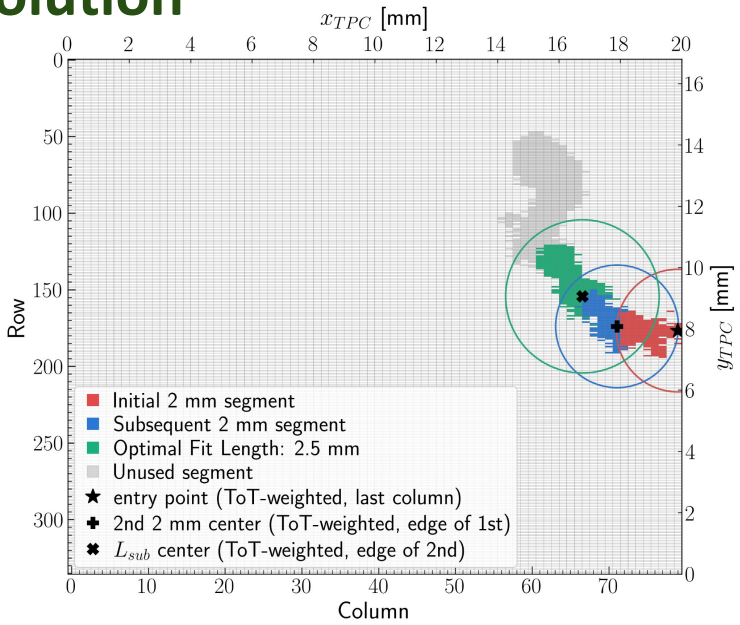
Selected Sr90 L v E distribution vs. simulated 20-30 keV electrons

Measuring Angular Resolution

Sample Sr90 MC



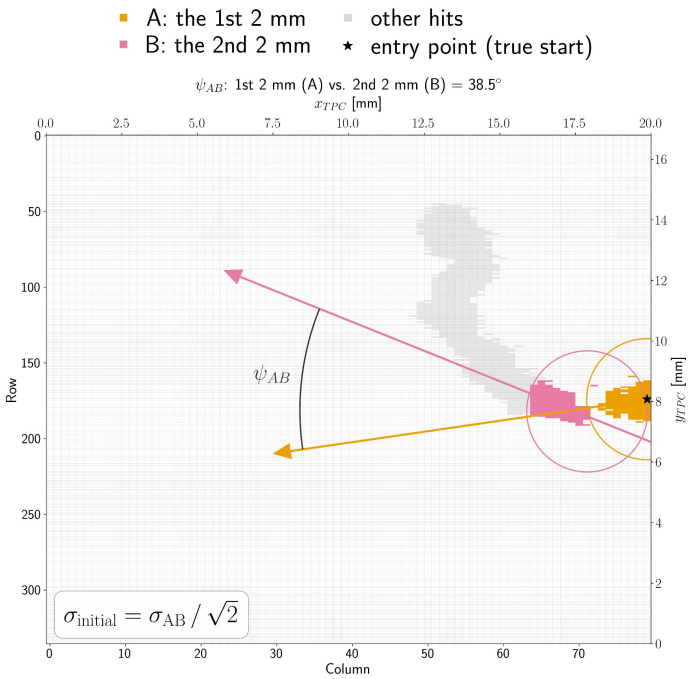
Ghrear & Vahsen, https://arxiv.org/abs/2502.12387 (2025)

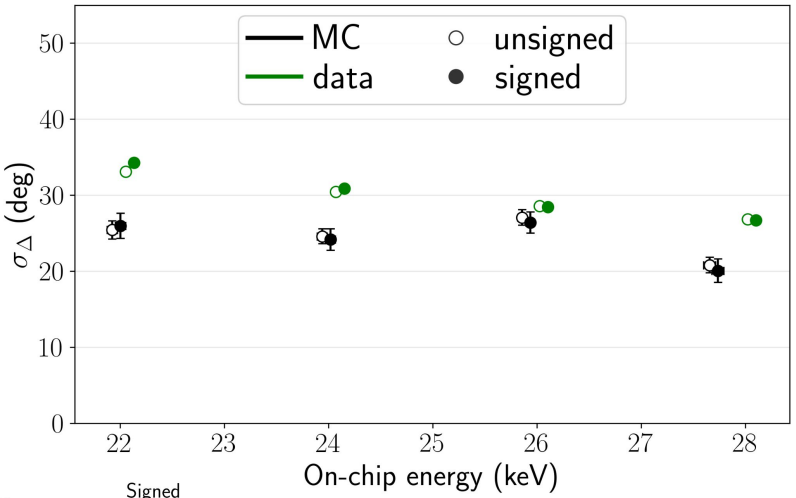


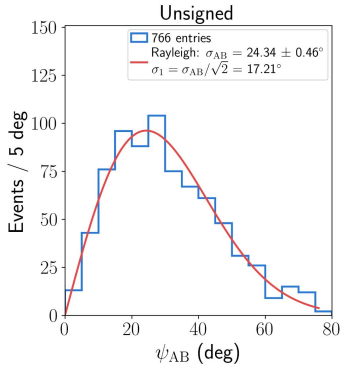
1. Estimate the initial direction of recoil
2. Vary L from 1-7 mm
3. Measure ψ, fit for sigma of scattering angle distribution

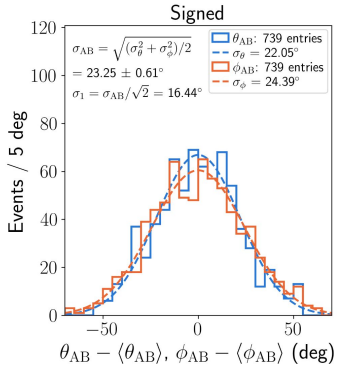
How to Estimate Initial Recoil Direction?

Use known true initial direction in MC to check



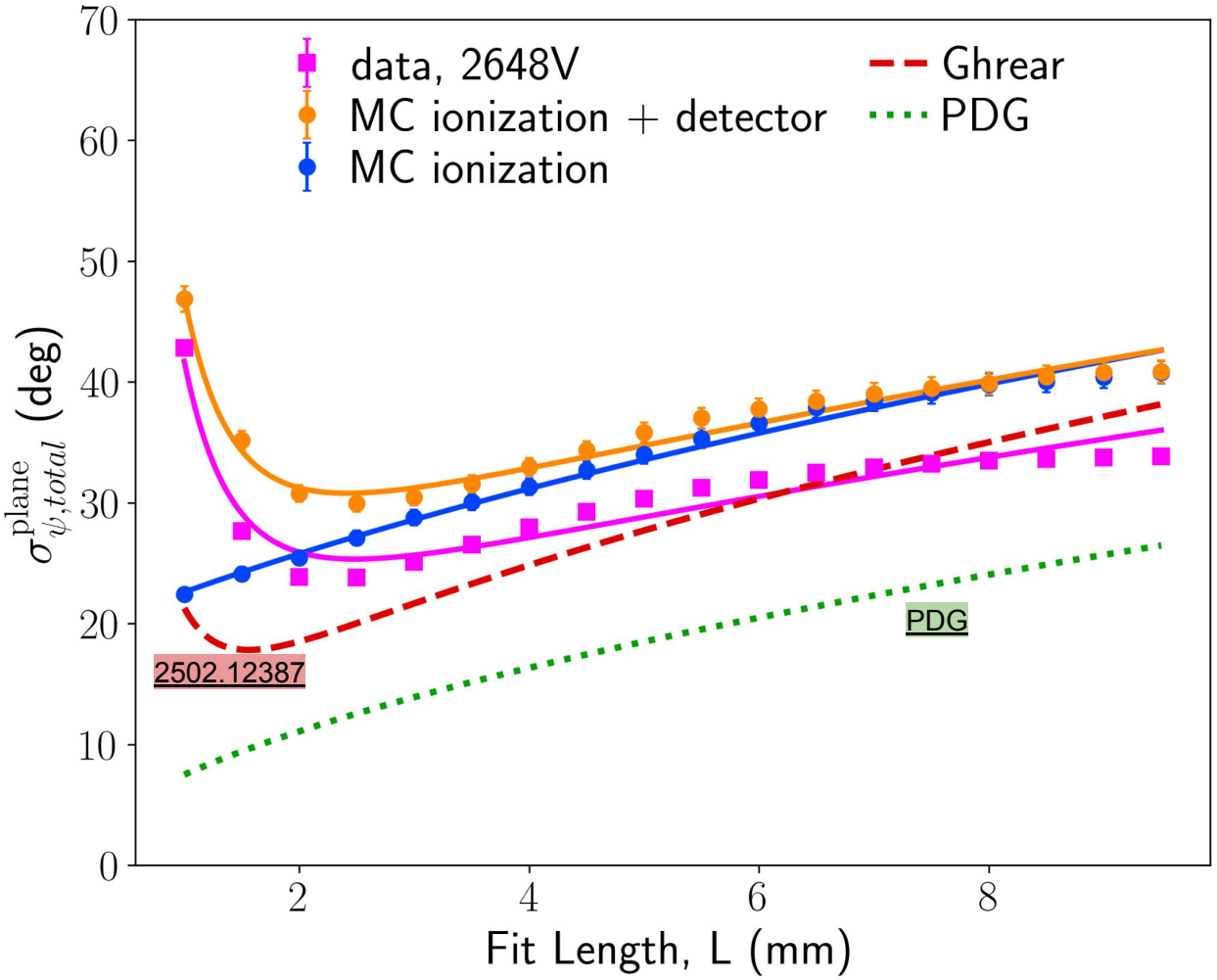




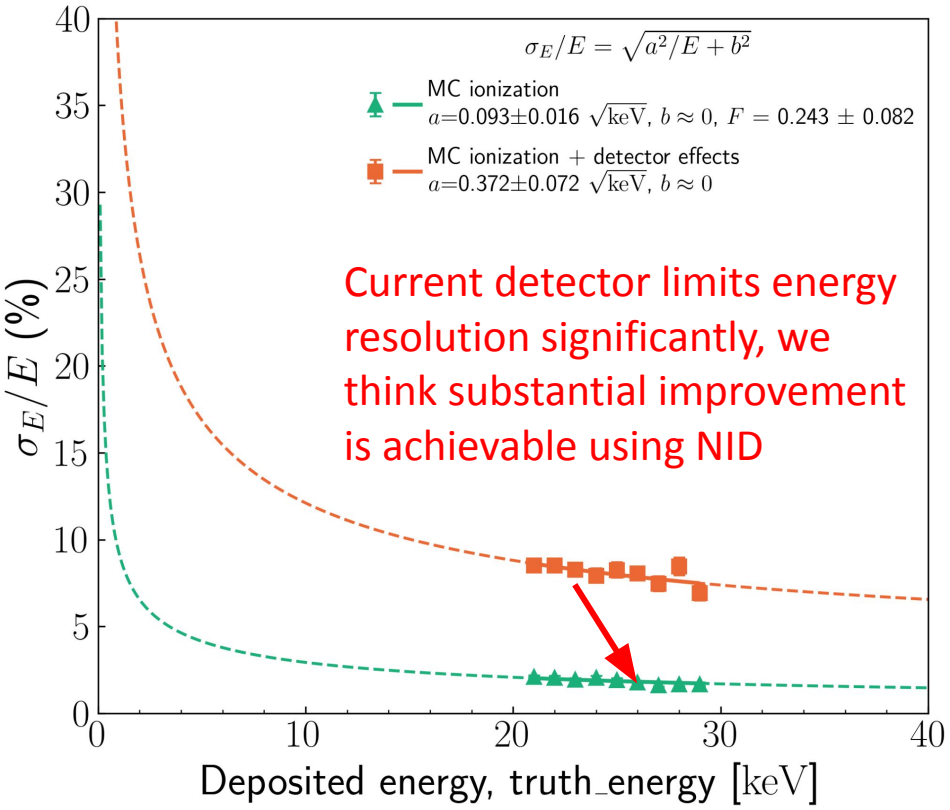


Preliminary Results

- Simulation shows that full detector contribution to the angular resolution is small at large L
- Experimental data suggests that electrons scatter more than predicted by the PDG approximation
- Simulation and data do not agree fully, systemic errors to be resolved



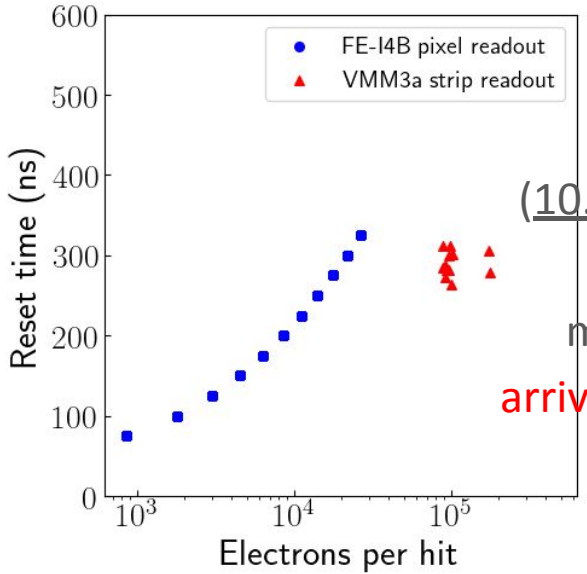
Energy Resolution: Towards Electron Counting



Current detector limits energy resolution significantly, we think substantial improvement is achievable using NID

For scalability, pixel readout is expensive (~ $18 / cm2 = $180k / m2), strip readout is cheaper per unit.

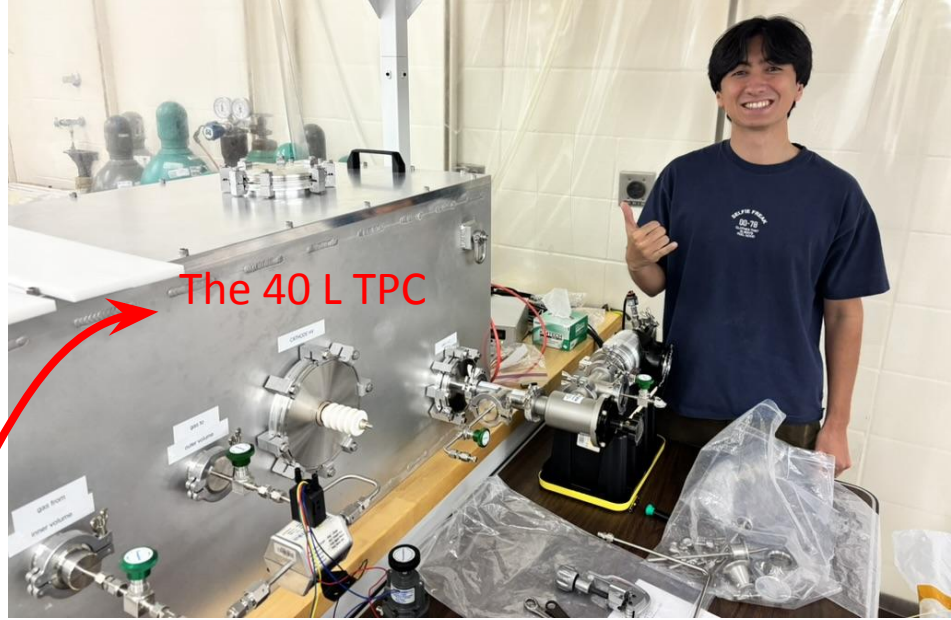
Key: both satisfy reset timing needed for single electron counting!



Sorensen et al. (10.1016/j.nima.2012.05.078, 2012) measured NID ion arrivals spaced 22 ms apart on average

Summary and Outlook

- Investigated modified electron MS predicted by Ghrear et al.
- Preliminary: Ghrear prediction is closer to experimental data than PDG approx.
- Established baseline detector performance to be improved with NID
  - Next: 1000x scale up being commissioned at U. Hawaii
  - Plan to operate with electronegative gas and glass GEMs



40 L status as of Oct 2026: measuring H_2O and O_2 levels inside the TPC.

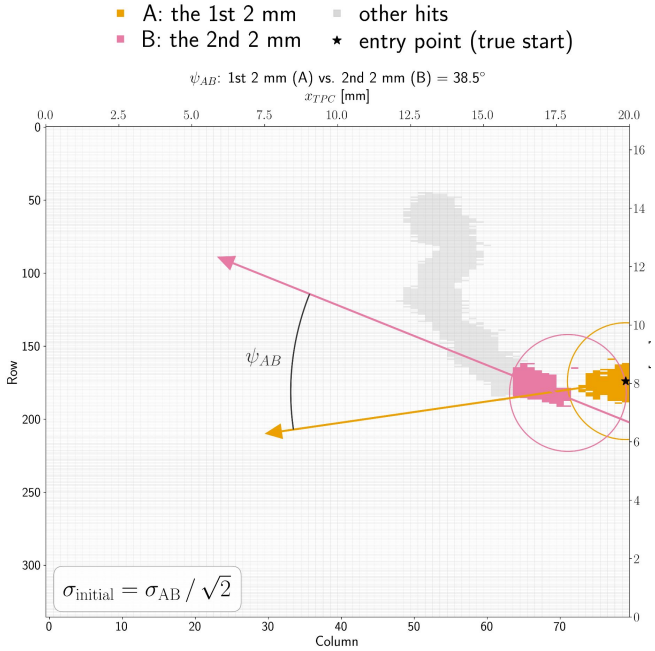
Thank you!

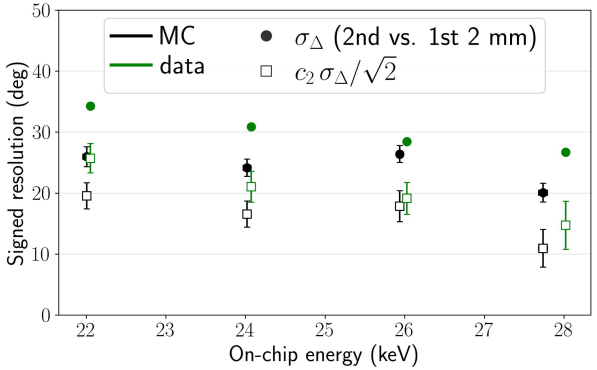
longhaiq@hawaii.edu

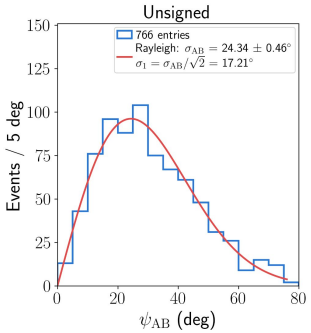
Back Up

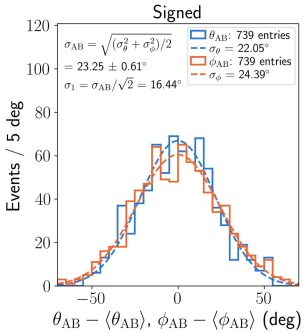
How to Estimate Initial Recoil Direction?

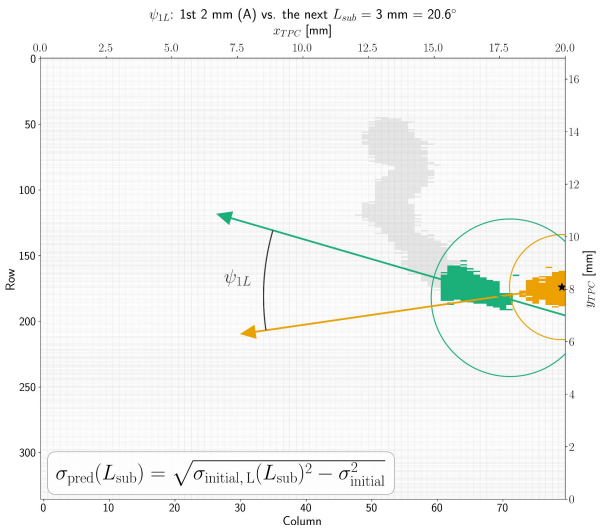
Use MC to check self-consistency, pending systematic error between MC and data

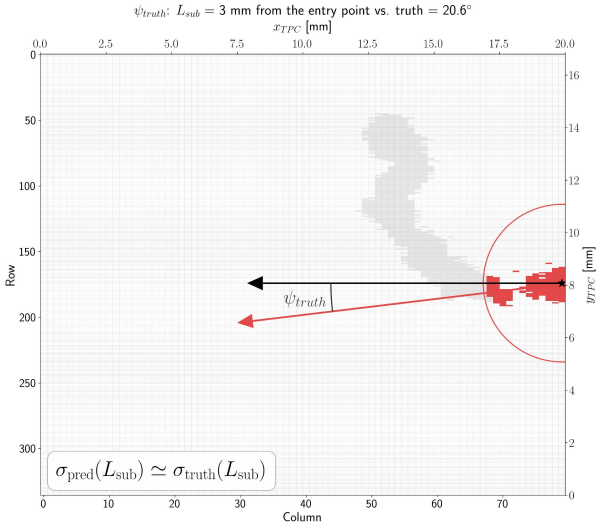


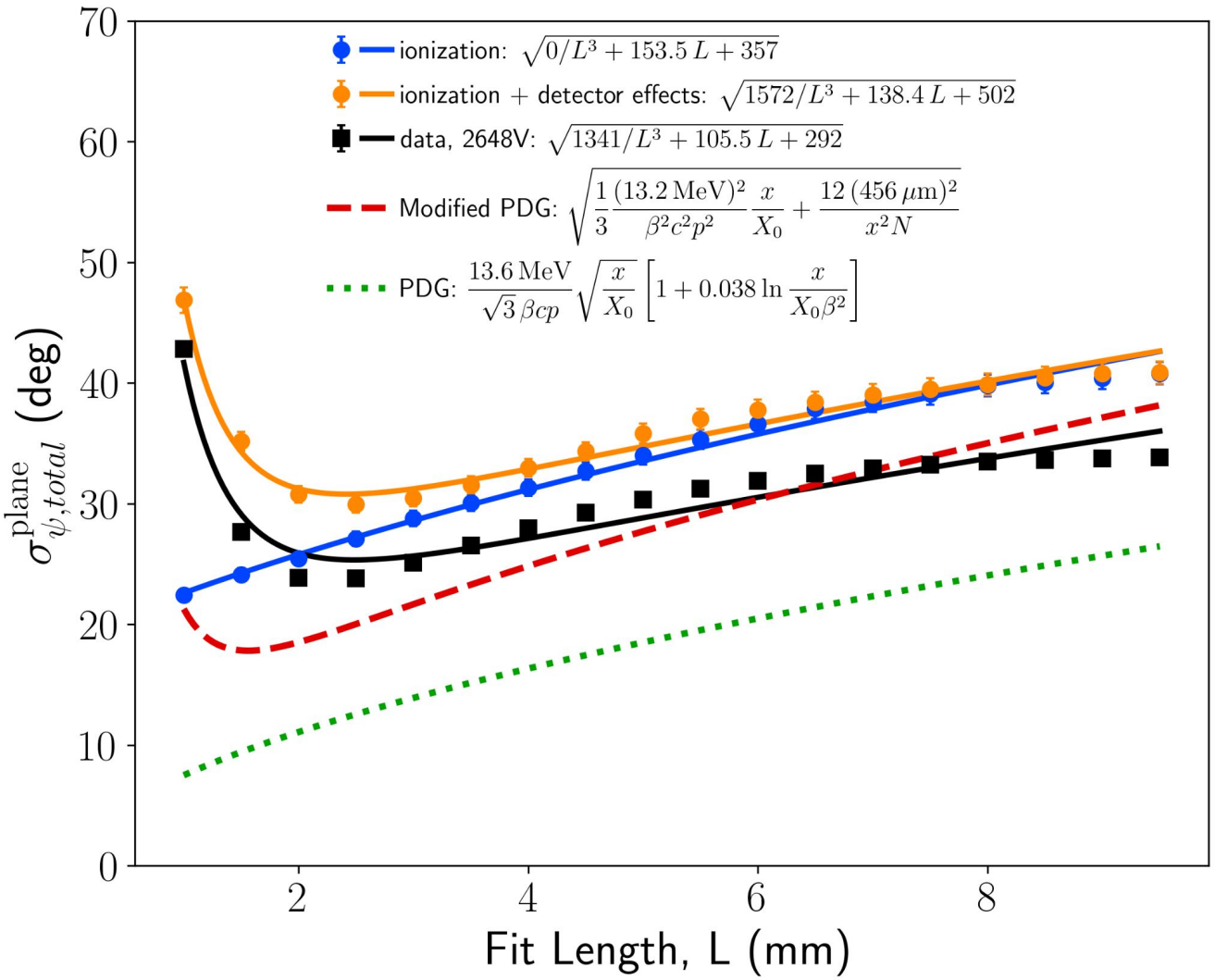











ionization: $\sqrt{0/L^3 + 153.5\,L + 357}$
ionization + detector effects: $\sqrt{1572/L^3 + 138.4\,L + 502}$
data, 2648V: $\sqrt{1341/L^3 + 105.5\,L + 292}$
Modified PDG: $\sqrt{\frac{1}{3}\frac{(13.2\,\mathrm{MeV})^2}{\beta^2c^2p^2}\frac{x}{X_0} + \frac{12\,(456\,\mu\mathrm{m})^2}{x^2N}}$
PDG: $\frac{13.6\,\mathrm{MeV}}{\sqrt{3}\,\beta cp}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\ln\frac{x}{X_0\beta^2}\right]$
$\sigma^{\mathrm{plane}}_{\psi,total}$ (deg)
Fit Length, L (mm)
0
10
20
30
40
50
60
70
2
4
6
8

Effective gain

Before: GEM voltage of 0.362*2548=922V

After: double GEM voltage of 0.362*2598=940V.

50V increase produces a 18V increase across both gems (9 for each GEM).

Eyeballing the fitted lines in the plot, and 18V increase will give roughly a 50% increase of the gain.

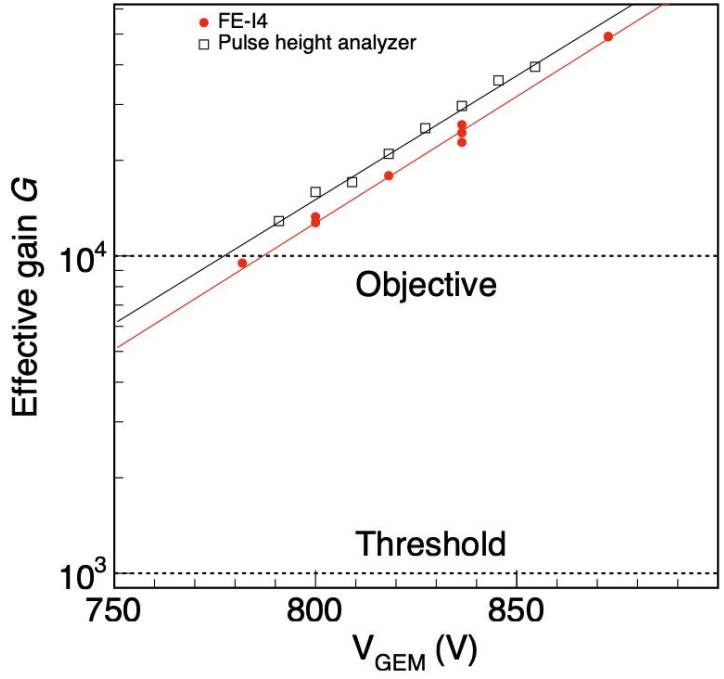
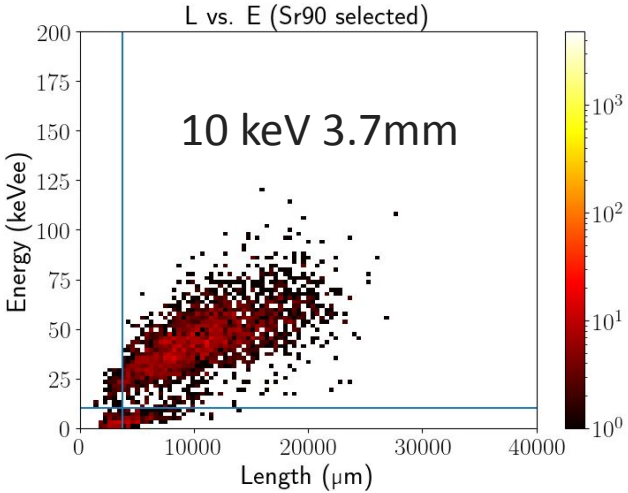


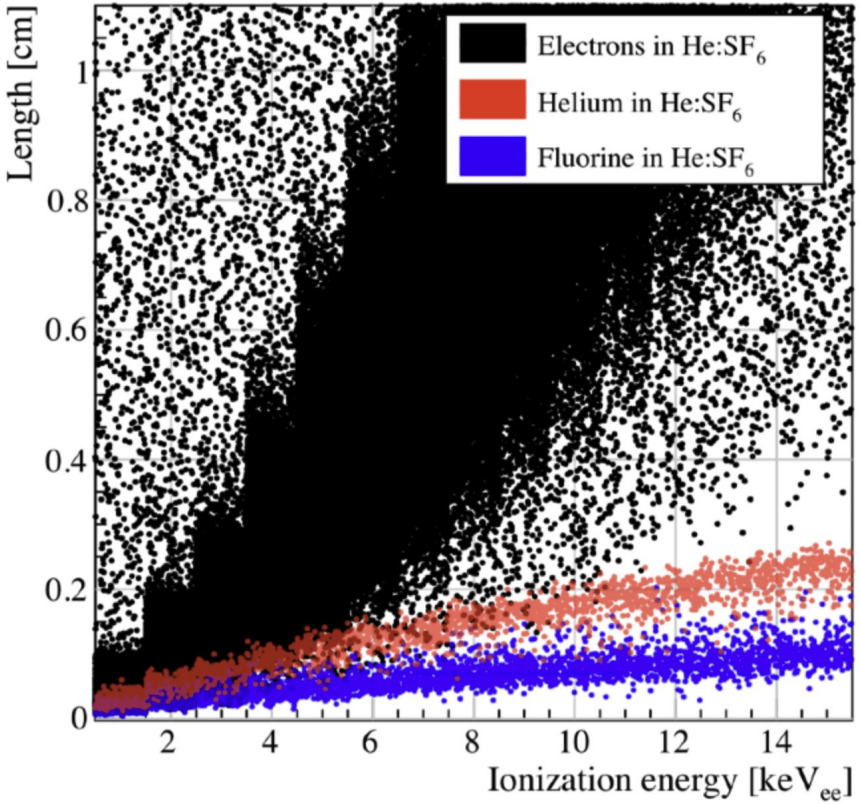
Figure 15: Effective gain, G, as function of the double-GEM voltage for a final TPC. Red points: chip measurements. Black open squares: copper pad measurements. The two dashed lines show the objective and threshold gain values.

LvE Band

The mass density in He:SF6 is 3.24 times lower than in He:CO2 70:30

To first order, dE/dX is proportional to mass (and hence electron) density of the target





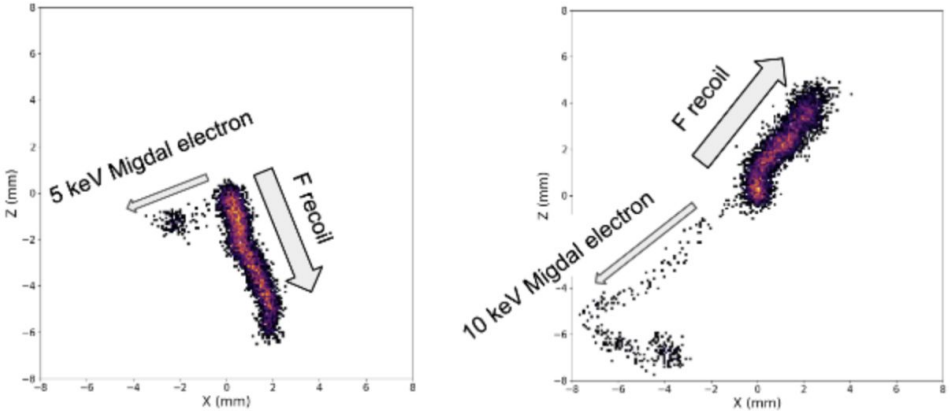
arXiv:2502.12387 **[physics.ins-det]**

Low-energy Electron Recoils

Free electron traverses a gaseous medium, undergoes multiple scattering, altering its trajectory and generating a track of secondary, ionized electrons.

Crucial fundamental process for detecting electron tracks in gaseous targets used in rare-event searches.

E.g. Directional analysis of overlapping nuclear and electron recoil tracks at the MIGDAL experiment.



An example image of tracks produced due to the Migdal effect from neutron bombardment of Fluorine.

https://migdal.pp.rl.ac.uk/

Multiple Scattering Through Small Angles

Standard Moliere scattering angular resolution approximation (PDG)

$$\sigma_{\psi}^{\text{plane}} = \frac{z}{\sqrt{3}} \frac{13.6\,\text{MeV}}{\beta cp} \sqrt{\frac{x}{X_o}} \left[1 + 0.038 ln(\frac{x z^2}{X_o \beta^2}) \right] \quad (3)$$

z: charge of the particle

β, p: speed, momentum of the particle

x/X_o: thickness of the scattering medium in radiation lengths

Fitted for heavy particles:

S_2 = 13.6 MeV and ε = 0.038

Inaccurate for electrons and does not consider detector resolution.

Angular Analysis - Scattering Angle

Signed Ψ

Change in angular components (θ, φ) using the distribution's standard deviation.

$$\sigma_{\psi}^{\text{plane}} = \frac{\sigma_{\psi}^{3D}}{\sqrt{2}}$$

Unsigned Ψ

3D angle between direction vectors, using the mean.

$$\sigma_{\psi}^{\text{plane}} = \frac{\langle \Delta\psi \rangle_{3D}}{\sqrt{\pi}}$$

