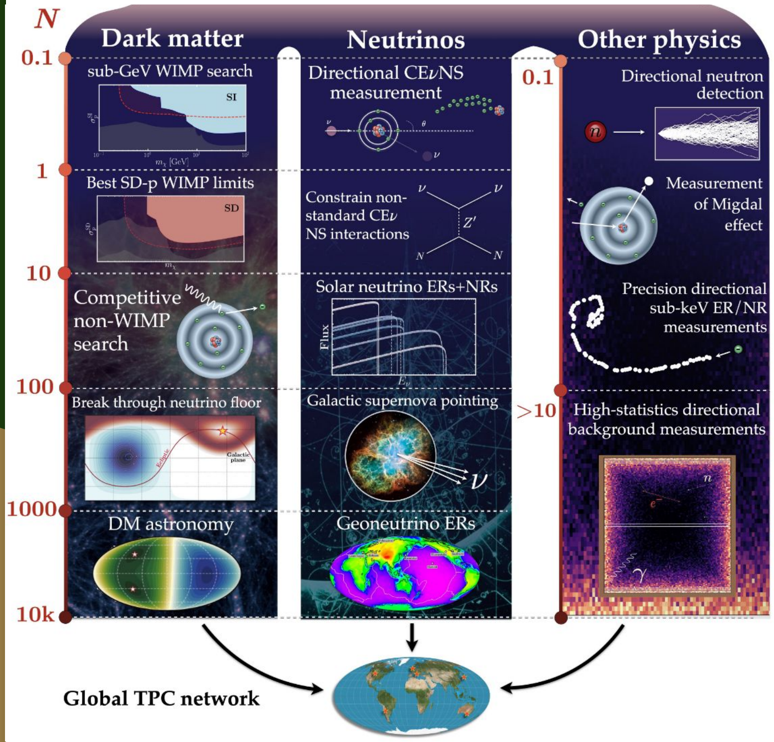
3D reconstruction of low-energy electron recoils in gas Time Projection Chambers with MPGD charge readouts

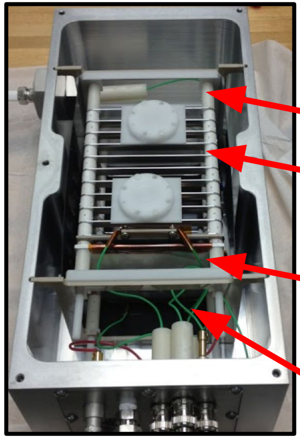
Majd Ghrear, Jeff Schueler, Sven Vahsen
majd@hawaii.edu

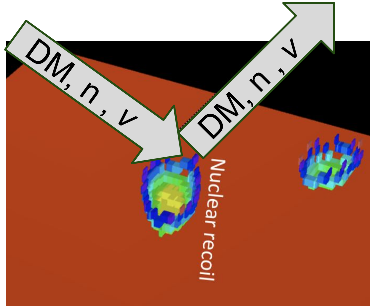
UNIVERSITY of HAWAIʻI®
MĀNOA

*This work was supported by the U.S. Department of Energy (DOE) via Award Number DE-SC0010504

Background





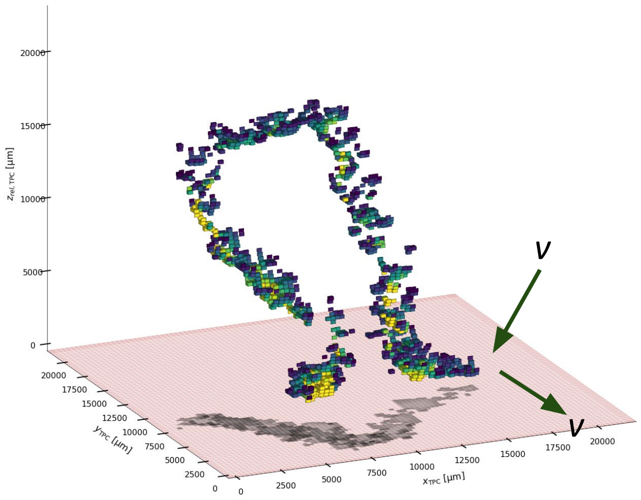


BEAST TPC

- 70:30 mixture of He:CO_2 at STP
- Cathode
- Field cage rings (~450 V/cm drift field => 220 μm / 25ns-time bin drift speed)
- Double GEM amplification capable of gains up to O(50,000)
- ATLAS FE-I4 pixel ASIC readout
- 80 x 336 grid of (250 x 50) μm^2 pixels
- 4-bit TOT charge quantization
- Noise floor ~100 electrons
- Single electron efficiency at ~20k gain

Directional Recoil Detection https://doi.org/10.1146/annurev-nucl-020821-035016
Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging https://doi.org/10.1016/j.nima.2019.06.037

Background



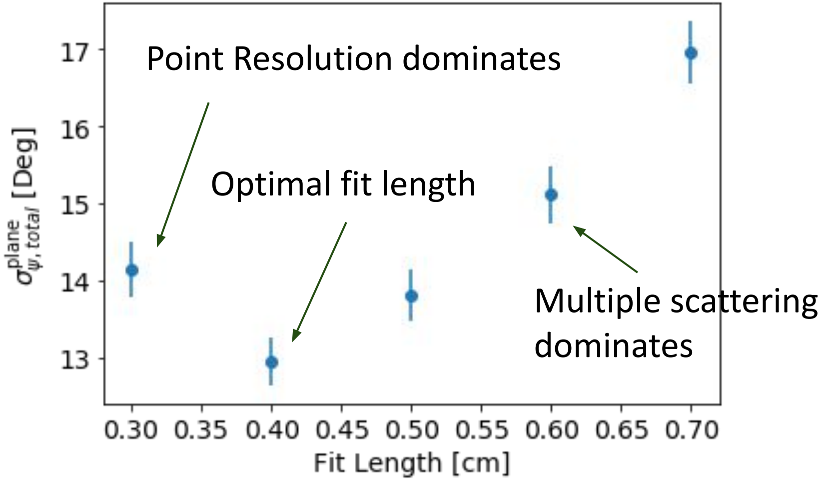
3D reconstruction of ~40 keV electron recoil in He : CO2 using BEAST TPC

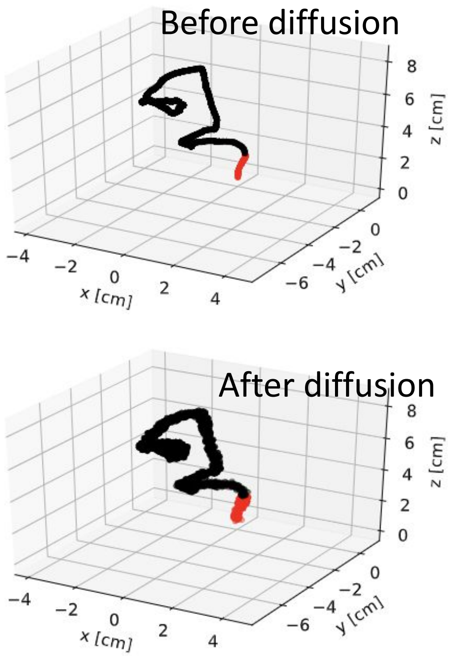
Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging, NIMA 2019. https://doi.org/10.1016/j.nima.2019.06.037

- 3D reconstruction of electron recoils widely applicable
  - Characterization of the Migdal effect
  - X-ray polarimetry
  - Neutrino detection
- Low charge densities and non-trivial topologies, requiring highly segmented and sensitive MPGD charge readouts
- **We focus on a method for estimating and optimizing the accuracy with which we can determine the initial direction (i.e. the angular resolution)**
  - **Goal 1:** validate with existing small pixel TPCs
  - **Goal 2:** use method to optimize design of future detectors

Electron recoils

- Two first-order effects influencing the angular resolution of electron recoils in gas TPCs:
  - Multiple scattering of the recoiling electron
  - Effective point resolution of the detector
- The multiple scattering effect dominates at longer fit length and the point resolution effect dominates at shorter fit lengths.





Degrad simulation of a 150 keV electron recoil in He : CF4.

Majd Ghrear
Majd@hawaii.edu

Multiple Scattering - History

Rossi and Greisen
“Cosmic-Ray Theory”

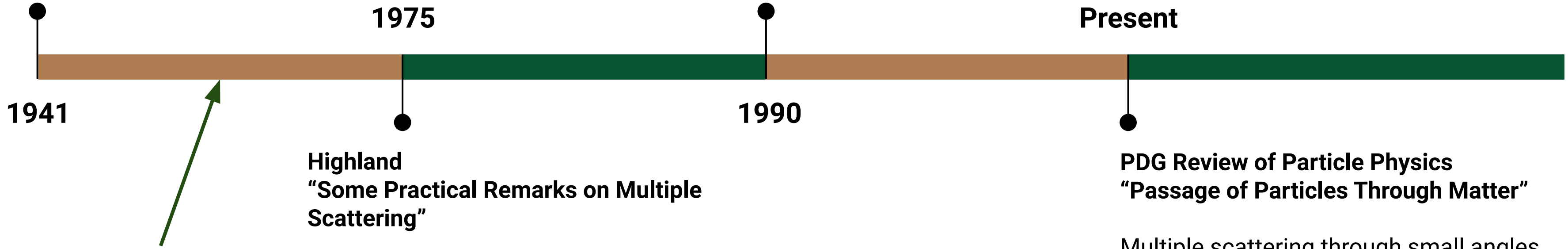
Derived first simple gaussian approximation of multiple scatter via statistical methods.

$$\sigma_{\Psi}^{\text{plane}}(x) = \frac{1}{\sqrt{3}} \frac{14.8\text{MeV}}{\beta cp} \sqrt{\frac{x}{X_o}}$$

Lynch and Dahl
“Approximations to multiple Coulomb Scattering”

Noted Highland didn’t use Bethe’s prescription of Moliere Theory. Refit the Highland’s equation, specifying the fit is for heavy particles.

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



Moliere Theory:
Moliere (1947)
Bethe (1953)

Highland
“Some Practical Remarks on Multiple Scattering”

Added a correction term and fit Rossi and Greisen’s equation to approximations of Moliere Theory.

$$\sigma_{\Psi}^{\text{plane}} = \frac{1}{\sqrt{3}} \frac{13.9\text{MeV}}{\beta cp} \sqrt{\frac{x}{X_o}} \left[1 + 0.048 \ln(\frac{x}{X_o \beta^2})\right]$$

PDG Review of Particle Physics
“Passage of Particles Through Matter”

Multiple scattering through small angles

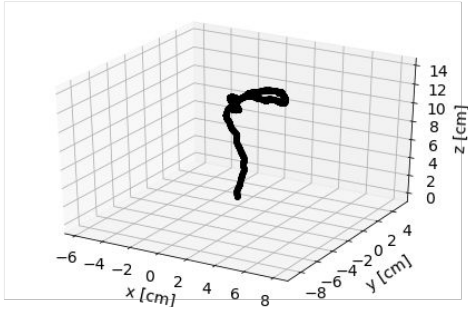
$$\sigma_{\psi}^{\text{plane}} = \frac{z}{\sqrt{3}} \frac{13.6\text{MeV}}{\beta cp} \sqrt{\frac{x}{X_o}} \left[1 + 0.038 ln(\frac{xz^2}{X_o \beta^2})\right]$$

Majd Ghrear
Majd@hawaii.edu

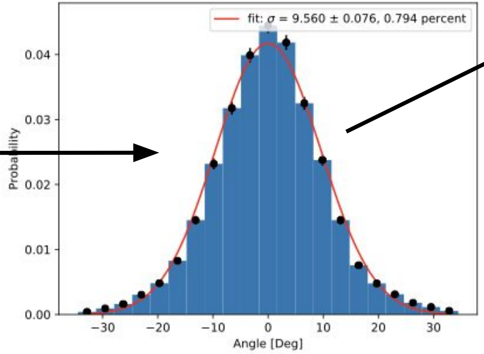
Multiple Scattering - Fitting

$$\sigma_{\psi}^{\text{plane}} = \frac{1}{\sqrt{3}} \frac{S_2}{\beta c p} \sqrt{\frac{x}{X_o}} \left[1 + \varepsilon \ln \frac{x}{X_o} \right]$$

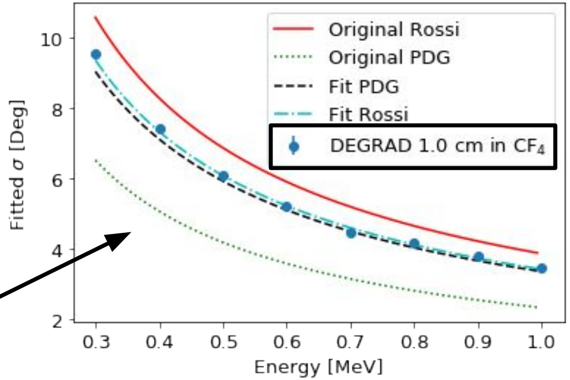
DEGRAD Electron Simulation
(CF_4 , 200 keV)

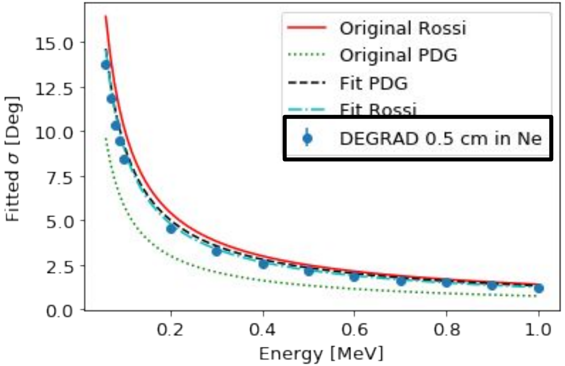


Angular distribution
(CF_4 , 300 keV, 1 cm)



Fitted Sigma vs Energy / Length / Gas





Electron recoils simulations

Gases: CF_4, CO_2, CH_4, C_2H_6, Ne, Ar, Xe

Energies: 100 - 1000 keV

Fit Length: 0.5 - 2 cm

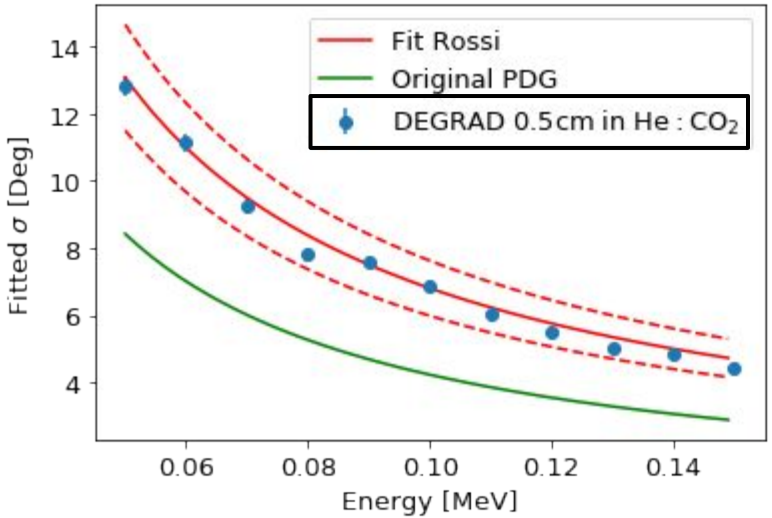
Majd Ghrear
Majd@hawaii.edu

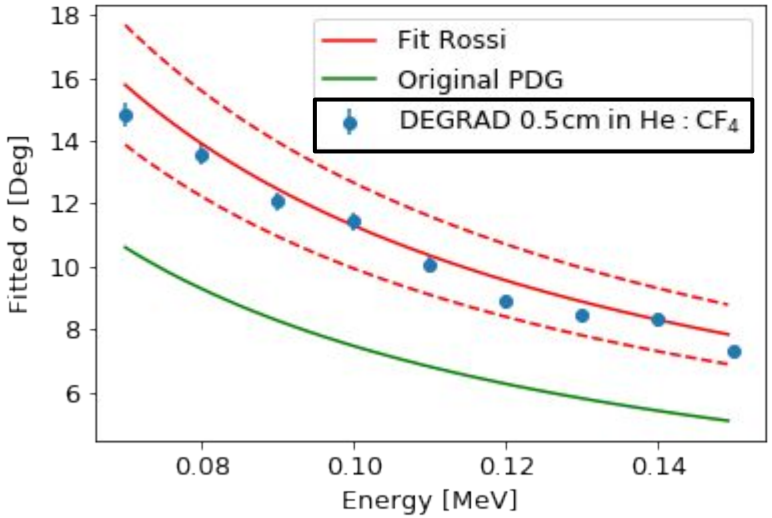
Multiple Scattering: Testing on indep. gas mixtures

Gas Mixture	Pressure [Torr]	Rad. Length [m]
60% He 40% CF4	760	220
70% He 30% CO2	760	606

The Lynch and Dahl equation quoted in the PDG is not accurate for electron recoils in gas

$$\sigma_{\psi,\mathrm{MS}}^{\mathrm{plane}} = \frac{1}{\sqrt{3}} \frac{13.1 \pm 1.5\mathrm{MeV}}{\beta c p} \sqrt{\frac{x}{X_o}}.$$





Majd Ghrear
Majd@hawaii.edu

Effective Point Resolution

- The Multiple Scattering formula alone is insufficient
- We need to consider effective point resolution for a more complete picture
- We have a conversion from point resolution to angular resolution

Angular resolution

Effective point resolution:
Diffusion and readout

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

- We combine the point resolution and multiple scattering effects in quadrature

3-D tracking in a miniature time projection chamber
https://doi.org/10.1016/j.nima.2015.03.009

Majd Ghrear
Majd@hawaii.edu

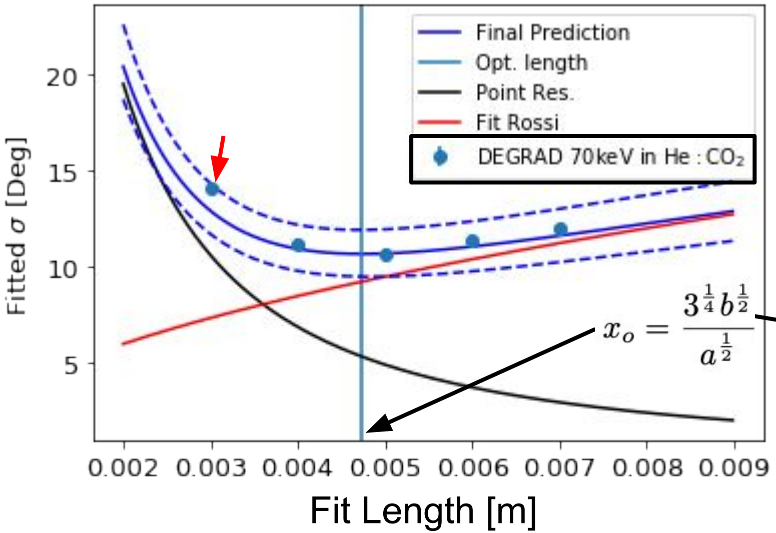
Results

$$\sigma_{\psi,\text{total}}^{\text{plane}} = \sqrt{a^2 x + b^2 x^{-3}}.$$

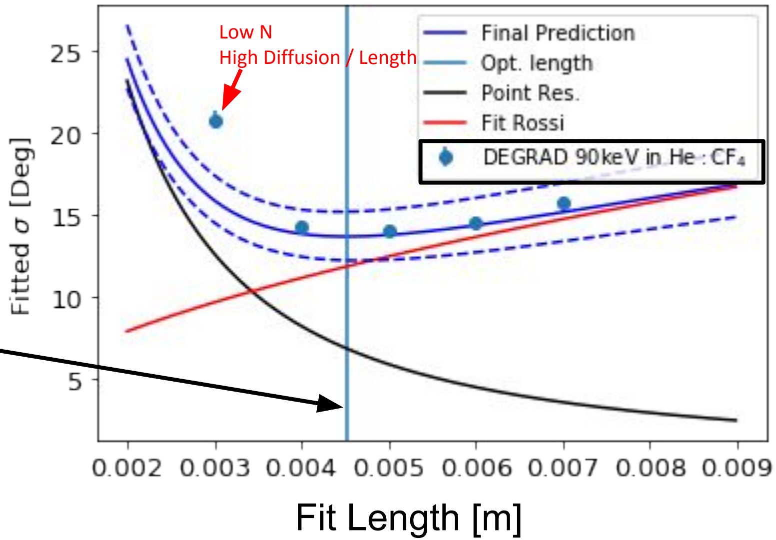
$$a \equiv \frac{1}{\sqrt{3}} \frac{13.1\text{MeV}}{\beta c p \sqrt{X_o}}$$

$$b \equiv \sigma_{x/y/z} \sqrt{\frac{12W}{dE/dx}}$$

70 keV electron recoils in 70% He 30% CO2



90 keV electron recoils in 60% He 40% CF4



- The optimal track length is well predicted
- The angular resolution near the optimal length is well predicted

Majd Ghrear
Majd@hawaii.edu

Findings

If we define

$$a \equiv \frac{1}{\sqrt{3}} \frac{13.1\text{MeV}}{\beta c p \sqrt{X_o}} \qquad b \equiv \sigma_{x/y/z} \sqrt{\frac{12W}{dE/dx}}$$

The angular resolution is approximated by

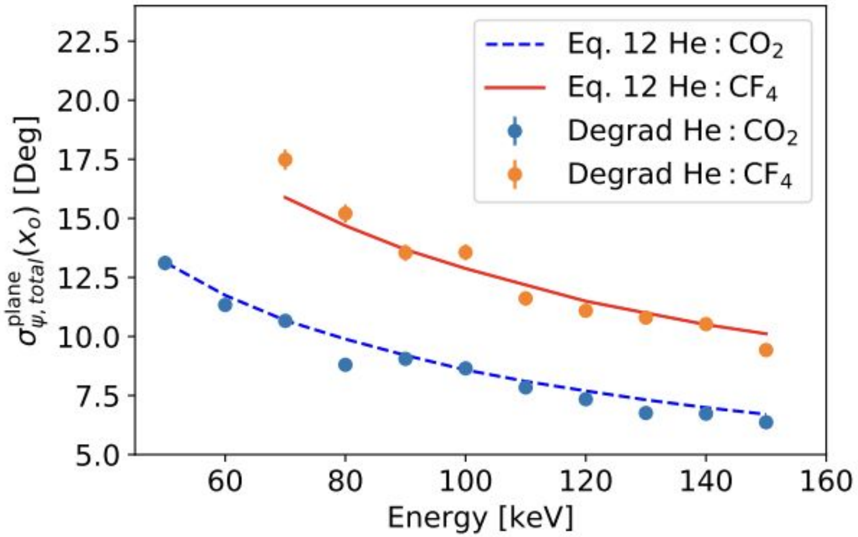
$$\sigma_{\psi,\text{total}}^{\text{plane}} = \sqrt{a^2 x + b^2 x^{-3}}.$$

which is minimized by

$$x_o = \frac{3^{\frac{1}{4}} b^{\frac{1}{2}}}{a^{\frac{1}{2}}}.$$

This provides a quick way to estimate the angular resolution of electron recoils as

$$\sigma_{\psi,\text{total}}^{\text{plane}}(x_o) = \frac{2a^{\frac{3}{4}} b^{\frac{1}{4}}}{3^{\frac{3}{8}}}.$$

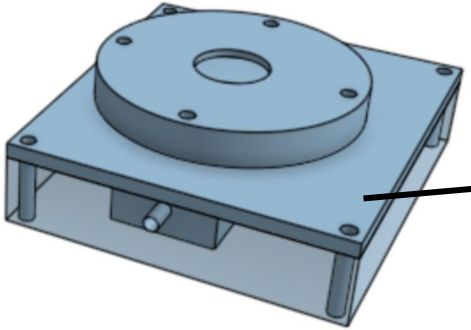


Majd Ghrear
Majd@hawaii.edu

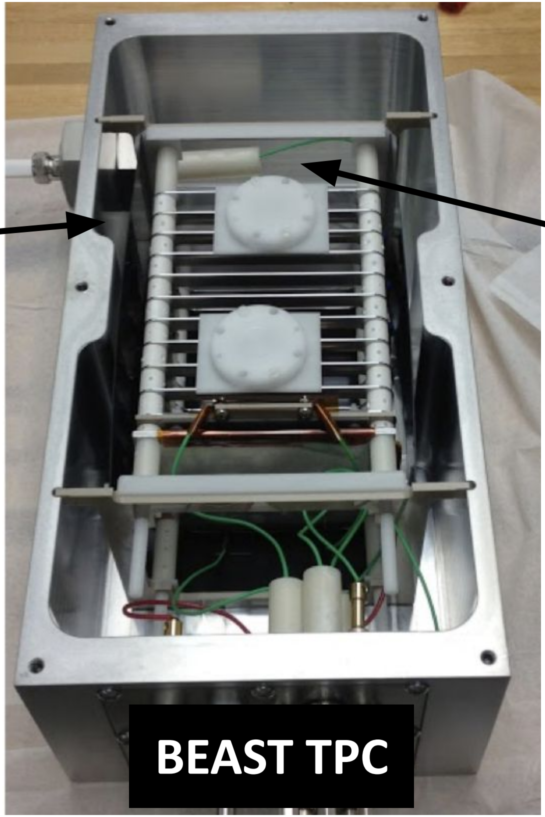
Experimental setup

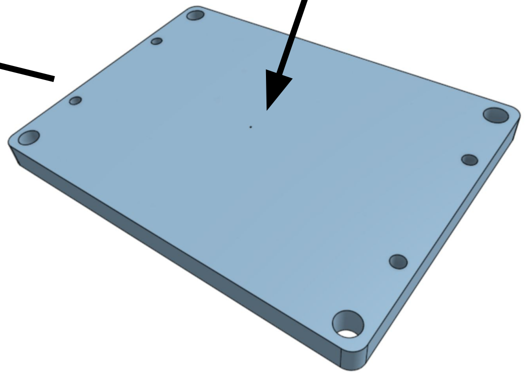
Cd-109 source

Electron signal source



Fe-55 gain/energy calibration source behind shutter

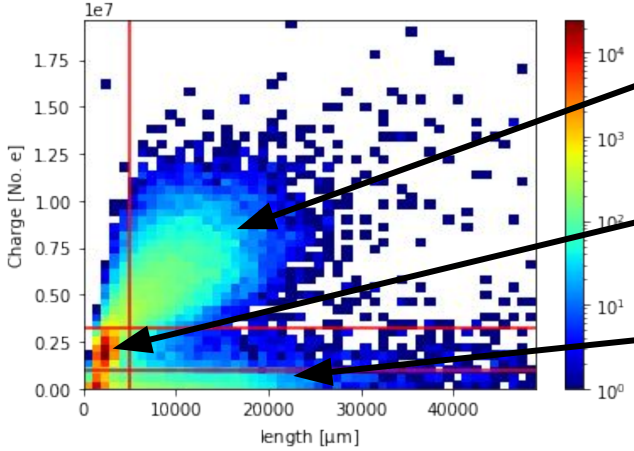




¼” aluminum sheet with 0.013” collimation hole

Majd Ghrear
Majd@hawaii.edu

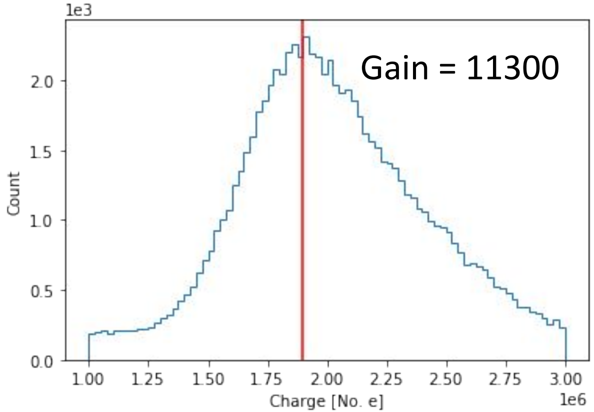
Preliminary experimental results: Fe-55 shutter open



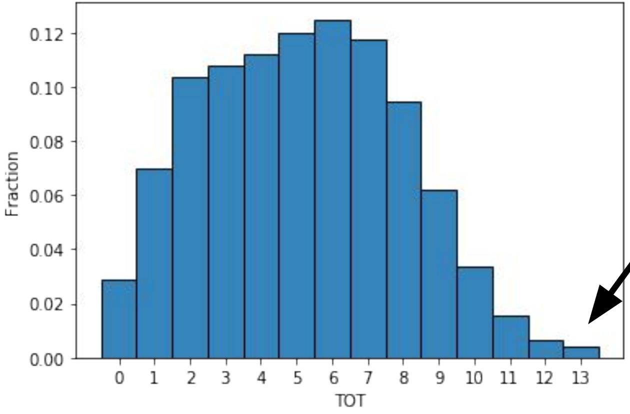
Cd-109 Electron Band

Fe-55 x-ray conversion peak

Cosmic ray band



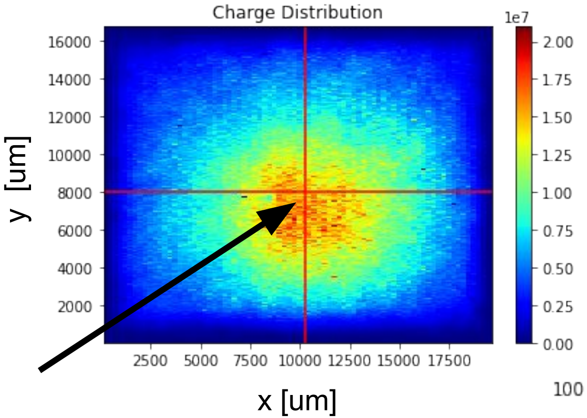
Fe-55 TOT distribution



No saturation

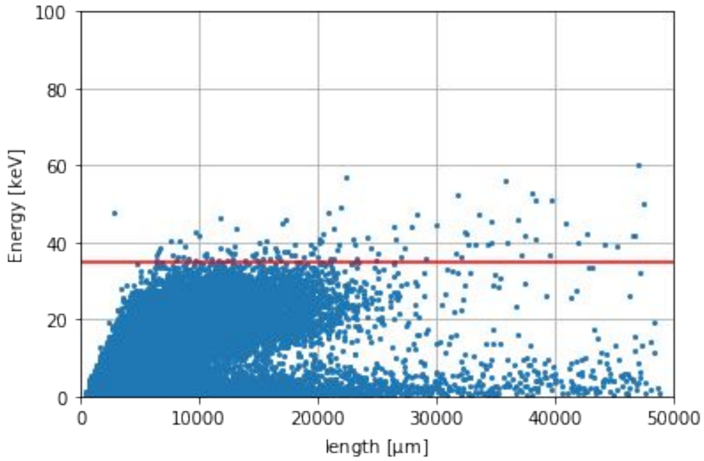
Majd Ghrear
Majd@hawaii.edu

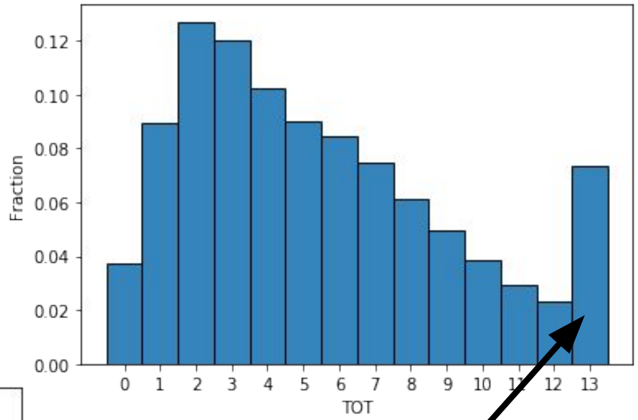
Preliminary experimental results: Fe-55 shutter closed



Collimation hole location over pixel chip

Signal candidates are events from the Cd-109 electron band with energy > 35 keV that start at the collimation hole location.

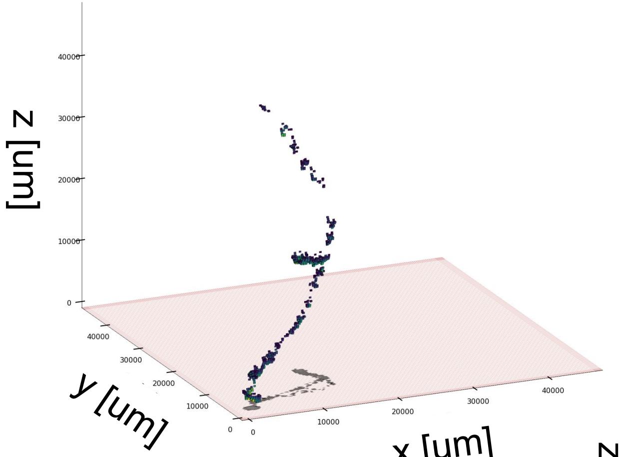


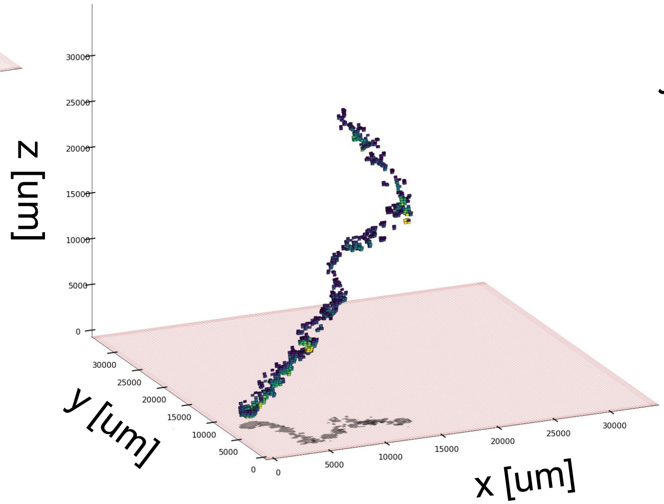


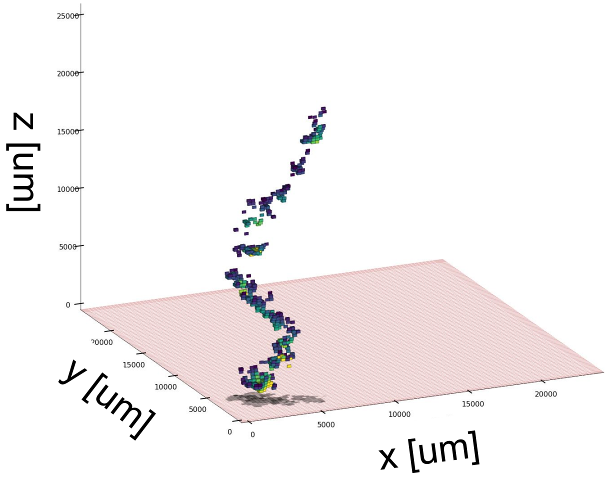
Saturation

Majd Ghrear
Majd@hawaii.edu

Visualizations of potential electron signal events







Majd Ghrear
Majd@hawaii.edu

Summary

- We investigated the angular resolution of electron recoils in gas TPCs
- The common PDG formula for multiple scattering does not describe electron recoils in gas accurately
- We improved the multiple scattering treatment, and included leading detector effects
- Our framework tells the analyst how much of a recoil track should be fitted to optimize angular resolution and predicts the resolution itself
- We have started lab measurements to validate our findings.

Thank you!
Questions?

Majd Ghrear
Majd@hawaii.edu