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CYGNUS HAWAI'I

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CYGNUS WORKSHOP 2023

Outline

1. Detector R&D at the University of Hawai’i
    a. Scaling up
    b. The 40L detector
    c. **Readout comparison**
2. Angular resolution of electron recoils
3. Machine Learning
    a. Distinguishing particle
    b. Predicting head/tail
    c. **Predicting directional distributions**
4. Experimental validation attempts

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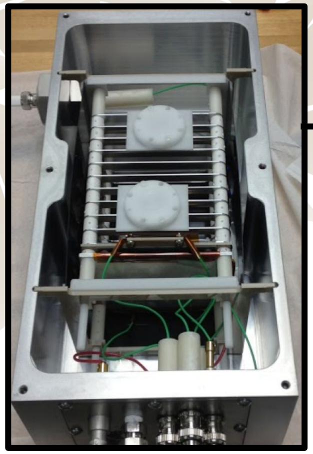
Detector R&D at University of Hawai'i

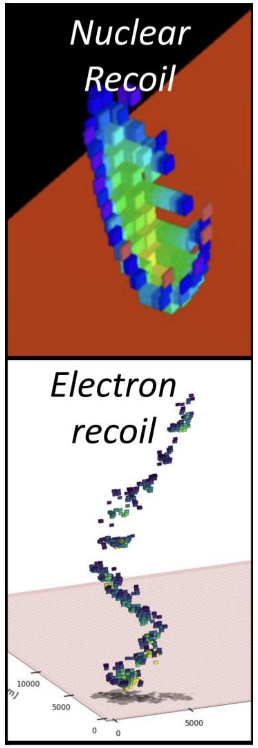
Scaling up

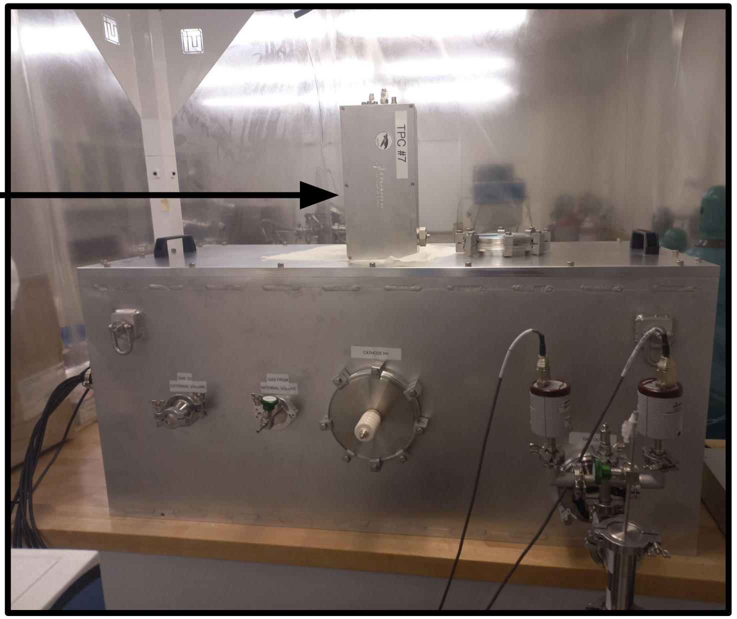


- Gains up to O(50,000)
- (250 x 50) μm^2 pixels
- Noise floor ~100 electrons
- Single electron efficiency at ~20k gain

40 cm^3 fiducial volume

Directional neutron detection





Majd Ghrear's Thesis Detector

40 L Fiducial volume

Readout selection

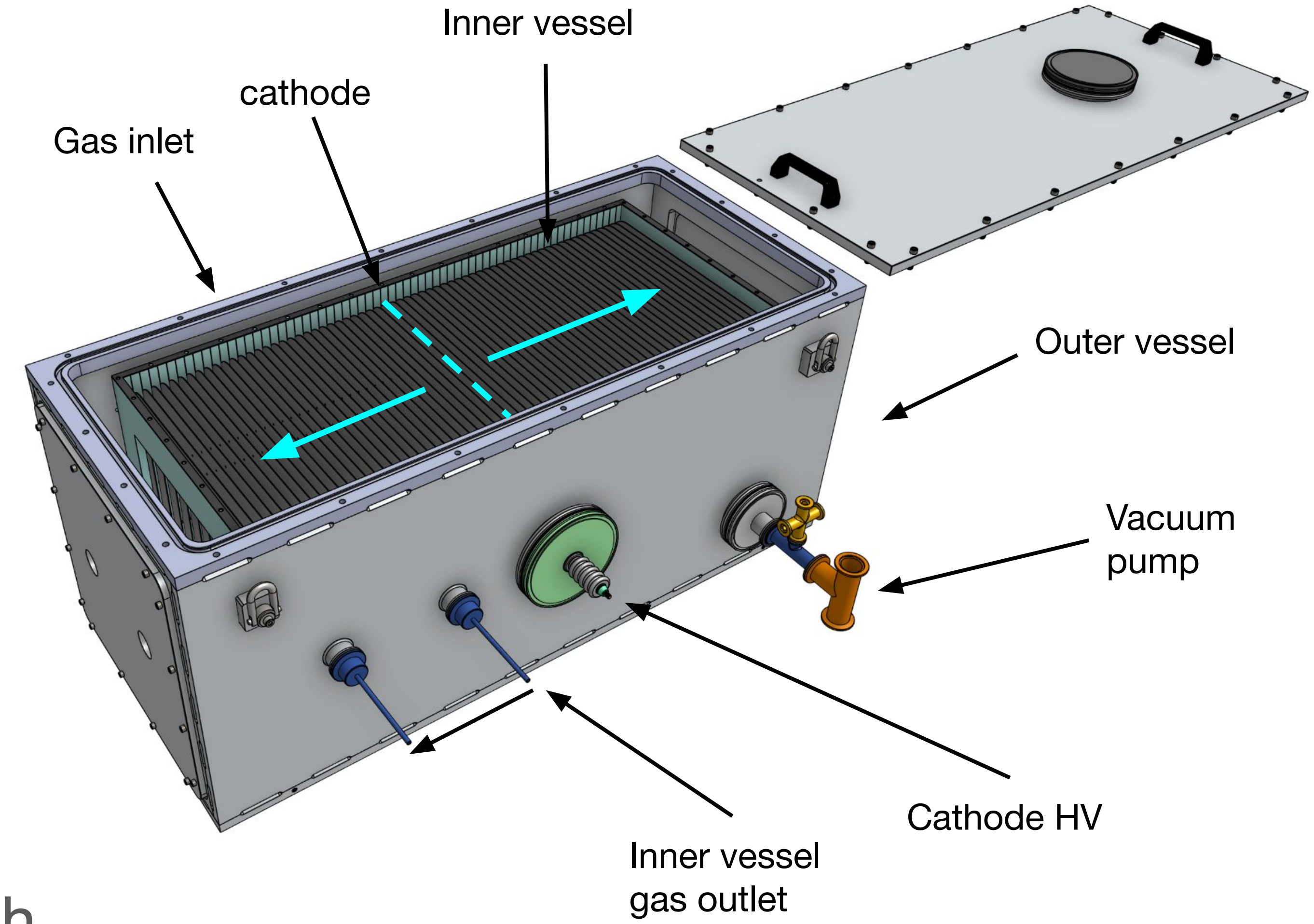
Michael Litke's Thesis Detector

1 m^3 Fiducial volume

Prototype CYGNUS unit cell

The 40L Detector

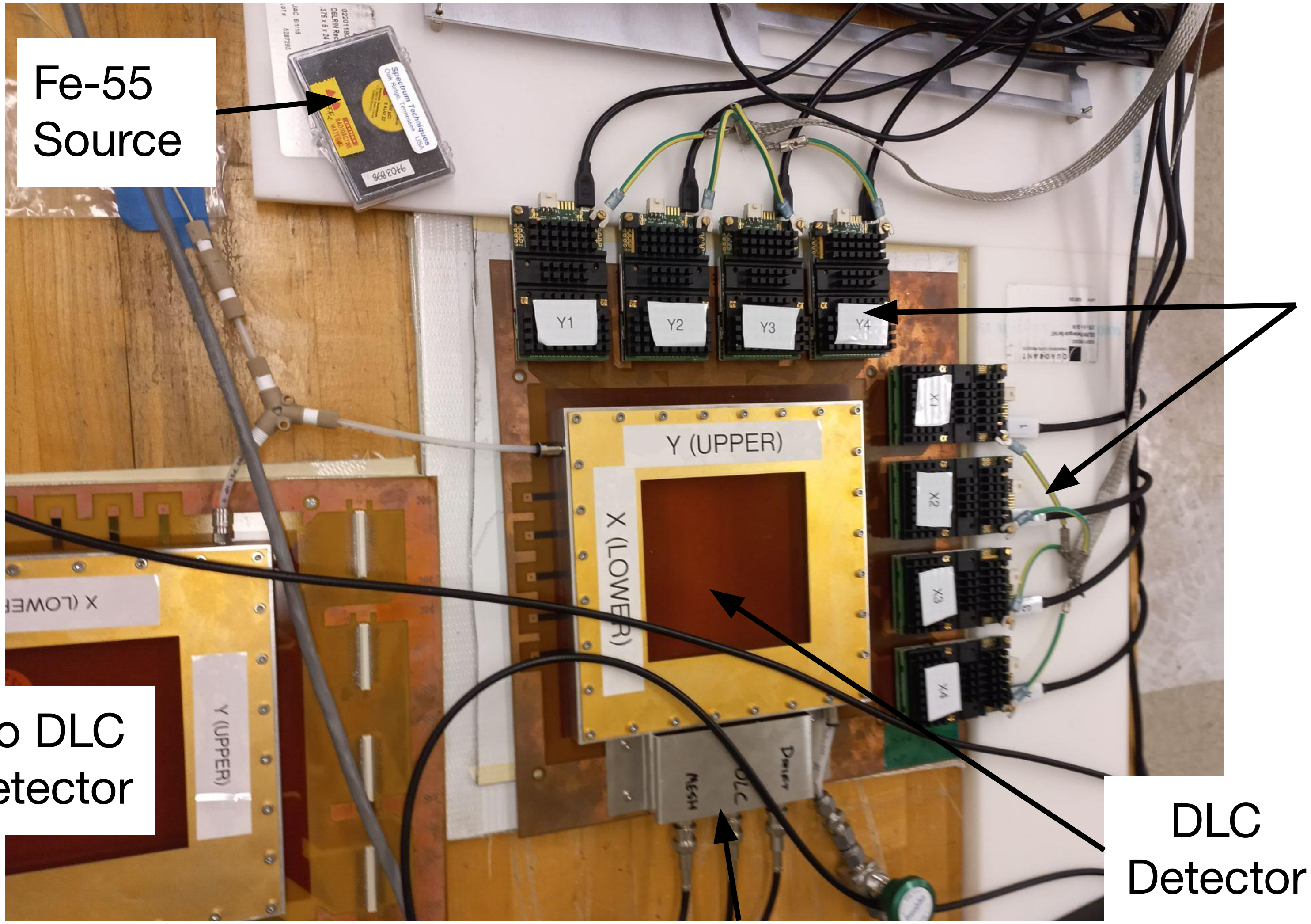
- 20 cm x 20 cm readout area
- Dual-sided readout
  - 0.5m drift length
  - Micromegas gain structure
  - 2D strip readout
  - 200 μm pitch
  - VMM3a / SRS DAQ
- Evaluating new gas flow approach
- Measurements with two prototype readouts from CERN ongoing



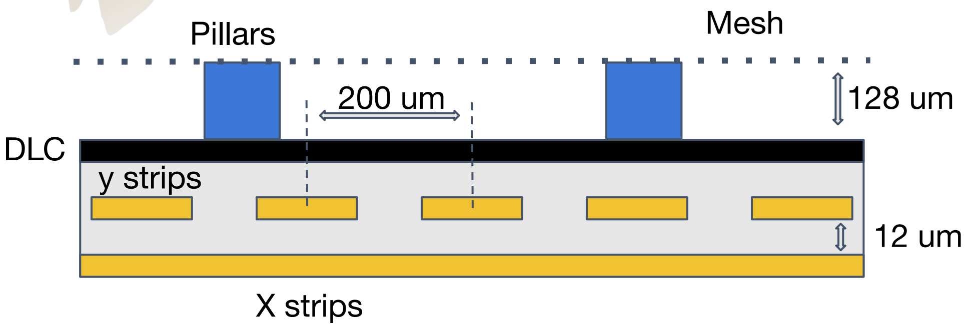
Micromegas Readout Comparison

10 cm x 10 cm prototype readouts from CERN

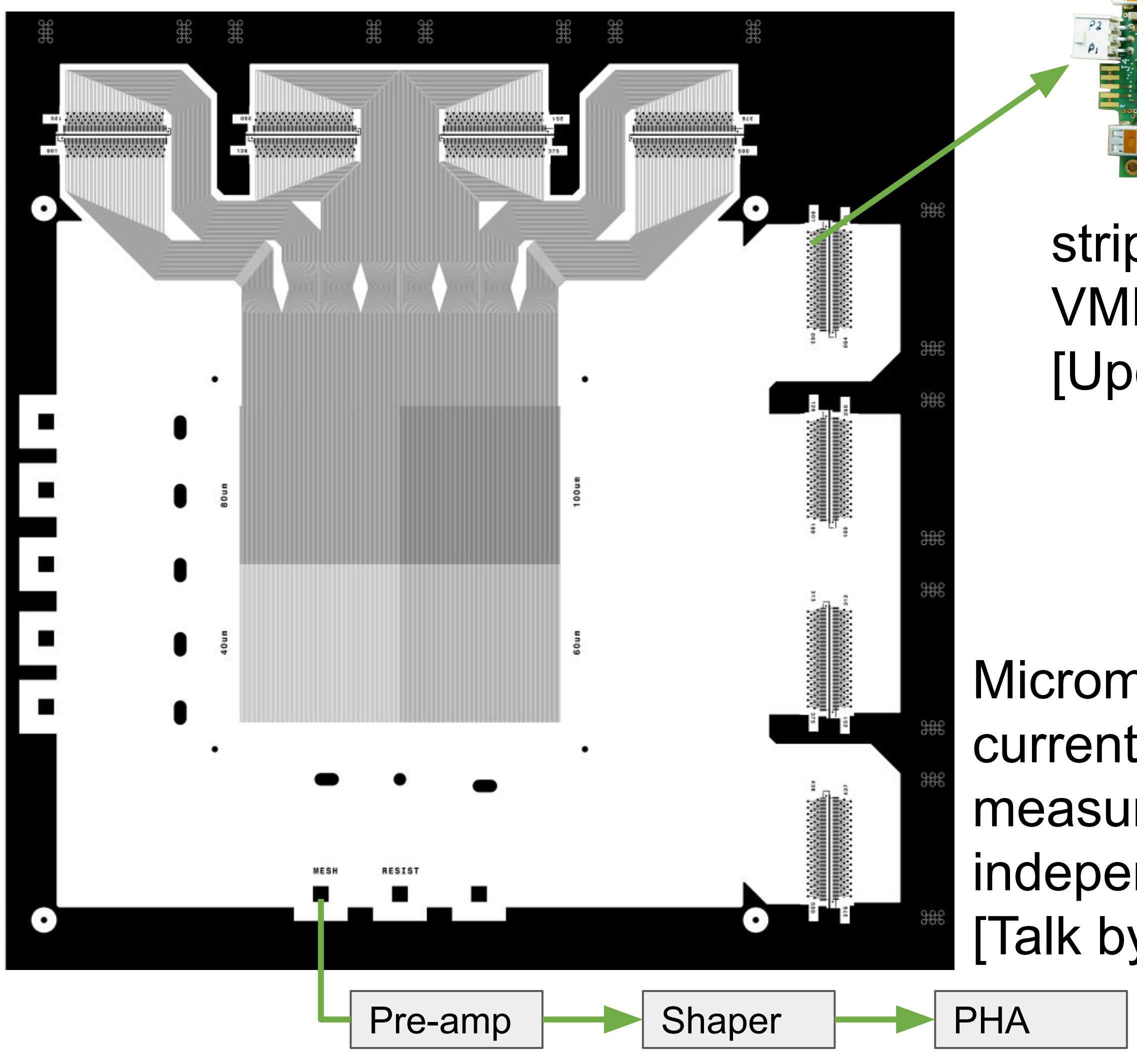
VMM/SRS DAQ system

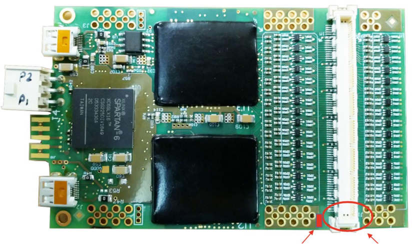


Micromegas Readout Comparison



Layout of our prototype readouts





strips read out by VMM/SRS [Upcoming slides]

Micromegas Mesh current pulses measured independently [Talk by Michael Litke]

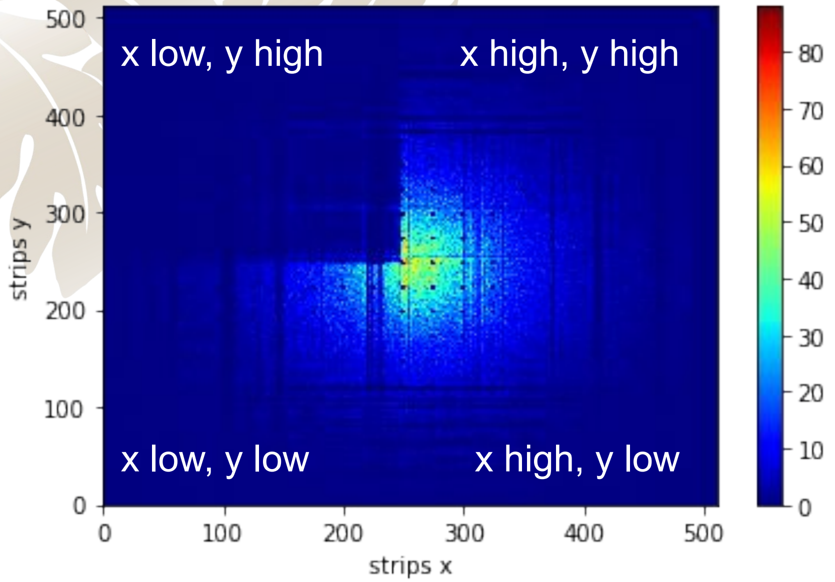
Micromegas Readout Comparison

Detector Name	UH DLC	UH NoDLC	UoS
Amplification gap [μm]	128	128	256
DLC Resistivity [MΩ/sq]	100	0	50
Pitch [μm]	100	100	250
Distinct Quadrants	True	True	False
Upper strip width [μm]	40, 60, 80, 100	40, 60, 80, 100	100
Lower strip width [μm]	140	140	220

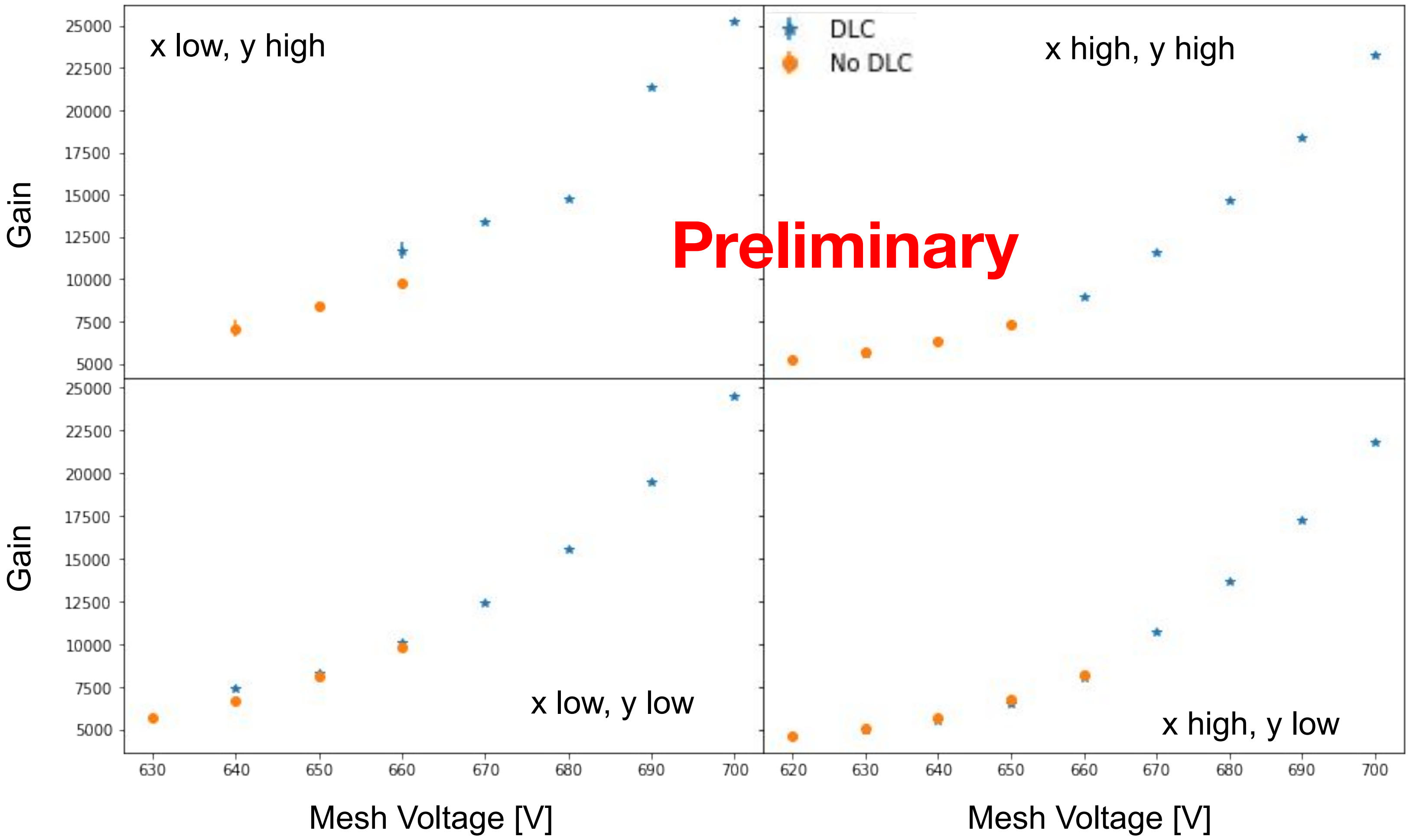
Sven Vahsen, Alasdair McLean, Majd Ghrear, Ferdos Dastgiri, Hima Korlanda

- We want to choose optimal Micromegas readout configuration
- Hawai'i (UH) purchased two 10 cm x 10 cm MICROMEGAS readouts (UH DLC, UH NoDLC) split into 4 quadrants (exploring different upper strip widths)
- Sheffield (UoS) supplied another 10 cm x 10 cm MICROMEGAS readout
- We are comparing
    - Gain
    - Gain Resolution
    - Charge Sharing in x/y
    - Point Resolution

Micromegas Readout Comparison



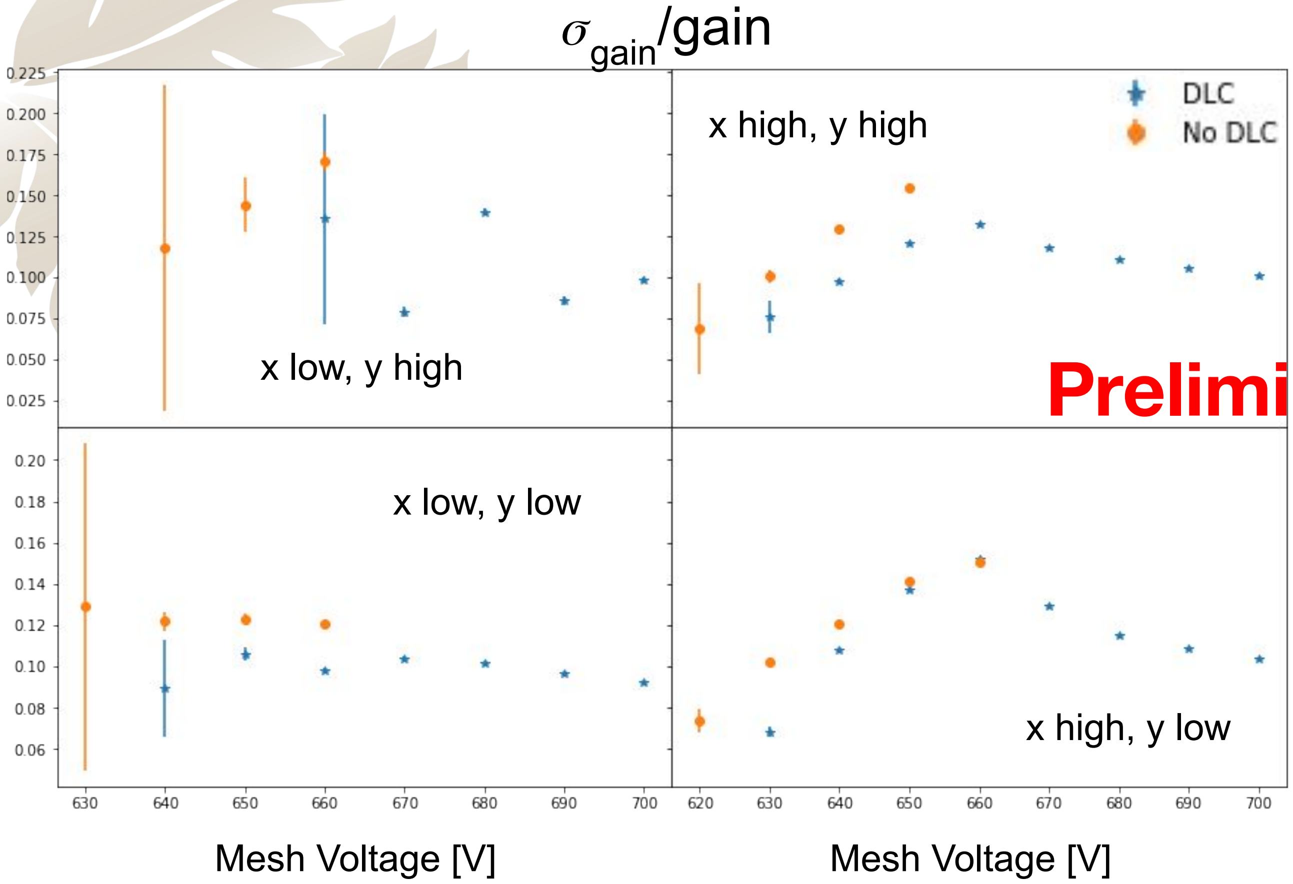
UH DLC Micromegas
690 Vmesh
Fe-55 distribution

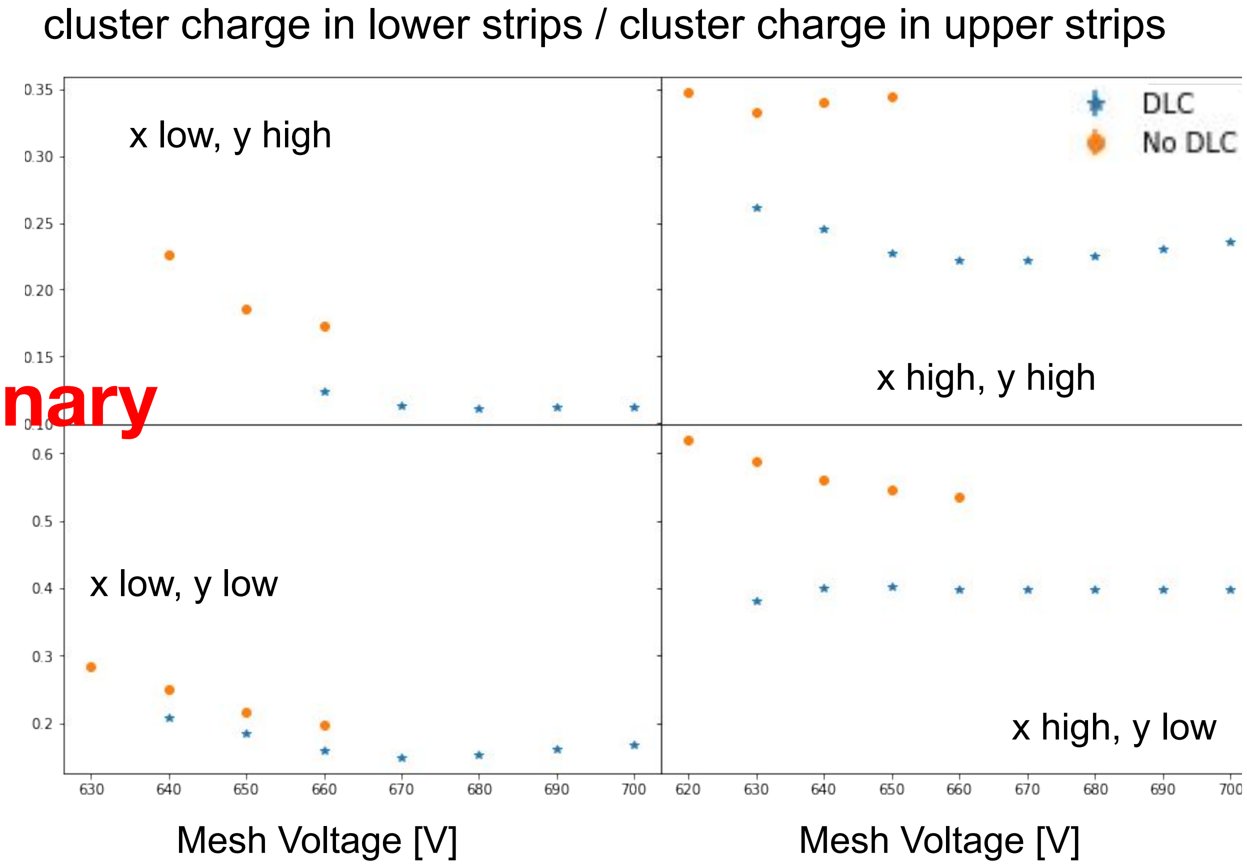


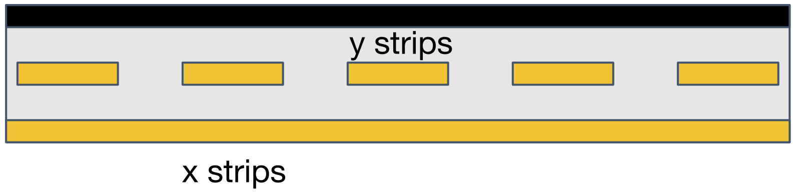
- DLC layer does not affect gain
- DLC allows higher mesh voltage without sparking
- Ideal for low pressure and NID.

**Based on digitized VMM/SRS data

Micromegas Readout Comparison





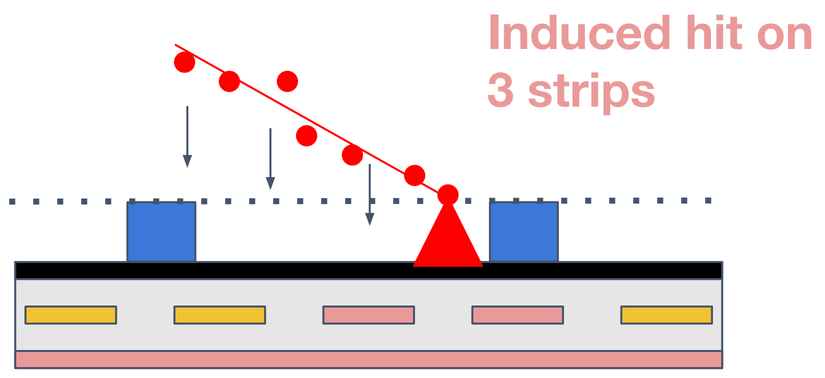


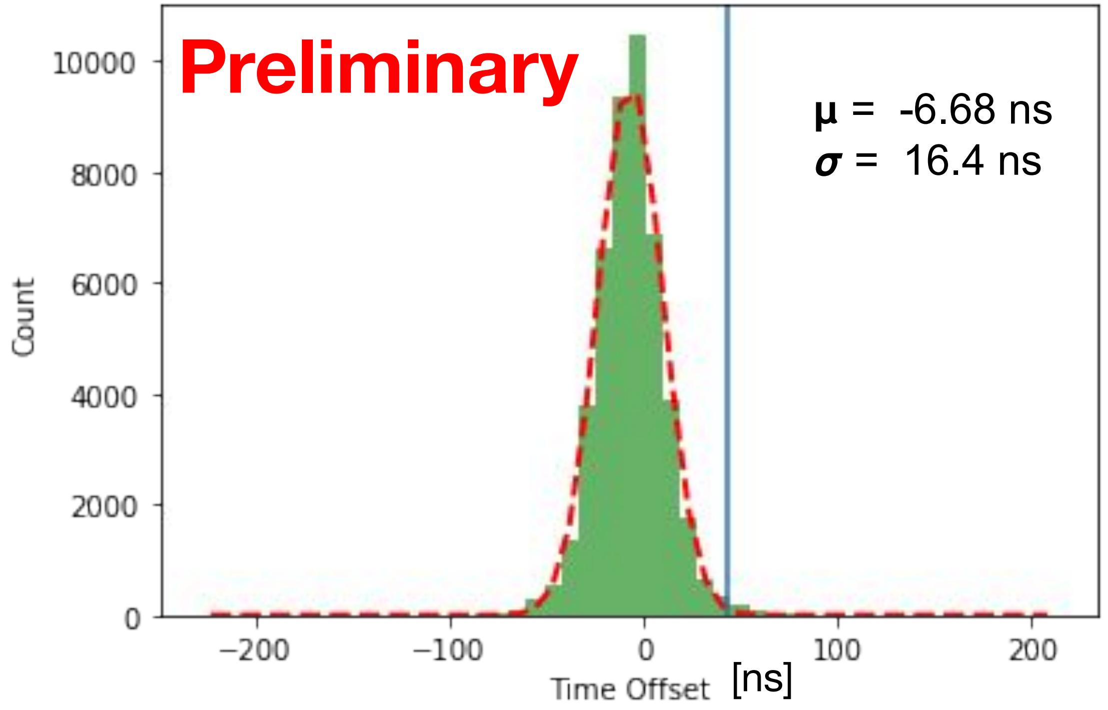
- Asymptotic fractional gain resolution is ~0.1
- DLC appears to affect cluster charge in lower strips / cluster charge in upper strips, we don't have a model explaining why yet

**Based on digitized VMM/SRS data

Micromegas Readout Comparison

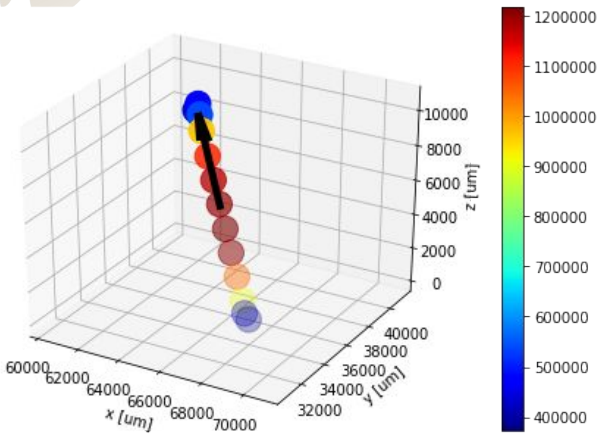
- We plot the time difference between the max ADC hit in x and y for each Fe-55 cluster
- This can be used to match x and y hits for 3D reconstruction
- This distribution does not strongly depend on the micromegas mesh voltage
- It does depend on the specific VMM chips used in x and y
- x and y strips are “matched” if they are within n=3 sigma



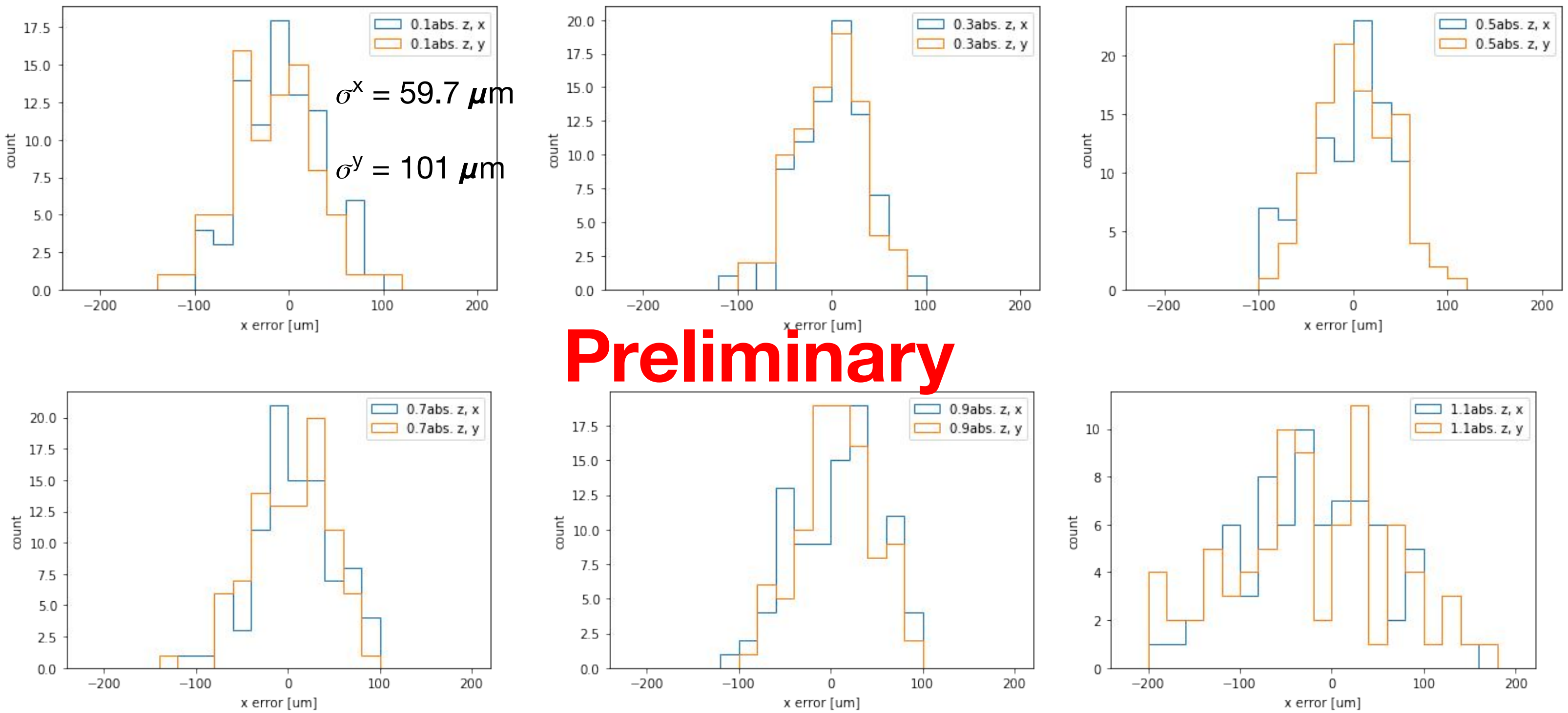


Micromegas Readout Comparison

Using Po-210 for alpha particles



UH DLC, xHyL quadrant



- The x and y strips have similar point resolution
- The readout resolution is 60-100 um

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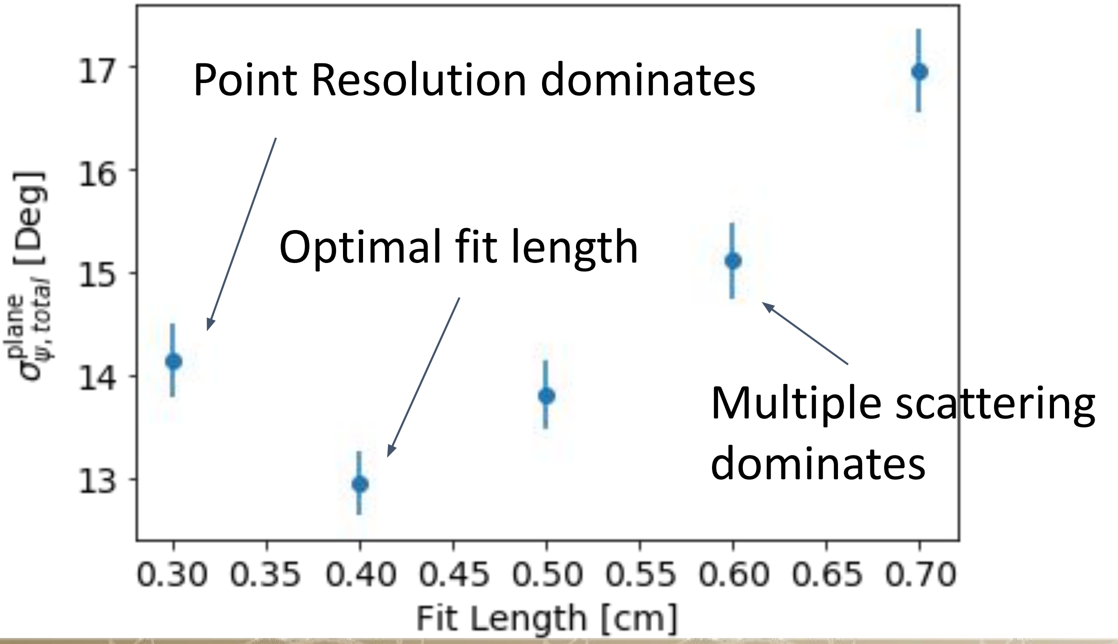
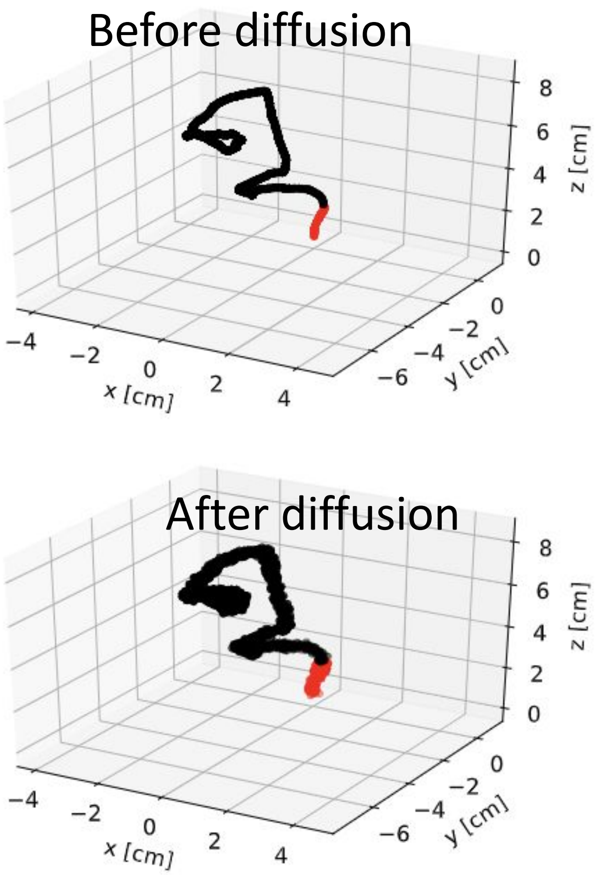
Angular Resolution of Electron Recoils

- Electron recoils could be interesting for directional neutrino detection
- Analytical / simulation based work assuming well optimized detector

Angular Resolution of 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.

Multiple Scattering - History

1941

Rossi and Greisen
“Cosmic-Ray Theory”

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

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

Moliere Theory:
Moliere (1947)
Bethe (1953)

1975

Highland
“Some Practical Remarks on Multiple Scattering”

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

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

1990

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.

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

Present

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

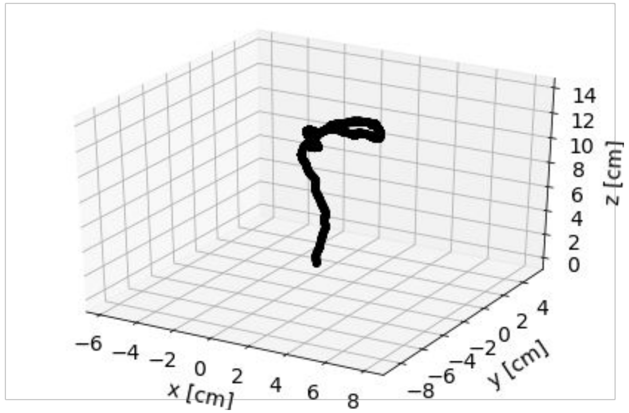
Multiple scattering through small angles

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

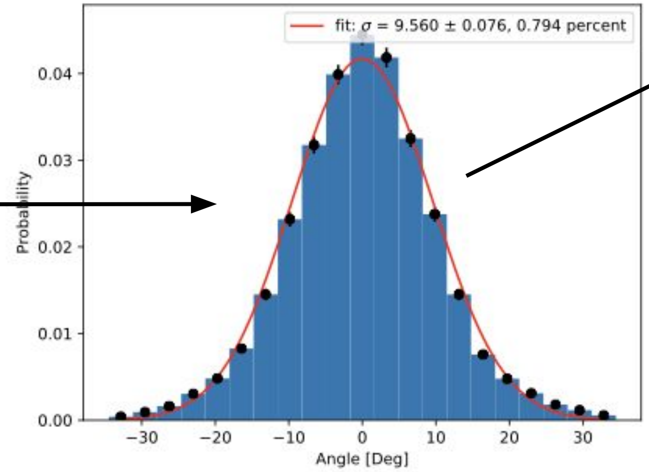
Multiple Scattering - Fitting

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

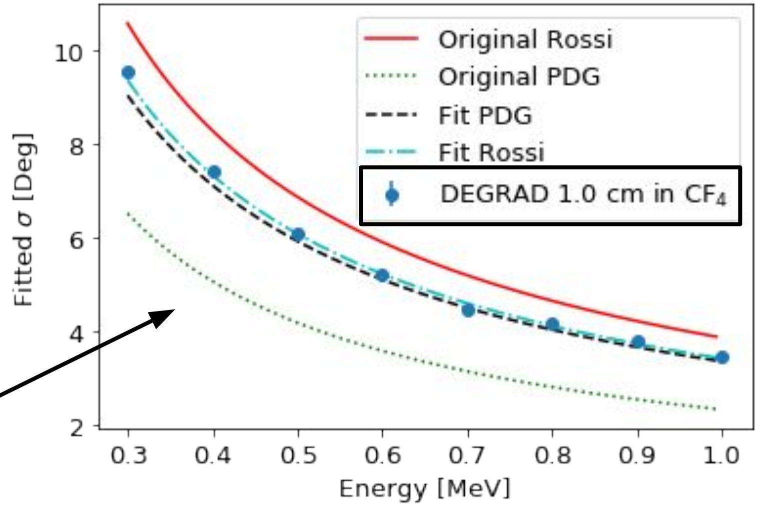
DEGRAD Electron Simulation
(CF_4 , 200 keV)

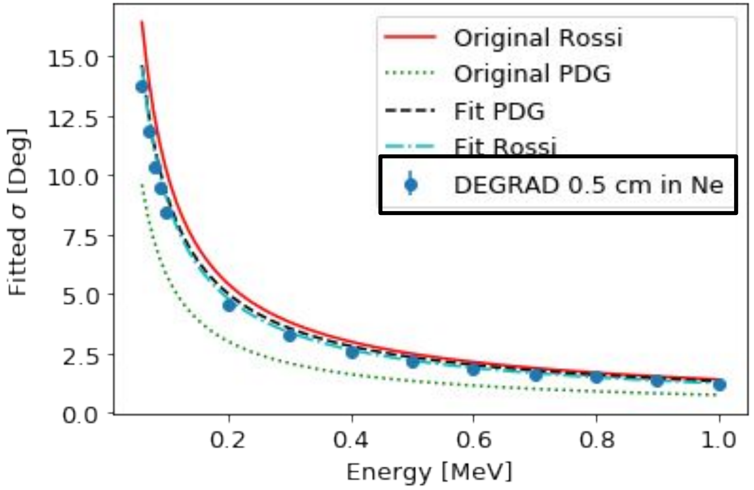


Angular distribution
(CF_4 , 300 keV, 1 cm)



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

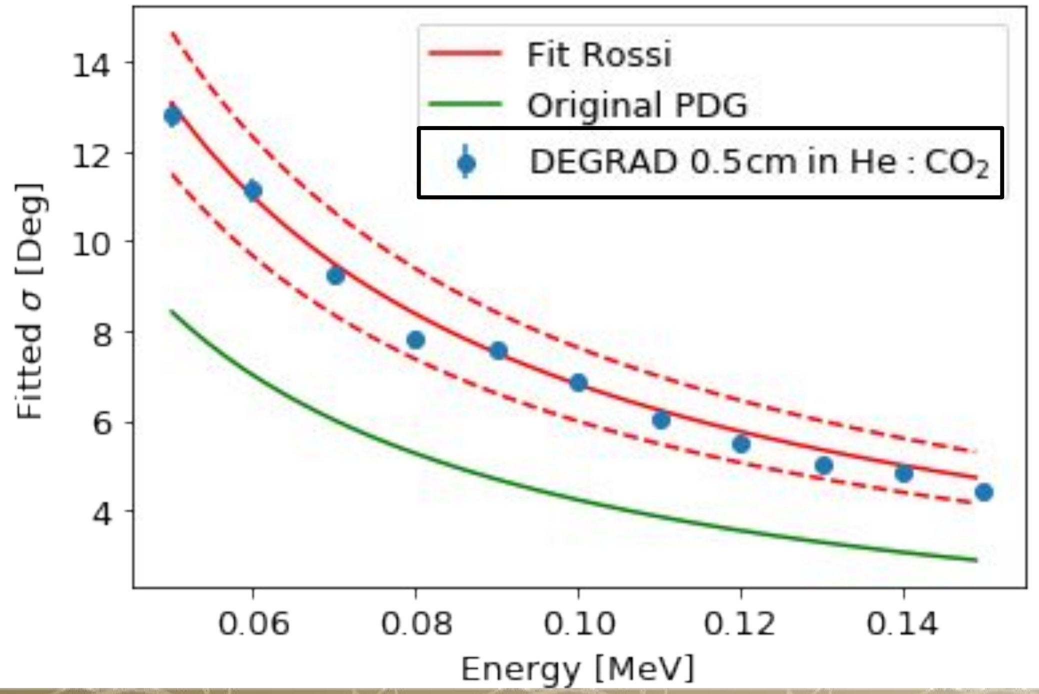
Fit Length: 0.5 - 2 cm

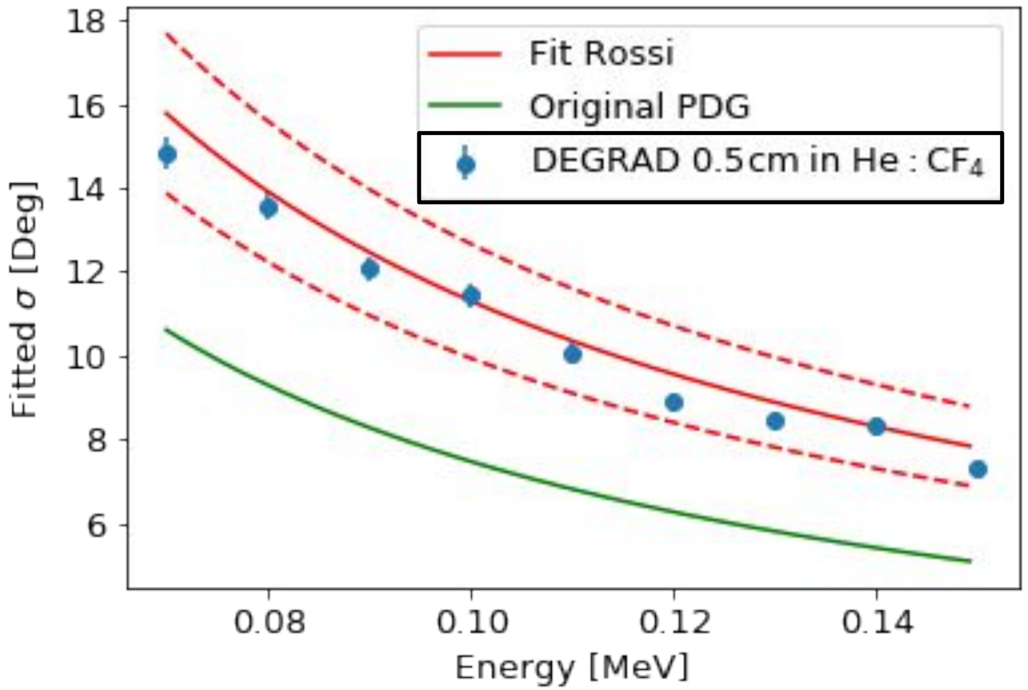
Multiple Scattering: Testing

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

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





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

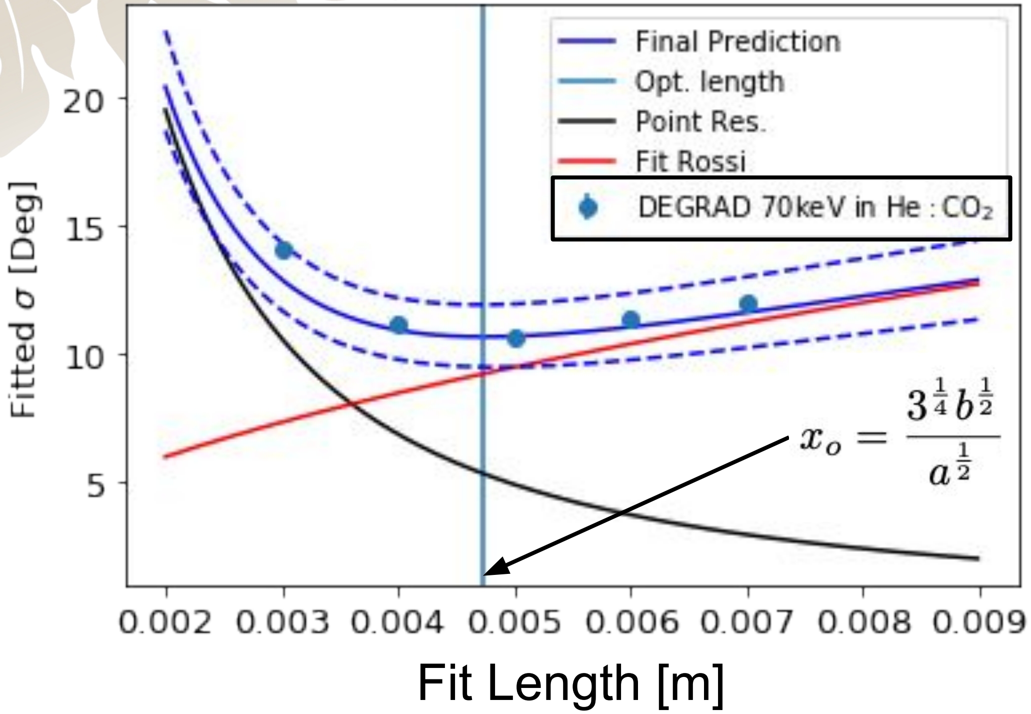
3-D tracking in a miniature time projection chamber https://doi.org/10.1016/j.nima.2015.03.009

Angular Res.

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

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

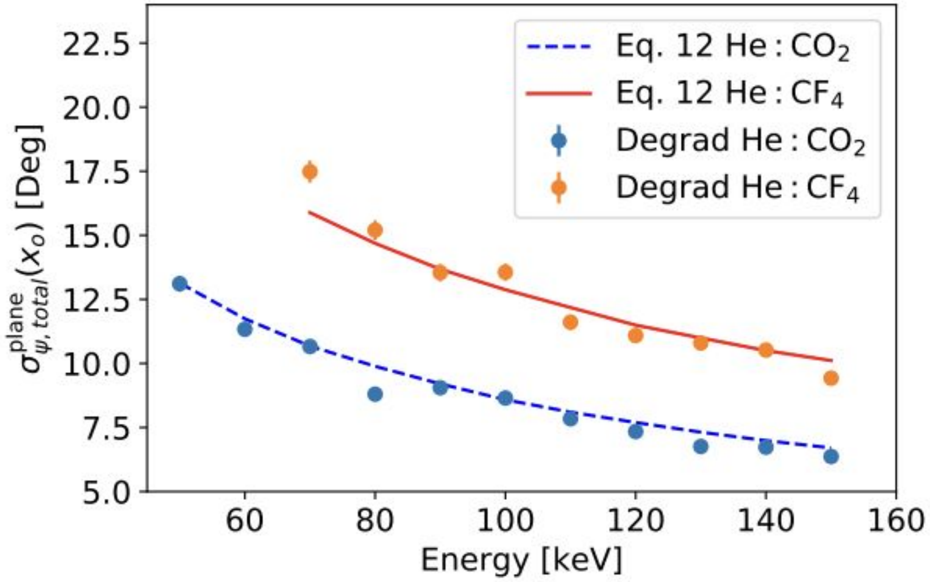
70 keV electron recoils in 70% He 30% CO2



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

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

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



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

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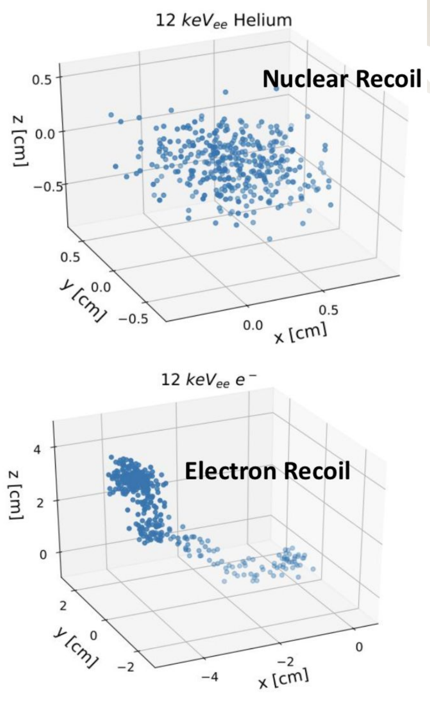
Machine Learning

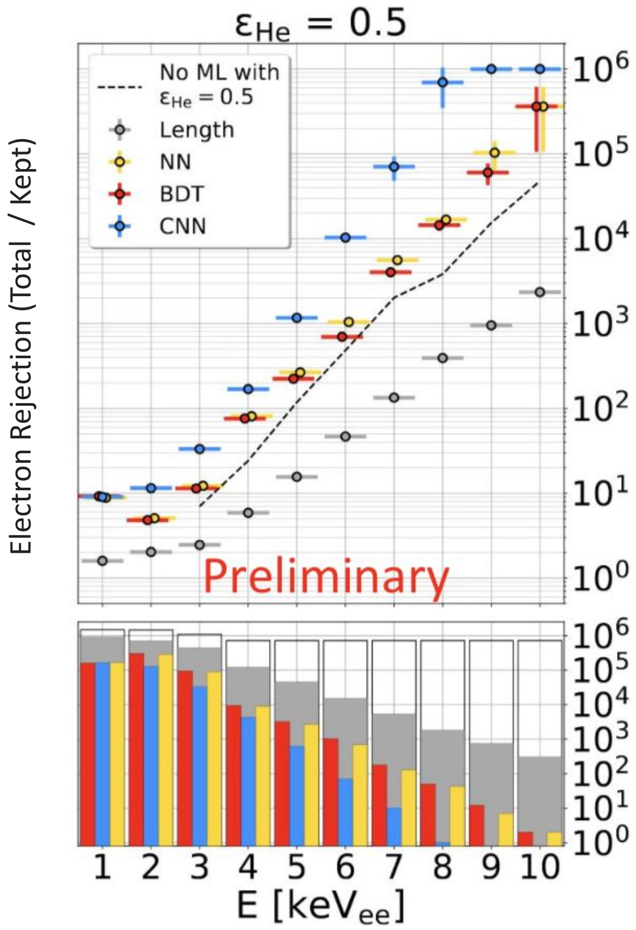
Particle ID and Head Tail

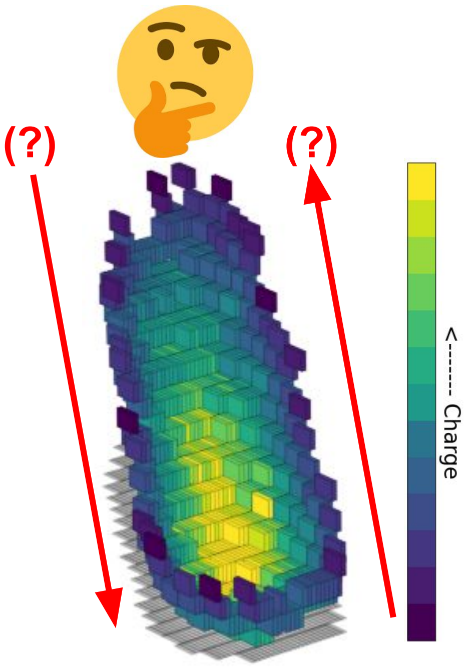
Jeff Schueler



In He:CF_4:CHF_3 at 40 Torr

- The 3D shapes of recoils can be used to distinguish them
- By combining physical observables we can improve electron rejection by 2 orders of magnitude https://arxiv.org/abs/2012.13649
- Further improvements expected via ML, see https://arxiv.org/abs/2206.10822



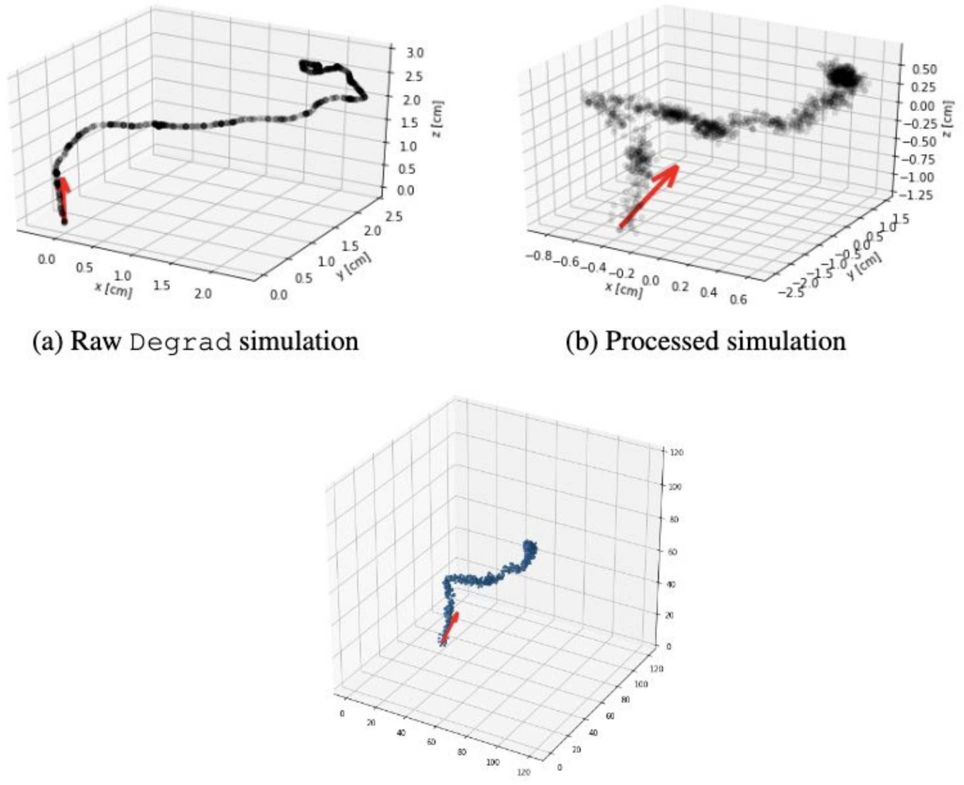


[More on this from Sven!]

Deep probabilistic 3D angular regression

Simulations:

- 10^6 electron recoils at 40,45,50 keV using DEGRAD
- 70% He : 30% CO_2 at 20 Celsius and 760 Torr
- Recoils are generated isotropically with known true direction
- Diffusion drawn uniformly between 160-466 μm
- Binned into $(500\ \mu m)^3$ voxels



(a) Raw Degrad simulation

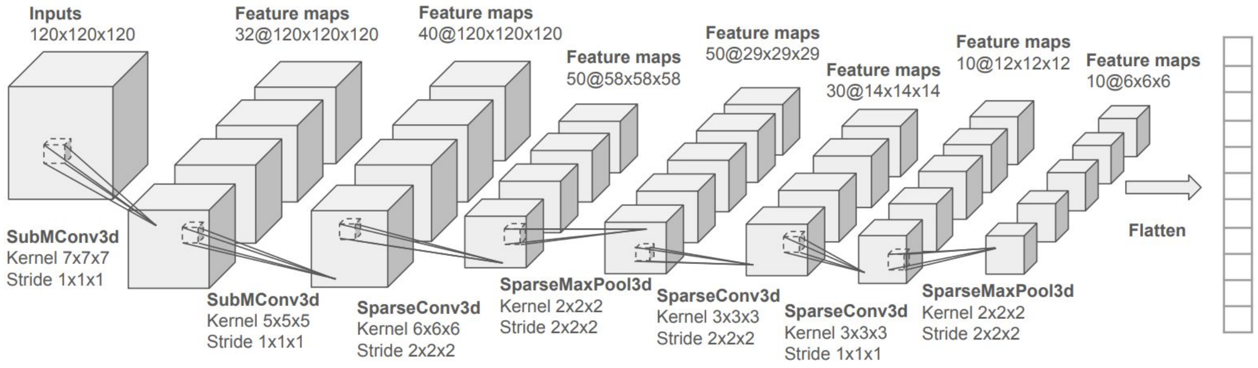
(b) Processed simulation

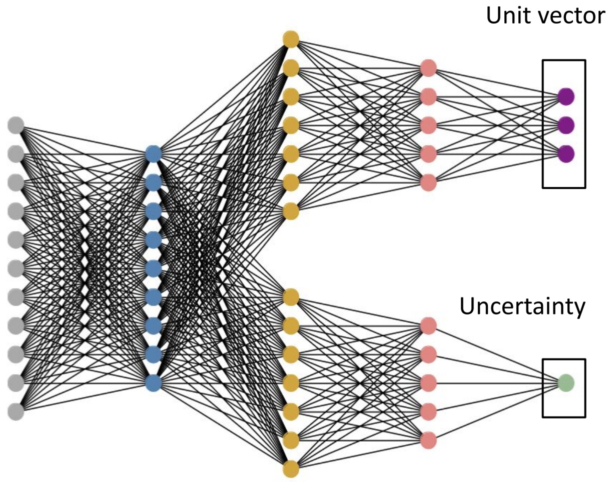
(c) Voxilized simulation

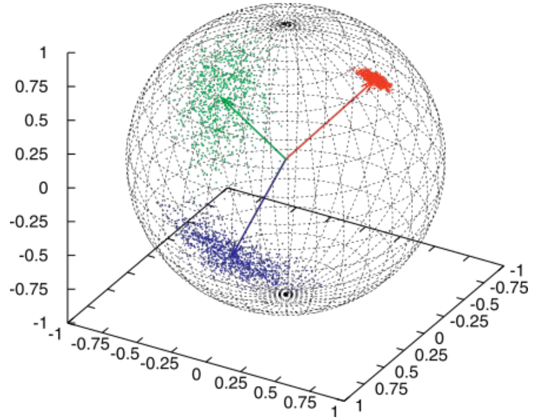
Deep probabilistic 3D angular regression

Architecture:

- Every event has 1,728,000 features.
- In a typical event, ~0.01% of the features are non-zero
- Sparsity is common in highly-segmented 3D data and it is essential to take advantage of it
- Dual-head architecture for heteroscedastic regression







Deep probabilistic 3D angular regression

Loss function

- Derived from the Kent / von Mises-Fisher distribution
- Requires approximations to stabilize training
- **This is the first probabilistic deep learning framework for predicting 3D directions**

Predicted Uncertainty

Label

$$\frac{-\ln \mathcal{L}}{N} = \frac{-1}{N}\sum_{i=1}^{N} \ln\left(\frac{\kappa_i}{4\pi \sinh(\kappa_i)}\right) + \kappa_i(\boldsymbol{y}_i \cdot \boldsymbol{y}_{pred_i})$$

Predicted direction

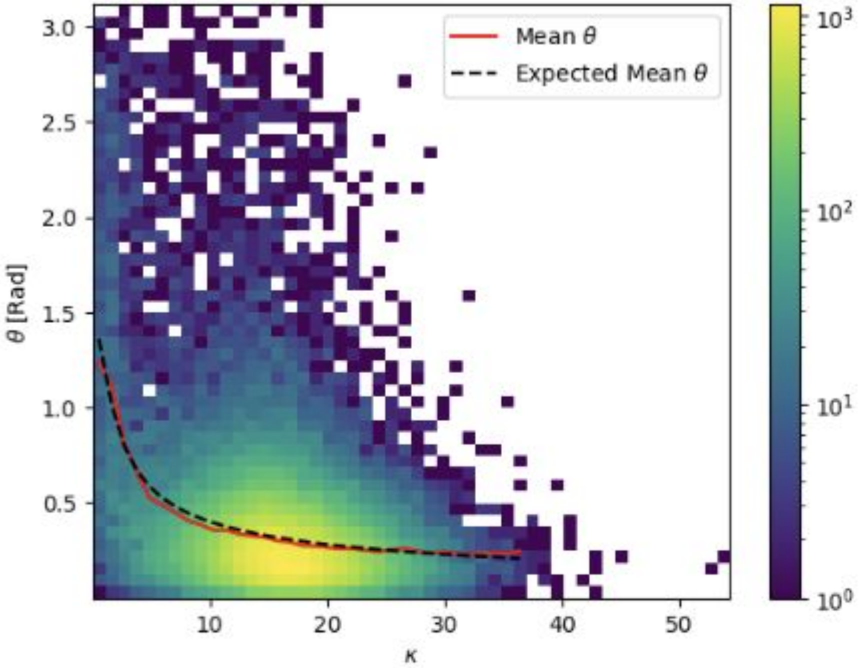
15th order Taylor series
about $\boldsymbol{\kappa}_i = 0$

$$NLL = \frac{-1}{N}\sum_{i=1}^{N} \text{where}\left(\kappa < 2.65, T_{15}\left(\ln \frac{\kappa_i}{4\pi \sinh(\kappa_i)}\right), ln\left(\frac{\kappa_i}{2\pi}\right) - \kappa_i\right) + \kappa_i(\boldsymbol{y}_i \cdot \boldsymbol{y}_{pred_i})$$

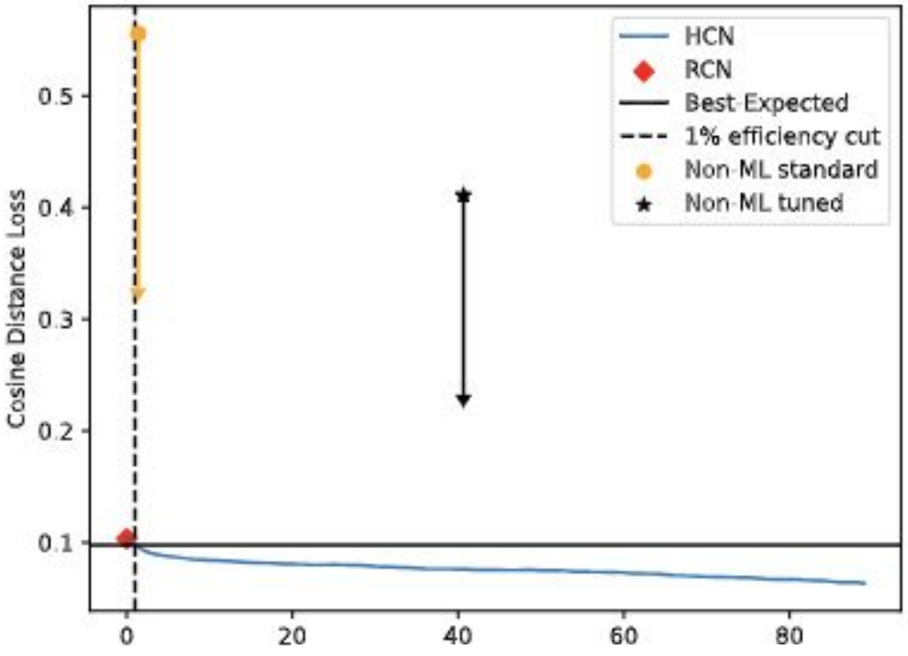
Deep probabilistic 3D angular regression

This framework solves 3 problems at once:

- It determines the Head/Tail
- It significantly improves angular resolution
- It estimates uncertainty accurately



40 keV electron recoils in He:Co2



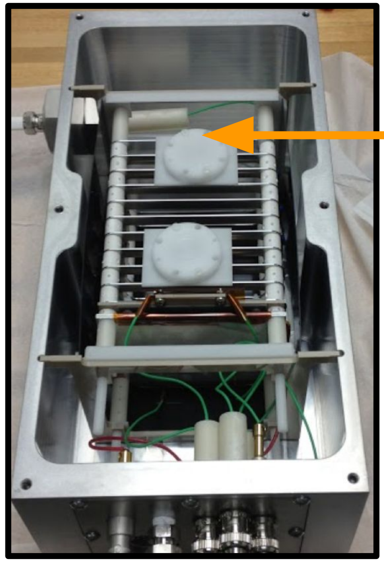
Efficiency Reduction

$$\text{CSLoss} = \frac{1}{N}\sum_{i=1}^{N} 1 - \frac{\boldsymbol{y}_i \cdot \boldsymbol{y}_{pred_i}}{\max(|\boldsymbol{y}_i||\boldsymbol{y}_{pred_i}|, \epsilon)},$$

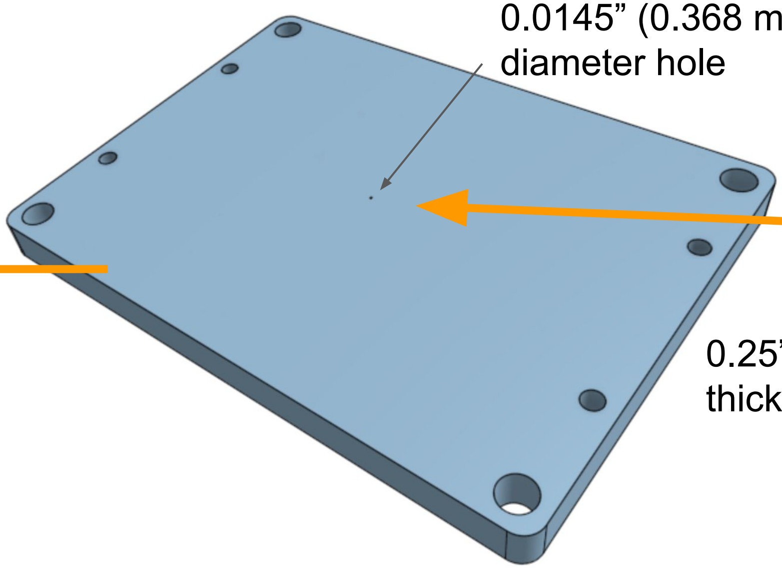
Paper under review

Experimental Validation Attempts

- Goal: Image electrons with known direction
- Designed a setup with a collimated cathode
- Appears to work normally for a few hours
- We observe a total saturation event, afterwards the GEMs stop working

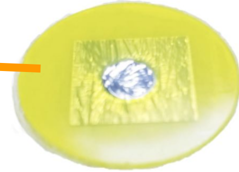


0.0145” (0.368 mm) diameter hole

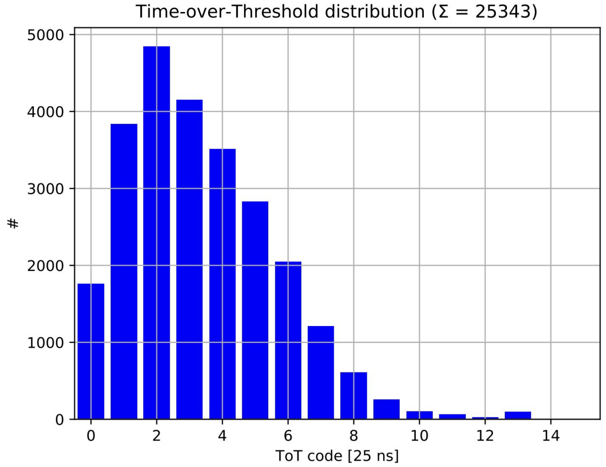


0.25” (6.35 mm) thick aluminum

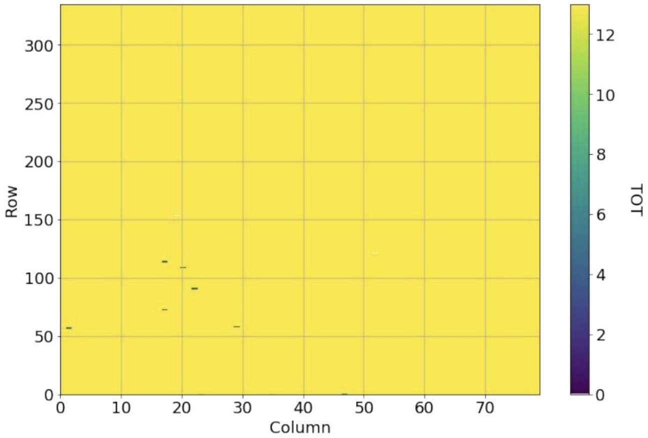
Sr-90 with Al/mylar window



Normal operation



every channel saturates



Summary

- University of Hawai'i is scaling up - currently developing a 40L 2D strip micromegas detector
- We developed a framework that enables us to quickly optimize gas mixtures for directional electron recoil detection.
- We developed novel deep learning techniques that
  - Improve our ability to determine the initial direction of recoils
  - Determines the head/tail
  - Estimates uncertainty

Thank you!

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