Directional Dark Matter Detection with High Definition 3D Charge Readout

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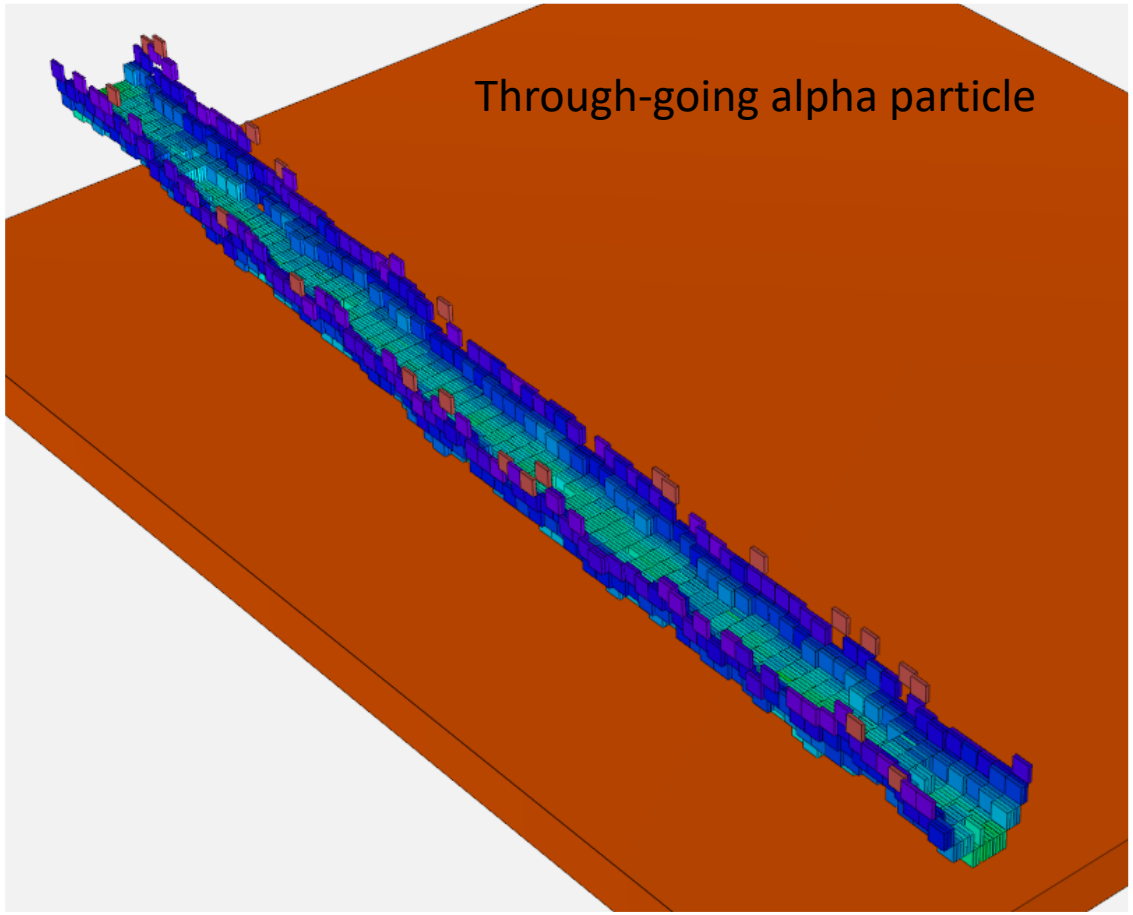
INFN LNGS

Outline

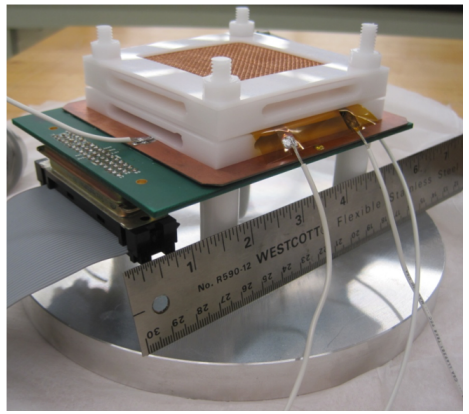
- Brief overview of work done in Hawaii
- BEAST II TPC performance
- Limit setting with data from BEAST II TPCs
- Length vs. energy selection
- Cluster counting selection



- Each block: 50x250x250 μm^3
- Color: ionization density
- Experimental data

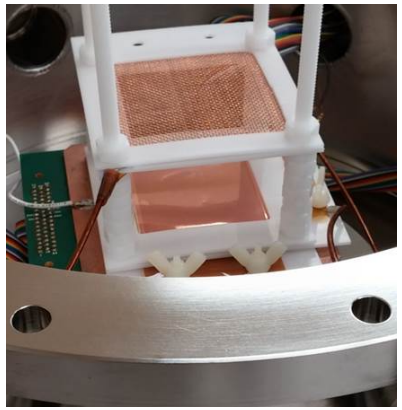
D^3 Chronological Overview at U. Hawaii

2011-2013



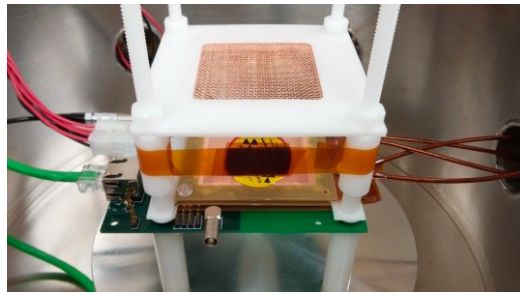
D^3 - micro ~ 1 cm^3

2013



~ 2.5 cm^3

2013

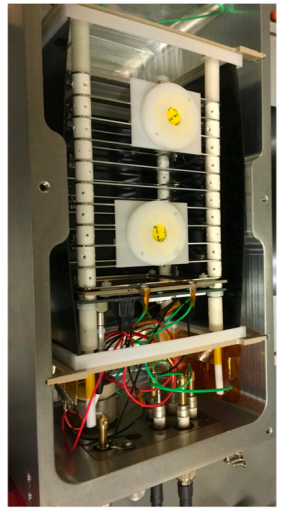


~ 20 cm^3

2014

~ 2 x 60 cm^3

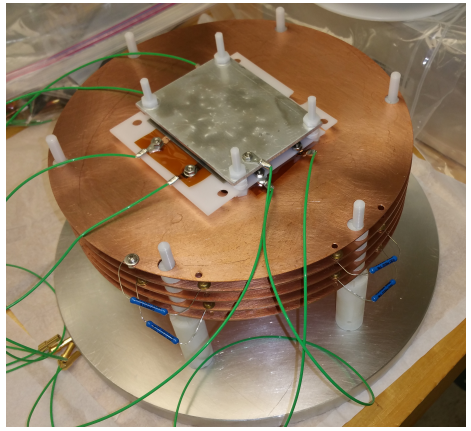
2015-2018



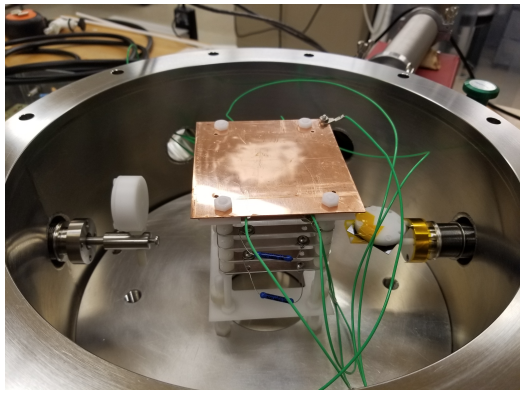
~ 8 x 40 cm^3

HD studies w/ pixels

D^3 - milli1 (2015-2017)

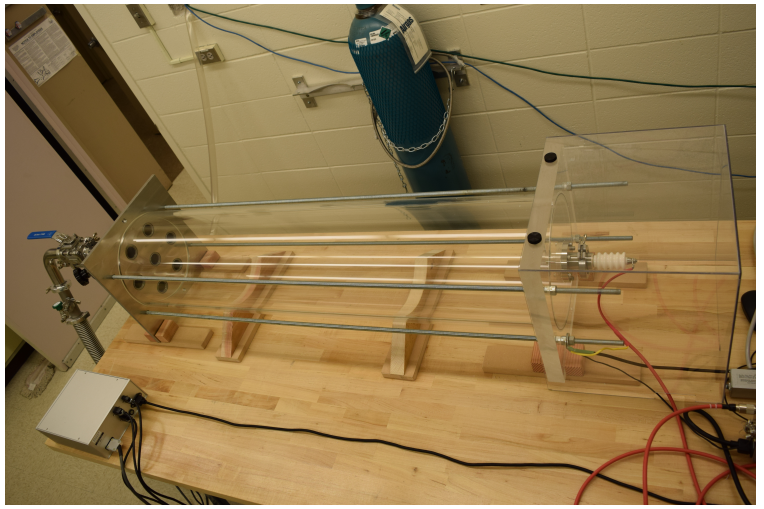


D^3 - milli2 (2018)



Gain studies

Need new student!



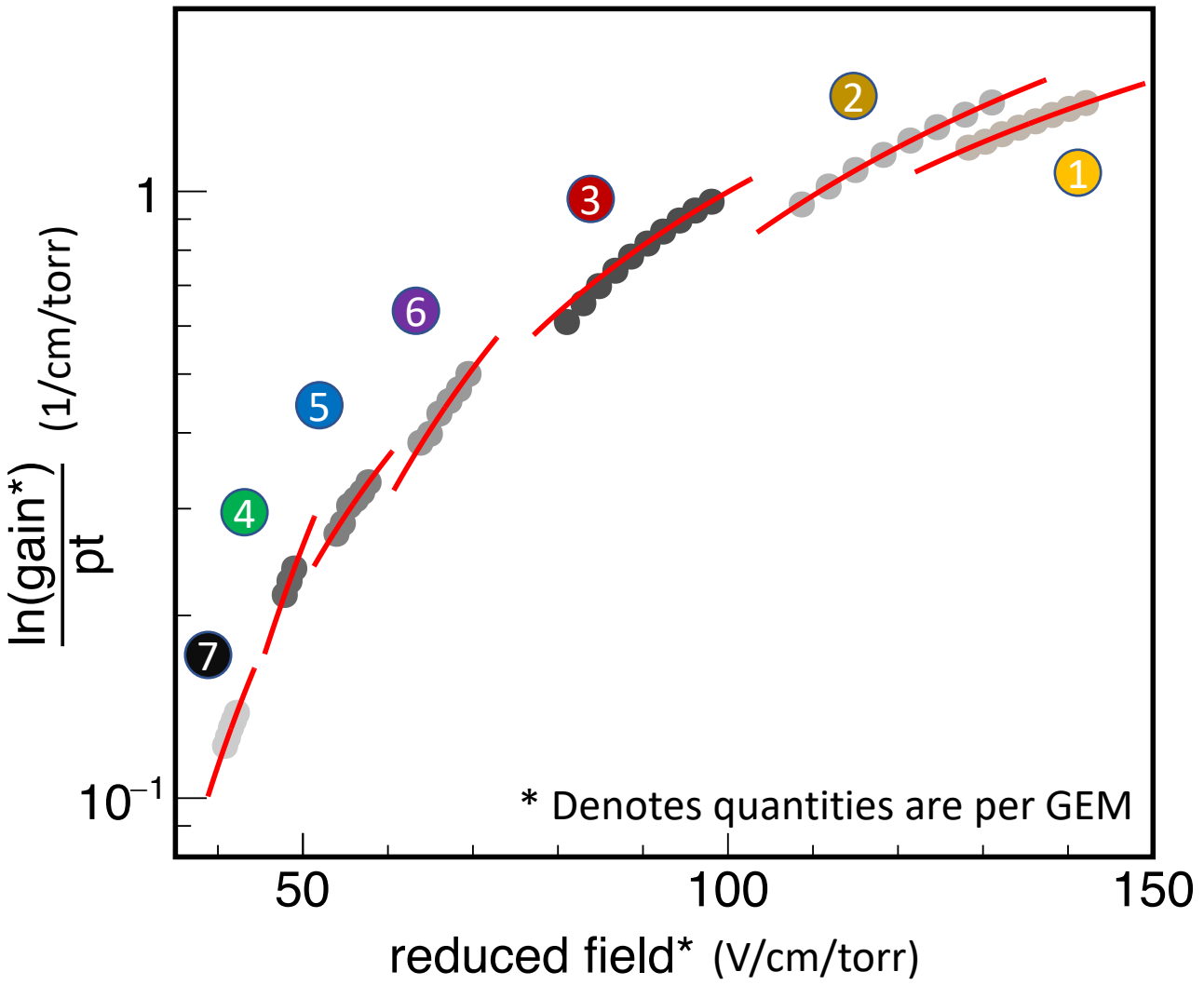
~ 400 cm^3 w/ one ASIC, 50 cm drift

Gas Gain Studies with $HeCO_2$

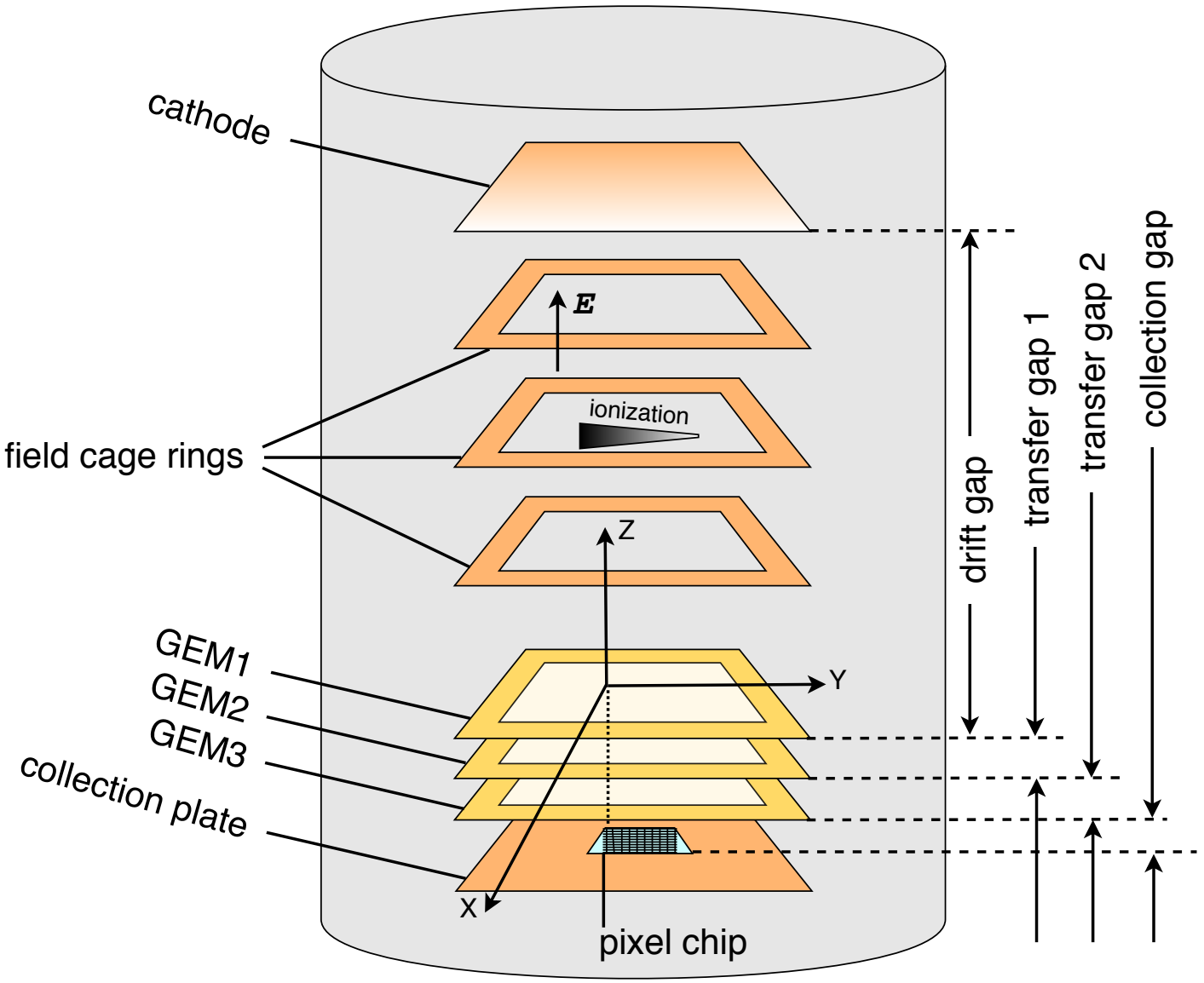
$$\frac{\ln(G)}{npt} = A\exp\left(-B\frac{npt}{V_{GEM}}\right)$$

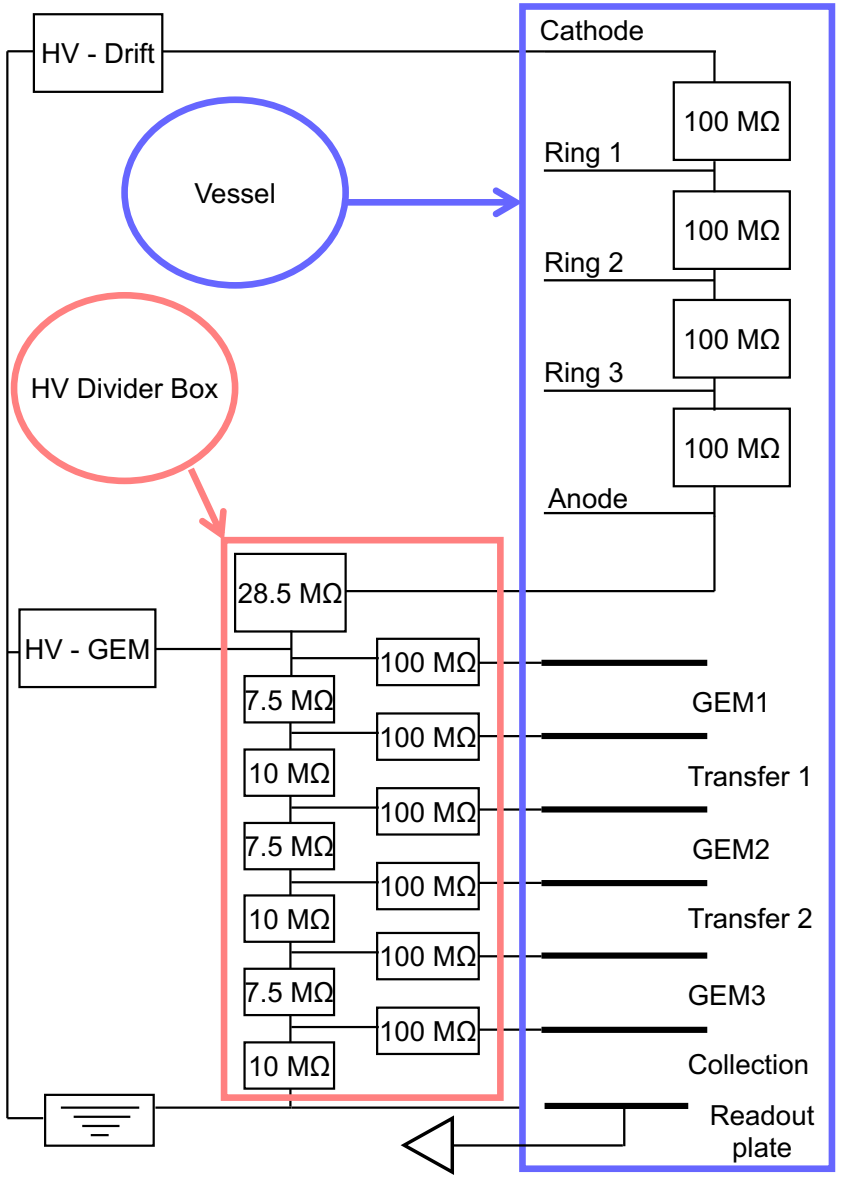
	Data set	B/A
1	Double thin GEMs (D^3 - Micro)	32.9 ± 0.7
2	Double thin GEMs (D^3 - Milli2)	27.2 ± 0.5
3	Triple thin GEMs	29.3 ± 0.6
4	THGEM - 1.0 atm	12.5 ± 0.3
5	THGEM - 0.75 atm	34.7 ± 0.7
6	THGEM - 0.5 atm	20.2 ± 0.4
7	Double THGEMs	29.6 ± 0.6
	Combined	37.0 ± 0.7

GAIN RESOLUTION STUDIES AND FIRST DARK MATTER SEARCH WITH NOVEL 3D NUCLEAR RECOIL DETECTORS, Ph.D Thesis, Thomas N. Thorpe, Dec. 2018.



Time Projection Chambers (TPCs)

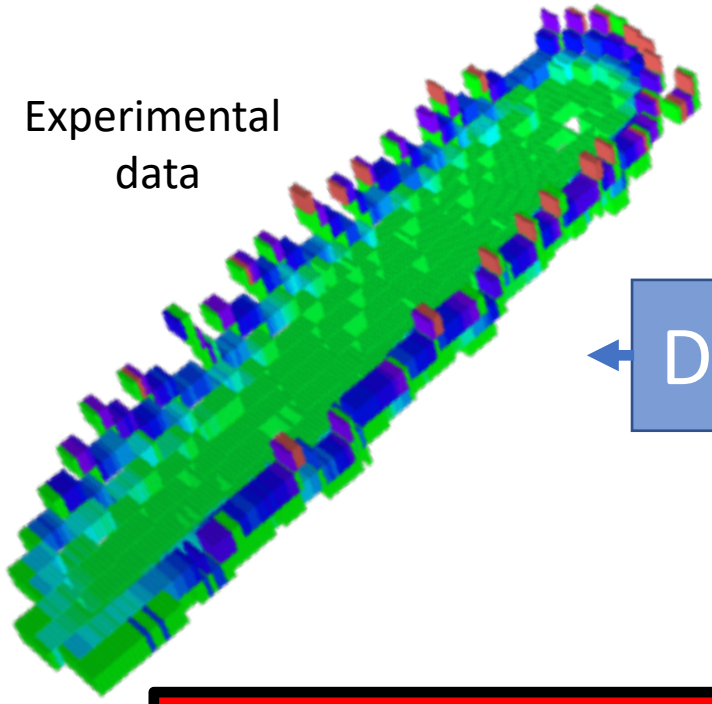




TPCs with GEMs and Pixel Chips

- Gas is $HeCO_2$ 70:30 @ atmospheric pressure
- Double thin (50µm) GEM amplification

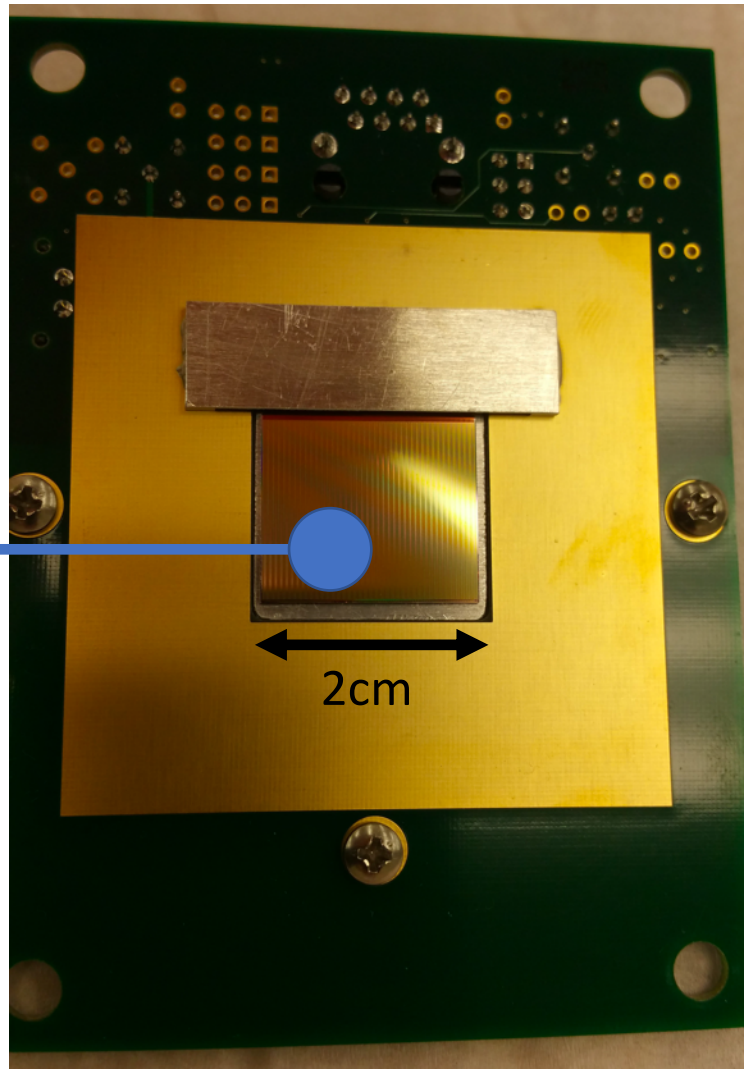
Experimental data

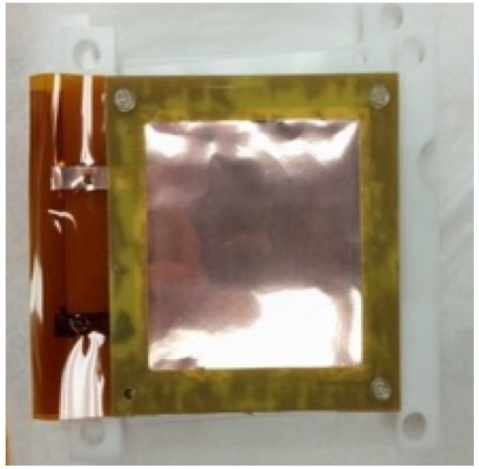


DAQ

Allows for vector 3D high resolution track reconstruction with high SNR

FE-I4B readout board

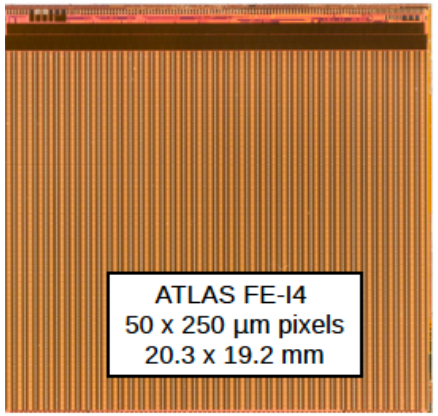




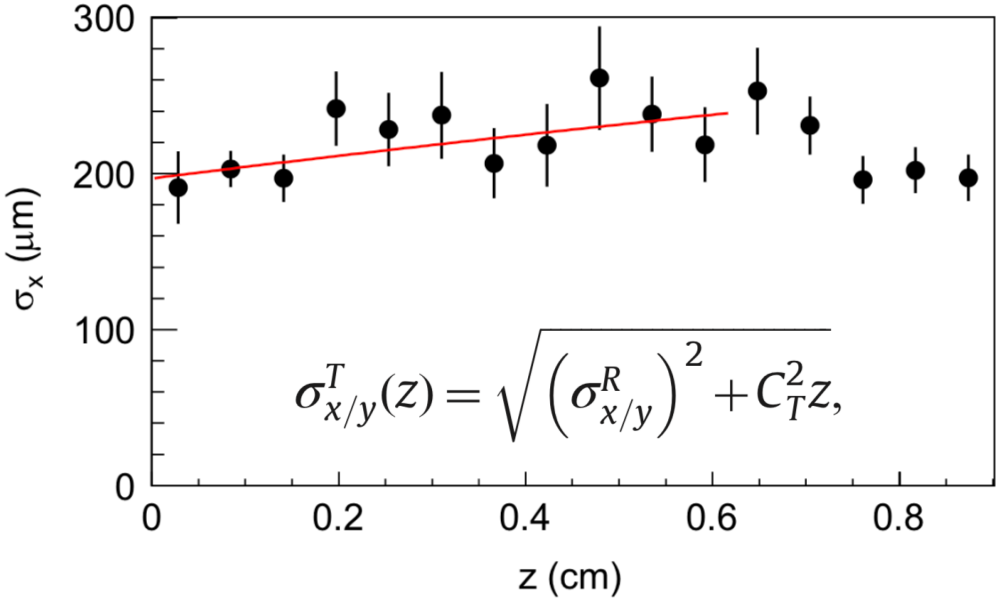
- **Gas Electron Multiplier (GEM)**
- Two layers of copper sandwiching a thin layer of Kapton
- Avalanches one electron into hundreds

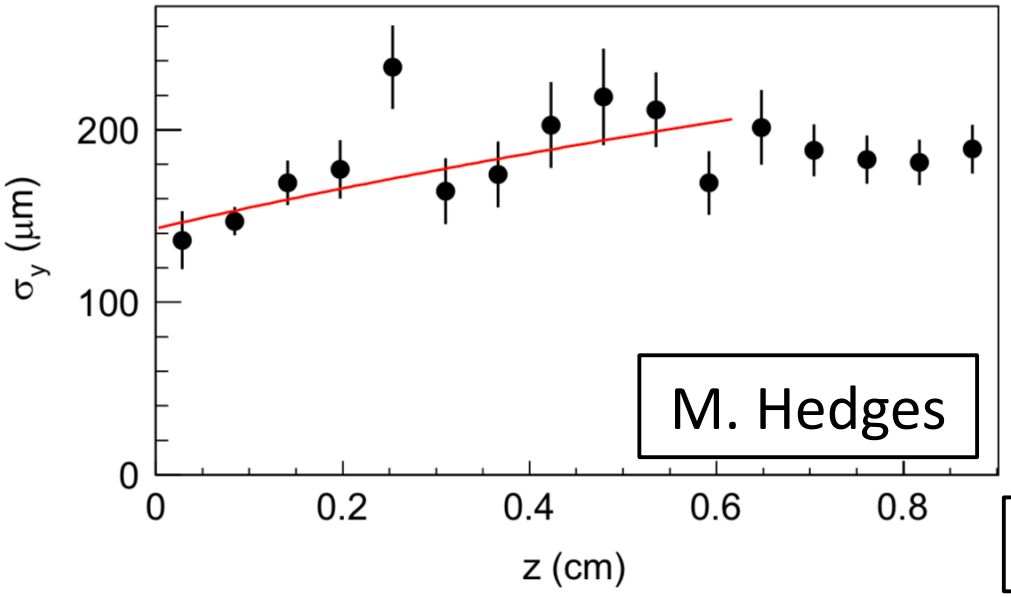
- **ATLAS FE-I4B**
- Digitizes @ 40Mhz
- Z (relative) is reconstructed from this and drift velocity
- X, Y come from pixel coordinates

2cm

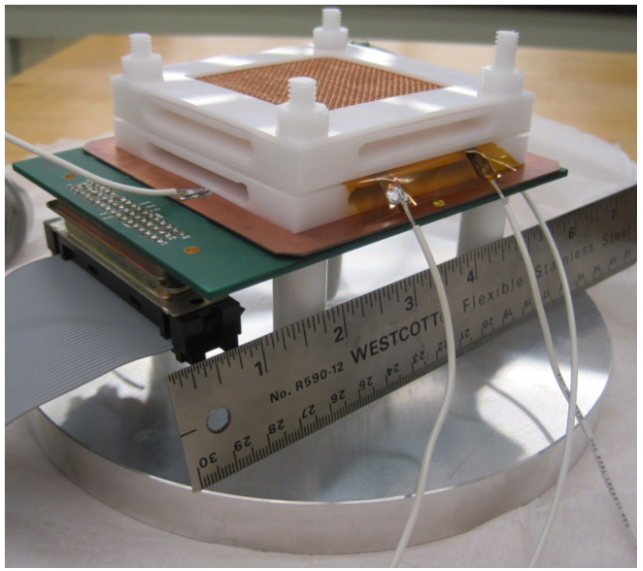


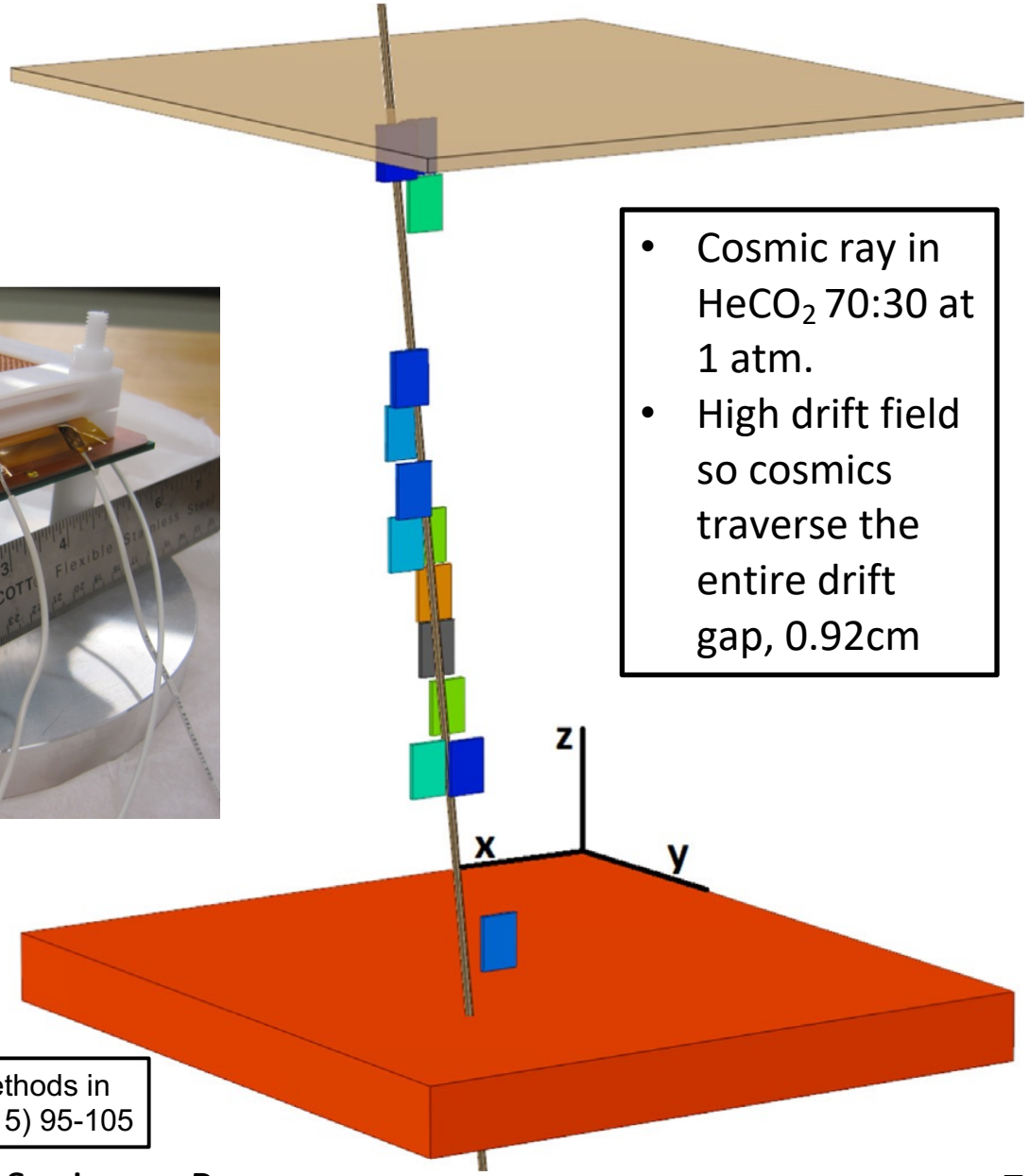
Measuring Detector Point Resolution





M. Hedges



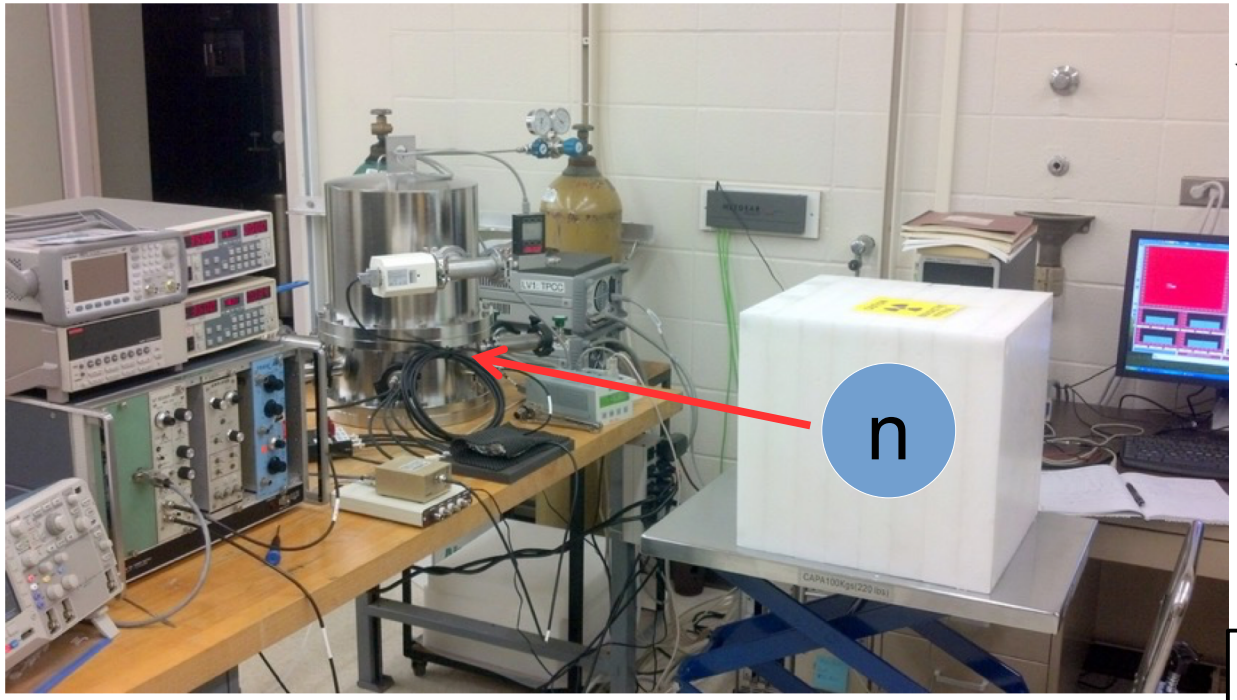


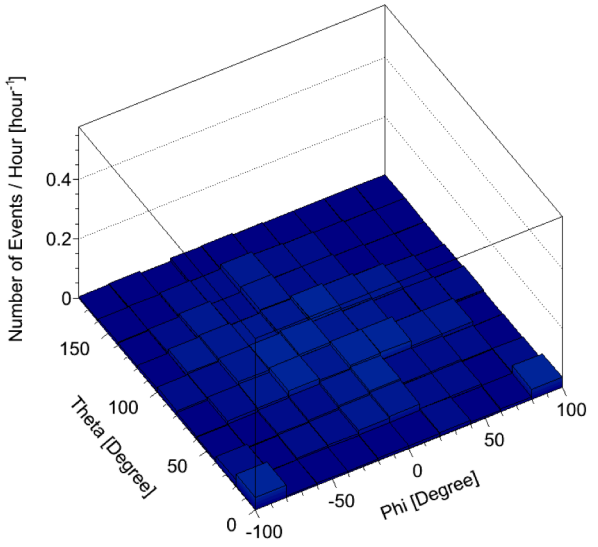
- Cosmic ray in $HeCO_2$ 70:30 at 1 atm.
- High drift field so cosmics traverse the entire drift gap, 0.92cm

Nuclear Instruments and Methods in Physics Research A 788 (2015) 95-105

Directional Neutron Detection

- D^3 - micro with increased drift length to ~5cm for higher efficiency to detect recoils
- Cf(252) source
- Vector 3D track reconstruction allows both angles to be determined – source location

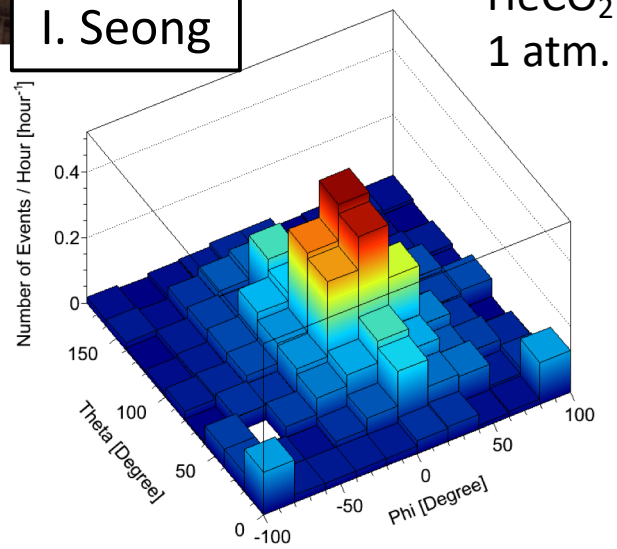




Background Run

I. Seong

$HeCO_2$
1 atm.



Source Run

This "neutron wind" in the lab frame is just like the "WIMP wind" in the galactic frame!

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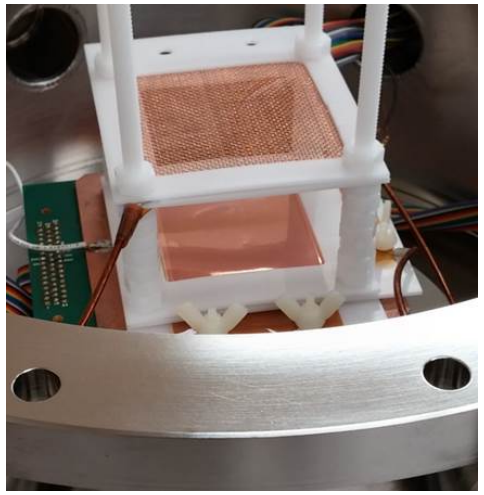
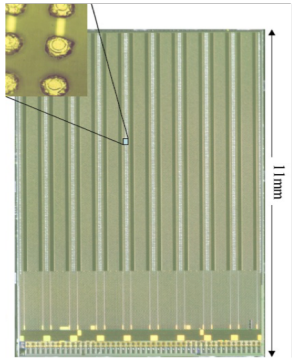
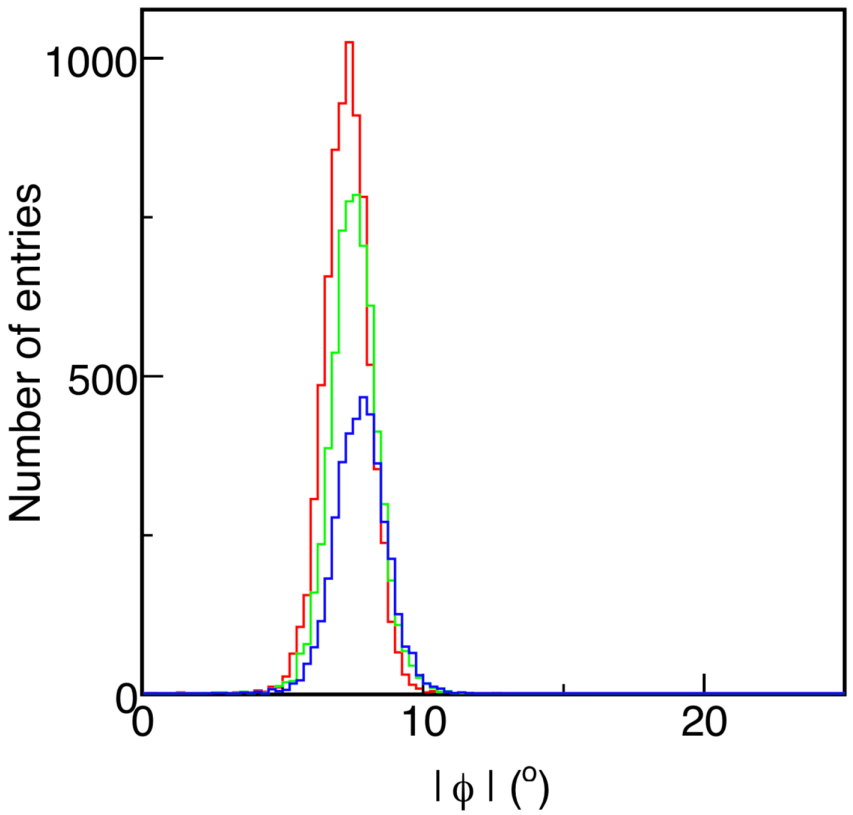




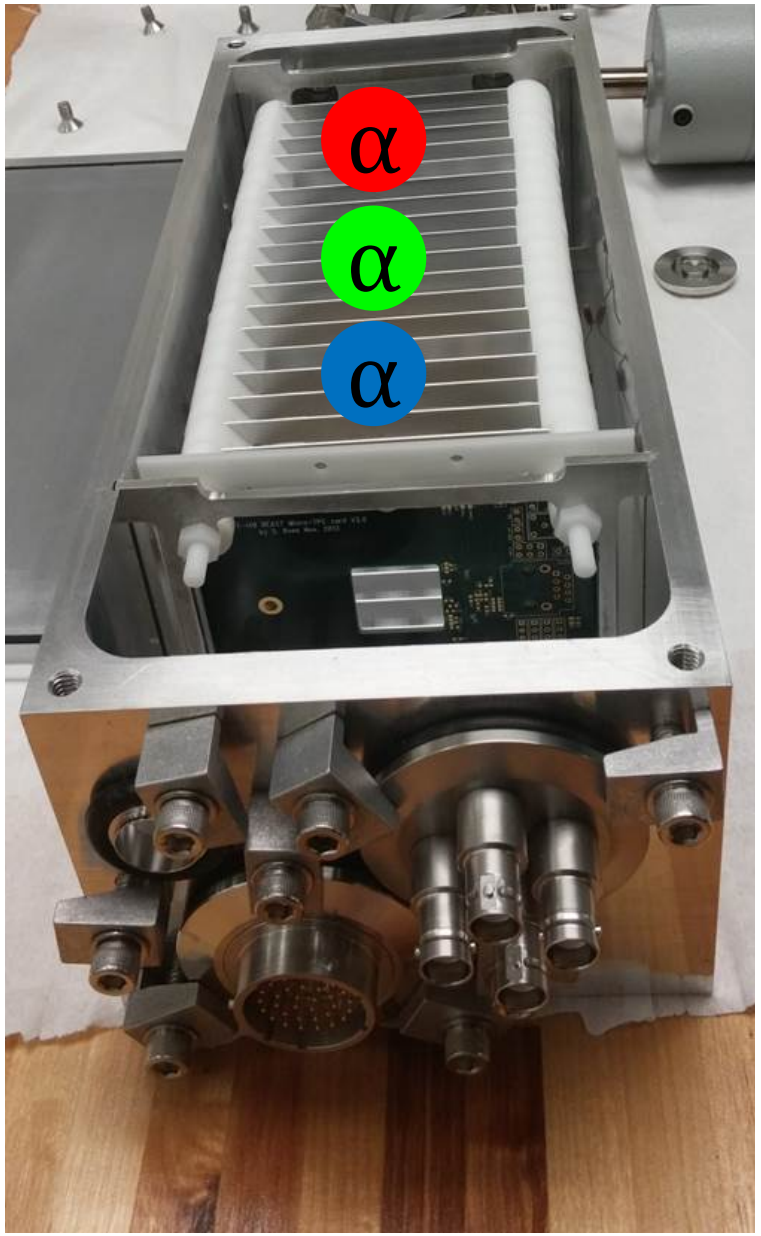
ATLAS FE-I3
50 x 400 μm pixels
7.4 x 11.0 mm

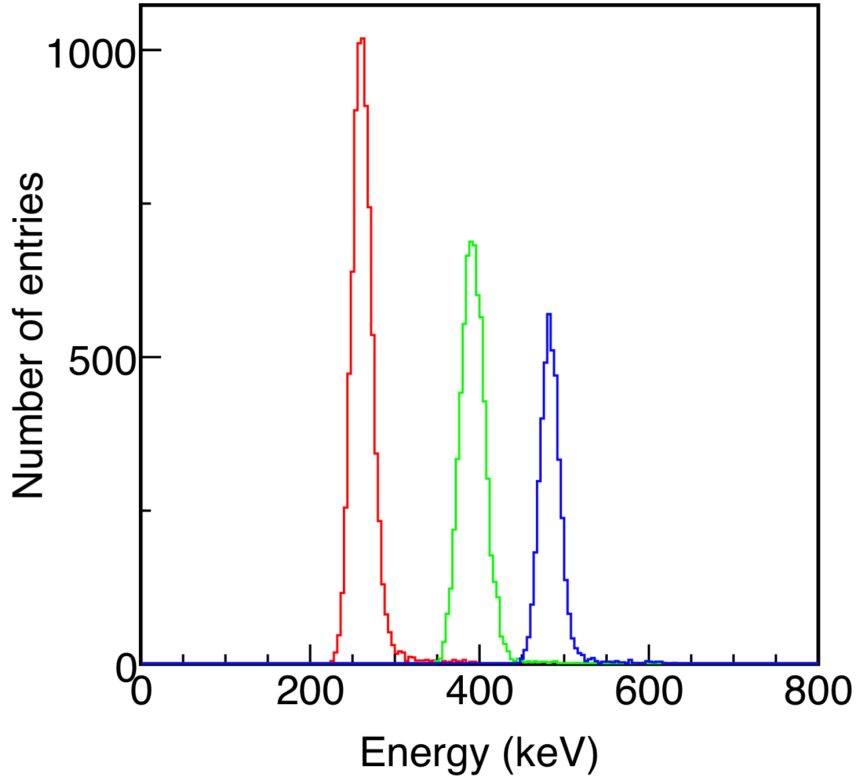
BEAST II Prototype Performance



- Alpha tracks are ~ 2.1 cm
- Sigma of above Gaussians are < 1°
- 1 cm long tracks resolution of ~2.5°

Similar performance is seen in the BEAST II production TPCs

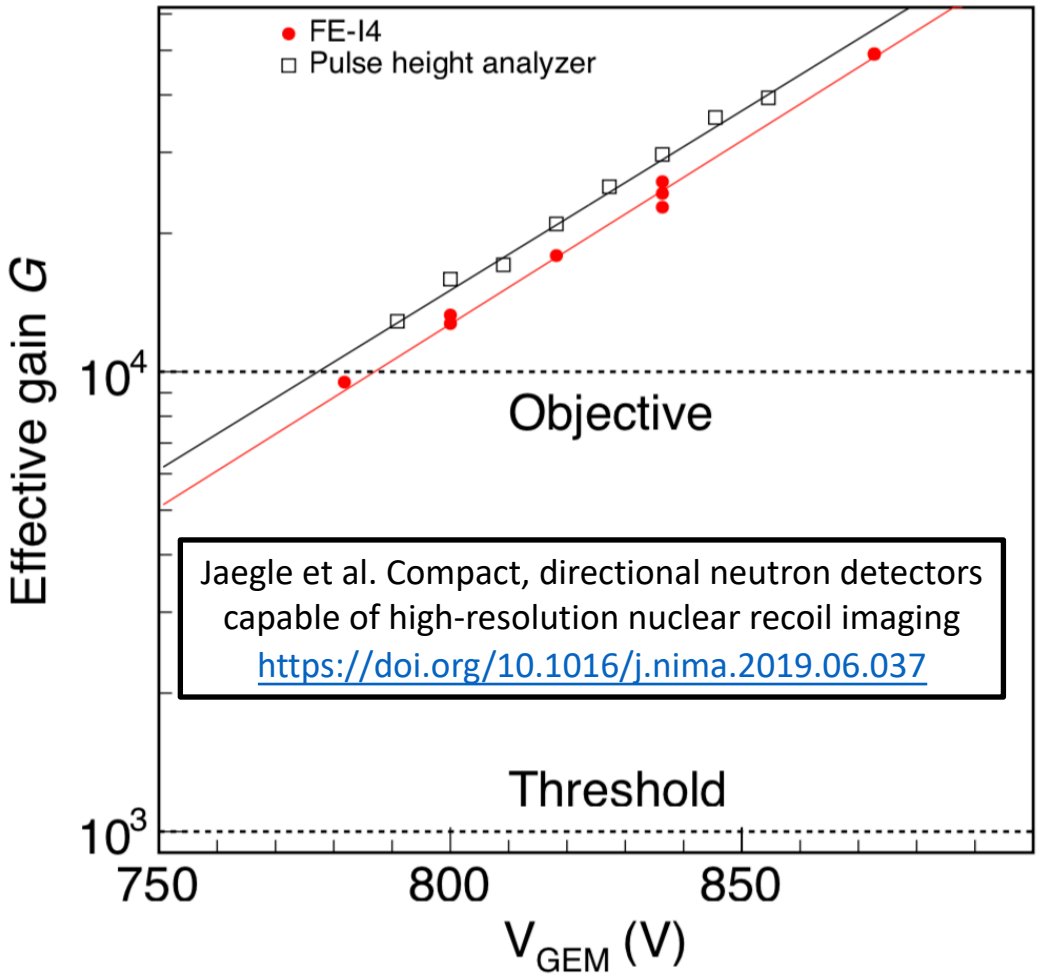




- The higher the z position, the less charge is detected due to diffusion
- Diffusion of the charge cloud results in lower charge density
- Edges of track can remain below pixel threshold

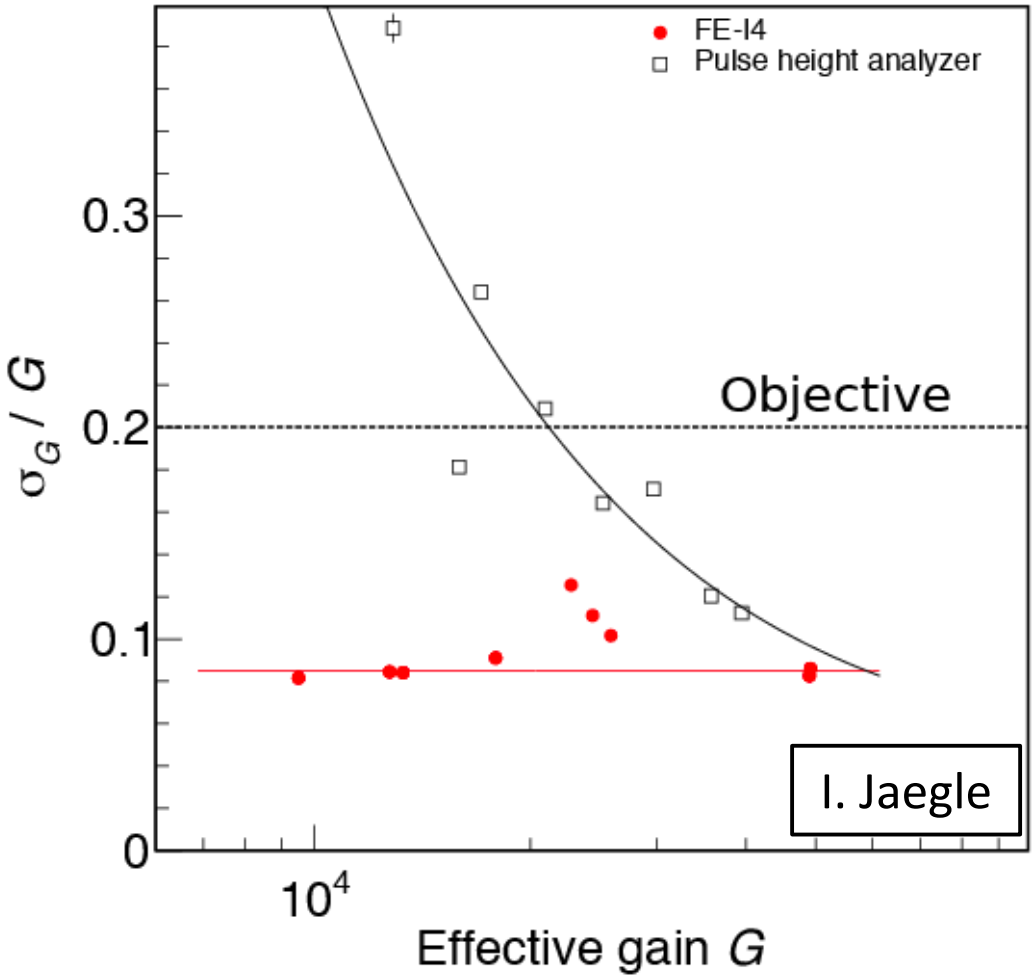
Jaegle et al. Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging https://doi.org/10.1016/j.nima.2019.06.037

BEAST II TPC Gain Performance



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

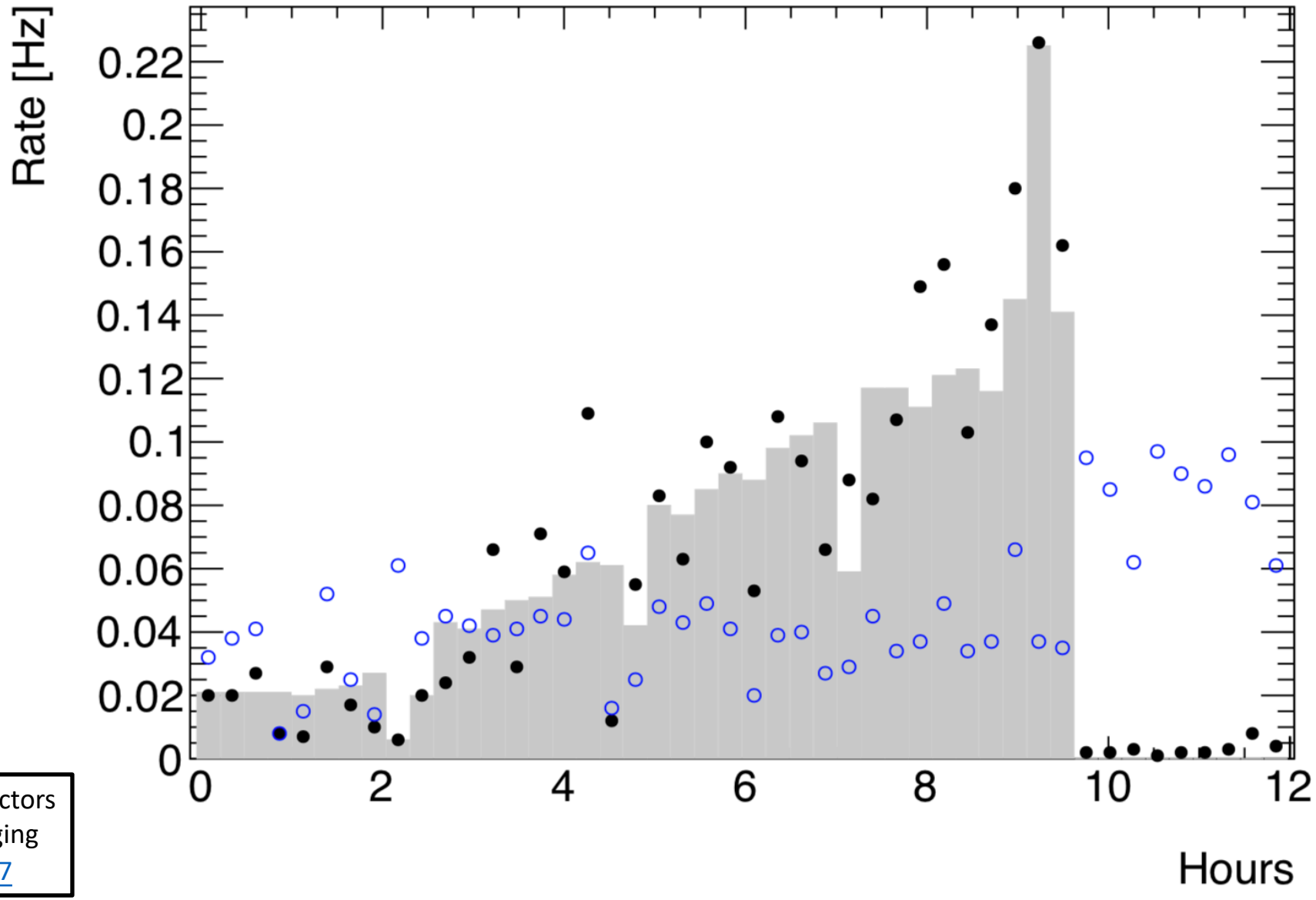
Quantity	Threshold	Objective	Specification	Achieved
Angular resolution (1-cm tracks)	n/a	15°	5°	2.5°
Gain	1,000	10,000	20,000	50,000
Gain stability, one week	n/a	20%	5 %	1%
Energy resolution at 5.9 keV	n/a	20%	12 %	10%



Pixel chip shows improved energy resolution at low gains when compared with noisier analog electronics for pulse height studies

D-D Generator Rate Measurements

- D-D generator run (testbeam)
- Large X-ray background
- Black circles are rates of the neutron candidates
- Open circles are rates of good alpha candidates
- Gray is D-D neutron rate



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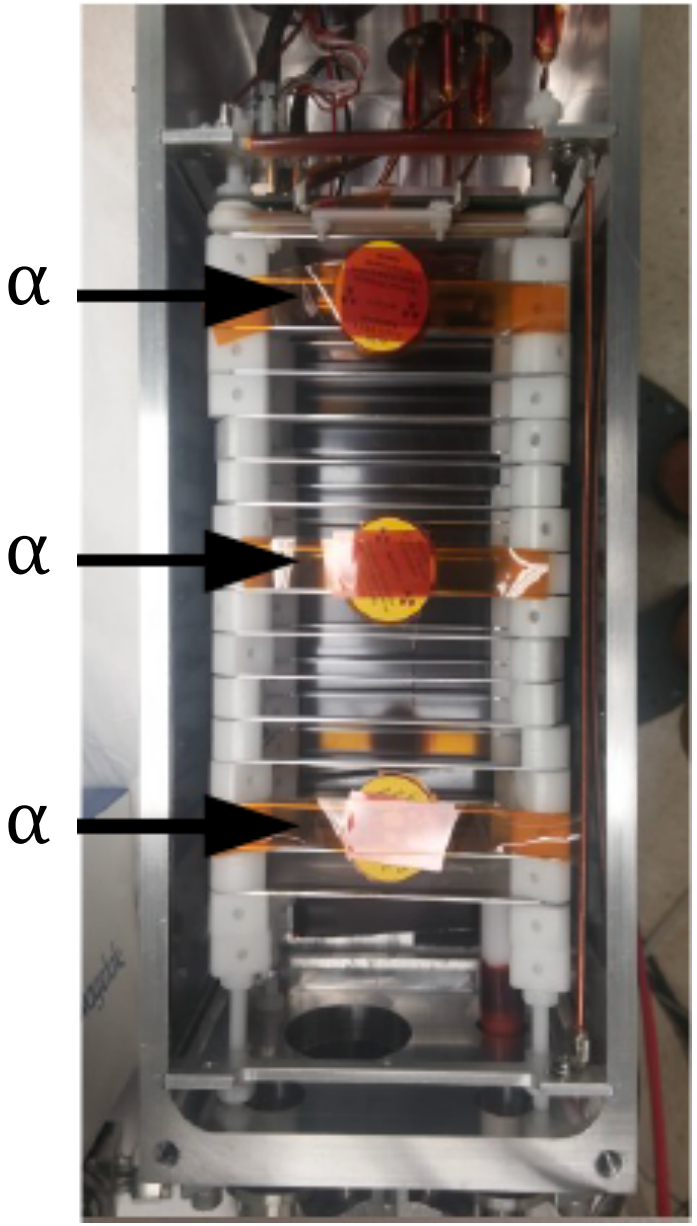
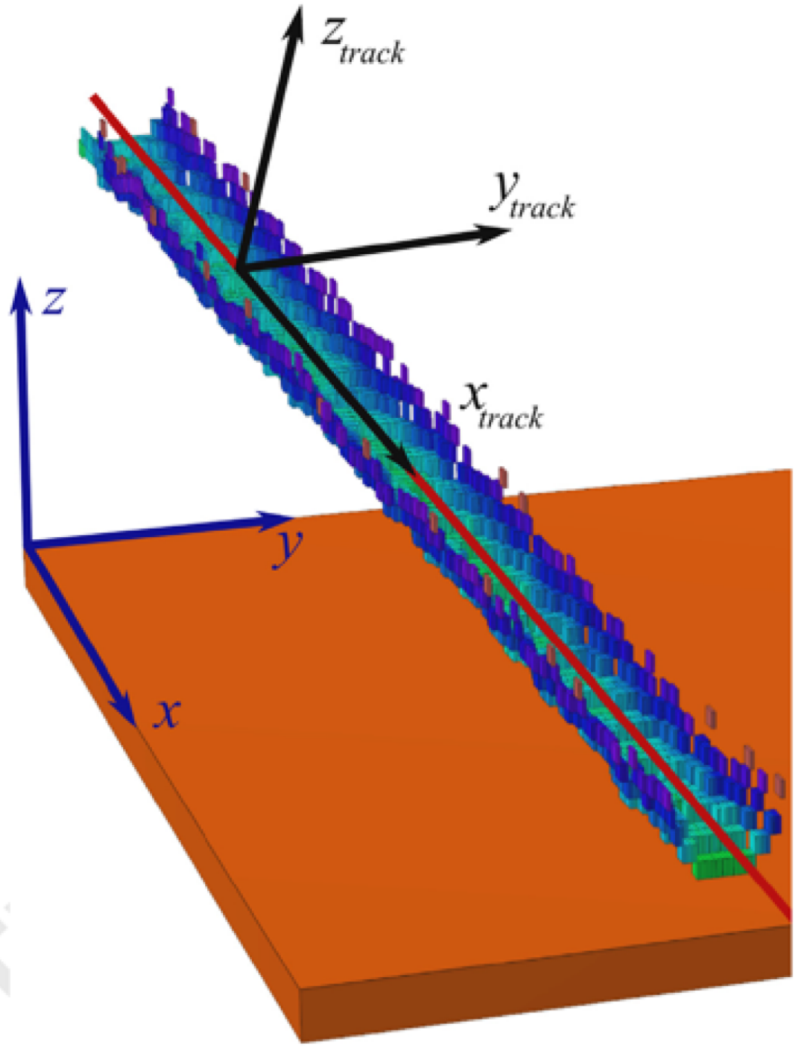
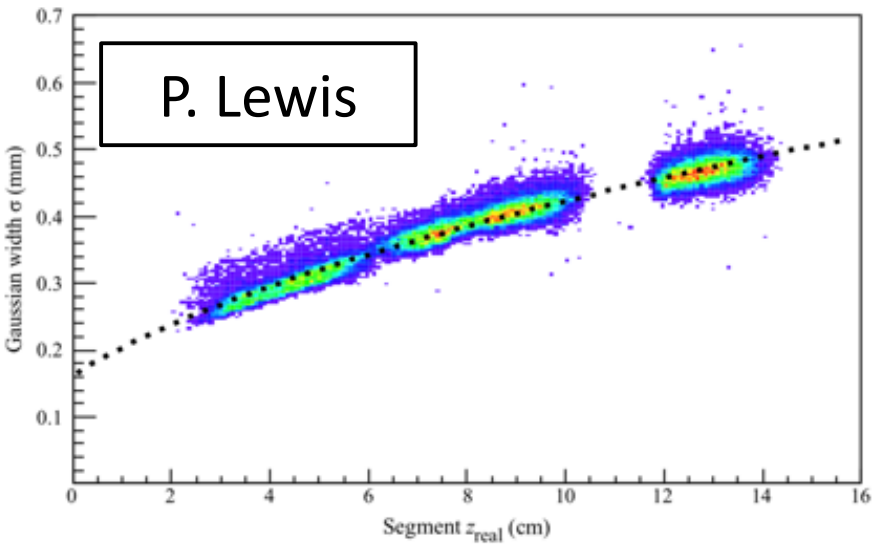
Full 3D Fiducialization



With HD charge readout Z can be fiducialized via charge cloud diffusion





- We know how the charge diffuses and where the sources are located in z
- This gives a one-to-one relationship between z and charge profile width
- This allows for absolute z to be measured within ~ 1 cm

Full 3D fiducializtion is necessary for background-free detectors

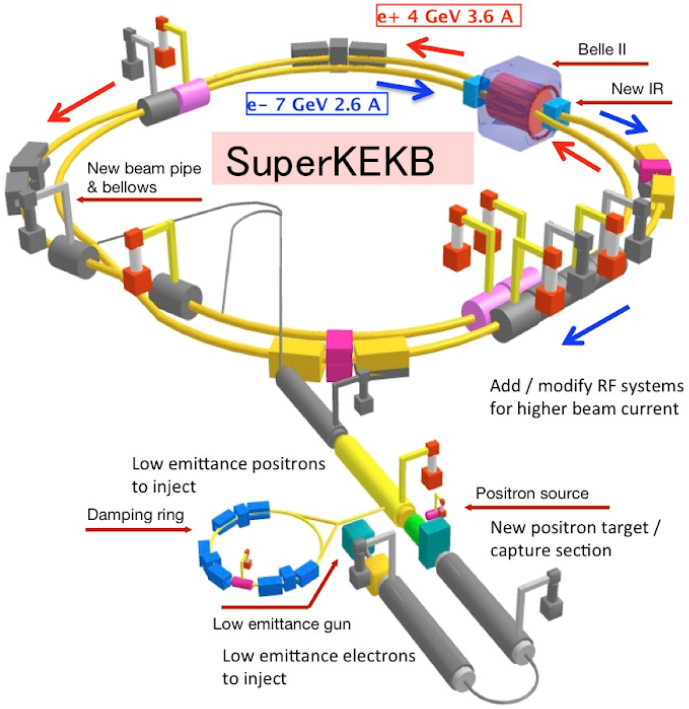
Nuclear Instruments and Methods in Physics Research A 789 (2015) 81-85

Limit Setting with FE-I4B ASIC

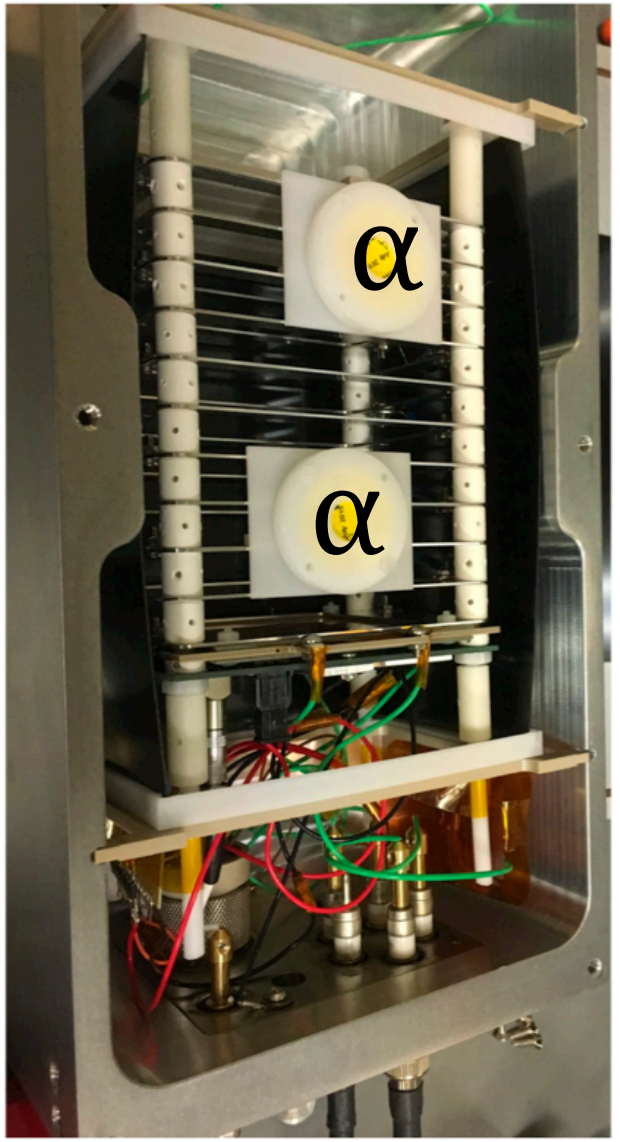
Data Sets for Limit Setting

- Upgrade to SuperKEKB expected to produce large backgrounds
- 8 small TPCs were deployed as part of BEAST II to monitor fast neutrons
- ~7.8 day set of beam-off, solenoid off data was used
- TPC fiducial dimensions are $1.6 \times 2 \times 10\ cm^3$
- Recorded with $HeCO_2$ (70:30) at atmospheric pressure
- Exposure = 2.44×10^{-5} kg x 7.8 days
- MC samples were produced (not by me) as part of the Cygnus effort
  - Helium recoils up to 90 keV
  - Electrons up to 30 keV

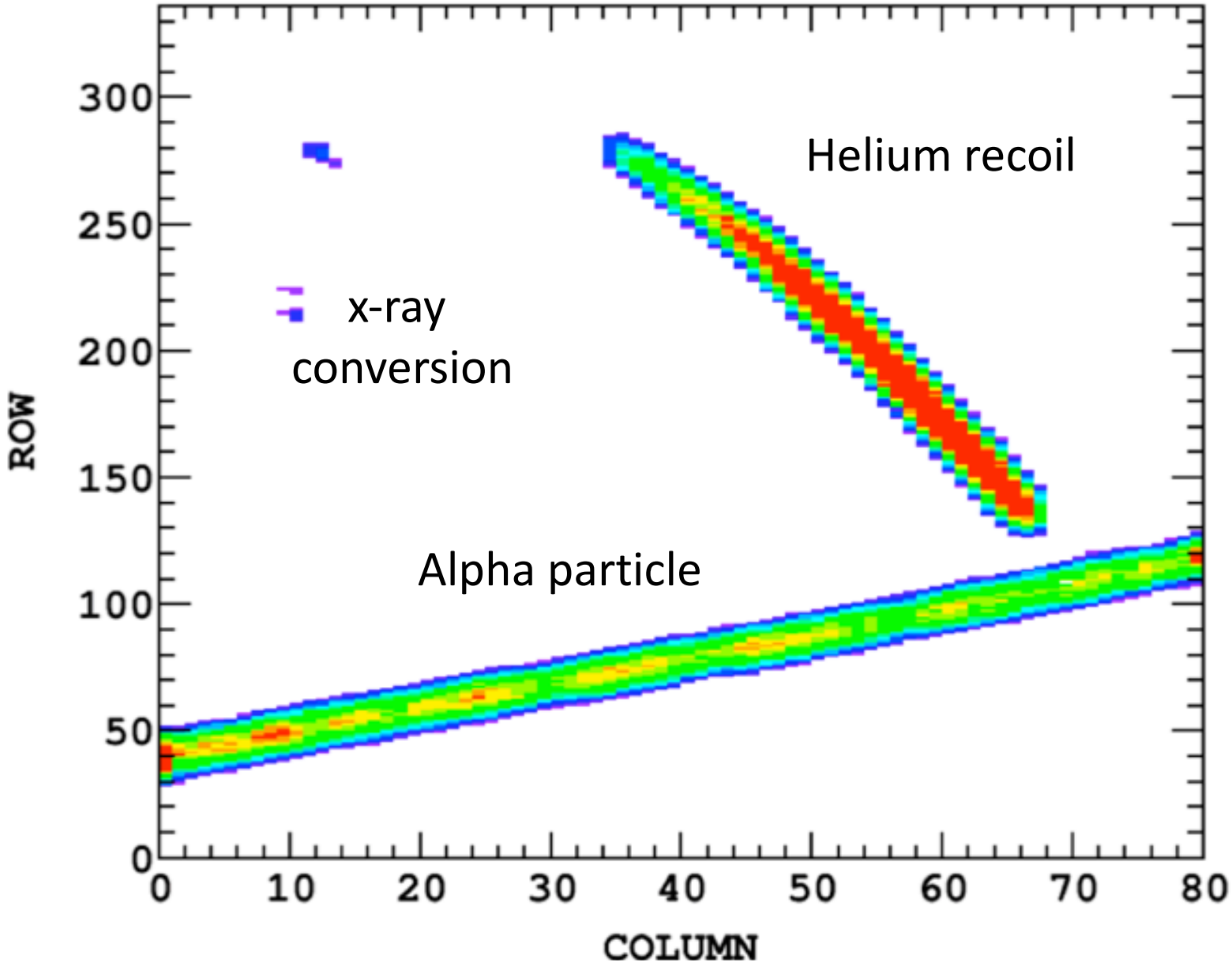
Thanks to neutrons! and BEAST II people!



BEAST II TPC

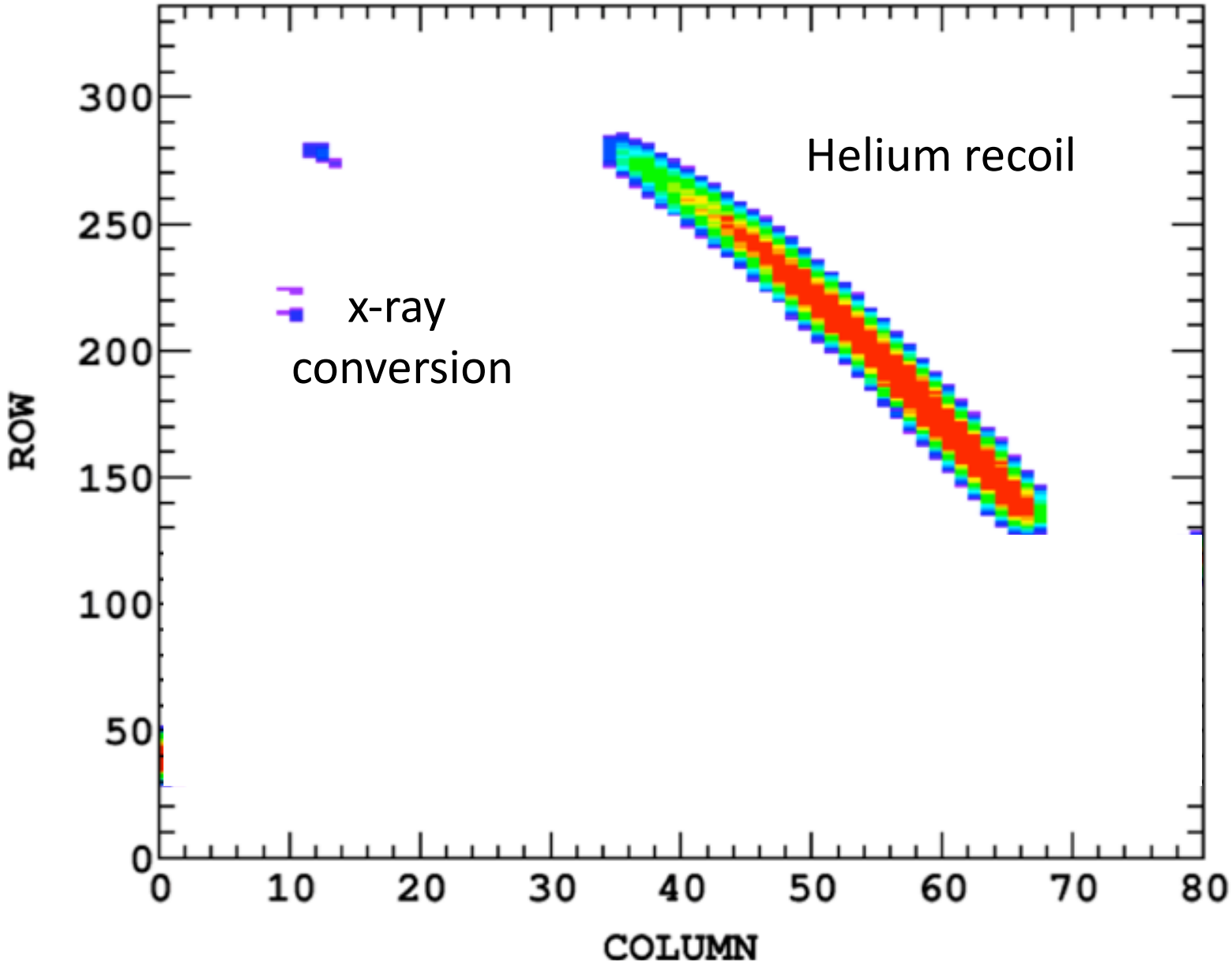


Three Events Superimposed



Event topology is very different

Edge Selection - Applied

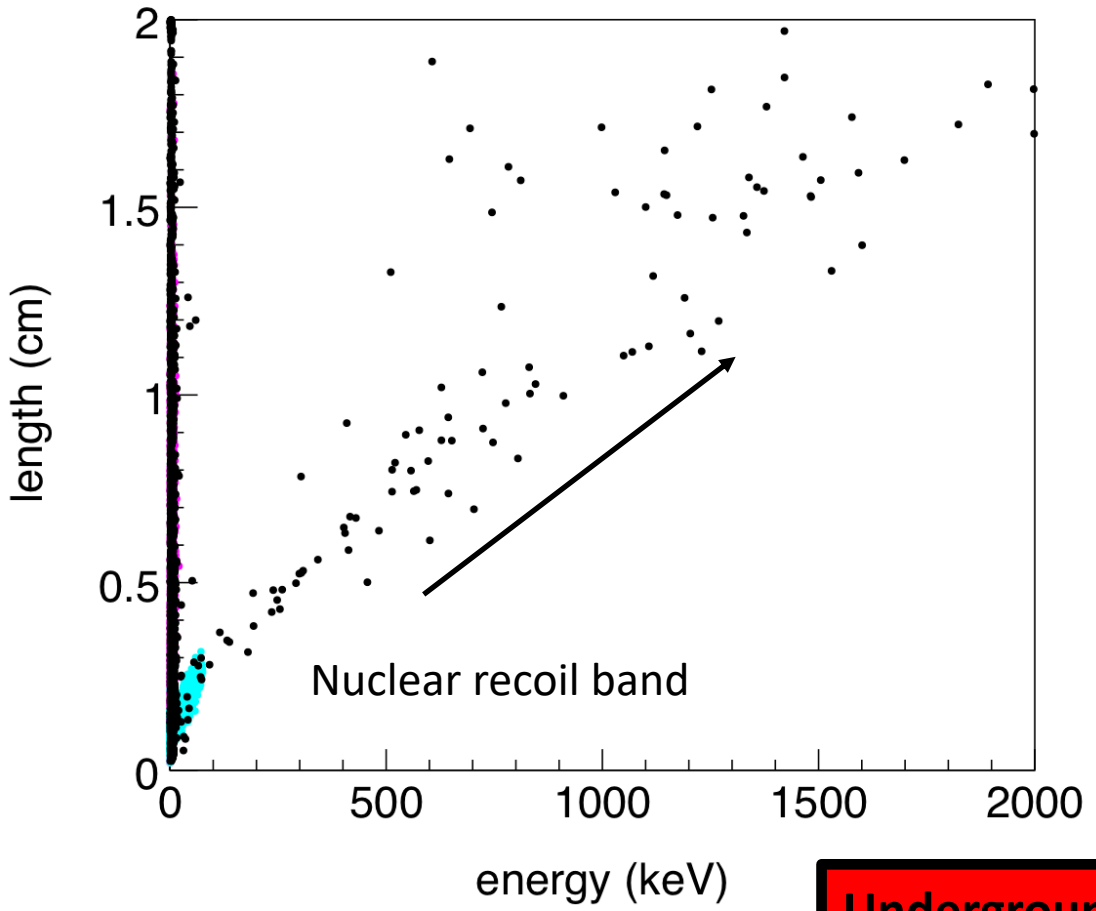


Event topology is very different

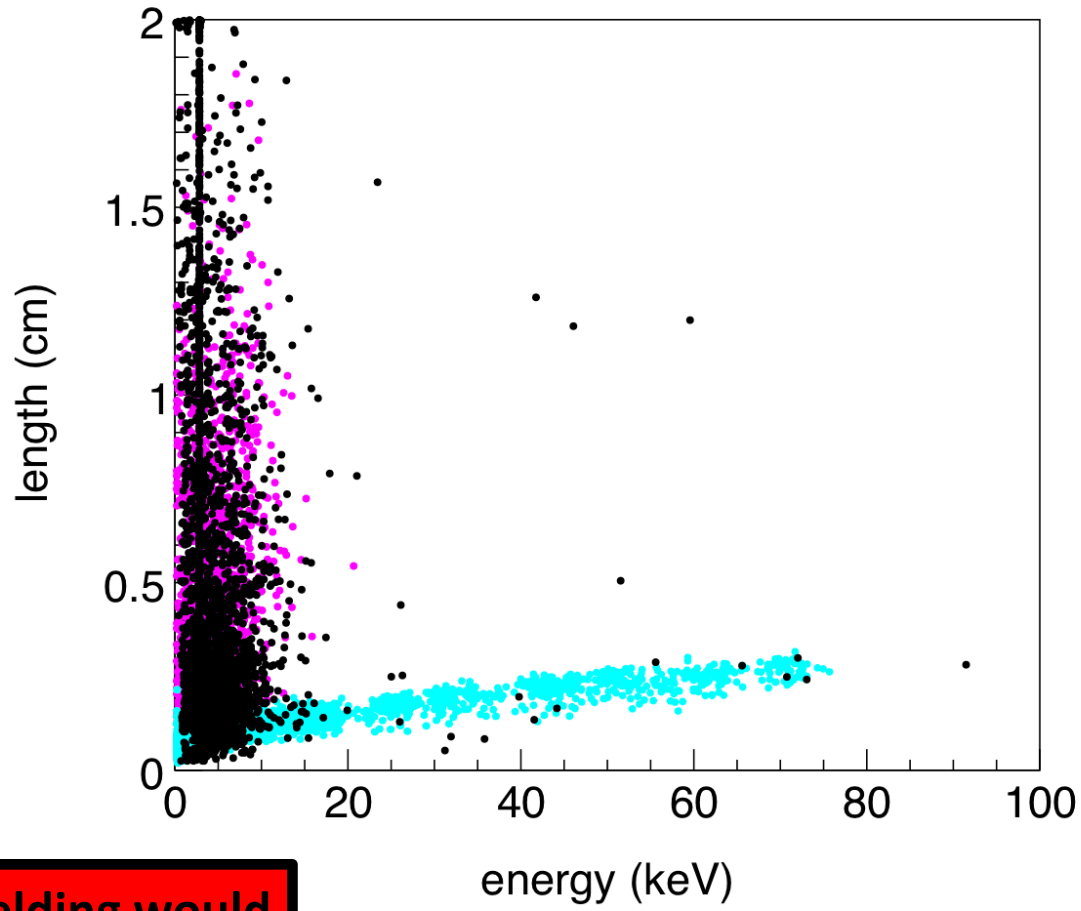
Length vs. Energy

MC Helium recoils | Experimental data | MC electrons

After edge selection



After edge selection - zoomed



Underground; shielding would eliminate many of these

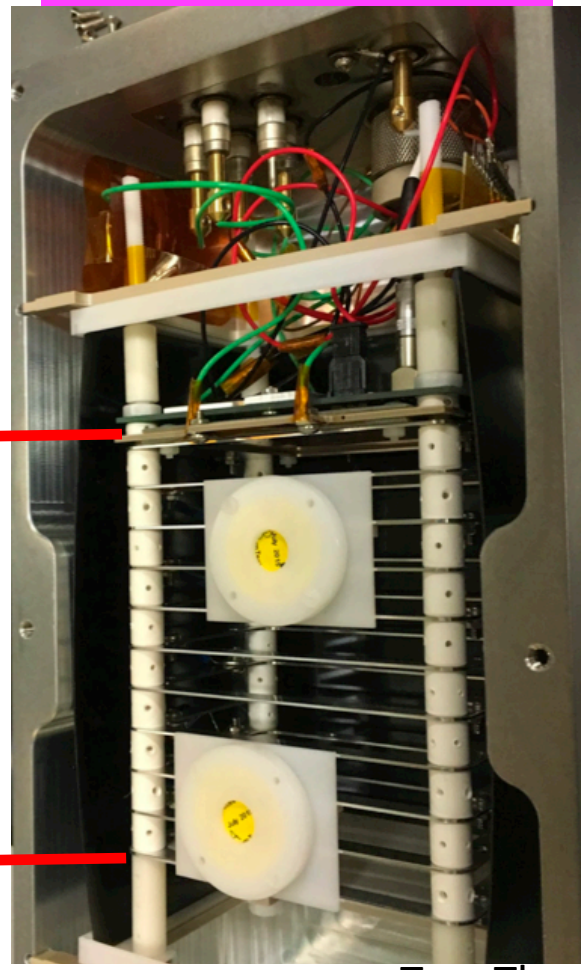
Absolute Z Selection

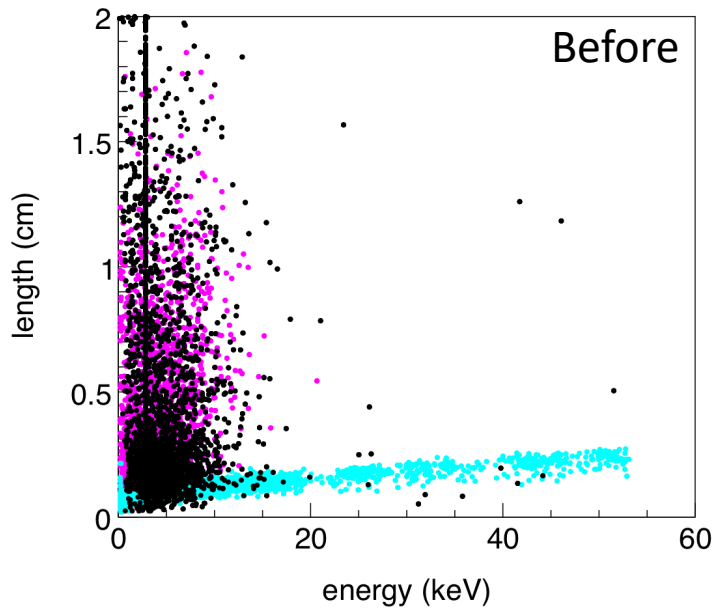
- TPCs have 10 cm field cage
- Veto events that originate from outside
- Very powerful
- Required for background free operation
- Still under study

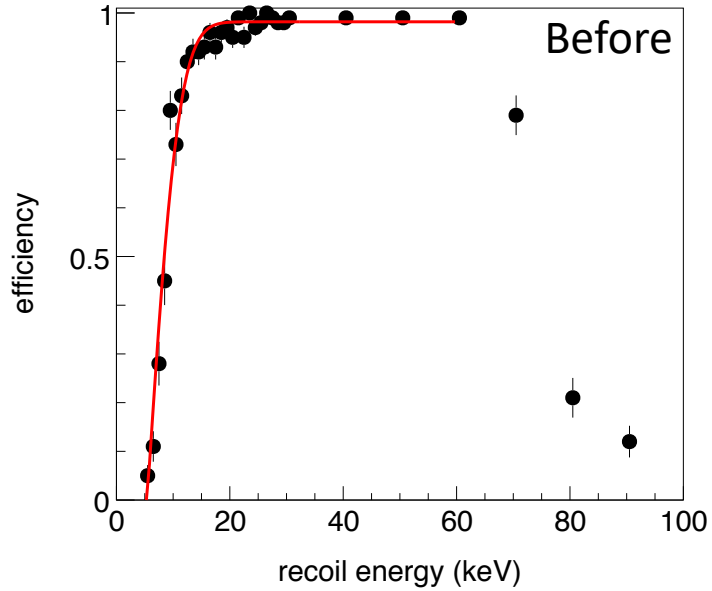
MC Helium recoils

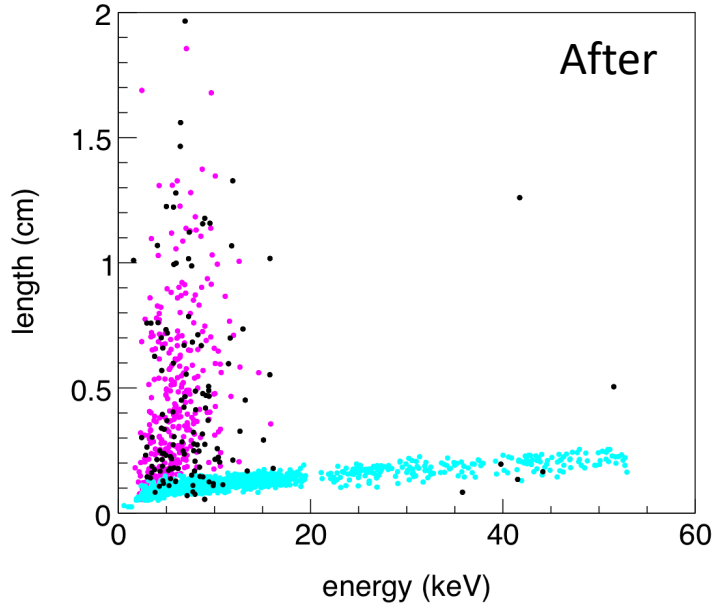
Experimental

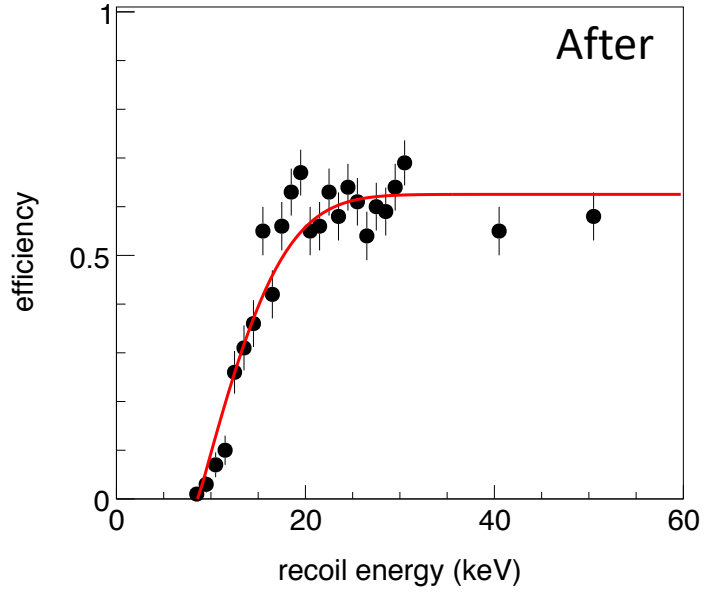
MC electrons



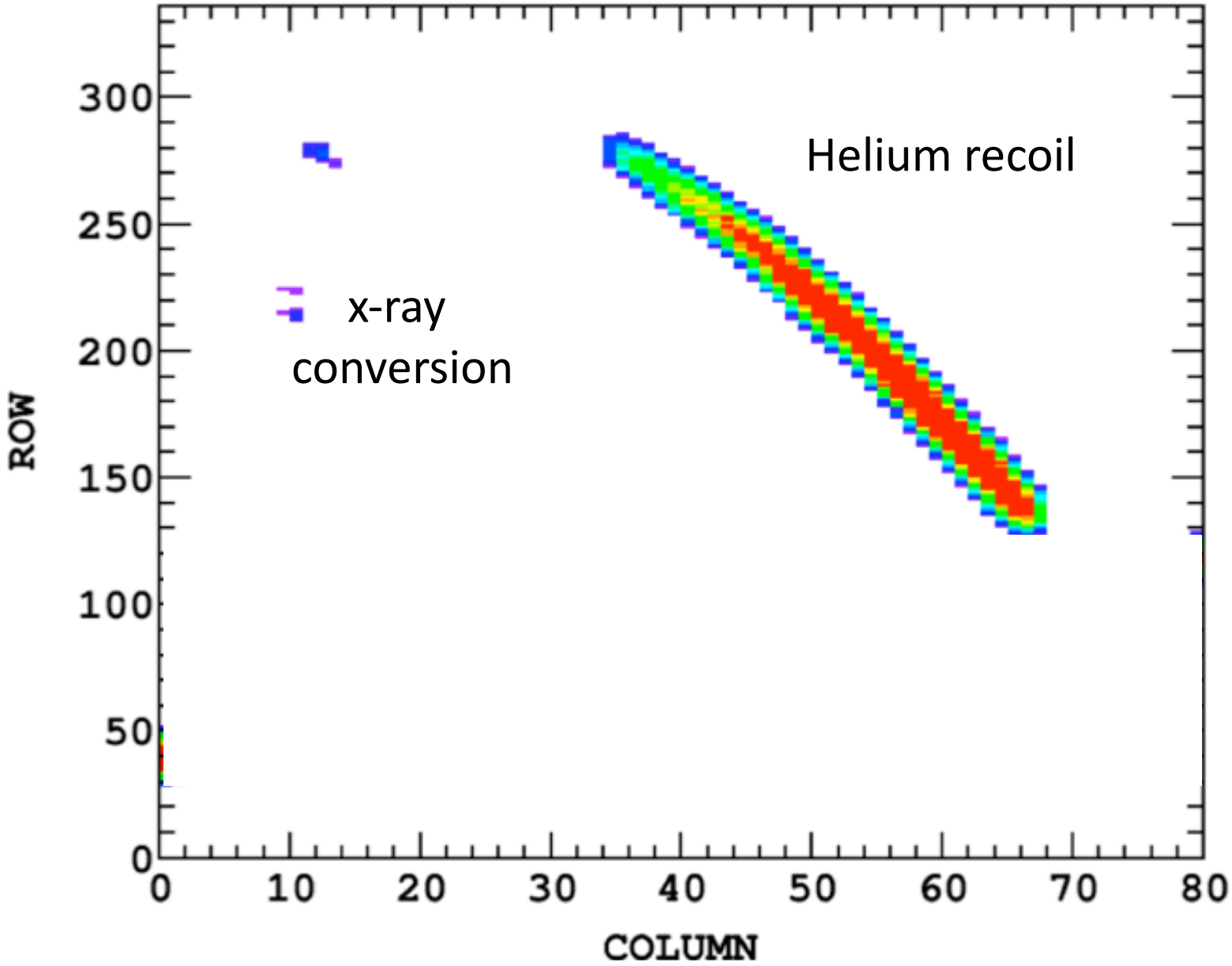








Now What?



Event topology is very different

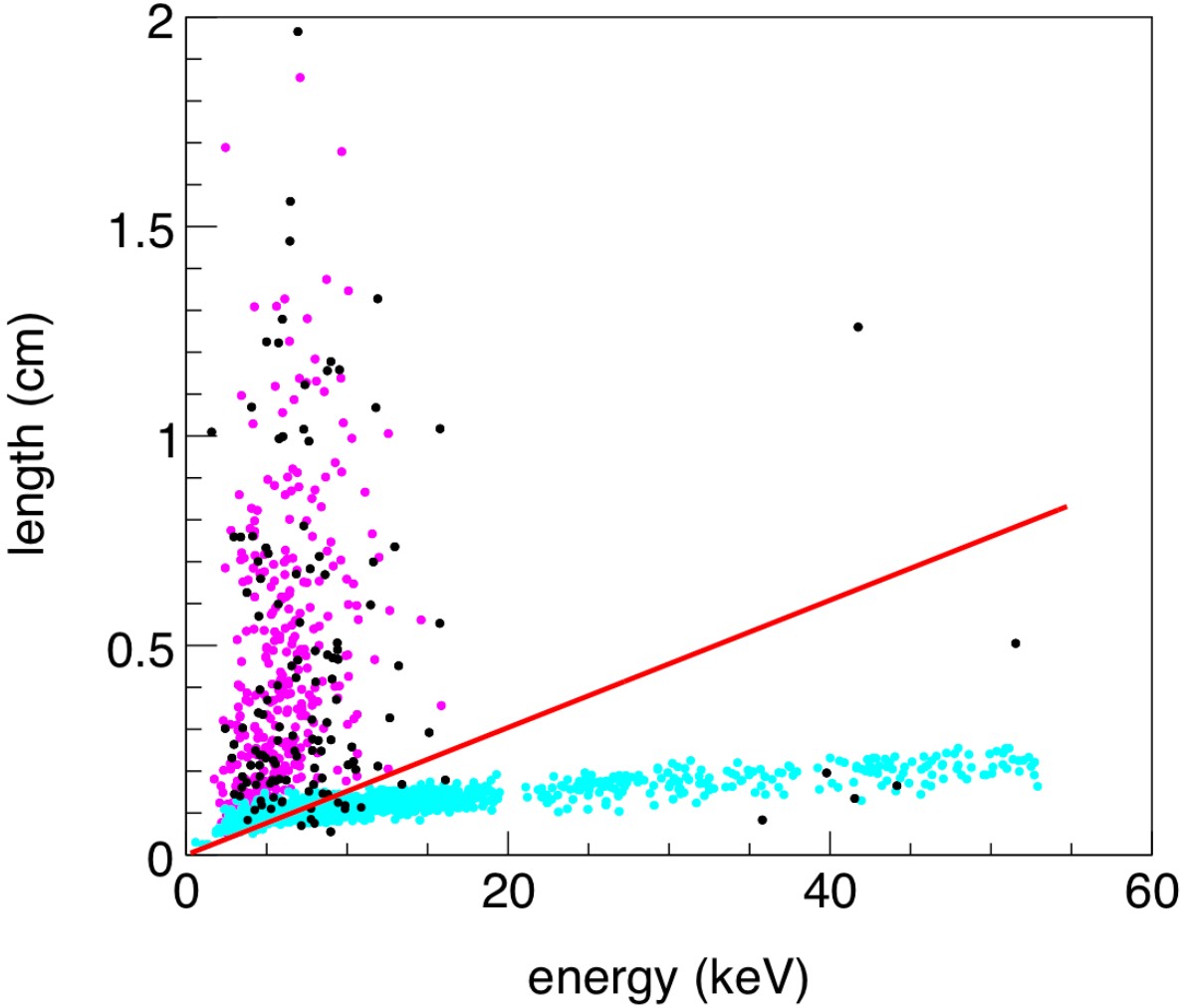
Length vs. Energy Selection

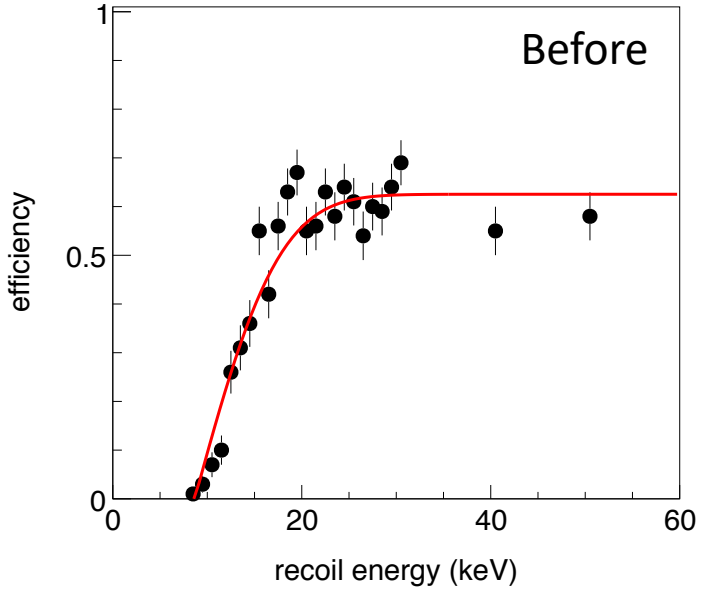
MC Helium recoils

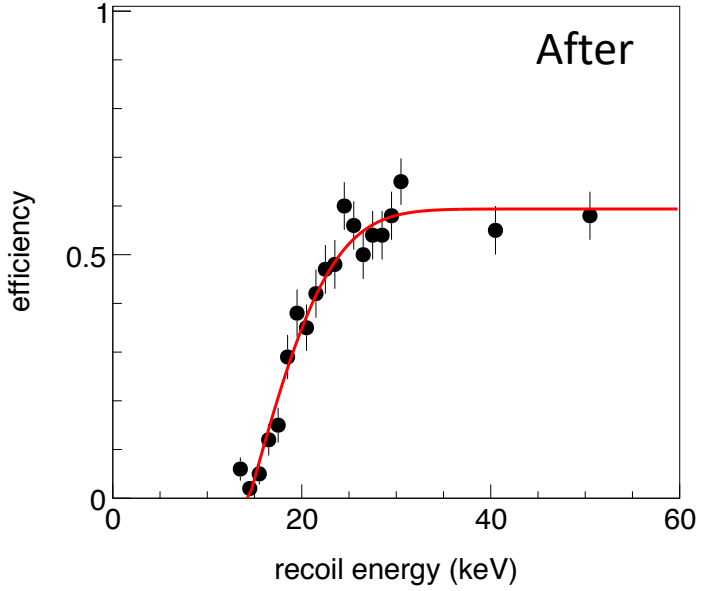
Experimental

MC electrons

- Preformed a scan on the length vs. energy value
- Optimization between moving the signal efficiency to higher energy and removing backgrounds
- Limit is set using the MC signal efficiency curve after this selection





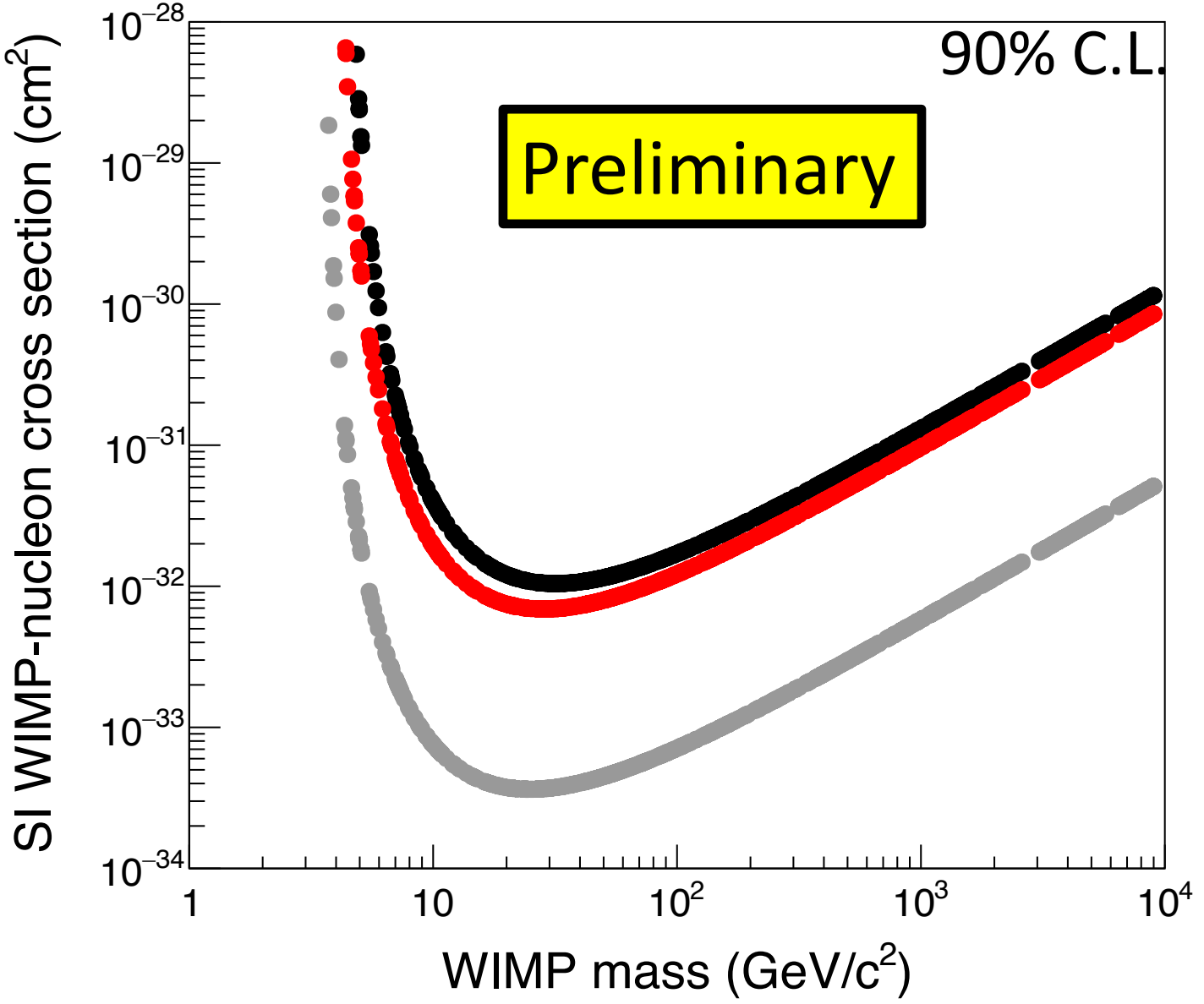


WIMP-nucleon SI Scattering Cross Section Limit

- Black curve
- For length vs. energy selection of 0.0192 cm/keV
- 16 experimental events remain

- Red curve
- For length vs. energy selection of 0.0192 cm/keV
- 19 experimental events remain

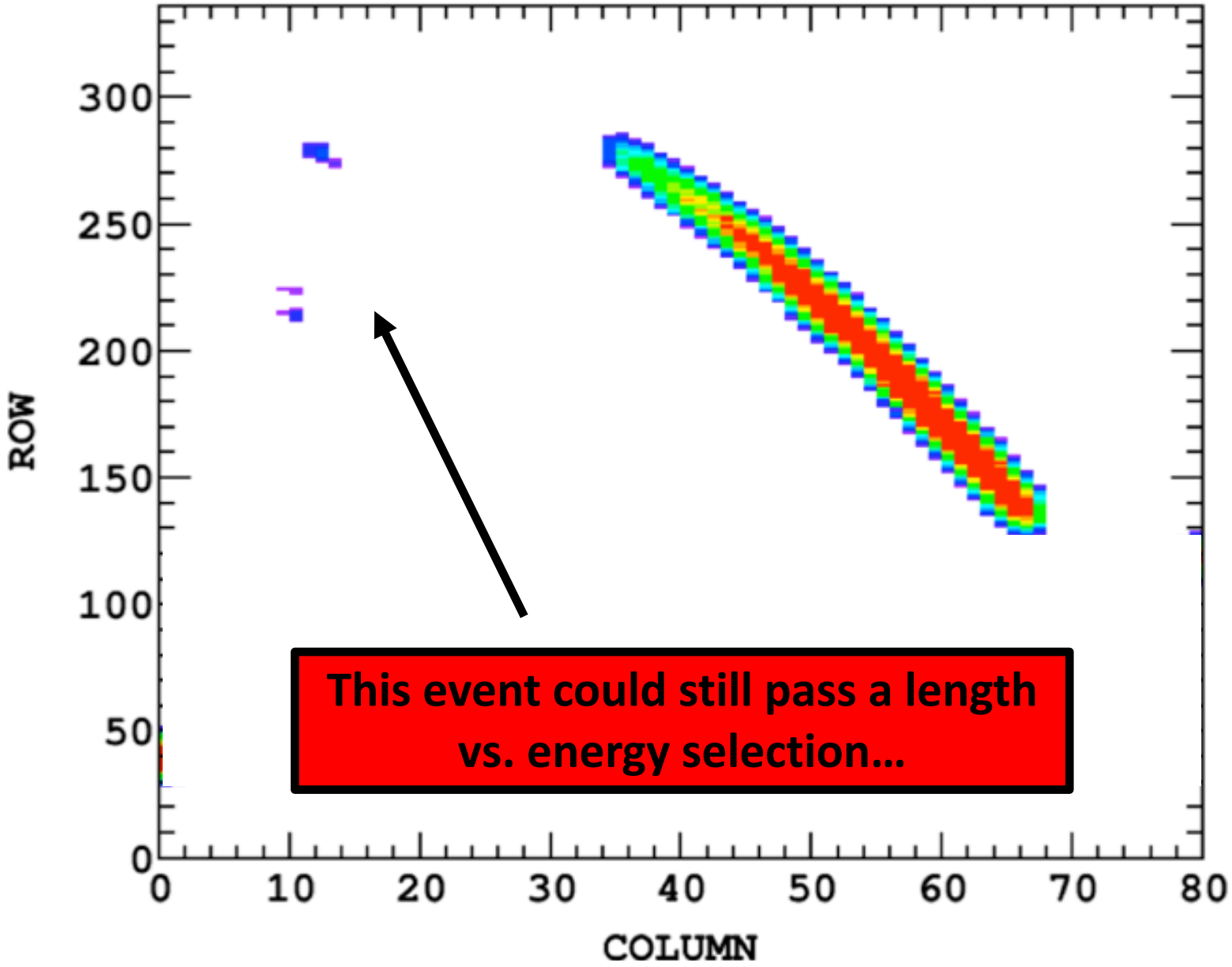
- Gray curve
- No length vs. energy selection
- Speculation with no background
- Possible with shielding/underground



Cluster Counting

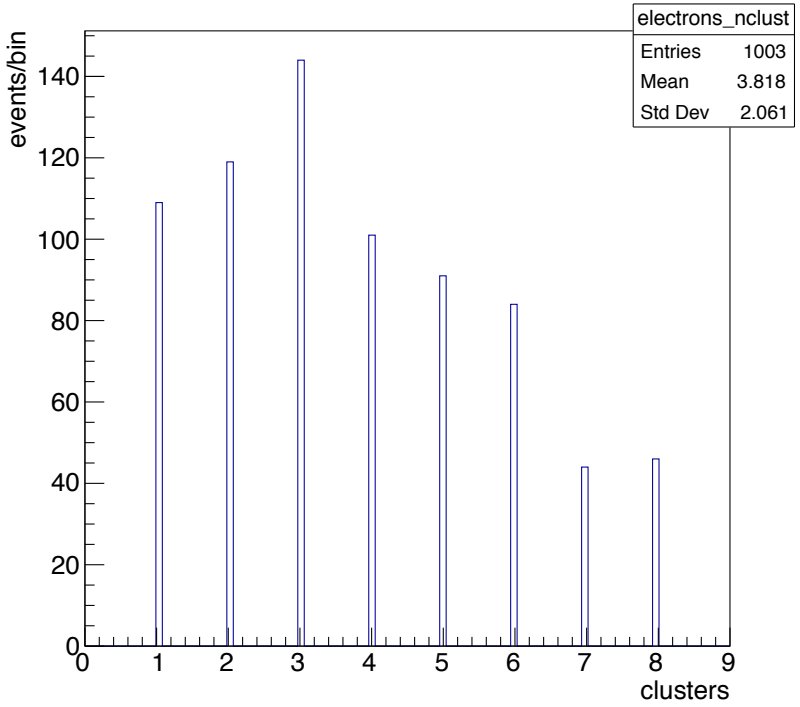
Cluster Counting Intro

- Idea is straightforward
- Electron tracks tend to have multiple clusters due to lower charge density
  - Pixels stay below threshold
- This can be broken down into gaps as well
  - x-gap
  - y-gap
  - z-gap
- Python scripts (S. Vahsen)
- Still optimizing selections

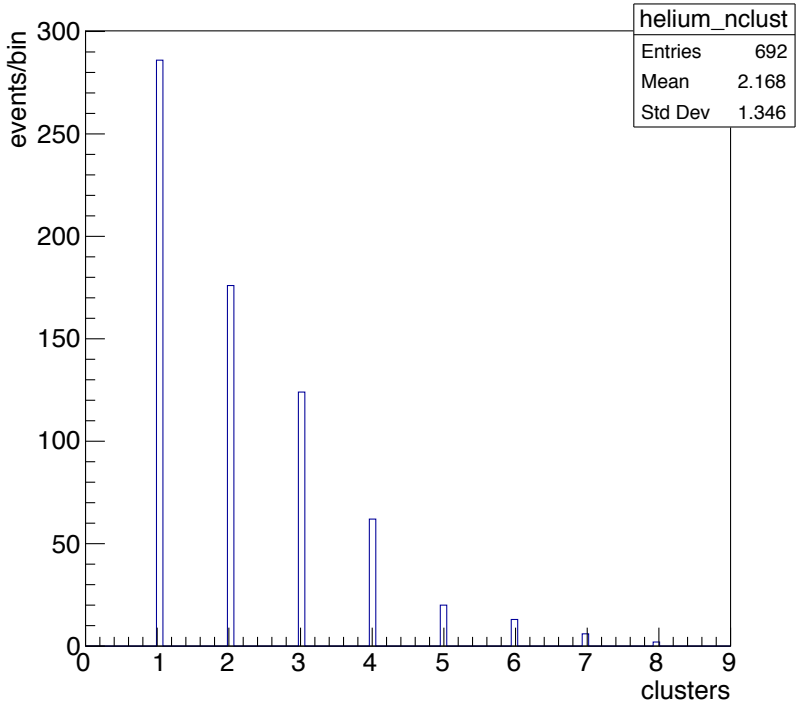


Number of Clusters Distributions

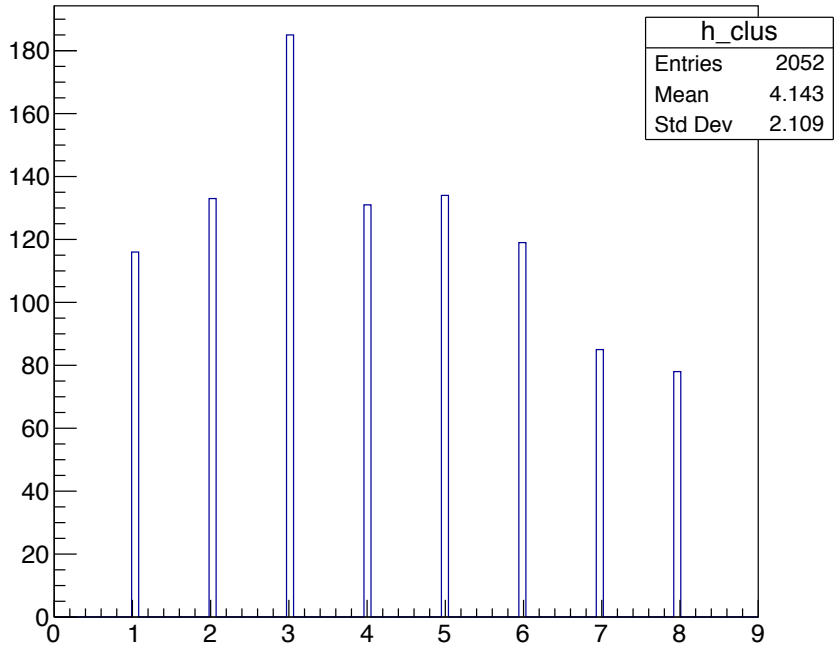
Electrons-MC



Helium-MC



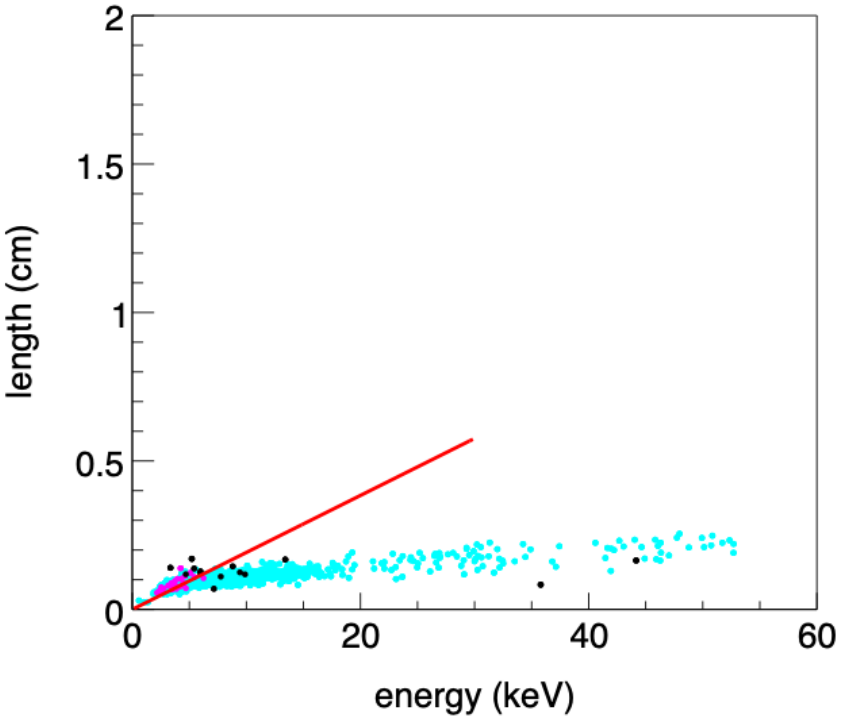
Experimental



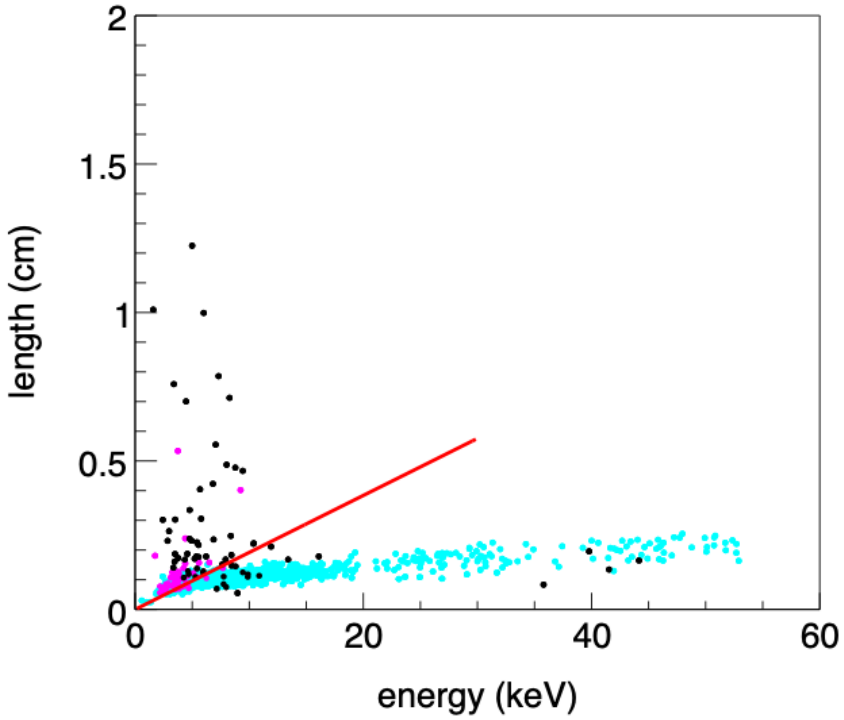
Number of clusters per event

Length vs. Energy Plots for Cluster Selections

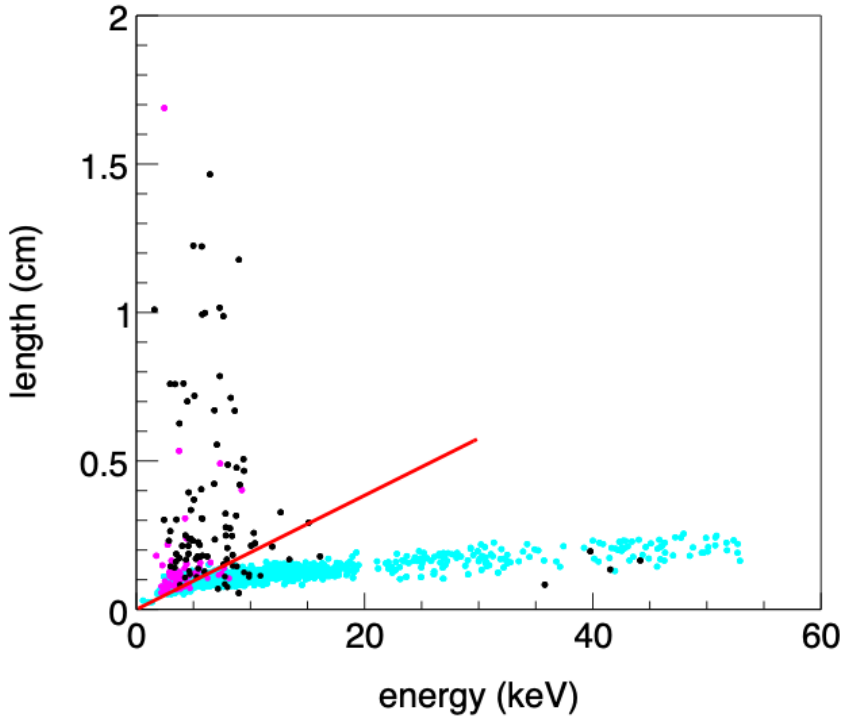
n_cluster < 2



n_cluster < 3



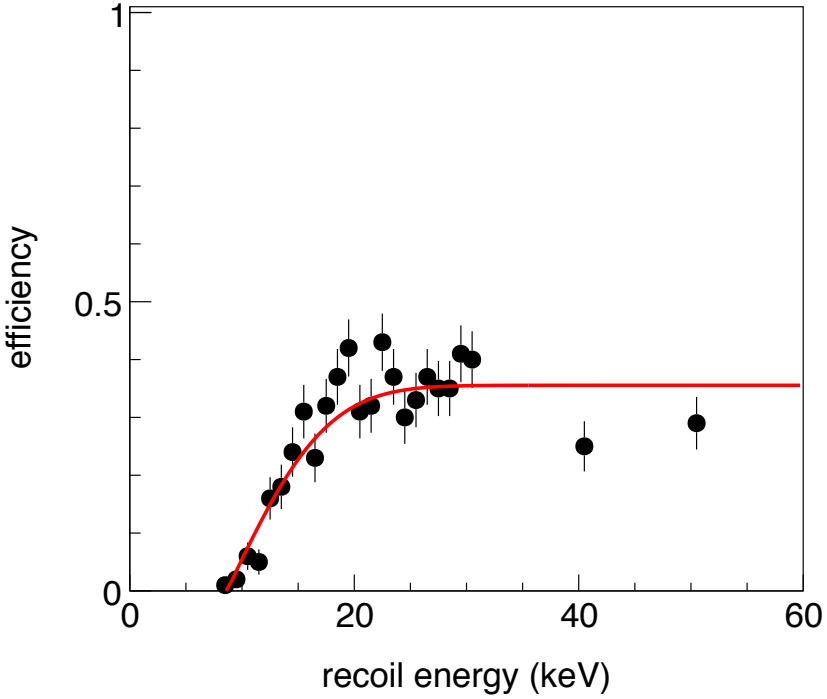
n_cluster < 4



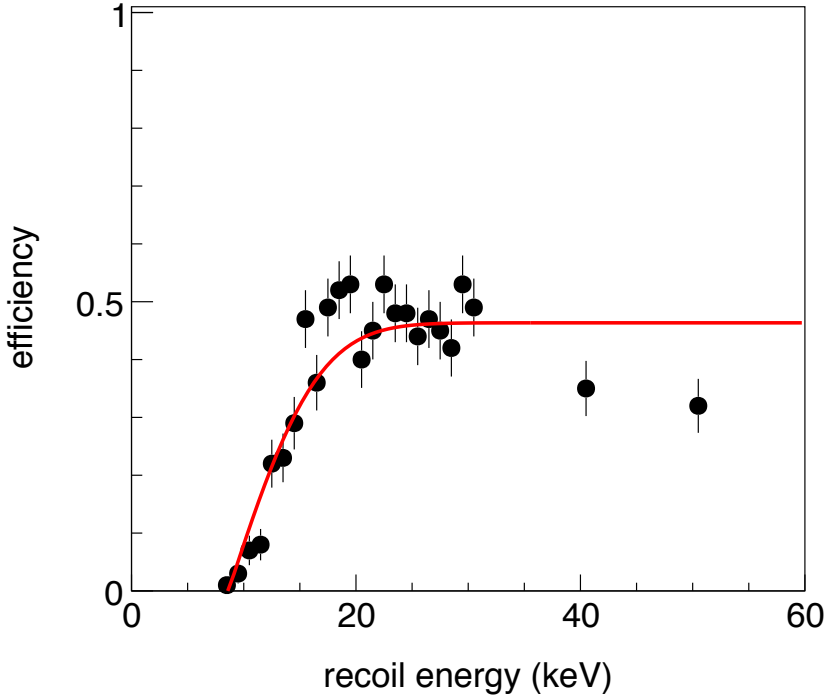
At low energies the length vs. energy selection has a large impact on the signal efficiency

Signal Efficiency (Helium MC) for Cluster Selections

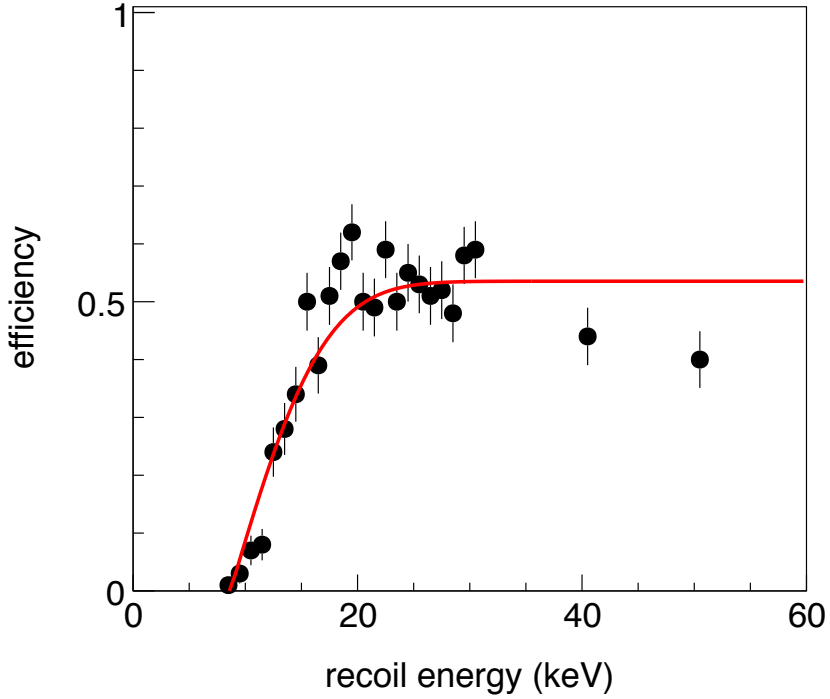
n_cluster < 2



n_cluster < 3



n_cluster < 4



However, the cluster selection retains efficiency down to ~10keV while removing as many background events

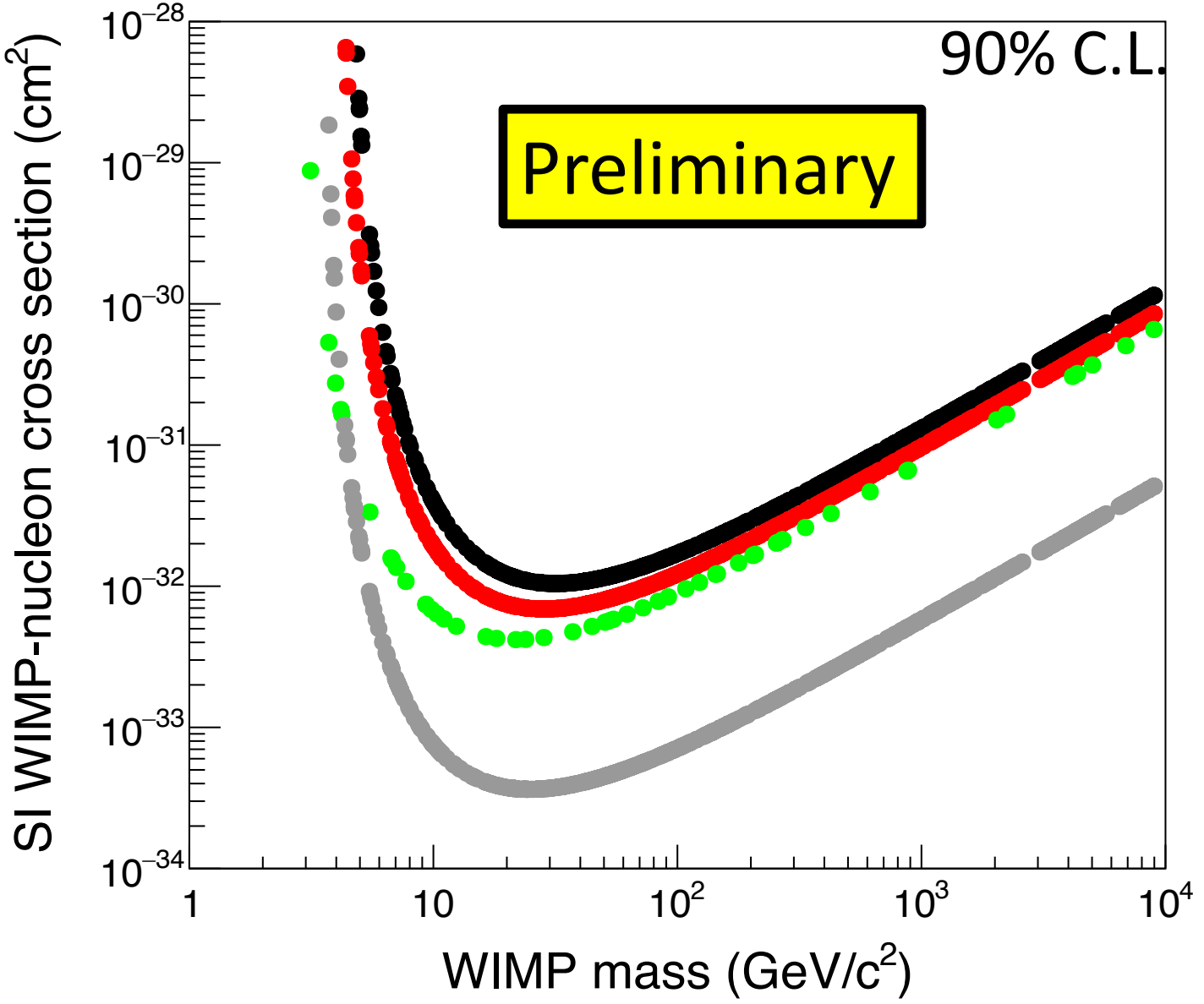
WIMP-nucleon SI Scattering Cross Section Limit - Cluster

- Black curve
- For length vs. energy selection of 0.0192 cm/keV
- 16 experimental events remain

- Red curve
- For length vs. energy selection of 0.0192 cm/keV
- 19 experimental events remain

- Gray curve
- No length vs. energy selection
- No background speculation
- Possible with shielding/underground

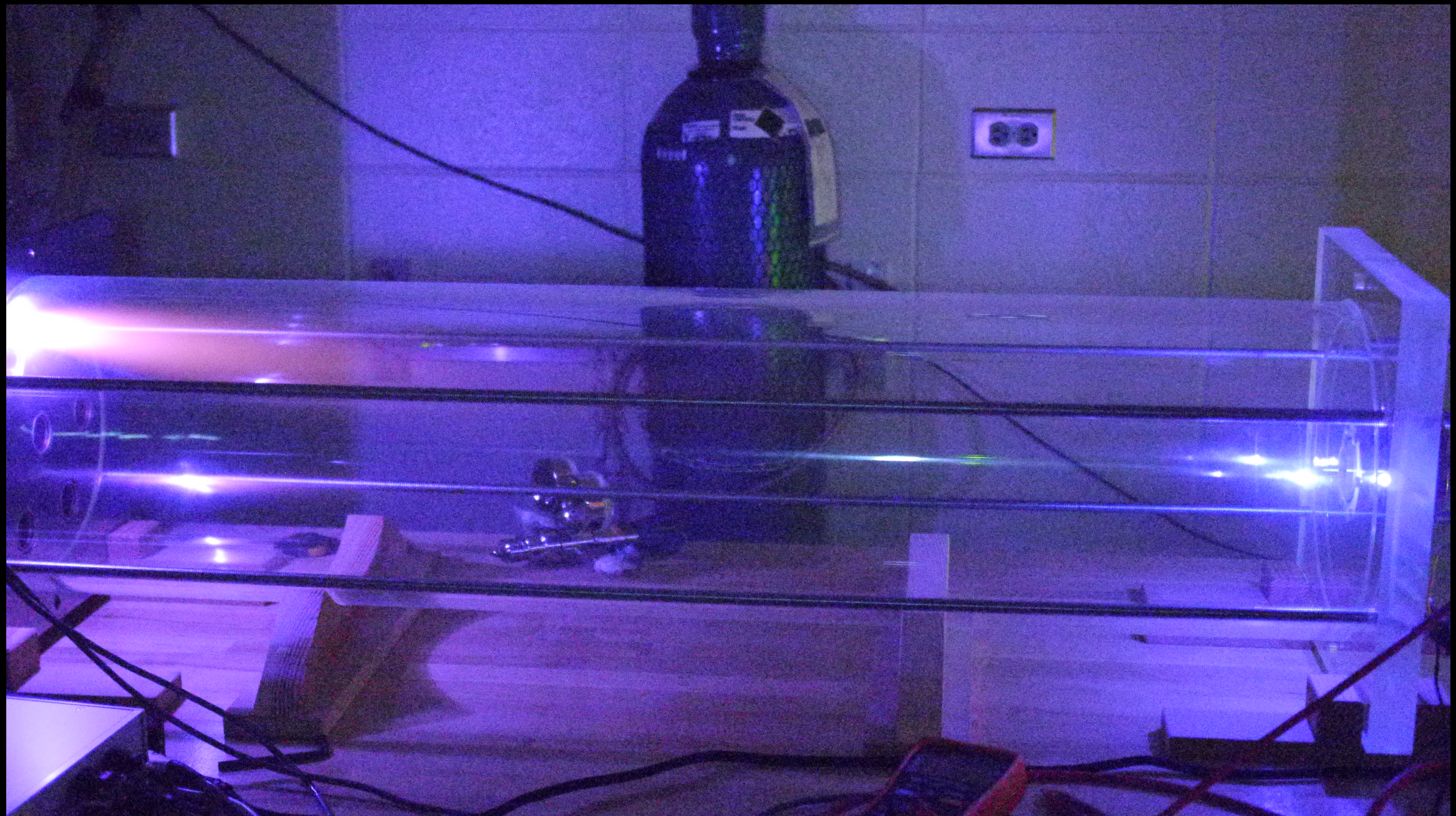
- Green curve
- Number of clusters < 2



Conclusions

- Work in Hawaii has been fruitful
- BEAST II TPCs have worked well and exceeded requirements
  - Allowed for our first scattering limit study
- HD charge readout exhibits powerful background suppression
- Need to optimize existing selections
- Working towards directional analysis techniques

Thank you!



Backup

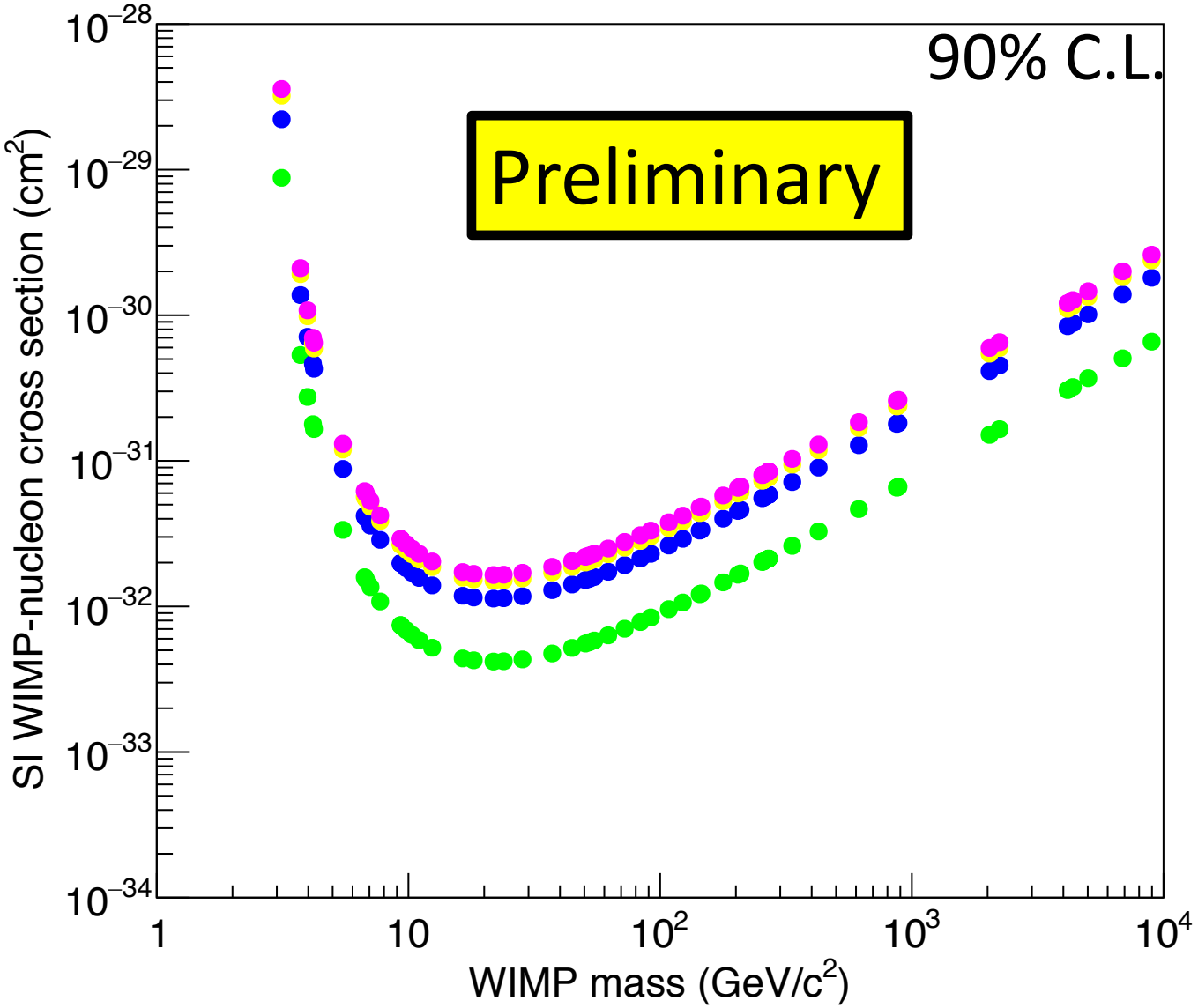
WIMP-nucleon SI Scattering Cross Section Limit - Cluster

- Magenta curve
- Number of clusters < 5

- Magenta curve
- Number of clusters < 4

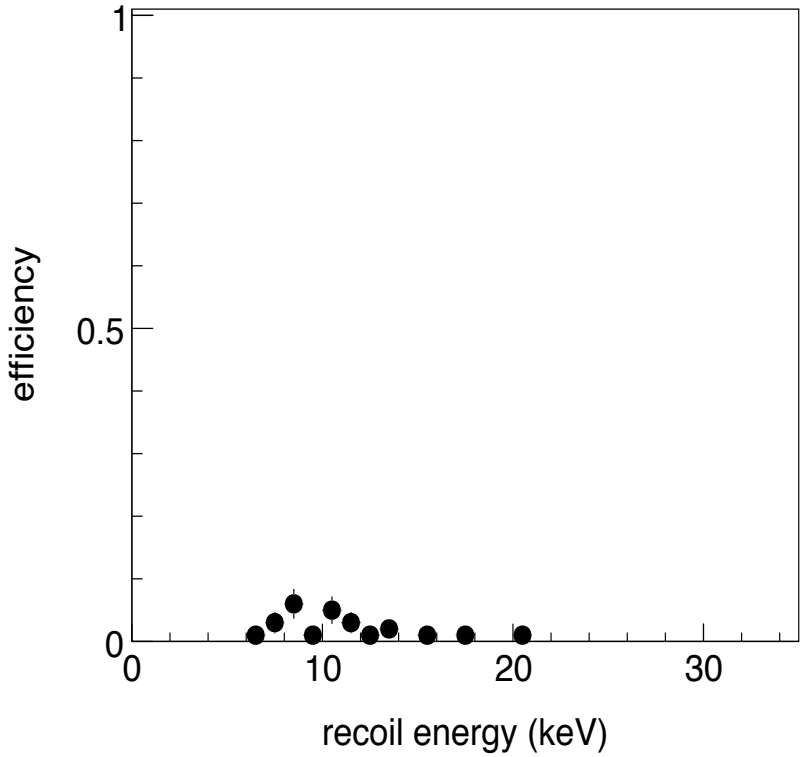
- Blue curve
- Number of clusters < 3

- Green curve
- Number of clusters < 2

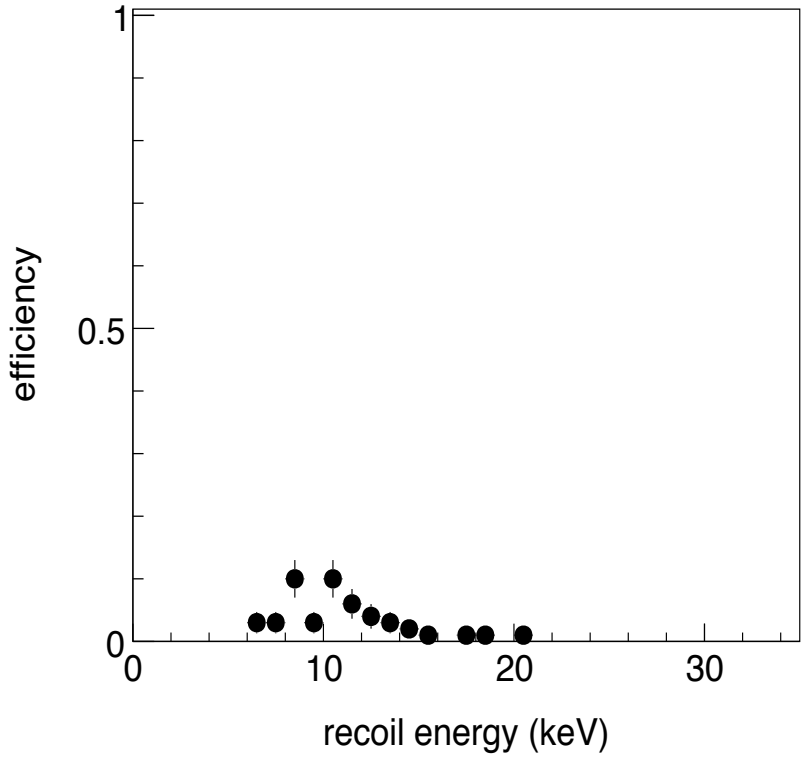


Electron (MC) Efficiency for Cluster Selections

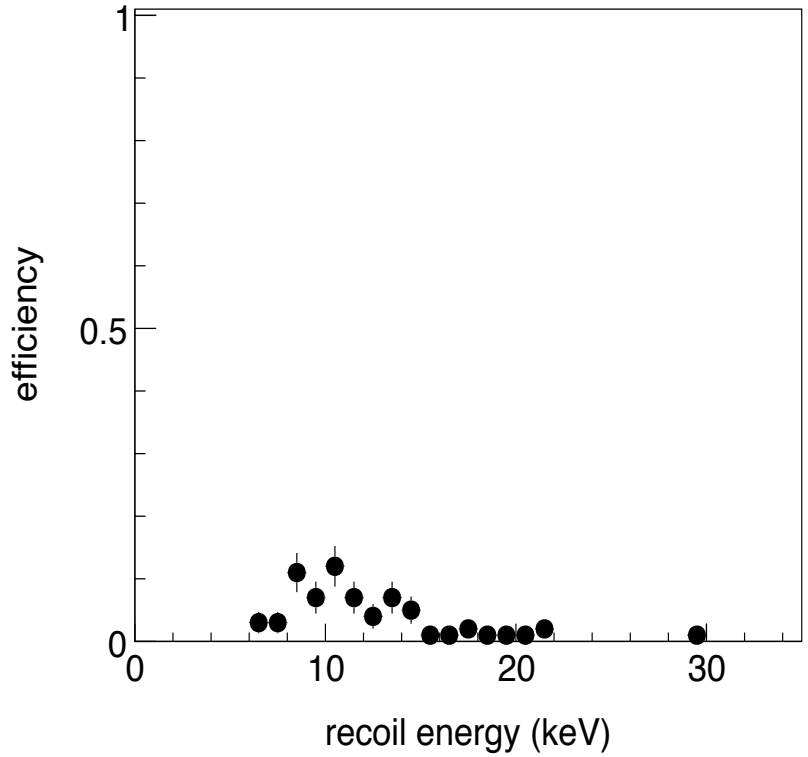
n_cluster < 2



n_cluster < 3



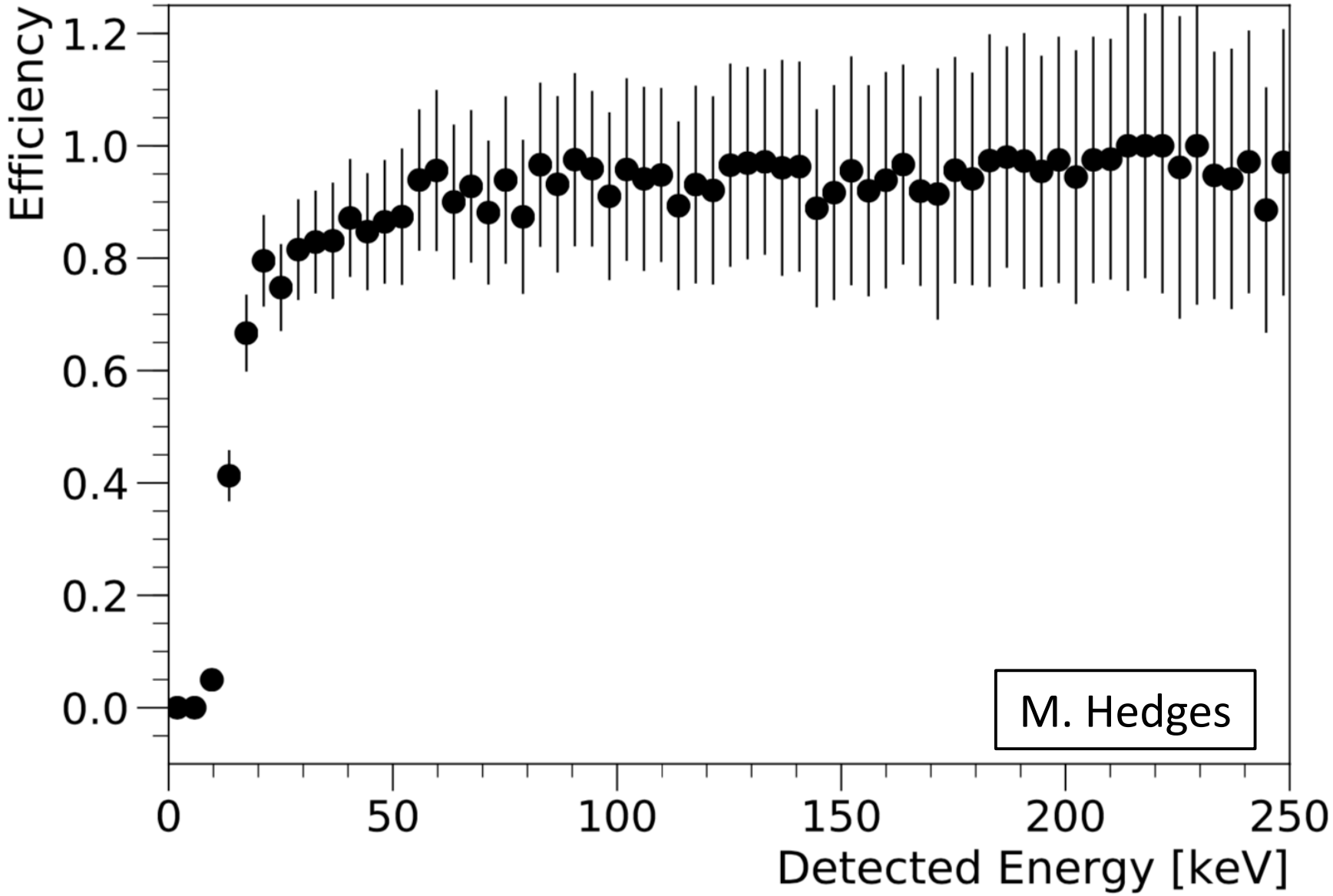
n_cluster < 4



Due to low MC statistics, a value of zero indicates that all electrons in that energy bin have been rejected

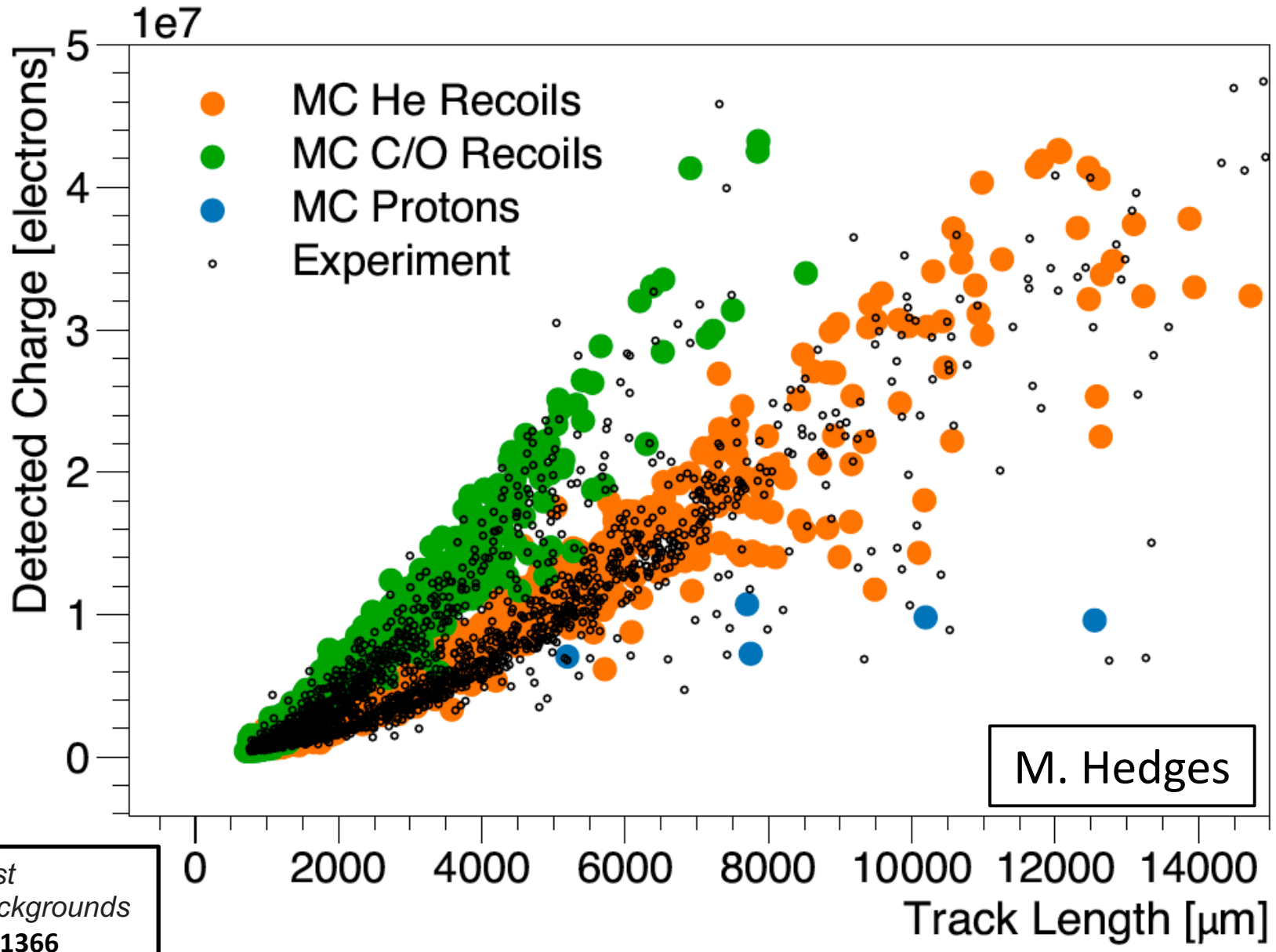
Signal Efficiency in BEAST II Run

- Helium recoils from fast neutrons during BEAST II run
- Selections are not optimized for low energy sensitivity
- Detectors are not optimized for low energy event detection



BEAST II Collaboration, *First Measurements of Beam Backgrounds at SuperKEKB*, **arXiv:1802.01366**

Recoil Species ID in BEAST II Run



BEAST II Collaboration, *First Measurements of Beam Backgrounds at SuperKEKB*, **arXiv:1802.01366**