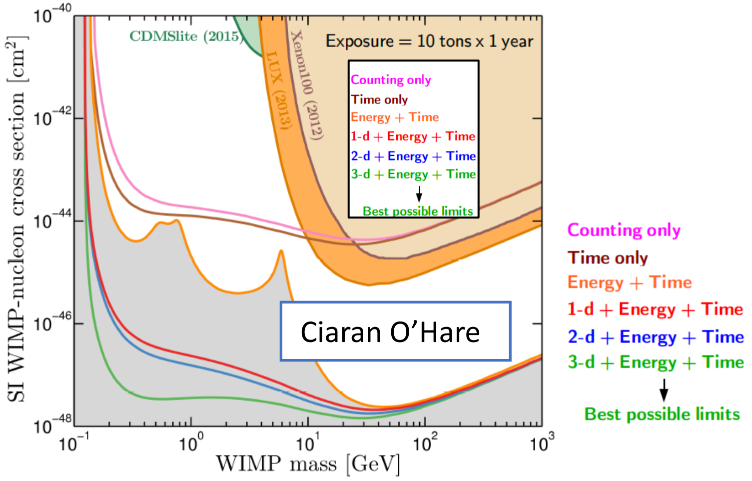
Comparing Gas Time Projection Chamber Readout Technologies

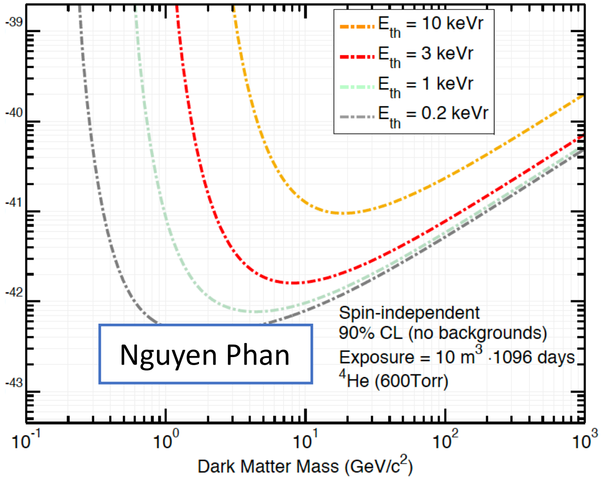
Sven Vahsen (University of Hawaii)
for the CYGNUS simulation group

Special thanks to Ciaran O'Hare (Nottingham) & Cosmin Deaconu (Chicago)

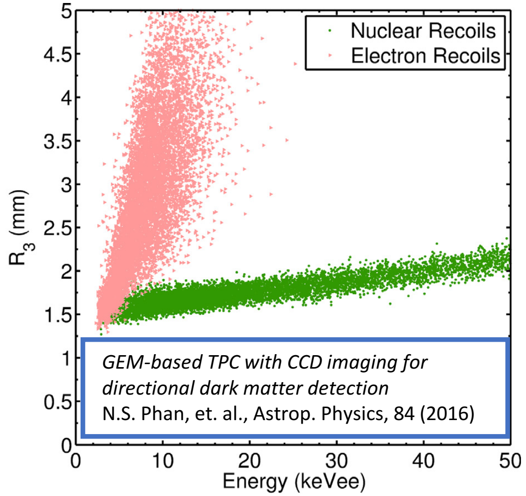
Motivation for this work



Ciaran O’Hare



Nguyen Phan



GEM-based TPC with CCD imaging for directional dark matter detection
N.S. Phan, et. al., Astrop. Physics, 84 (2016)

(b) 3D Reconstruction

3D TPC charge readout has excellent performance:

- best at separating WIMP and neutrino signals
- highest readout-plane segmentation → lowest noise → lowest energy threshold
- best electron background rejection

But, 3D readout has serious drawback

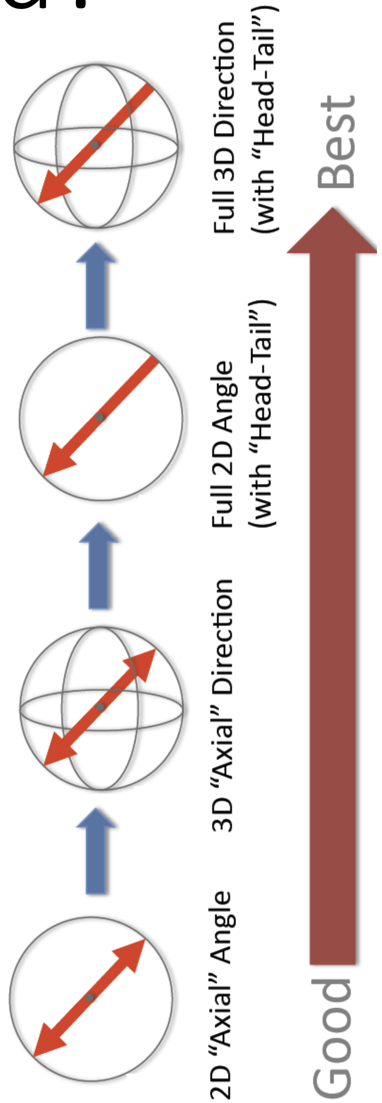
- *most costly option*
- *most labor intensive to construct (as readout ASICs are small)*
- *not yet radio-pure*

→Is 3D readout worth the high cost and development time?

Important general question: Which TPC readout technology is the best tradeoff between cost and performance?

Hasn’t 1d/2d/3d already been compared?

- Existing studies typically compare 1D/2D/3D with theoretical assumptions (readout is either axial or vector, energy threshold are sharp, etc)
- For real-life detector, however
  - Head/tail capability is a function of recoil energy and drift length
  - Minimum detectable energy is results of finite gain and detector noise, and noise depends on readout segmentation
  - Recoil-energy threshold is a result of electron background rejection factor versus energy
- Basic idea pursued here
  1. Implement strawman simulation of candidate TPC readout technologies (simulating finite gain, gain resolution, detector noise)
  2. Obtain more realistic, energy-dependent simulation of performance that accounts for effects of readout plane segmentation
  3. Use this simulation to inform choices we face in CYGNUS detector design



Looking at the following issues

- Distinguishing WIMP from neutrino signals
- Distinguishing nuclear recoils from electron recoils
- Optimizing the drift length
- Optimizing the width of x/y readout strips
- Which technology offers highest WIMP sensitivity per unit cost?

The basic simulation has been completed. Showing select first results today.
Goal: Publish CYGNUS TPC strawman design this summer.
Warning: everything is preliminary, needs careful checking!

Input parameters used to simulate ionization, drift, gas gain

Disclaimer: highly preliminary
-- needs more work!

- Gas mixture: SF_6
- Pressure: 20 torr
- W: 35.45 eV per ion pair [Hilal and Christophorou, alpha particles]
- Gas gain: 9000 (A. Scarf)
- Gain resolution: $\frac{\sigma_G}{G} = 20\%$ (A. Scarf, Sheffield)
- Diffusion: 116.2 $\frac{\mu m}{\sqrt{cm}}$
- Drift velocity: 140 μm/μs

[from D. Loomba, New Mexico: for 600-800 V/cm
which gave minimum diffusion at 20 Torr]

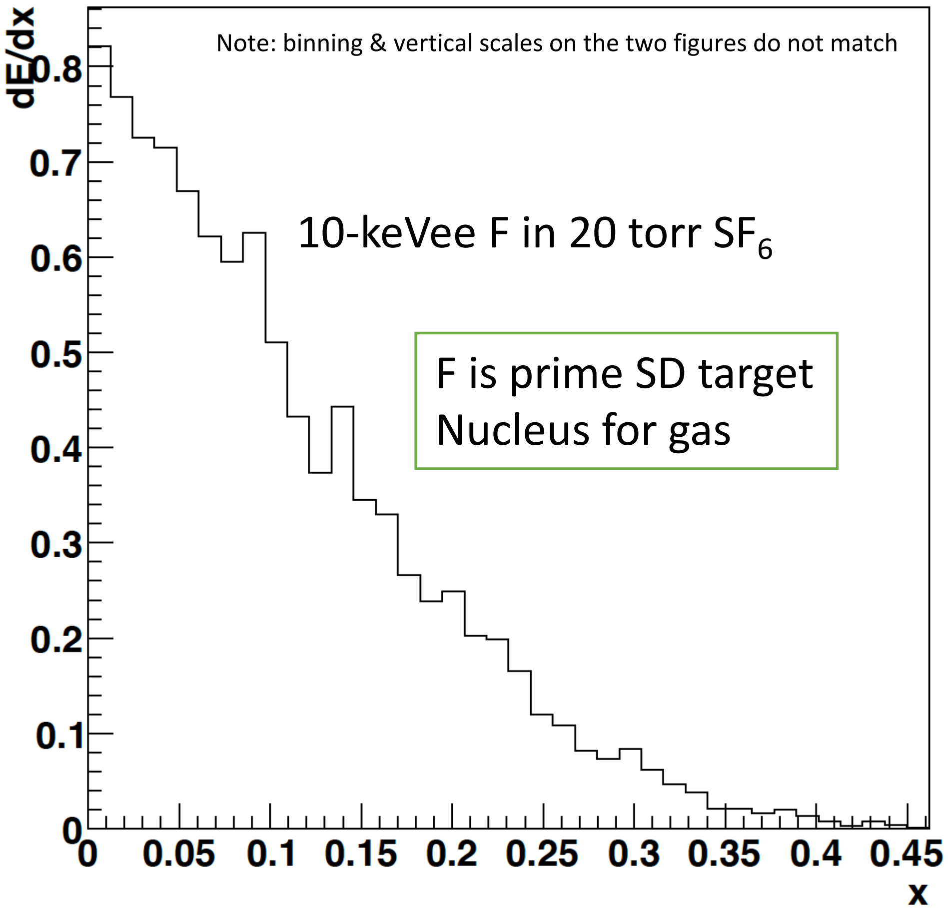
Input parameters for readout plane simulation

Disclaimer: *highly* preliminary -- needs more work!

Readout type	Dimensionality	Segmentation	Z binning (assume 1MHz sampling)	Detector Element Capacitance	Noise level	Noise level per 1-µs readout clock cycle	Threshold (avalanche charge)
planar	1D (z)	10 cm x 10 cm	140 µm	11,000 pF GEMs: 250pF (3cm*3cm, 100um) **3000pF** (10cm*10cm, 100um) 25000pF (30cm*30cm, 100um)	5400 e^- for 1000 pF, 1µs peaking time	18000 e^-	3 x noise
wires	2D (xz)	1m wires, 2mm pitch	140 µm	?	250e^- in 10 us	800 e^-	3 x noise
CMOS camera	2D (xy)	t.b.d.	n/a	n/a	?	?	?
resistive strip Micromegas	3D (xyz) with coincidence ambiguity	1 m strips, 200 µm pitch	140 µm	50 pF per 10 cm of strip → 500 pF	2800e^- for 1µs peaking time	2800 e^-	3 x noise
pixel ASIC	3D (xyz)	200 µm	140 µm	12-200 fF	~270 e^- (per 25 ns sample)	42 e^-	1500 e^-

(only charge readout for now. But can probably add 2d optical.)

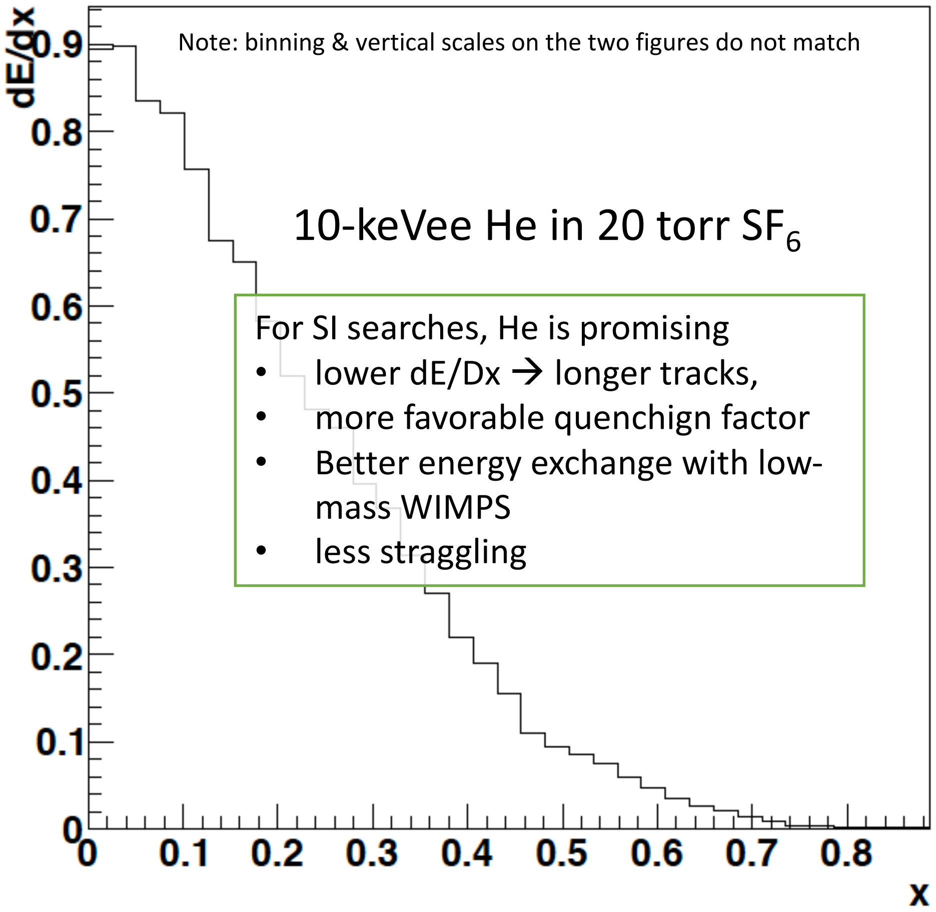
Nuclear Recoil Generator: SRIM



Note: binning & vertical scales on the two figures do not match

10-keVee F in 20 torr SF_6

F is prime SD target
Nucleus for gas



Note: binning & vertical scales on the two figures do not match

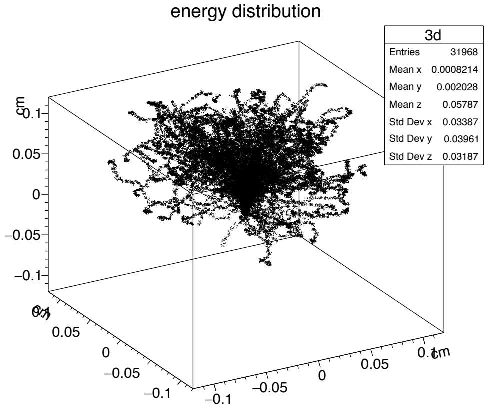
10-keVee He in 20 torr SF_6

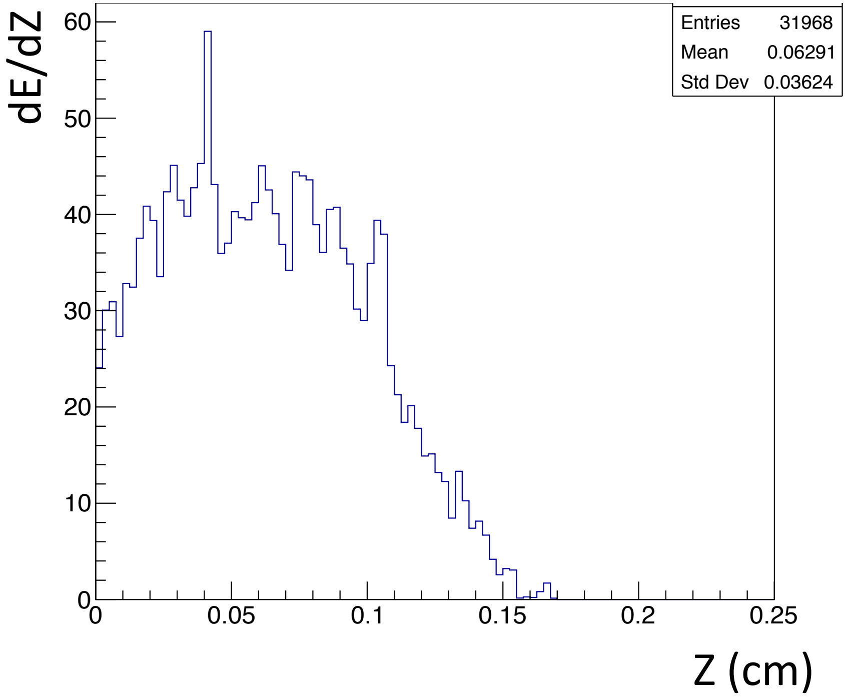
For SI searches, He is promising
- lower dE/Dx → longer tracks,
- more favorable quenchign factor
- Better energy exchange with low-mass WIMPS
- less straggling

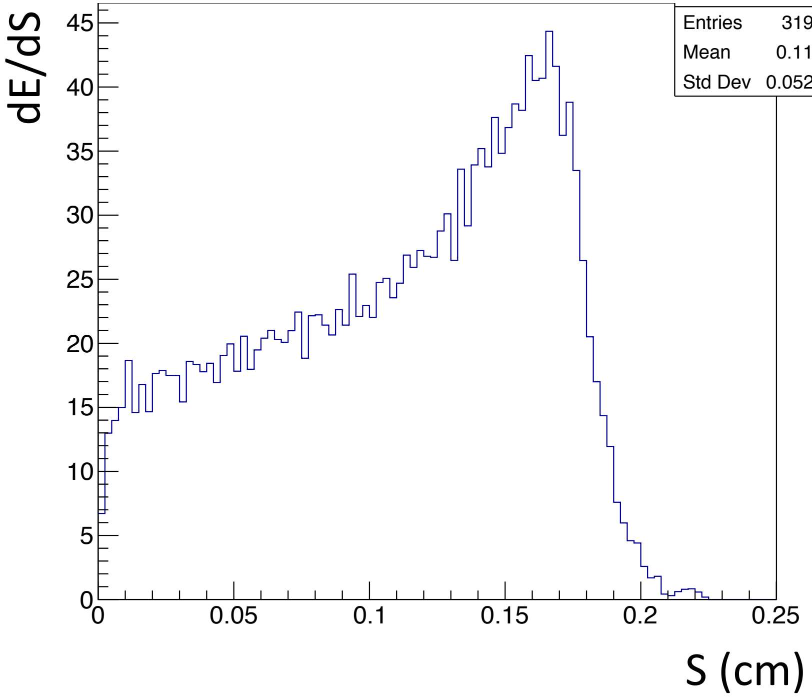
Note: F figure corresponds to higher *recoil* energy than He figure, due to differences in quenching factor.

Electron recoil generator: CASINO

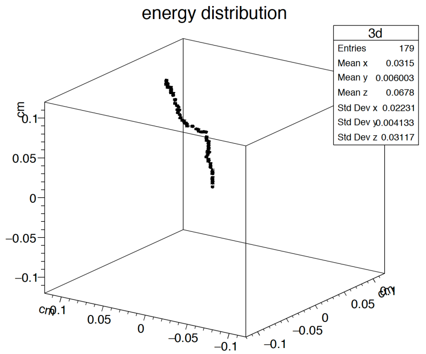
- 200 10-keV electrons
- starting from origin
- in z-direction



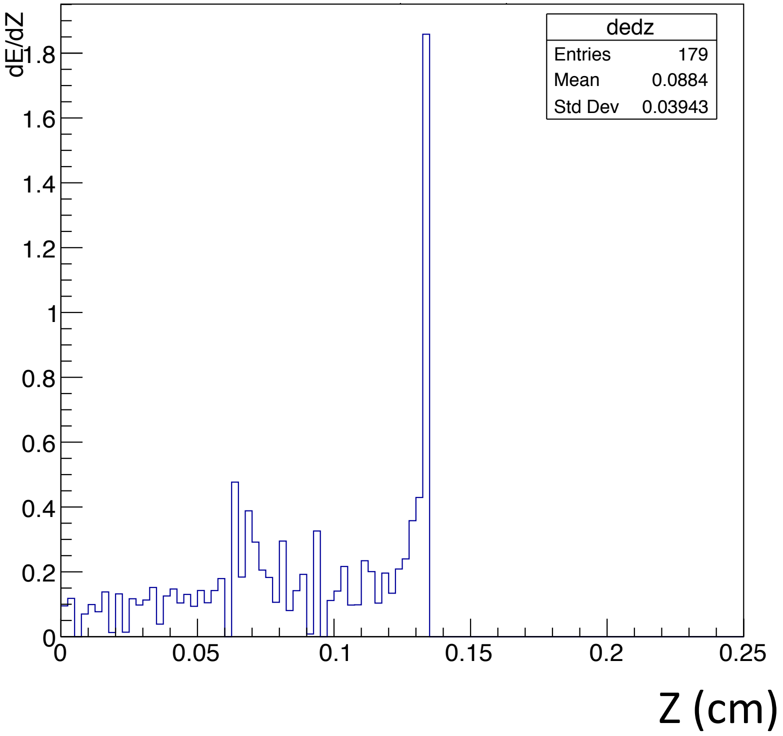


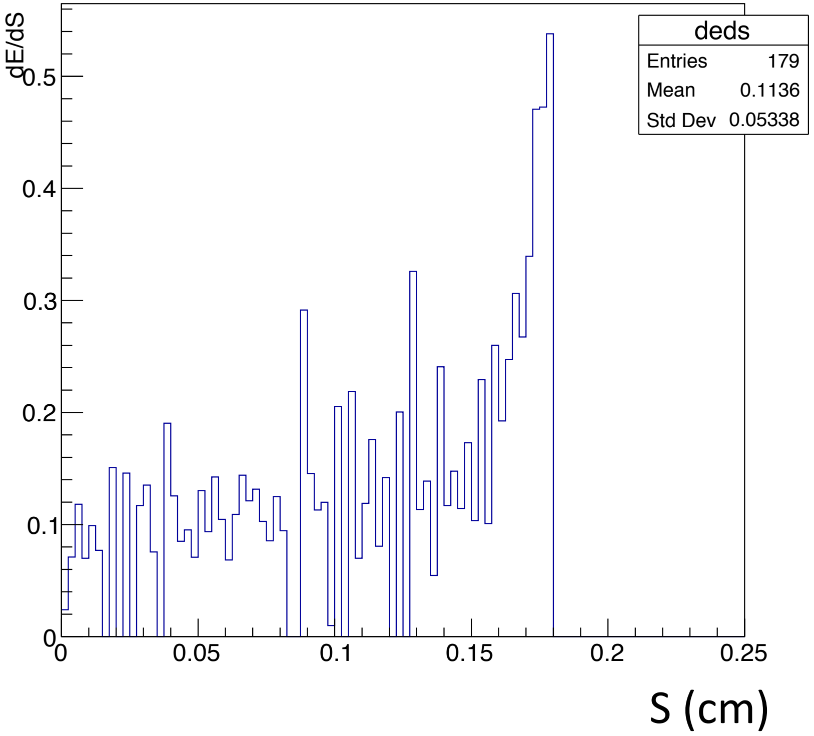


dE/dZ vs dE/dS

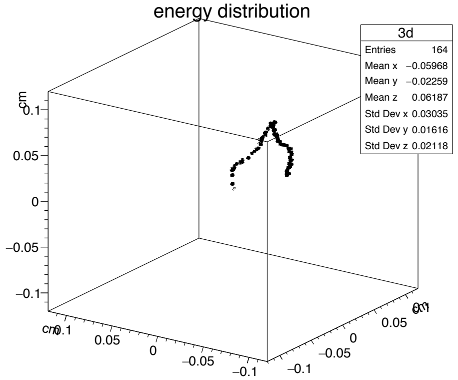


One 10-keV electron

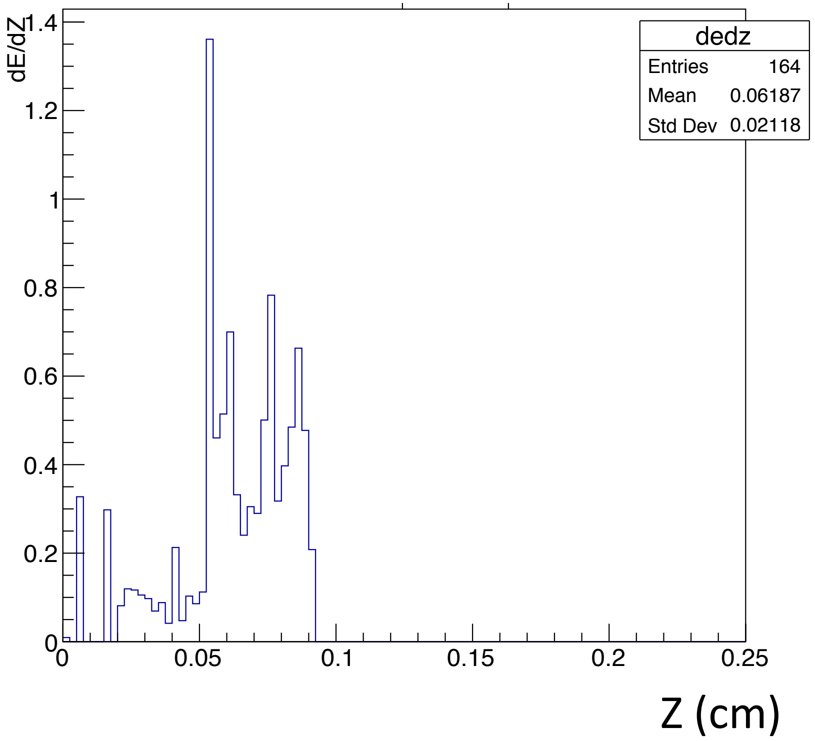


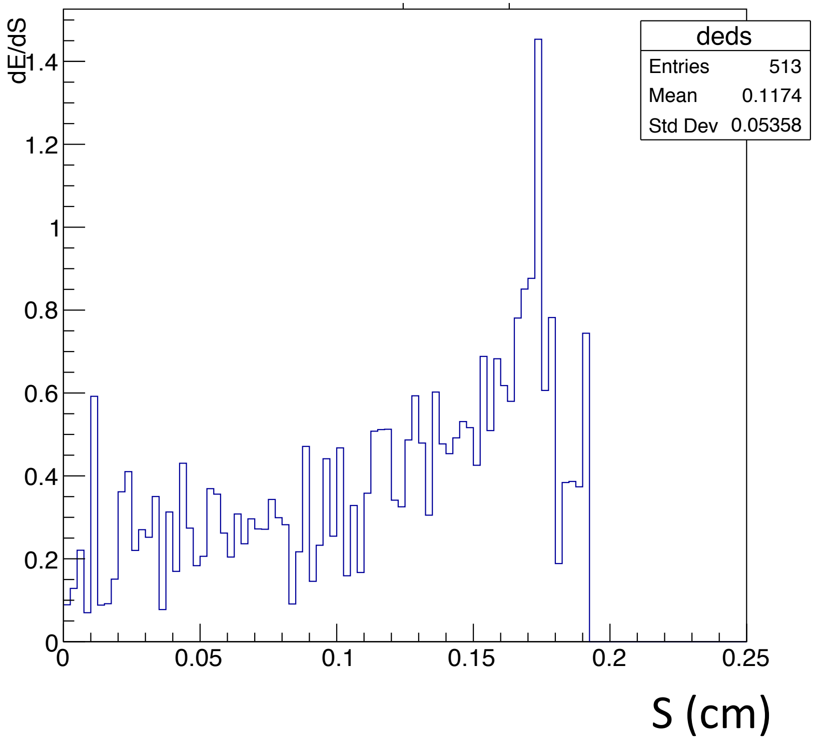


dE/dZ vs dE/dS

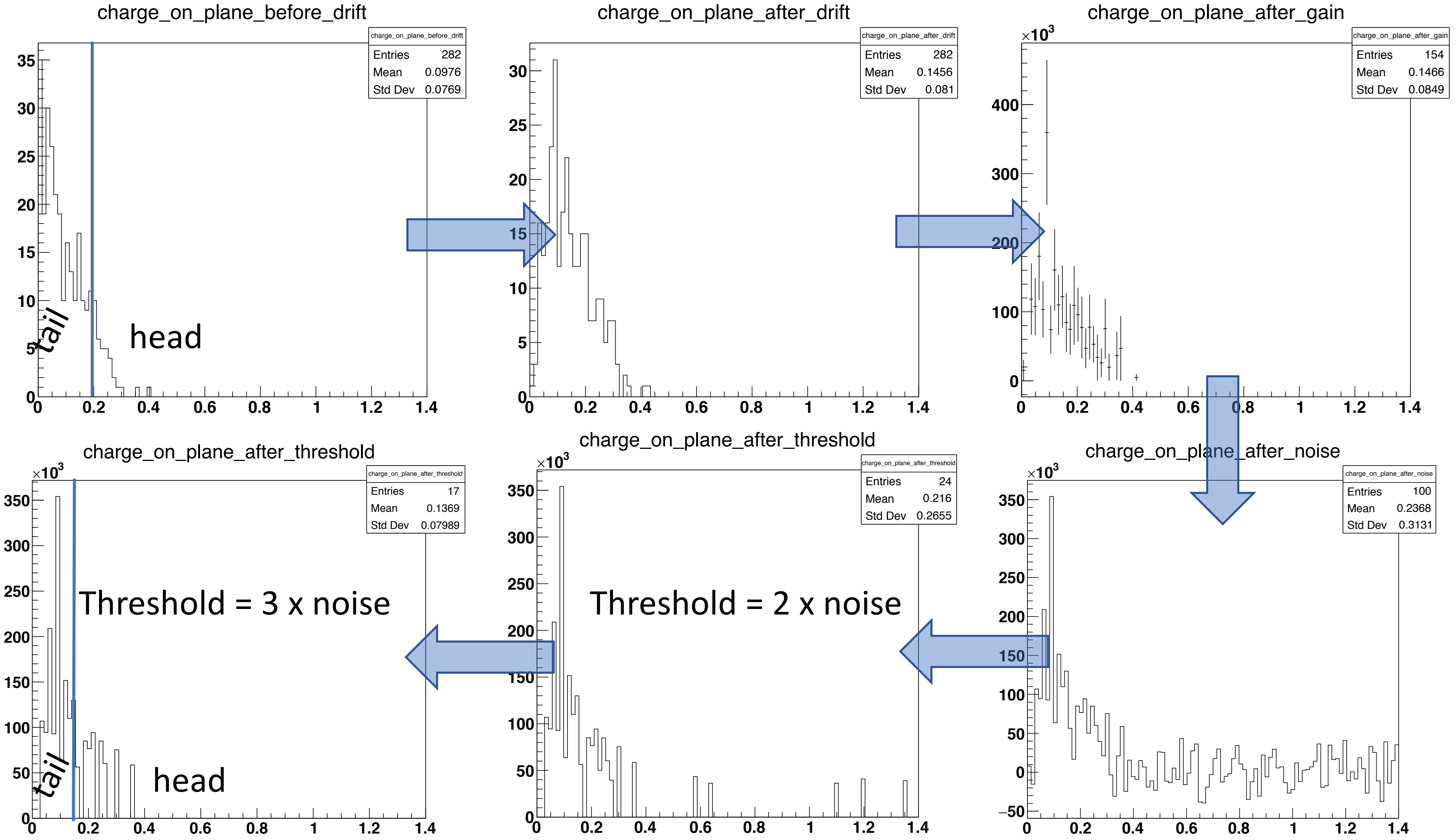


Another 10-keV electron



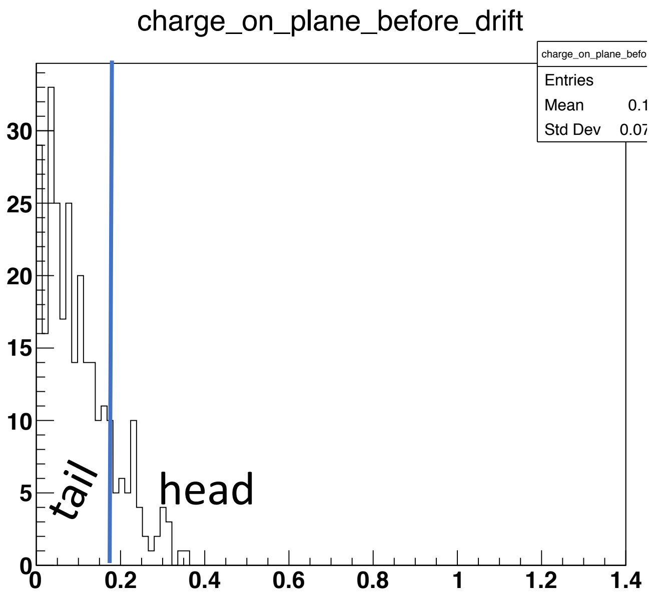


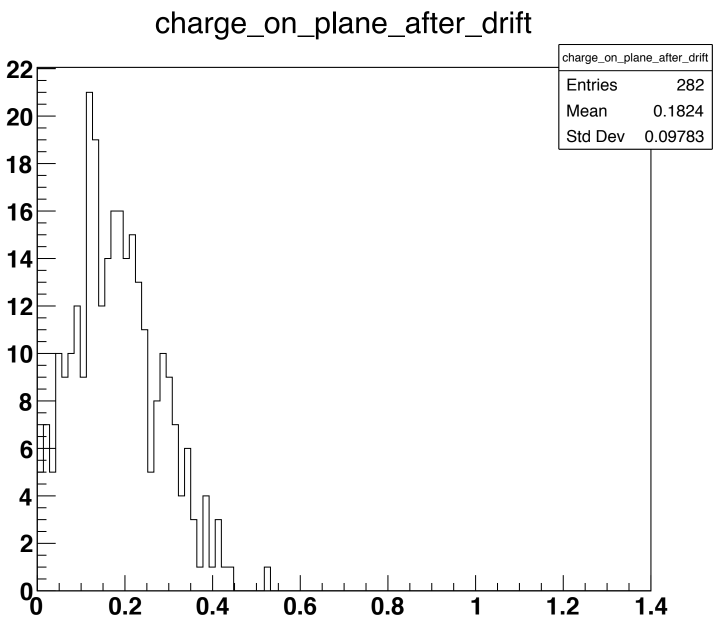
10-keV F Recoil with 1D planar readout, 5 cm drift

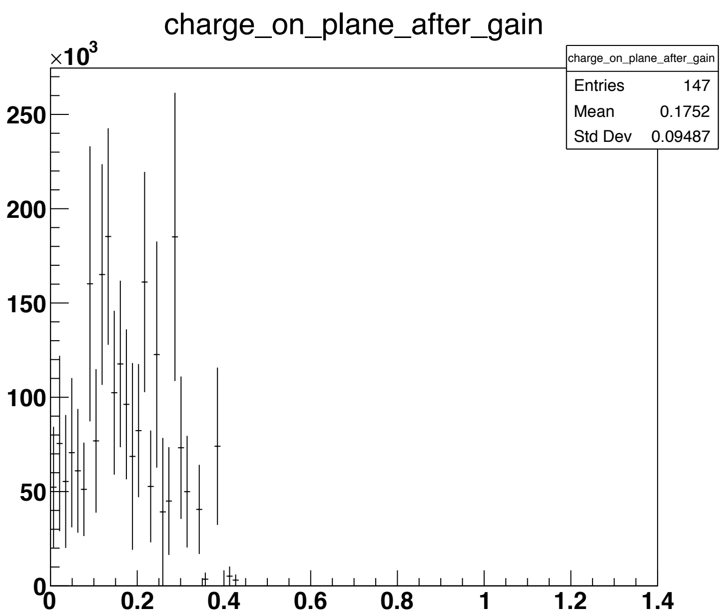


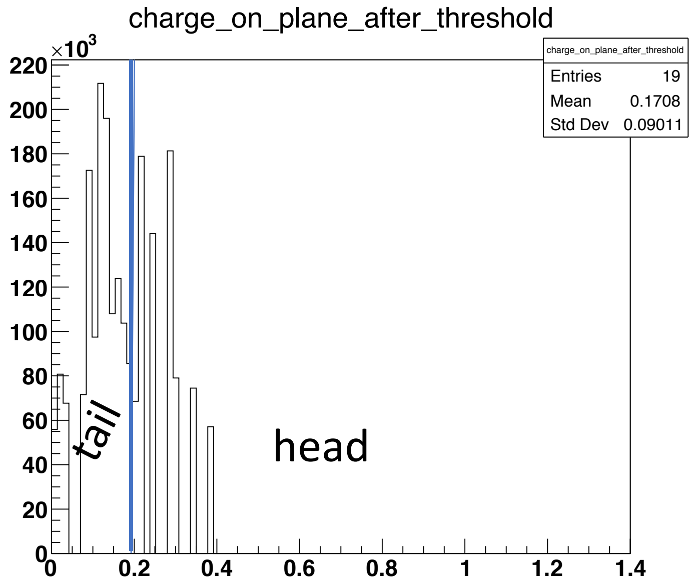
Recoils is pointing in +z direction (opposite of TPC drift direction)
Note higher charge density in tail than head. Effect reduced by diffusion during drift in the TPC.

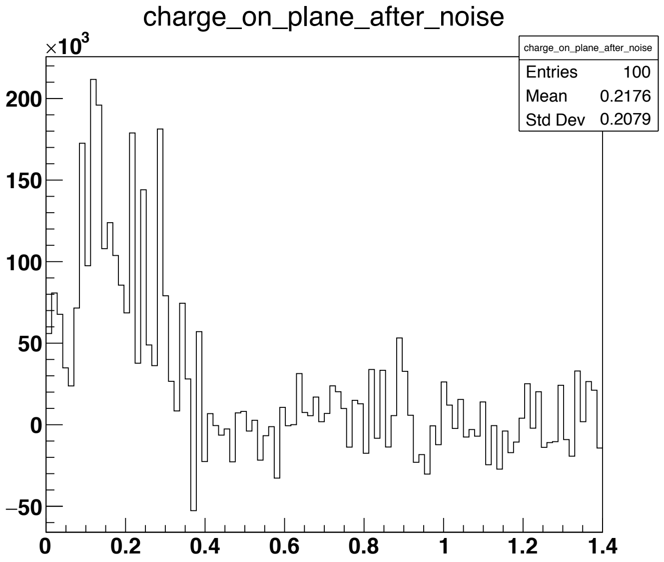
10-keV F Recoil with 1D planar readout, 50 cm drift





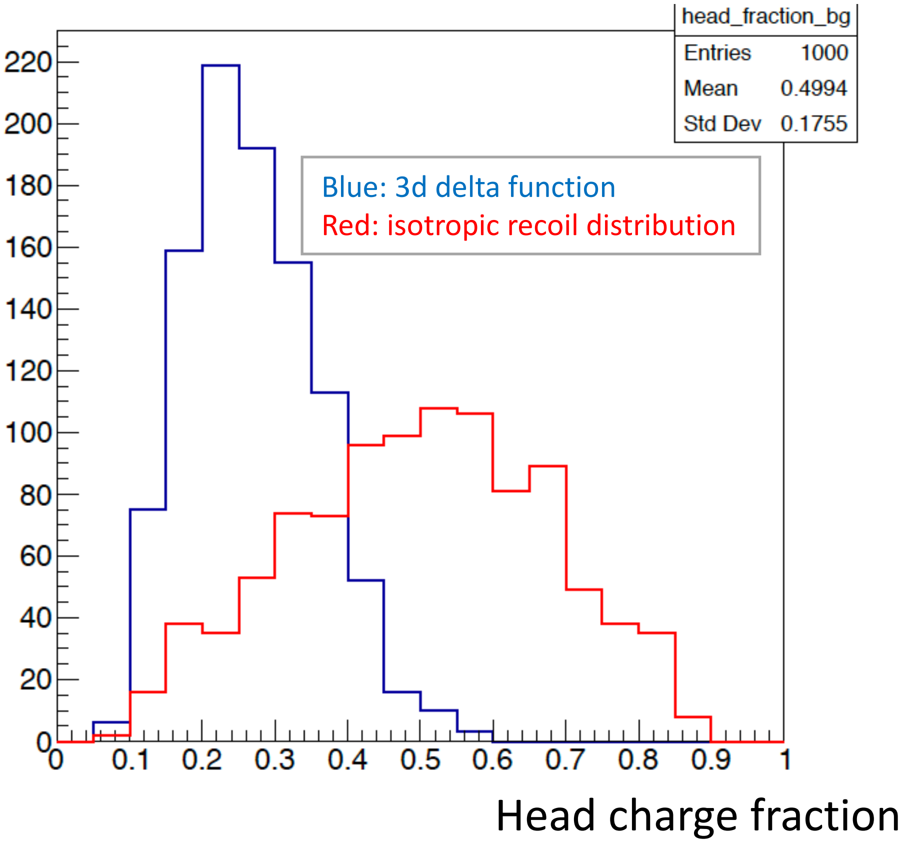


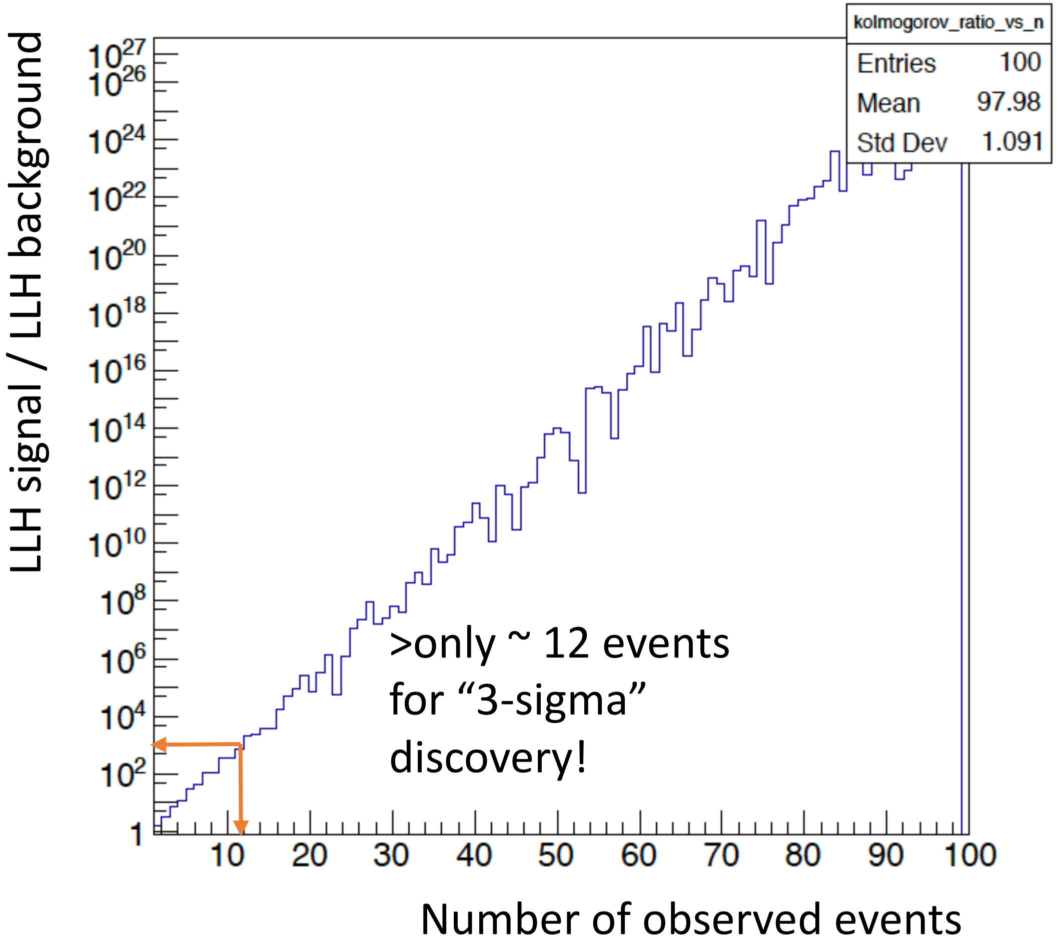




Strength of Head/Tail signature: 10 keVee F target in SF_6

Recoils are uniformly distributed in z (drift direction)



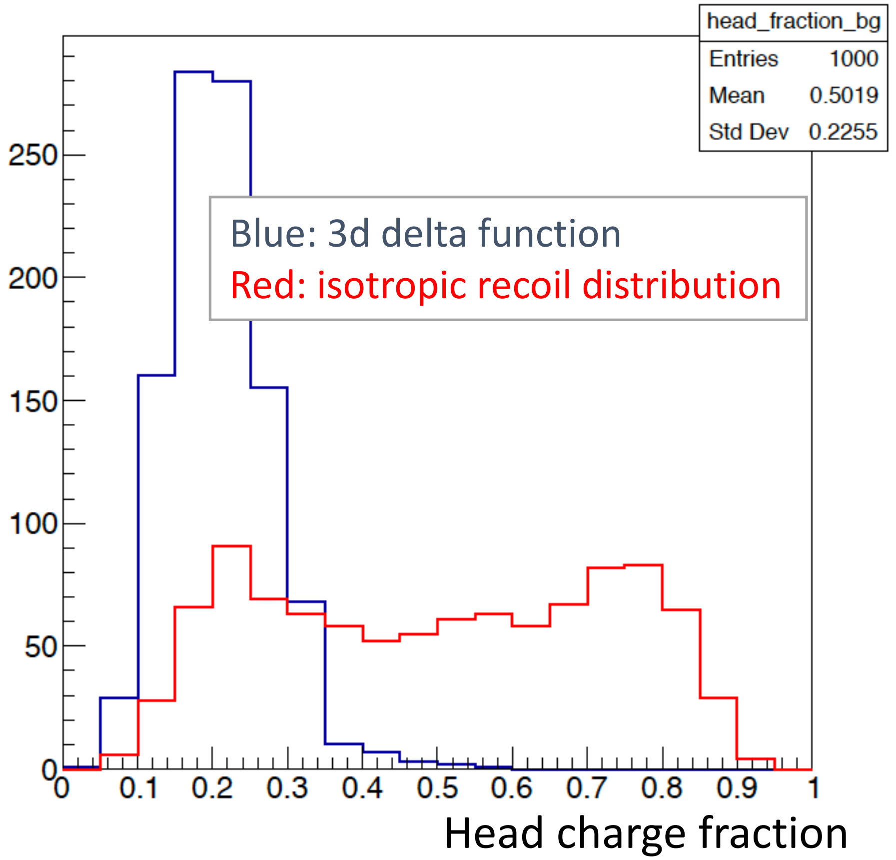


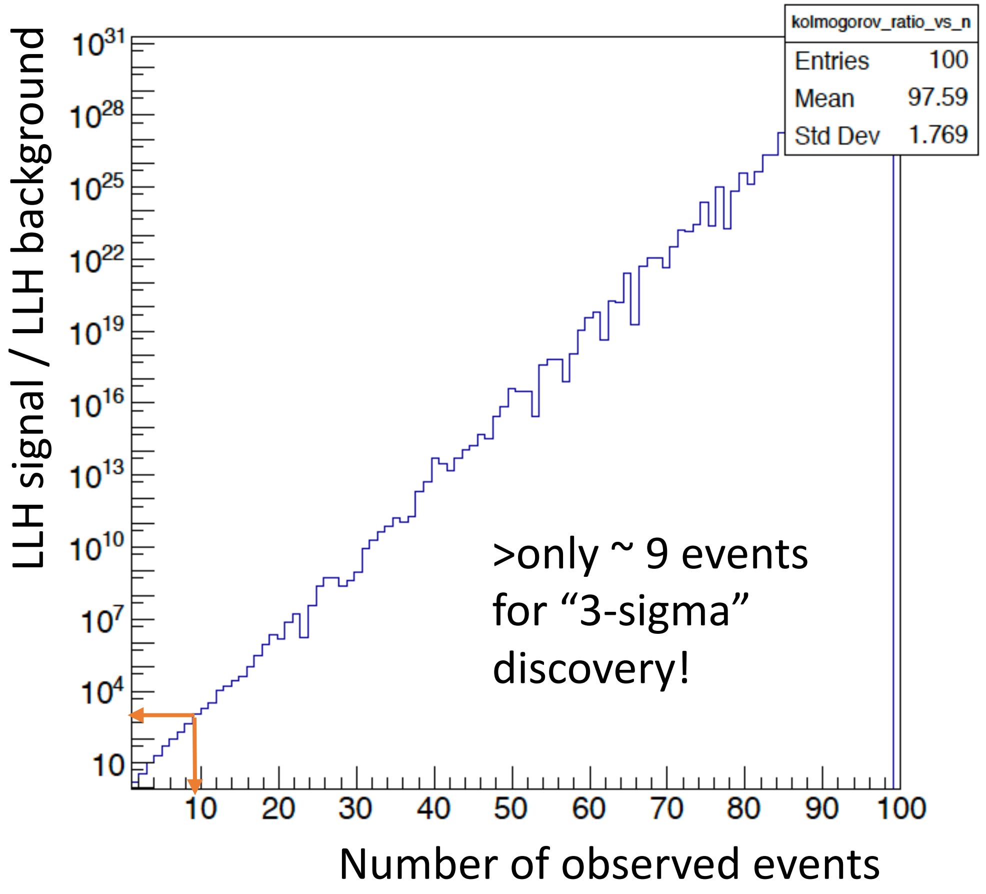
>only ~ 12 events
for “3-sigma”
discovery!

1D head/tail effect with 10 keVee F strong, even after diffusion during drift!

gain, noise, thresholds, disabled

Strength of Head/Tail signature: 10 keVee He target in SF_6





>only ~ 9 events for "3-sigma" discovery!

n

1D Head/tail effect with 10 keVee He strong, even after diffusion during drift!

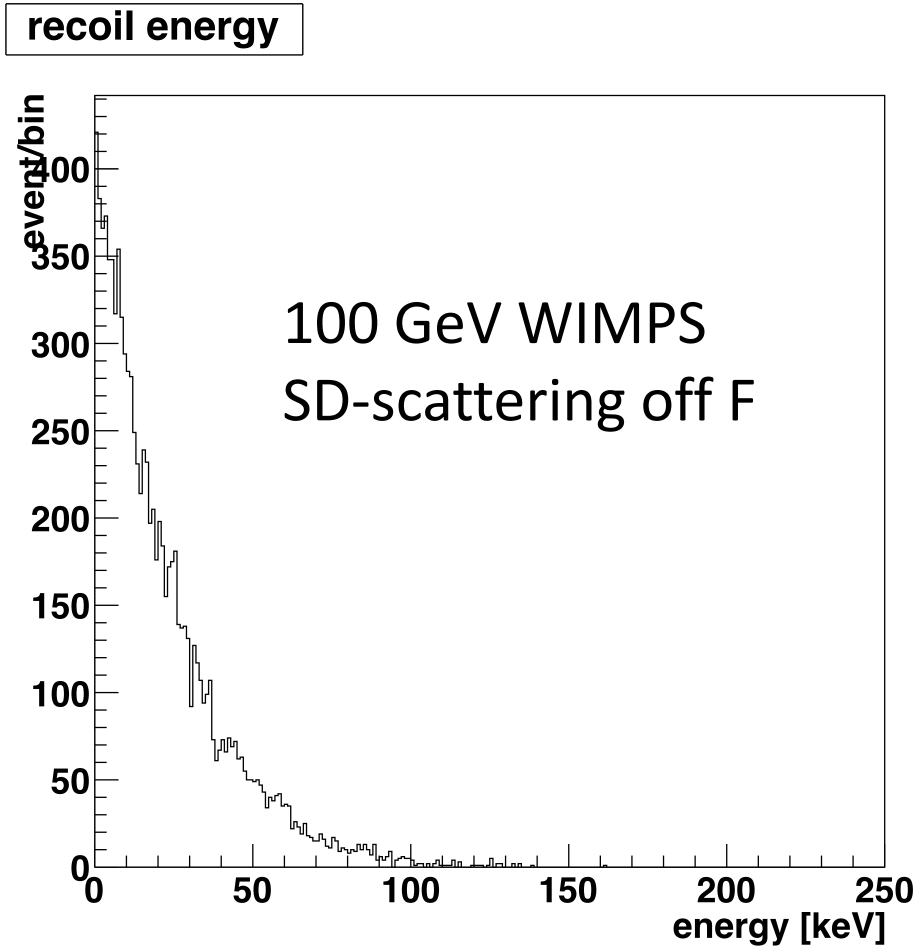
gain, noise, thresholds, disabled

Distinguishing WIMP recoils from neutrinos recoils

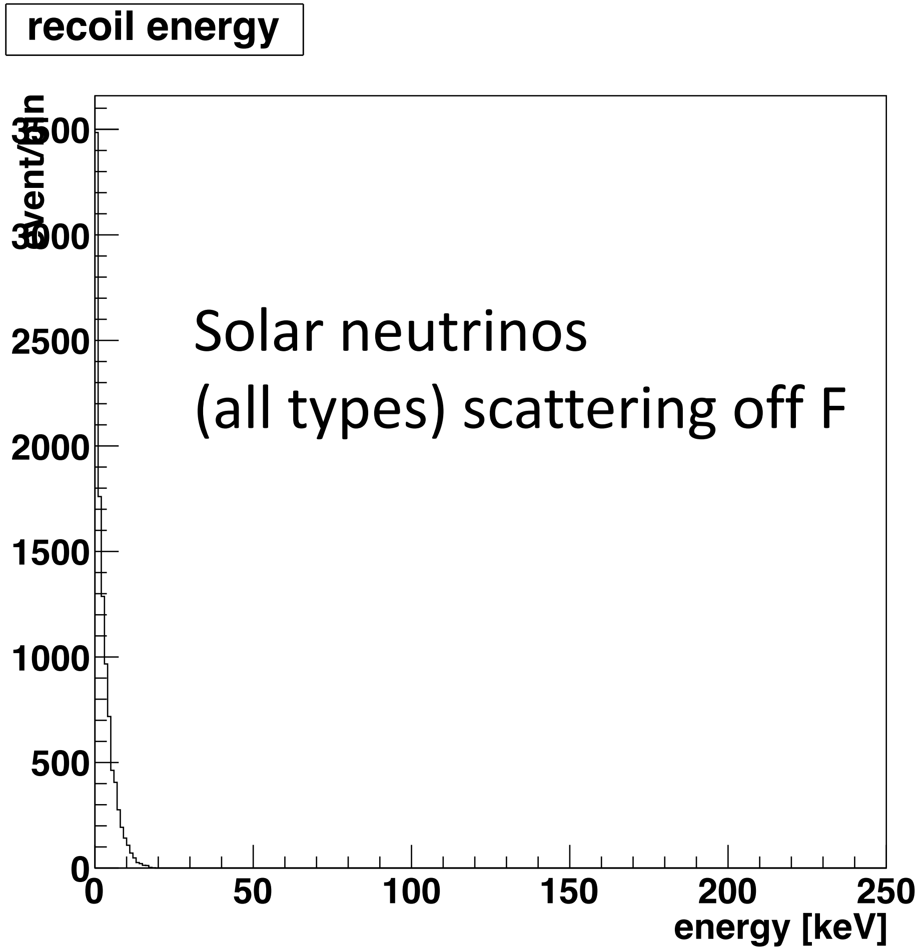
- Same TPC simulation as before: 20 torr SF_6 gas
  - <=50 cm drift (uniform distribution of recoil events in drift direction)
  - 1D planar readout
  - non-ideal detector effects (gain, noise, thresholds etc) disabled
  - Only diffusion and readout segmentation is enabled
- Now:
  - how many recoils required to distinguish 100-GeV WIMP from solar neutrinos, using measured 1D-head/tail signature only?
  - Energies quoted in remaining slides are _recoil_ energies
  - (Using average SRIM quenching factor < 150 keV - to be improved)

Recoil vectors provided by **Ciaran O'Hare (Nottingham)**

WIMPS versus neutrinos: Flourine target



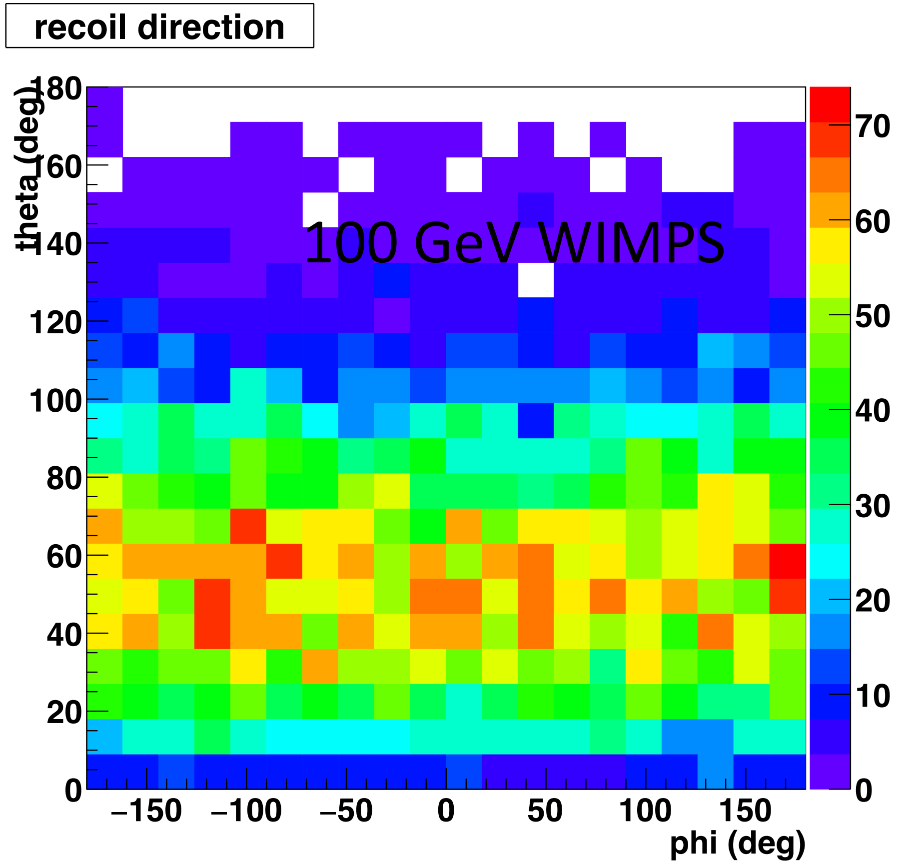
100 GeV WIMPS
SD-scattering off F

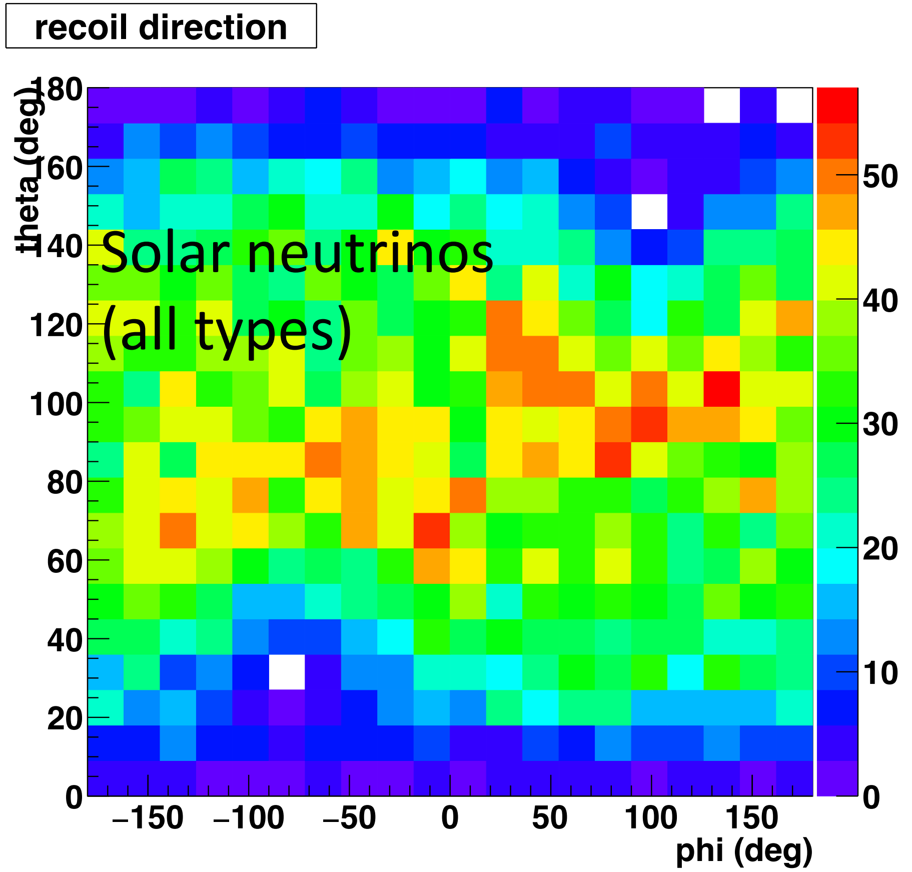


Solar neutrinos
(all types) scattering off F

Recoil vectors provided by **Ciaran O'Hare (Nottingham)**

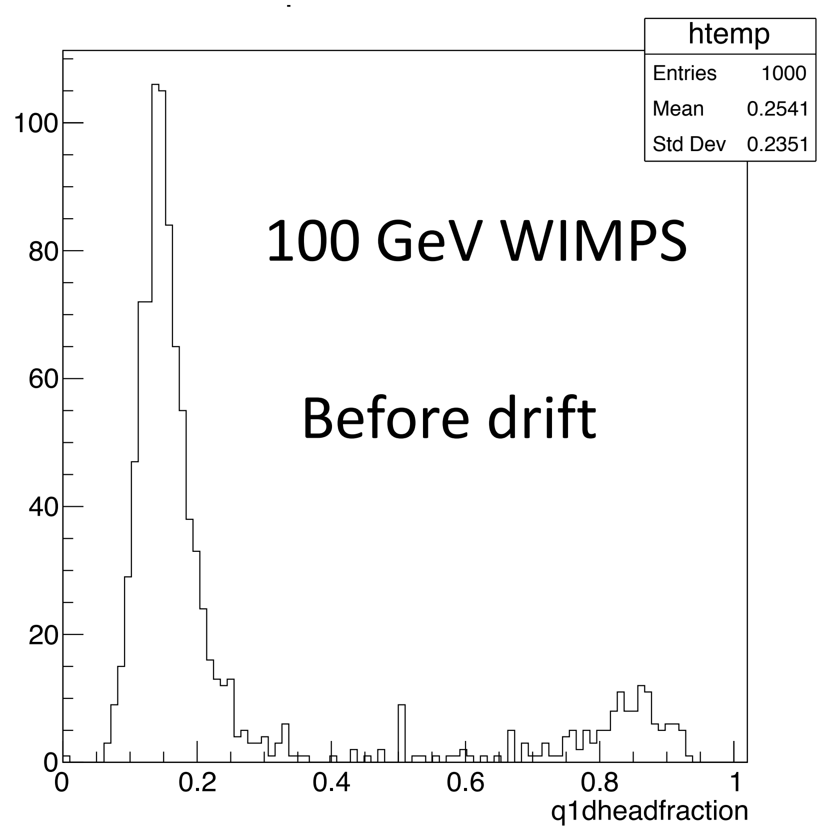
WIMPS versus neutrinos



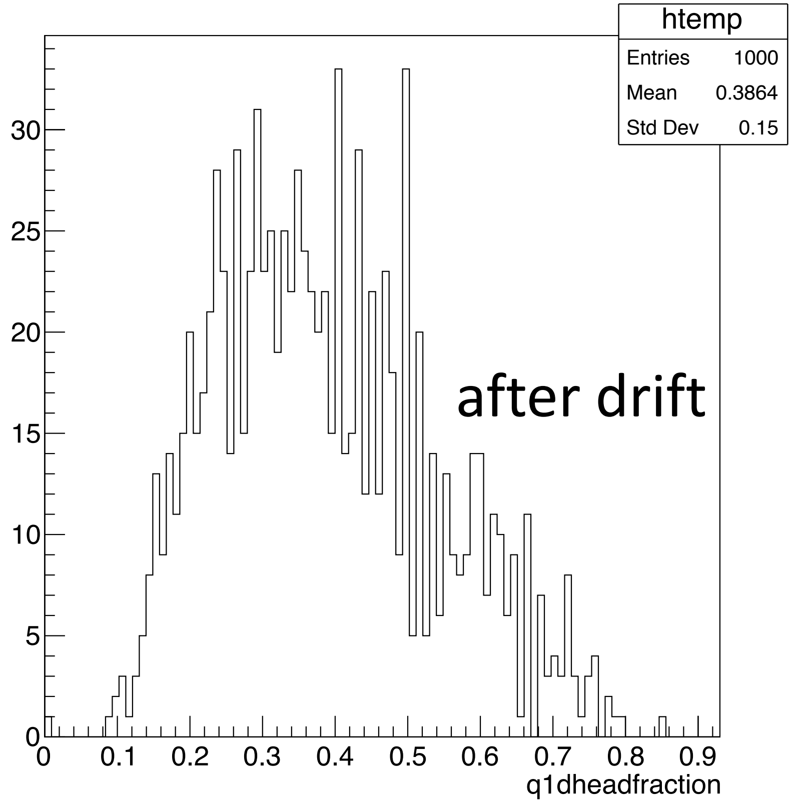


1D detector is oriented so that CYGNUS is in always –z direction; maximizing sensitivity

100 GeV WIMPs head/tail

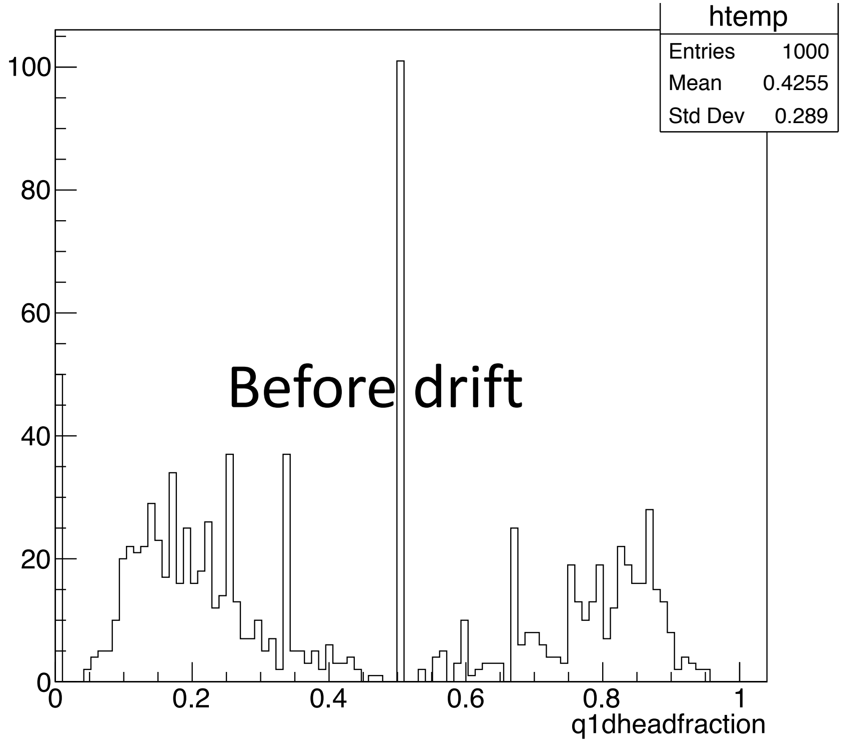

100 GeV WIMPS

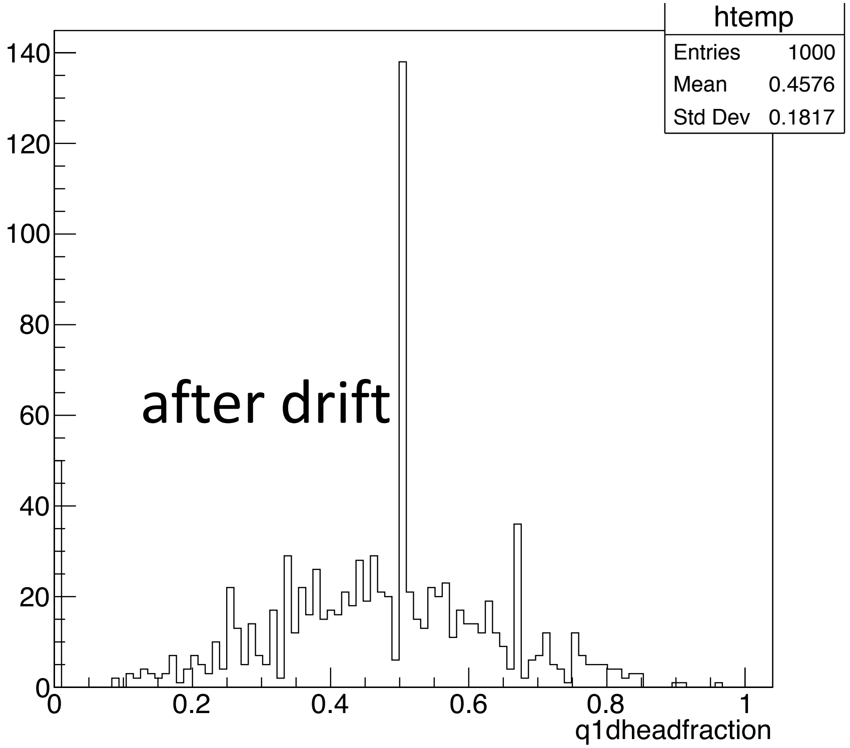
Before drift


after drift

After drift and charge diffusion, head/tail effect washed out some, but still present

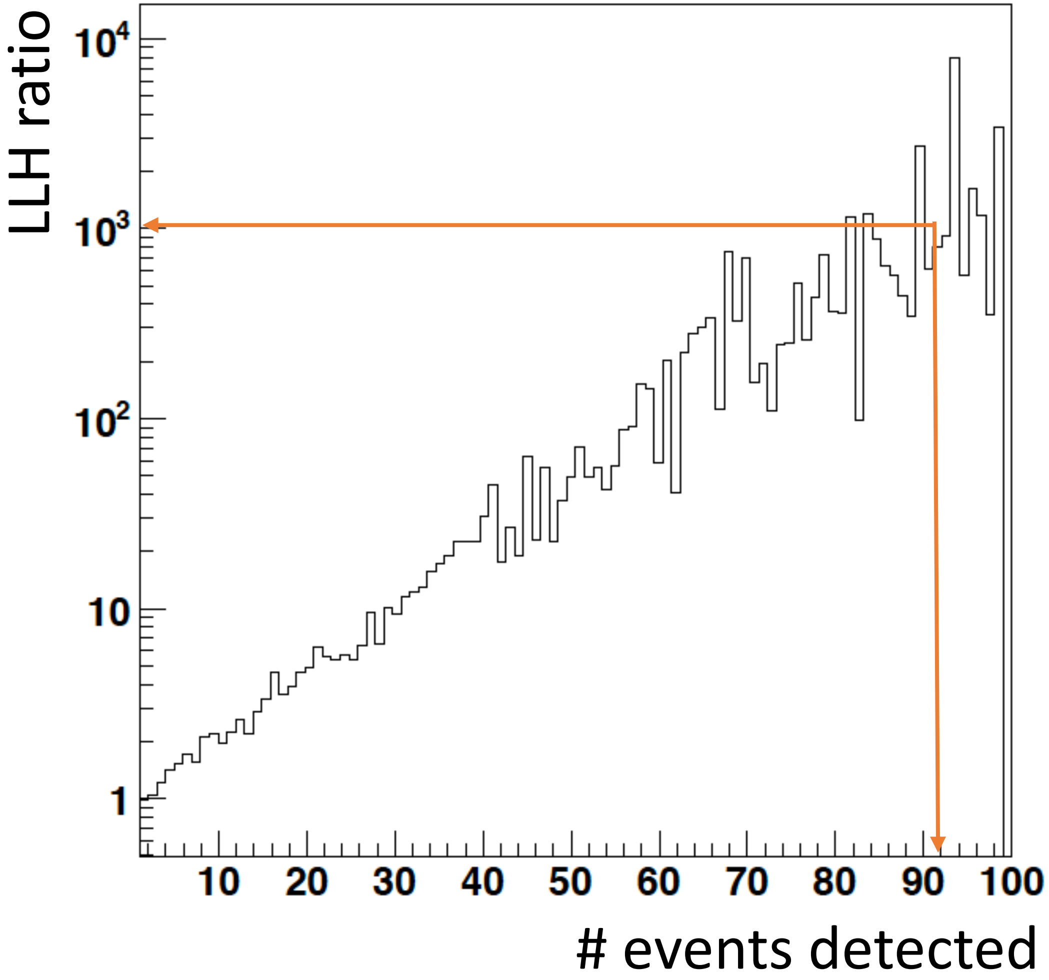
Solar Neutrinos





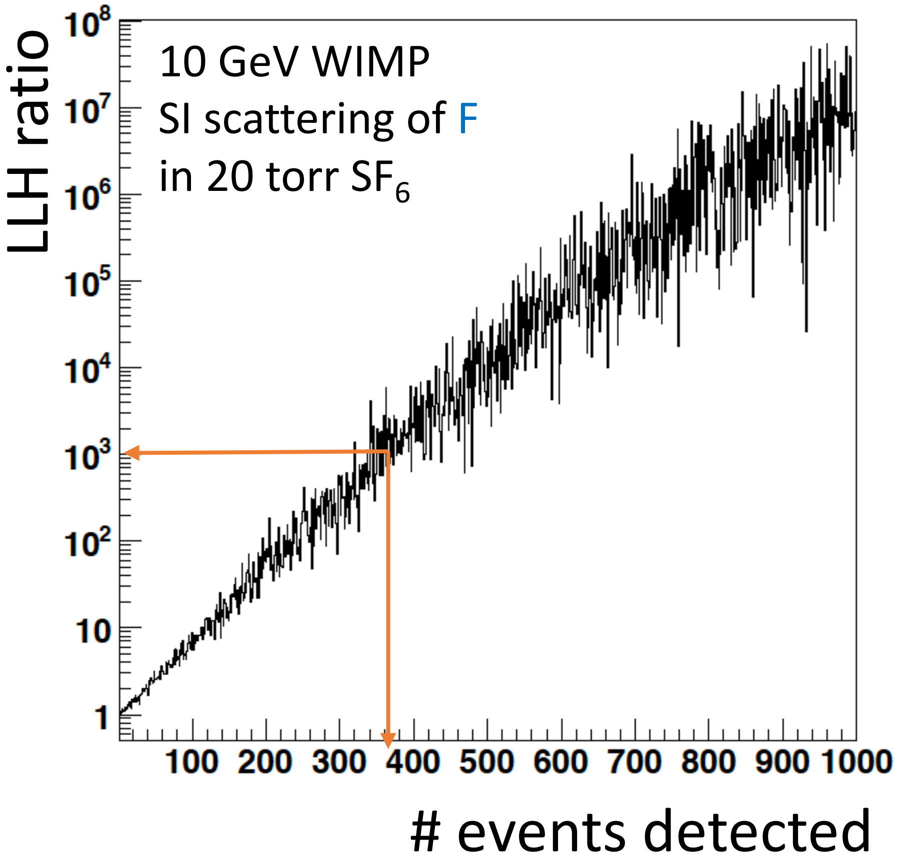
After drift, no clear head/tail signature, but distribution still differs from WIMP one (also, some quantization effects lead to spikes in histogram… to be improved)

How many events to tell 100 GeV WIMPs from solar neutrinos at 3-sigma?

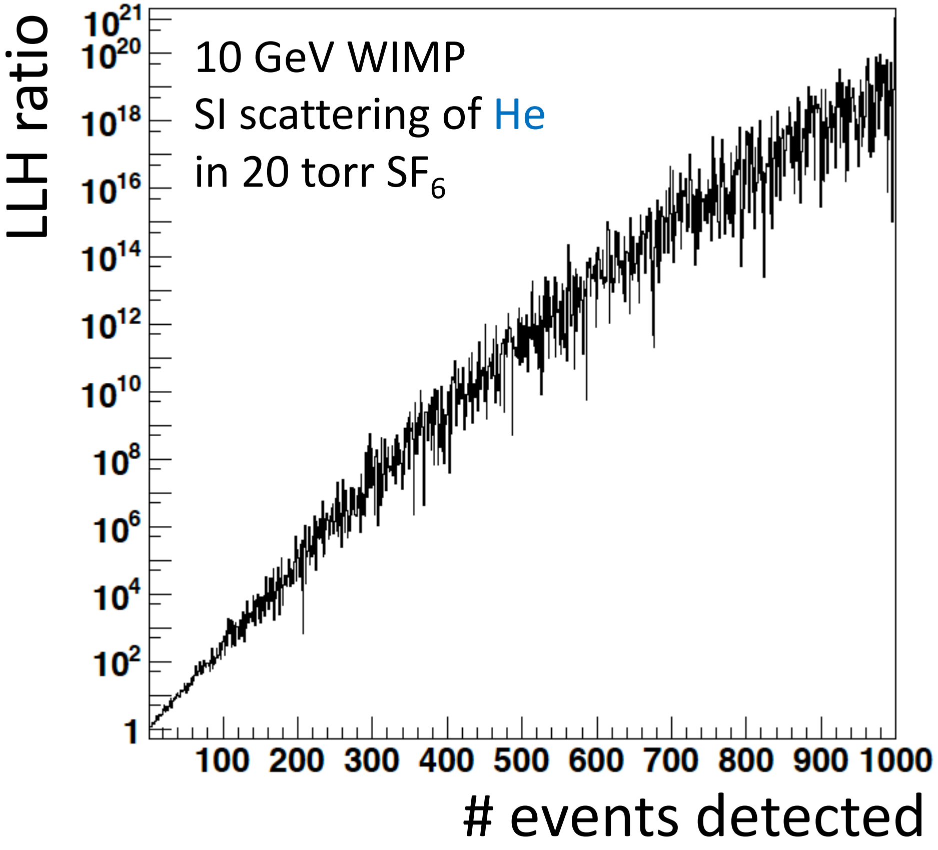


About 90 events with 1D planar readout. (Reminder: still excluding noise and threshold effects.)

2^{nd} physics scenario: m_{WIMP}=10 GeV, SI scattering



~360 detected events required



~115 detected events required

Discussion & Plan

- Strawman readouts simulation developed to optimize CYGNUS TPC detectors
- Example results discussed :
  - TPC with 1D planar readout with idealized assumptions (ignored threshold and noise effects)
  - 20 torr SF_6 gas
  - 50 cm drift length

  →90 events needed to distinguish 100-GeV WIMPs from solar neutrinos, using F target.

  →Similar for 10-GeV WIMPs, with He target.
- Sensitivity will be worse with noise floor of readout included, and fixed-direction detector
- Sensitivity should improve wit higher readout segmentation: wires, x/y strips, and pixels
- Planar 1D readouts, with small area, may also work
- Electron background rejection versus readout segmentation also being studied with same detector simulation.
- Approximately 2 weeks of work left, then write up. Publish this summer or early Fall.

Backup slides

Pixel noise versus input capacitance

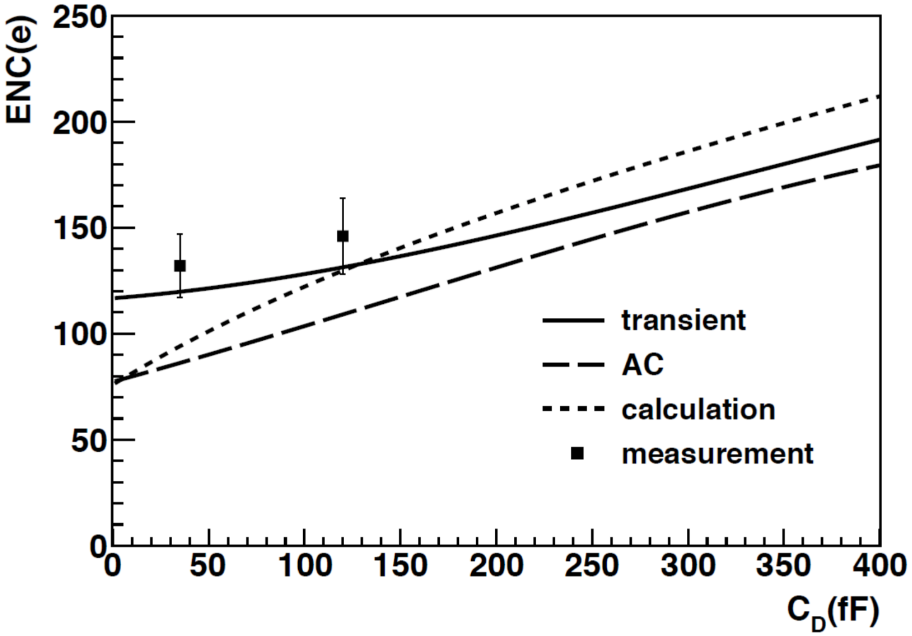
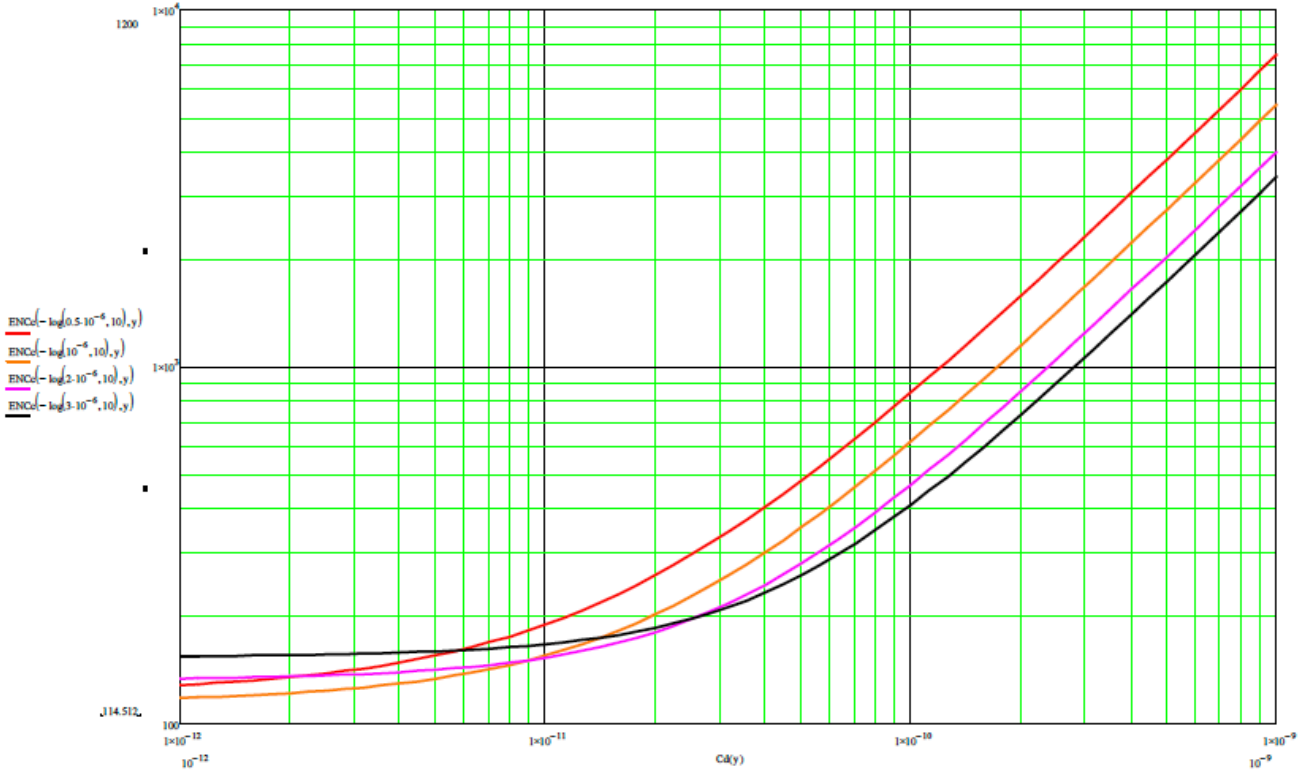


Figure 5.13: The calculated as well as the simulated ENC as a function of the detector capacitance [28].

BNL preamp noise curve (wires / micromegas)



$$\mathrm{ENC1c}(x,y) := \overrightarrow{\sqrt{2.6\times 10^{19}\cdot\frac{C(y)^2}{\tau p(x)}}}$$

Series (Input MOSFET)

$$\mathrm{ENC2c}(y) := \overrightarrow{\sqrt{2.6\times 10^{24}\cdot C(y)^2}}$$

Series (Input MOSFET)

$$\mathrm{ENC2cd} := \sqrt{3.4\times 10^{17}\cdot \mathrm{Cp}\cdot \mathrm{tgd}}$$

Dielectric loss (Cp=trace capacitance)

$$\mathrm{ENC3c}(x) := \sqrt{1.4\times 10^{19}\cdot \tau p(x)\cdot \mathrm{Ileak} + 10}$$

Parallel (Leakage, Reset) and Shaper (100)

$$\mathrm{ENC3Rc}(x,\mathrm{Rbias}) := \sqrt{3\times 10^{8}\cdot\frac{\tau p(x)}{\mathrm{Rbias}}}$$

Parallel from detector bias resistor (if applicable)

$$\mathrm{ENCc}(x,y) := \sqrt{\mathrm{ENC1c}(x,y)^2 + \mathrm{ENC2c}(y)^2 + \mathrm{ENC2cd} + \mathrm{ENC3c}(x)^2 + \mathrm{ENC3Rc}(x,\mathrm{Rbias})^2}$$