Deep learning for improved directional sensitivity to low-energy nuclear recoils in gas TPCs

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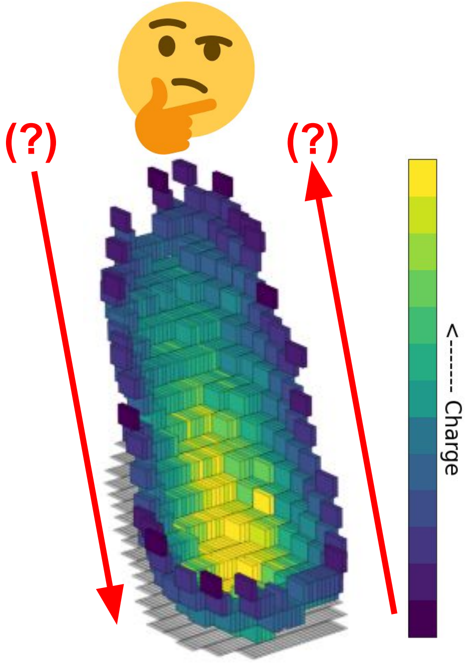
Overview

1. Introduction
   a. Our research group's TPCs
   b. Head/tail recognition
2. An experiment to measure head/tail recognition
   a. Set up and simulation
   b. Convolutional neural network architecture and training
   c. Results
3. Simulation study with better optimized gas mixture to achieve keV-scale head/tail sensitivity
4. Conclusions and outlook



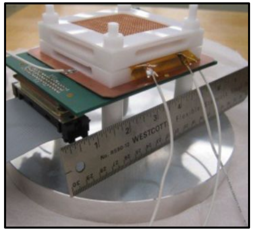
This talk is focused on improving *nuclear recoil head/tail identification* at *low energies* with the ultimate goal of achieving keV-scale head/tail sensitivity

Detector development in our lab at University of Hawaii

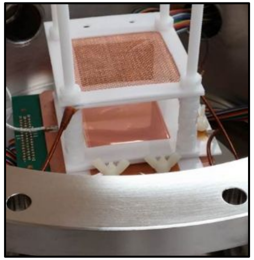
Double GEM amplification with ATLAS pixel ASIC readout

Micromegas with strip readout

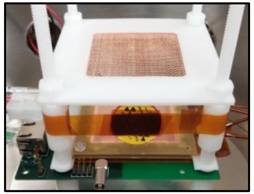
1st Generation (2011-2013):
Proof of concept



~1 cm^3



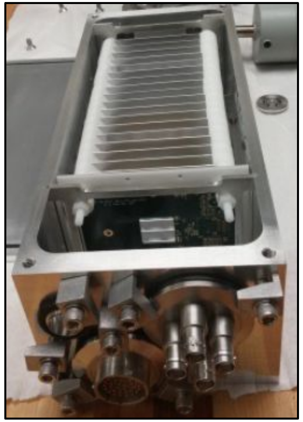
2.5 cm^3



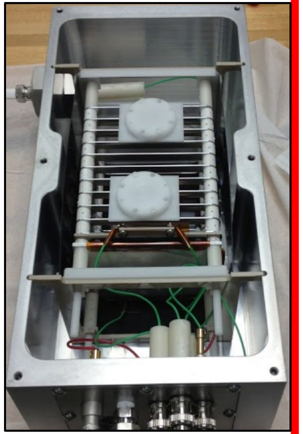
20 cm^3

2nd Generation "BEAST TPCs" (2014-2015): Compact directional neutron detectors. Still in operation both in our lab at UH and at the SuperKEKB e^+e^- collider where they monitor beam-induced neutron backgrounds

2 x 60 cm^3

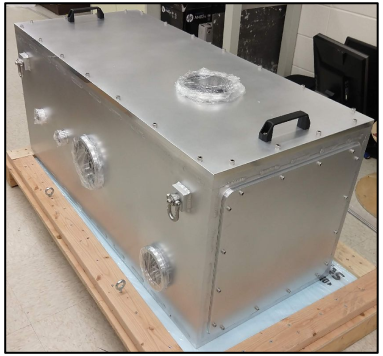


8 x 40 cm^3

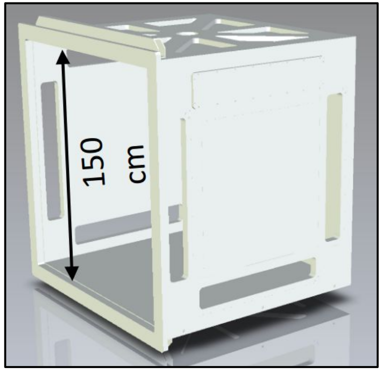


The studies presented today are conducted using one of the 40 cm^3 BEAST TPCs

3rd Generation (2020 —>):
Optimized for dark matter

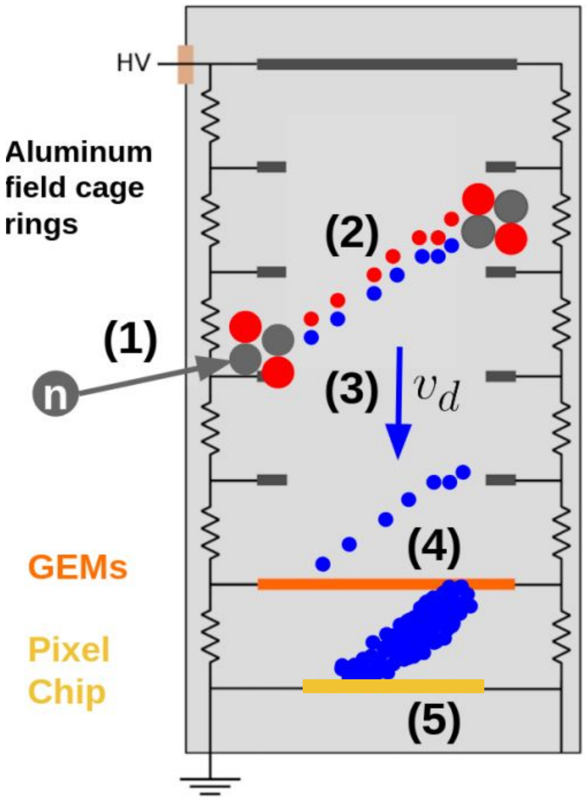


40 L



~1 m^3

BEAST TPC operation at a glance

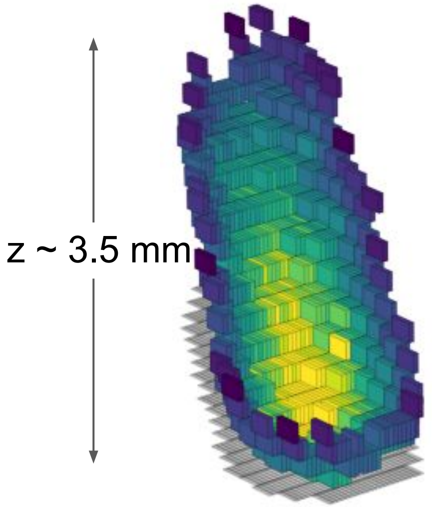


- Filled with a 70:30 mixture of He:CO_2 at STP

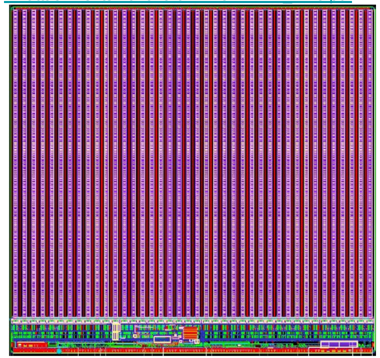
- Drift field of ~450 V/cm corresponding to drift speeds of about 220 µm / 25-ns time bin

- Double GEM amplification capable of gains up to O(50,000), single e^- efficiency at gain ~ 20k

~300 keV_{ee} He recoil at a gain of O(1,000)



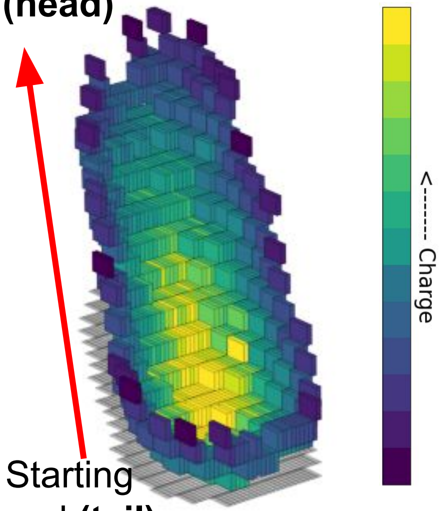
https://indico.cern.ch/event/261840/contributions/1594374/attachments/462649/641213/FE-I4B_V2.3.pdf



ATLAS FE-I4 pixel ASIC readout

- 80 x 336 grid of (250 x 50) μm^2 pixels
- (2 x 1.68) cm^2 readout area
- 4-bit TOT charge quantization
- Custom firmware → up to 256 consecutive 25-ns time bins

The head/tail effect



The starting (tail) and stopping (head) ends of nuclear recoil tracks can be identified using certain features of nuclear recoils →A well trained deep learning classifier should be able to extract the best features for identifying head/tail

In a directional dark matter experiment, head/tail identification will allow for the reconstruction of the galactic dipole → Strongest predicted direct detection signal

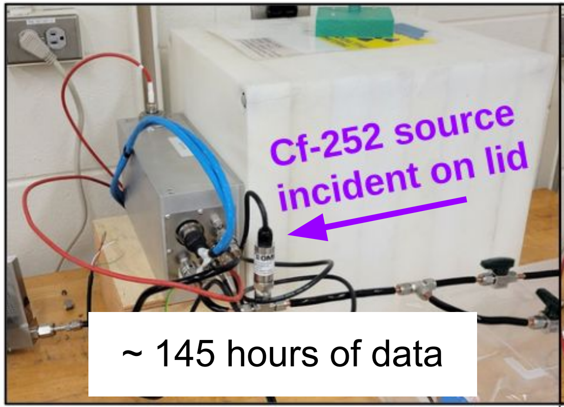
Head/tail recognition efficiency (ε_{ht}): Fraction of events where the scalar (dot) product of the reconstructed vector and the true initial recoil direction is positive

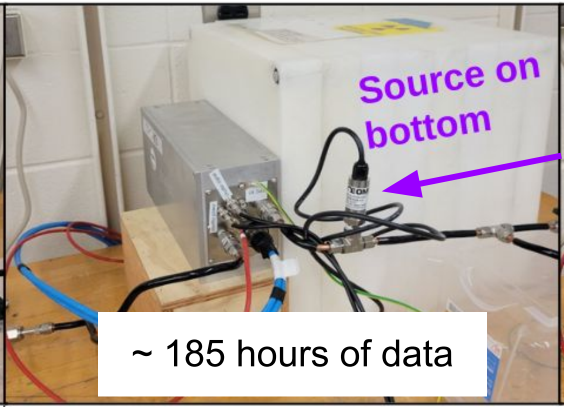
ε_{ht} = 0.5 ⇐⇒ No head/tail sensitivity
ε_{ht} = 1 ⇐⇒ Perfect head/tail sensitivity

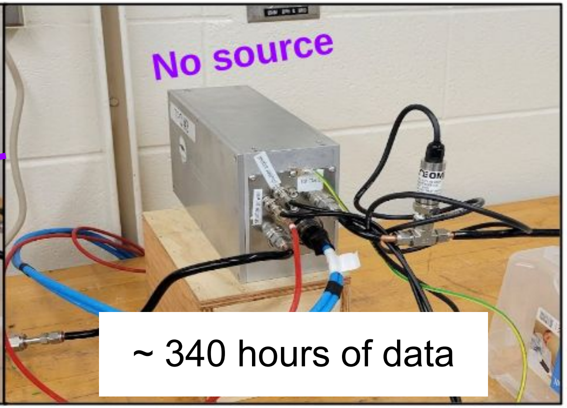
Our work is focused on improving ε_{ht} at *low energies* using deep learning

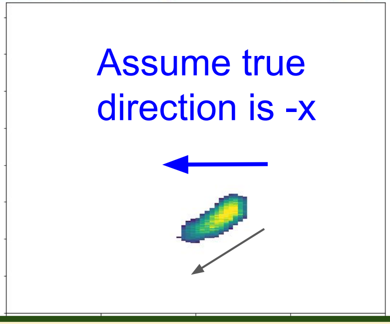
Measuring the head/tail recognition efficiency

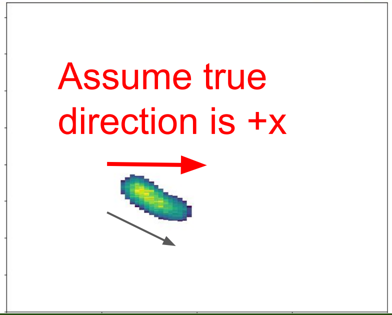
"-x" sample | **"+x" sample** | **Background sample**











In this experiment we assume the true recoil direction to be -x for the "-x" sample and +x for the "+x" sample ⇒ we will incorrectly identify back-scattered events so our measured ε_{ht} should be treated as a lower limit!

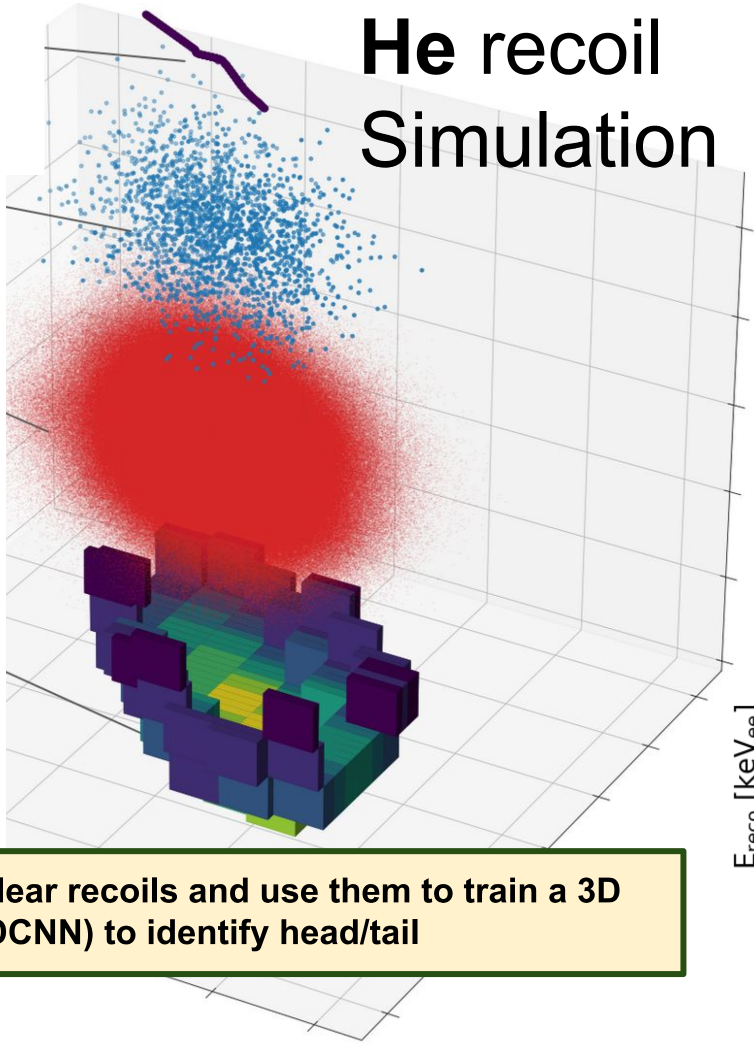
He recoil Simulation

Primary track: recoil trajectories simulated with SRIM* (isotropic angular distribution)

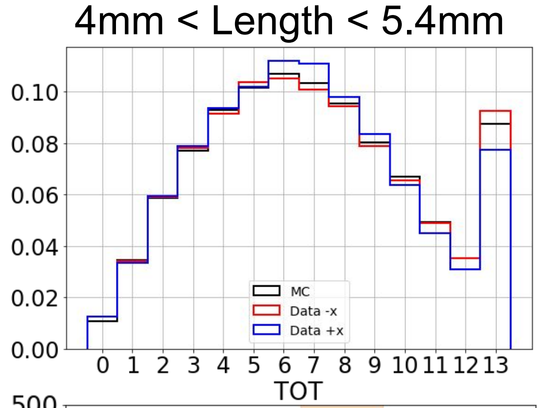
Drift tracks and apply diffusion:
Drift length = 4cm
σ_T = 133.1 μm/cm$^{1/2}$
σ_L = 122.9 μm/cm$^{1/2}$

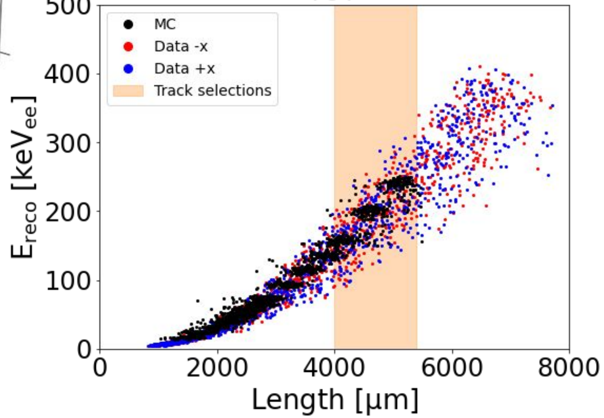
Amplify charge with a double GEM gain of 1,320 using a random exponential distribution

Digitize using the binning of the ATLAS pixel chip. For each bin above threshold, record the z position where the cumulative charge first passes above threshold as the time bin.



Data vs. MC agreement is crucial for models trained on simulation to generalize to measurement!

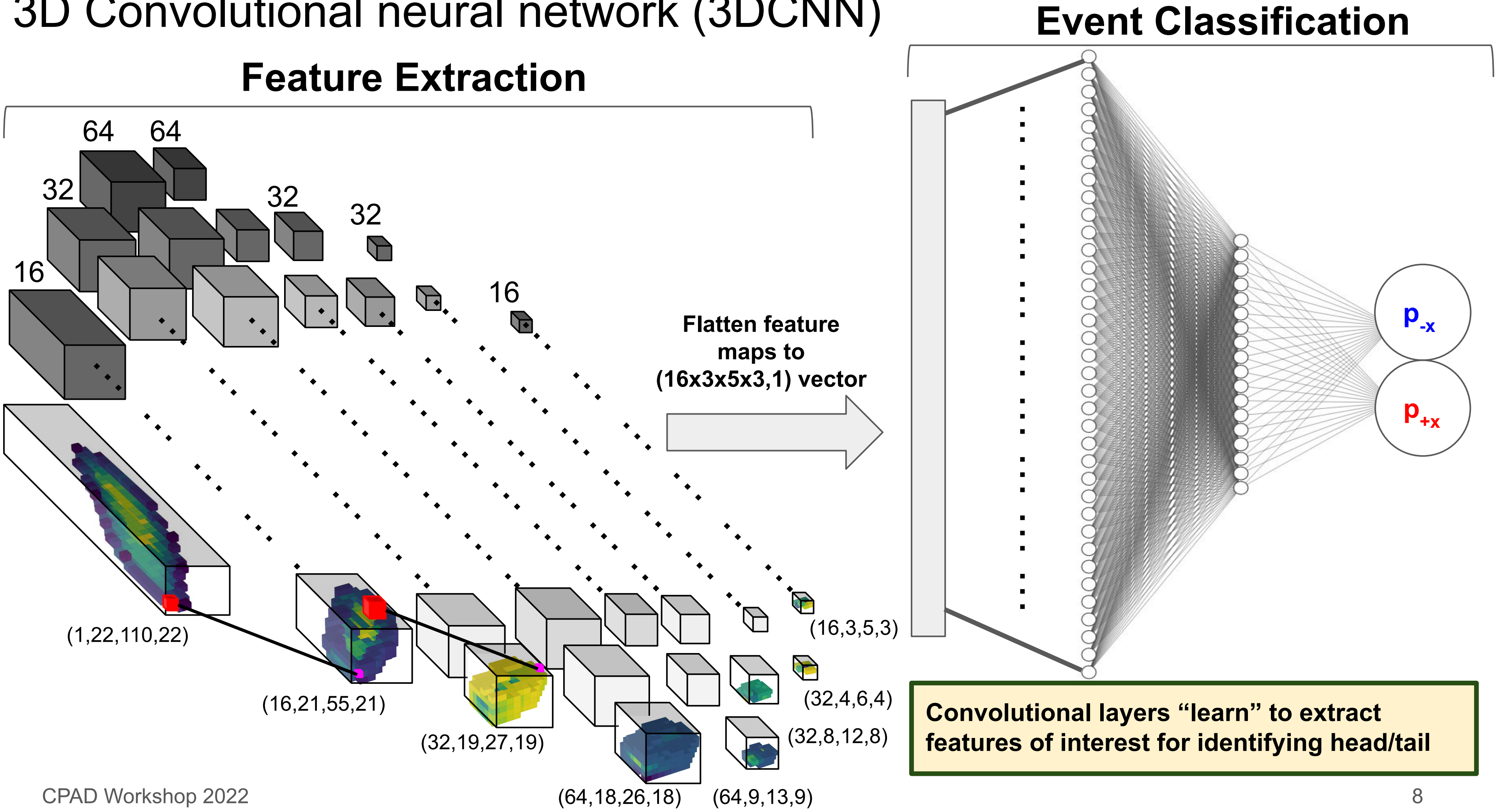




We simulate around 200,000 nuclear recoils and use them to train a 3D convolutional neural network (3DCNN) to identify head/tail

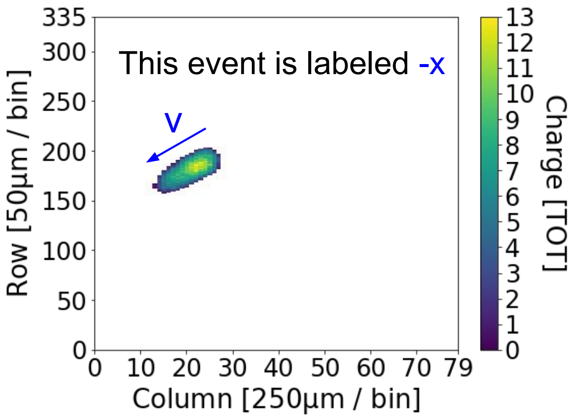
*Also used retrim

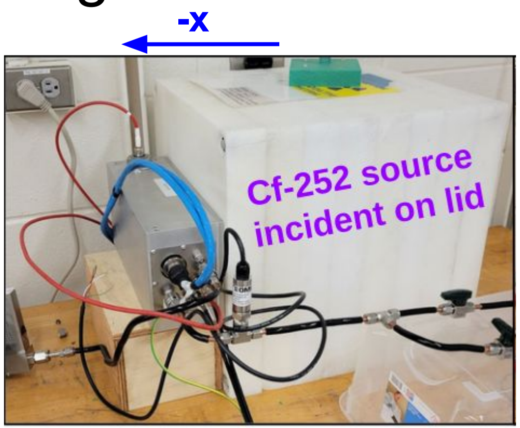
3D Convolutional neural network (3DCNN)

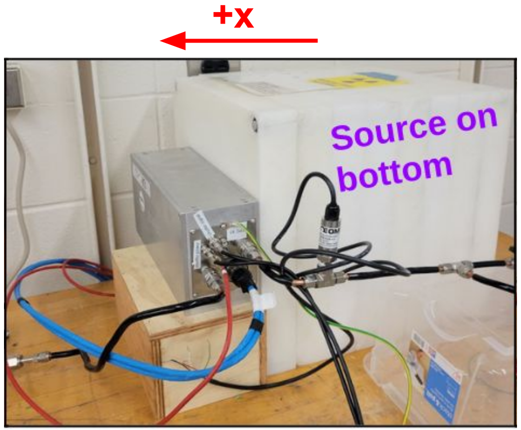


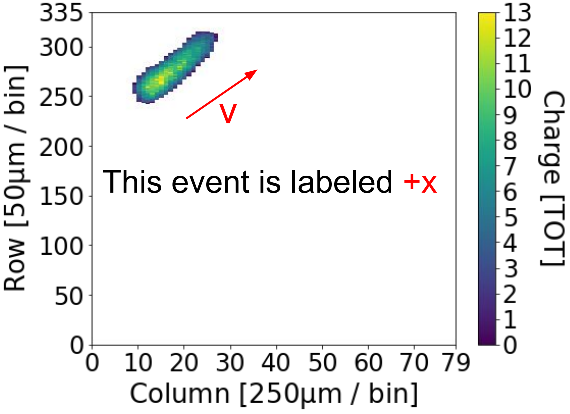
Convolutional layers "learn" to extract features of interest for identifying head/tail

How do we assign training labels?







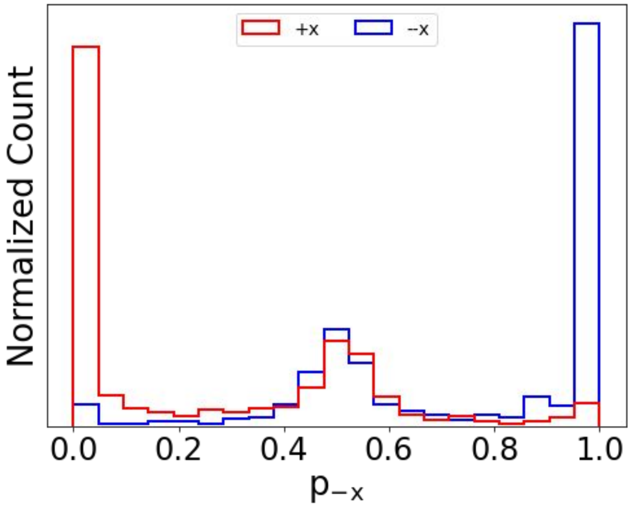


We label events based on the dot product between the **truth simulated recoil vector** $\hat{\mathbf{v}}$ and $\hat{\mathbf{x}}$

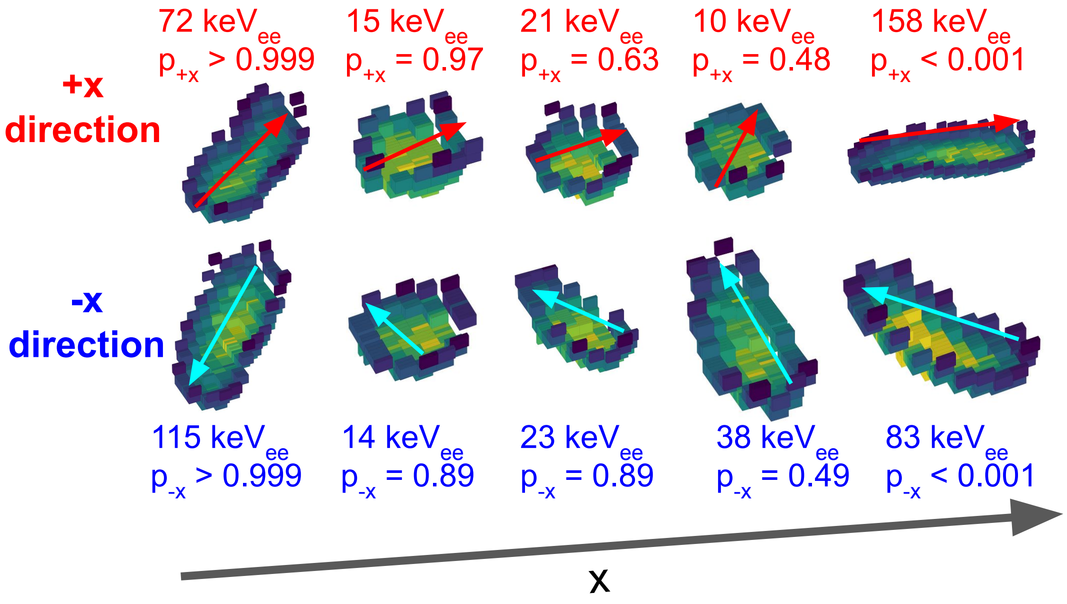
$\hat{\mathbf{v}} \cdot \hat{\mathbf{x}} < 0$ **is labeled 1 ⇒ -x direction**

$\hat{\mathbf{v}} \cdot \hat{\mathbf{x}} > 0$ **is labeled 0 ⇒ +x direction**

3DCNN output and predictions on selected measured He recoils

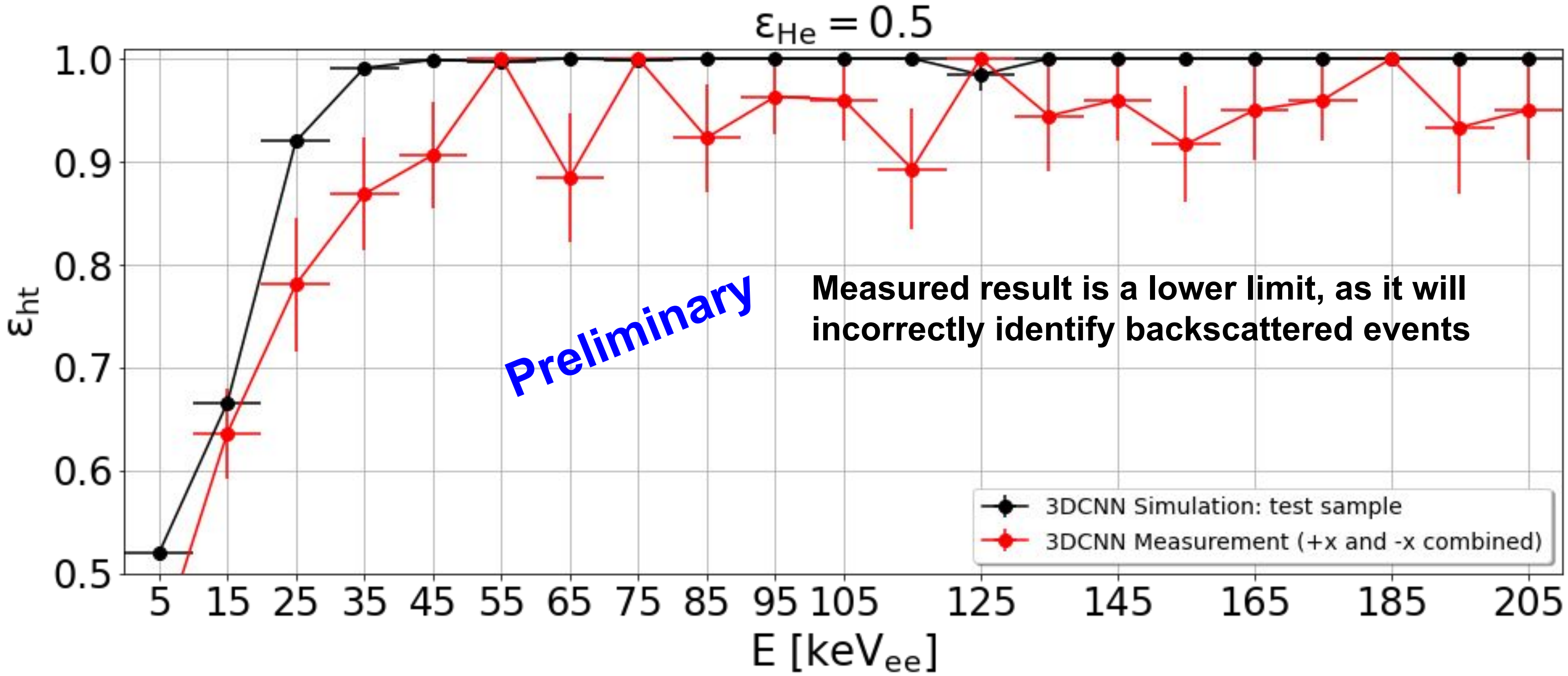


Event level head/tail predictions



3DCNN provides a confidence measure of it's head/tail prediction, allowing for event-level head/tail analyses

Results



ε_{ht} = 63.6 +/- 4.3% for 10-20 keV_{ee} recoils → first demonstration of significant *event-level* head/tail sensitivity below 20 keV_{ee} in measurement!

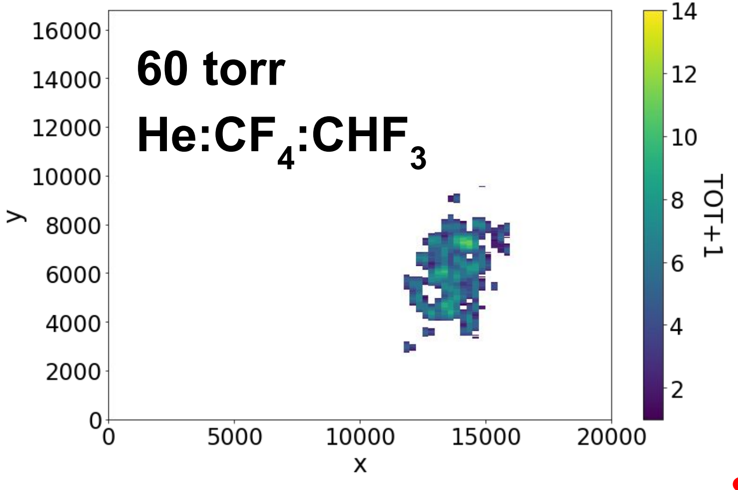
What if we use a better optimized gas mixture?

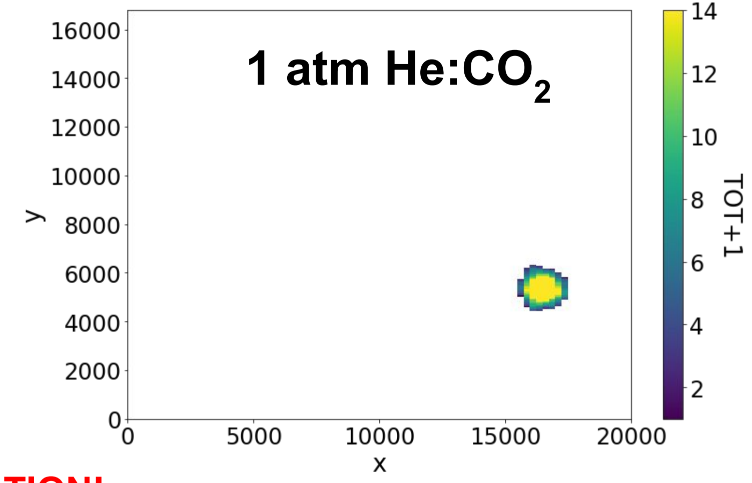
- Our current studies use a 1atm mixture of He:CO_2 which was optimized for fast neutron (E > 100 keV) measurements
  - Saturation limits high gain performance in 1atm He:CO_2
- Interested in choosing gas conditions that maximize L / σ_T (or 1 / ($\varrho \cdot \sigma_T$))

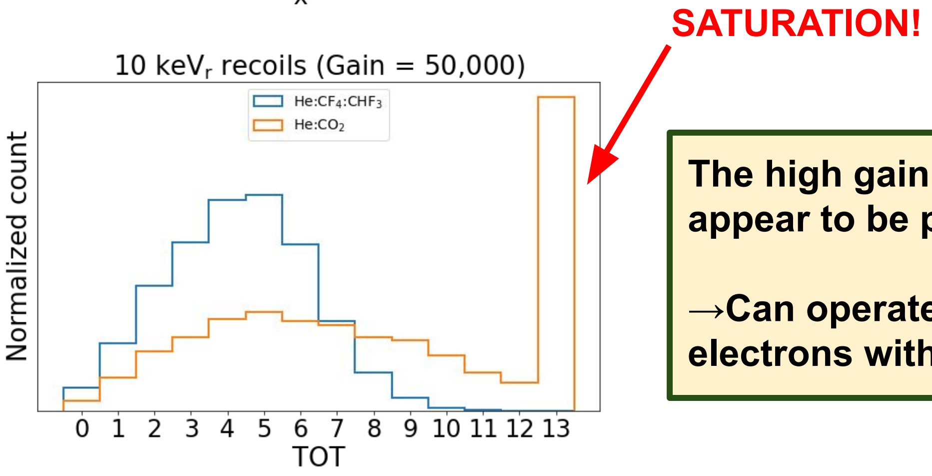
Mixture	Type of drift	Pressure [Torr]	Density [g/cm^3]	σ_T [µm/cm$^{1/2}$]	1 / ($\varrho \cdot \sigma_T$) [cm$^{7/3}$µm^{-1}g^{-1}]
70% He + 30% CO_2	e^-	760	7.2e-4	133	10.5
97.4% He + 2.6% SF_6	Negative ion	760	3.35e-4	78.6	38.0
80% He + 10% CF_4 + 10% CHF_3	e^-	60	6.7e-5	398	37.6

While a negative ion drift gas like He:SF_6 is an attractive future candidate, we opt to simulate an electron drift gas like He:CF_4:CHF_3 so we could operate the BEAST TPCs without modifying the detectors.

Simulation: 10 keV$_r$ comparison at Gain = 50,000



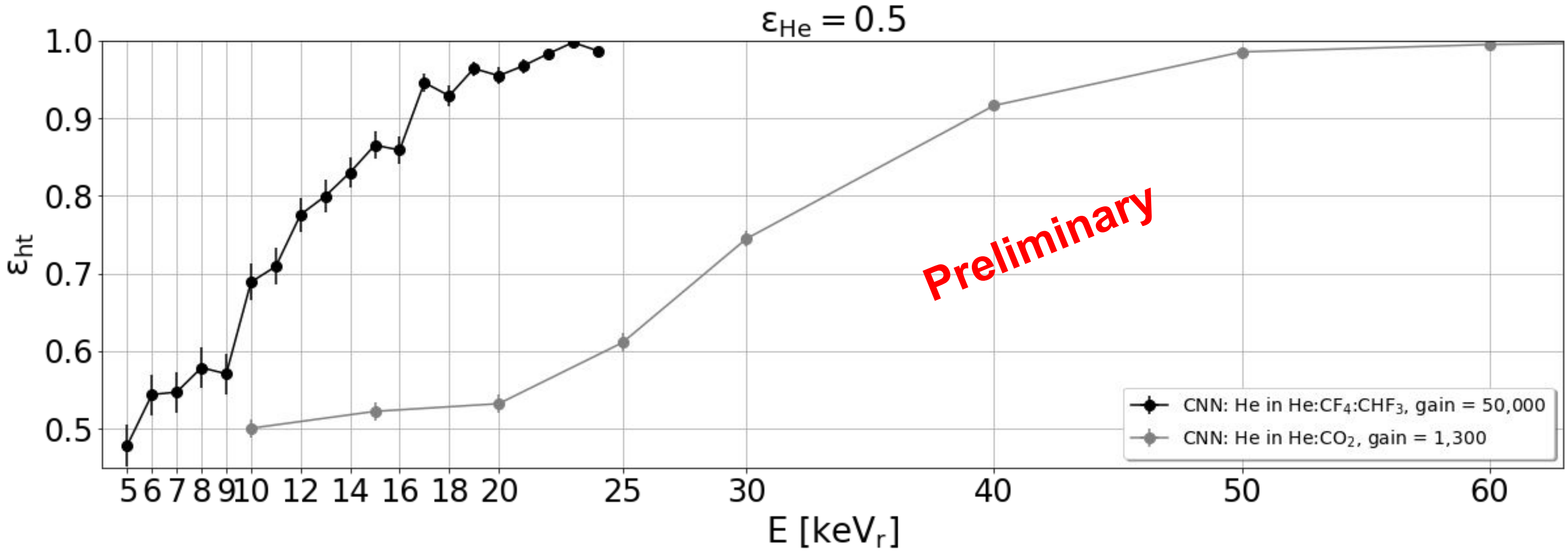




The high gain performance limitations of 1atm He:CO_2 don't appear to be present in He:CF_4:CHF_3 at 60 torr

→Can operate at high gains where we are sensitive to single electrons without being dominated by saturated pixels!

He recoil simulation: Expected peak performance in a BEAST TPC



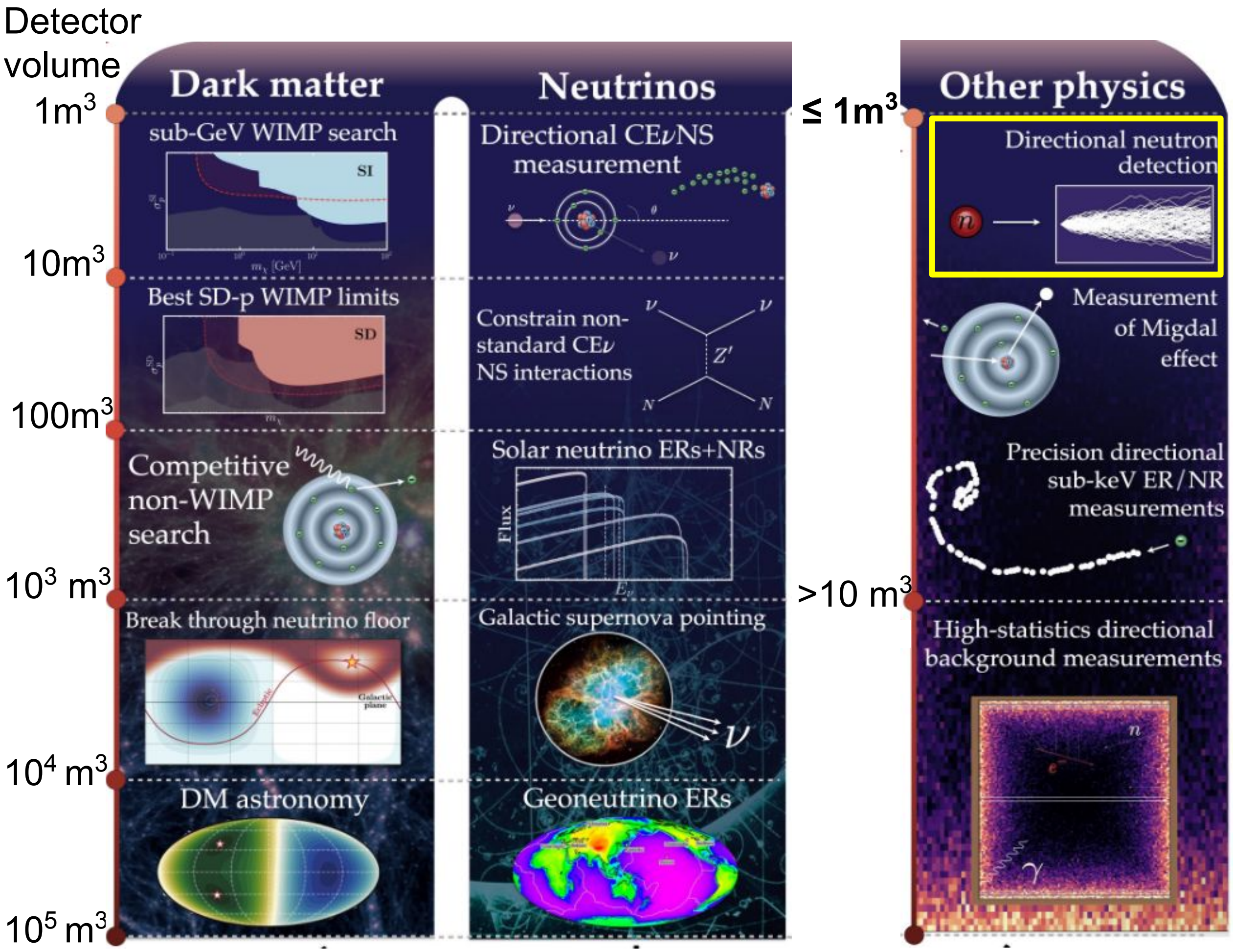
keV-scale head/tail sensitivity seems possible with current generation technology provided we use a well-optimized electron drift gas mixture.

Conclusions and outlook

1. Using deep learning, we experimentally demonstrated the first event-level head/tail sensitivity to below 20 keV_{ee}
2. With a more optimized electron-drift gas mixture, using this deep learning approach, we expect to achieve keV-scale nuclear recoil head/tail sensitivity with current generation technology
3. We expect an additional improvement in nuclear recoil head/tail sensitivity using negative ion drift gas and single electron counting
4. There is also renewed interest in reconstructing directions of *electron recoils* (see talk by Majd Ghrear)

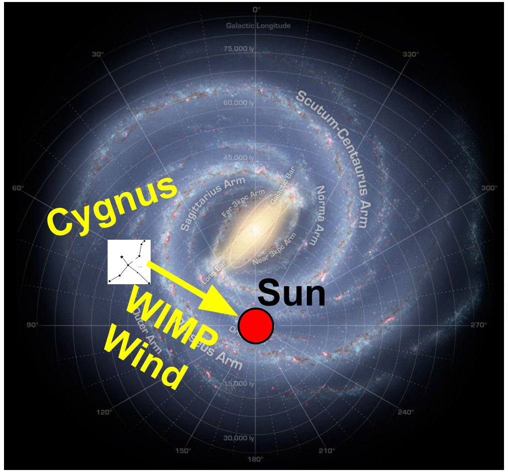
Backup

Applications of gas time projection chambers (TPCs)

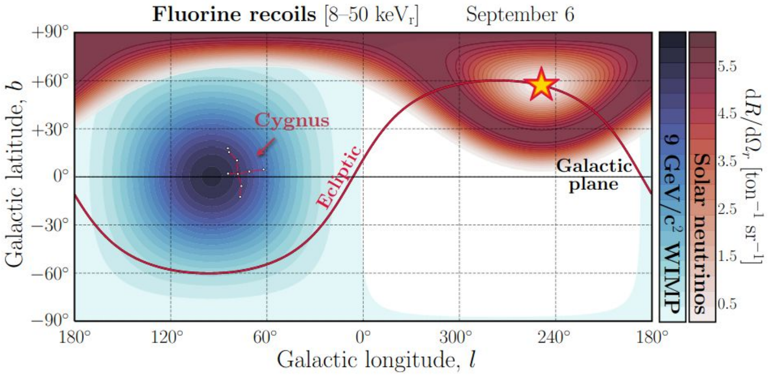


Importance of head/tail recognition

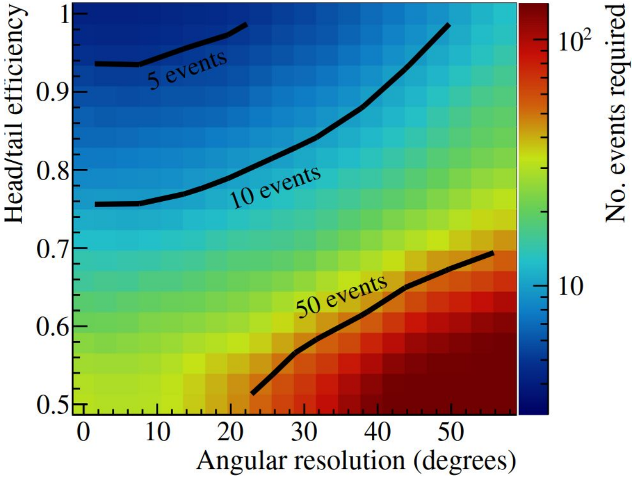
https://www.nasa.gov/mission_pages/sunearth/news/gallery/galaxy-location.html



https://arxiv.org/abs/2102.04596

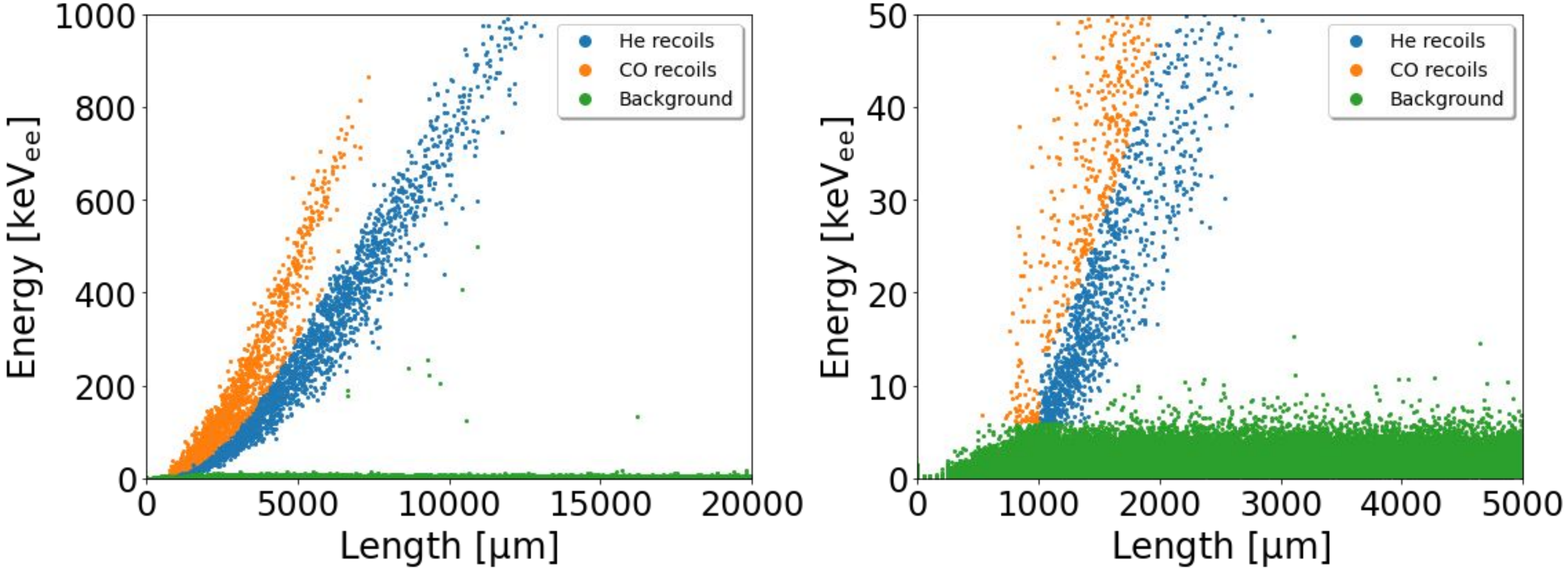


Simulation showing 90% C.L. exclusion of solar neutrino hypothesis assuming He recoils in He:SF_6, a 10 GeV WIMP mass and 1keV$_r$ threshold
https://arxiv.org/abs/2102.04596



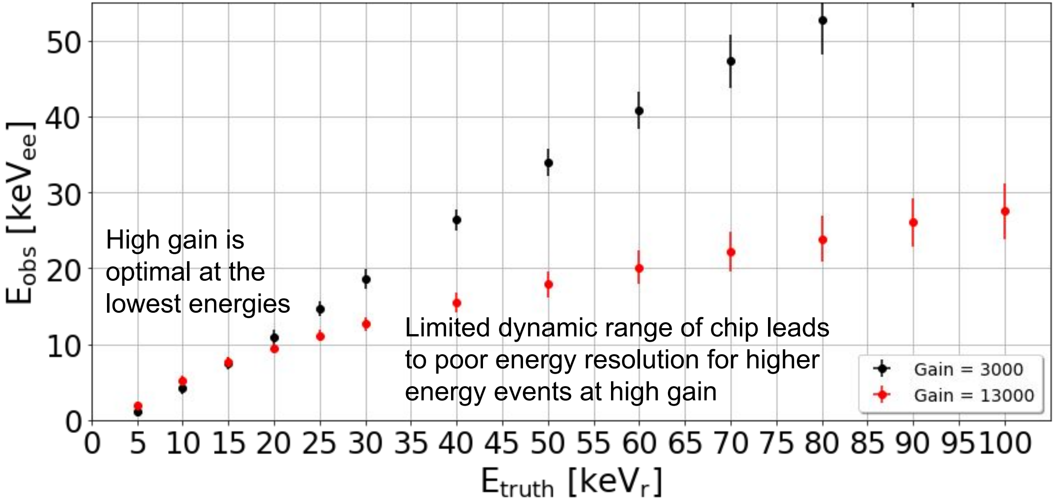
Head-tail identification allows for the reconstruction of the galactic dipole → Strongest predicted direct detection signal

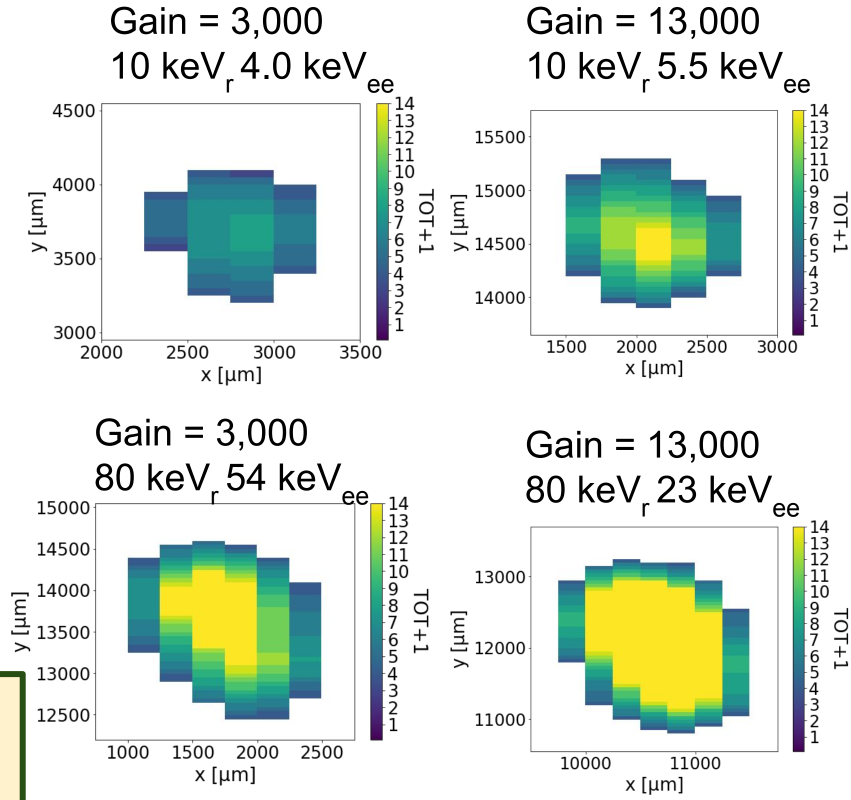
He recoil event selections on experimental data



- **Make selections based on dE/dx.**
- **X-ray background discrimination down to 6 keV$_{ee}$ and clear He vs. C/O discrimination at high energies**
- **Minimizing C/O contamination at low energies is important because C/O primary recoil tracks do not have as strong of a charge asymmetry as He primary tracks.**

Detector limitations



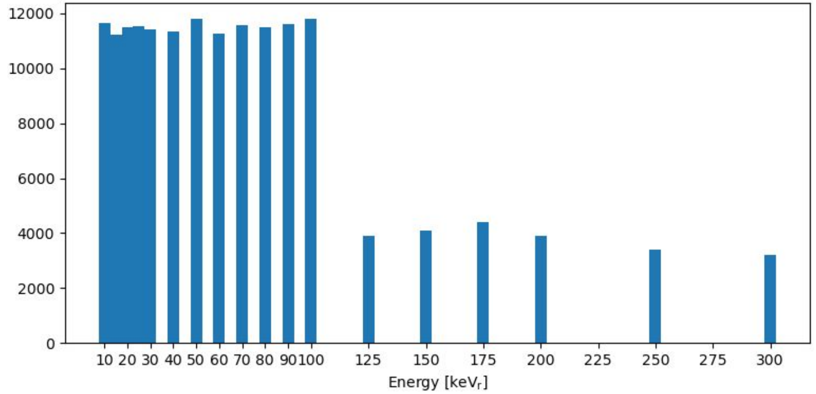


Increasing GEM gains to “single-electron efficiency” levels is ideal for maximizing low energy directional performance.

Problem: In He:CO_2 at STP, we’re dominated by saturation causing poor energy resolution and even worse, poor He and C/O recoil discrimination.

Training and evaluating 3DCNN

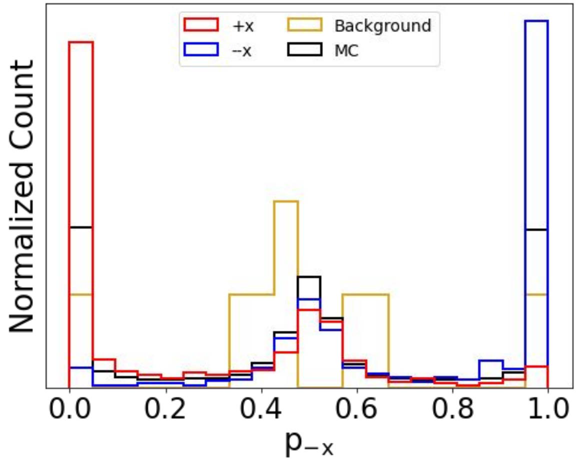
Training sample: 161,100 simulated He recoils isotropic directional distribution



- Train using 10-fold cross validation
    - Save model parameters each epoch where validation loss improves
- Employ early stopping
    - Stop if validation loss doesn't improve over 10 successive epochs

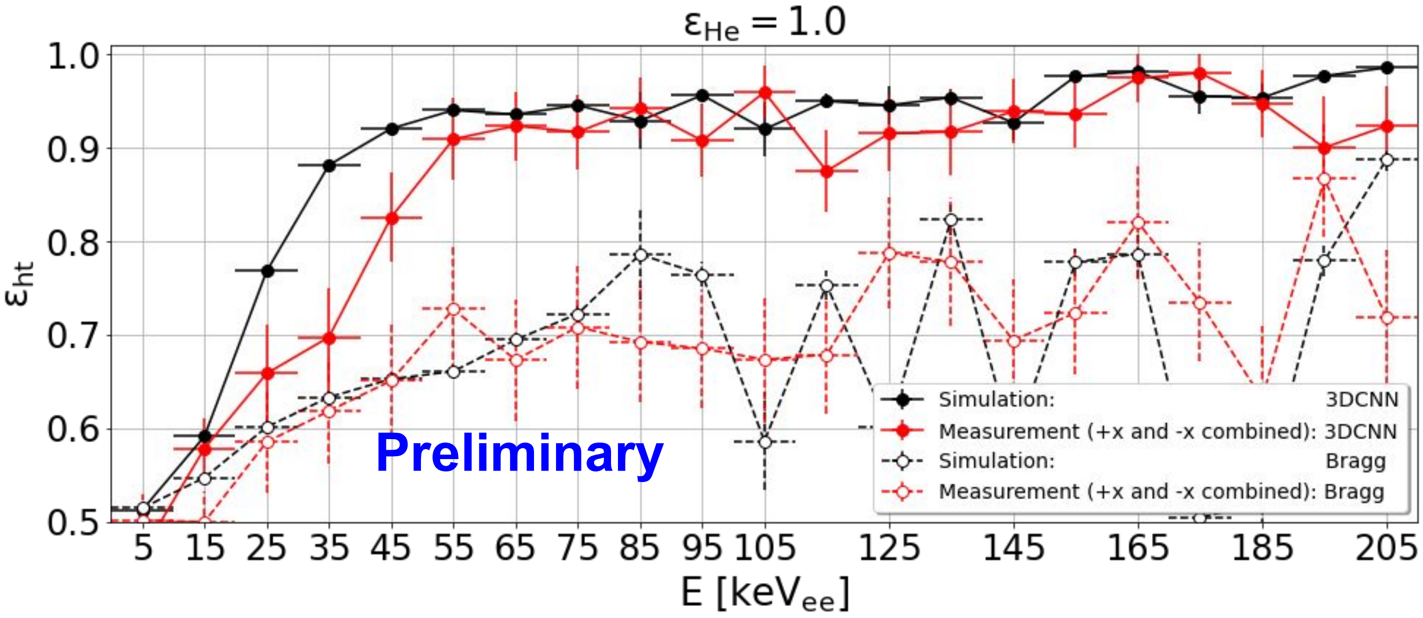
MC Test sample: 48,690 simulated He recoils isotropic directional distribution

Measured sample:
842 recoils in "-x" sample
887 recoils in "+x" sample
8 recoils in background sample

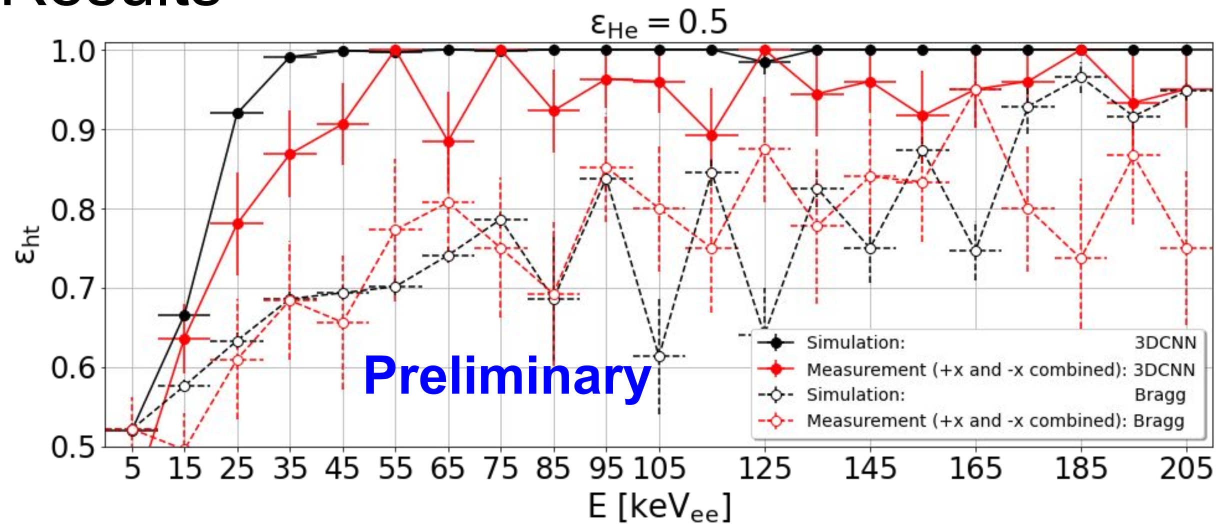


p_{-x} distribution is consistent with the expected direction of recoils from the source in both positions → Network is learning correctly!

100% efficiency

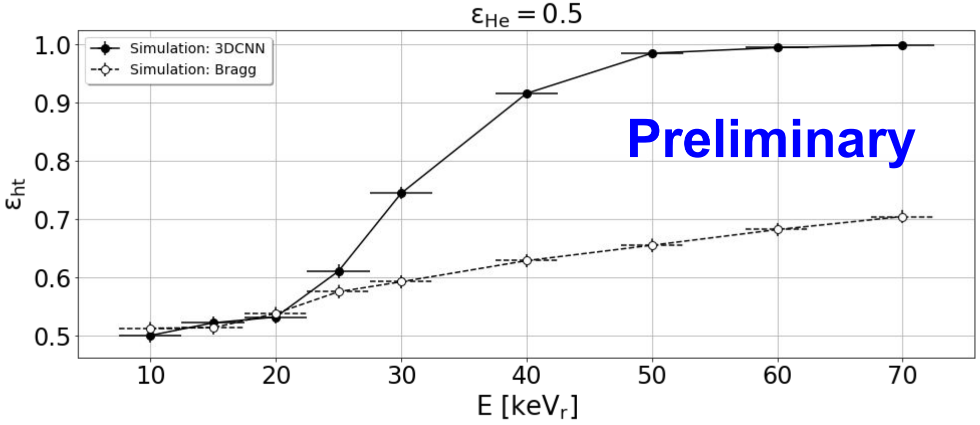


Results



Head/tail recognition efficiency versus observed reconstructed energy

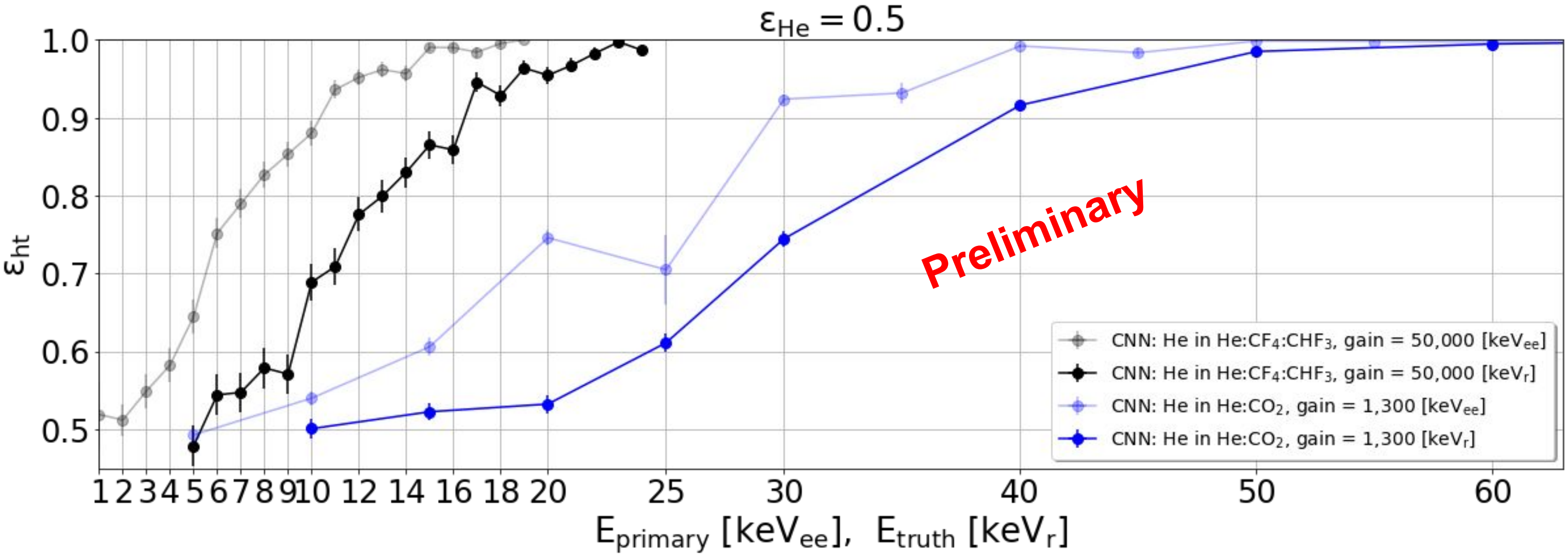
Significant head/tail efficiency in measurement down to 15 keV_{ee}!



Head/tail recognition efficiency versus true recoil energy

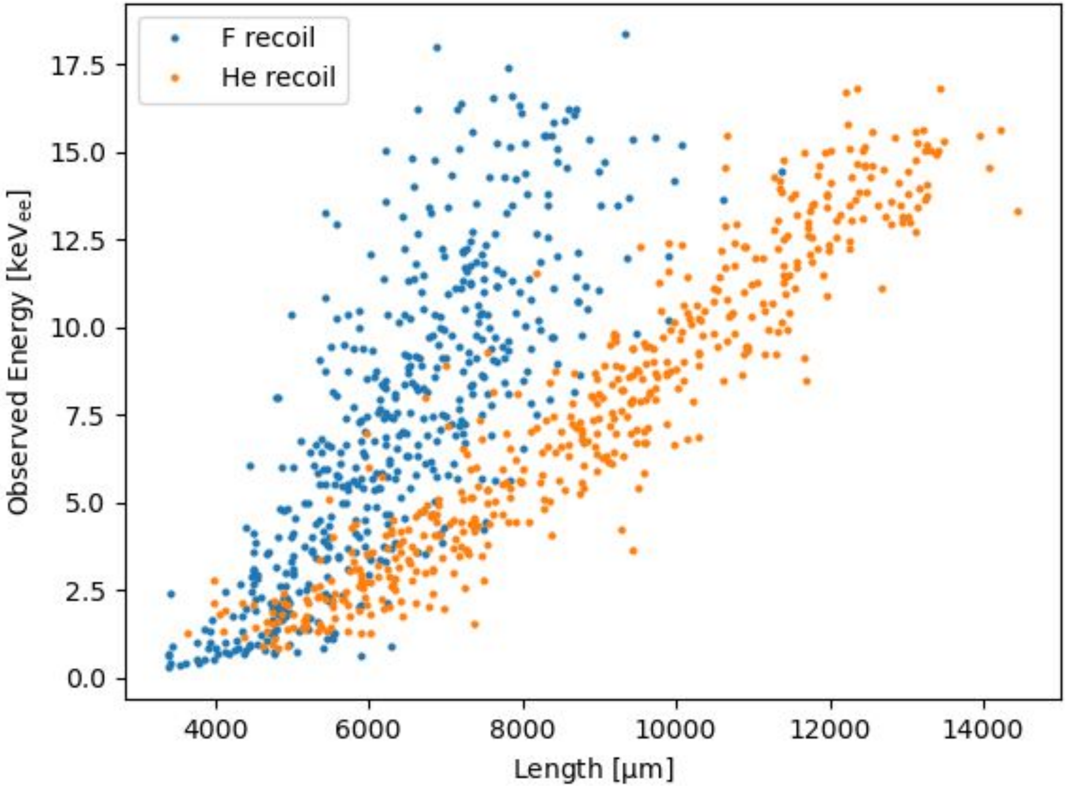
We expect 3DCNN head/tail sensitivity to turn on around 25 keV_r

He recoil simulation: Expected peak performance in a BEAST TPC



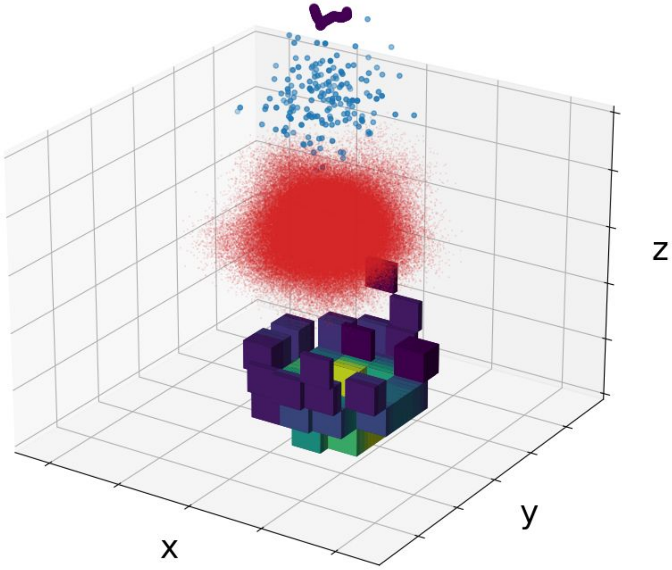
keV-scale head/tail sensitivity seems possible with current generation technology provided we use a well-optimized electron drift gas mixture.

He:CF_4:CHF_3 event selection



Motivation

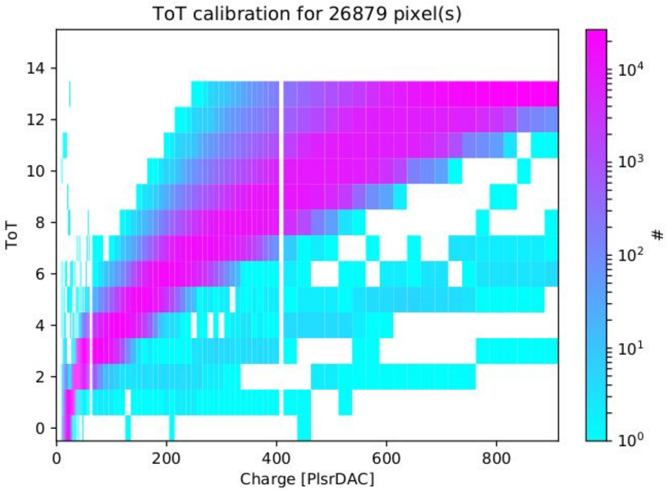
Simulation (SRIM + retrim)



Time over threshold (TOT) is the raw measured quantity of charge

We therefore need 3D spatial TOT distributions to on average agree between measurement and simulation to ensure 3DCNNs trained on simulation generalize well to measurement

Measurement



-In simulation we start with a binned charge distribution and then map that to TOT

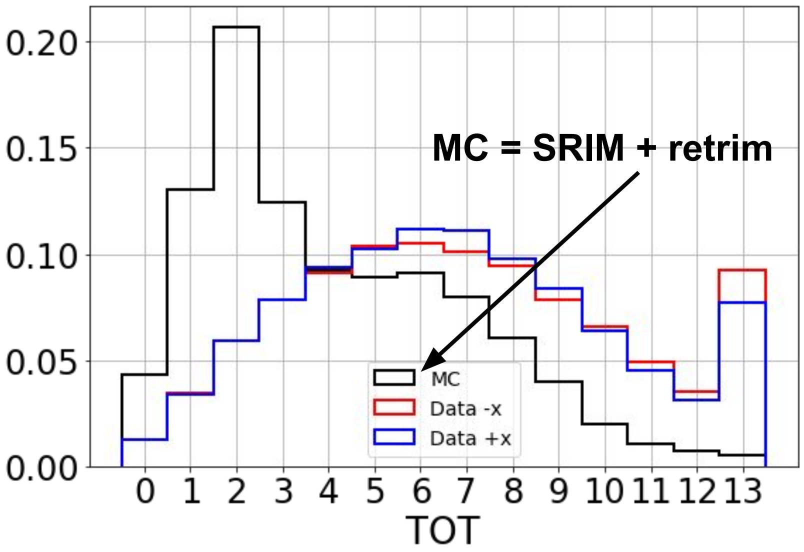
Order of processes is reversed

-In measurement we use a calibration curve like the above to map TOT to physical units of charge

To ensure agreement between simulated and measured TOT distributions we will use simulation-driven charge calibrations. The idea is we find the charge at each TOT step that makes simulated TOT distributions agree with measurement. We then use this same charge-to-TOT calibration for our measured data

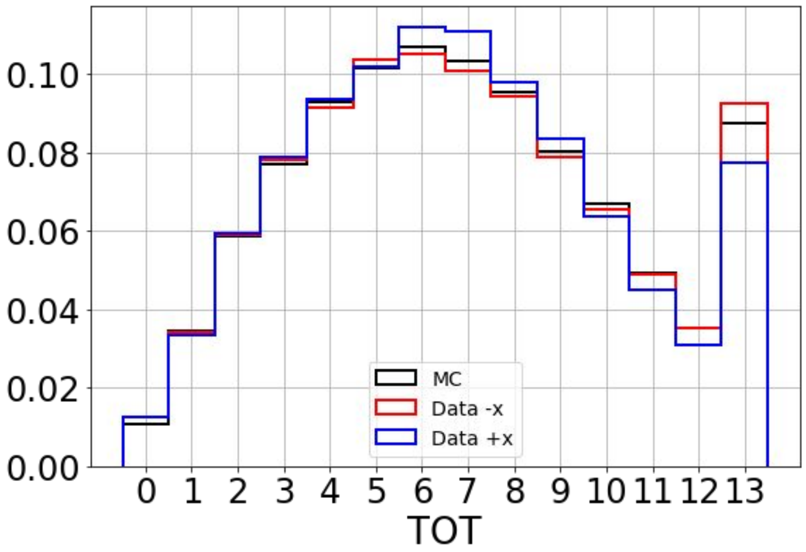
Comparing TOT distributions (4mm < L < 5.4mm)

Old



- Old procedure uses the charge-to-TOT calibration determined by our measured calibration curve
- This produces significantly different simulated and measured TOT distributions

New



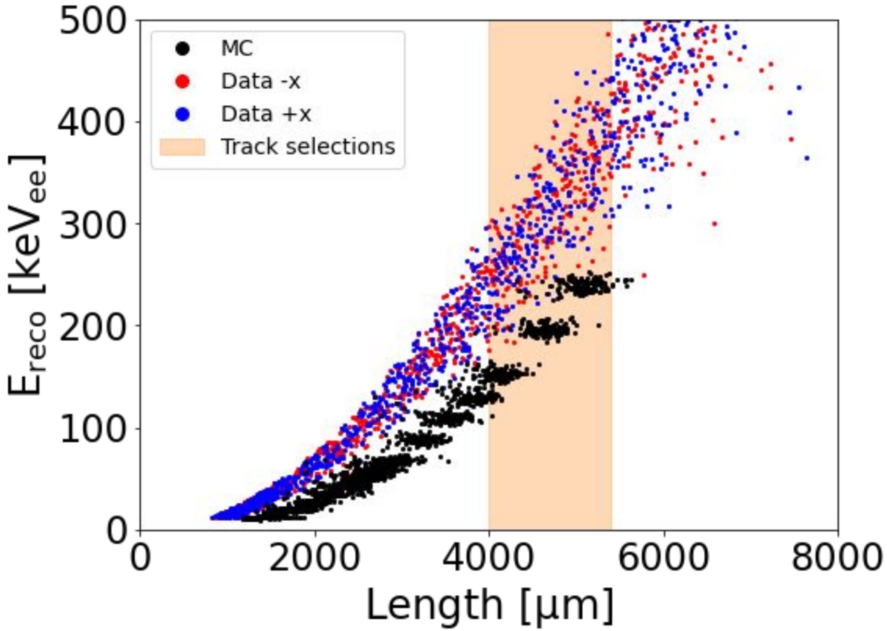
- Now we adjust our simulated charge-to-TOT mapping so that TOT distributions agree
- Use adjusted charge-to-TOT mapping on measurement

Simulation settings

Old

Gain = 909

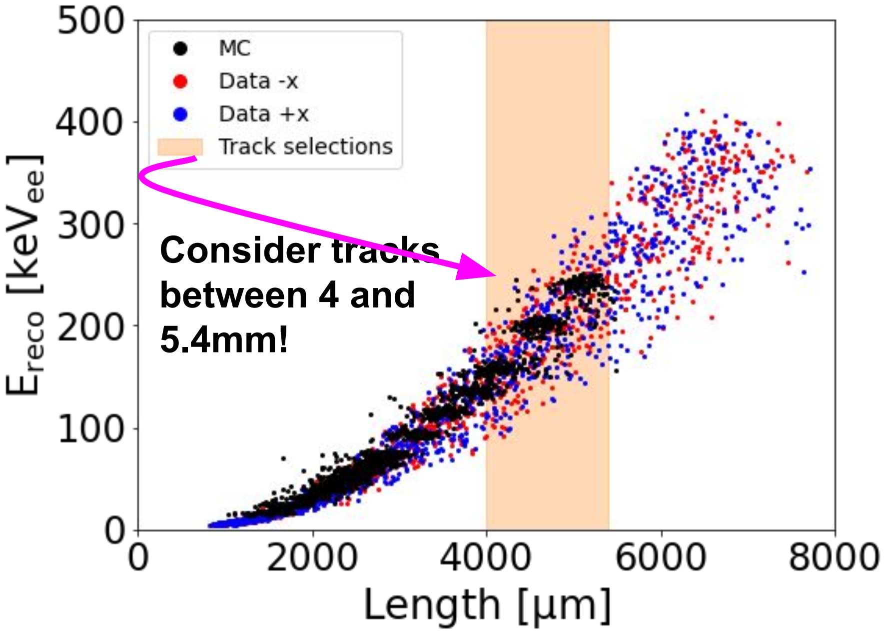
Q to TOT: [2087, 2385, 3530, 6407, 8929, 11300, 14107, 17631, 21486, 25435, 29486, 33851, 38838, 47199]



New

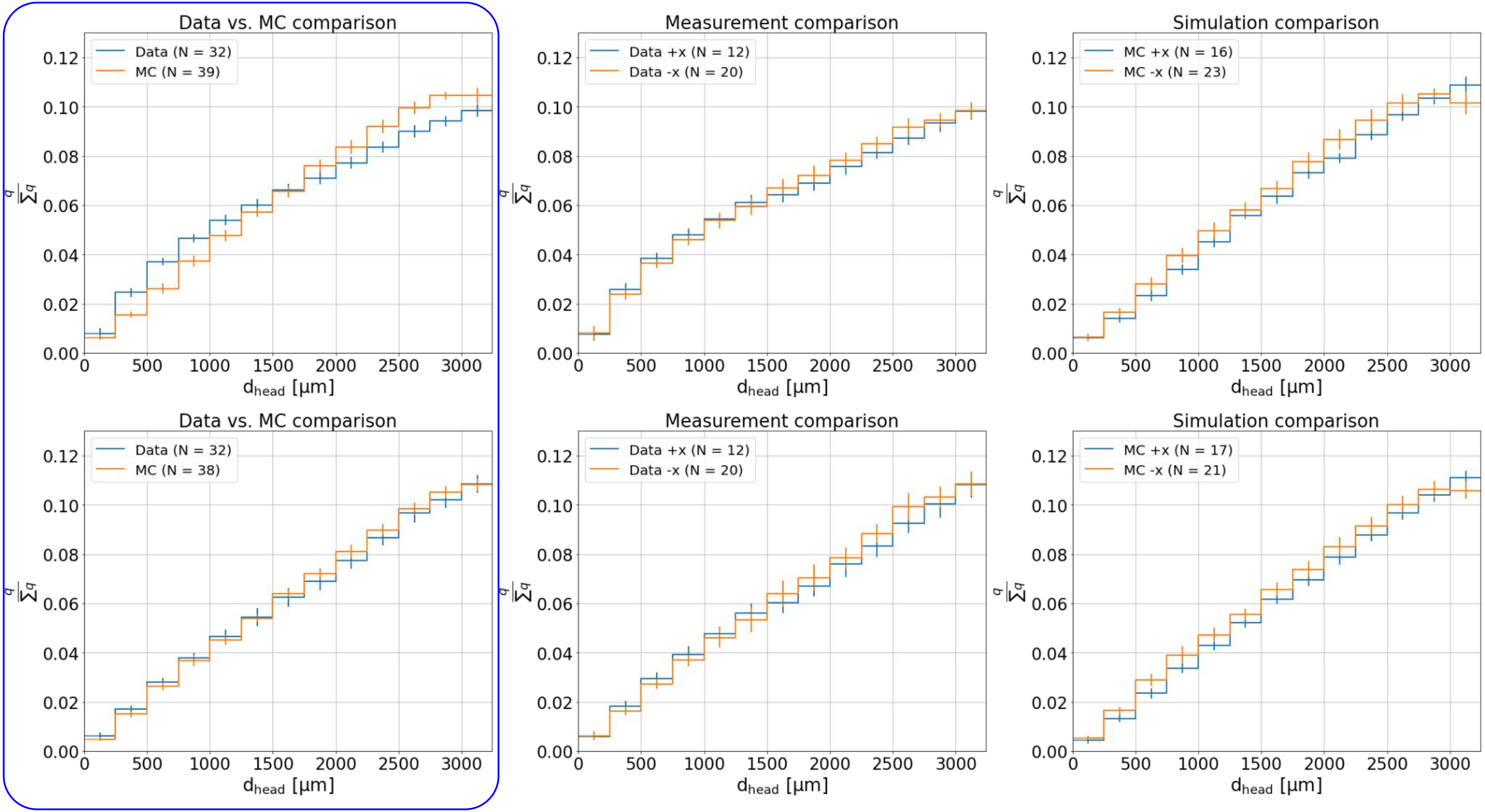
Gain = **1320**

Q to TOT: [2087, 2185, 2520, 3200, 4350, 6200, 9000, 13000, 18100, 24200, 30600, 37200, 43000, 47900]



dE/dx distributions agree much better after adjusting charge calibration and gain. Note: We never logged the expected drift length in this measurement campaign, so I treated drift length as an adjustable parameter to control diffusion

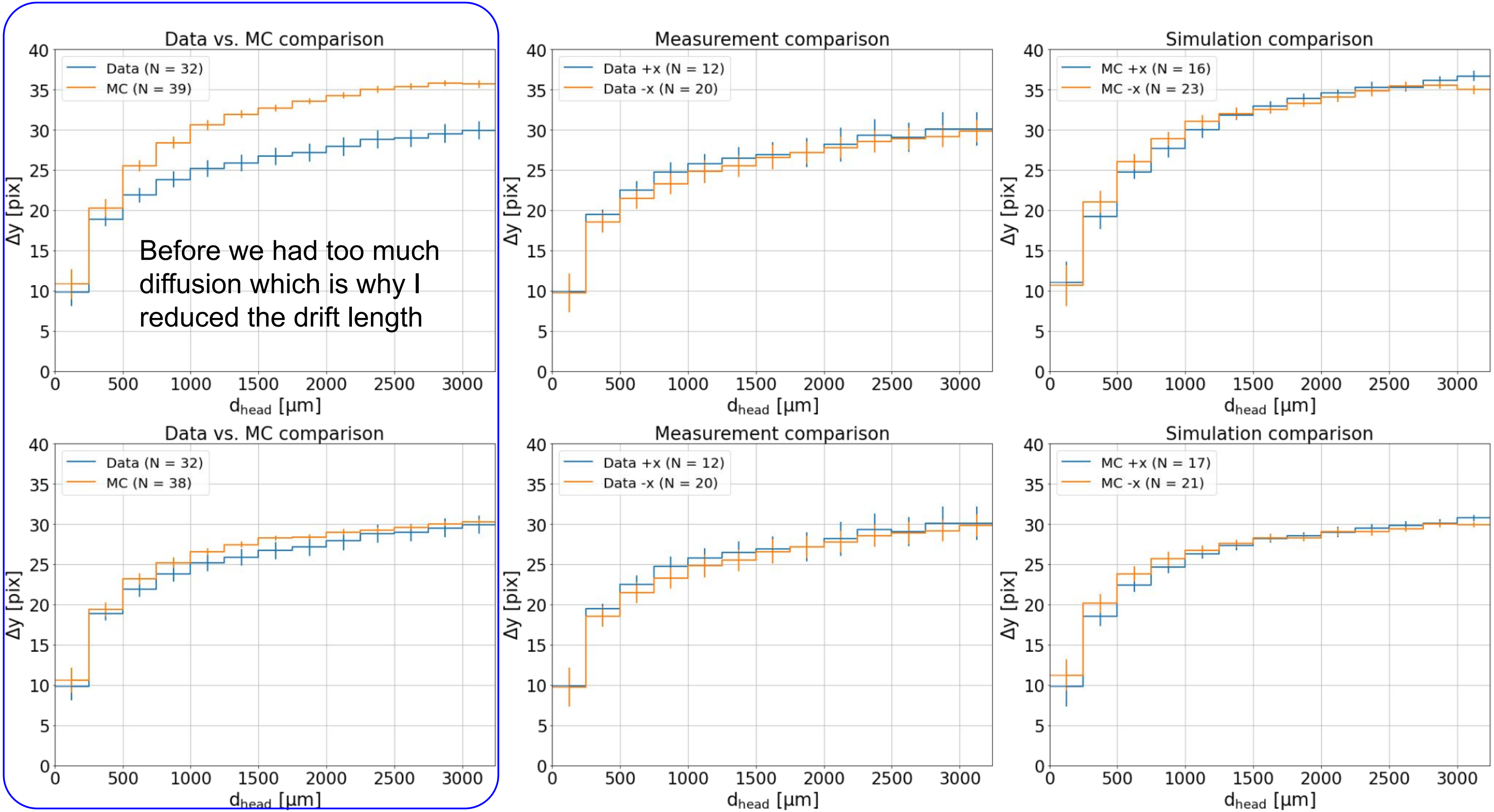
4000um < L < 5400um q vs. dist from head



Old

New

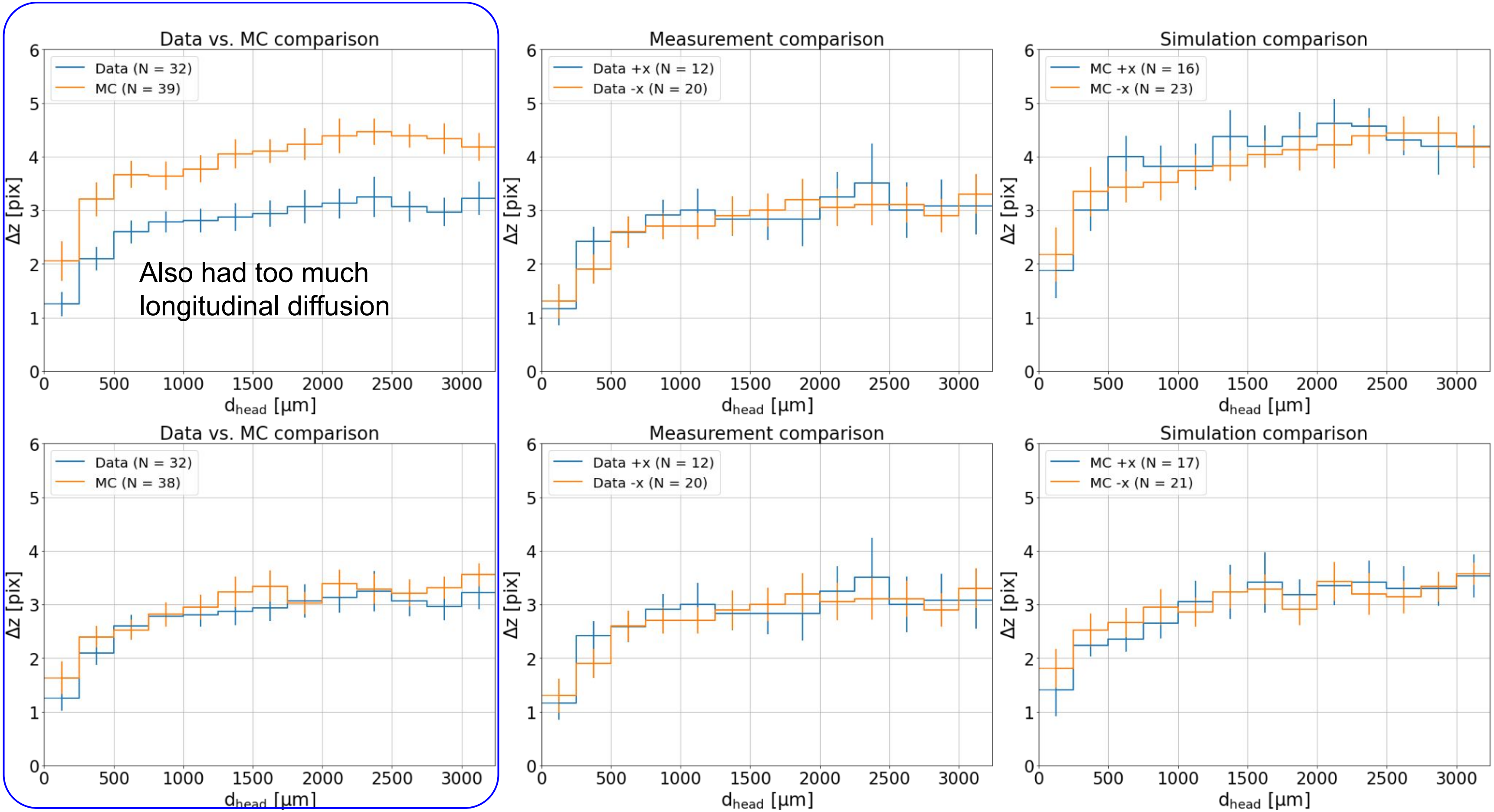
4000um < L < 5400um y-thickness vs. dist from head



Old

New

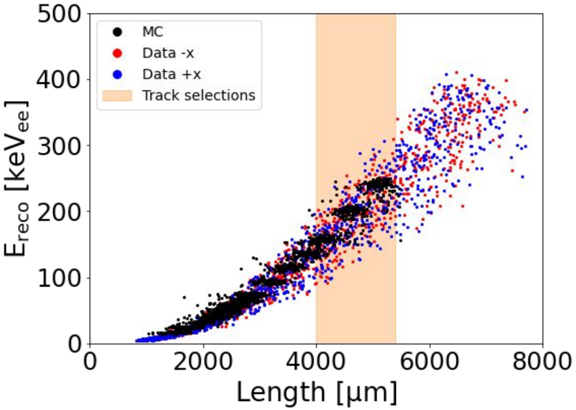
4000um < L < 5400um z-thickness vs. dist from head

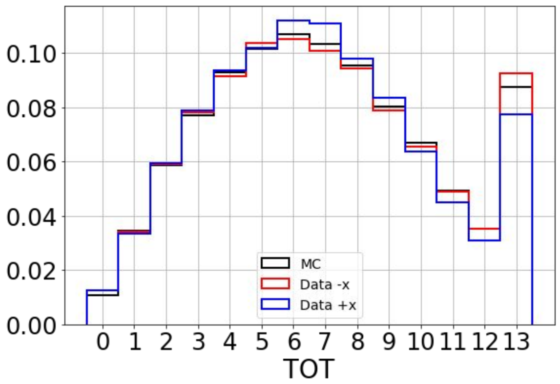


Old

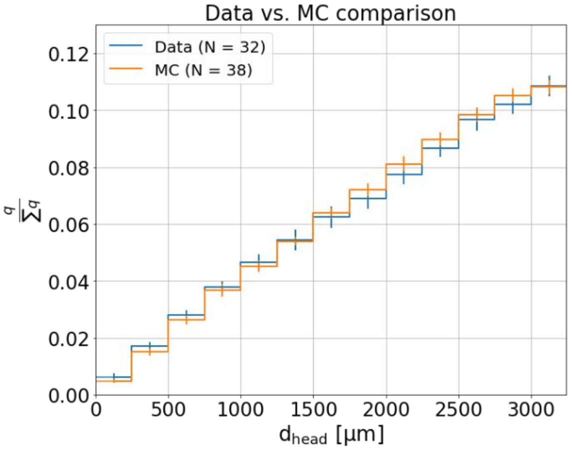
New

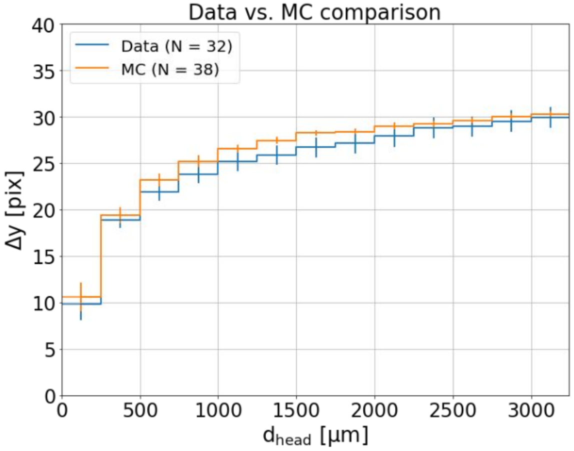
Summary for 4000um < L < 5400um

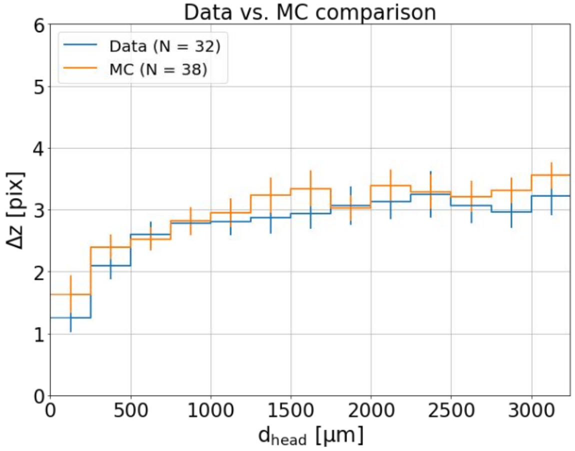




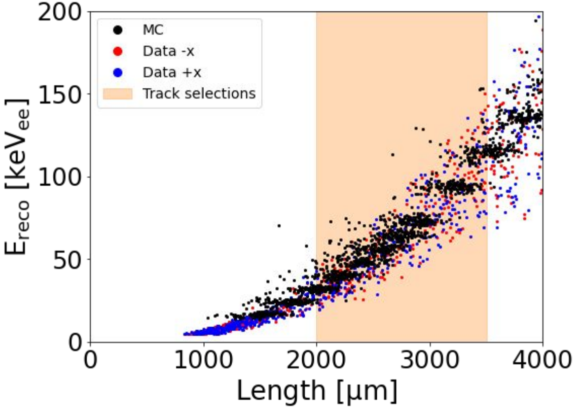
We now get excellent measurement vs. SRIM + retrim-simulated-agreement for He recoils between 4mm and 5.4mm

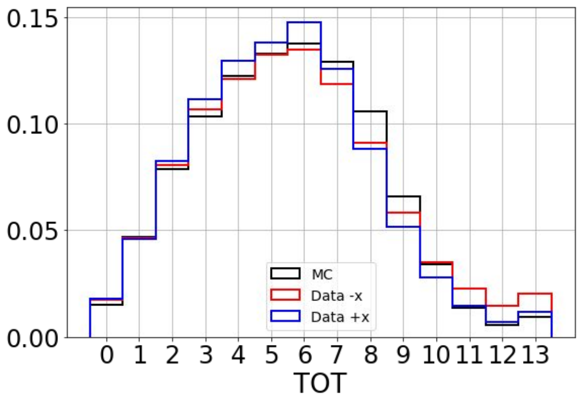






Summary for 2000um < L < 3500um





Excellent measurement vs. simulation agreement holds for He recoils between 2mm and 3.5mm