QPix Technology: Research and Development towards kiloTon scale pixelated LArTPC

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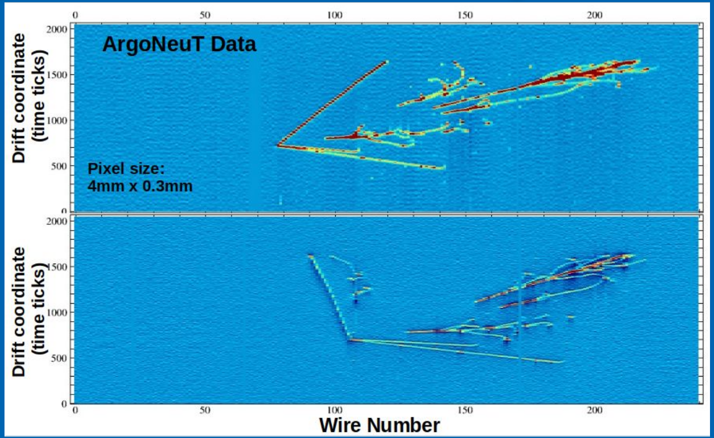
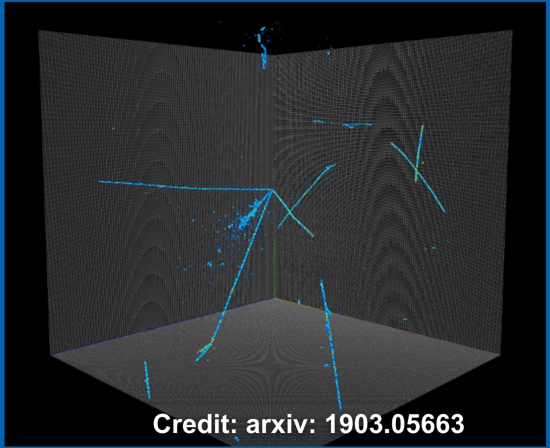
Work based on original paper by Dave Nygren (UTA) and Yuan Mei (LBNL): arXiv:1809.10213

Introduction

- Liquid Argon Time Projection Chambers (LArTPC's) offer access to very high quality and detailed information
- Leveraging this information allows unprecedented access to detailed neutrino interaction specifics from MeV - GeV scales
- Capturing this data w/o compromise and maintaining the intrinsic 3-D quality is an essential component of all LArTPC readouts!



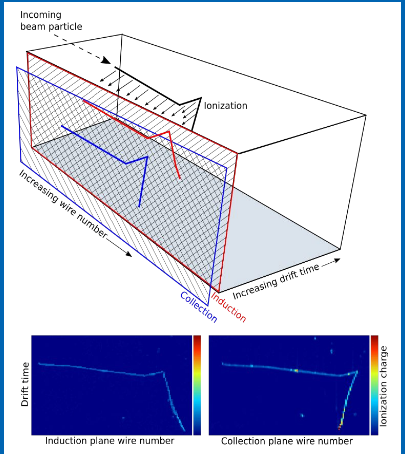
2D-Projective Readout

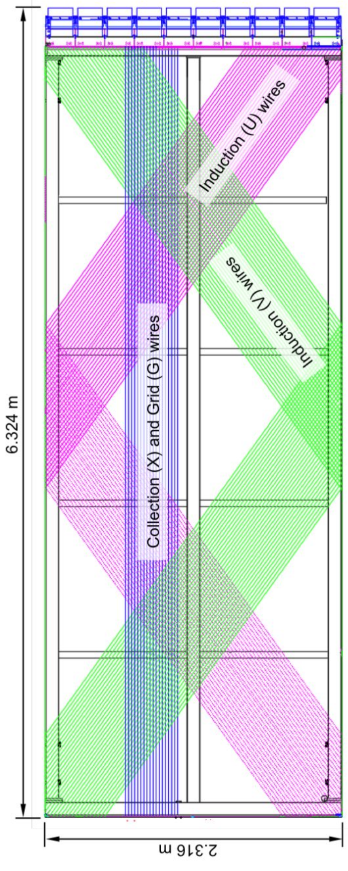


3D-Pixel Readout

Introduction

- **Conventional LArTPC's use sets of wire planes at different orientations to reconstruct the 3D image**
  - Challenge in reconstruction of complex topologies





- **kiloTon scale LArTPC's use "wrapped wire" geometries to reduce the number of readout channels**
  - Challenging to engineer such massive structures
- **Being able to readout using pixels instead of wires could off a solution**
  - "Cost" of many more channels! 2 meter x 2 meter readout
    - **3mm wire pitch w/ three planes = 2450 channels**
    - **3mm pixel pitch = 422,000 channels**
- **Requires an "unorthodox" solution**

Introduction

- **Simulation studies comparing the readout of 2D projective LArTPC's to 3D pixel LArTPC's shows that 3D based readout offers significant improvement in all physics categories!**
  - **ν_e-CC inclusive:** 17% gain in efficiency and 12 % gain in purity
  - **ν_μ-CC inclusive:** 10% gain in efficiency for 99% purity
  - **NCπ^0:** 13% gain in efficiency and 6% gain in purity
  - Also offers gains in Neutrino-ID classification and final state topology ID

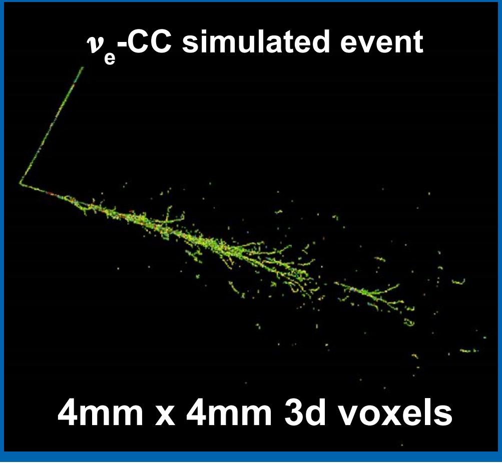


Table 2: Confusion matrix for neutrino interaction.

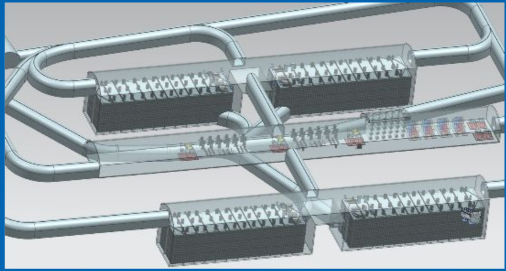
Predicted Label	3D Truth Label ν_e CC	3D Truth Label ν_μ CC	3D Truth Label NC	2D Truth Label ν_e CC	2D Truth Label ν_μ CC	2D Truth Label NC
ν_e CC	**0.96**	0.01	0.02	0.93	0.02	0.03
ν_μ CC	0.02	**0.95**	0.07	0.02	0.91	0.07
NC	0.02	0.04	**0.91**	0.05	0.07	0.90

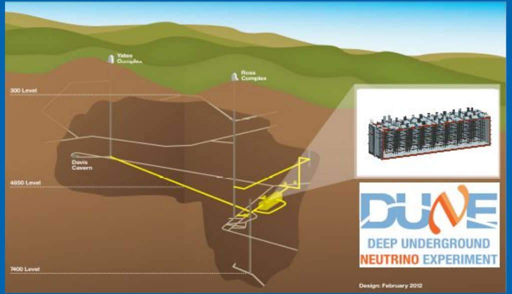
****** Improvements like these can lead to significantly shorter experimental running time required to meet desired physics goals!*

paper in preparation (additional details in backup)

Introduction

- Kiloton scale LArTPC's (such as DUNE) afford a huge "big data" challenge to extract all the details offered by LArTPC
  - 1 second of DUNE full stream data ~4.6 TB (for 1.5 million channels)
    - 1 year of full stream data ~ 145 EB (exabytes)
- However, most of the time there is "nothing of interest" going on in the detector
  - But you must be ready "instantly" when something happens (proton decay, supernova, beam event, etc)
- To readout such massive detectors with pixels requires an enormous number of channels
  - $\mathcal{O}$ (130 million) per 10 kTon at 4mm pitch
  - Requires an "unorthodox" solution

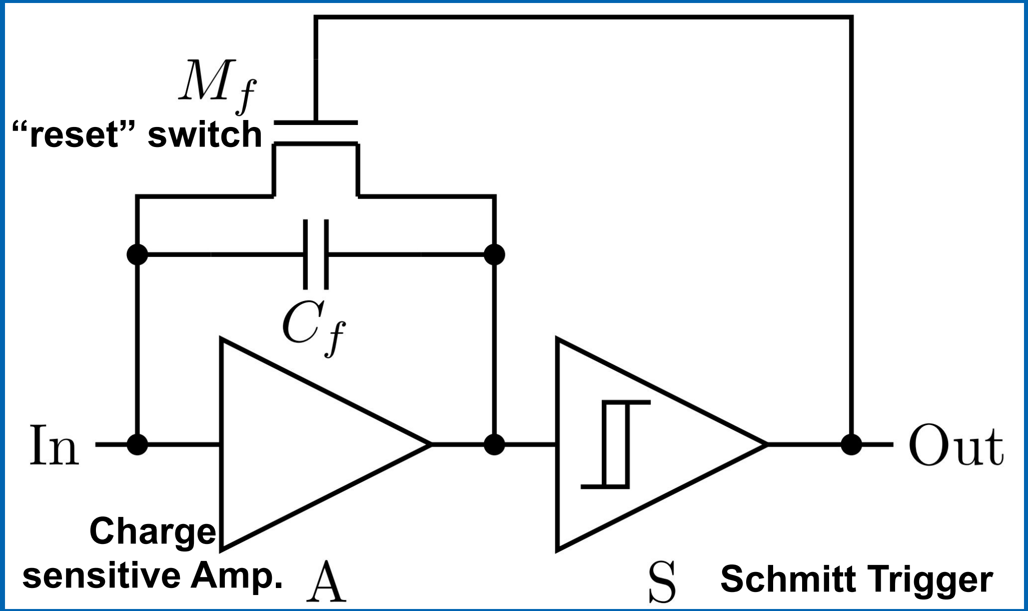




An "unorthodox" solution

- The Q-Pix pixel readout follows the "electronic principle of least action"
  - Don't do anything unless there is something to do
    - Offers a solution to the immense data rates
      - Quiescent data rate $\mathcal{O}$(50 Mb/s)
    - Allows for the pixelization of massive detectors
- Q-Pix offers an innovation in signal capture with a new approach and measures time-to-charge:(ΔQ)
  - Keeps the detailed waveforms of the LArTPC
  - Attempts to exploit ^{39}Ar to provide an automatic charge calibration
- "Novelty does not automatically confer benefit"
  - Much remains to be explored

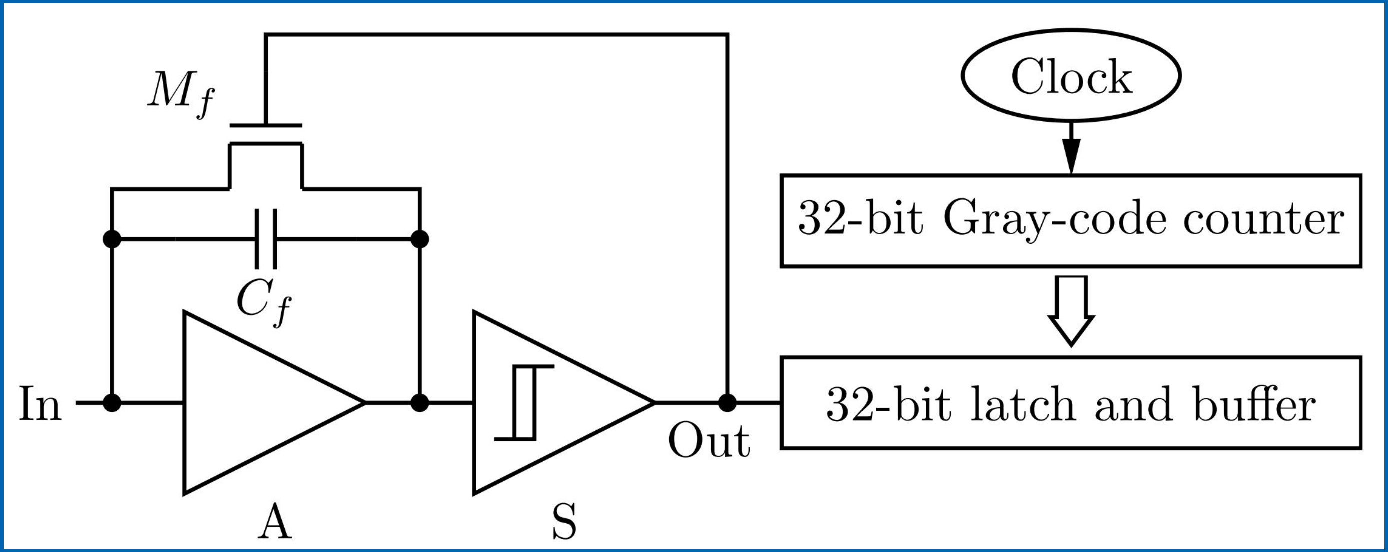
Q-Pix: The Charge Integrate-Reset (CIR) Block



- Charge from a pixel (In) integrates on a charge sensitive amplifier (A) until a threshold (V_{th}~$\Delta Q/C_f$) is met which fires the Schmitt Trigger which causes a reset (M_f) and the loop repeats

Q-Pix: The Charge Integrate-Reset (CIR) Block

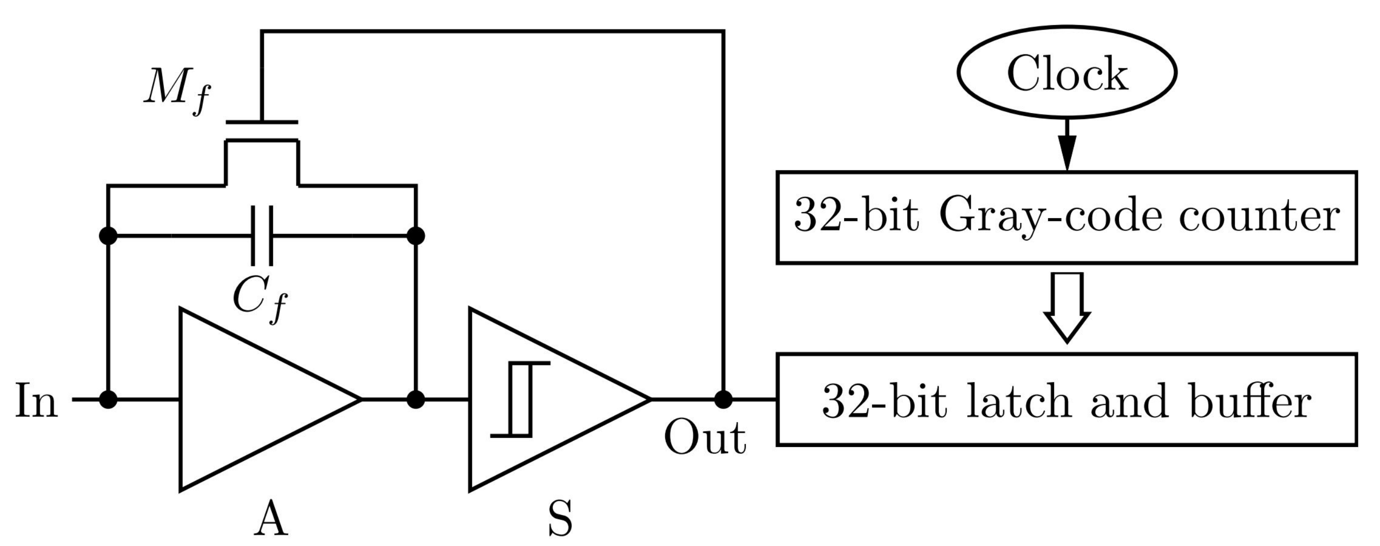
- **Measure the time of the "reset" using a local clock (within the ASIC)**
- **Basic datum is 64 bits**
  - 32 bit time + pixel address + ASIC ID + Configuration + ...

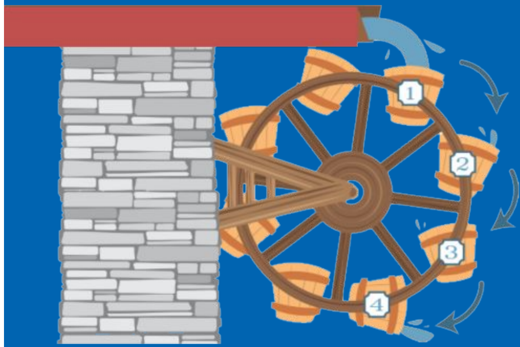


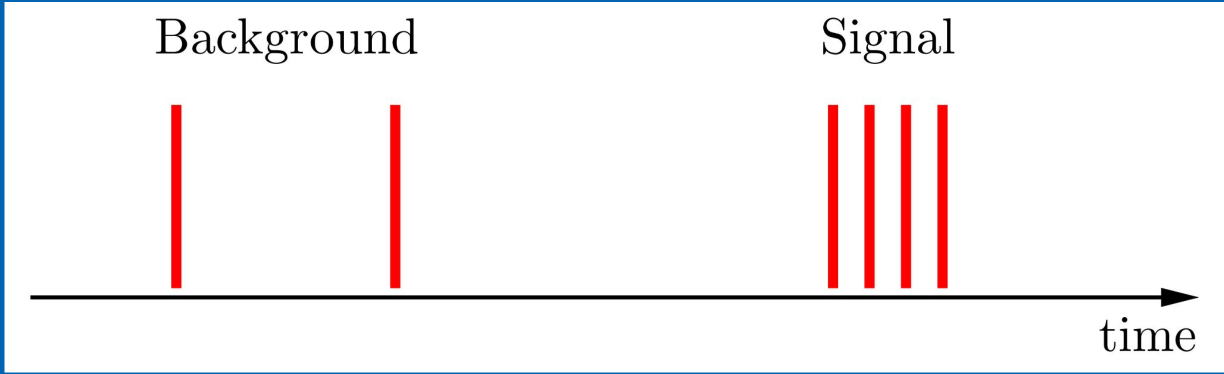
What is new here?

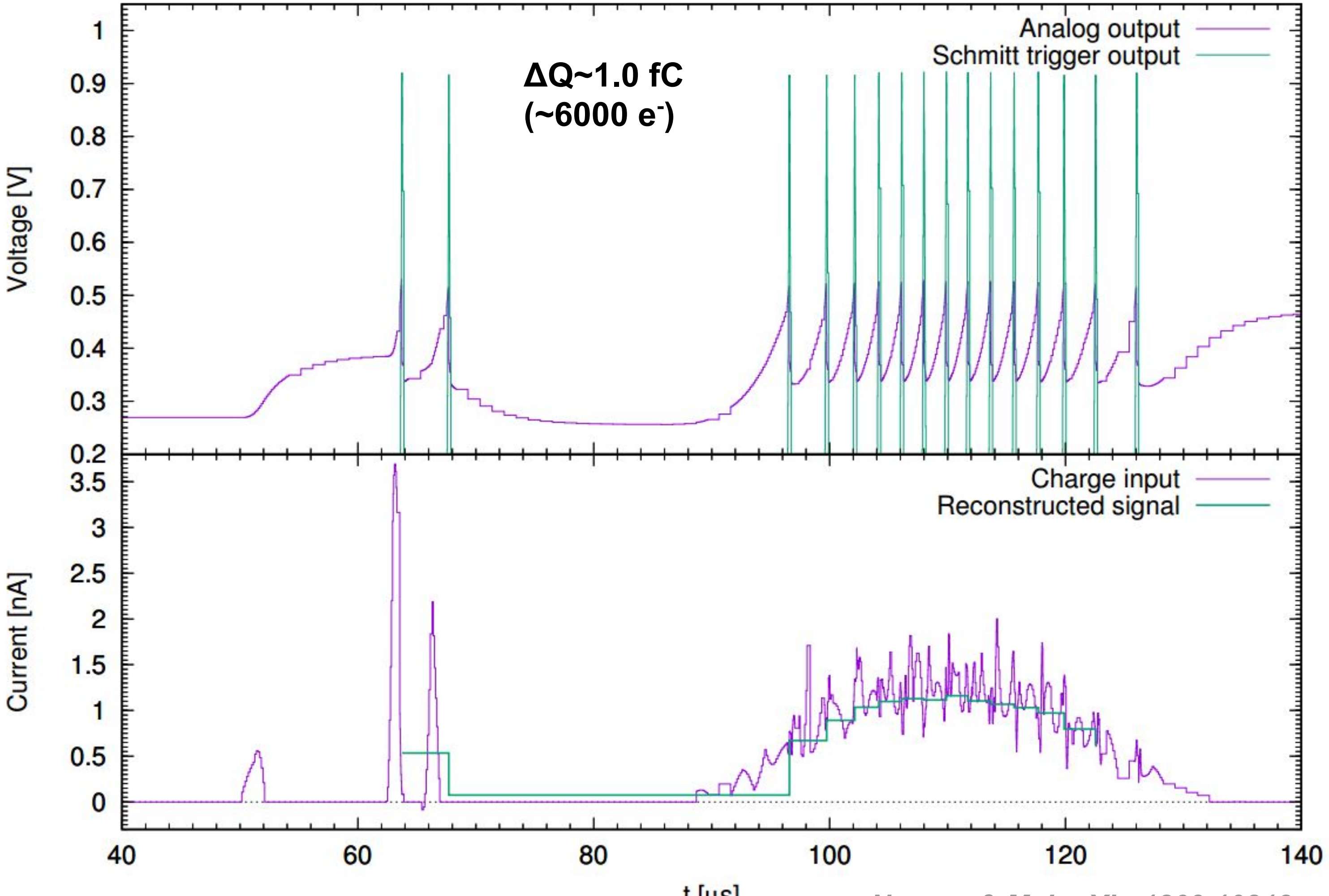
- Take the difference between sequential resets
  - Reset Time Difference = RTD
- Total charge for any RTD = ΔQ
- RTD's measure the instantaneous current and captures the waveform
  - Small average current (background) = Large RTD
    - Background from ^{39}Ar ~ 100 aA
  - Large average current (signal) = Small RTD
    - Typical minimum ionizing track ~ 1.5 nA
- Signal / Background ~ 10^7
  - Background and Signal should be easy to distinguish
  - No signal differentiation (unlike induction wires)

Reset Time Difference

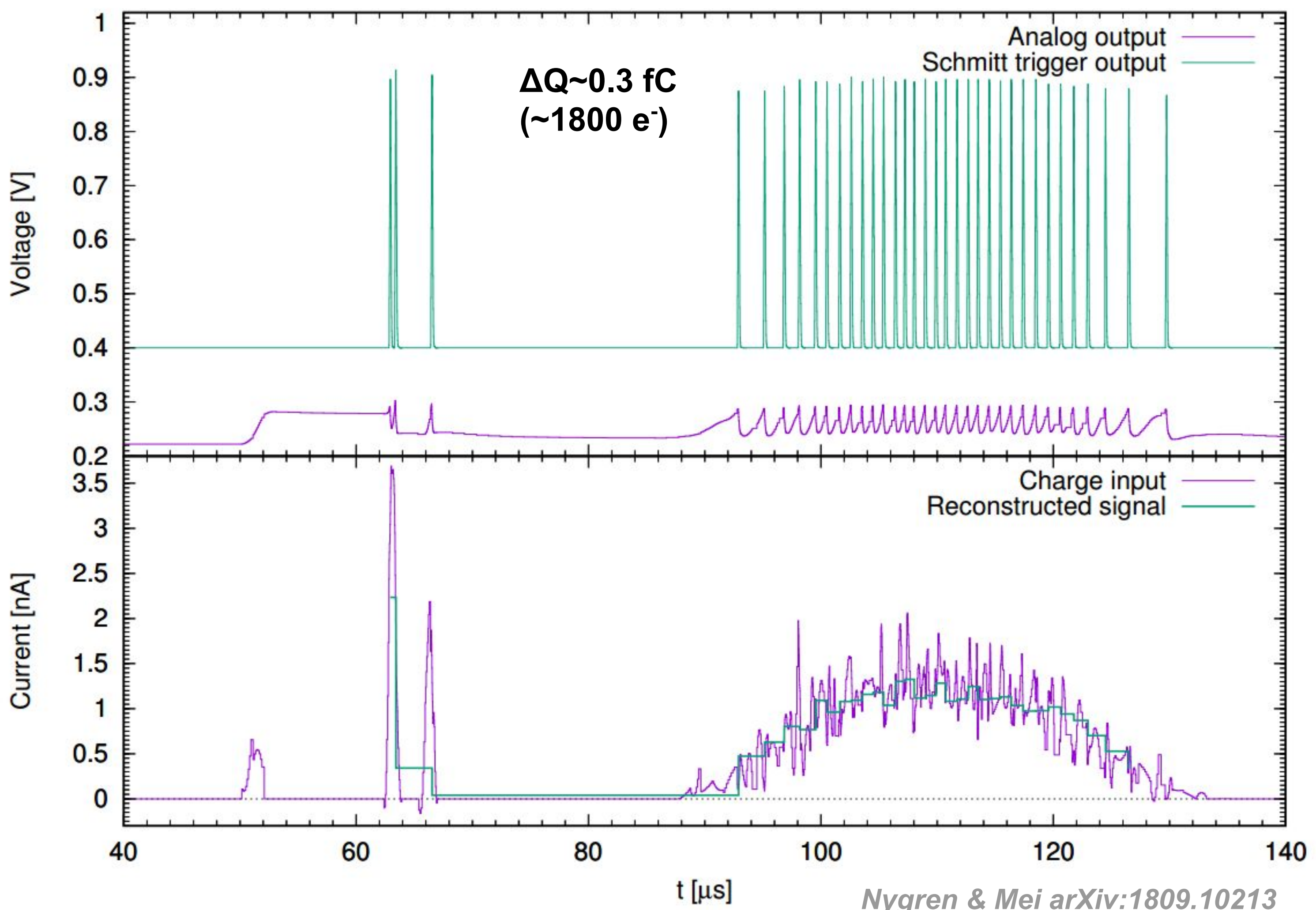








Nygren & Mei arXiv:1809.10213



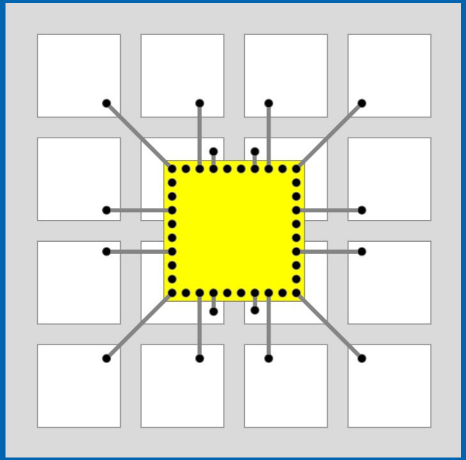
Nygren & Mei arXiv:1809.10213

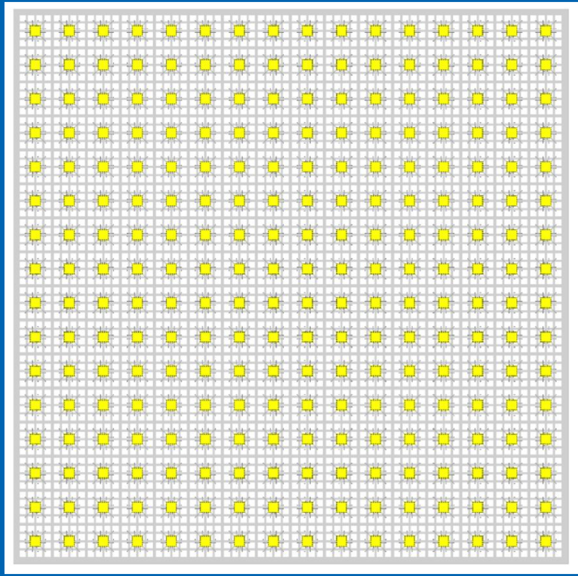
How the time stamping works

- **One free running clock per ASIC (50-100 MHz)**
  - **Required precision for DUNE $\delta f/f \sim 10^{-6}$ per second**
    - Expect this to be easily achieved in liquid argon
- **Time stamping routine has the ASIC asked once per second "what time is it?"**
  - **ASIC captures local time and sends it**
  - **Simple linear transformation to master clock synced to GMT**
  - **RTD's calculated "off chip"**
- **Has this idea been realized before?**
  - **YES! In ICECUBE (by Nygren)**
    - Oscillator precision achieved > 10^{-10} /s (hard to measure)

Q-Pix ASIC Concept

- **16-32 pixels / ASIC**
  - 1 Free-running clock/ASIC
  - 1 capture register for clock value, ASIC, pixel subset
  - Necessary buffer depth for beam/burst events
  - State machine to manage dynamic network, token passing, clock domain crossing, data transfer to network (many details to be worked out)
- **Basic unit would be a "tile" of 16x16 ASICs (4092 4mm x 4mm pixels)**
  - Tile size 25.6 cm x 25.6 cm



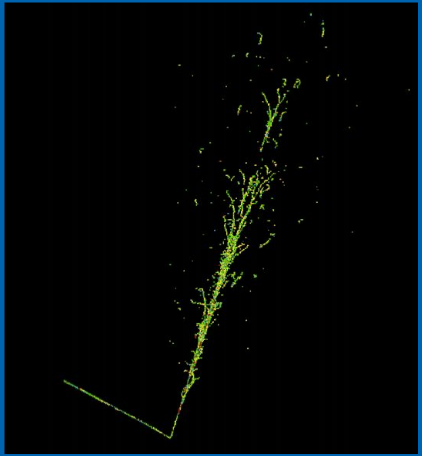


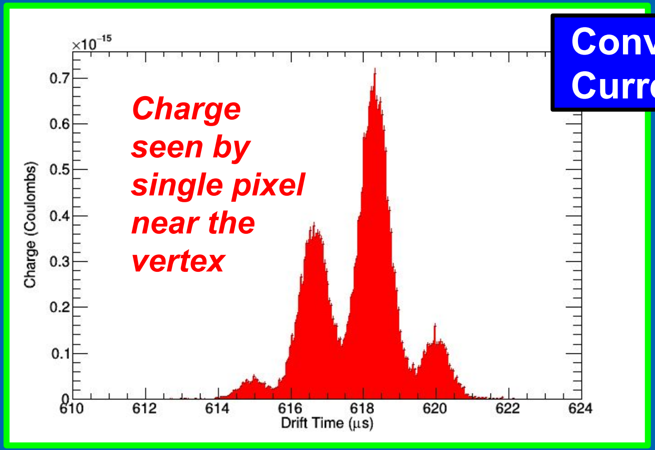
Q-Pix Consortium

- **A consortium of universities and labs has formed to realize the Q-Pix concept**
  - Done in close collaboration with LArPix (JINST 13 P10007) readout for the DUNE near detector
- **Four central ideas being worked on**
  - **Physics Simulations: Quantify the conferred benefit of pixel vs. wire readout and the requirements of the ASIC design**
  - **CIR Input: all extraneous leakage current at the input node needs to be small (aA)**
  - **Clock: $\delta f/f \sim 10^{-6}$ per second**
  - **Light Detection: Exploring new ideas using photoconductors on the surface of the pixels** ***(see the next talk from E. Gramellini)***

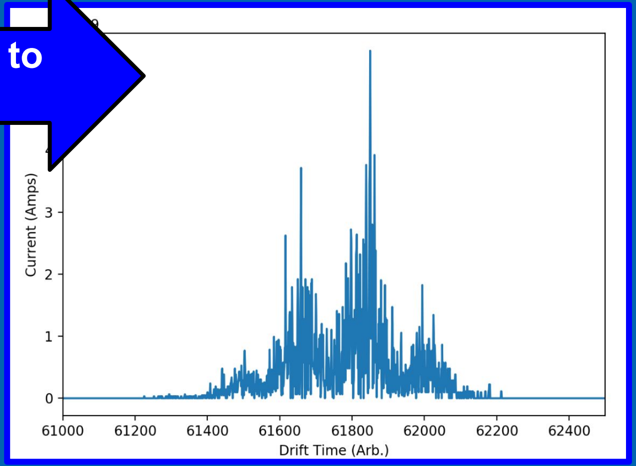
Physics Simulation

- To quantify the range of currents the Q-Pix ASIC will see we are using simulations of neutrino interactions in argon





Convert to Current



- We can take the charge seen by a pixel and translate this into current as a function of time
- We can then use this simulation to set the physics requirements on the Q-Pix ASIC
    - Allowed reset time, minimum ΔQ, etc…

Physics Simulation

Calculation from: https://arxiv.org/pdf/1508.07059.pdf

- **Measurement of Longitudinal Diffusion**
  - Using a small sample muons a novel technique in Q-Pix can be seen

The electron current measured on a plane perpendicular to the drift direction at a distance d from a point source is given by

$$j(t) = \frac{n_0}{\sqrt{4\pi D_L t}} \exp\left(-\frac{(d-vt)^2}{4D_L t} - \lambda vt\right) \quad (2)$$

where n_0 is the initial electron density, v is the drift speed, t is the arrival time of the electrons on the plane, and λ is equal to the inverse of the mean free path of the electron.

This function approaches a true Gaussian when $d \cdot v$ is large and D_L is small. For the case being considered $v = 0.1648cm/\mu s$ and $d > 10cm$ so, $d \cdot v \geq 1.6 \times 10^5 cm^2/s$. This is large when compared to $D_L = 6.82cm^2/s$.

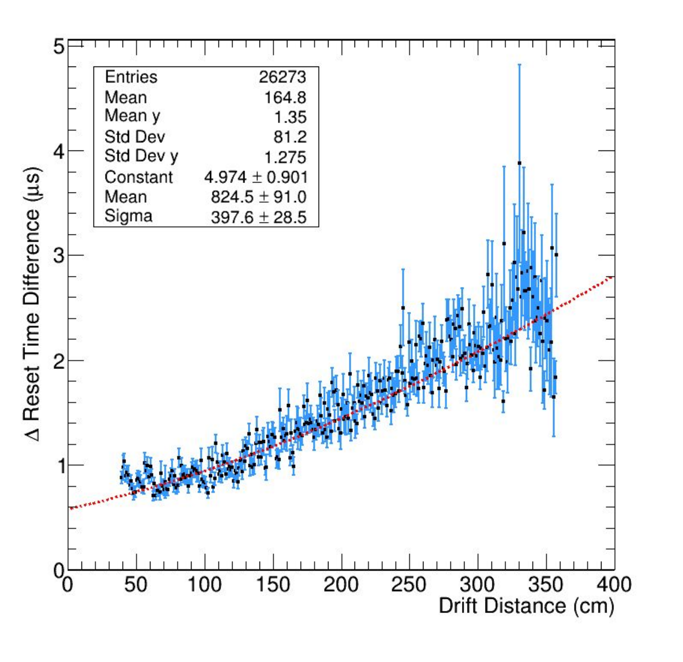
The Reset Time Difference (RTD) literally stands for

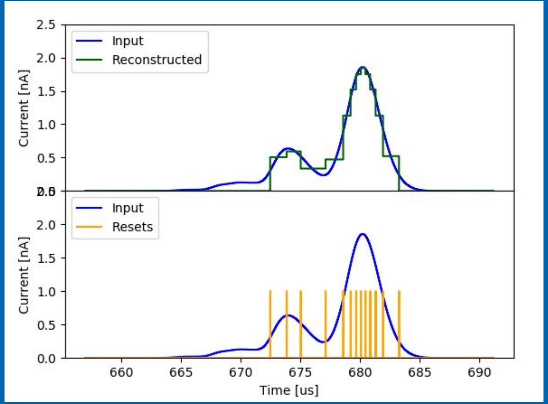
$$RTD = \frac{\Delta Q}{\Delta t} = j(t) \quad (6)$$

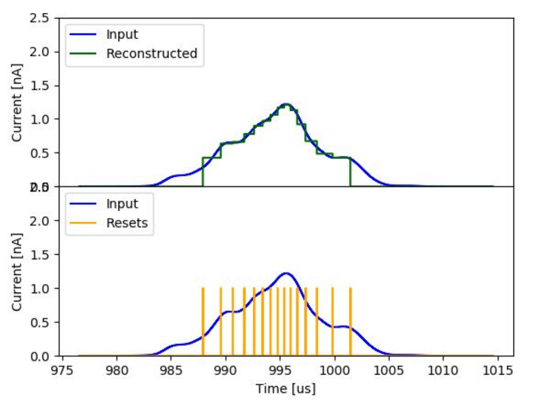
Thus if we plot the average RTD seen over a sample as a function of the drift distance, we should see the Gaussian relationship

Physics Simulation

- **Measurement of Longitudinal Diffusion**
  - The average RTD versus the drift length carries the diffusion information
- **Allows for a fundamental measurement with few statistics**
- **$D_L^{Measured} = 6.47 \pm 0.97\ cm^2/s$**
  - $D_L^{Simulation} = 6.82\ cm^2/s$







Conclusions

- Readout requirements for kiloton scale LArTPC's offer many challenges to fully exploit the rich data they have to offer
    - We must optimize for discovery!!!
- Low threshold pixel based readout can optimize for discovery the impact of these detectors
    - Requires an unorthodox solution
- The Q-Pix concept may afford a way to pixelize a kiloton scale LArTPC and retain all the details of data
    - The devil lives in the details, but an effort is underway with promising preliminary results
    - Stay tuned for more updates!

Q-Pix consortium would like the thank the DOE for its support via DE-SC0020065 award

Backup Slides

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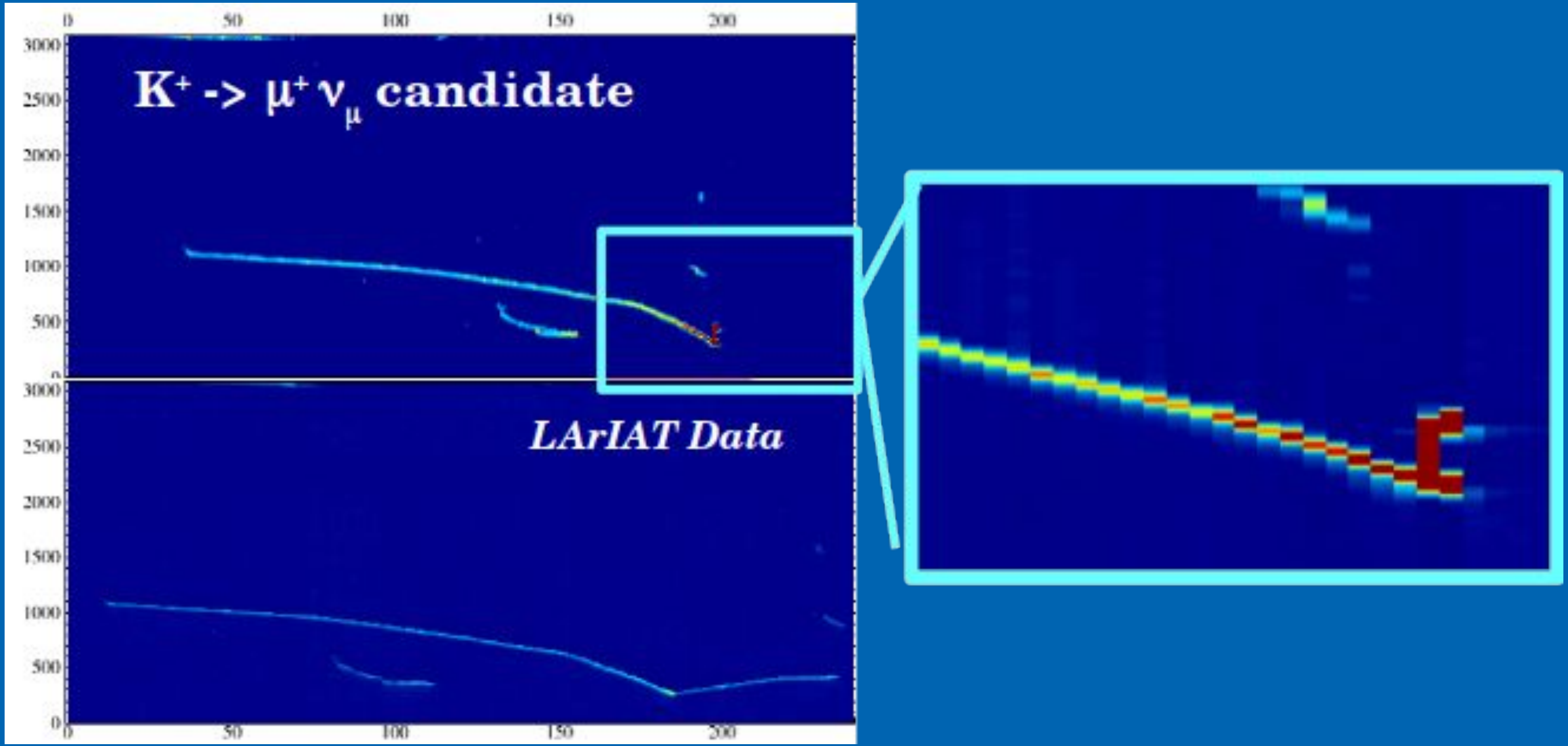
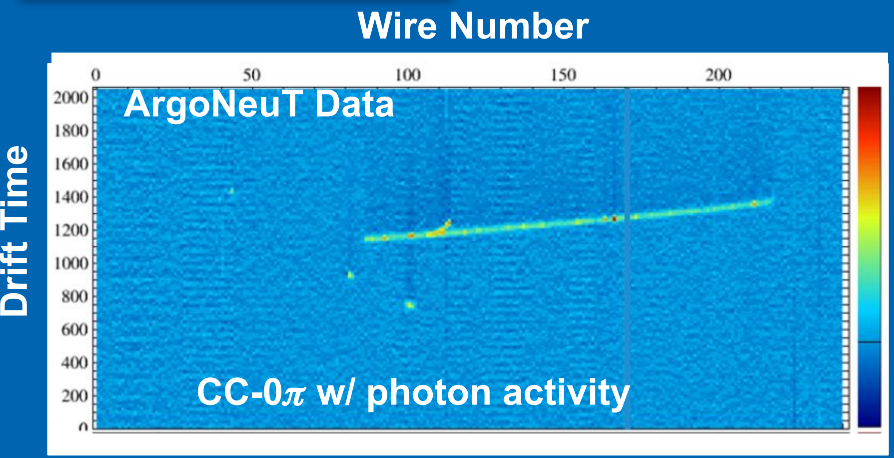
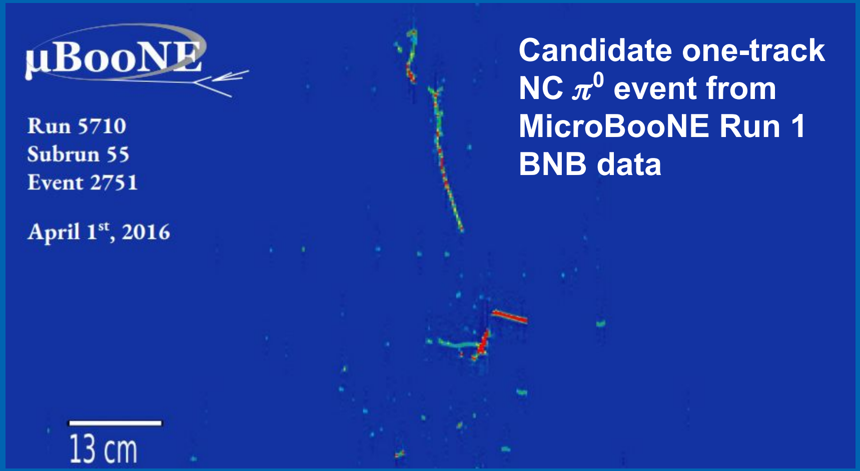
Introduction

Intrinsic reconstruction pathologies associated with charge deposited along the direction of the wires



Introduction

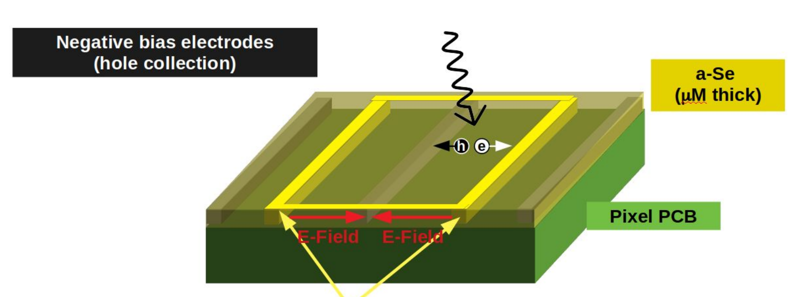




- **Liquid Argon Time Projection Chambers (LArTPC's) offer access to very high quality and detailed information**
- **Leveraging this information allows unprecedented access to detailed neutrino interaction specifics from MeV - GeV scales**
- **Capturing this data w/o compromise and maintaining the intrinsic 3-D quality is an essential component of all LArTPC readouts!**

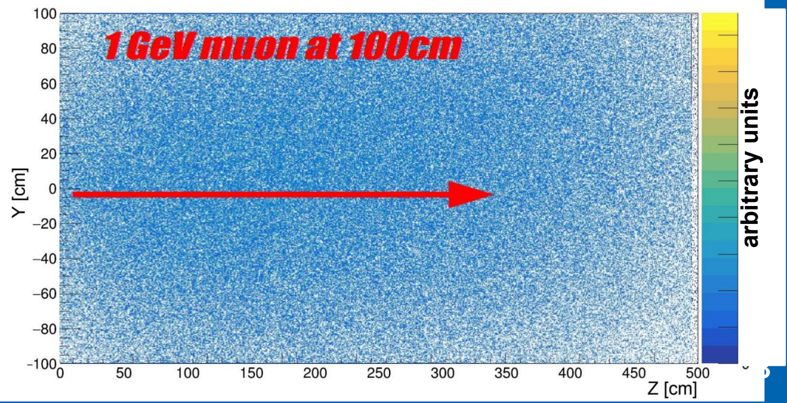
Light Detection

- **One very "blue sky" idea currently being considered is to see if the same pixels which collect ionization charge can be used to detect UV photons**
  - Currently exploring different thin-film photo-conductors which may offer an opportunity
  - Exploring amorphous Selenium's properties
    - Commonly used in X-Ray digital radiography devices



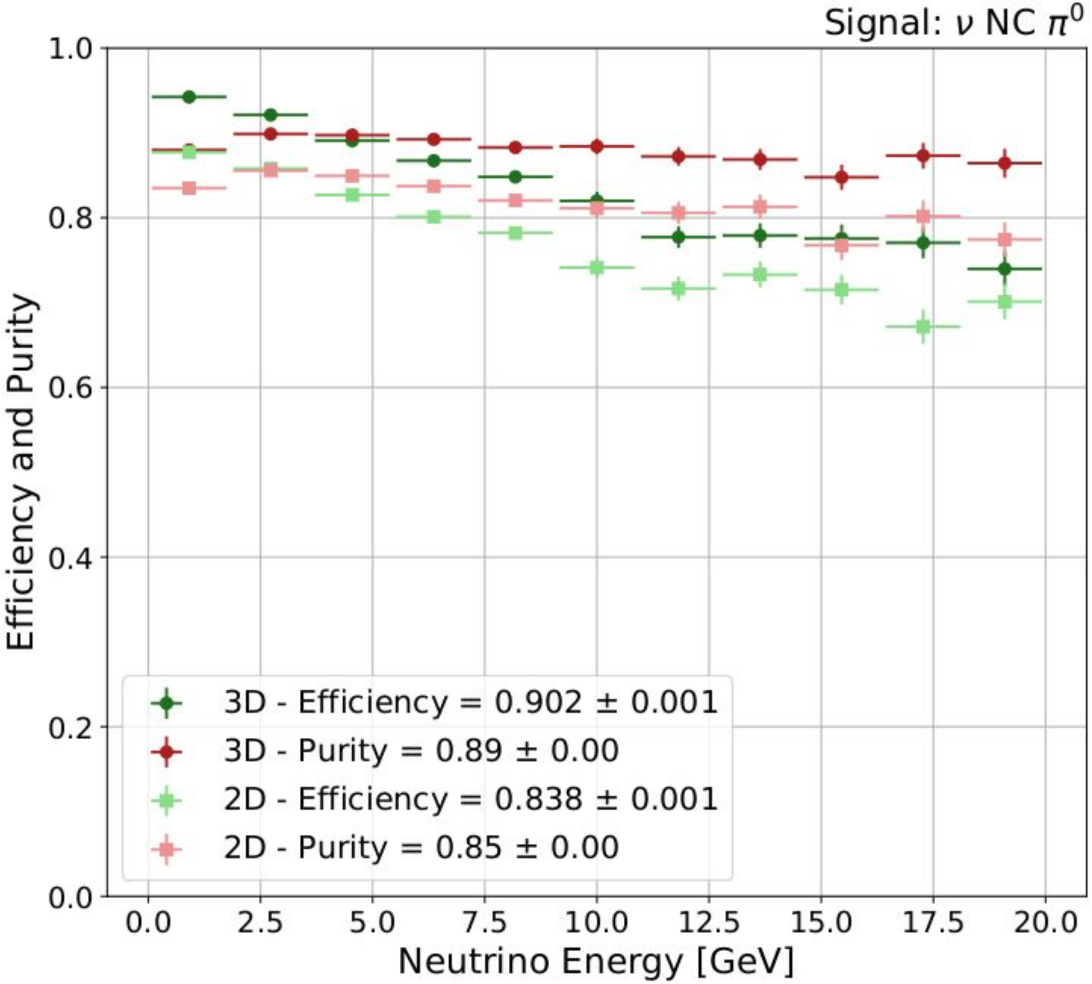
Conceptual sketch of device

Incident photons from a 1 GeV muon at 100 cm

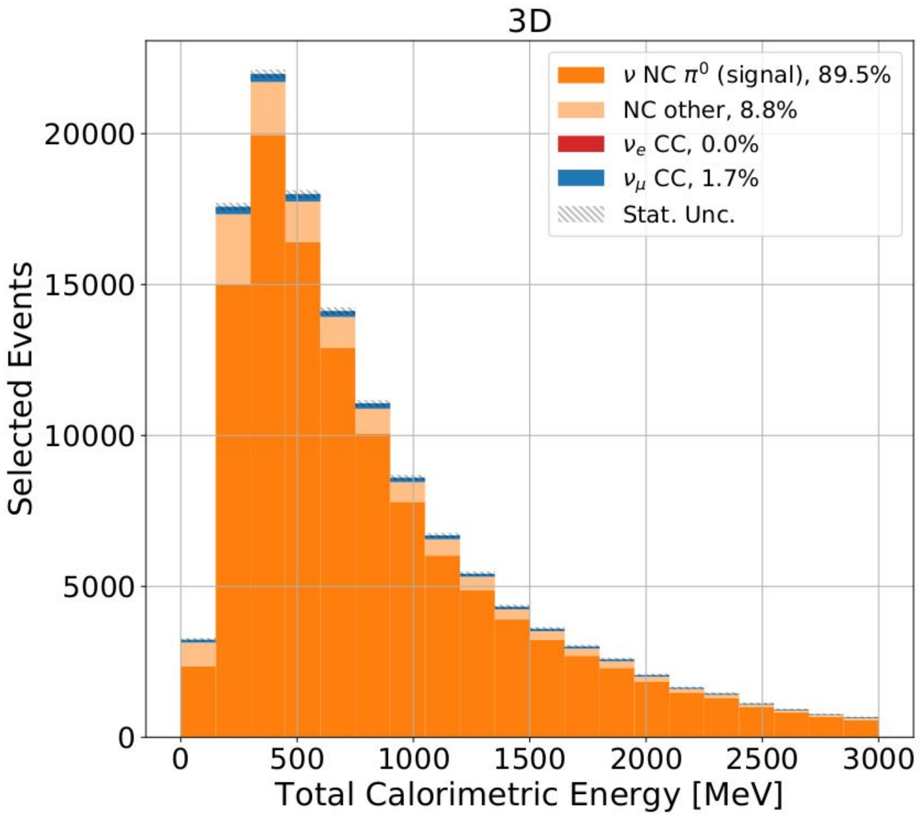


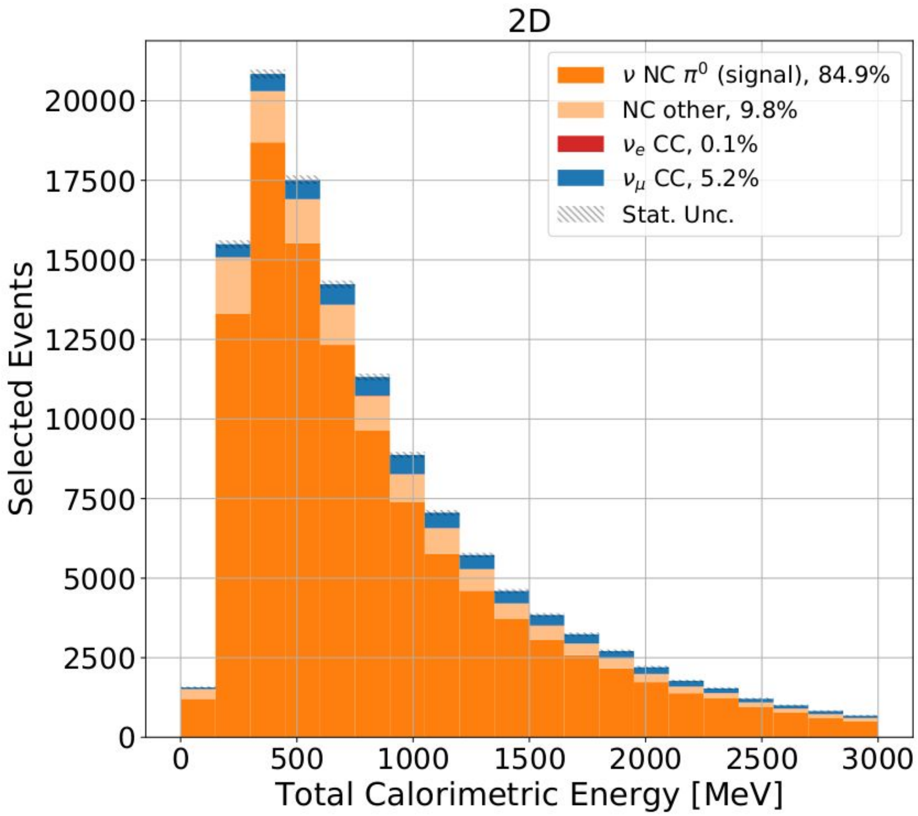
2 - 10 photons per pixel

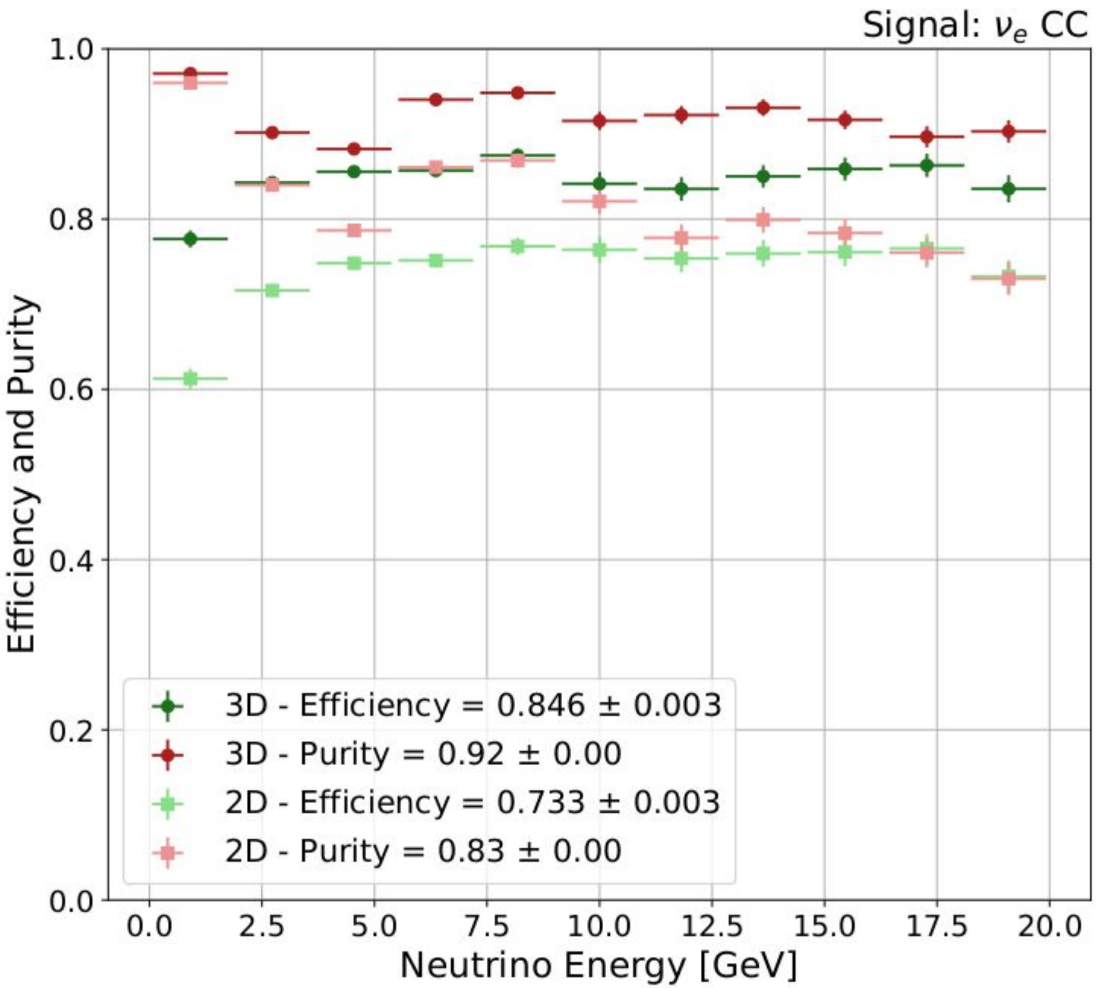
- **If realized, offers a transformative opportunity in LArTPC's**

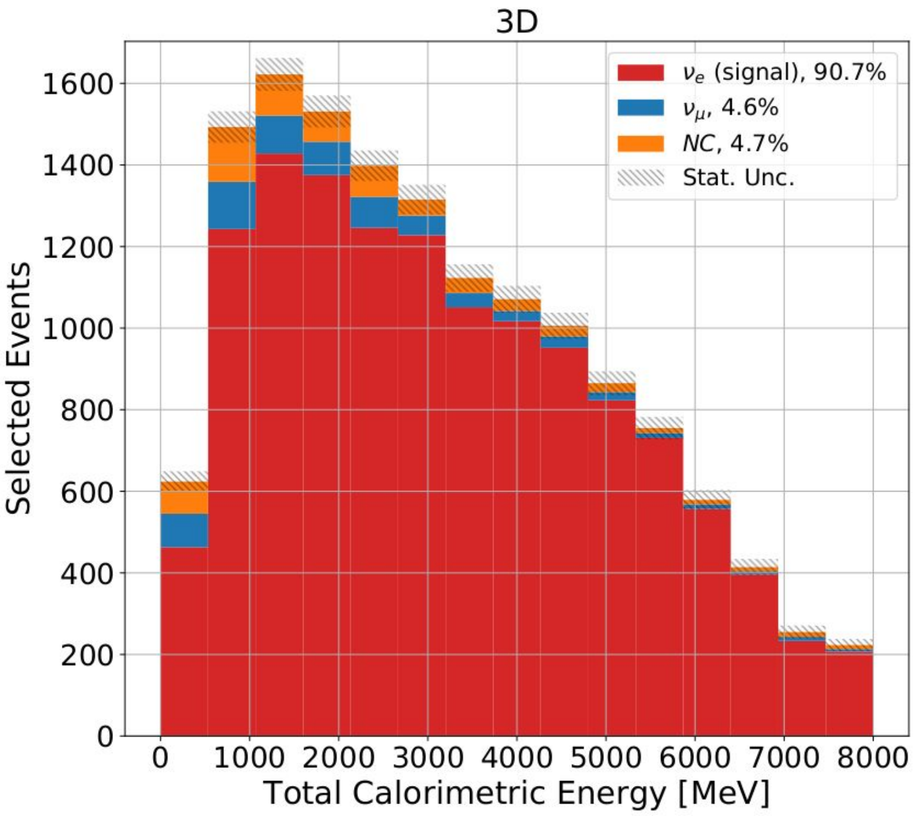


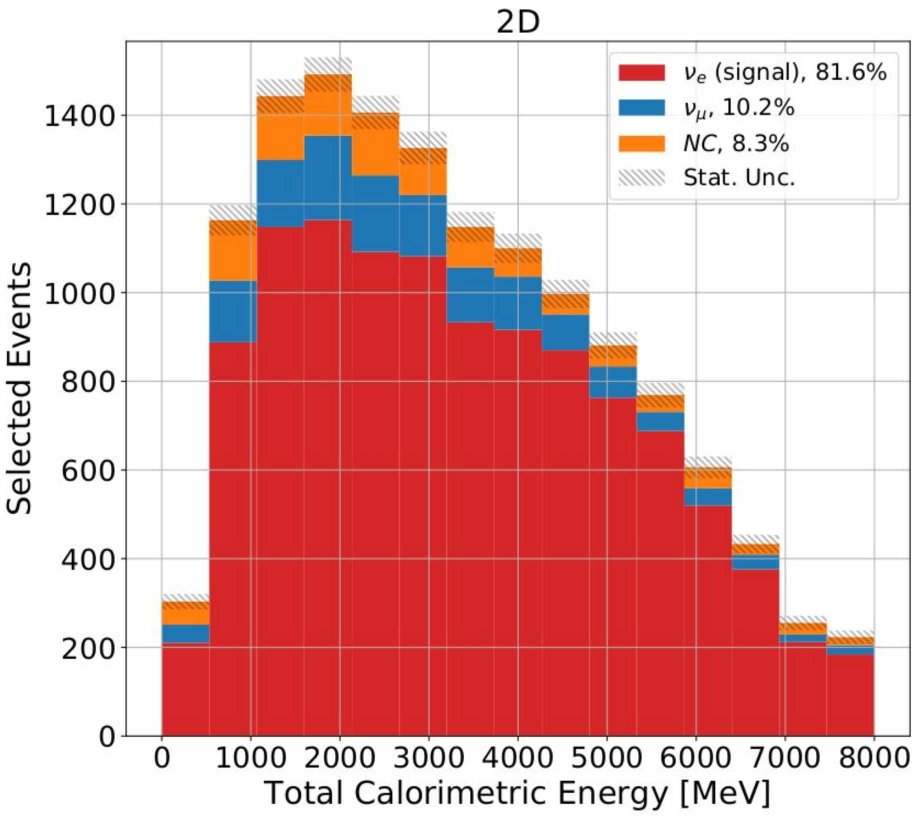
Signal: ν NC π^0
Efficiency and Purity
Neutrino Energy [GeV]
3D - Efficiency = 0.902 ± 0.001
3D - Purity = 0.89 ± 0.00
2D - Efficiency = 0.838 ± 0.001
2D - Purity = 0.85 ± 0.00
1.0
0.8
0.6
0.4
0.2
0.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

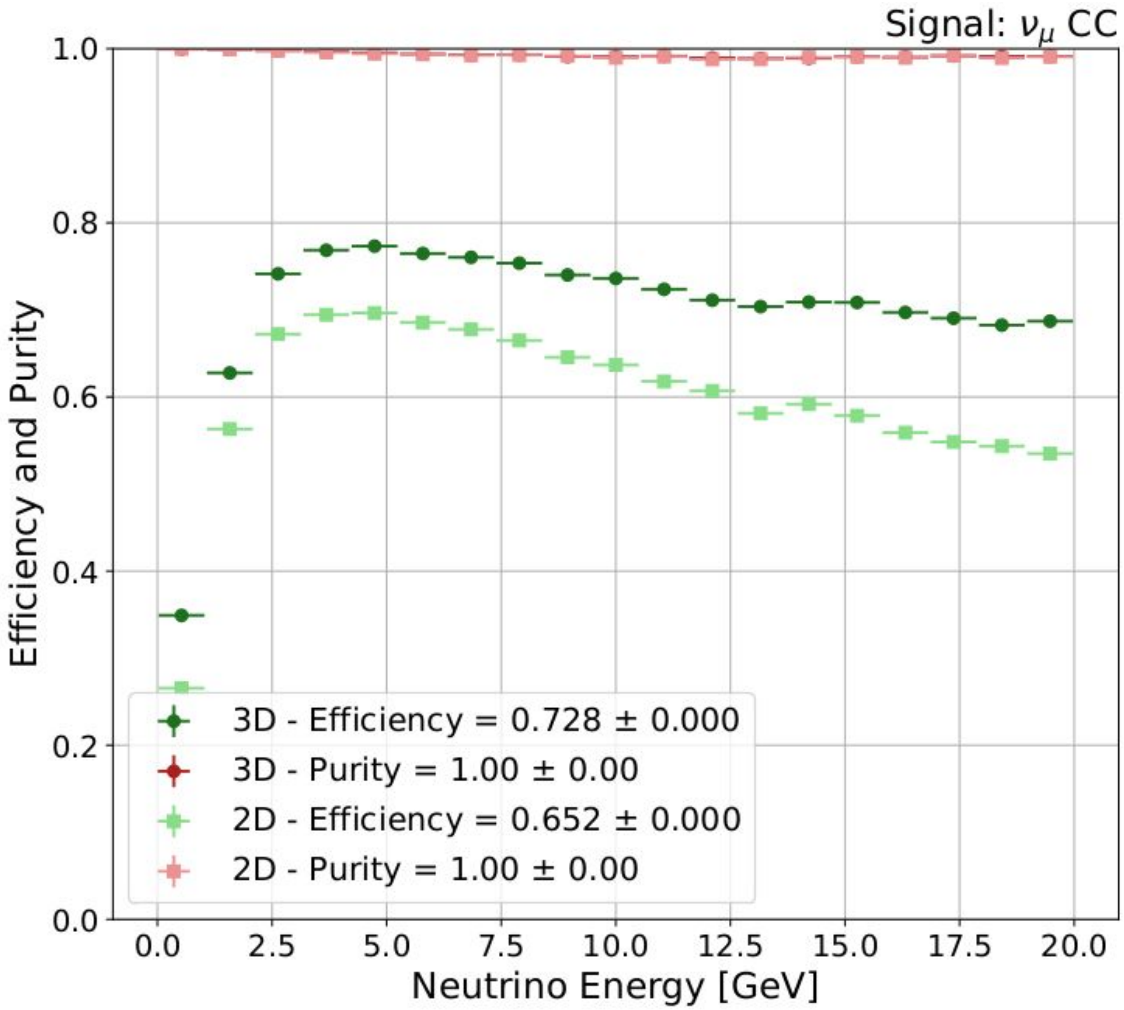

3D
ν NC π^0 (signal), 89.5%
NC other, 8.8%
ν_e CC, 0.0%
ν_μ CC, 1.7%
Stat. Unc.
Selected Events
0
5000
10000
15000
20000
0
500
1000
1500
2000
2500
3000
Total Calorimetric Energy [MeV]

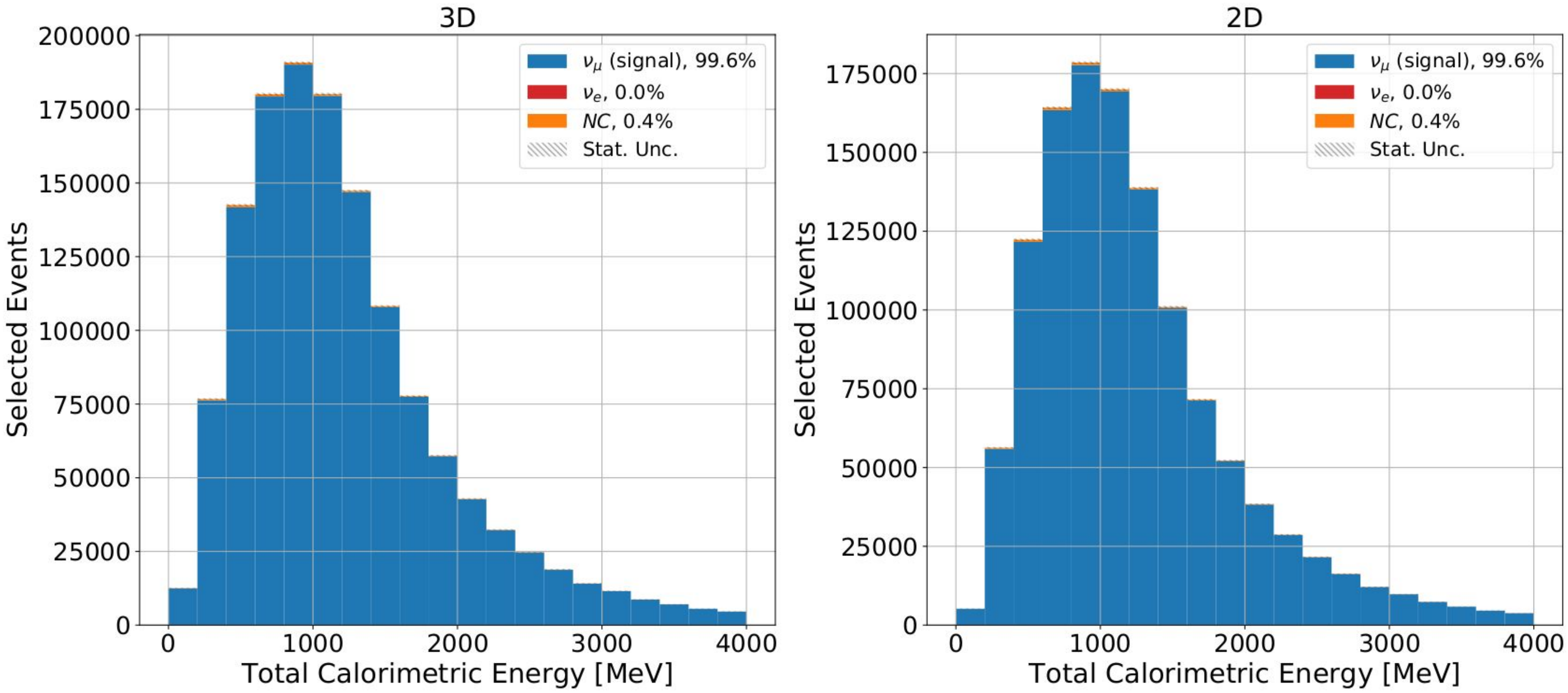

2D
ν NC π^0 (signal), 84.9%
NC other, 9.8%
ν_e CC, 0.1%
ν_μ CC, 5.2%
Stat. Unc.
Selected Events
0
2500
5000
7500
10000
12500
15000
17500
20000
0
500
1000
1500
2000
2500
3000
Total Calorimetric Energy [MeV]


Signal: ν_e CC
Efficiency and Purity
1.0
0.8
0.6
0.4
0.2
0.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Neutrino Energy [GeV]
3D - Efficiency = 0.846 ± 0.003
3D - Purity = 0.92 ± 0.00
2D - Efficiency = 0.733 ± 0.003
2D - Purity = 0.83 ± 0.00


3D
ν_e (signal), 90.7%
ν_μ, 4.6%
NC, 4.7%
Stat. Unc.
Selected Events
Total Calorimetric Energy [MeV]
0
200
400
600
800
1000
1200
1400
1600
0
1000
2000
3000
4000
5000
6000
7000
8000


2D
ν_e (signal), 81.6%
ν_μ, 10.2%
NC, 8.3%
Stat. Unc.
Selected Events
Total Calorimetric Energy [MeV]
0
200
400
600
800
1000
1200
1400
0
1000
2000
3000
4000
5000
6000
7000
8000


Signal: ν_μ CC
1.0
0.8
0.6
0.4
0.2
0.0
Efficiency and Purity
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Neutrino Energy [GeV]
3D - Efficiency = 0.728 ± 0.000
3D - Purity = 1.00 ± 0.00
2D - Efficiency = 0.652 ± 0.000
2D - Purity = 1.00 ± 0.00


3D
2D
200000
175000
150000
125000
100000
75000
50000
25000
0
Selected Events
ν_μ (signal), 99.6%
ν_e, 0.0%
NC, 0.4%
Stat. Unc.
0
1000
2000
3000
4000
Total Calorimetric Energy [MeV]