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!

Credit: arxiv: 1903.05663

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!**
  - $\nu_e$-CC inclusive: 17% gain in efficiency and 12% gain in purity
  - $\nu_\mu$-CC inclusive: 10% gain in efficiency for 99% purity
  - NC$\pi^0$: 13% gain in efficiency and 6% gain in purity
  - Also offers gains in Neutrino-ID classification and final state topology ID

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**Table 2: Confusion matrix for neutrino interaction.**

<table>
<thead>
<tr>
<th>Predicted Label</th>
<th>3D Truth Label</th>
<th>2D Truth Label</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_e$ CC</td>
<td>$\nu_\mu$ CC</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>0.96</td>
<td>0.01</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>0.02</td>
<td>0.95</td>
</tr>
<tr>
<td>NC</td>
<td>0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

***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
  ○ \(\mathcal{O}(130\ \text{million})\) 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 $\mathcal{O}(50 \text{ Mb/s})$
    - Allows for the pixelization of massive detectors
- Q-Pix offers an innovation in signal capture with a new approach and measures time-to-charge: $(\Delta Q)$
  - Keeps the detailed waveforms of the LArTPC
  - Attempts to exploit $^{39}\text{Ar}$ 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 ($V_{th} \sim \Delta Q/C_f$) 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 + ...

![Diagram](image)
What is new here?

- Take the **difference** between **sequential** resets
  - Reset Time Difference = RTD

- **Total charge for any** RTD = $\Delta Q$

- **RTD's measure the instantaneous current** and captures the waveform
  - Small average current (background) = Large RTD
    - Background from $^{39}$Ar $\sim$ 100 aA
  - Large average current (signal) = Small RTD
    - Typical minimum ionizing track $\sim$ 1.5 nA

- **Signal / Background $\sim 10^7$**
  - Background and Signal should be easy to distinguish
  - No signal differentiation (unlike induction wires)
$\Delta Q \approx 1.0 \text{ fC}$

(\sim 6000 \text{ e}^{-})
$\Delta Q \sim 0.3 \text{ fC}$

($\sim 1800 \text{ e}^-$)
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.

- 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

- **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

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

(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 $\lambda$ 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

\[
RTD = \frac{\Delta Q}{\Delta t} = j(t)
\]

(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**
  - $D_L^{\text{Measured}} = 6.47 \pm 0.97 \text{ cm}^2/\text{s}$
  - $D_L^{\text{Simulation}} = 6.82 \text{ cm}^2/\text{s}$
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 to thank the DOE for its support via DE-SC0020065 award
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Intrinsic reconstruction pathologies associated with charge deposited along the direction of the wires
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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
- If realized, offers a transformative opportunity in LArTPC’s