LArTPC physics and reconstruction

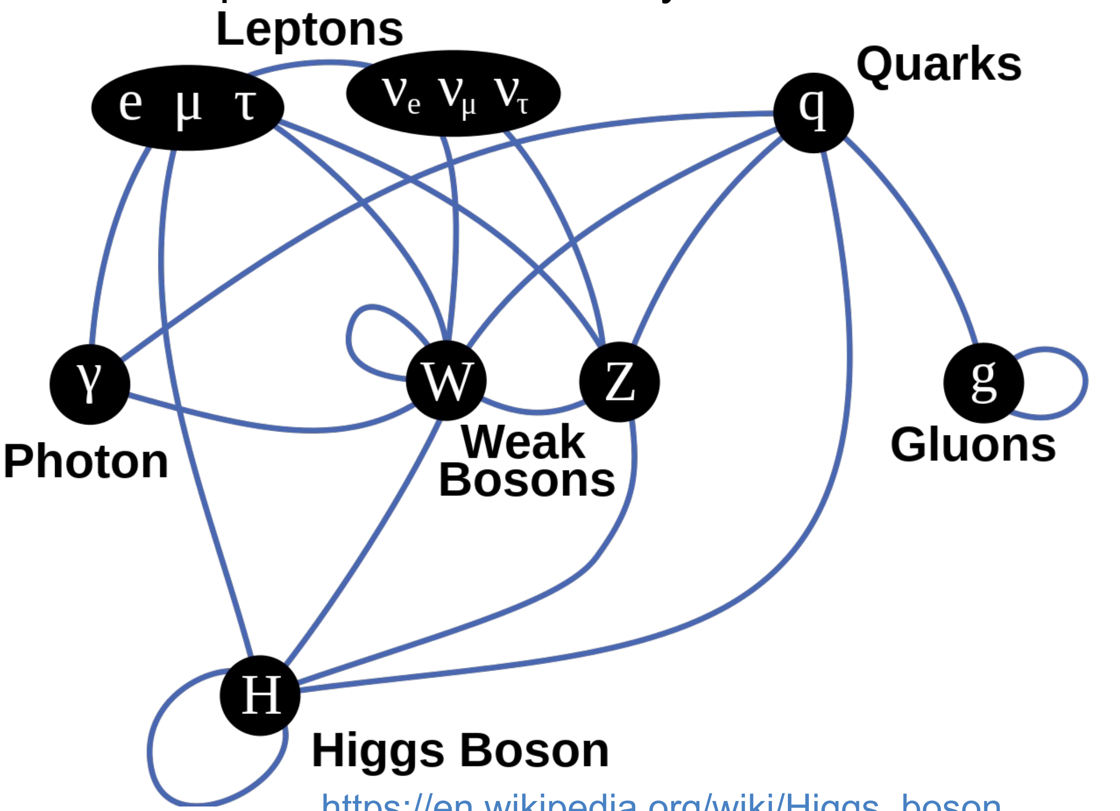
Haiwang Yu
Electronic Detector Group, Physics Department

10/17/23

Excellence in Detector and Instrumentation Technologies/EDIT School 2023

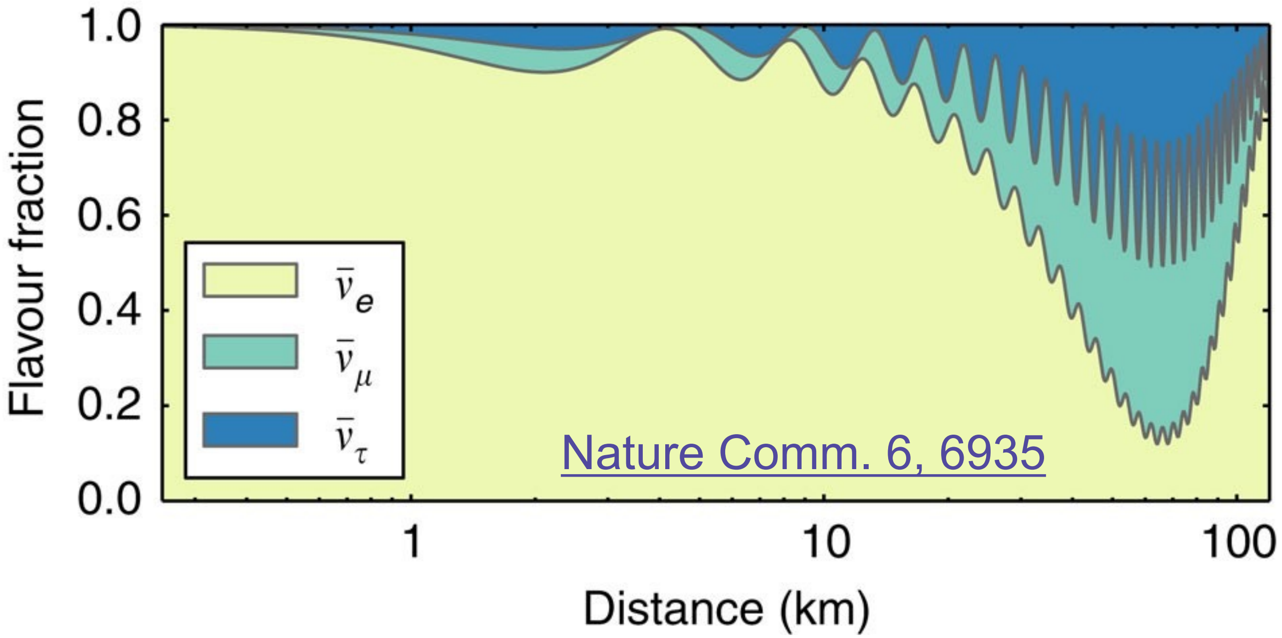
Neutrino Oscillation

Summary of interactions between
certain particles described by the Standard Model



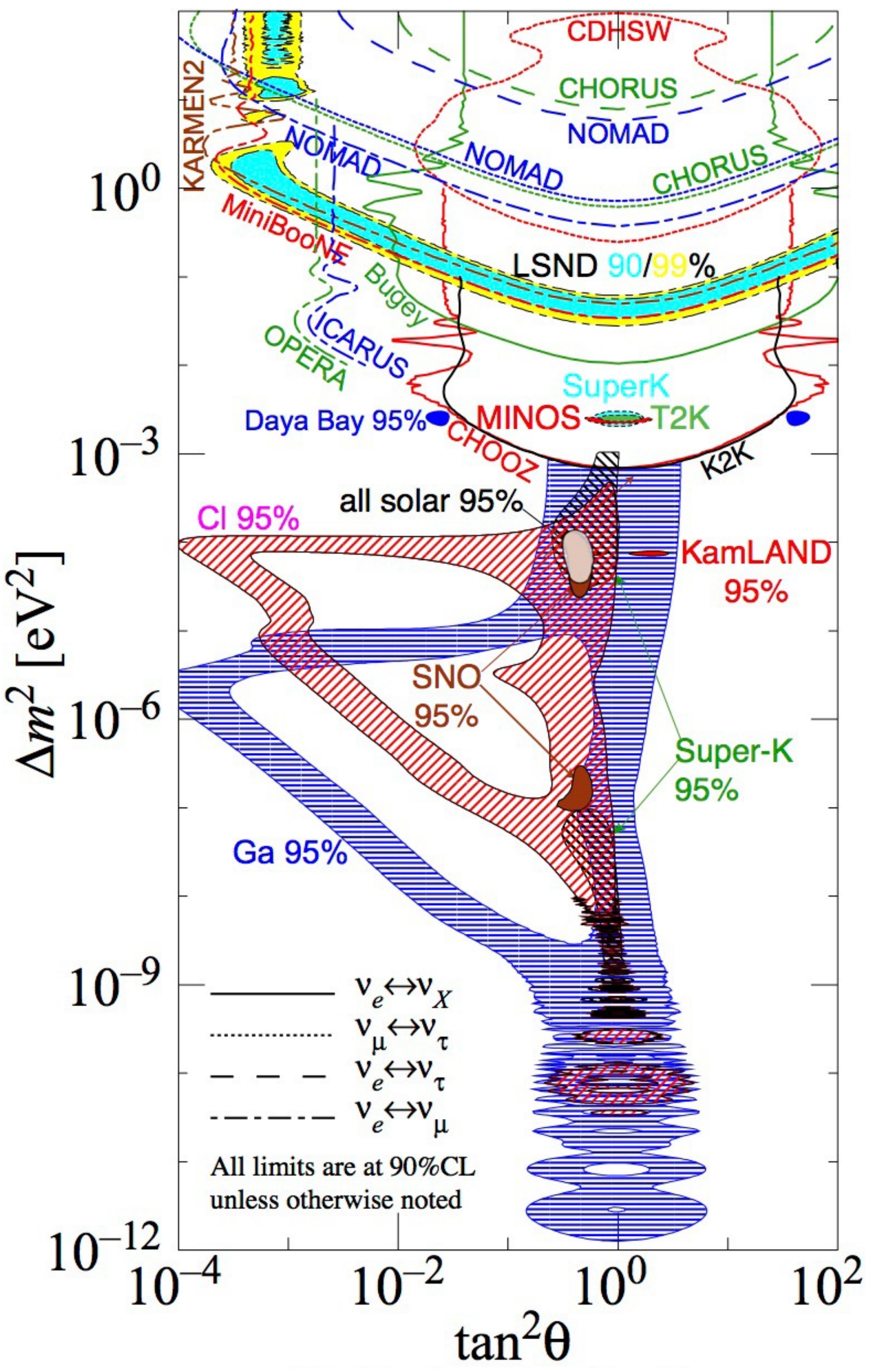
https://en.wikipedia.org/wiki/Higgs_boson

Illustration of neutrino oscillations



Nature Comm. 6, 6935

Neutrino oscillation experiments have provided the first evidence for physics beyond the Standard Model of particle physics



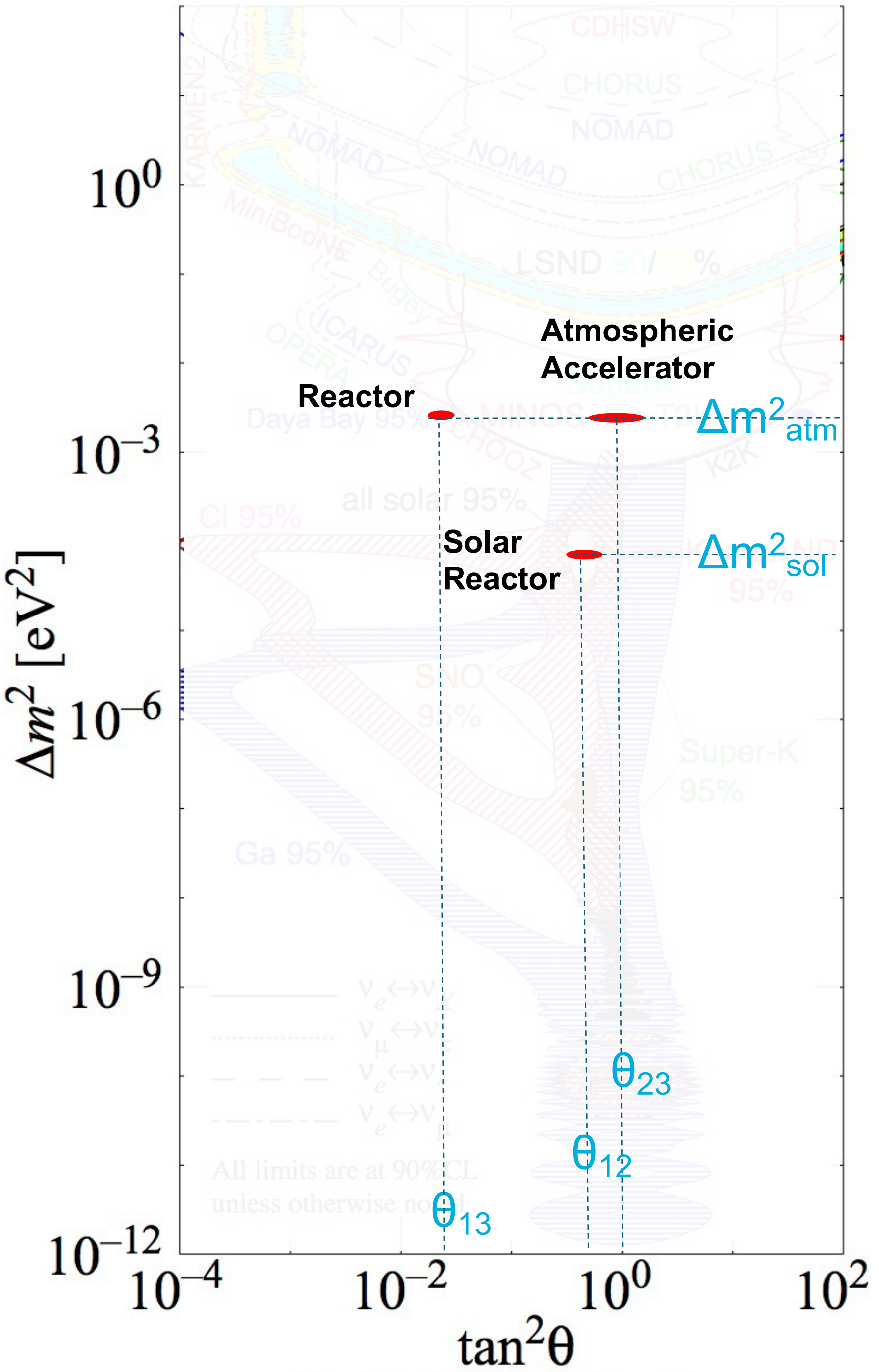
Neutrino Oscillation Experiments

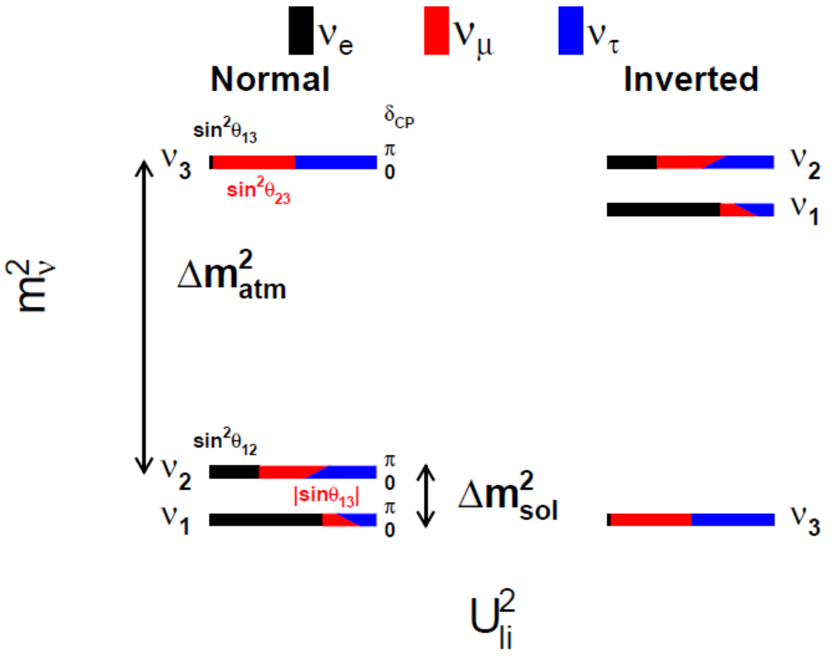
- > 50 years
- > 30 experiments
- > Phase space over tens of orders of magnitude

Courtesy: Hitoshi Murayama
http://hitoshi.berkeley.edu/neutrino/

3

Three-ν Paradigm



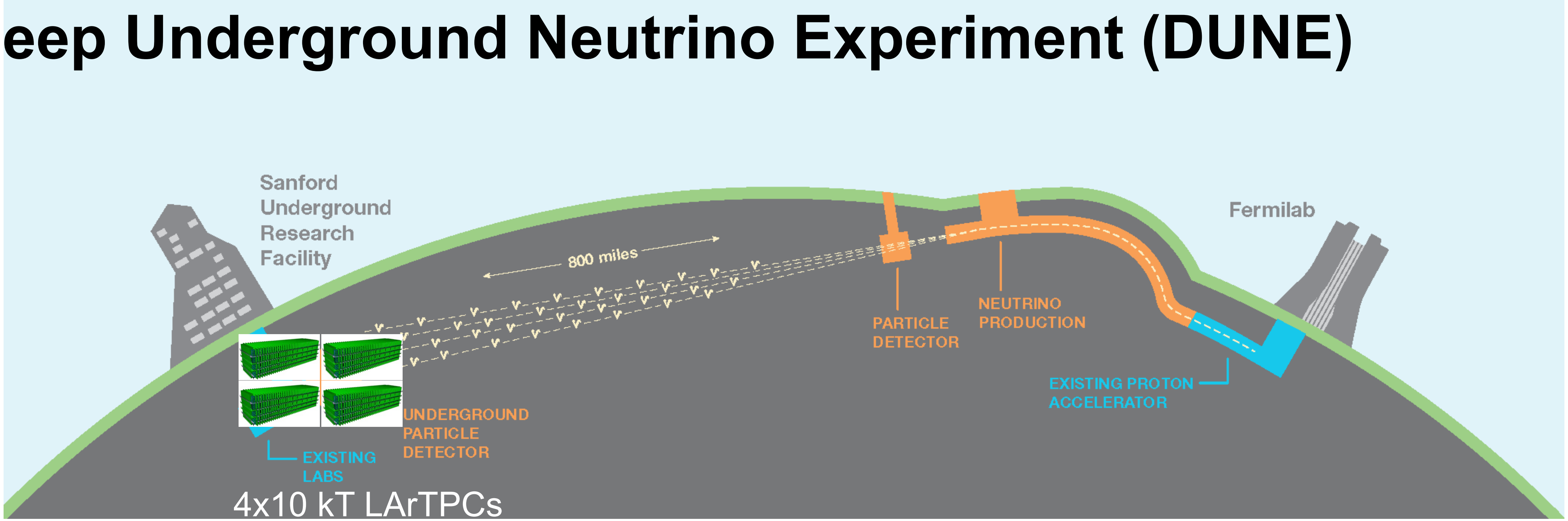


Unknowns: CP phase, normal or inverted mass ordering?

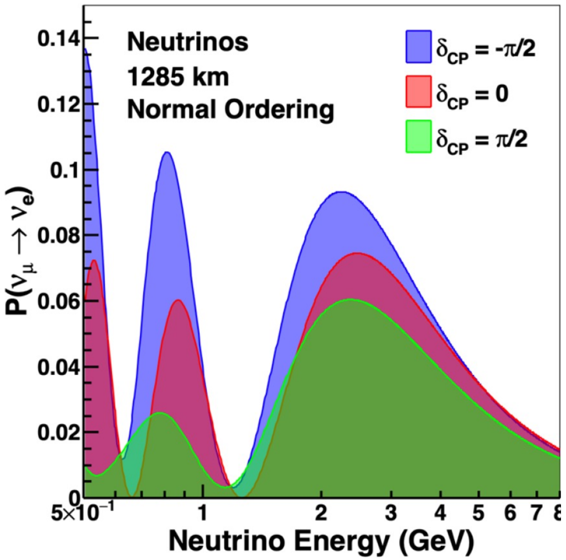
2015 Nobel Prize
Takaaki Kajita & Arthur B. McDonald

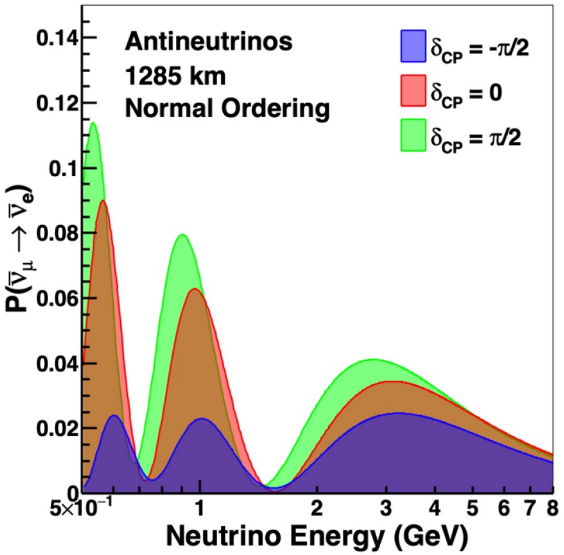
4

Deep Underground Neutrino Experiment (DUNE)



- Search for new CP violation and determine the mass ordering through precision measurement of **(anti)ν_μ→(anti)ν_e oscillation**
  - Also search for proton decay and detection of supernova neutrinos
- Four 10 kT LArTPC detectors (each 20 x 20 x 70 m^3)

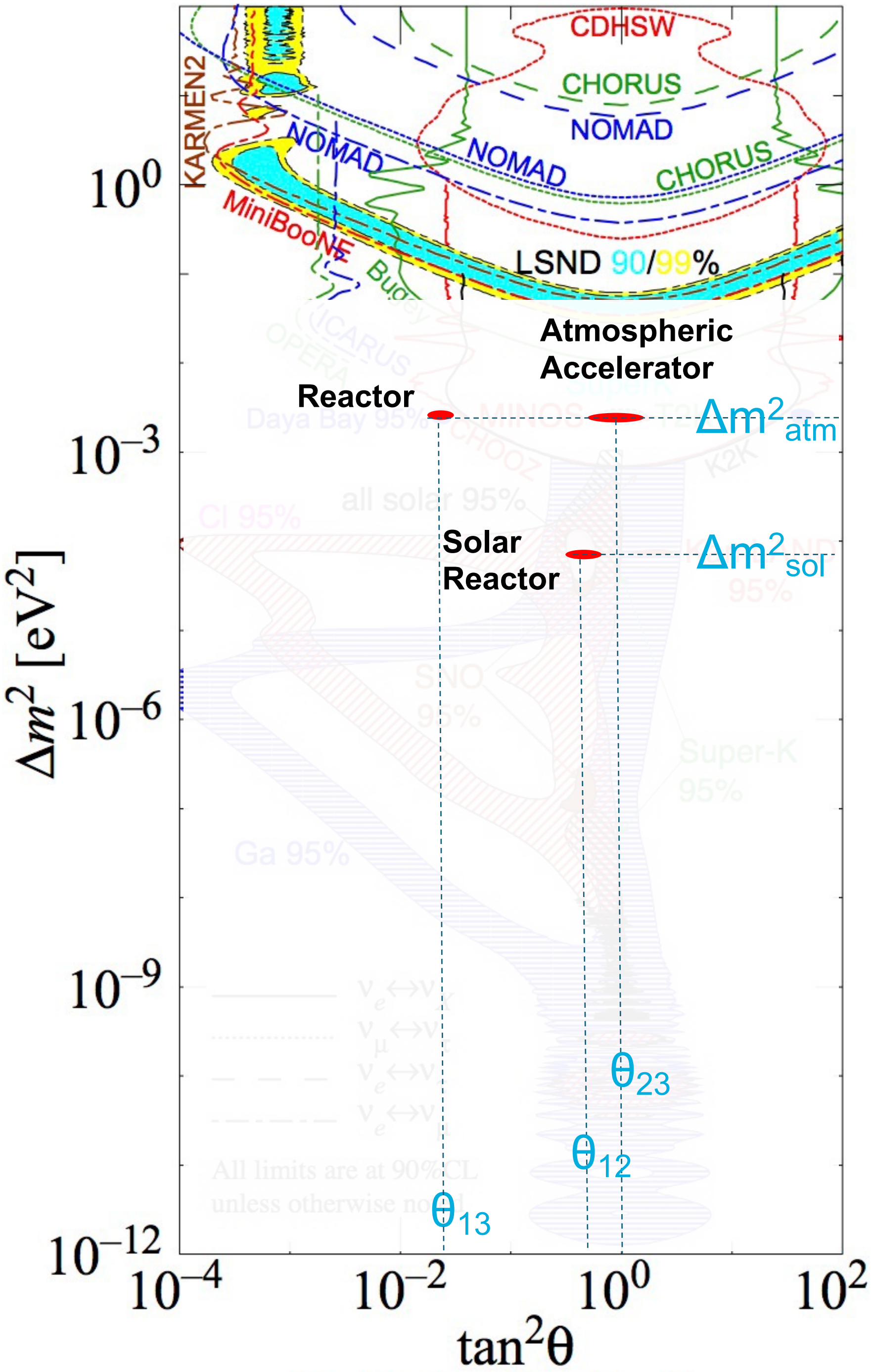




EPJC 80, 978

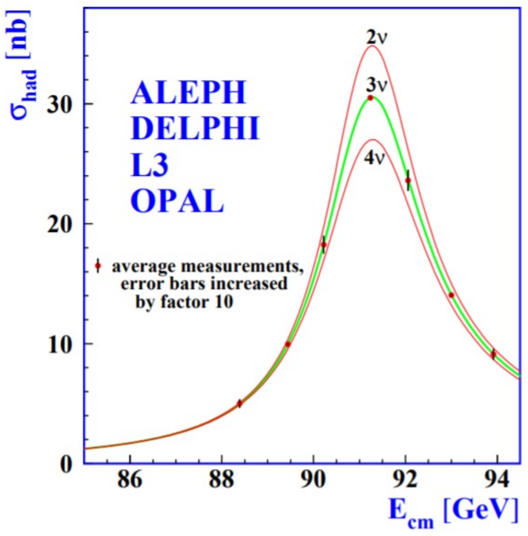
Brookhaven National Laboratory

Experimental Anomalies



There are a series of experimental anomalies hinting towards eV scale sterile neutrino(s)

- Reactor anomaly (missing anti-ν_e?)
- Gallium anomaly/BEST (missing ν_e?)
- Neutrino-4 (anti-ν_e oscillation?)
- LSND and MiniBooNE (anti-ν_e & ν_e appearance?)



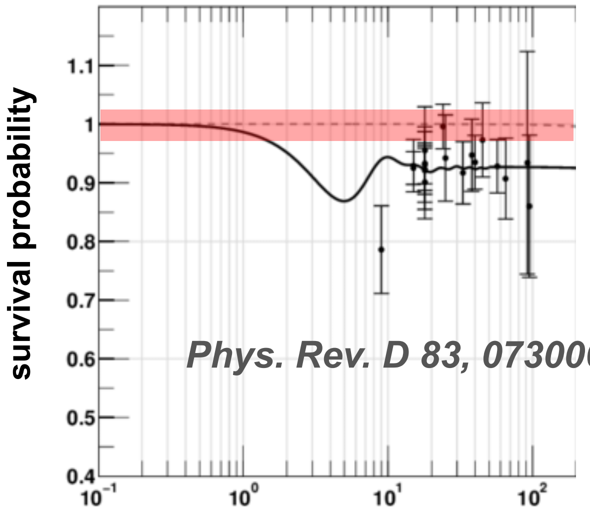
Phys. Rept. 427, 257 (2006)

$N_\nu = 2.9840 \pm 0.0082$

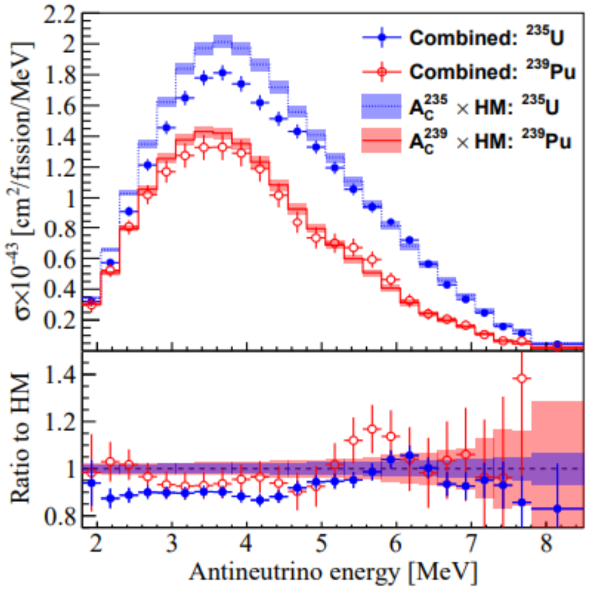
If there are additional neutrinos beyond three, they just don’t participate in weak interactions (i.e., “sterile”)

6

Reactor Antineutrino "Anomaly"



Phys. Rev. D 83, 073006 (2011)



Daya Bay + PROSPECT
arXiv:2106.12251 (2021)

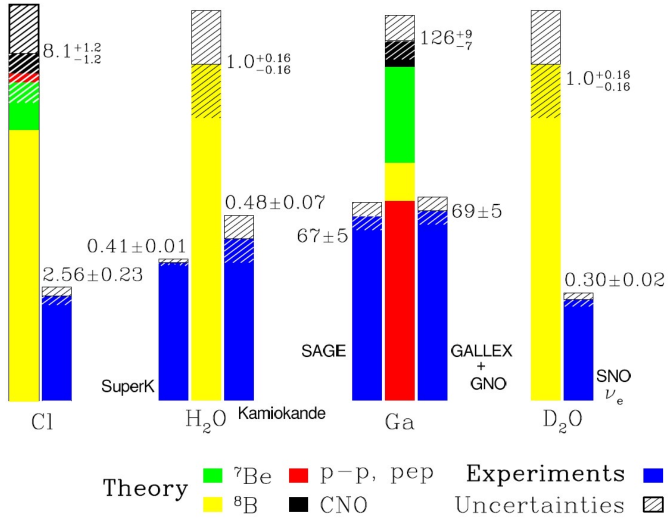
Anomaly in Neutrino Physics

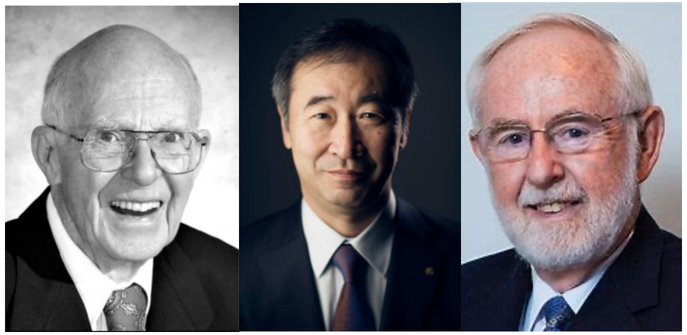
Mistake?

- mistake in experiment?
- mistake in theory?

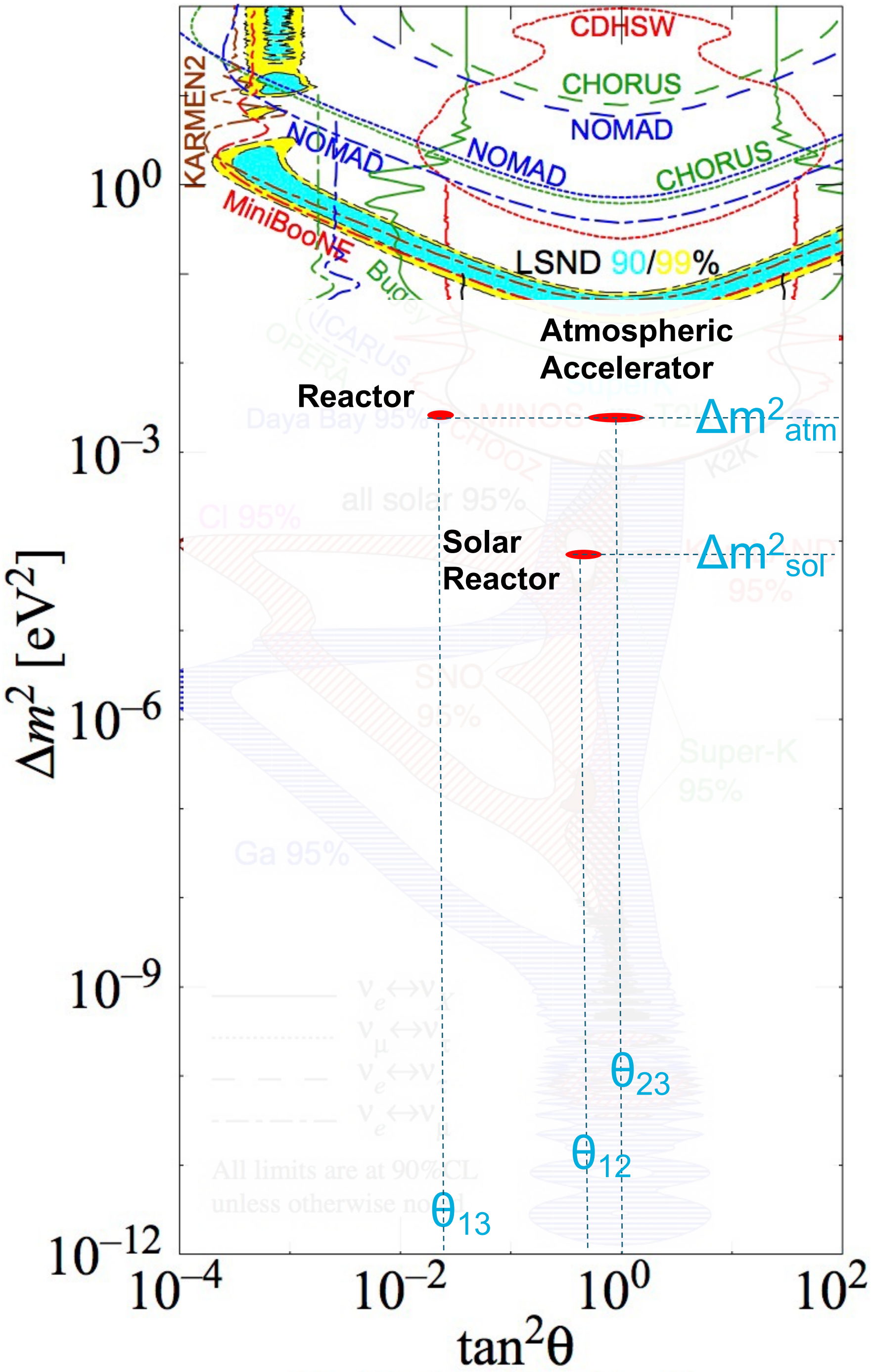
Discovery?

Solar Neutrino "Anomaly"

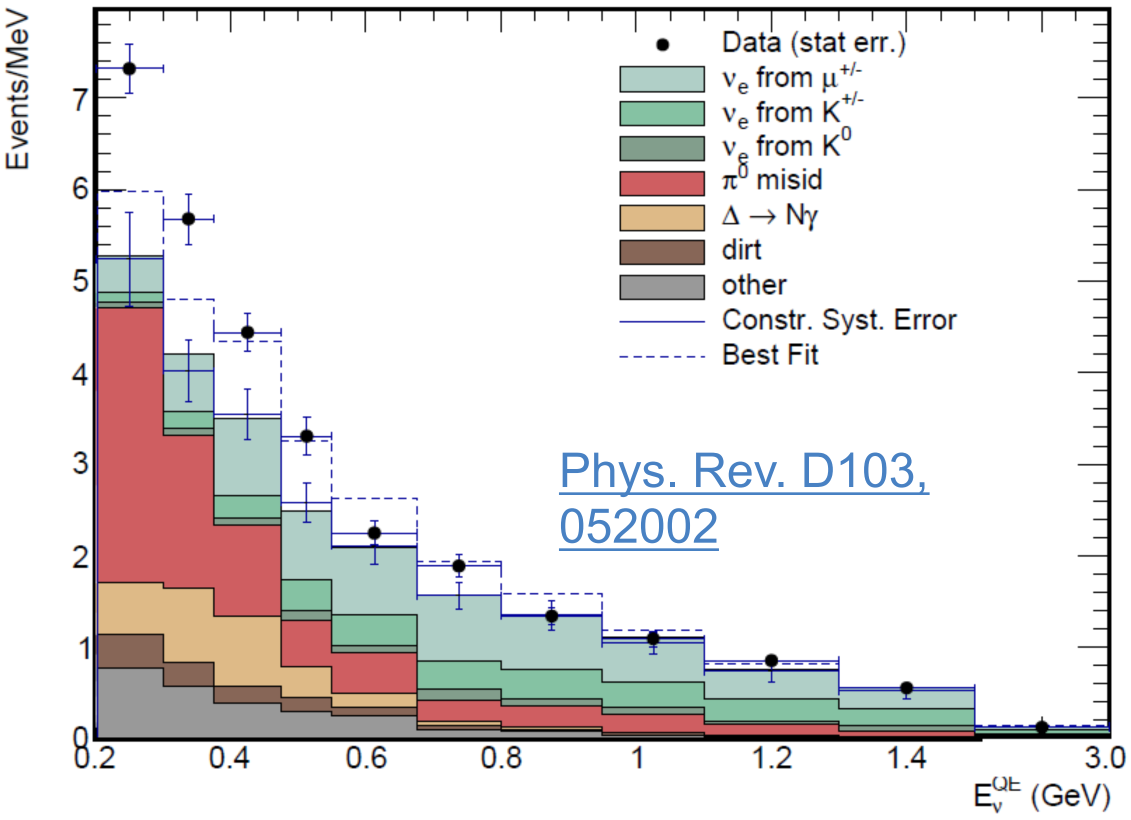




R. Davis T. Kajita A. Mcdonald

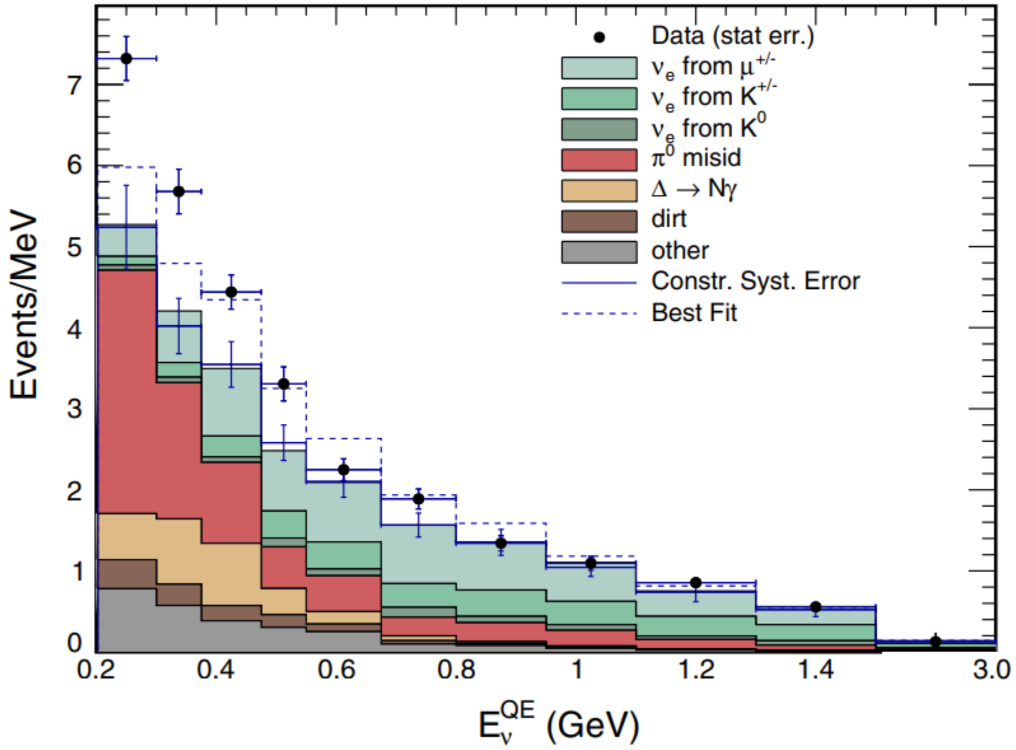


MiniBooNE Anomaly

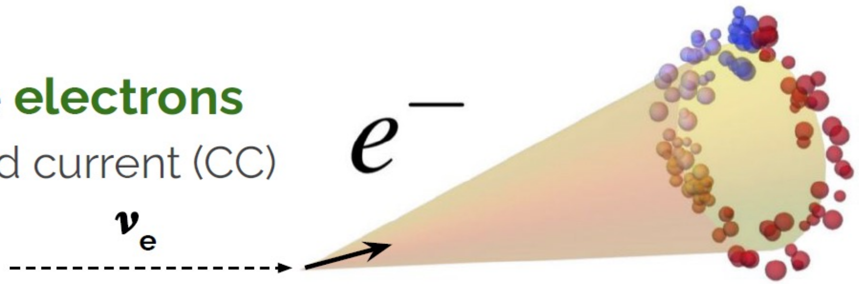


- MiniBooNE (2002-2019) observed low-energy excess (LEE) with 4.8σ (systematics limited) significance
- If LEE is interpreted as ν_e appearance in the primarily ν_μ beam, would suggest 4th (sterile) neutrino

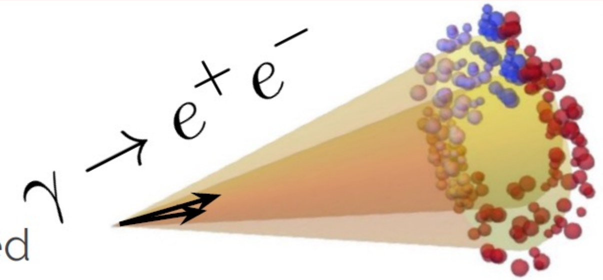
MiniBooNE: A Cherenkov Detector



It detected ν_e by the **electrons** produced in charged current (CC) interactions.



However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring

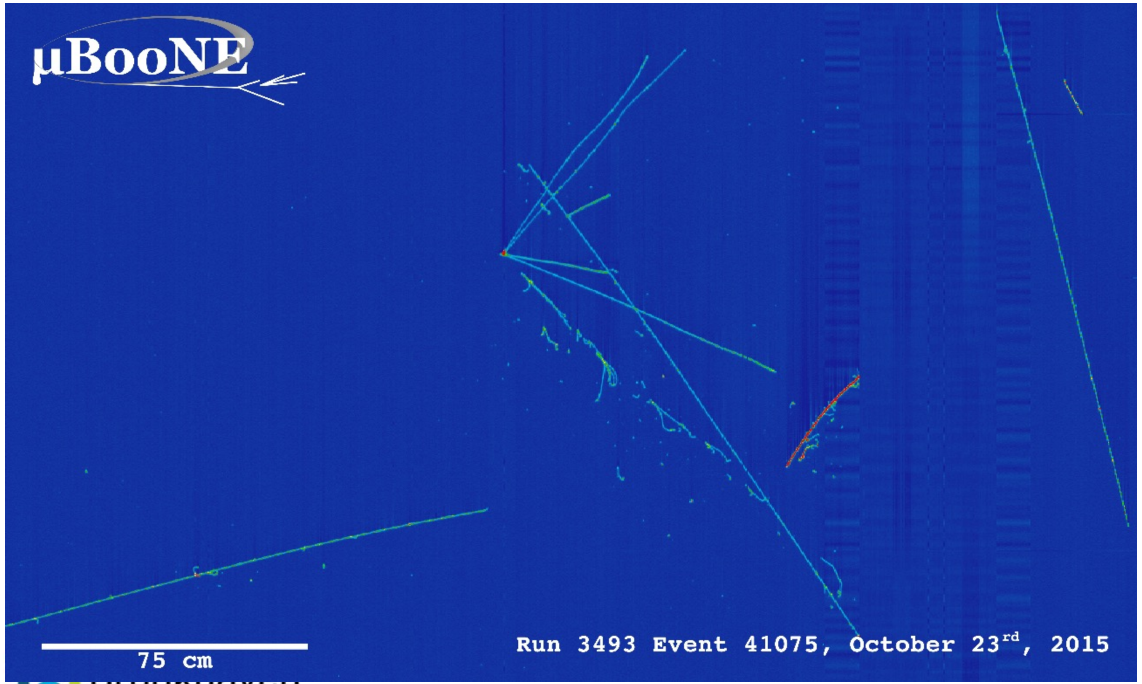


An excellent e/ γ separation can be achieved with
the Liquid Argon Time Projection Chamber (LArTPC) technology →
MicroBooNE is built to understand the nature of MiniBooNE LEE (e? γ? or what?)

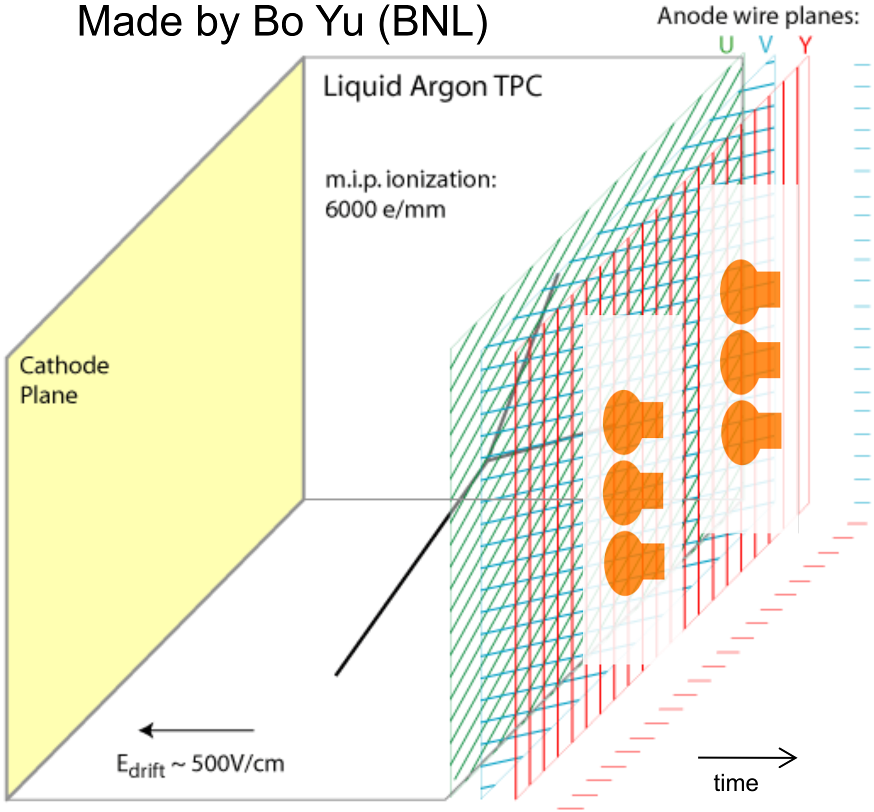
Brookhaven National Laboratory

Principle of Single-Phase Liquid Argon Time Projection Chamber (LArTPC)

- ~mm scale position resolution with multiple 1D wire readouts
- Particle identification (PID) with energy depositions and topologies

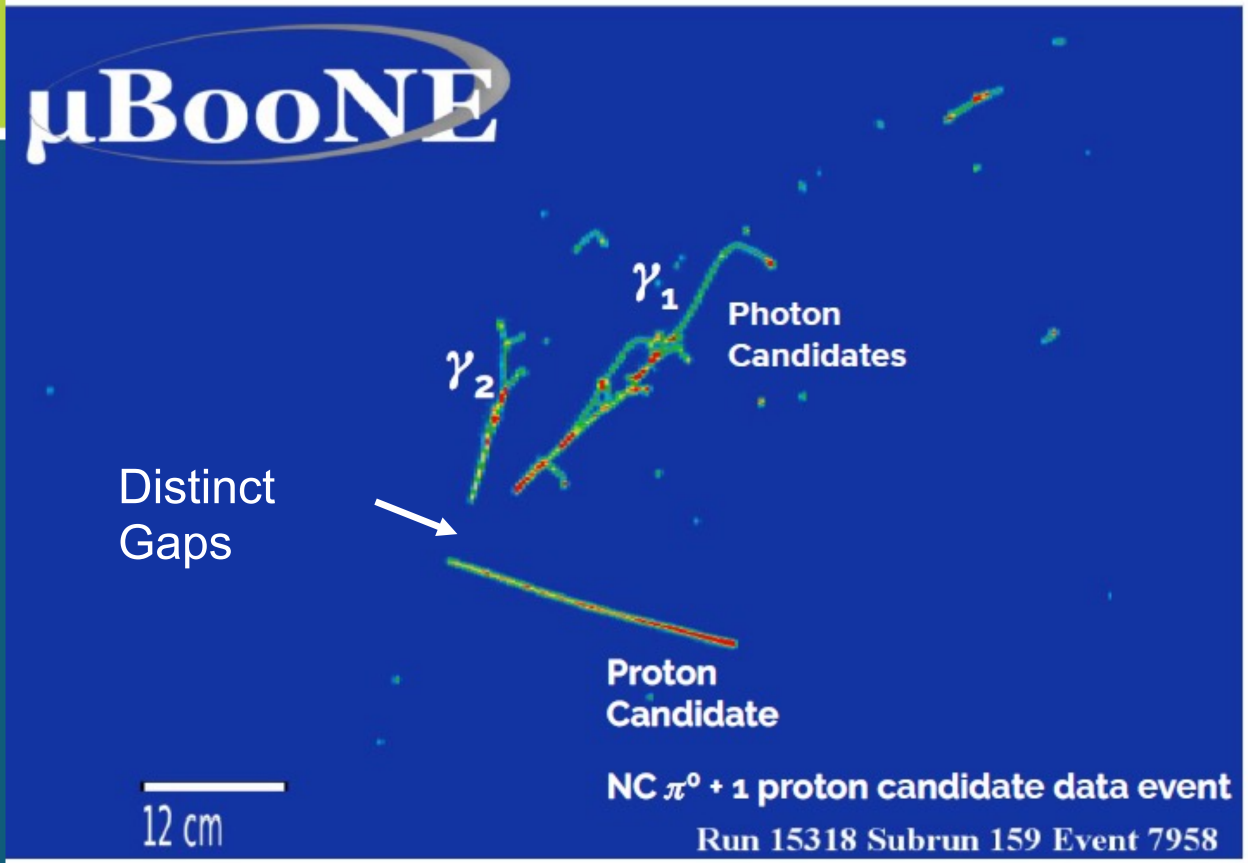


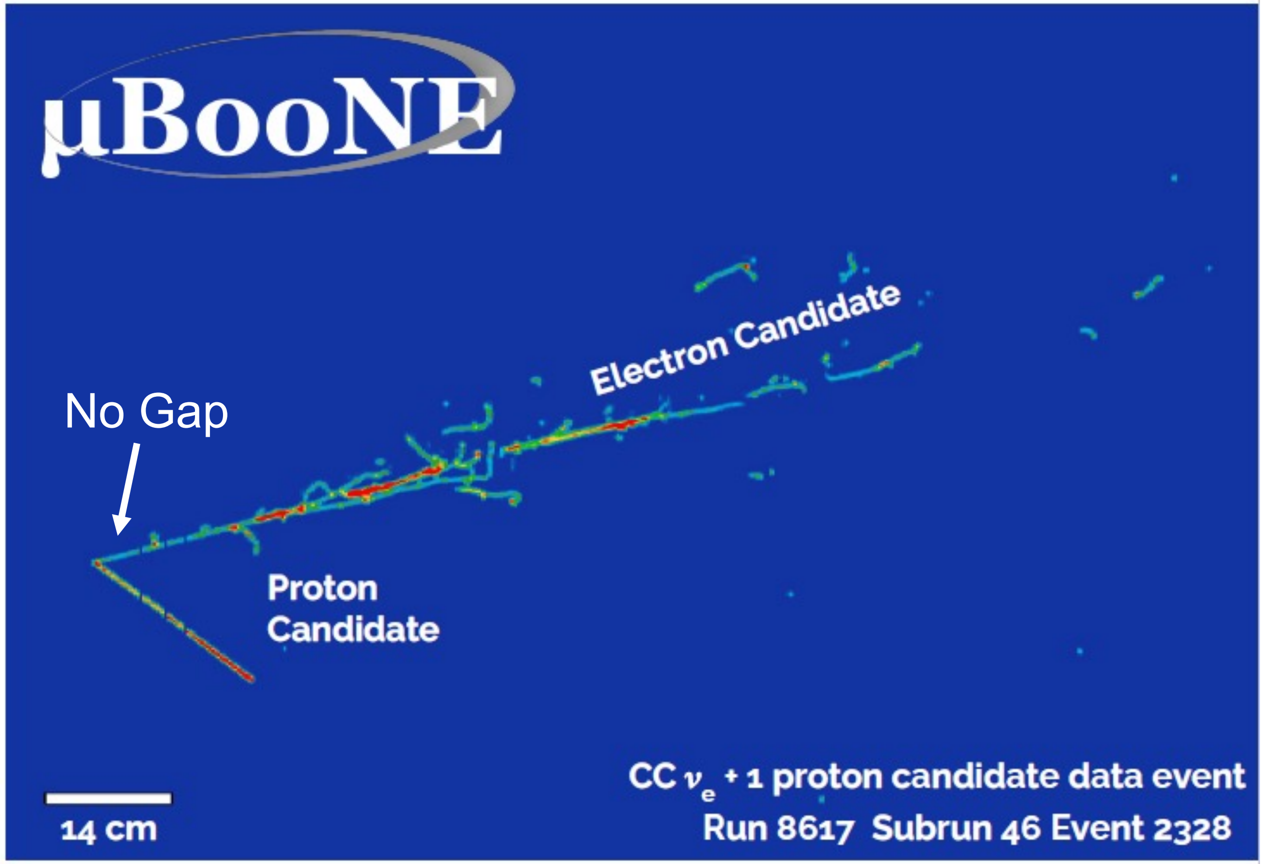
Made by Bo Yu (BNL)



Drift velocity 1.6 km/s → several ms drift time

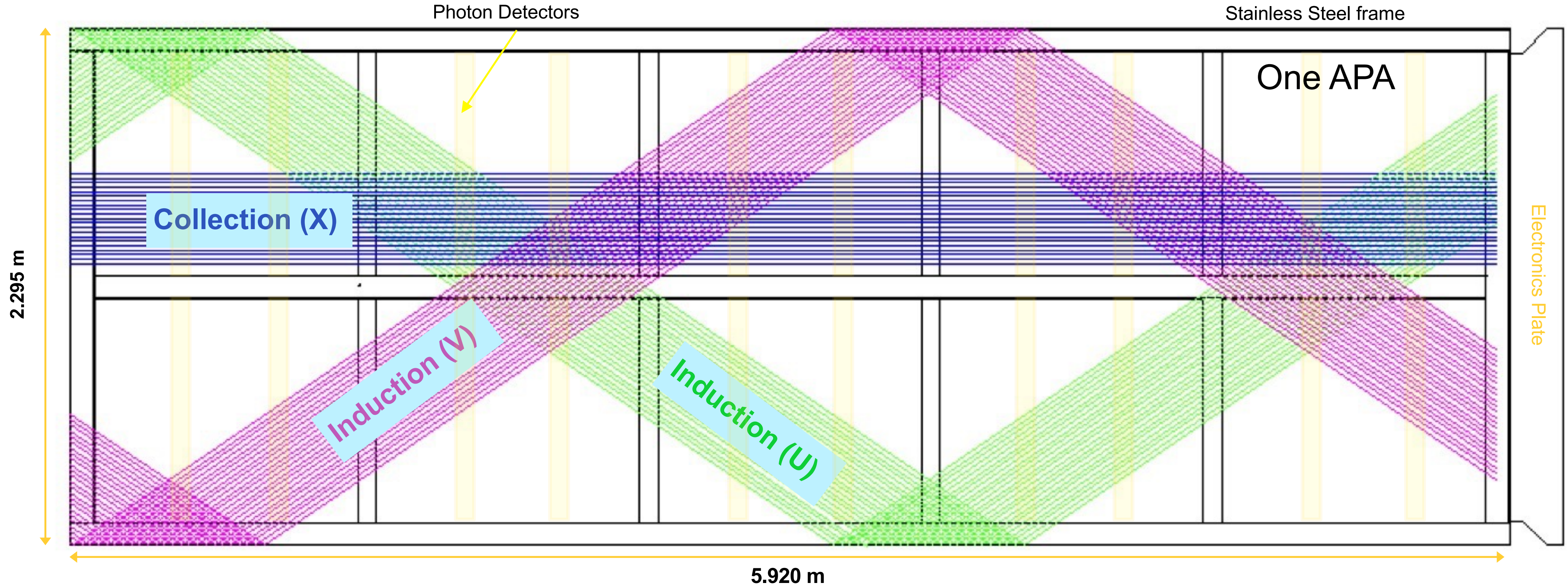
Why high res?





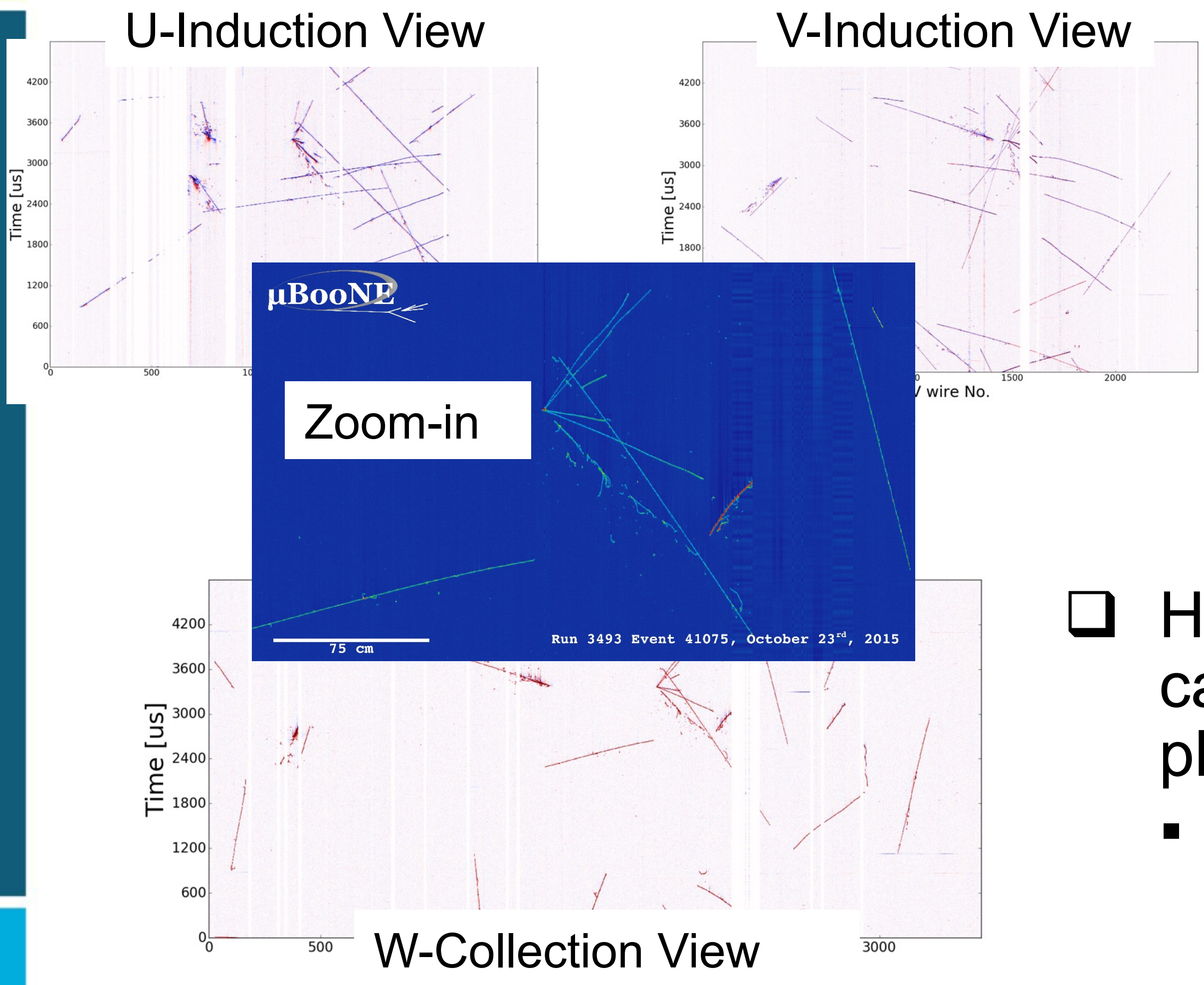
- ❑ Event topology to separate EM showers (e/γ) from tracks (proton, muon)
- ❑ Separation of e and γ : Gap Identification

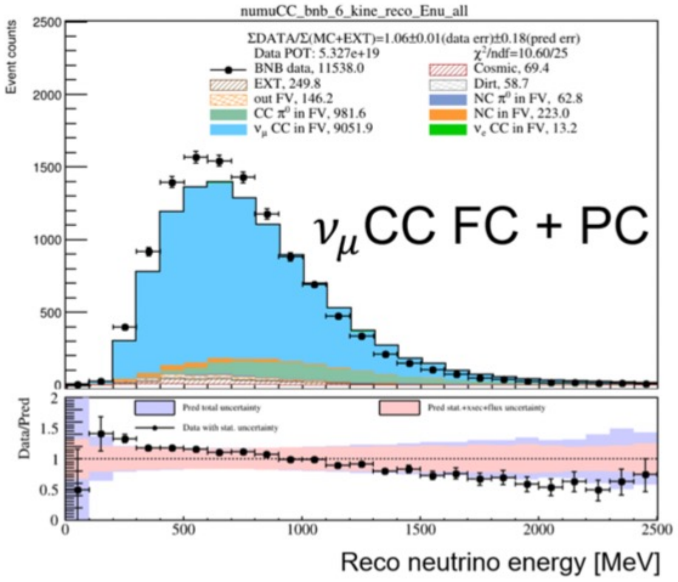
Why Wire?



- ❑Modular design for transportation and underground installation
- ❑Three (1D) wire planes with ~ **2560** readout channels. In comparison, would require half million channels for a 2D pixel readout with similar resolution (~ 5 mm pitch)
  - Considerations of cost and power consumption of electronics inside LAr

Challenge in Automated Event Reconstruction



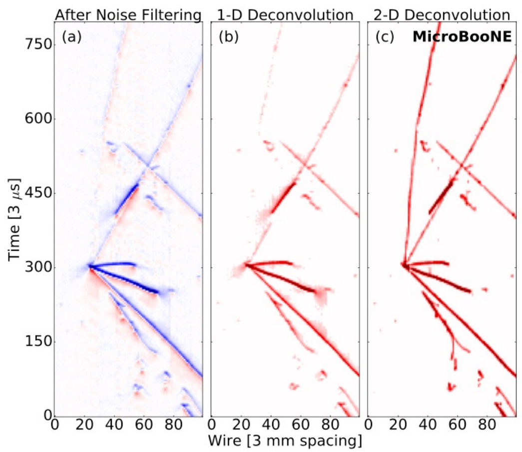


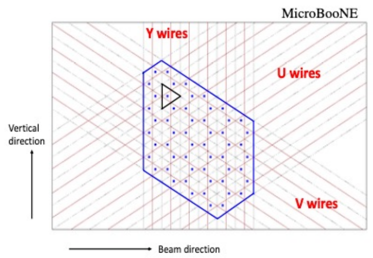
- ❑ How to convert the excellent resolution and calorimetry in these pictures to rigorous physics analyses?
  - Massive amount of information with tiny signal to background ratio → a big challenge for automated event reconstruction

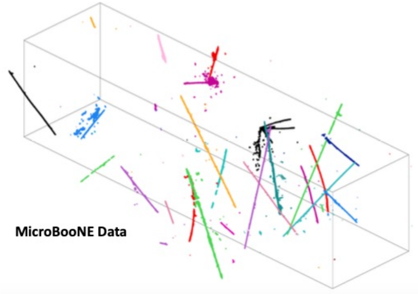
13

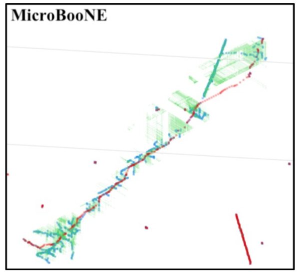
Wire-Cell Event Reconstruction

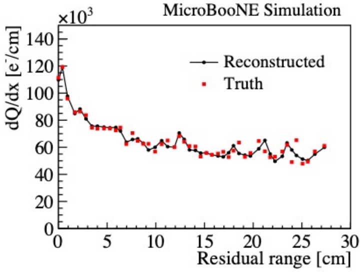
TPC simulation noise filtering signal processing	3D imaging clustering charge-light matching	3D trajectory & dQ/dx fitting cosmic muon tagger	multi-track fitting DL-3D vertexing particle identification

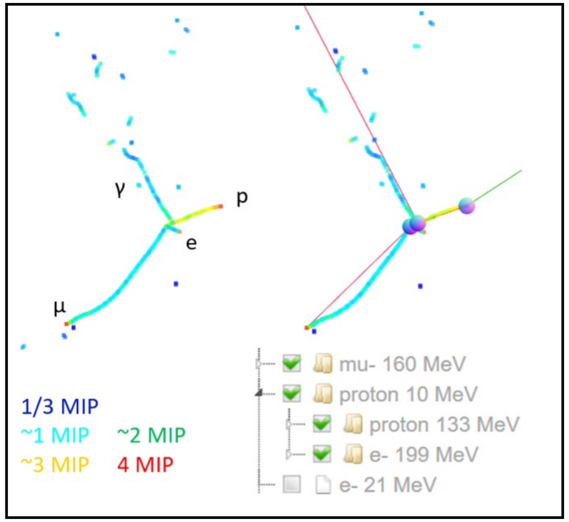












JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)
JINST 16 P01036 (2020)

JINST 13 P05032 (2018)
JINST 16 P06043 (2021)

Phys. Rev. Applied 15 064071 (2021)
arXiv:2012.07928

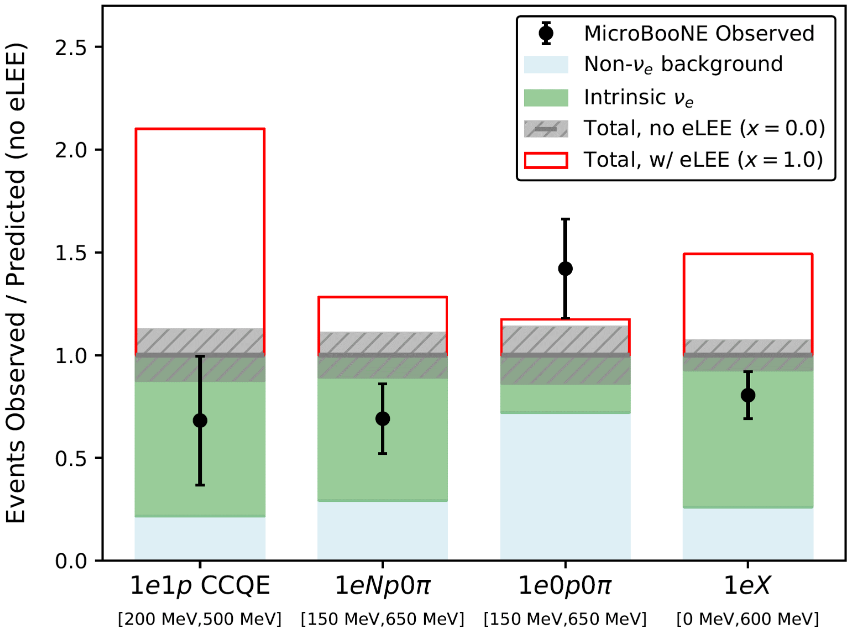
JINST 17 P01037 (2022)

Search for Low-Energy Excess in ν_eCC

Comprehensive search for (examination of) the MiniBooNE low-energy excess in ν_eCC with multiple final-state topologies with different reconstruction paradigms

Channels	Reconstruction	Purity	Efficiency	Selected Events	References
CCQE 1e1p	Deep Learning	75%	6.6%	25	PRD **105**, 112003
1e0p0π	Pandora	43%	9%	34	PRD **105**, 112004
1eNp0π	Pandora	80%	15%	64	PRD **105**, 112004
Inclusive 1eX	**Wire-Cell**	**82%**	**46%**	**606**	PRD **105**, 112005

Wire-Cell based inclusive ν_eCC analysis (46% efficiency) currently leads sensitivity in searching for the LEE



Phys. Rev. Lett. **128**, 241801 (2022)

No excess of low-energy ν_e candidates!

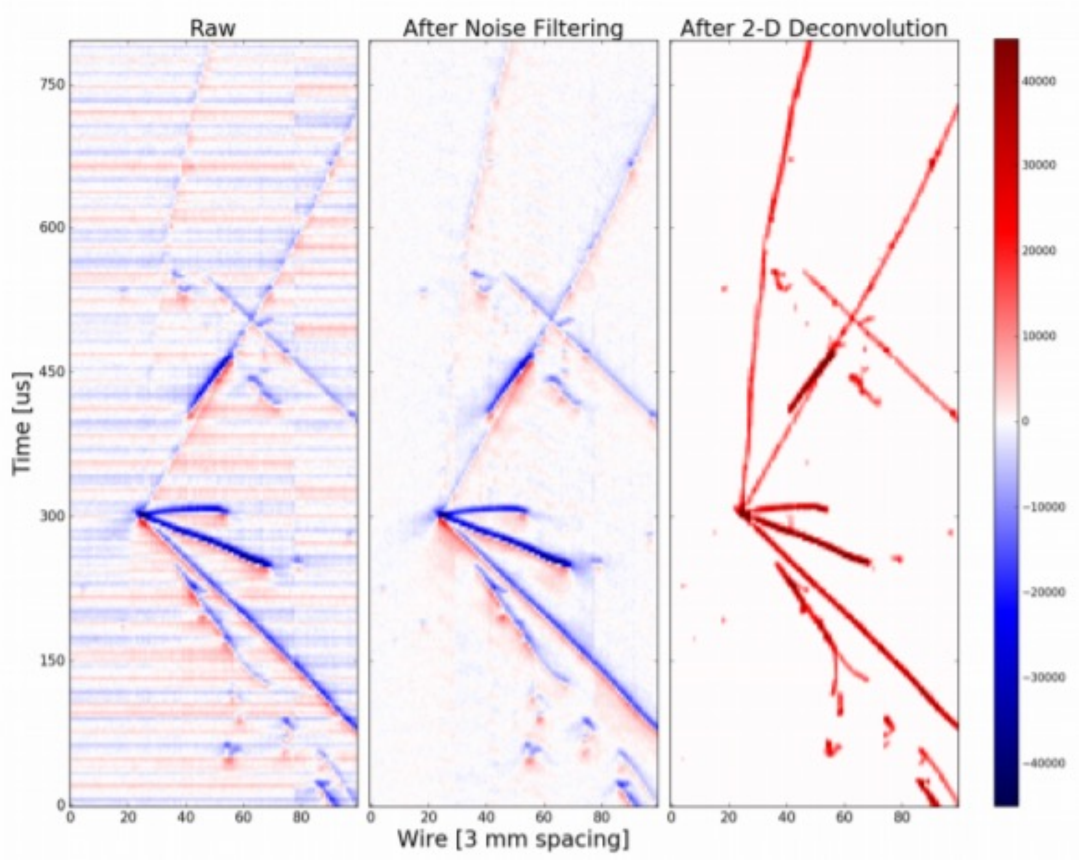
Brookhaven National Laboratory

15

Wire-Cell Low Level Signal Processing

- ❑ Noise filtering
  - Coherent noise – channel-by-channel correlated
- ❑ Signal processing
  - Reverse the "field response" and "electronic response"

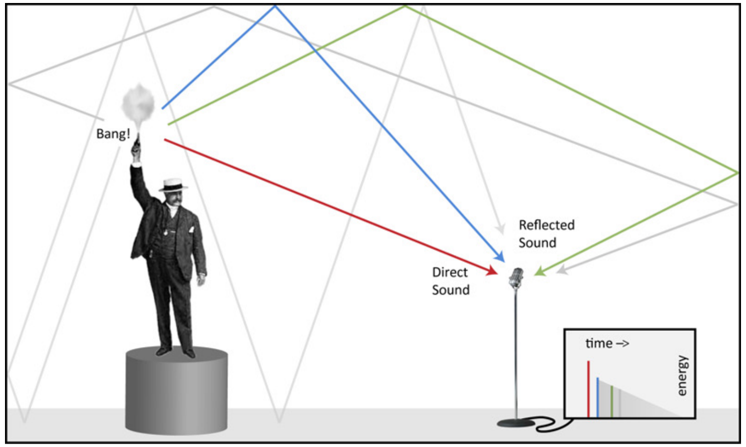
$$M(x',t') = \int_{-\infty}^{\infty}\int_{-x_0}^{x_0} R(x-x',t-t')S(x,t)dxdt$$



Online display:
http://lar.bnl.gov/magnify/

Impulse response

Room acoustic response



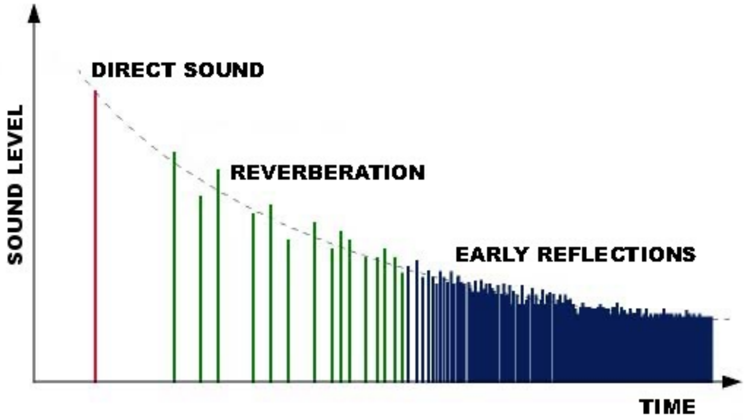
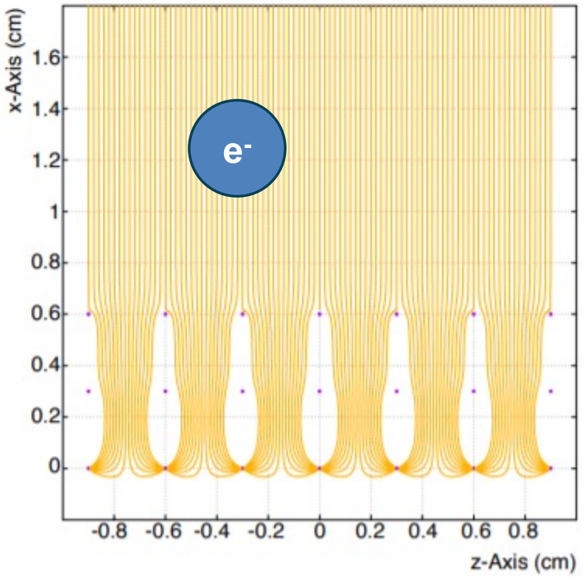
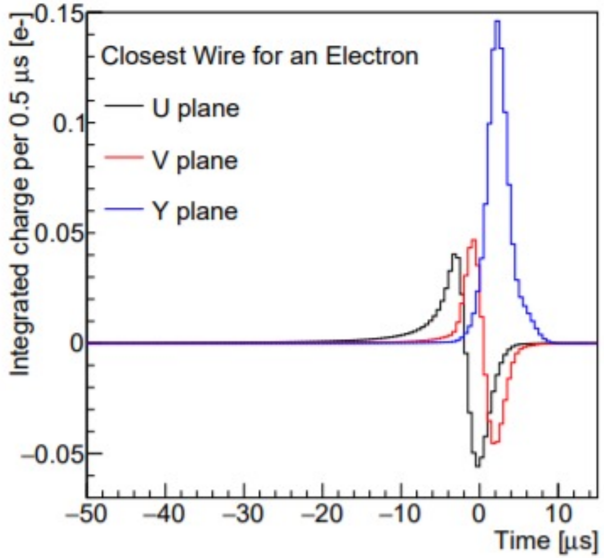


Image credit: www.prosoundweb.com

$h(t)$

LArTPC
field + electronic
response

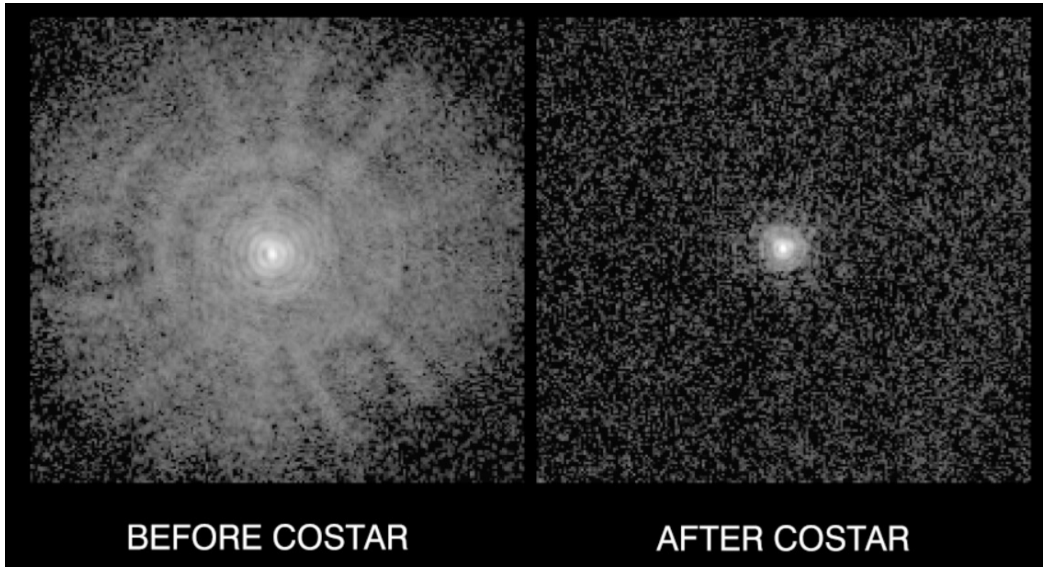




JINST 13 P07006 (2018)

2D Impulse response

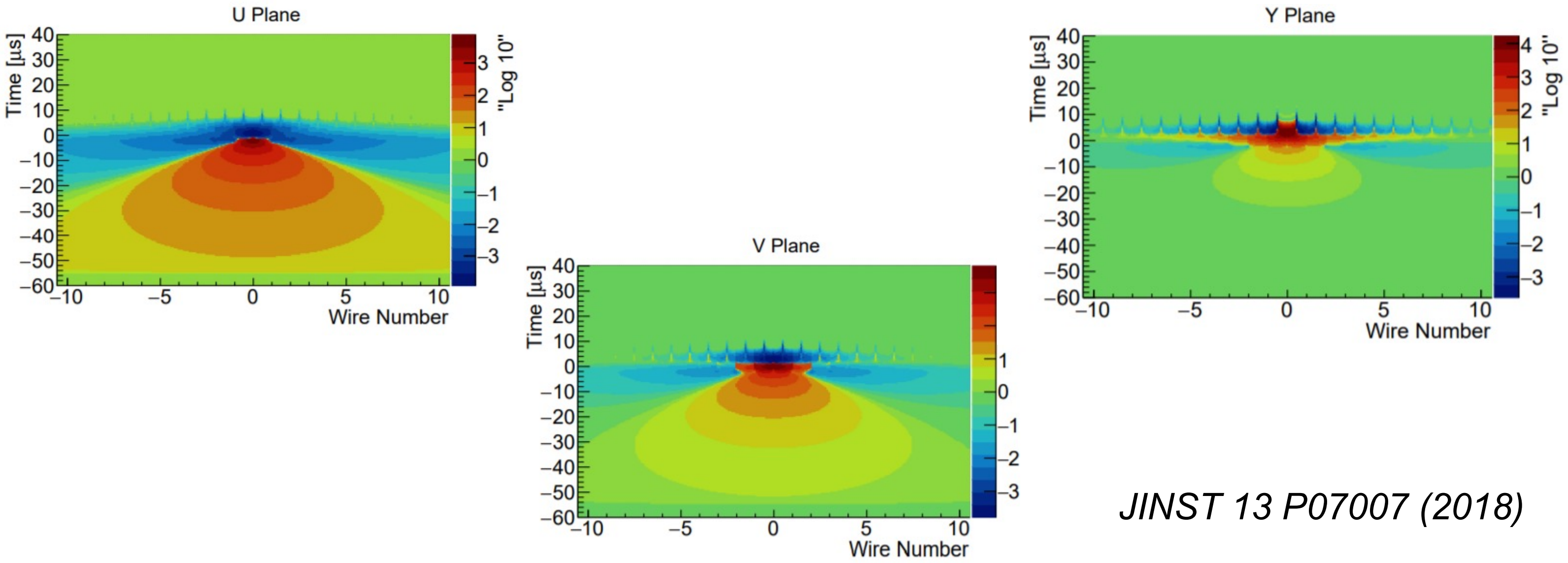
Camera optical response



Hubble telescope impulse response (Image credit: http://web.mit.edu)

$h(x, y)$

LArTPC 2D response:
y: t * drift velocity
x: wire number * pitch



JINST 13 P07007 (2018)

2-D Deconvolution

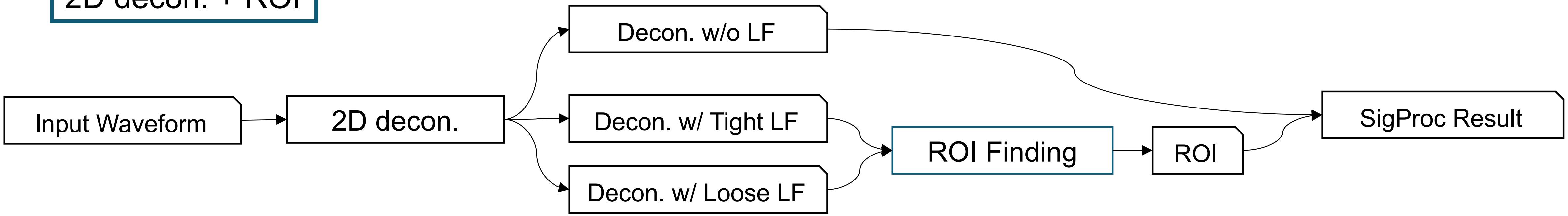
2D measurement formation

$$M(t',x') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R(t,t',x,x')\cdot S(t,x)dtdx + N(t',x')$$

2D deconvolution

$$S(\omega_t,\omega_x) \sim \frac{F(\omega_t,\omega_x)\cdot M(\omega_t,\omega_x)}{R(\omega_t,\omega_x)} \xrightarrow{IFT} S(t,x)$$

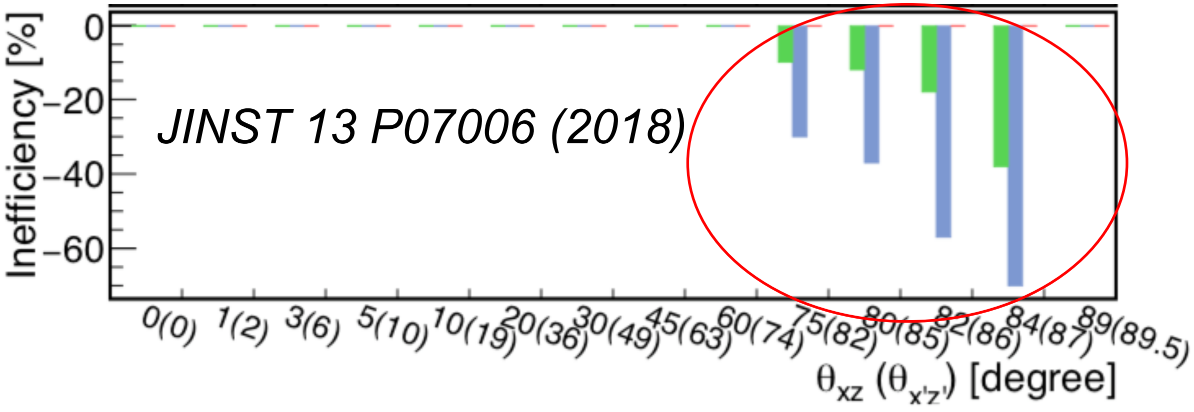
2D decon. + ROI

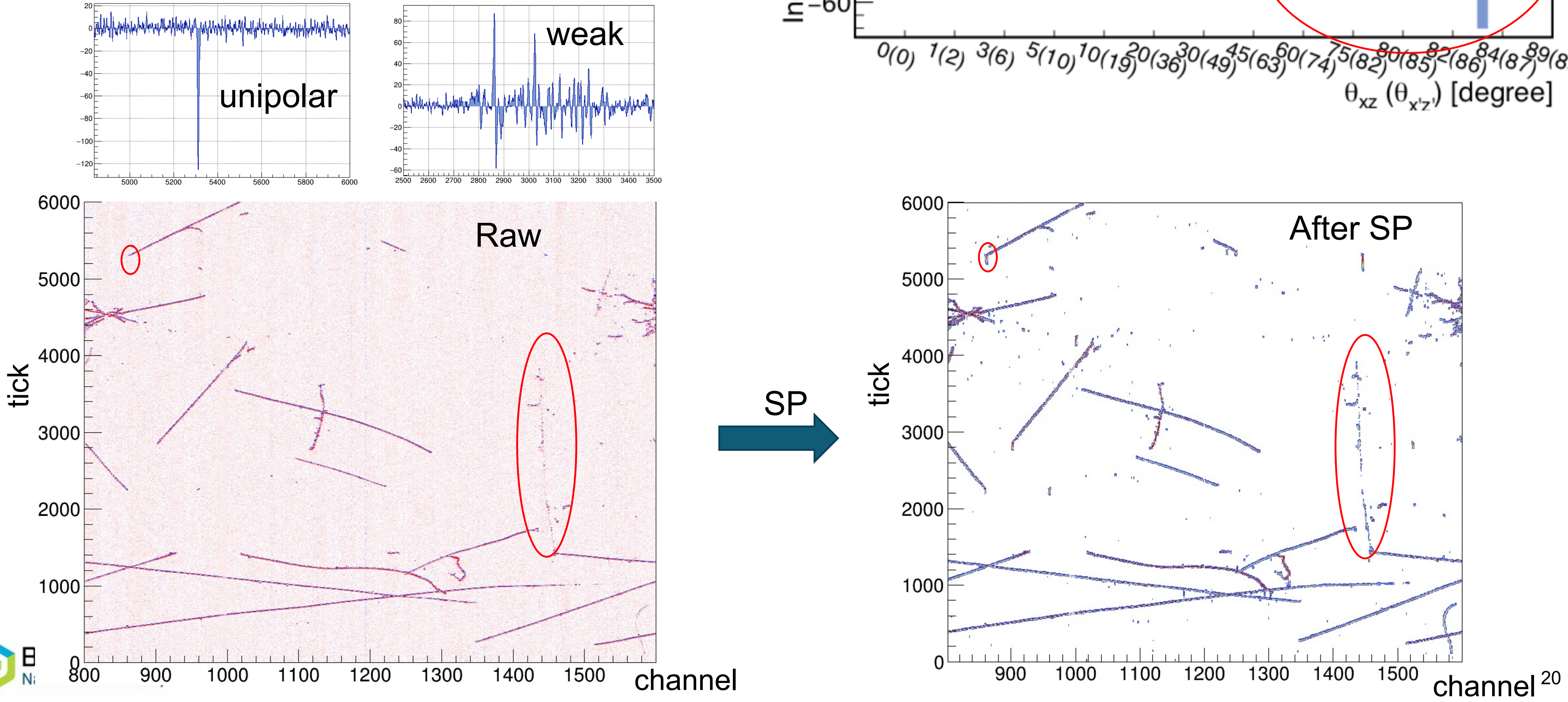


19

Further improvement of LArTPC Signal Processing

- "Prolonged Track" – weak signal
- "Tear Drop" - distorted waveform
- Noisy dots - noise



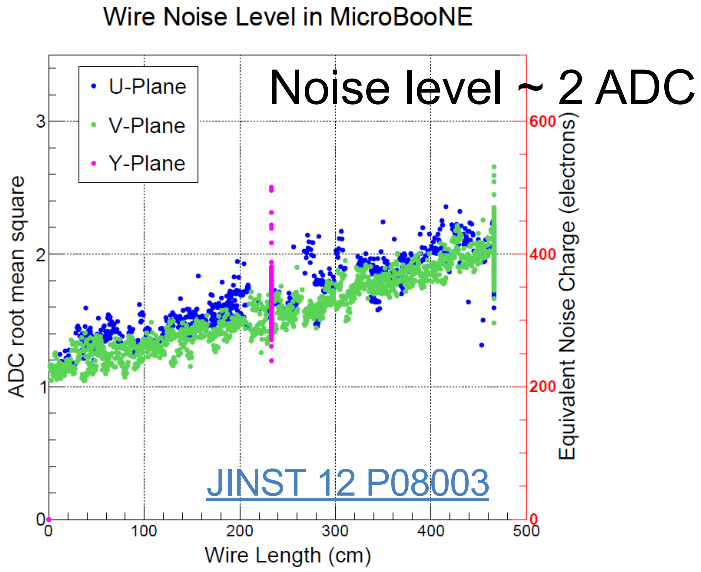


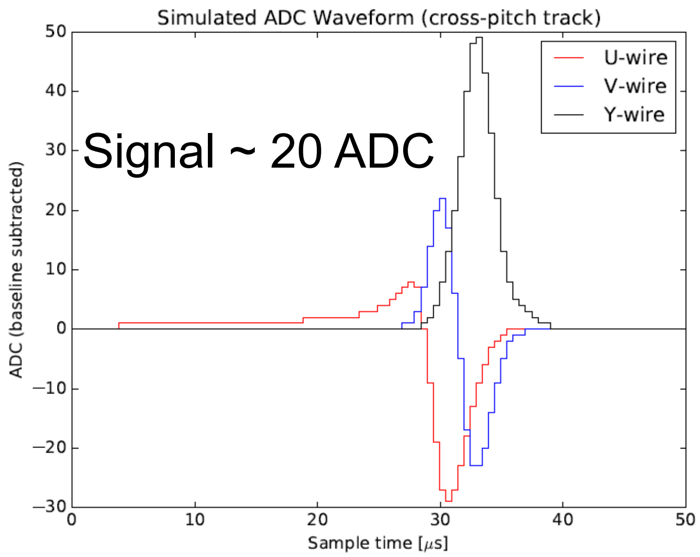
Cold Electronics

Placing the preamplifier inside LAr significantly reduced the electronics noise

- 5-6 times compared to past warm electronics → **60:1** MIP peak-to-noise ratio in the collection

- Significantly improve the performance of induction wire plane → **An enabling technology**





Cold electronics for "Giant" Liquid Argon Time Projection Chambers

Veljko Radeka[1*], Hucheng Chen[1], Grzegorz Deptuch[2], Gianluigi De Geronimo[1], Francesco Lanni[1], Shaorui Li[1], Neena Nambiar[1], Sergio Rescia[1], Craig Thorn[1], Ray Yarema[2], Bo Yu[1]

[1] Brookhaven National Laboratory, Upton, NY 11973-5000, USA
[2] Fermi National Laboratory,

*Correspondence, e-mail: radeka@bnl.gov

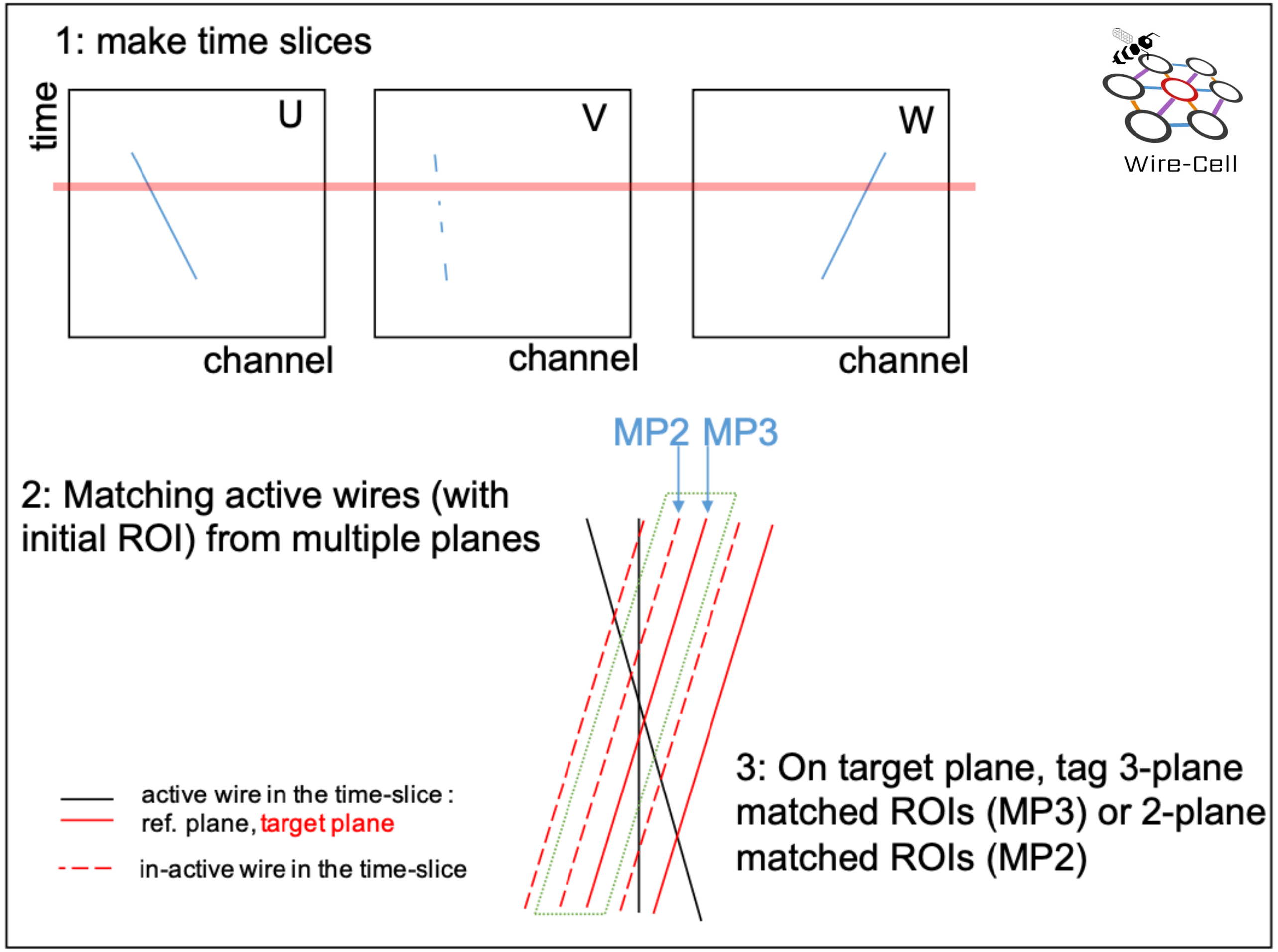
Abstract. The choice between cold and warm electronics (inside or outside the cryostat) in very large LAr TPCs (>5-10 ktons) is not an electronics issue, but it is rather a major cryostat design issue. This is because the location of the signal processing electronics has a direct and far reaching effect on the cryostat design, an indirect effect on the TPC electrode design (sense wire spacing, wire length and drift distance), and a significant effect on the TPC performance. All these factors weigh so overwhelmingly in favor of the cold electronics that it remains an optimal solution for very large TPCs. In this paper signal and noise considerations are summarized, the concept of the readout chain is described, and the guidelines for design of CMOS circuits for operation in liquid argon (at ~89 K) are discussed.

1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (2011)

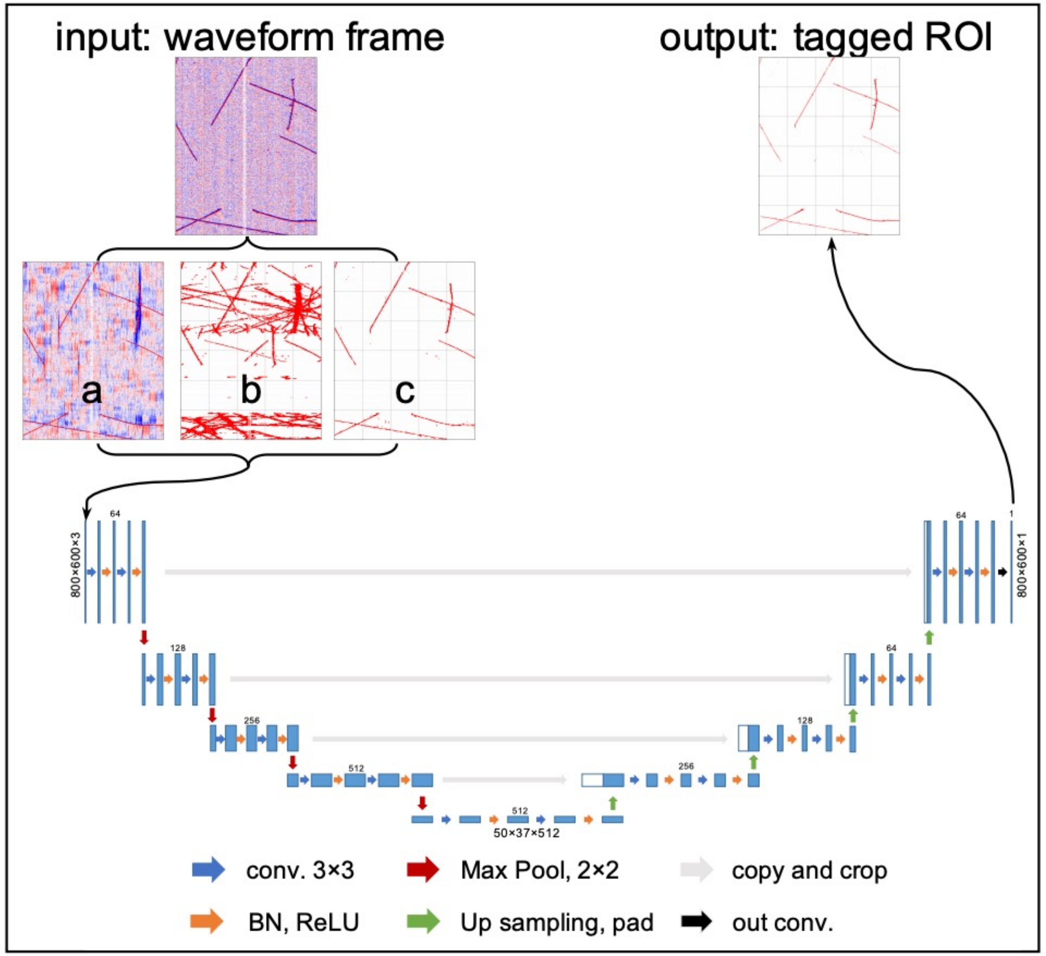
DNN ROI finding with multi-plane information

JINST 16 P01036 (2021)

Multi-plane information in Signal Processing

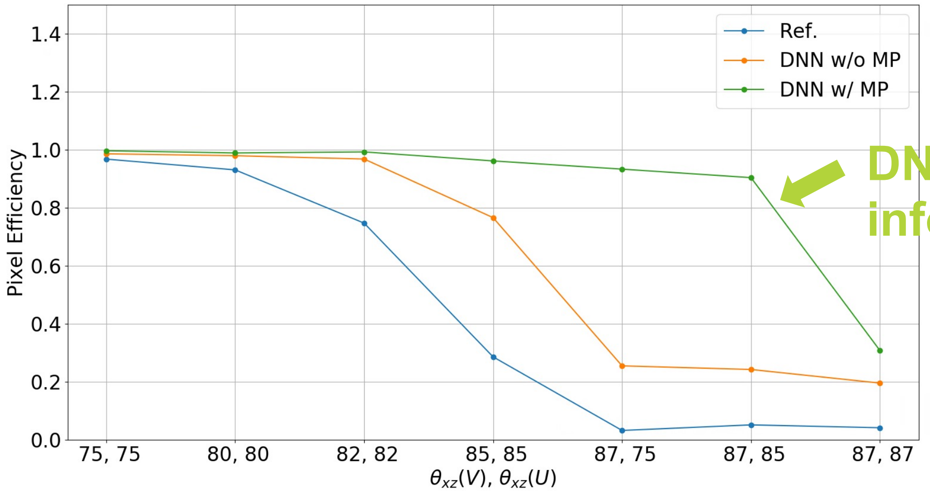


DNN ROI finding with multiple input channel

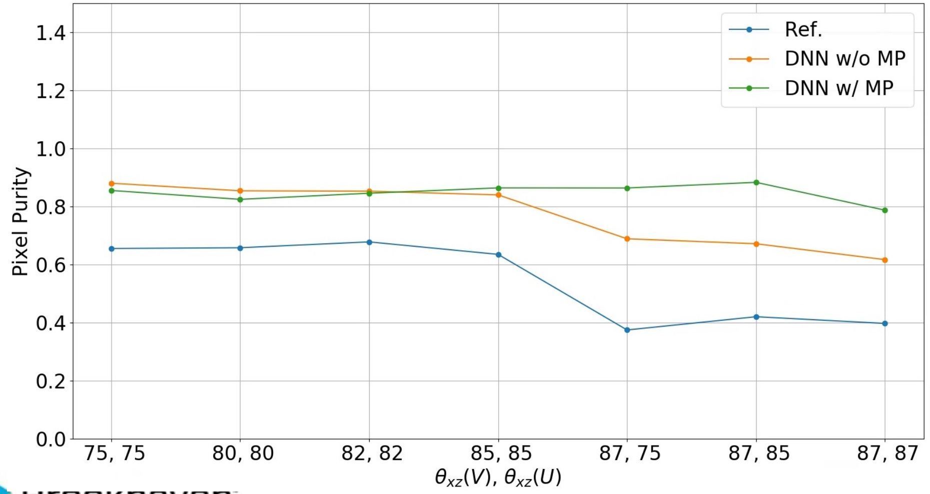


DNN ROI finding with multi-plane information

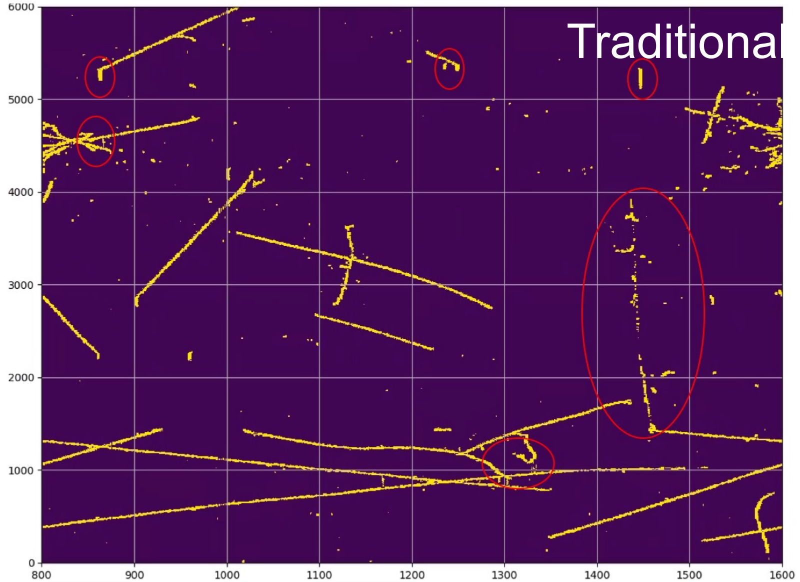
ProtoDUNE simulation
ROI finding on V plane (2nd induction)

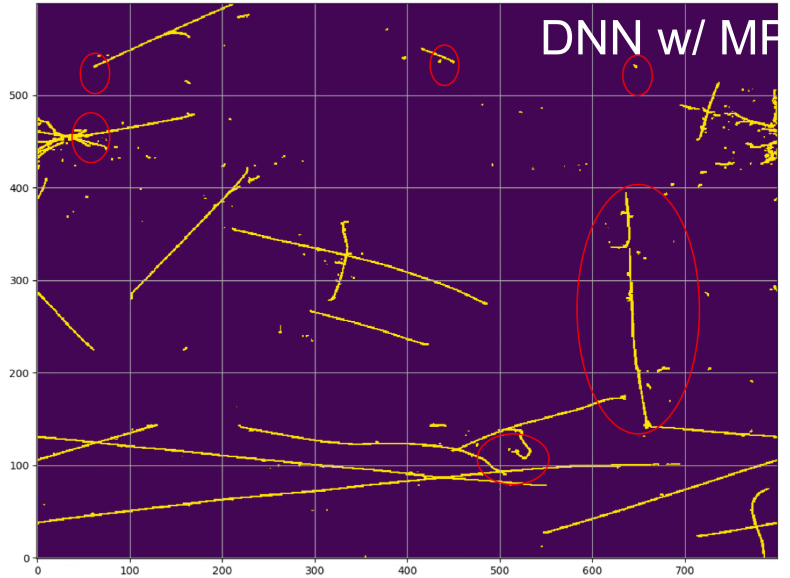


DNN With 3-plane information



tested on ProtoDUNE data

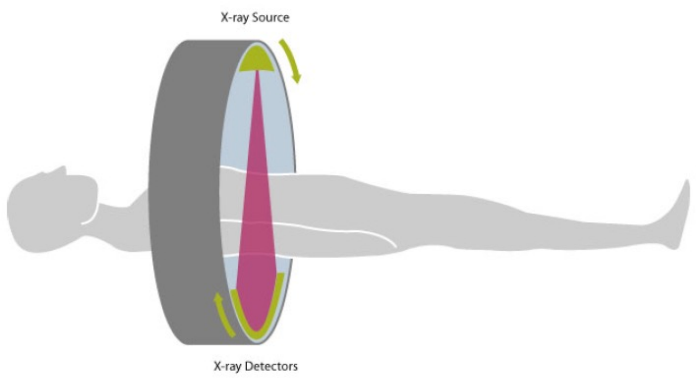


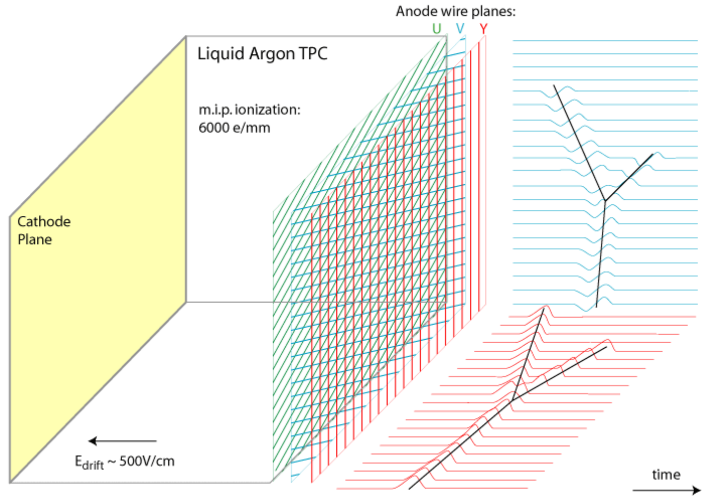


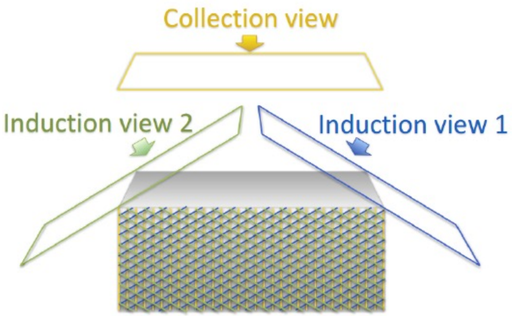
Brookhaven National Laboratory

JINST 16 P01036 (2021)

Wire-cell Tomographic Reconstruction







- CAT Scan
  - Detector (x-ray generator/receiver) moves across the object (body)
  - Axial projections (~180) by detector rotation
  - Cross section can be reconstructed at each position along detector movement

- LArTPC
  - Objects (ionizing electrons) move across detectors (wire planes)
  - Axial projections (~3) by wire orientation
  - Cross section can be reconstructed at each time slice along electron drift

Wire-Cell 3D Imaging Principle

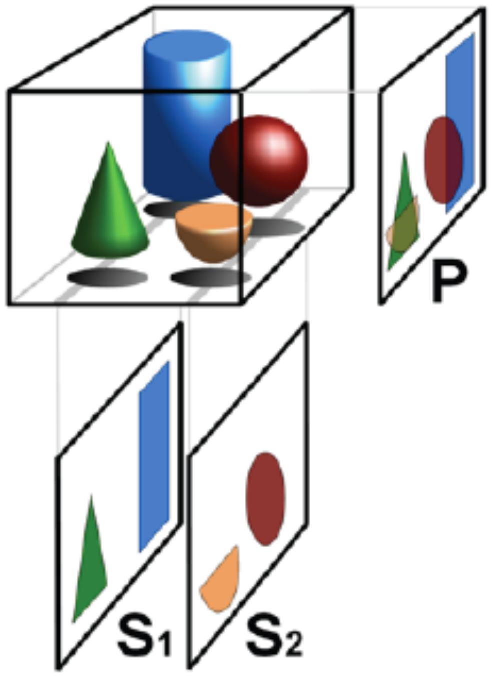
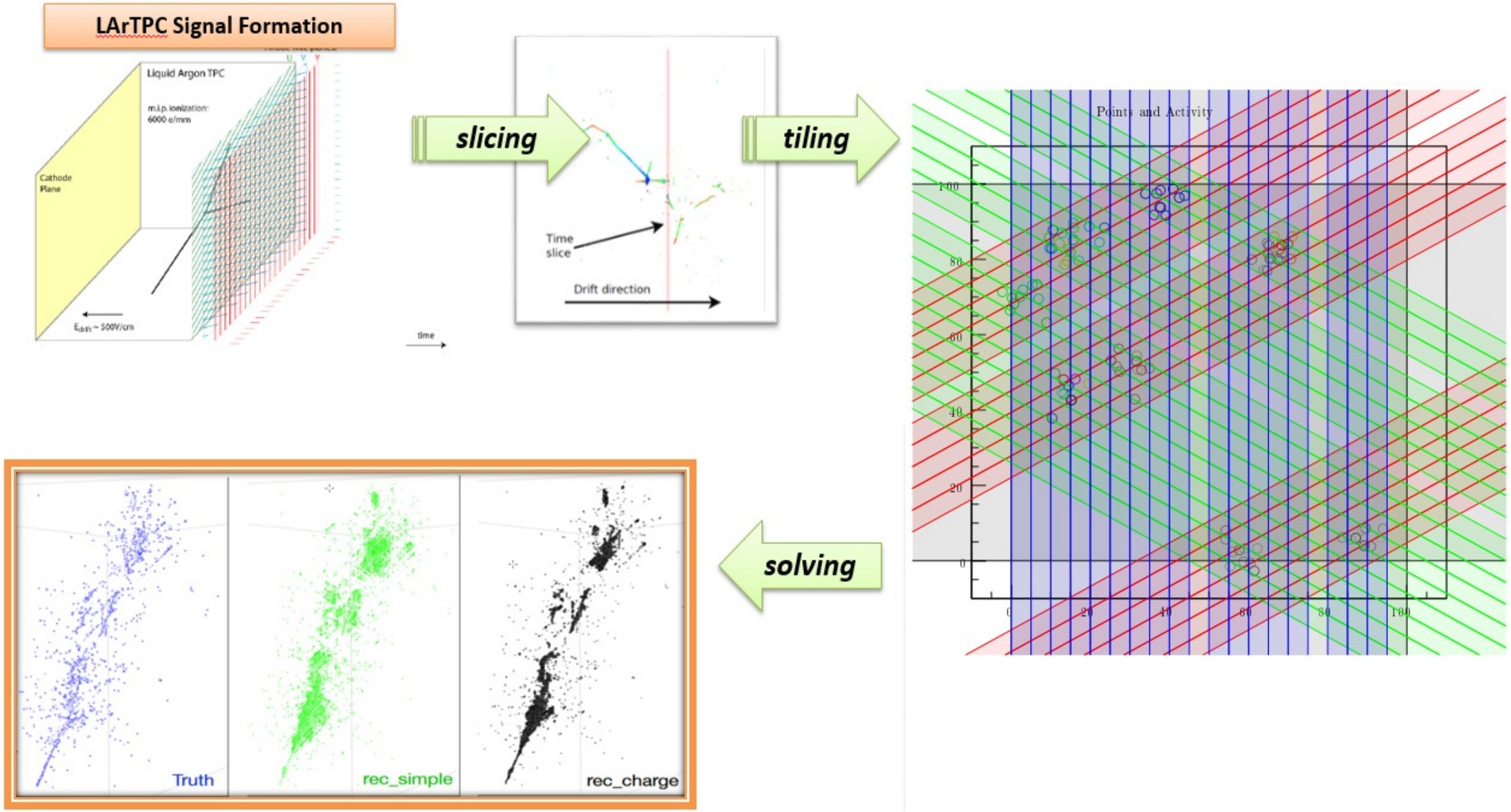


Fig.1:Basic principle of tomography: superposition free tomographic cross sections S1 and S2 compared with the projected image P

https://en.wikipedia.org/wiki/Tomography



Brookhaven National Laboratory

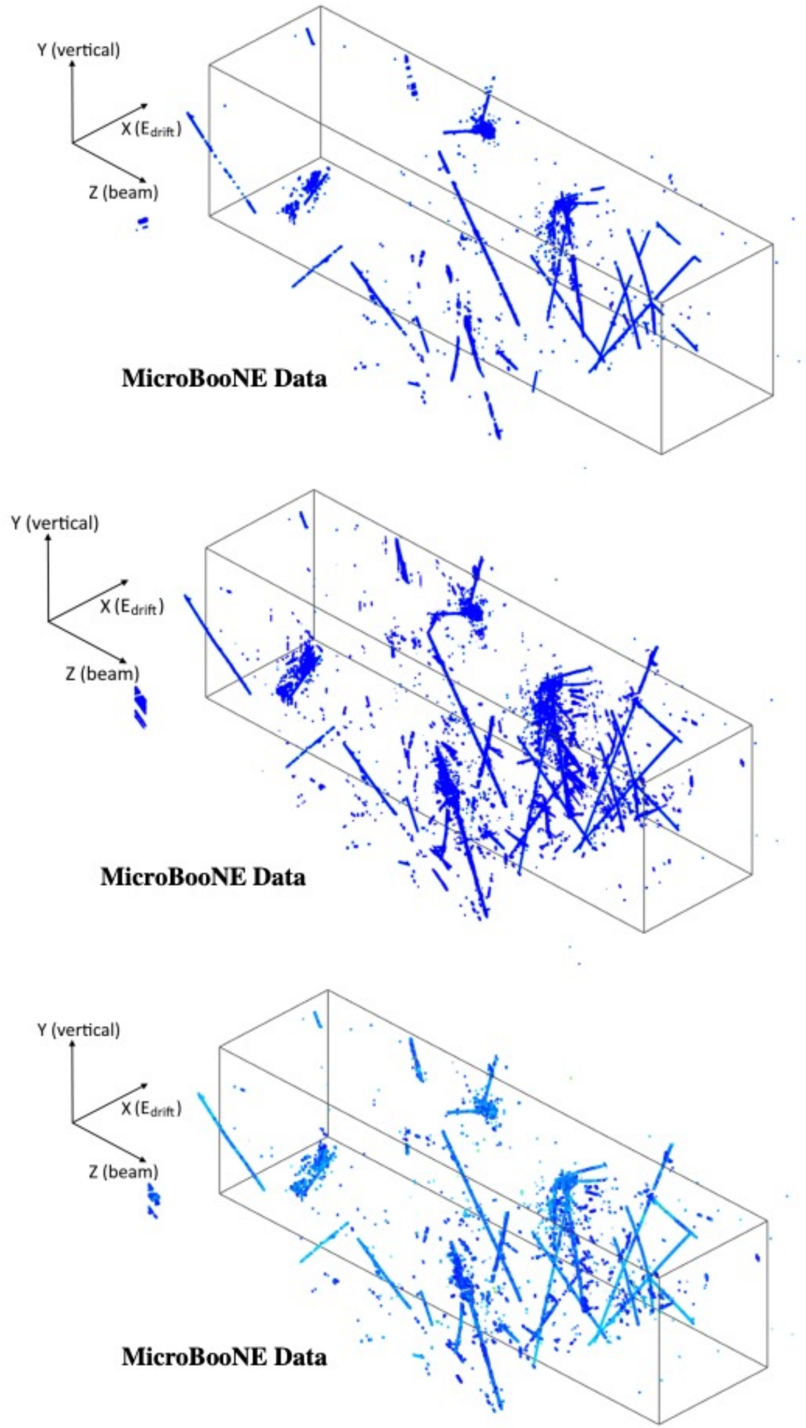
"Three-dimensional Imaging for Large LArTPCs", [JINST 13, P05032 (2018)]


Bee
Run 10711 | Subrun 140 | Event 7036
View
System
cluster
Size
1
8
Opacity
0
1
Plain Color
General
Helper
Monte Carlo
Optical Flash
3-D Imaging
Box of Interest
Time Slice
sliced mode
opacity
0
width
6
position
84
Camera
Ortho Camera
Multi-view
2D View
Reset Camera
Fullscreen
Voice Control
Close Controls
µBooNE
slice #: 35 | slice x: 212.5

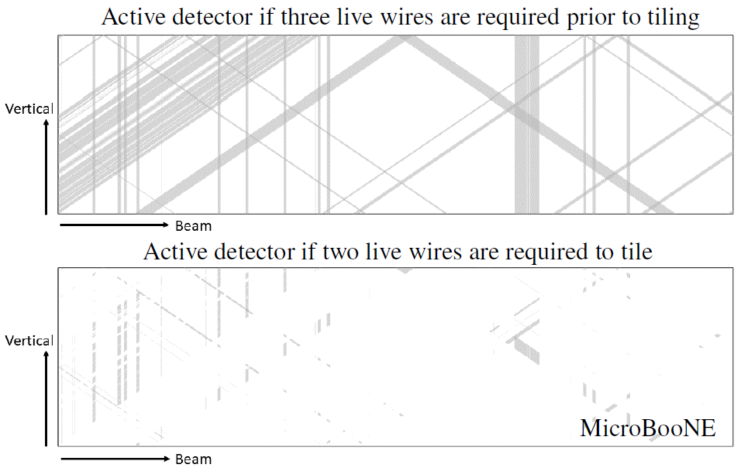
26

de-ghosting

- Solving alone cannot eliminate all ghosts
- In MicroBooNE, the situation is worse when 2-view blobs are allowed
  - 10% dead channels → 3view only is not acceptable
  - **2view tiling is needed → more ghosts**
  - https://arxiv.org/abs/2011.01375
- de-ghosting: larger, connected blobs tends to be true
  - future AI/ML opportunity

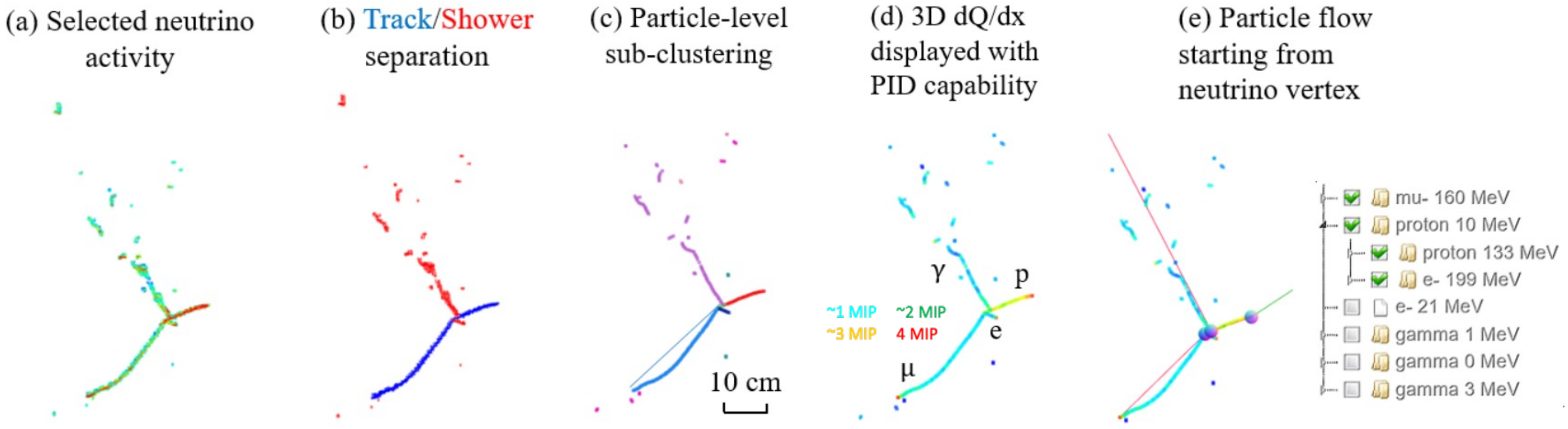


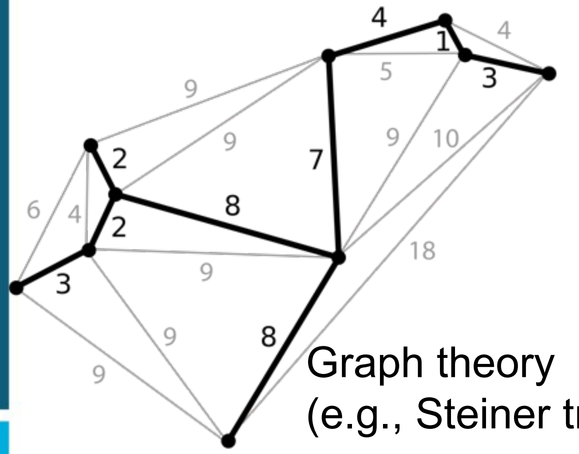
dead regions



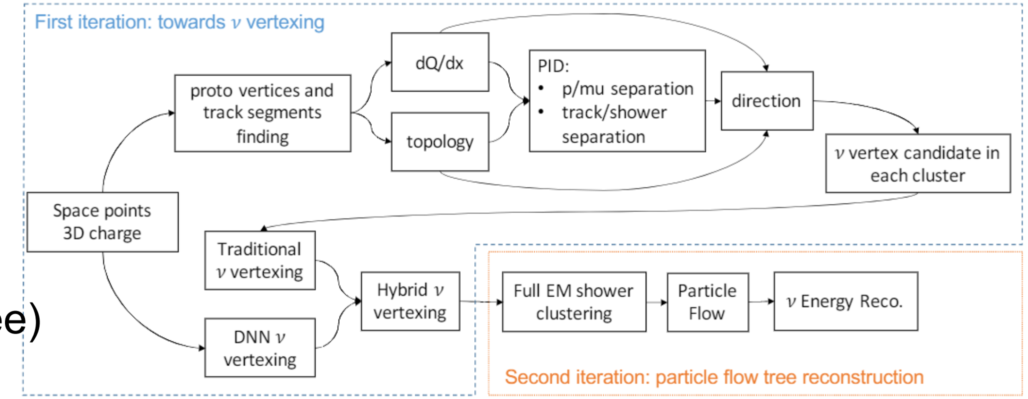
27

3D Pattern Recognition

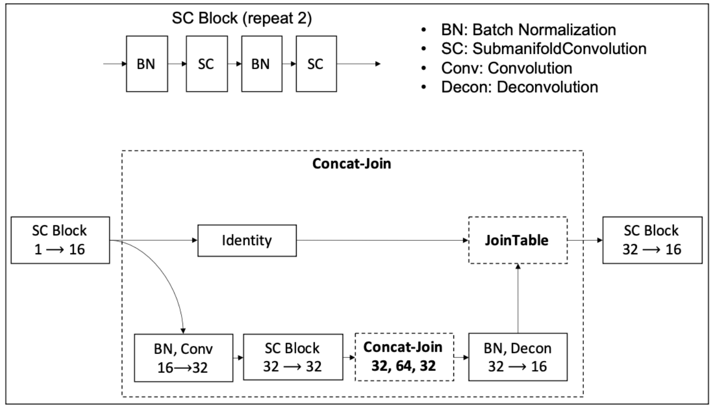




Graph theory
(e.g., Steiner tree)



Sparse Regression U-Net



JINST 17 P01037 (2022)

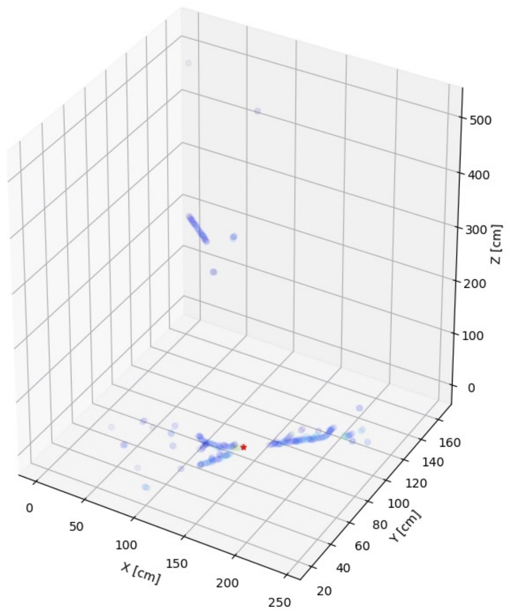
28

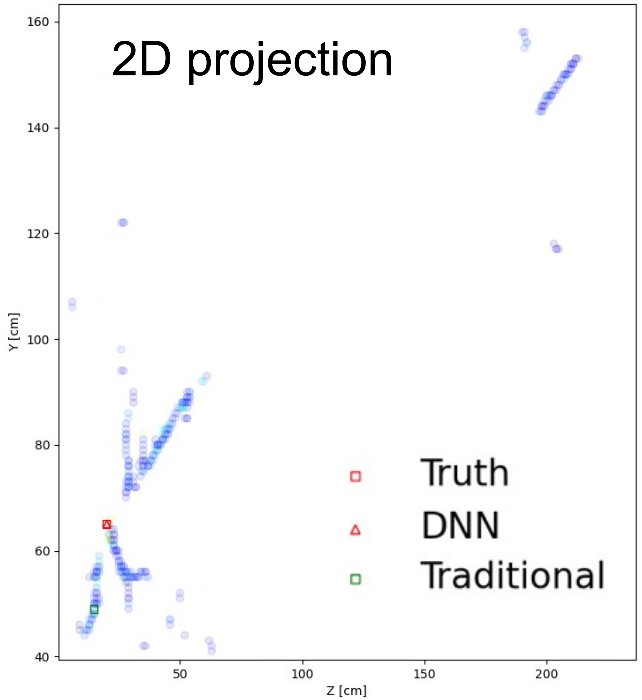
Deep Learning based Neutrino Interaction Vertex Finding

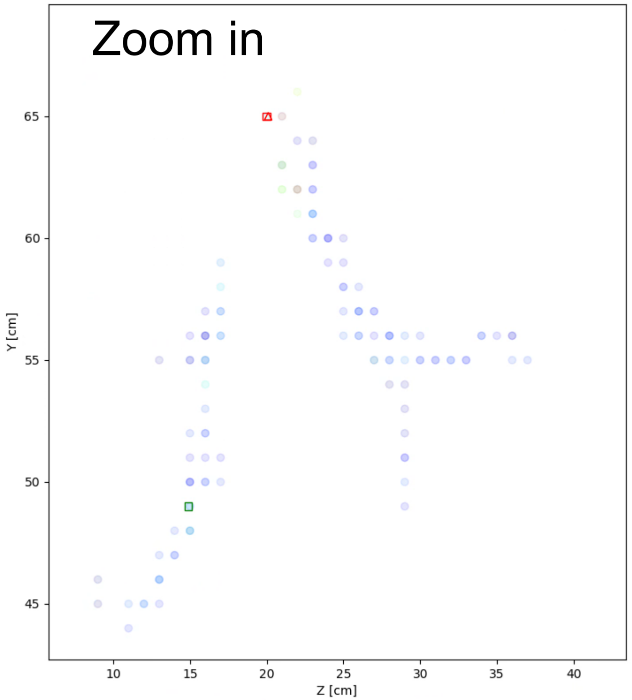
Regressional segmentation with a sparse U-Net

- U-Net: efficiently use geometry info which is critical
  - compared to graph networks
- Regressional loss on distance based “confidence map” to use a region of points instead of only one
  - otherwise, data is highly imbalanced (Z. Cao etc, arXiv:1812.08008)
- Sparse: boosted computing efficiency with our sparse 3D data
  - Submanifold Sparse Convolutional Networks (B. Graham etc, arXiv:1706.01307)

3D points from Wire-Cell







29

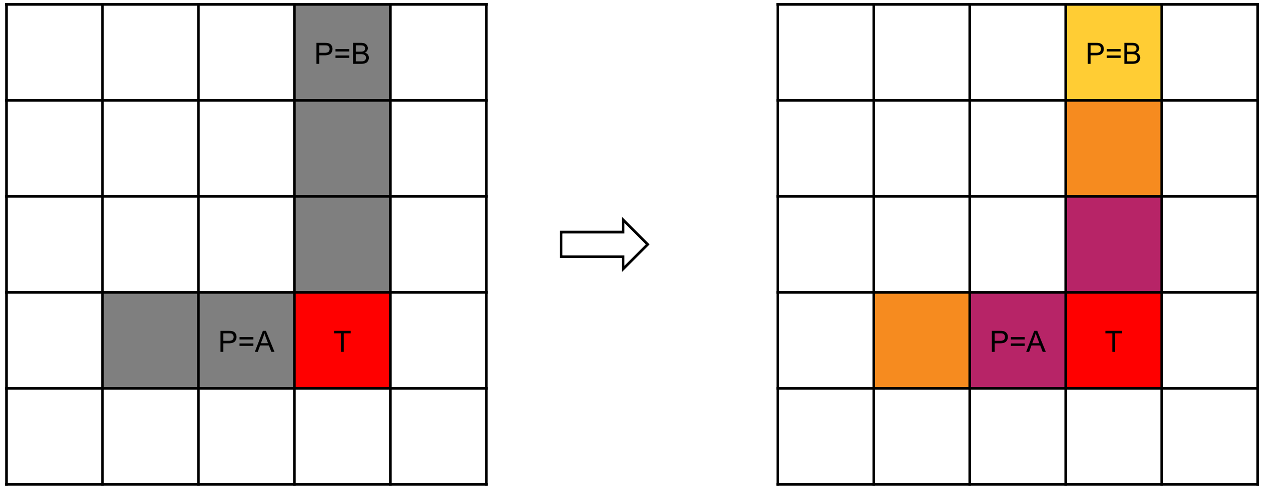
Regressional segmentation

Initially we used Cross Entropy loss
- effectively only use the vertex information for one space point
- doesn’t care about the distance between the prediction and the target.
    - while our main metric is this distance.

⟶ encode the distance information for a region of points
- predicting the full “confidence map” instead of only one point

- current mapping: $\mathrm{Conf}_{\mathrm{truth}} = \exp\left(-\frac{\|\vec{x} - \vec{v}_{\mathrm{truth}}\|^2}{2\sigma^2}\right)$

OpenPose:
https://arxiv.org/pdf/1812.08008.pdf



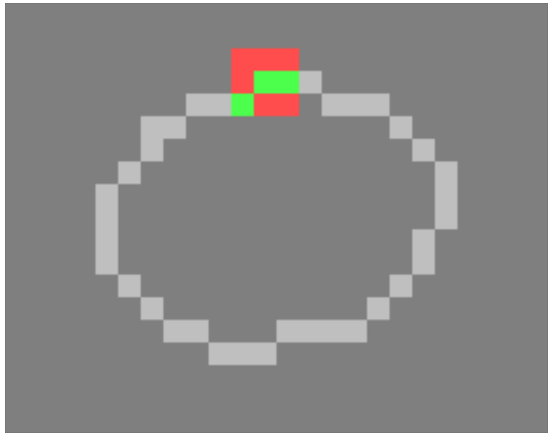
30

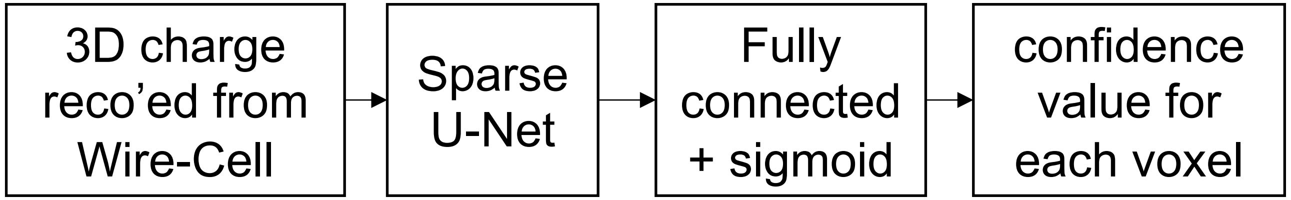
Network structure and data format

Used *SparseConvNet* to realized 3D sparse conv. DNN
https://github.com/facebookresearch/SparseConvNet

This work: https://github.com/HaiwangYu/uboone-dl-vtx

SparseConvNet

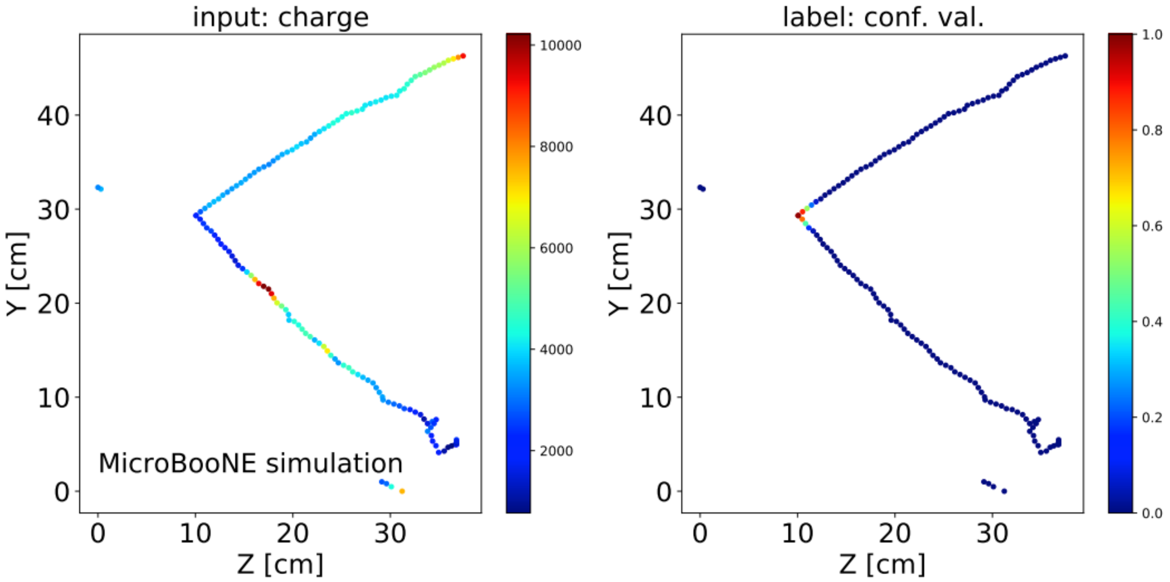




coordinates			features		label
x	y	z	q	…	conf.
int	int	int	float	…	float
int	int	int	float	…	float
int	int	int	float	…	float
…	…	…	…	…	…

input: color is charge

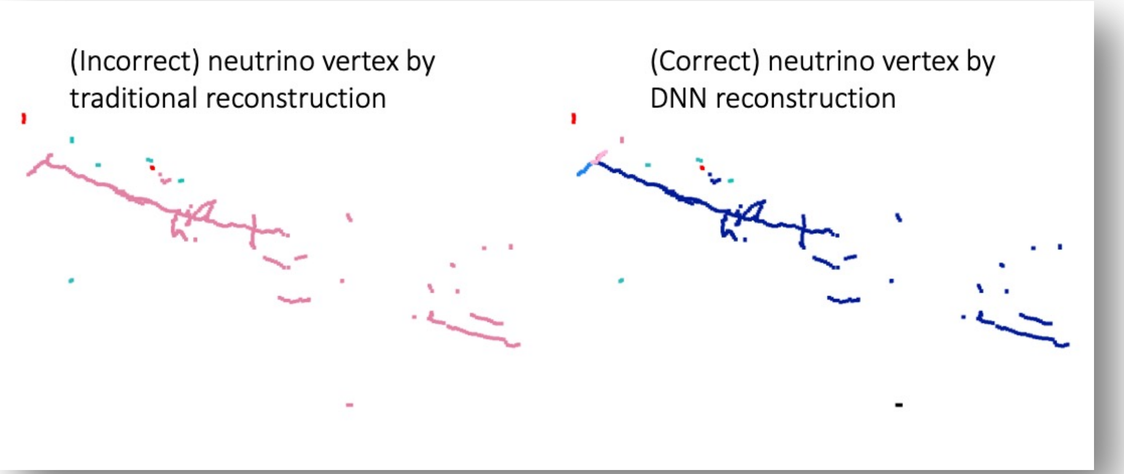
label: color is truth confidence map



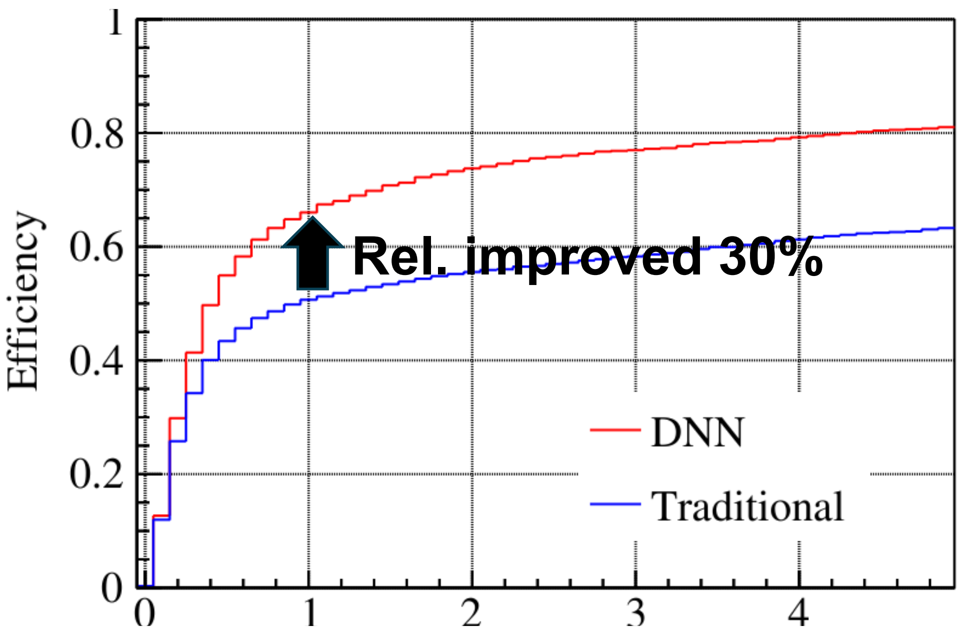
Deep Learning based Neutrino Interaction Vertex Finding

JINST 17 P01037 (2022)

Illustration of impact of vertex ID on the full event reconstruction



ν_eCC vertex identification efficiency



Distance between reco. and true vertex (cm)

32

Summary

- ❑ LArTPC technology provides unique opportunities for new physics
- ❑ Successful of LArTPC based experiment requires efforts made to both hardware and software
  - Software can not solve everything
  - AI/ML fits many tasks in LArTPC reconstruction
    - Human understanding of LArTPC is also important

backup

Demo

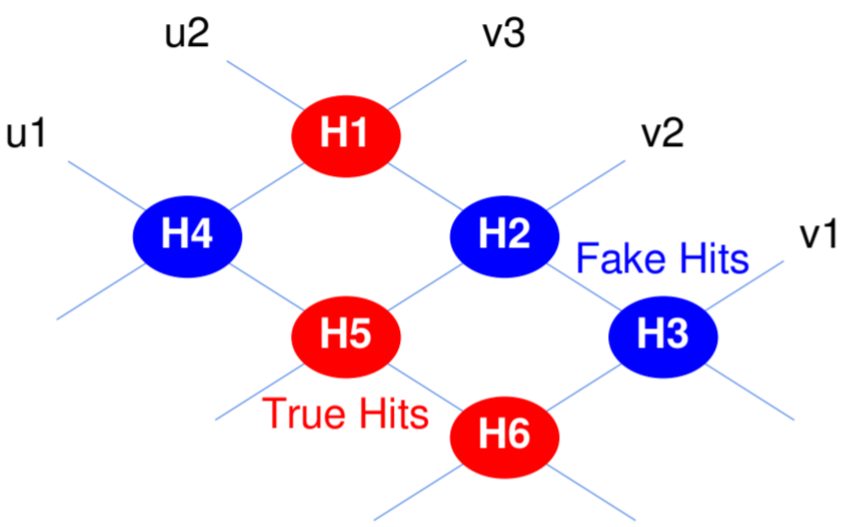
- Prerequisites: Linux OS (bare metal or VM)
- https://github.com/HaiwangYu/wct-demo
- Tools used in the demo:
  - git, Linux commands, singularity container, bash script, editor
  - wire-cell-toolkit (C++, jsonnet)
    - gen/src/DepoTransform.cxx
    - sigproc/src/OmnibusSigProc.cxx
  - ROOT

Construct Linear Equations

$$y = Ax$$

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

Use two planes as an illustration



At one time slice

y: measured charge signal on each wire
x: the (unknown) true charge deposition in each possible cell
A: bi-adjacency matrix connecting wires and cells (determined solely by wire geometry)

Desired Solution $x = \begin{pmatrix} H1 \\ 0 \\ 0 \\ 0 \\ H5 \\ H6 \end{pmatrix}$

Solve underdetermined linear problem: regularization

$$\chi^2 = (y - Ax)^T \cdot V^{-1} \cdot (y - Ax)$$
$$\equiv \|y' - A'x\|_2^2,$$

- Previous example has 6 unknowns, 5 equations: under-determined system

$$x = (A^T V^{-1} A)^{-1} A^T V^{-1} \cdot y$$

↓ non-invertible, 2 zero-eigenvalues out of 6.

- Adding constraints: find the sparsest solution (applies to most physics events): L0-regularization

minimize $\|x\|_0$, subject to: $y = Ax$

(L0-norm: number non-zero elements)

NP-hard!

https://web.stanford.edu/~yyye/lpmin_v14.pdf

Procedure

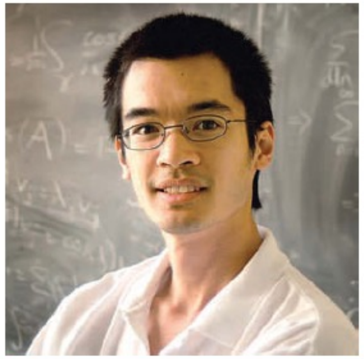
- Remove unknowns until equations can be solved, then find the best solution with the minimum χ^2
- a combinatorial problem
  - 2 out of 6: 15 combinations
  - 10 out of 40: 0.8 billion combinations

Compressed Sensing (L1-regularization)

- Breakthrough: mathematical proof that L0 problem can be well approximated by the L1 problem (Compressed Sensing, *Candes, Romberg, and Tao, 2005*.)

Emmanuel Candes. *(Photo courtesy of Emmanuel Candes.)*

Justin Romberg. *(Photo courtesy of Justin Romberg.)*



Terence Tao. *(Photo courtesy of Reed Hutchinson/UCLA.)*

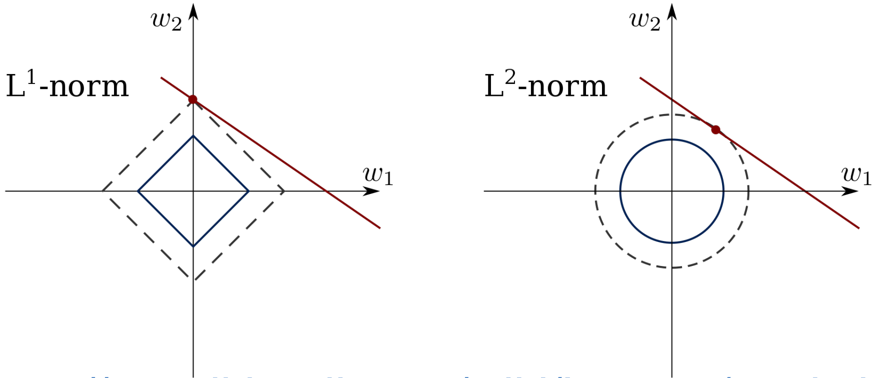
https://arxiv.org/abs/math/0503066

minimize $||x||_1$, subject to: $y = Ax$

(L1-norm: sum of absolute values of the elements)

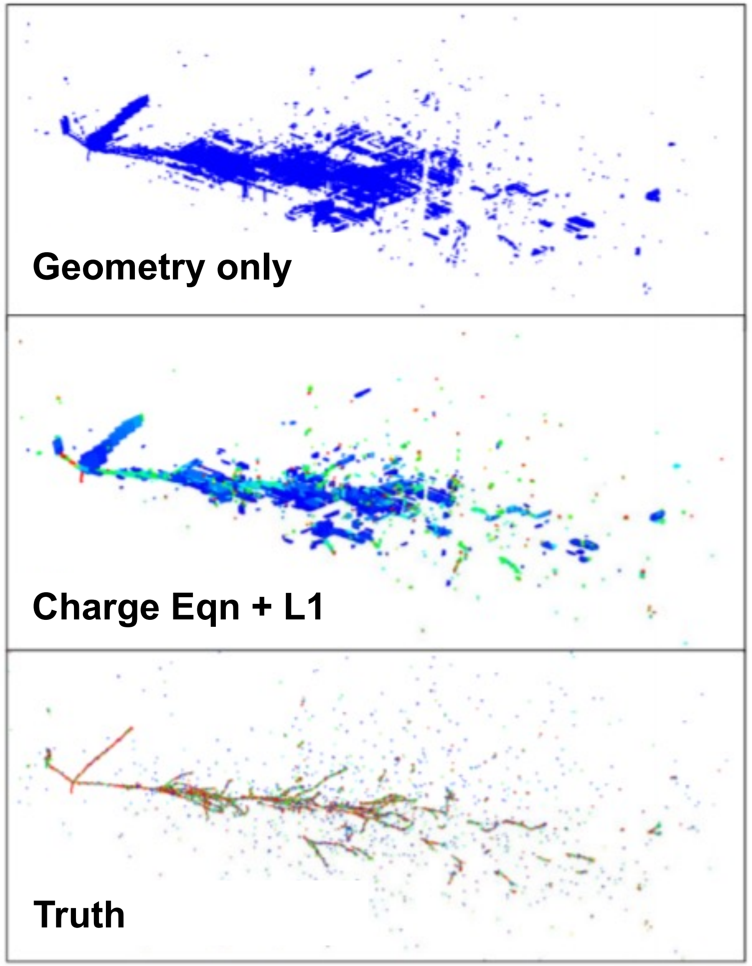
Or, equivalently, minimize

$$\chi^2 = (y - Ax)^T \cdot V^{-1} \cdot (y - Ax) + \lambda||x||_1$$

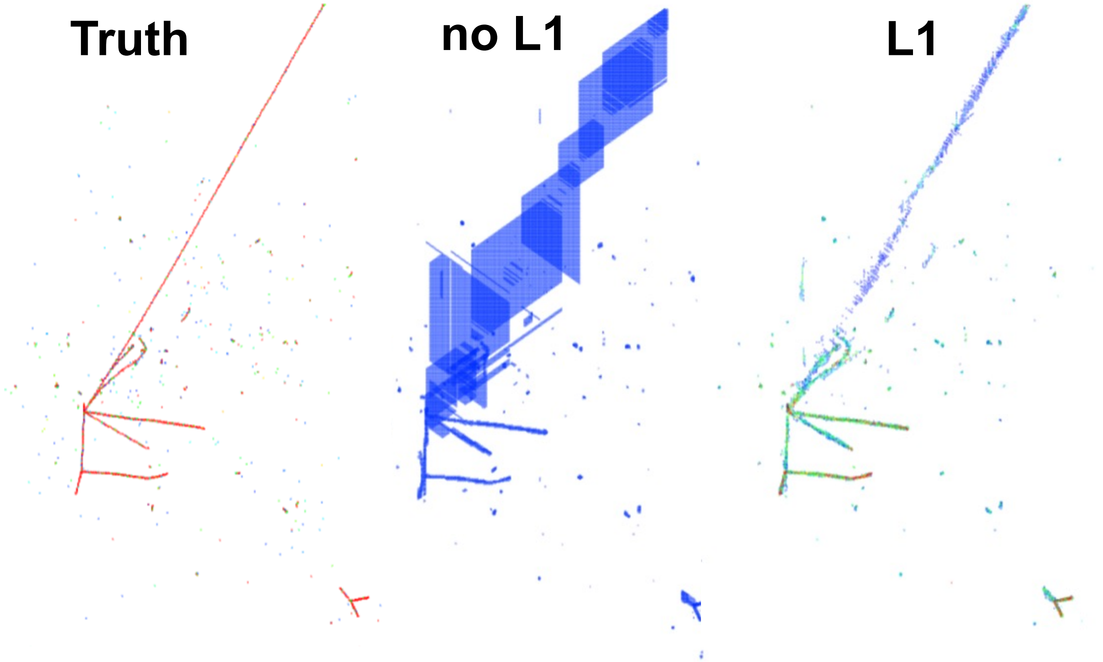


https://en.wikipedia.org/wiki/Lasso_(statistics)

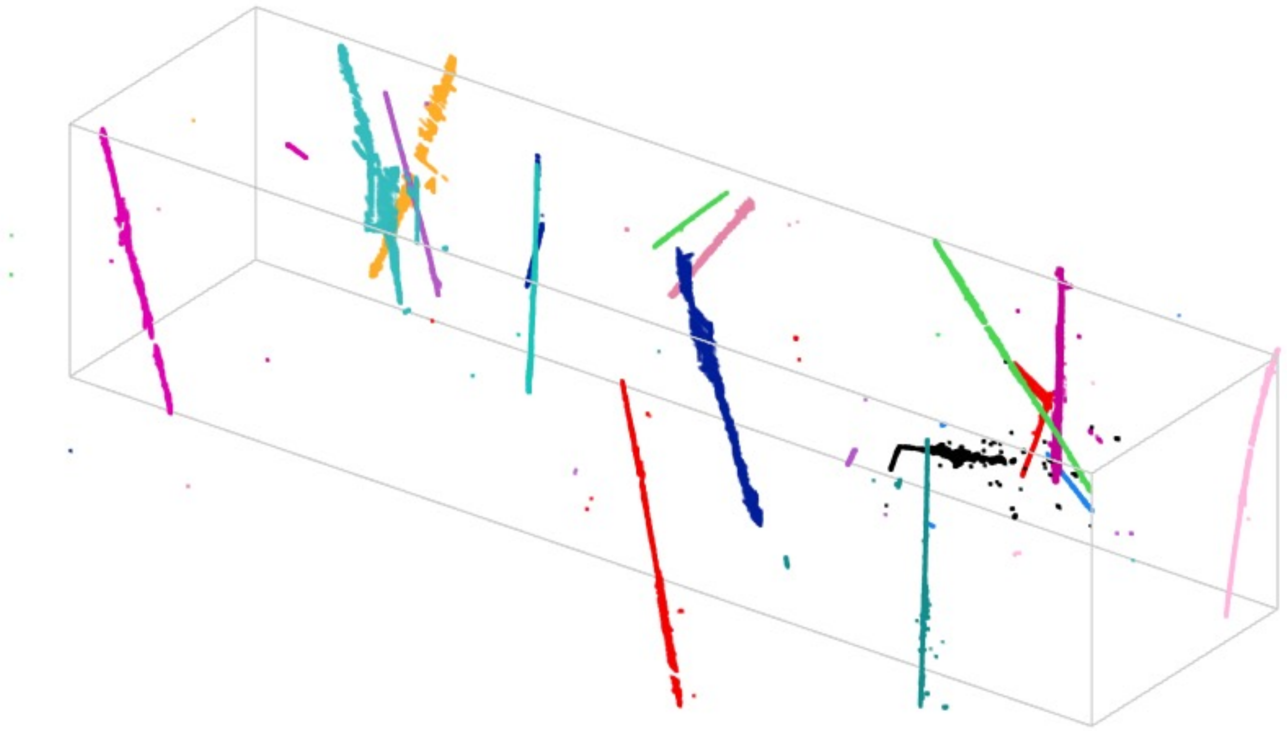
Performance in Wire-Cell



JINST 13, P05032 (2018)



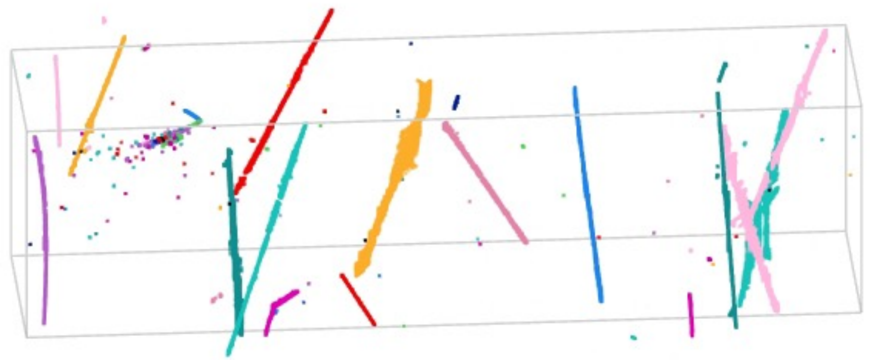
- Typically, ~tens of seconds to reconstruct the whole 3D image (originally a few hours)



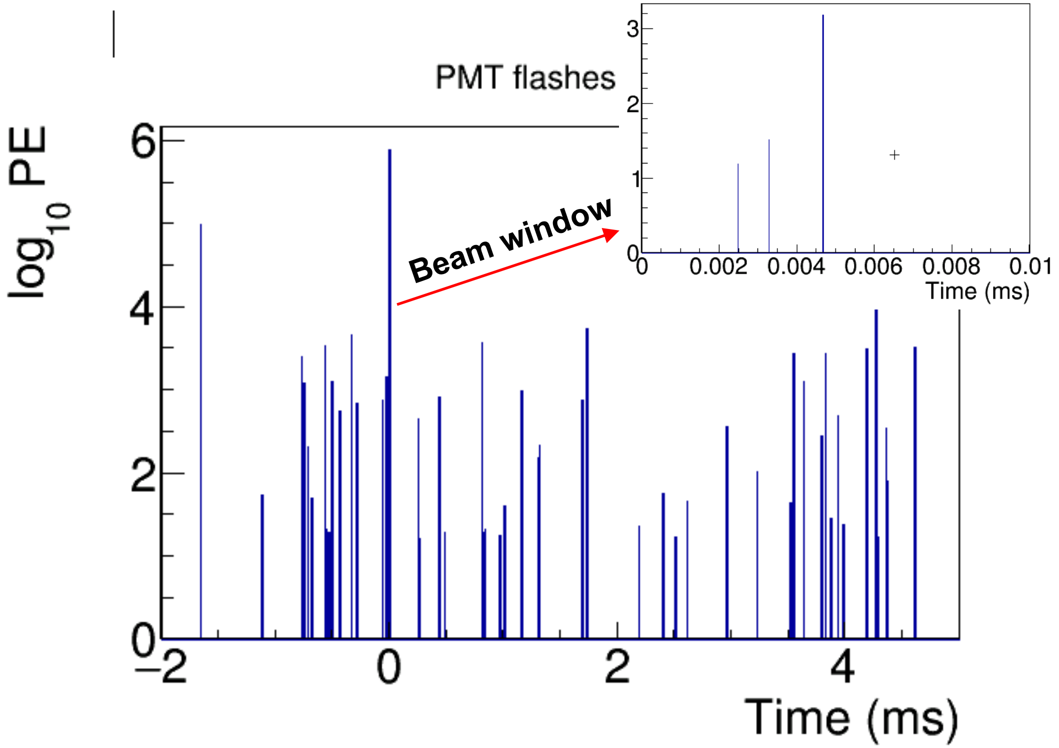
An example MicroBooNE event after 3D reconstruction

Finding Neutrino Interaction

4.8 ms drift window



20-30 TPC activities



40-50 PMT activities

- ❑ 3D Cluster based on proximity (kd-tree)
- ❑ associate the light flash to the corresponding TPC cluster based on light pattern

- BEST, Baksan Experiment on Sterile Transitions, nue source
- C. Zhang, Neutrino Mass Hierarchy