Event Reconstruction for High Precision Neutrino Physics in LArTPCs

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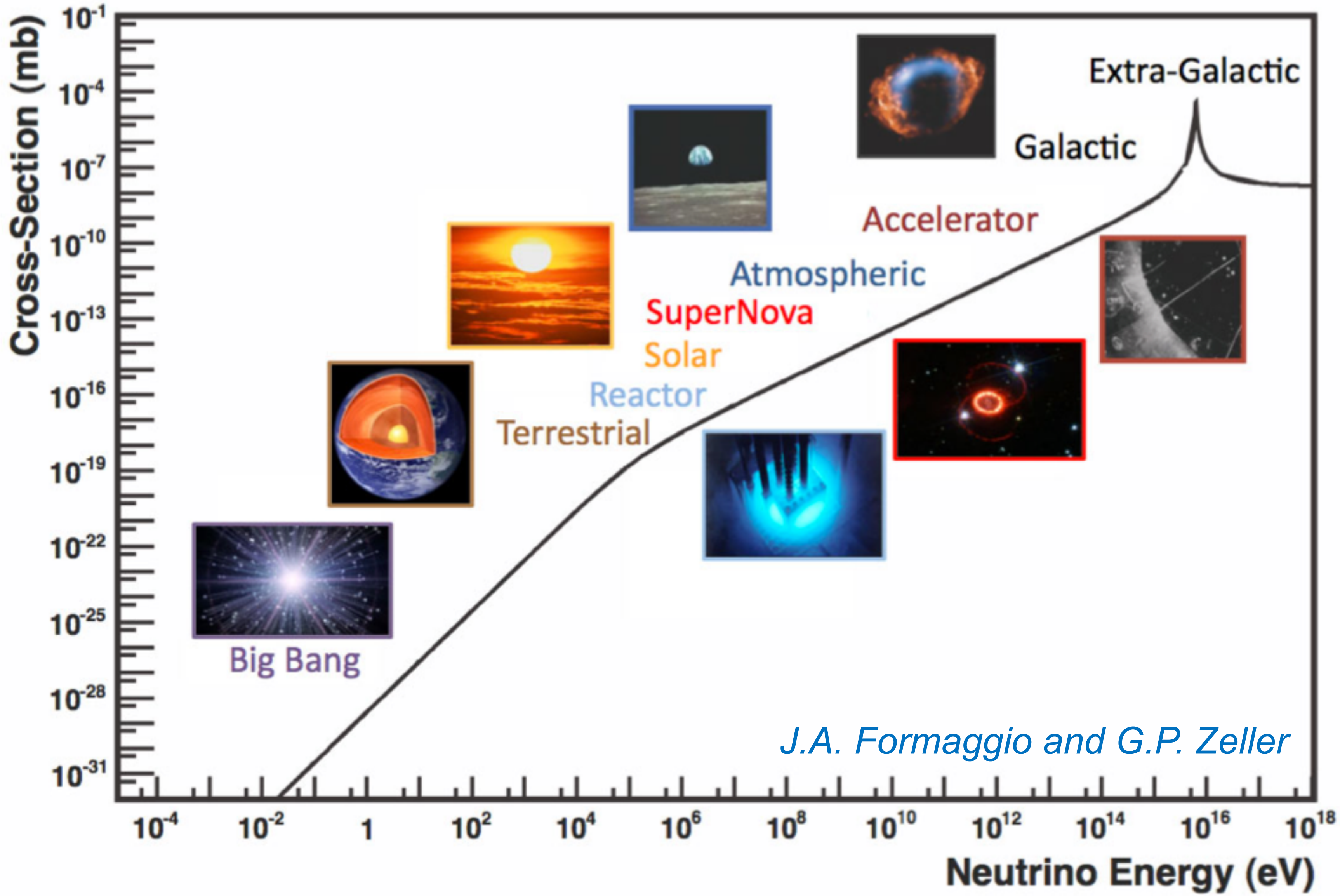
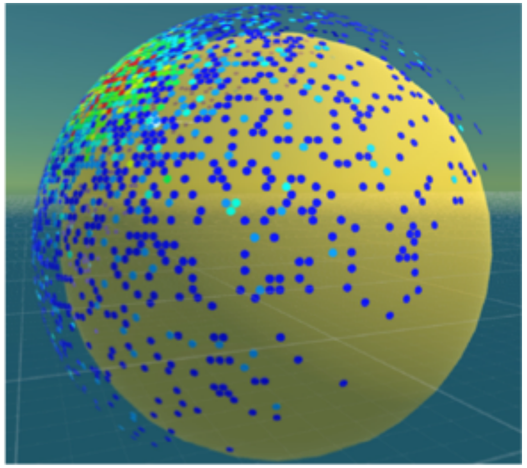
Apr. 7th, 2020 @ Home (ZOOM)



Neutrinos come in a wide variety of energies & physics!

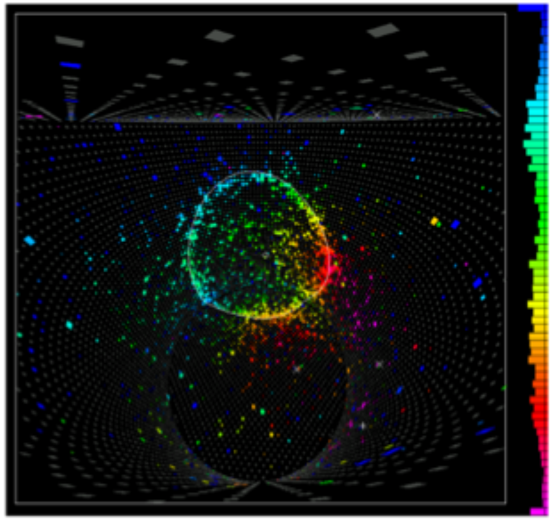
Neutrino Detection

- **Scintillator + PMT** -- Cowan-Reines experiment in 1956, first detection of neutrinos (reactor neutrinos)
- **Spark chamber** (segmented) – L. Lederman*, et al.* experiment in 1962, the discovery of ν_μ (first measurement of accelerator neutrinos)
- **Radiochemical reaction** (counter) -- R. Davis's experiment in 1967, (first measurement of solar neutrinos)



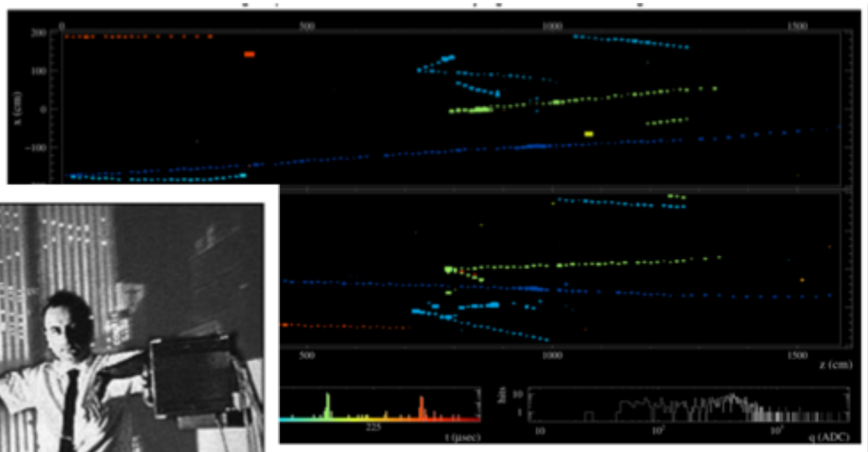
JUNO
Scint. + PMT

Super-K
Cherenkov + PMT



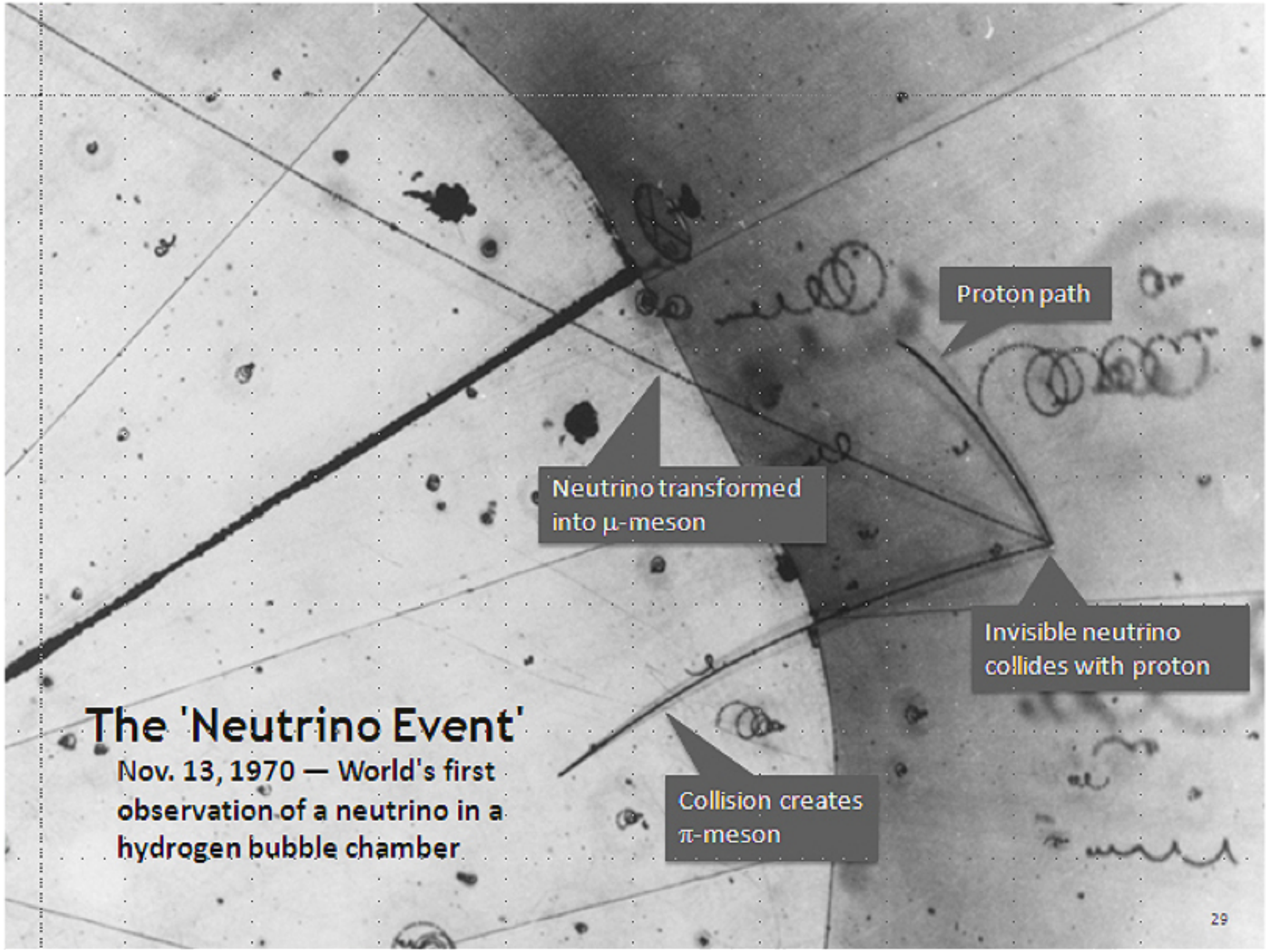
Mel Schwartz
Spark chamber

Large sampling (segmented scintillator)



NOvA
Scint. cells

First *Image* of Neutrino Interaction – Bubble chamber



Bubble chamber: Gargamelle
 -- discovery of neutral current
Nuclear emulsion: DONUT, OPERTA
 -- discovery of ν_τ

Neutrino Detectors

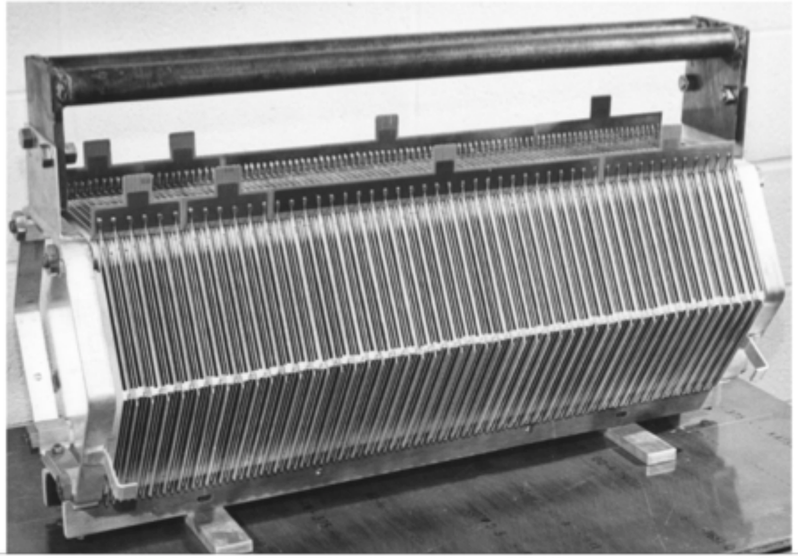
- ***Massive (**only weak interactions**)***
- ***Calorimeter***
- ***Topology***
- ***Massive + Calorimeter + Topology? – powerful particle identification***

Liquid Argon (LAr) Calorimeter

- During 1972-1974, Bill Willis (Yale) and Veljko Radeka (BNL) designed and built the first LAr sampling electromagnetic calorimeter (200 1.5 mm plates + 2 mm LAr gaps)

→ CERN Intersecting Storage Rings (ISR)
→ ATLAS

Electronics readout
Integral system design



LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

W. J. WILLIS†

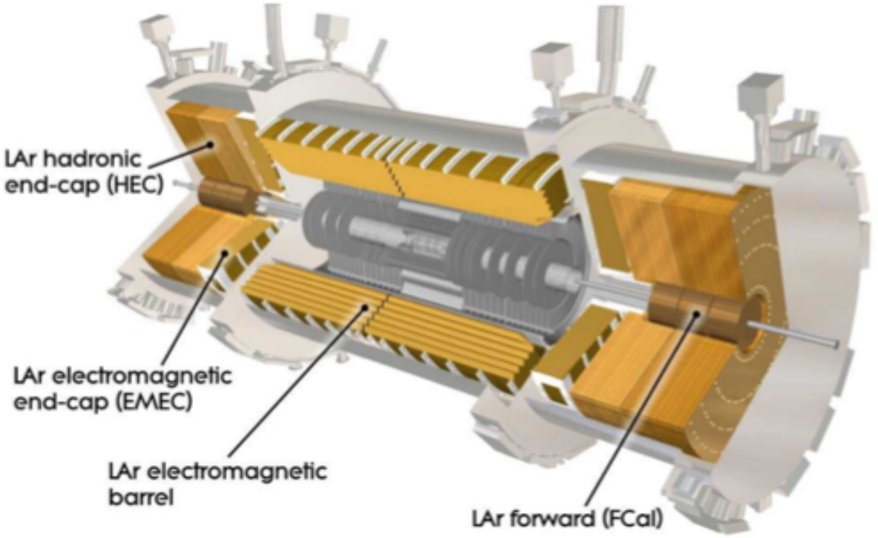
Department of Physics, Yale University, New Haven, Connecticut 06520, U.S.A.

and

V. RADEKA

Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

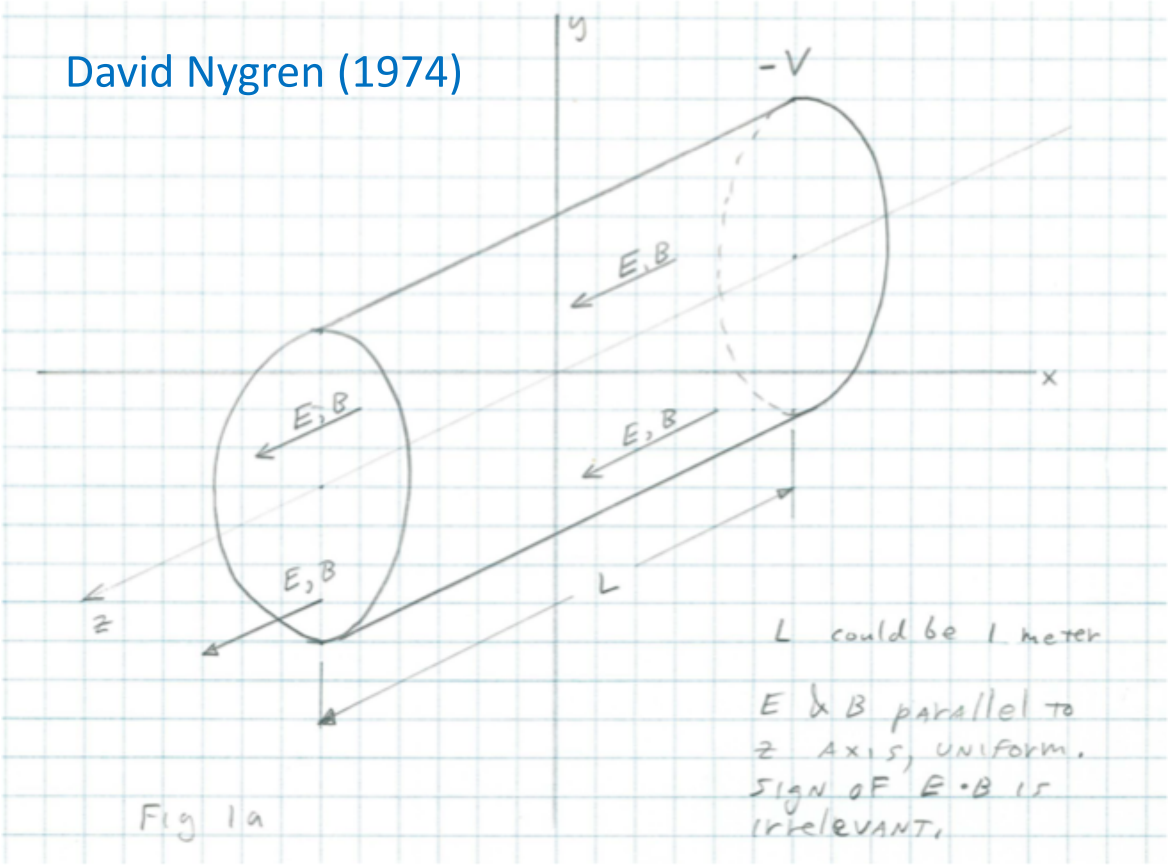
Received 14 May 1974



ATLAS Lar Calorimeter System

Time Projection Chamber (TPC)

- In 1974, David Nygren (LBNL) proposed a novel concept of TPC in a LBL internal report “Proposal to Investigate the Feasibility of a Novel Concept in Particle Detection”



LAr + TPC

"There has been a growing need for novel device which combines the large amount of specific information on the topology of the events of a bubble chamber with the much larger mass, timing, and geometrical flexibility of a counter experiments" – C. Rubbia

A NEUTRINO DETECTOR SENSITIVE TO RARE PROCESSES

I. A STUDY OF NEUTRINO ELECTRON REACTIONS

H. H. Chen, P. E. Condon
University of California
Irvine, California 92717

B. C. Barish, F. J. Sciulli
California Institute of Technology
Pasadena, California 91109

1976 Herbert Chen
FNAL proposal 496

1977 Carlo Rubbia
CERN internal report

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

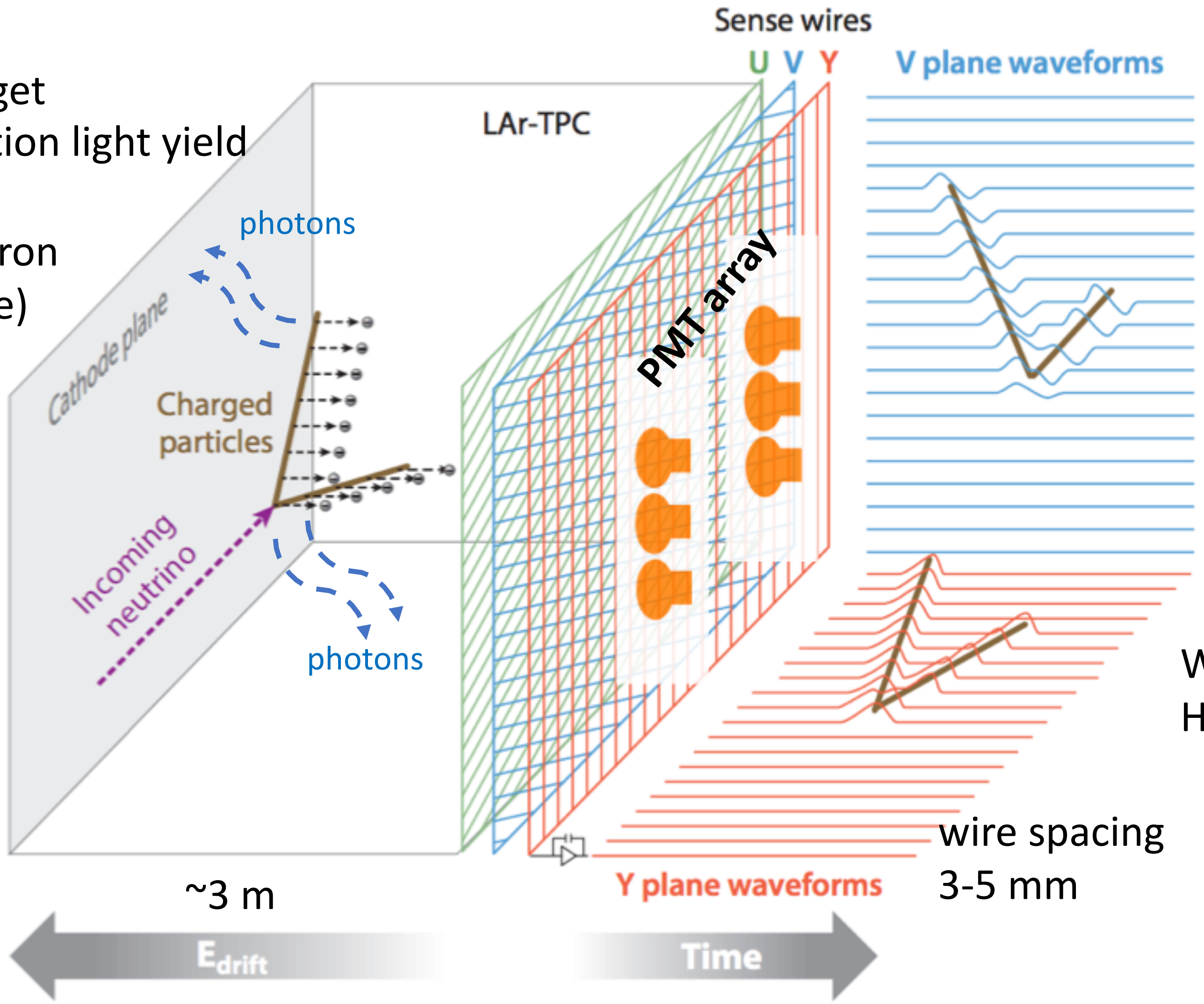
A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

A typical LArTPC design (single-phase)

Liquid Argon

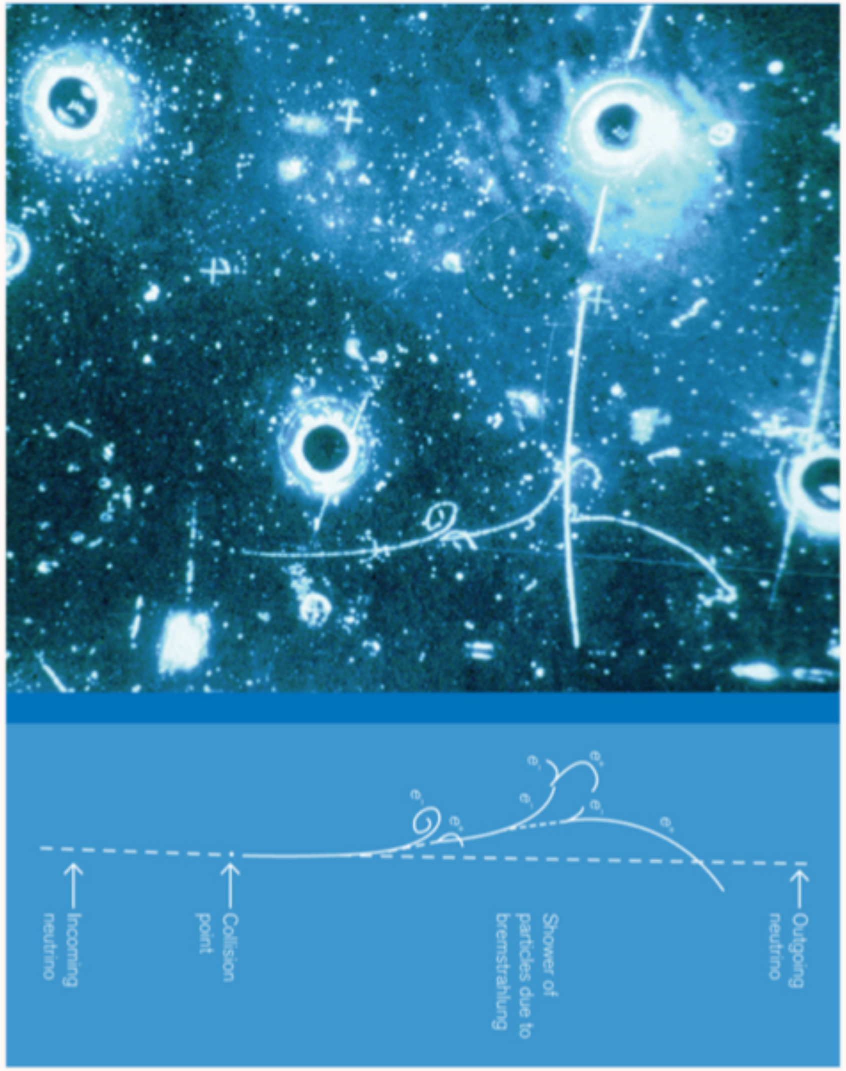
- Dense, homogeneous, active target
- High ionization electron/scintillation light yield
- High electron mobility
- can be made pure with low electron attachment (long drift, large scale)
- Abundant (low cost)



Wire readout scheme:
Heat loads & Cost

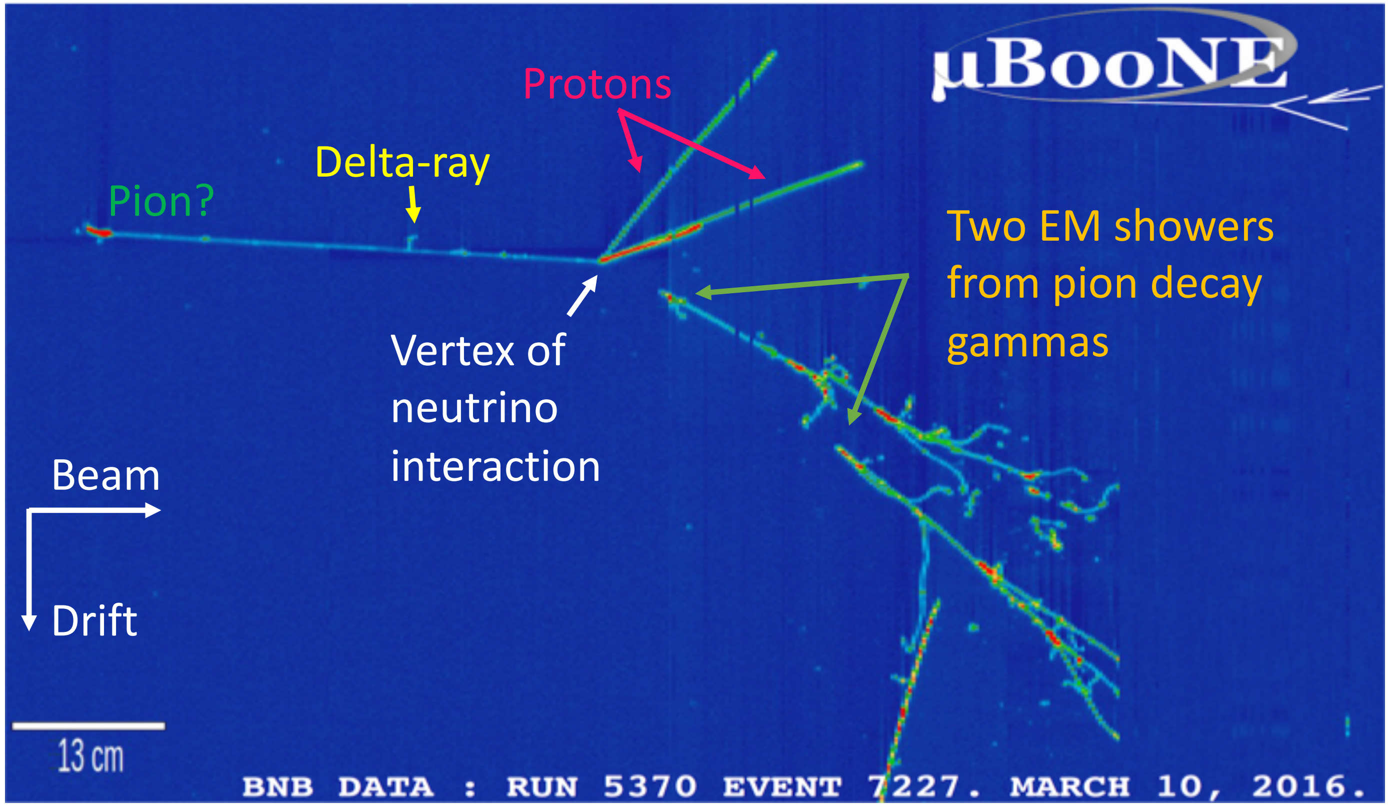
wire spacing
3-5 mm

50 years: from Bubble chamber to LArTPC



Gargamelle (1973): discovery of weak neutral current [$\nu_\mu e^- \to \nu_\mu e^-$]

Fun facts: $CBrF_3$ (bubble chamber liquid) is very similar to LAr in many aspects, e.g. density, dE/dx, radiation length, absorption length, etc.



MicroBooNE (2016): probably a neutral current interaction of ν_μ
Full time electronics readout (cold ASIC)

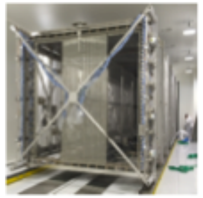
LArTPC detectors

1977 — 2009 — 2010 — 2015 — 2018/9 — 202?

Membrane cryostat technology
Argon purging
High-voltage system
Integral system design
Cold electronics
…

Argonneut @ FNAL
240 kg, 2009-2010

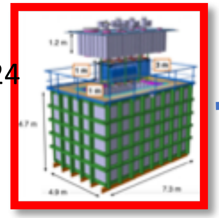
ICARUS T-600 @ CNGS, 760 ton,
2010-2014, moved to Fermi 2017



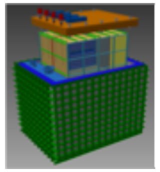
MicroBooNE @FNAL 170
ton, 2015-

35-t prototype
@FNAL 2015-2016

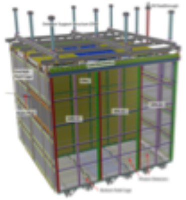
WA105 3x1x1 m^3 24
ton, 2016



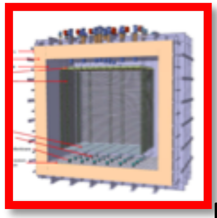
SBND @ FNAL
112 ton active, 2019



protoDUNE-SP (NP04) 0.77kt,
2018- @CERN

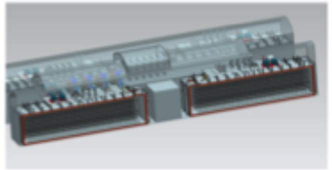


protoDUNE-DP (NP02)
0.7kt, 2018 @CERN

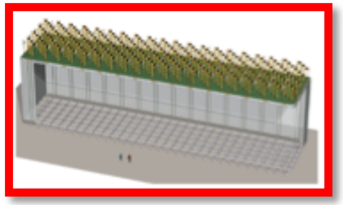


Dual-Phase

DUNE reference design
10-kt module

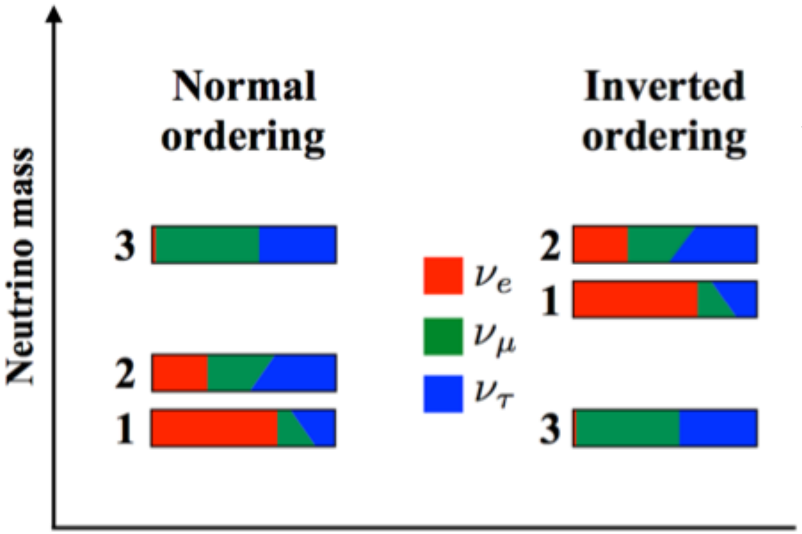


4×10-kt modules



Neutrino Oscillation

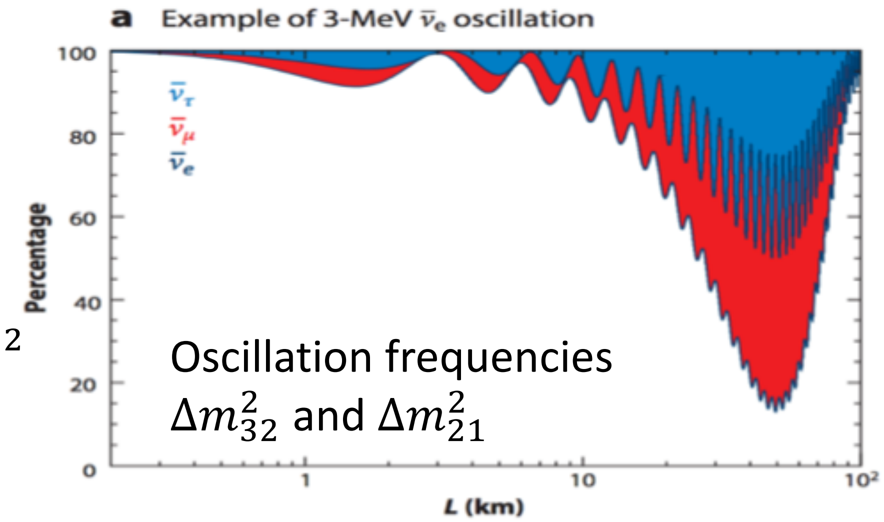
Neutrino flavor eigenstate = mixture of mass eigenstates



$\Delta m_{21}^2 \simeq 7.4\times10^{-5}\ eV^2 (\pm1.3\%)$

$|\Delta m_{32}^2| \simeq 2.5\times10^{-3}\ eV^2\ (\pm2.8\%)$

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$



Oscillation frequencies Δm_{32}^2 and Δm_{21}^2

Known unknowns:

θ_{23} octant
Dirac CP phase
Mass ordering

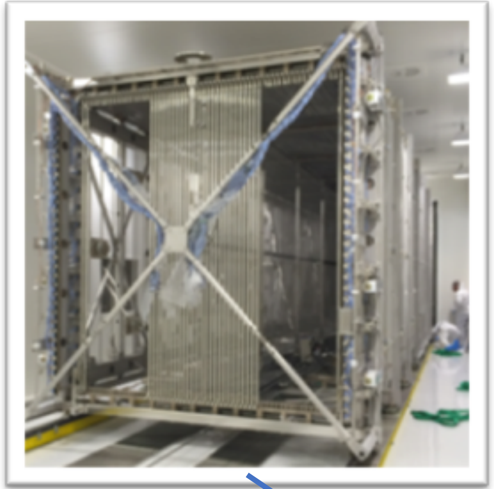
Unknown unknowns:

Majorana particle?
Sterile neutrino (>3 flavor)?
Beyond standard model?

Short-Baseline Neutrino Program

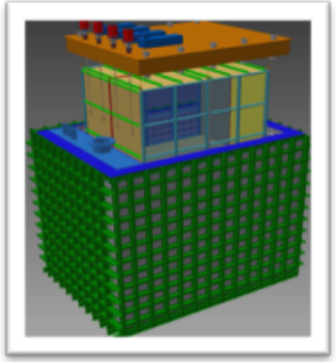
Three detectors (LArTPCs) to perform sensitive searches for ν_e appearance and ν_μ disappearance in the Booster Neutrino Beam.
MicroBooNE is the first detector taking data in SBN program.

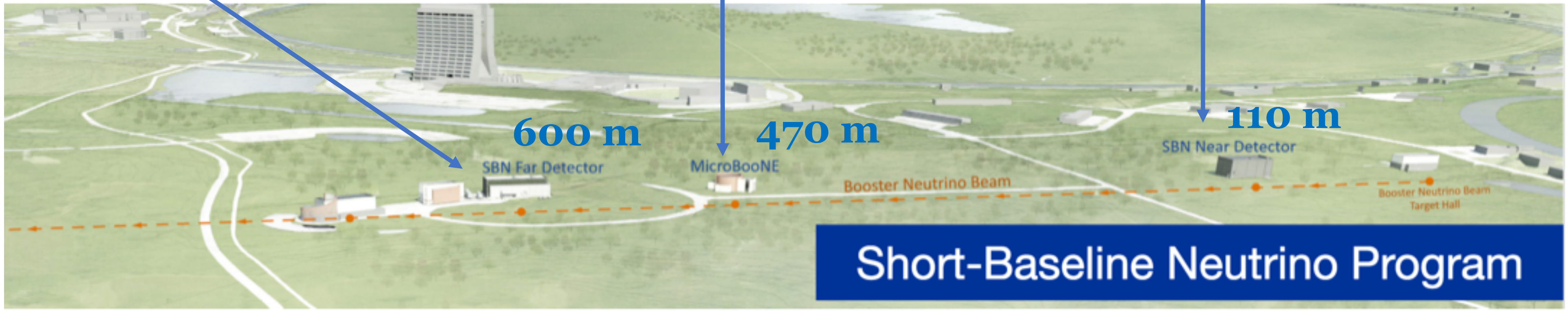
ICARUS T-600, 760 ton
moved to Fermi 2017



MicroBooNE 170 ton
2015-

SBND 112 ton

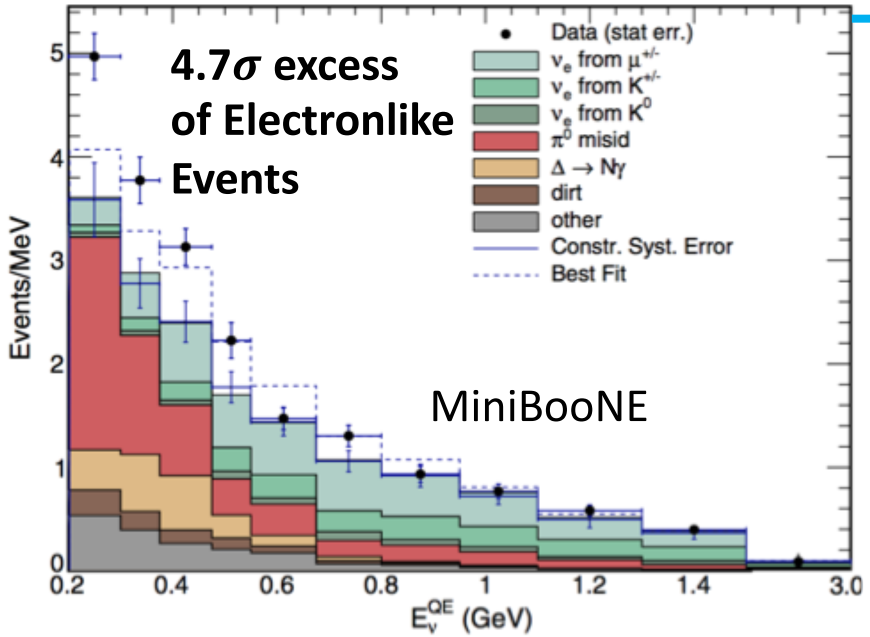




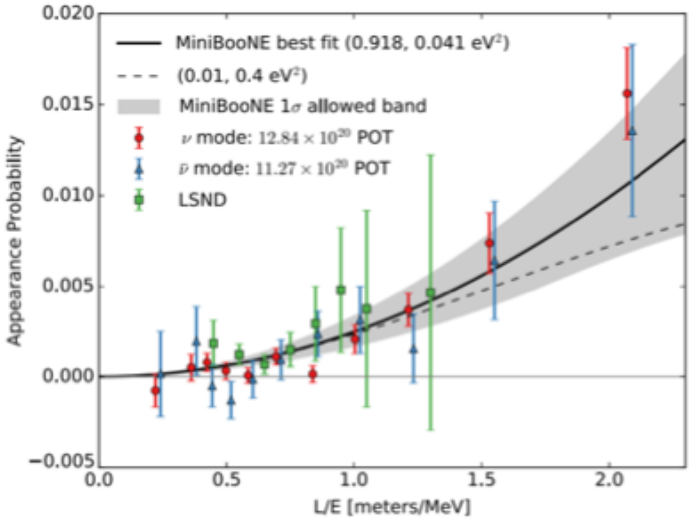
Negligible ν_e appearance ($\nu_\mu \rightarrow \nu_e$ oscillation) in 3 active neutrino scenario

Physics of Short-Baseline Neutrino Program

Phys. Rev. Lett. 121, 221801 (2018)

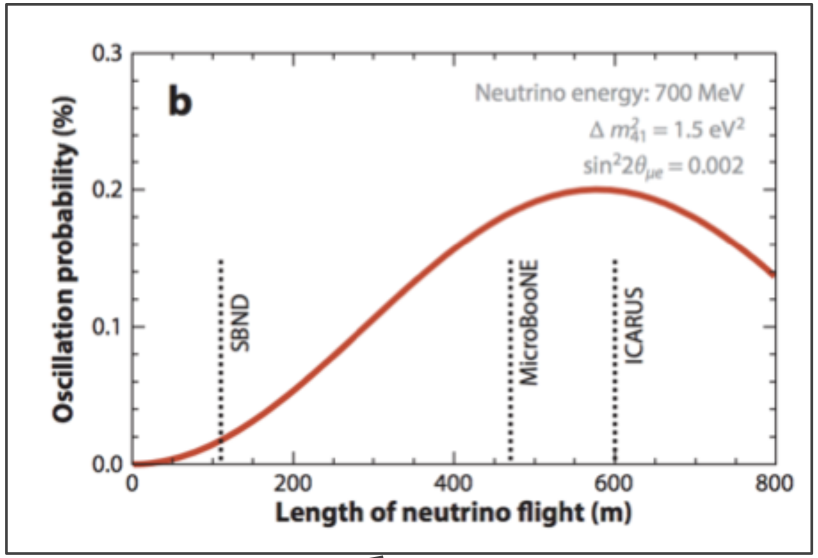


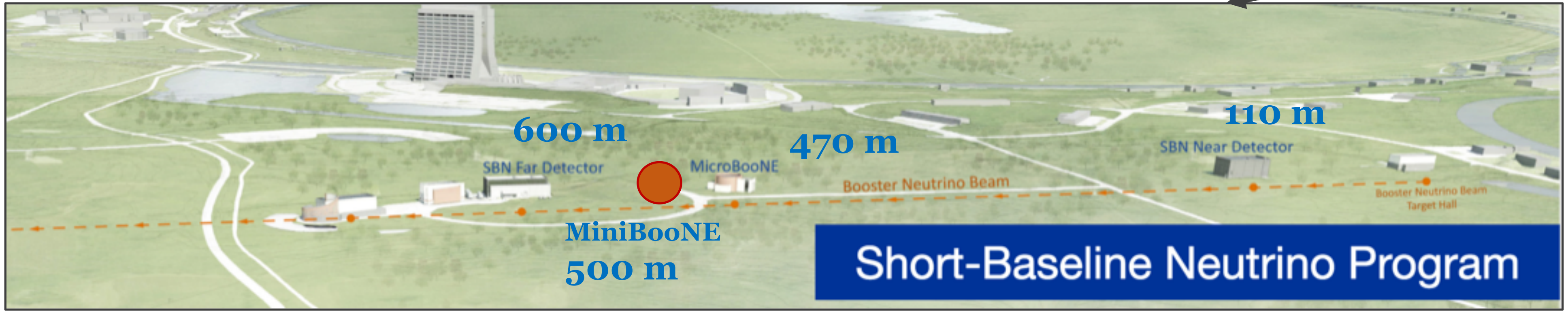
2+1 **sterile neutrino fit**



ν_e appearance (+ sterile neutrino)

Annu. Rev. Nucl. Part. Sci. 2019. 69



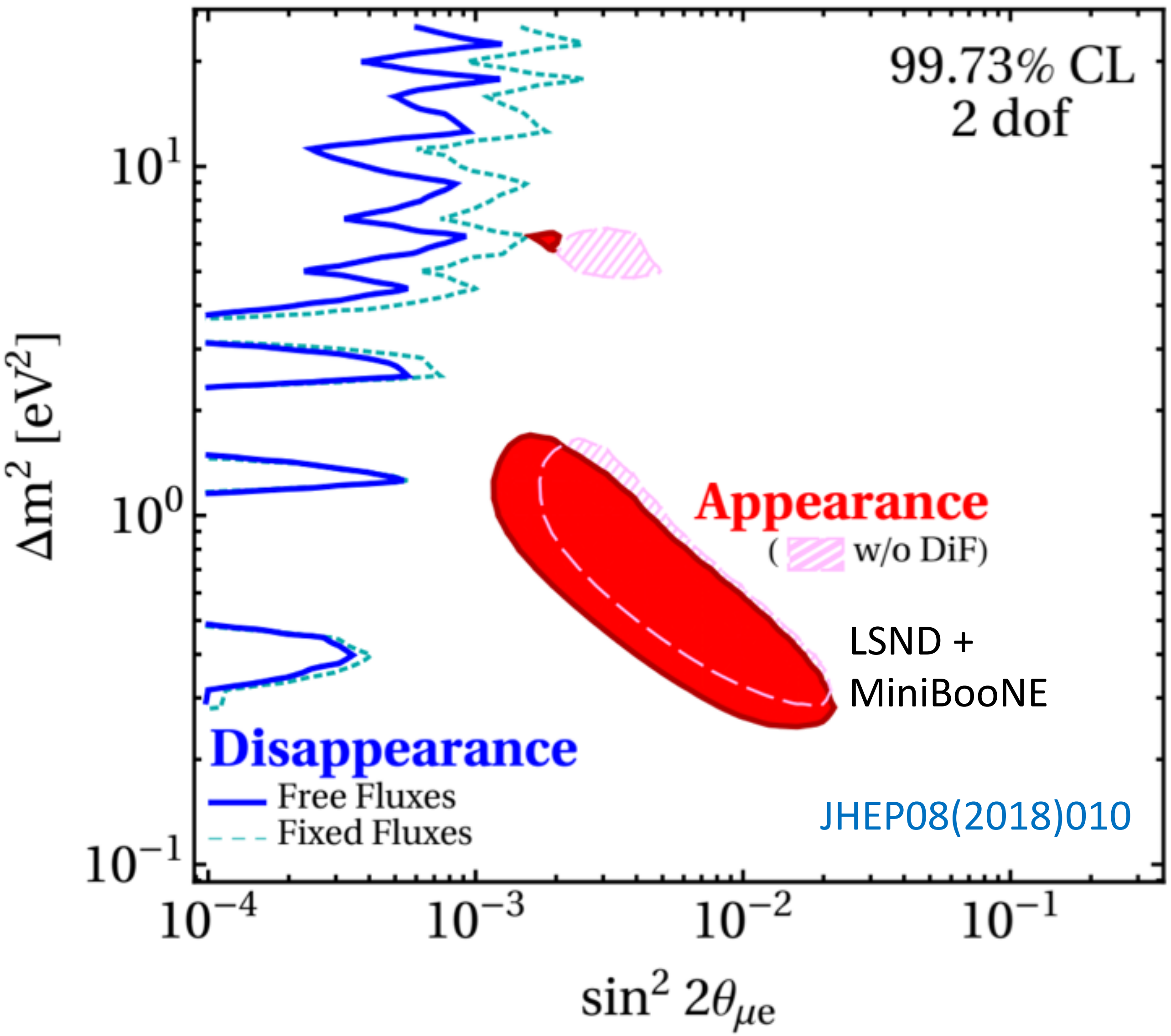


Origin of the short-baseline anomalies?

Negligible ν_e appearance ($\nu_\mu \to \nu_e$ oscillation) in 3 active neutrino scenario

Other explanations of Low Energy Excess

Global fit in a 3+1 sterile neutrino scenario



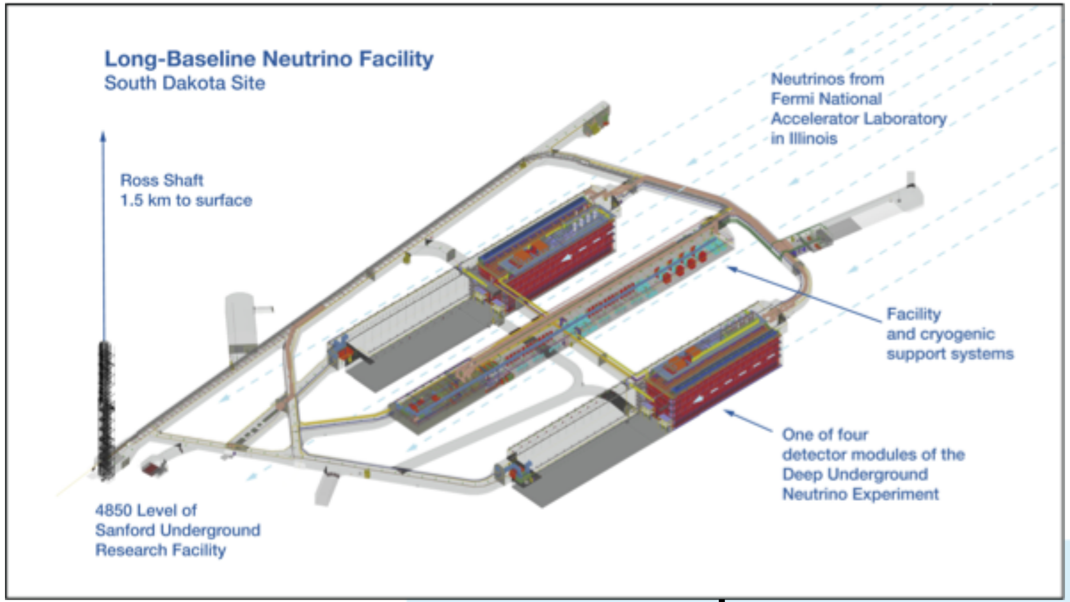
Other models except 3+1 sterile:

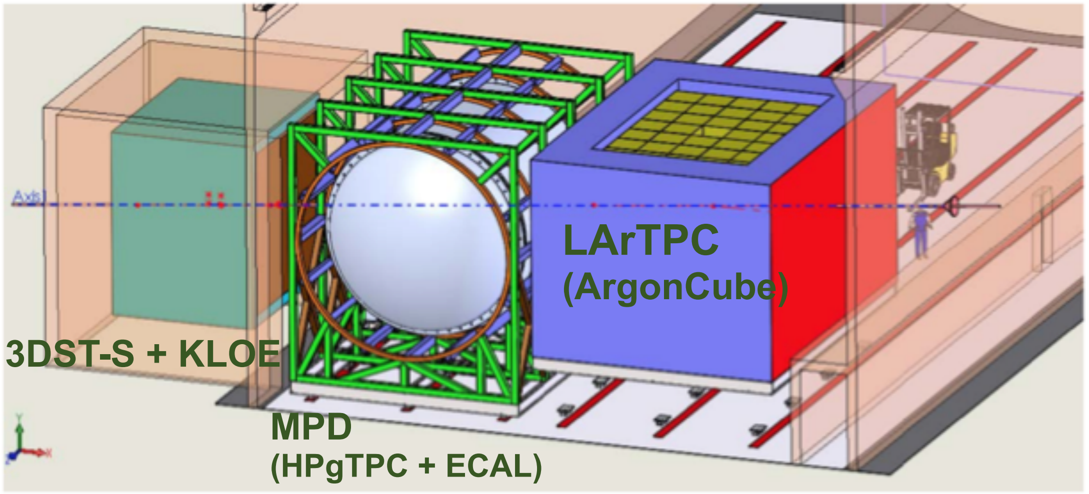
- Single-photon production via resonance $\Delta \to N\gamma$
- Dark neutrino portal $Z_D \to e^+e^-$
- Heavy sterile neutrino radiative decay $\nu_h \to \nu\gamma$
- Misidentification of π^0 decay γ
- Single-photon (γ) background in the dirt and material surrounding the detector

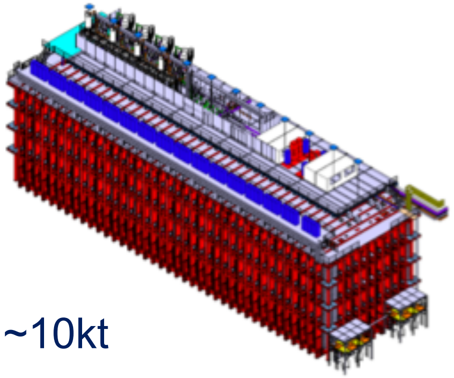
e/γ (or e^+e^-) discrimination is the key.

Select References:
Annu. Rev. Nucl. Part. Sci. 69 (2019)
CERN-TH-2019-152, arXiv: 1909.08571
IPPP/19/19 arXiv:1903.07589
Phys. Rev. Lett. 121, 241801 (2018)
J. Phys.: Conf. Ser. 1056 012001 (2018)
Phys. Rev. Lett. 103, 241802 (2009)

Deep Underground Neutrino Experiment

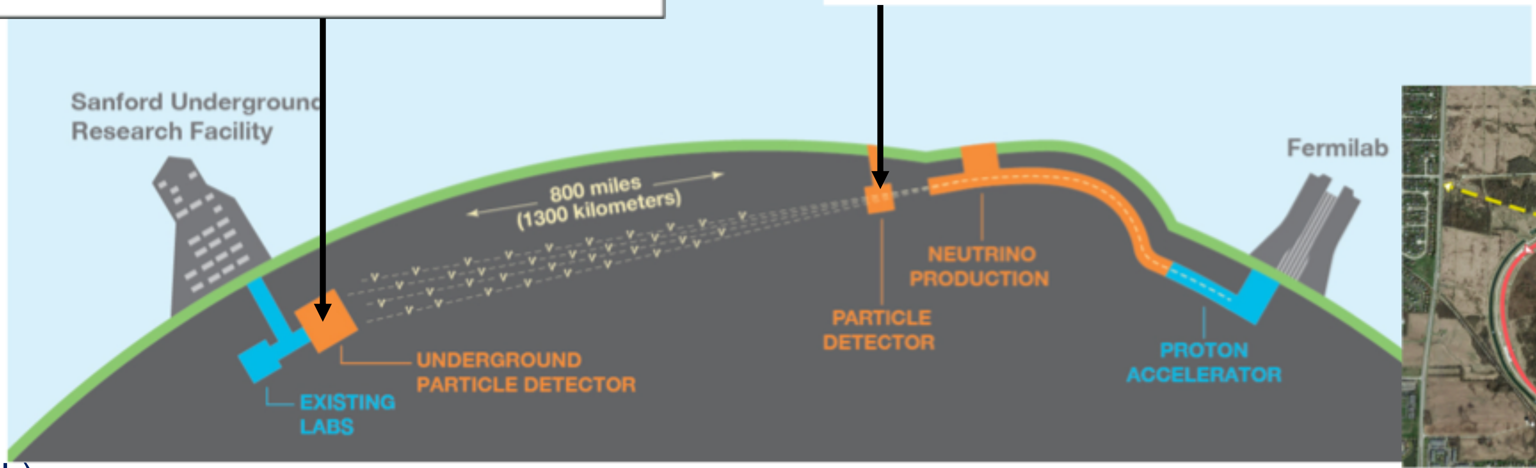






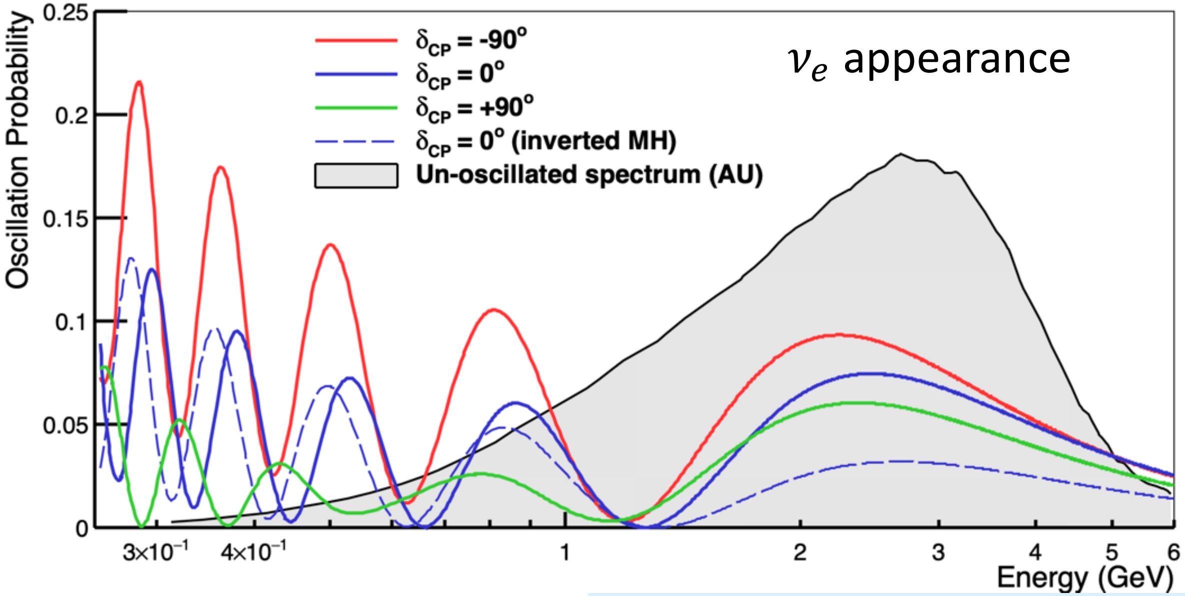
~10kt

12 m (H) X 12 m (W) X 60 m (L)



The Deep Underground Neutrino Experiment (DUNE)

Neutrino Oscillation Physics of DUNE



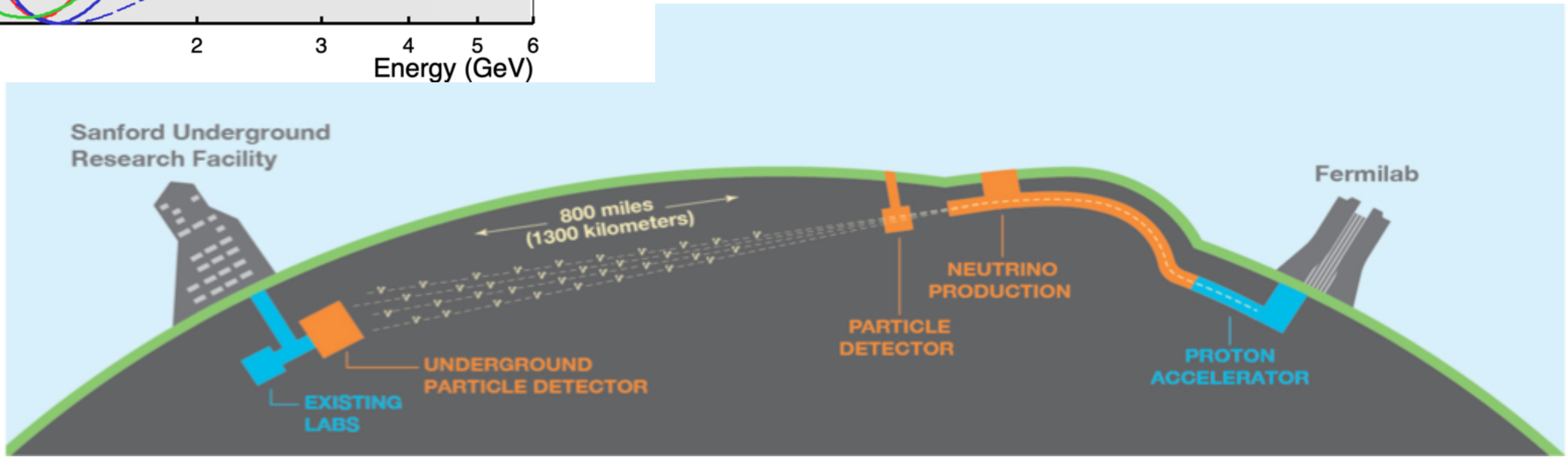
Phys. Rev. D64, 053003 (2001), JHEP 04, 078 (2004)

$$P_{\nu_\mu\to\nu_e,(\bar{\nu}_\mu\to\bar{\nu}_e)} \approx 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2\Delta}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\,J_{CP}^{max}\cos(\Delta\pm\delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{1-A},$$

"A" → matter effect

CP violation ($\delta_{CP} \neq 0$ or π)?
Mass ordering?
θ_{23} octant?

- Long baseline (MSW, decouple mass ordering and CP violation)
- Optimized L/E
- Near-far detector to constrain systematics



More discussions later about DUNE physics!

Detector + ? = Physics
(Hardware + ? = Miracle)

Software (Event Reconstruction) -- game changer!

SJ: "Apple is fundamentally a software company."

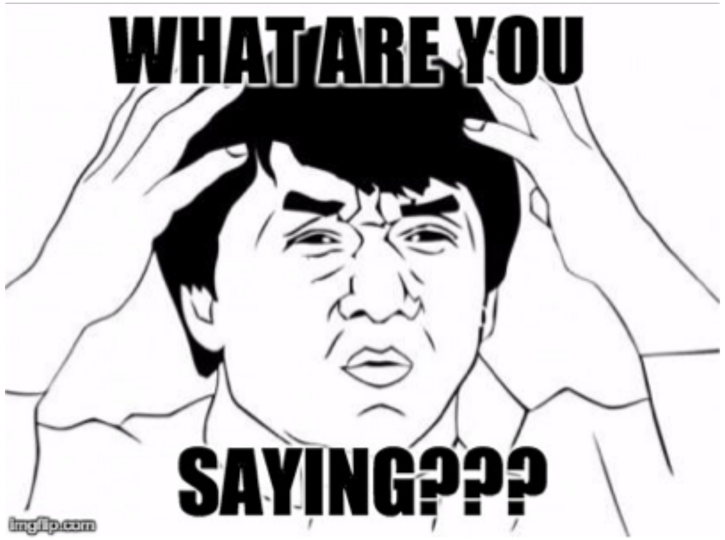
BG: "Well, Steve and I worked together, creating the Mac. We [Microsoft] had more people on it, did the key software for it."

SJ: "..."

True words but fictional dialogue

LArTPC Event Reconstruction

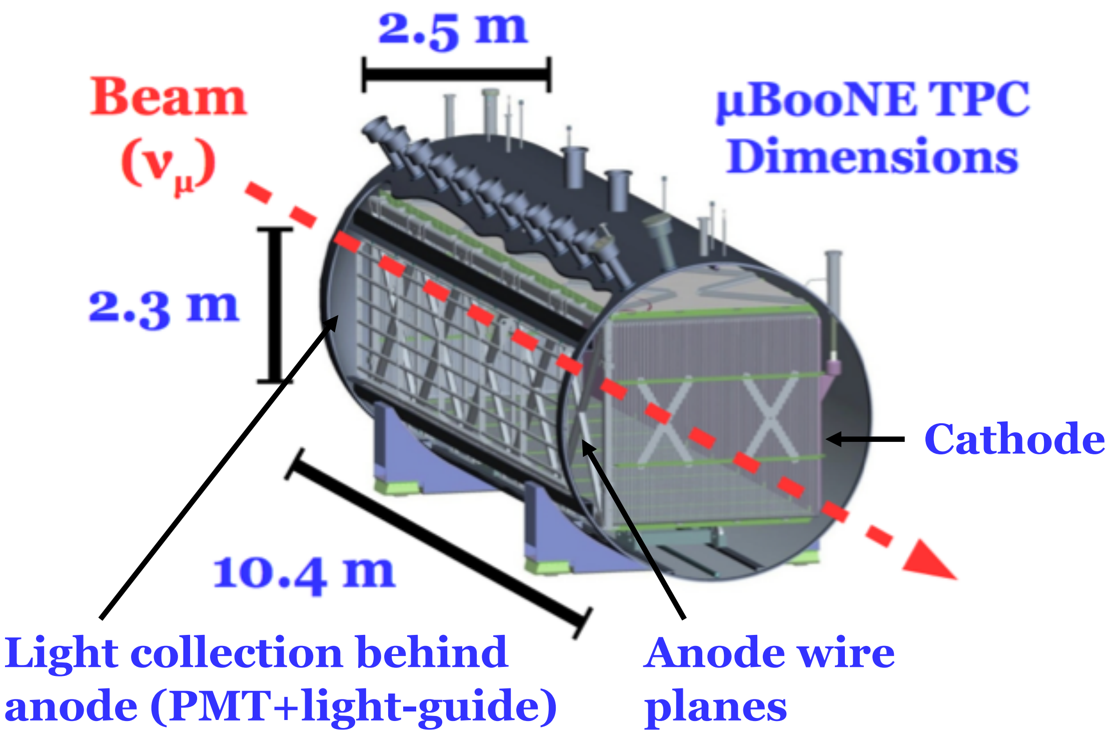
- *Inverse problem: deconvolution of detector response*
- Event reconstruction is critical in realizing the full scientific capability of LArTPCs
- Full of challenges and an open problem at many fundamental aspects
- An accurate and efficient reconstruction chain has yet to be demonstrated in real data analyses of LArTPC experiments



µBooNE

Use MicroBooNE as an example

Focus on *Wire-Cell* reconstruction chain



Physics analysis challenges

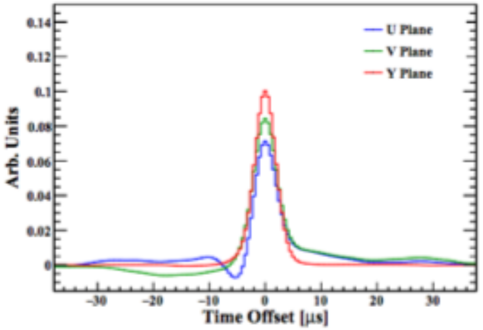
With great power comes ~~great responsibility~~ complex response.

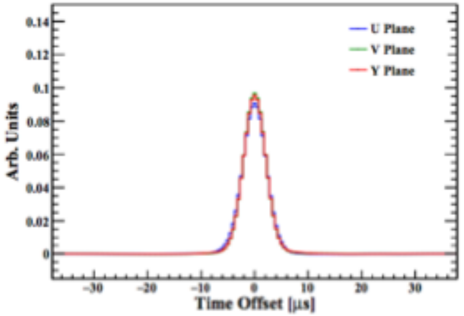
Lack of understanding of real detector (data)

What we observed

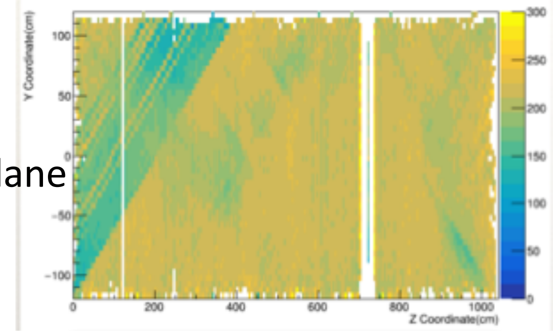
What we want

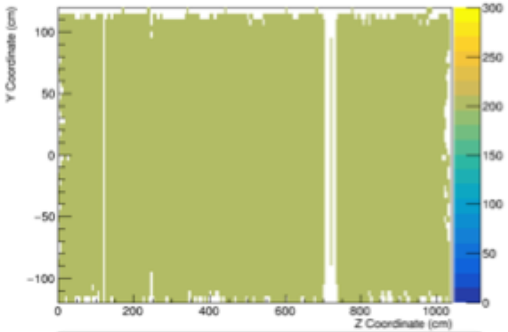
Ionization electron (charge)



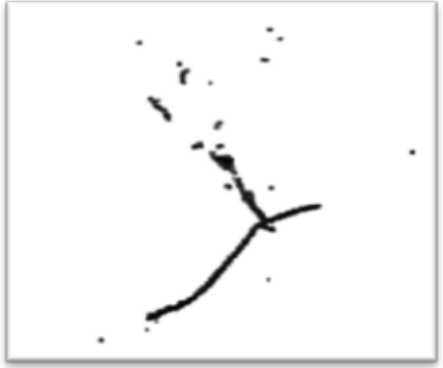


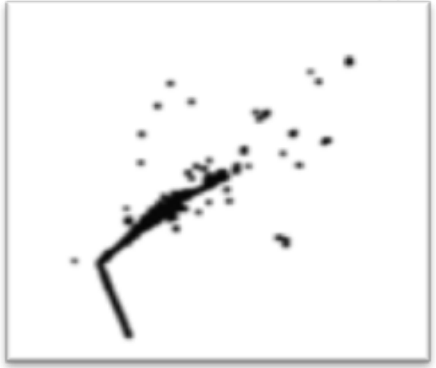
dE/dx anode plane view





1e1p event candidate





Calibration

General strategy: correction to adjust MC to DATA! Always introduce unclear & incoherent impacts on different analyses.

MC ≠ DATA

Low efficiency & complicated systematics.

Need:

Robust Event Reconstruction (deconvolve detector response)

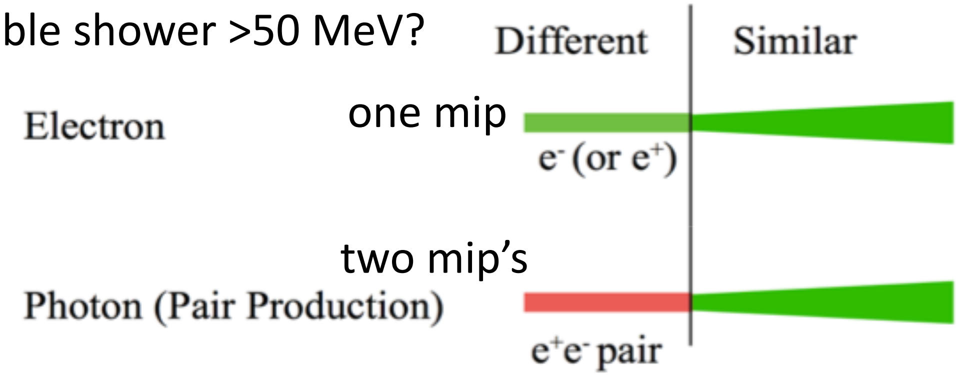
→ Highly rely on data

→ Benefit both Monte-Carlo and calibration

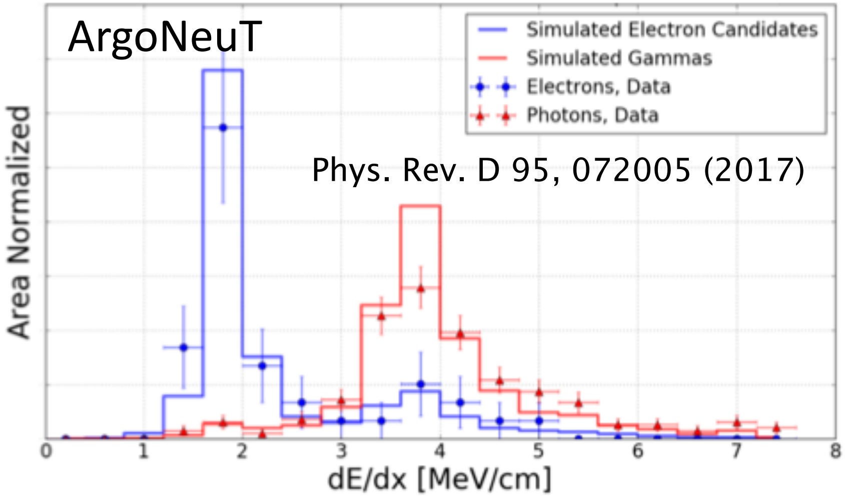
e/γ(or e^+e^-) discrimination

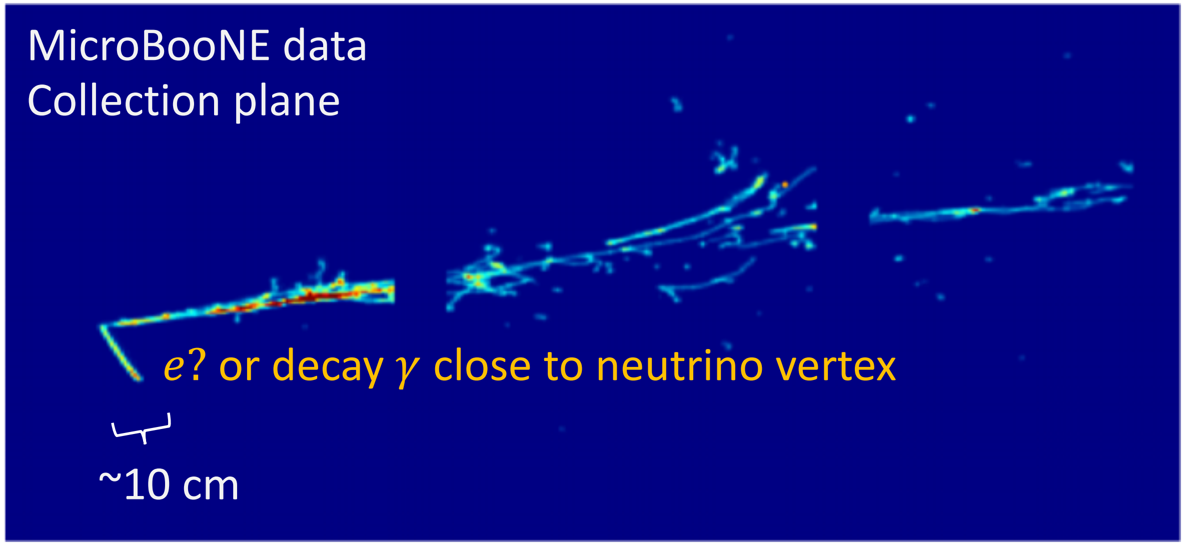
An e bremsstrahlung every few cm in LAr --> electromagnetic shower

Visible shower >50 MeV?



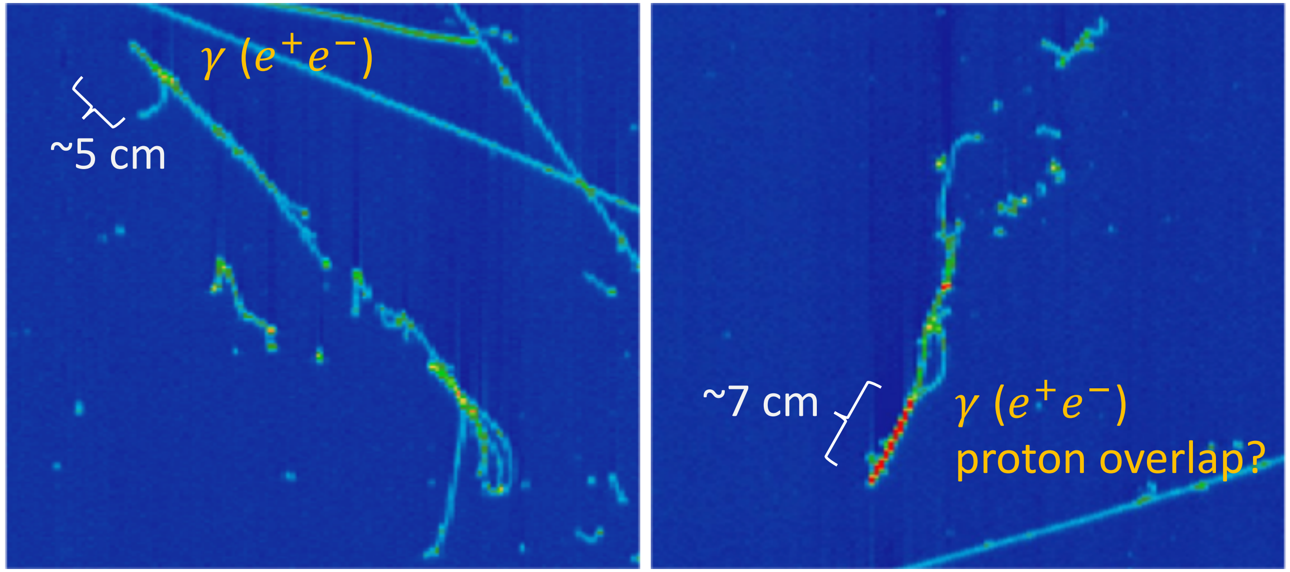
dE/dx in the first few centimeters





ν_μ CC : NC : ν_e CC interactions = 3 : 1 : 0.6%
CC/NC pi0 decay γ's ($\pi^0 \rightarrow \gamma\gamma$) is the predominant <u>known background</u> → γ's close (<1 cm) to neutrino vertex is >5 × ν_e CC

LArTPC 3D reconstruction



Color scale: charge (ionization electrons)

2D projection has very limited capability to do physics.
The real physics is "visible" in a reliable 3D reconstruction.

- 3D reconstruction is the key to maximize the potential of LArTPC.

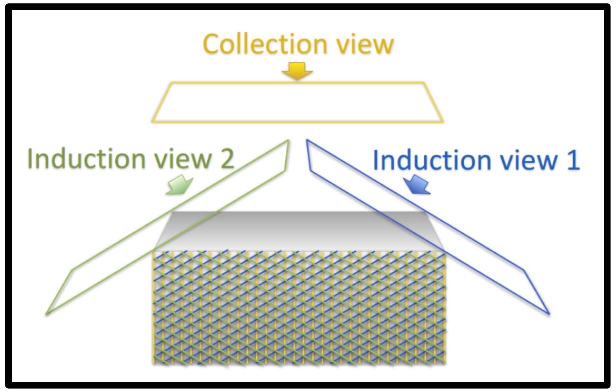
Isn't this straightforward since LArTPC is a 3D imaging detector?

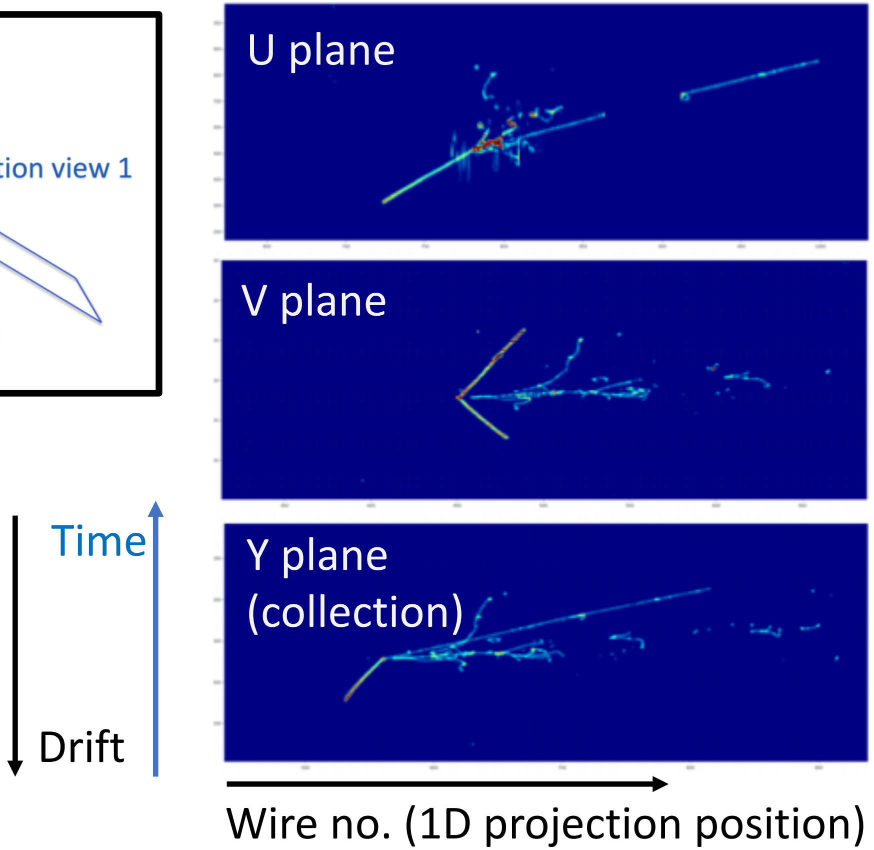
Challenges of LArTPC 3D Reconstruction

TPC: 2D image + 1D drift

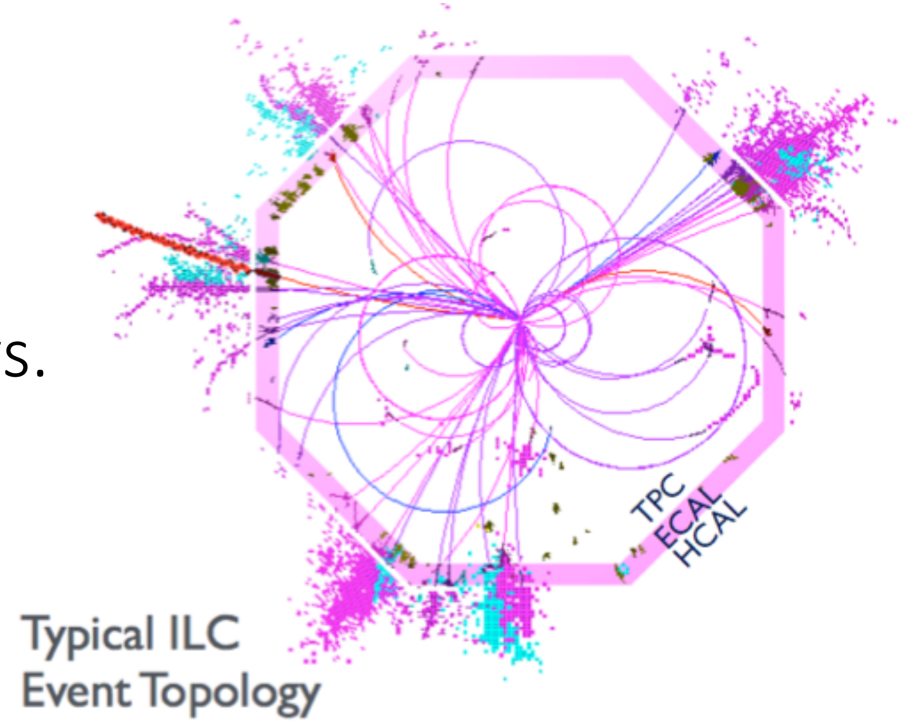
LArTPC (typical single-phase)**:**

- Integrated charge along the wire → THREE wire planes ($3\times n$) $\neq$ 2D pixel readout (n^2)
- Unknown vertex , EM showers, etc. in LAr





vs.

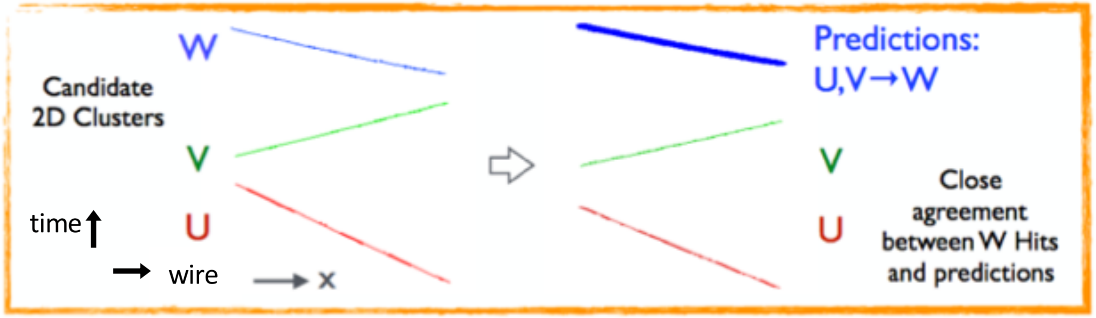


Philosophy of LArTPC 3D Reconstruction

Charge extraction (raw waveform
to number of ionization electrons)

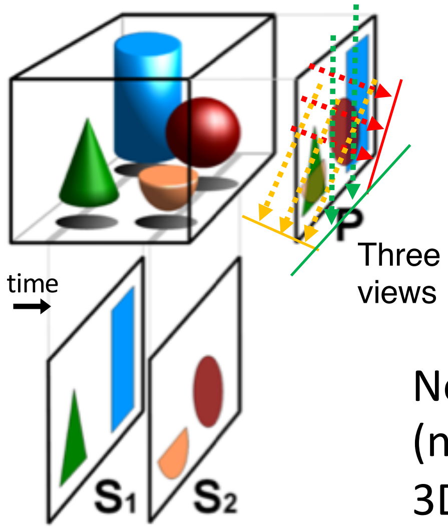
2D pattern recognition on each
time vs. wire measurement

Matching 2D patterns into a 3D object



Tomography
2D image on each time slice, topology-agnostic
(only charge, geometry information)

3D image (time)



3D pattern recognition
on 3D images

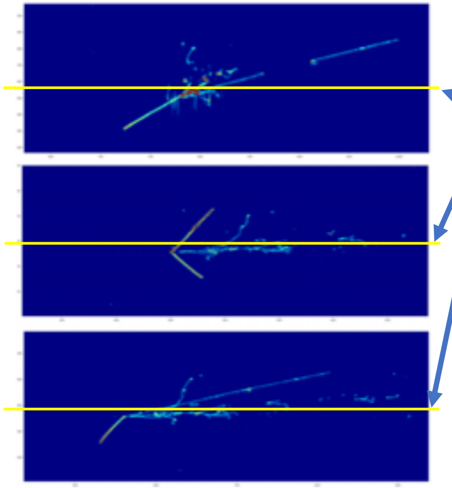
No heuristic assumptions in 3D imaging
(no information condense/loss) prior to
3D pattern recognition.

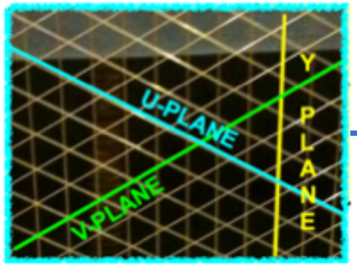
Pattern recognition: *vertex finding, particle-level clustering, track/shower identification, trajectory fitting, dQ/dx fitting, etc.*

Wire-Cell 3D imaging

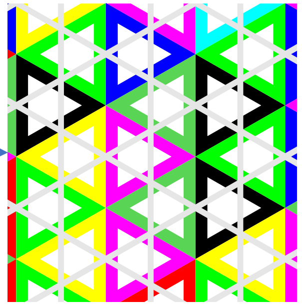
JINST 13 P05032, C. Zhang, X. Qian, B. Viren, and M. Diwan

- Strictly follows the tomography philosophy





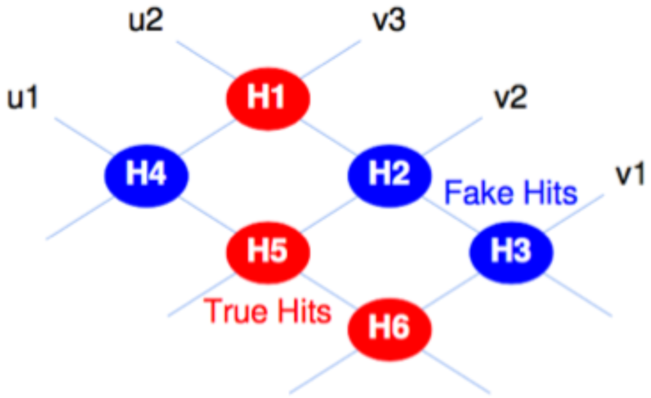
Cells



Grey lines: wires

A **time** slice on each wire plane measurement

Use two planes for illustration

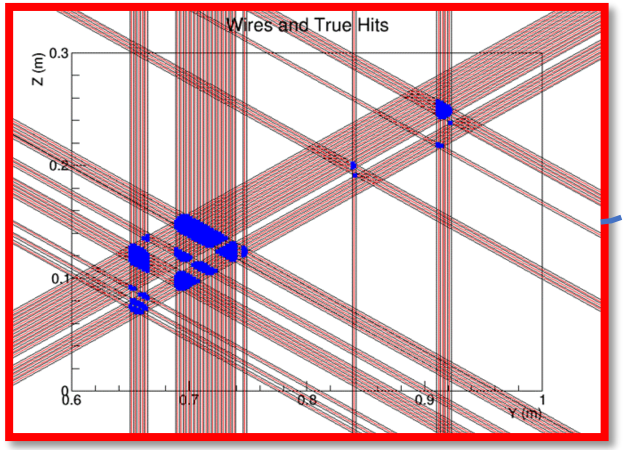


Relate charge along wires to the charge (to be solved) on possible hits

(charge, geometry)

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

Hit cells (merged if connected) from fired wires



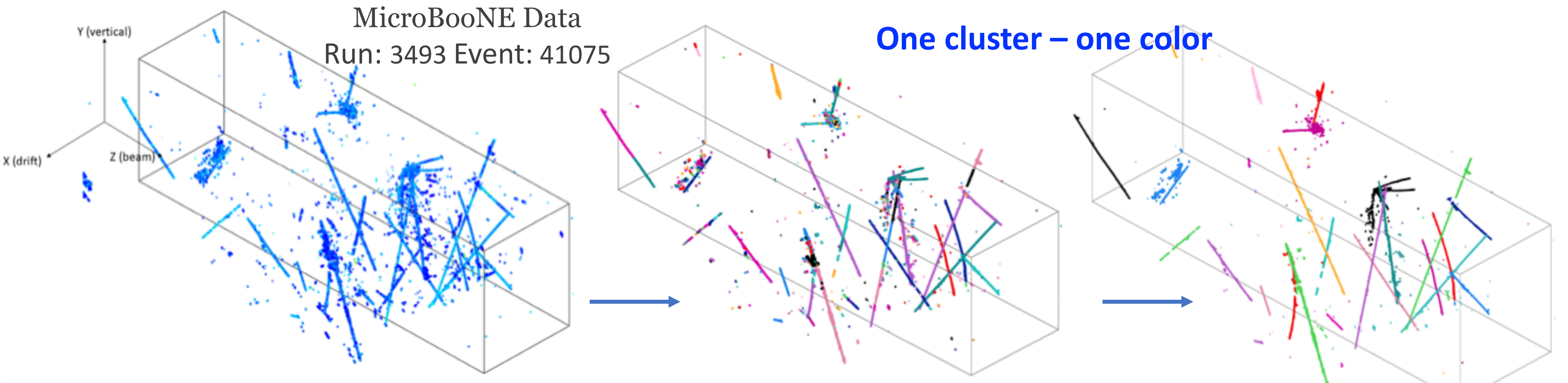
Under-determined linear system (equations)

- more unknowns than knowns
- Incomplete or inaccurate measurement

Method of exhaustion? NP-hard …

Wire-Cell 3D Imaging

- <u>Compresses sensing technique (L1-regularization)</u> is used to ***rapidly & reliably*** remove the fake hits, but it is not magic and just to approximate the "best" solutions considering the fundamental equation, charge uncertainty, ***sparsity***, etc.
- Other realistic issues have to be addressed: nonfunctional wires/channels, gaps in charge measurement, clustering of space points for each individual TPC activity



Before deghosting

After deghosting/initial clustering

Final clustering

~27% region has only two active planes

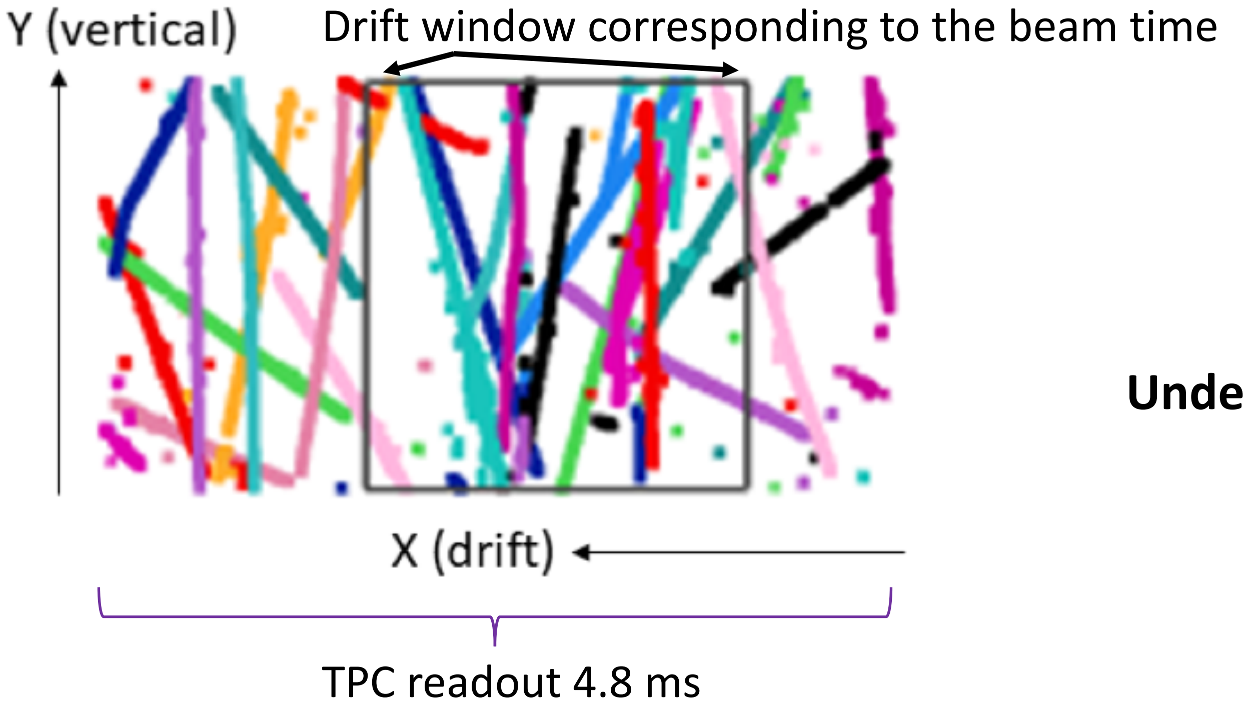
Initial separation of neutrino and cosmic

TPC/charge-PMT/light Matching

MicroBooNE is operating near the surface (5.5 kHz cosmic-ray muons)
TPC readout 4.8 ms; beam spill within 1.6 us
1 neutrino interaction in TPC active volume per ~700 beam spills

Neutrino : Cosmic **= 1 : 20k** (object level)
= 1 : 200 (in-beam PMT flash found)

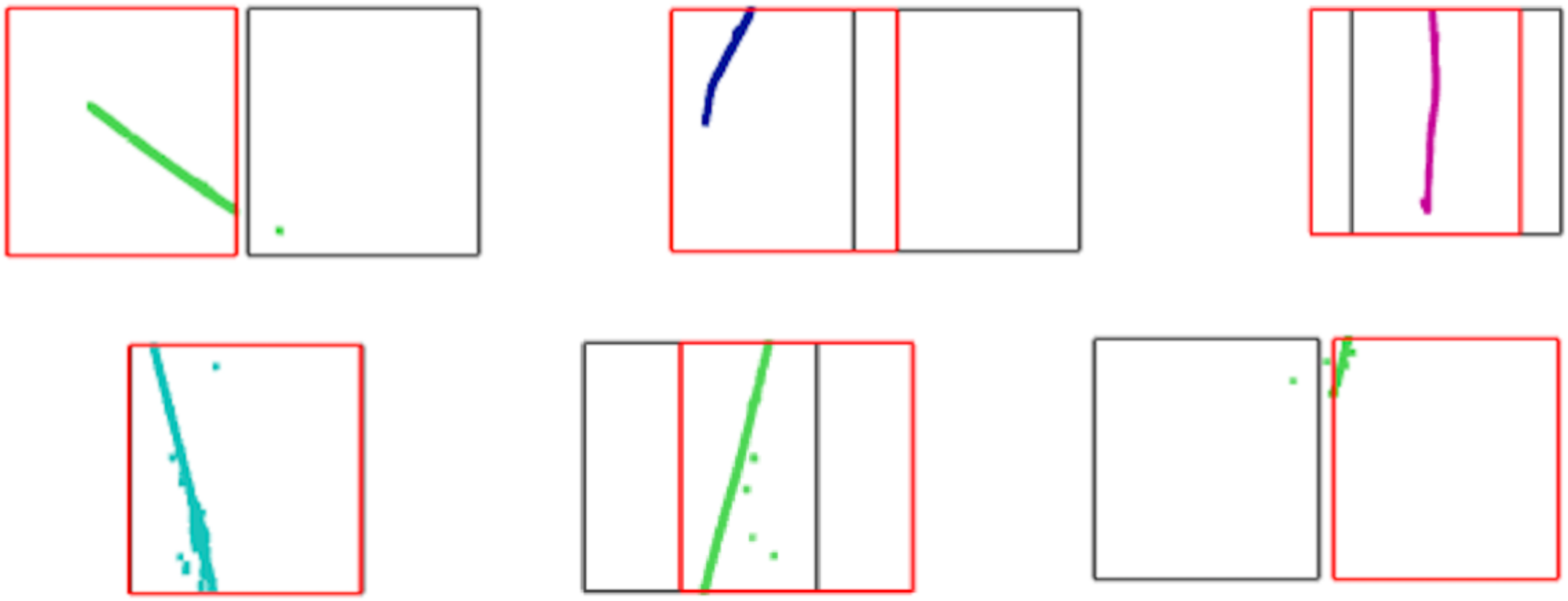
PMT flash (within 100 ns) for a TPC activity
Circle size = PE
32 PMTs in back of anode plane



All possible (PMT, TPC) pairs go through this procedure to find the most compatible ones
- ONE cluster to at most ONE flash
- ONE flash to >=0 clusters (to solve under-clustering issues)

Under-determined system: compressed sensing technique

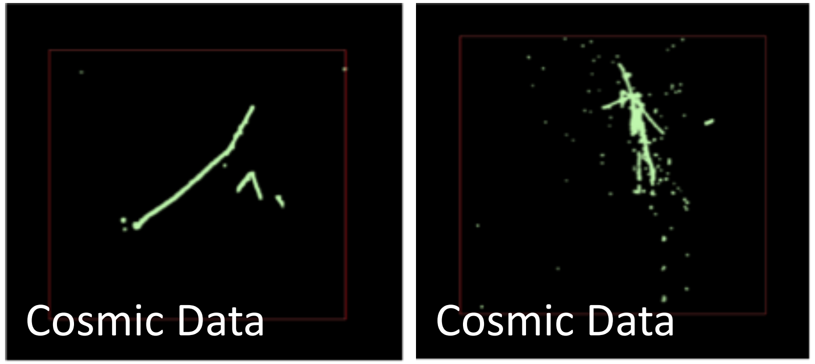
Without 3D image and proper clustering, such many-to-many matching cannot be done!



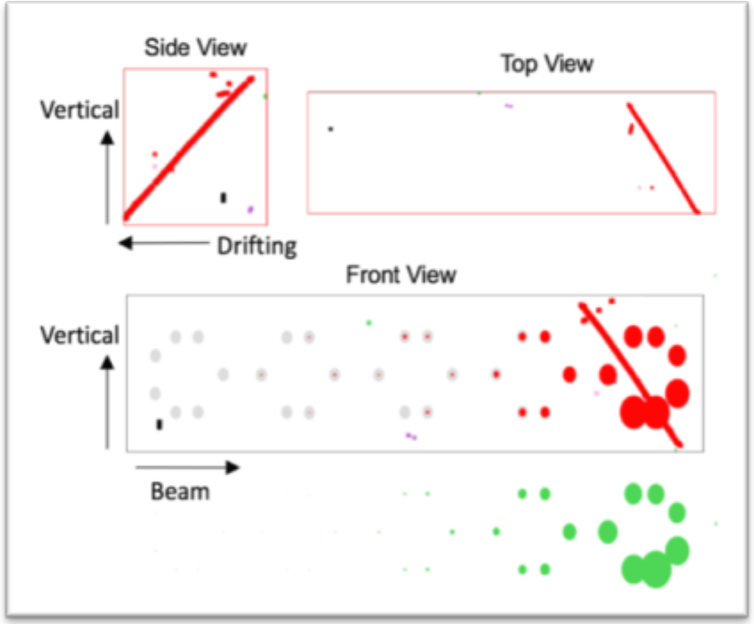
Examples of matching results
Red box: TPC drift window with t0 (provided by PMT flash) correction

Selected in-beam neutrino candidate

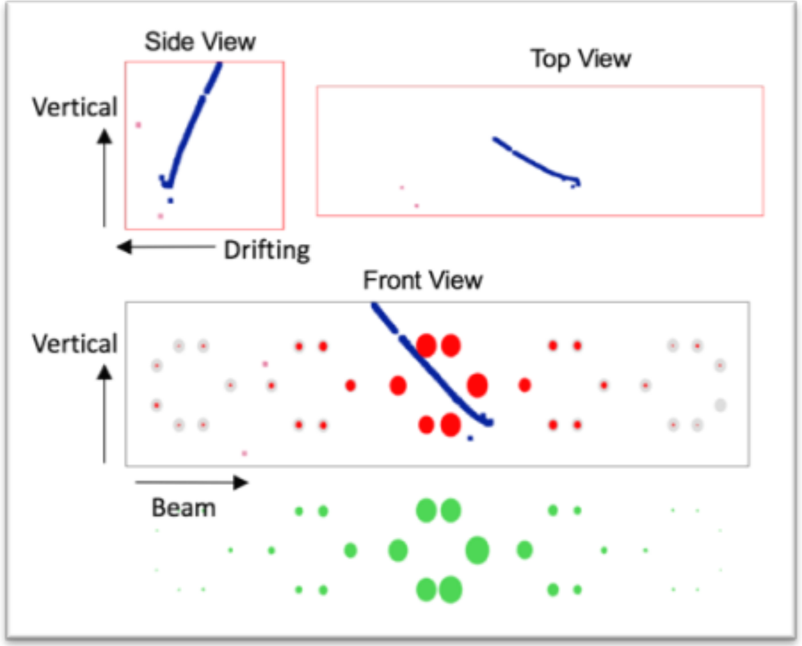
Neutrino : Cosmic = **1 : 20k** (object level)
= **1 : 200** (in-beam PMT flash found)
= **1 : 5** (matched to in-beam PMT flash)



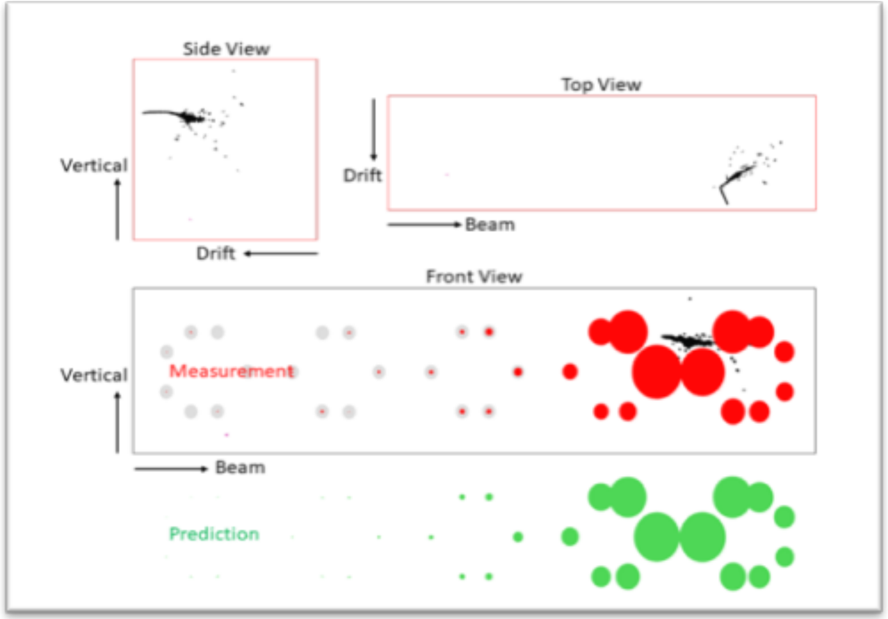
~3% neutrino-like cosmic-induced



~70% through-going cosmic muon



~10% stopped cosmic muon



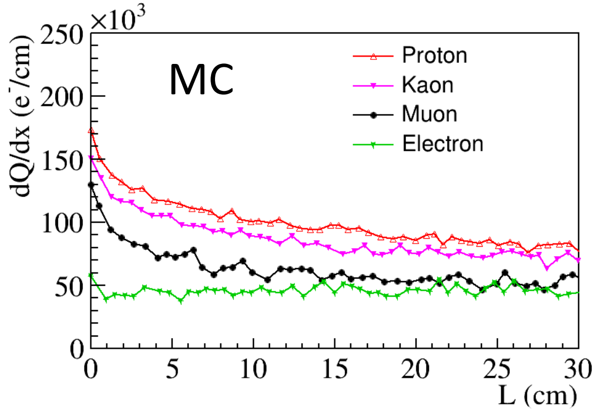
~17% neutrino

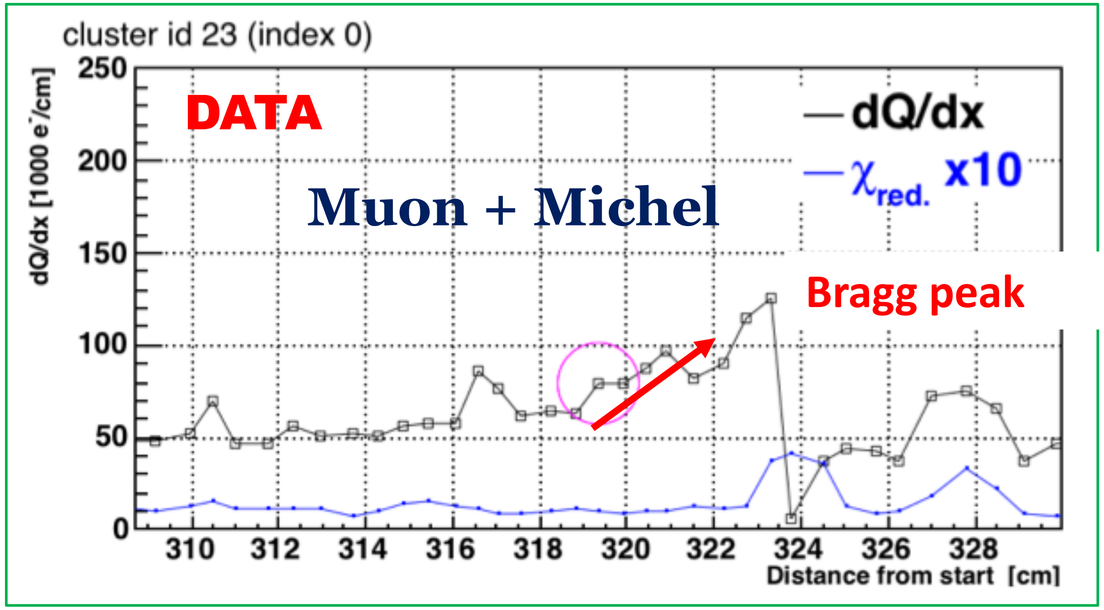
In-beam coincidence cosmic rejection

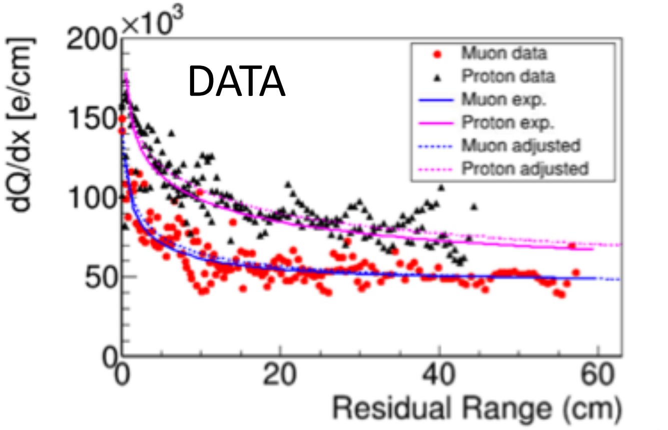
Through-going cosmic muon -- relatively straightforward, but requires knowledge of distorted TPC boundary [space charge effect]

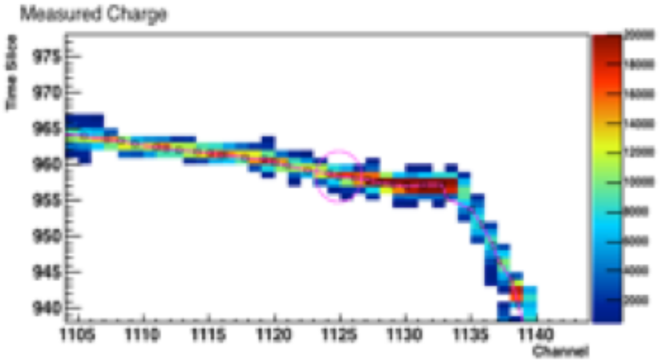
Stopped cosmic muon (incoming particle) – directionality ← dQ/dx Bragg peak

dQ/dx =
(1) 3D trajectory fitting [charge-weighted center]
Advanced 3D operations and graph theory algorithms on 3D cluster (point cloud)
(2) associate ΔQ to $\Delta \vec{x}$
Good knowledge of charge smearing in drift & offline processing

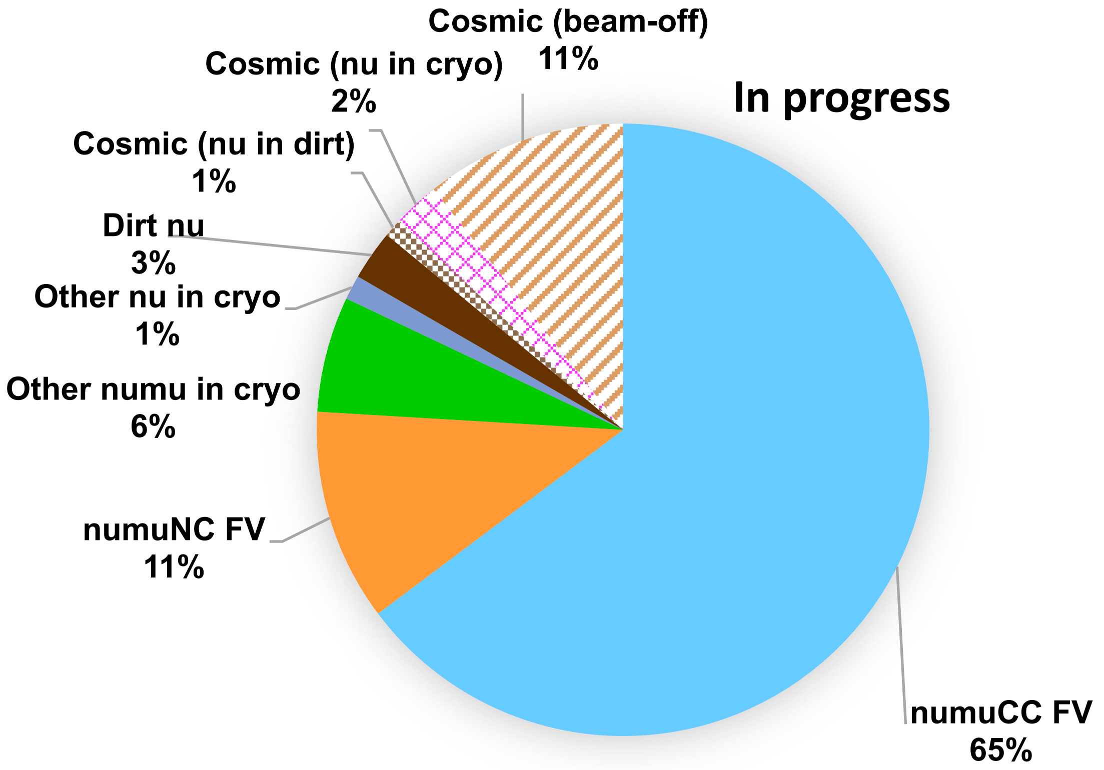




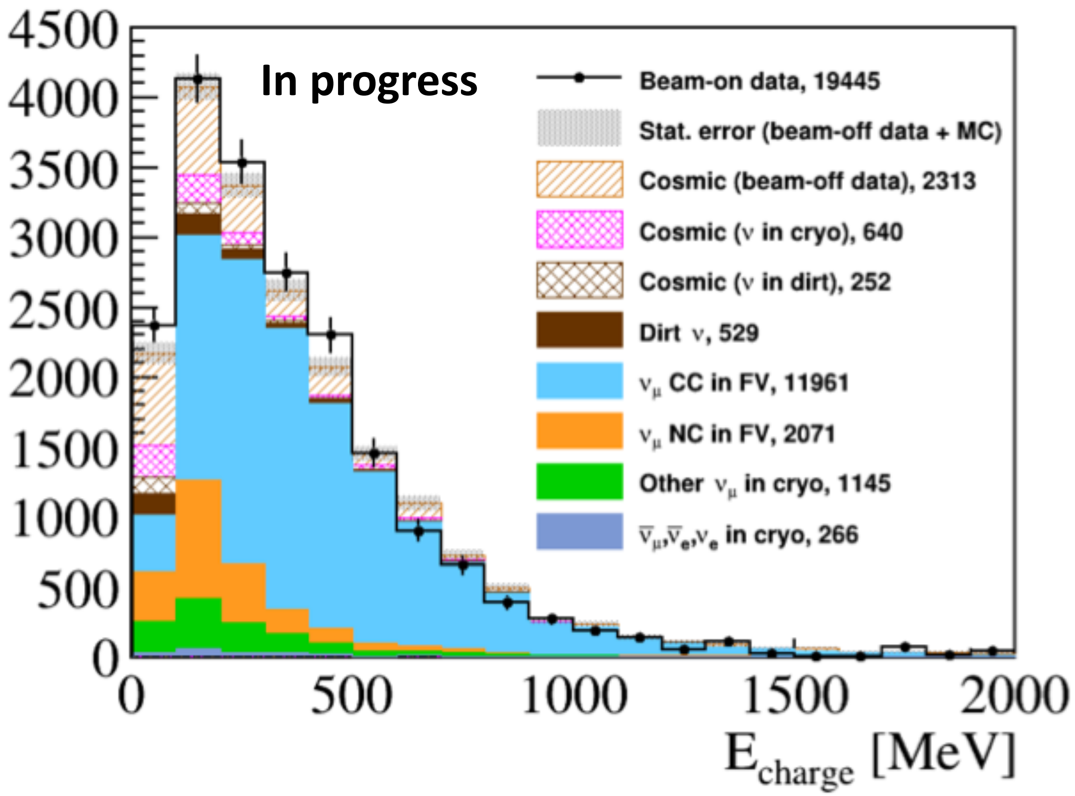




Neutrino candidates after cosmic rejection



Scaled to 5E19 POT



Neutrino : Cosmic = 1 : 0.16

(1 : 5 before in-beam cosmic rejection)

ν_μ CC efficiency: 83%

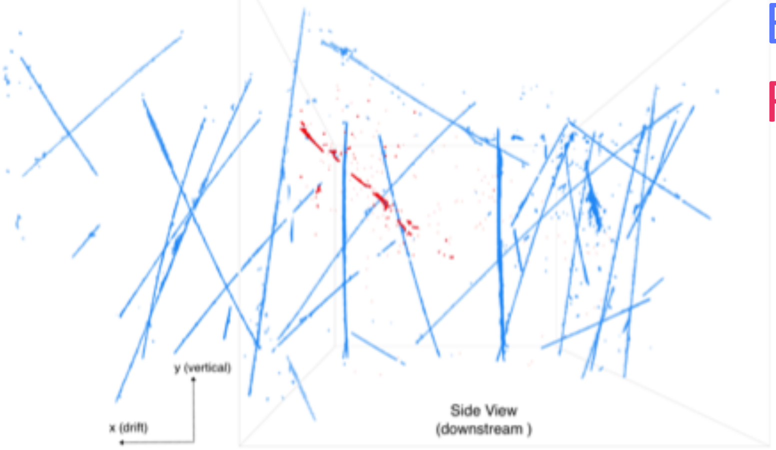
ν_μ NC efficiency: 36%

ν_e CC efficiency: 86%

MicroBooNE 2019 PRL numuCC inclusive
Neutrino : Cosmic = 1 : 1 and efficiency ~60%

3D image of selected neutrino activity

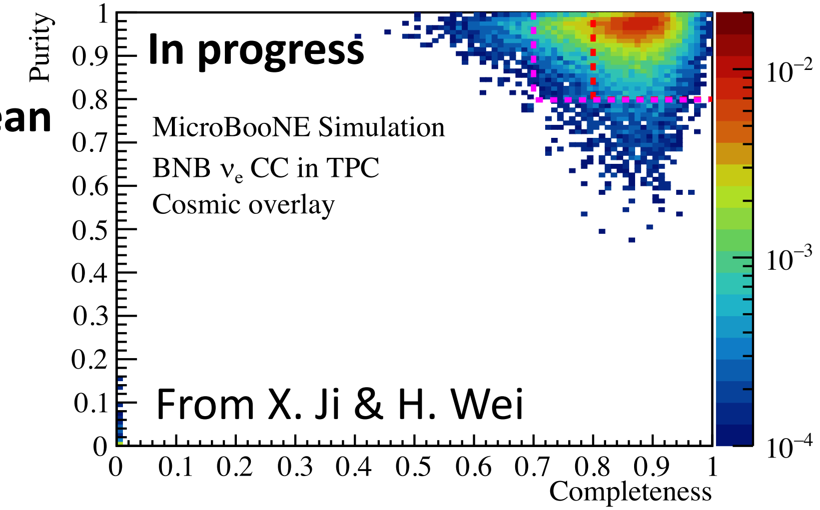
MicroBooNE Simulation



Blue: reconstructed space points

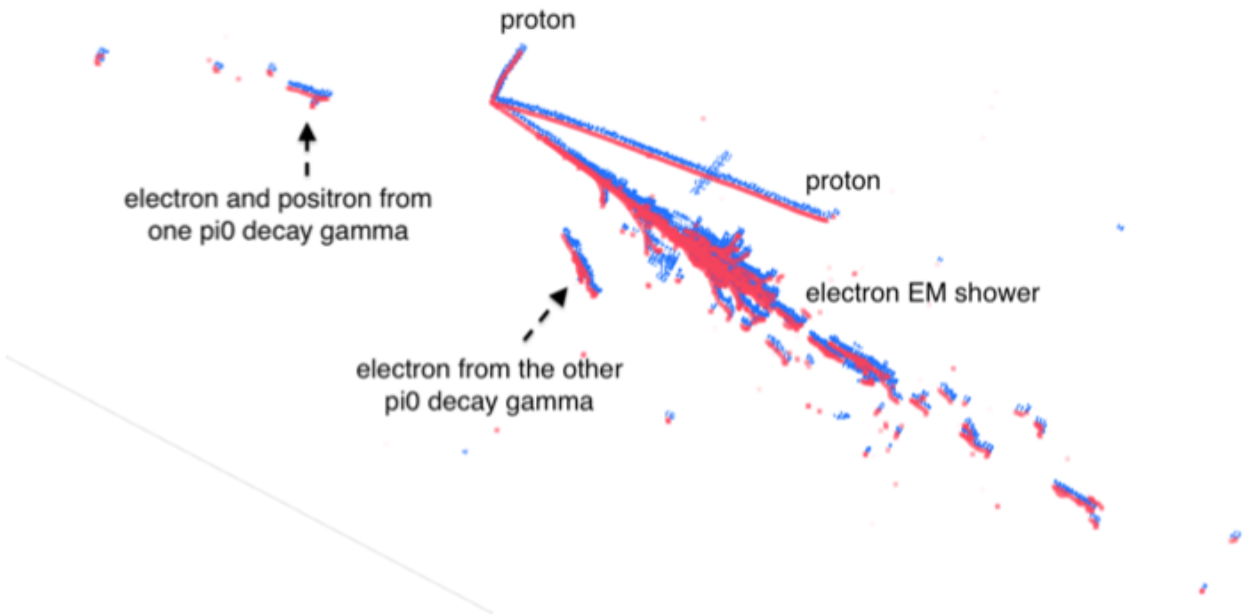
Red: true space points

clean



intact

MicroBooNE Simulation

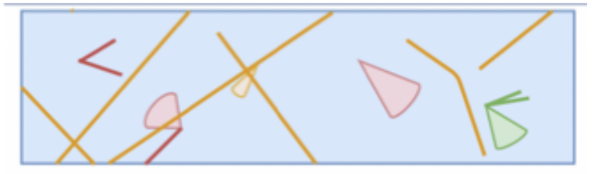


Such an efficient method to reconstruct clean & intact 3D images of neutrino activities has never been demonstrated before! (at least in MicroBooNE)

Pattern Recognition Strategy

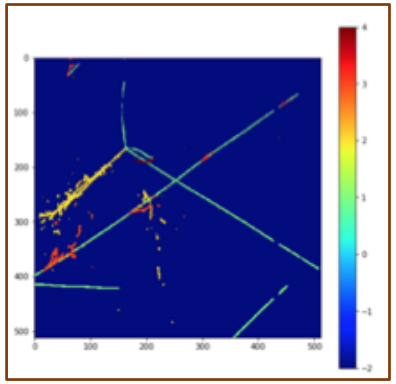
PATH A

3 × 2D time-verus-wire views



Neutrino slicing

Cosmic rejection?



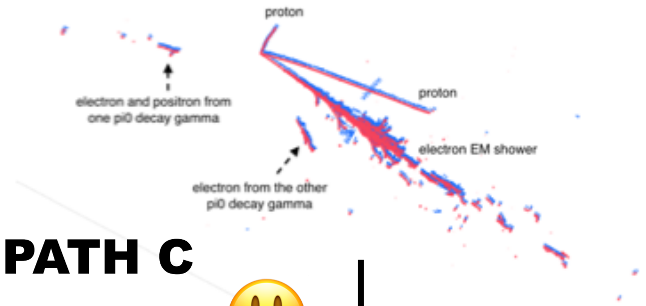
Cosmic rejection?

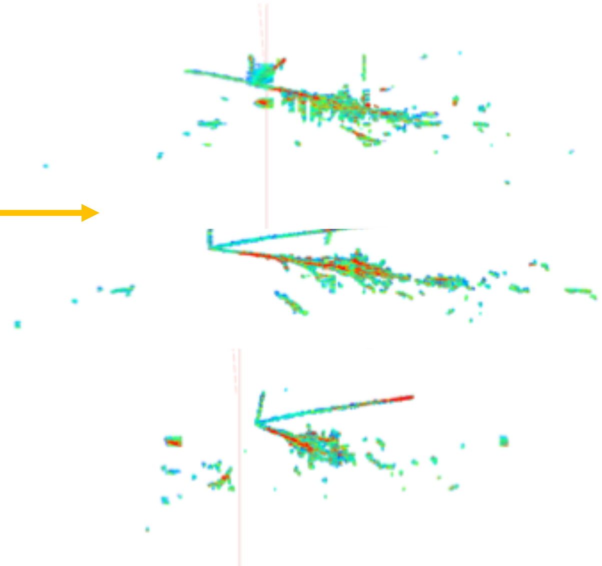
Pandora, DL, etc.

2D pattern recognition

PATH B

Clean & intact 3D image





3 × 2D time-verus-wire views

People are exploring this path and have seen big improvements

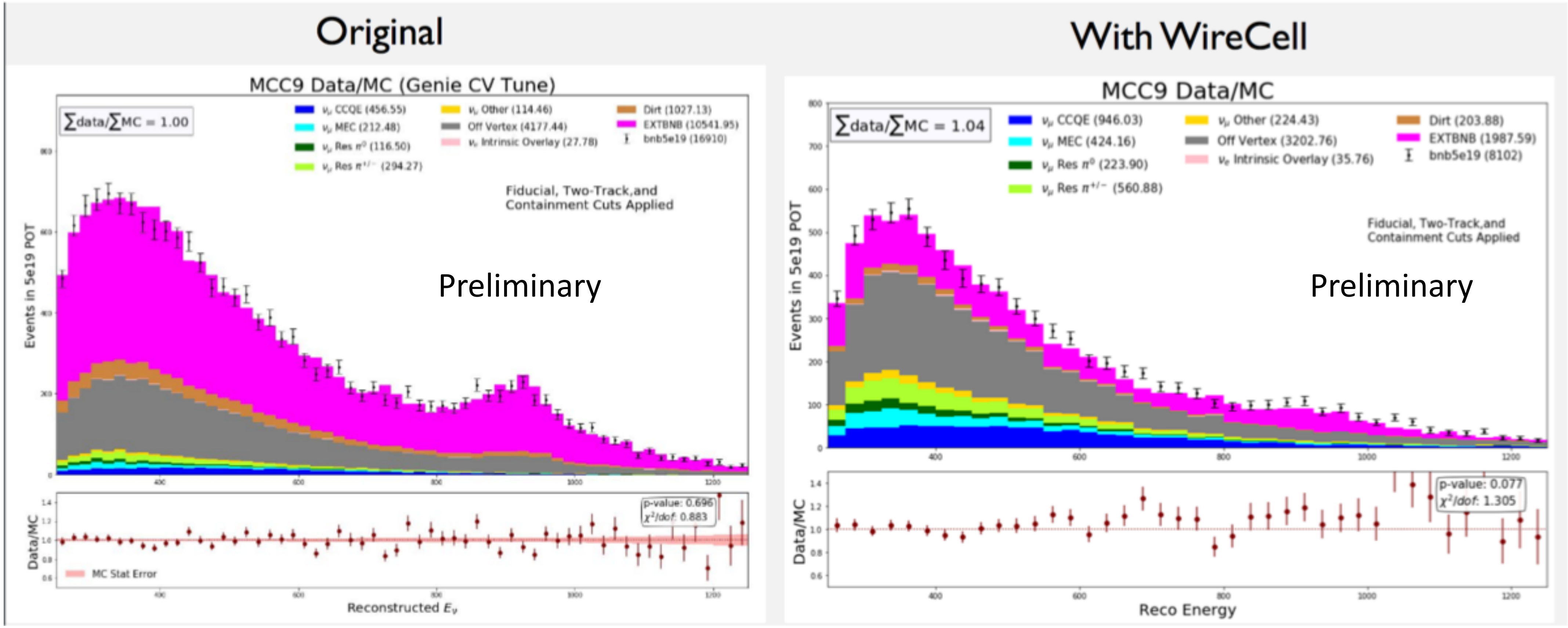
PATH C

3D pattern recognition

- Traditional ?
- Deep learning ?
- Traditional + Deep learning ?

MicroBooNE Deep Learning ν_μ CC selection

PATH A **PATH B**

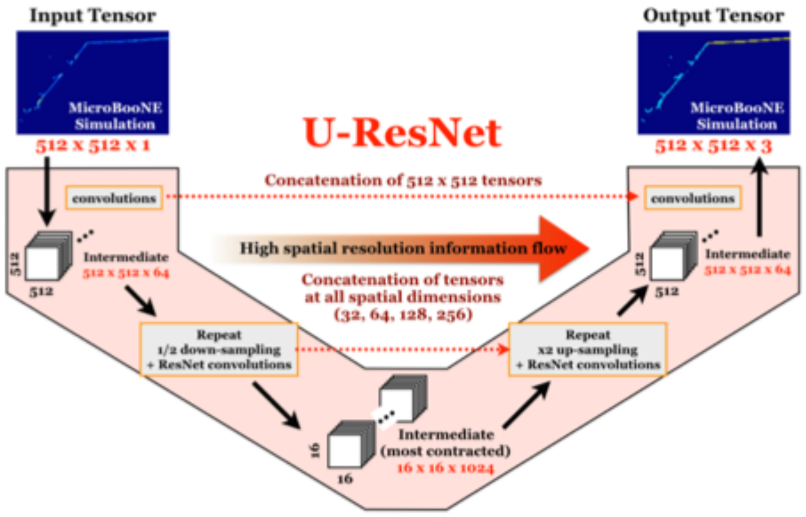


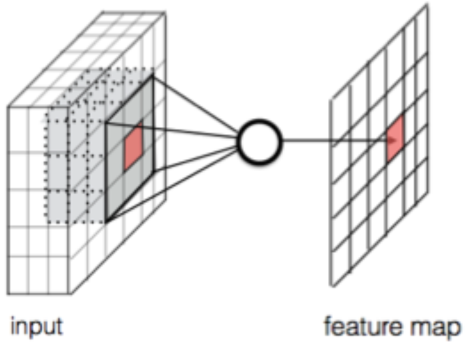
Drastically reduced cosmic background (magenta)!
Considerably improved selection efficiency!

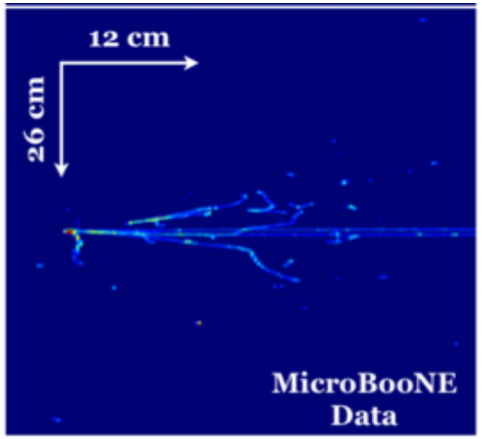
2D pattern recognition – **Deep Learning**

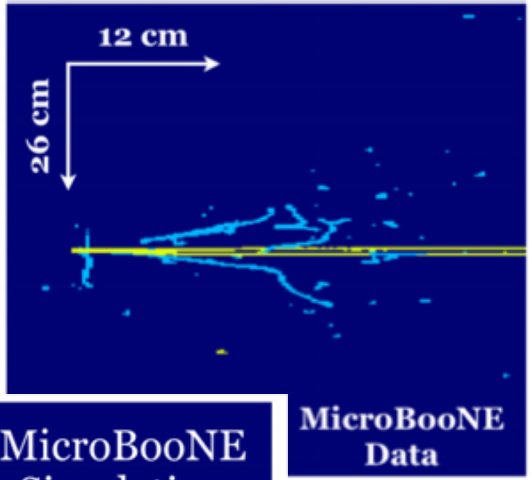
- In particular, Convolutional Neural Networks (CNNs)
- Scalable technique, generalizable to various tasks
- Superb performance on image data analysis
- Robust MC for training purpose

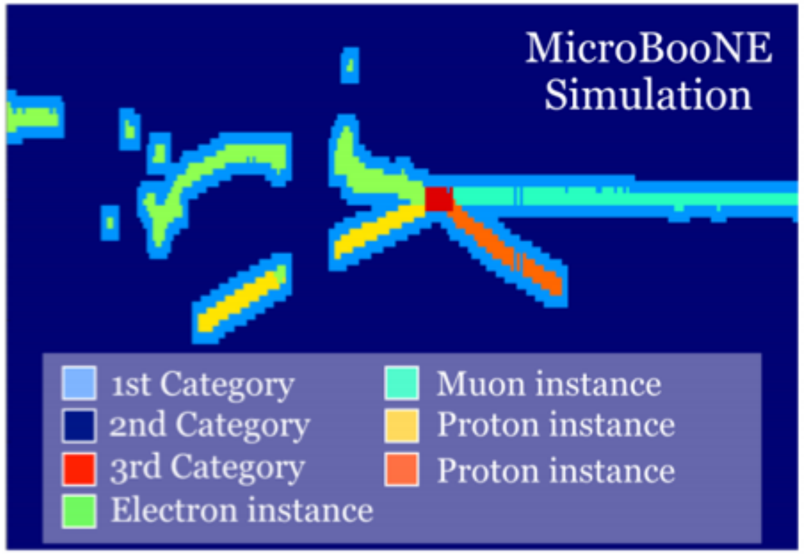
1. 2017 JINST 12 P03011
2. Phys. Rev. D 99, 092001









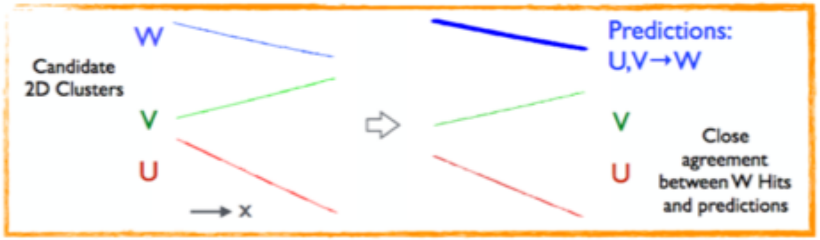


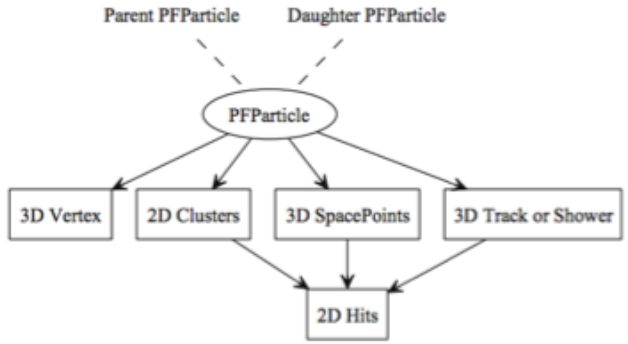
Neutrino image and particle-level segmentation
Track/shower identification
Multiple particle identification (regression)

2D pattern recognition -- **Pandora**

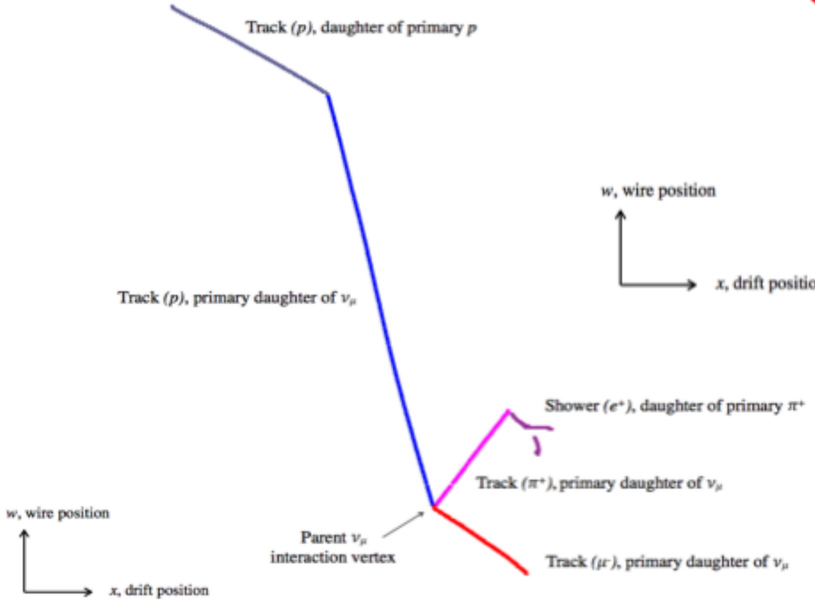
- **Traditional** reconstruction algorithms
- Sophisticated pattern recognition software
- **Neutrino vertexing, particle-level clustering, track/shower identification, particle flow**

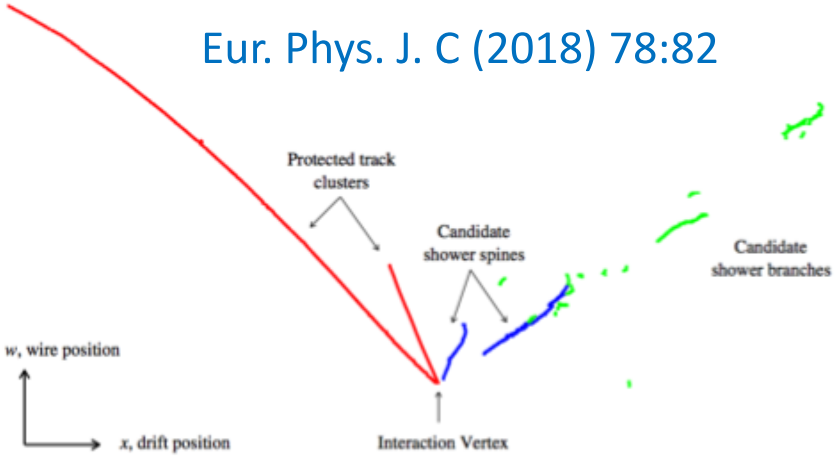
Matching 2D patterns into 3D





Eur. Phys. J. C (2018) 78:82





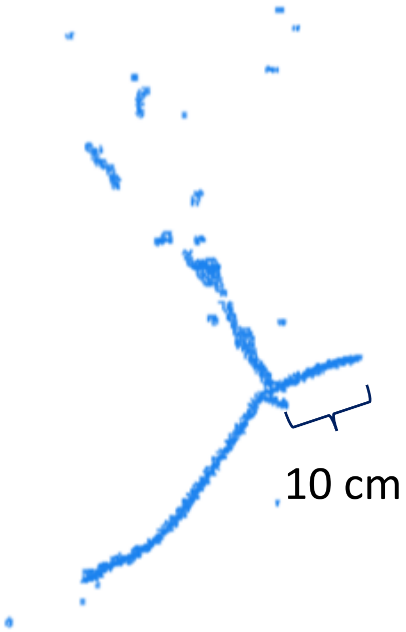
Wire-Cell 3D pattern recognition current status

From X. Qian

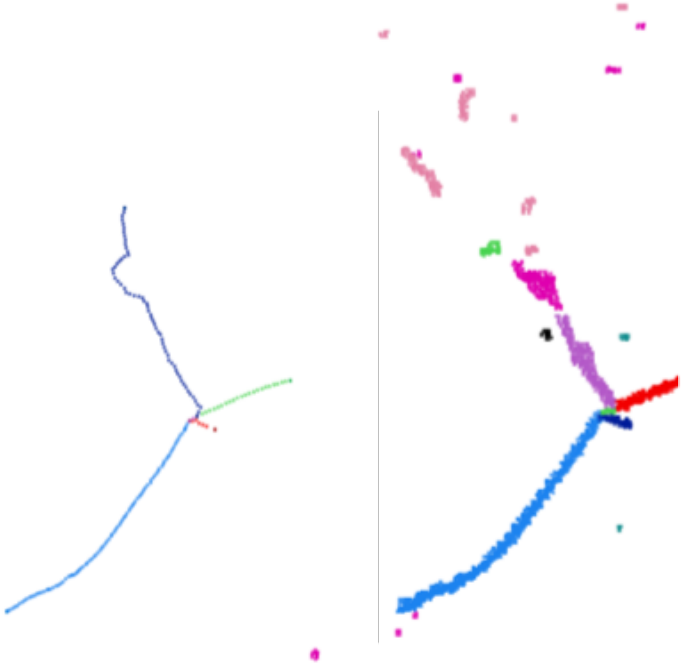
A neutrino candidate from MicroBooNE data

Complex topology

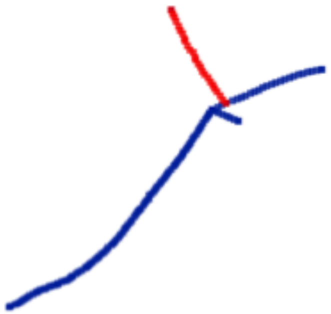
3D image
(2D snapshot)



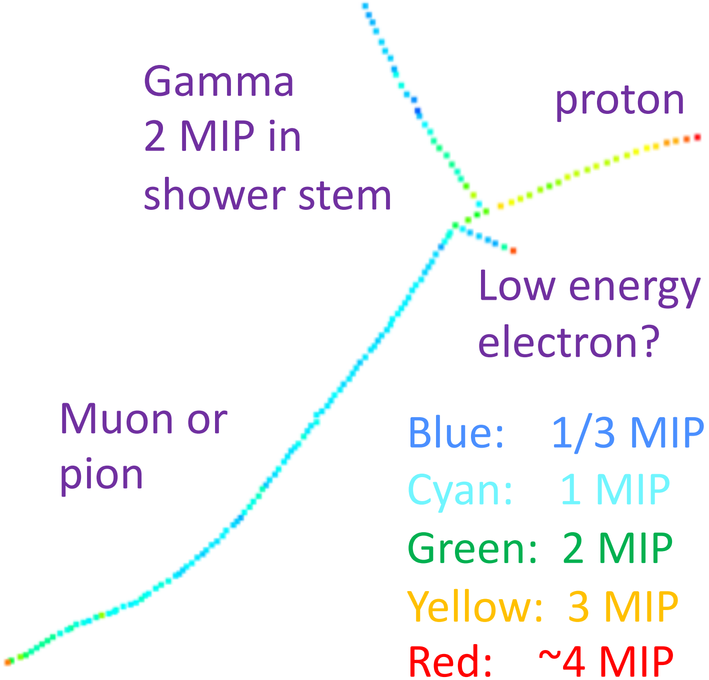
Trajectories and
particle-level clustering



Track/shower (stem)
identification

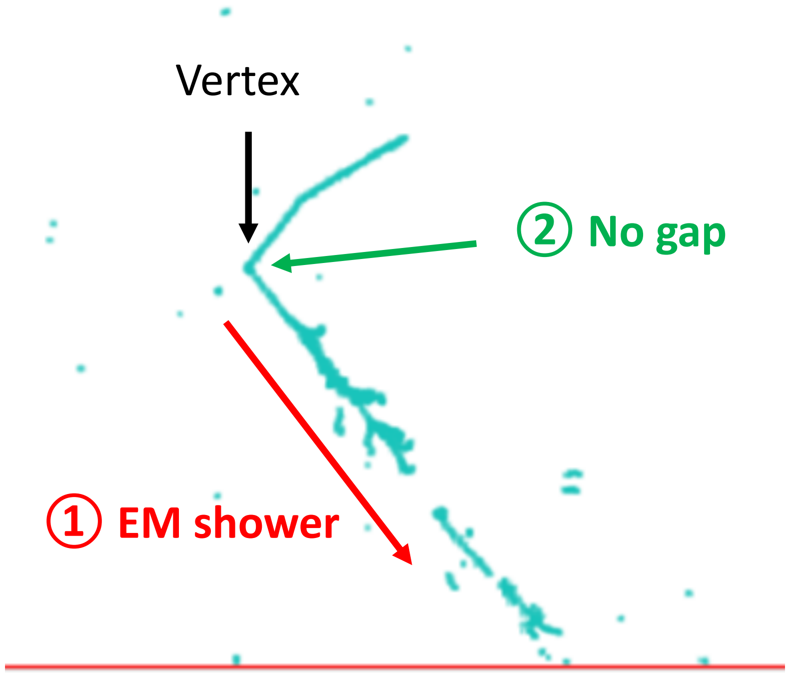


dQ/dx (3D)
best fit



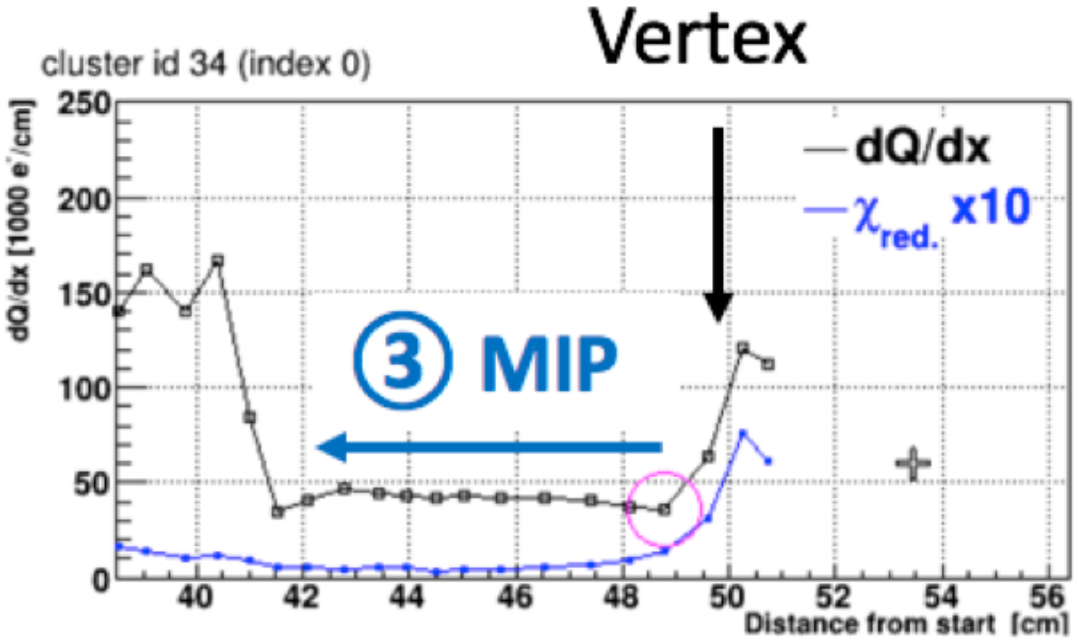
Traditional approaches so far, stay tuned!

ν_e Selection Strategy



On-going efforts.

Goal: S:B = 10 : 1



1) Track/shower separation
2) No gap
3) MIP dQ/dx within shower stem

Last but not least

A good example to demonstrate the importance of fundamental event reconstruction

Charge Extraction (Signal Processing)

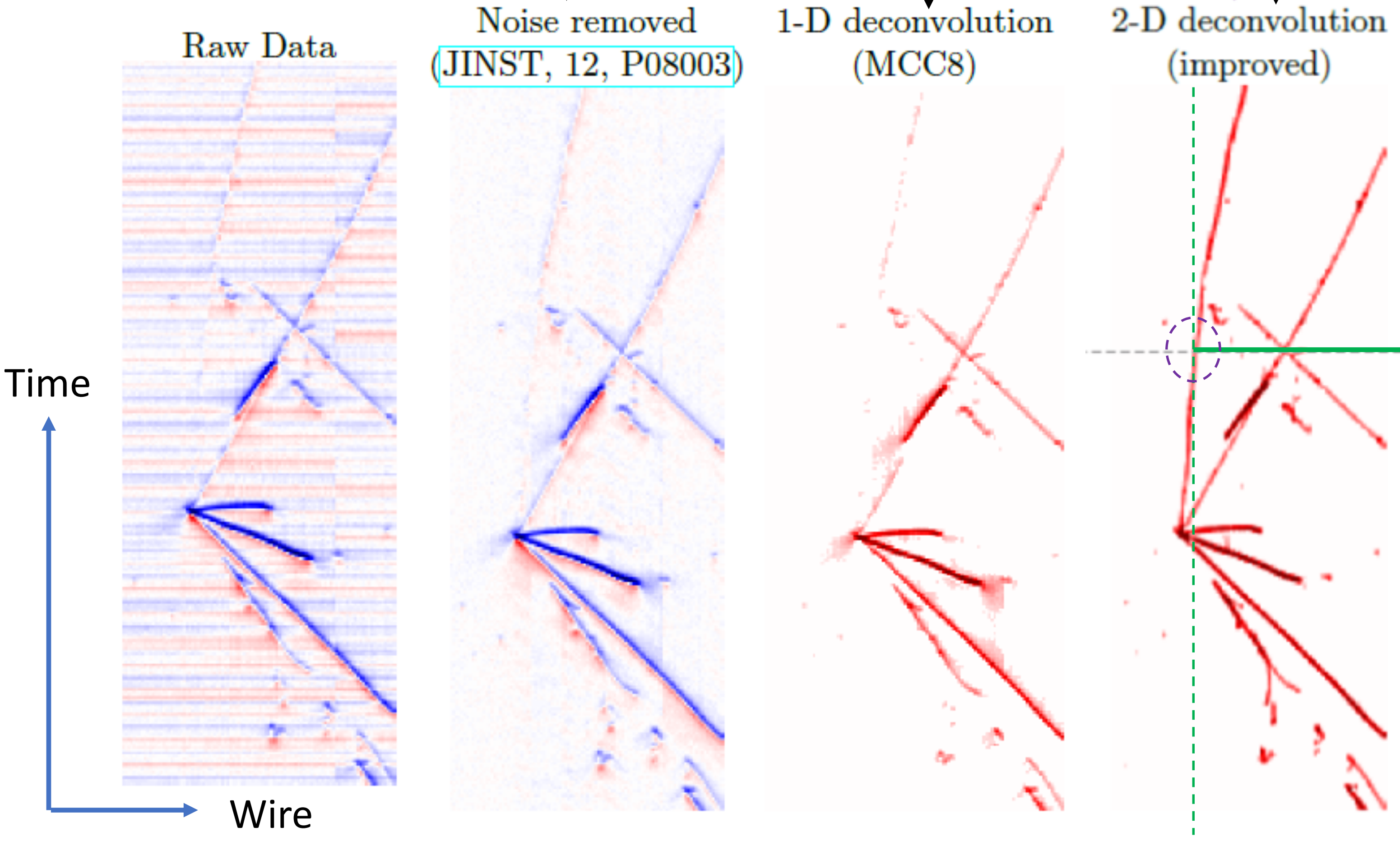
JINST 12 P08003
JINST 13 P07006
JINST 13 P07007

MicroBooNE Data
Induction plane

Low noise enabled by the cold electronics (BNL)

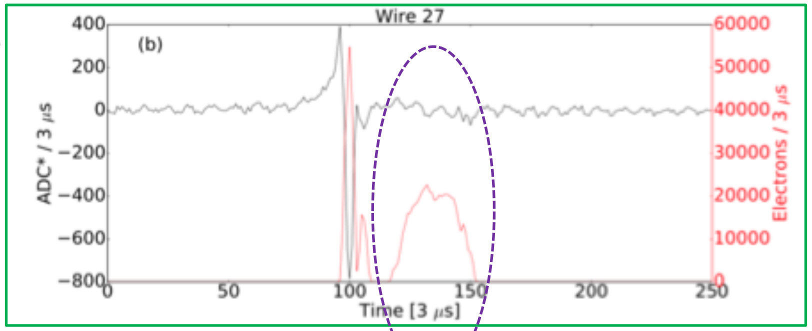
This works for collection plane, but not induction plane.

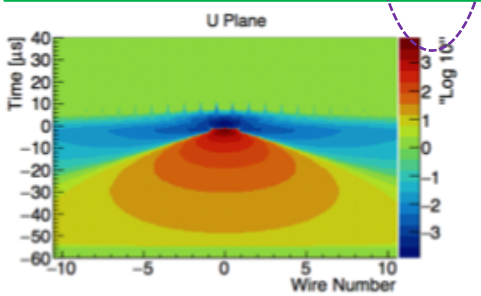
2D signal processing (time + wire domains)



Consistent charge extraction across all three wire planes has been first demonstrated using MicroBooNE data.

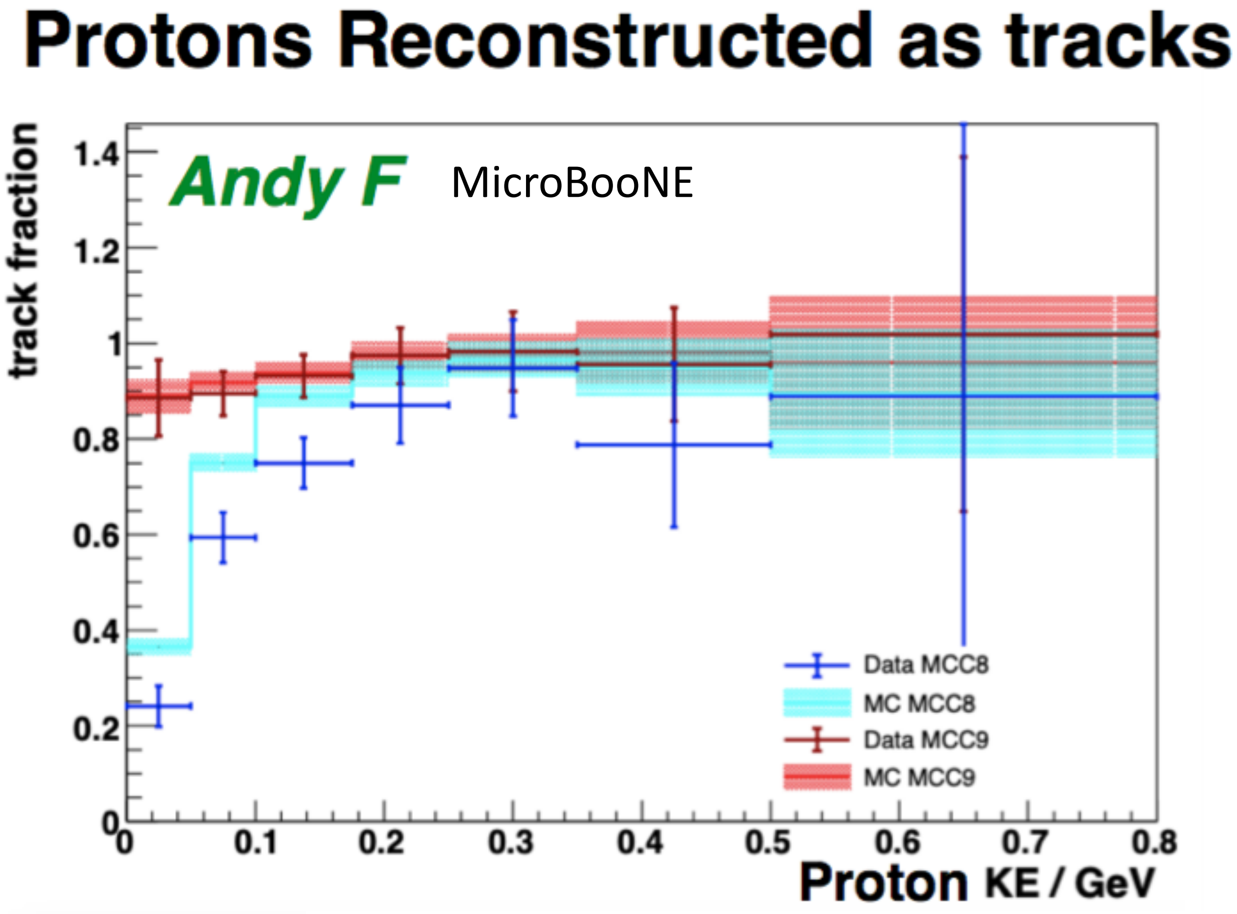
Black: raw ADC waveform
Red: deconvolved charge spectrum





Long-range induction in ±10 adjacent wires

Impact on high-level reconstruction

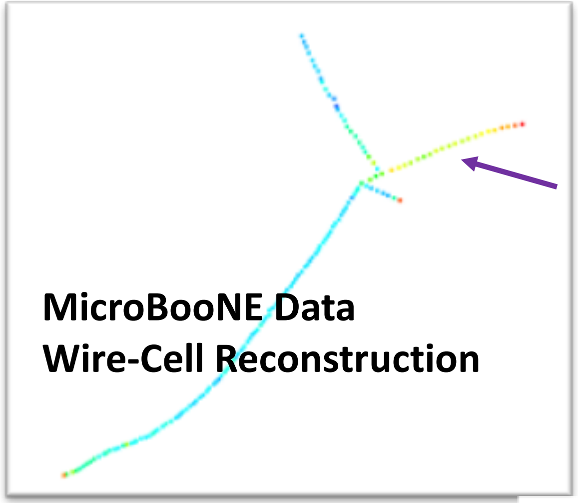


- Neutrino energy reconstruction
- Topology information
- Cross section measurements

Red: 2D kernel (simulation, signal processing)

✓ Better MC/data agreement

✓ High proton track eff. At low energy



Proton ~10 cm
(~0.1 GeV)

or

CCQE

DIS

Summary: *Wire-Cell* reconstruction chain

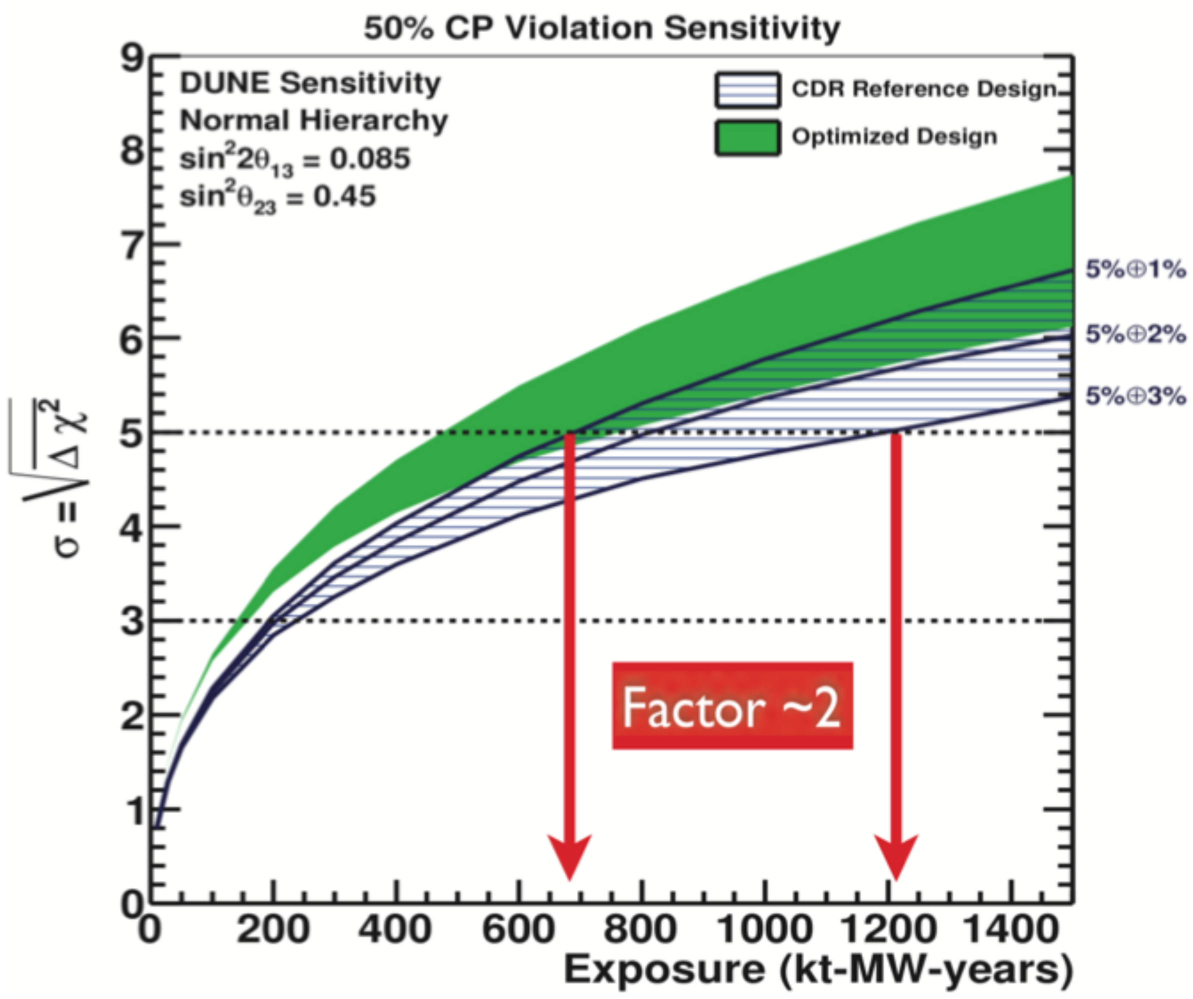
- Signal Processing
- 3D imaging & clustering
- Many-to-many TPC-PMT matching
- In-beam cosmic rejection
- 3D pattern recognition
  - Neutrino vertexing
  - Particle-level clustering
  - Trajectory & dQ/dx fitting
  - Track/shower identification
- Energy & kinematics reconstruction (not covered in this talk)

Summary: what we learned

- Never take for granted → excess noise, 2D signal processing
- Expand your vision and be creative → Wire-Cell 3D imaging & matching
- Be brave → 3D trajectory fitting and dQ/dx fitting
- Professional software → Time & mem optimization, architecture & framework, integration, etc. [B. Viren]
- To be continued …
- Something really challenging → new detector design (vertical drift, number of wire planes, pixel readout, …)
  - Prolonged track → bipolar signal cancellation (further improvement using deep learning, H. Yu, etc.)
  - Isochronous track → large hit multiplicity in a time slice maximizing the wire readout ambiguity
  - Nonfunctional (dead, too noisy, abnormal response) wires → missing vertex, gaps, ghost tracks, large dQ/dx uncertainties

Discussions on DUNE physics

DUNE Neutrino Oscillation Physics

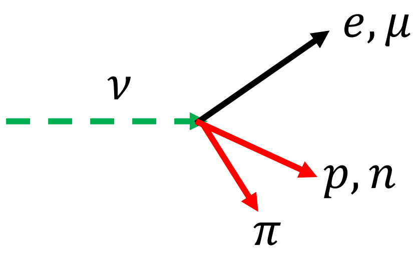


How to bring down uncertainties?

- Flux uncertainty
- Cross section uncertainty
- Detector uncertainty

DUNE Neutrino Oscillation Physics

Where LArTPC event reconstruction can play an important role

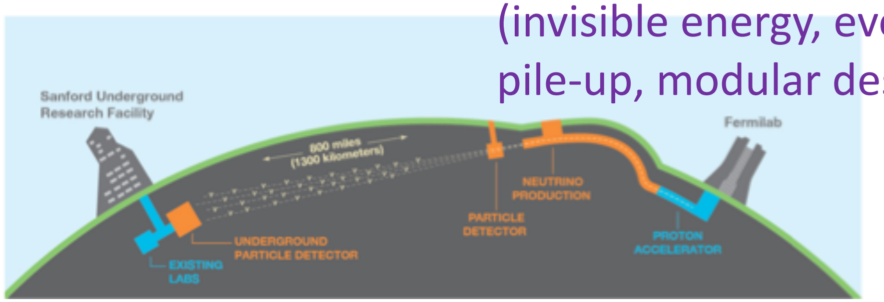


Invisible particles?
Bad clustering?
Kinematics?

Far detector
Large & deep

=?

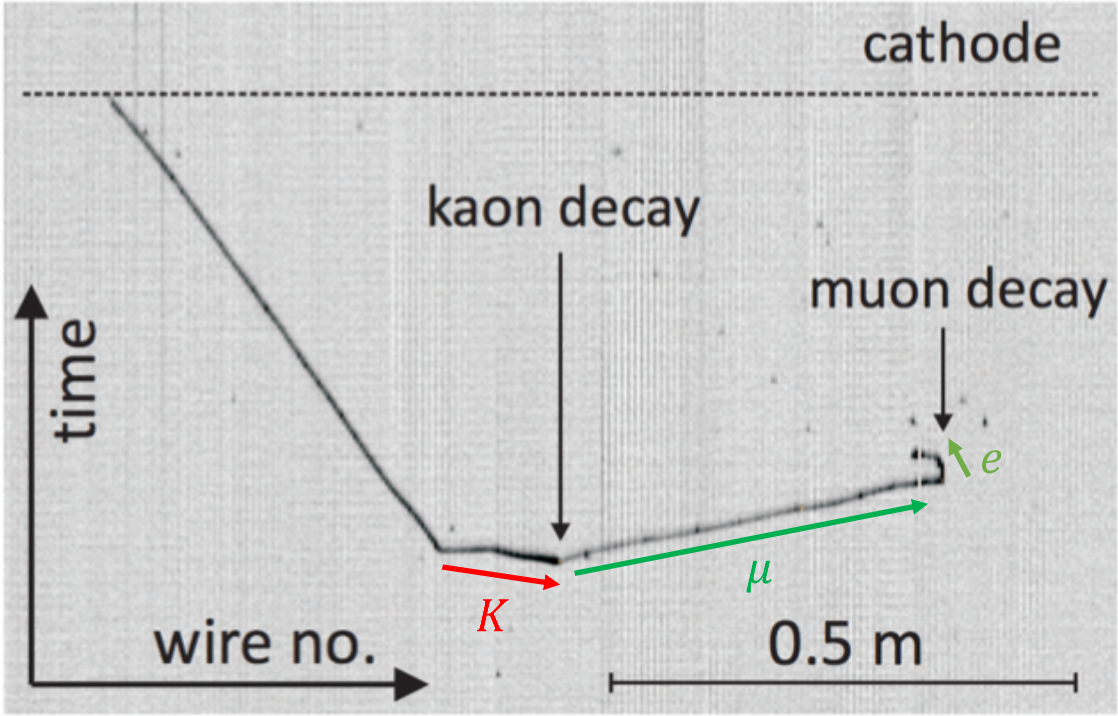
Near detector
Small & shallow
(invisible energy, event pile-up, modular design)



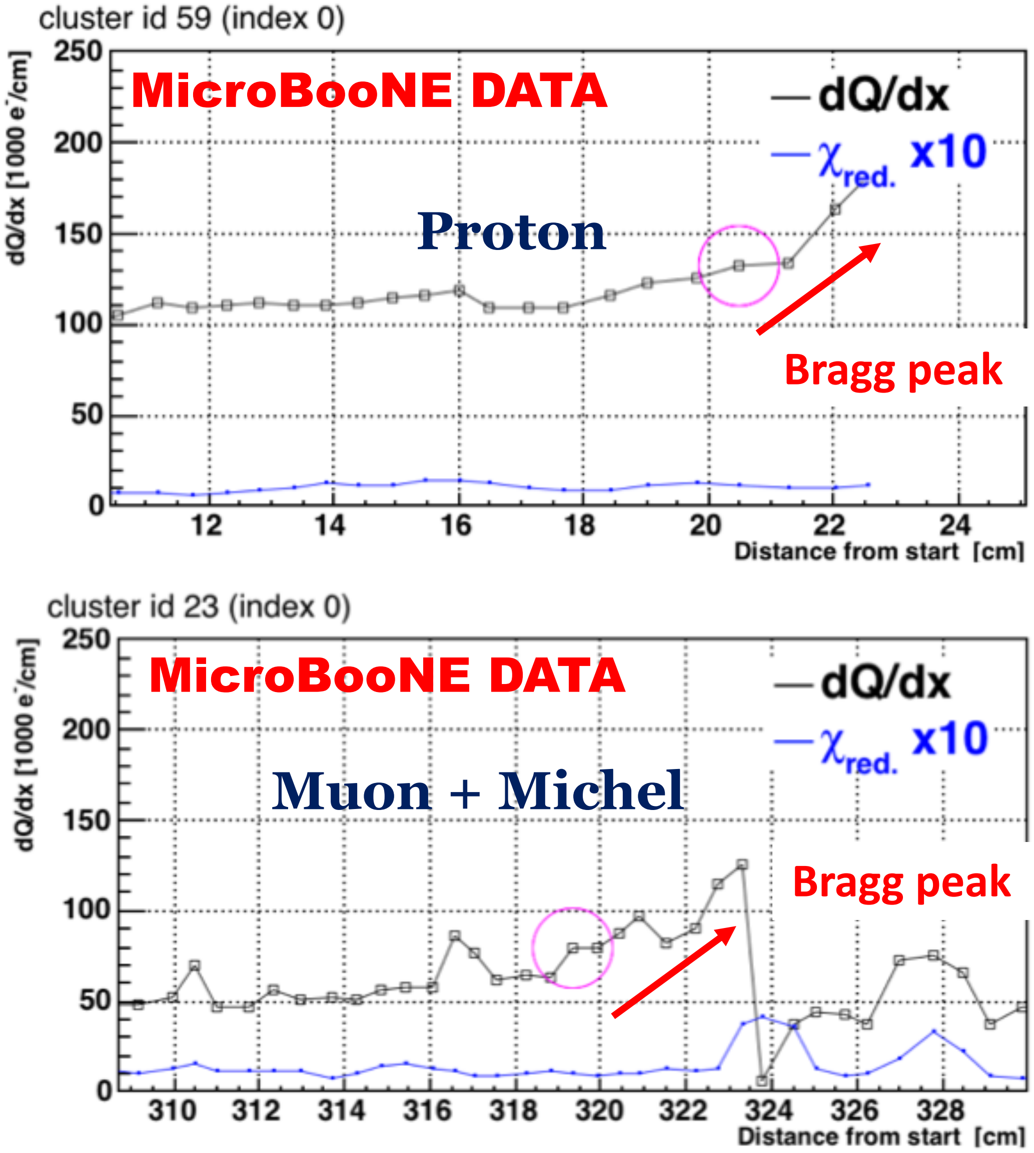
How to accurately reconstruct Argon 39 (low energy) and neutron (low visible & separate) events?

- Flux uncertainty: low energy transfer method
  - Cross section independent on Enu
  - neutrino-Hydrogen, neutrino-electron scattering
- Detection response: cross section + detector effect: DUNE-PRISM
  - Measurements at various off-axis positions in a near LArTPC detector (ArgonCube) → predict far detector unoscillated energy spectrum
  - Near detector flux → far detector flux?
- Detector effect uncertainties: calibration
  - Argon 39, neutron source, etc.

DUNE nucleon decay physics

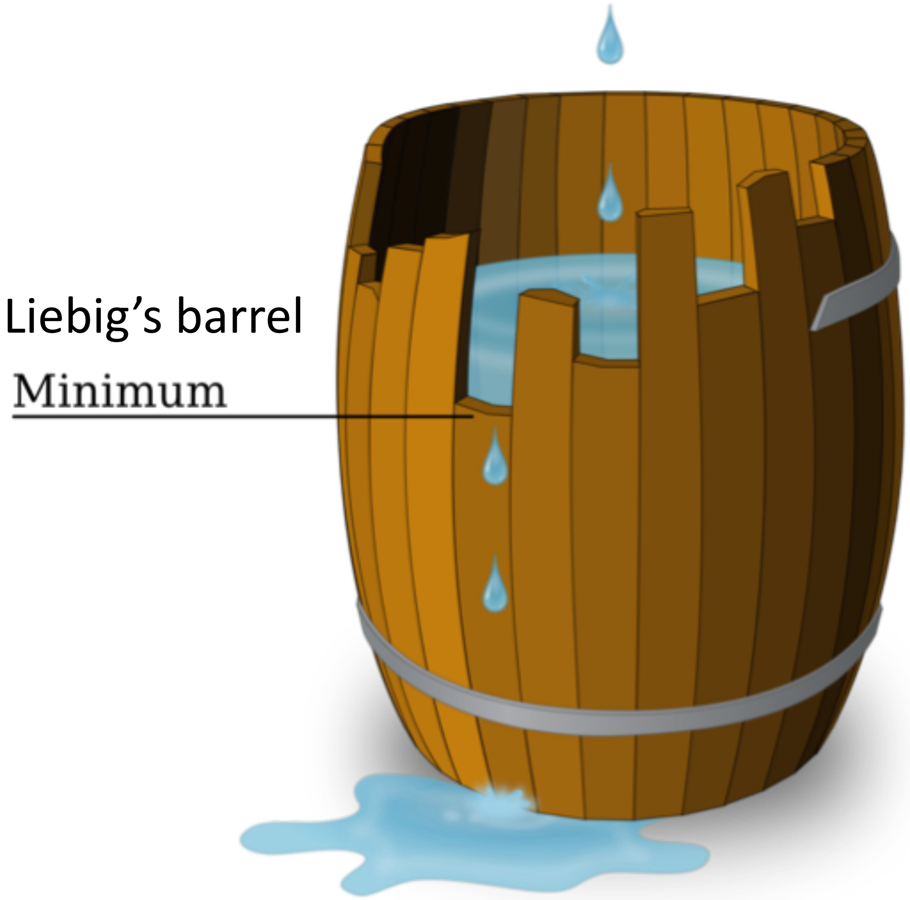


Kaon decay candidate in the ICARUS T600 LArTPC observed in the CNGS data



Thanks for your attention!

- Event reconstruction is fundamental
- Interplay with the understanding of detector → realistic simulation, high performance physics analysis, reliable calibration, new detector technology
- LArTPC event reconstruction is an open question and needs more attention and efforts.



My work

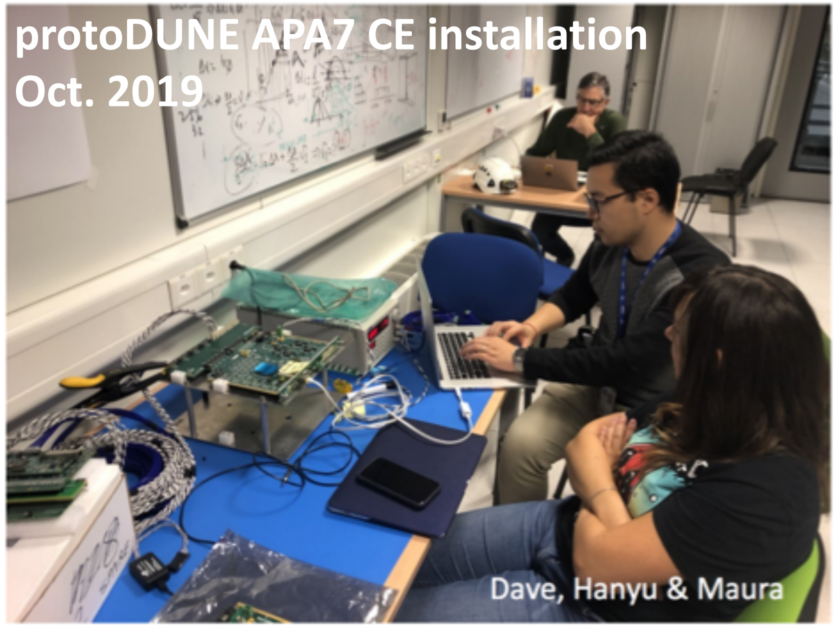
MicroBooNE

- Simulation group co-convener
- Reconstruction group co-convener

- Validation, evaluation, and optimization of Wire-Cell event reconstruction techniques.
- Wire-Cell software integration & large-scale production
- Generic neutrino selection analyses

- Signal processing paper
- Imaging/matching paper preparation [JINST]
- Generic neutrino selection (cosmic rejection) paper preparation [PRD/PRL]

DUNE cold electronics



Additional Slides

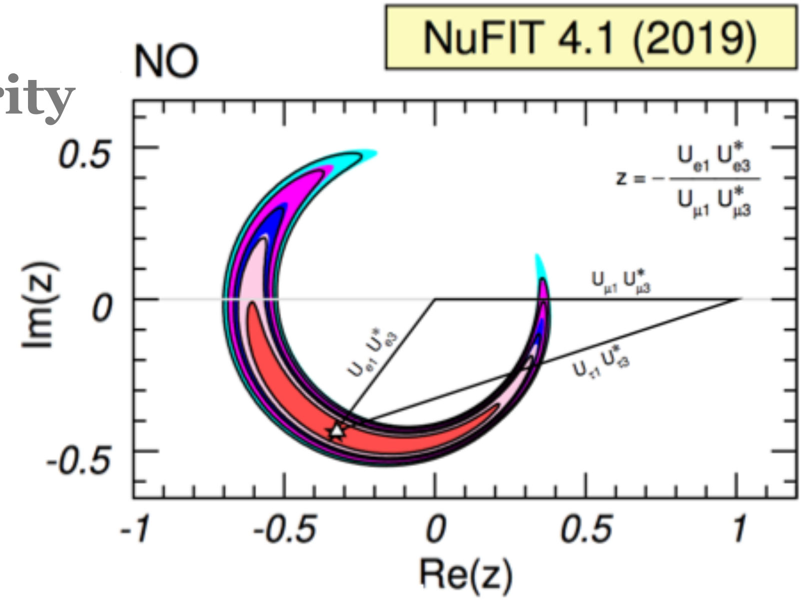
What we don't know?

$\theta_{23} \sim 49.6° \ (\pm 4.1\%)$

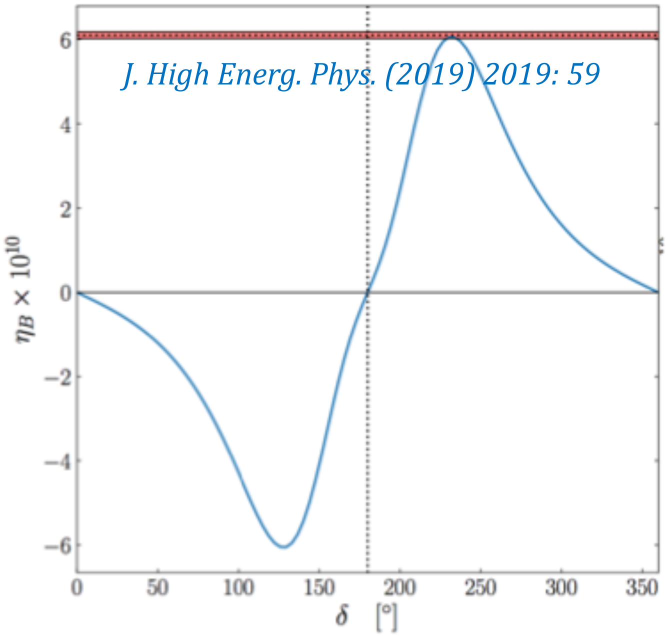
The precision is unsatisfactory

- ✓ Octant degeneracy ($>, <, or = \pi/4$)
  - → underlying symmetries
- ✓ Impact the measurements of CP-violation and mass hierarchy

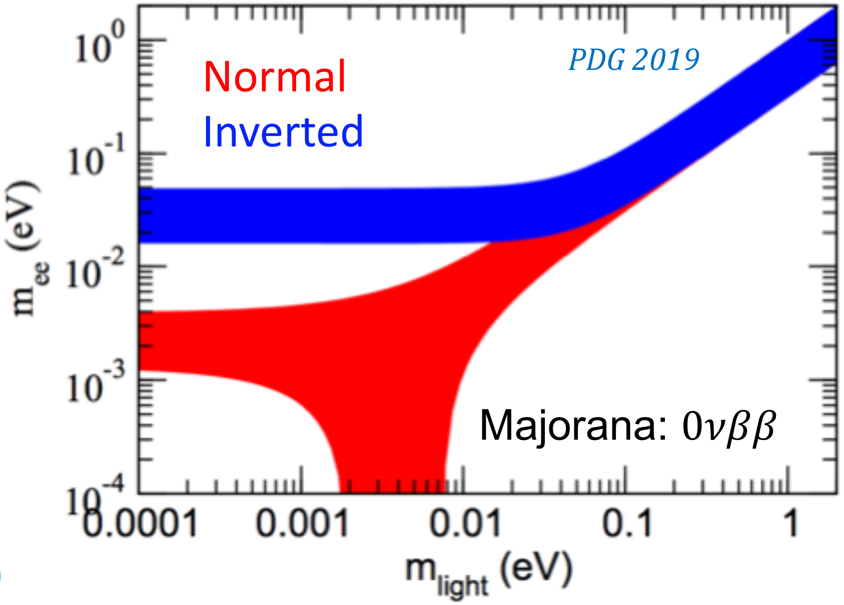
Leptonic Unitarity



Matter and anti-matter asymmetry



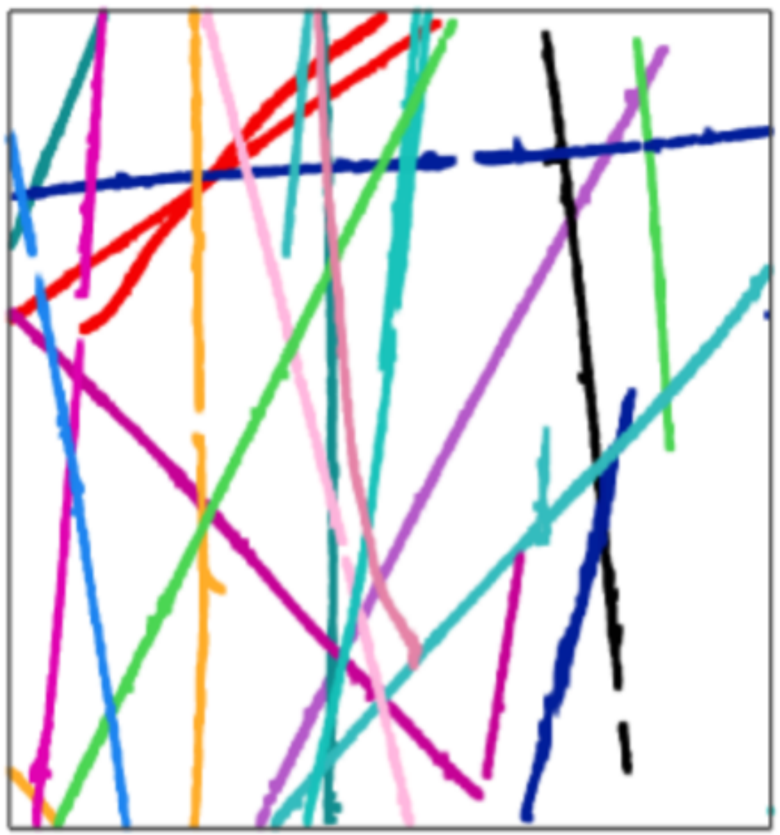
Leptonic CP violation ($\delta_{CP} \neq 0, \pi$?)

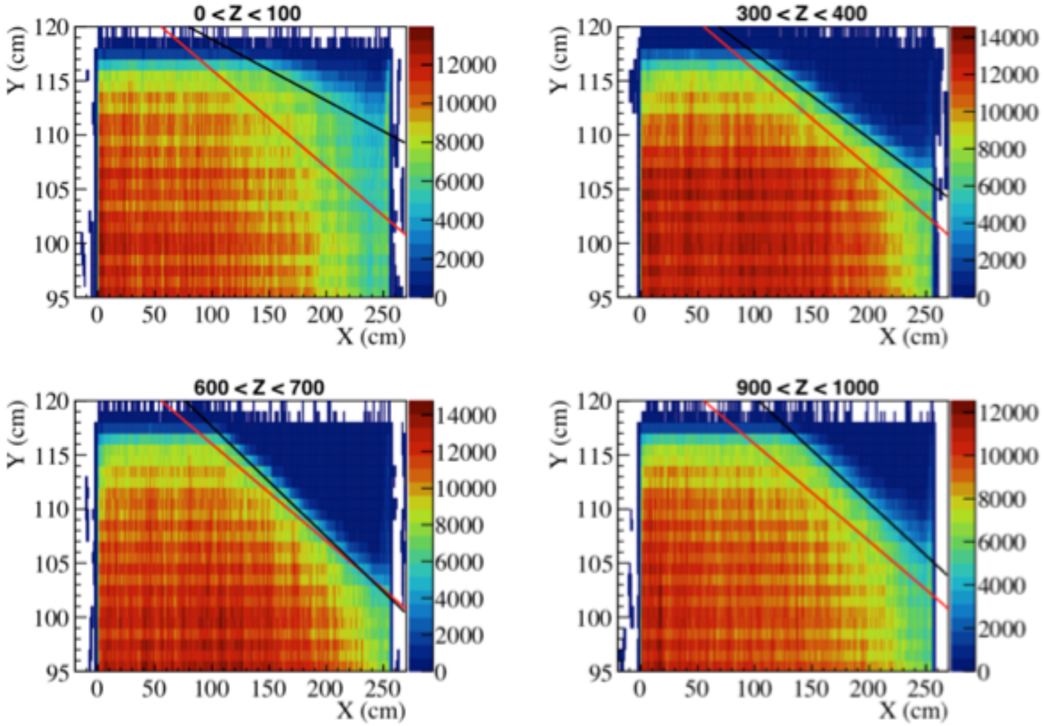


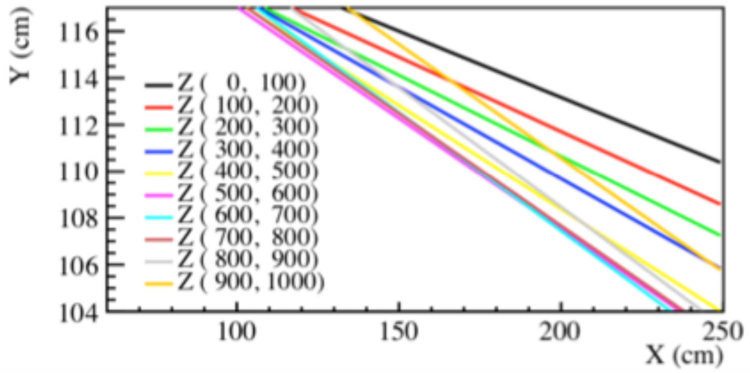
Mass hierarchy

$m_1 < m_2 < m_3$
or $m_3 < m_1 < m_2$

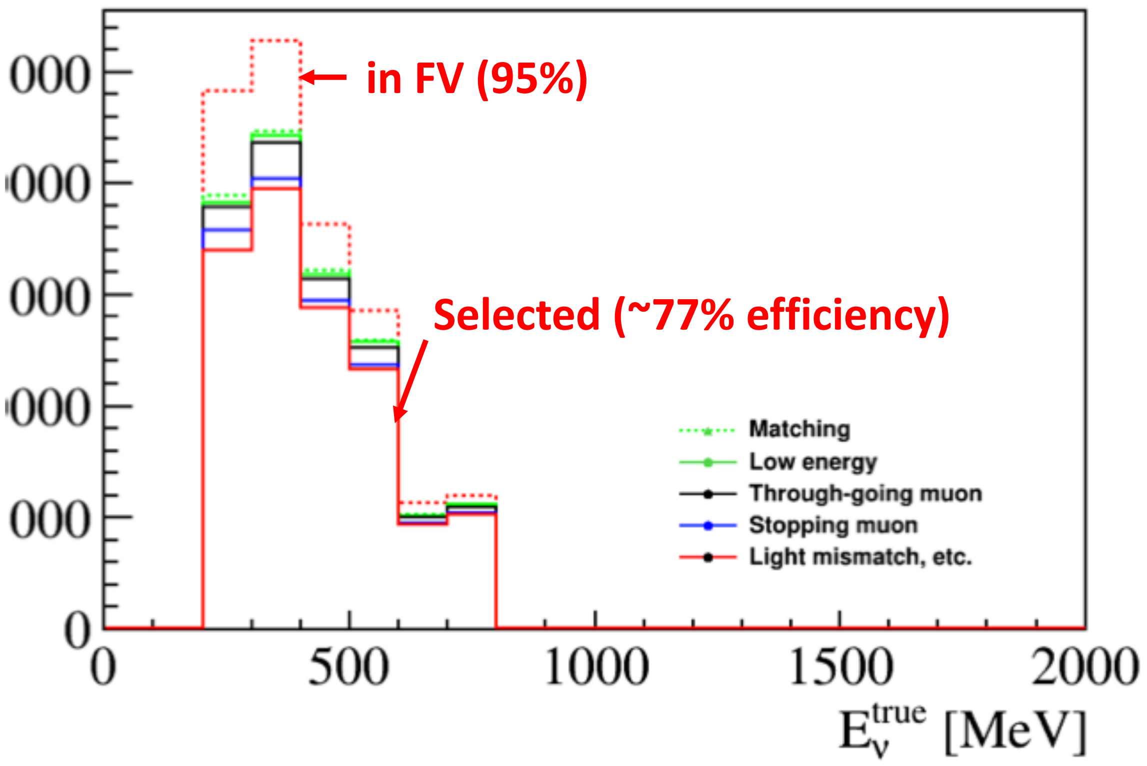
Space charge boundary

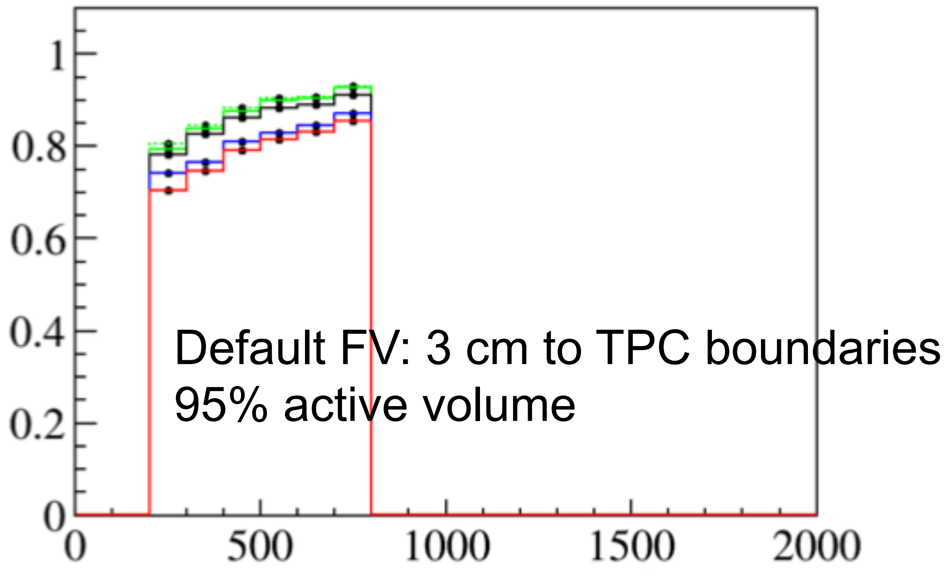


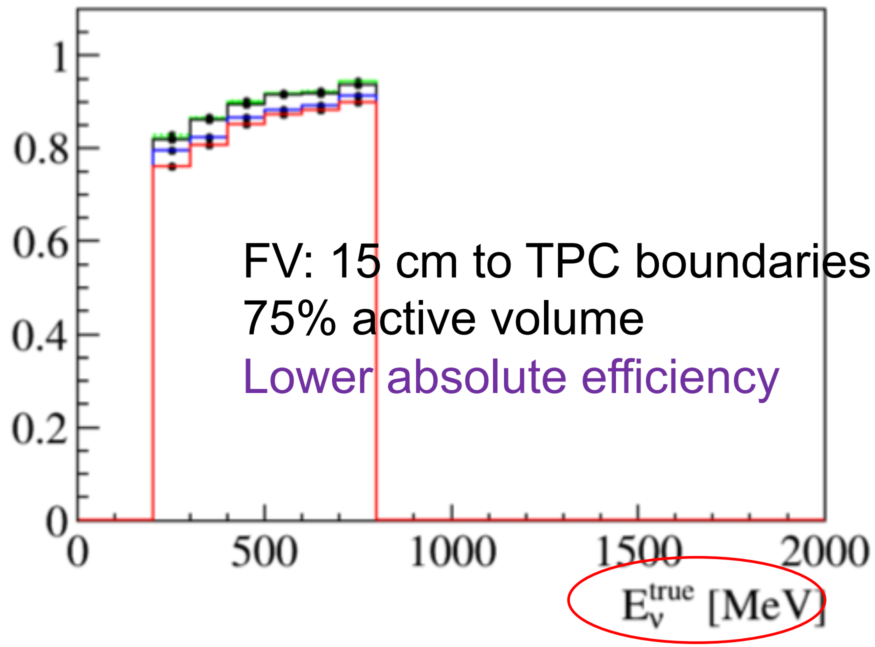




eLEE nue efficiency







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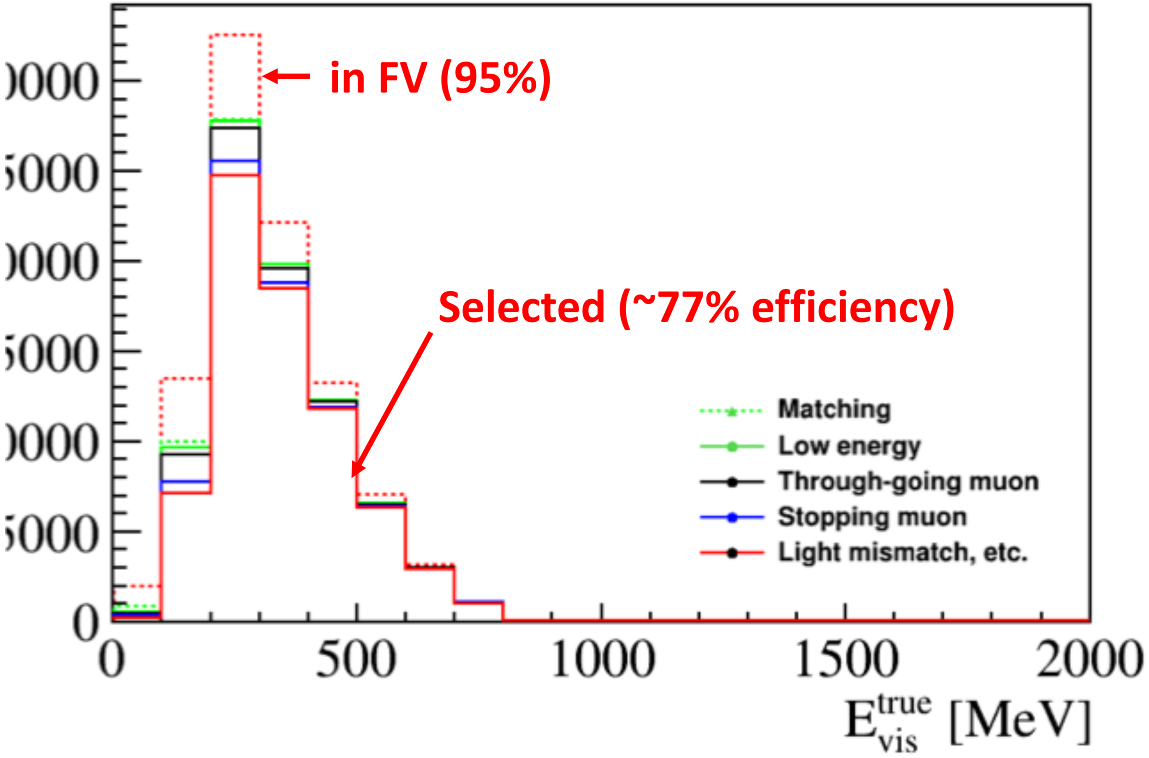
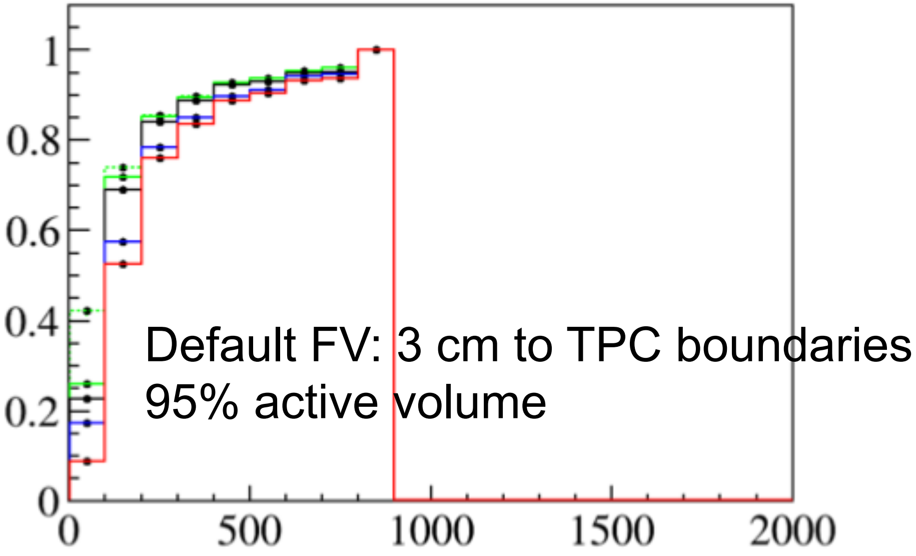
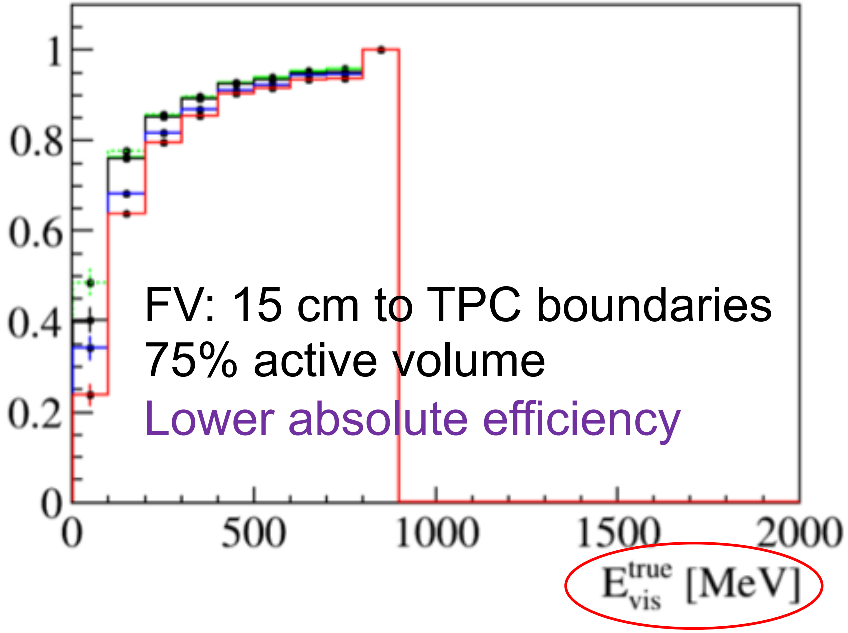
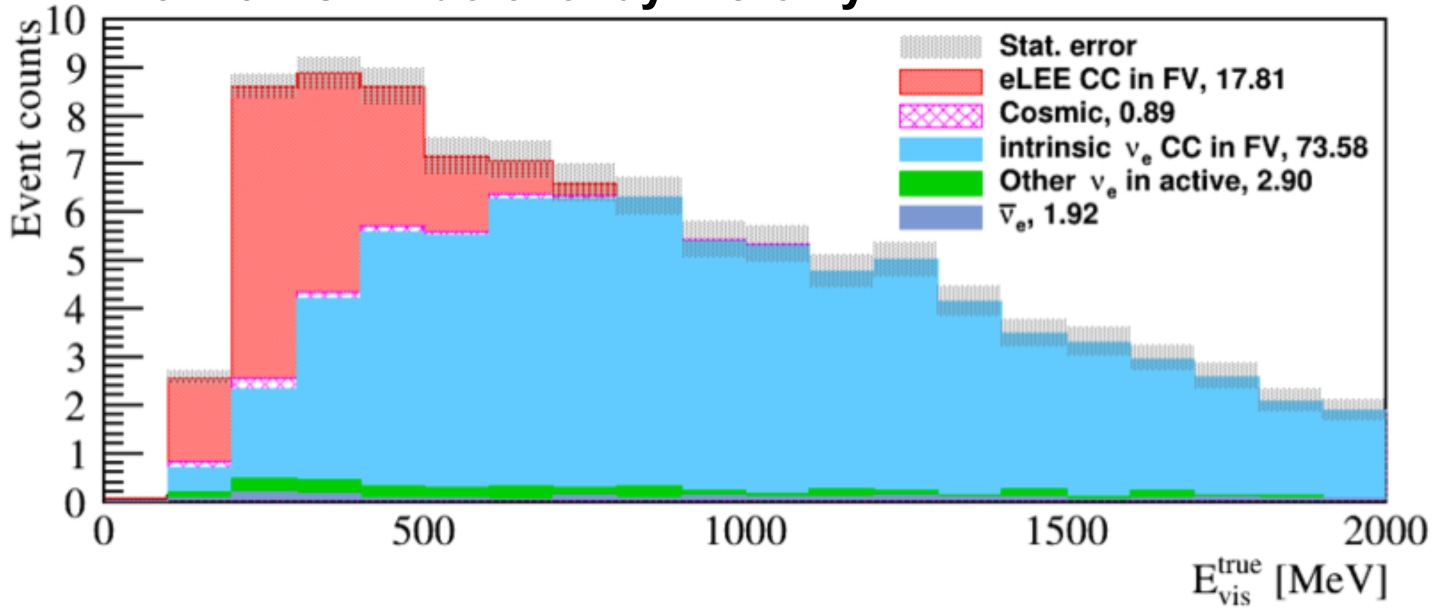






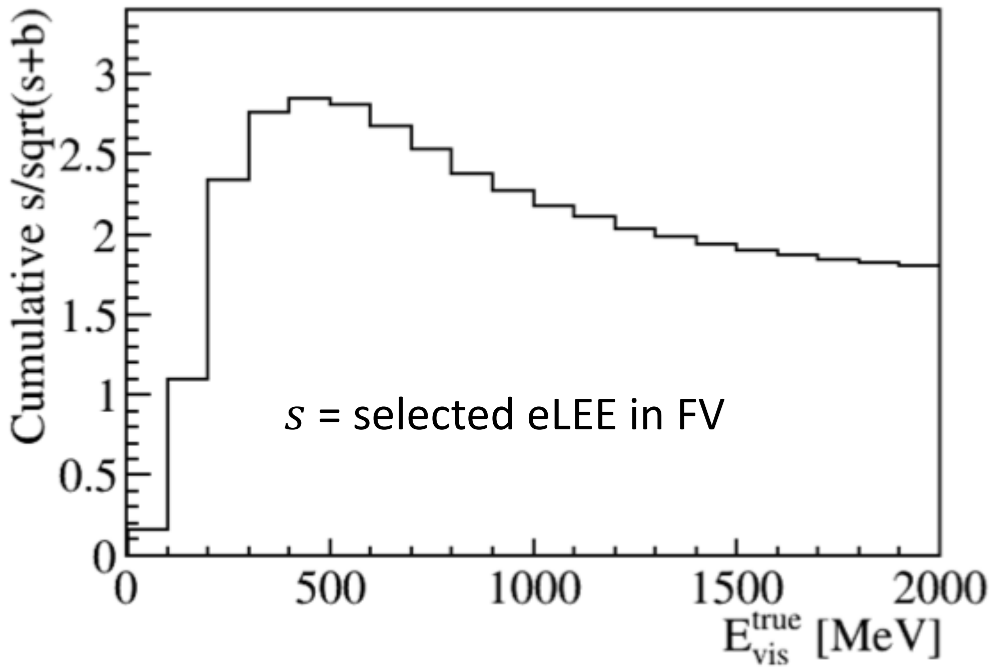
Selected intrinsic nue + eLEE

5E19 POT nue overlay MC only



Without ν_μ background and beam-off cosmic background.

Cumulative $s/\sqrt{(s+b)}$ at each bin

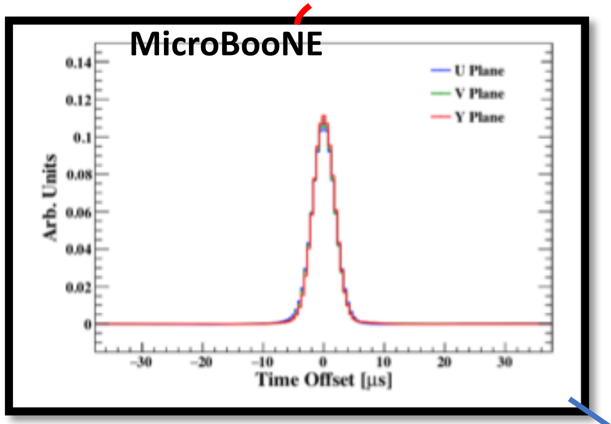


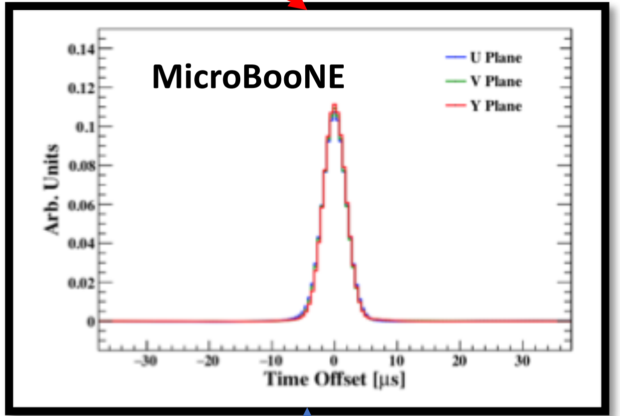
s = selected eLEE in FV

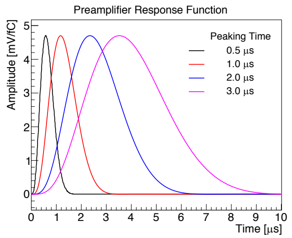
Last but not least

Charge Extraction (Signal Processing)

- The most fundamental technique, provides a solid foundation to all the downstream reconstruction.
- To make induction planes ≅ collection plane

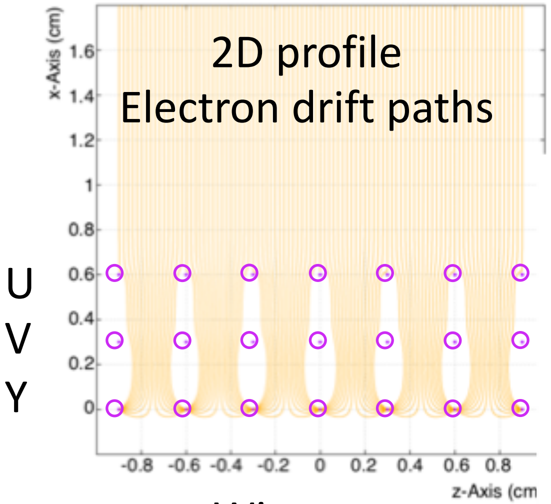


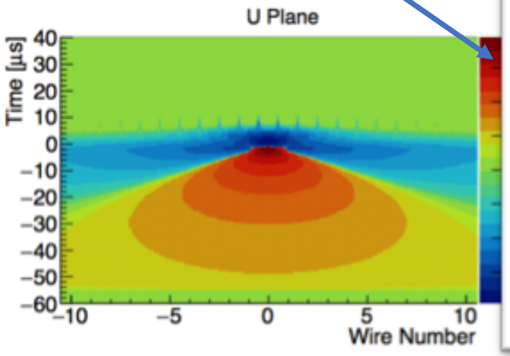


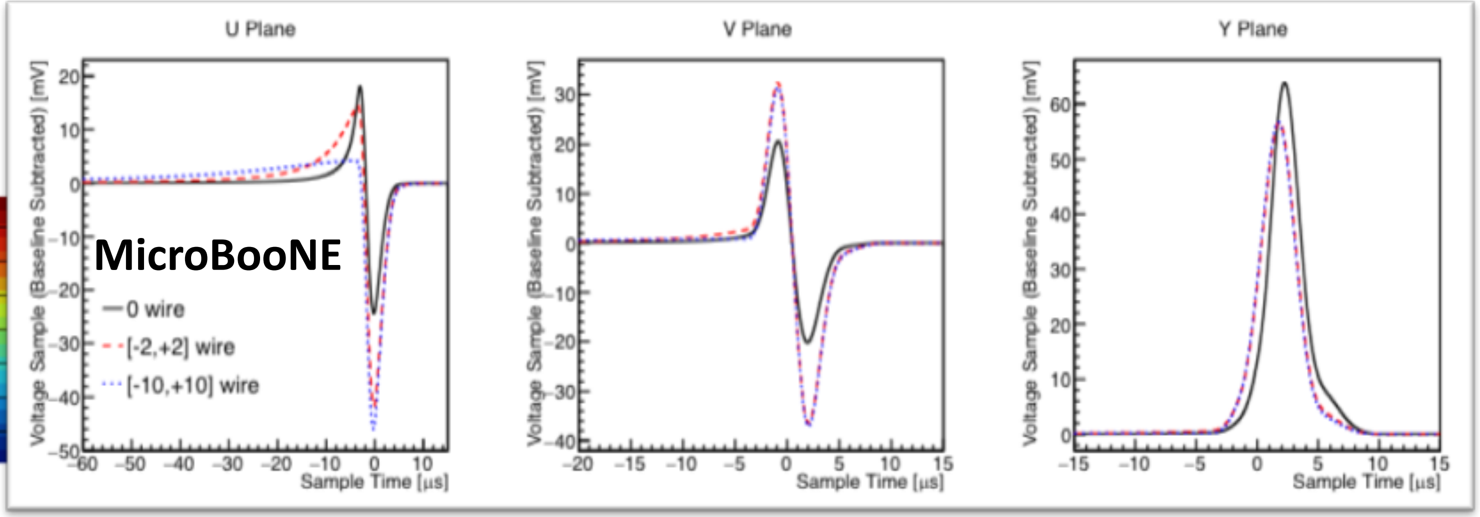


Electronics response

Raw waveform



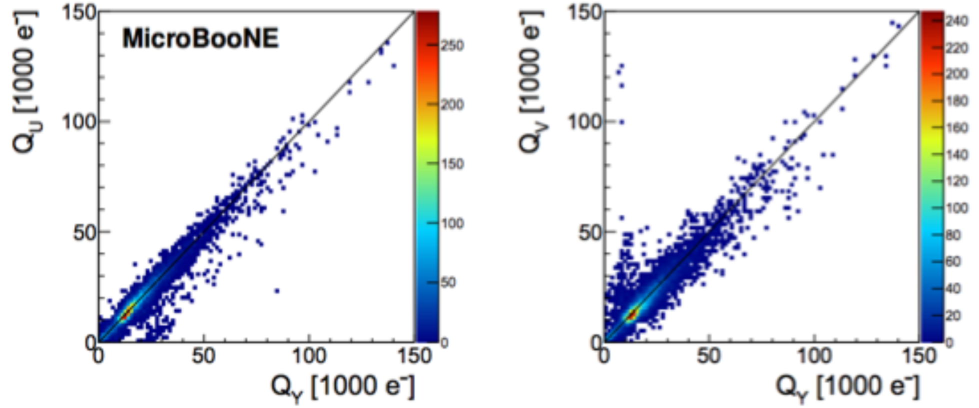




Wire response
(long-range static electric field response)

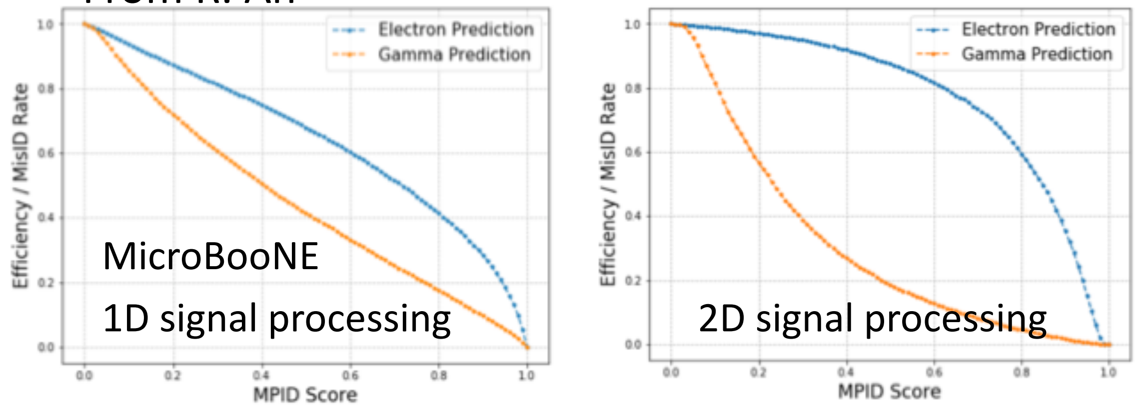
Merits of advanced signal processing

- Significantly improved signal processing for induction wire planes

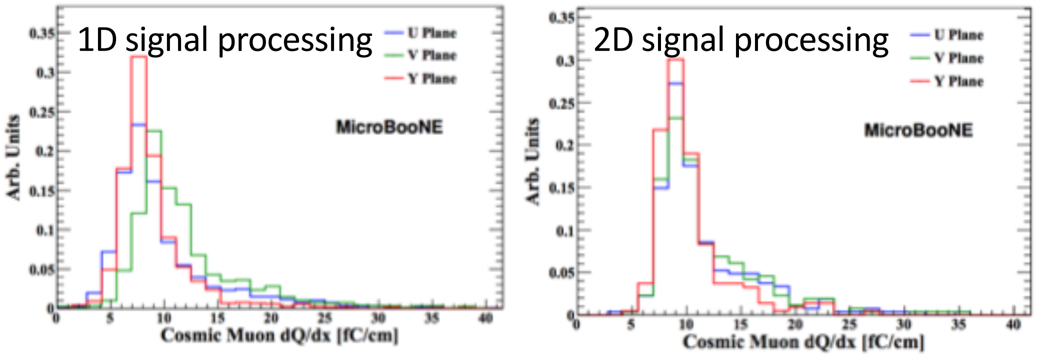


Consistent reconstructed charge across all three wire planes

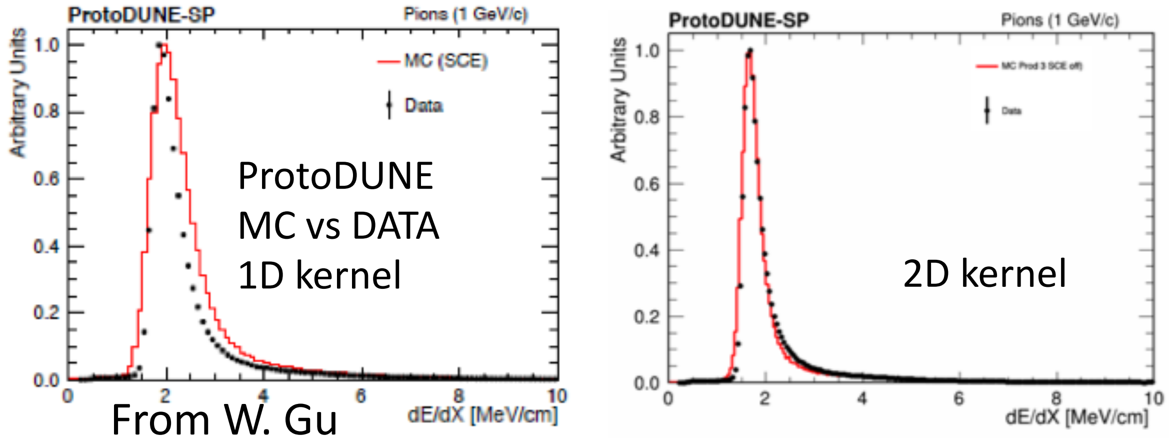
From R. An



Deep learning electron/gamma separation in 1e1p sample



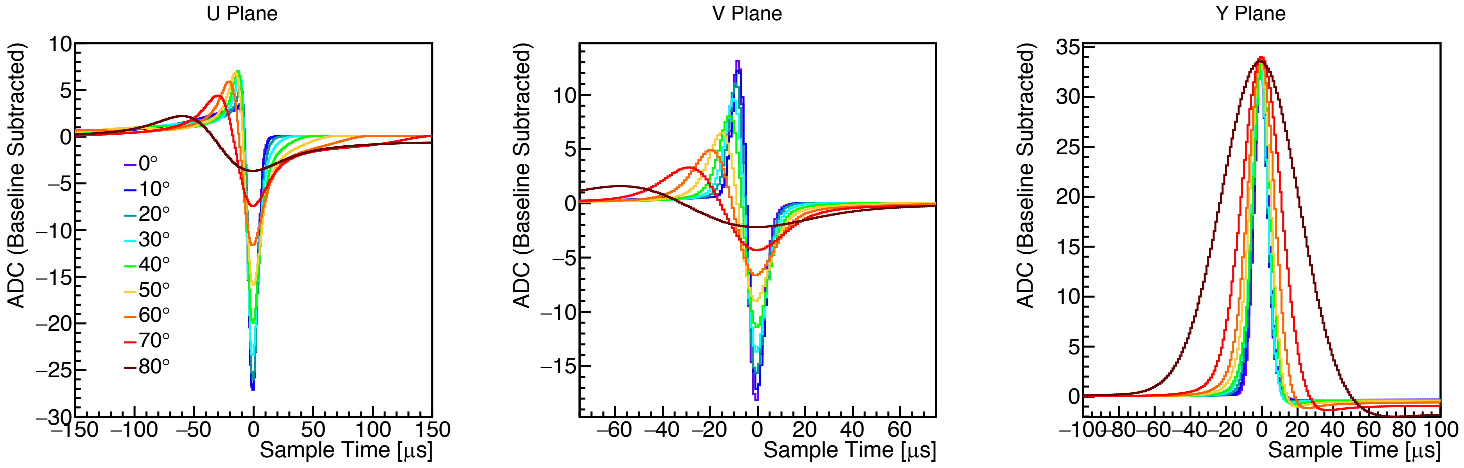
Consistent dQ/dx spectra!



From W. Gu

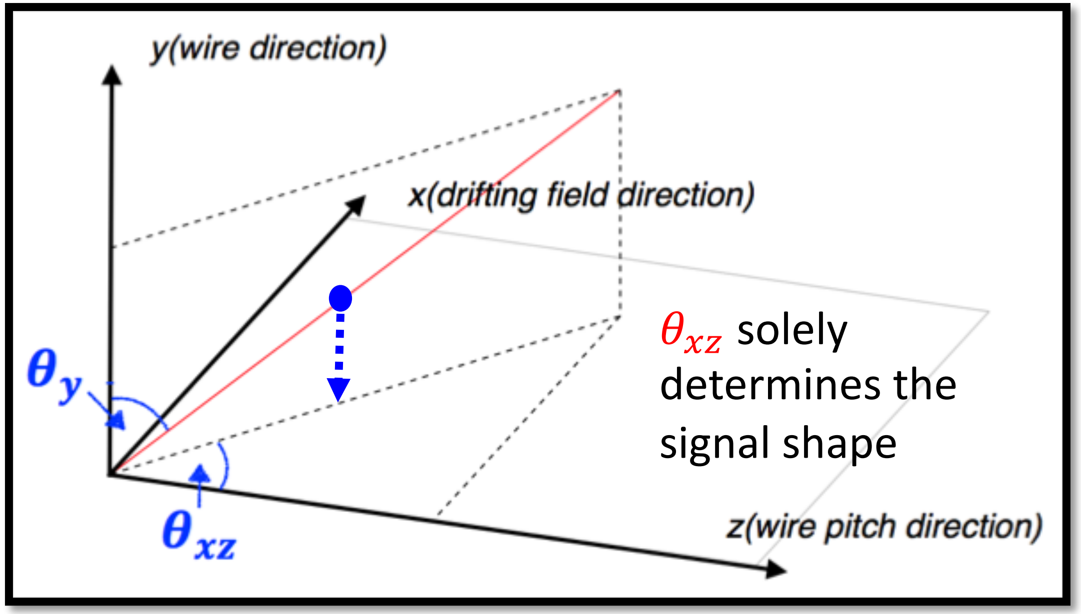
Topology-dependent waveforms ***SIMULATION!***

Varying θ_{xz}
given $\theta_y = 90°$ (perpendicular to wire orientation)



- *Project/Move charge onto x-z plane*
- *Time stretch (shape) of the ionization charge determines the signal shape*

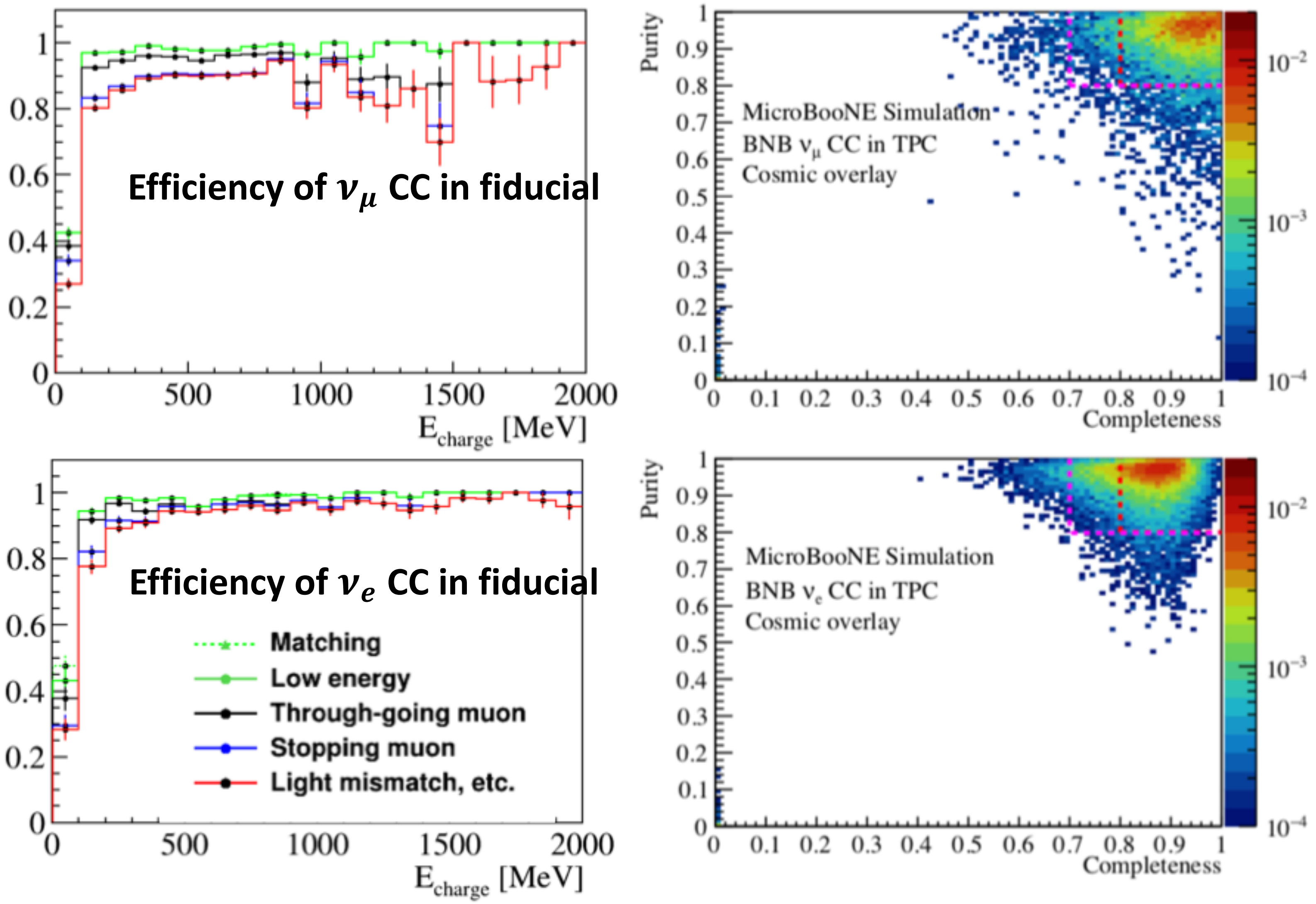
$$q(t,z) \otimes Field(t,z)$$



3D image of selected neutrino activity

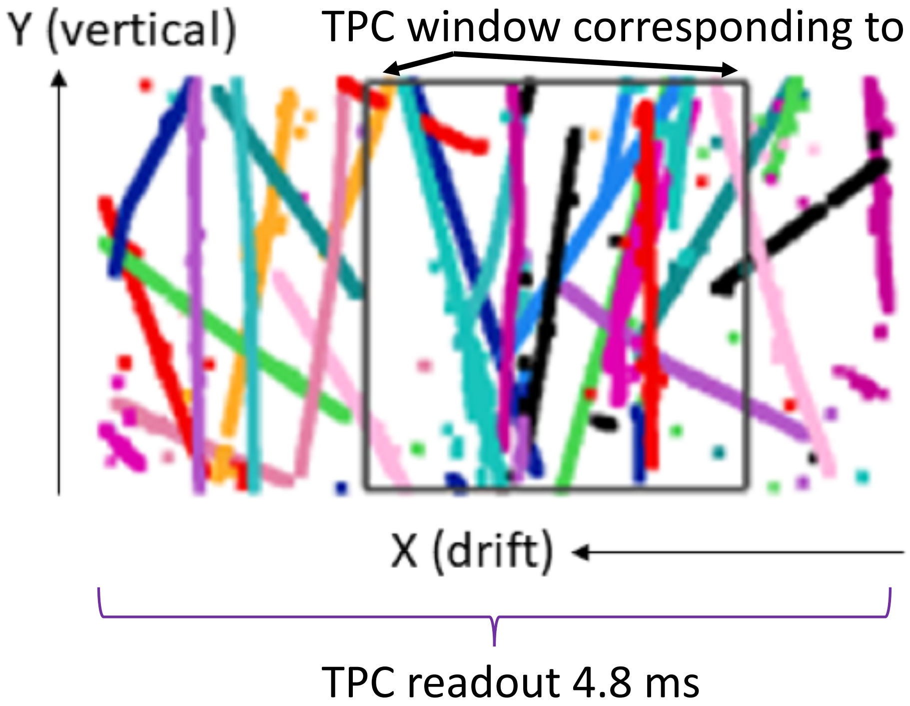
Such an efficient method to reconstruct clean & intact 3D images of neutrino activities has never been demonstrated before (at least in MicroBooNE)

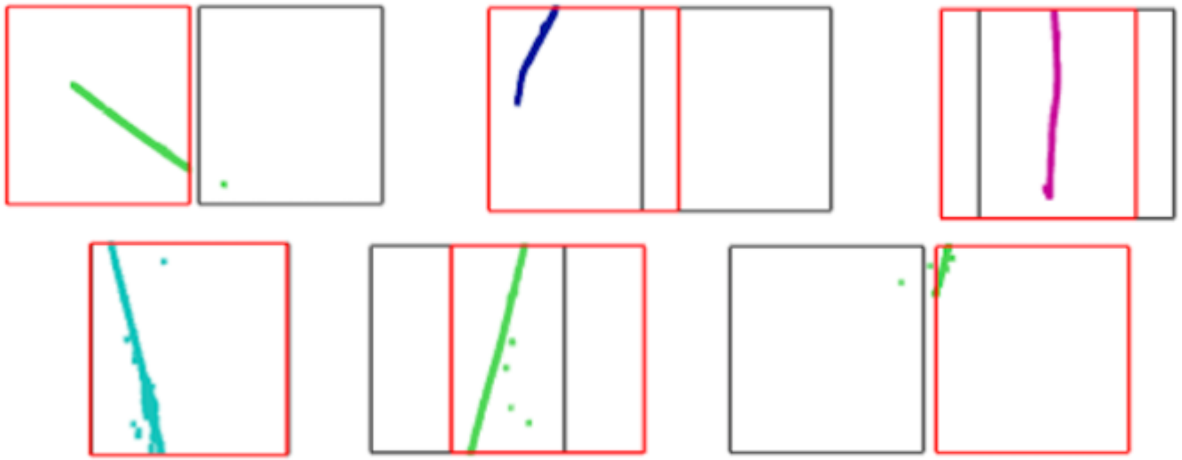
Events have neutrino interactions in TPC active volume



Low visible energy
(low energy or close to TPC boundary)
events are challenging!

TPC/charge-PMT/light Matching



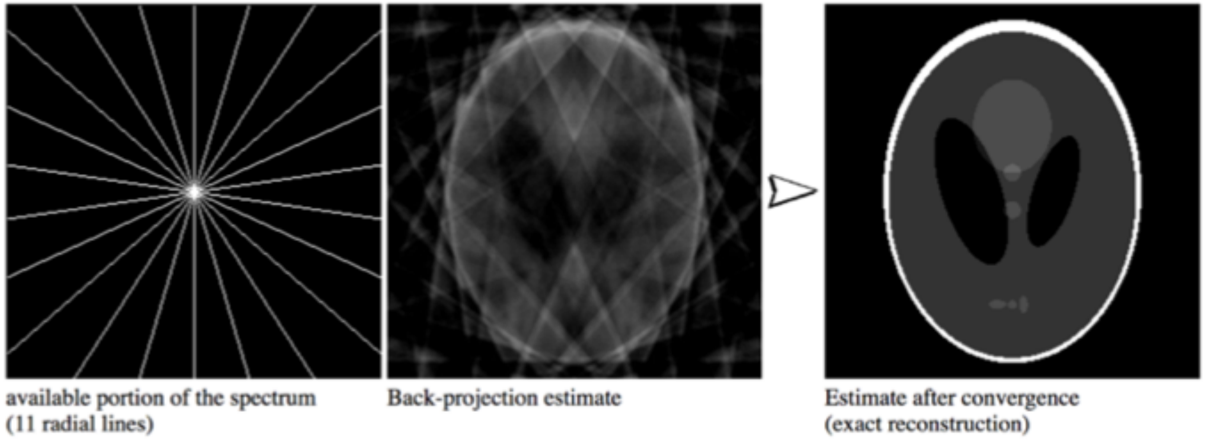


Examples of matching results by comparing the predicted PMT signals with the measured ones

Compressed sensing (L1-regularized minimization)

A signal processing technique for efficiently reconstructing ***sparse*** signal, by finding solutions to ***underdetermined linear systems***

E.g. tomography with sparse projections



Enabled by the **sparse** LArTPC activities

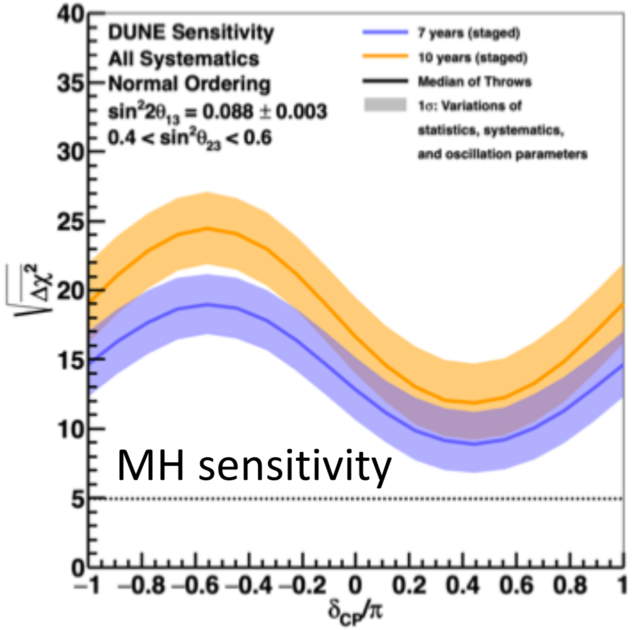
Also incorporate **positivity** *(ionization charge only drift towards wire plane – positive charge value)* and **proximity** *(continuous energy depos)*

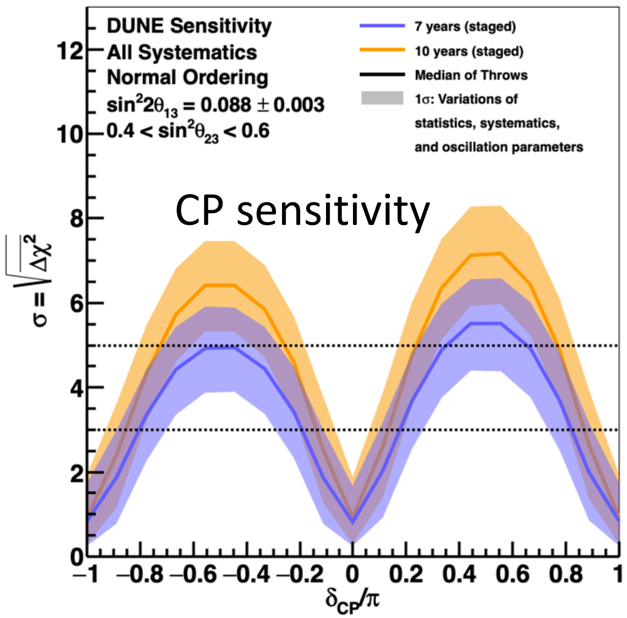
L1-regularization (hours to mins for a MicroBooNE event)

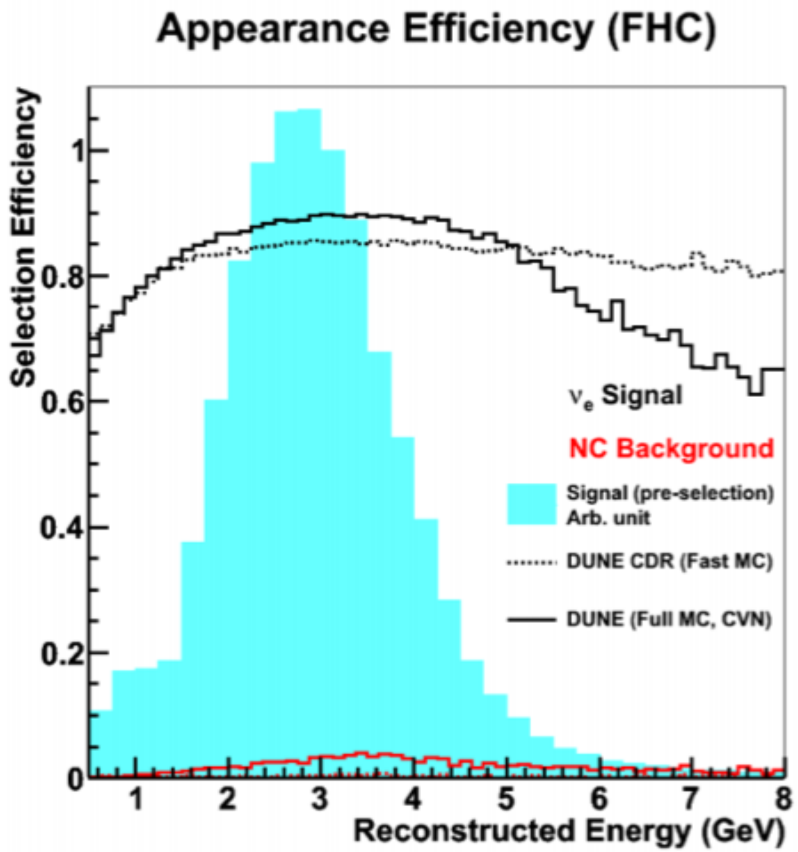
- ✓ Minimize $\chi^2 = (y - Ax)^2 + \lambda ||x||_1$, L1-norm is the sum of the absolute value of each element of vector x
- ✓ Convex, local minimum = global minimum [fast algorithms]

DUNE Neutrino Oscillation Physics

DUNE TDR







The median (central) value of these sensitivity curves highly rely on the detection efficiency of $\nu_e(\bar{\nu}_e)$

This is a challenging event reconstruction task as shown in MicroBooNE.