## HEP PI Meeting

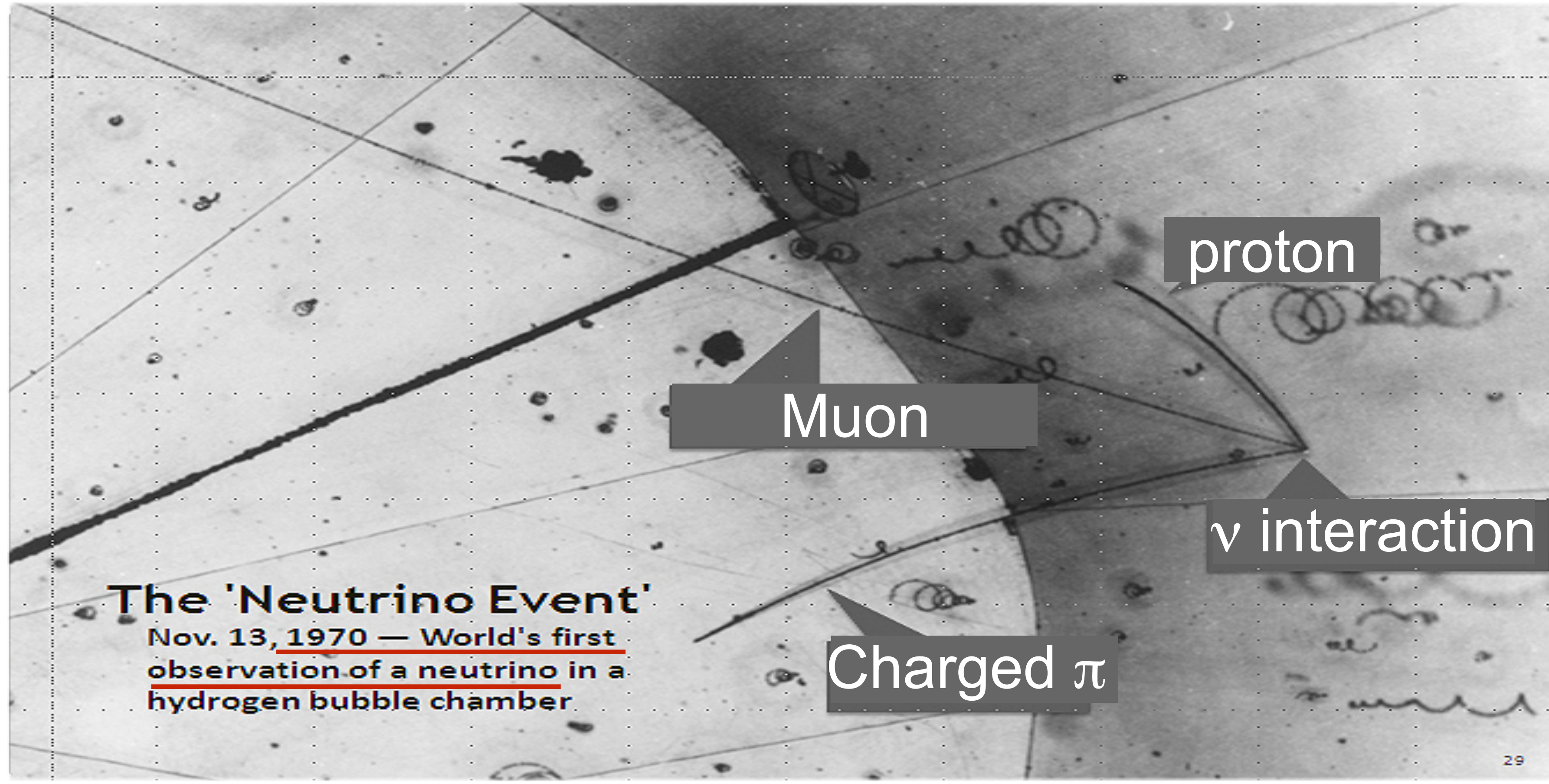
Sponsored by the U.S. Department of Energy
Office of Science
Hilton Washington, DC/Rockville Hotel, Rockville, MD
June 16-17, 2014

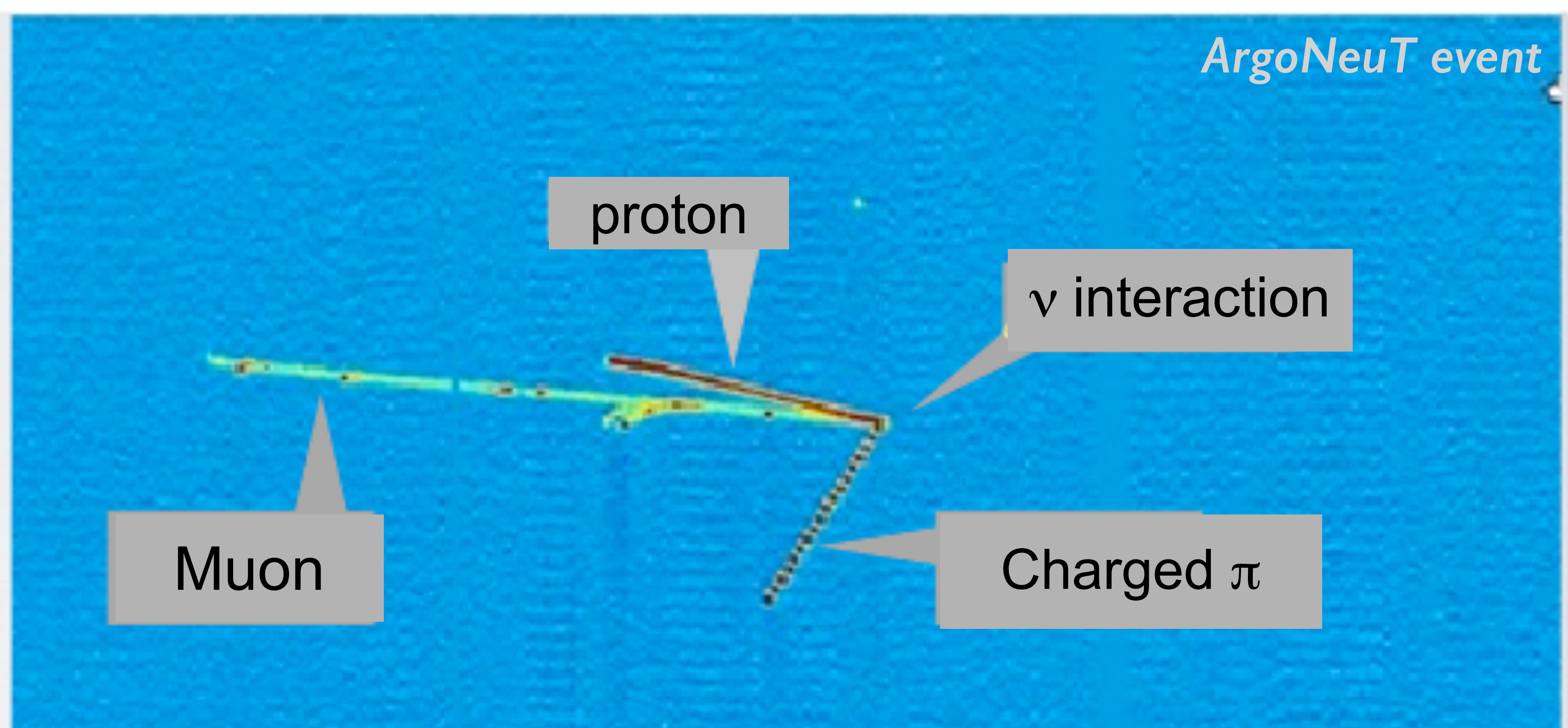
# Short-Baseline Neutrino effort (SBN)

# with emphasis on LAr R&D

F. Cavanna, B. Fleming,
M. Kordosky, C. Mauger
O. Palamara, D. Schmitz,

ArgoNeuT, MicroBooNE, LAr1-ND, ICARUS, LArIAT and CAPTAIN



# $\nu$ Measurements, new physics

**Short Baseline**
***L/E ~1 km/GeV***
Hints of sterile neutrinos
New physics?

**Long Baseline**
***L/E ~ 1000km/GeV***
Measuring Mass Hierarchy and Looking for CP Violation

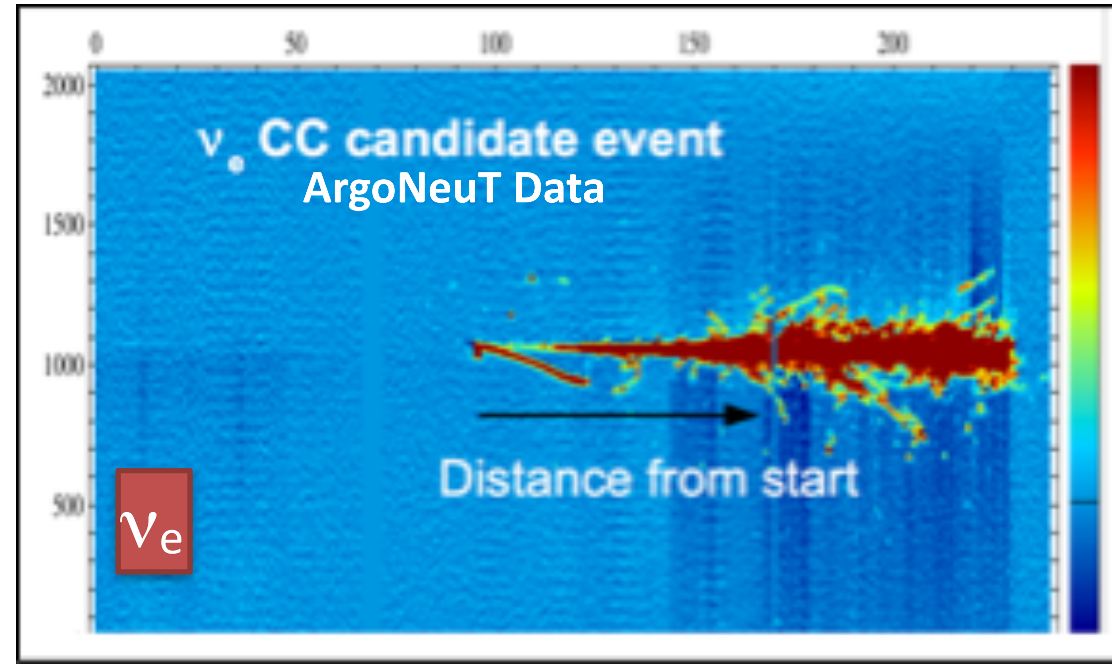
$\nu_\mu \rightarrow \nu_e$ appearance experiments
$E_\nu$ 1-10 GeV
Precision detectors are required:

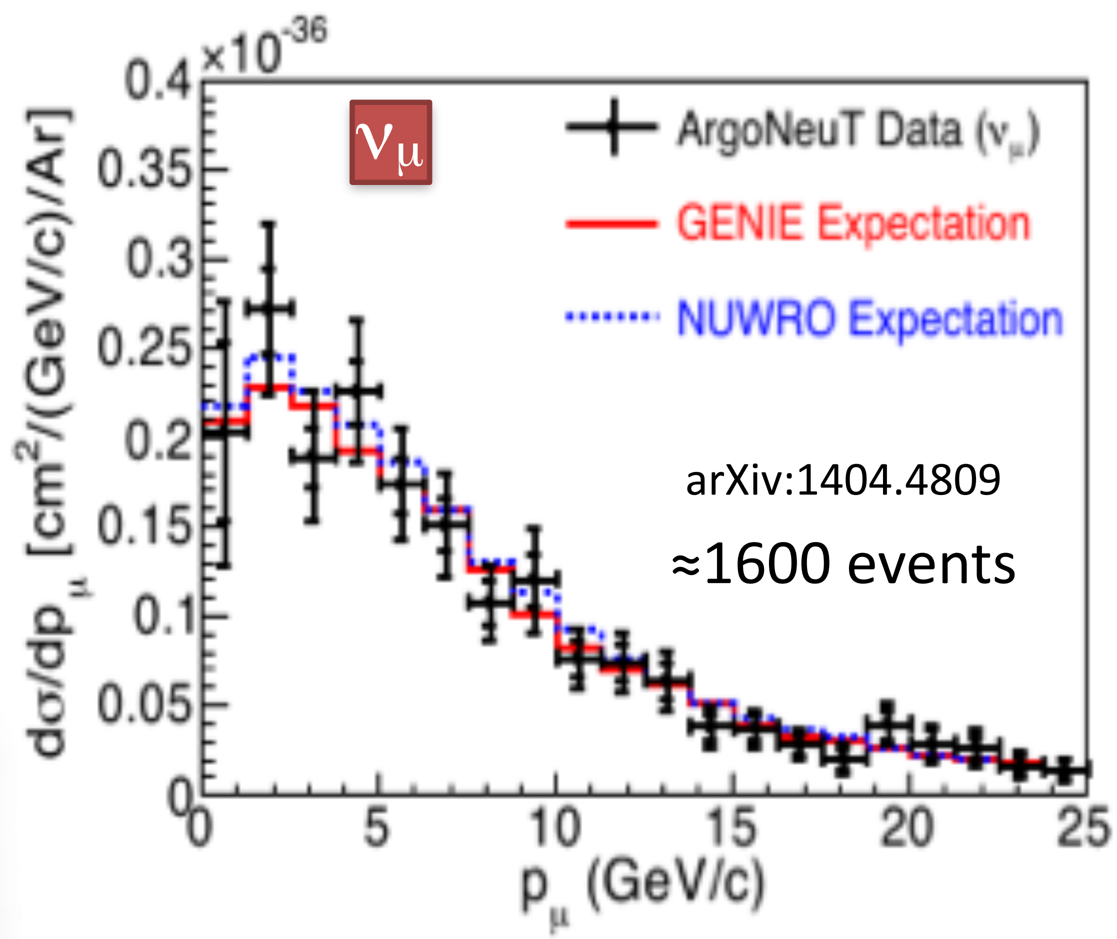
**Liquid Argon TPCs**

# SBN Synergy with the Long-Baseline Program

- SBN Program has important synergies with on-going lab efforts and the future long-baseline neutrino program
  - SBN experiments offer a great opportunity for use of mid-scale detectors which will see large neutrino exposures.
    - Continued LArTPC technology development and prototyping
    - Development and validation of LArTPC event reconstruction with large $\nu_\mu$ and $\nu_e$ data sets
    - Measure important $\nu$-Ar cross sections in GeV energy range
    - Demonstrate sensitive multi-detector $\nu_\mu \rightarrow \nu_e$ appearance and disappearance oscillation measurements with LAr detectors

**Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.**



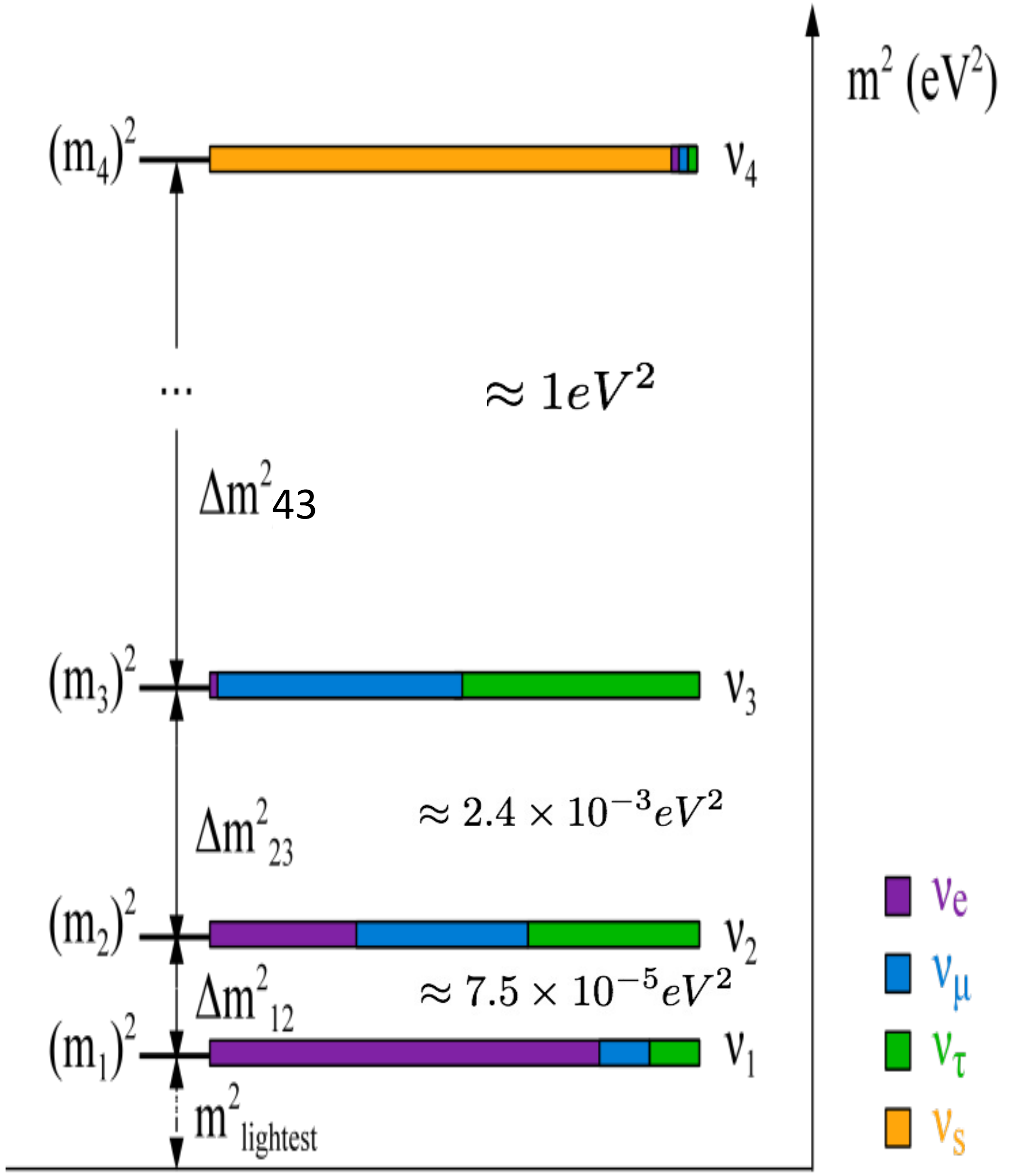



# Expands the Neutrino Physics Science Program

- SBN Program expands the science reach of the world-class neutrino physics program at Fermilab
  - While each of these measurements alone lack the significance to claim a discovery, together they could be hinting at important new physics

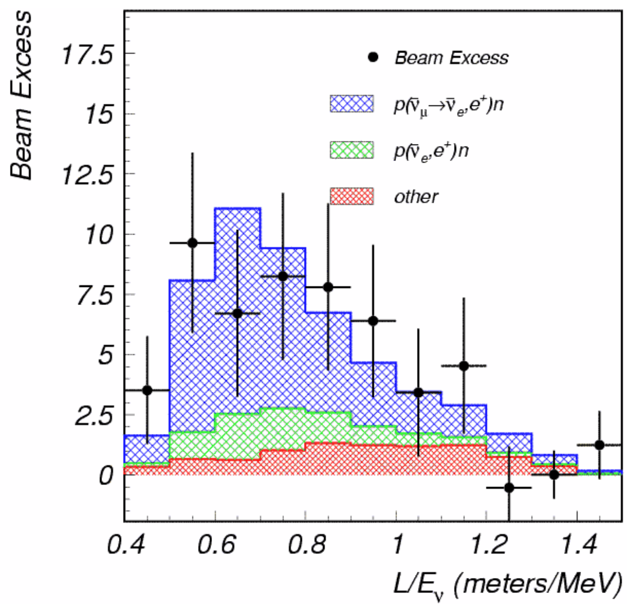
| Experiment | Type | Channel | Significance |
|---|---|---|---|
| LSND | DAR | $\bar{\nu}_\mu \to \bar{\nu}_e$ CC | $3.8\sigma$ |
| MiniBooNE | SBL accelerator | $\nu_\mu \to \nu_e$ CC | $3.4\sigma$ |
| MiniBooNE | SBL accelerator | $\bar{\nu}_\mu \to \bar{\nu}_e$ CC | $2.8\sigma$ |
| GALLEX/SAGE | Source - e capture | $\nu_e$ disappearance | $2.8\sigma$ |
| Reactors | Beta-decay | $\bar{\nu}_e$ disappearance | $3.0\sigma$ |

*K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)*




One thing is certain…

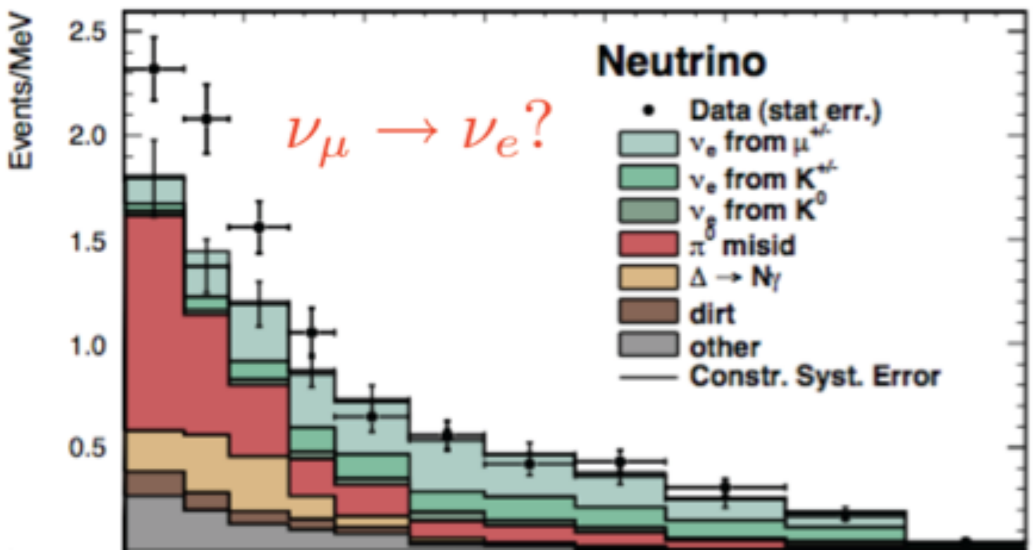
**The discovery of a light sterile neutrino would be monumental for particle physics as well as cosmology**




# LSND: Liquid Scintillator Neutrino Detector
## Decay at rest $\overline{\nu}_{\mu} \rightarrow \overline{\nu}_{e}$ oscillation search

Observed 87.9 ± 22.4 ± 6.0 events
above background
Oscillation Probability: 0.26%

## MiniBooNE



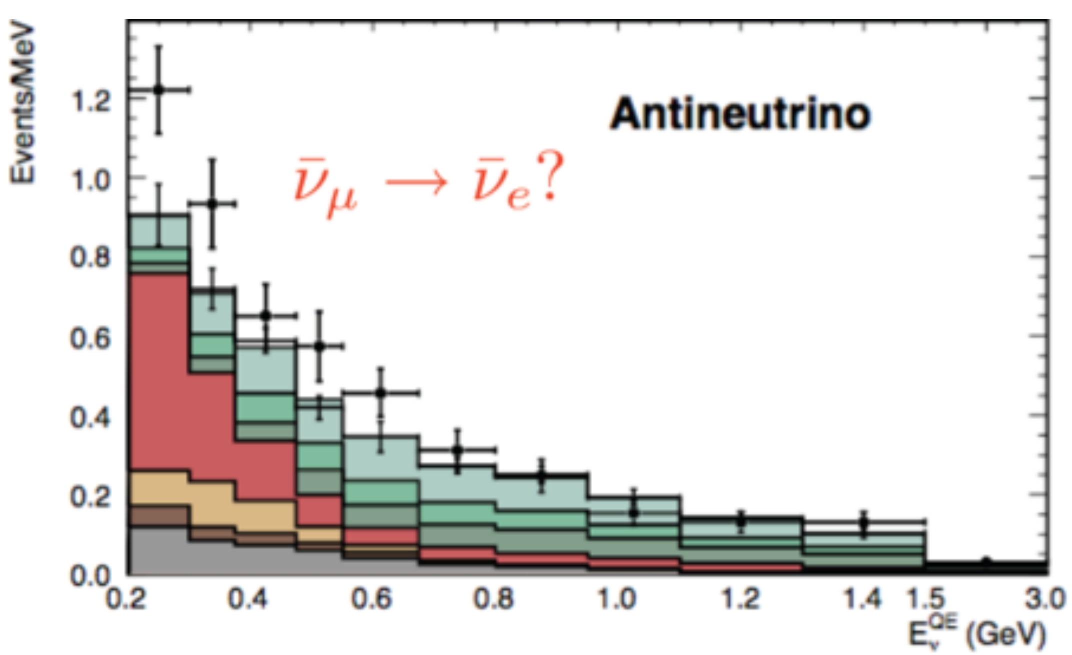

3.4σ excess in neutrino mode

$$162.0 \pm 28.1(\mathrm{stat}) \pm 38.7(\mathrm{syst})$$

Excess of low energy electromagnetic events in neutrino and antineutrino mode

Backgrounds primarily from events producing a single gamma are rising at low energies

**MiniBooNE cannot differentiate electrons from gammas**




2.8σ excess in antineutrino mode

$$78.4 \pm 20.0(\mathrm{stat}) \pm 20.3(\mathrm{syst})$$

# How can we confirm/rule out these signals?

- Two philosophies:
  - Test exactly what has been seen with a more sensitive experiment
  - Look for “smoking gun” oscillation wiggles over very short baselines but the right L/E

Worldwide program proposing/building experiments to do this!

| | | |
|---|---|---|
| Radioactive neutrino sources | $\nu_e/\bar{\nu}_e$ dis. | $100s$ of keV, $10s$ of cm |
| Nuclear reactor antineutrinos | $\bar{\nu}_e$ dis. | $< 10$ MeV, $< 20$ m |
| Stopped π beams | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | $\sim 30$ MeV, 30 m |
| Stopped K beams | $\nu_\mu \rightarrow \nu_e$ | 235.5 MeV, 160 m |
| Decay in flight π/K beams | $\nu_\mu \rightarrow \nu_e$ , $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$<br>$\nu_\mu/\bar{\nu}_\mu$ dis. , $\nu_e/\bar{\nu}_e$ dis. | 500 MeV – 2 GeV<br>100 m – 2000 m |
| Atmospheric neutrinos | $\nu_\mu/\bar{\nu}_\mu$ dis. | $< 20$ GeV, 15 – 130 km<br>100 GeV – 400 TeV, $< 1.3 \times 10^4$ km |
| Cosmology | indirect $N_s, m_\nu$ | |

# π Decay-In-Flight Experiments

- DIF beam provides a rich oscillations program with a single facility:
  - $\nu_\mu \rightarrow \nu_e$ appearance
  - $\nu_\mu$ and $\nu_e$ disappearance
  - both neutrinos and antineutrinos possible
  - CC and NC interactions
- Anomalies exist here (MiniBooNE neutrino and antineutrino) and these need to be addressed
- However:
  - Need detectors that can distinguish electrons from photons in order to reduce key backgrounds
  - Multiple detectors at different baseline are key for reducing systematic uncertainties

# US based LAr R&D program

The choice of the experimental technology is a key element: A coherent SBN and LBN program based on LAr technology is now emerging and taking shape.

### Yale TPC

Location: Yale University
Active volume: 0.002 ton
operational: 2007

### Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

*This talk*

### ArgoNeuT

Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

*This talk*

### MicroBooNE

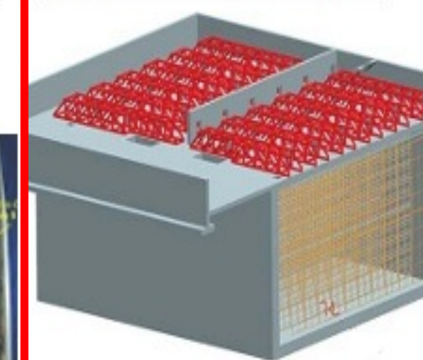
Location Fermilab
Active volume: 0.1 kton
Operational: 2014

*This talk*

### SBN @ FNAL

Location: Fermilab
Active volume: 0.05 + 0.6 kton
Construction start: 2017

### LBNE



Location: Homestake
Active volume: 35 kton
Construction start 202?

### Luke

Location: Fermilab
Purpose: materials test st
Operational: since 2008

### LAPD

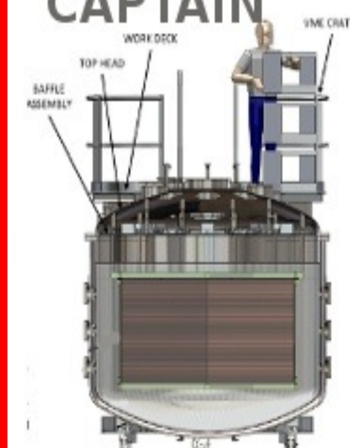
Location: Fermilab
Purpose: LAr purity dem
Operational: 2011

### LArIAT

Location: Fermilab
Purpose: LArTPC calibration
Operational: 2014 (phase 1)

*This talk*

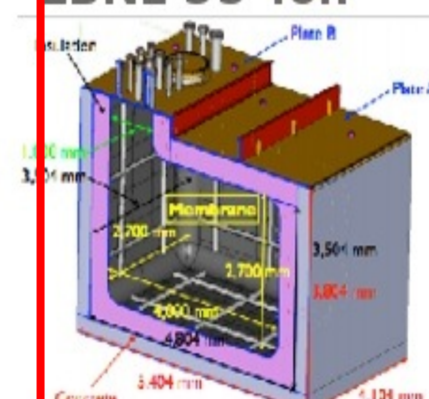
### CAPTAIN



Location: LANL
Purpose: LArTPC calibration
Operational: 2014

*This talk*

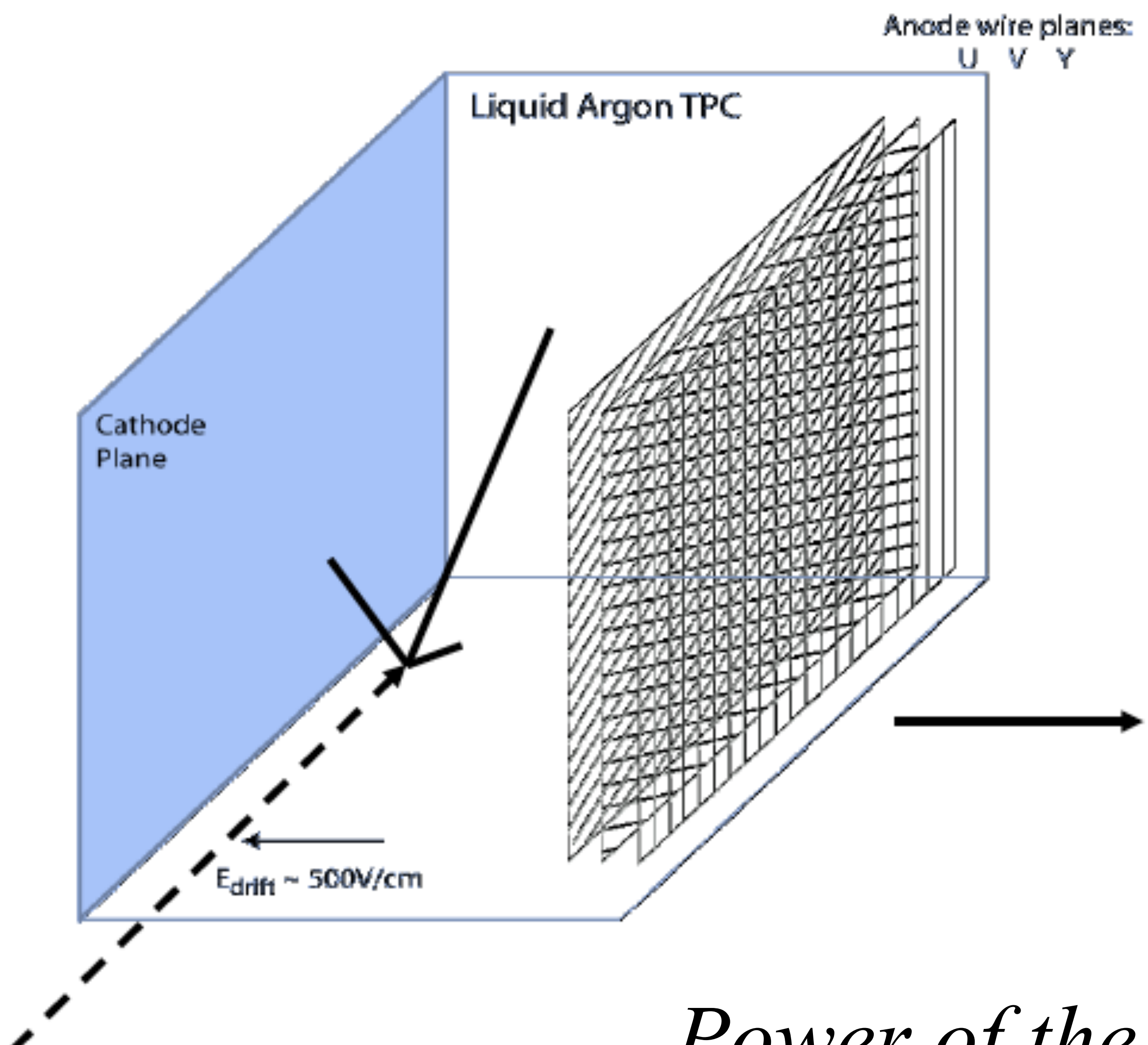
### LBNE 35 Ton



Location: Fermilab
Purpose: purity demo
Operational: 2013

# LArTPCs

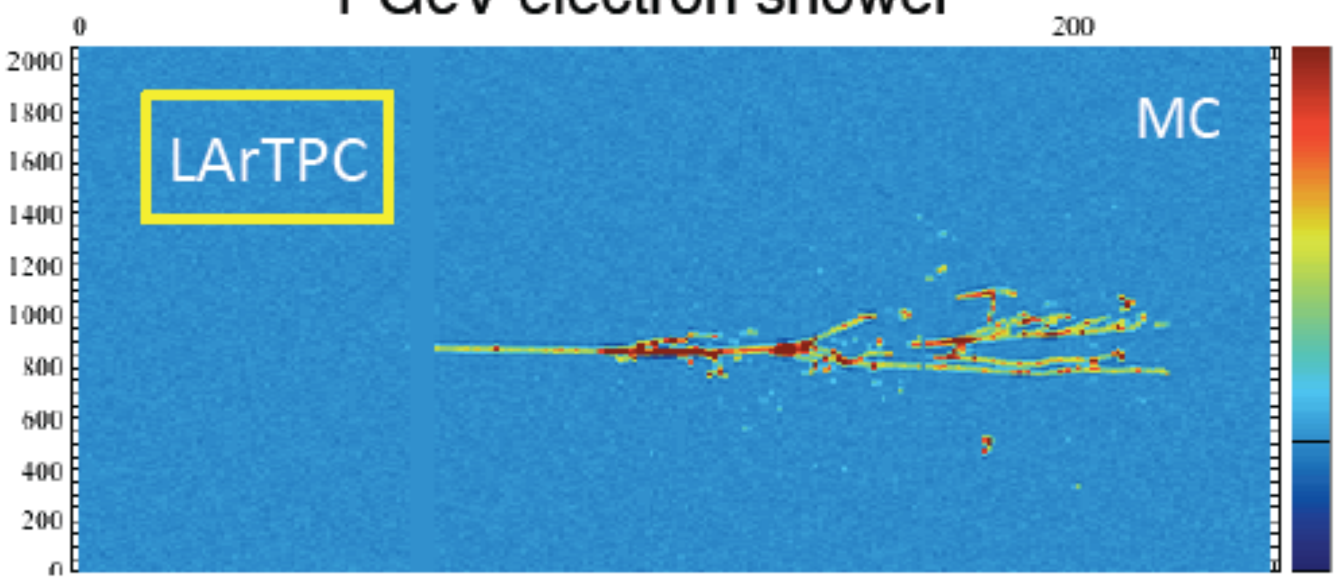
- Passing charged particles ionize Argon
- Electric fields drift electrons meters to wire chamber planes
- Induction/Collection planes image charge, record dE/dx



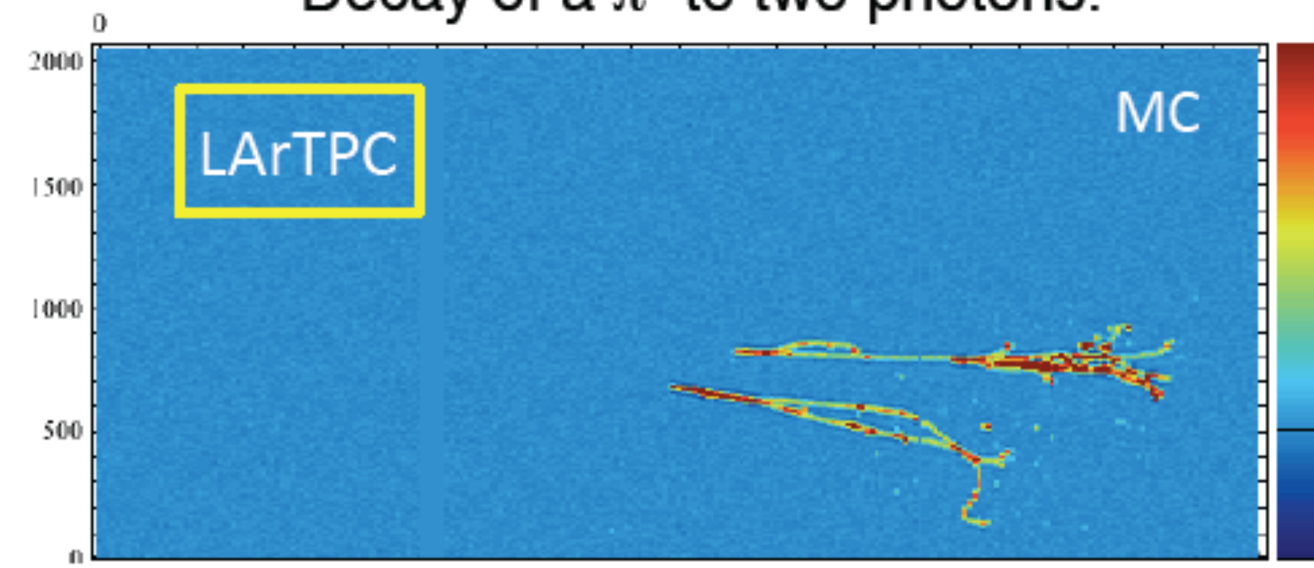

*Power of the LArTPC technology:*
*Excellent resolution and calorimetry*

# Electron/Photon Separation with LArTPCs

1 GeV electron shower

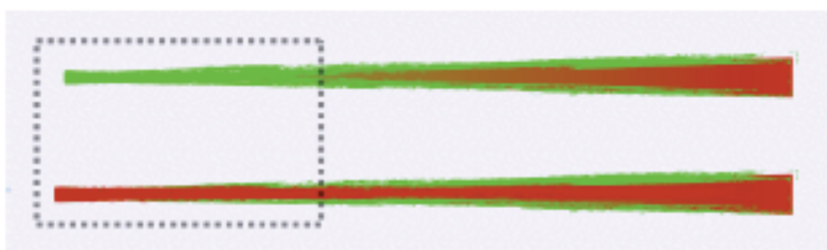


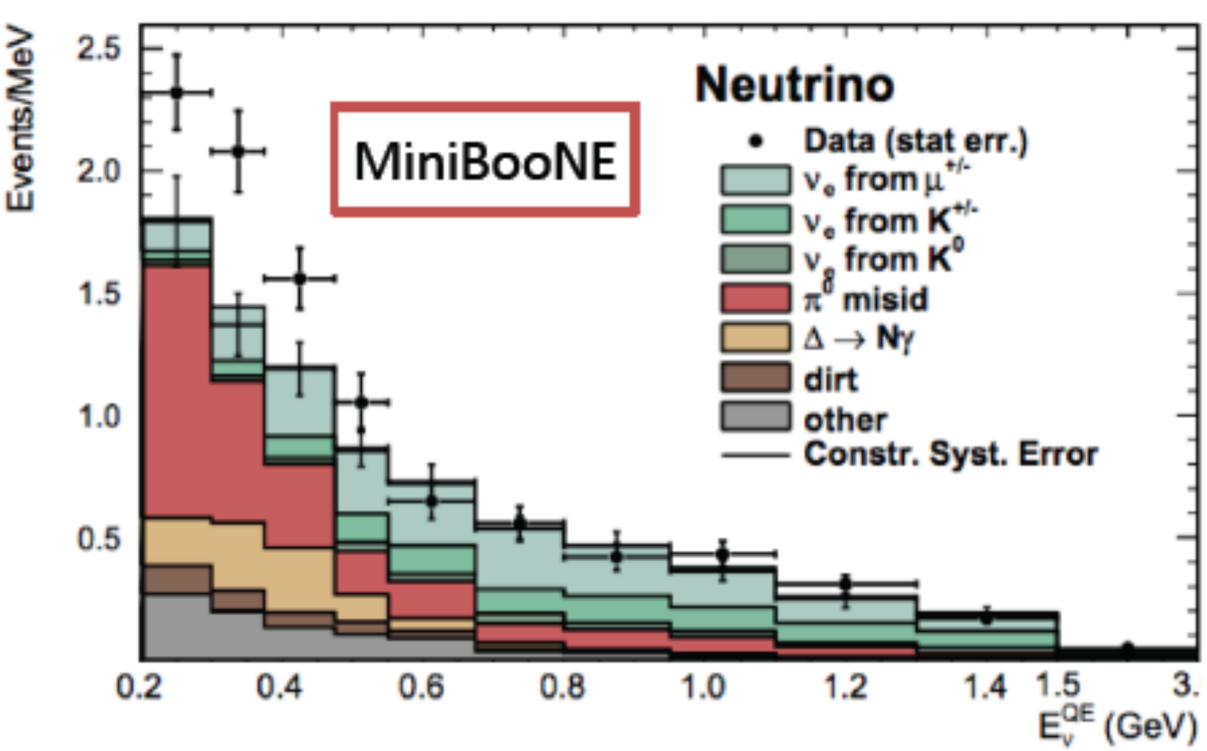

Decay of a $\pi^0$ to two photons.

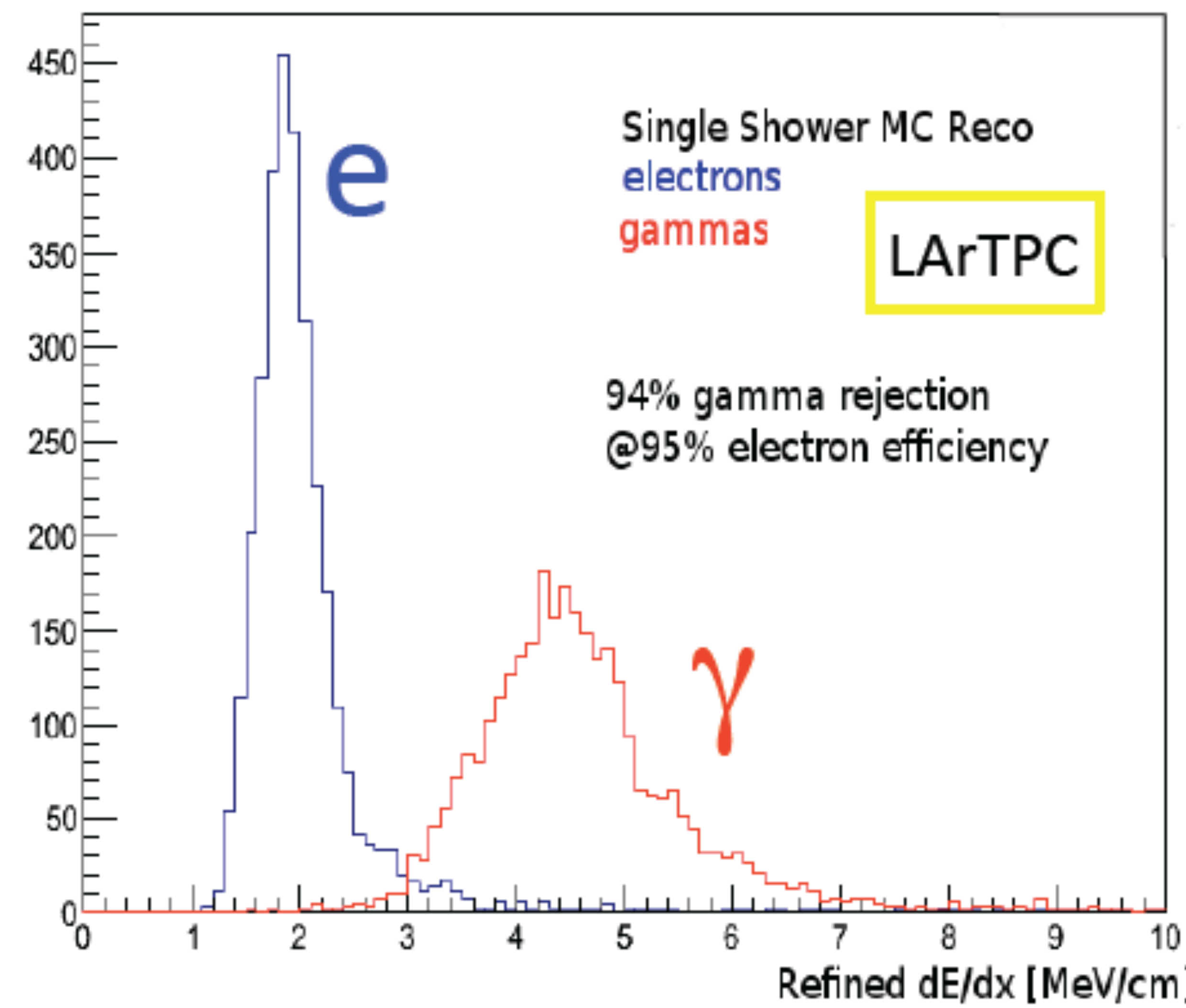



Electron

$$\gamma \rightarrow e^+ + e^-$$

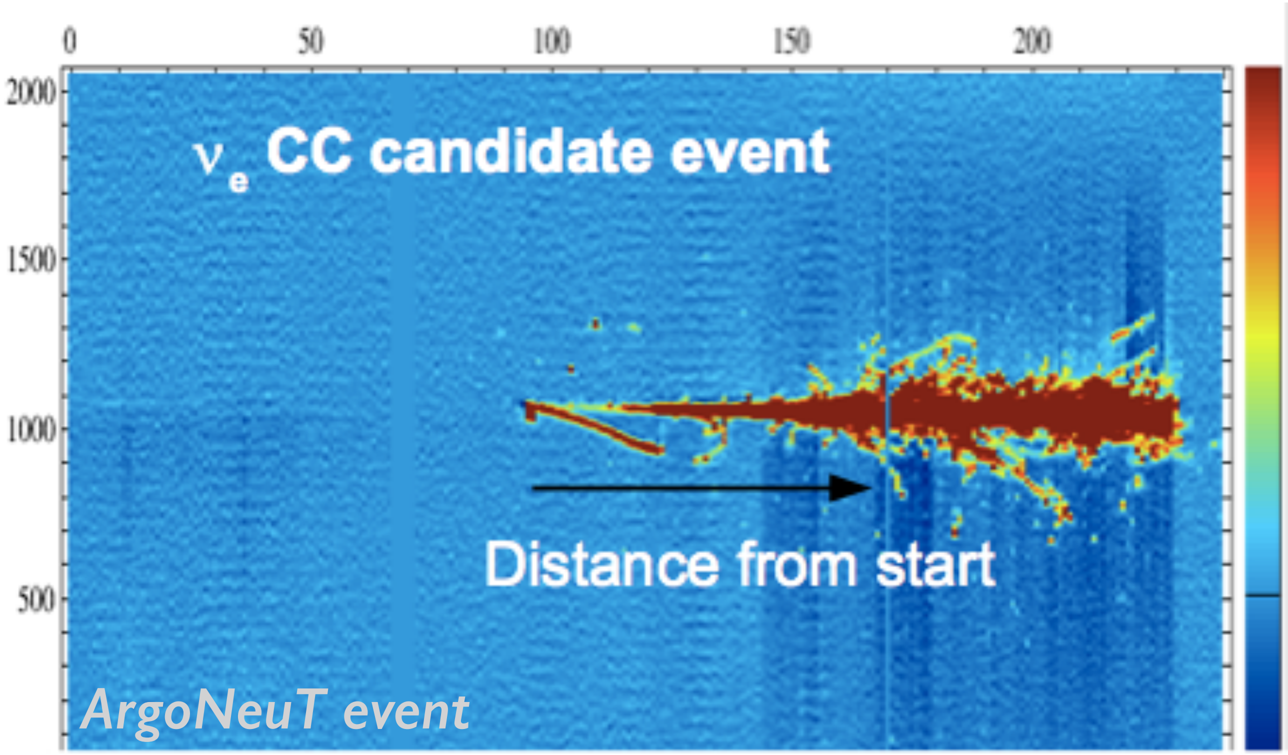


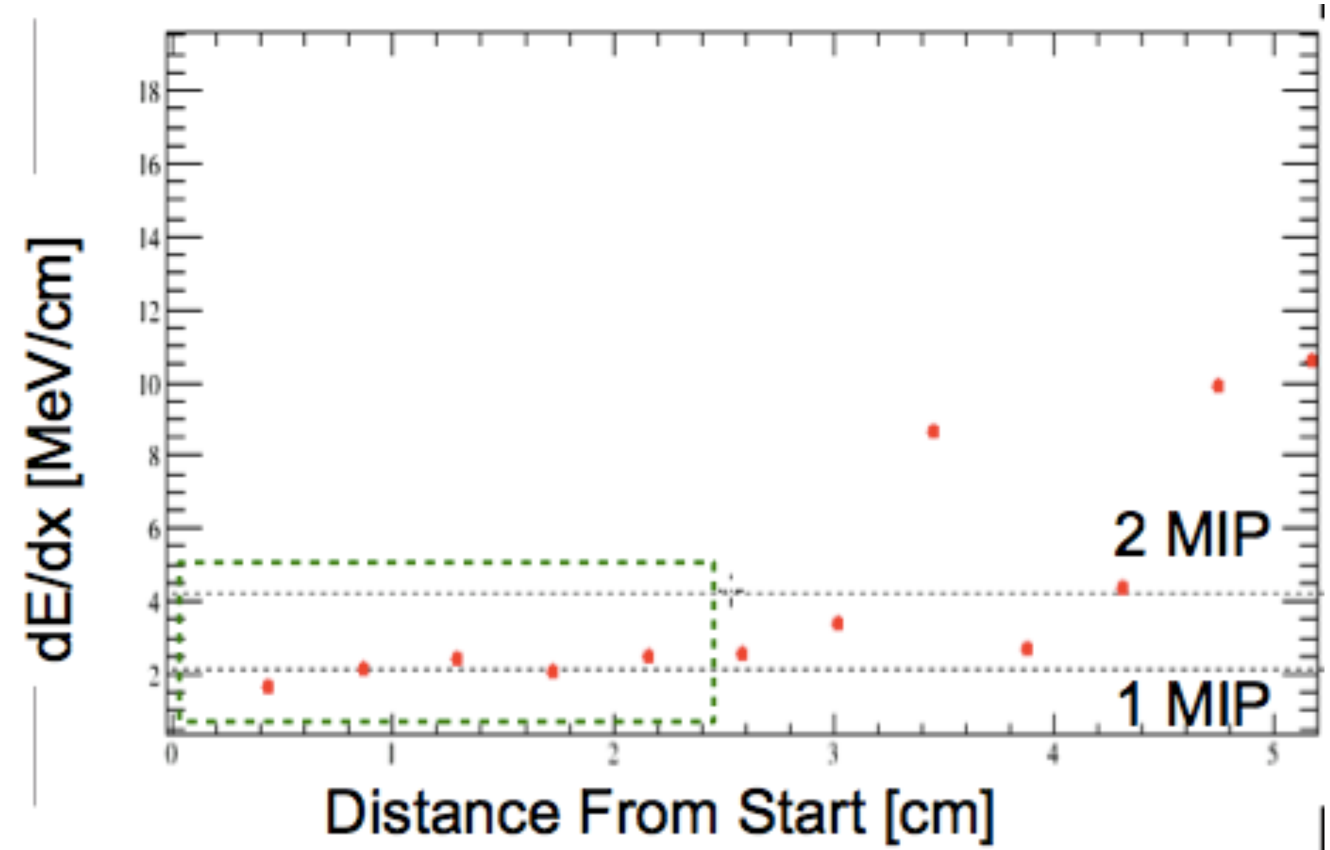


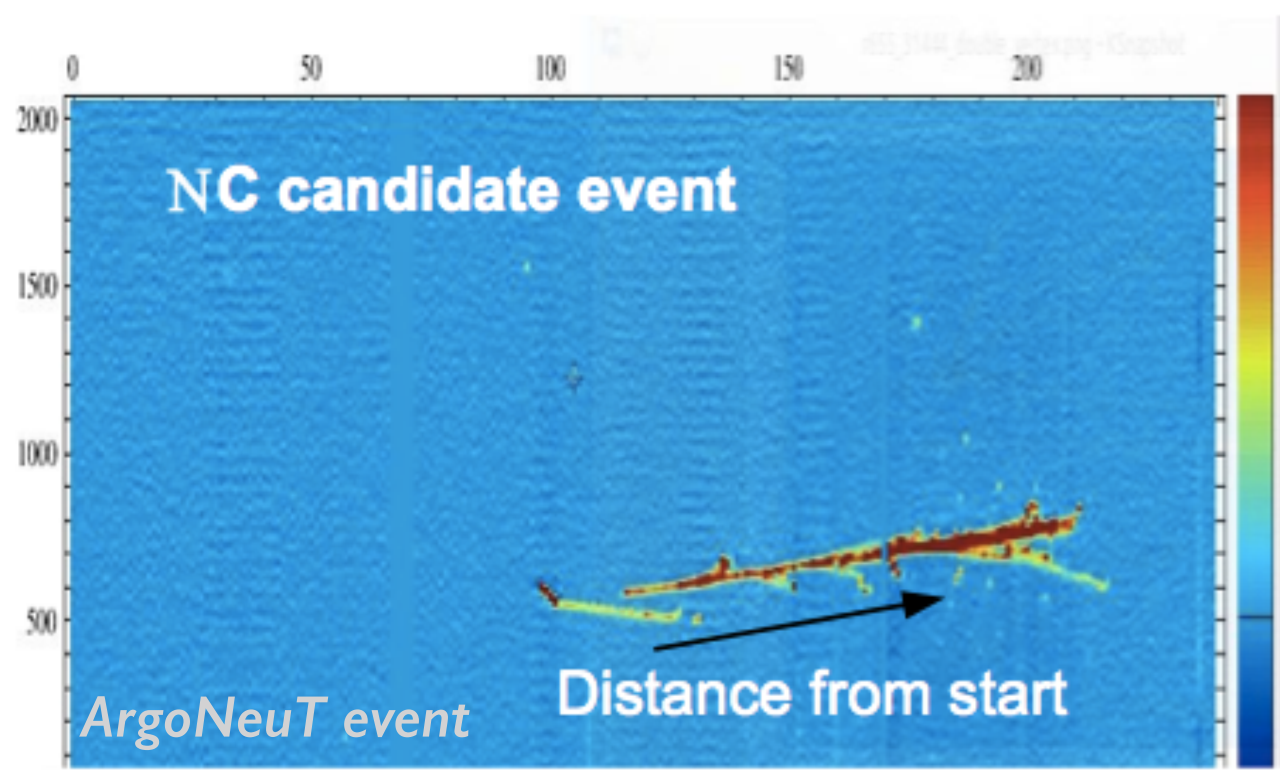



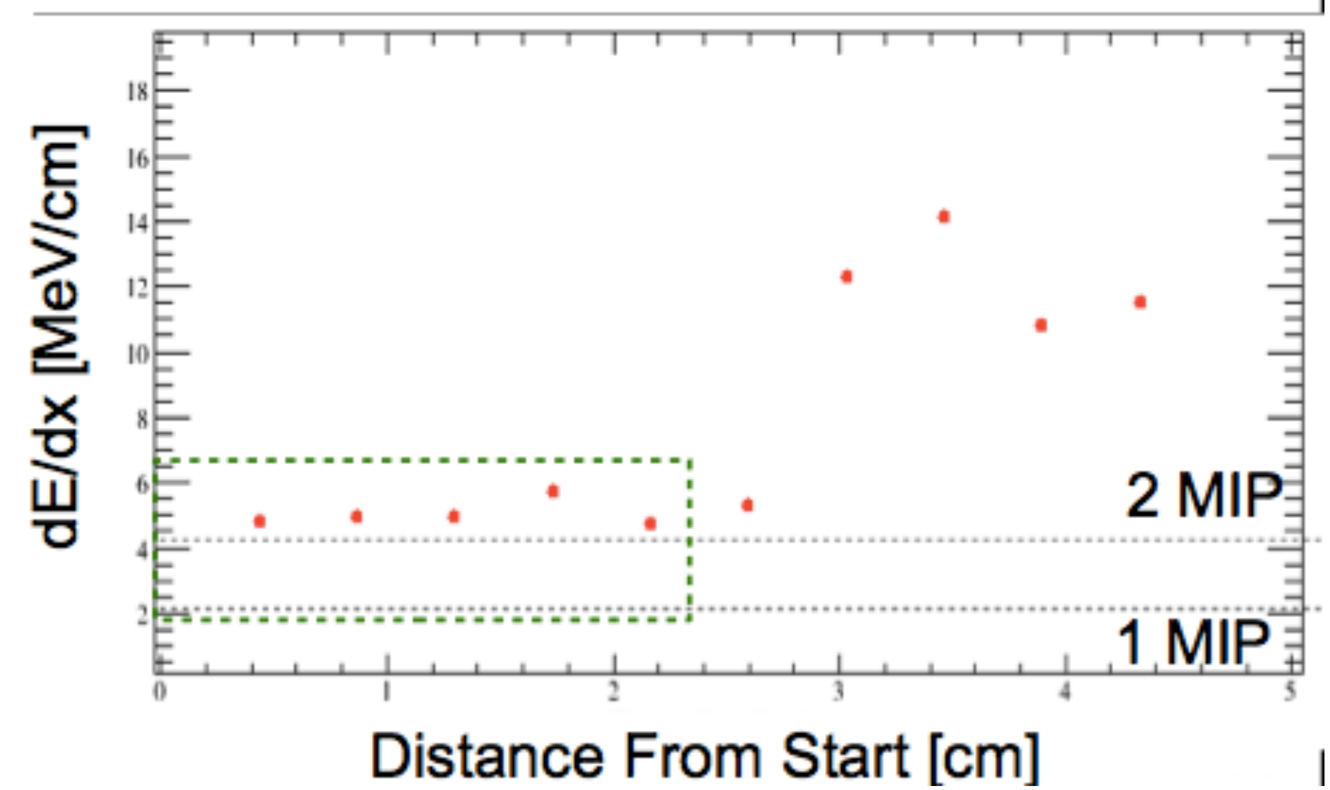
# Recent results from ArgoNeuT

# EM shower events



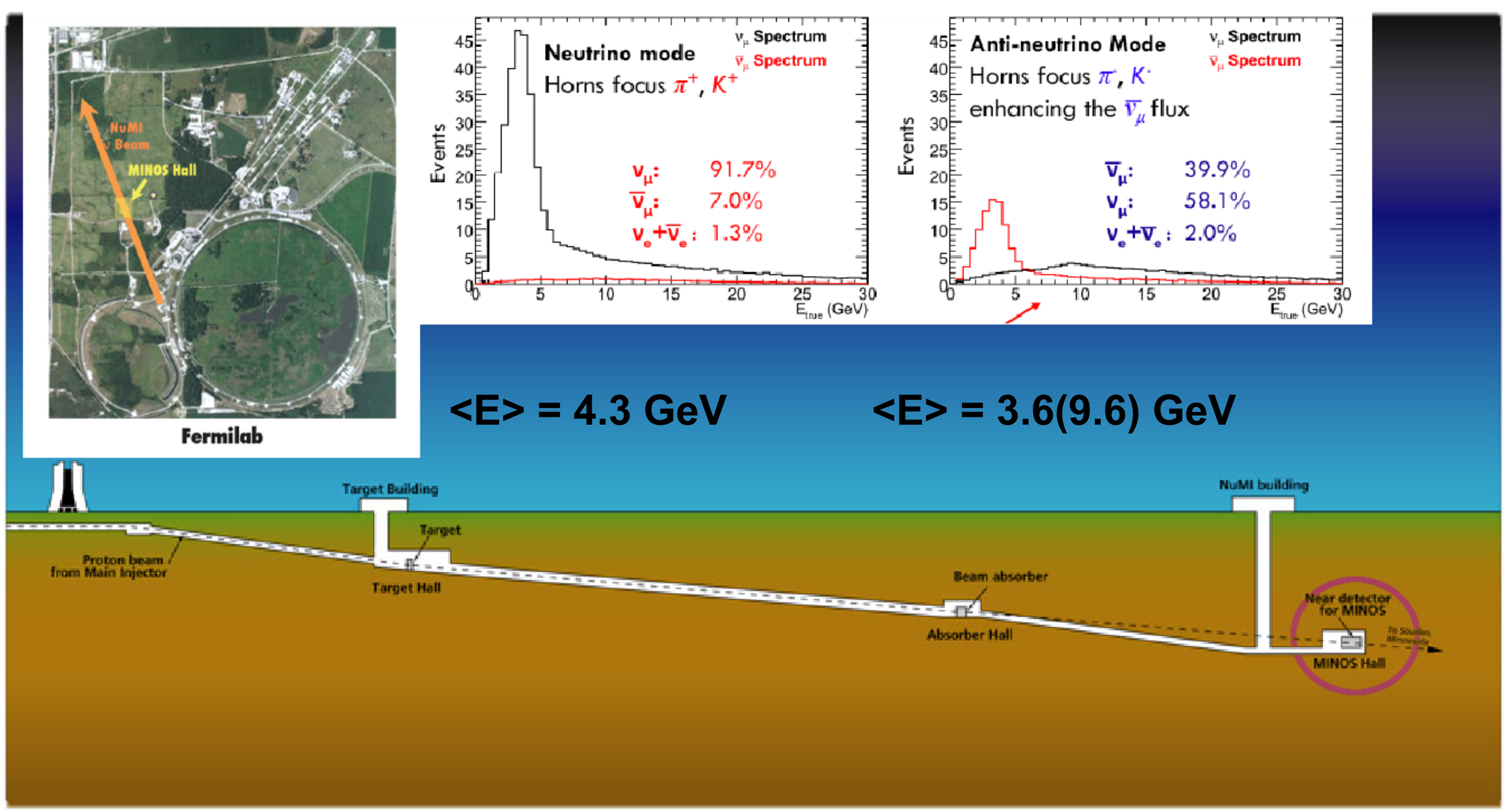
# ArgoNeuT in the NuMI beam line

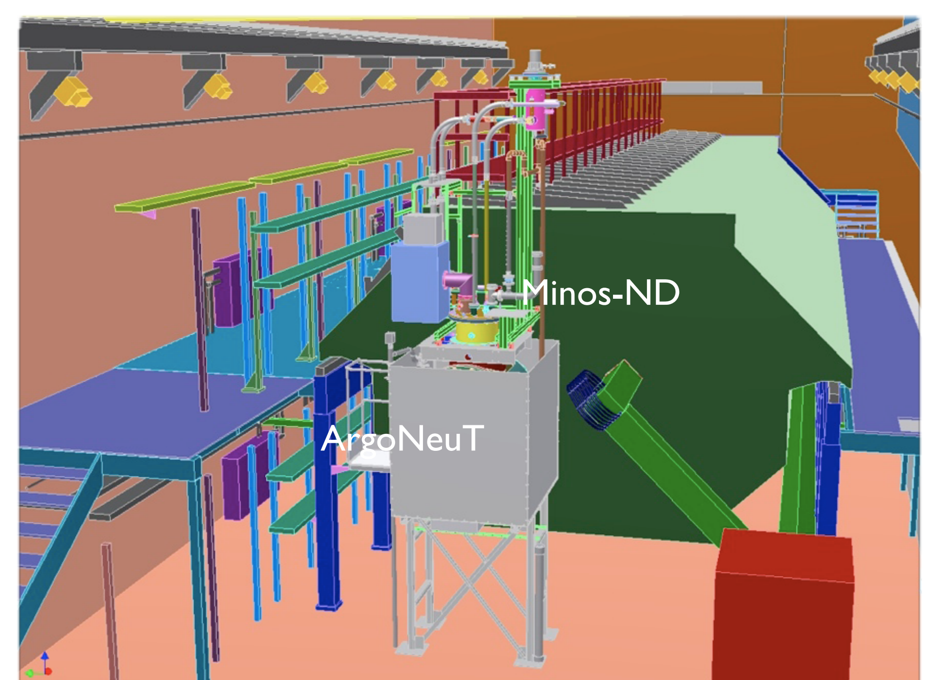
## First LArTPC in a low (1-10 GeV) energy neutrino beam

Acquired $1.35 \times 10^{20}$ POT, mainly in $\bar{\nu}_\mu$ mode

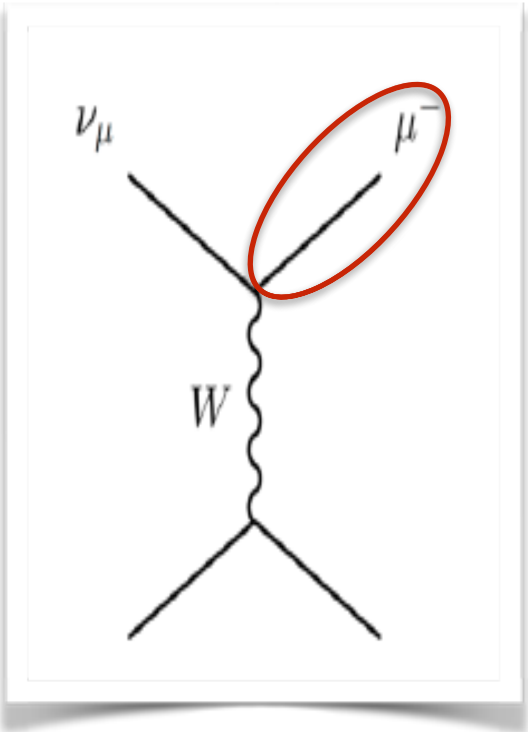
Designed as a test experiment.

But obtaining physics results!



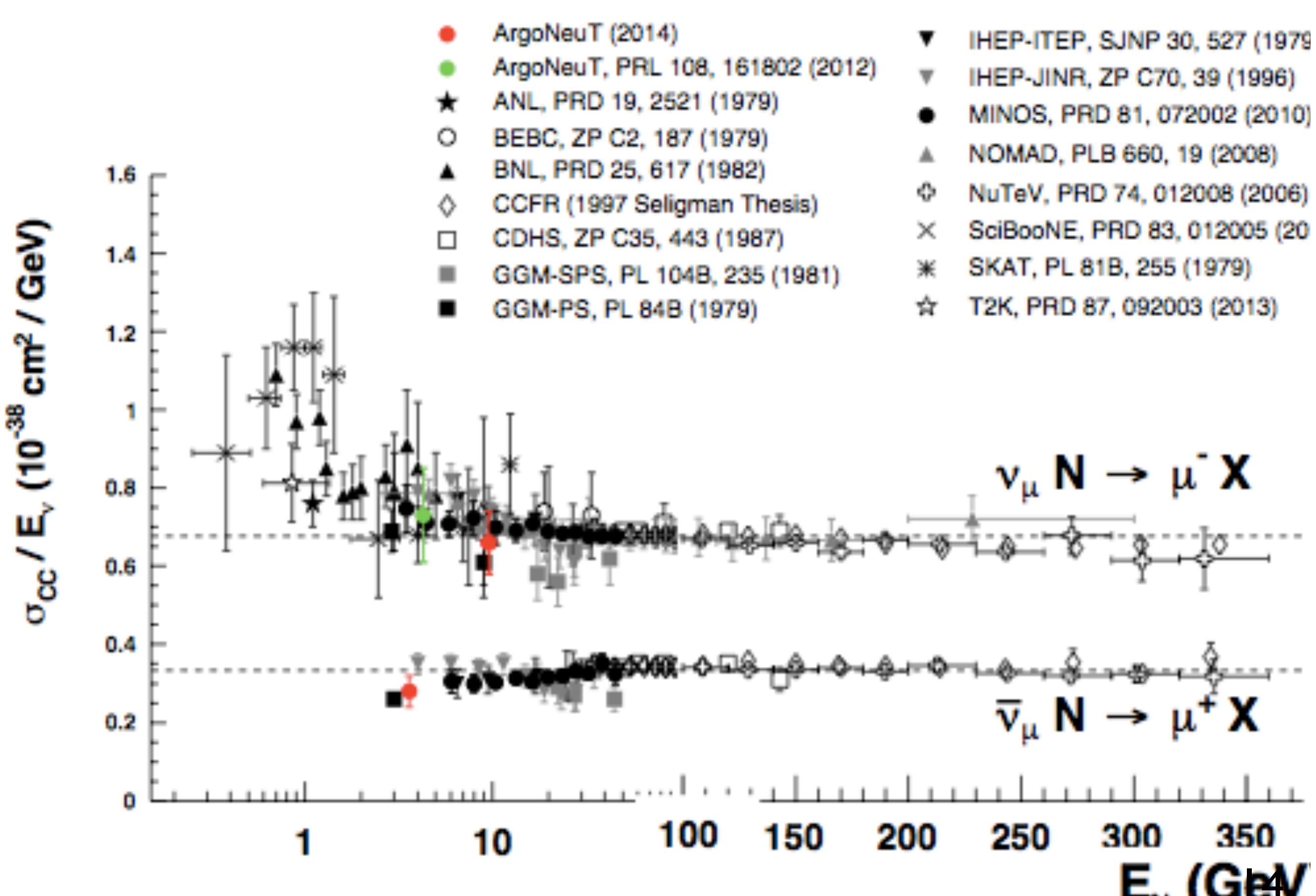
## CC Inclusive cross-section in $\nu_\mu$ mode




First Measurement for $\bar{\nu}_\mu$ in argon!

New physics result (standard candle)

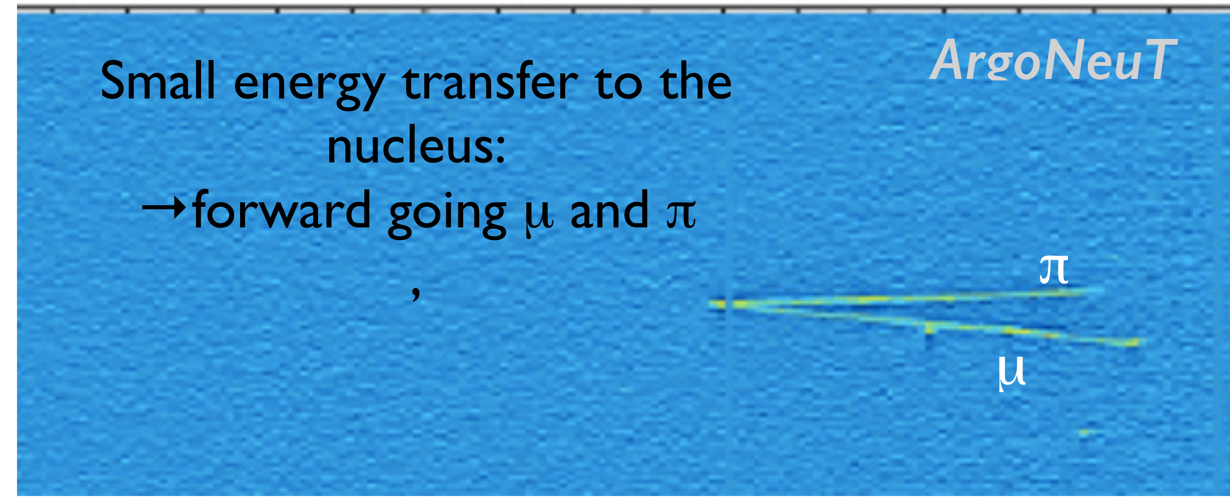
*R. Acciarri et al. ,Phys. Rev. D 89, 112003*

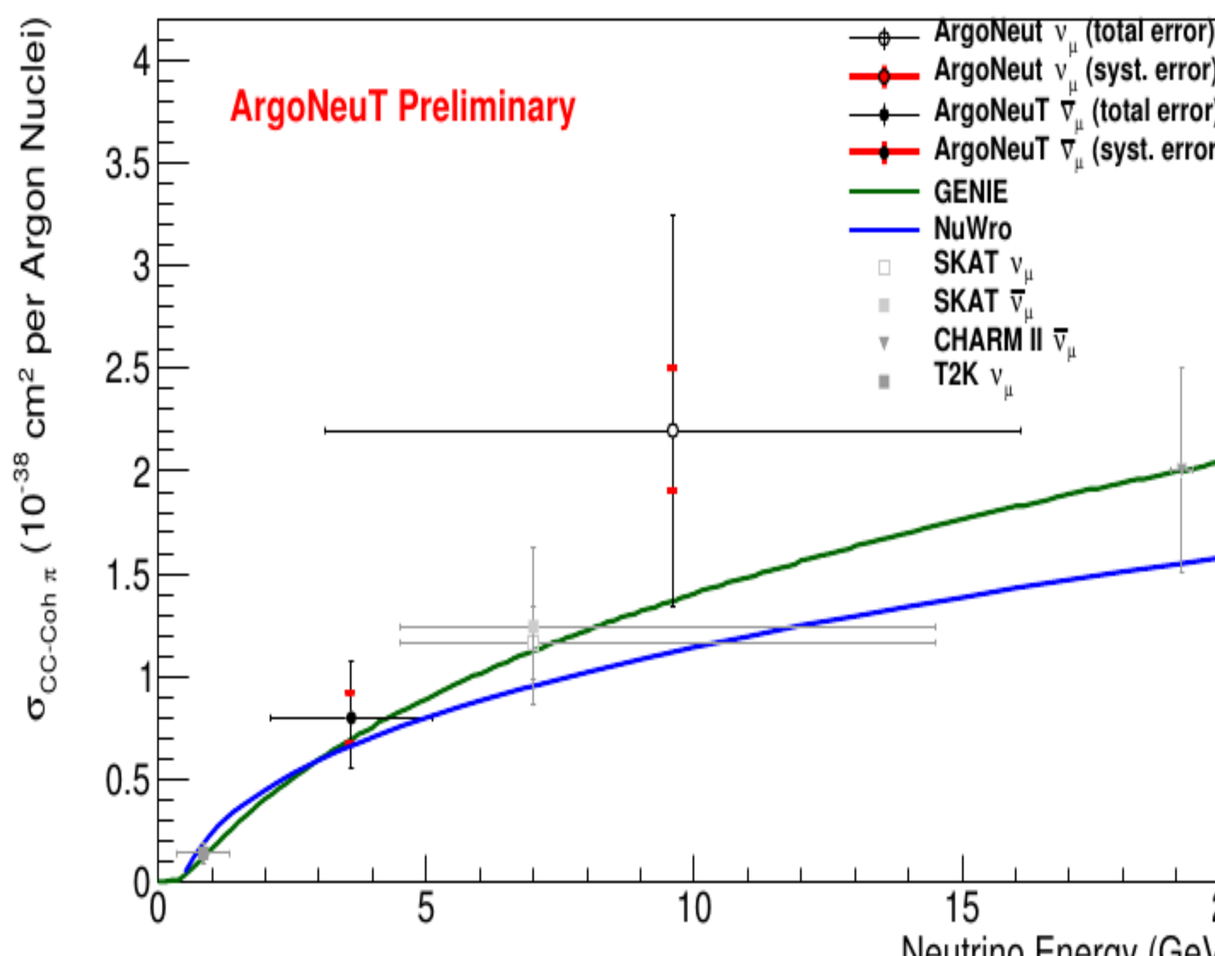



## Coherent charged Pion Production

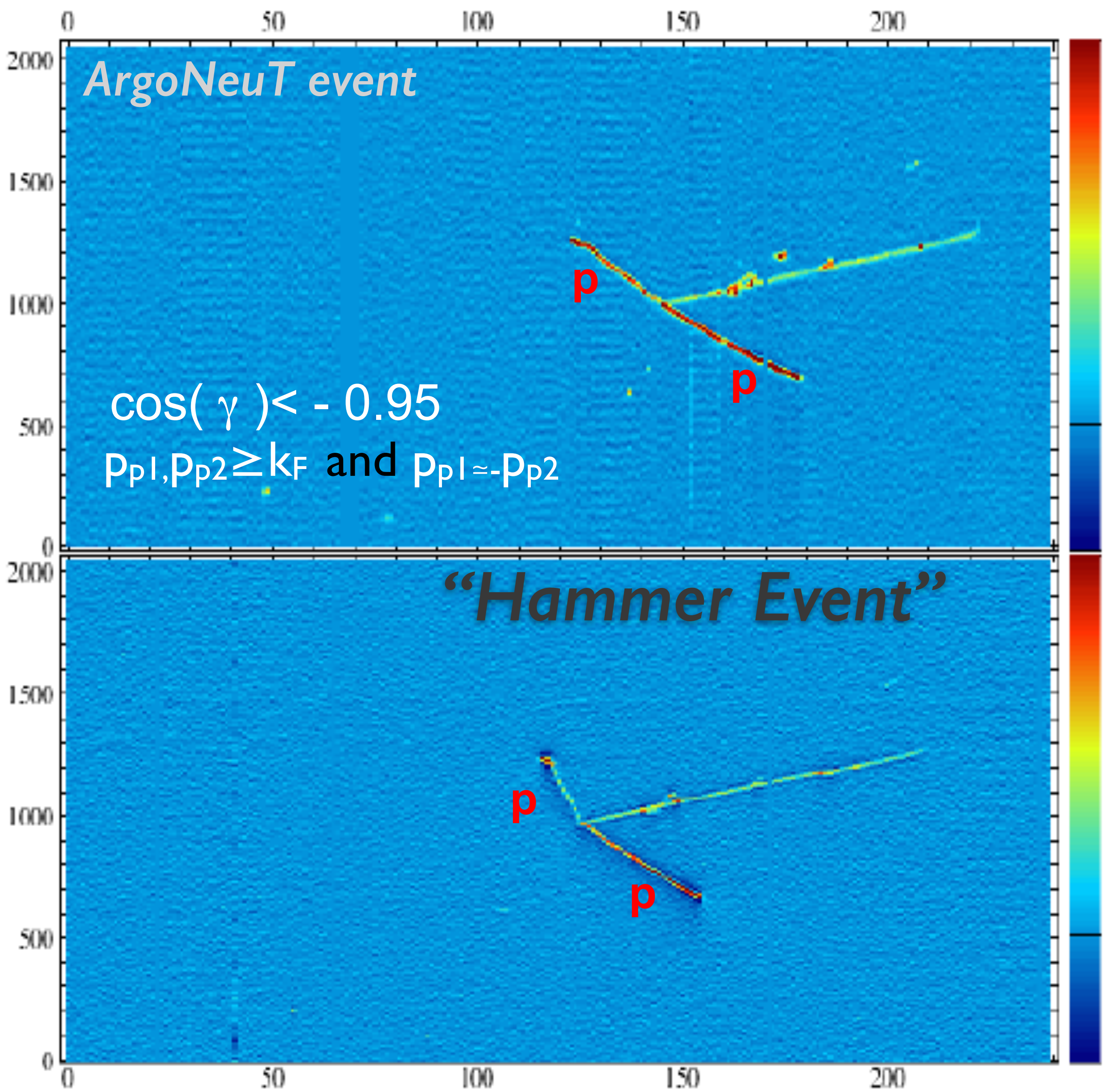
$$\nu_\mu + A_{g.s.} \rightarrow \mu^- + \pi^+ + A_{g.s.}$$

$$\bar{\nu}_\mu + A_{g.s.} \rightarrow \mu^+ + \pi^- + A_{g.s.}$$



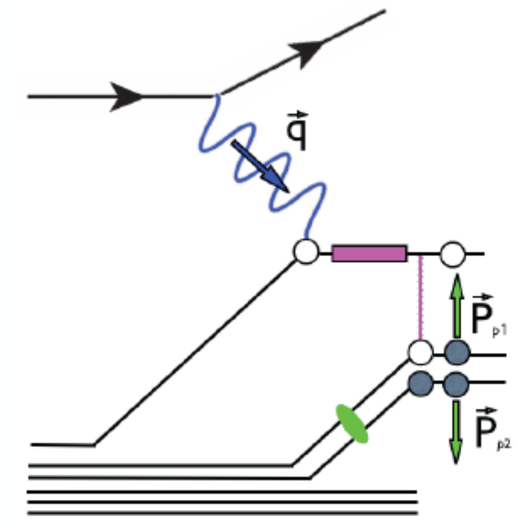



# Detection of back-to-back proton pairs



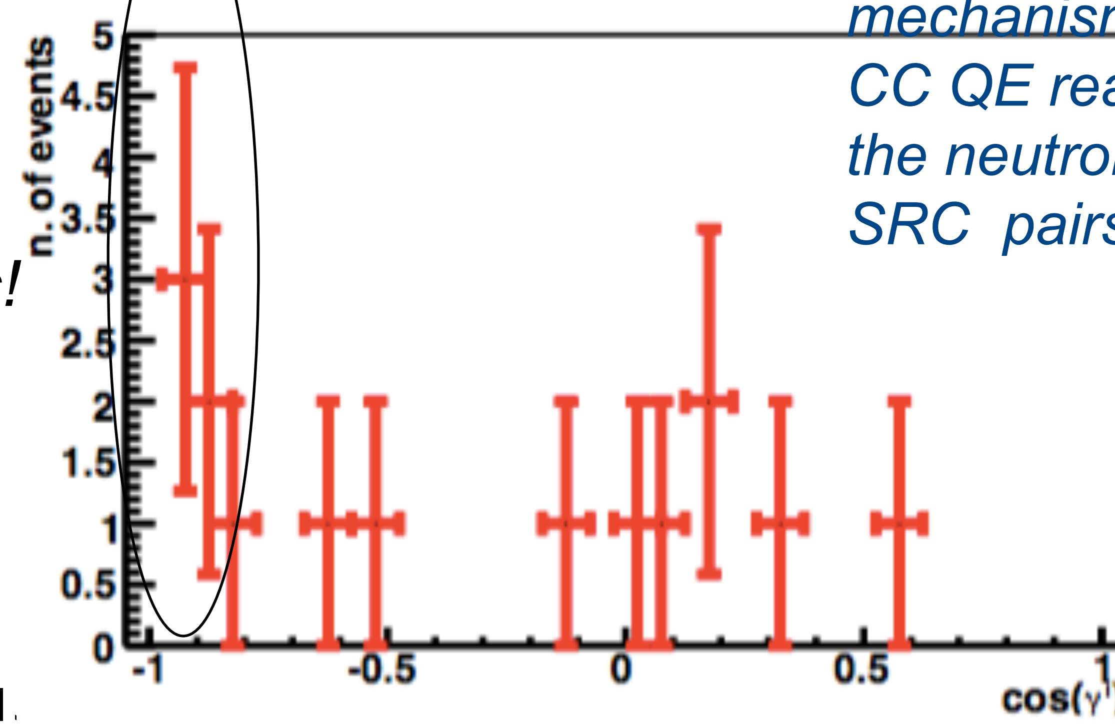

**4 back-to-back proton pairs events observed in Lab frame.**

*Possible mechanism is CC RES pionless reactions involving pre-existing SRC np pairs.*




*We can see nuclear effects!*

**4 back-to-back protons in CM frame as well!**




*Possible mechanism is CC QE reaction on the neutron of a np SRC pairs.*

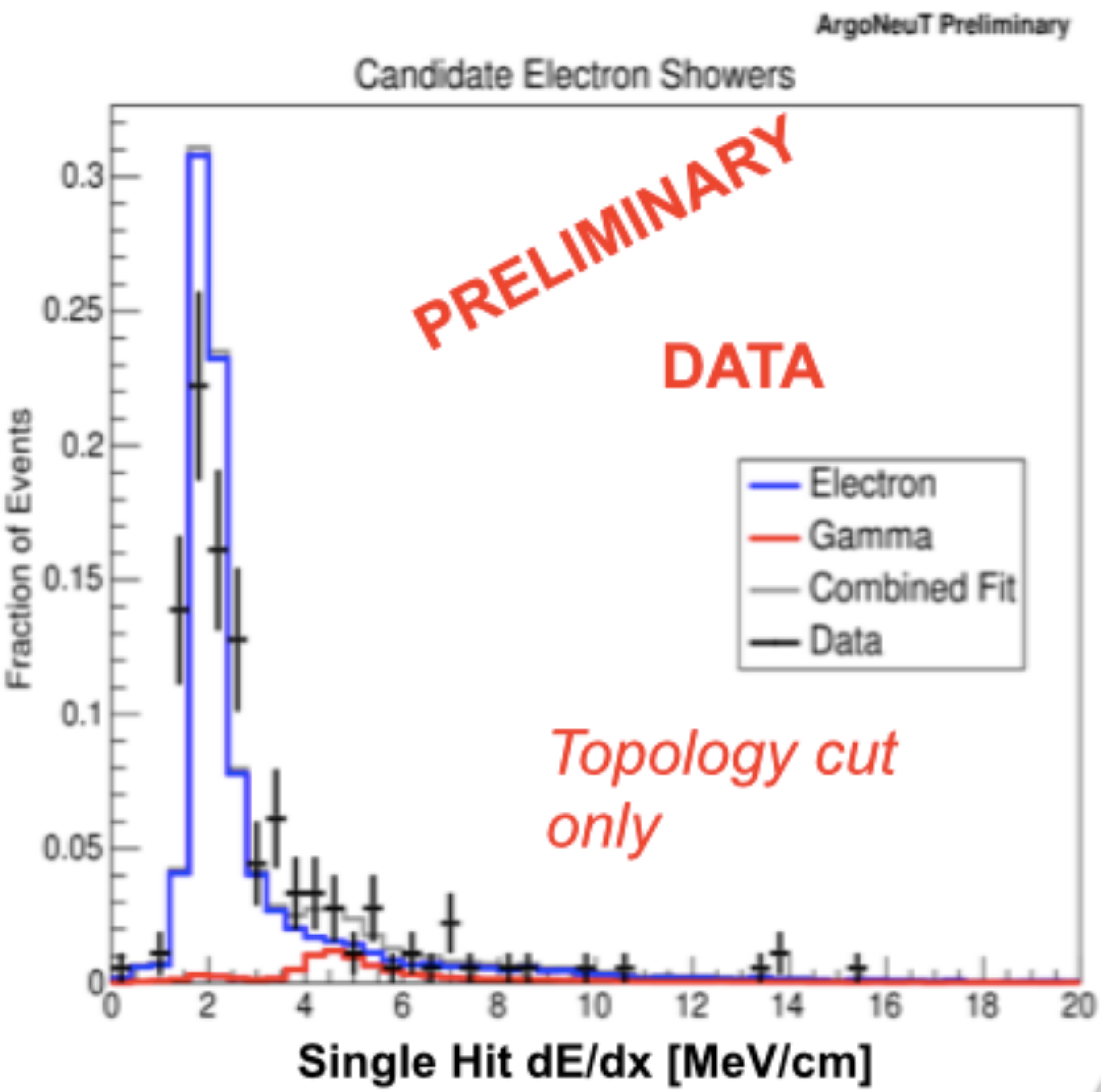
**New, LArTPC enabled, physics result!**

***R. Acciarri et al., ArXiv:1405.4261 Submitted to PRD***

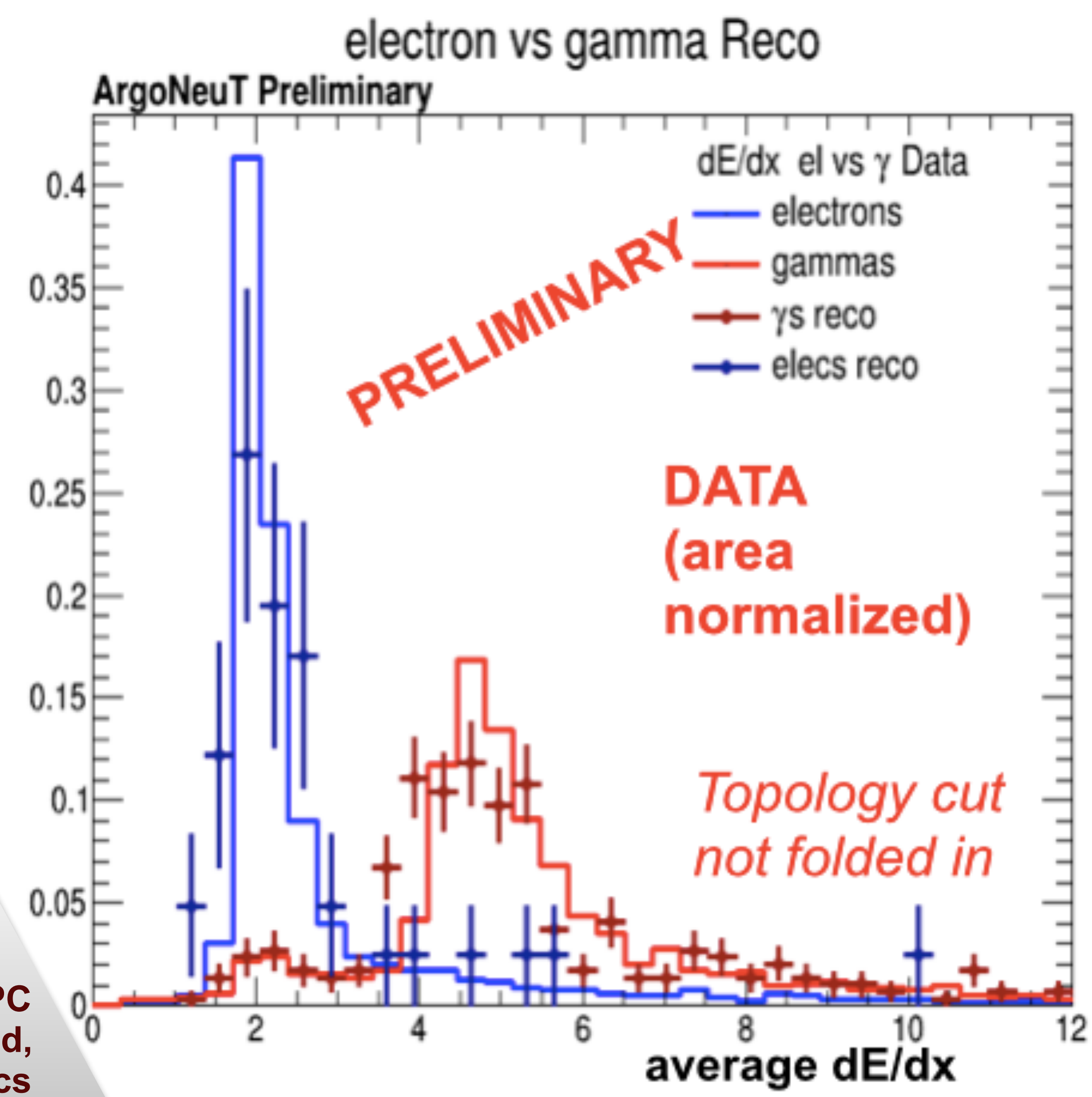
# Data-based dE/dx plot

- Gammas defined as EM showers detached from visible vertex.
- Electrons defined as EM showers with visible vertex activity and no gap.
- Electron events require no track matched to MINOS muon.

Landau-like distribution of electron event.
Single hit charge depositions.




Electron/single gamma separation




New, LArTPC enabled, physics result!

# ArgoNeuT Collaboration


F. Cavanna
**University of L'Aquila**

A. Ereditato, M. Weber
**University of Bern**

R. Acciarri, B. Baller, H. Greenlee, C. James, G. Rameika, B. Rebel, T. Yang, G. Zeller
**Fermi National Accelerator Laboratory**

E. Santos
**Imperial College London**

O. Palamara
**Gran Sasso National Laboratory**

T. Bolton, S. Farooq, G. Horton-Smith
**Kansas State University**

C. Bromberg, D. Edmunds, P. Laurens, B. Page
**Michigan State University**

J. Asaadi, M. Soderberg[3]
**Syracuse University**

K. Lang, R. Mehdiyev
**The University of Texas at Austin**

C. Adams, E. Church, B. Fleming, E. Klein, K. Partyka, J.Spitz, A. Szelc
**Yale University**

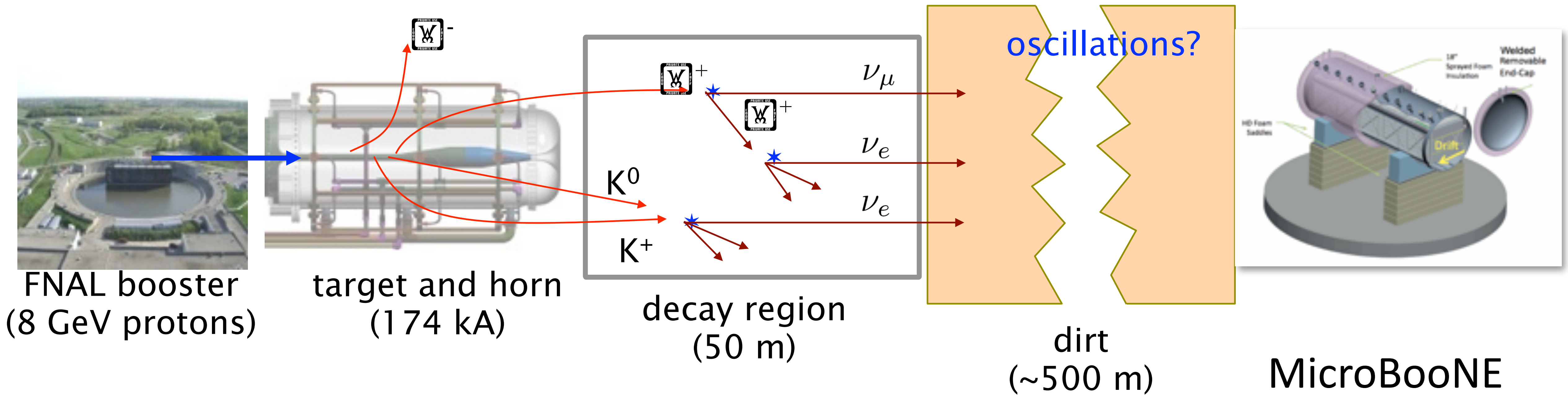

# Summary

Despite the ArgoNeuT modest active LAr mass (~1/4 T) and its short exposure (~5 months) to neutrino beams, the experience and the results obtained are highly relevant.

**ArgoNeuT primary goal was to serve as technology demonstrator, but indeed made much more than that: ArgoNeuT has provided a wealth of physics results on neutrino interaction mechanisms yet not fully resolved, and is still yielding new intriguing outputs from the on-going studies.**

microboone

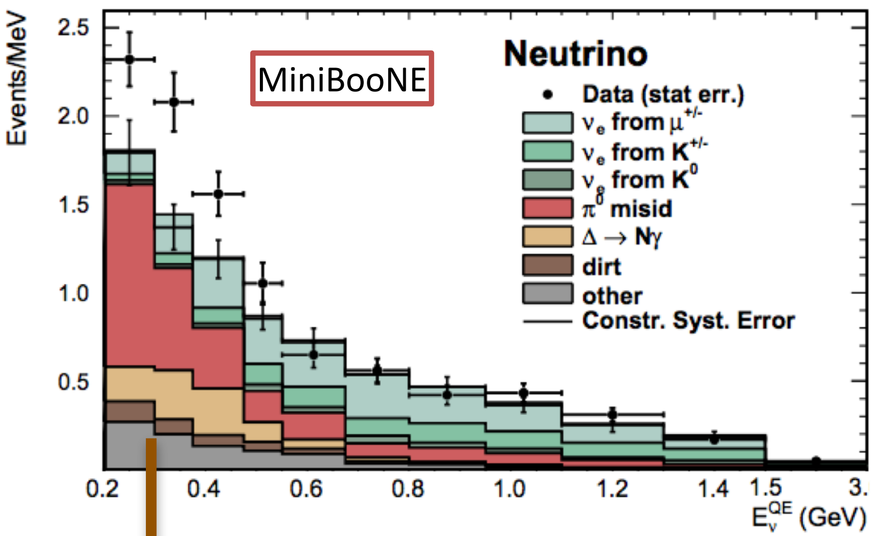
# The MicroBooNE Experiment

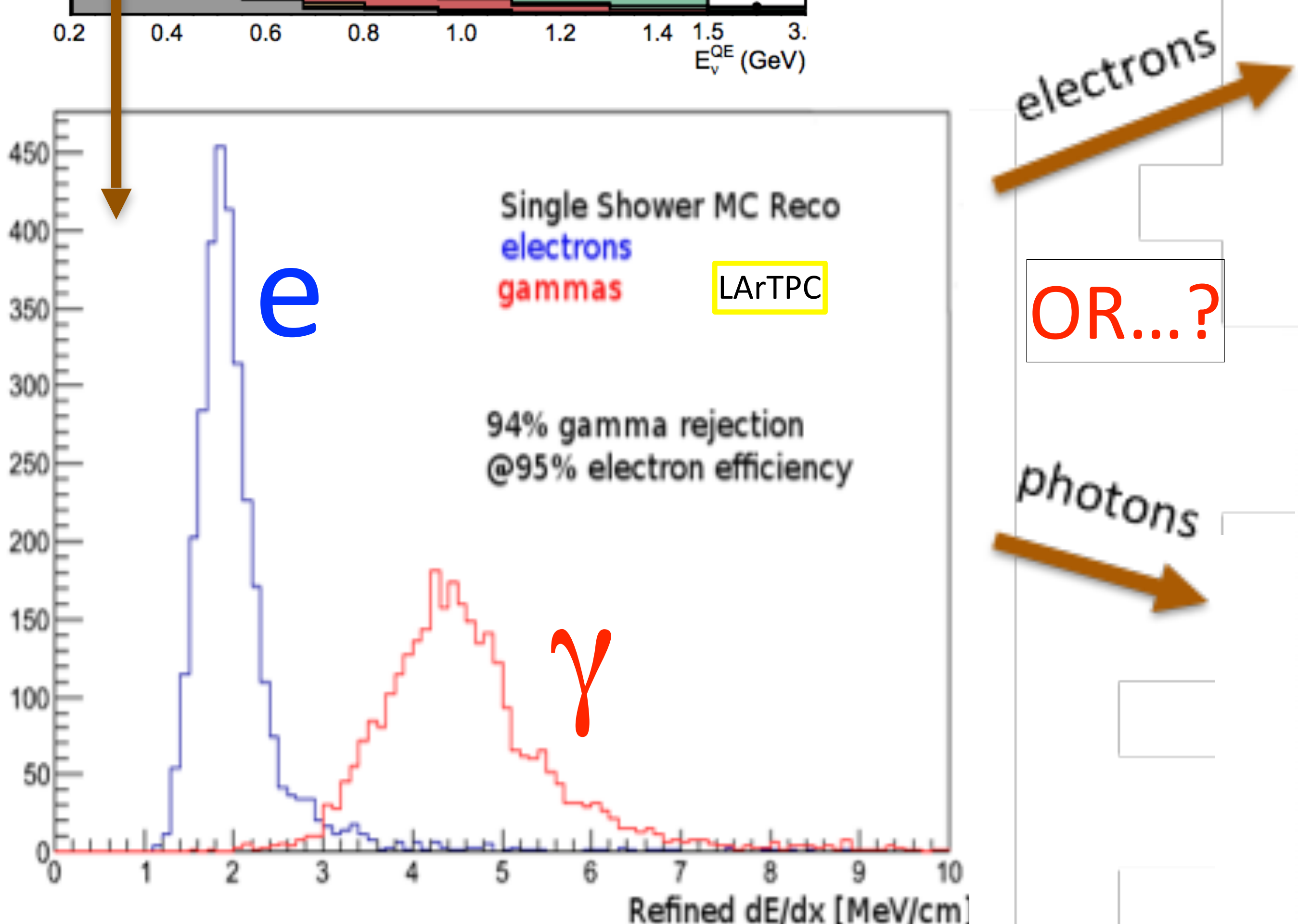


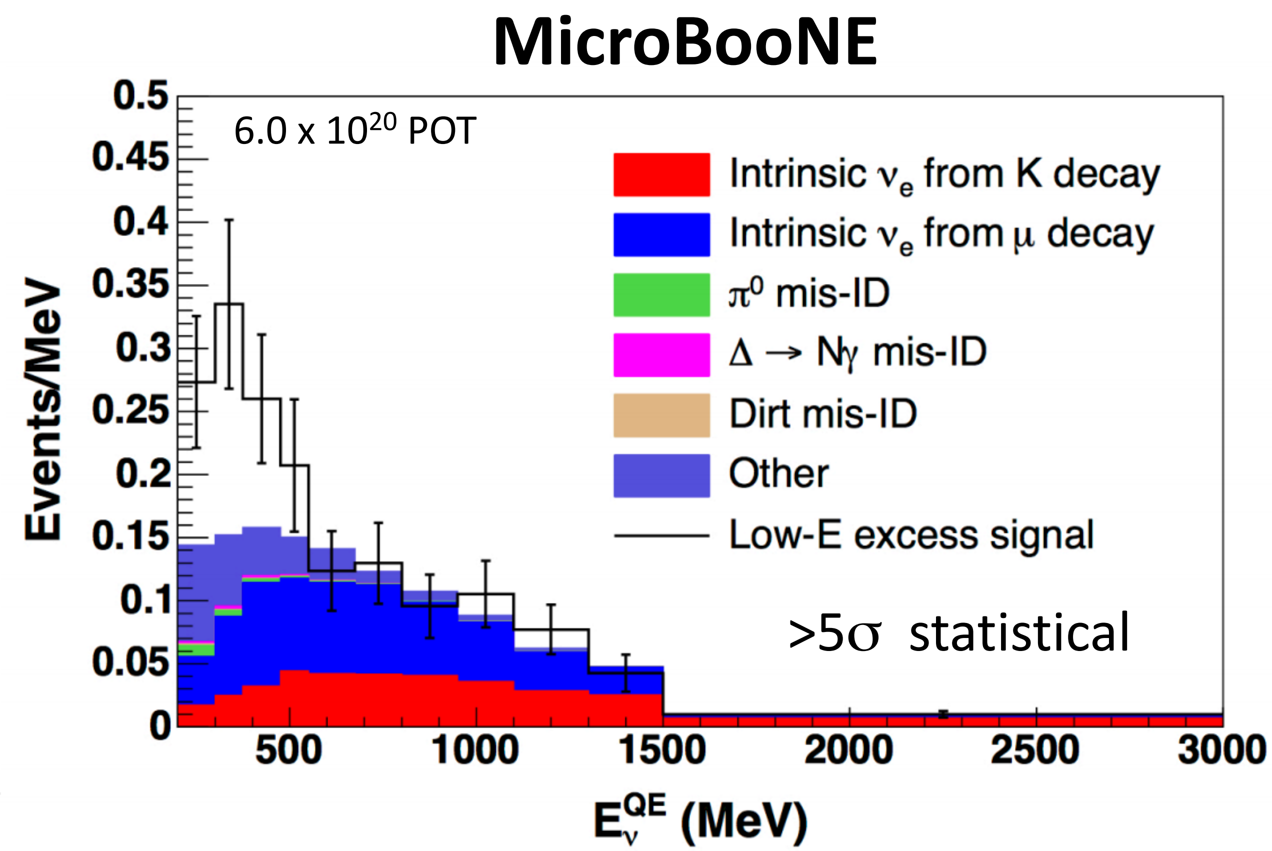

Test exactly what has been seen in MiniBooNE with a more sensitive experiment

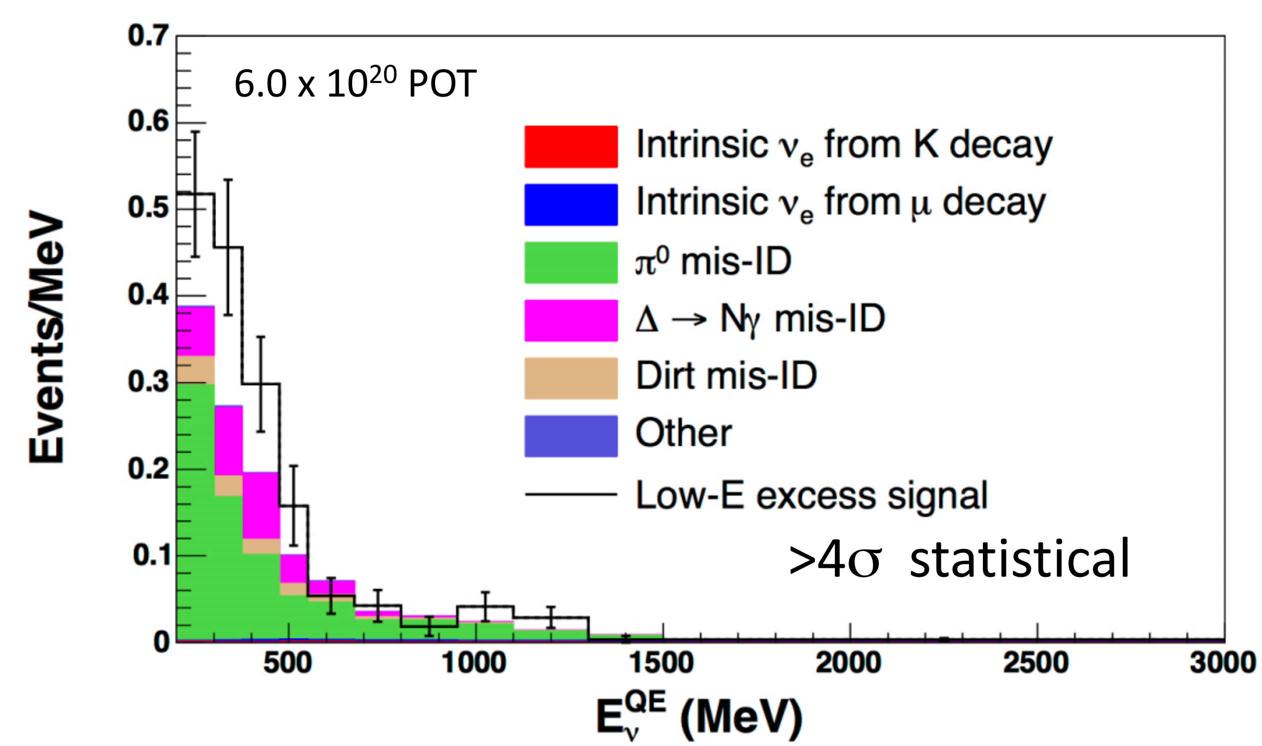
**Differentiate signal $\nu_e$ electrons from background single photons**
so that it is 5 sigma significant but ~x10 smaller than MiniBooNE

# MicroBooNE and the MiniBooNE Excess



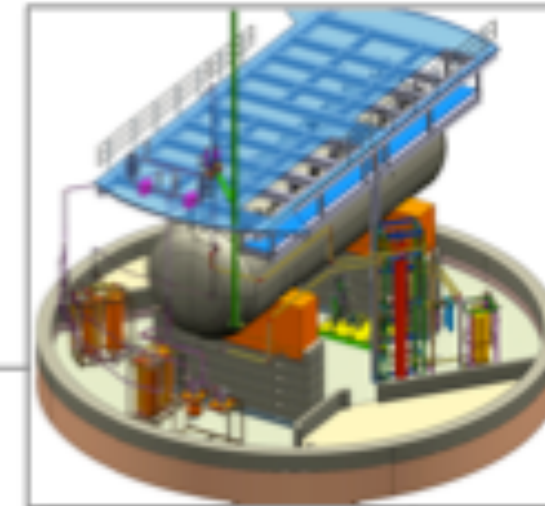



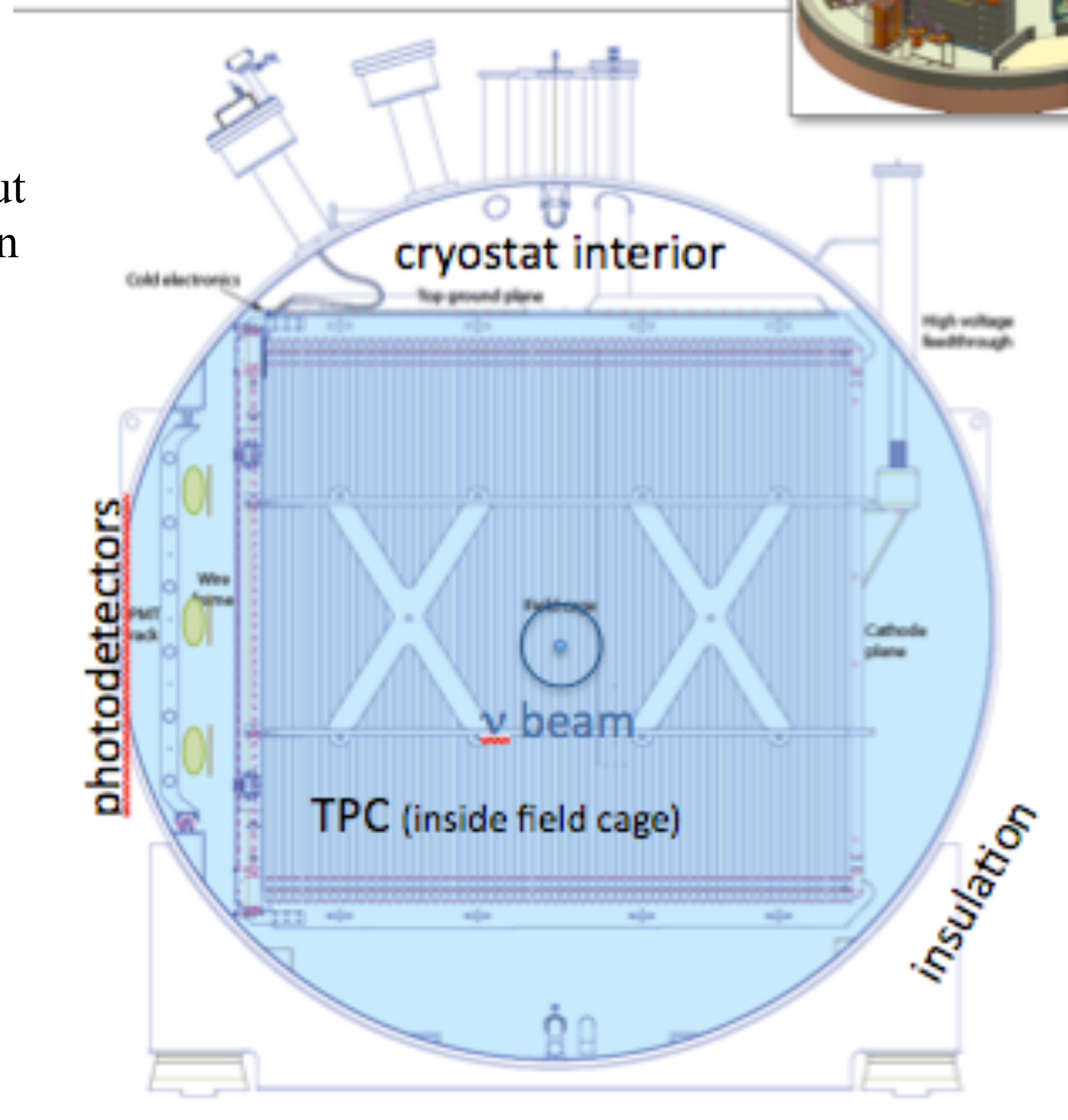




MicroBooNE can investigate a critical piece of the puzzle: **are the excess events seen by MiniBooNE electrons or photons?**

# MicroBooNE

- Physics Goals
  - Low energy excess
  - Neutrino Cross sections
  - “Physics R&D”
    - SN detection
    - PDK background measurements
- Development Goals
  - cold electronics/continous readout
  - achieve purity without evacuation
  - Devleopment of Analysis Tools
  - Laser calibration system






## Status

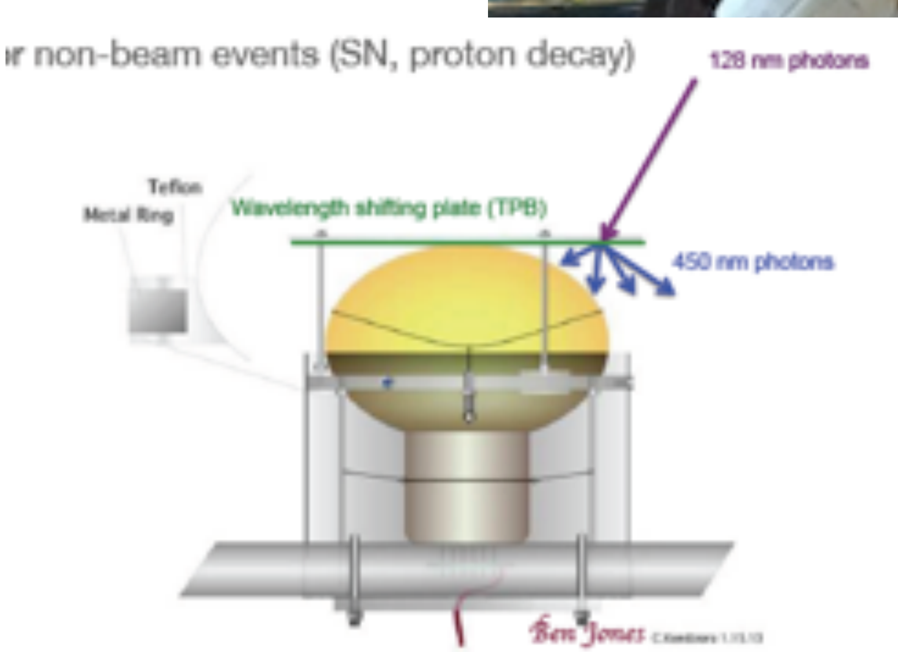
- Final Pre-commissioning checks
- Commissioning summer 2014
- Data taking late 2014

Final TPC assembly step:
Installation of the wound wires
on the TPC frame
Summer 2013

# Cryostat Delivery March 2013

PMT array peaks through the wire chambers to record scintllation light produced in LAr

Flasher system calibrates PMTs



December 20th, 2013

Fermilab *Today*

**MicroBooNE installs time projection chamber inside vessel, prepares for move**

*Detector sealed up May 20th, ready to move to detector hall next week!*

Liquid Argon Test Facility: 470 m from BNB target at FNAL

# MicroBooNE Collaboration

## MicroBooNE Collaboration + Project Team

*Brookhaven:* M. Bishai, H. Chen, K. Chen, S. Duffin, J. Farrell, F. Lanni, Y. Li, D. Lissauer, G. Mahler, D. Makowiecki, J. Mead, X. Qian, V. Radeka, S. Rescia, A. Ruga, J. Sondericker, C. Thorn, B. Yu, C. Zhang

*University of Cambridge*: A. Blake, J. Marshall, M. Thomson

*University of Chicago*: W. Foreman, J. Ho, D. Schmitz, J. Zennamo

*University of Cincinnati*: R. Grosso, J. St. John, R. Johnson, B. Littlejohn

*Columbia University*: N. Bishop, L. Camilleri, D. Caratelli, C. Chi, V. Genty, G. Karagiorgi, D. Kaleko, B. Seligman, M. Shaevitz, B. Sippach, K. Terao, B. Willis

*Fermilab*: R. Acciarri, L. Bagby, B. Baller, D. Bogert, B. Carls, H. Greenlee, C. James, E. James, H. Jostlein, M. Kirby, S. Lockwitz, B. Lundberg, A. Marchionni, S. Pordes, J. Raaf, G. Rameika+, B. Rebel, A. Schukraft, S. Wolbers, T. Yang, G.P. Zeller*

*Kansas State University:* T. Bolton, S. Farooq, S. Gollapinni, G. Horton-Smith

*Los Alamos:* G. Garvey, J. Gonzales, W. Ketchum, B. Louis, G. Mills, Z. Pavlovic, R. Van de Water, K. Yarritu

*MIT:* W. Barletta, L. Bugel, G. Collin, J. Conrad, C. Ignarra, B. Jones, J. Moon, M. Moulai, J. Spitz, M. Toups, T. Wongjirad

*Michigan State University:* C. Bromberg, D. Edmunds

*New Mexico State University*: T. Miceli, V. Papavassiliou, S. Pate, K. Woodruff

*Otterbein University*: N. Tagg

*University of Oxford*: G. Barr, M. Bass, R. Guenette

*University of Pittsburgh*: S. Dytman, D. Naples, V. Paolone

*Princeton University*: K. McDonald, B. Sands

*Saint Mary's University of Minnesota*: P. Nienaber

*SLAC*: M. Convery, B. Eberly, M. Graham, D. Muller, Y-T. Tsai

*Syracuse University*: J. Asaadi, J. Esquivel, M. Soderberg

*University of Texas at Austin:* S. Cao, J. Huang, K. Lang, R. Mehdiyev

*University of Bern, Switzerland:* A. Ereditato, D. Goeldi, I. Kreslo, M. Luethi, C. Rudolf von Rohr, T. Strauss, M. Weber

*INFN, Italy:* F. Cavanna, O. Palamara *(currently at Yale)*

*Virginia Tech:* M. Jen, L. Kalousis, C. Mariani

*Yale University*: C. Adams, E. Church, B. Fleming*, E. Gramellini, A. Hackenburg, B. Russell, A. Szelc

total team (collaboration + project):
- 3 countries
- 23 institutions
- 134 collaborators (includes project team)

* spokespeople,
\+ project manager

# Proposed Next Phase of the FNAL SBN program

**Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.**

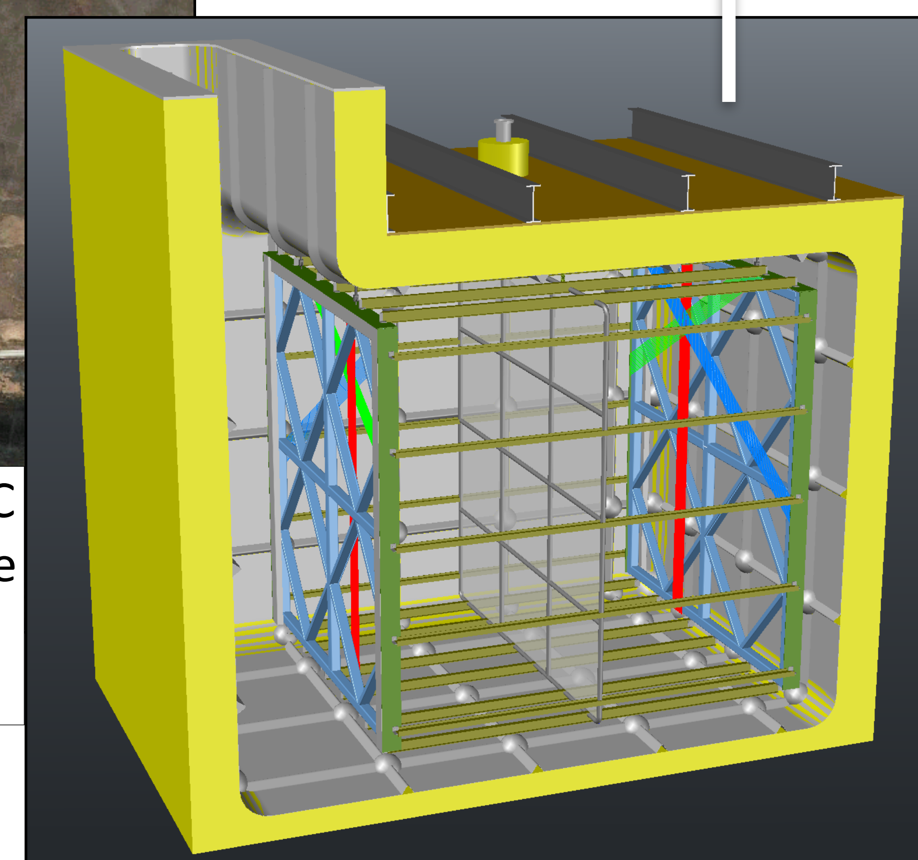
# Some Recent History

- MicroBooNE is opening the LAr-based SBN program at Fermilab, but MicroBooNE was not designed to explore the complete sterile neutrino oscillation parameter space on its own
- Summer 2012, an LOI was submitted to the Fermilab PAC for the "LAr1" project. This was a 1-kton FV LArTPC, based on designs for LBNE, to serve as a second detector along with MicroBooNE. Estimated cost was $80M.

- Fast forward to the January 2014 PAC where two new proposals were put forward:
  - P-1053: LAr1-ND http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/LAr1ND_Proposal.pdf
    - Realizing the importance of a near detector to measure the unoscillated fluxes and the physics program enabled in a first phase with a ND + MicroBooNE, LAr1-ND was proposed as the next phase in the SBN program.
  - P-1052: ICARUS@FNAL http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/ICARUS.pdf
    - Was proposed to relocate the updated existing ICARUS T600 LArTPC detector (~450-ton FV) to the BNB and to construct a new one-fourth scale detector based on the same design to serve as a near detector for oscillation searches.

# LAr1-ND Proposal


82 ton TPC membrane cryostat design

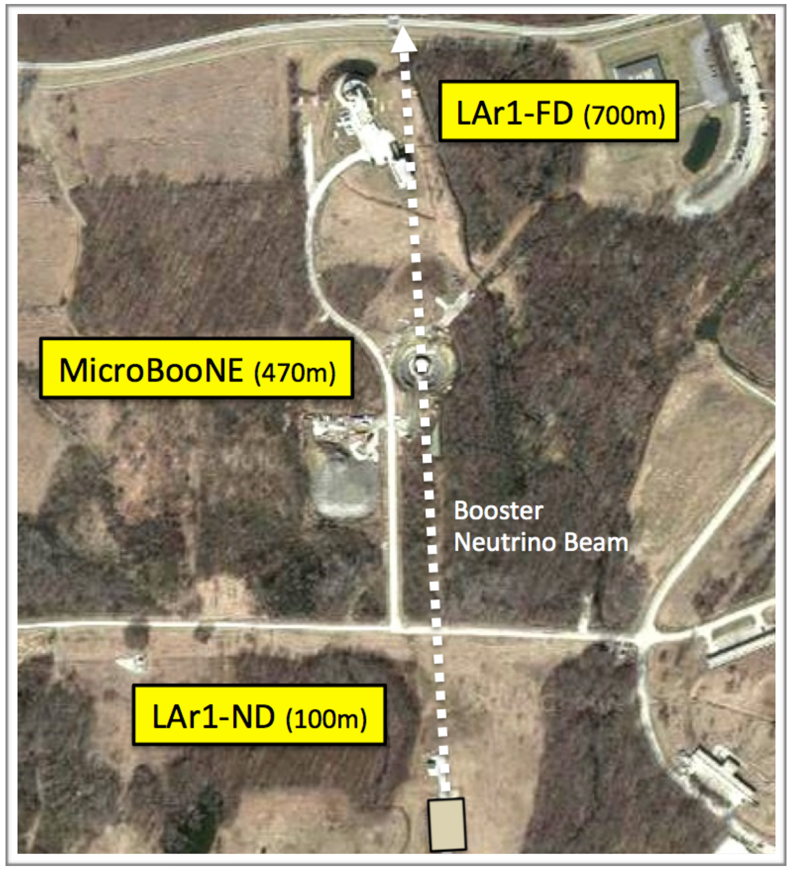


http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/LAr1ND_PAC_2014_01_23_v3.pdf

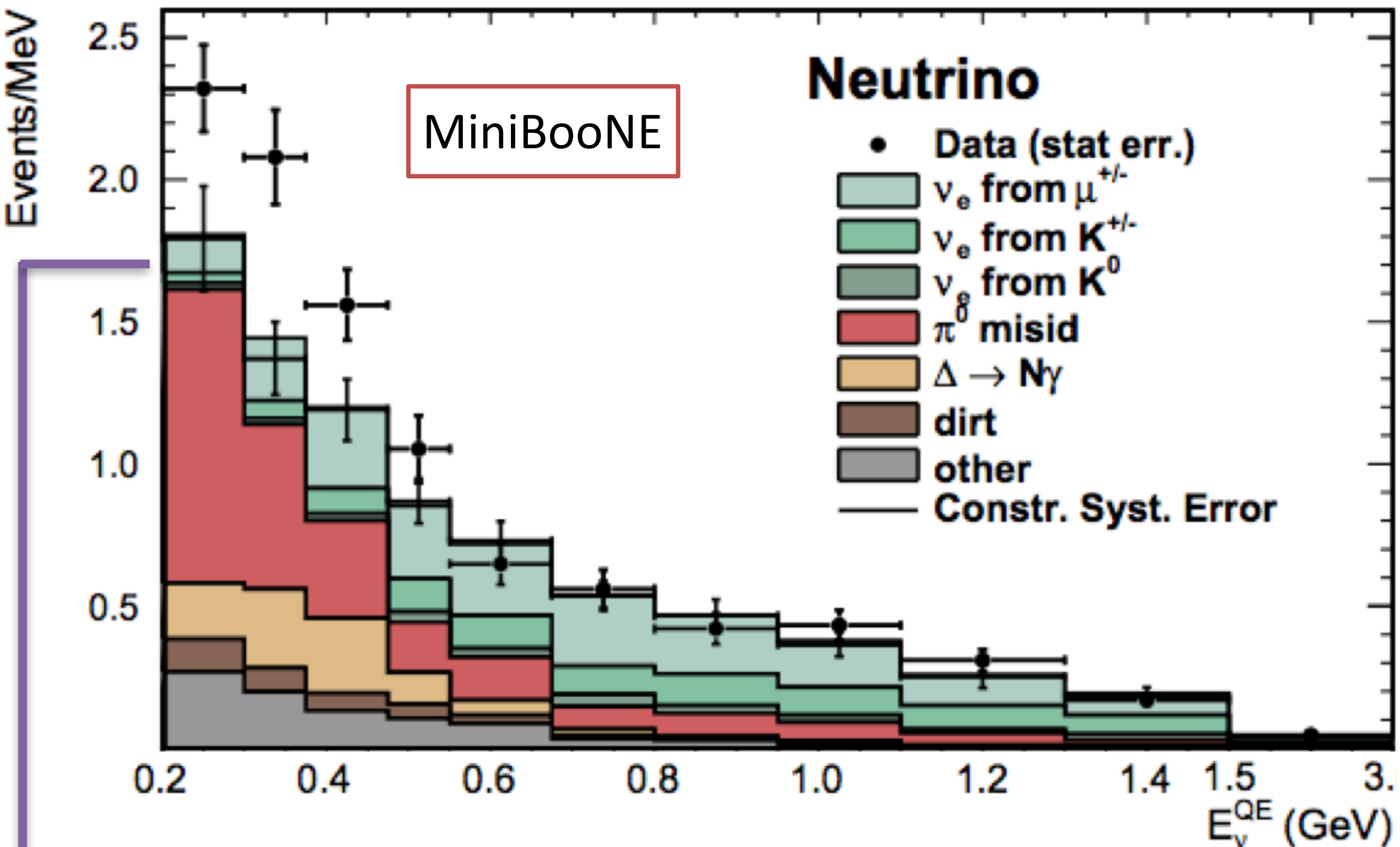
# LAr1-ND Physics Goals

- MiniBooNE low-energy excess
  - Directly test the anomalous excess of electron neutrino events reported by MiniBooNE
- Oscillations: $\nu_\mu \rightarrow \nu_e$ appearance
  - In combination with MicroBooNE, much improved sensitivity with a near detector (ND)
- Oscillations: $\nu_\mu$ disappearance
  - Only possible with a ND
- Oscillations: Neutral-current disappearance
  - Direct test for sterile neutrino content. Only possible with a ND
- Neutrino-argon interaction physics
  - Huge event samples for event reconstruction development and precision cross section measurements
  - If low-energy excess determined to be a Standard Model photon production mechanism, LAr1-ND can make measurements of the rate and kinematics with 100s of events per year

# Sensitivity to MiniBooNE Low-Energy $\nu_e$ Excess




A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. 110 161801 (2013)




*By scaling directly from observed rates in MiniBooNE, MicroBooNE expects to see ~50 background and 50 excess events in 6.6x10$^{20}$ POT run*

*Assuming NO L/E dependence LAr1-ND would expect to see ~320 background and 300 excess events in 2.2x10$^{20}$ POT run*

An estimate of systematics based on MiniBooNE analysis indicates a **>6.5σ** observation of a MiniBooNE-like excess

# “Physics R&D” Neutrino-Argon Interactions, LArTPC Reconstruction, Oscillation Analysis

*GENIE estimated event rates*
*$2.2\times10^{20}$ POT exposure for LAr1-ND*

| Process | | No. Events |
|---|---|---|
| | *$\nu_\mu$ Events (By Final State Topology)* | |
| CC Inclusive | | 787,847 |
| CC 0 $\pi$ | $\nu_\mu N \rightarrow \mu + Np$ | 535,673 |
| | · $\nu_\mu N \rightarrow \mu + 0p$ | 119,290 |
| | · $\nu_\mu N \rightarrow \mu + 1p$ | 305,563 |
| | · $\nu_\mu N \rightarrow \mu + 2p$ | 54,287 |
| | · $\nu_\mu N \rightarrow \mu + \geq 3p$ | 56,533 |
| CC 1 $\pi^{\pm}$ | $\nu_\mu N \rightarrow \mu + \text{nucleons} + 1\pi^{\pm}$ | 176,361 |
| CC $\geq 2\pi^{\pm}$ | $\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 2\pi^{\pm}$ | 14,659 |
| CC $\geq 1\pi^0$ | $\nu_\mu N \rightarrow \text{nucleons} + \geq 1\pi^0$ | 76,129 |
| NC Inclusive | | 300,585 |
| NC 0 $\pi$ | $\nu_\mu N \rightarrow \text{nucleons}$ | 206,563 |
| NC 1 $\pi^{\pm}$ | $\nu_\mu N \rightarrow \text{nucleons} + 1\pi^{\pm}$ | 39,661 |
| NC $\geq 2\pi^{\pm}$ | $\nu_\mu N \rightarrow \text{nucleons} + \geq 2\pi^{\pm}$ | 5,052 |
| NC $\geq 1\pi^0$ | $\nu_\mu N \rightarrow \text{nucleons} + \geq 1\pi^0$ | 54,531 |
| | *$\nu_e$ Events* | |
| CC Inclusive | | 5,883 |
| NC Inclusive | | 2,098 |
| Total $\nu_\mu$ and $\nu_e$ Events | | 1,096,413 |
| | *$\nu_\mu$ Events (By Physical Process )* | |
| CC QE | $\nu_\mu n \rightarrow \mu^- p$ | 470,497 |
| CC RES | $\nu_\mu N \rightarrow \mu^- N$ | 220,177 |
| CC DIS | $\nu_\mu N \rightarrow \mu^- X$ | 82,326 |
| CC Coherent | $\nu_\mu Ar \rightarrow \mu Ar + \pi$ | 3,004 |

*LAr1-ND provides a good venue to conduct high statistics precision cross section measurements and oscillation searches in the 1 GeV energy range*

almost 6,000 $\nu_e$ events

1M total events per ~year

# LAr1-ND Collaboration

C. Adams[1], C. Andreopoulos[2], J. Asaadi[3], B. Baller[4], M. Bishai[5], L. Bugel[6], L. Camilleri[7], F. Cavanna[1], H. Chen[5], E. Church[1], D. Cianci[8], G. Collin[6], J.M. Conrad[6], G. De Geronimo[5], A. Ereditato[9], J. Evans[10], B. Fleming[1], W.M. Foreman[8], G. Garvey[11], R. Guenette[12], J. Ho[8], C.M. Ignarra[6], C. James[4], C.M. Jen[13], B.J.P. Jones[6], L.M. Kalousis[13], G. Karagiorgi[7], W. Ketchum[11], I. Kreslo[9], V.A. Kudryavtsev[14], D. Lissauer[5], W.C. Louis[11], C. Mariani[13], K. Mavrokoridis[2], N. McCauley[2], G.B. Mills[11], Z. Moss[6], S. Mufson[15], M. Nessi[16], O. Palamara*[1], Z. Pavlovic[11], X. Qian[5], L. Qiuguang[11], V. Radeka[5], R. Rameika[4], C. Rudolf von Rohr[9], D.W. Schmitz*[8], M. Shaevitz[7], M. Soderberg[3], S. Söldner-Rembold[10], J. Spitz[6], N. Spooner[14], T. Strauss[9], A.M. Szelc[1], C.E. Taylor[11], K. Terao[7], L. Thompson[14], M. Thomson[17], C. Thorn[5], M. Toups[6], C. Touramanis[2], R.G. Van De Water[11], M. Weber[9], D. Whittington[15], B. Yu[5], G. Zeller[4], and J. Zennamo[8]

[1] *Yale University, New Haven, CT*
[2] *University of Liverpool, Liverpool, UK*
[3] *Syracuse University, Syracuse, NY*
[4] *Fermi National Accelerator Laboratory, Batavia, IL*
[5] *Brookhaven National Laboratory, Upton, NY*
[6] *Massachusetts Institute of Technology, Boston, MA*
[7] *Columbia University, Nevis Labs, Irvington, NY*
[8] *University of Chicago, Enrico Fermi Institute, Chicago, IL*
[9] *University of Bern, Laboratory for High Energy Physics, Bern, Switzerland*
[10] *University of Manchester, Manchester, UK*
[11] *Los Alamos National Laboratory, Los Alamos, NM*
[12] *University of Oxford, Oxford, UK*
[13] *Center for Neutrino Physics, Virginia Tech, Blacksburg, VA*
[14] *University of Sheffield, Sheffield, UK*
[15] *Indiana University, Bloomington, IN*
[16] *CERN, Geneva, Switzerland*
[17] *University of Cambridge, Cambridge, UK*

*Spokespersons

***10 US institutions***
- 3 DOE National Laboratories
- 6 NSF institutions

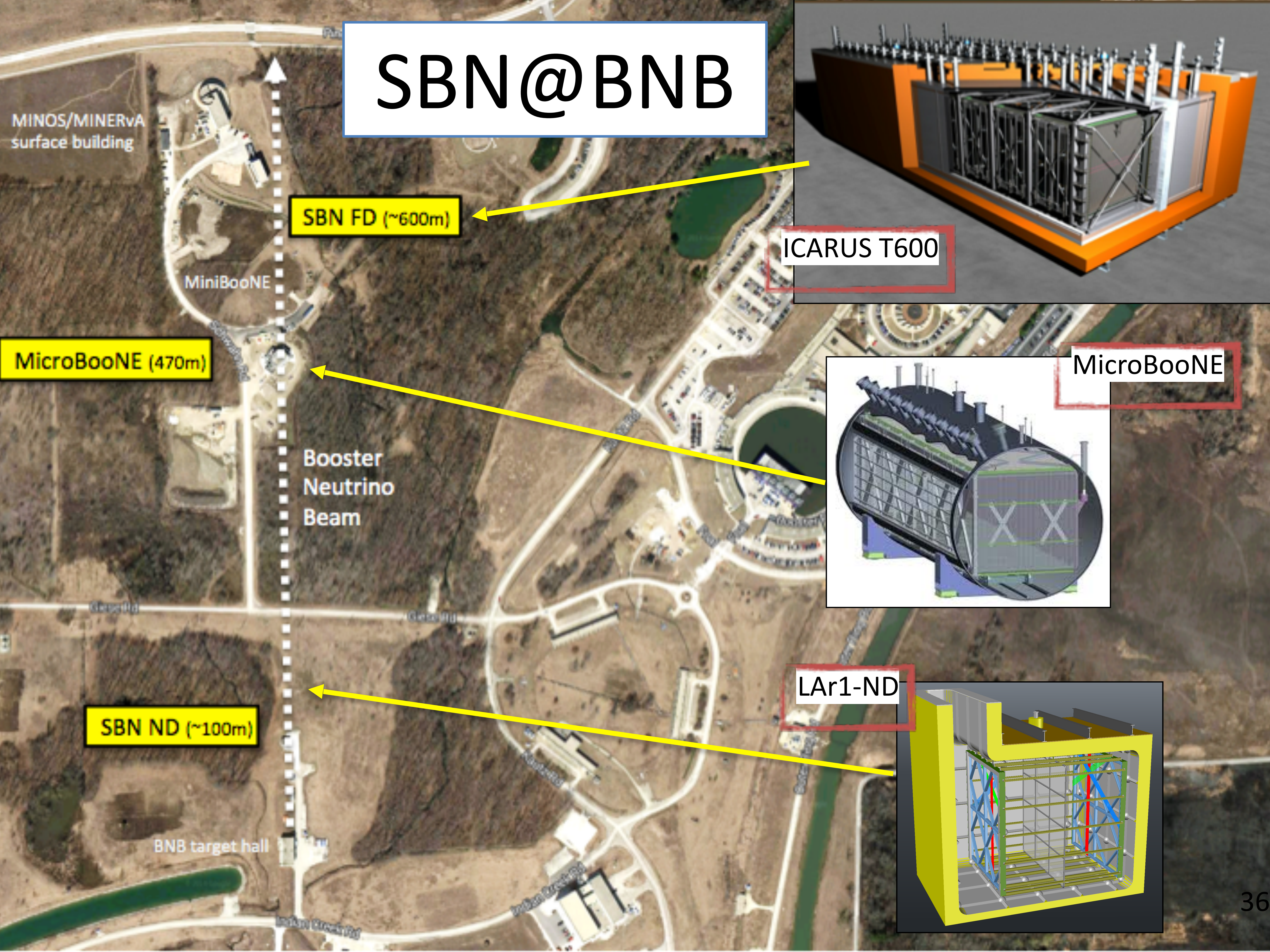
***7 European institutions***
- 5 UK institutions
- 1 Swiss institution
- CERN

11 institutions also on MicroBooNE.
Most also LBNE collaborators.

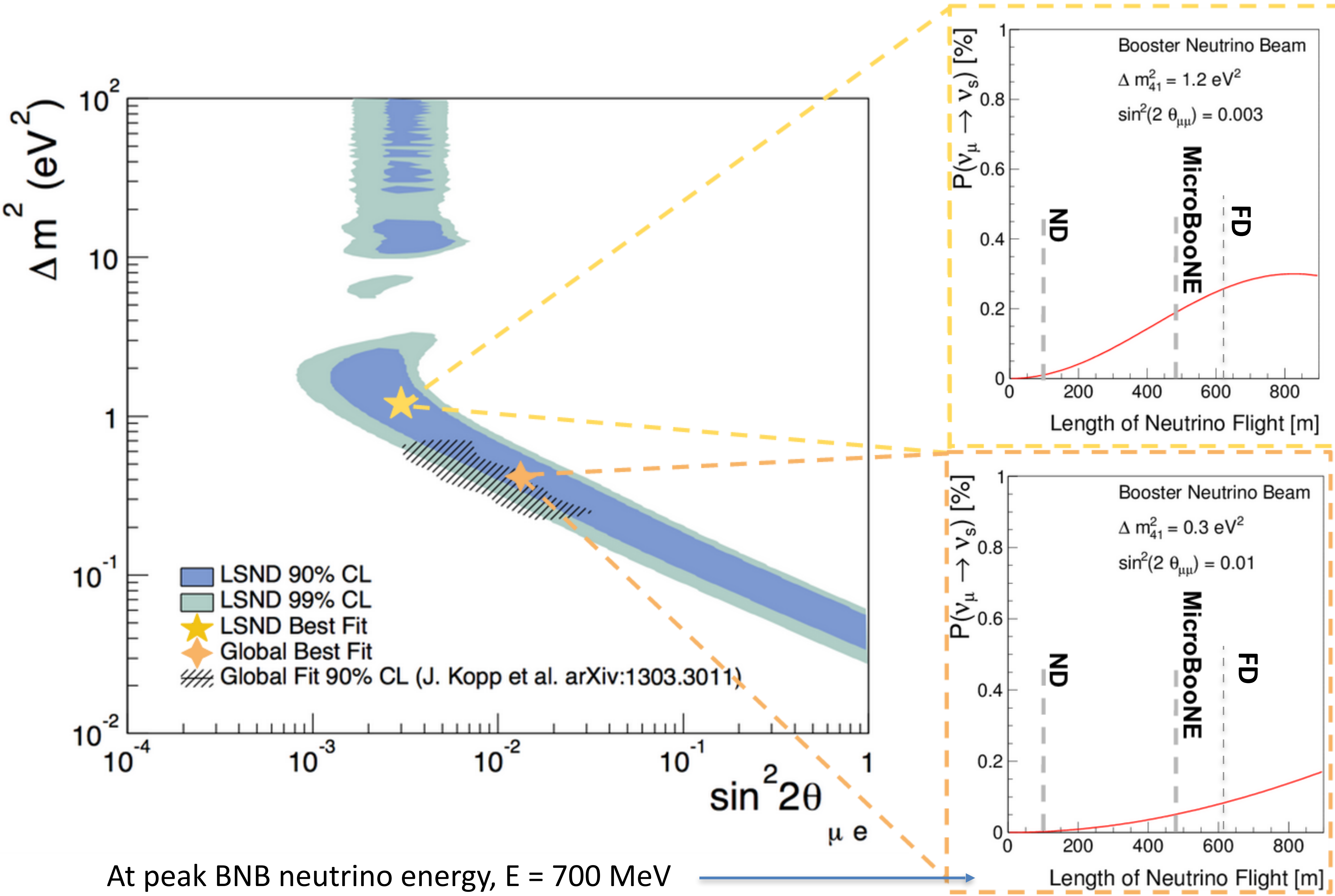
# SBN Program Development

- Since the January PAC, proponents of the LAr1-ND and ICARUS proposals, members of the MicroBooNE collaboration, as well as representatives from Fermilab, INFN and CERN, have been working together to develop plans for a coherent SBN program on the BNB.
  - An international team is currently leading the preparation of a joint proposal to be submitted to the PAC for their next meeting in July.
  - This proposal will include physics sensitivities for a multi-LArTPC detector program with a LAr1-ND type near detector at 100-150m, MicroBooNE at 470m, and the ICARUS T600 detector at 600m along the BNB.

# SBN@BNB

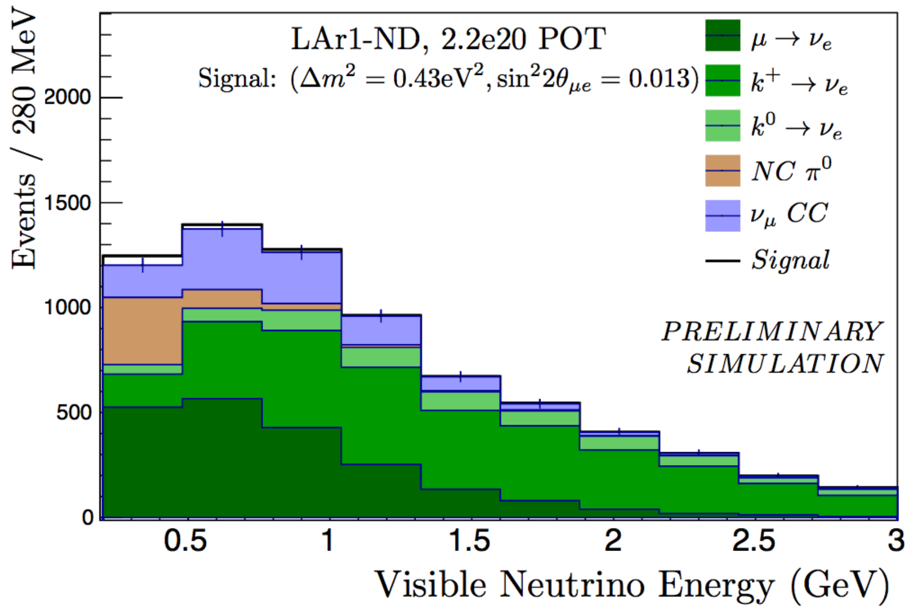

MINOS/MINERvA surface building
SBN FD (~600m)
MiniBooNE
MicroBooNE (470m)
Booster Neutrino Beam
SBN ND (~100m)
BNB target hall
ICARUS T600
MicroBooNE
LAr1-ND

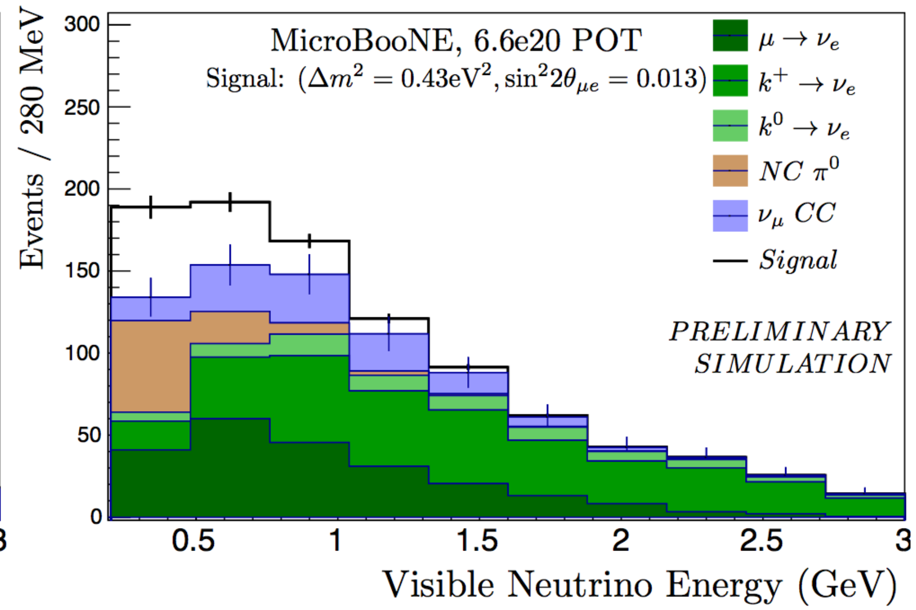
# Sterile Neutrino Oscillations on the BNB

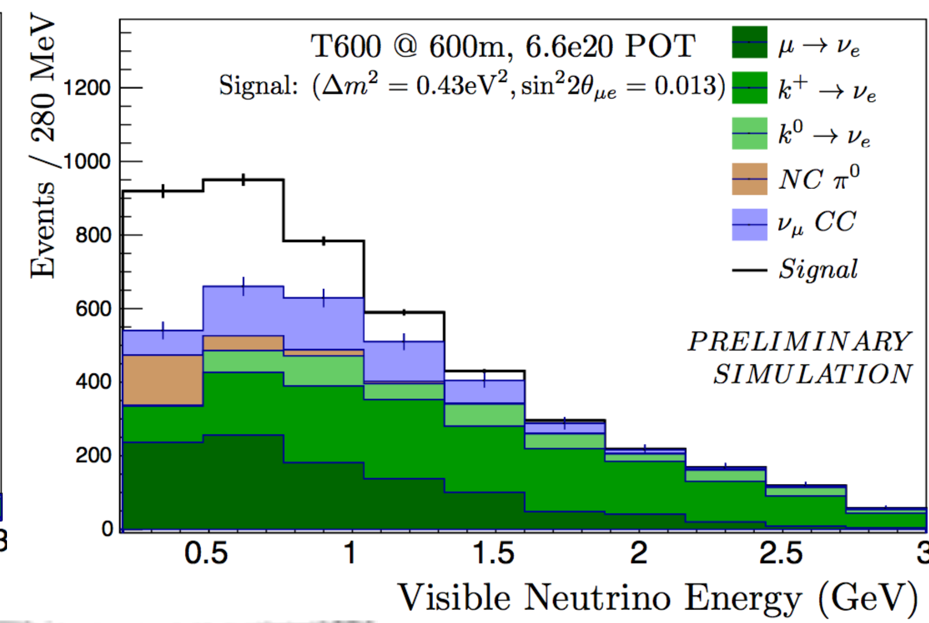


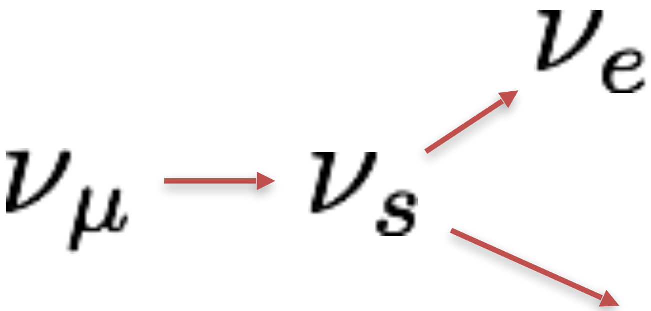

At peak BNB neutrino energy, E = 700 MeV

## ND @ 100 m | MicroBooNE @ 470 m | ICARUS T600 @ 600 m



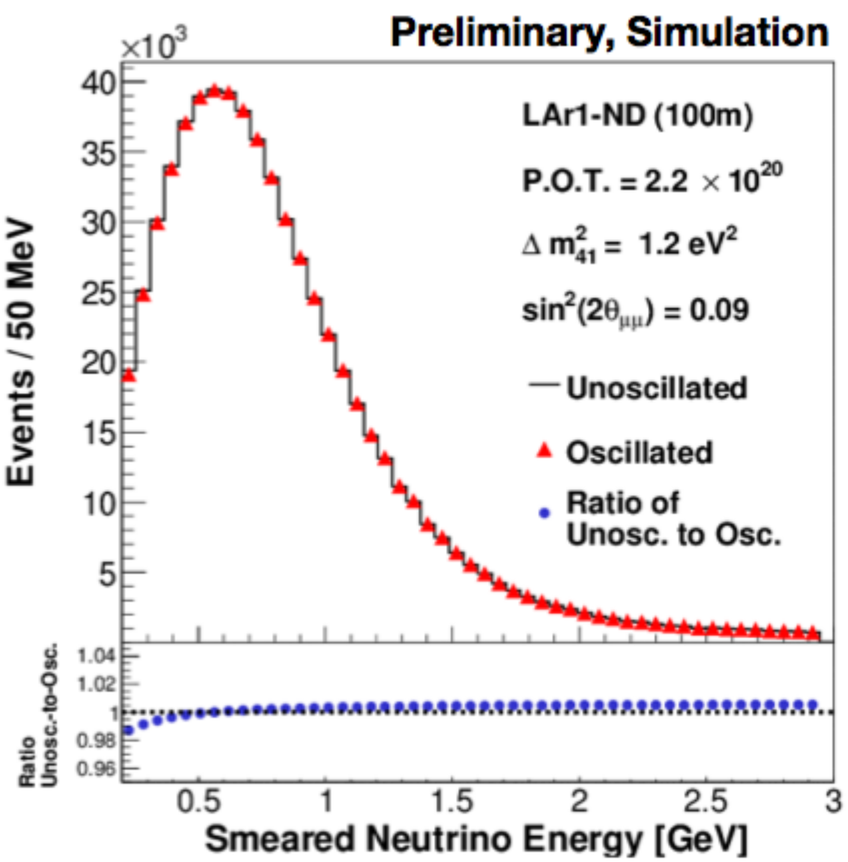



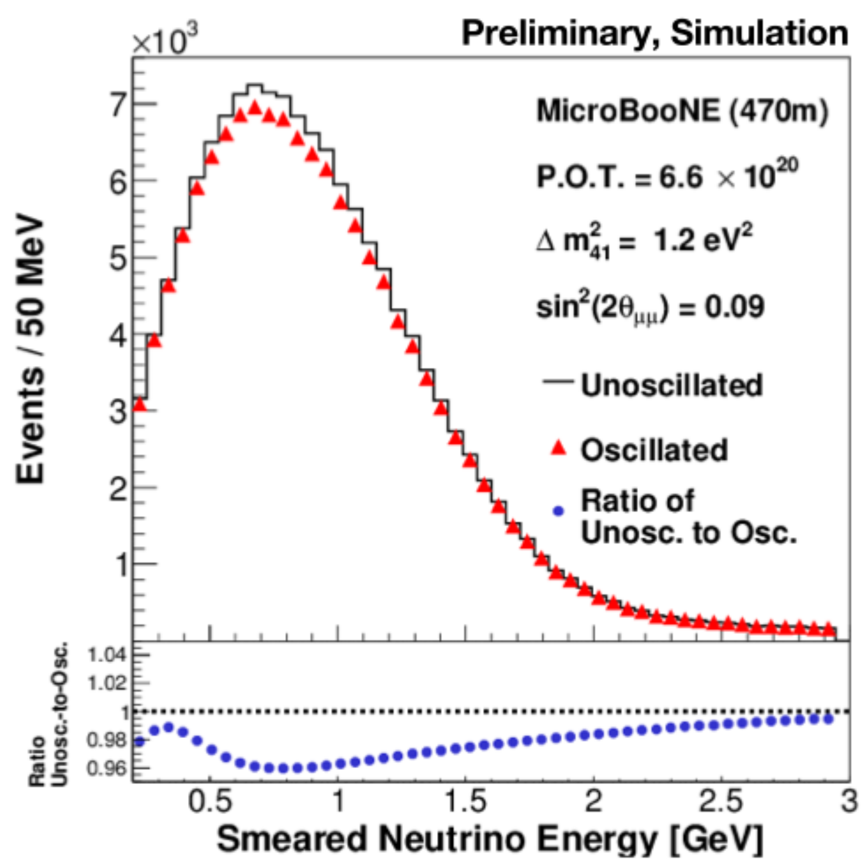



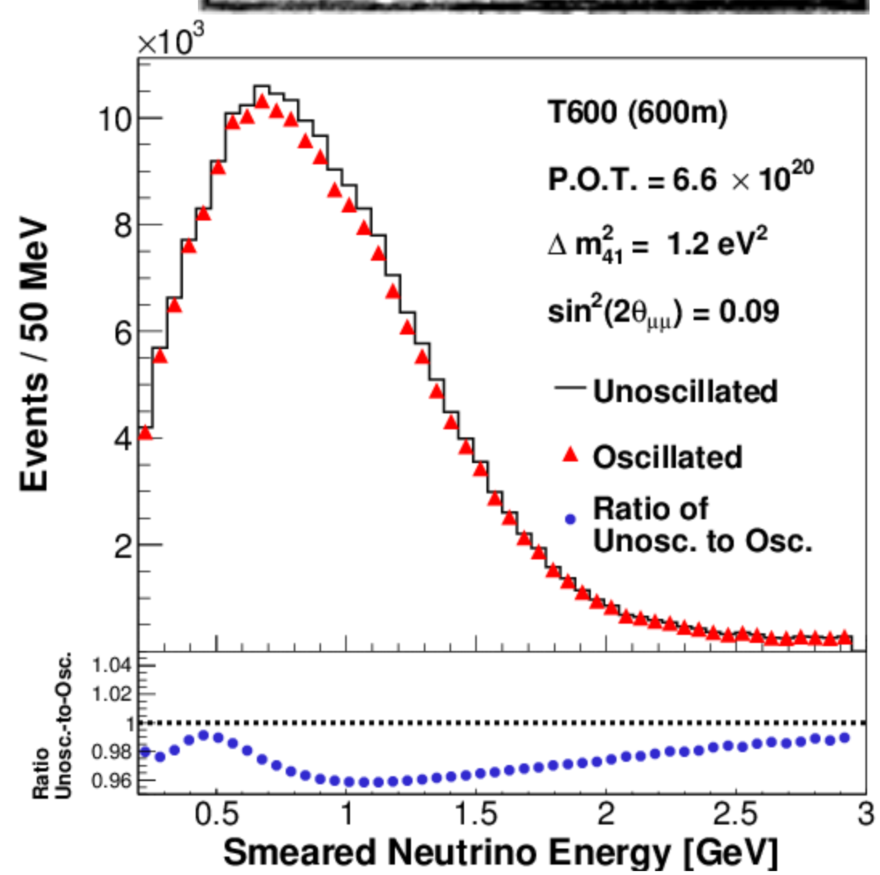




**$\nu_e$ Appearance**

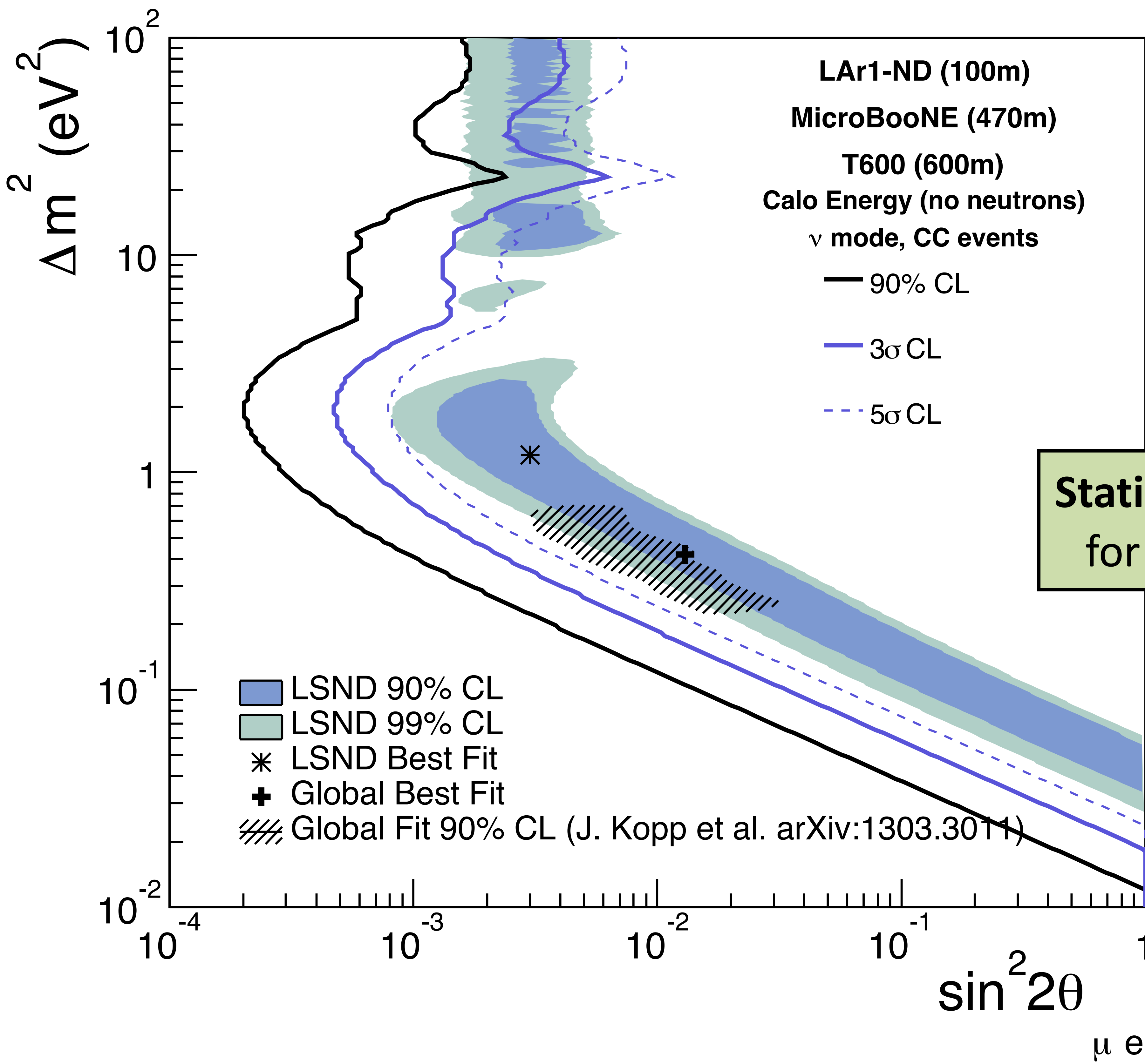
**$\nu_\mu$ Disappearance**

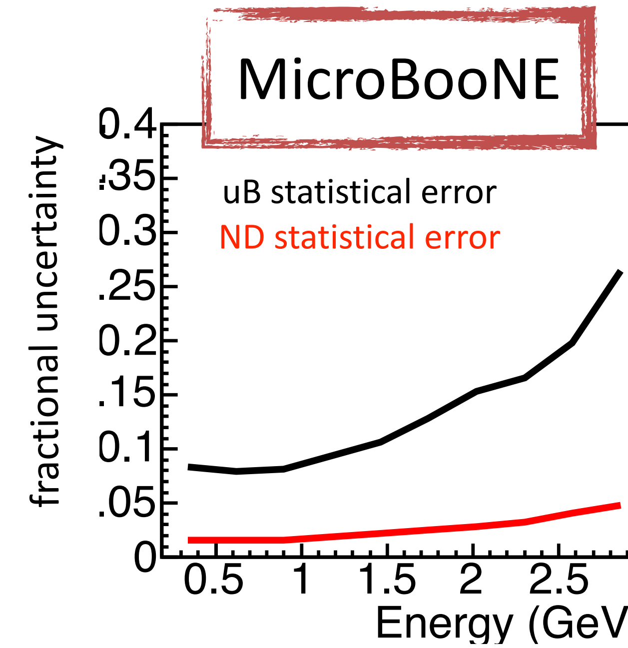


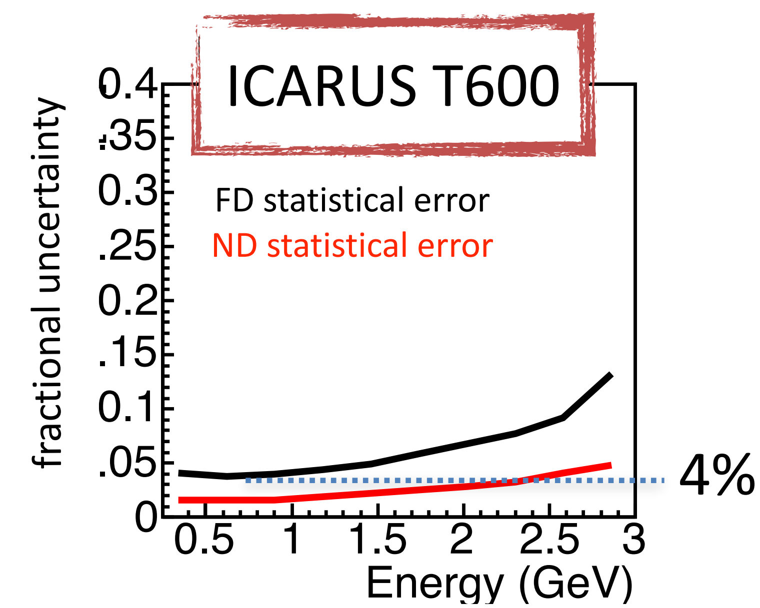



# $\nu_\mu \rightarrow \nu_e$ Appearance

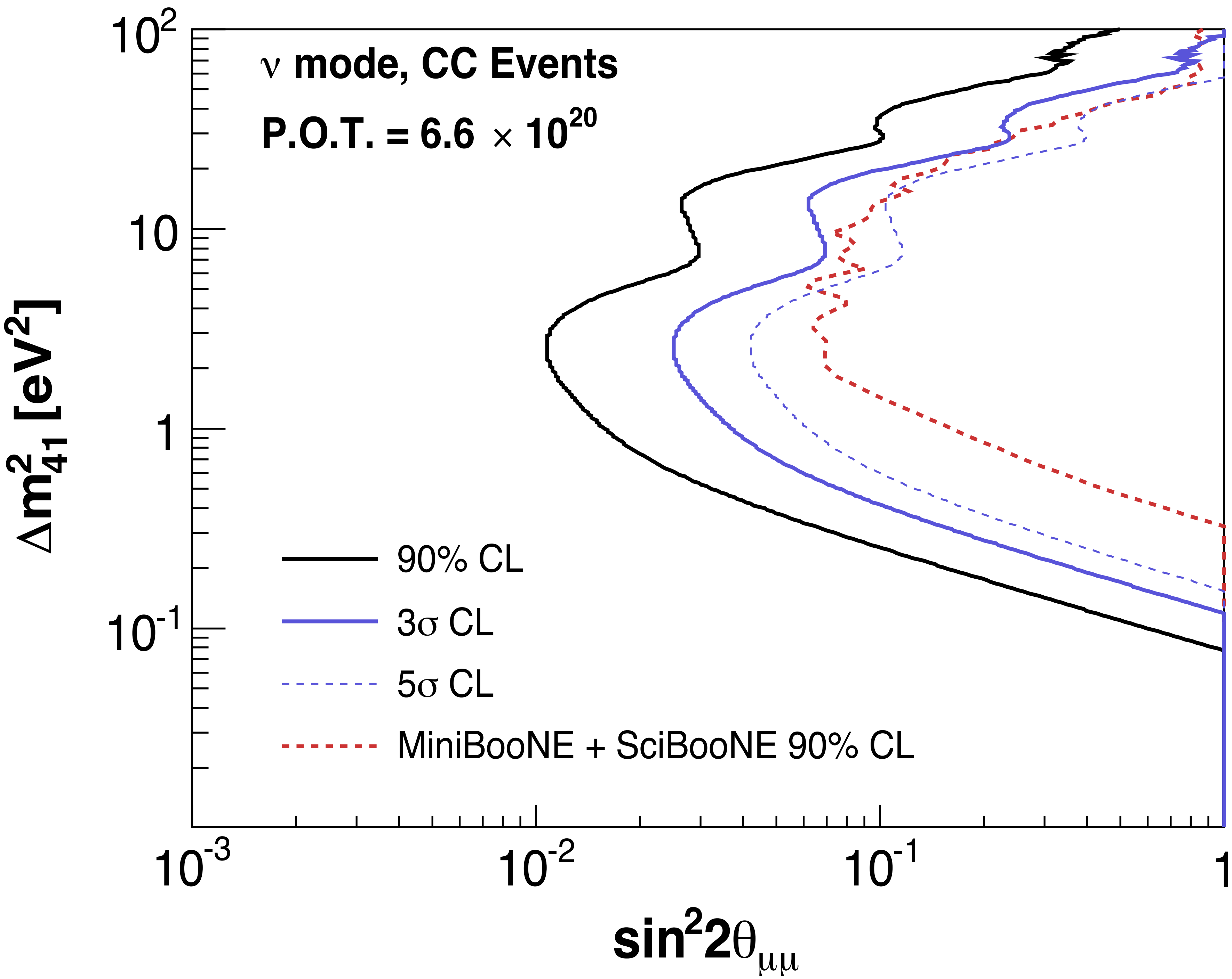



**Statistical** Uncertainty Limit for 6.6e20 POT exposure



# $\nu_\mu$ Disappearance



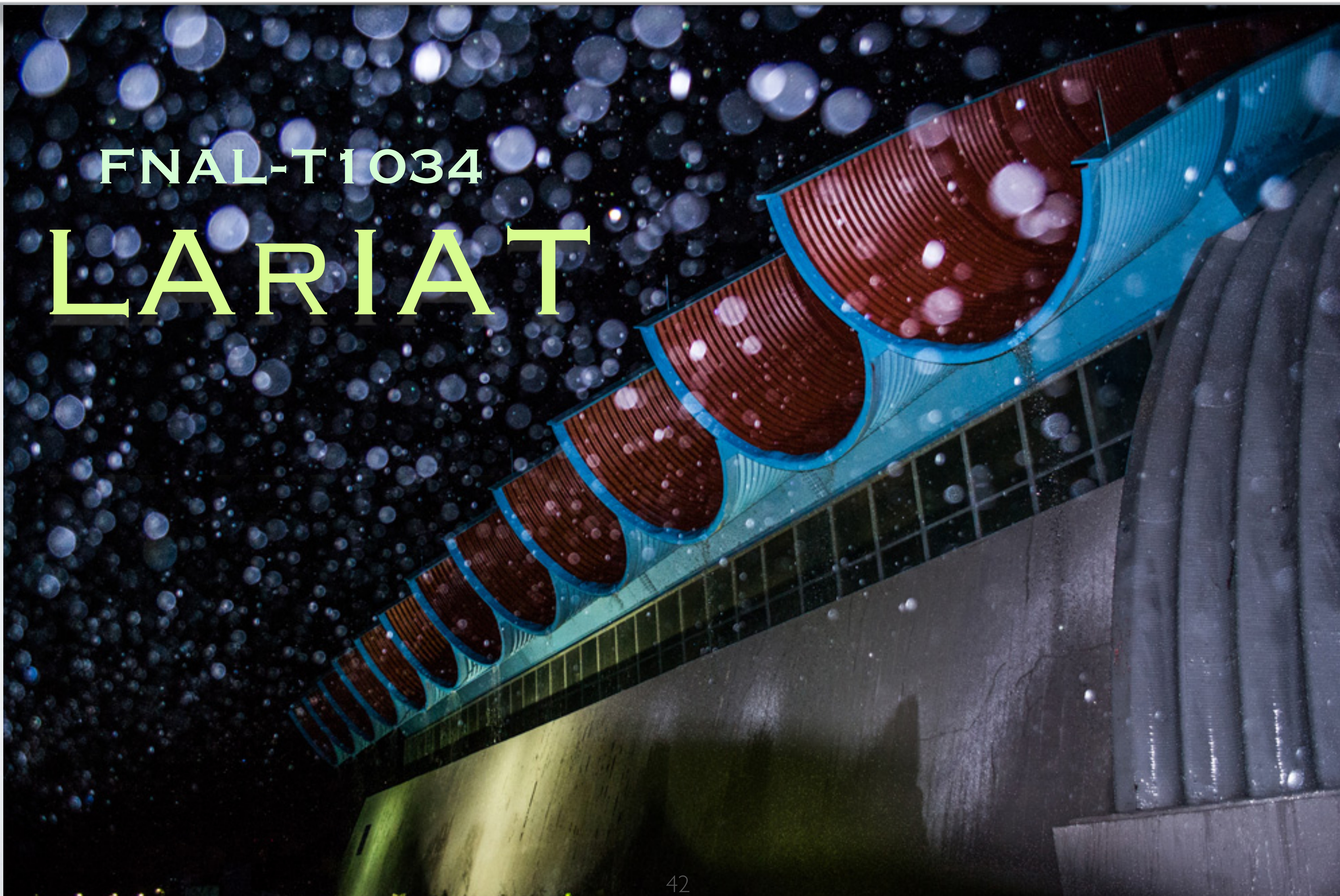

$\nu_\mu$ disappearance not a statistics limited search. Here shown with a 4% systematic uncertainty on the near to far extrapolation.

Previous limit at high $\Delta m^2$ limited by near and far detectors being different technologies

# SBN Summary

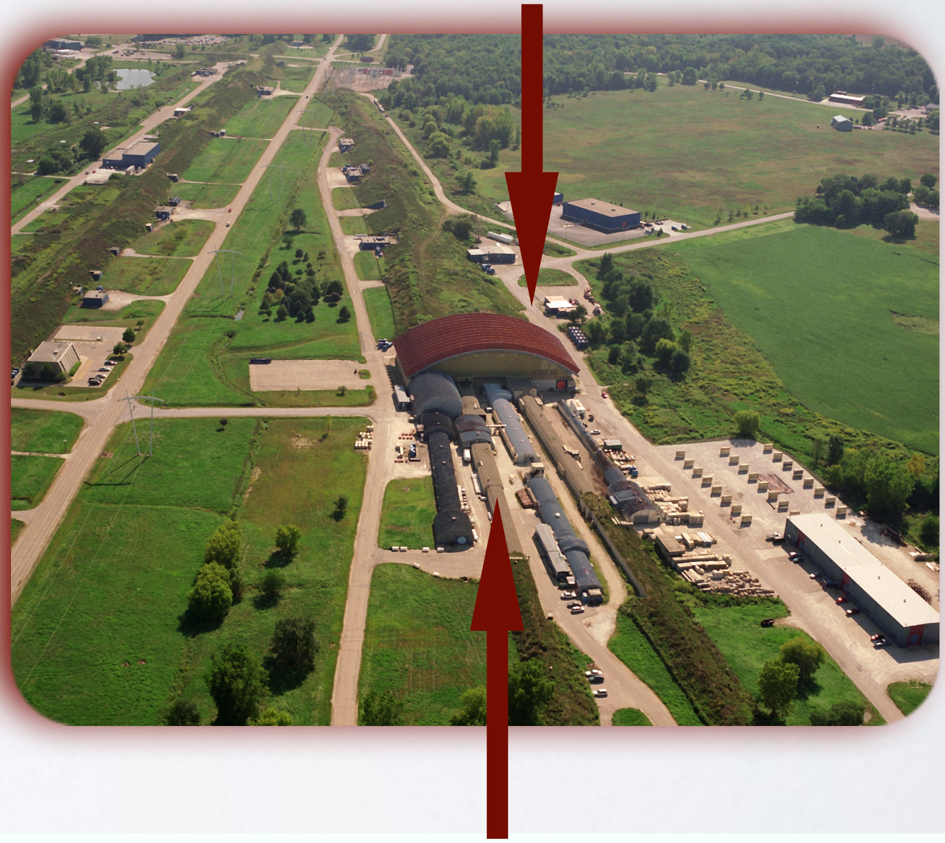
- Fermilab is well positioned to play a key role in resolving the existing hints for new physics happening at short-baseline
- A discovery would be revolutionary
- A short-baseline program additionally provides opportunities for important physics measurements and detector R&D toward the future neutrino program
- Such a program has been endorsed by the recent P5 Report
- An international group is currently developing a proposal to build a world-leading program at Fermilab, utilizing the existing BNB. An optimization of this program, integrating recent proposals by the ICARUS and LAr1-ND collaborations, is under development for the summer PAC next month.

# Liquid ARgon TPC In A Testbeam



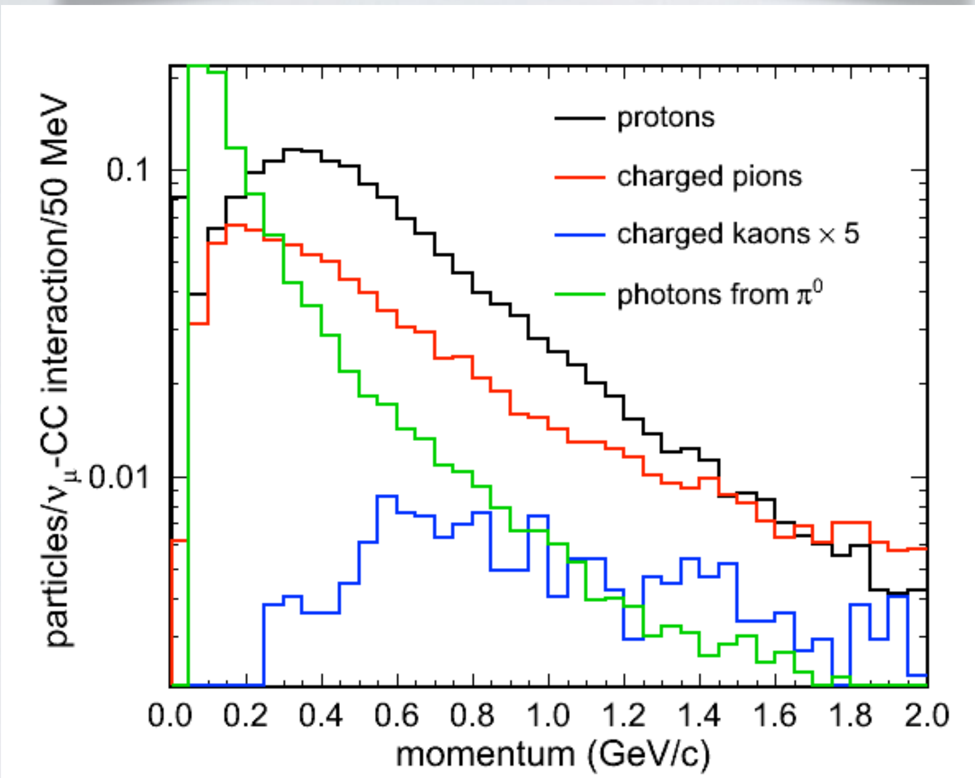
# LArIAT: what, where, when, why

- LArIAT is a test beam experiment designed to measure details of the detector response to charged particles of known energy and type.
  - LArIAT will be the first precision **charged particle** test beam with LAr TPC !
    (Only earlier LAr-TPC test beam was T32 at JPARC)
- The experiment is being assembled at FNAL Test Beam Facility (FTBF).
- The experiment is foreseen as taking place in several phases
  - *Phase I* renovate the ArgoNeuT cryostat&TPC and add a new cryogenics system, new cold electronics, new scintillation light read-out and new DAQ.
  - *Phase II* will re-use the cryogenics system and add a larger cryostat&TPC to provide hadronic shower containment.
- *Phase I* should take data starting in 2014
- *Phase II* could take data starting in ≥ 2016



FROM THE RESUMED MCENTRAL BEAM-LINE AT FTBF, A DEDICATED TERTIARY BEAM LINE HAS BEEN DESIGNED, INSTALLED AND IS NOW READY TO OPERATE

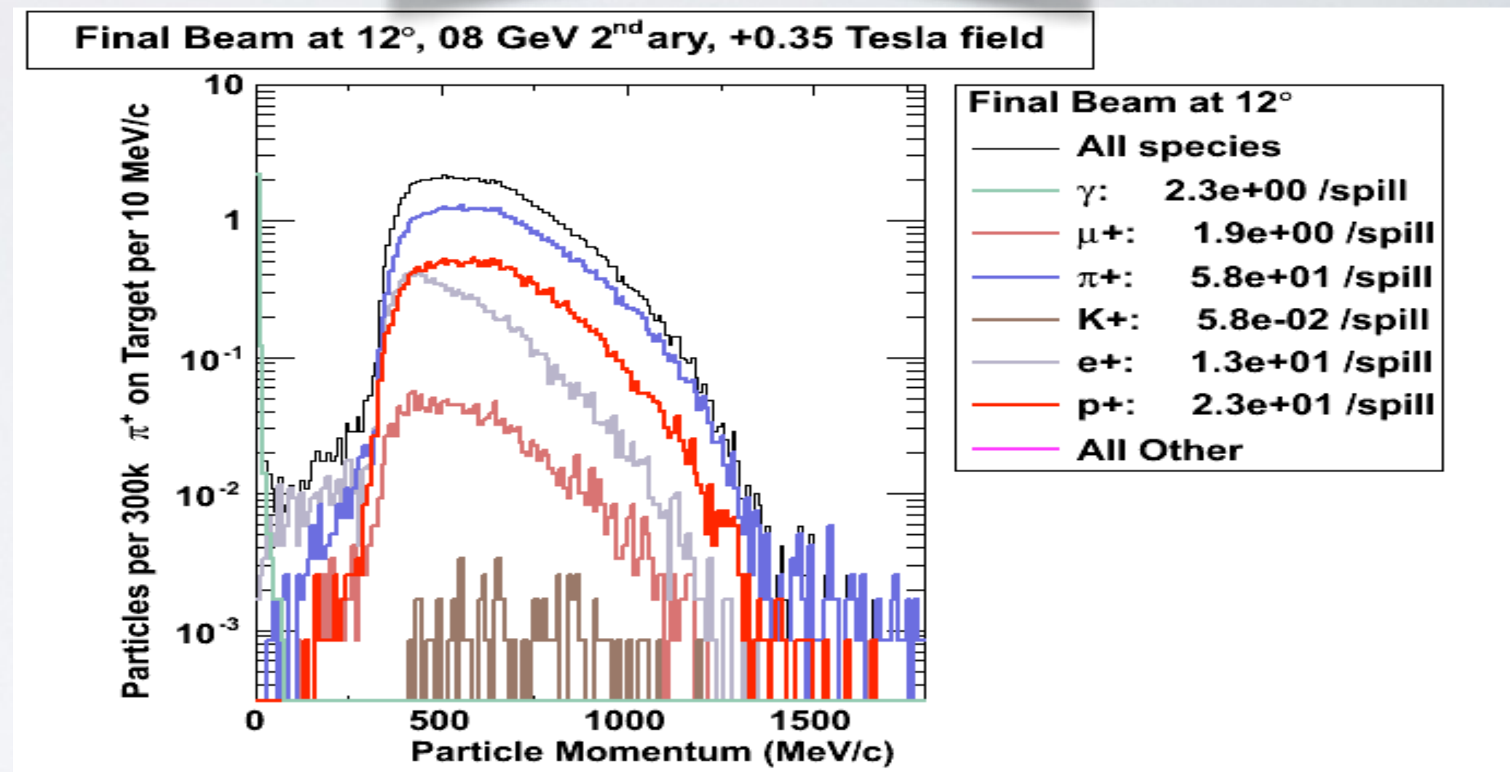
## Motivation




**NuMI LE on-axis Beam**

Study in LArTPC Particles emerging from ν **Interactions** (in the energy range relevant for SBN & LBN)

## Method

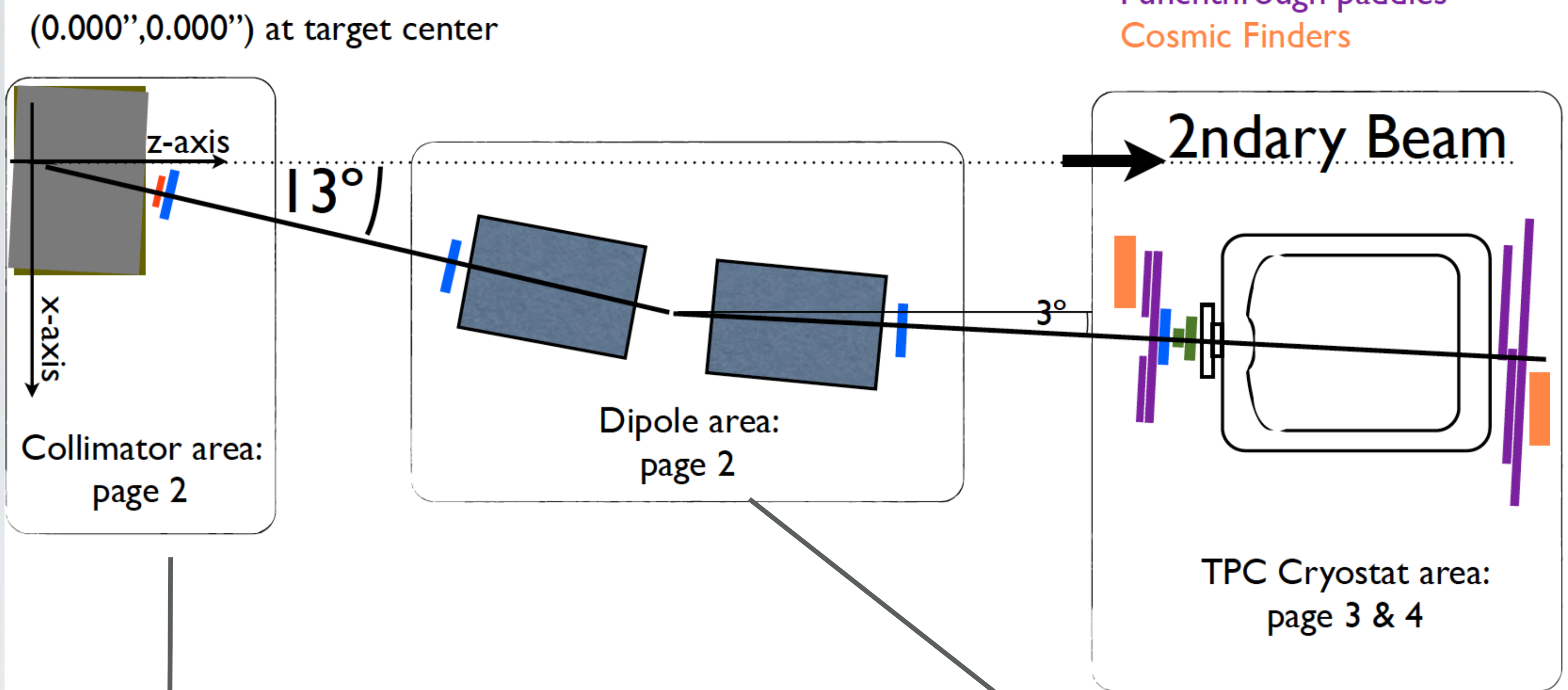



**LArIAT Test Beam**

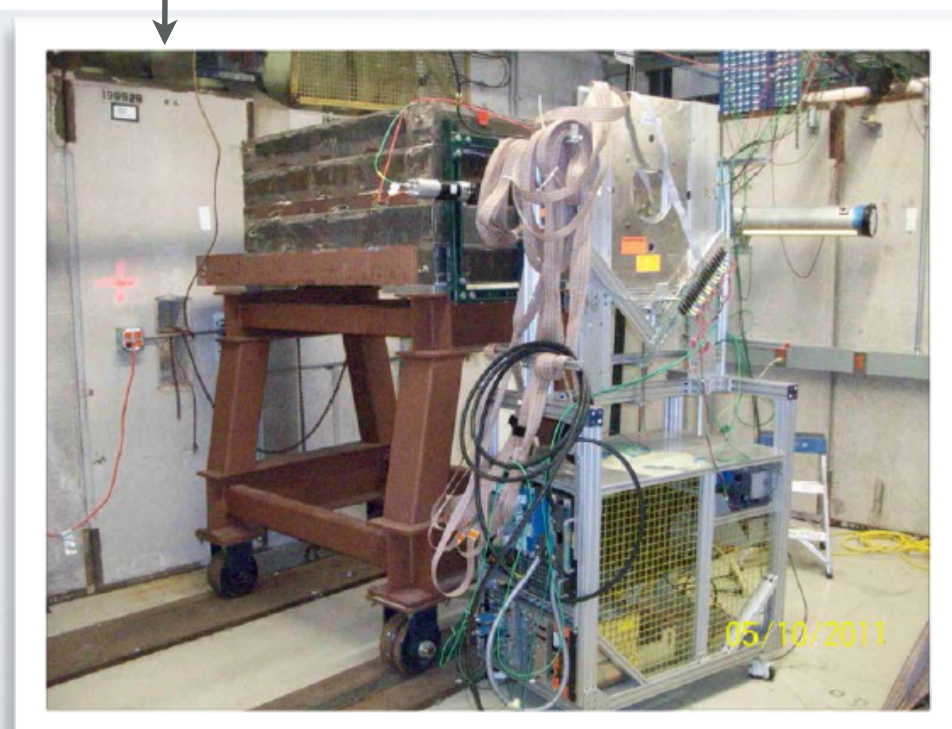
Study in LArTPC Particles emerging from the *LArIAT dedicated* **Tertiary Beam** at FTBF (MCentral)

# LAriaT Tertiary Beamline Instruments

US TOF paddle
DS TOF crossed paddles
Wire Chambers 1,2,3,4
Halo Veto paddles
Punchthrough paddles
Cosmic Finders




Block diagrams for beamline layout and use in mechanical support design

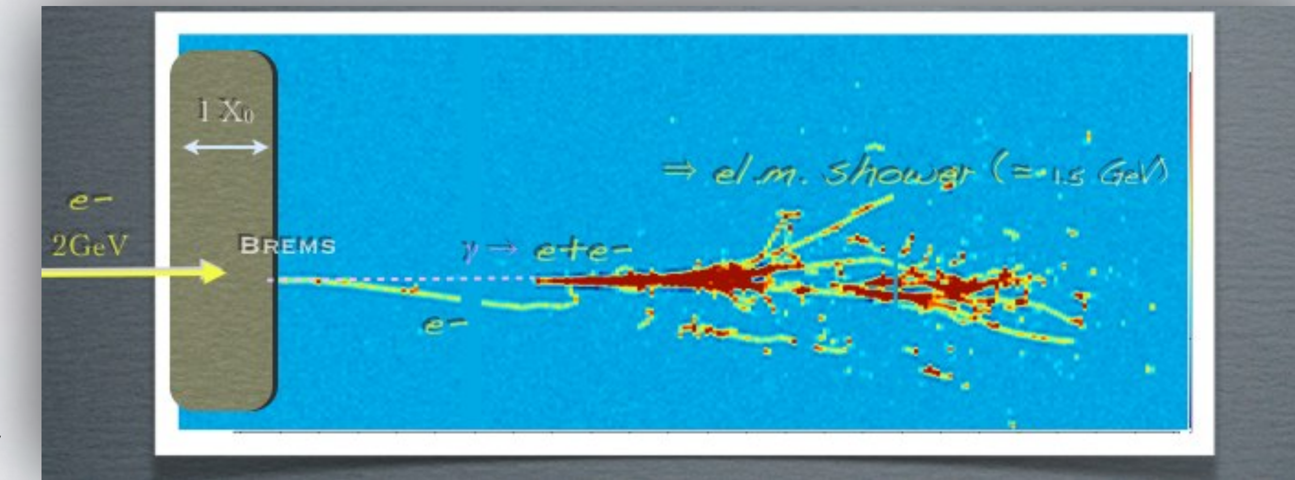



# SCIENCE:

## Electron vs Photon Shower Discrimination

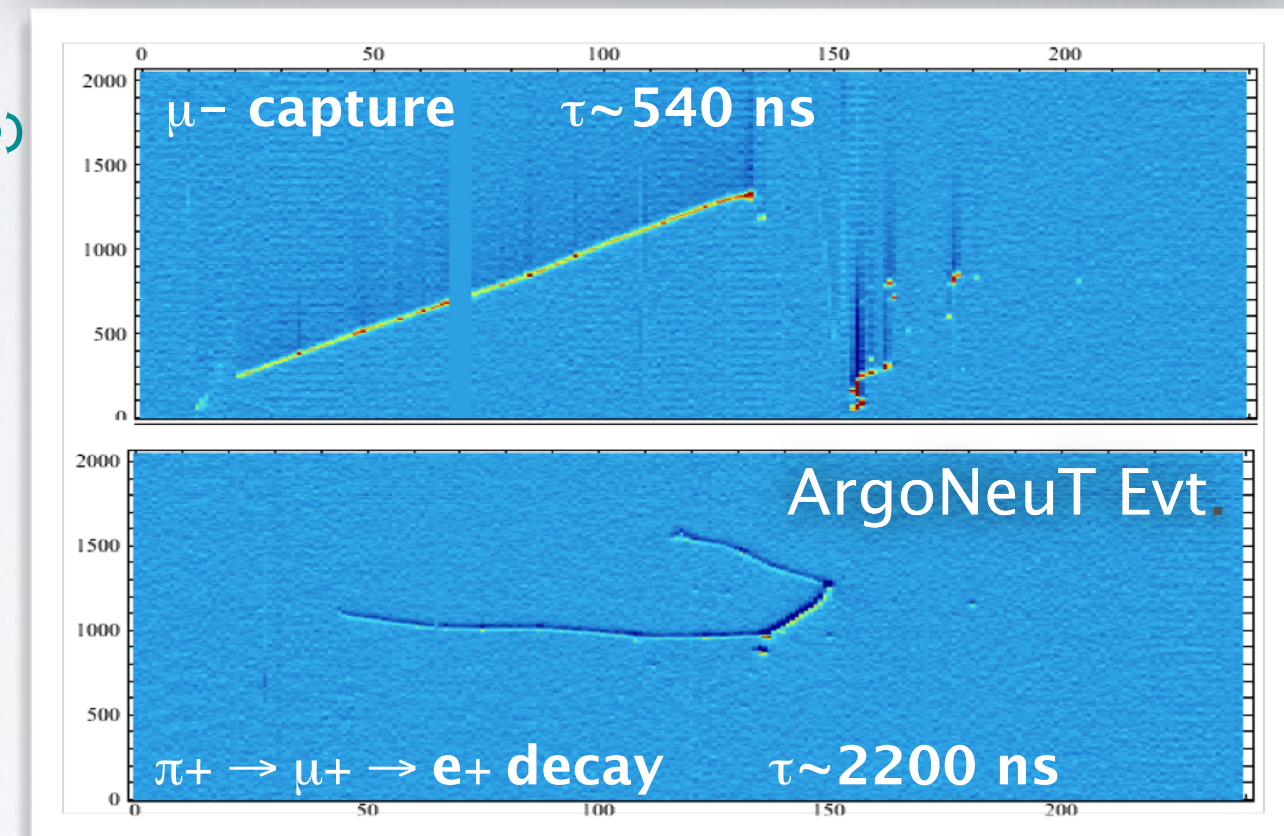
Experimental confirmation for the separation efficiencies (MC determined) - key feature of LArTPC technology

Enable ultimate development and most reliable separation criteria/ algorithms in off-line reconstruction codes




## Muon sign determination (w/out magnetic field)

Explore a LArTPC feature never systematically considered (decay vs capture in LAr)



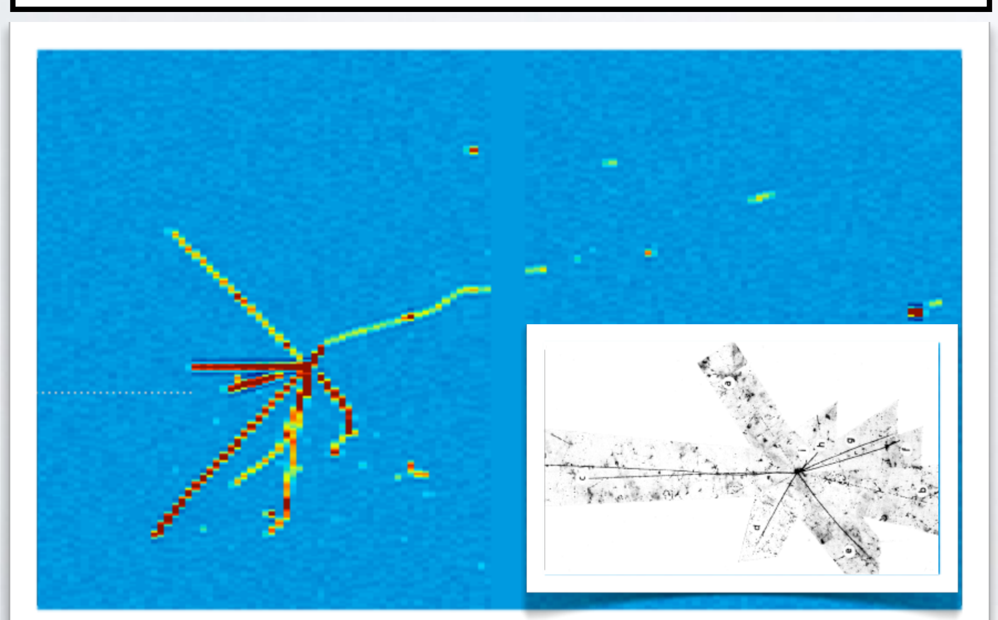

## Study of Nuclear Effects

Pion Absorption, $\pi^0$ from $\pi^\pm$ Charge Exchange

and

Antiproton annihilation (relevant for n-nbar oscillations)

**Simulation of Antiproton Star in LAr**

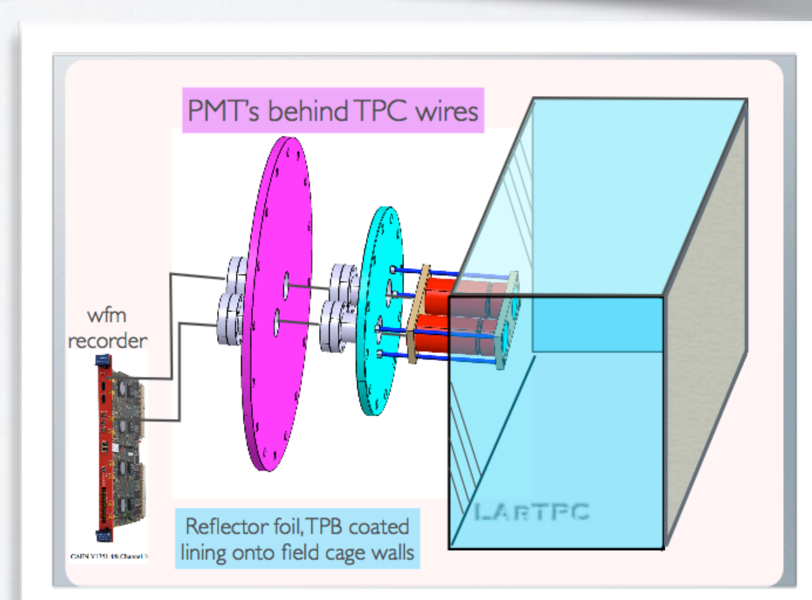


## Development of a new concept in LAr Scintillation Light Collection

Relate energy deposited

to charge and light

for an improved calorimetric energy resolution



# LARIAT SUMMARY

- LArIAT is a main component of the LAr R&D program in US
- Widely supported in the LAr community
- Well aligned with the SBN and LBN program
- Strong support from FNAL permitted the realization of the LAr Test Facility at FTBF
- DOE&NSF funding & Significant contributions from Labs and University Groups permitted detector realization.
- LArIAT will create a new cadre of experimenters with deep experience in LArTPC technology: Training of (young) physicists during extended beam operation and real data analysis is an invaluable add-on in view of future SBN & LBN/ Underground LArTPC experiments
- Data and conclusions available to global LArTPC community
- *Long history of test beam exposures prior to major experiments shows this is the right thing to do*

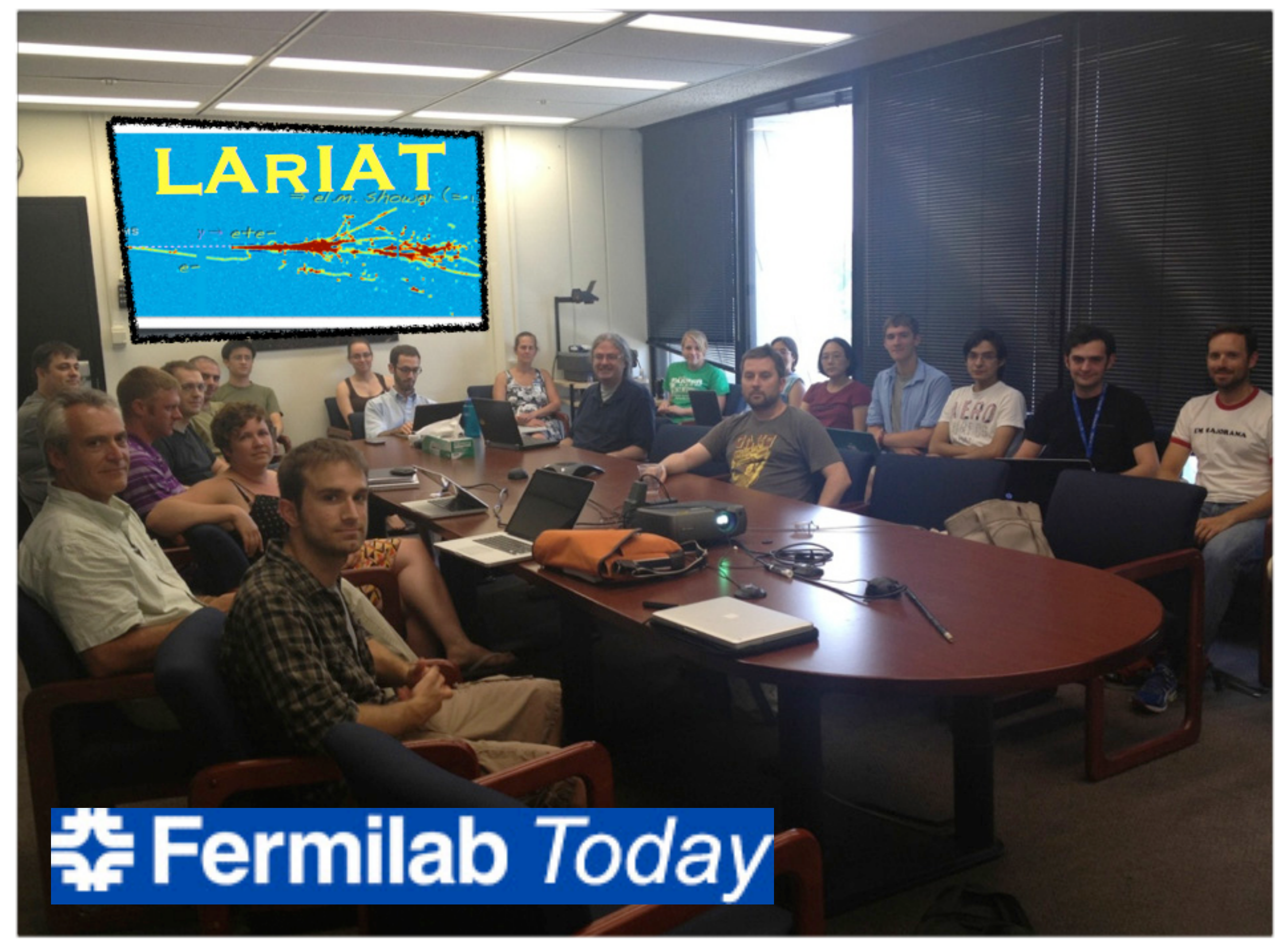
# THE LARIAT COLLABORATION

- 66 Collaborators
- 3 US national labs
- 13 US universities
- 6 foreign institutions (Japan, UK, Italy)

*and 20+ students in summer*

*several new non-US groups are now showing interest to join*

| | |
|---|---|
| Argonne | J. Paley |
| Boston U. | E. Kearns, D. Gastler, R. Linehan |
| Caltech | R. Patterson |
| Chicago | W. Foreman, J. Ho, D. Schmitz |
| Cincinnati | R. Johnson, J. St John |
| Fermilab | R. Acciarri, P. Adamson, M. Backfish, W. Badgett,B. Baller, A. Hahn, D. Jensen, T. Junk, M. Kirby, T. Kobilarcizk, P. Kryczynski, H. Lippincot, A. Marchionni, K. Nishikawa, J. Raaf*, E. Ramberg, B. Rebel, M. Stancari, G. Zeller |
| Imperial Col. London | M. Wascko |
| KEK (joined in 2014) | T. Maruyama, E. Iwai, S. Kunori |
| Los Alamos | C. Mauger |
| Louisiana State | F. Blazsczyk, W. Metcalf, A. Olivier, M. Tzanov |
| Manchester | J. Evans, P. Guzowski |
| Michigan State | C. Bromberg, D. Edmunds, D. Shooltz |
| Minnesota – Duluth | R. Gran, A. Habig, K. Kaess |
| Pittsburgh (joined in 2014) | S. Dytman |
| Syracuse | J. Asaadi, M. Soderberg, J. Esquivel |
| Texas – Arlington | A. Farbin, S. Park, J. Yu |
| Texas – Austin | J. Huang, K. Lang |
| University Col. London | R. Nichol, A. Holin, J. Thomas |
| William and Mary | M. Kordosky, M. Stephens, P. Vahle |
| Yale | F. Cavanna*, E. Church, B. Fleming, E. Gramellini, O. Palamara, A. Szelc |

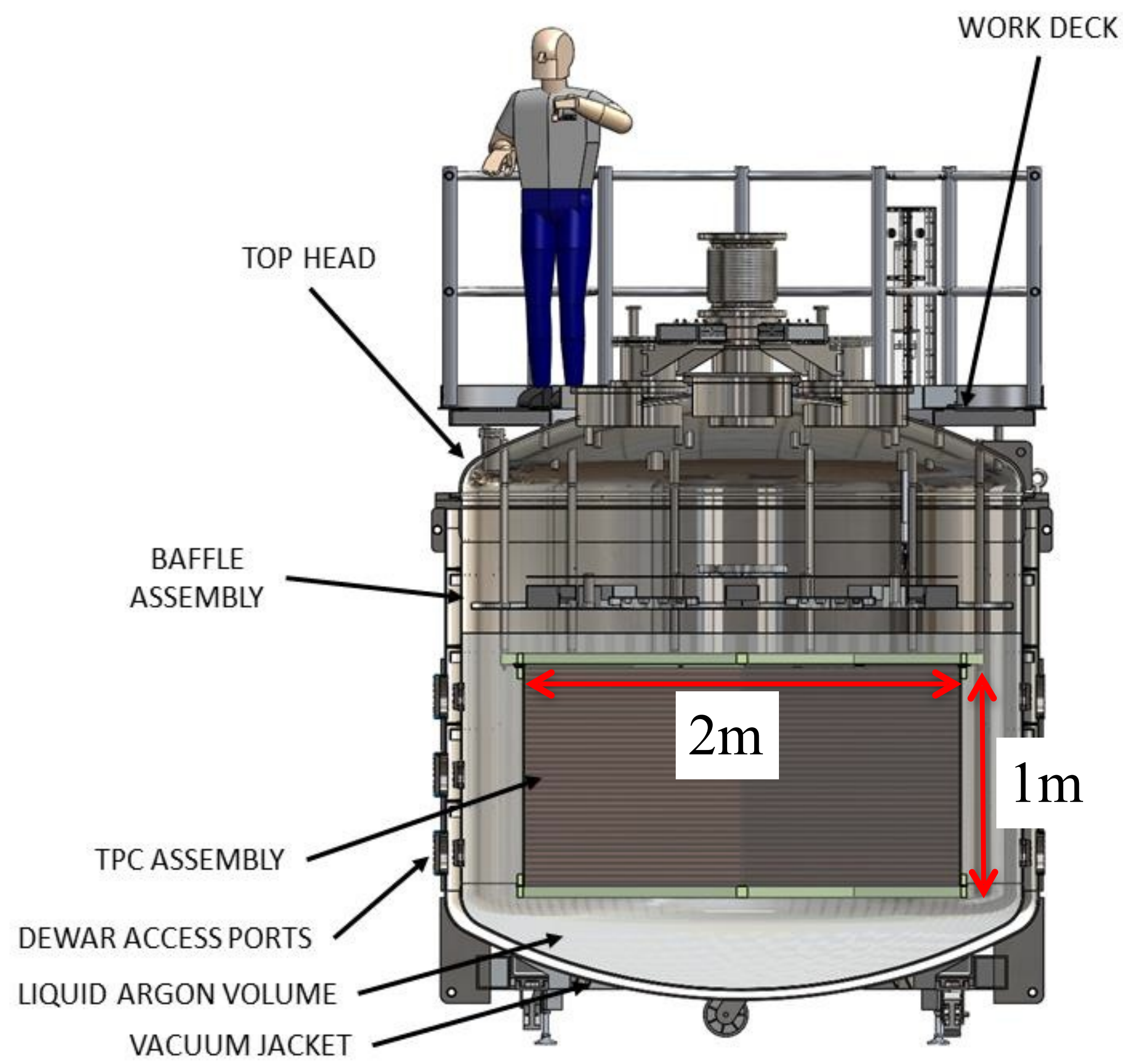



* elected spokespersons (Phase I)

# The CAPTAIN Detector

CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

- CAPTAIN Detector
  - hexagonal TPC with 1m vertical drift, 1m apothem, 2000 channels, 3mm pitch, 5 instrumented tons
  - cryostat 7700 liter capacity, evacuable, portable, operable safely at multiple locations
  - all cryogenic connections made through top head
  - indium seal – can be opened and closed
  - photon detection system and laser calibration system
  - using same cold electronics and electronics chain as MicroBooNE (front end same as LBNE)
- CAPTAIN prototype
  - Hexagonal TPC with 30 cm drift, 50cm apothem, 1000 channels, 3mm pitch, 400 instrumented kilograms
- Physics program focused on challenges to LBNE low-energy neutrino (supernova) and medium-energy neutrino (long-baseline and atmospheric) programs



# CAPTAIN Collaboration

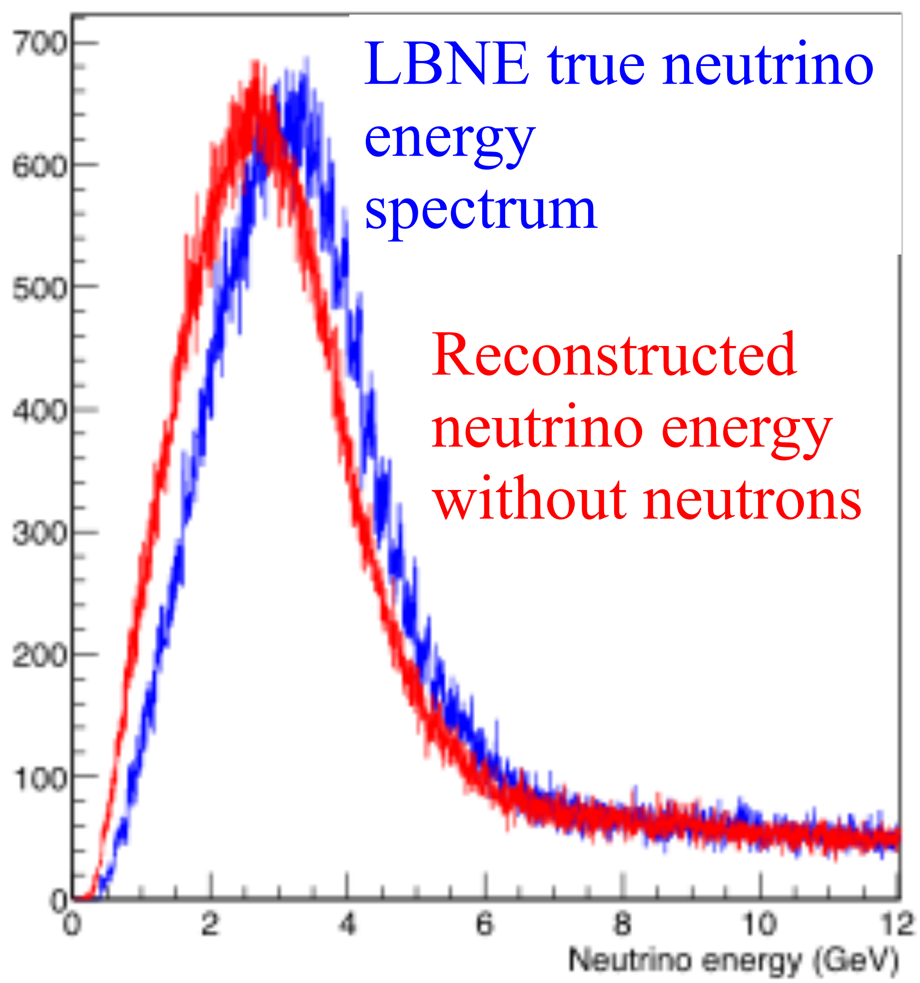
60 Collaborators and more welcome

- Alabama: Shak Fernandes, Ion Stancu
- ANL: Zelimir Djurcic
- LBL: Vic Gehman, Richard Kadel, Craig Tull
- BNL: Hucheng Chen, Veljko Radeka, Craig Thorn
- UC Davis: Hans Berns, Dan Danielson, Chris Grant, Aaron Manalaysay, Emilja Pantic, Robert Svoboda, Matthew Szydagis
- UC Irvine: Michael Smy
- UC Los Angeles: David Cline, Kevin Hickerson, Kevin Lee, Elwin Martin, Jasmin Shin, Artin Teymourian, Hanguo Wang, Lindley Winslow
- FNAL: Oleg Prokoviev, Jonghee Yoo
- Hawaii: Jelena Maricic
- Houston: Babu Bhandari, Lisa Whitehead
- Indiana: Stuart Mufson
- LANL: Jeremy Danielson, Steven Elliott, Gerald Garvey, Elena Guardincerri, Todd Haines, Wesley Ketchum, David Lee, Qiuguang Liu, William Louis, Christopher Mauger, Geoff Mills, Jacqueline Mirabal-Martinez, John Ramsey, Keith Rielage, Constantine Sinnis, Walter Sondheim, Charles Taylor, Richard Van de Water, Kevin Yarritu
- Louisiana State University: Flor de Maria Blaszczyk, Thomas Kutter, William Metcalf, Martin Tzanov
- New Mexico: Franco Giuliani, Michael Gold
- South Dakota: Chao Zhang
- South Dakota State: Robert McTaggart
- Stony Brook: Clark McGrew, Chiaki Yanagisawa

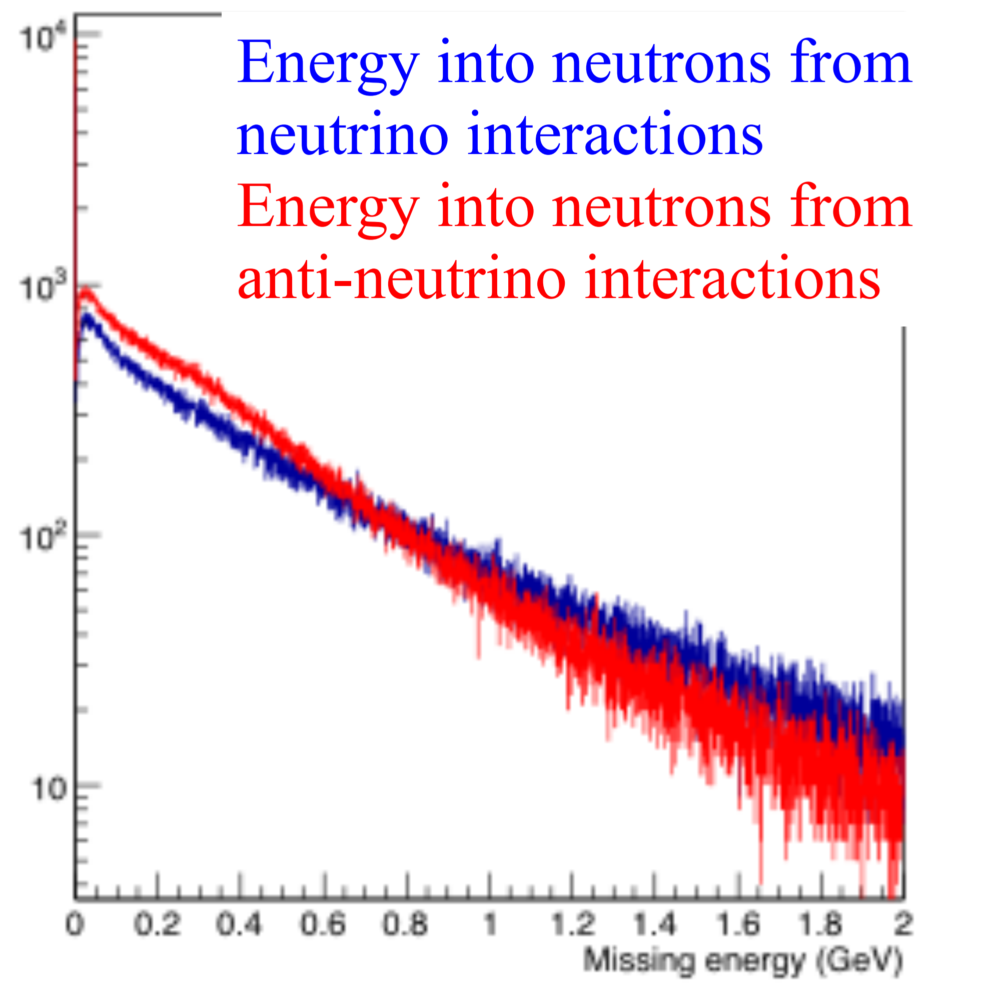
http://p25ext.lanl.gov/people/lee/LArTPC/LANL_LDRD.htm

# CAPTAIN Physics Program: Neutrons

LBNE Neutrino Energy Spectrum

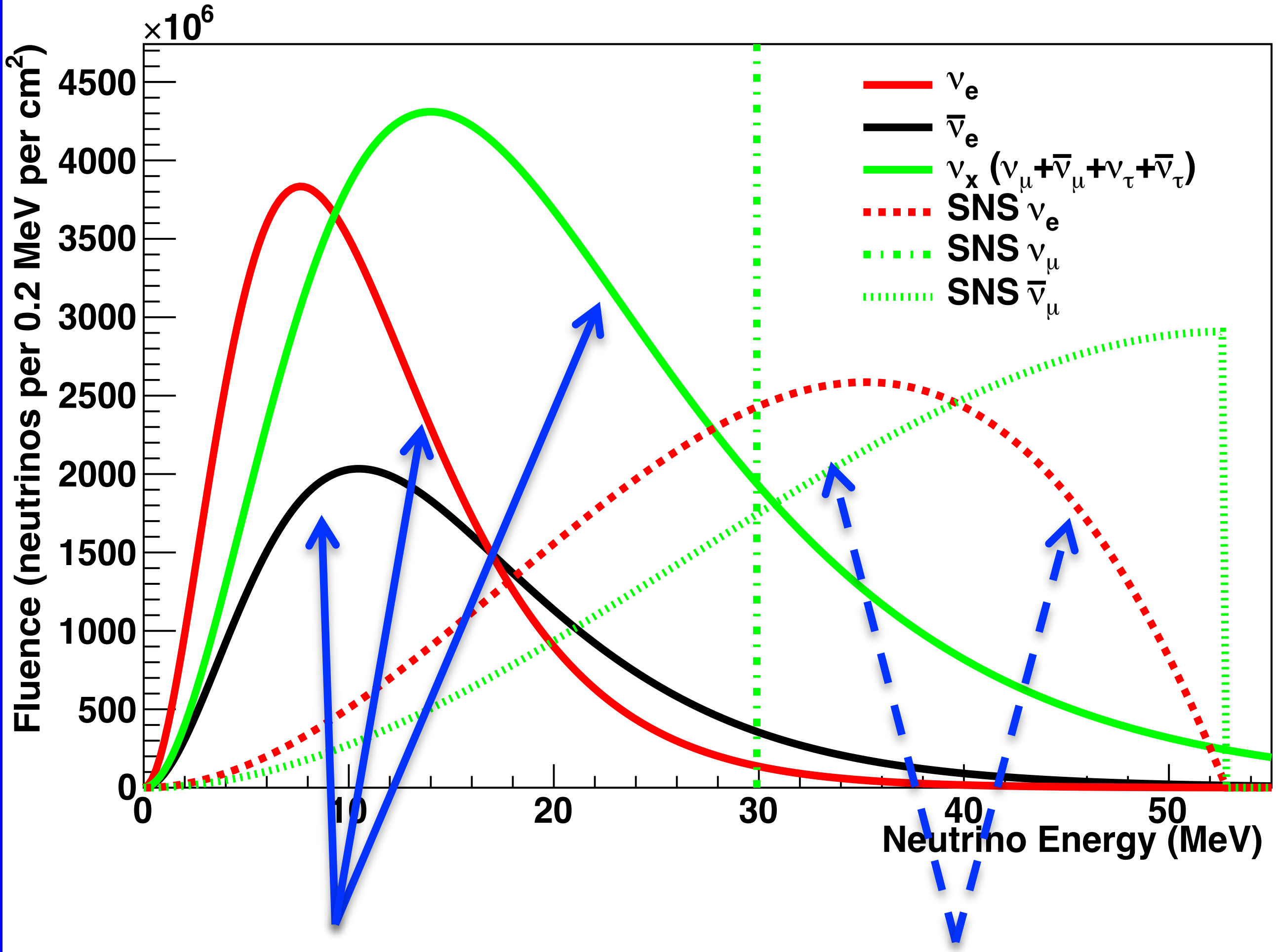



Outgoing energy in neutrons




- At LBNE neutrino energies, neutrons can carry away significant energy
- Uncertainties on the energy carried away are large and unconstrained
- The energy carried away differs between neutrinos and anti-neutrinos
- To determine how to use these neutrons, we will deploy CAPTAIN in a neutron beam

# CAPTAIN Physics Program: Low-energy neutrinos




Supernova neutrino spectra

Stopped π/μ spectra

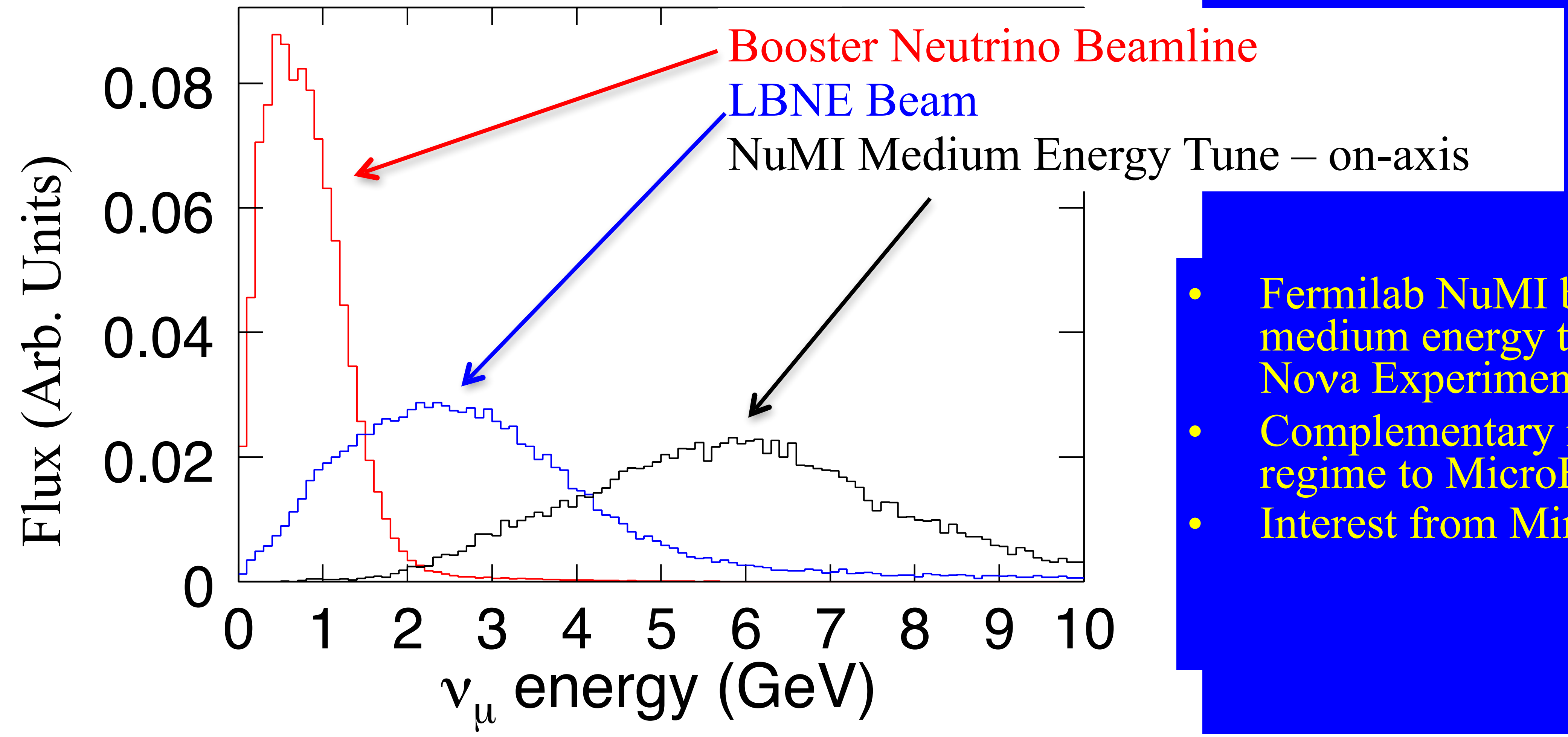
From:arXiv:1211.5199

Plot for SNS, but spectra are generic for a stopped π/μ source

- P5 report: ``The experiment (LBNE) should have demonstrated capability to search for supernova bursts"
- Neutrinos in the supernova energy regime have never been detected with a liquid argon TPC
- Cross-section uncertain
- Detection efficiencies unknown

- Exploring opportunities at FNAL using the BNB as a stopped pion source

# CAPTAIN Physics Program: medium-energy neutrinos




- Fermilab NuMI beamline – will run in medium energy tune to support the Nova Experiment
- Complementary neutrino energy regime to MicroBooNE
- Interest from Minerva Collaboration

- Approximately 1 million contained events per year ($4x10^{20}$ POT) (containing all but lepton)
  - detailed exploration of threshold region for multi-pion production, kaon production
  - high-statistics data for algorithm development required for LBNE
  - employment of methods for neutron energy reconstruction
  - early development of multi-interaction challenge – must solve if wish to usefully employ a near liquid argon TPC

# Prototype Detector

LANL postdoc Charles Taylor prepares the prototype

# Summary

❖ The Short-Baseline Neutrino program brings together physics opportunities and detector development goals through SBN program and test beam efforts

> **Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neu-trino program hosted at Fermilab.**

# BACK-UP SLIDES

## The choice of the experimental technology is a key element:

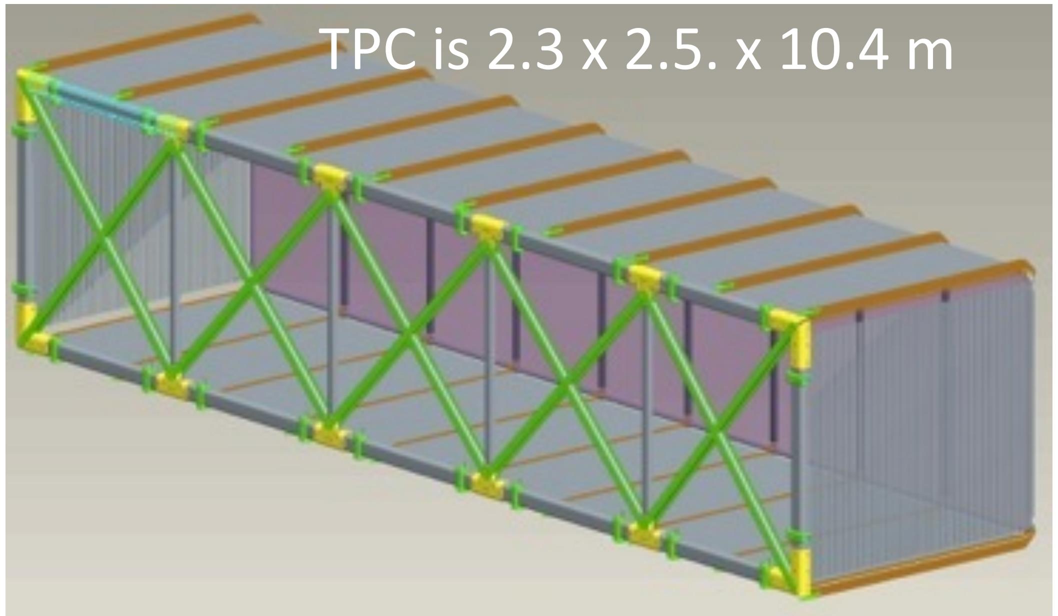
The LArTPC detector with its full 3D-imaging, excellent particle identification (PID) capability and precise calorimetric energy reconstruction represents the most advanced experimental technology for neutrino physics and proton decay search especially in the K-neutrino decay mode

The ICARUS collaboration pioneered this technology in Europe and demonstrated its feasibility on large mass scale and for underground applications.

Interest in LArTPCs in the US has rapidly grown in recent years, experimental efforts on both Short- and Long-Baseline physics based on this technology have been launched.

A coherent SBN and LBN program based on this technology choice is now emerging and taking shape.

# Time Projection Chamber drifts and reads out ionization electrons

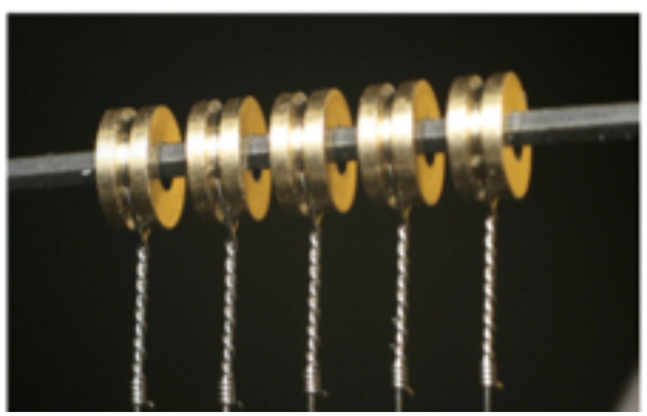


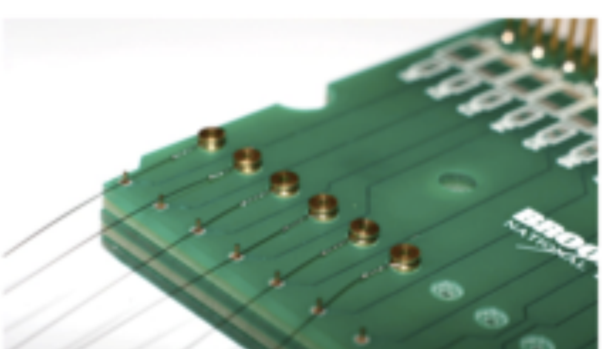

1.1M NSF MRI for MicroBooNE TPC:
Field cage, anode and cathode planes
and PMT system

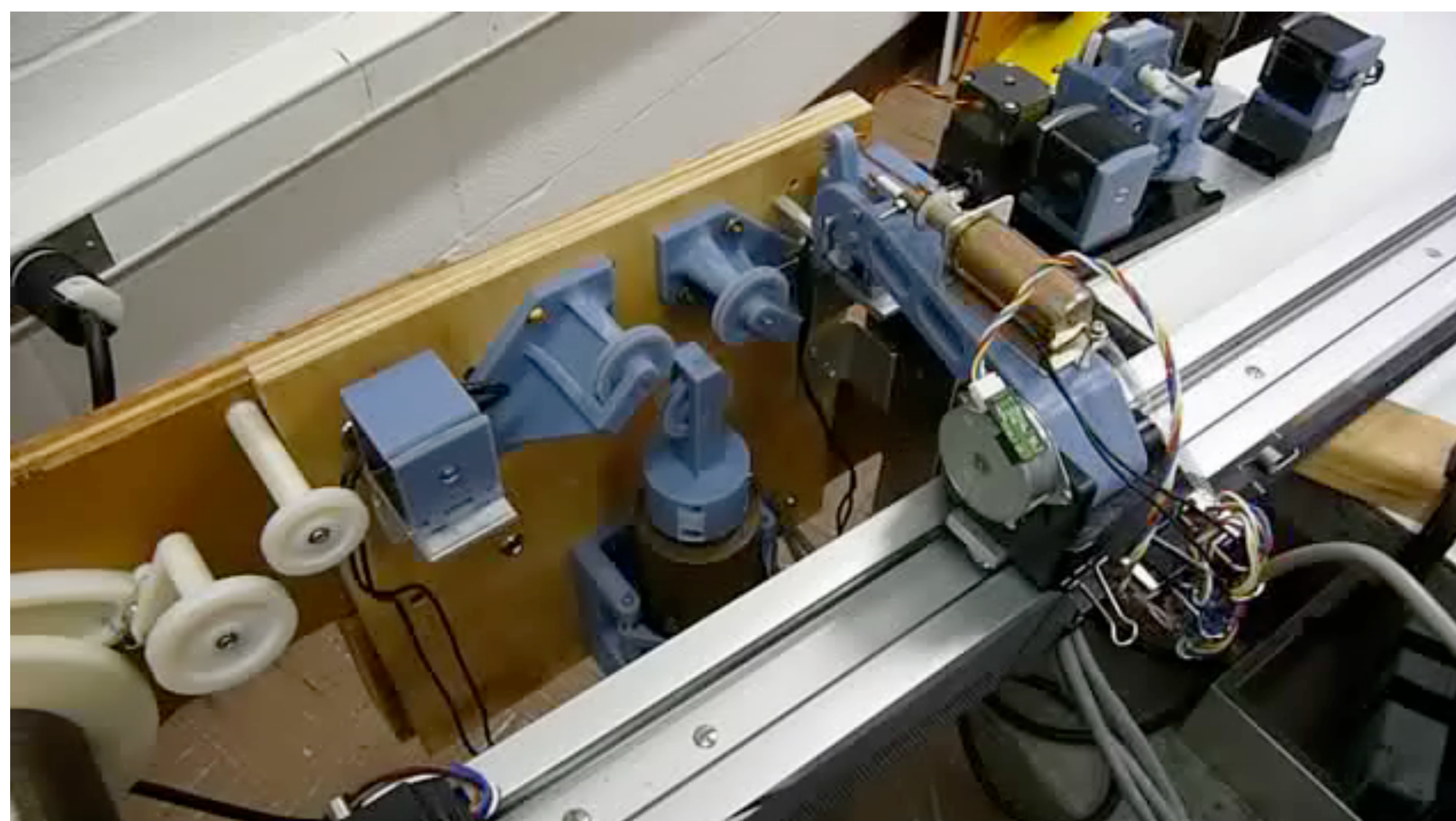
Three wire planes (U,V,Y)

- 3mm wire pitch
- Wires are 150 micron, stainless steel coated with copper and a gold flash
- Wires under ~1kg tension
- About 8000 wires total

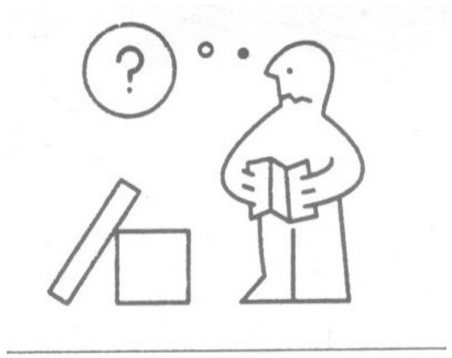
Wires wound by teams at Yale and Syracuse and shipped to FNAL for assembly

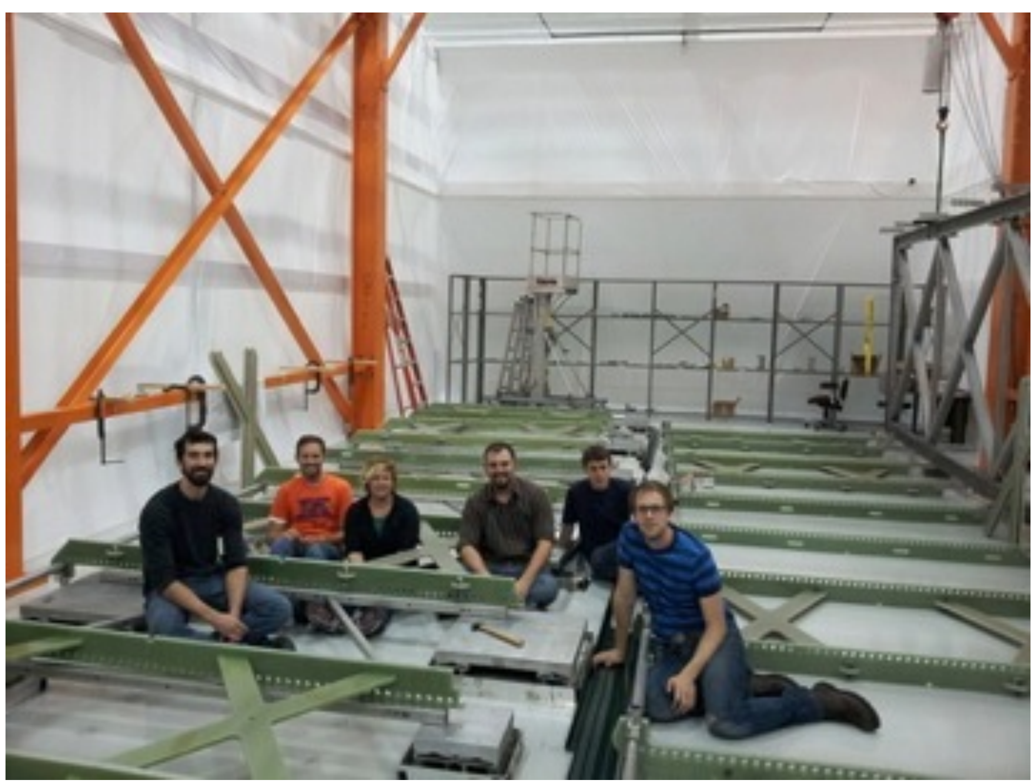






Lots of parts...





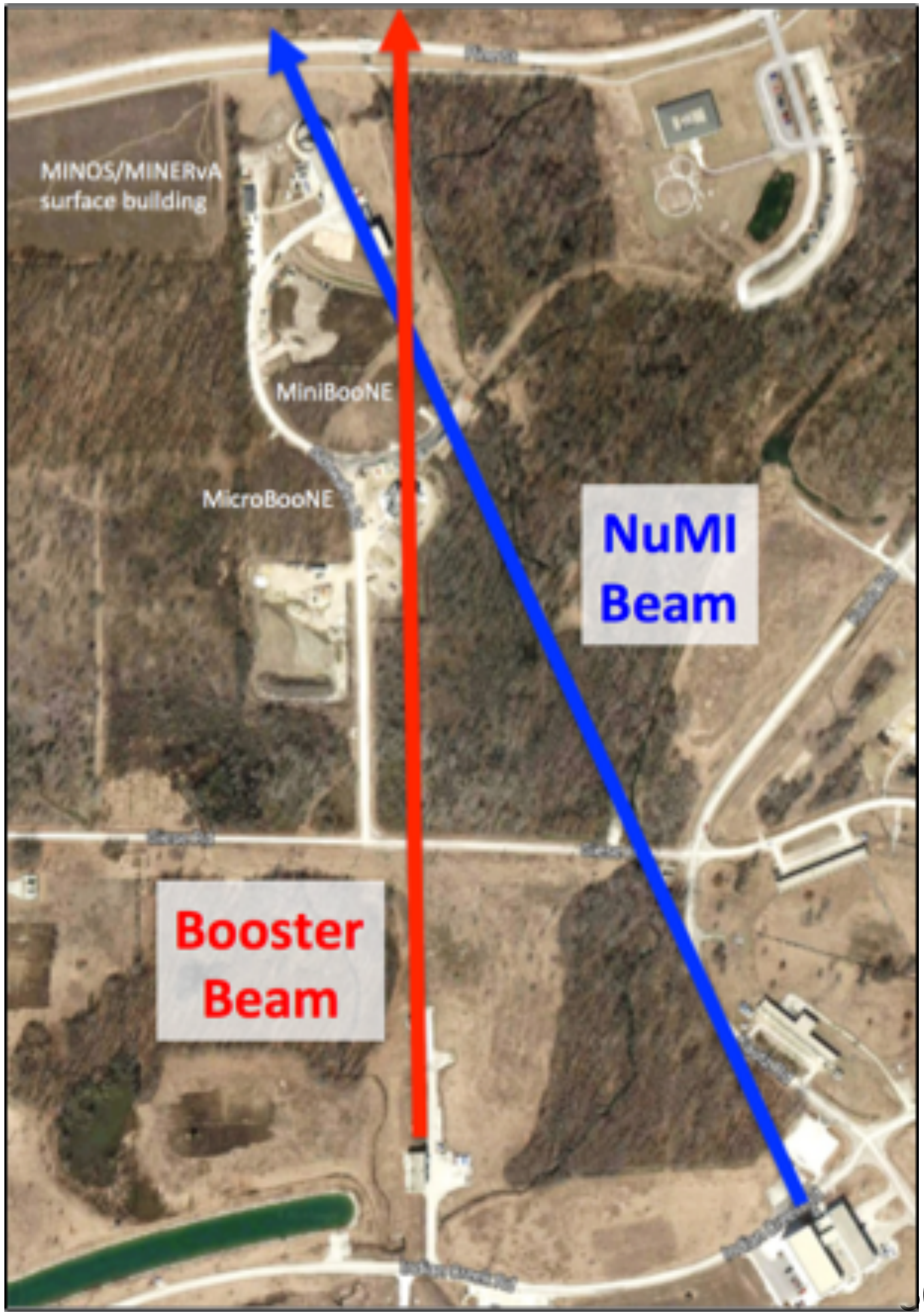
Start of Frame Assembly

Final Product!

# BNB Short-Baseline Neutrino Program

Fermilab makes an ideal host for a next generation short-baseline neutrino oscillation experimental program

- SBN Program builds upon existing capabilities and infrastructure, such as the Booster Neutrino Beam (BNB)
  - The NuMI Beam is deep and aimed down toward Minnesota, but the BNB is shallow (~10 m detector hall depth at all baselines)
  - BNB neutrino fluxes are well understood due to dedicated hadron production data (the HARP experiment @ CERN) and 10+ years of study by MiniBooNE and SciBooNE



# P5 Report Recommendations

**Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.**

| Project/Activity | Scenario A | Scenario B | Scenario C | | ν | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Short Baseline Neutrino Portfolio | Y | Y | Y | | ✓ | | | | I |

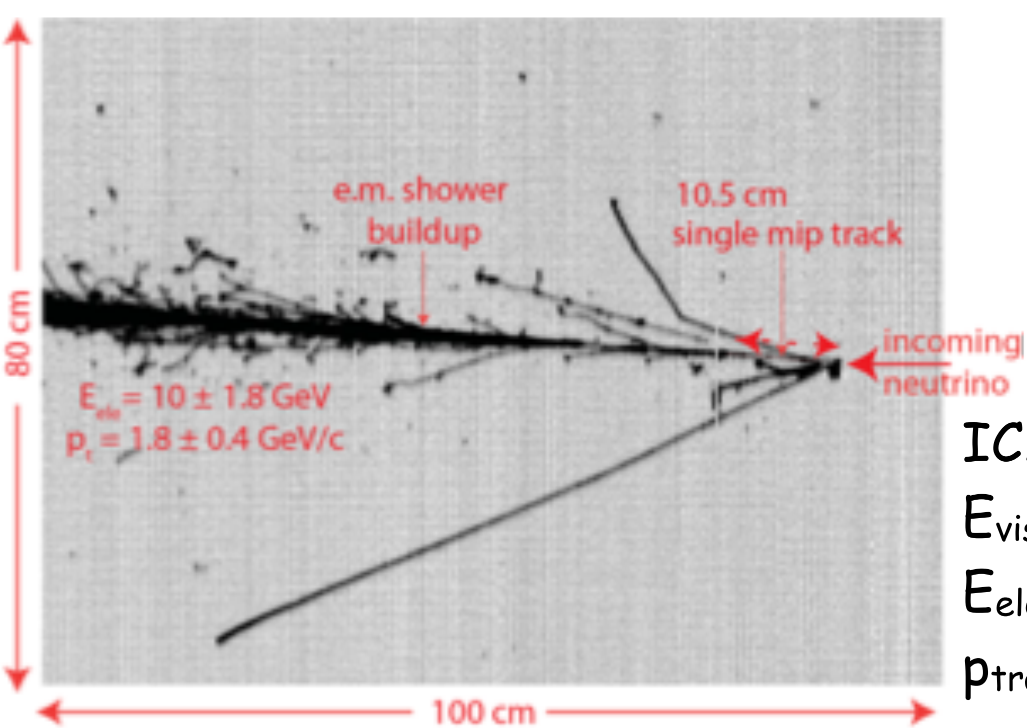
**Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.**

# MicroBooNE

❖ The first phase of the next generation SBN Program begins soon with MicroBooNE coming online later this year!

# ICARUS@FNAL Proposal

- ICARUS T600 detector to be located along the BNB at ~700 m from the target
- A new T150 detector based on the ICARUS design to be located at about 150±50 m from the target
- T600 would also receive $\nu$'s from the off-axis NuMI neutrino beam peaked at ~2 GeV with an enriched $\nu_e$ flux
- The dual presence of T600 and new T150 would extend the information coming from MicroBooNE


ICARUS data event with:
$E_{visible}$ = 11.5 ± 1.8 GeV
$E_{electron}$ = 10 ± 1.8 GeV
$p_{transverse}$ = 1.8 ± 0.4 GeV/c

http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/PAC_presentation.jan2014.F.pptx

# The LAr1-ND Proposal

- Our approach has been to consider a staged short-baseline neutrino program that builds upon the existing FNAL Booster Neutrino Beam and the MicroBooNE detector
  - There are important physics questions to be answered, and Fermilab can be the first in the world to address them
  - A SBL program builds upon existing infrastructure, investments, expertise, and physics interests within the Fermilab community
  - A SBL program offers an ideal opportunity for continued development of the liquid argon TPC technology, combining timely neutrino physics measurements with vital experience in detector development for a community working toward LBNE
- In this proposal, we present the next stage, the Liquid Argon Near Detector, or LAr1-ND
  - This phase (LAr1-ND + MicroBooNE) enables a compelling and important physics program
  - A detector design that is time- and cost-effective could allow LAr1-ND to run near the end of the already approved MicroBooNE neutrino-mode run of $6.6 \times 10^{20}$ POT
  - LAr1-ND can also serve as a near detector in future phases of the program that include a larger-scale far detector at longer baseline

# LAr1-ND Detector Overview

## ➢The LAr1-ND detector design is based on:

- Implementing technology that builds upon the current experience from the T600, MicroBooNE and the 35 ton prototype
- Utilizing as many of the design elements developed for the LBNE Far Detector as feasible

## ➢Brief overview of the design:

- A foam insulated, corrugated stainless steel membrane cryostat supported by outer concrete walls of the existing SciBooNE enclosure.
- The interior dimensions of the cryostat (slide 13) are 4.4 m long in the neutrino beam direction, 6.1 m wide and 4.8 m tall, amounting to 180 tons total of liquid argon
- The TPC consists of two APAs (Anode Plane Assemblies) near the walls of the cryostat (beam left and beam right), and one CPA (Cathode Plane Assembly) centered between the two APAs
- Analog front-end, analog-to-digital conversion, and FPGA for multiplexing performed with cold electronics

# LAr1-ND: Time Projection Chamber Layout

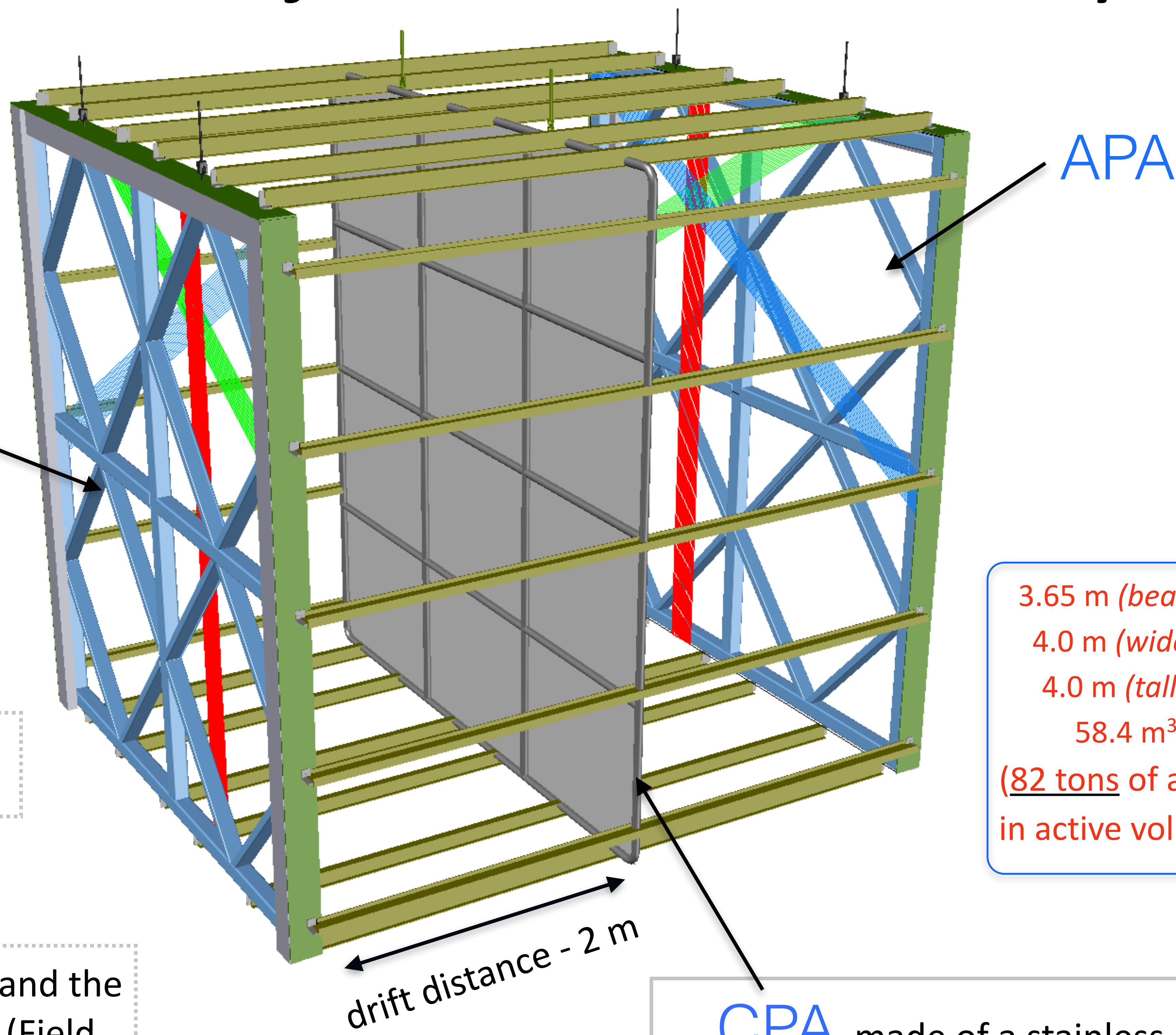
APA

active area:
3.65 m wide x 4.0 m tall

Each pair of facing CPA and APA forms a 2.0 m electron-drift region

For 500 V/cm drift field, cathode plane biased at -100 kV

Open sides between each APA and the CPA are surrounded by 4 FCA (Field Cage Assemblies) modules, constructed from FR4 printed circuit panels with parallel copper strips to create a uniform drift field



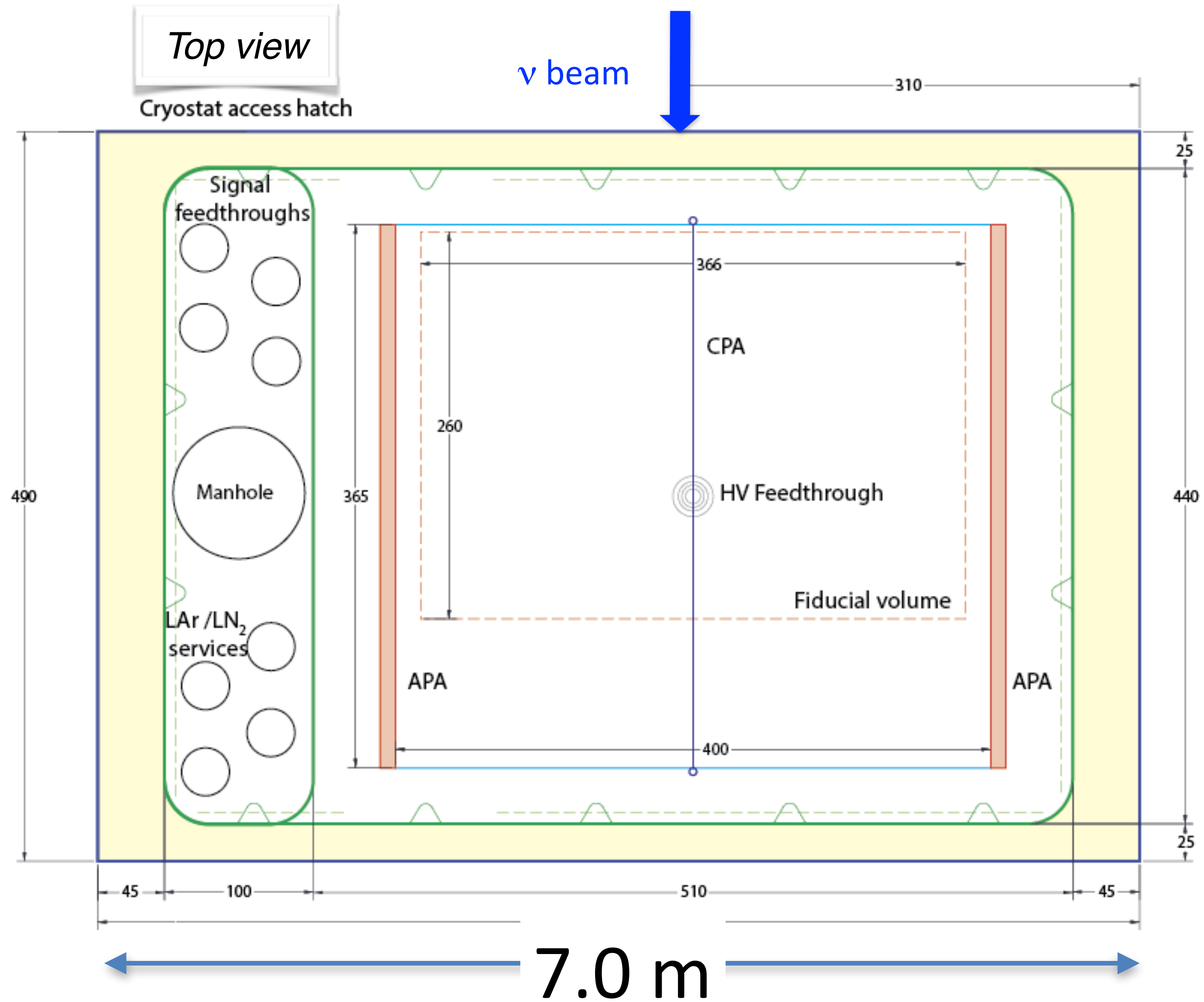

3.65 m *(beam)* x
4.0 m *(wide)* x
4.0 m *(tall)* =
58.4 $m^3$
(82 tons of argon in active volume)

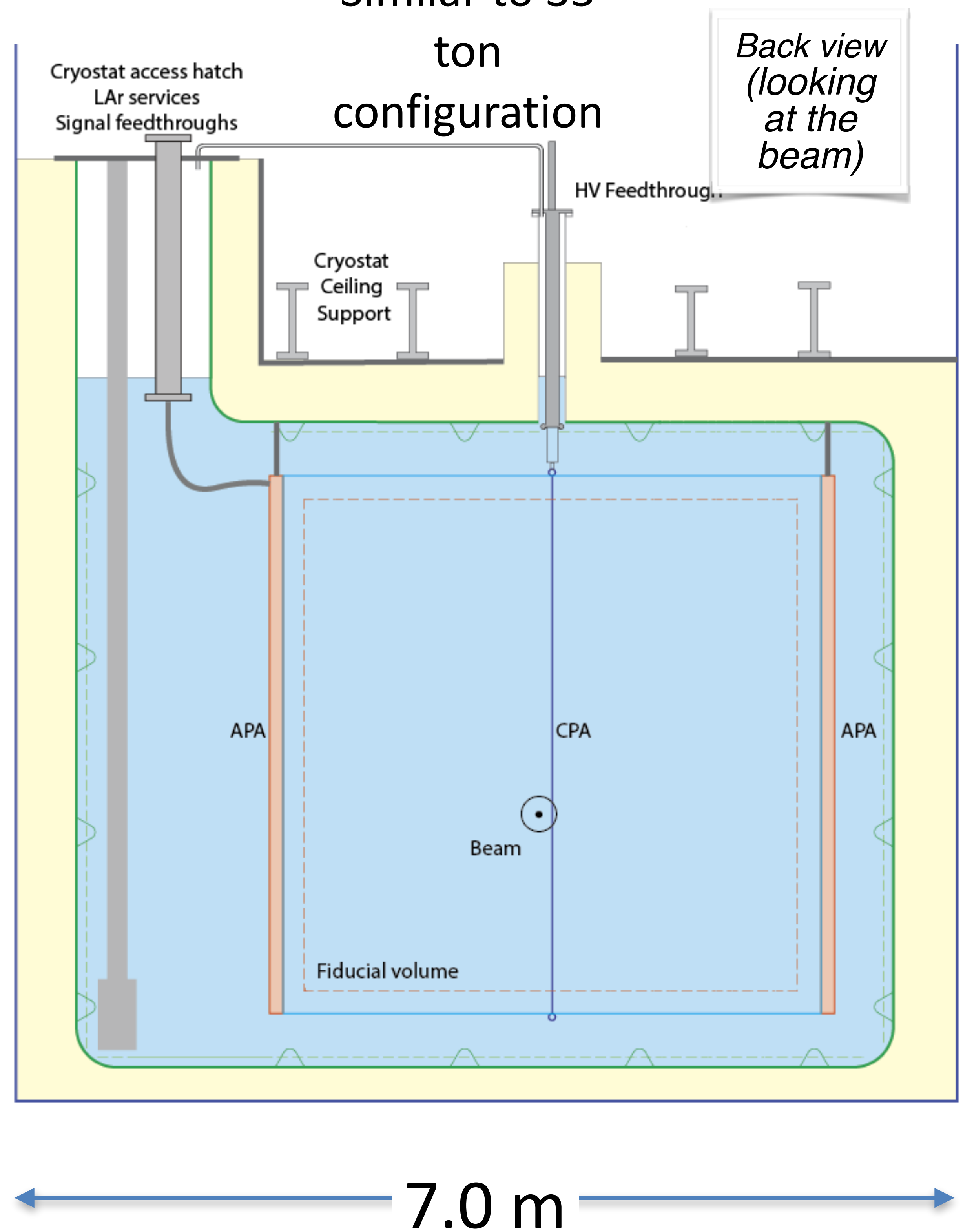
CPA made of a stainless-steel framework, with an array of stainless-steel sheets mounted over the frame openings

# LAr1-ND: Membrane Cryostat

- <u>Recent design concept</u> shown here
- Main volume still wetted on top
- LAr pump in non-active volume allows LAr circulation when necessary
- Long “cold” signal feed-throughs still an option
- High voltage FT does not pass through expansion tank

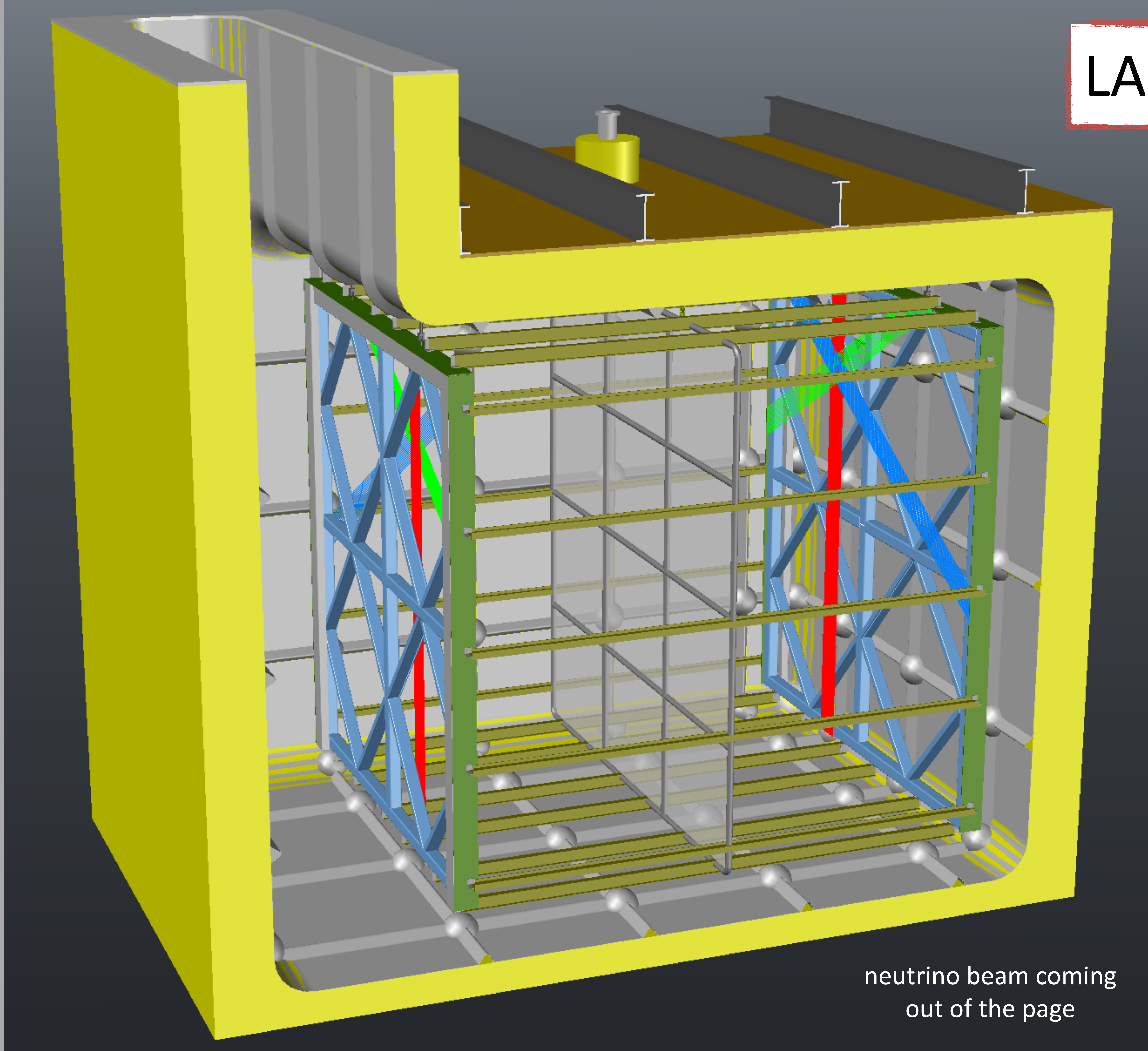
Similar to 35 ton configuration



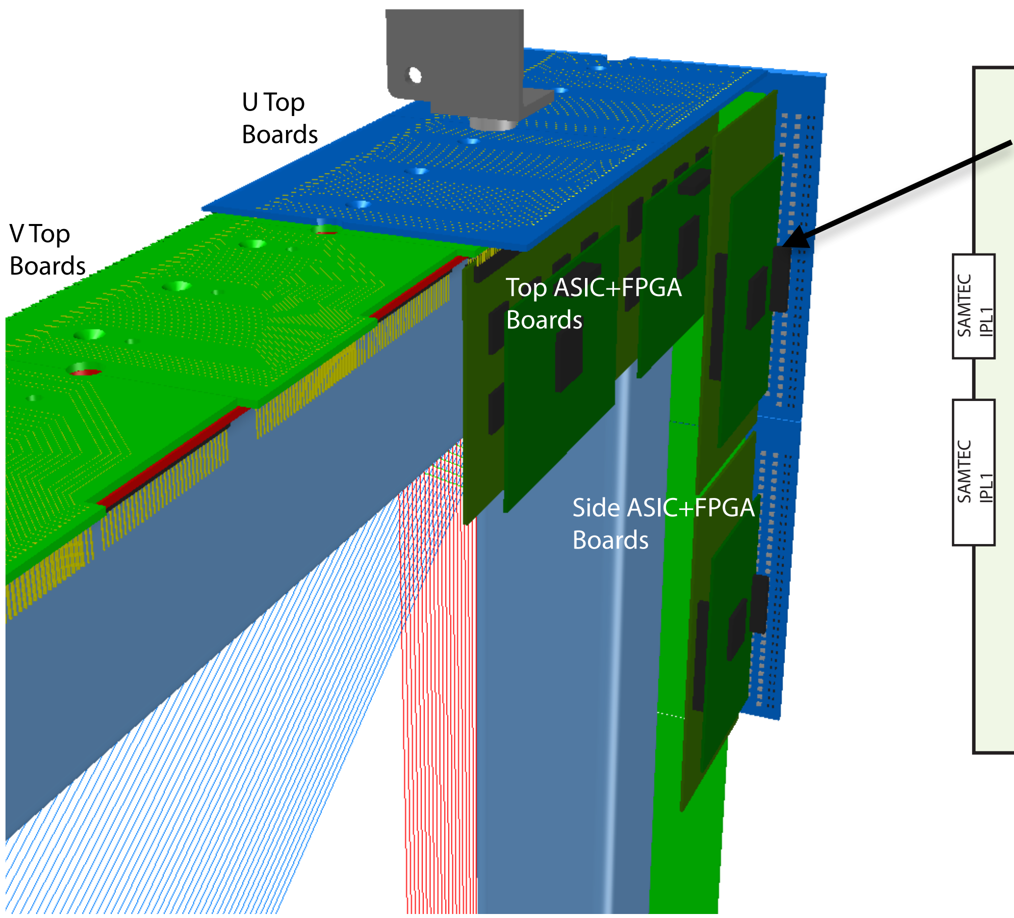

Shielding blocks removed in favor of an access region over LAr but not the active

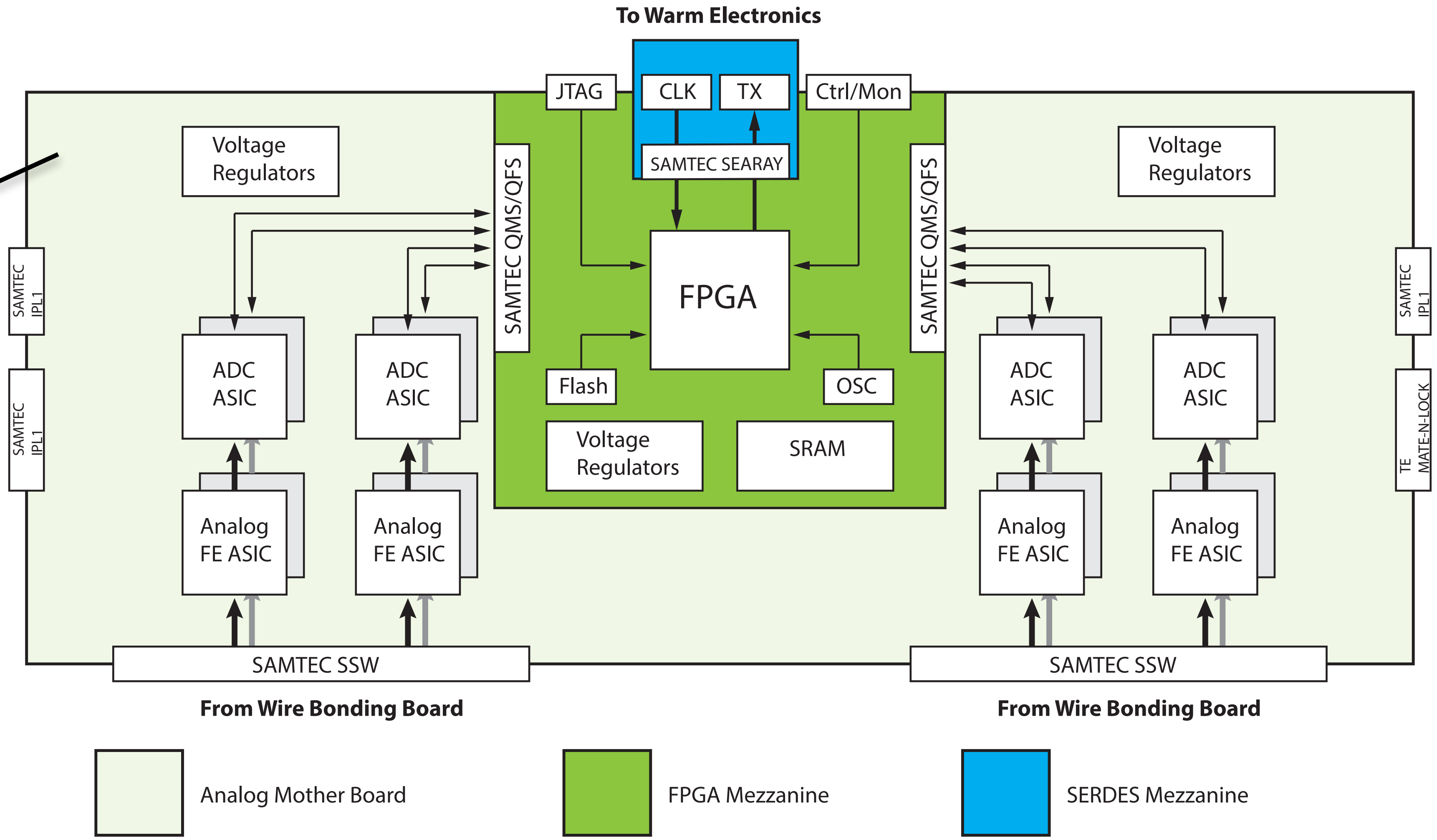
# LAr1-ND



# Readout Electronics

- Analog Front End ASIC and ADC ASIC have been developed for LBNE; Analog Front End ASIC is being used in MicroBooNE; Commercial FPGAs for multiplexing in the cold; similar to that used in 35 ton, with opportunity for longer term running and large data samples.
- After on-board multiplexing, 4 cold cable bundles to 4 signal feed-throughs




Front End Mother Board

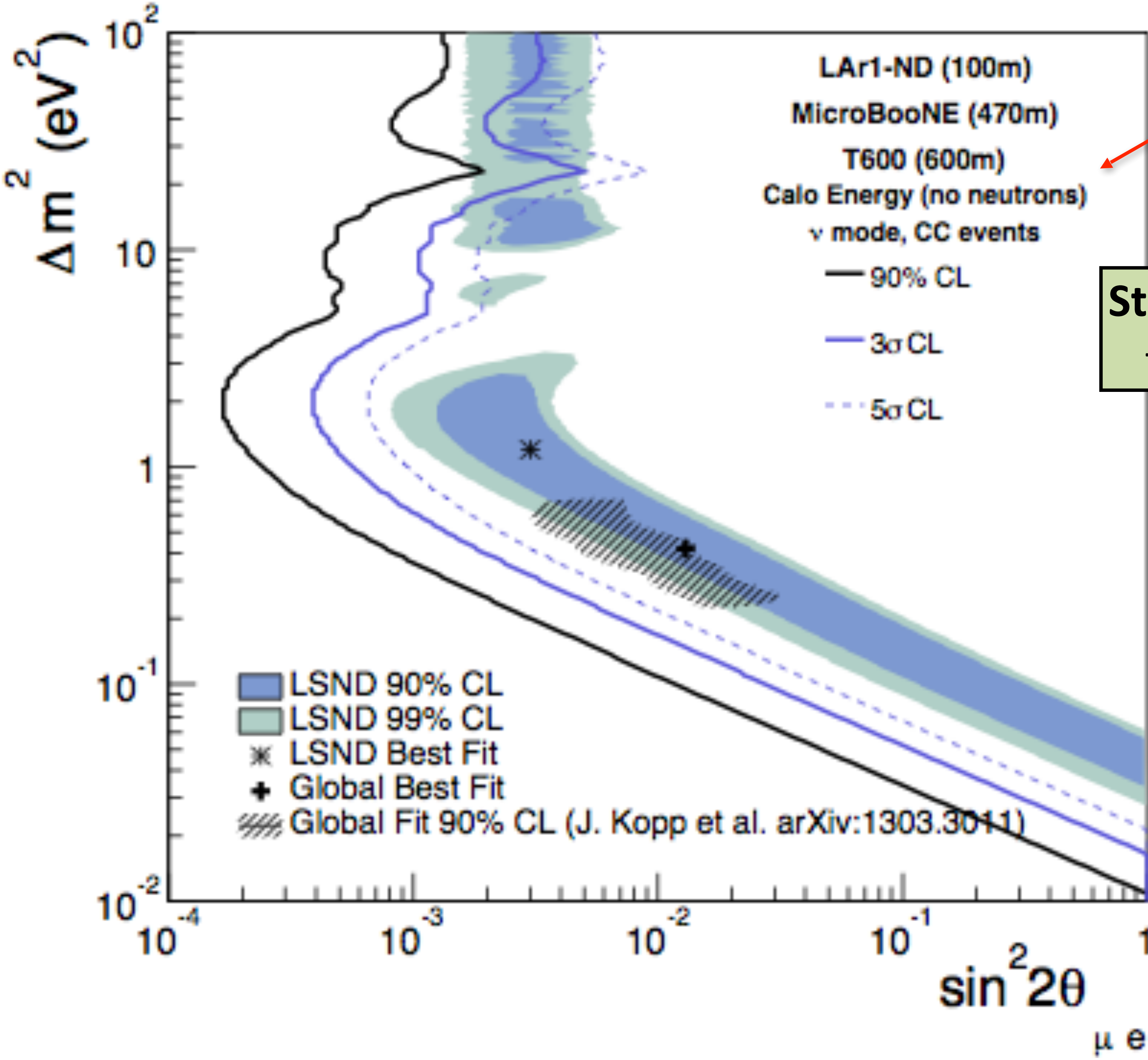
# The LAr1-ND Experiment

- The aim of the LAr1-ND experiment is to provide a high-statistics measurement of the intrinsic muon and electron neutrino content in the Booster Neutrino Beam. This will allow for a near-to-far extrapolation between LAr1-ND and downstream detectors and thus a precision search for high mass-squared neutrino oscillations through both appearance and disappearance channels.

- A detector design that is time- and cost-effective would allow LAr1-ND to run near the end of the already approved MicroBooNE neutrino-mode run of $6.6 \times 10^{20}$ POT

- The LAr1-ND detector, an 82 ton active volume liquid argon TPC, provides an opportunity for combining timely physics measurements with additional experience in use of LArTPC technology for a neutrino experiment

# $\nu_\mu \rightarrow \nu_e$ Appearance




Impact of increased exposure by 50%

**Statistical** Uncertainty Limit for 10e20 POT exposure

Projecting integrated POT onto a time axis is clearly important and depends on proton economics after ~2018.

PIP-I/PIP-II goals very valuable to success of this program!

# phased { LArIAT-1 / LArIAT-2 } and CAPTAIN

A complementary R&D program

**LArIAT-I: Charged Ptcl.s + γ's– Mid Energies: 200 MeV – 1.5 GeV with (existing) ArgoNeuT TPC [2 wire-planes, 4 mm pitch], 2014–15**

- PID: e/γ, μ+/μ-
- PID studies of p/K/π via dE/dx.
- Single track charge → energy calibration
- Low energy calorimetry (protons & electrons)

**LArIAT-II: Charged Ptcl.s – Mid / High Energies: 200 MeV – 3 GeV with new 2x2x3 m³ detector TPC option LBNE-like design, ≥ 2015**

- containment for calorimetry of higher energy showers
- Energy Calibration – e/π ratio, invisible component in showers
- Surface operation in high cosmic ray environment

**CAPTAIN (LANL LDRD): neutral ptcl.s (n & ν)- Low energies**

- Neutron Beam (LANL)
- Stopped-Pion Neutrino Source (e.g. SNS)

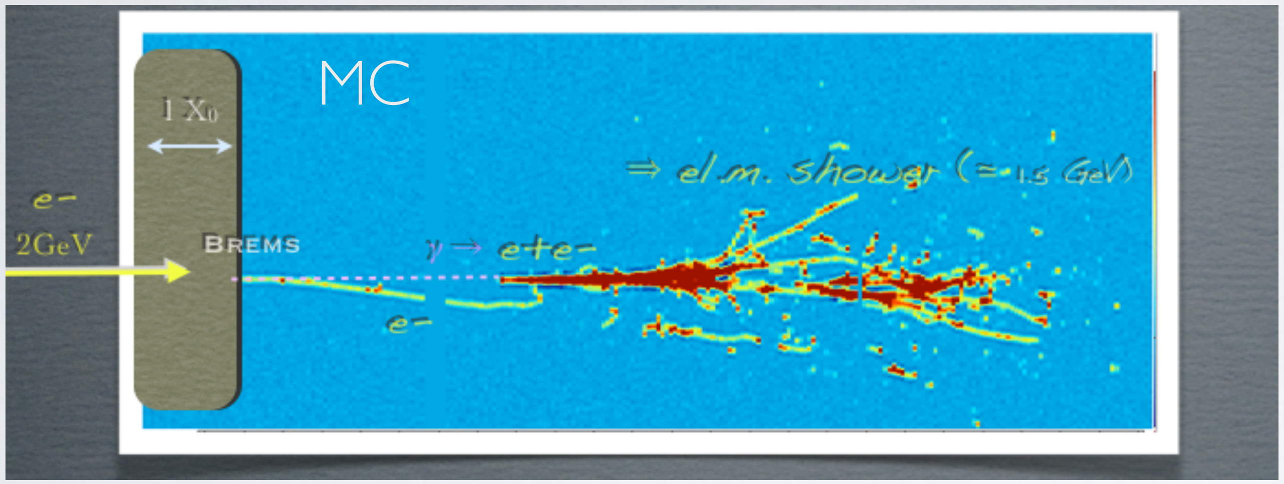
**CAPTAIN (LANL LDRD): neutral ptcl.s (n & ν)- Mid energies**

- Neutron Beam
- Neutrino Beam (e.g. NuMI)

details in C. Mauger Talk

# PARTICLE IDENTIFICATION

### $e$ vs $\gamma$ shower discrimination




Bremsstrahlung from upstream radiator plate
Tagged with incoming electron PID in beamline
+ deviated track + gap.

- Experimental confirmation for the separation efficiencies (MC determined) - key feature of LArTPC tech

- Enable ultimate development and most reliable **separation criteria/algorithms** in the LArSoft off-line reconstruction code

- Support measurement of the low-energy elm evt. excess from MiniBooNE - primary goal of MicroBooNE, and of the CP violating phase from oscillation into electron (anti)neutrinos (LBNE goal)

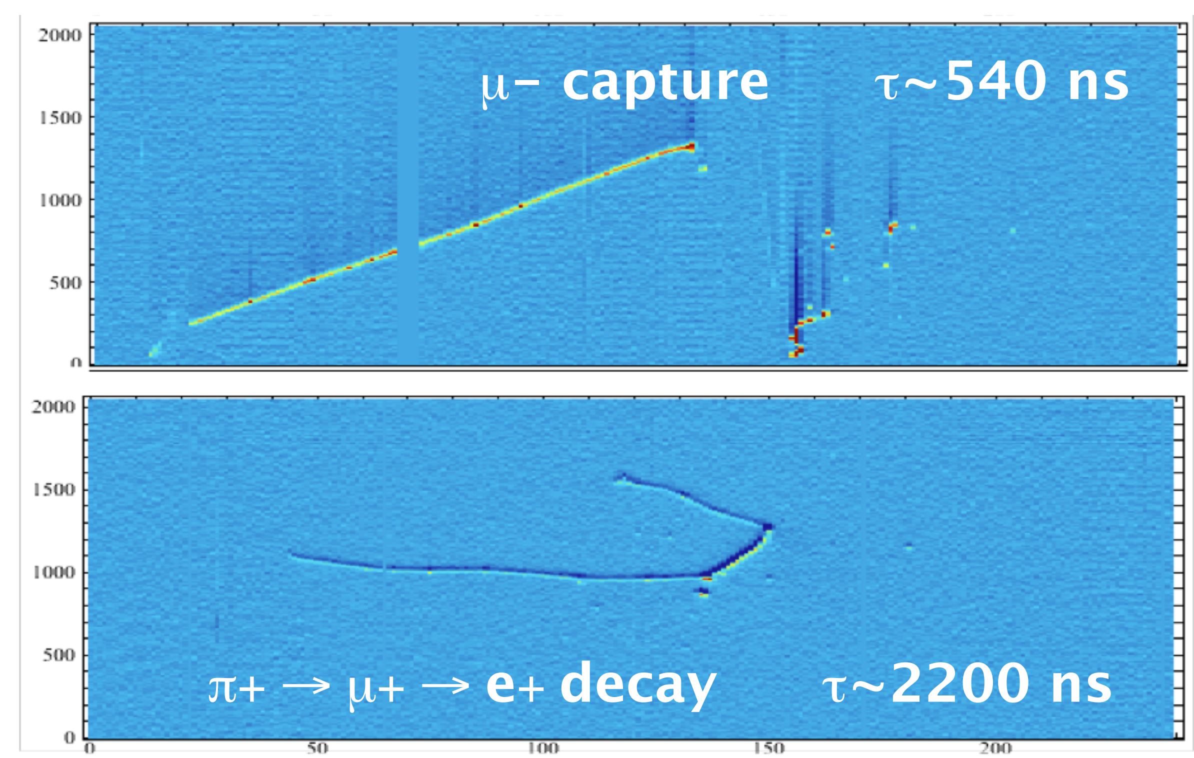
### Muon sign determination (w/out magnetic field)

**Timing and pattern recognition**

- Explore a LArTPC feature never (systematically) considered (decay vs capture in LAr)

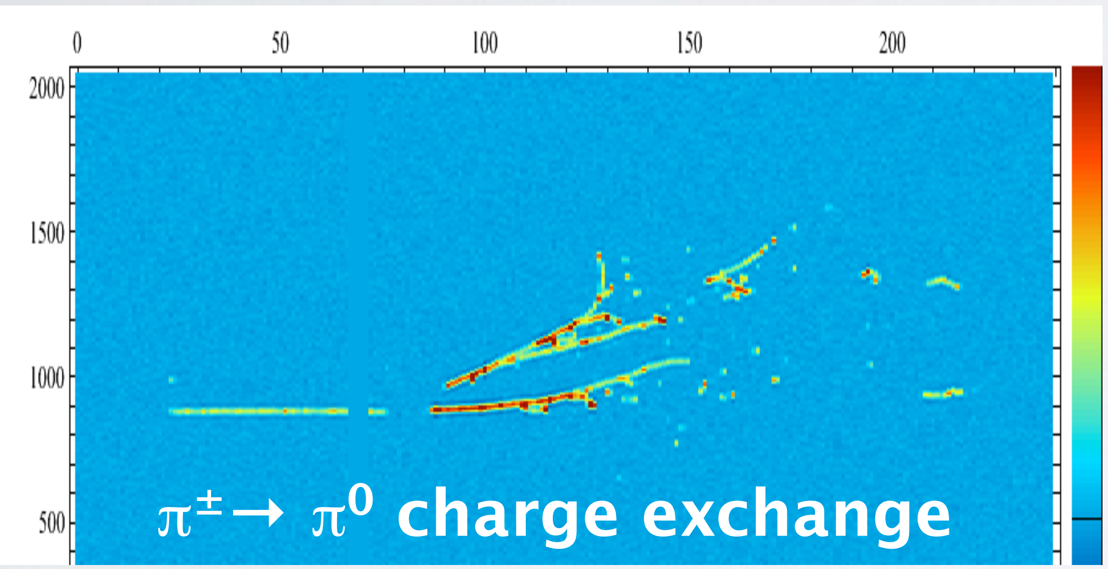
- Constrain the capability to charge-ID the primary lepton in muon neutrino CC interactions of particular interest for CP violation with LBNE

## ArgoNeuT Data



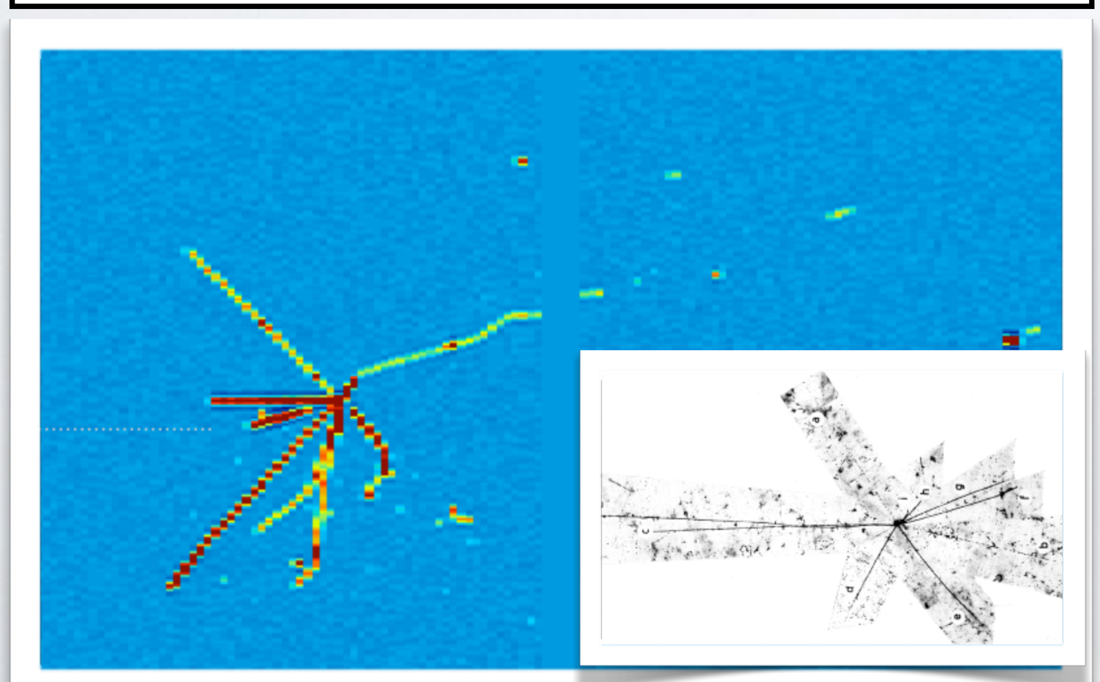
# PARTICLE IDENTIFICATION

## Study of Nuclear Effects




- Study/constrain the features of the most dangerous background in ν-Oscillation physics

**Simulation of Antiproton Star in LAr**



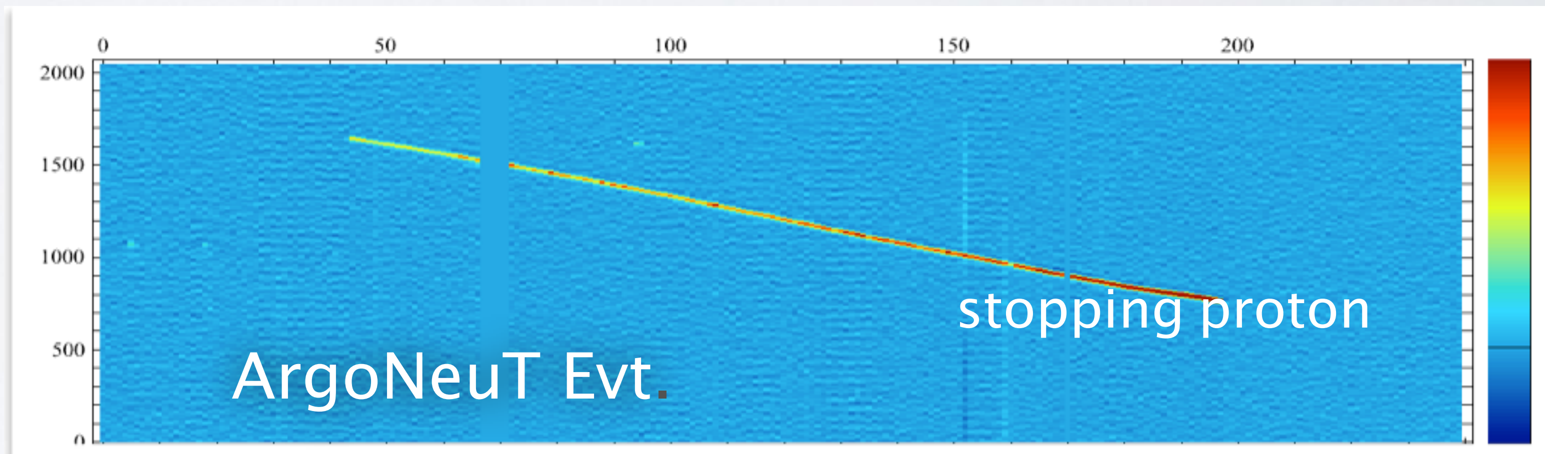
Antiproton annihilation (relevant for n-nbar oscillations)

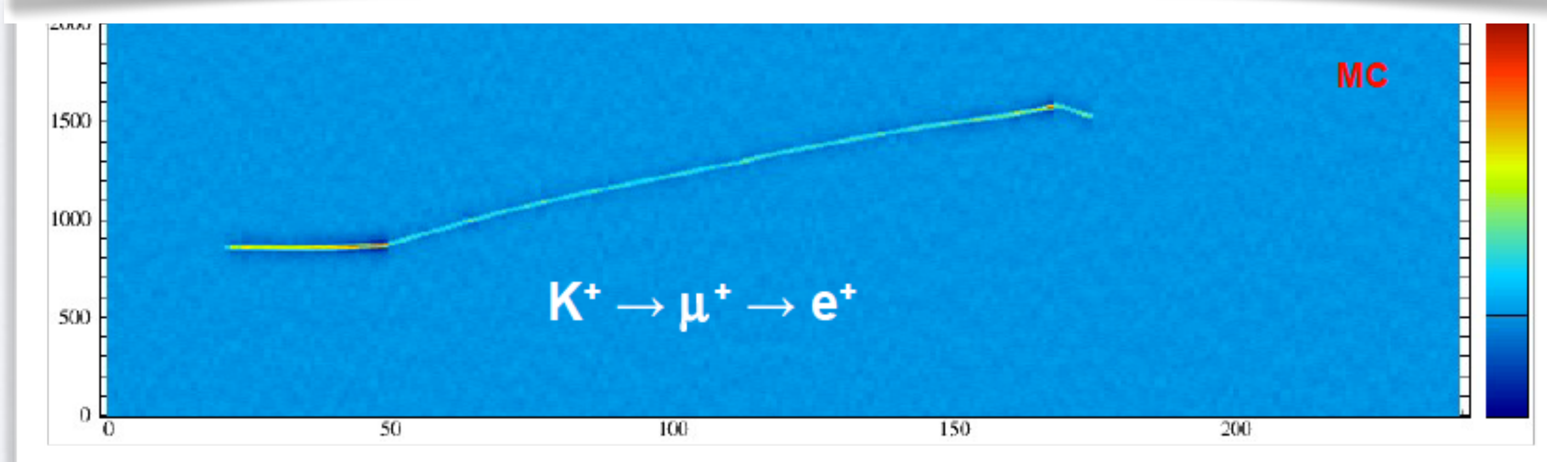
## Kaon discrimination

Study recombination along stopping tracks:

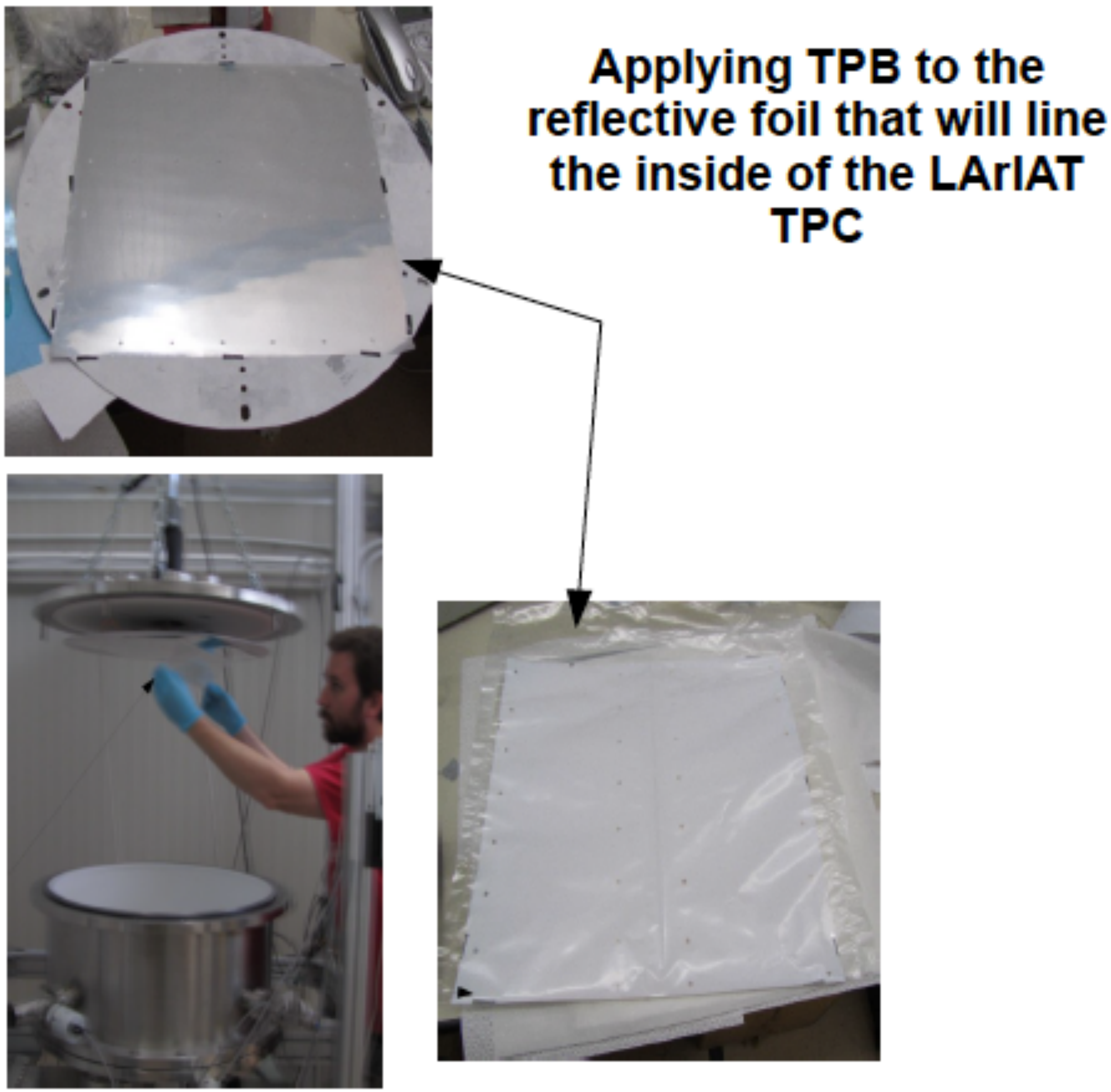
- Kaon to proton separation
- Kaon to pion separation

p-decay (LBNE UG)



# Development of a new concept in LAr Scintillation Light Collection

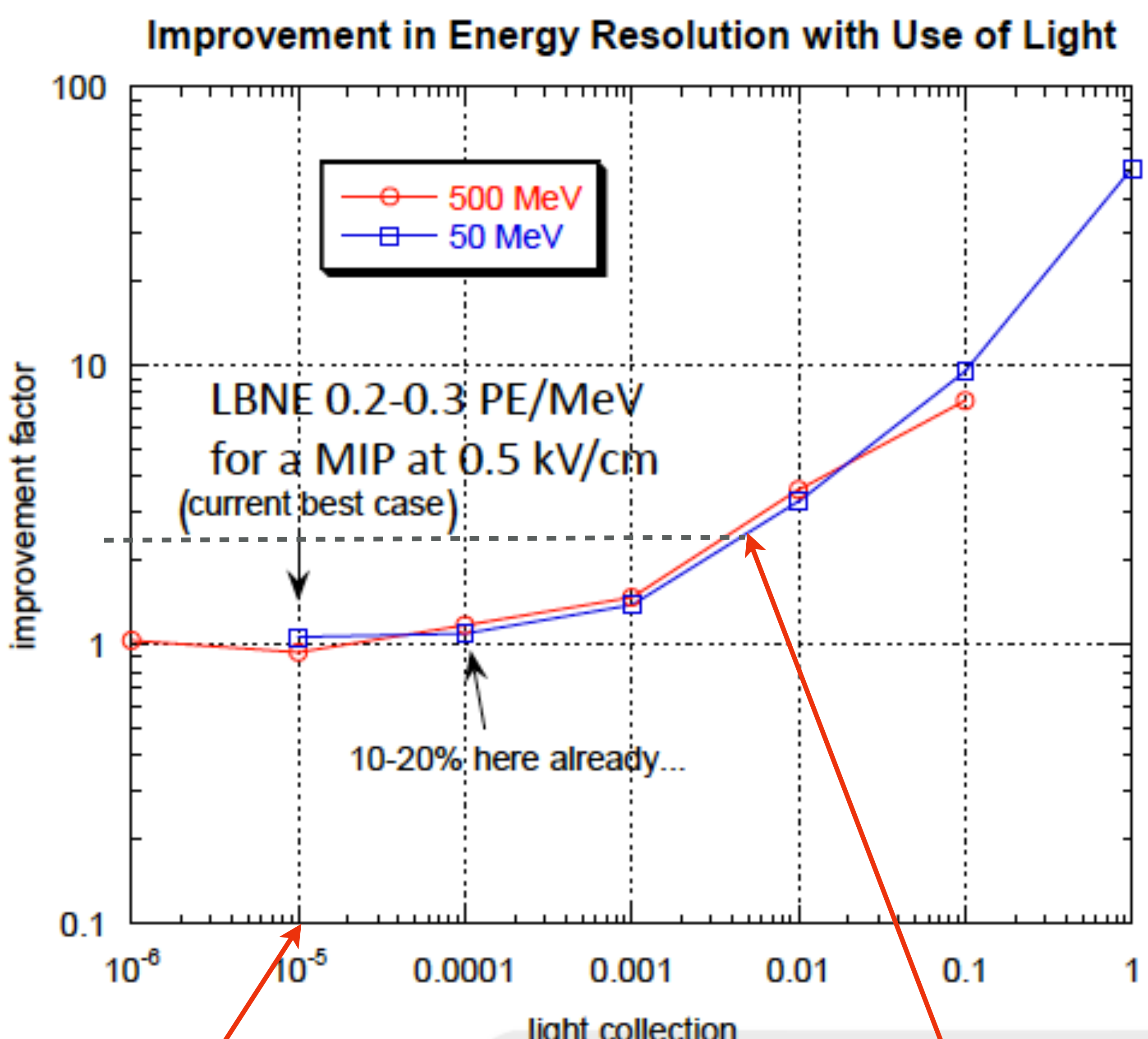



To enhance efficiency of light collection one has to increase the detector active surface.
his can be achieved by increasing the . of PMTs (expensive) OR by adding a reflector coated by wl.s. on the boundary of the detector volume. Scintillation VUV photons thus are wl.shifted when hitting the TPB and en reflected from the mirror surface beneath multiple times up to collection at the PMT

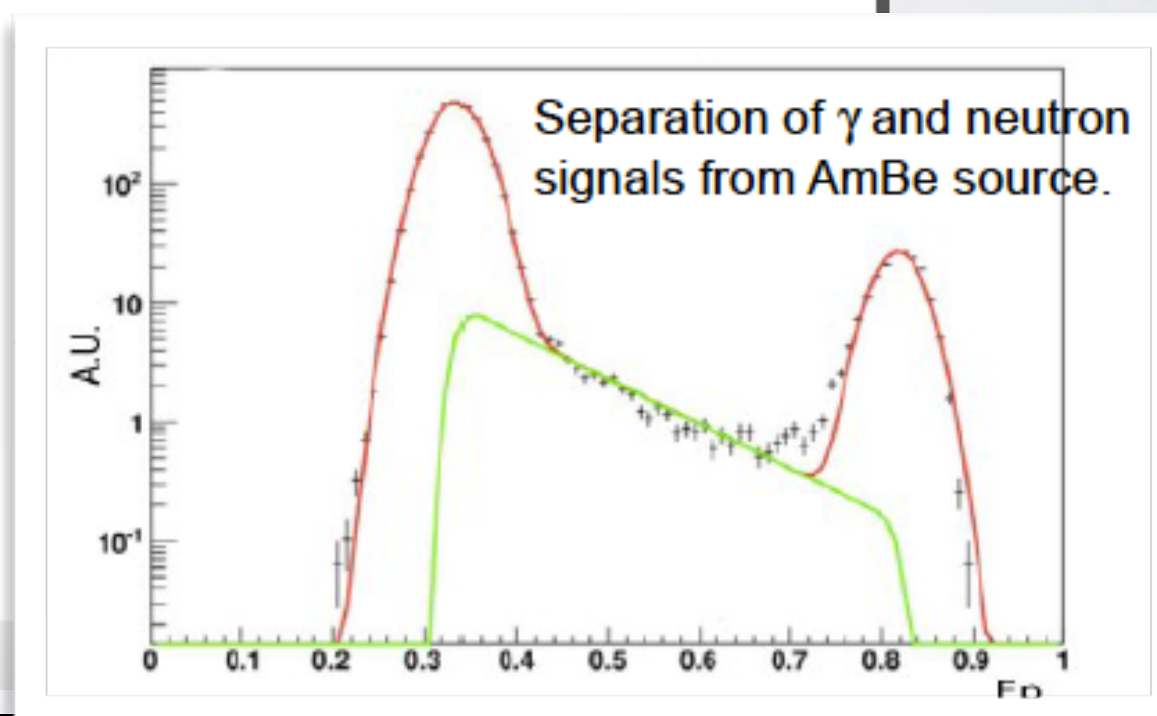
Matthew Szydagis, UC Davis

*FNAL, Software Workshop, Thursday 3-21-13*

# Energy Resolution




| | LC (frac) | CY [%] | LY [%] | comb [%] | opt [%] | <-- with | improv |
|---|---|---|---|---|---|---|---|
| 500 MeV | 1.00E-06 | 0.33 | 79.32 | 0 | 0.32 | 0.001 | 1.0313 |
| | 1.00E-05 | 0.31 | 9.07 | 3.28 | 0.33 | 0.1 | 0.93939 |
| | 1.00E-04 | 0.34 | 3.96 | 1.19 | 0.29 | 900 | 1.1724 |
| | 0.001 | 0.34 | 1.2 | 0.33 | 0.23 | 300 | 1.4783 |
| | 0.01 | 0.36 | 0.72 | 0.12 | 0.1 | 90 | 3.6 |
| | 0.1 | 0.27 | 0.48 | 0.037 | 0.036 | 11 | 7.5 |
| | | | | | | | |
| 50 MeV | 1.00E-06 | 0.98 | 100 | | | | |
| | 1.00E-05 | 1.21 | 29.01 | 10.96 | 1.14 | 0 | 1.0614 |
| | 1.00E-04 | 1.01 | 9.95 | 3.51 | 0.92 | 900 | 1.0978 |
| | 0.001 | 0.93 | 3.8 | 1.11 | 0.67 | 300 | 1.3881 |
| | 0.01 | 1.11 | 2.39 | 0.37 | 0.34 | 90 | 3.2647 |
| | 0.1 | 1.05 | 2.18 | 0.11 | 0.11 | 10 | 9.5455 |
| | 1 | 0.97 | 1.91 | 0.019 | 0.019 | 1 | 51.053 |



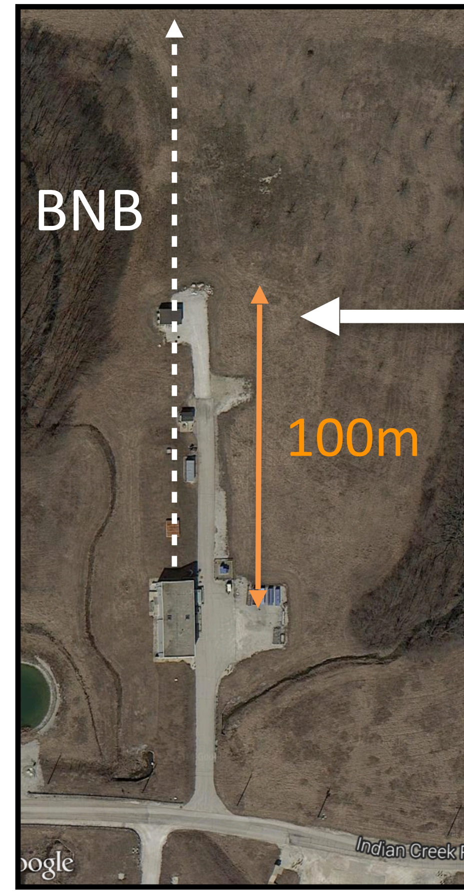

0.2 PE/MeV ≃ 10 ppm
of the available light

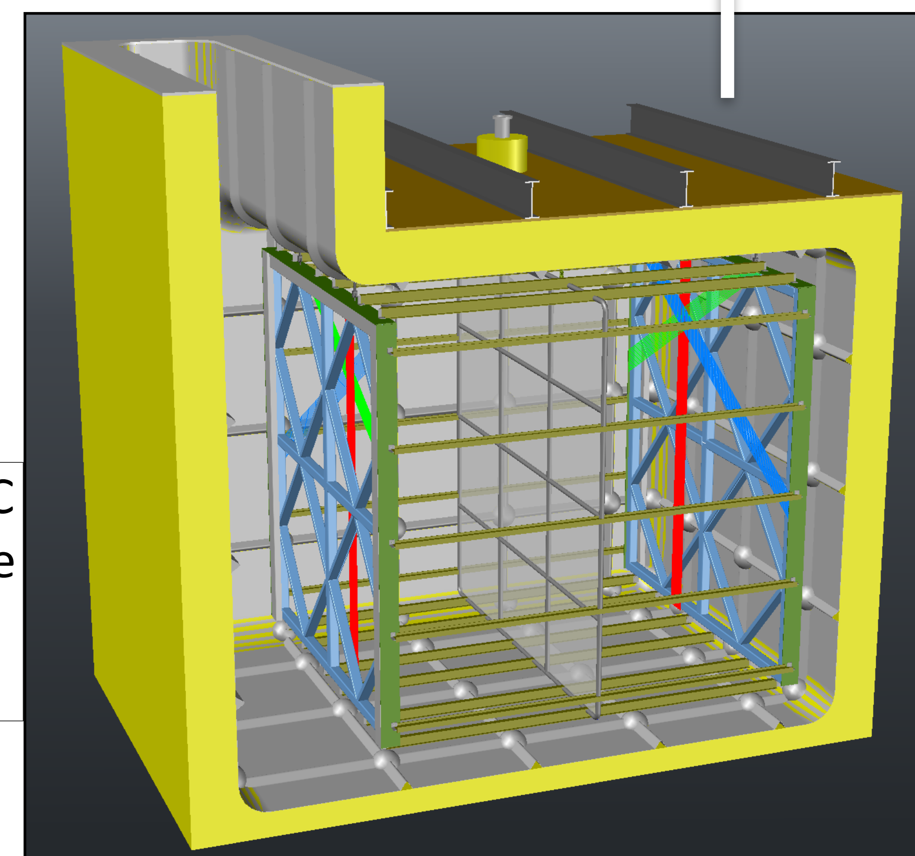
~100 PE/MeV ≈ 1%
of the available light

➪ factor >2 improvement
in energy resolution

# LAr1-ND Proposal

- LAr1-ND detector design approach:
  - utilize as many design elements developed for the LBNE Far Detector as feasible
  - implement technology that builds upon experience from the T600, MicroBooNE and the 35-ton membrane cryostat prototype
  - control project cost by reusing the empty SciBooNE detector hall at 100 m on the BNB
- LAr-ND would provide high-statistics measurement of the intrinsic BNB content, enabling sensitive oscillation searches in combination with downstream detectors
- Together with MicroBooNE, provide a complete interpretation of the MiniBooNE excess. Photons or electrons? Intrinsic to the beam or appearing?
- Valuable "physics R&D" such as reconstruction development and GeV $\nu$-Ar cross sections.
  ~1M $\nu_\mu$ events per year, 6,000 $\nu_e$ per year!



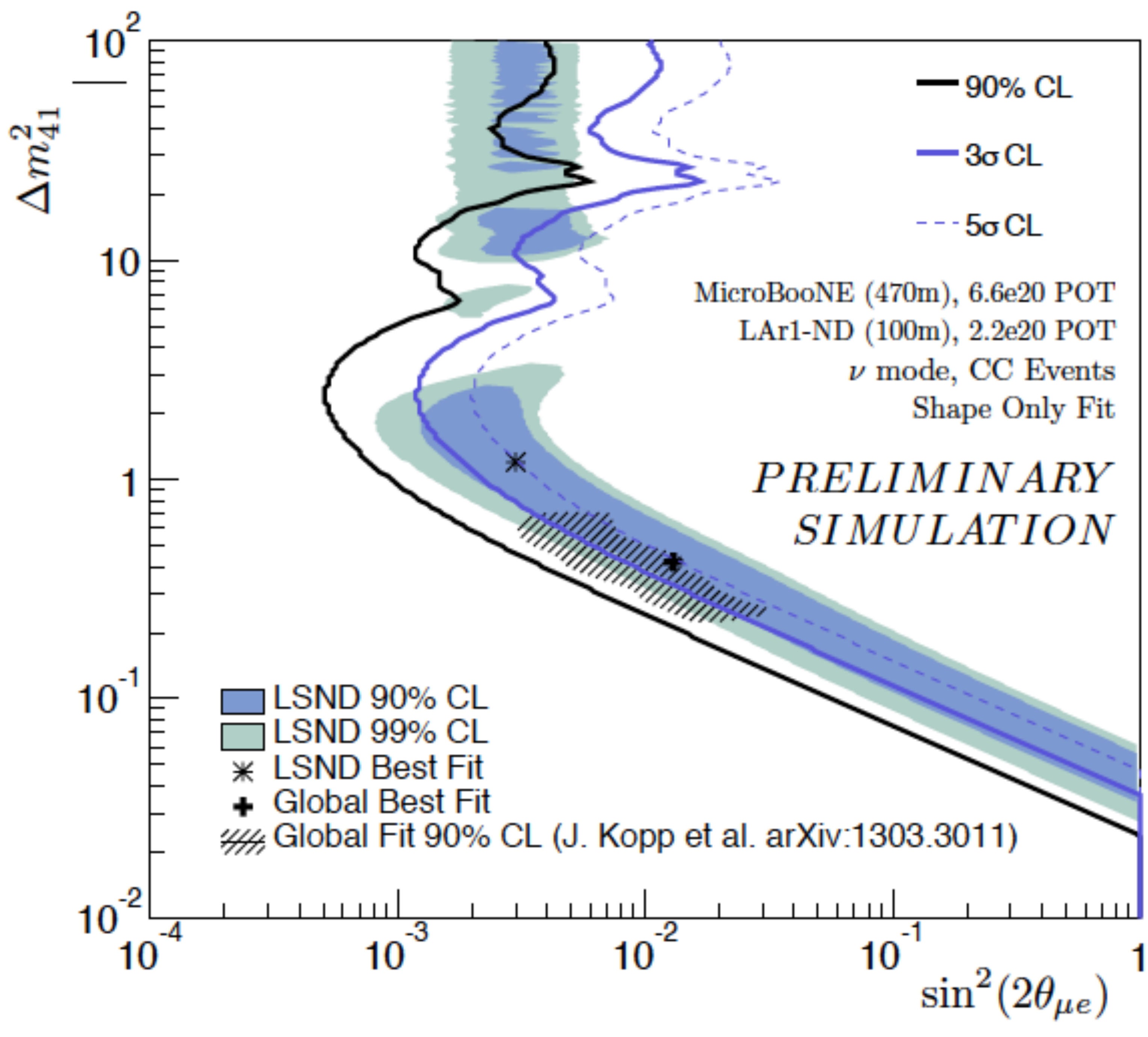



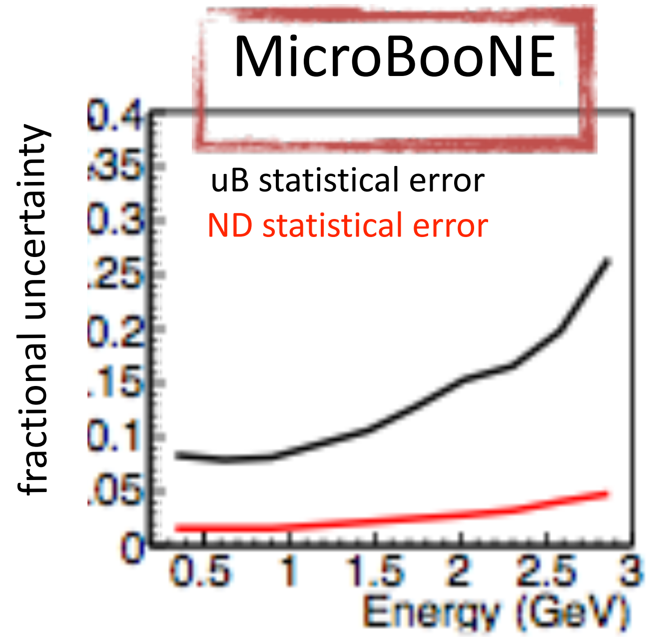
82 ton TPC membrane cryostat design

http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/LAr1ND_PAC_2014_01_23_v3.pdf

# $\nu_\mu \rightarrow \nu_e$ Appearance

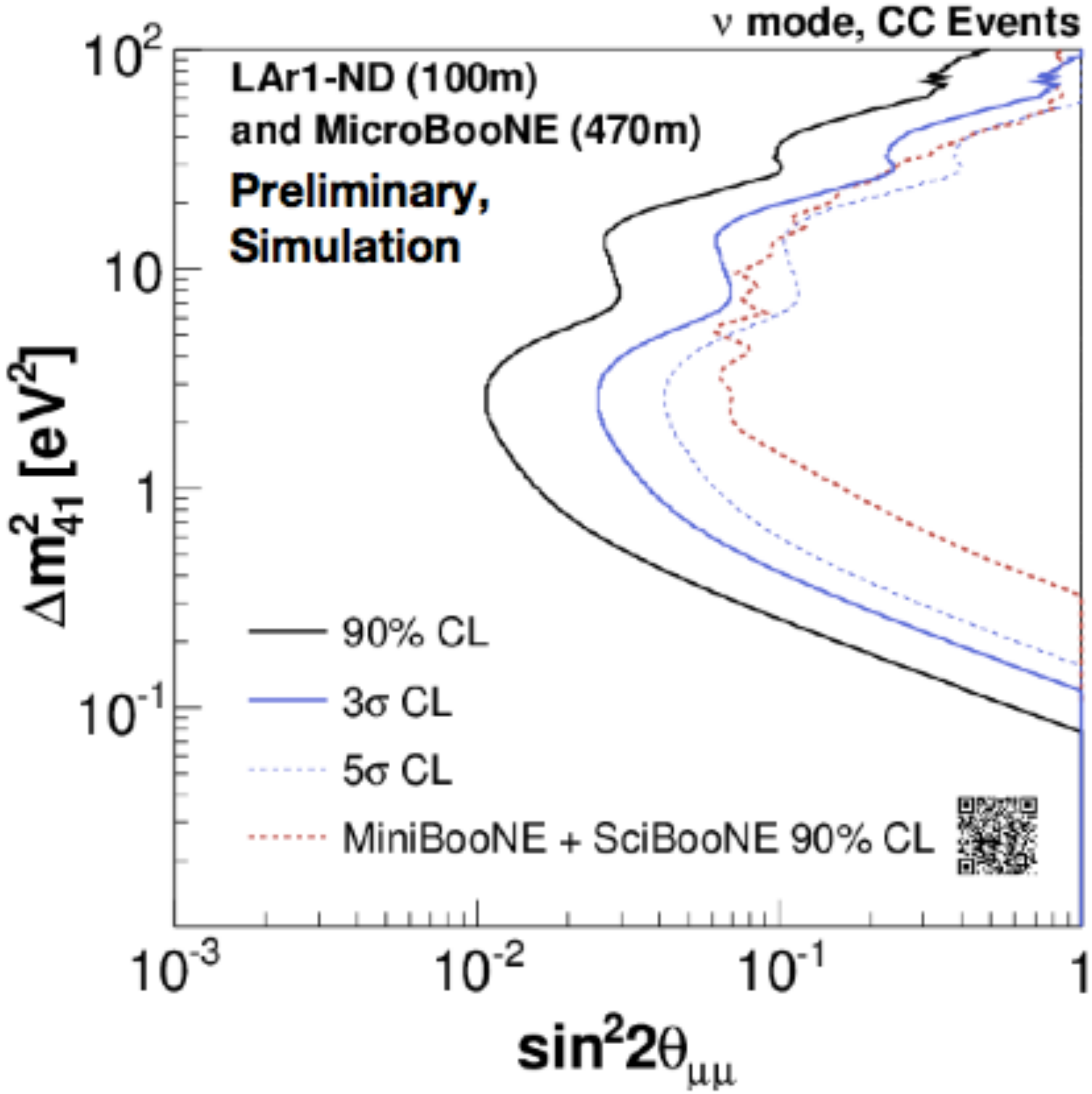
6.6x10[20] POT exposure for MicroBooNE and
2.2x10[20] POT exposure for LAr1-ND



# $\nu_\mu$ Disappearance

6.6x10[20] POT exposure for MicroBooNE and
2.2x10[20] POT exposure for LAr1-ND




Including a 3% systematic uncertainty on the near to far extrapolation.

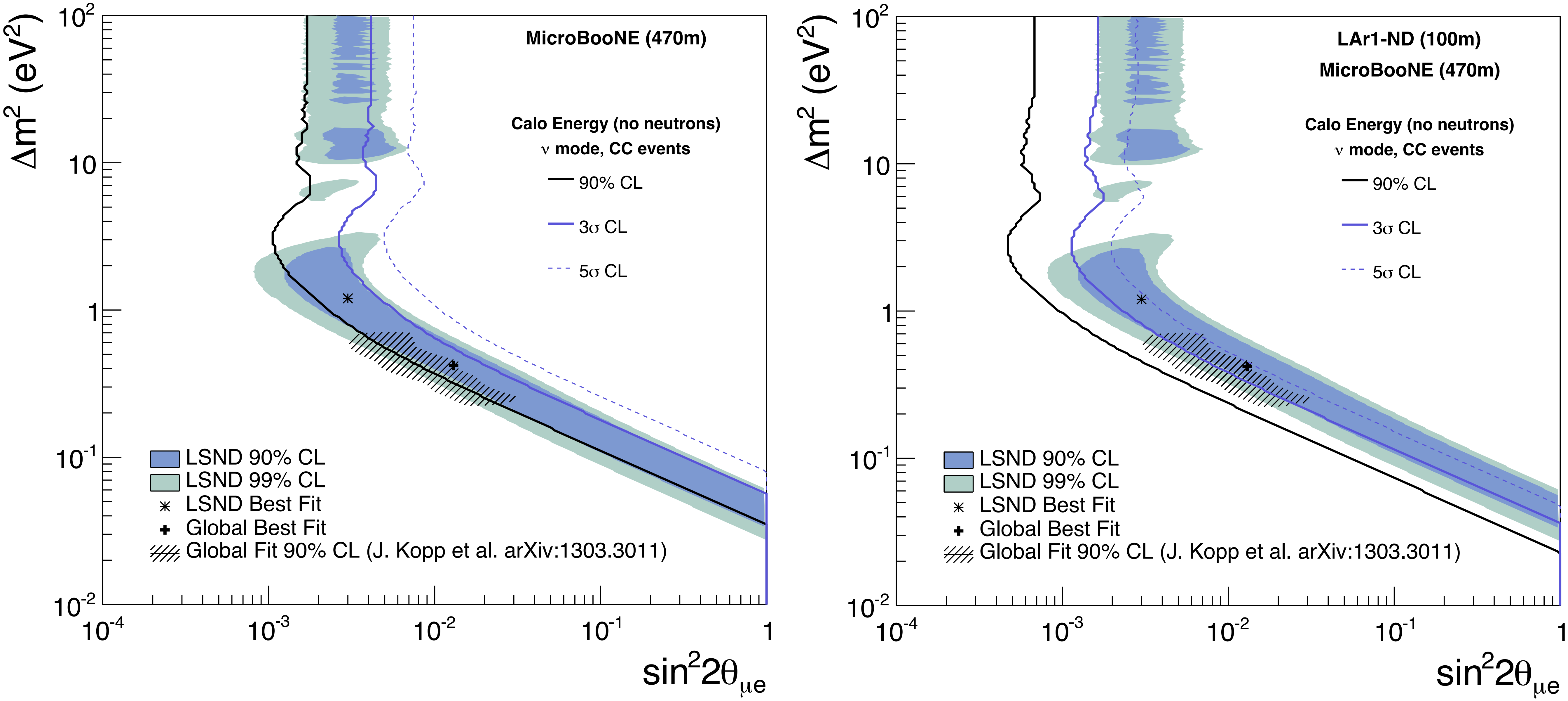
- Previous result from MiniBooNE+SciBooNE (red dashed contour) - unlike here, detectors were different technologies, and detector related uncertainties did NOT cancel

# $\nu_\mu \rightarrow \nu_e$ Appearance

6.6x10[20] POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on $\nu_e$ background prediction

+ND

Same MicroBooNE exposure + 2.2x10[20] POT exposure for LAr1-ND to constrain background prediction

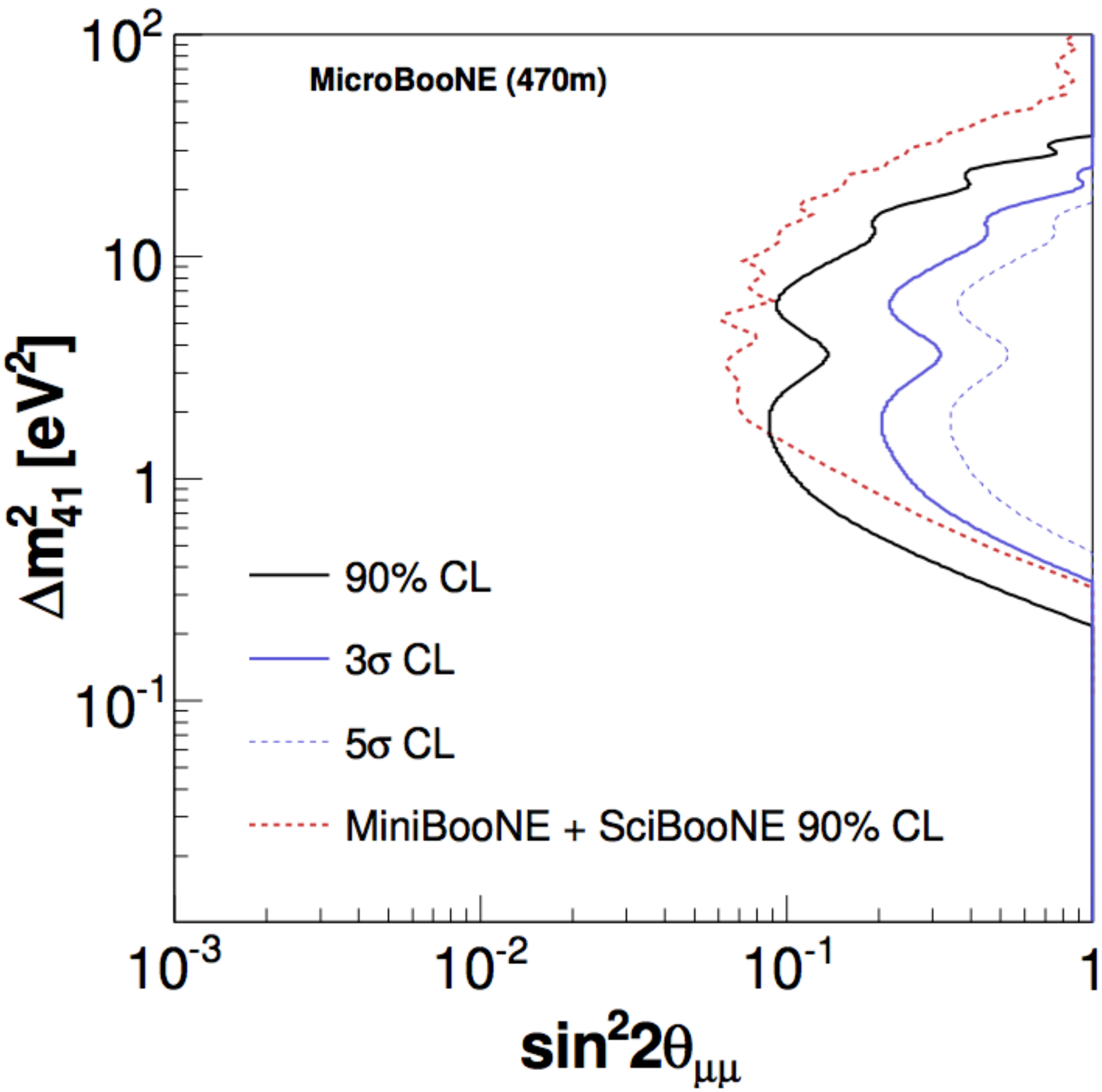


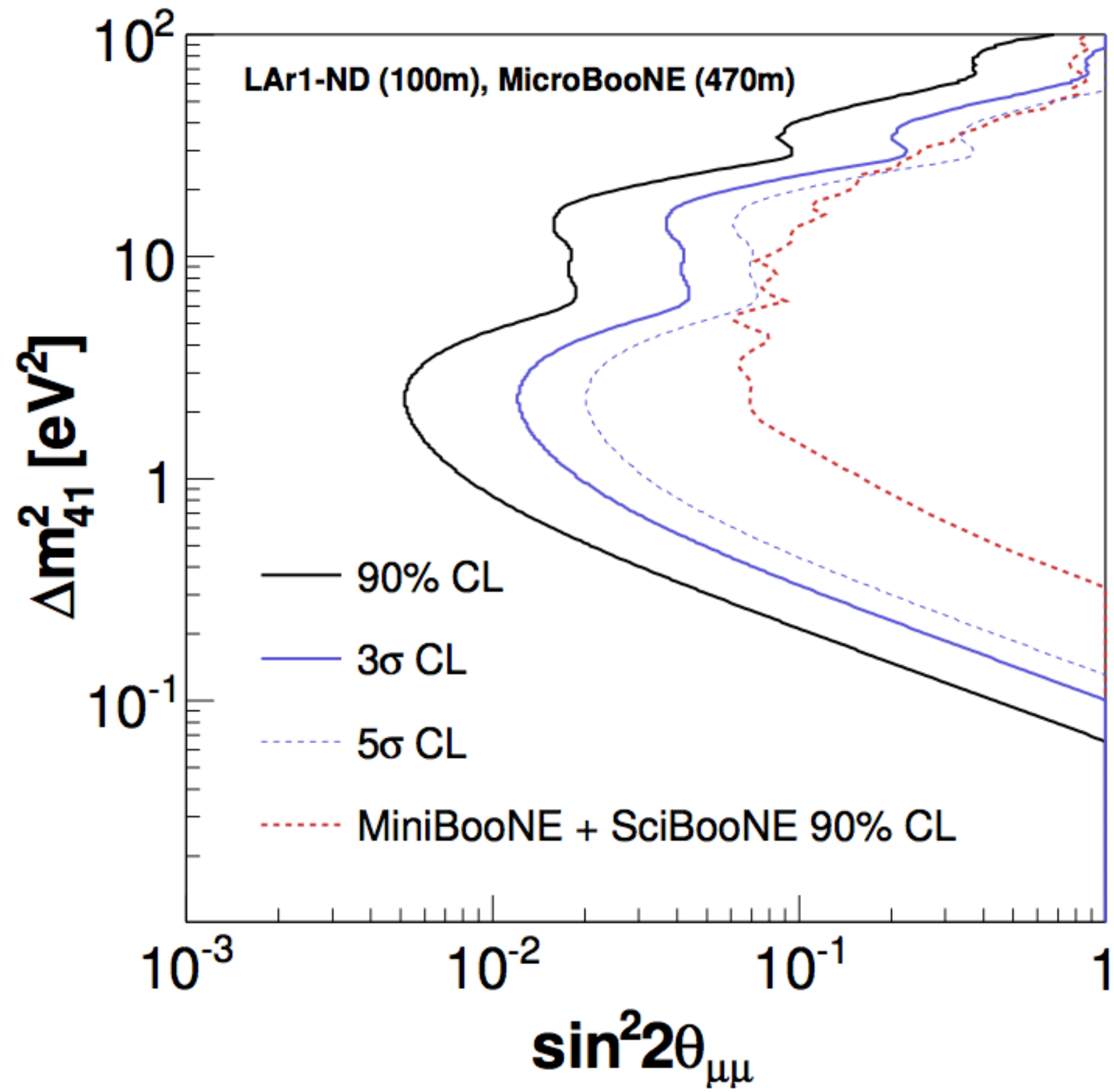
# $\nu_\mu$ Disappearance

6.6x10$^{20}$ POT exposure for MicroBooNE alone, assuming 15% systematic uncertainties on the absolute $\nu_\mu$ event rate

+ND

Same MicroBooNE exposure + 2.2x10$^{20}$ POT exposure for LAr1-ND to measure unoscillated $\nu_\mu$

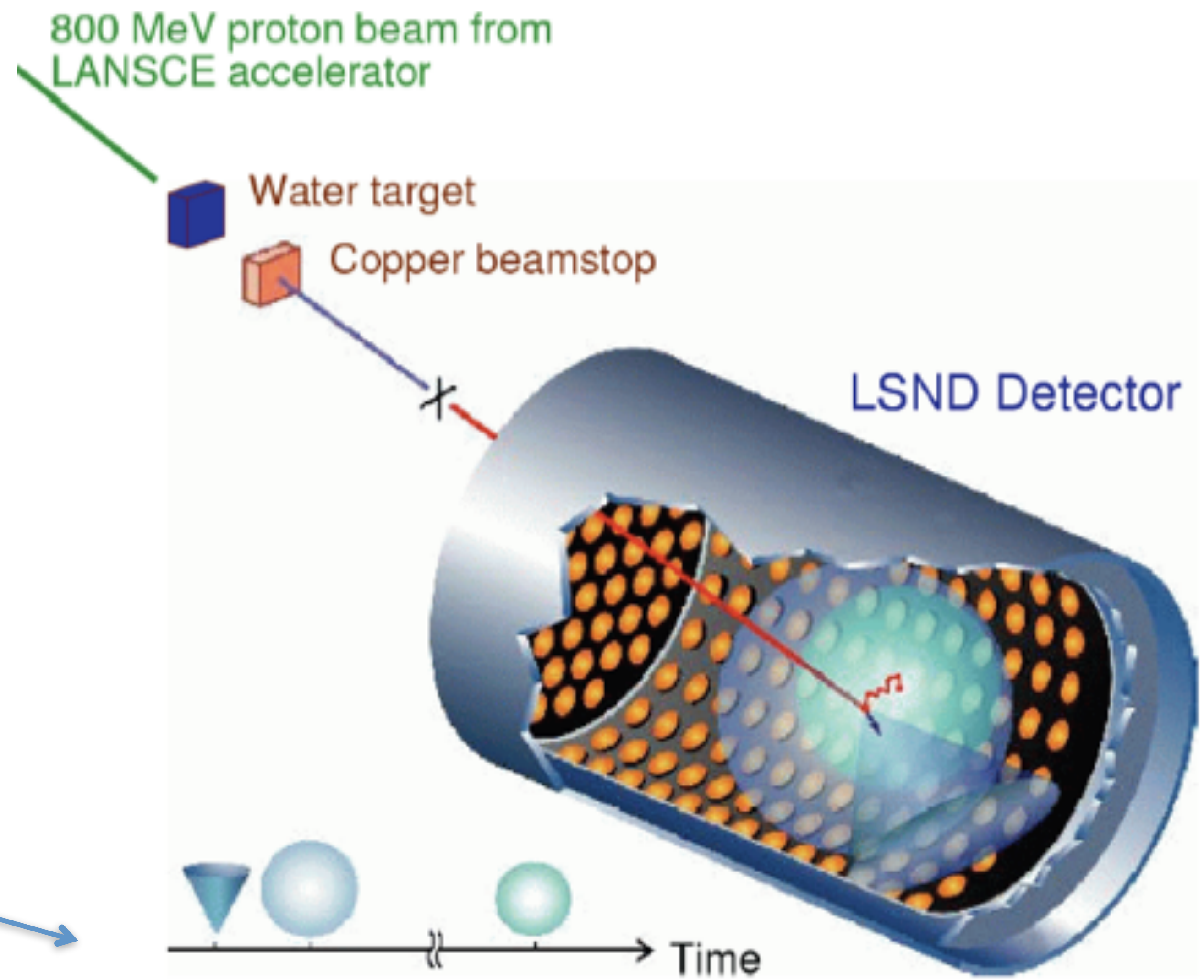



❖ Previous result from MiniBooNE+SciBooNE (red dashed contour) - unlike here, detectors were different technologies, and detector related uncertainties did NOT cancel

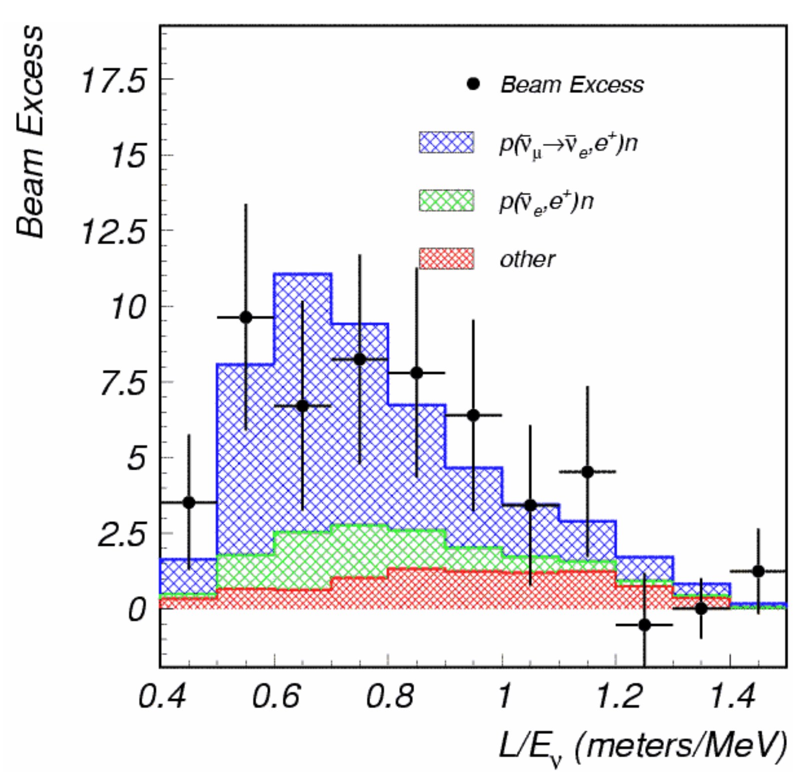
# LSND: Liquid Scintillator Neutrino Detector

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\overset{?}{\hookrightarrow} \bar{\nu}_e$$




$\nu_e$ appearance

$\nu + p \rightarrow e^+ n \qquad n + p \rightarrow d + \gamma(2.2\text{MeV})$




Observed 87.9 ± 22.4 ± 6.0 events
above background
Oscillation Probability: 0.26%

Consistent with a $\Delta m^2$ on the order of 1 eV$^2$
(not consistent with 3 flavor picture)