Short Baseline Neutrino Physics

Brooke Russell

Wright Laboratory at Yale University

On behalf of the MicroBooNE collaboration

*International Workshop on **N**ext Generation*

***N**ucleon Decay and **N**eutrino Detectors*

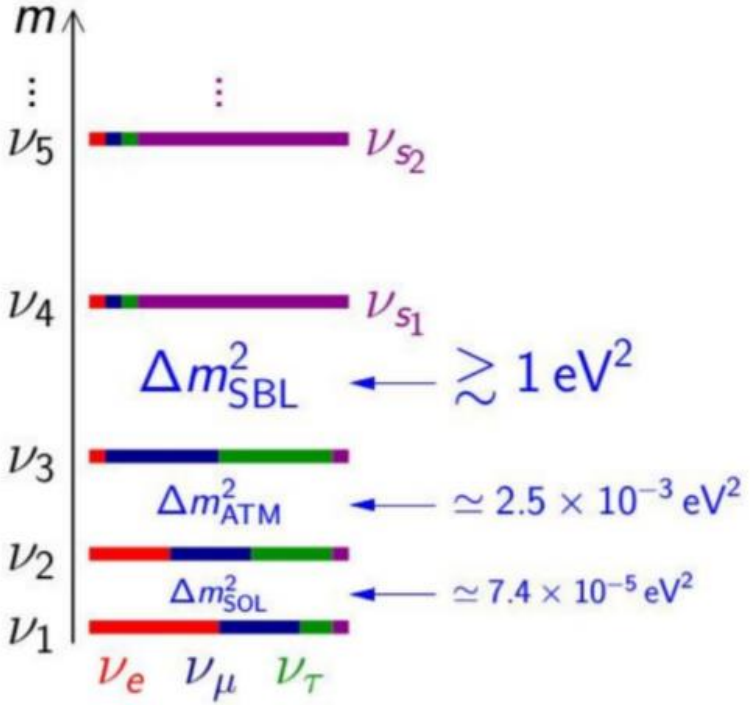
November 3rd 2018

ν landscape

- Three flavor neutrino states is well established by complimentary ν oscillation physics reach in solar, atmospheric, reactor, and accelerator domains

- However, there exist a number of *hints* of additional neutrino states with masses at the eV scale
  - *LSND anomaly*
  - *Gallium anomaly*
  - *Reactor antineutrino anomaly*

- Here, I discuss the present, rapidly changing landscape and future prospects for definitive resolution of the sterile neutrino problem



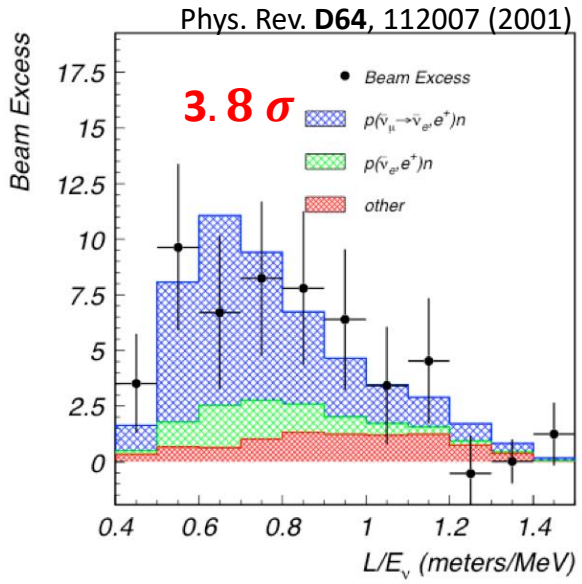
Hints of additional neutrino states

from particle accelerators – "LSND Anomaly"

LSND

1990-2001

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess over background suggests evidence for oscillation at $\Delta m^2 \approx 1\ eV^2$
- Measurement incompatible with the three active neutrino picture



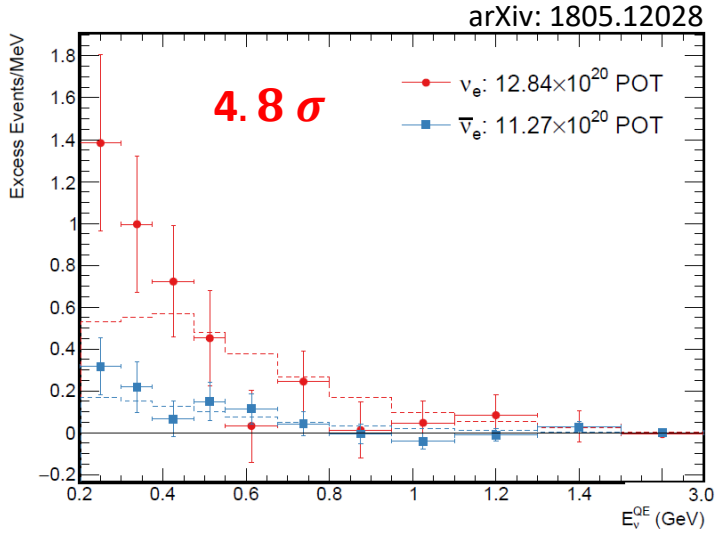
$L \approx 30\ m$

$E \approx 30\ MeV$

MiniBooNE

1998-present

- Purpose: direct test of LSND measurement
- Measured $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
- The excess of events corresponding to $200 < E_\nu < 475$ MeV is in an L/E range outside that which LSND searched



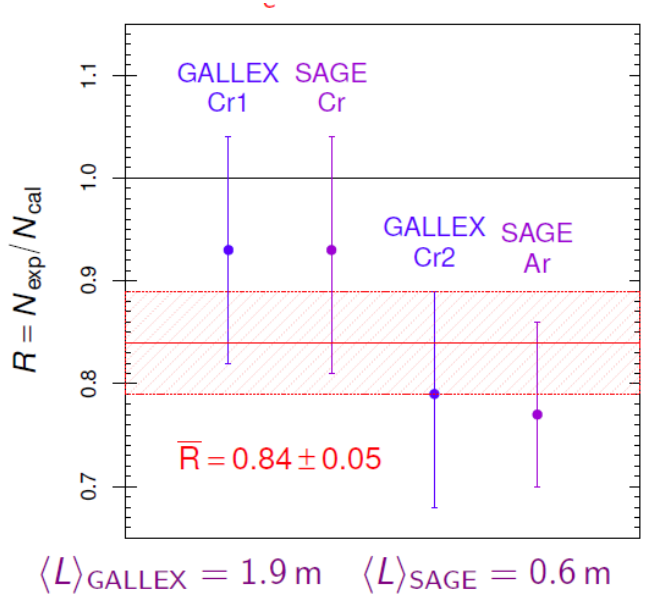
$L \approx 500\ m$

$E \approx 500\ MeV$

Hints of additional neutrino states

from radioactive sources – "Gallium Anomaly

- Solar neutrino experiments GALLEX and SAGE employed MCi ^{51}Cr and ^{37}Ar radioactive sources to calibrate ν_e + ^{71}Ga → ^{71}Ge + e^-
- Both experiments measured a ν_e flux deficit relative to predicted values
- Possible hint of ν_e disappearance (3σ deficit)

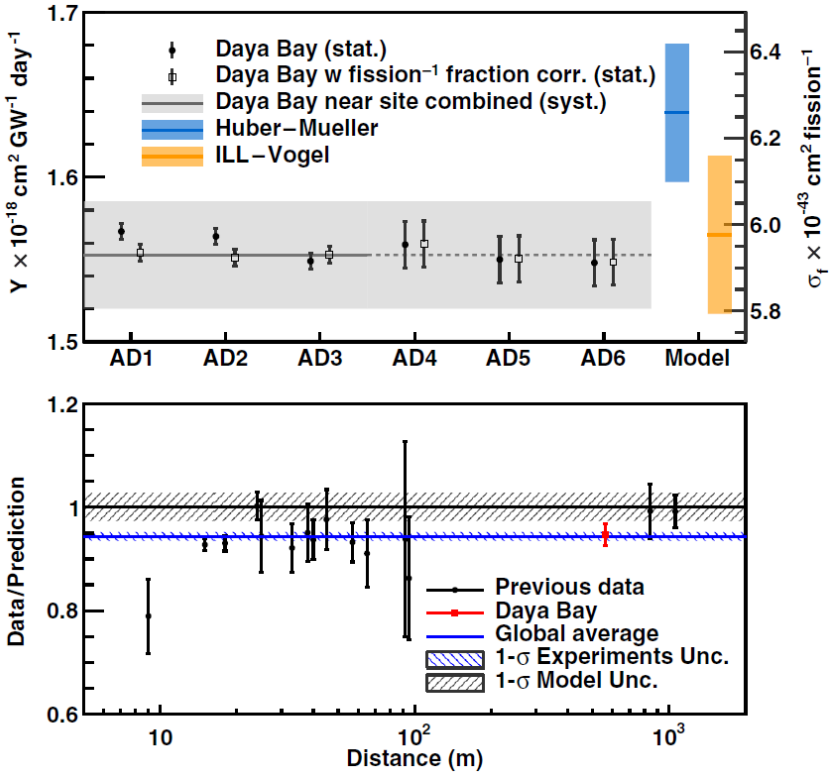


C. Giunti *et al*. Phys. Rev. **D86** (2012) 113014.

Hints of additional neutrino states

from reactors – "reactor antineutrino anomaly" (RAA)

- Reactor $\bar{\nu}_e$ flux predictions revised (by Huber, Mueller) in 2011
  - Resulted in a ~6% deficit in rates measured by short-baseline reactor experiments, suggests hints of a $\bar{\nu}_e$ disappearance
  - Bevy of short-baseline reactor neutrino experiments on-line to understand if this deficit is indicative of sterile neutrinos – PROSPECT, DANSS, SoLiD, STEREO, Neutrino-4
- RENO[1] and Daya Bay[2] measurements indicate a fuel dependence of the deficit, with RENO also suggesting ^{235}U may explain the spectrum distortion at 4-6 MeV
  - See H. Band's plenary talk for detailed discussion

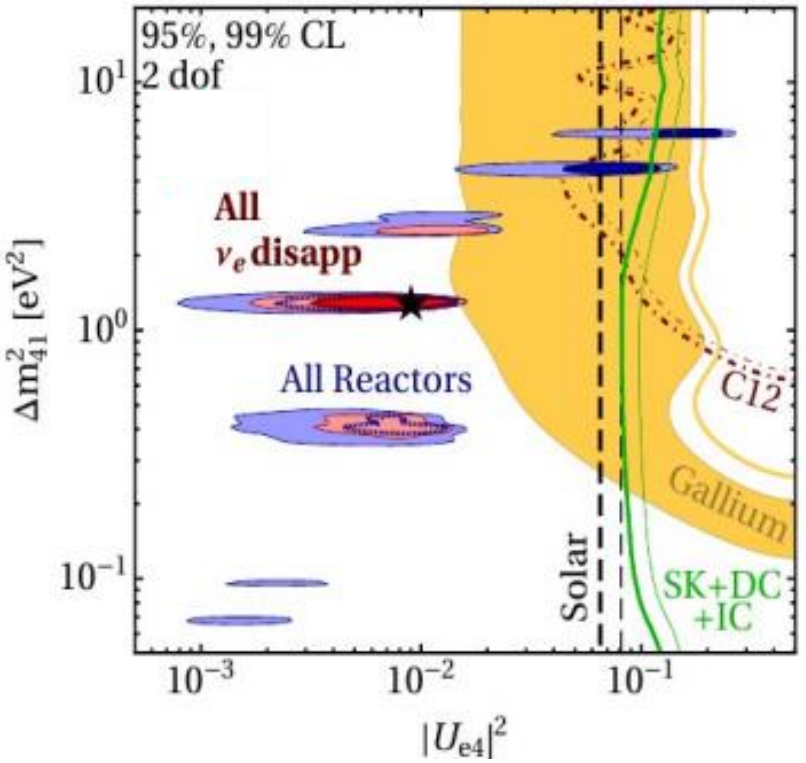


[2]Daya Bay PRL 116 (2016) 061801

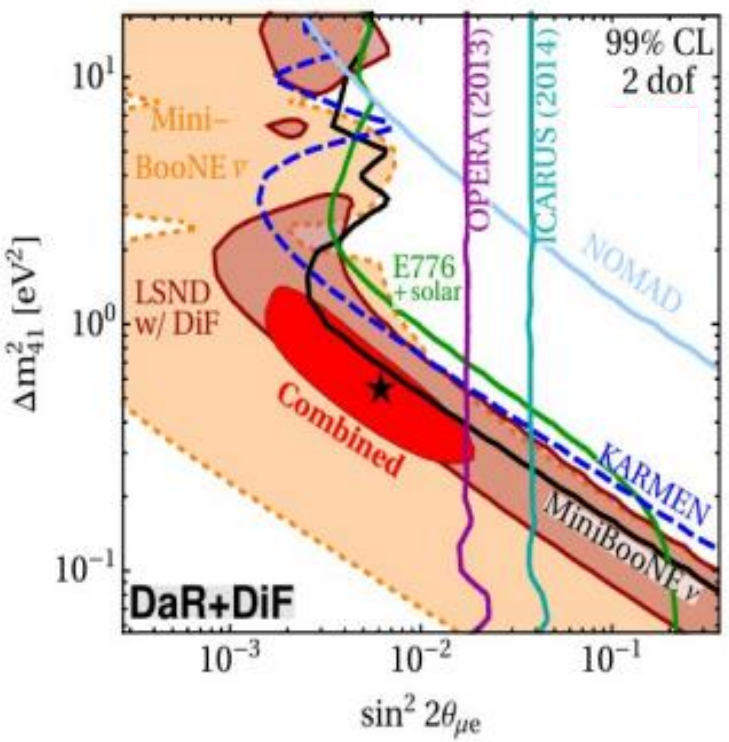
[1]Reno arXiv:1806.00574

Tension abounds

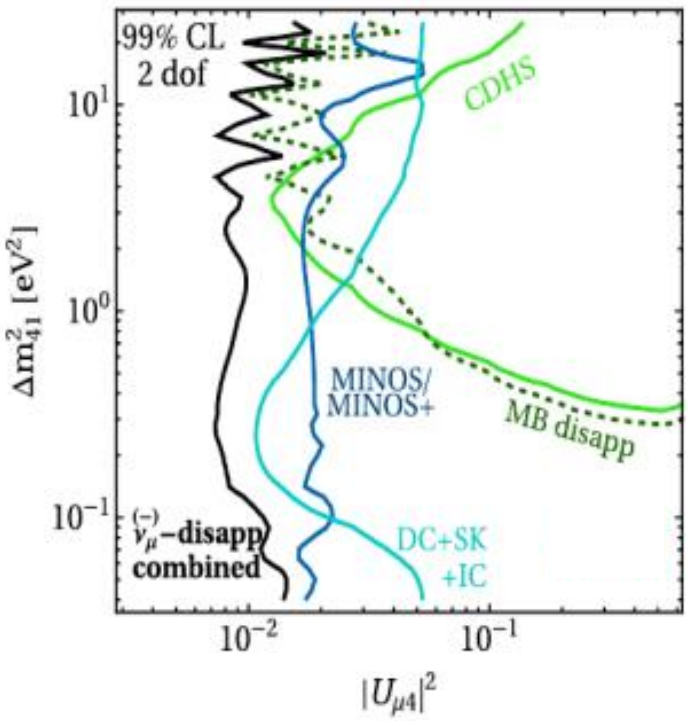
$\nu_e \rightarrow \nu_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$



$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



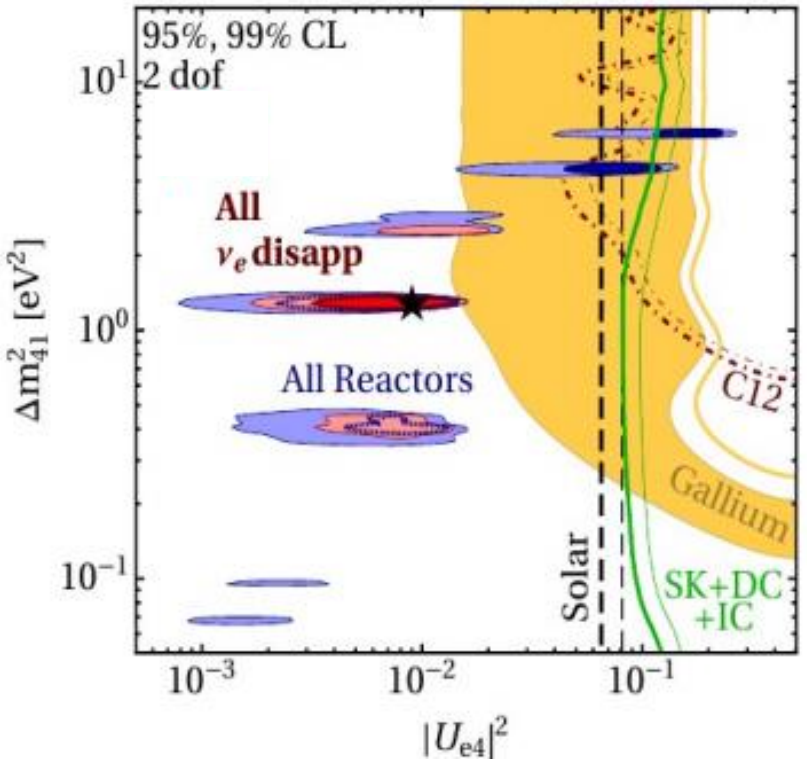
$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$



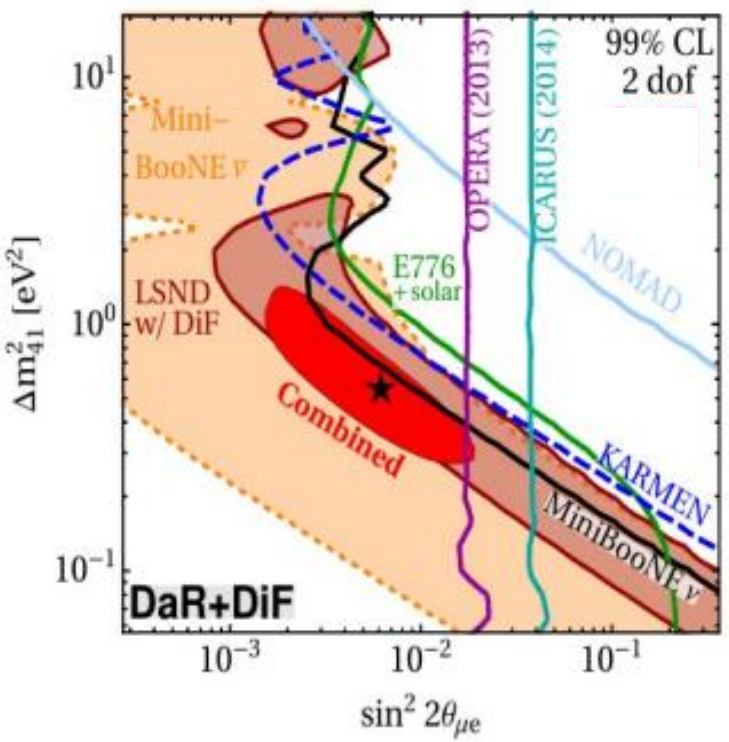
Dentler *et al.,* arXiv: 1803.10661

Tension abounds

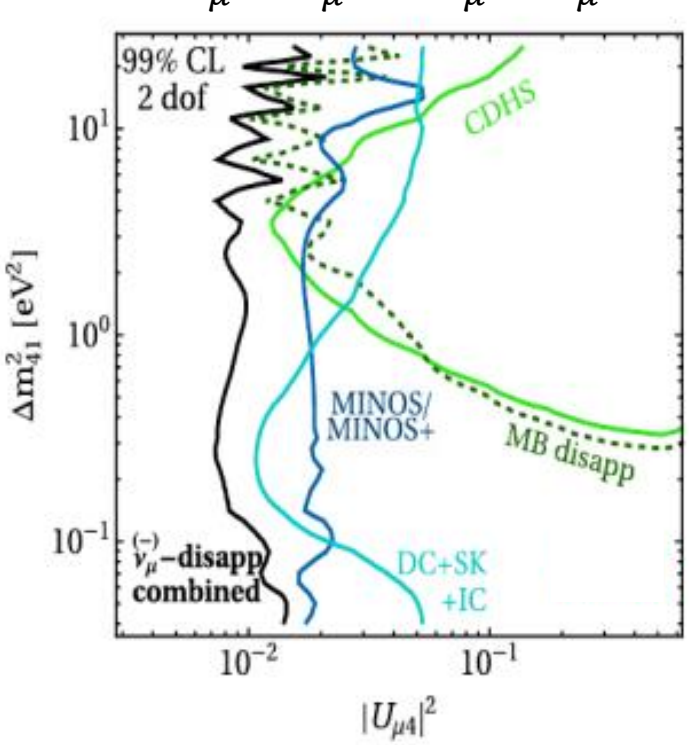
$\nu_e \rightarrow \nu_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$



$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

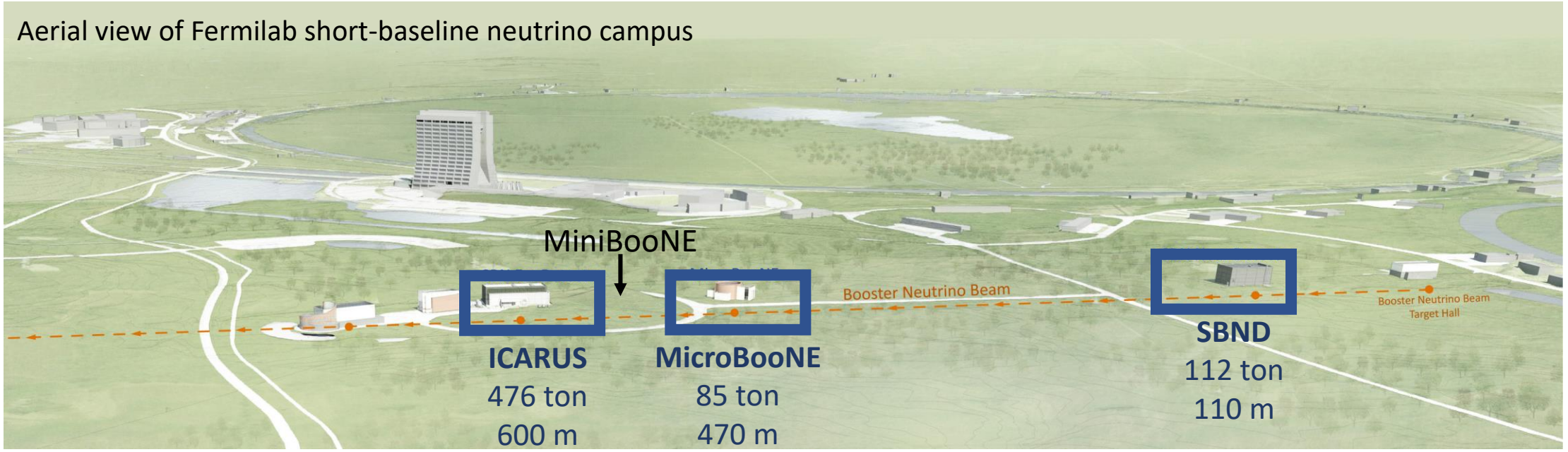


Dentler *et al.,* arXiv: 1803.10661

Fermilab SBN program will test ν_e appearance and ν_μ disappearance

Fermilab SBN program

Staged approach to address short baseline anomalies
Phase 1: MicroBooNE – definitive test of the MiniBooNE low energy excess
Phase 2: SBND + MicroBooNE + ICARUS – ν_e appearance and ν_μ disappearance searches

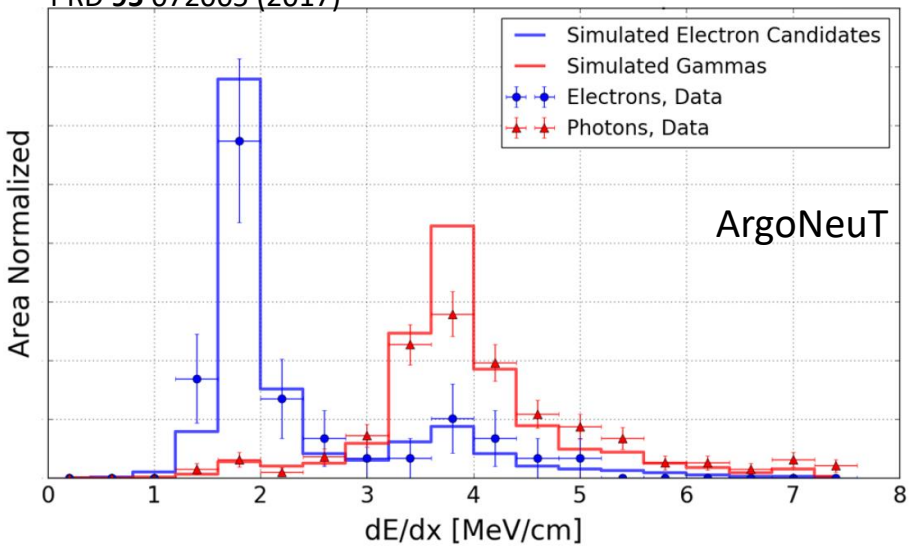


- Reduce statistical uncertainties with *large mass* far detector
- Reduce systematic uncertainties with *same detector technology*

Modern era implementation of single-phase LArTPC

- Excellent particle identification, particularly *electron/photon discrimination*
- Efficient for triggering on *low energy objects*, such as final states with a single proton
- Ability to observe and reconstruct *complicated* topologies

PRD **95** 072005 (2017)



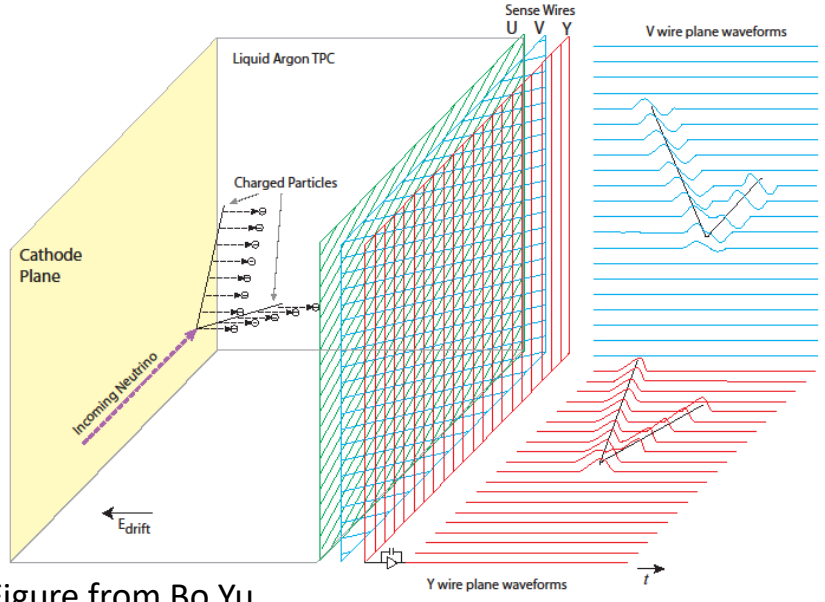
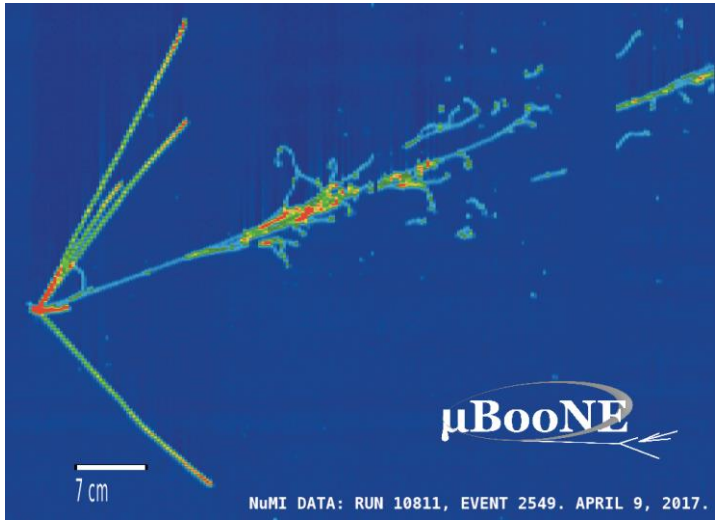


Figure from Bo Yu

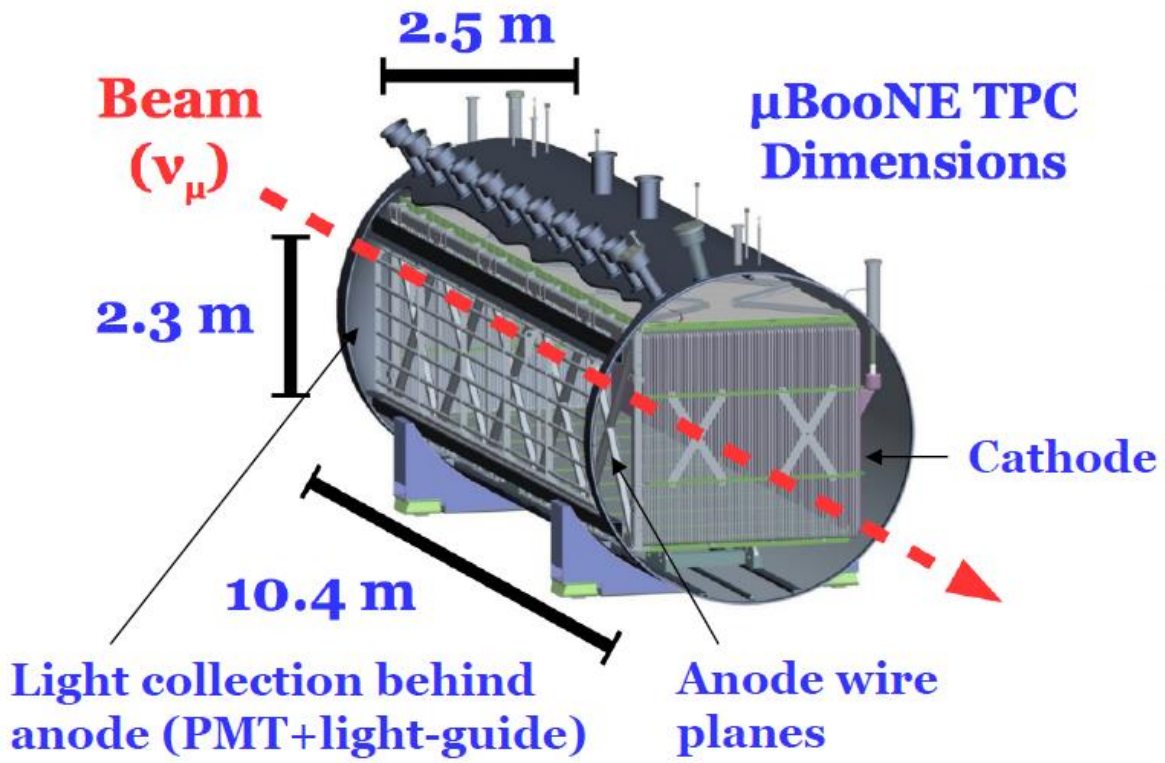
- ✓ Calorimetry - local dE/dx information
- ✓ Topology – fine-grained 3D tracking
- ✓ Mass – scalable to multi-ton, fully active target volumes



MicroBooNE

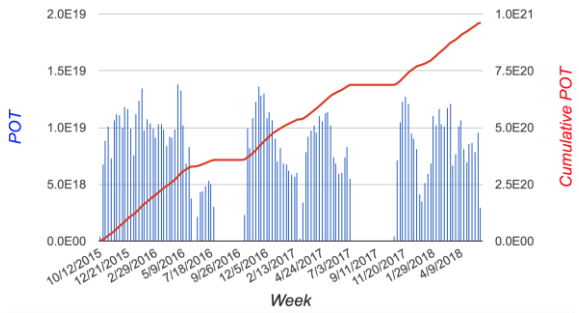
- Physics goals
  - Definitively address the MiniBooNE low energy excess
  - ν-Ar cross section measurements
  - LArTPC R&D

  → Applications to SBN & DUNE
- LArTPC engineering pioneer
  - Excellent LAr purity with a non-evacuable cryostat
  - Ultra-low noise cryogenic electronics
  - Parallel continuous readout stream for astroparticle and exotic physics
    - See parallel talk by J. Crespo-Anodon
  - Surge protection for HV discharge
  - >96% detector uptime



- 85 tons LAr active volume
- Near surface operation
- *Two* detectors
  - TPC – 8256 anode sense wires divided among 3 planes
  - PMT array – 32 8-inch PMTs

μBooNE Roadmap



Signal processing I and II
JINST 13, P07006 (2018) JINST 13, P07007 (2018)

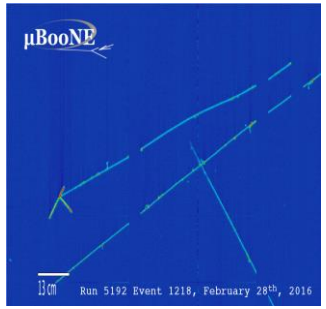
Pandora
Eur. Phys. J. C78, 1, 82 (2018)

Multiple Coulomb Scattering
JINST 12 P10010 (2017)

Cosmic ray studies
JINST 12, P12030 (2017)

CNN use for LArTPC
JINST 12, P03011 (2017)

Detector paper
JINST 12, P02017 (2017)



Purity of the LAr
Neutrino identification
Noise dependence on temperature

Public notes with preliminary results

Noise and filtering
JINST 12, P08003 (2017)

Charged particle multiplicity
arXiv:1805.06887

Deep neural net electromagnetic PID
arXiv:1808.07269

Proton ID
MCC7 Data/MC
Detector stability
3D shower reconstruction
CC events from 5E19 POT
NC event selection in MC
Cosmic shielding
MC study of expected events

Drift electron lifetime
Side piercing tracks with t0
Space charge
Signal formation

Reconstruction performance
Booster neutrino Flux
Ar-39 use for calibration
Wire Cell reconstruction
dE/dx calibration

Electron neutrino selection
1mu1p selection and reconstruction
Search for single photon events
Unfolding the MB signal
CC-Np cross section
CCpi0 cross section
Inclusive CC cross section

2015
- Detector turn on
- Cosmic and beam data
- Immediate identification of neutrinos

2016
- First software release for automated LArTPC reconstruction (MCC7)
- Performance results and Data/MC discrepancies
- “Open development” phase, investigate novel ideas, major effort on low level and high level reconstruction

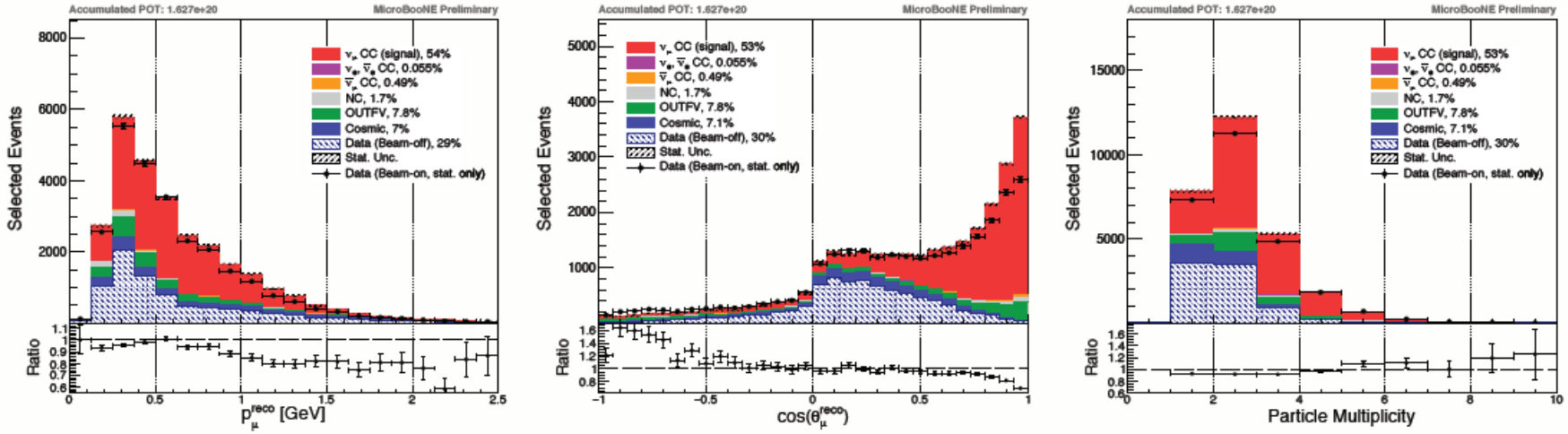
2017
- CRT installation
- Converging on a new robust software release (MCC8)
- Efforts on modelling, calibration, particle ID, systematics, computing speed up

2018
- MCC8 release and exploiting it for physics results
- Identified limitations in signal processing and efficiencies, targeted development of the next software release MCC9

Future
- Flagship results with flagship software release

On analysis and systematic uncertainty experience from MicroBooNE, see parallel talk by D. Porzio

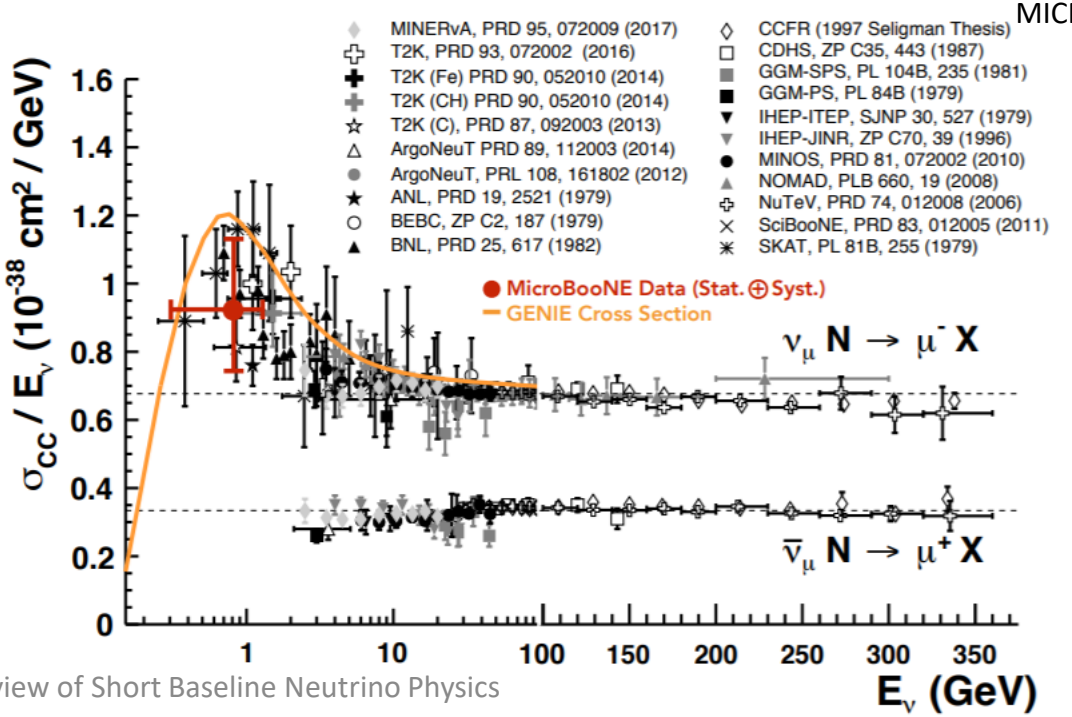
Understanding $\nu - Ar$ interaction



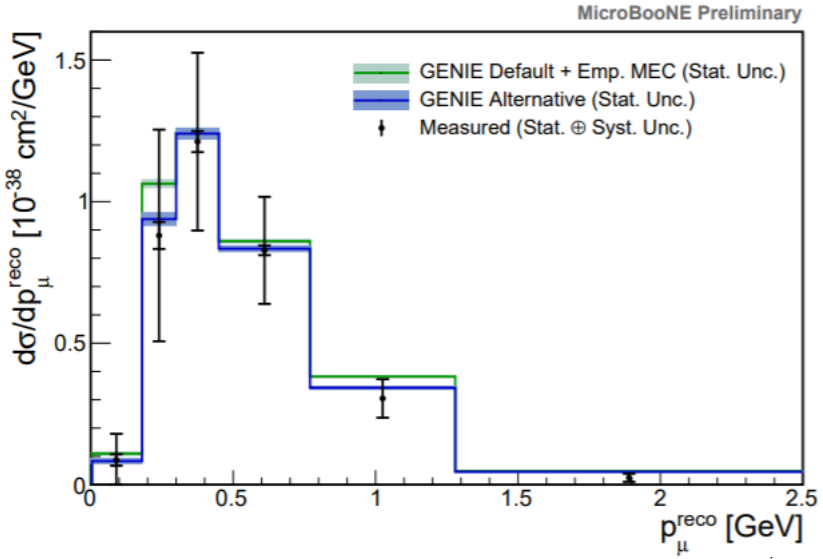
$\nu_\mu CC$ inclusive – standard candle measurement

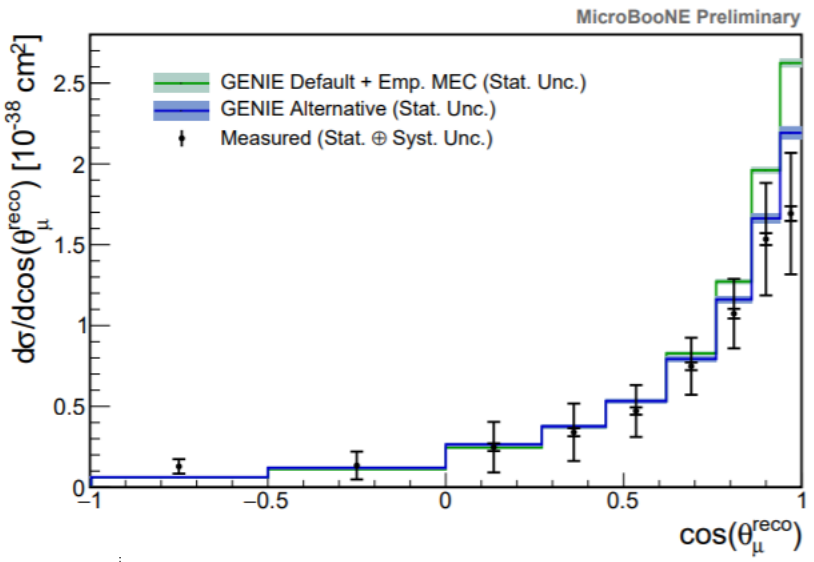
MICROBOONE-NOTE-1045-PUB

- ✓ Full muon momentum coverage with MCS momentum reconstruction
- ✓ Full angular acceptance
- ✓ Starting point for more exclusive channels
- ✓ First measurement on Ar at low energy



Single-differential $\nu_\mu CC$ inclusive cross section on Ar





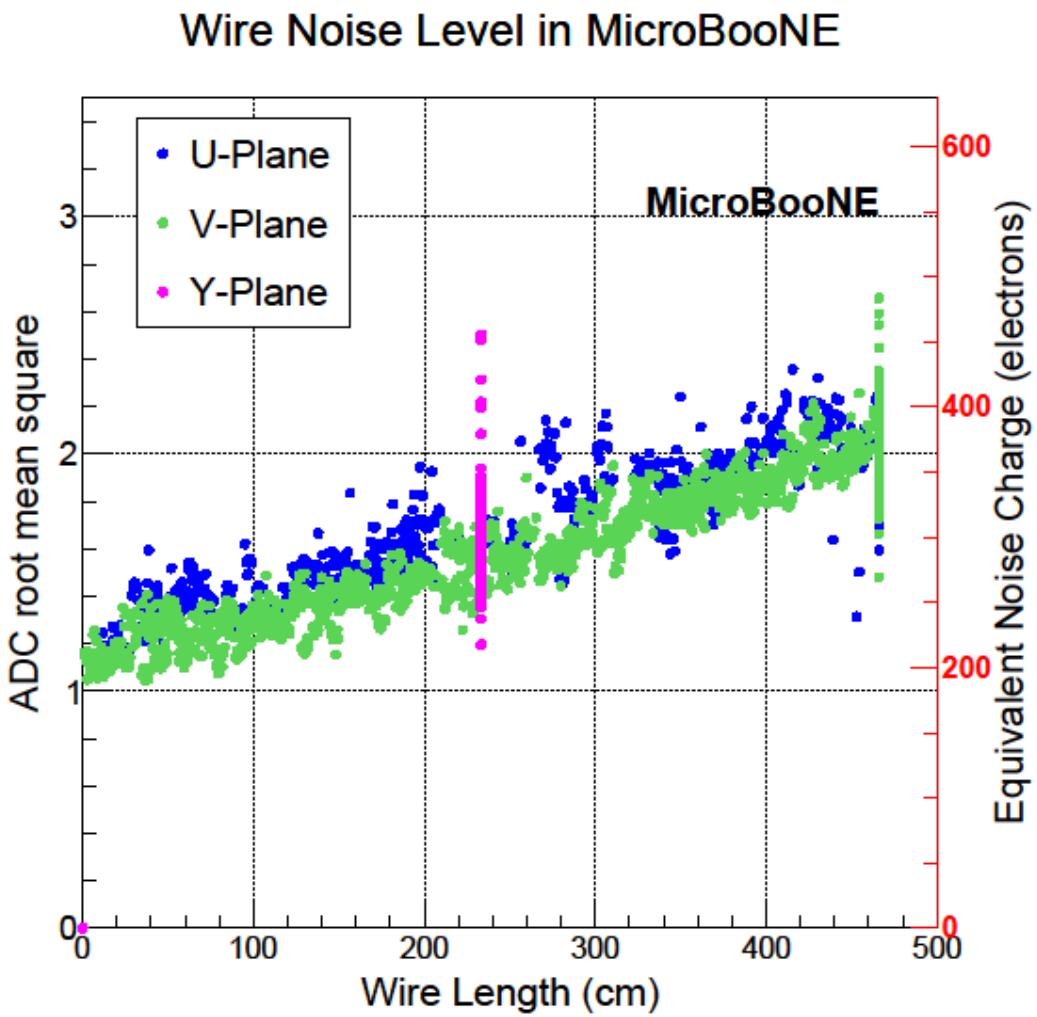
Model Element	Default GENIE + Emp. MEC	GENIE Alternative
Nuclear Model	Bodek-Ritchie Fermi Gas	Local Fermi Gas
Quasi-elastic	Llewellyn-Smith	Nieves
Meson-exchange Currents	Empirical	Nieves
Resonant	Rein-Seghal	Berger-Seghal
Coherent	Rein-Seghal	Berger-Seghal
FSI	hA	hA2014

MICROBOONE-NOTE-1045-PUB

Bringing out the full capability of single-phase LArTPC

✓Low inherent electronics noise

Lessons learned from MicroBooNE have led to improvements in cold ASIC design for SBND & DUNE



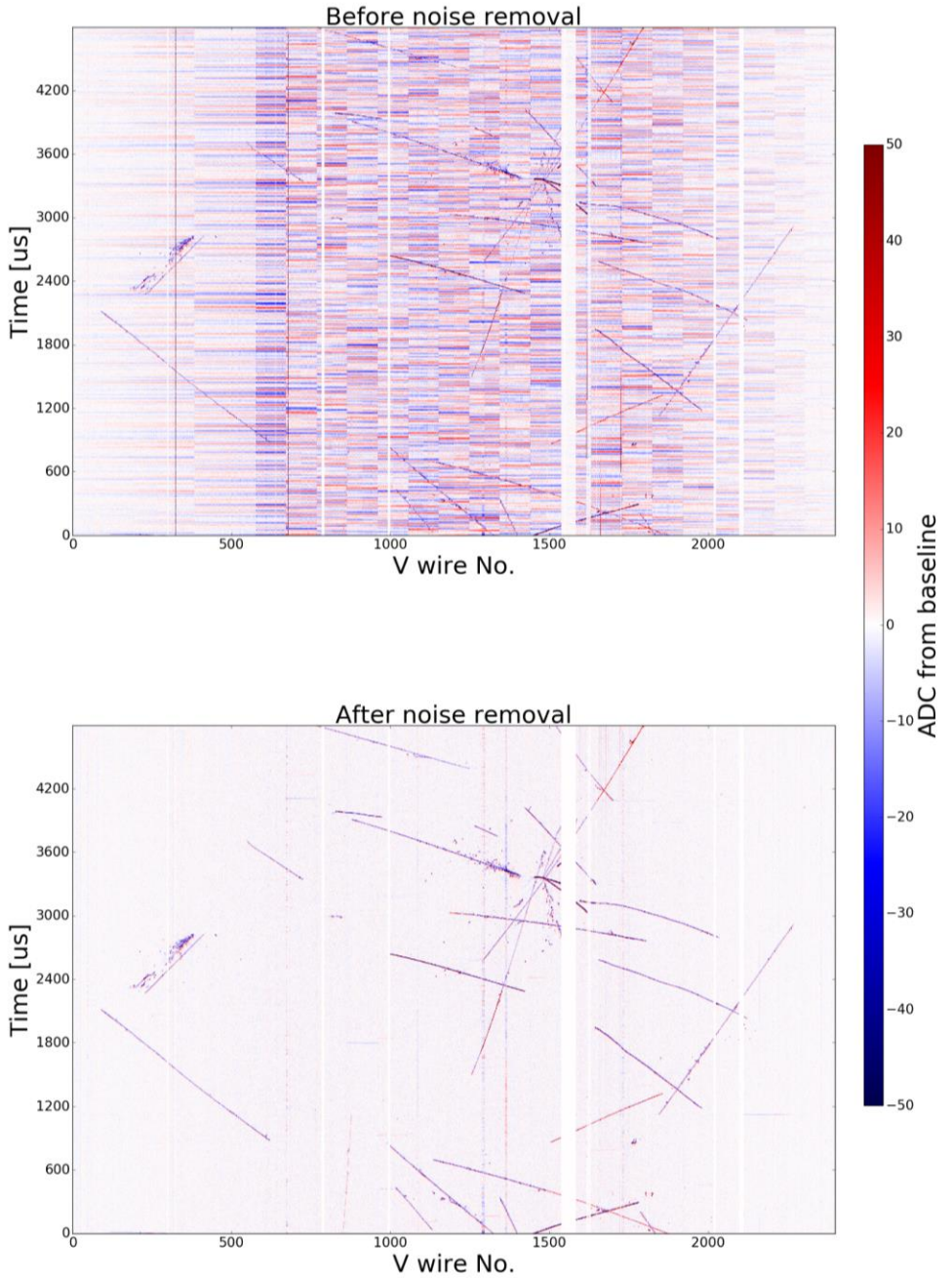
JINST **12** P08003 (2017)

Bringing out the full capability of single-phase LArTPC

✓Low inherent electronics noise

✓Mitigate excess noise

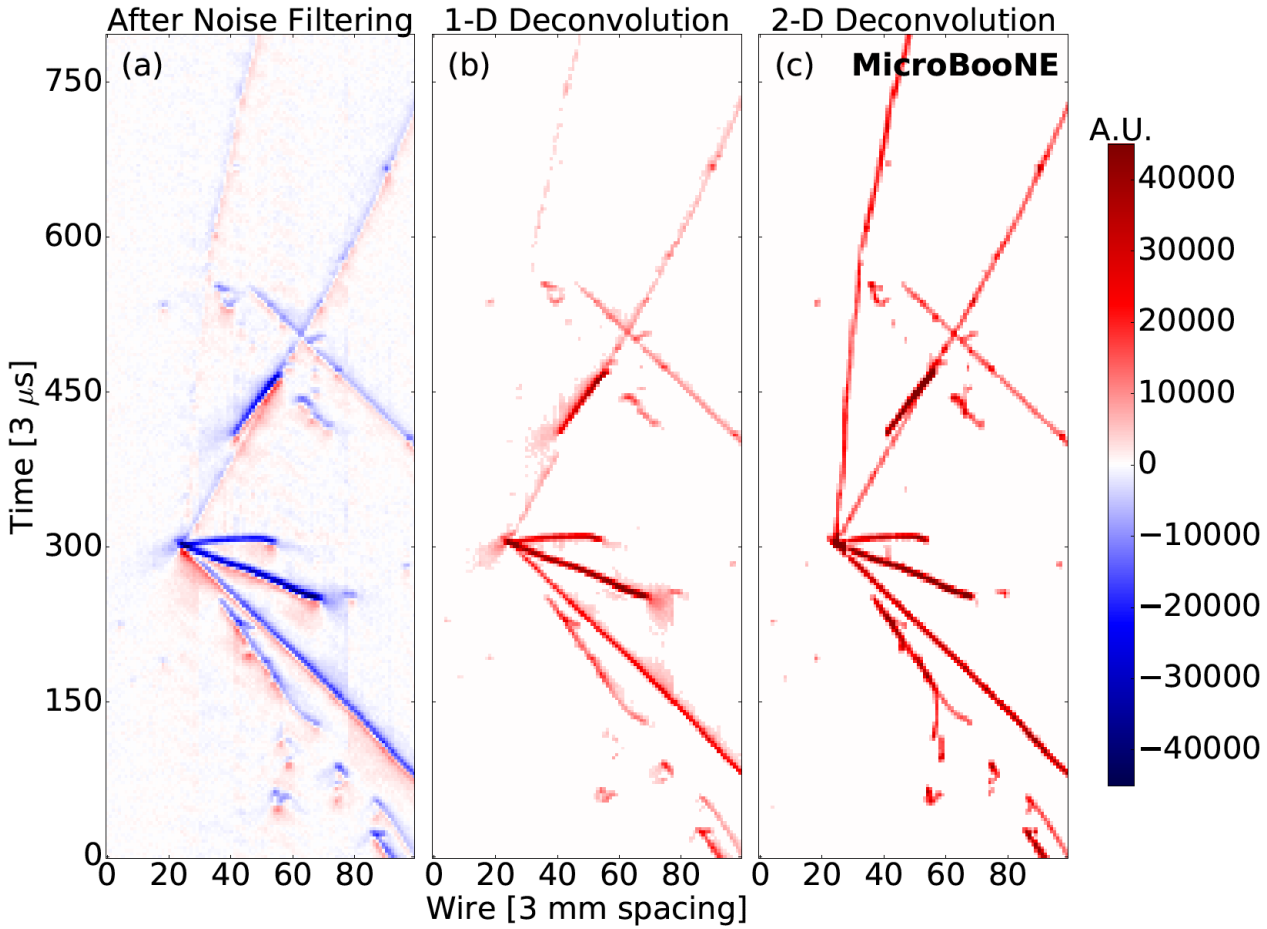
Demonstrated best noise performance ever achieved in multi-ton scale single-phase LArTPC



JINST **12** P08003 (2017)

Bringing out the full capability of single-phase LArTPC

- ✓Low inherent electronics noise
- ✓Mitigate excess noise
- ✓Careful signal extraction



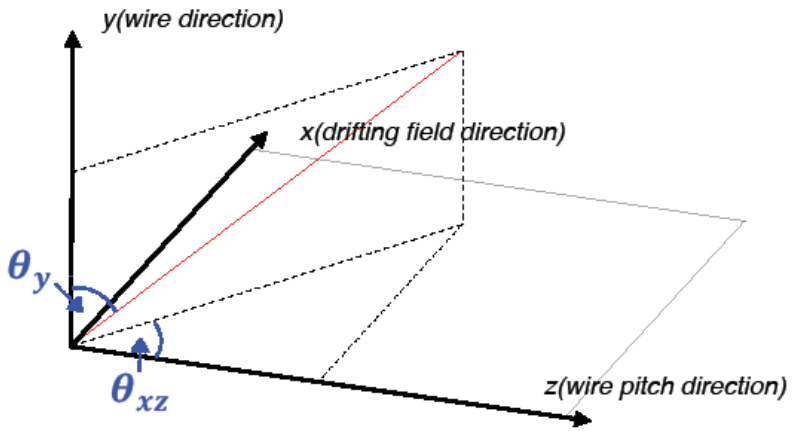
Improved understanding of detector response

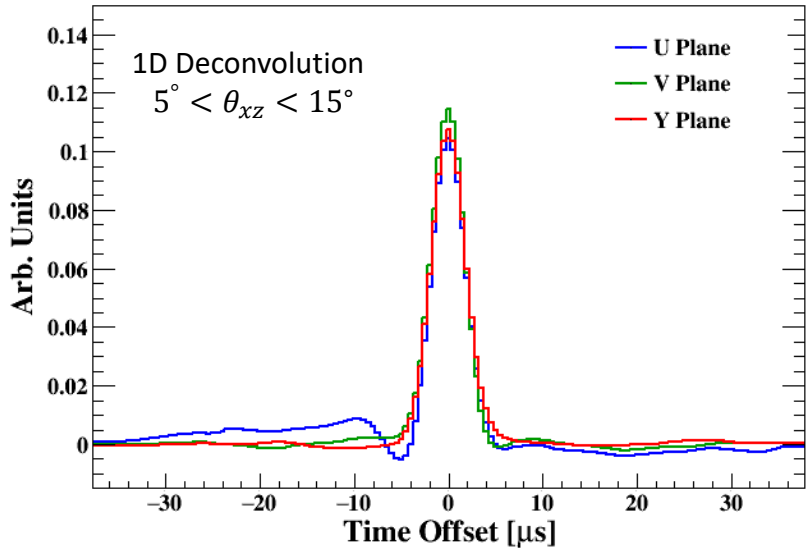
See parallel talk by H. Rogers

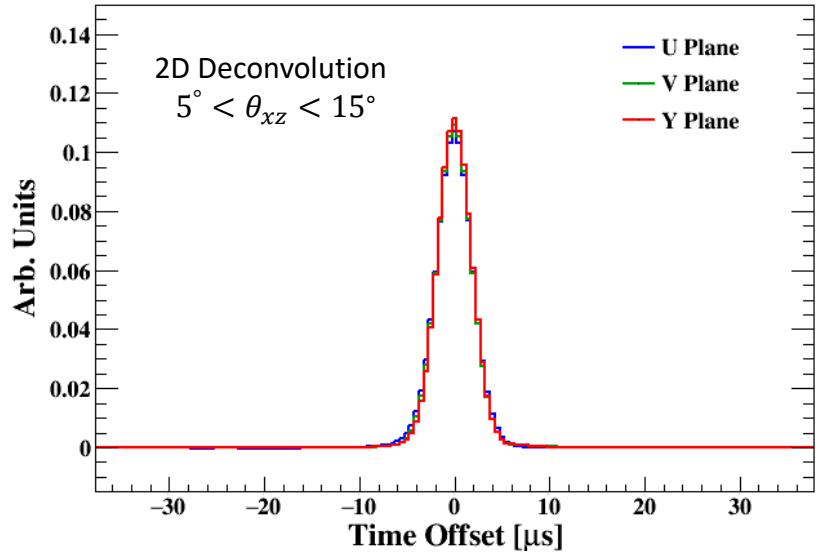
JINST **13** P07006 (2018)

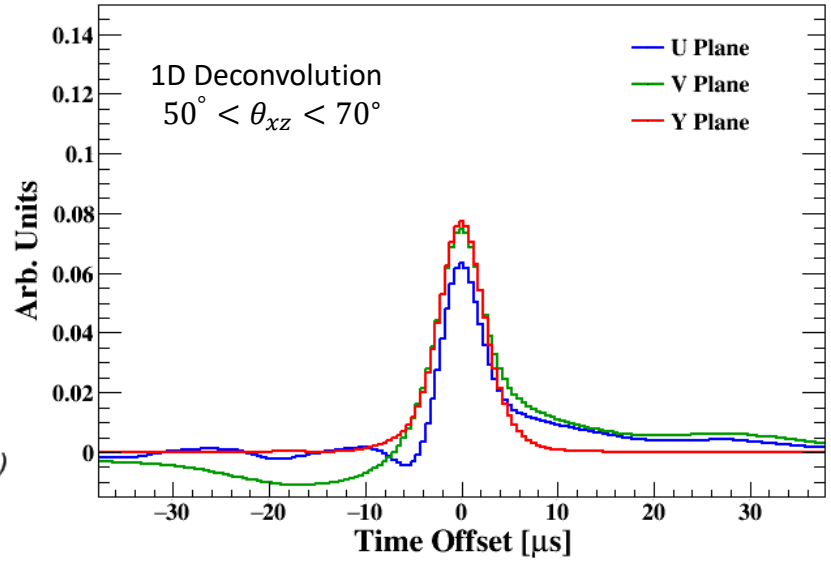
First demonstration of charge matching across planes

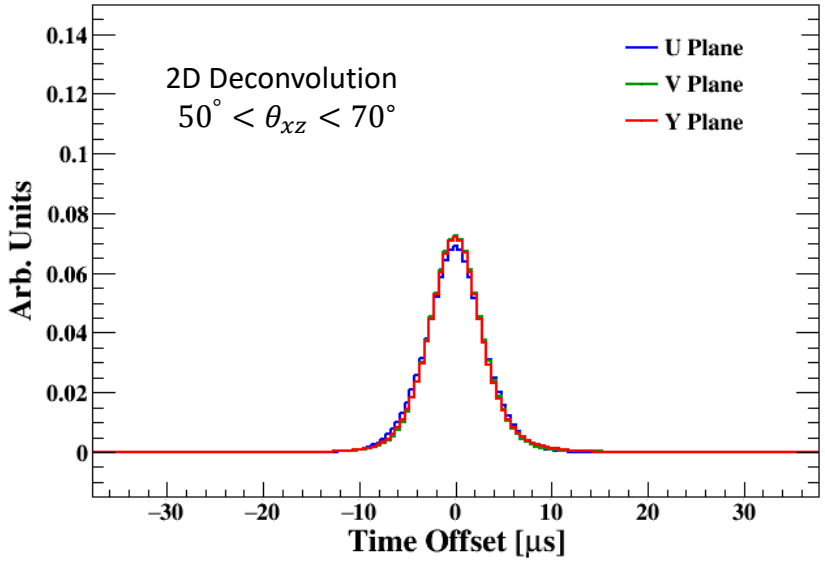
Critical for accessing robust calorimetric & topological information for downstream reconstruction









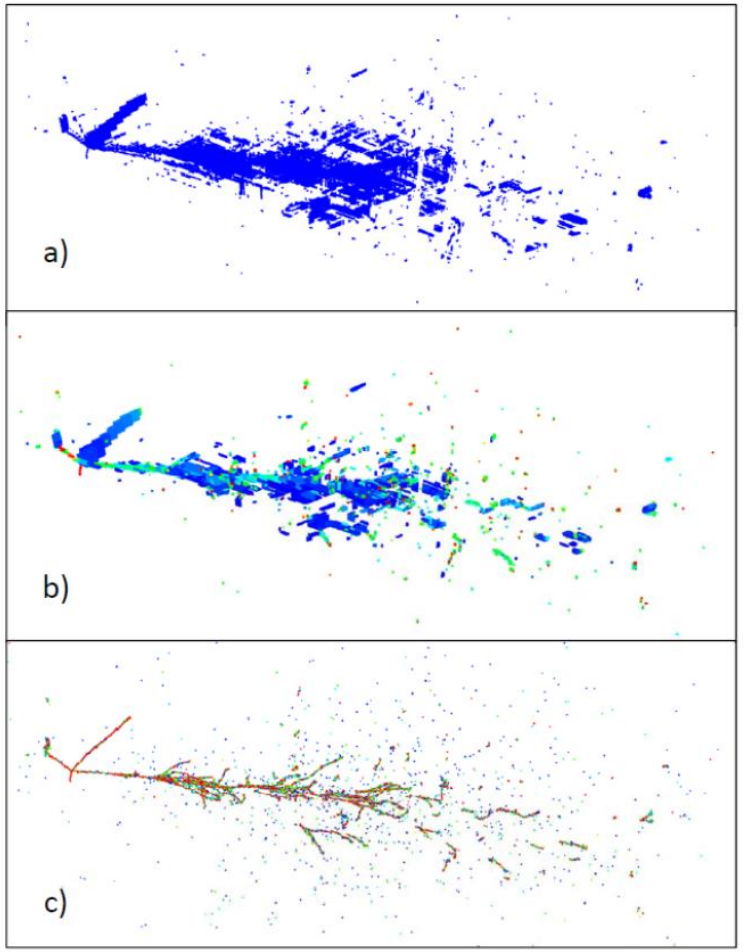


JINST 13 P07007 (2018)

Event reconstruction

Wire-Cell tomographic event reconstruction

X. Qian, C. Zhang, B. Viren, M. Diwan
JINST **13** P05032 (2018).

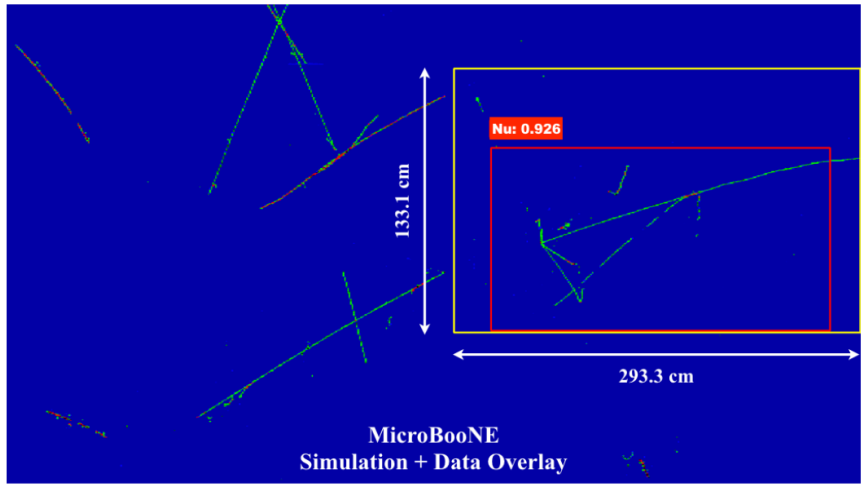


Convolutional Neural Networks applied to LArTPC image

See parallel talk by T. Wongjirad

MicroBooNE
JINST **12** P03011 (2017)

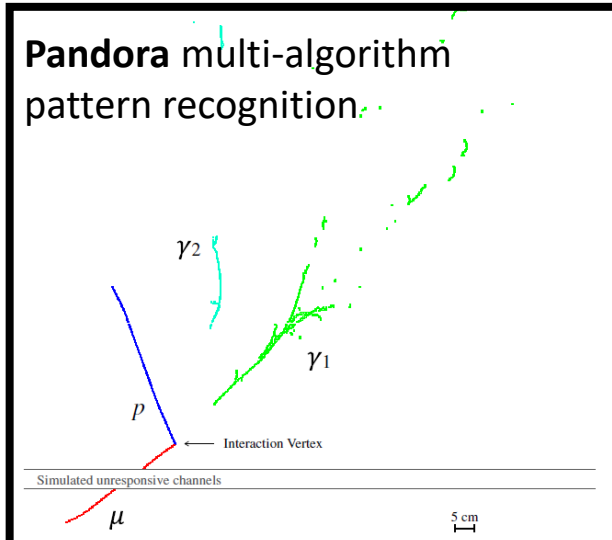
MicroBooNE
arXiv: 1808.07269



Multiple reconstruction paradigms in development at MicroBooNE

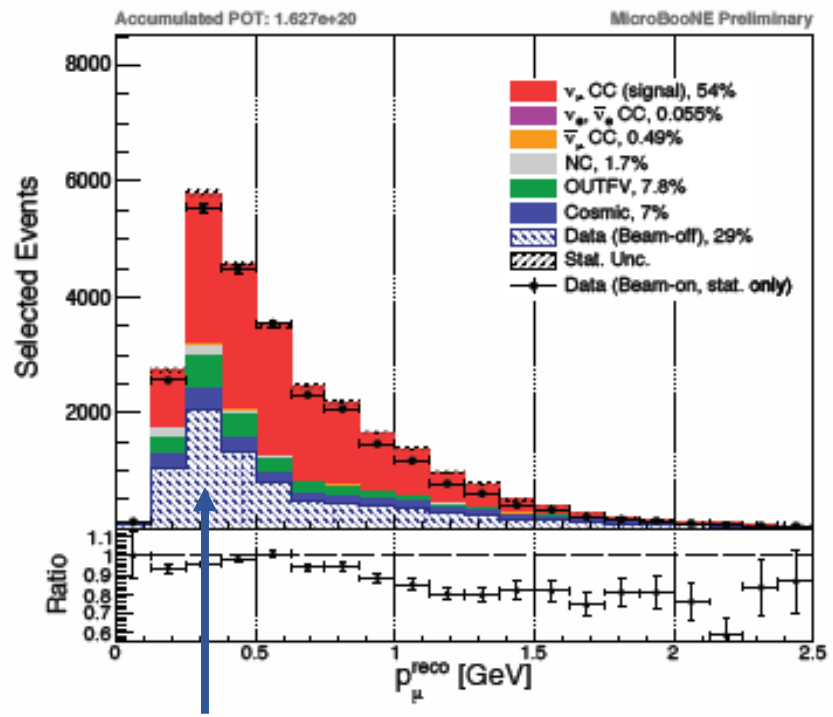
Each approaches getting to final state particle kinematics & identification differently

Pandora multi-algorithm pattern recognition

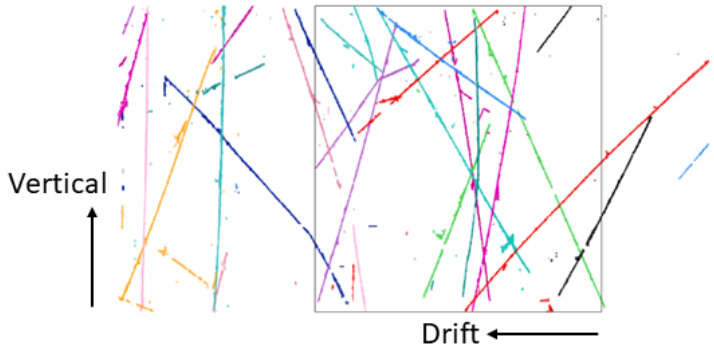


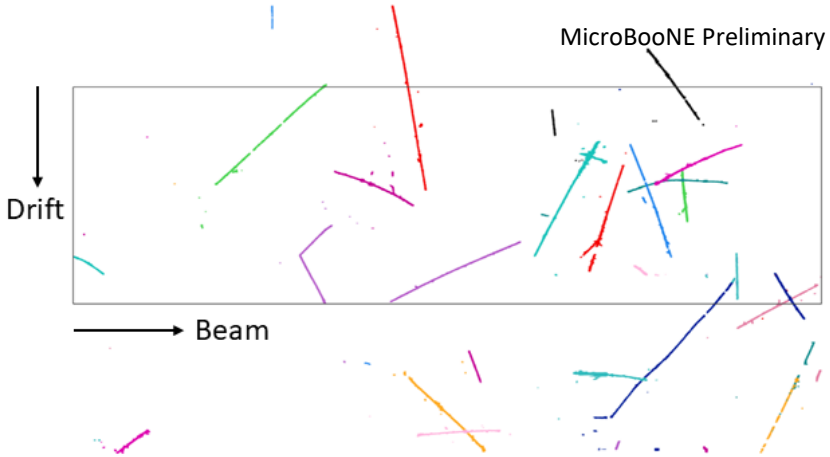
MicroBooNE
Eur. Phys. J. C (2018) 78:82

Contending with near-surface operation



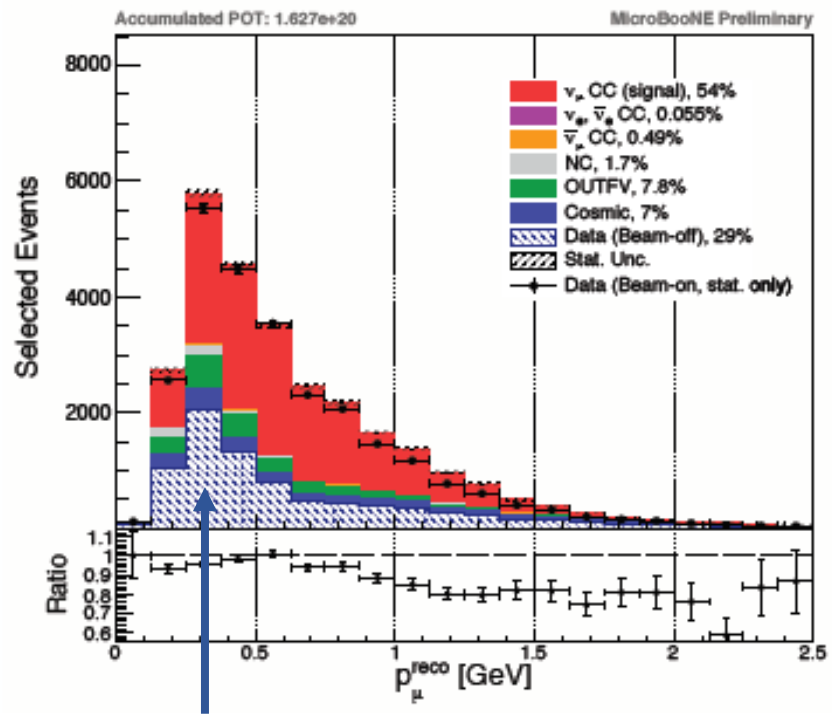
For first generation physics analyses, cosmic rays were the leading backgrounds





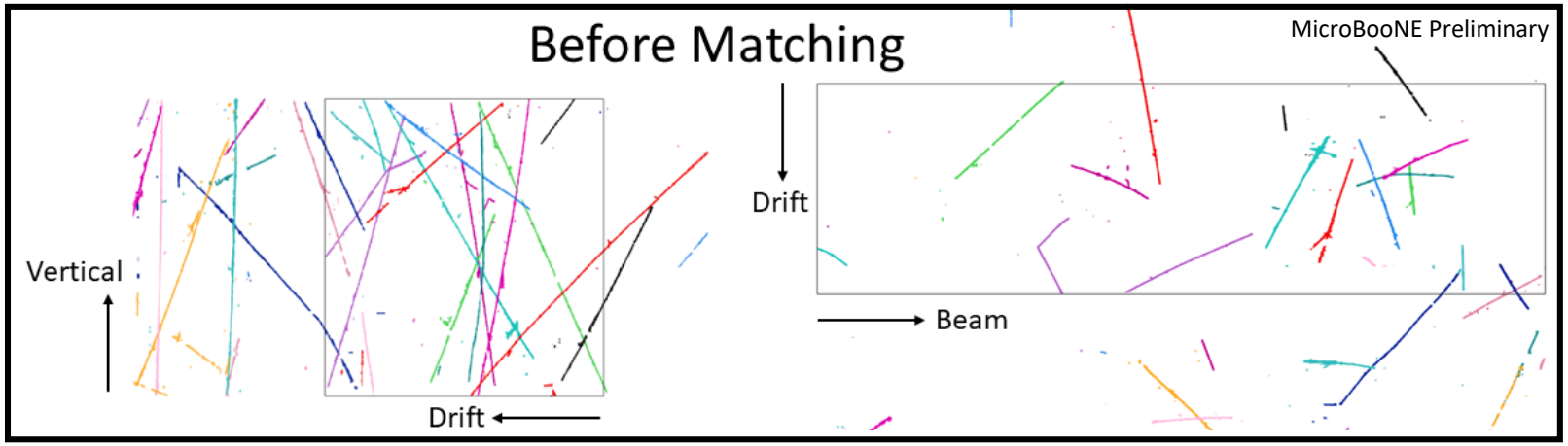
- Recall, MicroBooNE has **two detector systems**: TPC and PMTs
- Each event is comprised of ~25 charged particles measured by the TPC and ~50 flashes of light detected by the PMTs
- We can **match** each cluster of ionization charge TPC signals to scintillation light PMT measurements

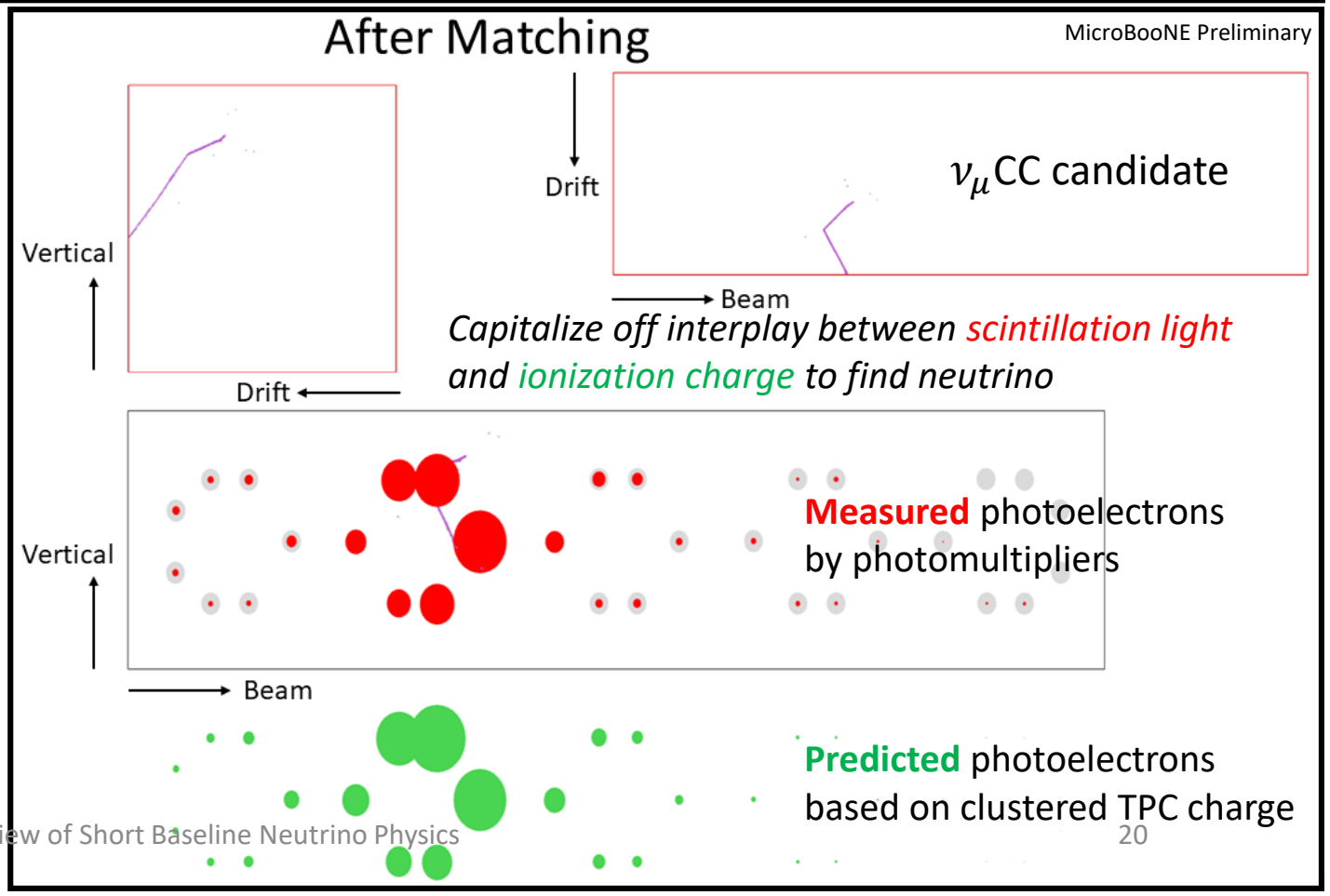
Contending with near-surface operation



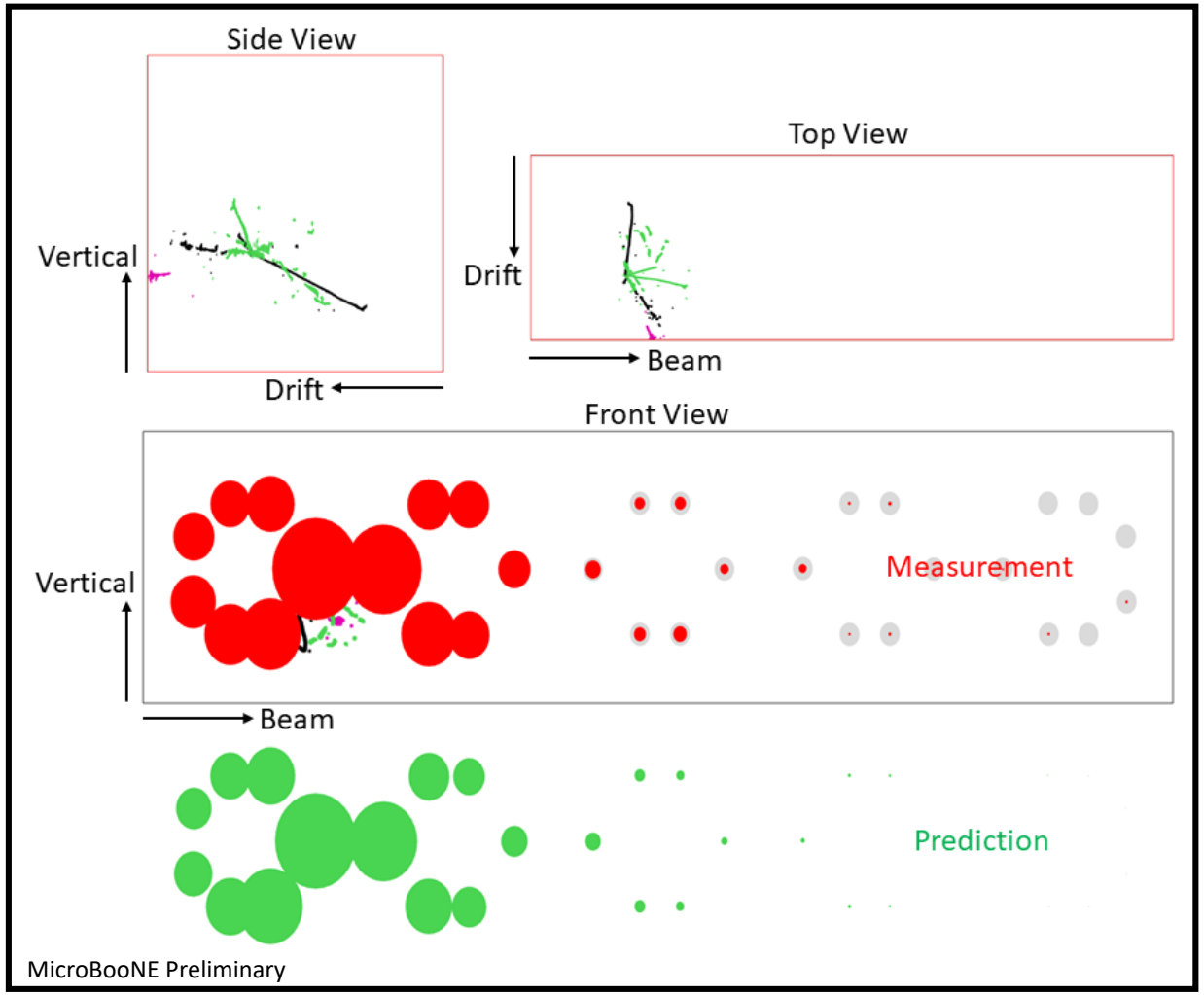
For first generation physics analyses, cosmic rays were the leading backgrounds

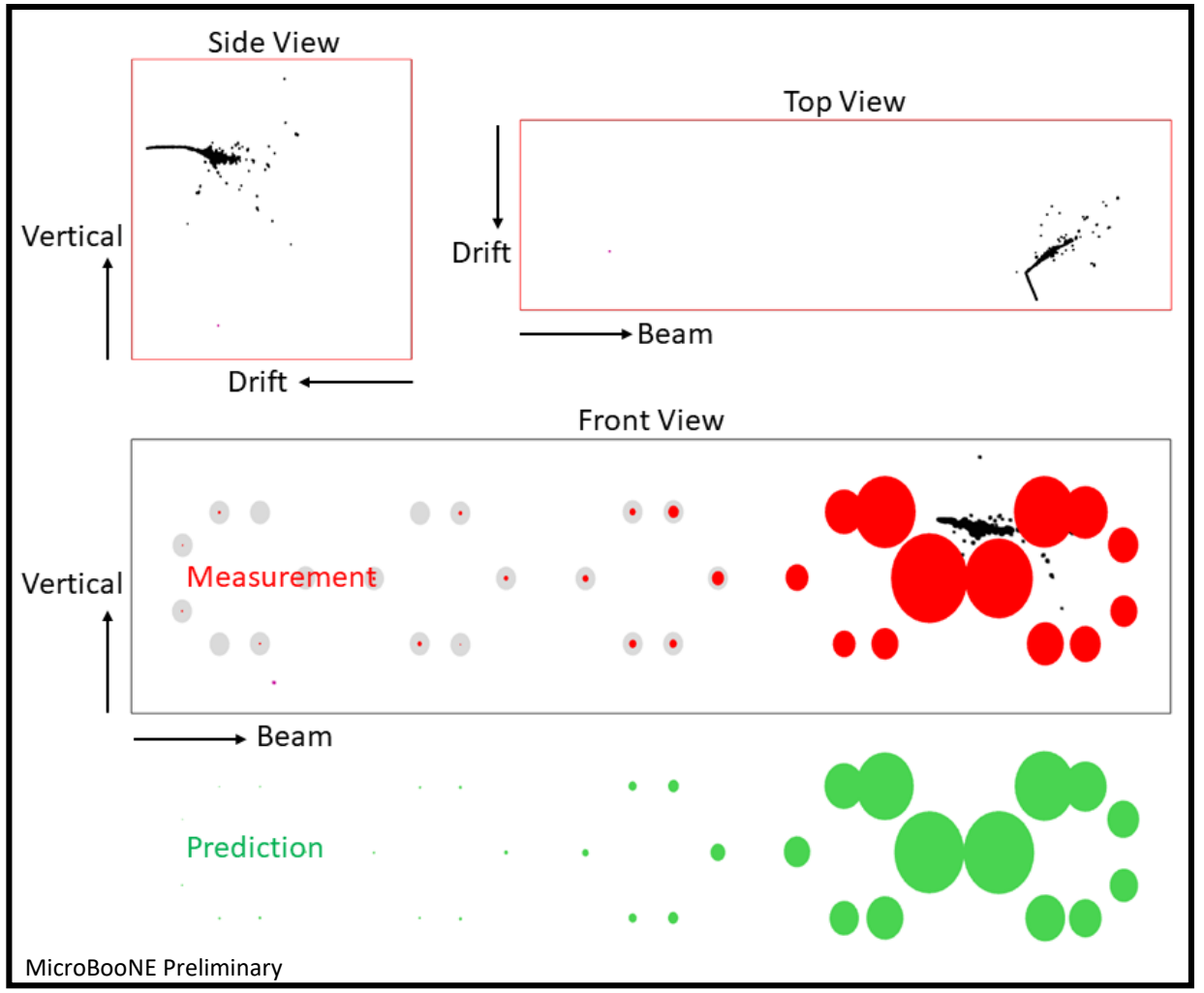
For next generation physics analyses, new techniques have been devised to identify neutrino candidates and disambiguate neutrino candidate activity from cosmic activity



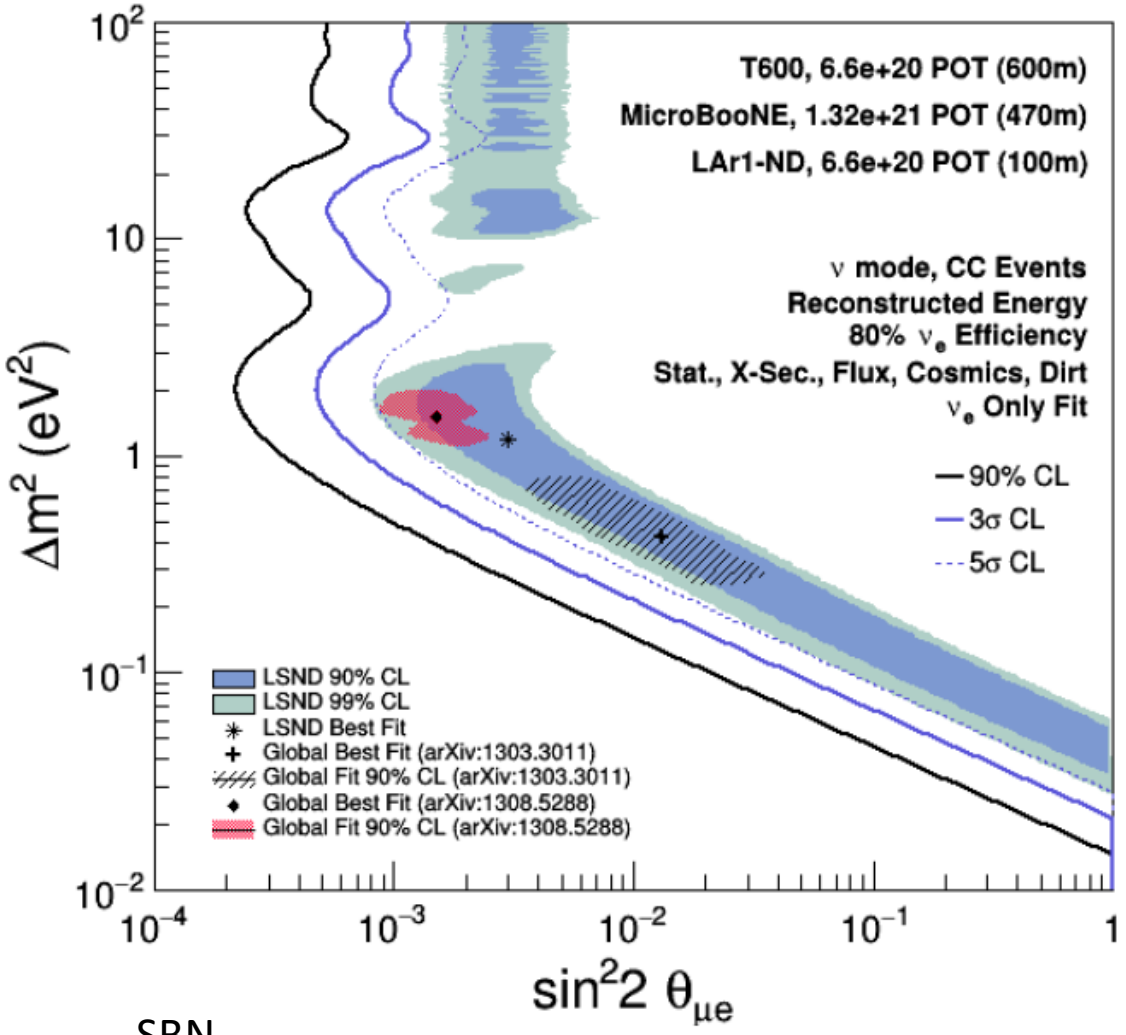


A topology agnostic method

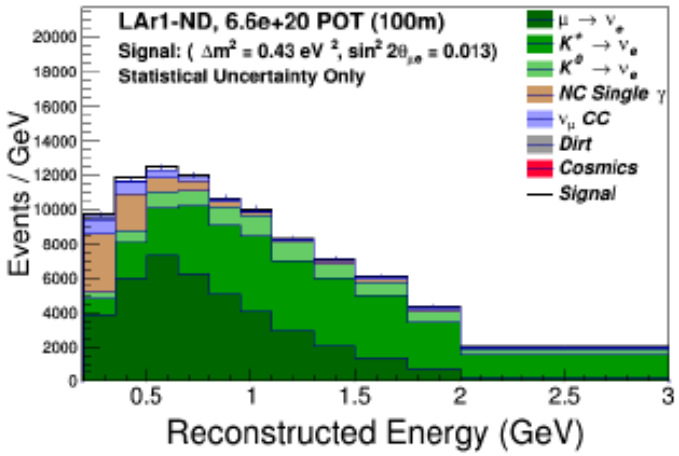


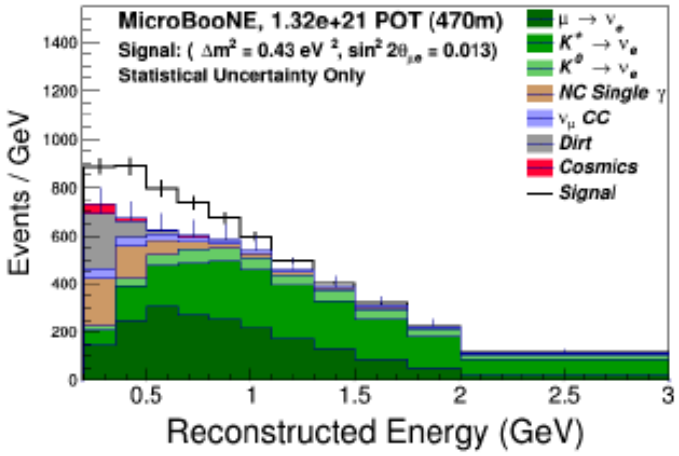


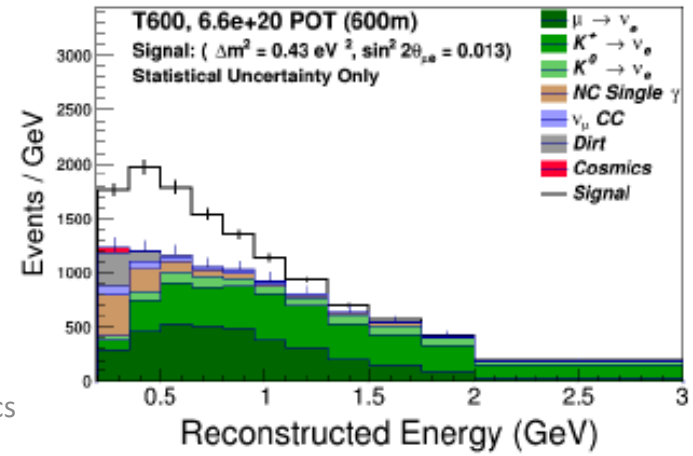
SBN $\nu_\mu \rightarrow \nu_e$



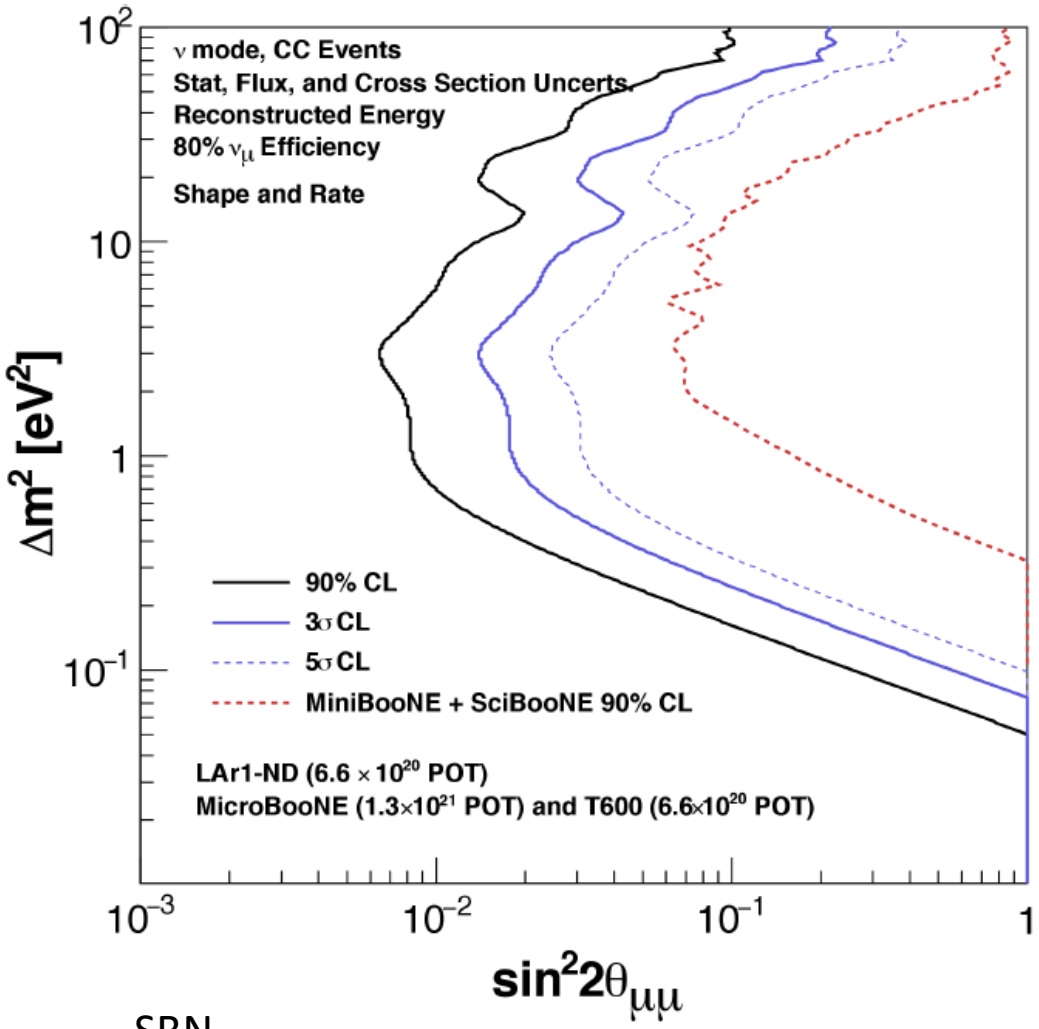
SBN
arXiv: 1503.01520

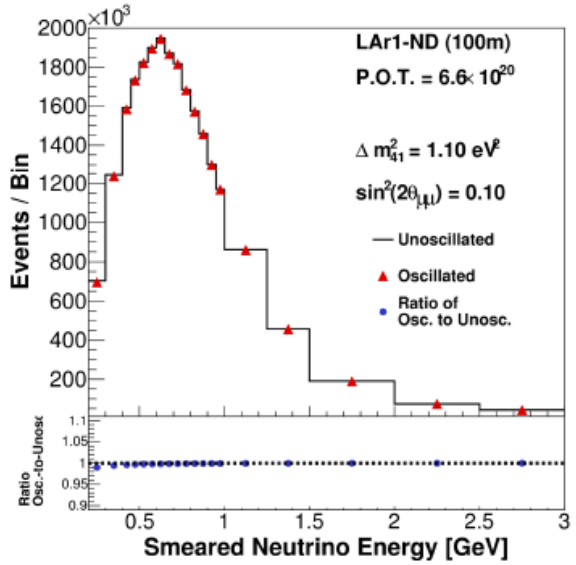


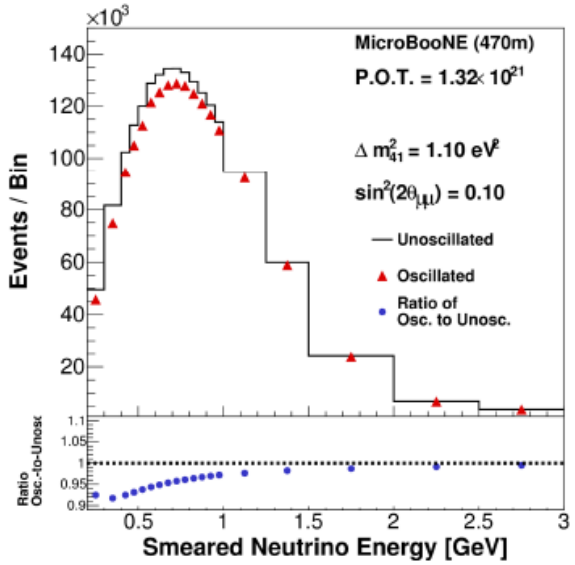


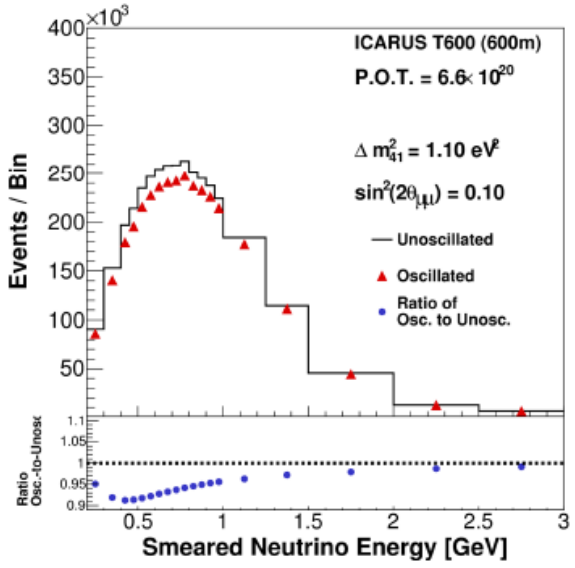


SBN $\nu_\mu \rightarrow \nu_\mu$









SBN
arXiv: 1503.01520

SBND

- CRT (cosmic ray tagger) panels installed in detector hall
- Detector construction on-going
- Plan to begin taking data in 2020

APA (anode plane assembly) prior to shipment to Fermilab from UK

From S. Soldner-Rembold (U. Manchester)

ICARUS

- Currently instrumenting and commissioning the detector
- Plan to begin taking data in 2019
- See parallel talk by H. Rogers

2nd detector module lowered into cryostat

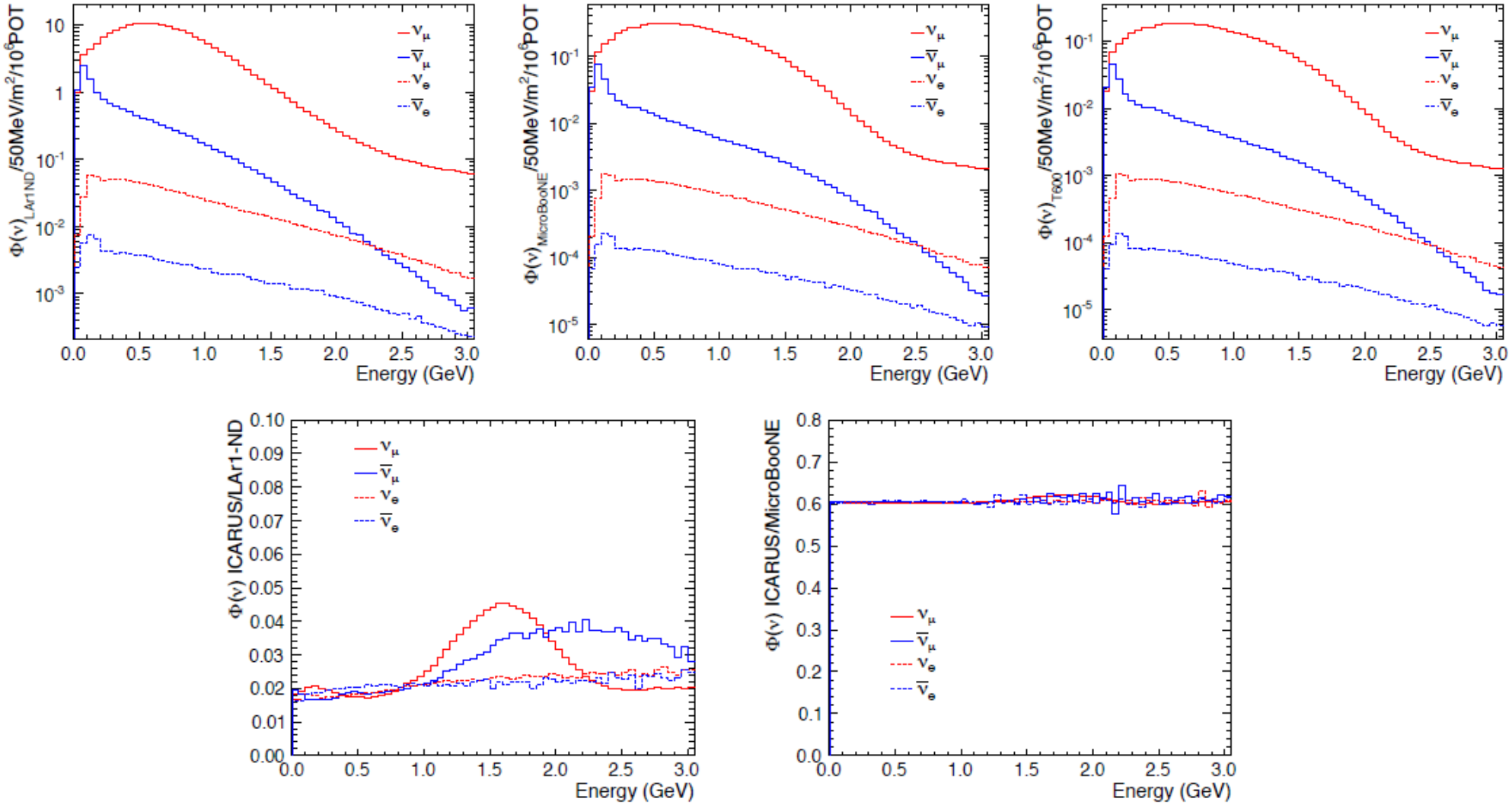
From R. Hahn (FNAL)

Summary

- The sterile neutrino picture is changing rapidly
  - Resolution of this problem is critical to the interpretation of long-baseline neutrino oscillation physics
- MicroBooNE is performing critical physics measurements *now*
  - In the vanguard of understanding and characterizing the innate detector response unique to single-phase LArTPCs
  - Making steady progress to fully address the MiniBooNE anomaly
- The SBN program expects to be in a position to definitively resolve the LSND anomaly
  - Study the baseline dependence of appearance and disappearance channels

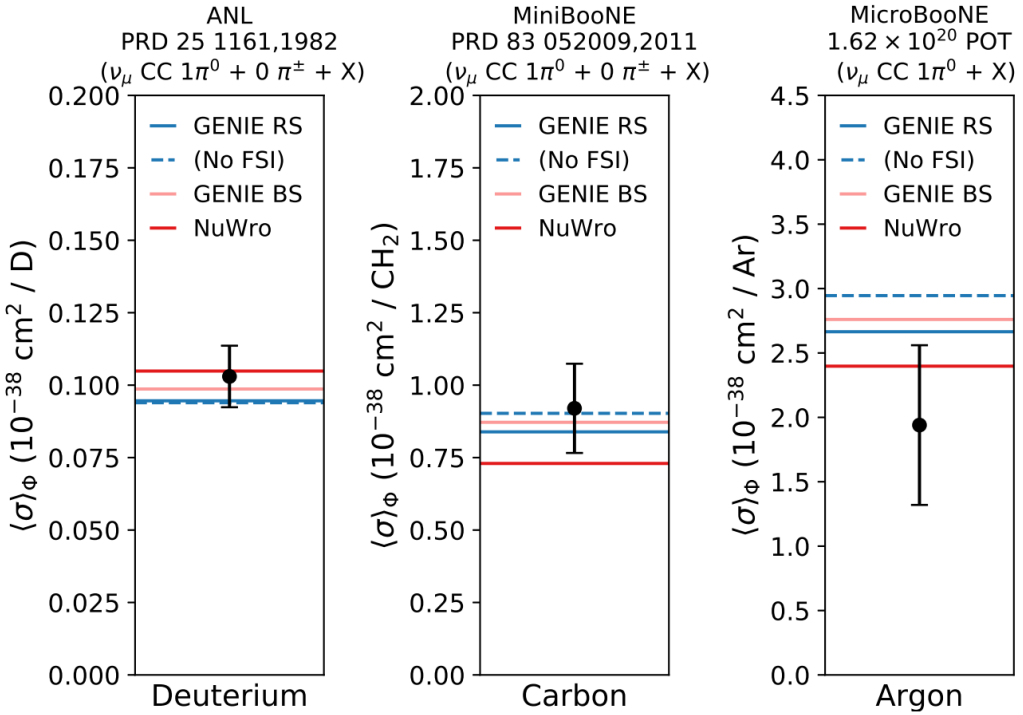
Backup slides

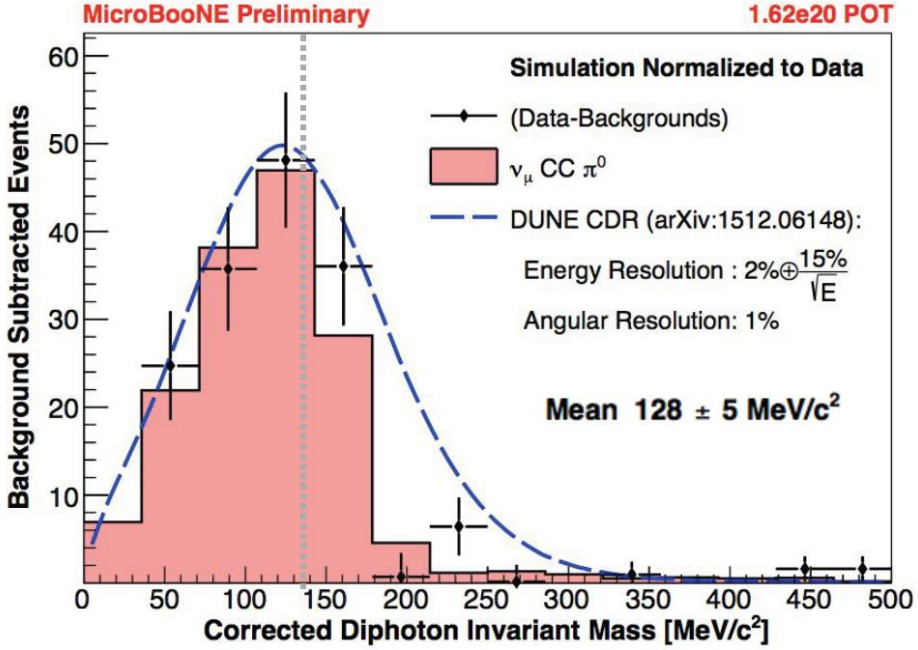
Booster neutrino beam flux @ SBN

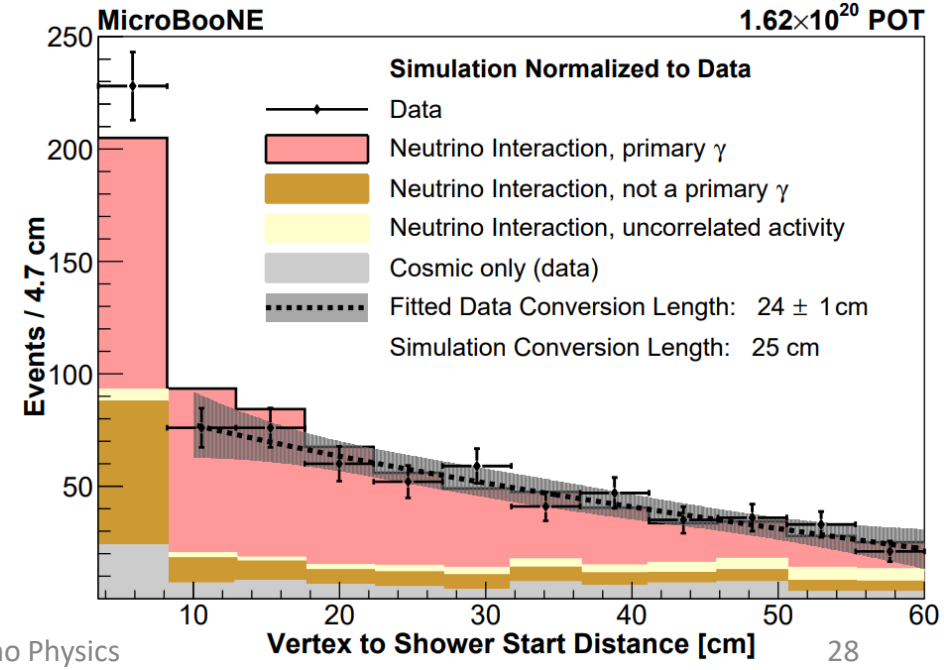


$\nu_\mu CC\pi^0$ total cross section

- First measurement on Ar
- A vital step towards low-energy excess analysis







Progress on MicroBooNE LEE analysis

- Selection of ν_μ events for the MicroBooNE deep learning low energy excess analysis --- MICROBOONE-NOTE-1051-PUB
- First muon-neutrino charged-current inclusive differential cross section measurement for MicroBooNE run 1 data --- MICROBOONE-NOTE-1045-PUB
- MicroBooNE low-energy excess signal prediction from unfolding MiniBooNE Monte-Carlo and data --- MICROBOONE-NOTE-1043-PUB
- The MicroBooNE Search for Single Photon Events --- MICROBOONE-NOTE-1041-PUB
- Tomographic event reconstruction with MicroBooNE data --- MICROBOONE-NOTE-1040-PUB
- Electron-neutrino selection and reconstruction in the MicroBooNE LArTPC using Pandora multi-algorithm pattern recognition --- MICROBOONE-NOTE-1038-PUB
- First measurement of muon neutrino charged current single neutral pion production on argon with the MicroBooNE LArTPC --- MICROBOONE-NOTE-1032-PUB
- Measurement of reconstructed charged particle multiplicities of neutrino interactions in MicroBooNE --- MICROBOONE-NOTE-1024-PUB