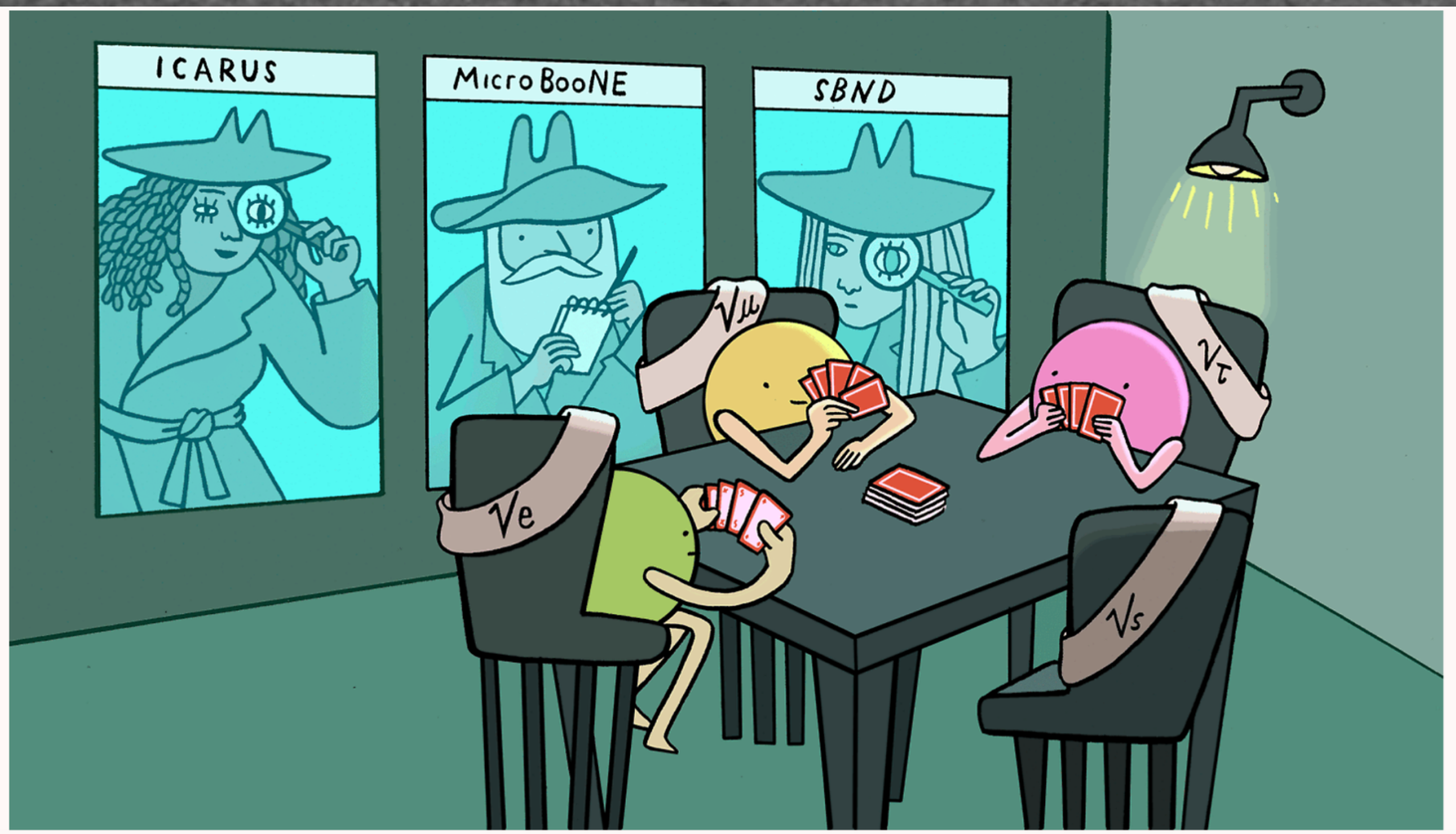
The Short Baseline Neutrino Oscillation Program at Fermilab



from Symmetry Magazine

Artwork by Sandbox Studio, Chicago with Corinne Mucha

Jyoti Joshi

Brookhaven National Laboratory

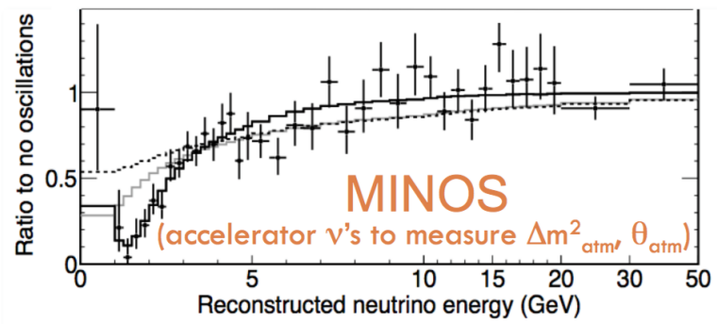
CIPANP 2018, May 29 - June 3, Palm Springs

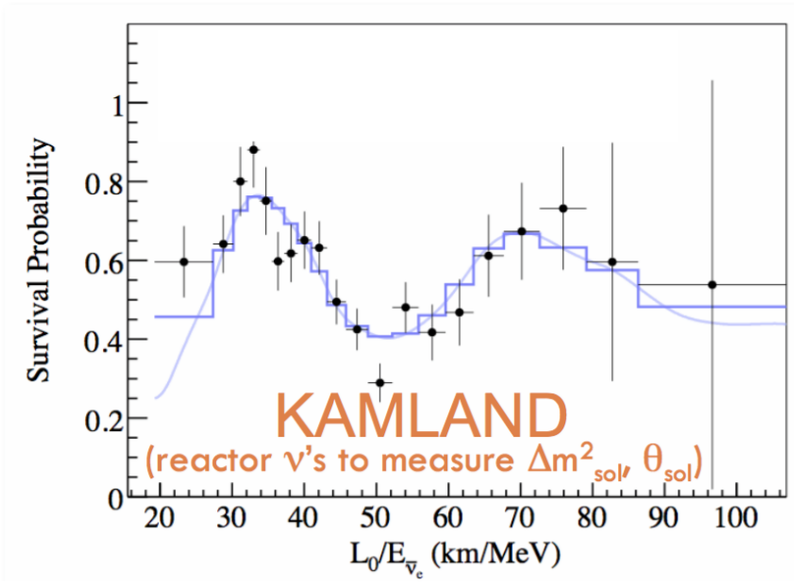
Outline

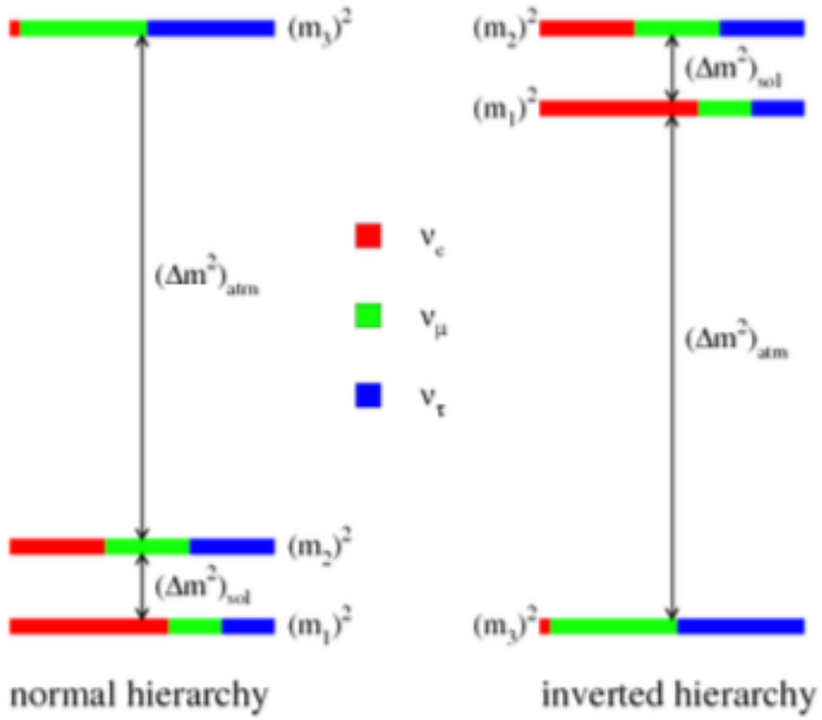
- Current state of the field and anomalies
- The SBN program
- Liquid Argon Time Projection Chambers
- Phase I: MicroBooNE
- Phase II: Full SBN (ICARUS and SBND)
- Conclusions

Current State of the Field

* Established evidence for neutrino flavor oscillations with multiple experiments using different detector technology and neutrino sources







Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.56 ± 0.19
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.55 ± 0.04
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	2.49 ± 0.04
$\theta_{12}/^\circ$	$34.5^{+1.1}_{-1.0}$
$\theta_{13}/^\circ$	$8.44^{+0.18}_{-0.15}$
$\delta/^\circ$	252^{+56}_{-36}
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$
$\theta_{23}/^\circ$	41.0 ± 1.1
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$
$\theta_{23}/^\circ$	50.5 ± 1.0

arxiv:1708.01186

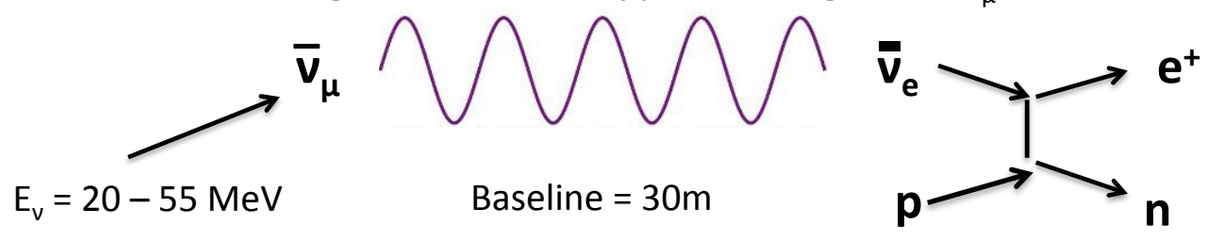
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

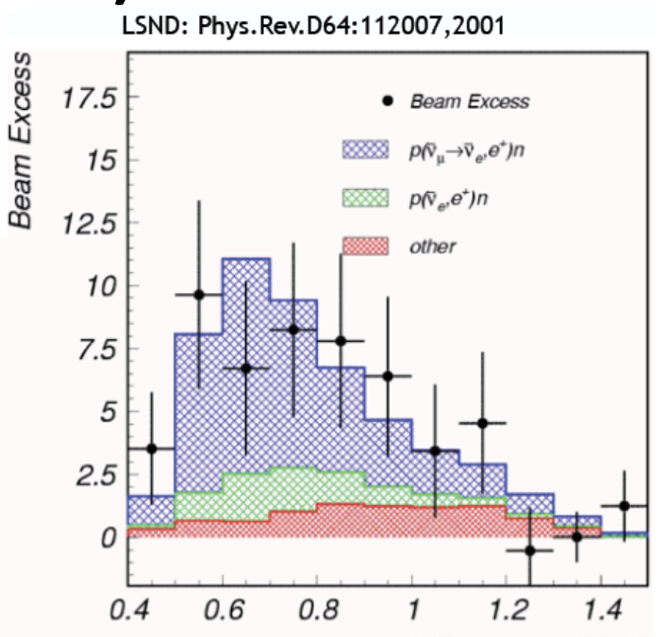
* θ_{13}, mixing angle, opens the way to measurement of δ_{CP}

SB Anomalies: LSND

LSND (Liquid Scintillator Neutrino Detector):

Looking for an electron appearance signal in a ν_μ beam.





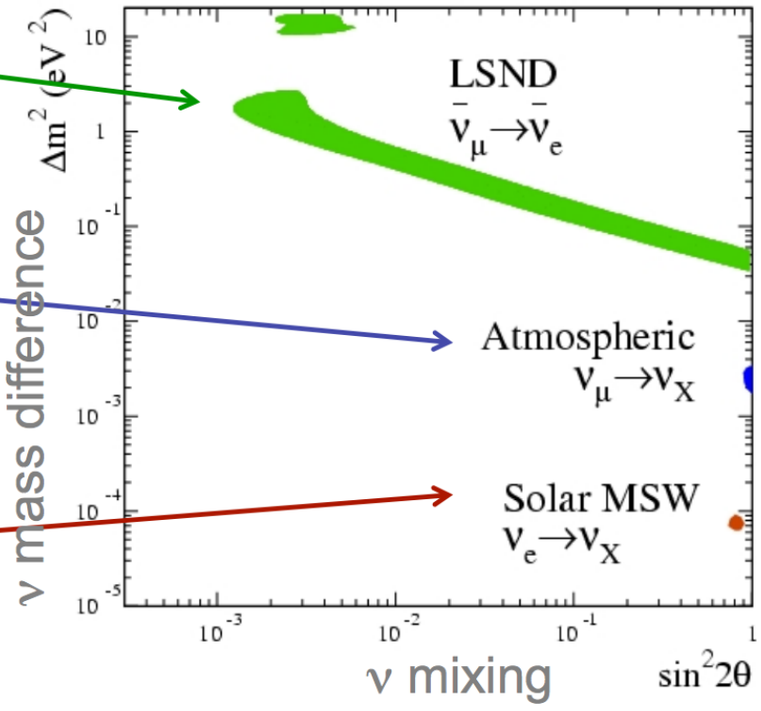
Observed 87.9 ± 22.4 ± 6.0 events above background
Oscillation Probability: 0.26%

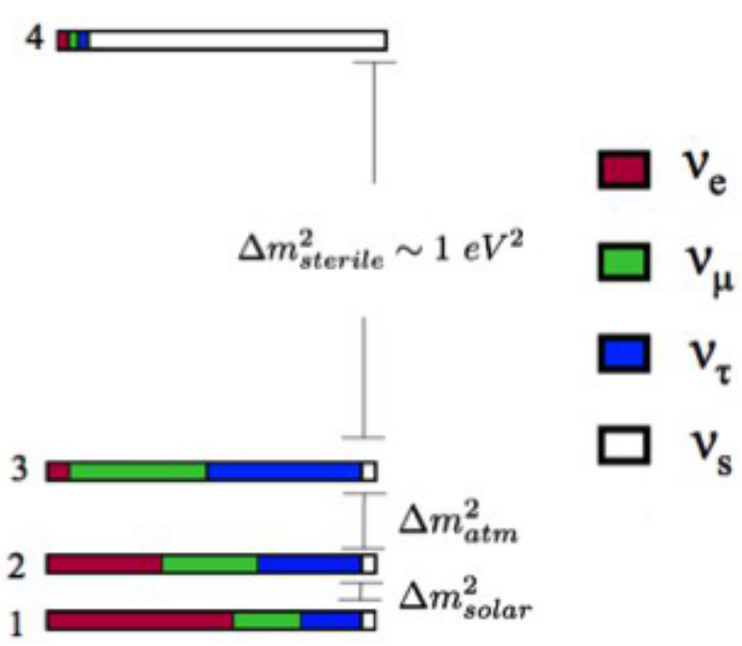
Consistent with a Δm^2 on the order of 1 eV^2 (not consistent with 3 flavor picture)

LSND
$\Delta m^2 \sim 1\ eV^2$
$\theta \sim 2^0$

atmospheric oscillations
$\Delta m^2 \sim 10^{-3}\ eV^2$
$\theta \sim 45^0$

solar oscillations
$\Delta m^2 \sim 10^{-5}\ eV^2$
$\theta \sim 34^0$

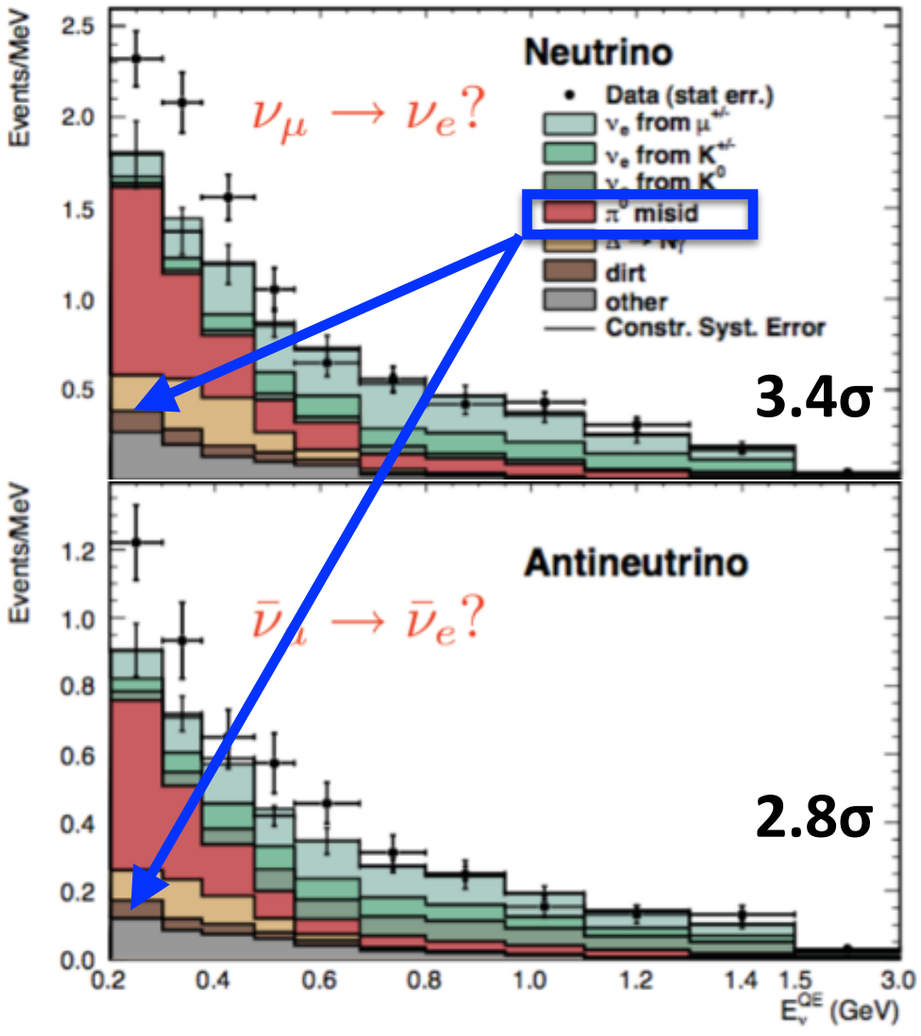




One possible interpretation: at-least one extra ν (sterile neutrino ?)

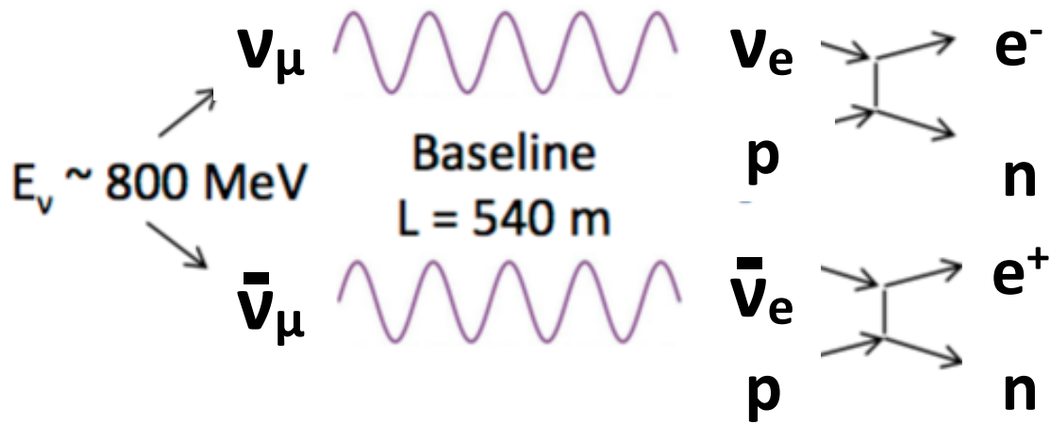
SB Anomalies: MiniBooNE

PRL 110, 161801 (2013)



Excess of low energy electromagnetic events in neutrino and antineutrino mode.

Same L/E as LSND



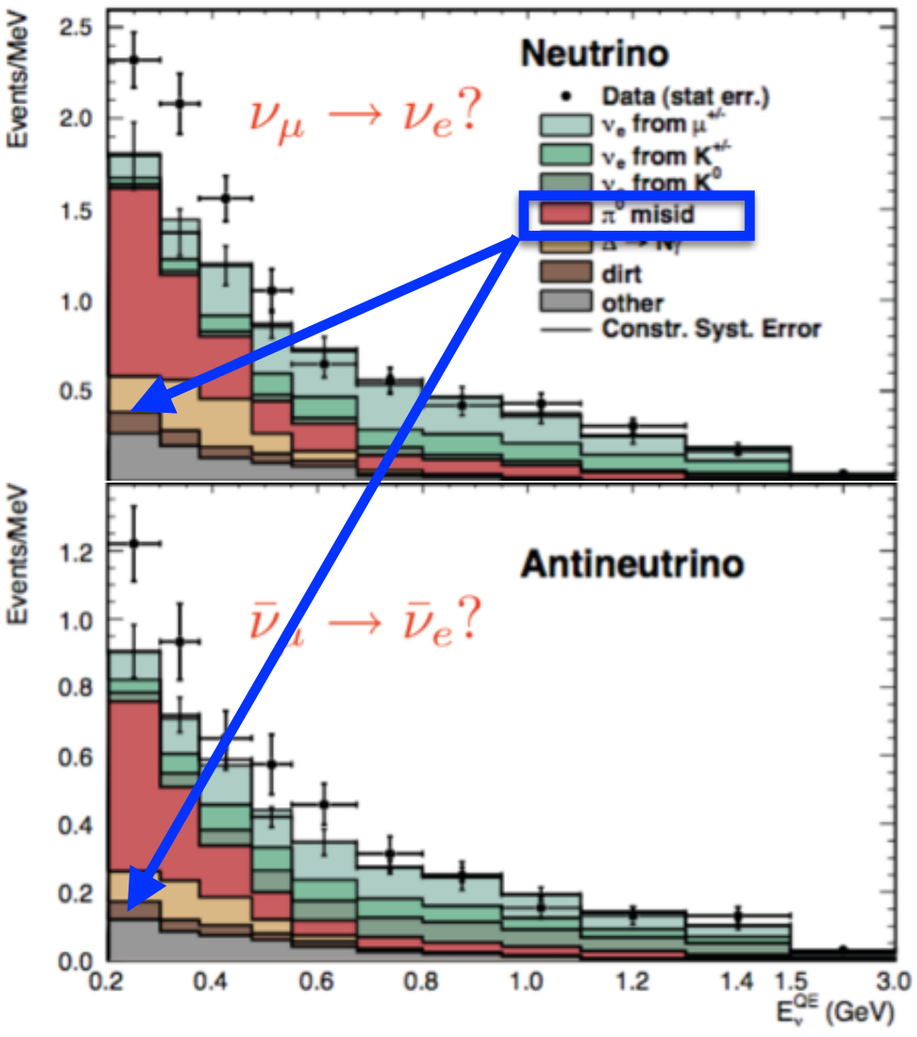
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay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

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

Tension between appearance and disappearance experiments

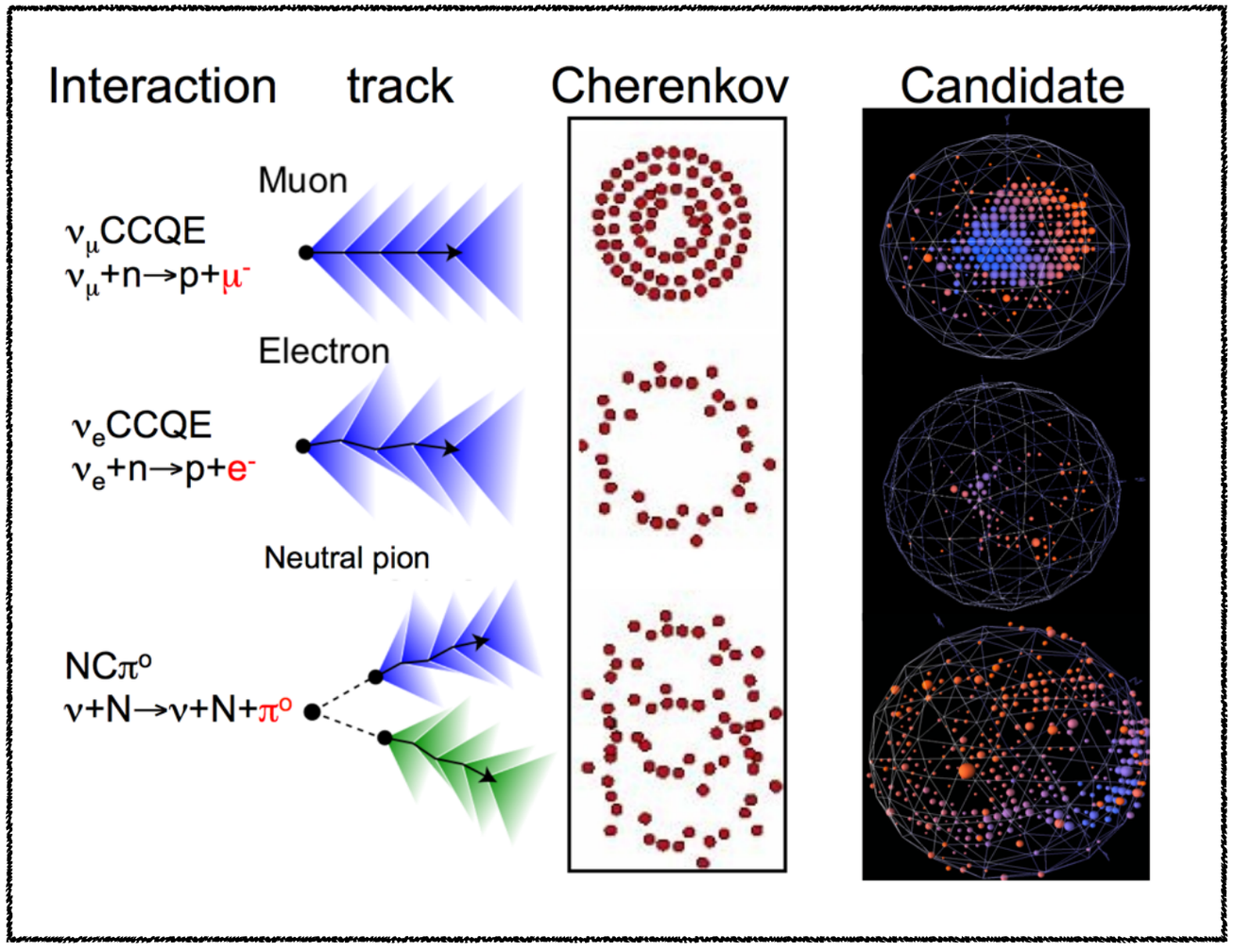
SB Anomalies: MiniBooNE

PRL 110, 161801 (2013)



Excess of low energy electromagnetic events in neutrino and antineutrino mode.

But!



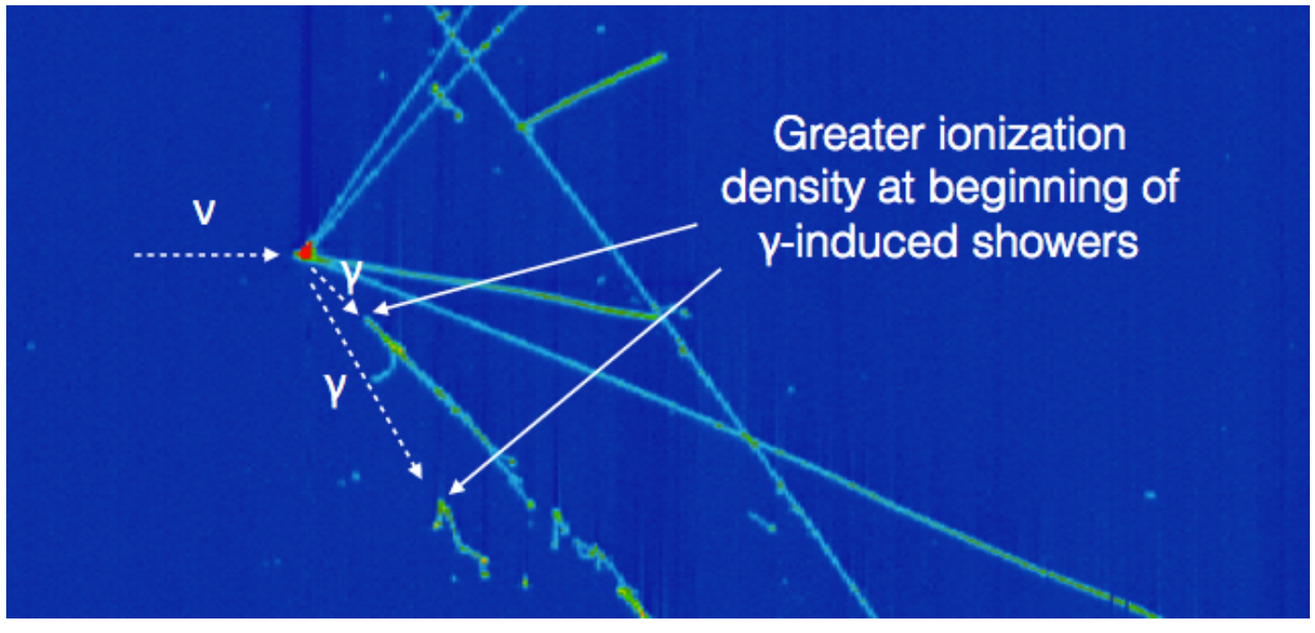
At MiniBooNE low energy, γ was the biggest background, which was hard to distinguish from e^- in Cherenkov detector

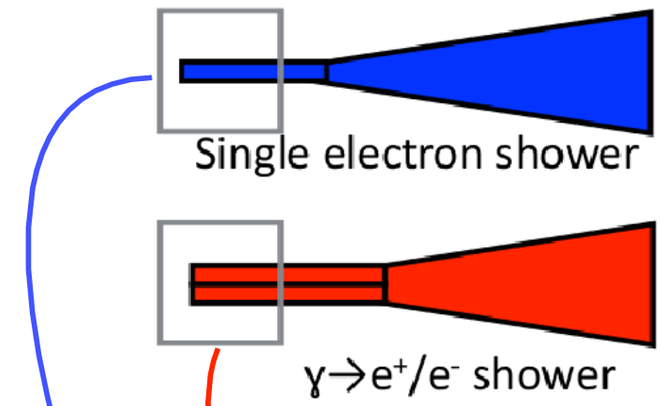
Introducing LArTPC…e/γ Separation

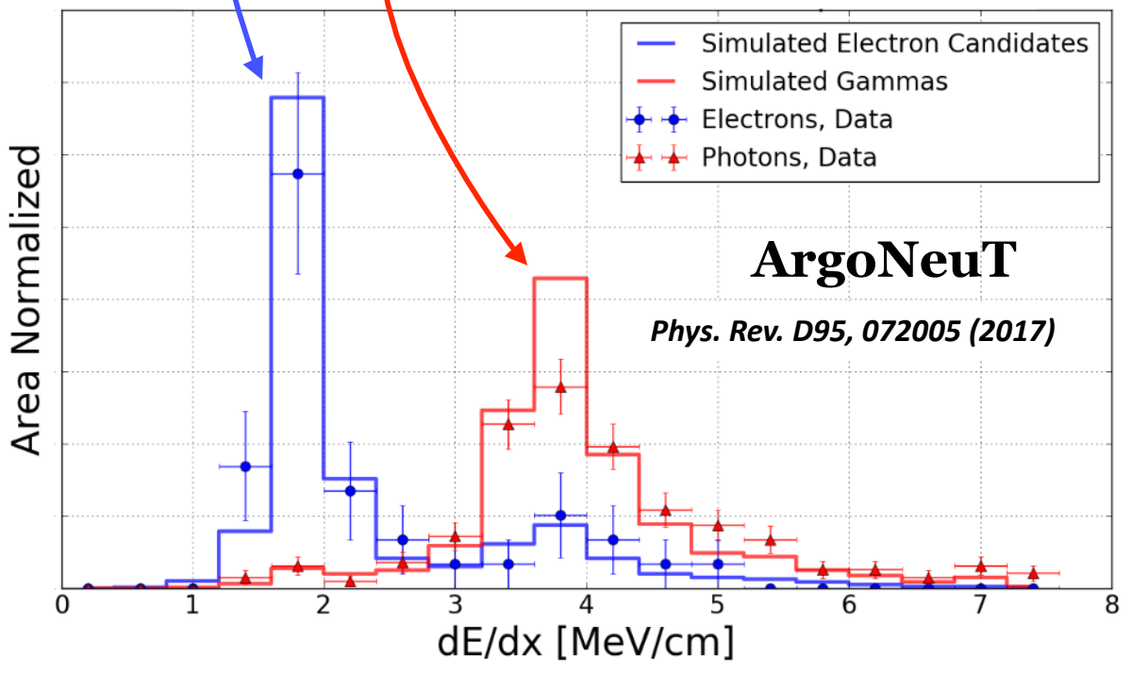
Liquid Argon Time Projection Chambers:

* Digitized bubble chamber-like images
* Excellent resolution and Calorimetry
* Scalability to large mass

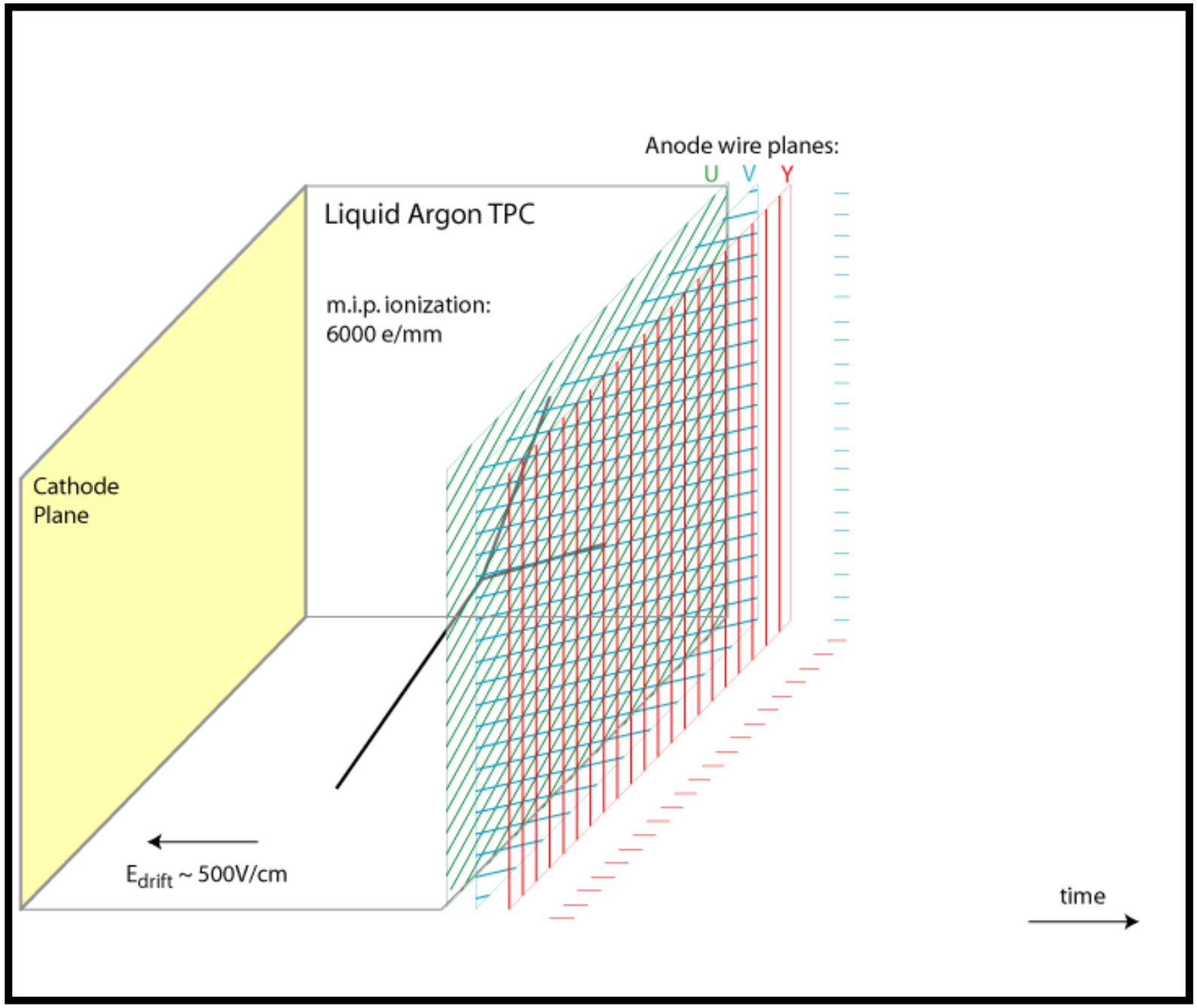
* Can discriminate $e^{\pm}/\gamma$ with LArTPC
  - Shower displacement from vertex ("gap") for γ provides separation
  - Separation with dE/dx

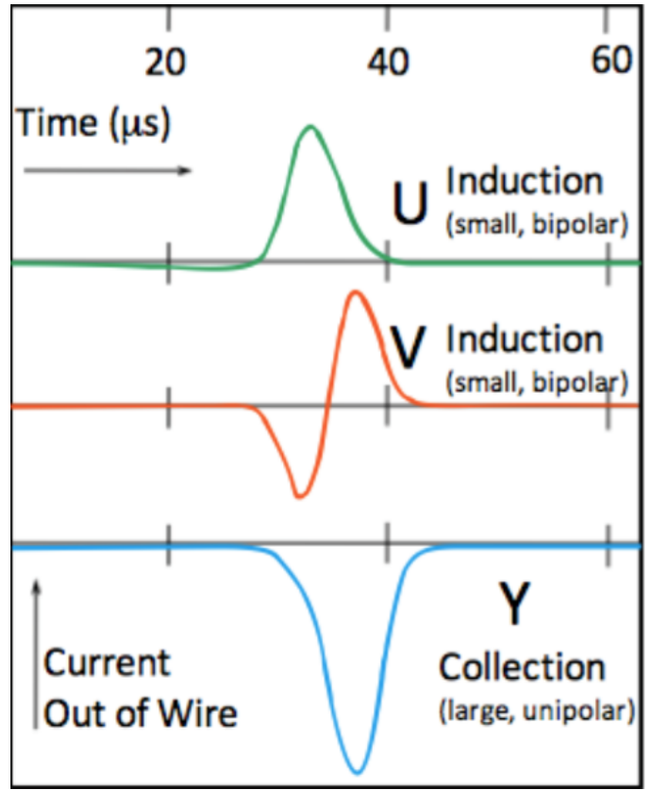






LArTPC Signal Formation





* Fine grained 3D tracking
* Fully active calorimetry

SBN Program: three LArTPC detectors

Linac
Length: 150m
Proton Energy: 400 MeV

Booster
Circumference: 468m
Proton Energy: 8 GeV

BNB

NuMI

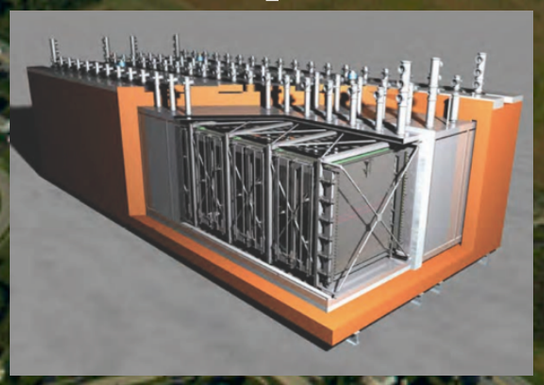
Protons

Neutrinos

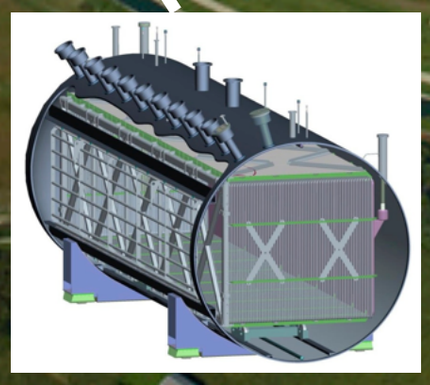
(600 m)
476 tons

(470 m)
85 tons

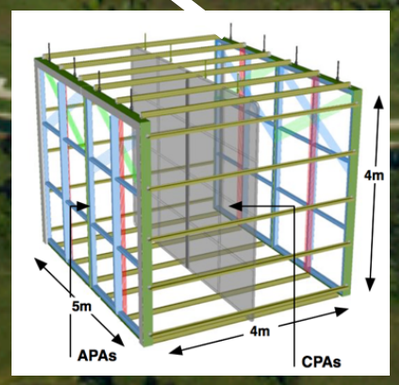
(110 m)
112 tons



ICARUS-T600



MicroBooNE



Short Baseline Near Detector (SBND)

SBN Program Goals

* Resolve the “low-energy excess” anomaly
  - Confirm the MiniBooNE result by repeating measurement at similar location, same beam and similar baselines
  - Determine if the excess is electron-like or photon-like in nature

* Search for ν_e appearance and ν_μ disappearance
  - Multiple detectors at different baselines reduce systematics uncertainties with same target and same beam

* Lay groundwork for future long-baseline program
  - Further develop Liquid Argon TPC detector technology
  - Measure ν-Ar cross sections at energies relevant to DUNE

Phase I: The MicroBooNE detector

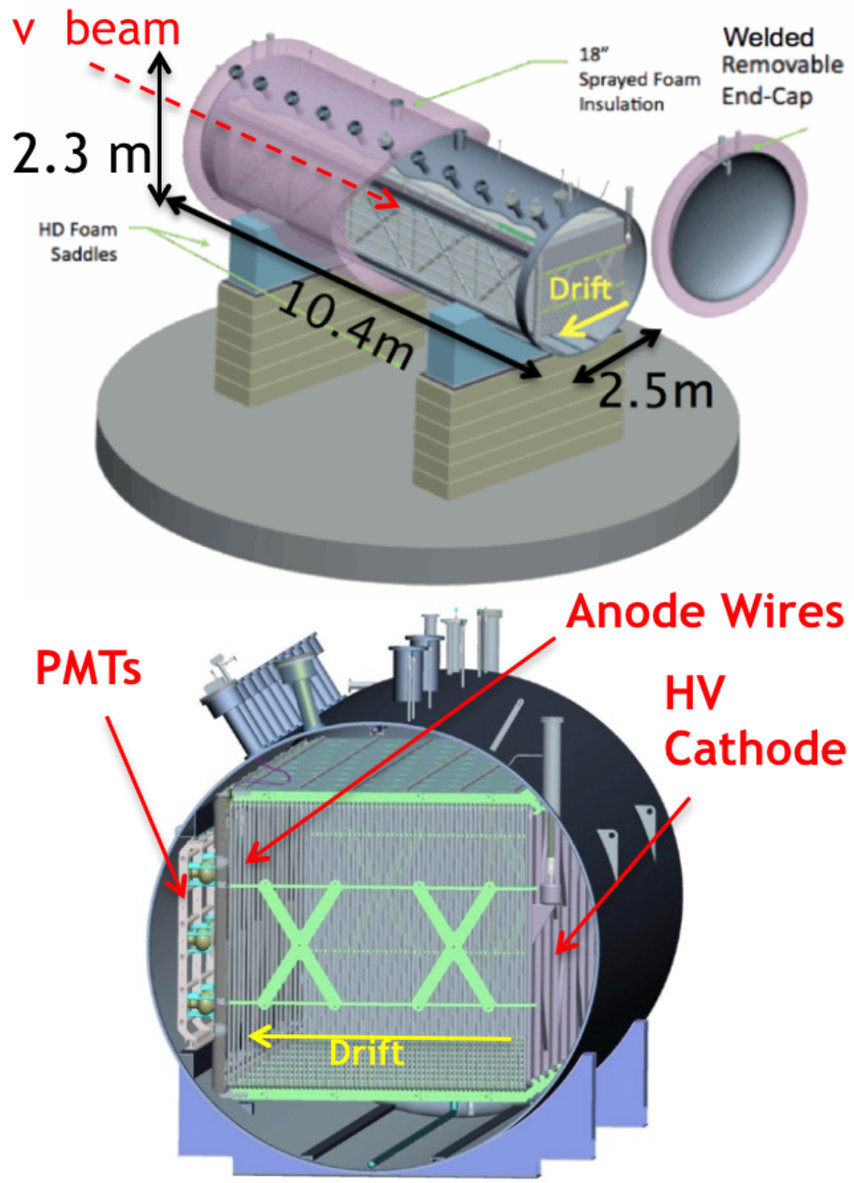
First detector to come online from the SBN Program
Running Stably since 2015!

* **Liquid Argon Time Projection Chamber:**
  - Three planes of wire at 3mm pitch
    - One Collection plane at 0° from vertical
    - Two induction planes at ±60°
  - Total 8192 channels
  - 2.5 m drift length

* **Optical System:**
  - 32 cryogenic photomultiplier tubes (PMT)
  - LED based light injection system

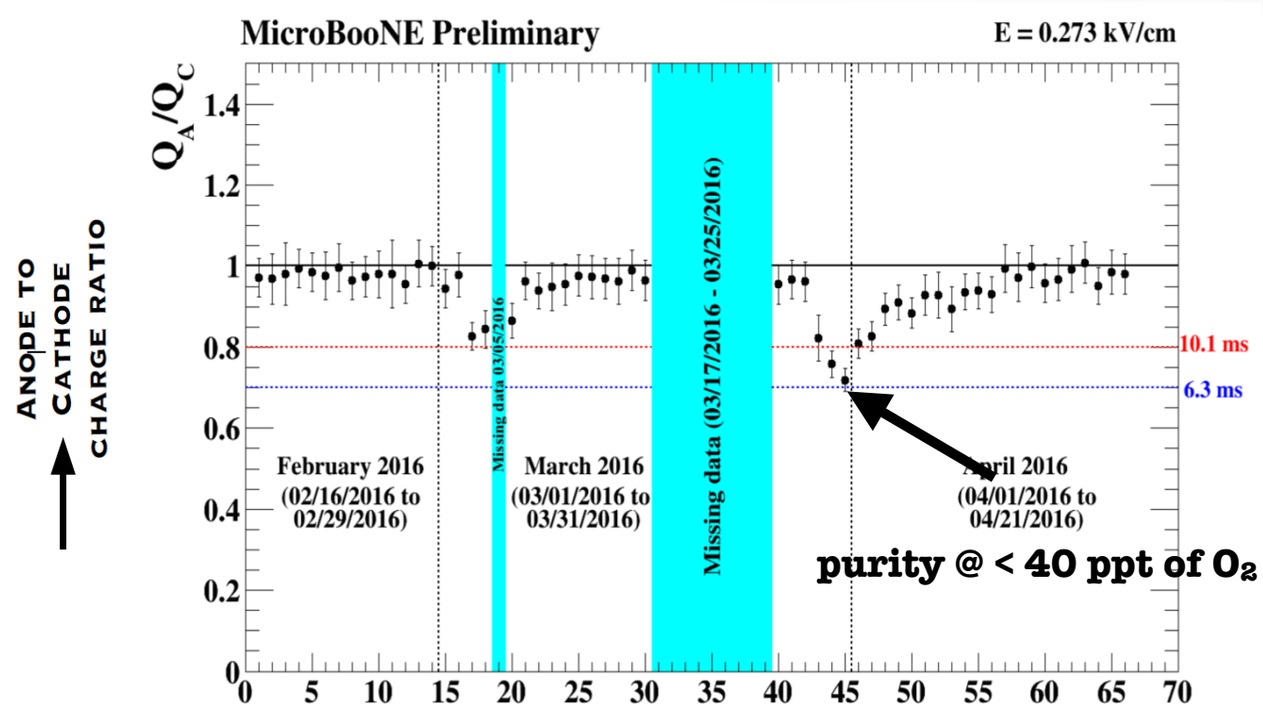
* **UV Laser Calibration System**

* **External Muon Tagger System**



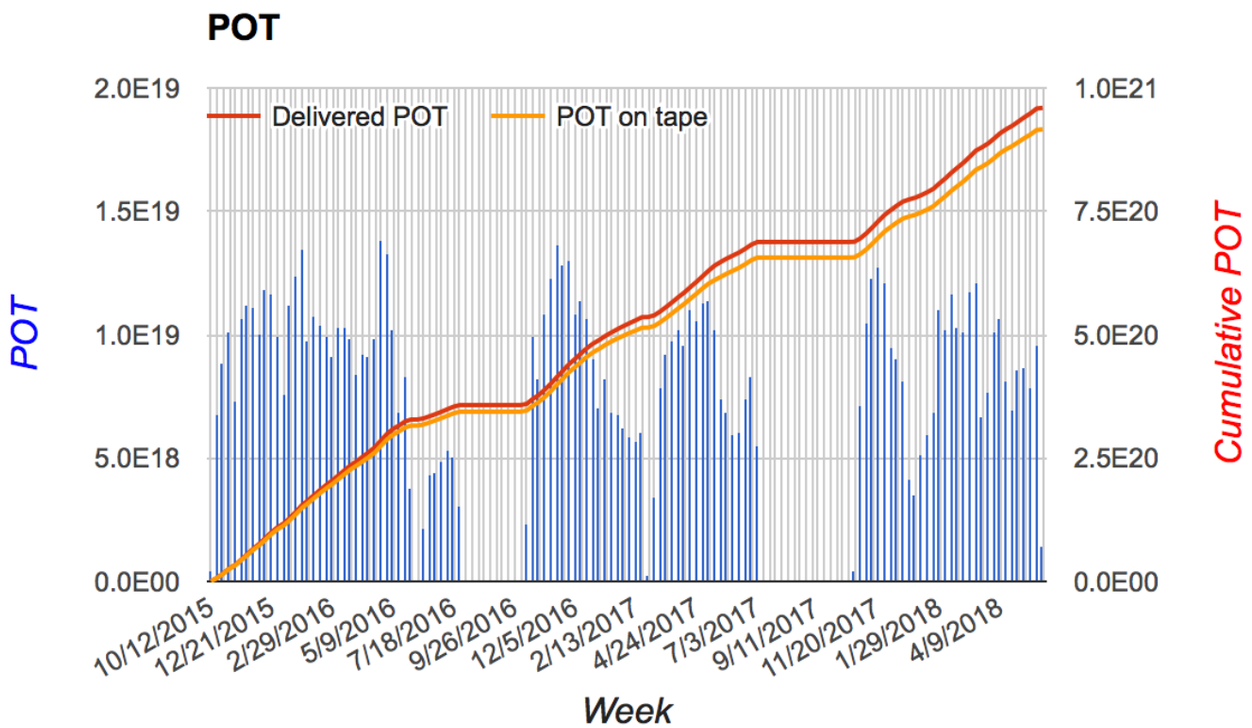
**** 170 tons of purified LAr (active mass ~85 tons)***

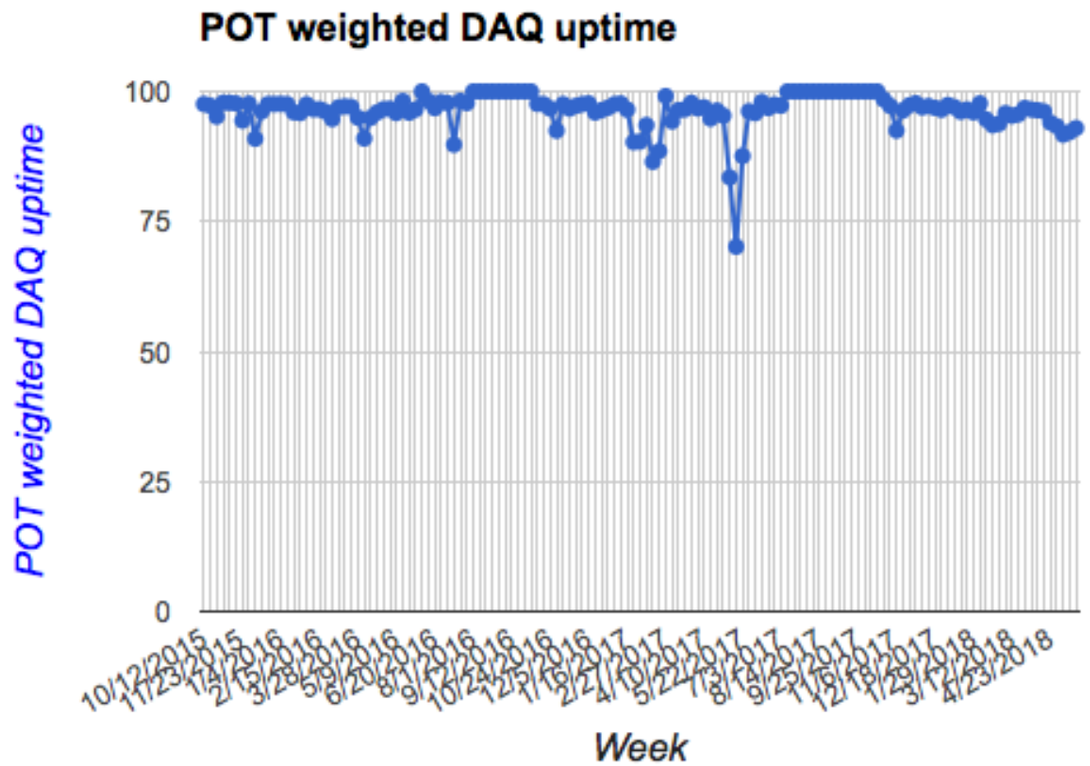
Detector Performance & Stability



- High DAQ uptime - greater than **97%** POT-weighted DAQ uptime on average
- Electron lifetime is very high (steadily above **6 ms**), measured by purity monitors as the fraction of charge detected at its anode relative to its cathode

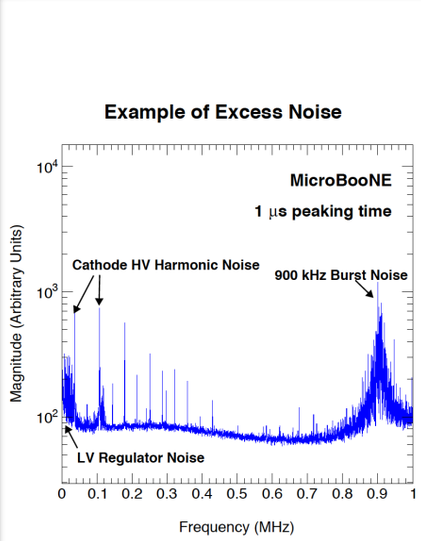
[MicroBooNE-NOTE-1003-PUB.pdf]

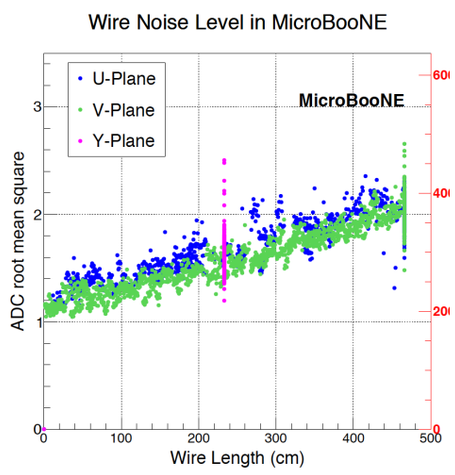


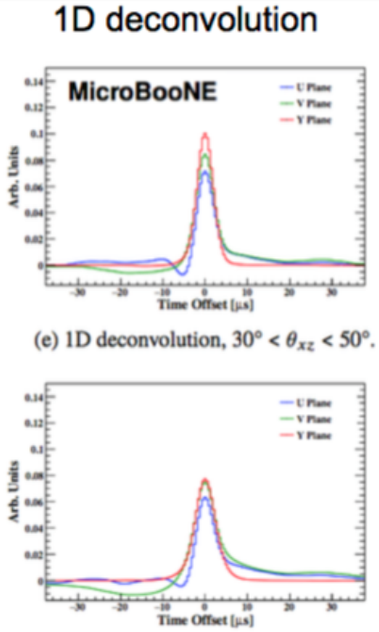


Active Detector Physics Program

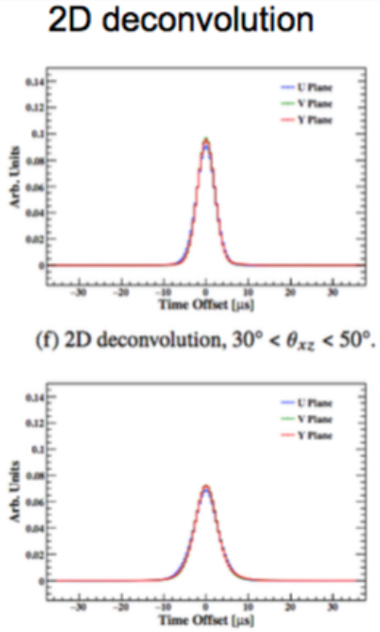
* Develop foundational knowledge of LArTPC design, capabilities, and operation
  - Essential for SBN and DUNE
  - Purity, Noise studies, wire response, energy scale, cosmic ray rate, space charge effects, e^- lifetime, diffusion etc.







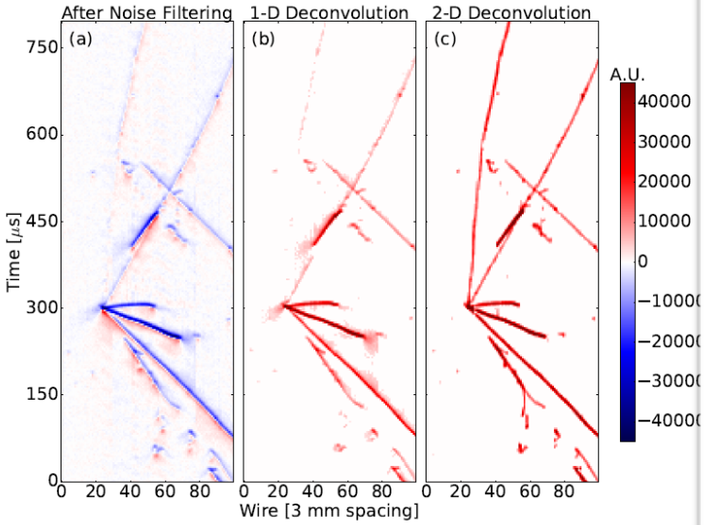
(e) 1D deconvolution, $30° < \theta_{xz} < 50°$.

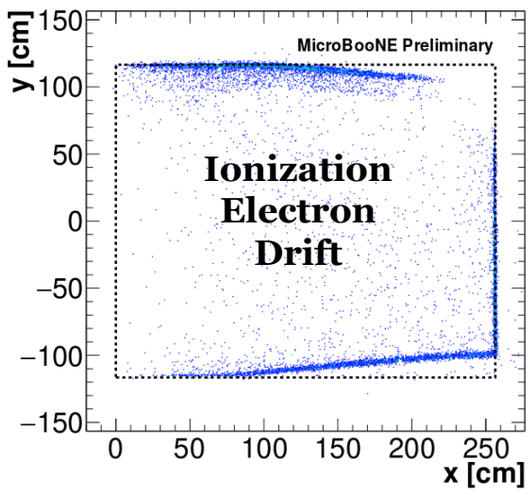


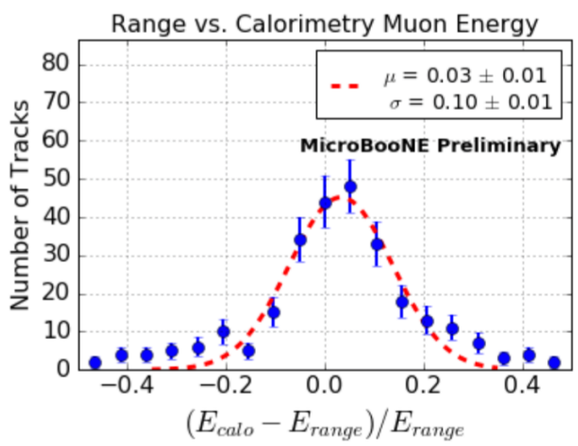
(f) 2D deconvolution, $30° < \theta_{xz} < 50°$.

(g) 1D deconvolution, $50° < \theta_{xz} < 70°$.

(h) 2D deconvolution, $50° < \theta_{xz} < 70°$.







Active Detector Physics Program

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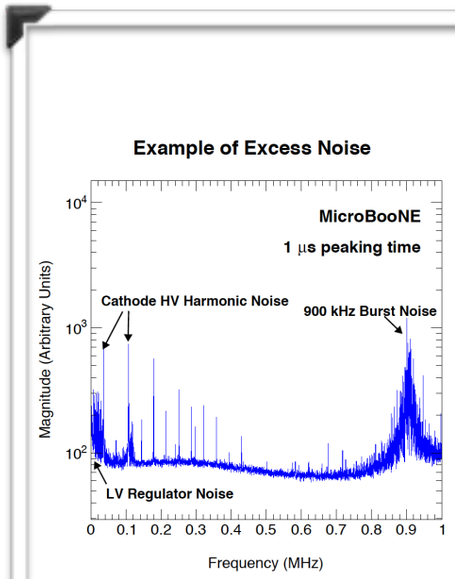
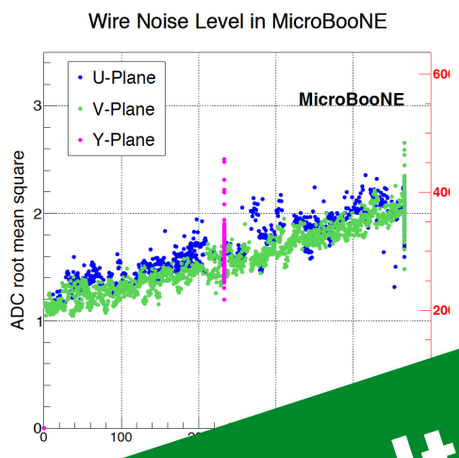
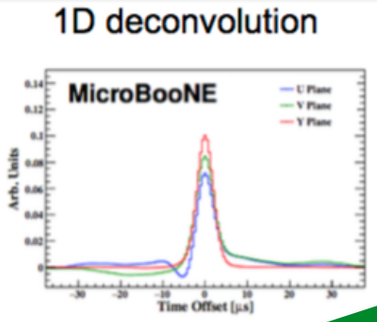
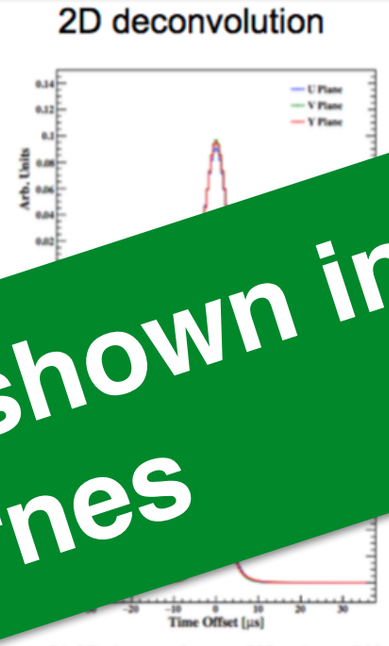


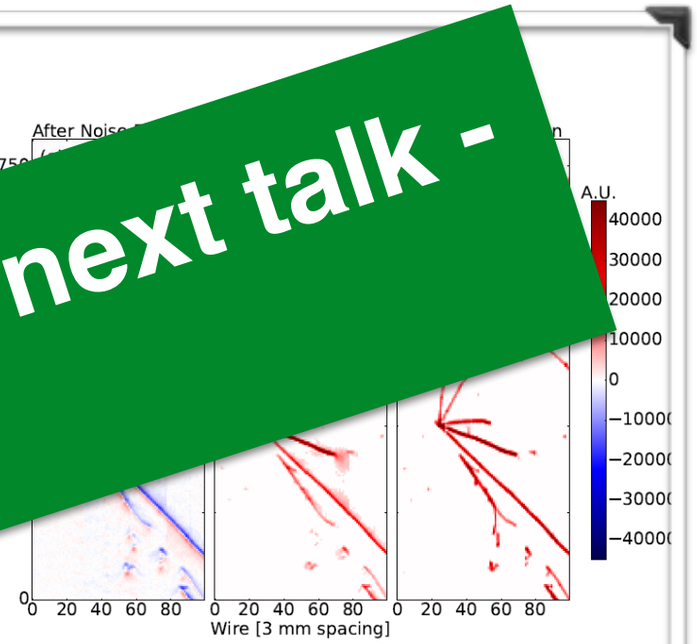


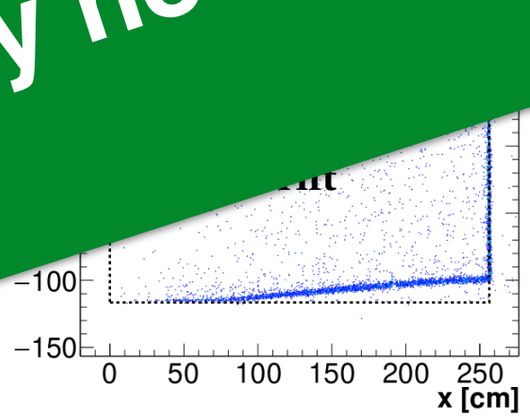


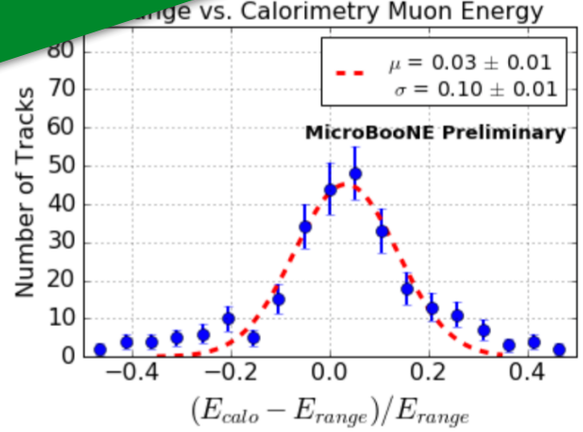
(e) 1D deconvolution, 30°



(h) 2D deconvolution, $50° < \theta_{xz} < 70°$.

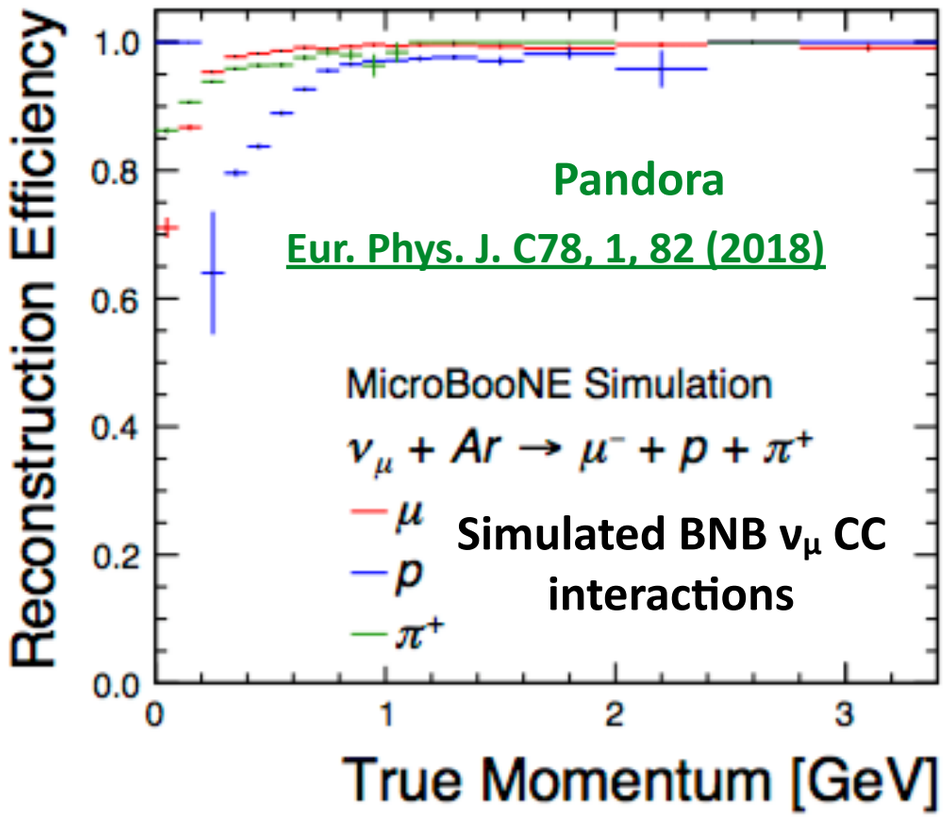


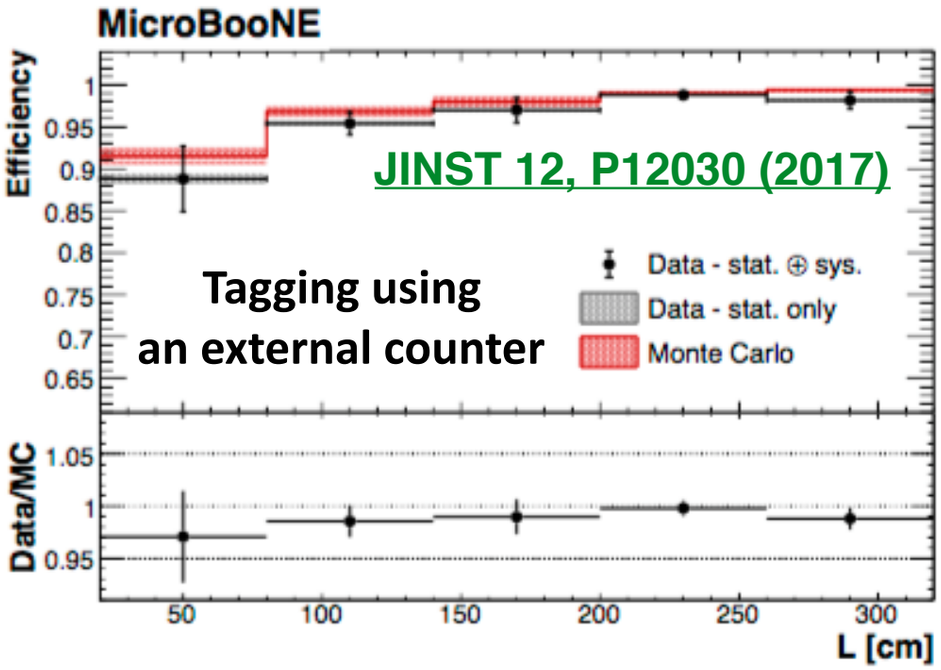


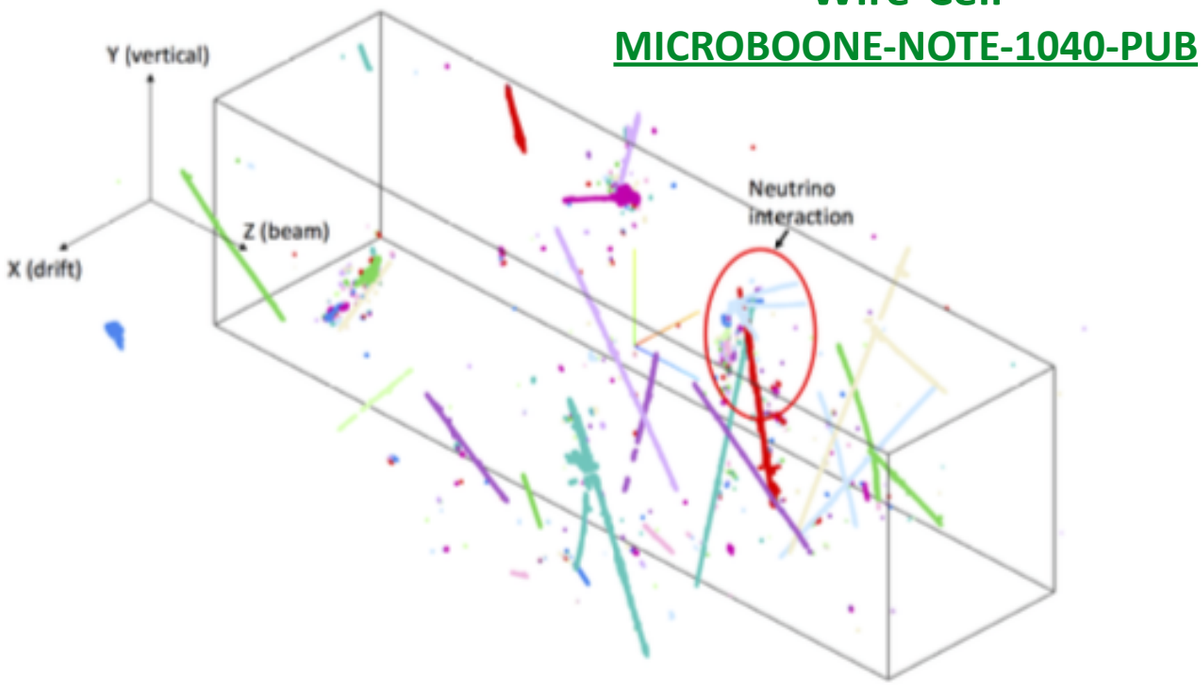


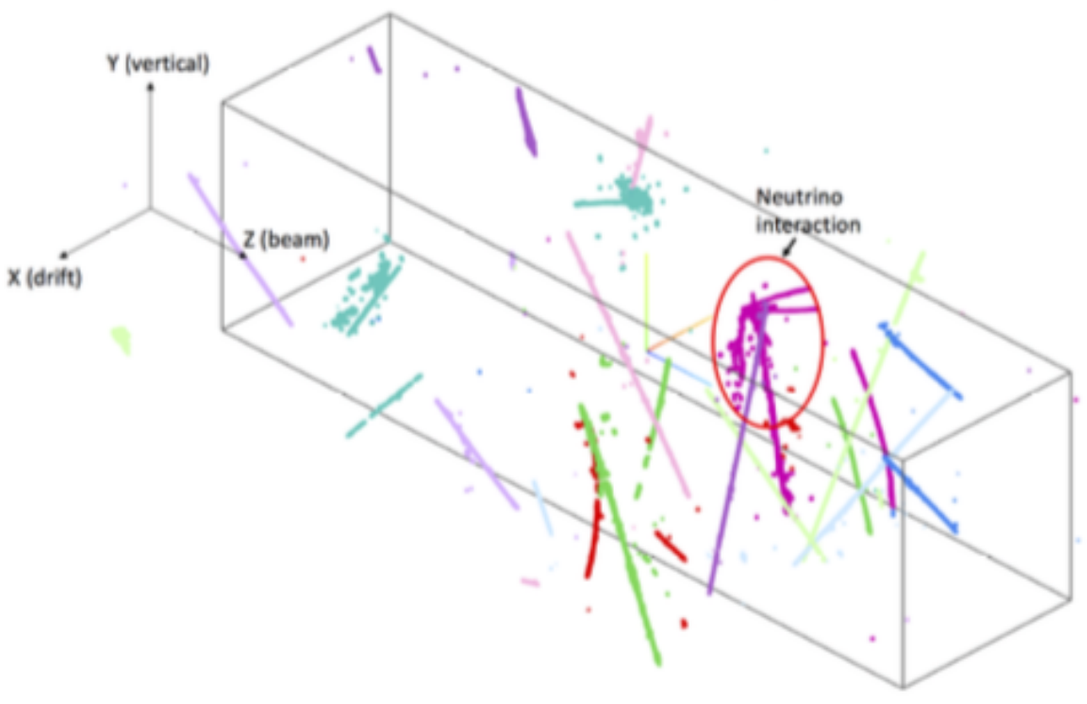
Many new results will be shown in next talk - Chris Barnes

Developing LAr Reconstruction



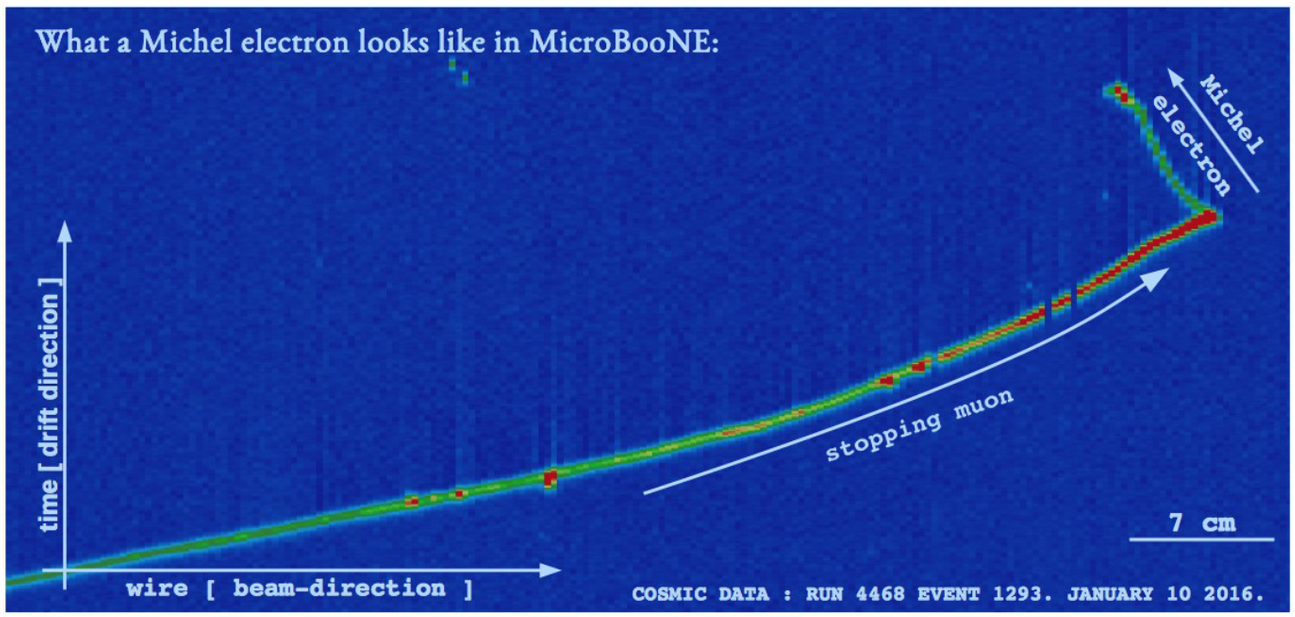






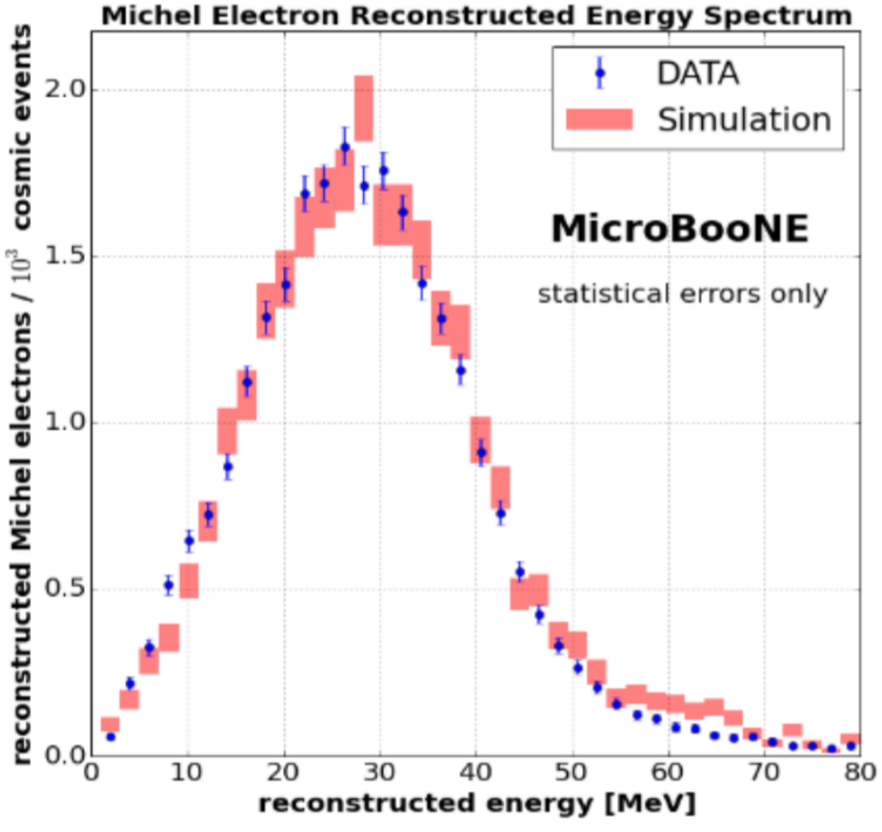
Standard Candle: Michel Electrons

Tons of cosmic data available due to the detector being at the surface!



[JINST 12, P09014 (2017)]

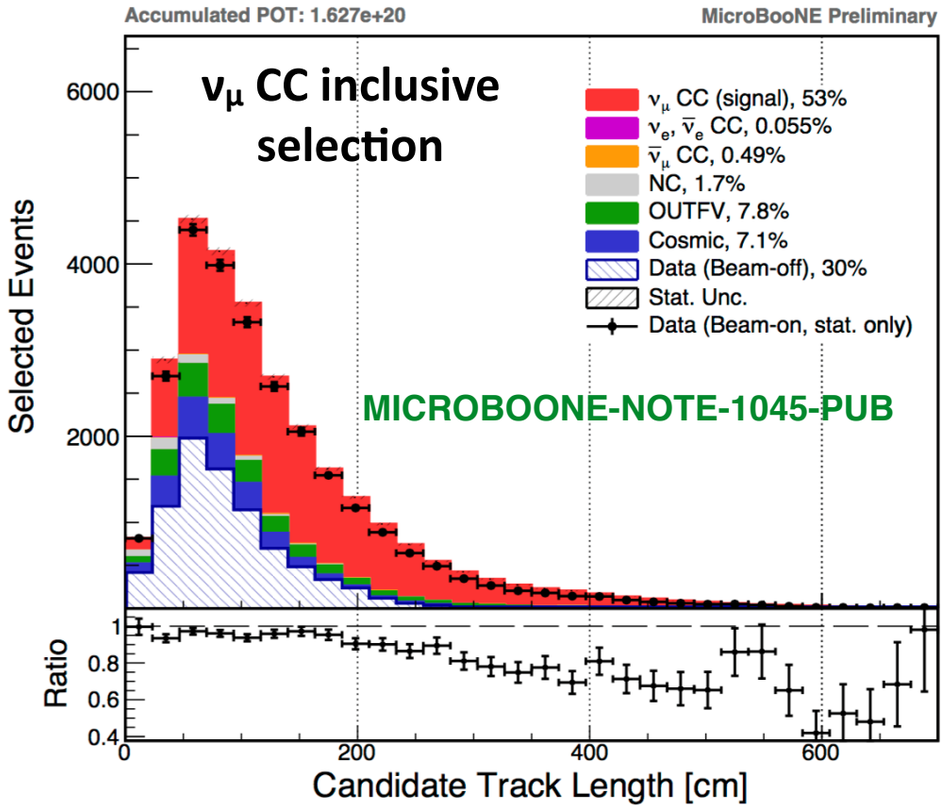
* Ideal to study detector's response to electrons in the tens of MeV energy scale and further develop reconstruction
* Michel electron identified by Bragg peak and kink in the track
* Preliminary calibration using stopping muons depositing known dE/dx
* Missing energy from radiated photons accounts for spectral distortions

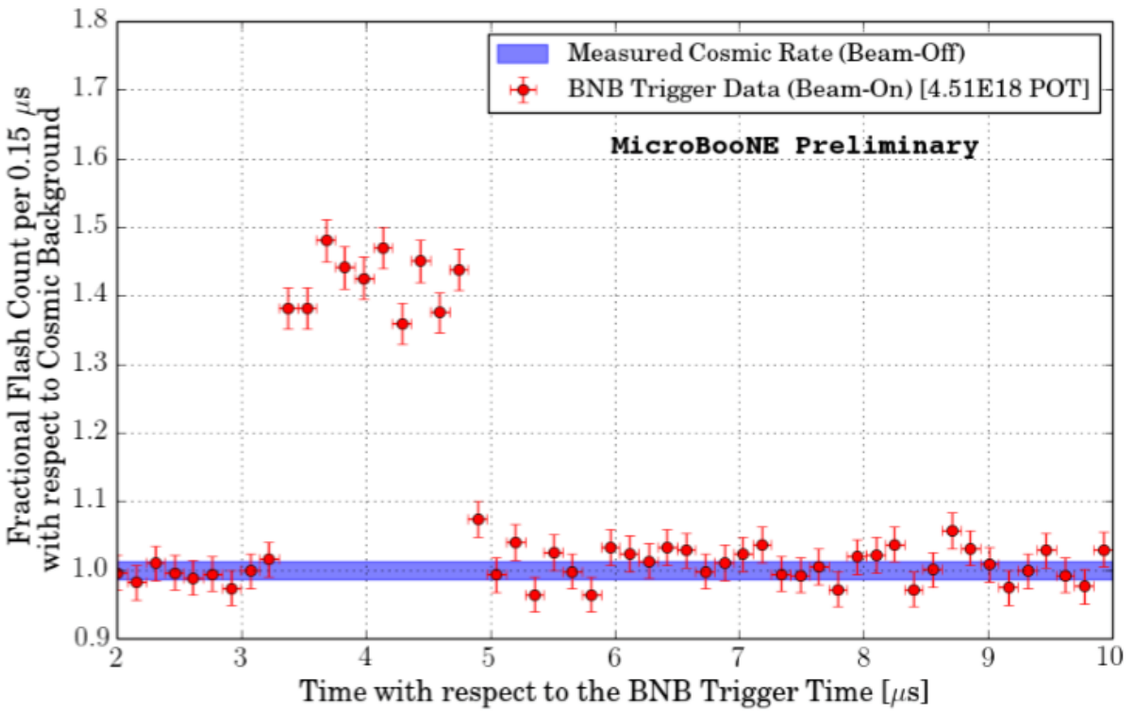


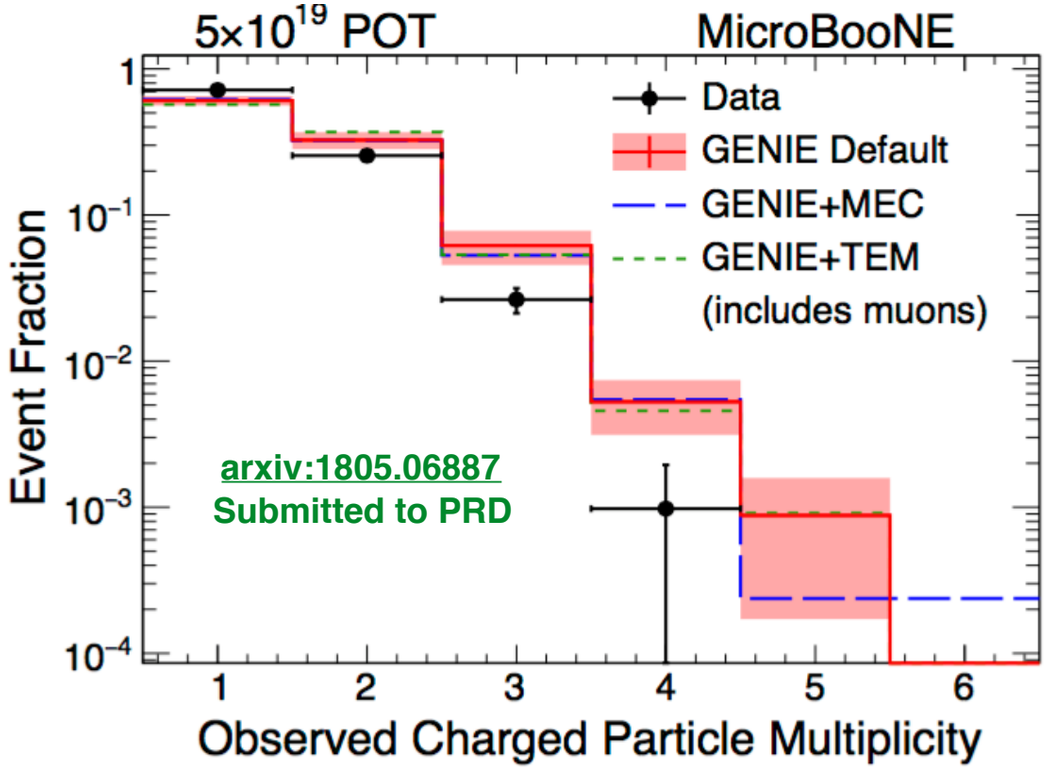
Physics Results

* Many physics results are coming out:
  - First ν_μ CC Inclusive differential cross-section
  - First ν_μ CCπ^0 cross-section
  - Single photon LEE search
  - Updated charged particle multiplicity
  - And more! - **12 New Public Notes**

More in Vassili P. talk - NMNM Session 6 on May 31st

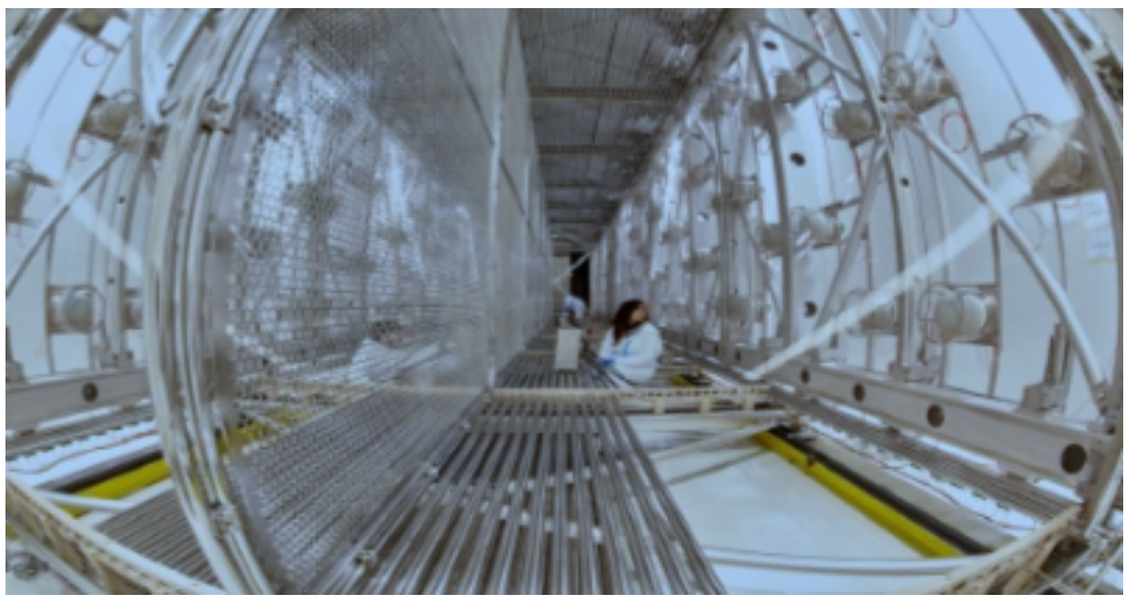


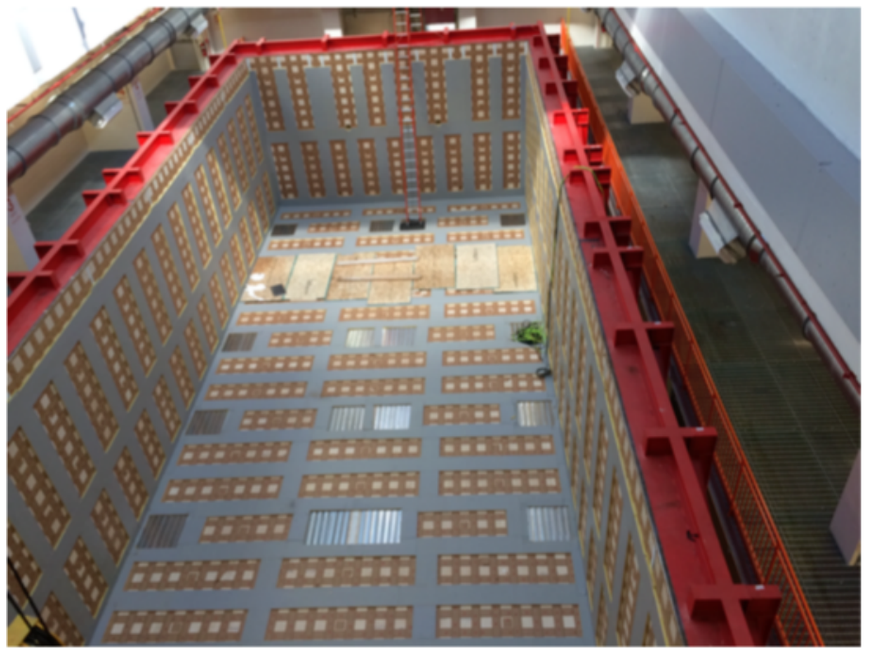




Phase II: ICARUS - the far detector

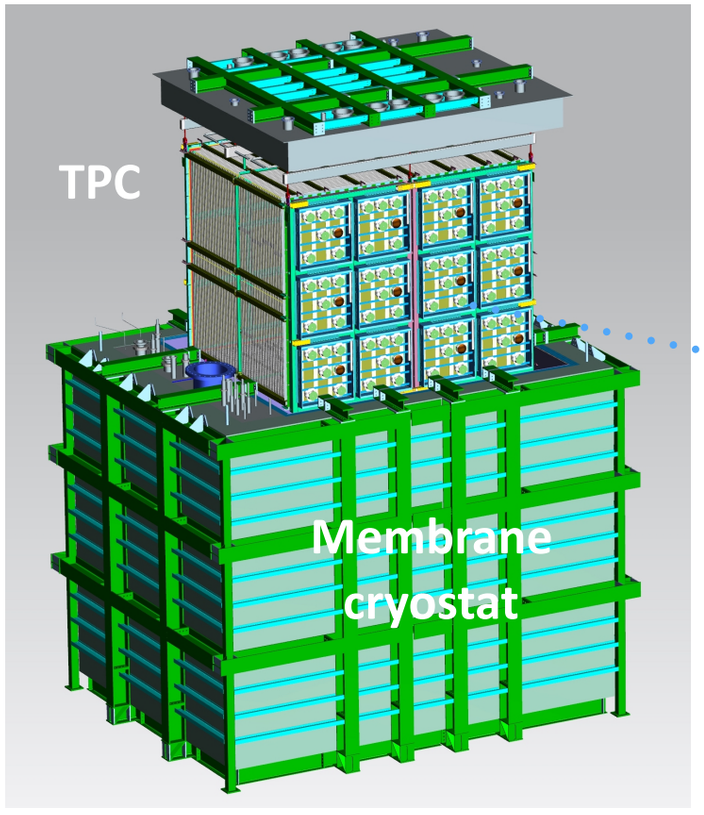
* High sensitivity to neutrino oscillation effects given its large mass and relatively large distance from the source
* ICARUS underwent refurbishment at CERN after operation at Gran Sasso
  - Updated PMTs and electronics
  - Cathode plane smoothing
  - Recirculation/purification
* Detector arrived at Fermilab last summer
* Currently in installation phase
  - Expecting commissioning in early 2019

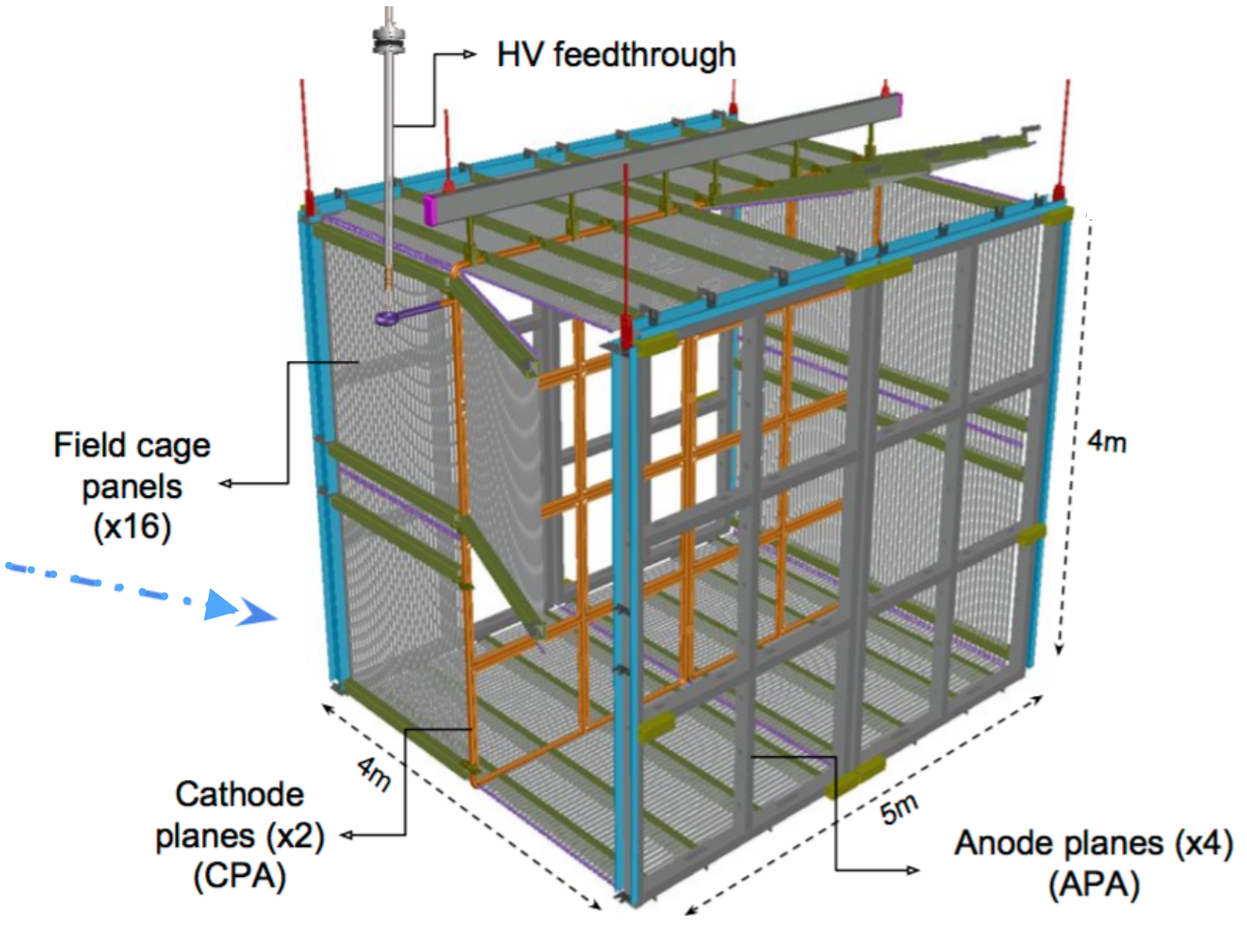




Phase II: SBND - the near detector

* The short baseline near detector will be located closest to the source of neutrinos
  - high statistics flux measurement
  - measure beam neutrino composition before they oscillate
* Completely new detector with new techniques relevant to scaling up to DUNE
  - four APA and 2 CPA assemblies
  - cold readout electronics
* Detector design finalized and under construction
* Expecting first data in 2020

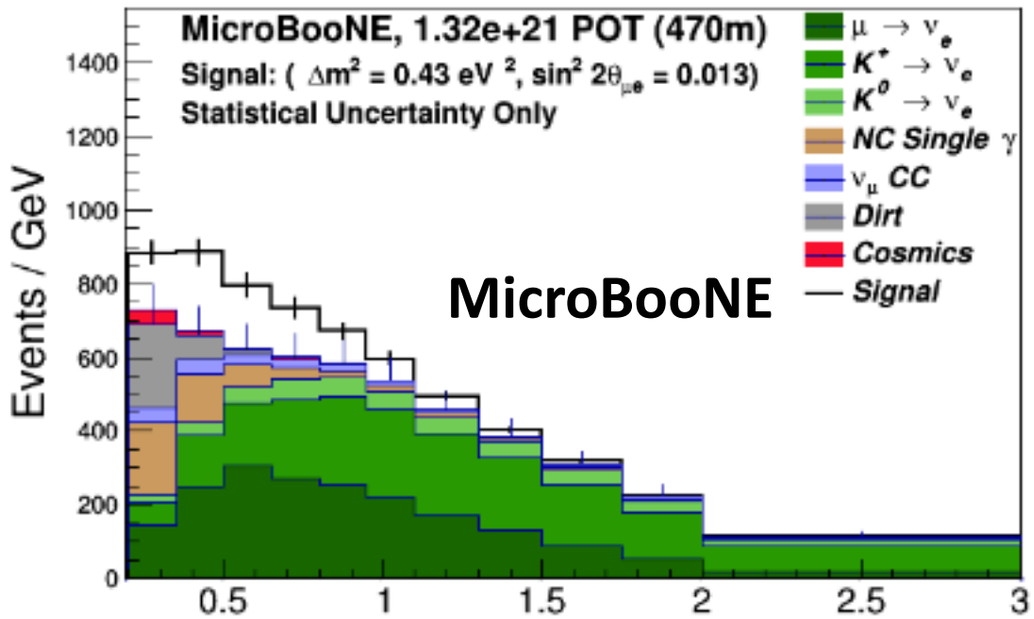


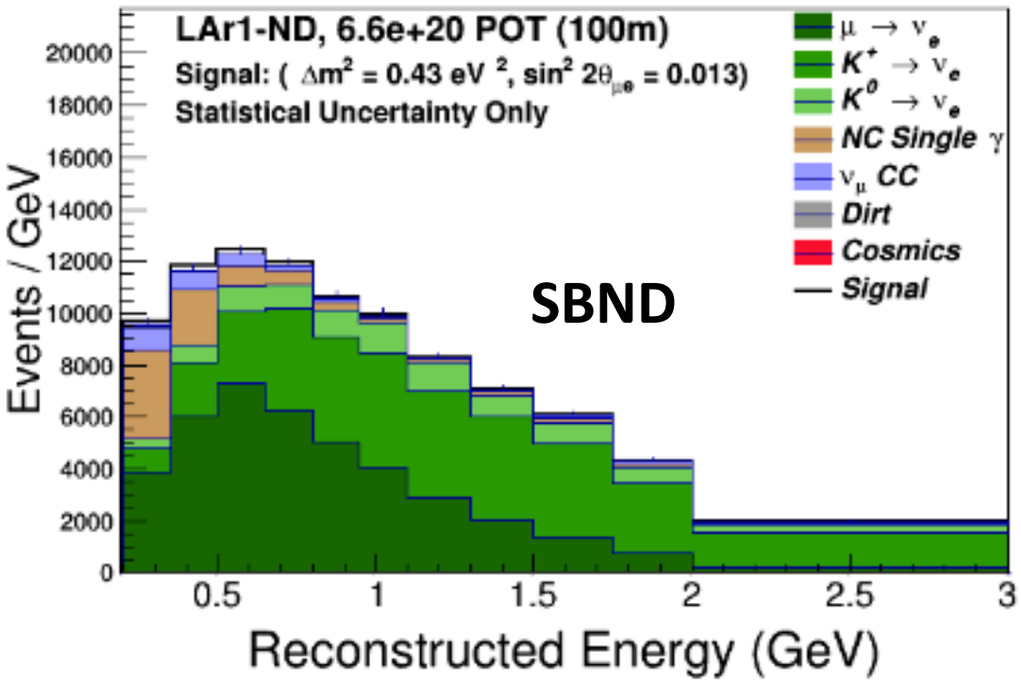


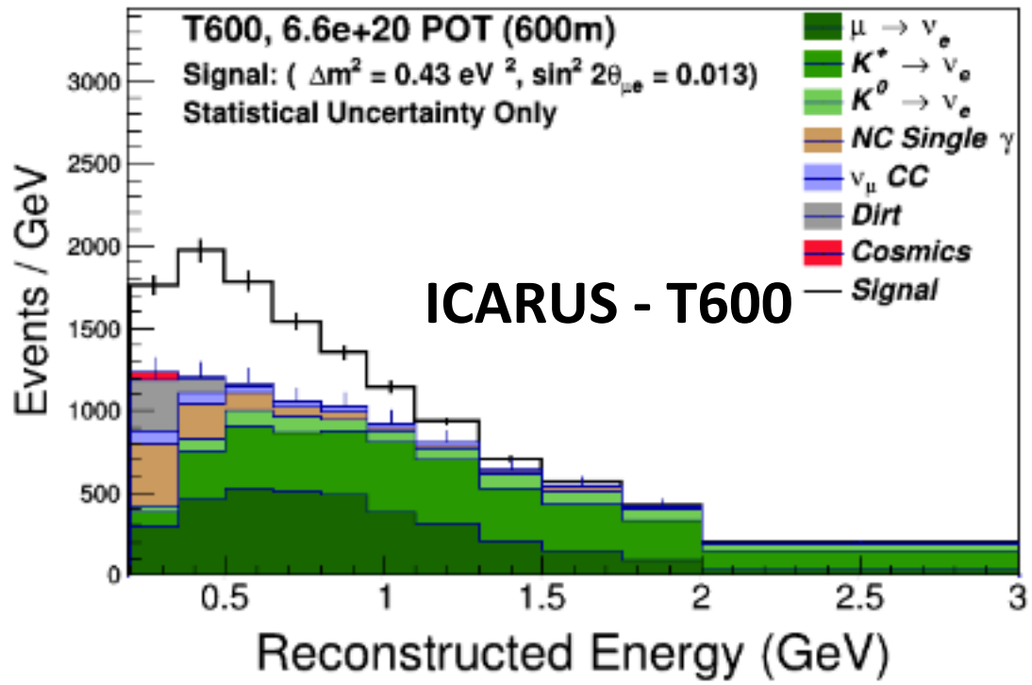
Phase II: Full SBN Running

* Three-detector combined fit:
  - SBND provides flux and cross section constraints
  - MicroBooNE and ICARUS-T600 provides signal events
* Good energy resolution, small background w/ LArTPCs

ν_e charged-current distributions



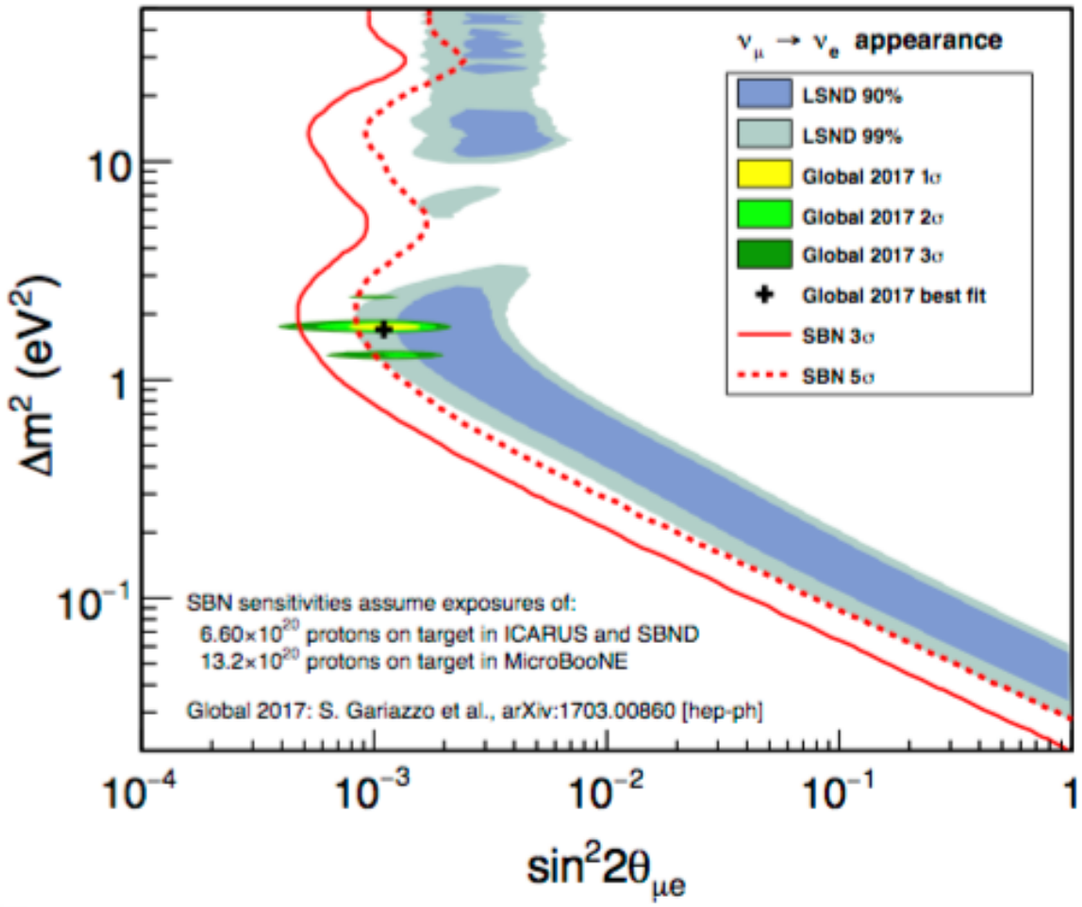




arxiv:1503.01520

SBN Sensitivity

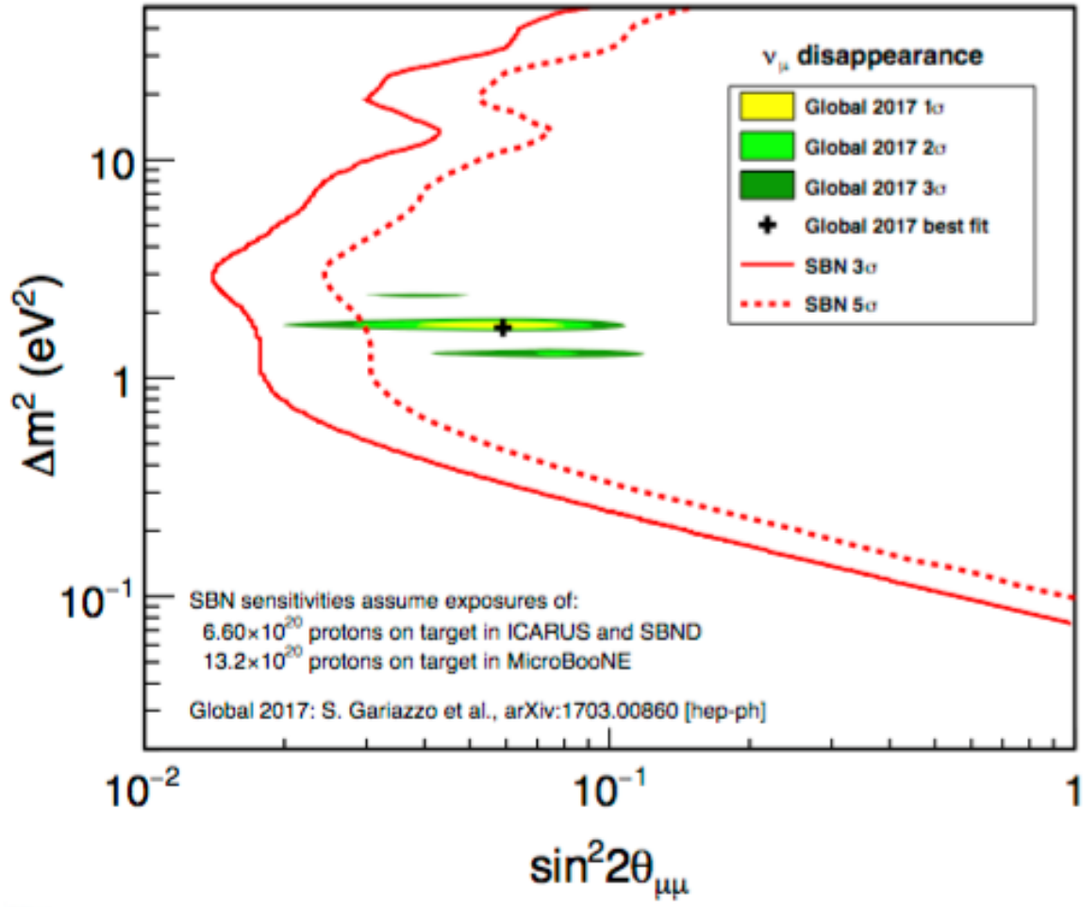
ν_e Appearance



$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2(1.27\Delta m^2_{41} L/E)$$

Cover the LSND allowed region at 5σ

ν_μ Disappearance



$$P_{\mu\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2(1.27\Delta m^2_{41} L/E)$$

Search for ν_μ disappearance which ν_e appearance implies

Summary

* The SBN program is on track to address the eV-scale sterile neutrino anomalies with 5σ coverage of LSND signal and best global fits

* MicroBooNE continue to pave the way in understanding how to operate, calibrate, and perform physics analyses with LArTPCs
  - Many new physics results coming out next week!
  - Advancing LArTPC technology for future multi-kiloton detectors

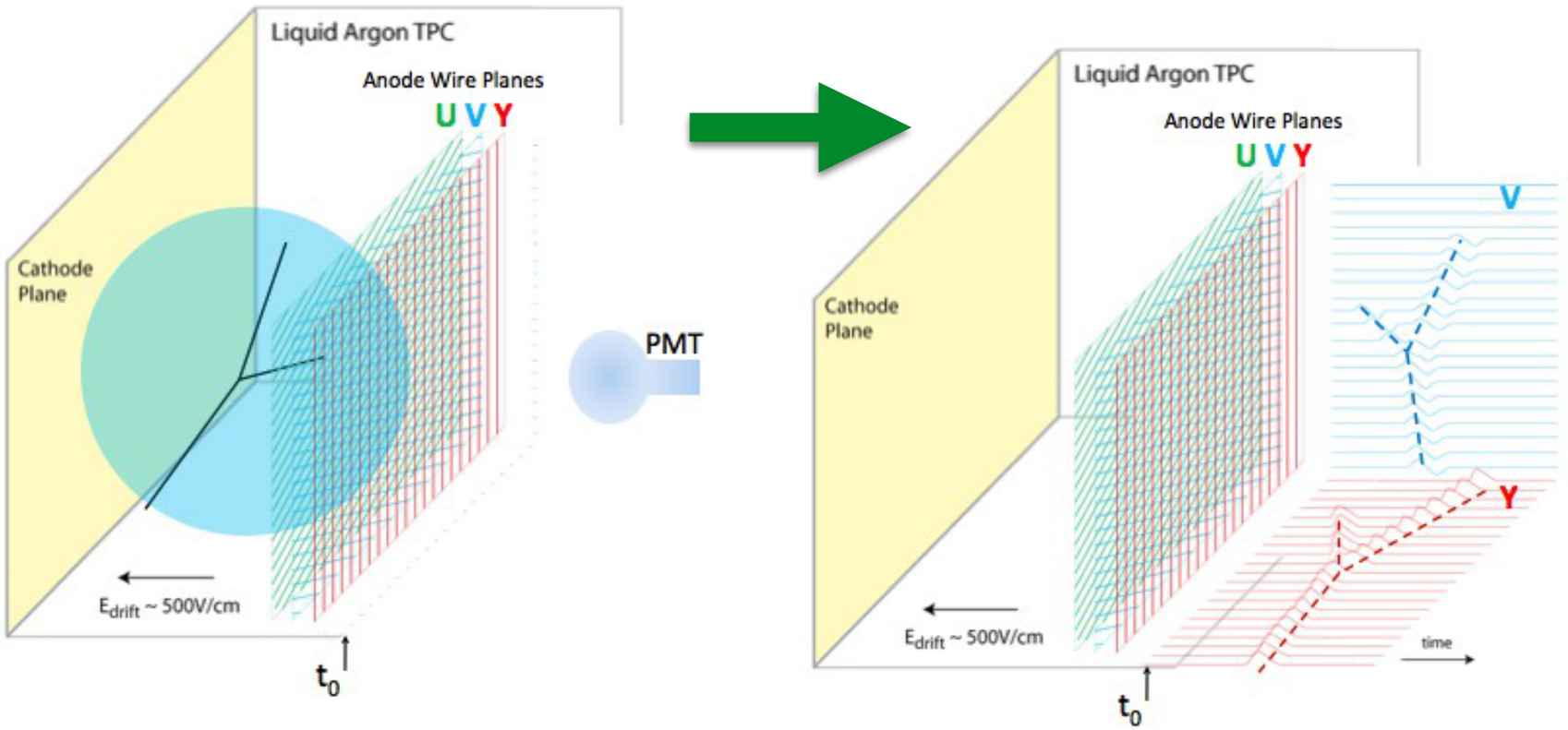
* ICARUS and SBND will come online in next two years

Thanks for your attention!

Back-Up

LArTPC Principle

- Ionization from neutrino interaction drifts past two **induction** planes (U, V) and collected on **collection** plane (Y) – three planes in total
  - High drift E field (~500 V/cm), ~uniform via surrounding field cage
  - Front-end electronics in liquid argon to reduce noise levels
- 3D event reconstruction by combining signals from all three planes
- Trigger event with scintillation light from PMTs (or similar)

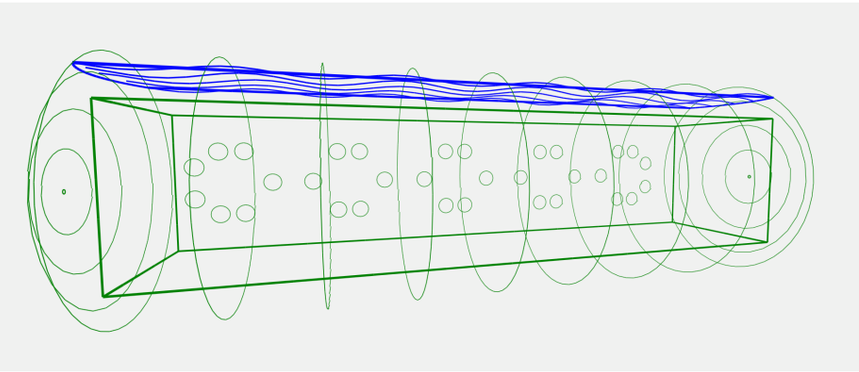


MicroBooNE Timeline

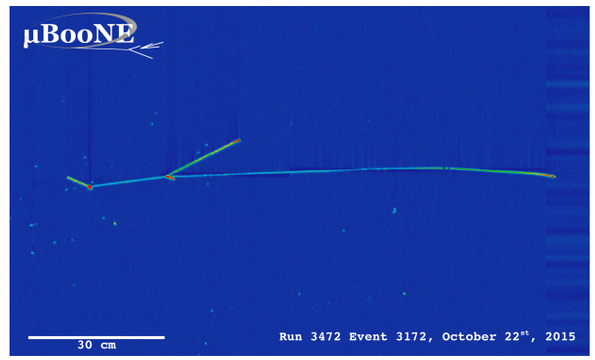
December, 2013
TPC inserted into Cryostat

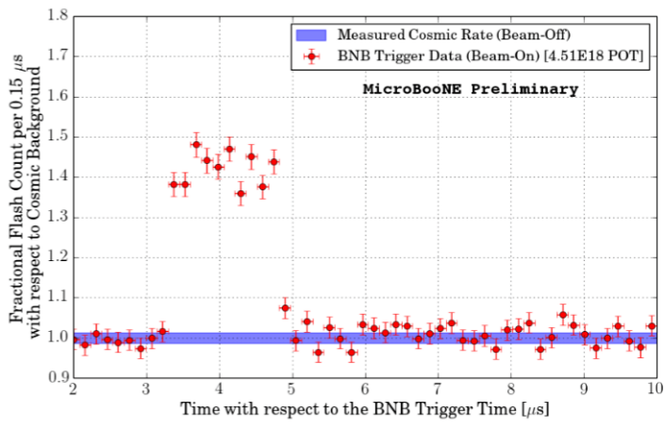
June, 2014
Moved to LArTF

July, 2015
Fill with 170 ton LAr

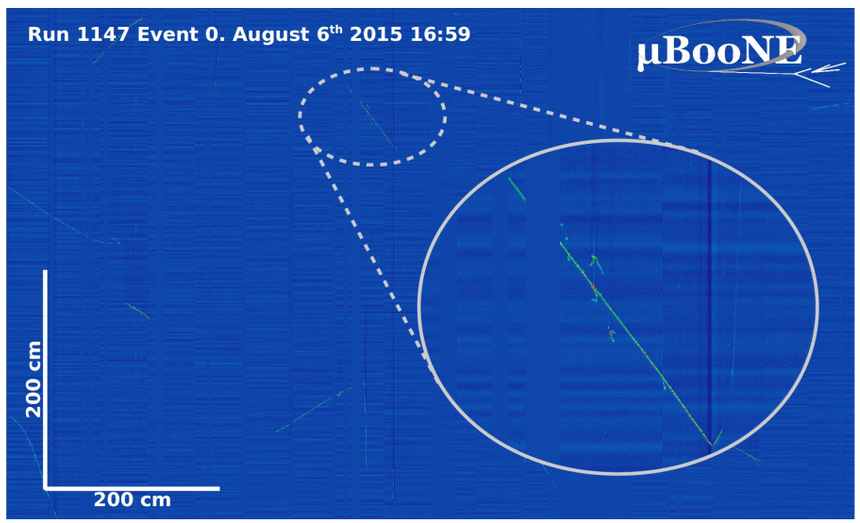


November, 2015
First Public Result





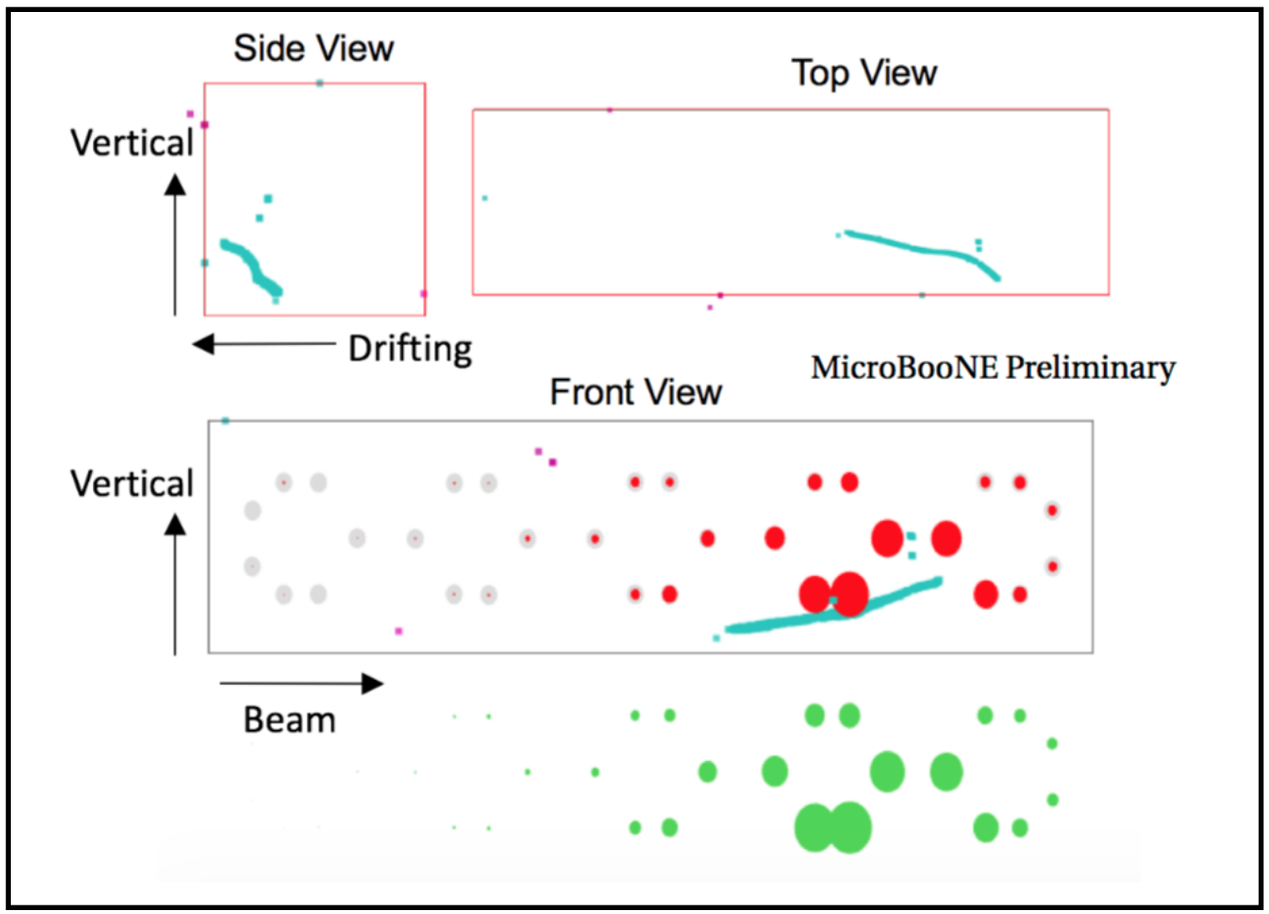
August, 2015
First Cosmic tracks with HV



October, 2015
First Neutrino Beam

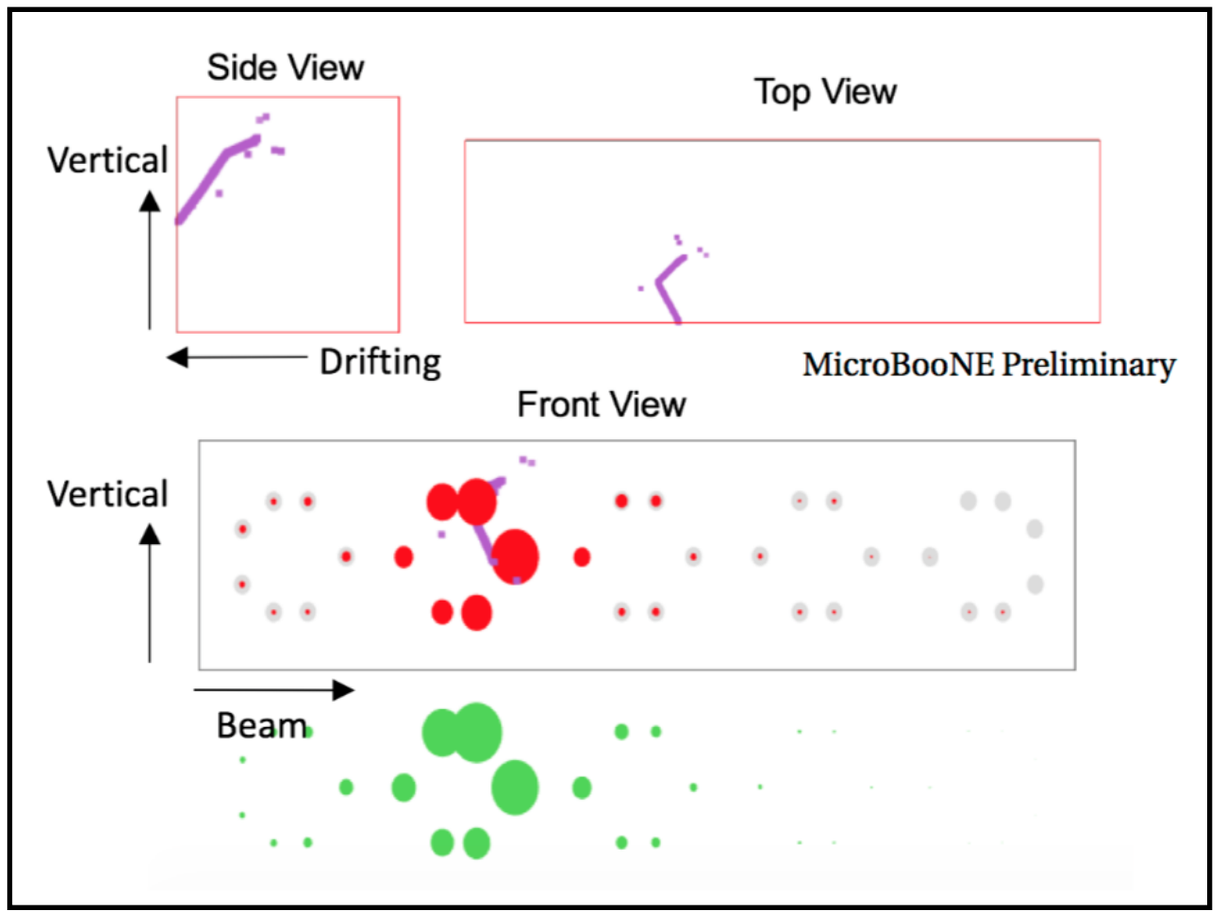
Selected Events

Fully Contained ν_μ CC event



[BEE Link]

Partially Contained ν_μ CC event



[BEE Link]