Probing Neutrino Anomalies at Fermilab's Booster Neutrino Beam

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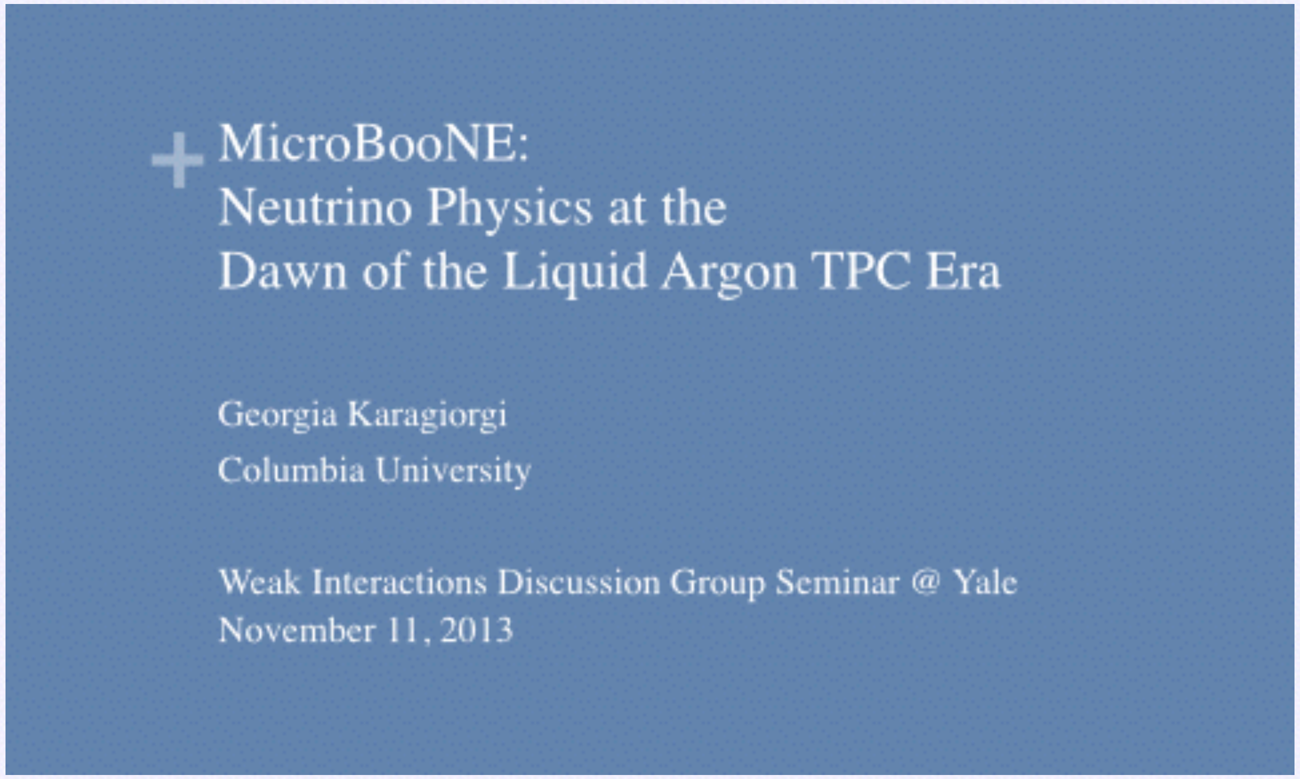
WIDG Seminar
April 1, 2014

Introduction

- Neutrino Oscillations and Anomalies
- MicroBooNE
- Microboone and LAr1-ND



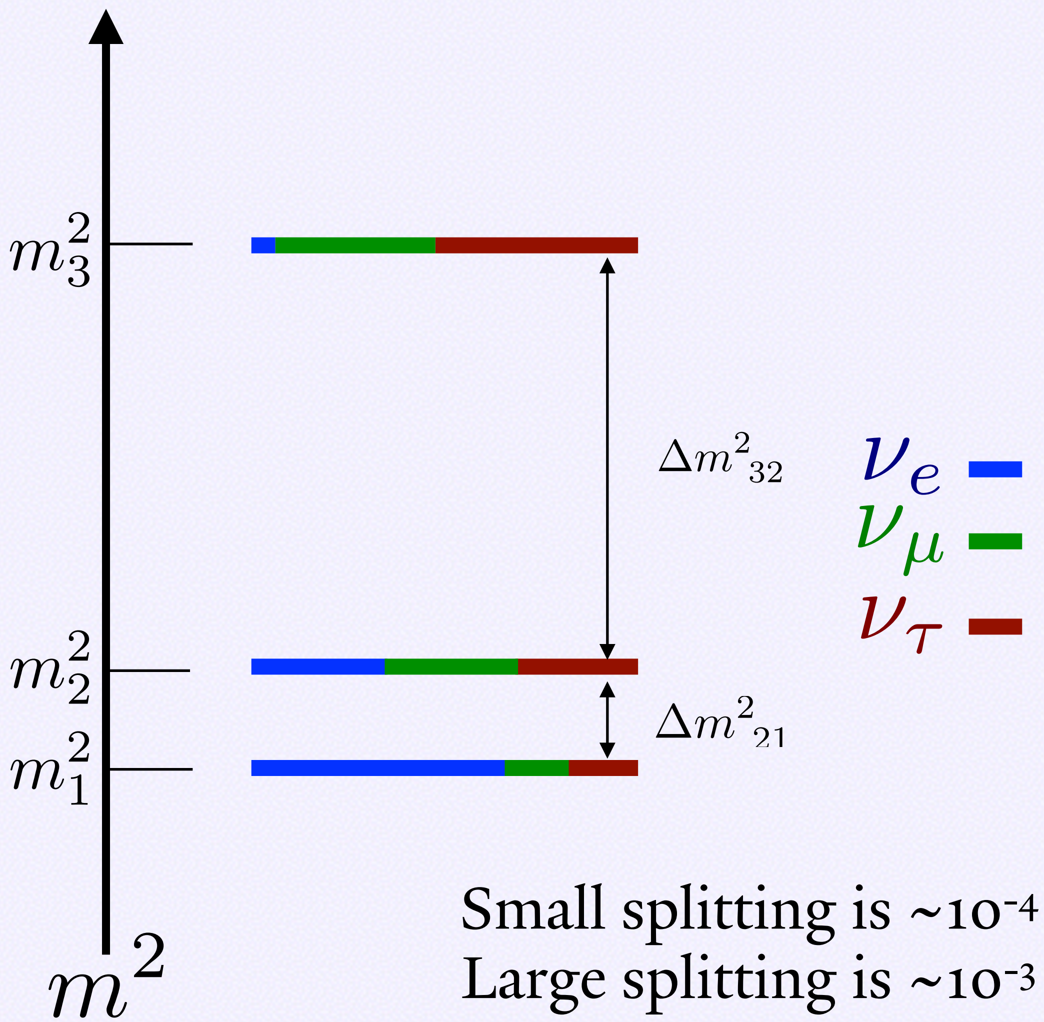
WIDG Seminar last December

Neutrino Oscillations

Neutrinos Produced in "flavor" states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Energy eigenstate is mass state.



Small splitting is ~10^{-4} eV^2
Large splitting is ~10^{-3} eV^2

This gives rise to neutrino oscillations. For situations where only one mass splitting is relevant:

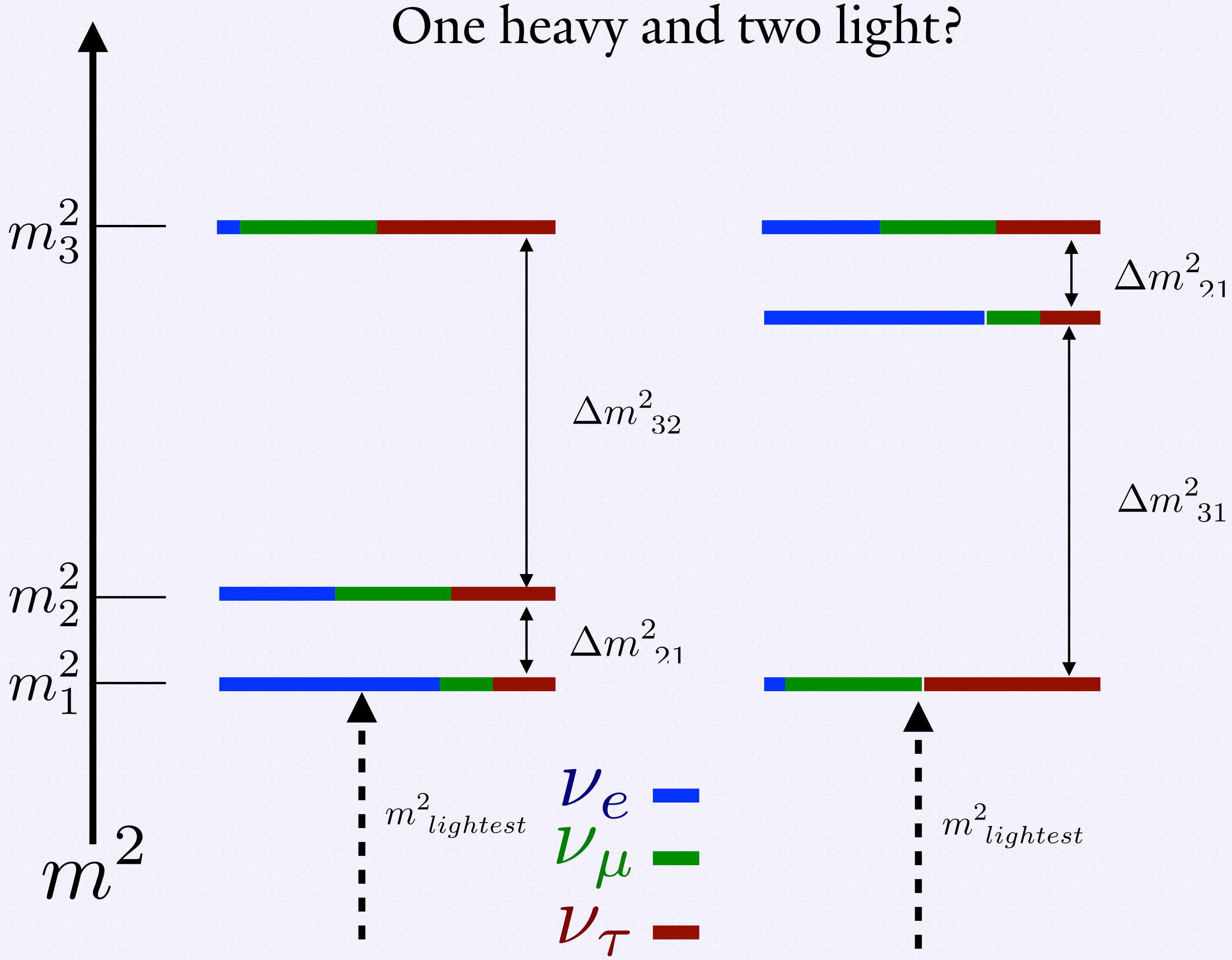
$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4}\left(\frac{L}{E}\right)\right)$$

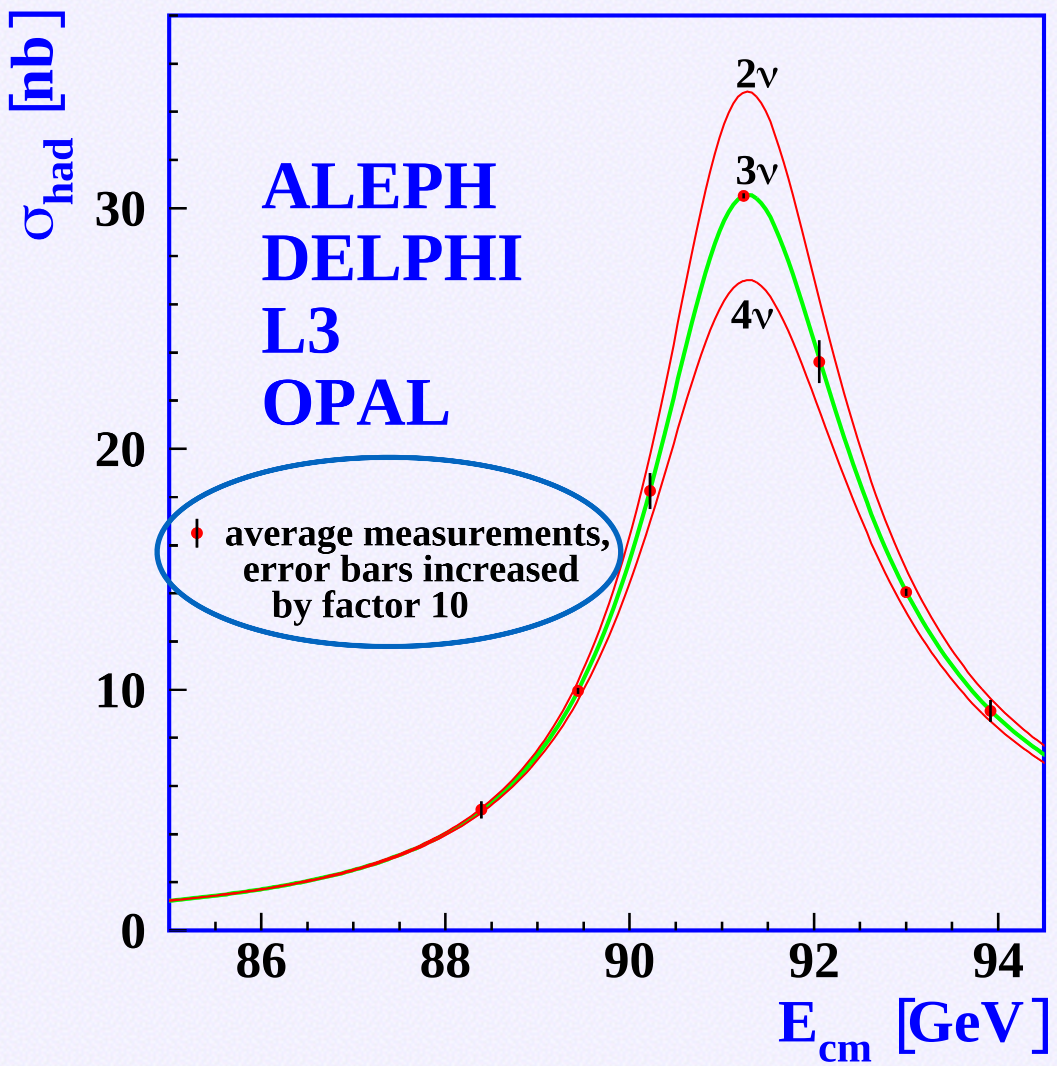
Amplitude and frequency set by nature

L/E is the experimentally configurable variable (mostly)

Neutrino Questions

Two heavy and one light?
One heavy and two light?



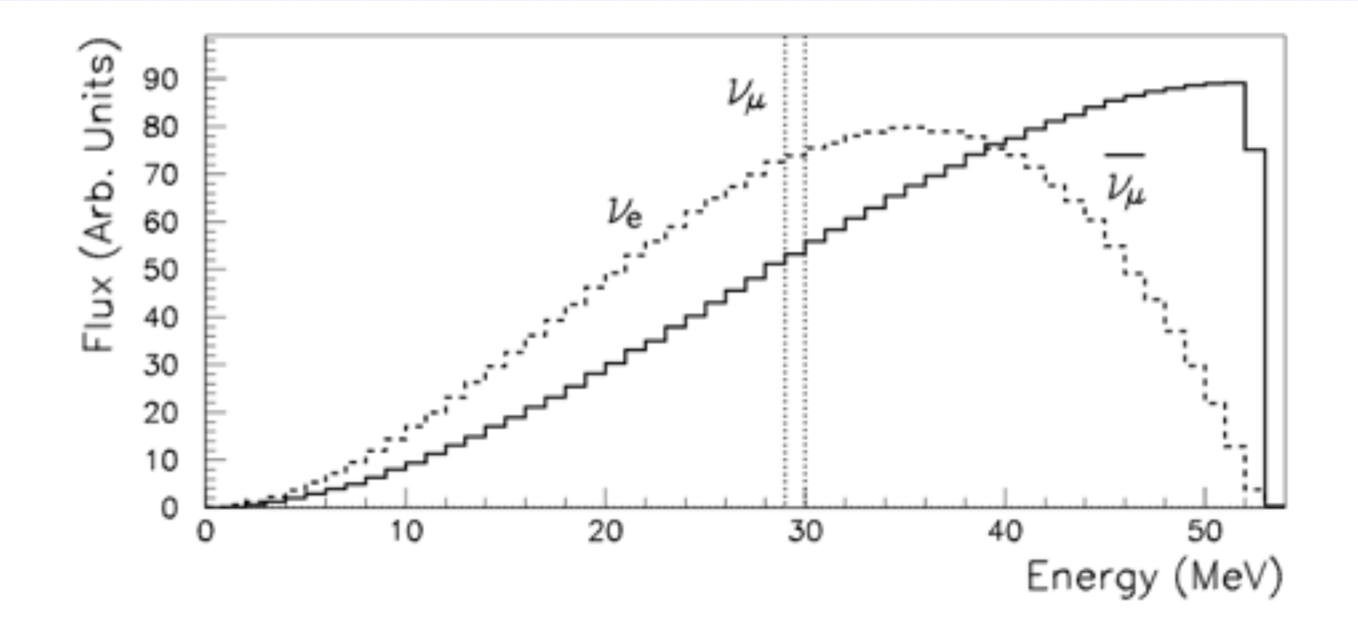


Good reason to believe there are 3 active neutrinos
(experimentally, n = 2.9840 +/- 0.0082)

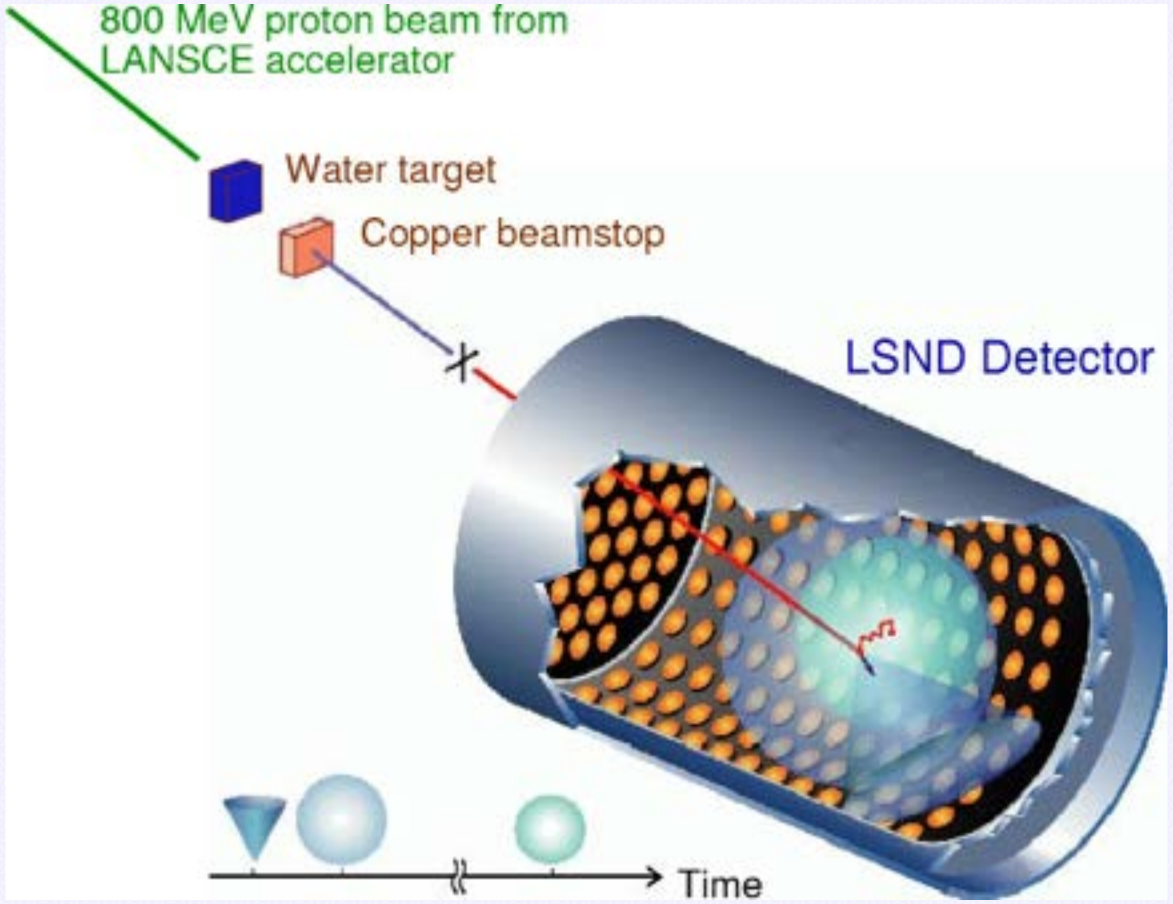
Liquid Scintillator Neutrino Detector

Create a beam of neutrinos through pion and muon decay-at-rest.
Very precisely known flux.

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



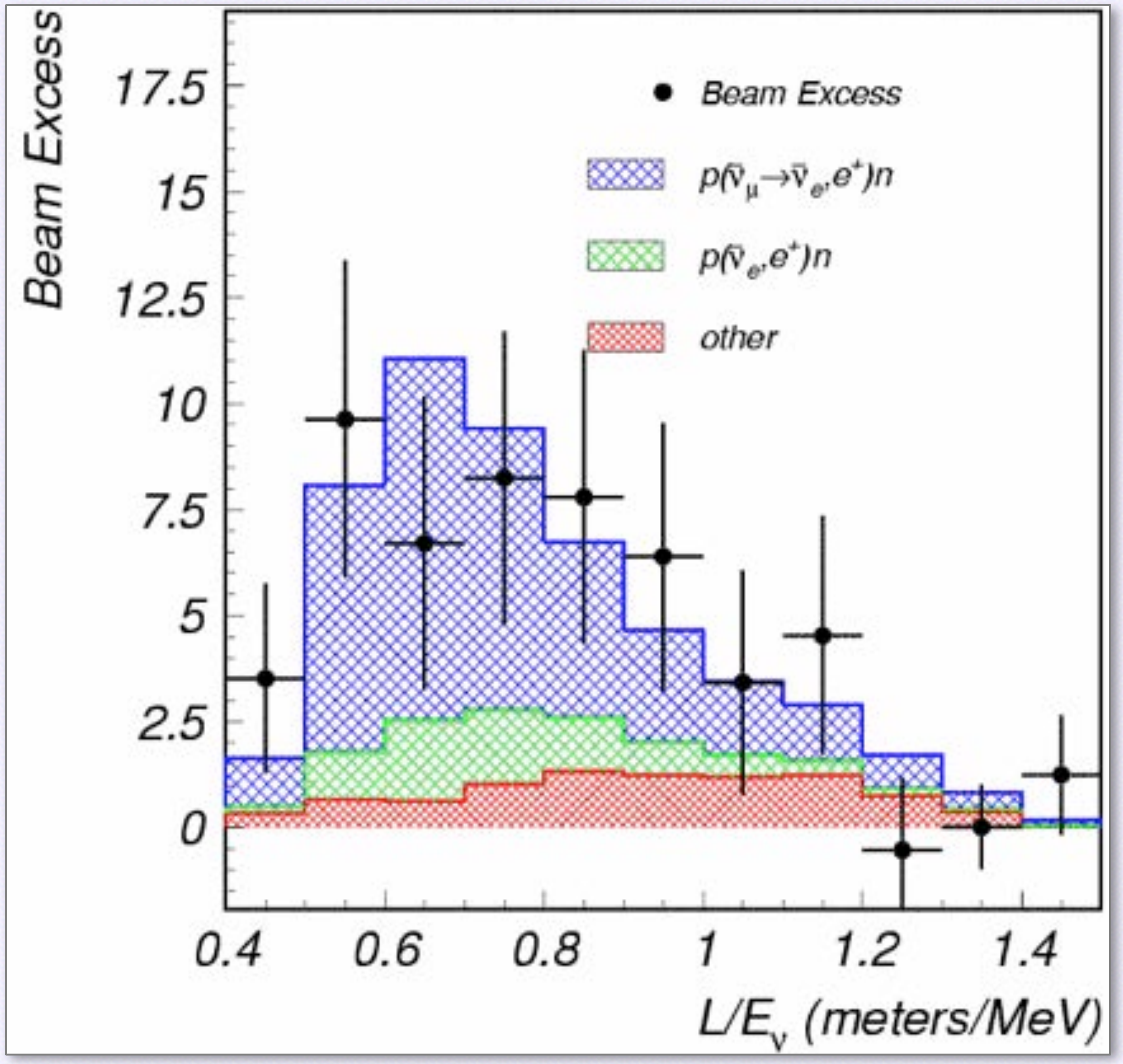
Contamination with electron antineutrinos is very small.



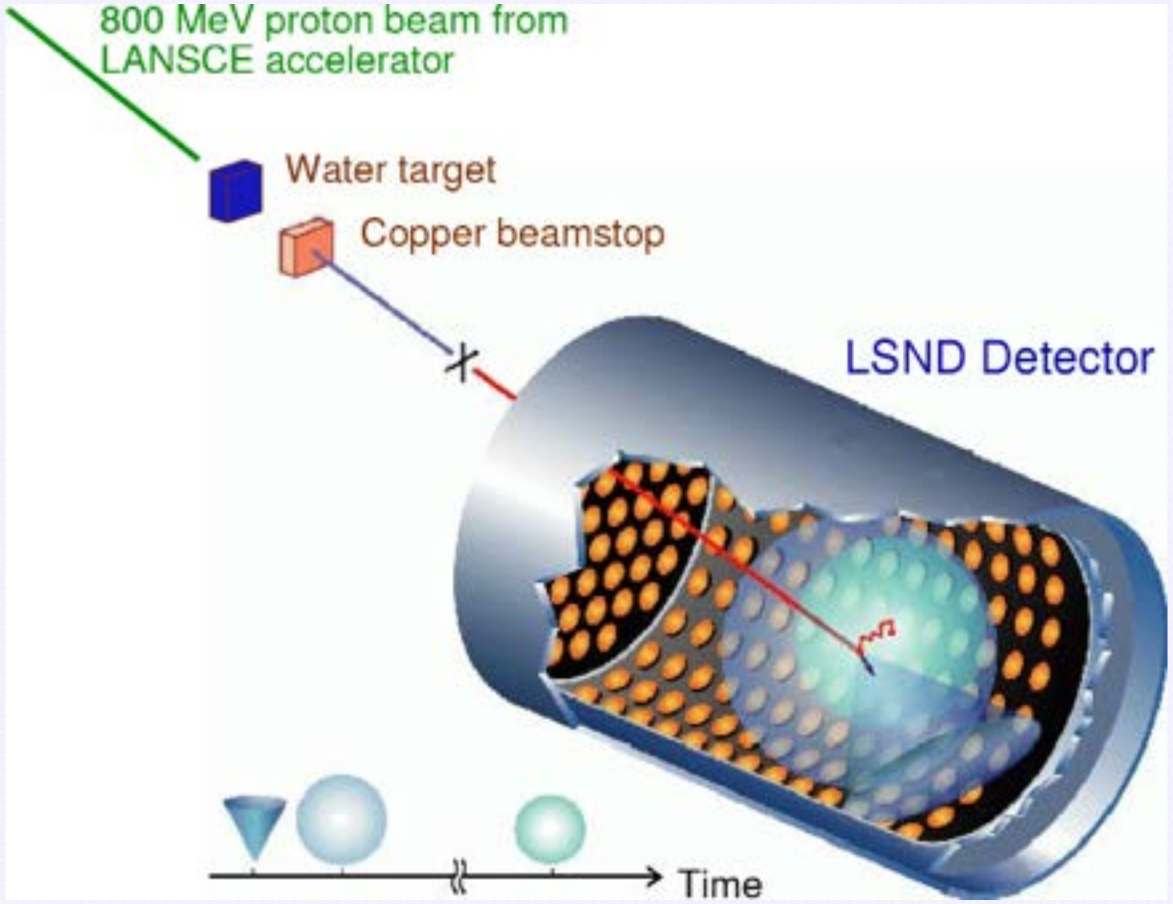
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Tag events by positron signal followed by neutron capture.

The LSND Anomaly

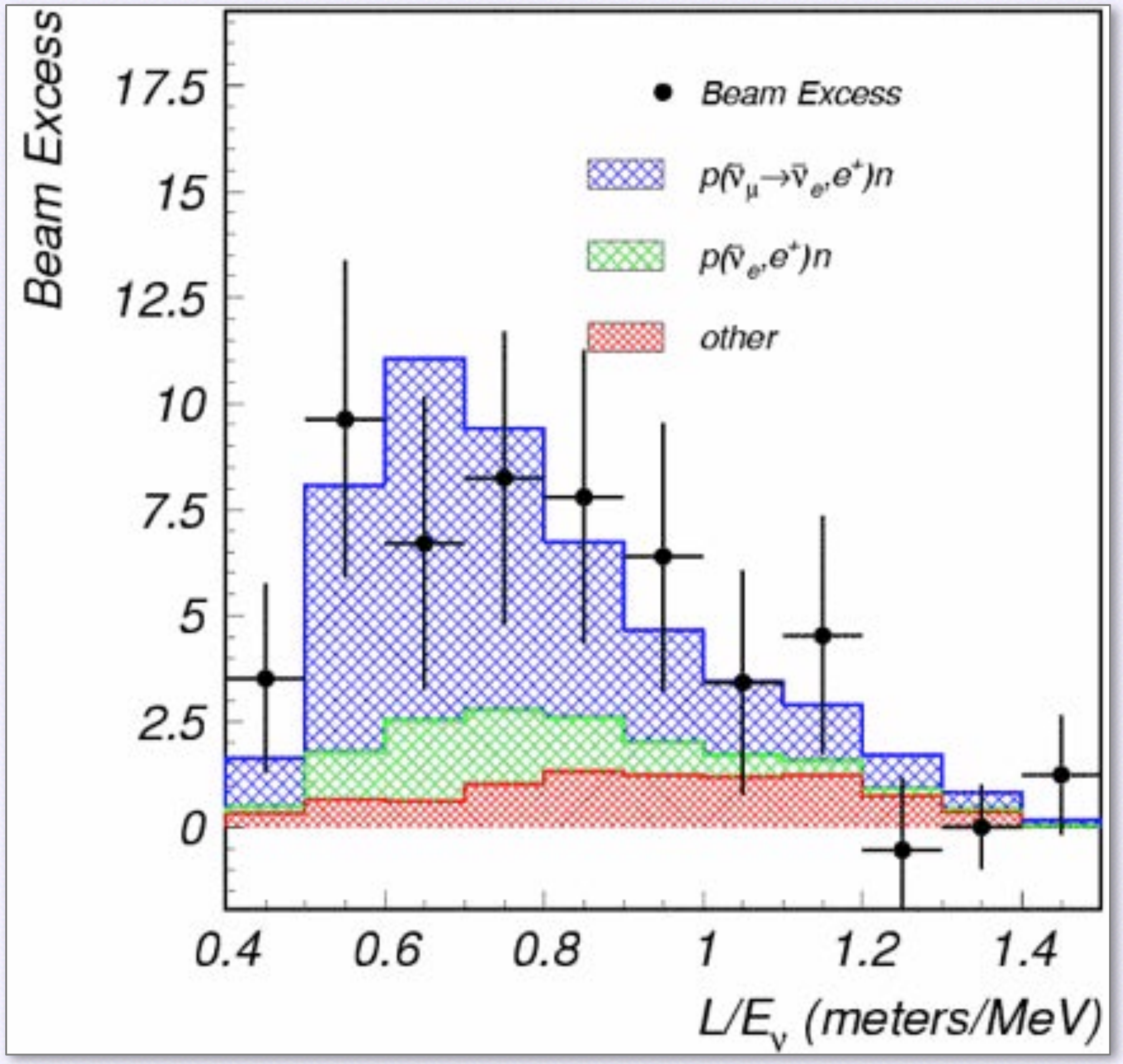


[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilaretal., Phys. Rev. D64, 112007(2001).]



$$\bar{\nu}_e + p \to e^+ + n$$

LSND Anomaly - Oscillations?



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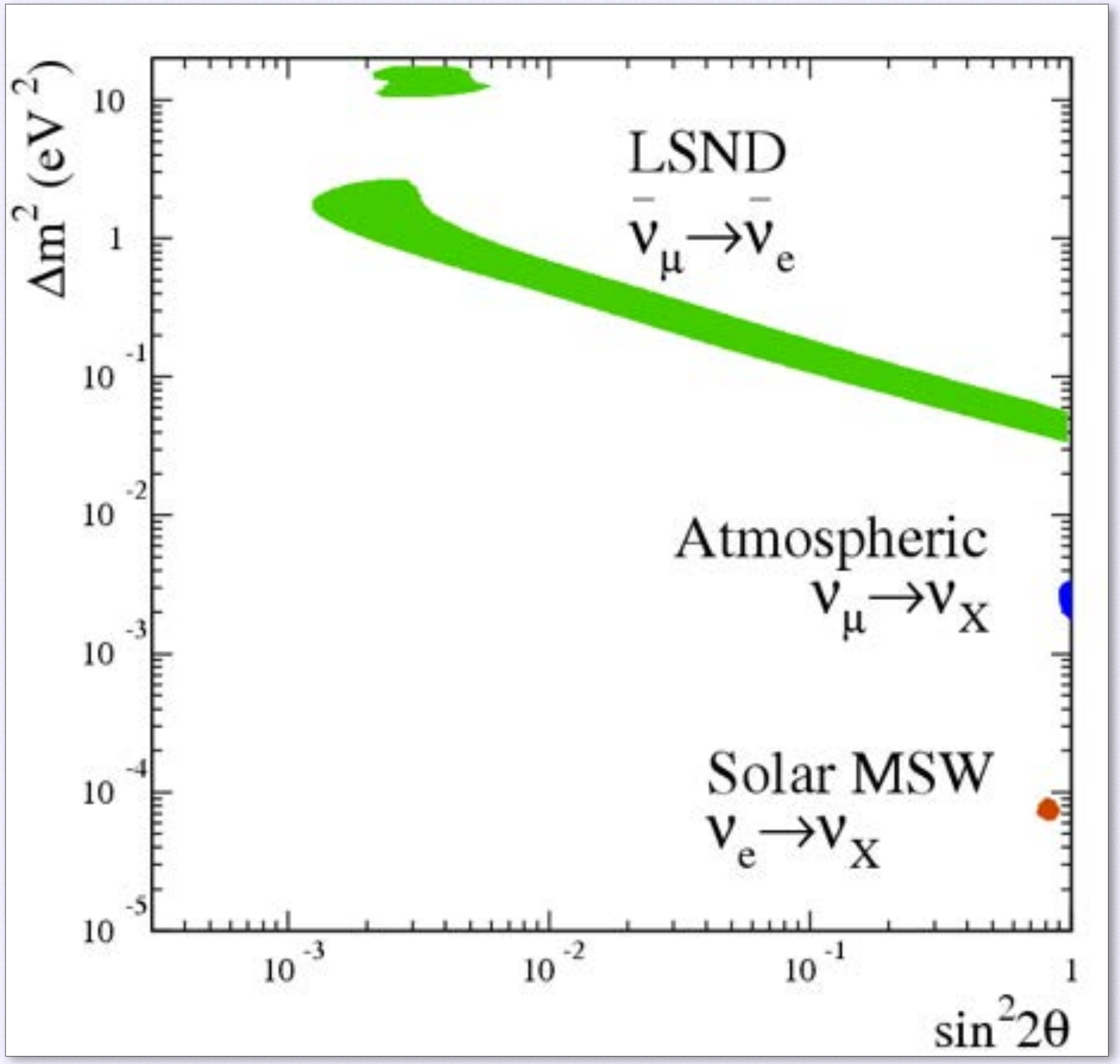
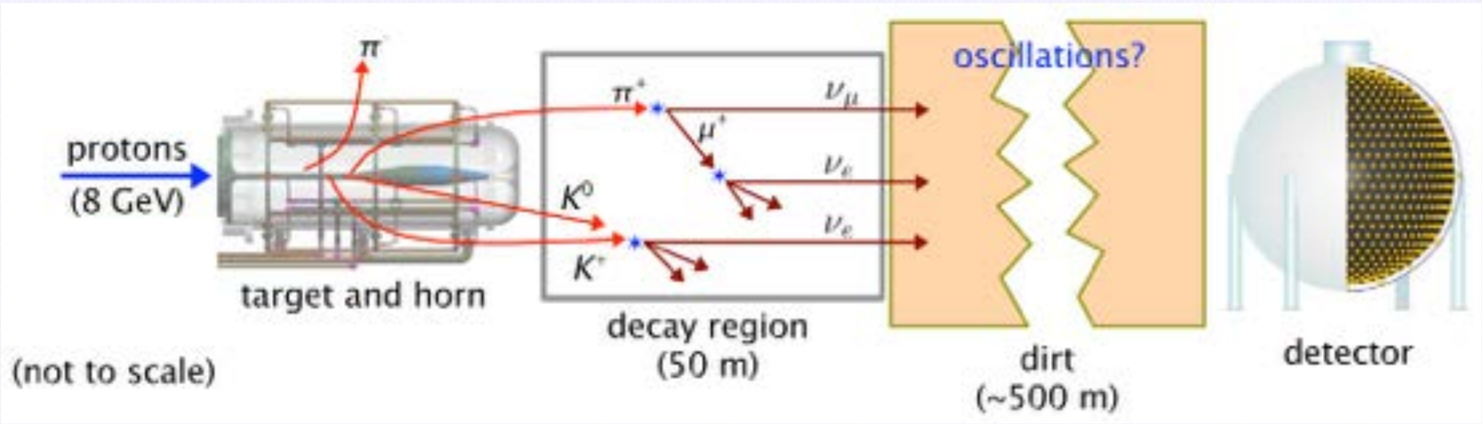
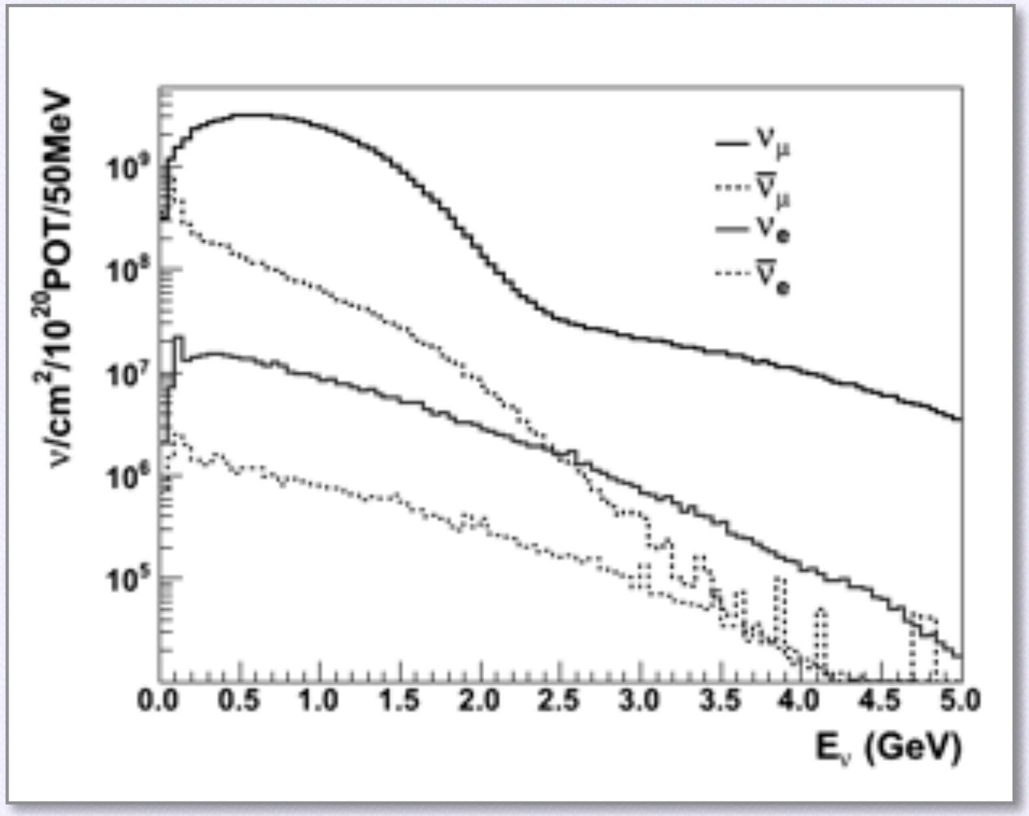


If a neutrino oscillation explains the LSND result, it is inconsistent with the mass splittings we already know.

MiniBooNE Excess

MiniBooNE at Fermilab: different source, different detector, different systematic errors, same L/E.



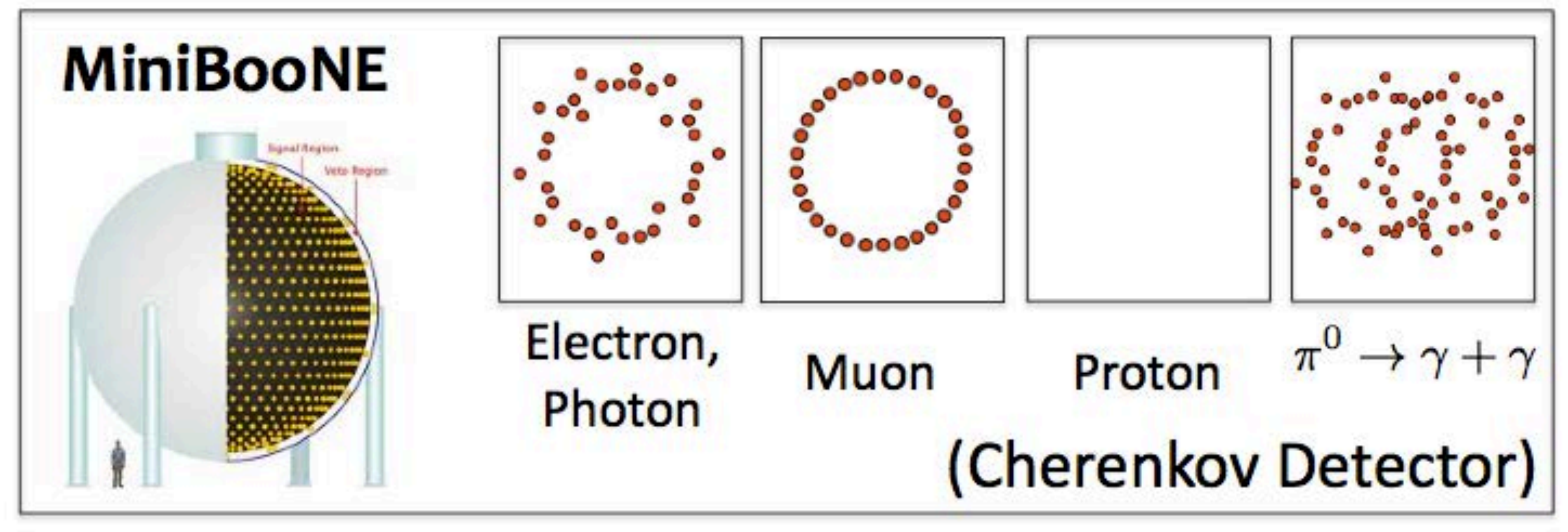


Searching for appearance of electron (anti) neutrinos in a predominantly muon (anti) neutrino beam

Neutrino Flux at the MiniBooNE Detector

$$\nu_e + n \rightarrow e^- + p$$

MiniBooNE Detector Signature



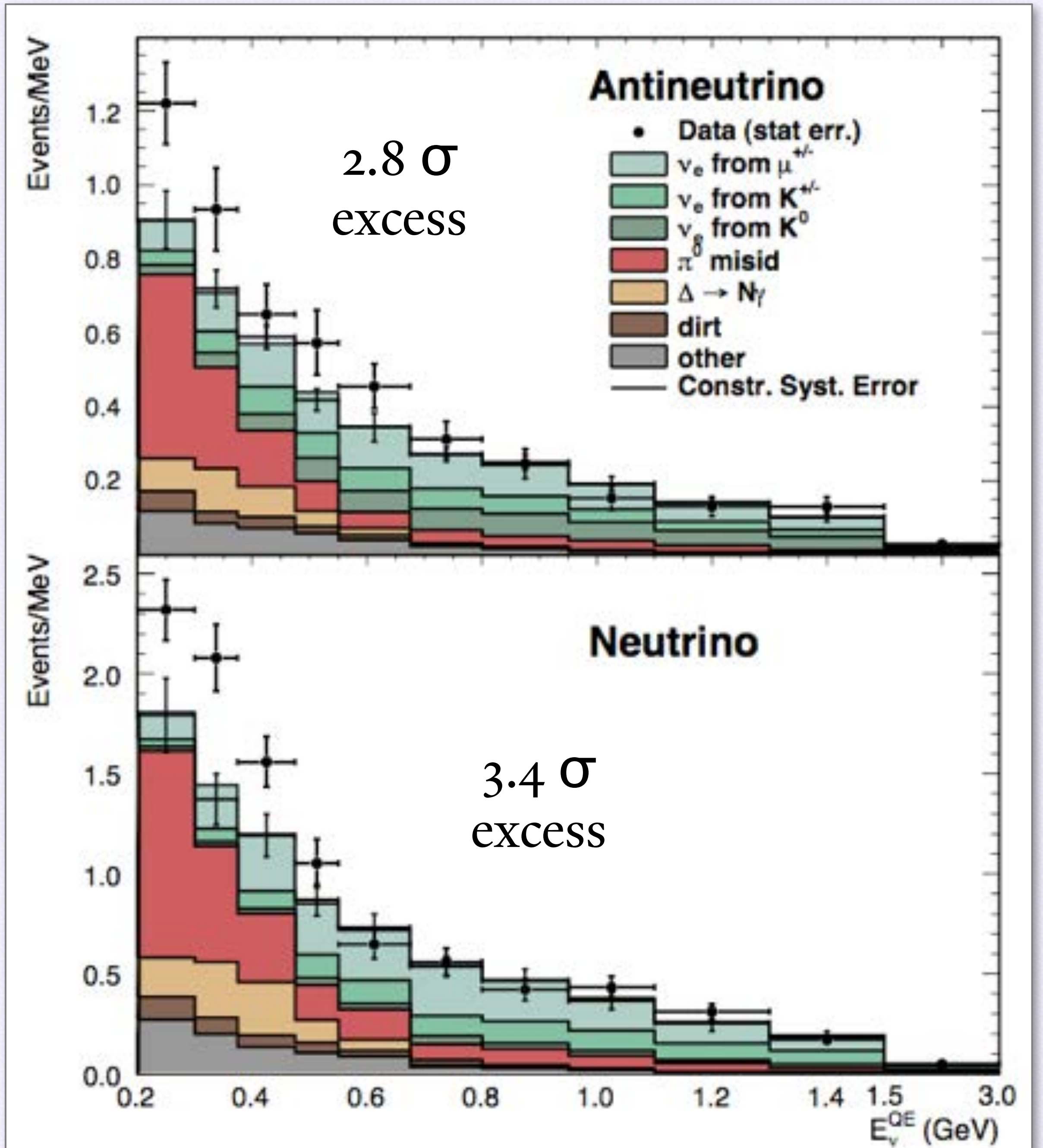
Signal: $\nu_e + n \rightarrow e^- + p$

Primary Background: $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$

$\quad \hookrightarrow \gamma\ \gamma$

Failure to observe **both** photons in a neutral pion decay can look like an electron event

MiniBooNE Results



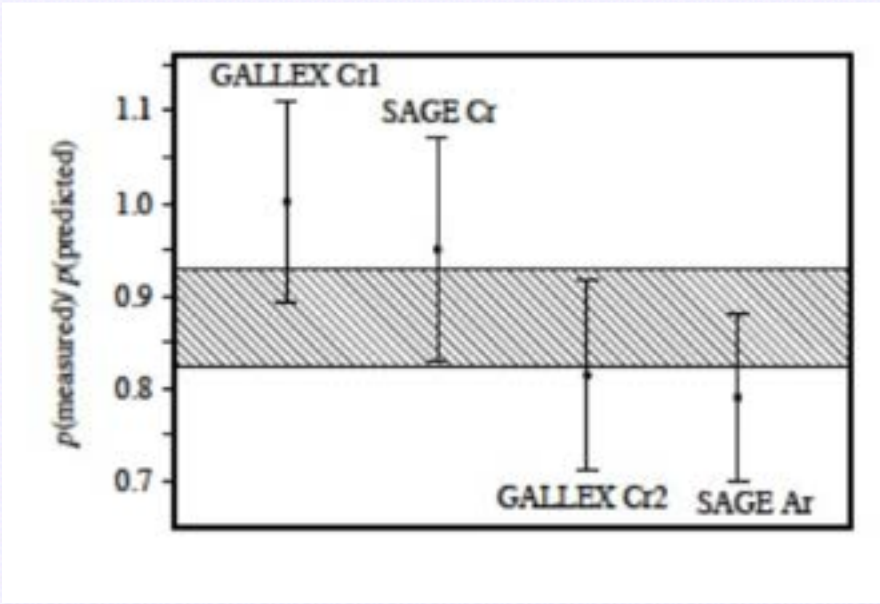
A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 110 161801 (2013)

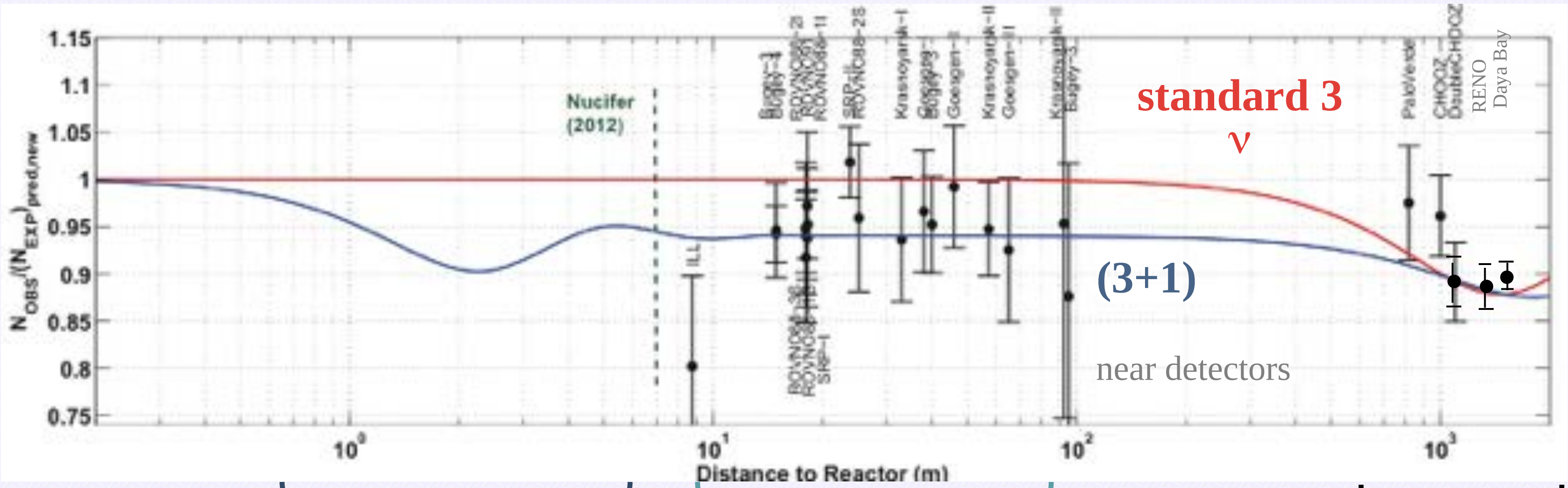
Single photons cause reconstructed energy to be lower than the true energy.

Is the MiniBooNE excess **photons** or **electrons?**

This is a question MicroBooNE is perfectly setup to answer.

Reactor and GALLEX/SAGE Anomalies





region to explore for sterile neutrinos

older reactor exps at close distances
R = 0.927 ± 0.023 (3.0σ)
1.4σ when θ_{13} included
[arXiv:1303.0900]

current reactor experiments

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

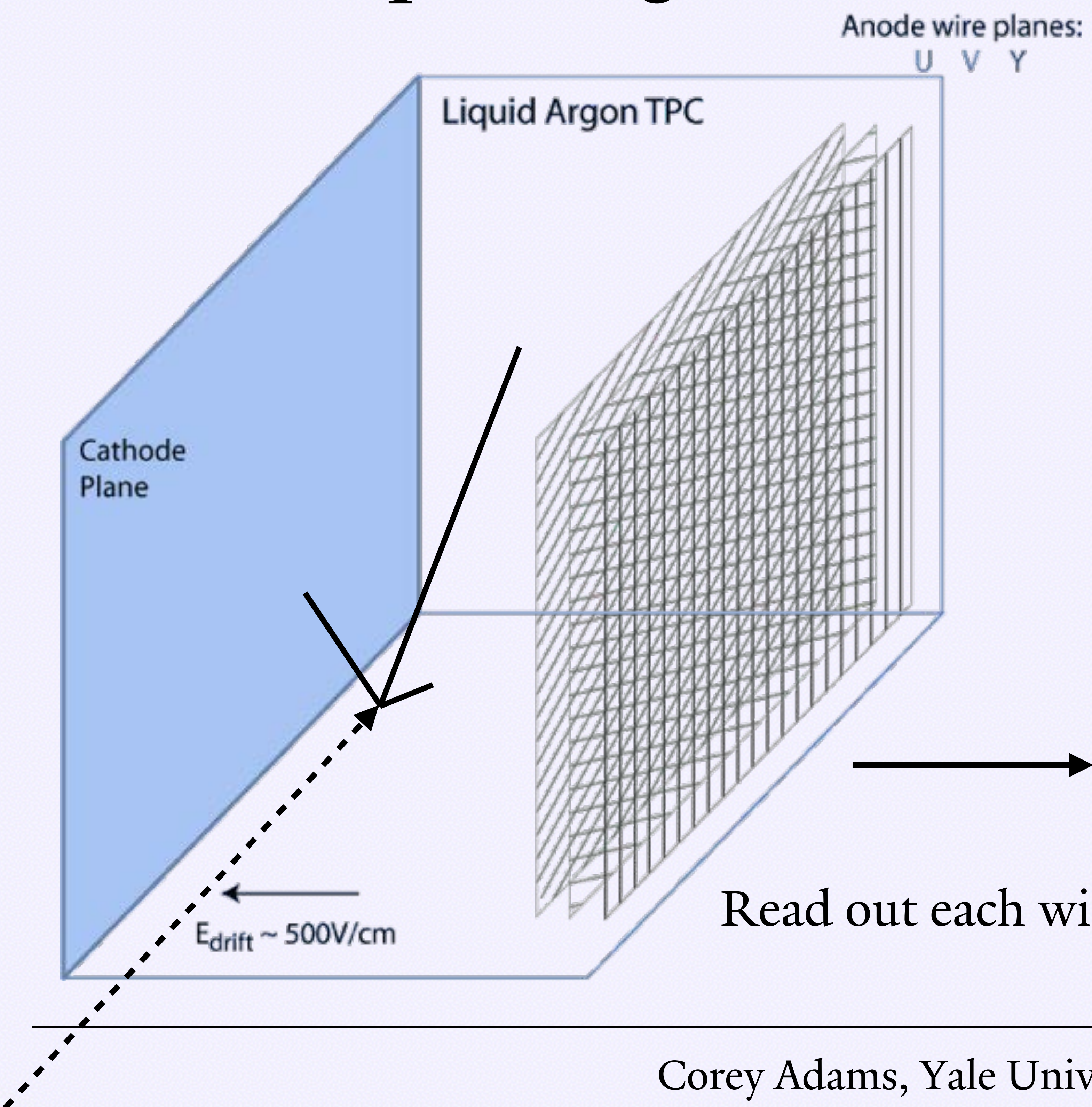
K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

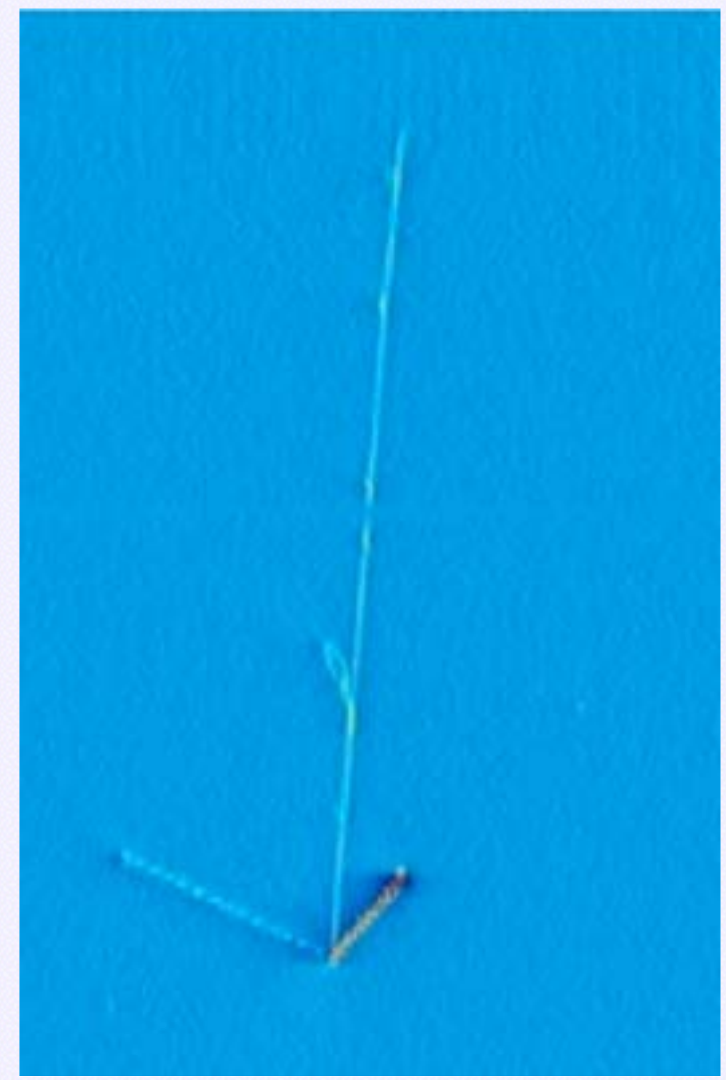
MicroBooNE

and the Liquid Argon Time Projection Chamber

LArTPC

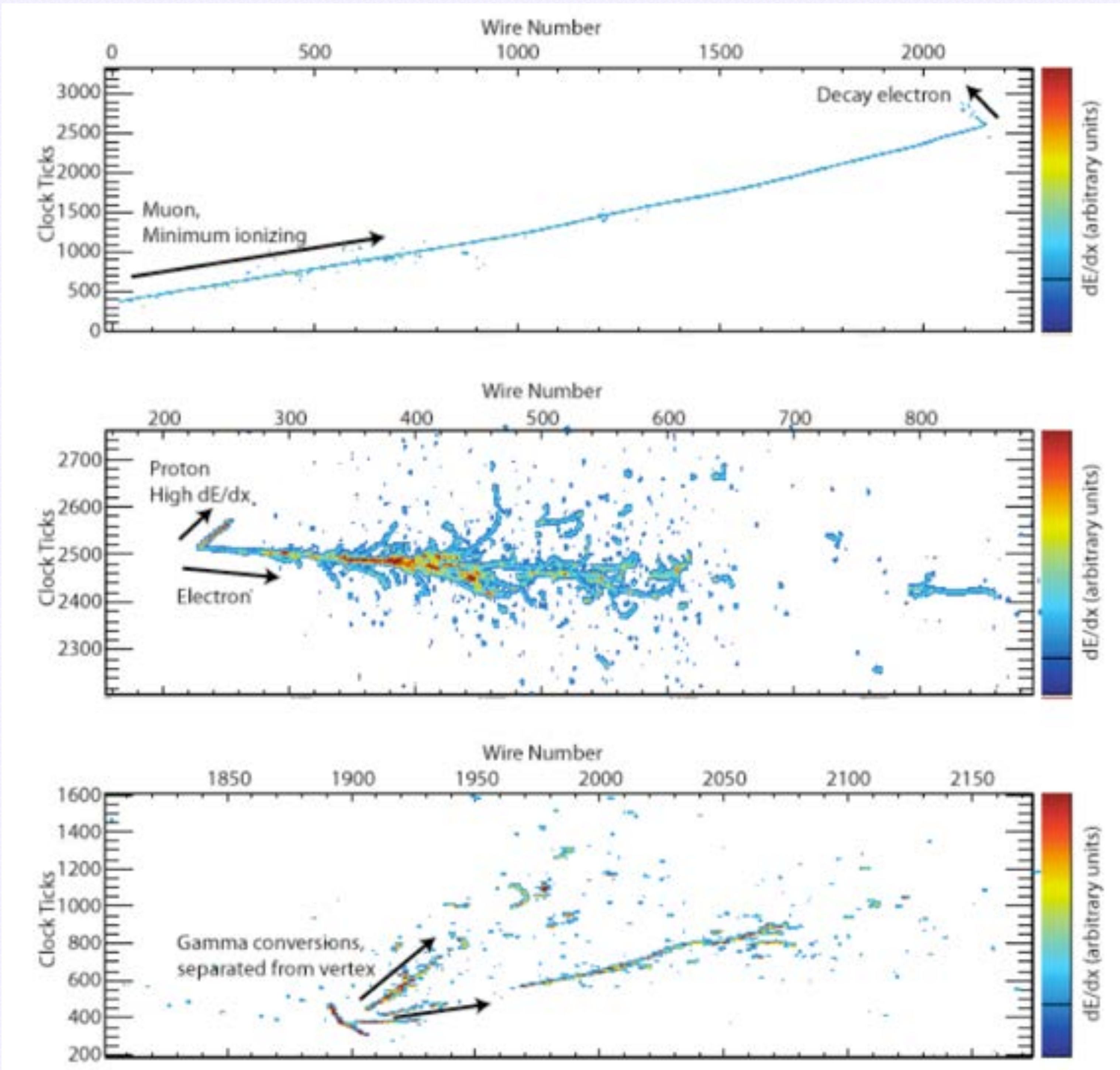
The Liquid Argon Time Projection Chamber

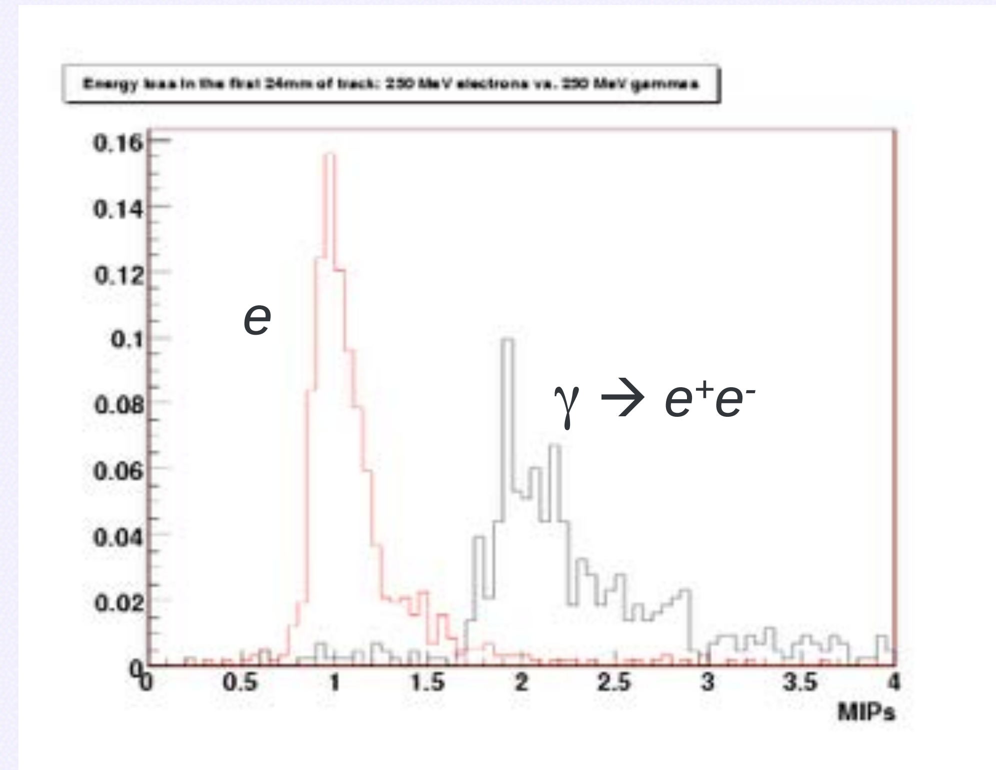




Read out each wire

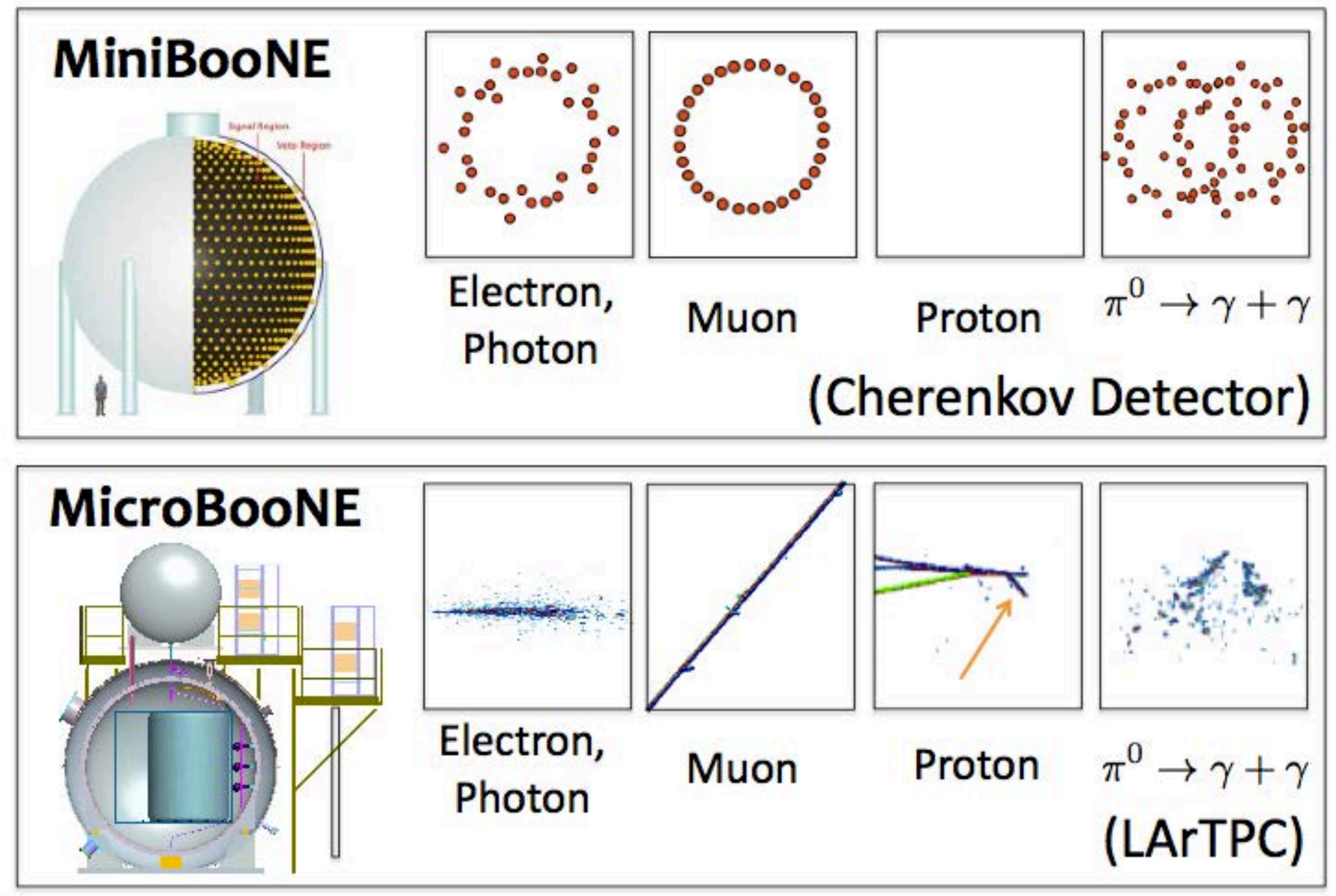
Why LArTPC?



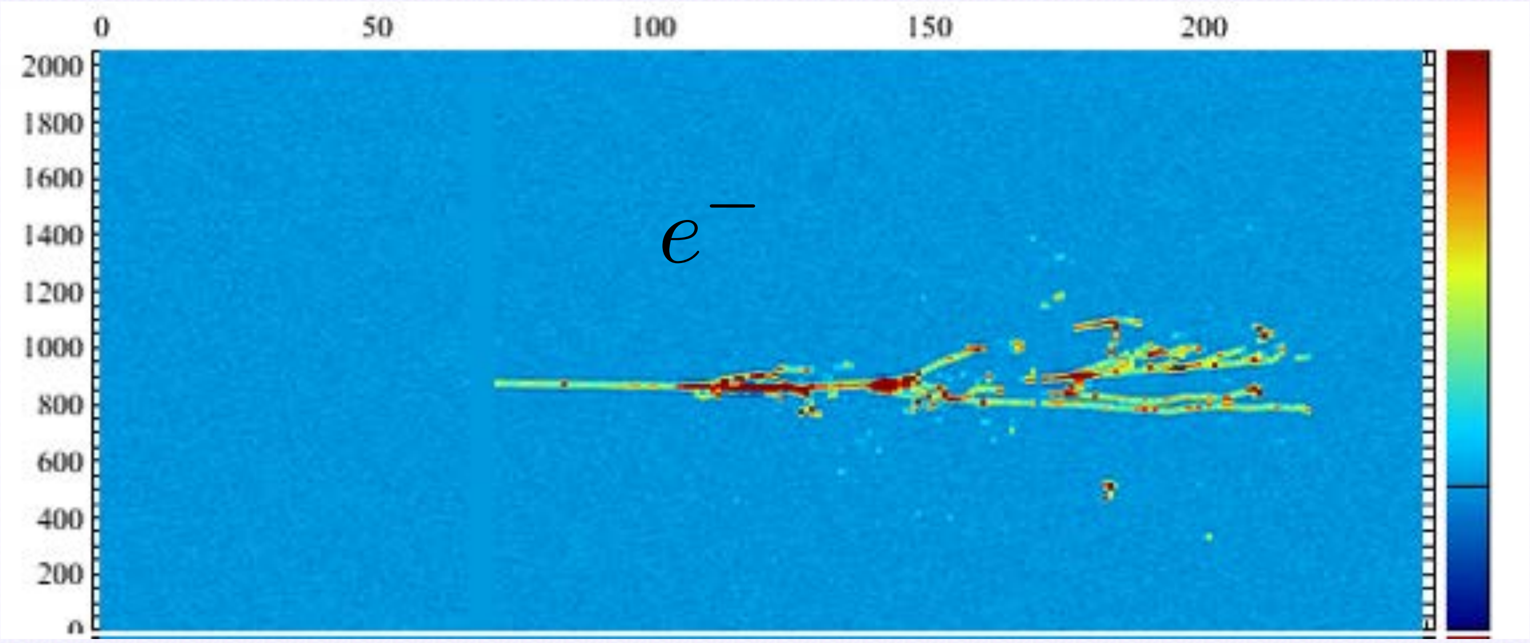


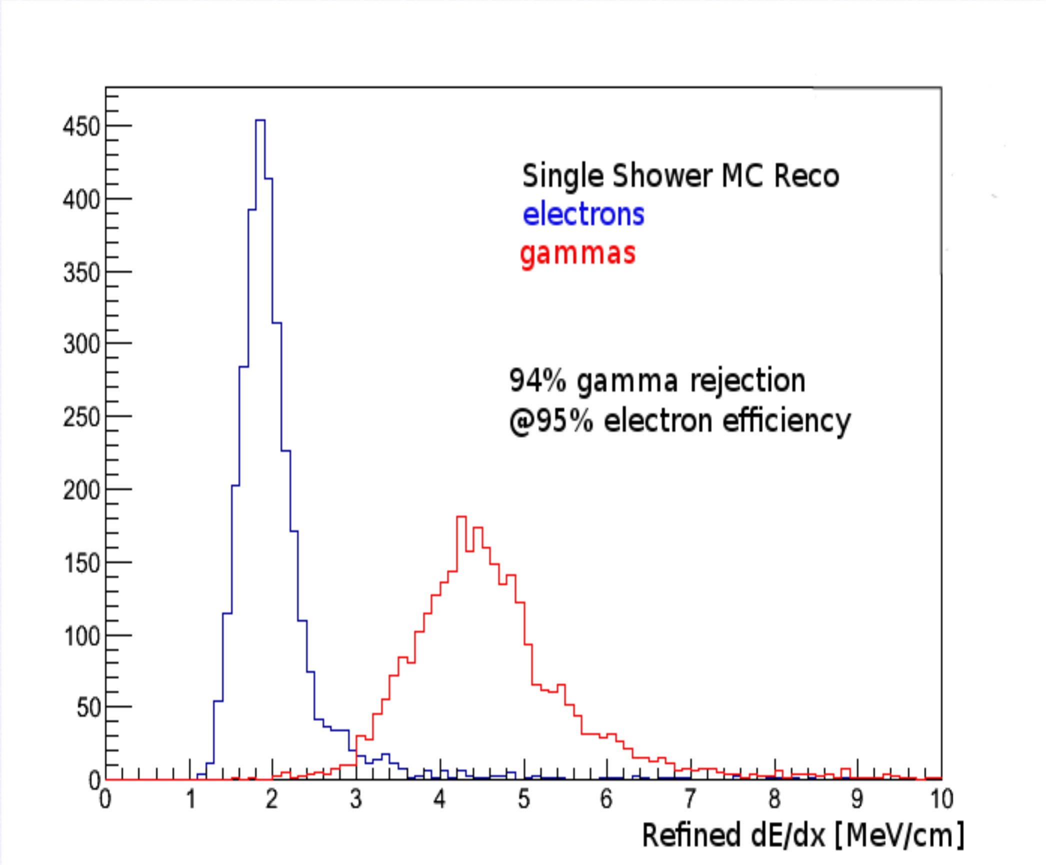
Separate electrons from photons (the main background in MiniBooNE)

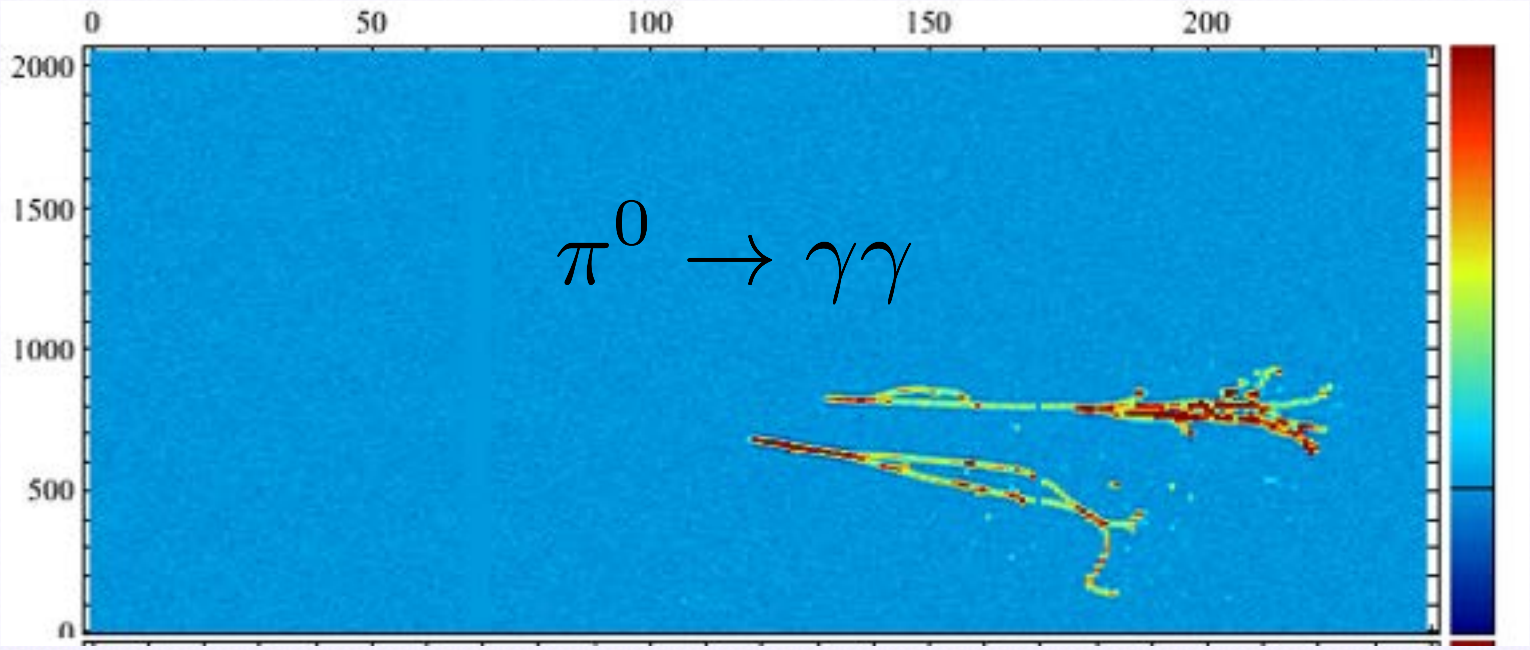
Improvement from MiniBooNE



Electron/Photon Separation







$$\gamma \to e^+ + e^-$$

Two electrons means twice as much ionization in the first few centimeters of a shower

The MicroBooNE Detector

TPC Assembly began 2012

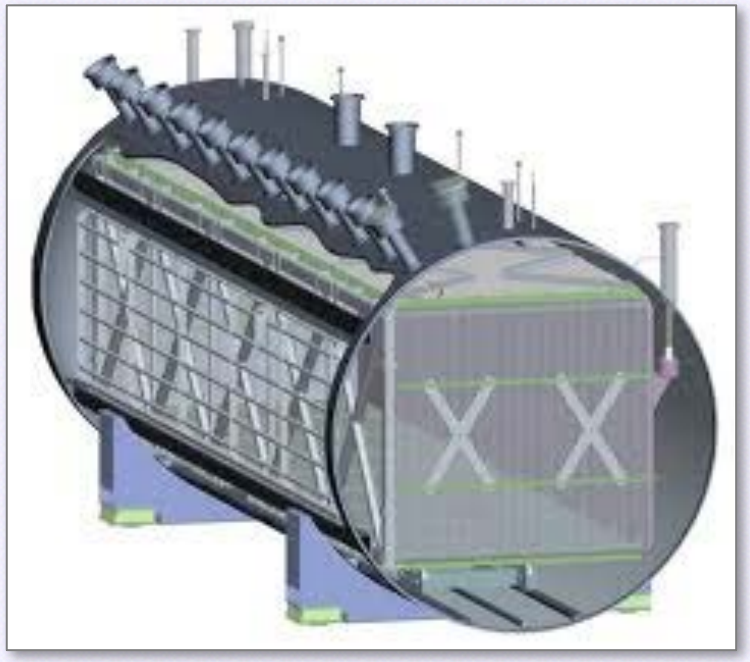
Cryostat Arrival mid 2013

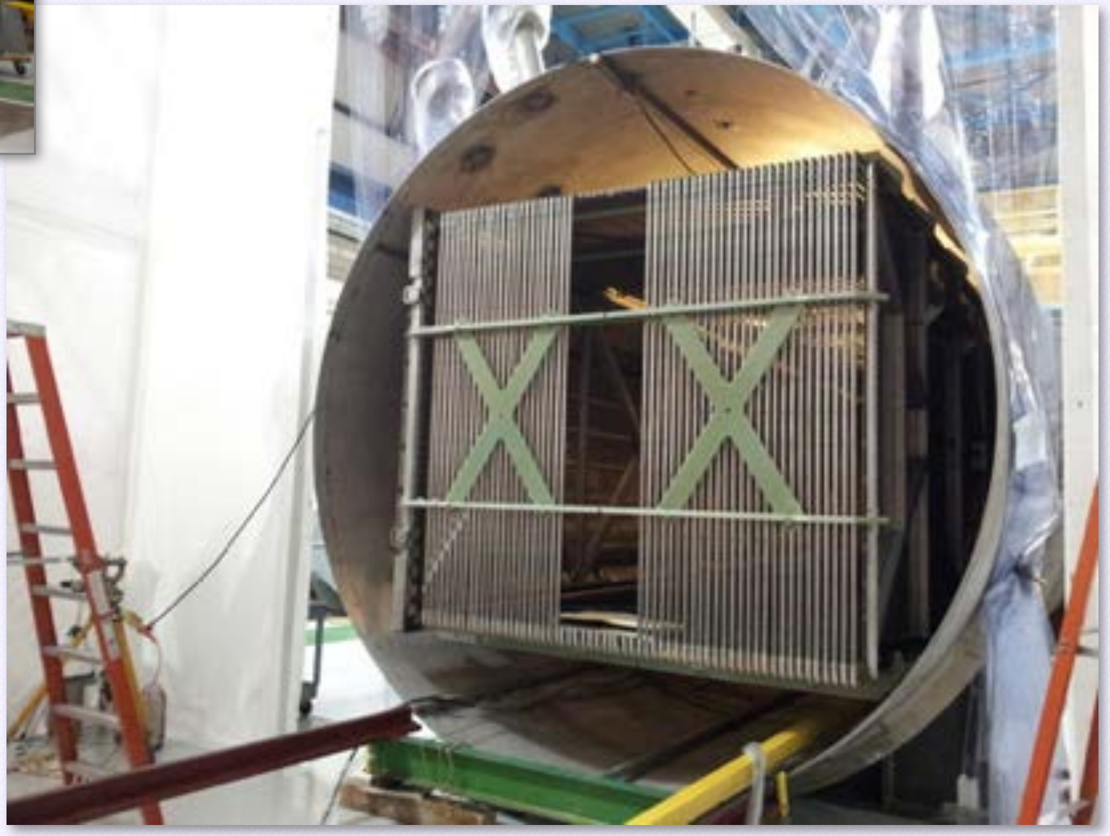
TPC Insertion Dec. 2013

Endcap Welding mid 2014

Commissioning 2014

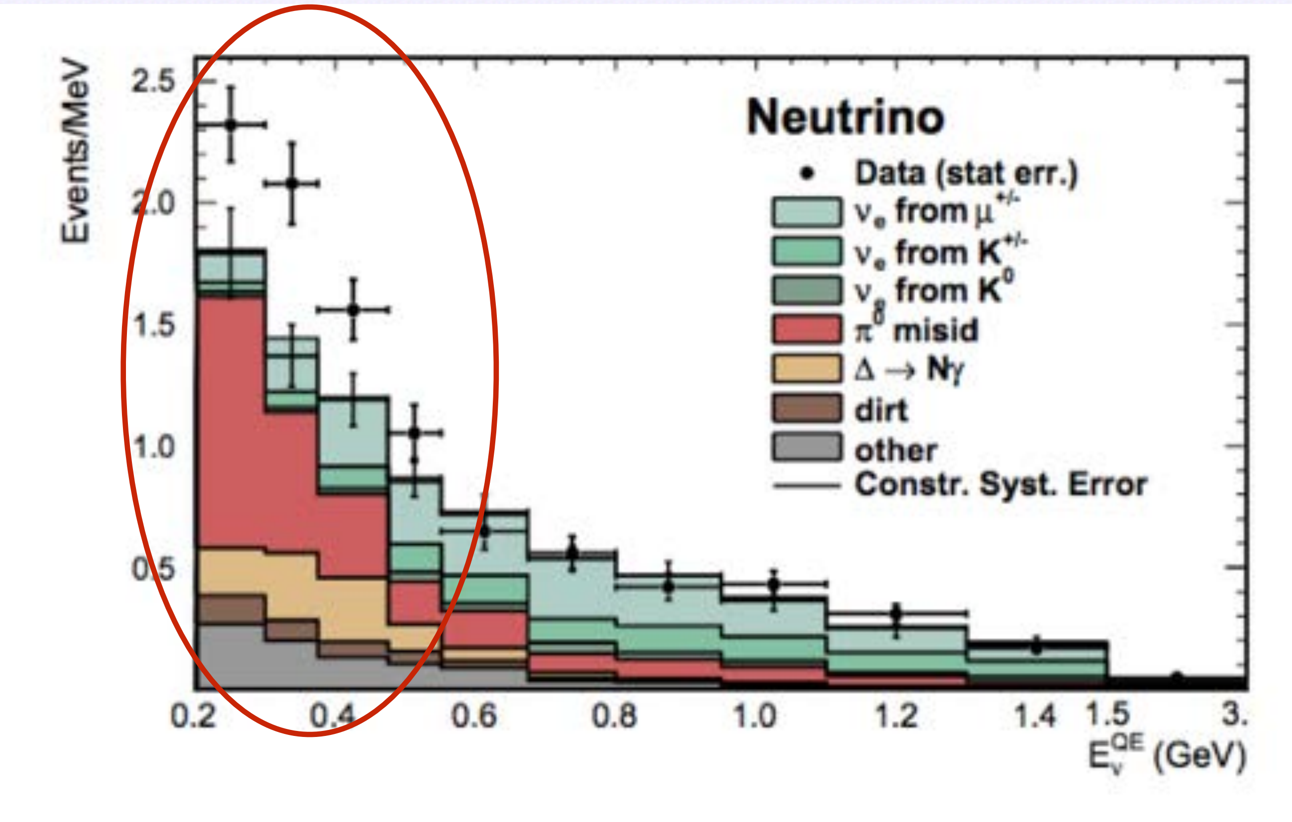
Data taking 2014/15 and on!



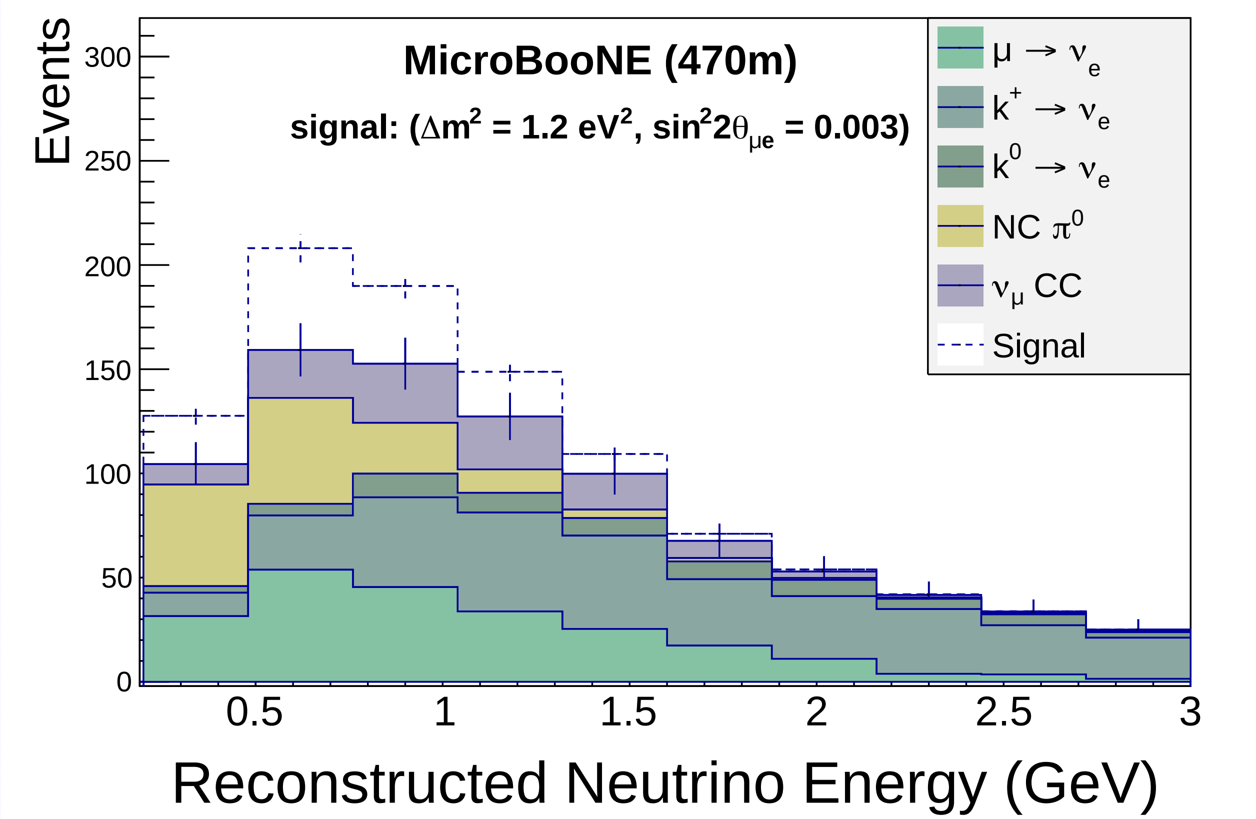


MicroBooNE Physics

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



MiniBooNE predicted backgrounds and observed excess.

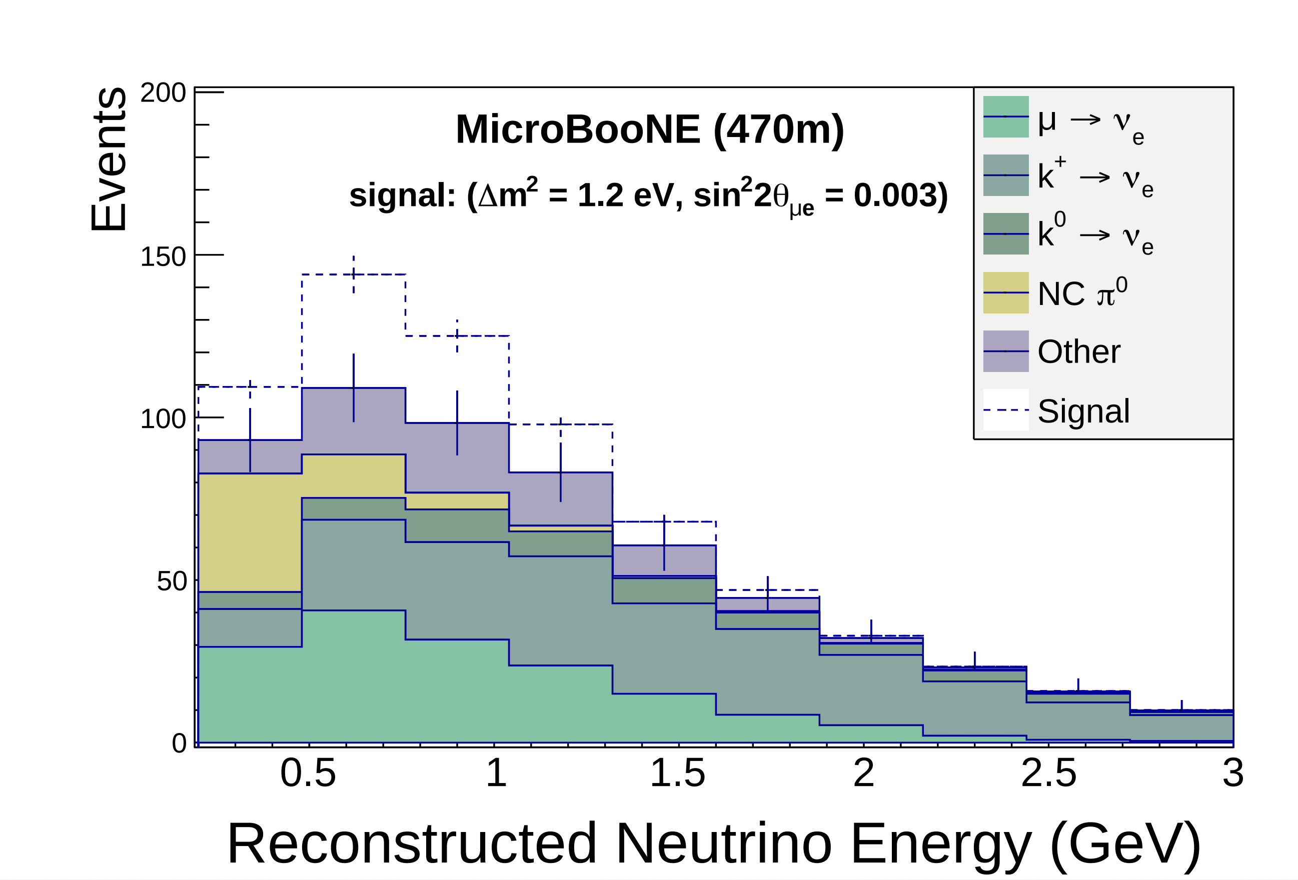


MicroBooNE predicted backgrounds and simulated (3+1) oscillation signal

The MicroBooNE primary physics result will be to confirm or refute the MiniBooNE “Low Energy Excess.”

Single photon rejection greatly reduces the primary background from MiniBooNE

MicroBooNE Alone



Microboone will need to confirm the excess as photons or electrons.

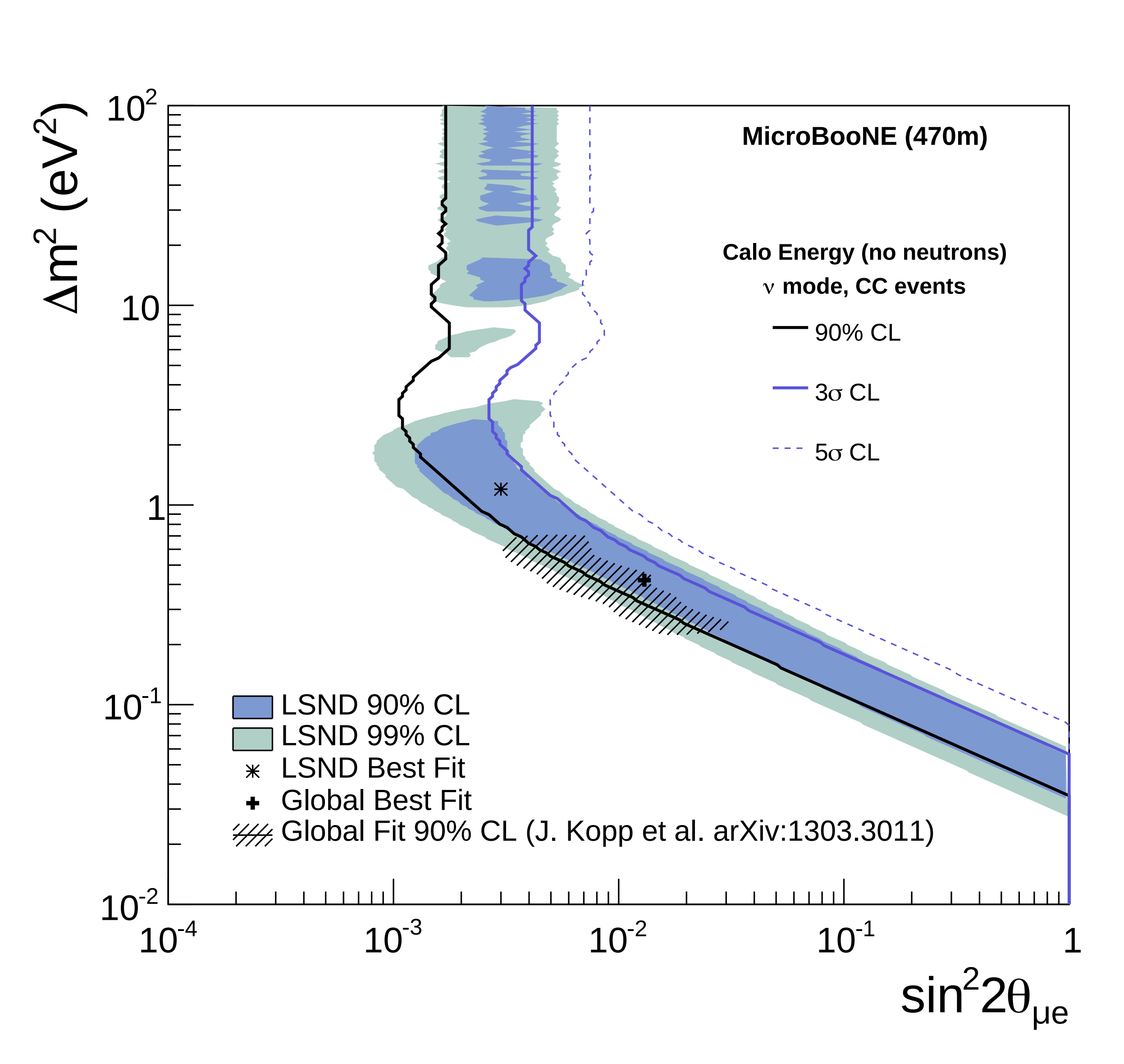
Photons could imply unexpected interaction cross sections

Electrons could imply the existence of sterile neutrinos!

The significance of any observed excess will depend on both the size and certainty of predicted background. Many sources of uncertainty:

- Neutrino Flux (Same as MiniBooNE)
- Neutrino Cross Section
- Photon Containment
- Event Selection Efficiency
- dE/dx separation of photons/electrons
- Neutrino Energy Reconstruction

Projected MicroBooNE Sensitivity



MicroBooNE Sensitivity to sterile neutrinos in 3+1 model after ~3 years (6.6e20 POT) of running

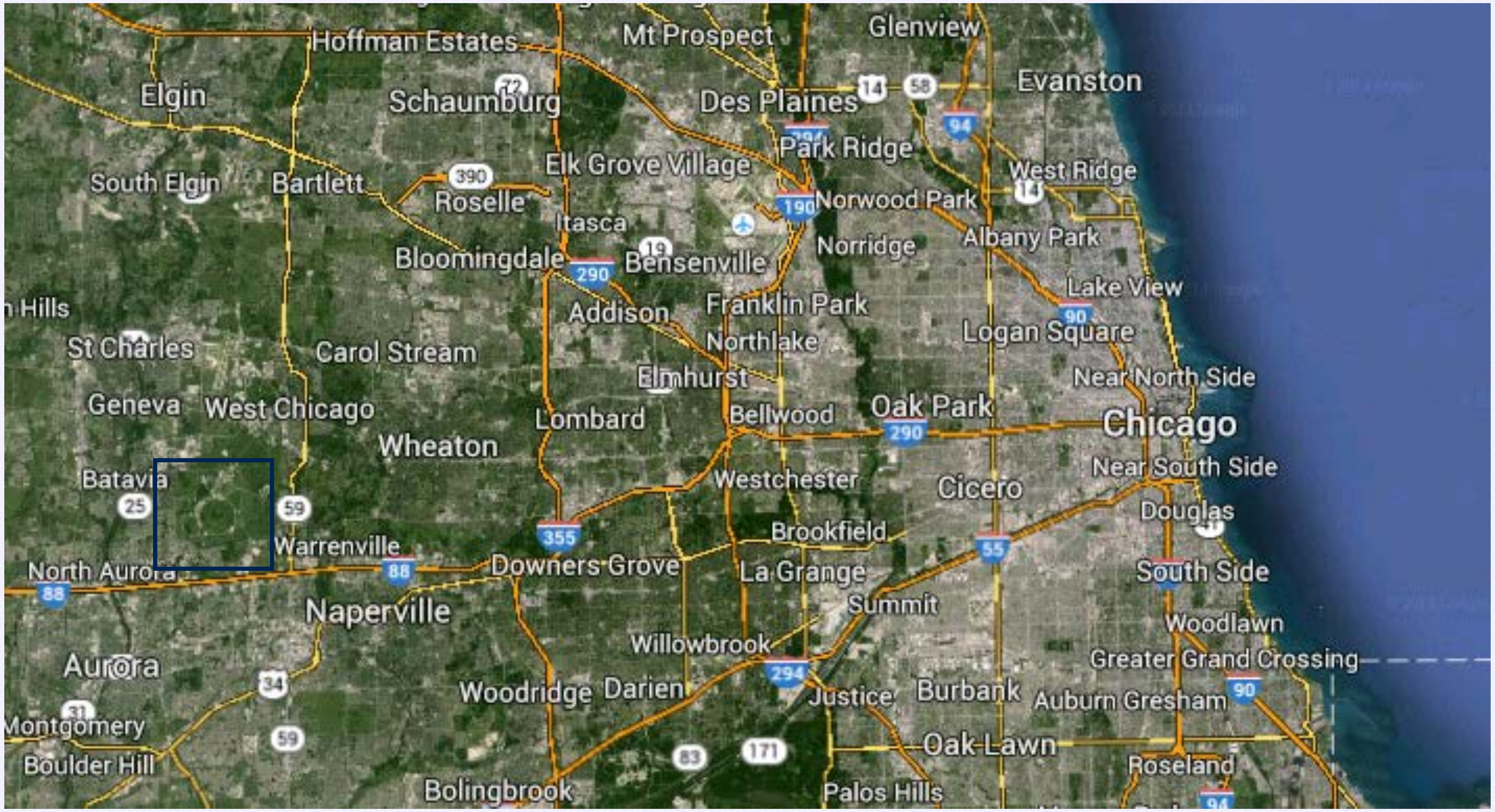
MicroBooNE is well positioned to make a definitive measurement and characterization of the MiniBooNE excess, but has limited reach in addressing further questions if the excess points toward possible oscillations.

The uncertainties on the predicted backgrounds are the limiting factor in a MicroBooNE measurement.

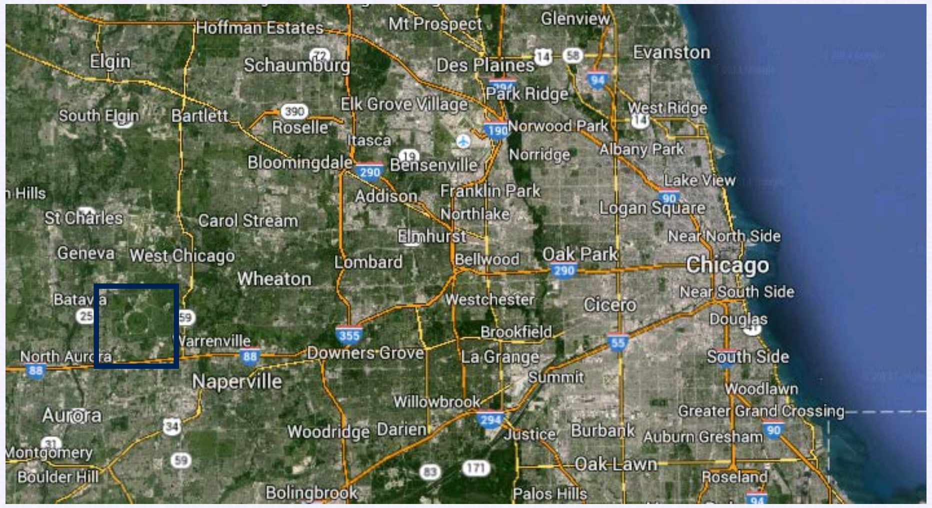
LAr1 - ND

A near detector with MicroBooNE

What? Where? When?



What? Where? When?



What? Where? When?

Booster Neutrino Beam

MiniBooNE

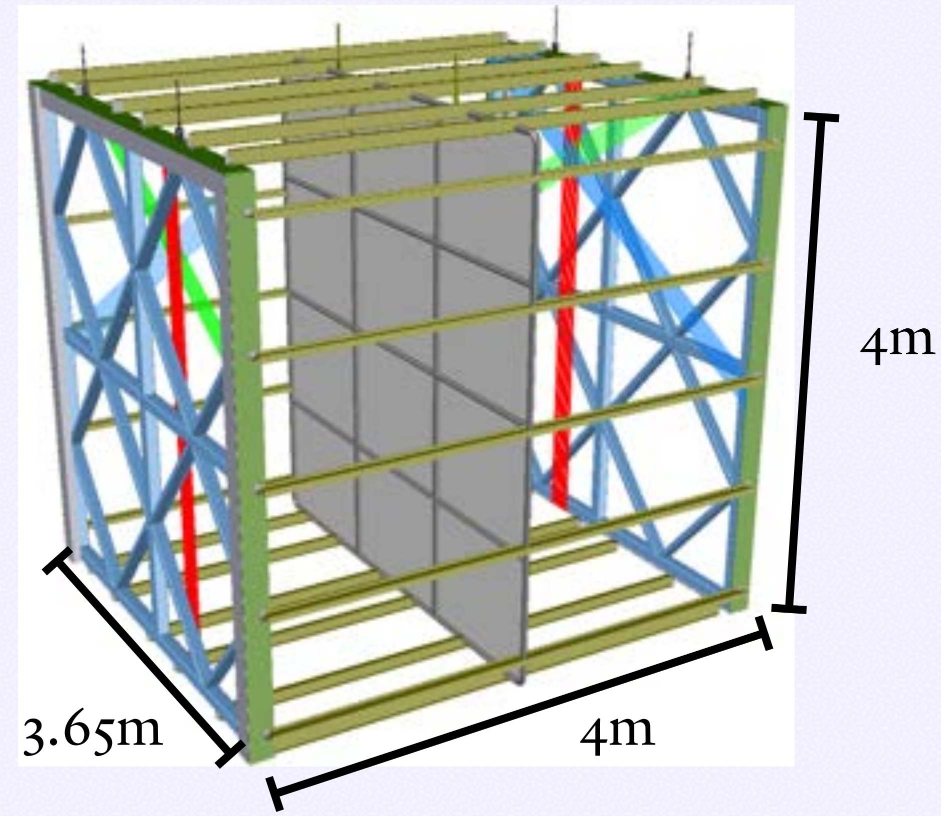
MicroBooNE
(2015)

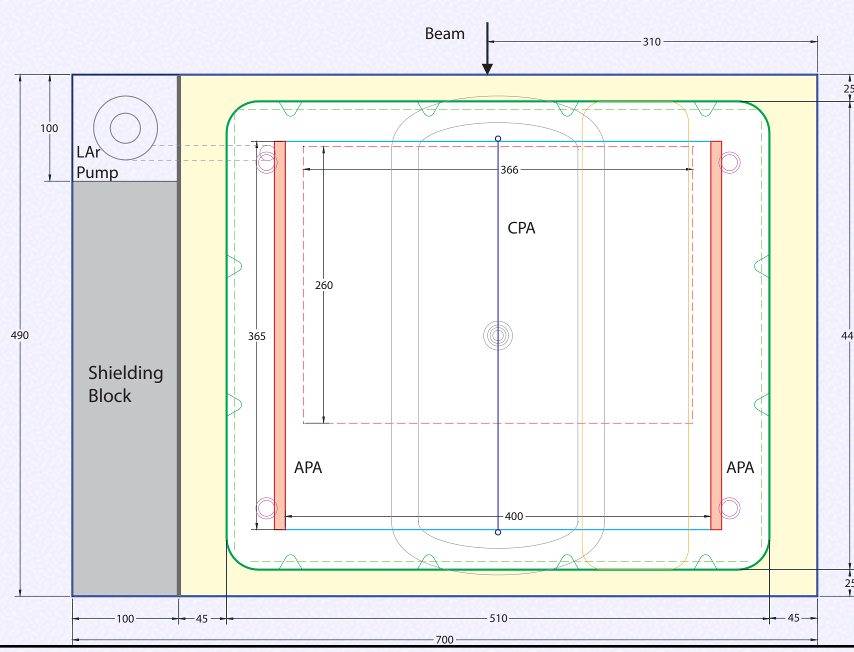
LAr1 - ND
(2018)

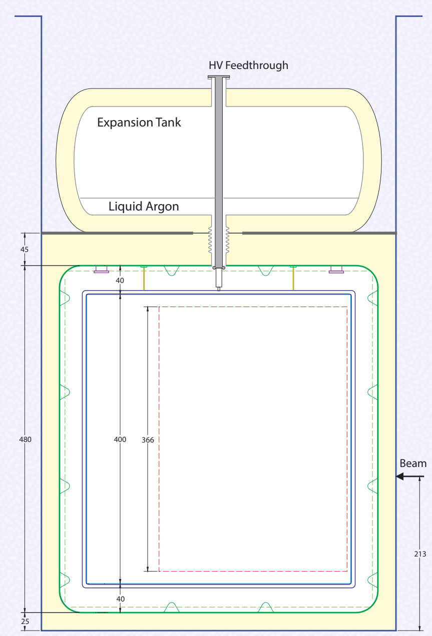
Detector Concept

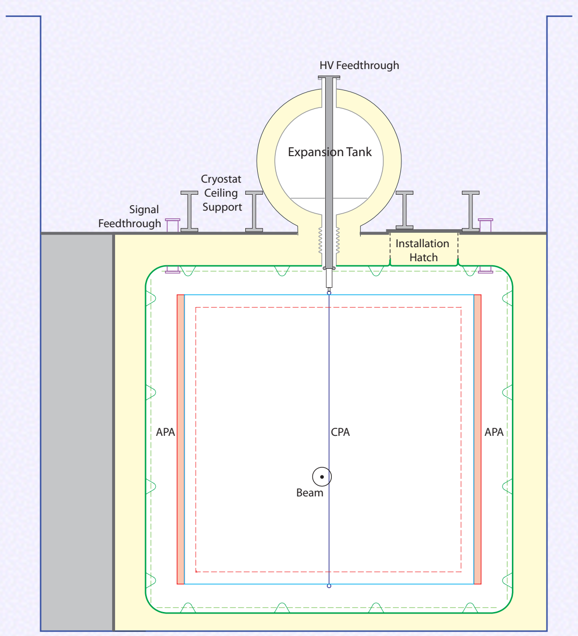
Existing Enclosure!

82t of argon in
active volume

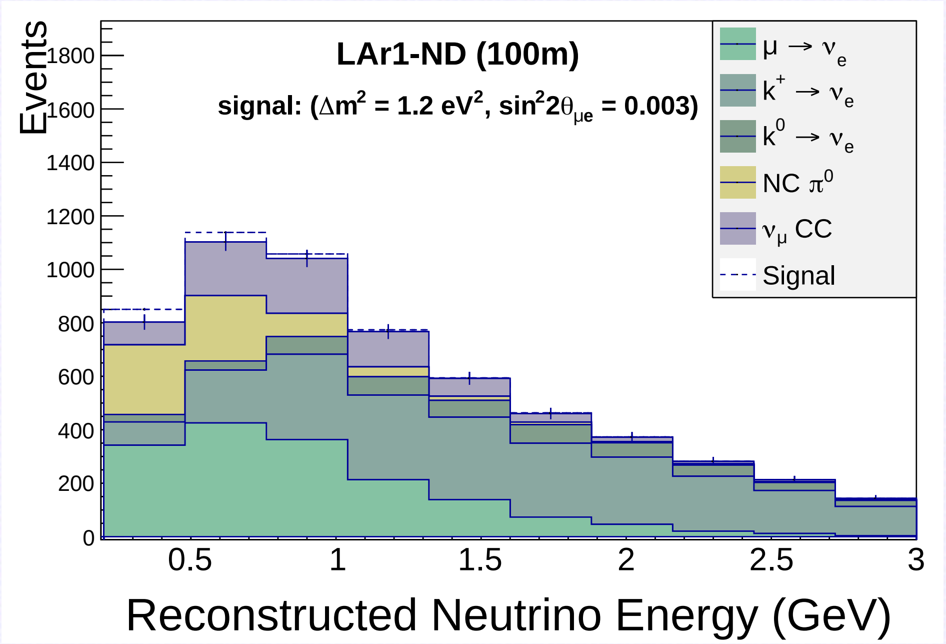


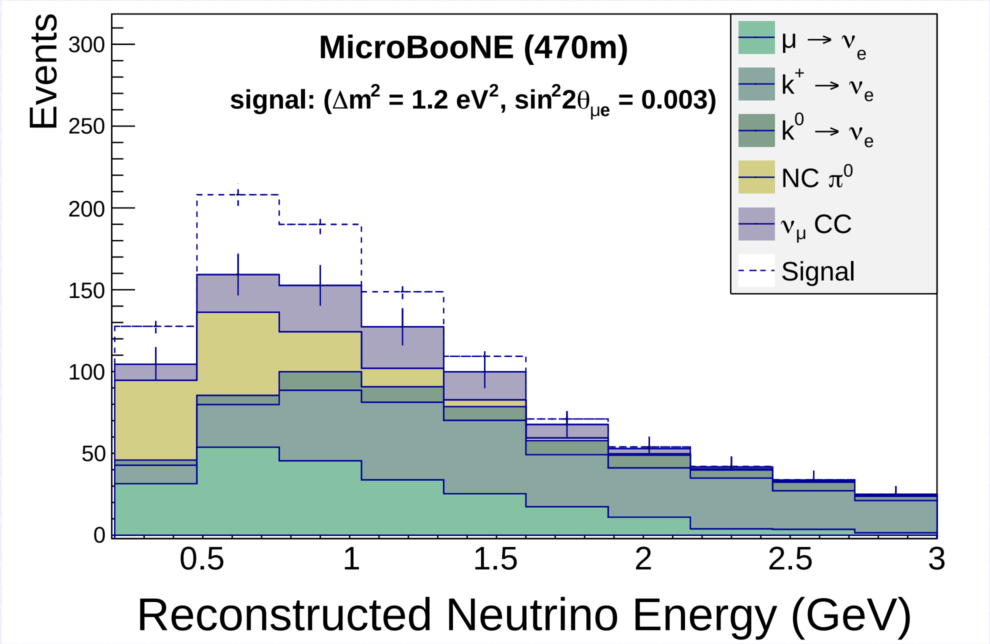




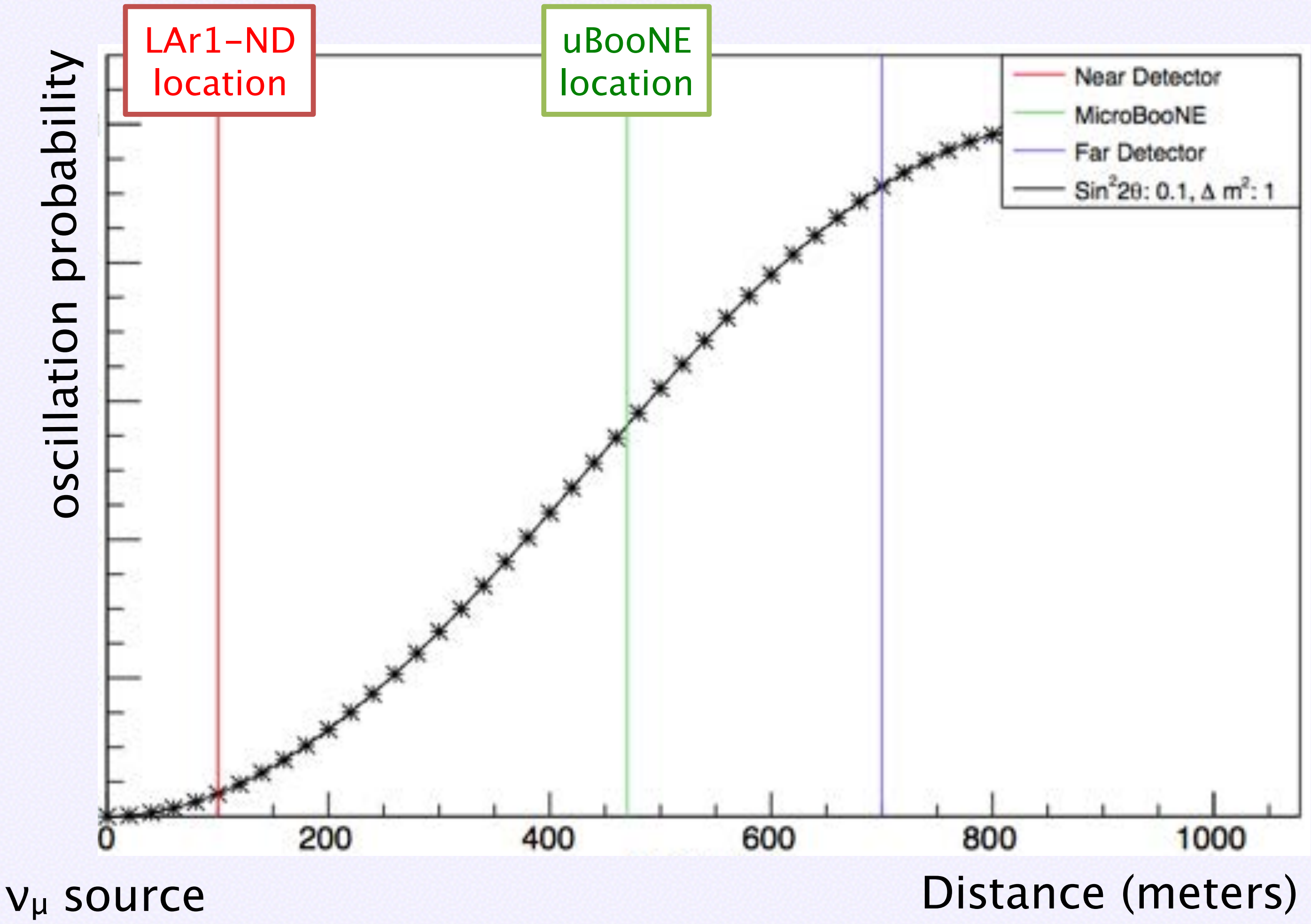


What to do with a Near Detector





Provide a high statistics measurement of event rate **before** any oscillation signal develops



ν_μ disappearance probability at $\mathbf{E}_\nu$ = 700 MeV as a function of distance in a sterile neutrino model with $\boldsymbol{\Delta m^2 = 1.0}$ $\mathbf{eV^2}$

Constrain Intrinsic Event Rate

The LAr1-ND prediction of event rates at MicroBooNE can increase the significance of a MicroBooNE measurement through the correlation of errors:

Correlated

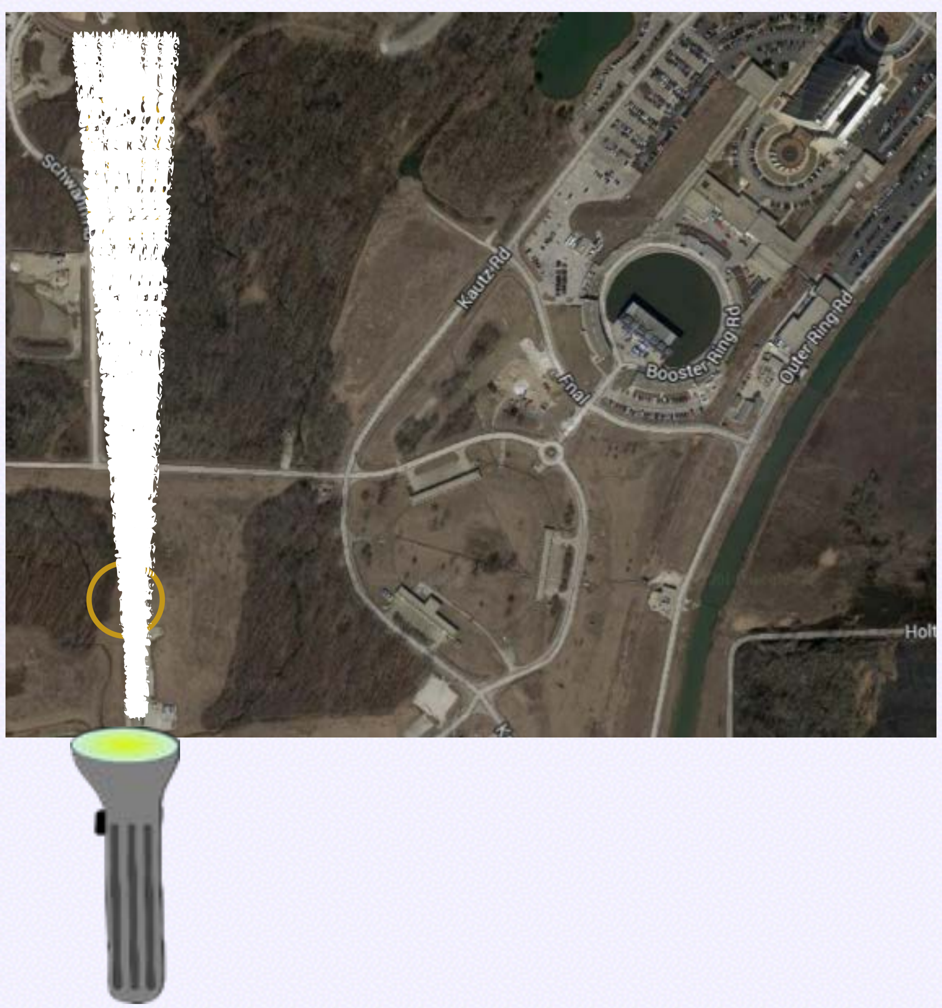
- Photon Containment
- Neutrino Flux
- Neutrino Energy Reconstruction
- Event Selection Efficiency

Strongly Correlated

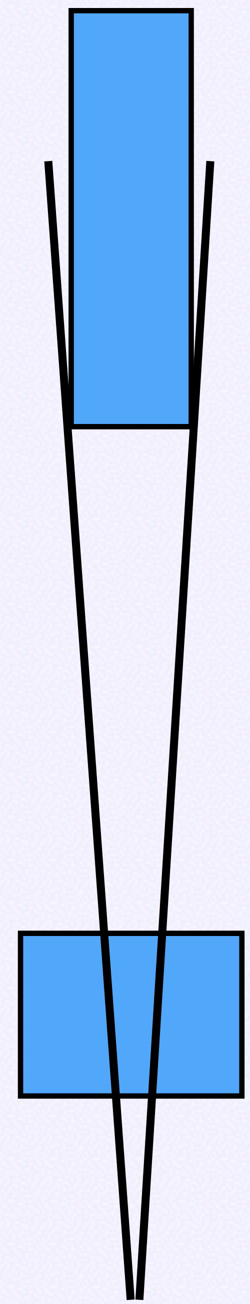
- Neutrino Cross Section
- dE/dx separation of photons/electrons

Intrinsic Error Sources

Neutrino Flux and Cross Section
or
How many neutrinos and how often do they interact?



MicroBooNE



LAr1 - ND

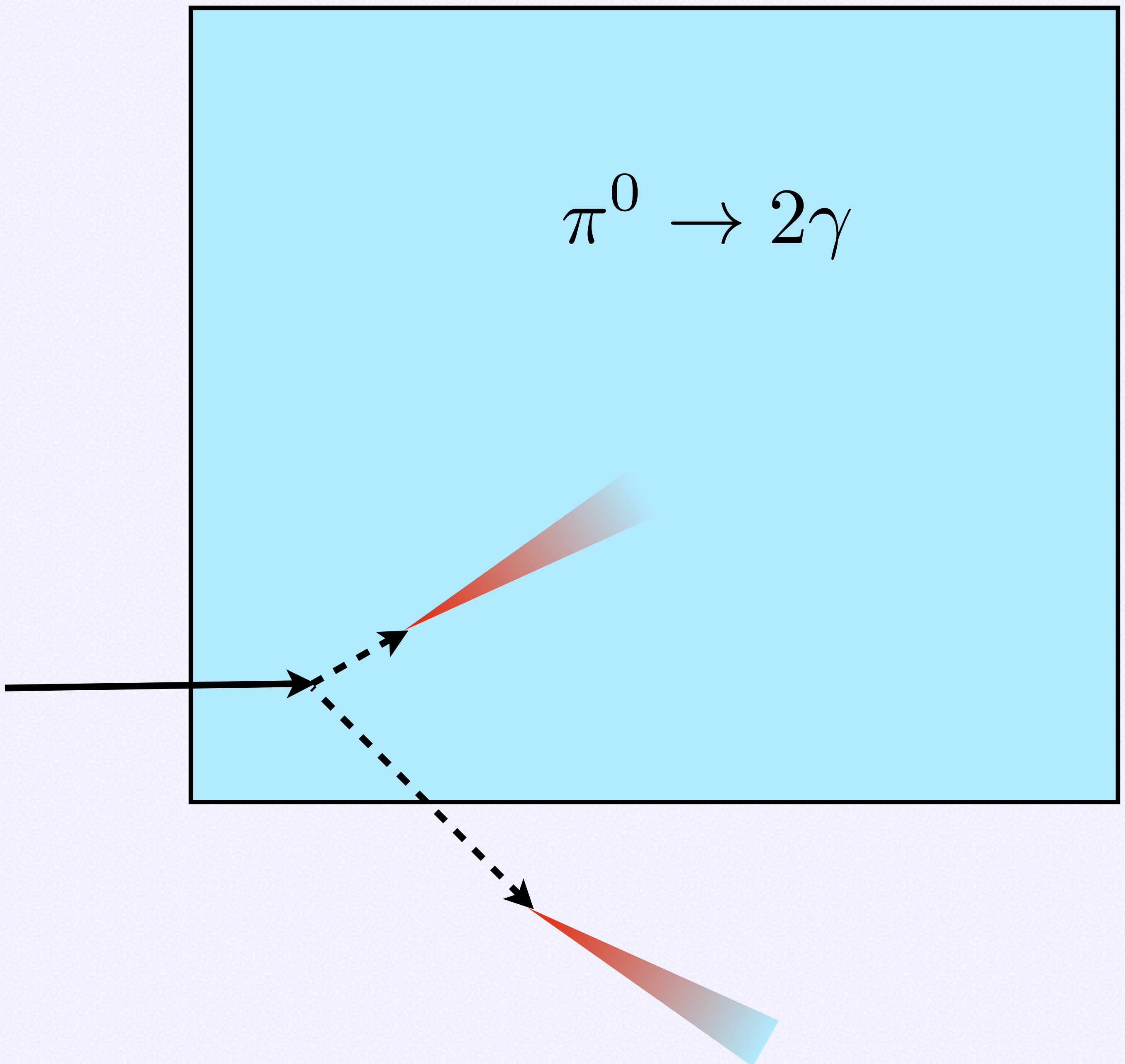
Differences in solid angle with respect to the beam complicate this correlation

Cross sections are completely correlated.

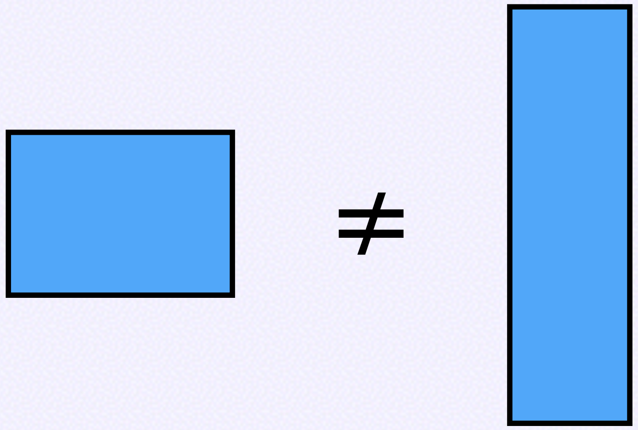
The addition of a near detector measurement strongly reduces flux and cross section uncertainties in MicroBooNE

Detector Error Sources

Photon Containment



A neutral pion can look like an electron if one photon escapes, **and** it passes the dE/dx cut

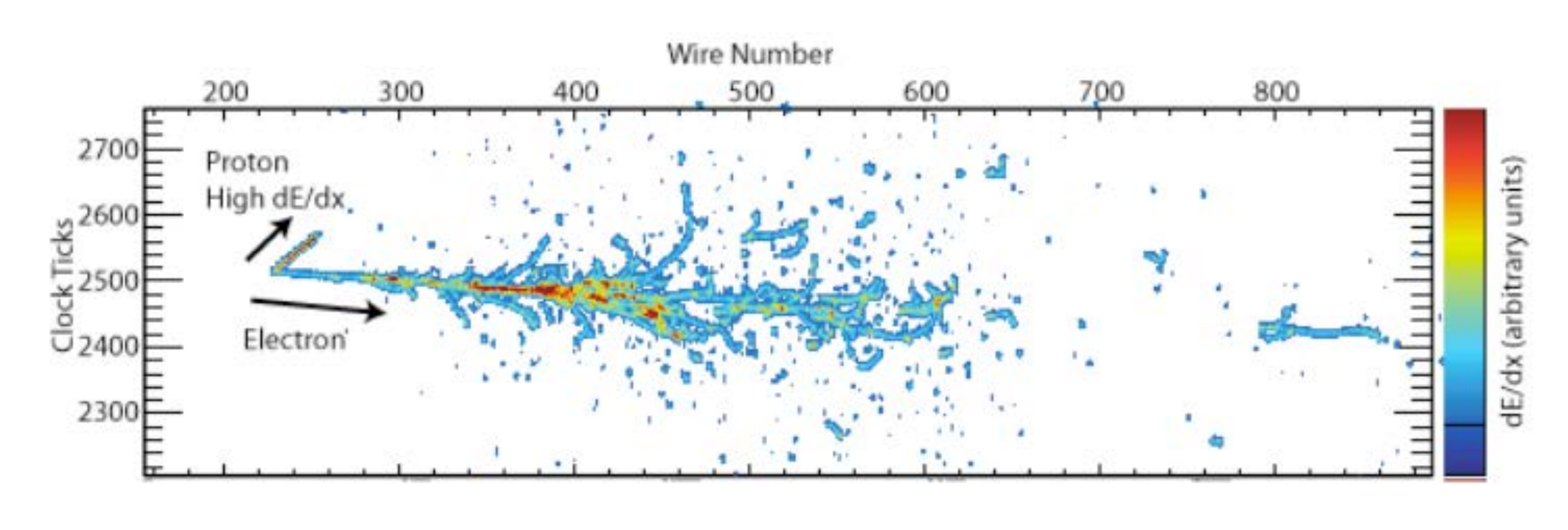


Detector geometry has a big impact on photon containment, so this is not an easily correlated source of error.

Can be constrained by the events with both photons contained - high statistics

Detector Error Sources

dE/dx separation of photons/electrons

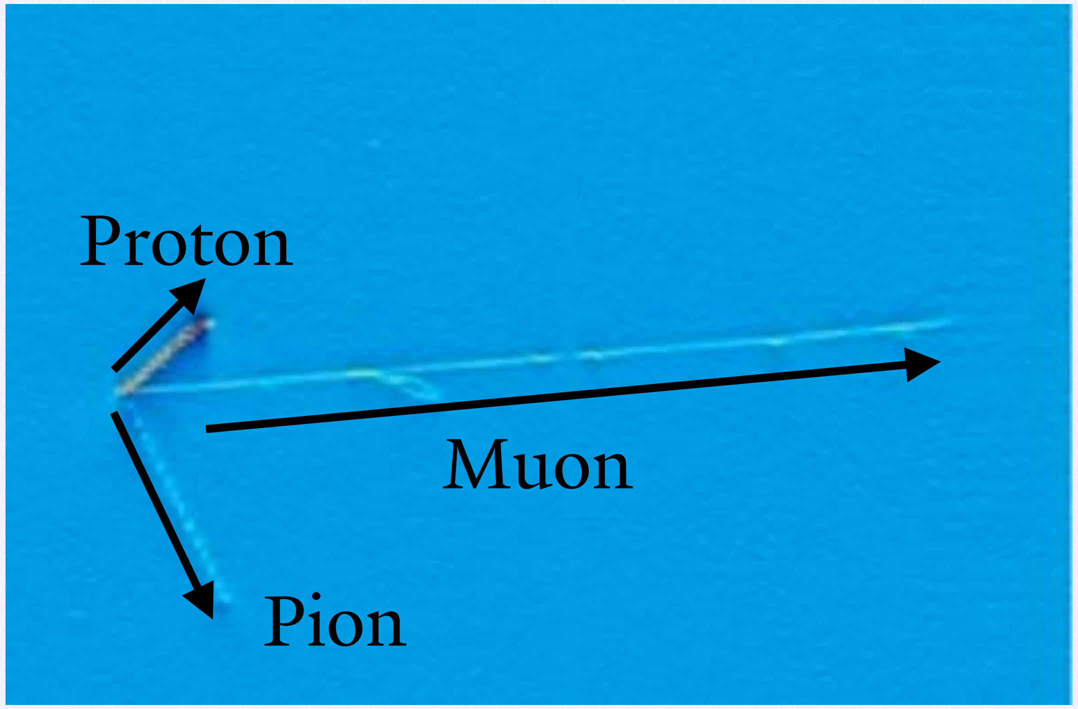


Only the first few centimeters of a shower are needed for dE/dx tagging as electron or photon.

LAr1-ND designed to be identical to MicroBooNE in wire pitch and angles - intended to keep detector calibration systematics as close as possible

Detector Error Sources

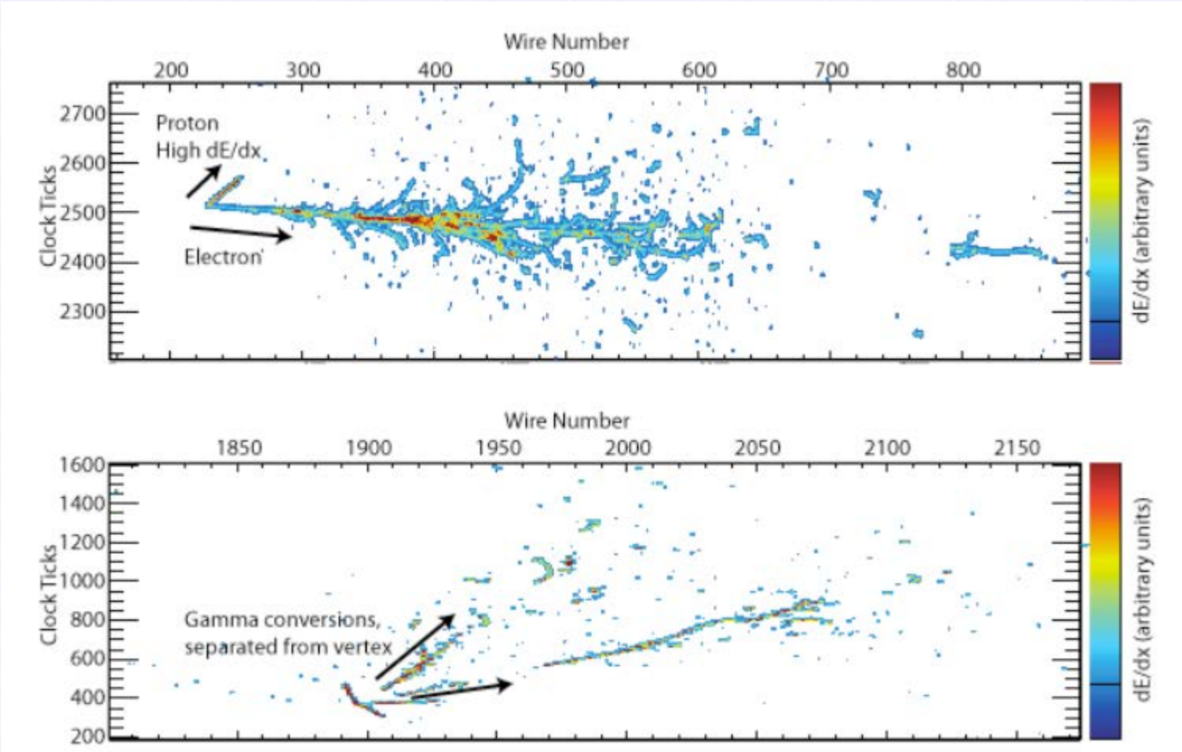
Neutrino Energy Reconstruction



$$E_\nu = E_{lep} + \sum KE + E_{missing}$$

Fine grained resolution and tracking allows accurate, calorimetric reconstruction of many event topologies.

Event Selection Efficiency



Detailed event data allows the use of calorimetry (dE/dx) **and** topology to reject backgrounds

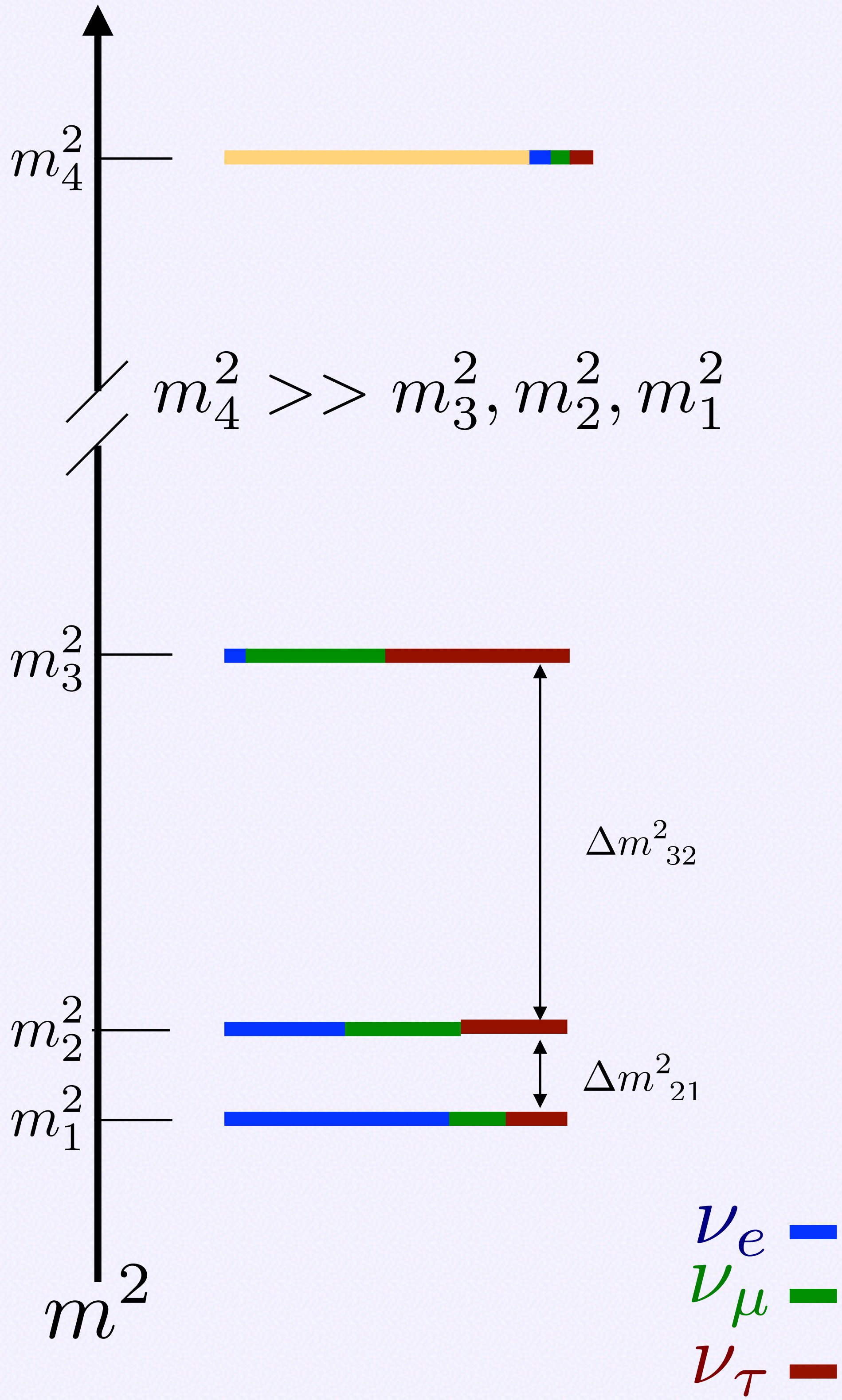
Except for containment, errors between detectors are very correlated.

Is an Excess an Oscillation?

An electron like excess of events in MicroBooNE by itself is not evidence for a new mechanism of neutrino oscillations.

	Observed Interaction
LAr1-ND increases the significance of ν_e appearance	$\nu_e + n \rightarrow e^- + p$
LAr1-ND **enables** the measurement of ν_μ appearance	$\nu_\mu + n \rightarrow \mu^- + p$
LAr1-ND **enables** the measurement of Neutral Current disappearance	$\nu_x + N \rightarrow \nu_x + N + \pi^0$

Oscillation Scenarios



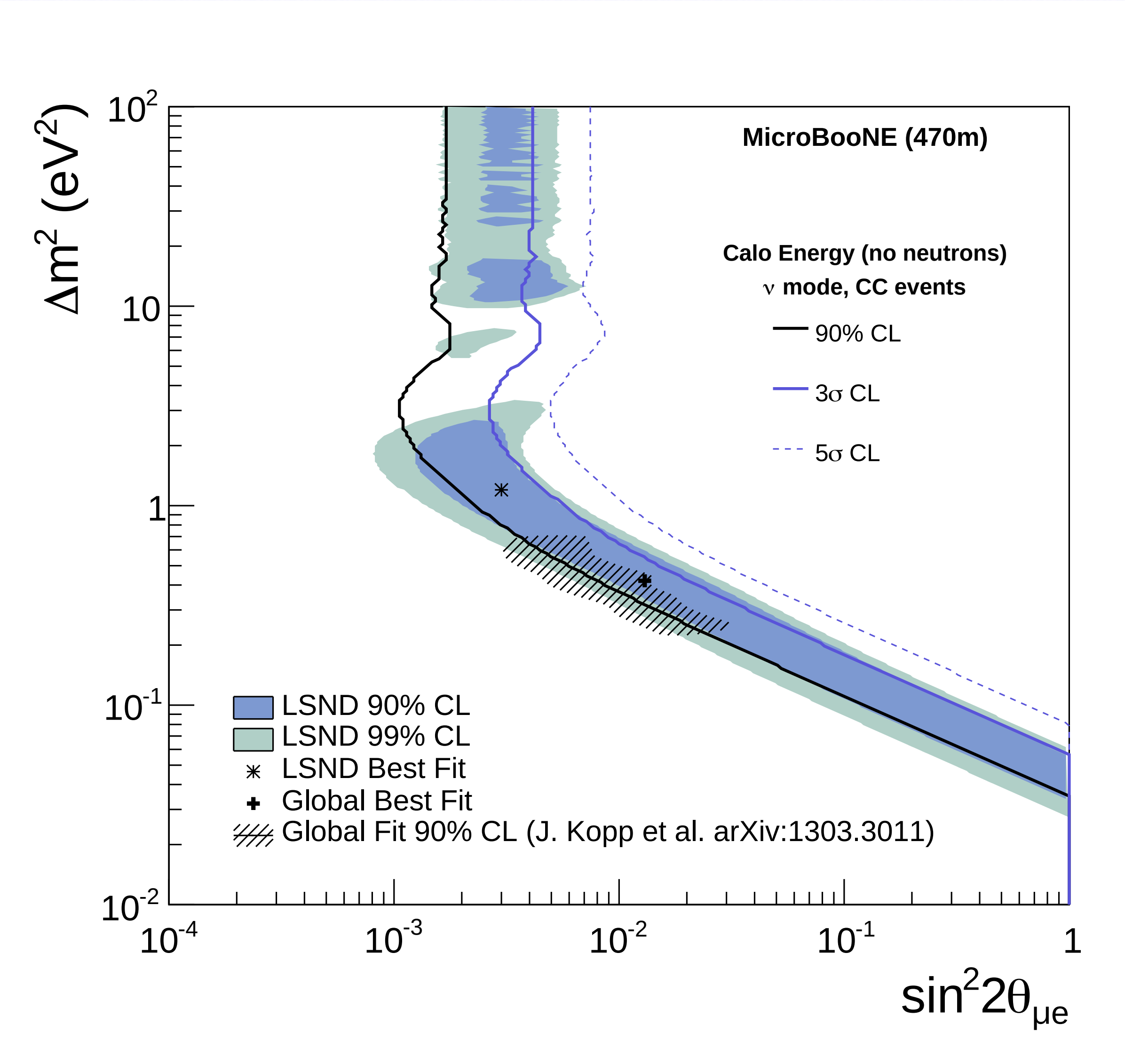
ν_μ disappearance: oscillation from ν_μ to sterile

ν_e appearance: oscillation from ν_μ to sterile to ν_e

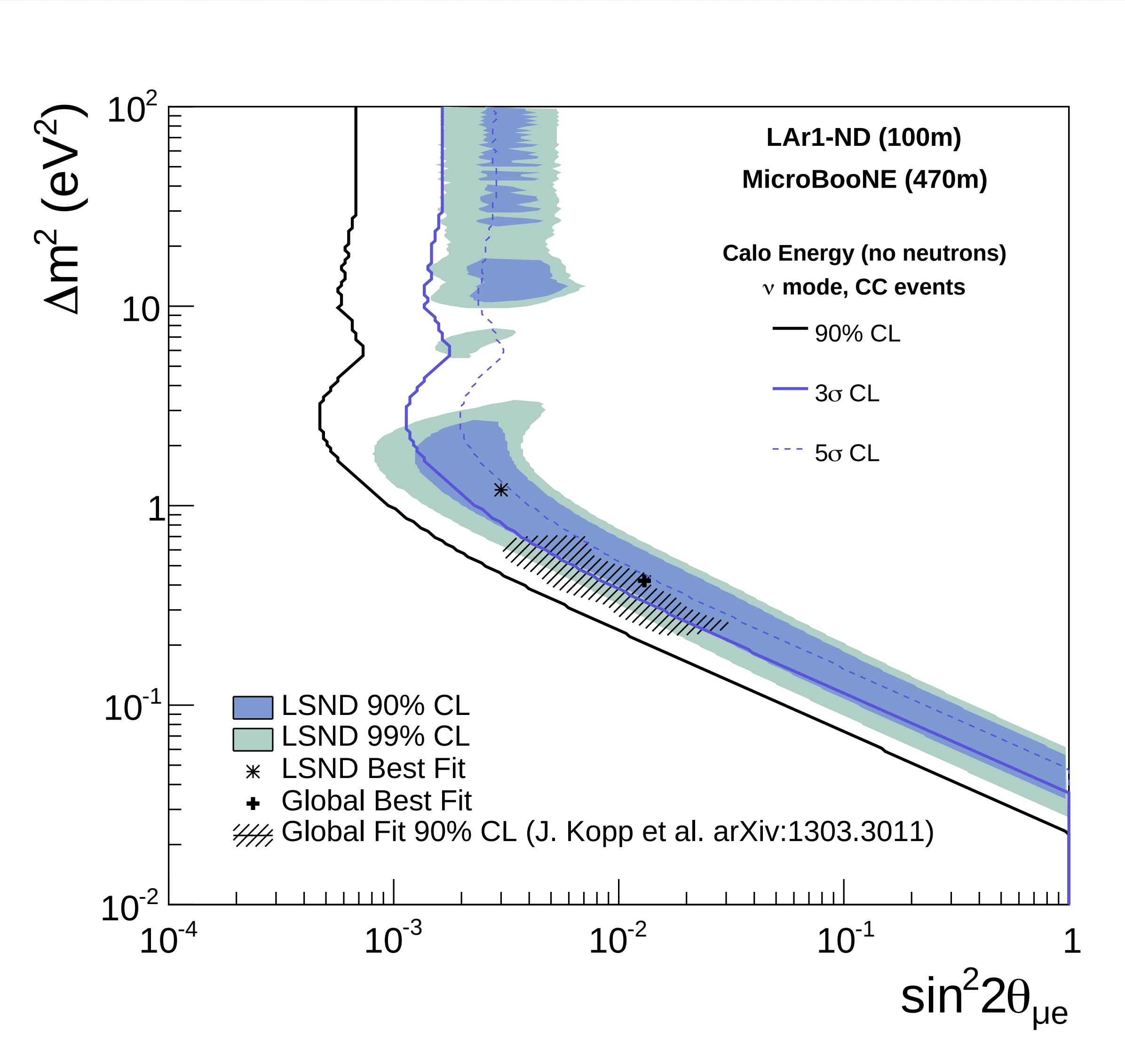
Neutral Current disappearance: All active flavors oscillate to sterile

Not independent signals.

ν_e Appearance

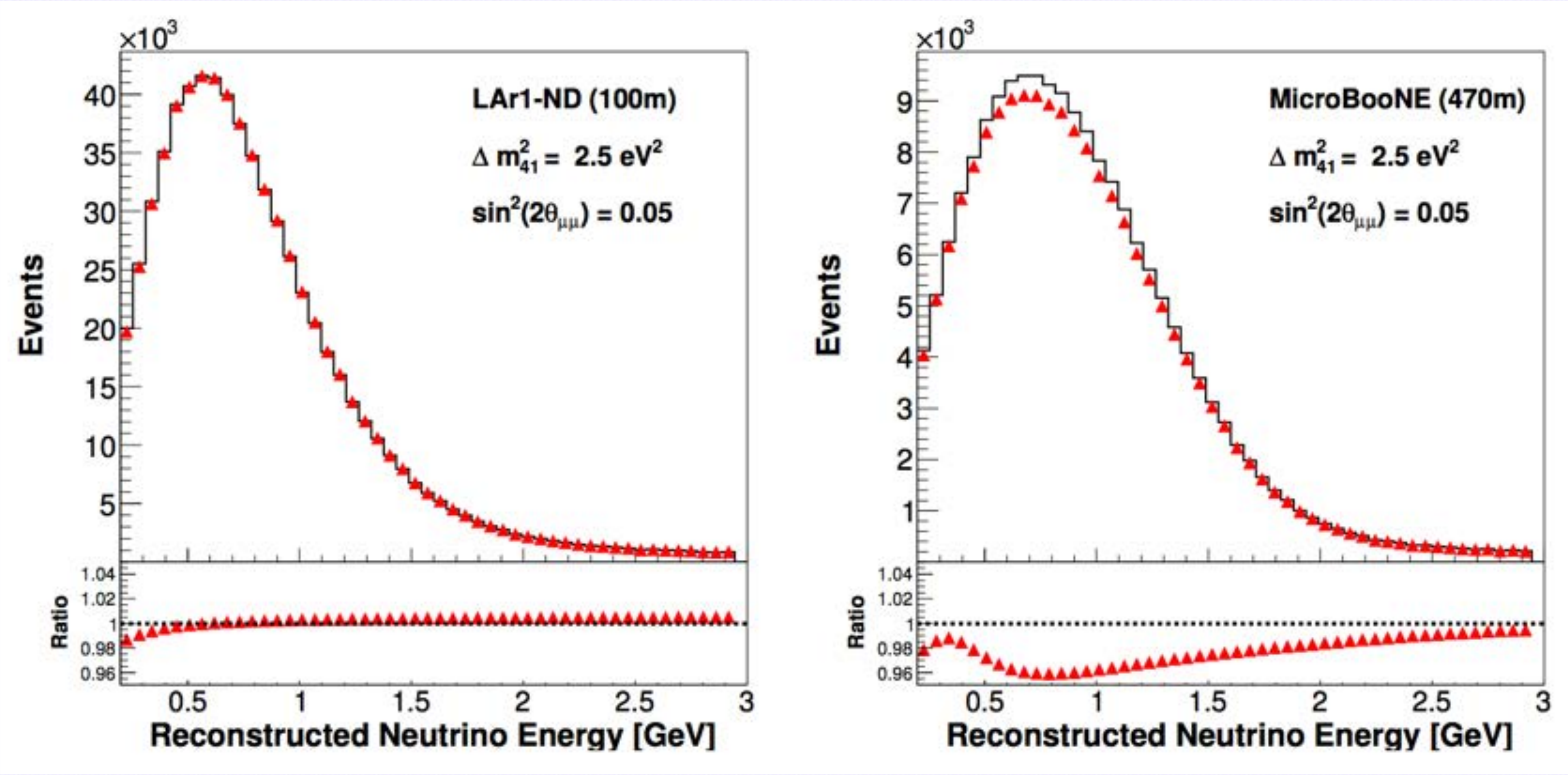


MicroBooNE Sensitivity to sterile neutrinos in 3+1 model after ~3 years (6.6e20 POT) of running



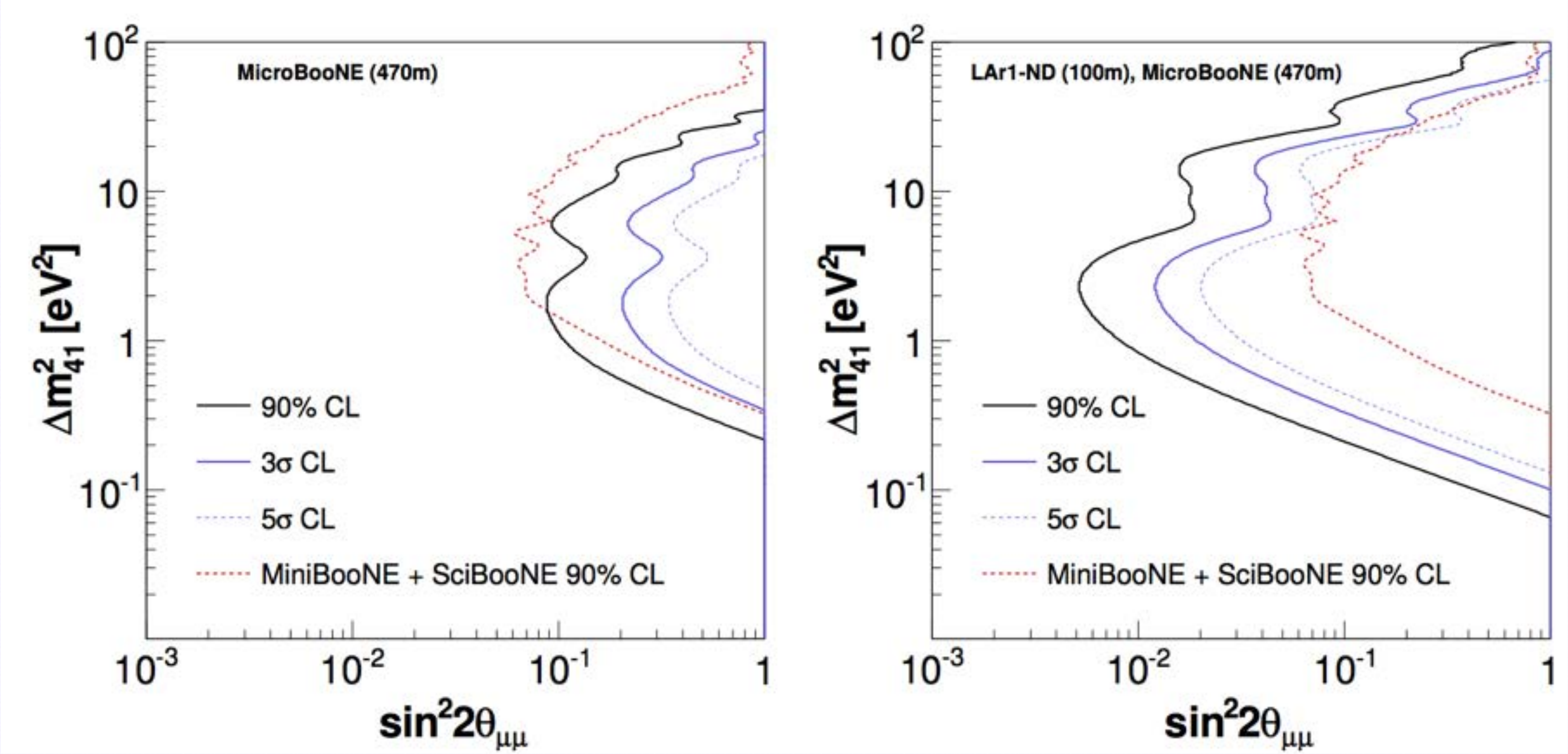
MicroBooNE + ~1 year (2.2e20 POT) of LAr1-ND data. Covers entire LSND allowed region at >90% C.L.

ν_μ Disappearance



The possible oscillation signal in MicroBooNE is completely obscured by 15-20% flux and cross-section errors without a near detector.

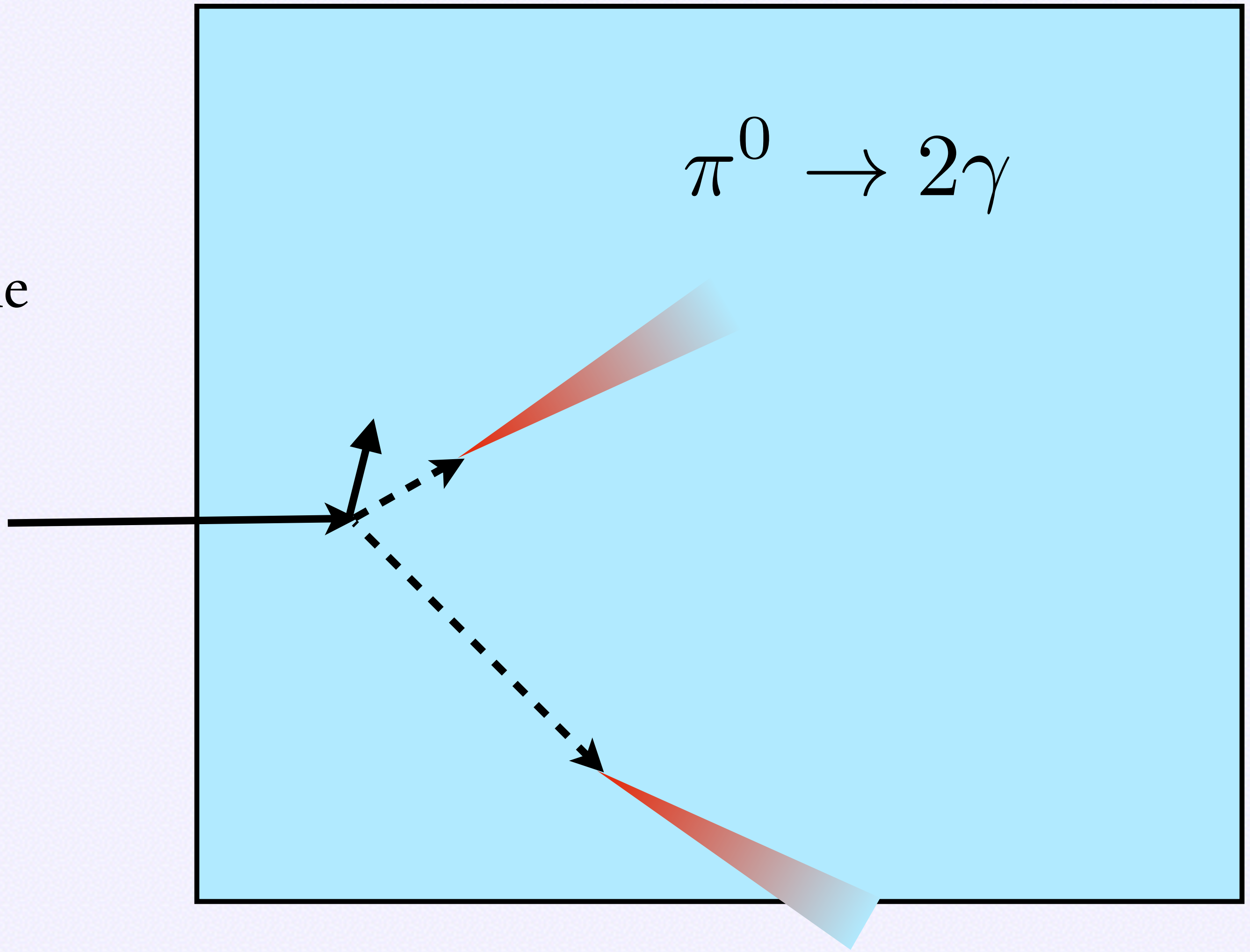
ν_μ Disappearance



Again, the addition of 1 year of LAr1-ND data reduces the uncertainty in predicted rates in MicroBooNE.

Neutral Current Disappearance

An overall deficit of neutrino interactions from LAr1-ND to MicroBooNE will confirm that neutrinos are oscillating to a sterile channel.



Possible event signature:

$$\nu_x + p \to \nu_x + p + \pi^0$$

Vertex activity with two photons pointing towards it is a clear sign of a neutral current interaction.

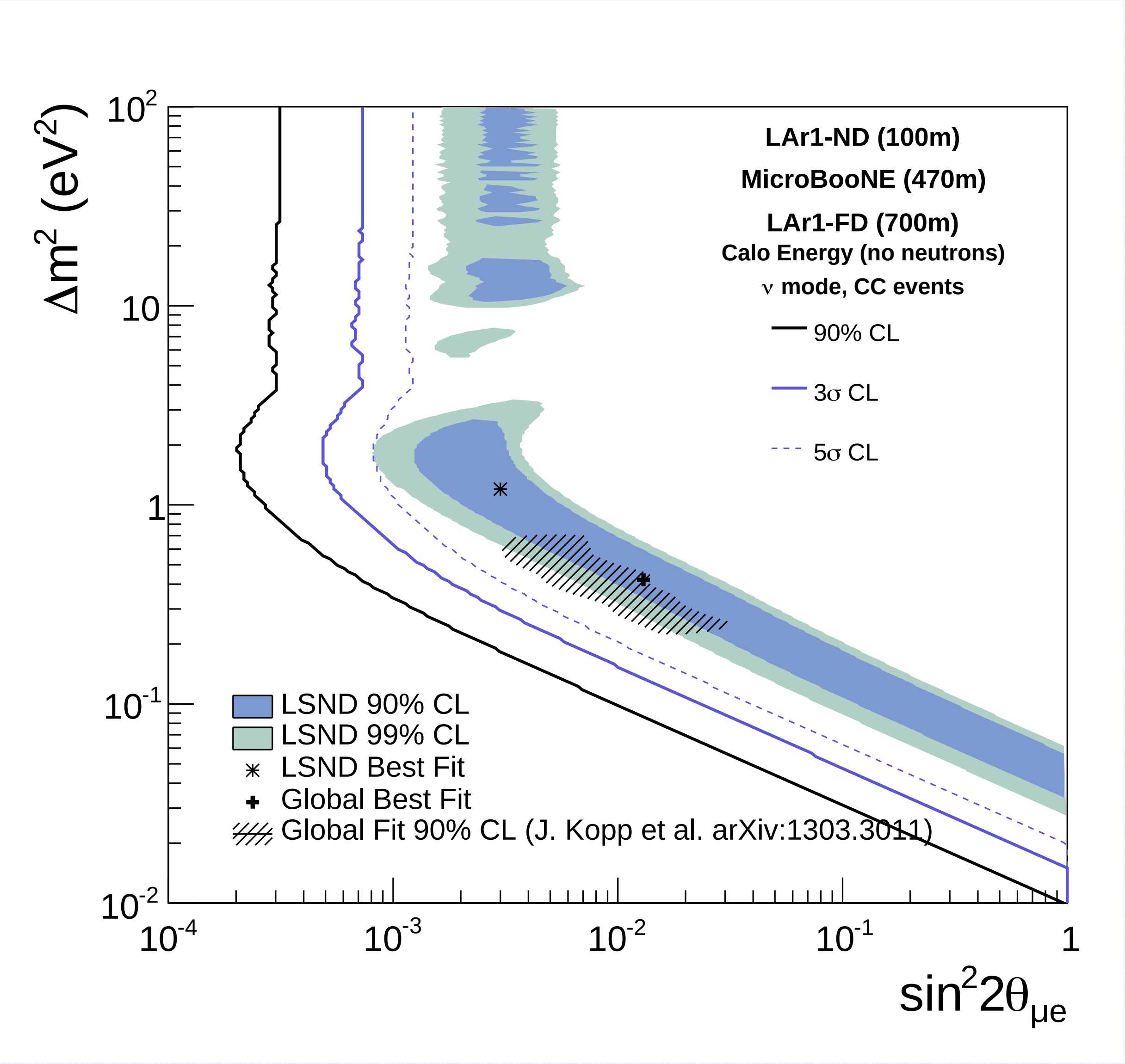
Summary of Oscillation Potential

Beyond increasing the statistical significance of MicroBooNE results, LAr1-ND enables a search for sterile neutrinos in multiple channels

Not independent - for the sterile neutrino explanation to be established, multiple predicted channels (electron neutrino appearance, muon neutrino disappearance) must be observed.

If oscillations seem probable after LAr1-ND and MicroBooNE, can serve as a near detector for large scale program at FNAL

Electron neutrino appearance



Inclusion of 3 years with a 1 kTon detector at 700m

No Oscillation?

Due to the proximity of the detector to the source, LAr1-ND will have an unprecedented amount of Neutrino Interactions in a LArTPC.

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

1 million events **per year**

LAr1-ND can make precision measurements of neutrino cross sections.

If the MiniBooNE excess is **not** an oscillation, LAr1-ND will be able to observe hundreds of anomalous events/year in the low energy regime.

This type of event classification - by Final State Topology - is only possible with a fine grained detector like a LArTPC

LAr1-ND Timescale

Based on experience from MicroBooNE, the LAr1-ND detector construction could be **completed in about two years**

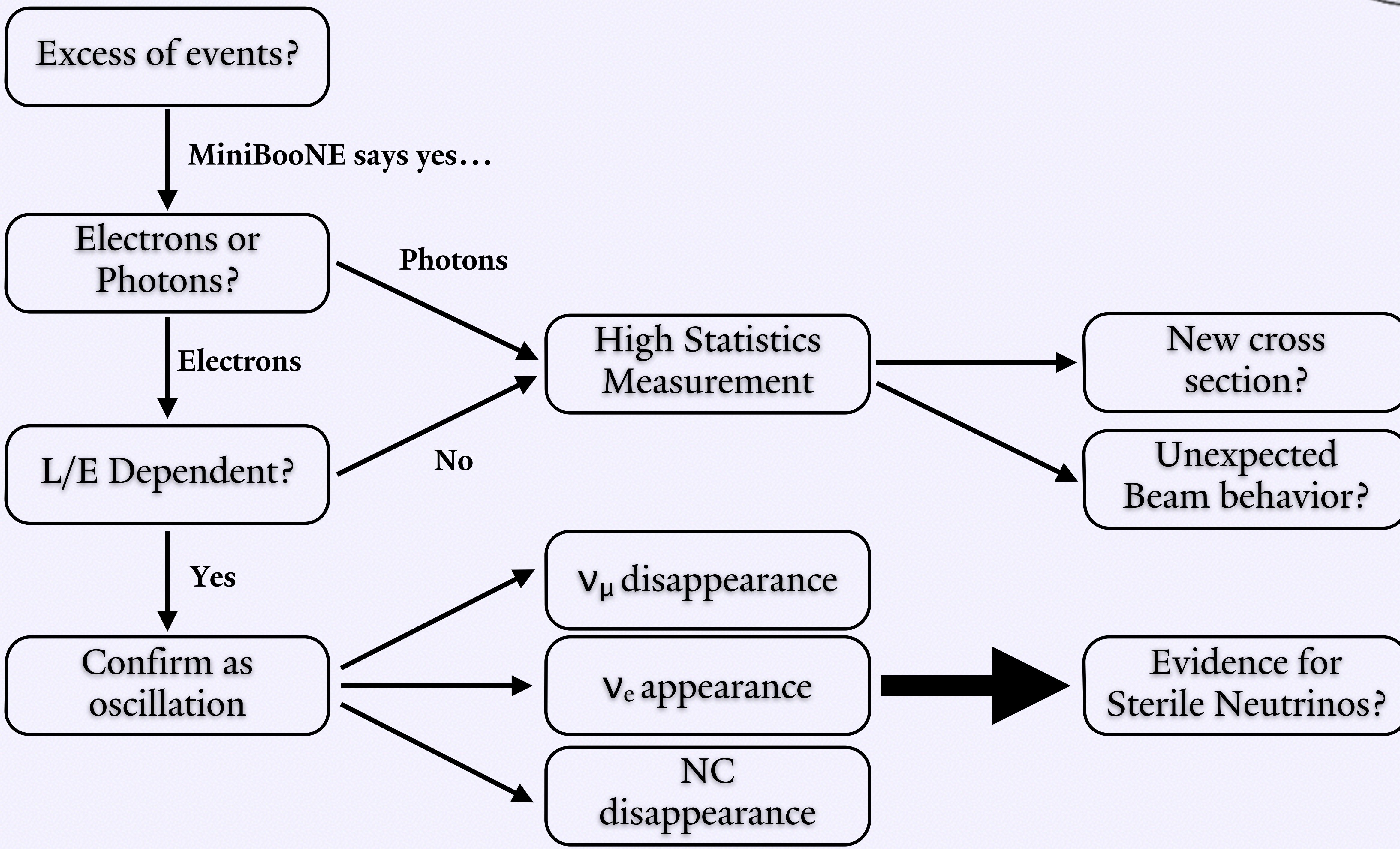
2014	2015	2016	2017	2018
Develop full technical design & project schedule	Procurement and fabrication of detector sub-components (wire planes, photon detectors, etc)	TPC component assembly (APAs, CPA, FCA) Cryostat and cryogenic system construction	Install TPC components in cryostat Liquid Ar fill Commissioning	

LAr1-ND running

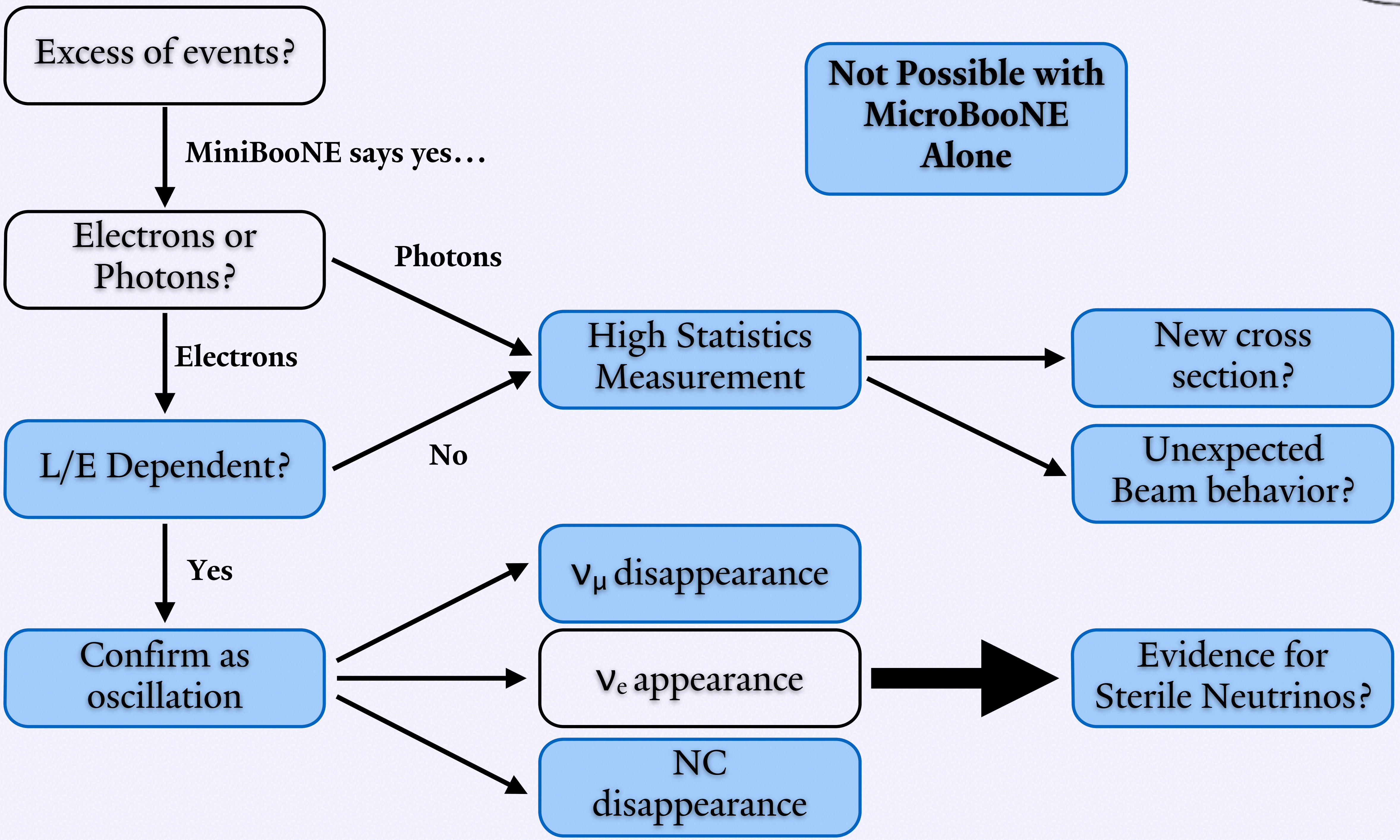
MicroBooNE running

This schedule would allow LAr1-ND to run in the final year of MicroBooNE data taking.

In the Event of an Excess…



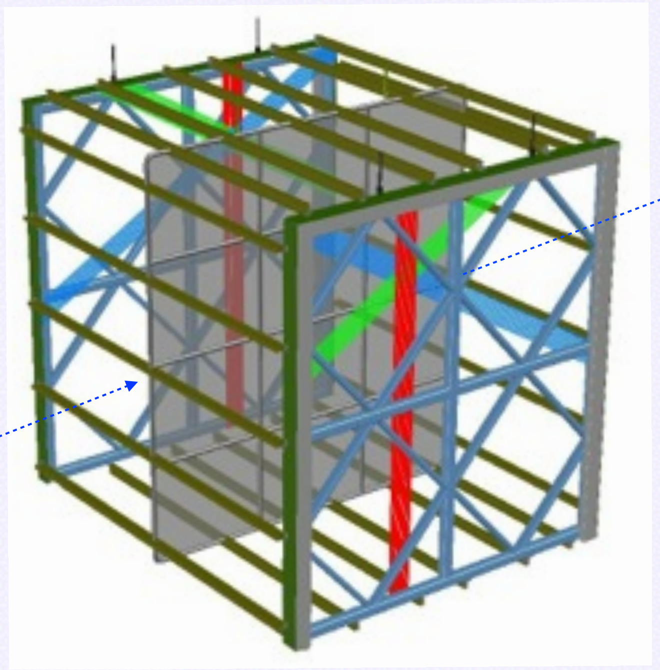
In the Event of an Excess…

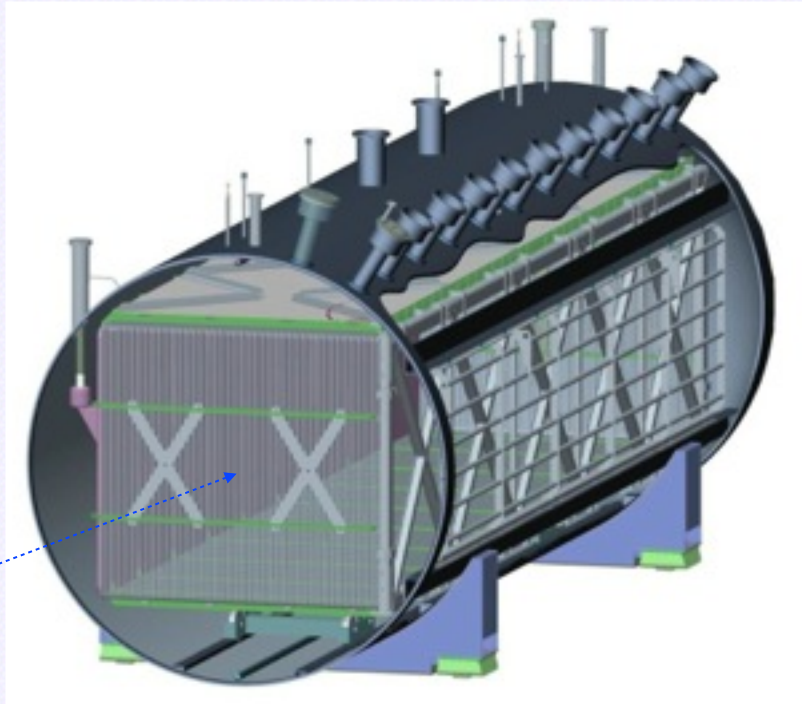


Summary

The addition of a near detector to the Booster Neutrino Beam greatly increases the significance of any MicroBooNE result and extends the physics reach of Fermilab's short baseline neutrino program.

LAr1-ND
at 100 m



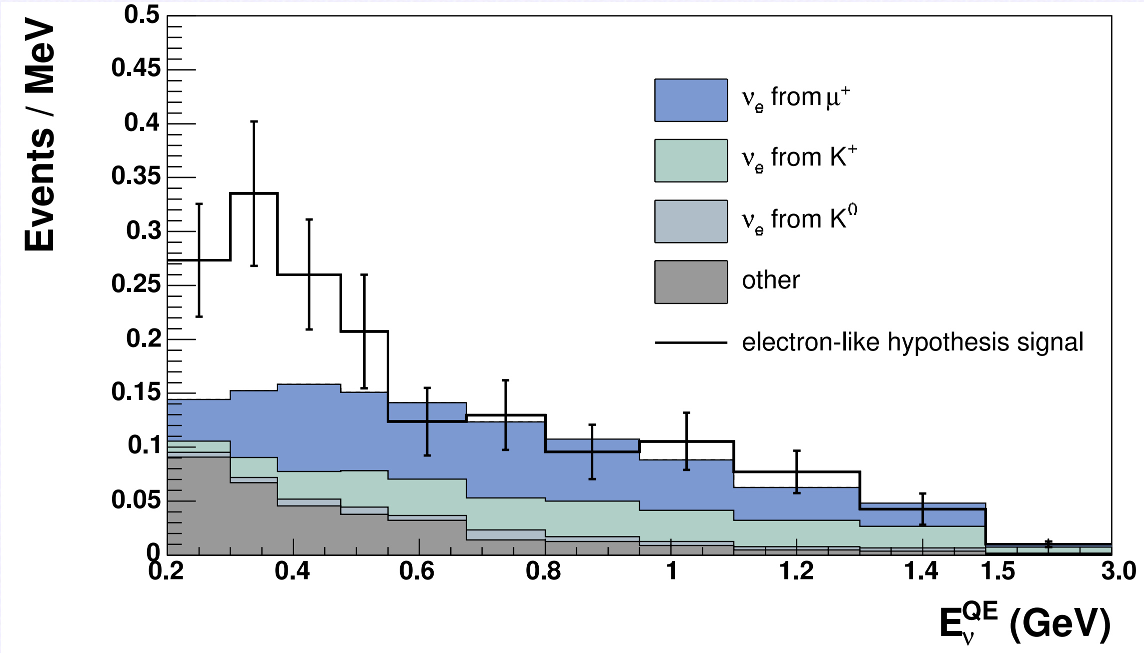


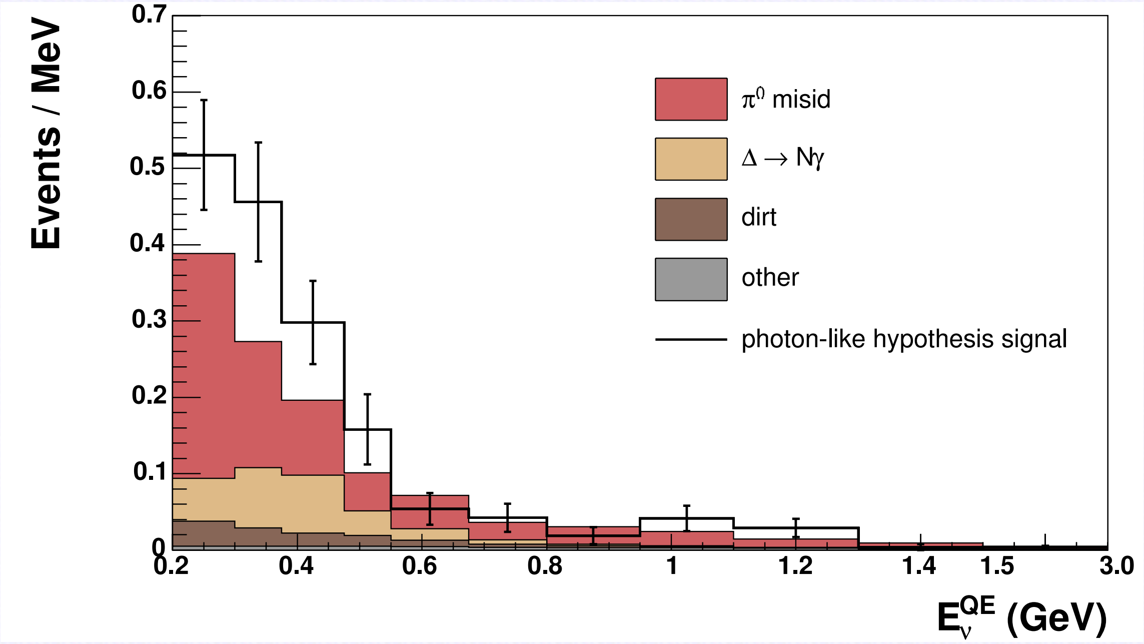
MicroBooNE
at 470 m

The proximity to the neutrino source means that the event rate in the near detector is ~15 times that in MicroBooNE. This means that much less time is needed to collect sufficient data, and can be completed on a time scale with the MicroBooNE oscillation result.

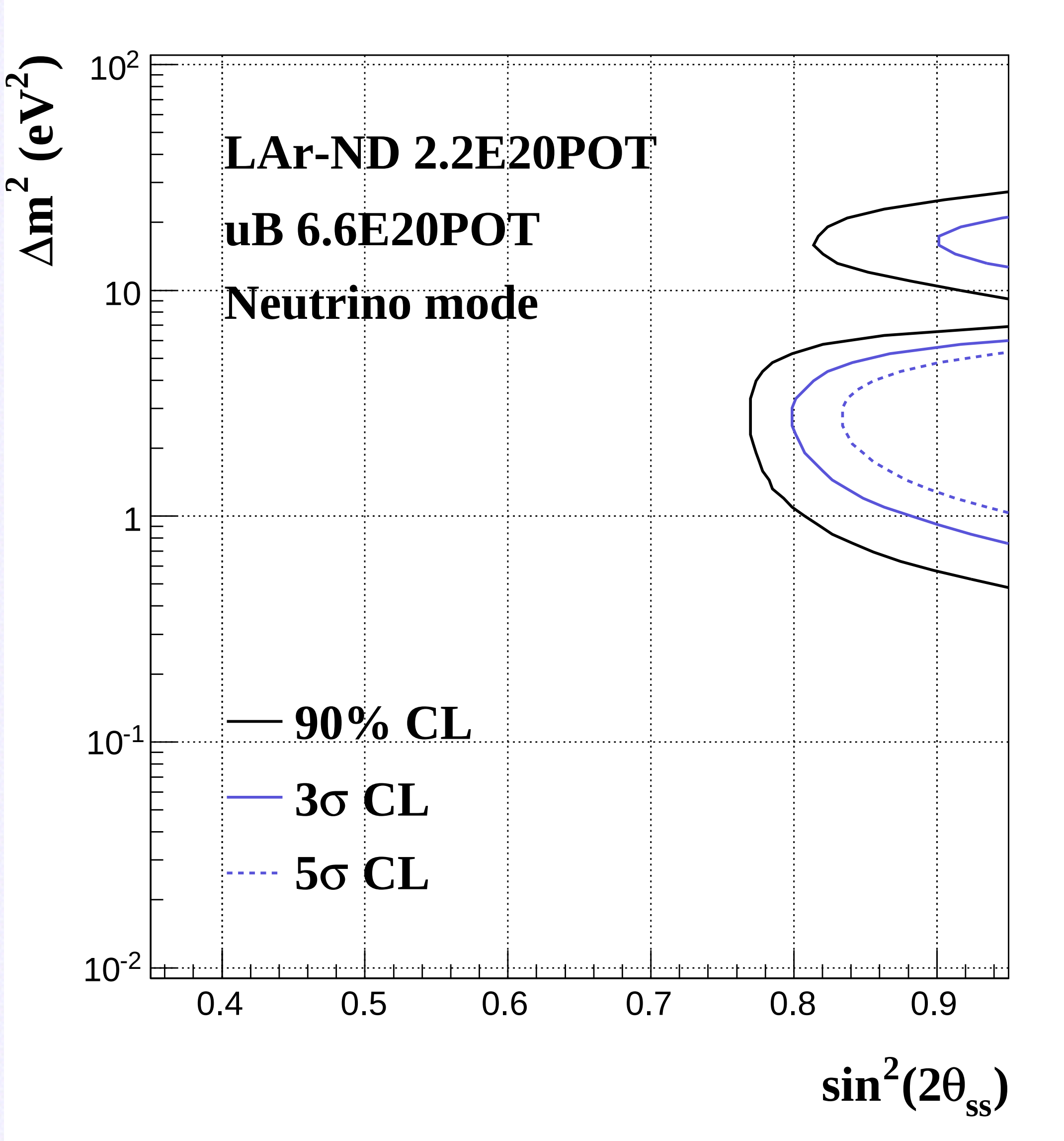
Backup

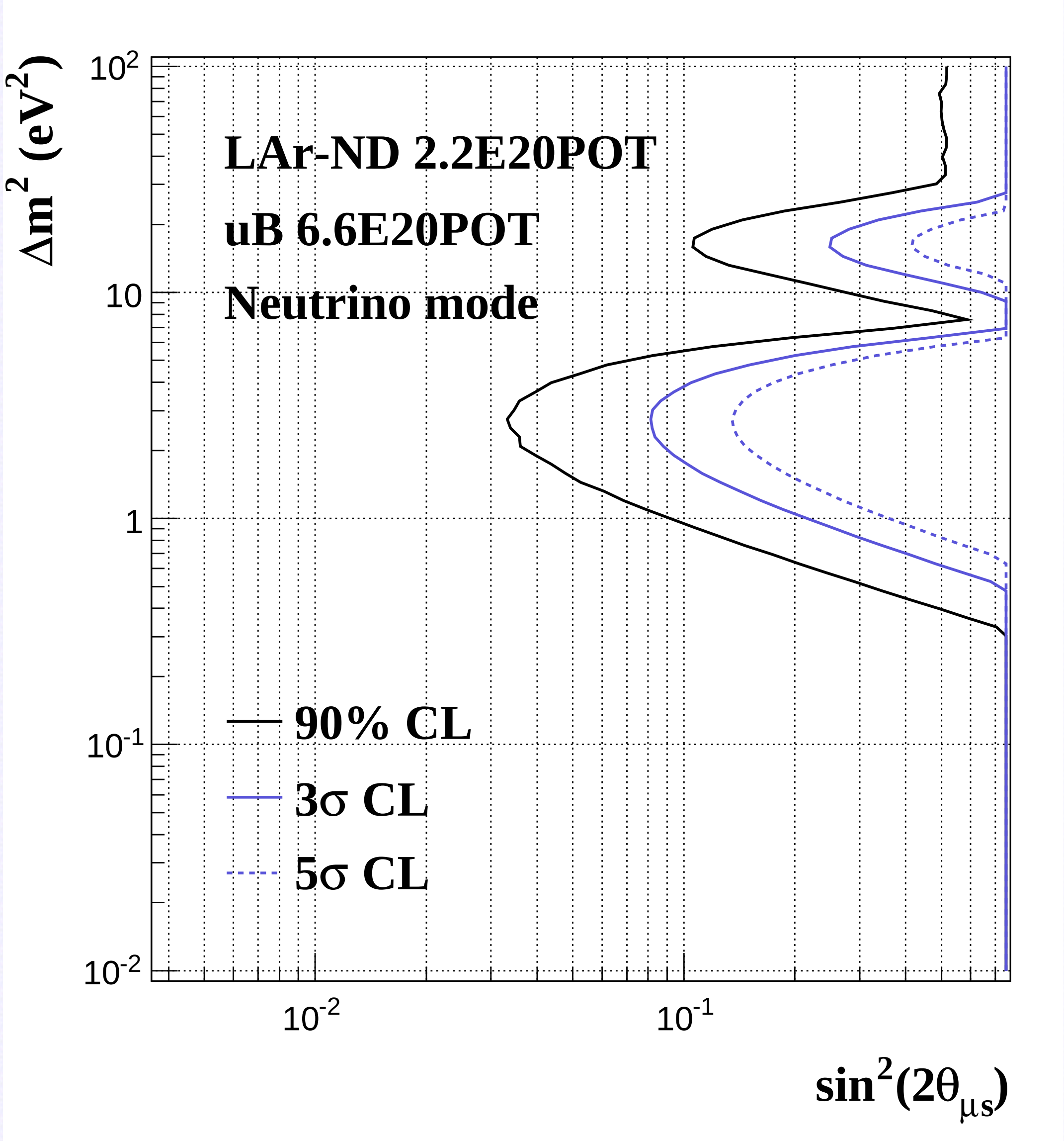
MicroBooNE Electron/Photon Rates





Neutral Current Disappearance





MiniBooNE / LSND