LAr1-ND: Testing Neutrino Anomalies with Multiple LAr TPC Detectors at Fermilab

(P-1053)

CERN-LAr1/ND meeting

CERN, February 16th 2013

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Outline

- ❖ Motivations for the LAr1-ND Proposal
- ❖ Fermilab Short-Baseline Neutrino Program
- ❖ Physics Reach of LAr1-ND
- ❖ The LAr1-ND Detector
- ❖ Schedule Estimates
- ❖ Conclusions

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
  - A SBL program builds upon existing infrastructure, investments, expertise, and physics interests within the neutrino physics 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
- The LAr1-ND proposal is 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 6.6×10^{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

Existing Anomalies in Neutrino Physics @ SBL

- Experimental anomalies ranging in significance (2.8–3.8σ) have been reported from a variety of experiments studying neutrinos over baselines less than 1 km.

Current anomalies from:
accelerator beams
radioactive sources
reactor neutrinos

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ 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)

- Most common interpretation is as evidence for high mass-squared neutrino oscillations and the existence of one or more additional, mostly "sterile" neutrino states with masses at or below a few eV

- While each of these measurements taken separately lack the significance to claim a discovery, together these signals could be hinting at important new physics that requires further exploration

A Staged Multi-LAr TPC Short-Baseline Neutrino Program

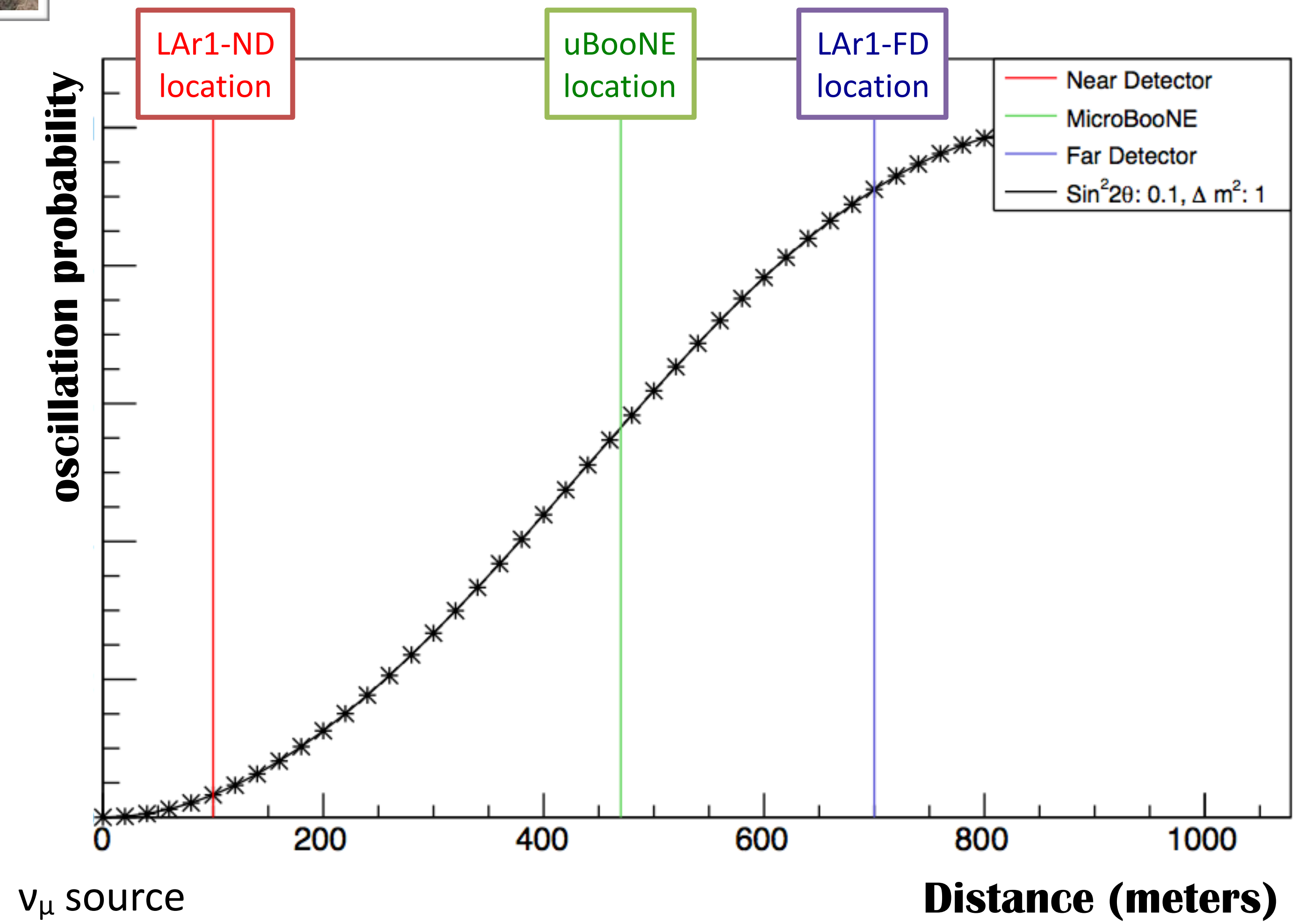
Phase 0: MicroBooNE
86 t active volume TPC
L = 470 m
start in 2014

Phase 1: LAr1-ND
82 t active volume TPC
L = 100 m
2017-2018

Phase 2: LAr1-FD
1000 t active volume TPC
L = 700 m
2020+

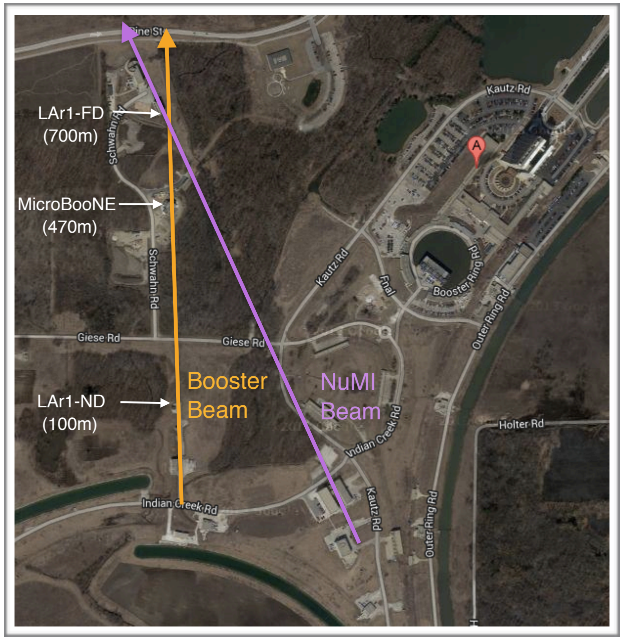
ν_μ disappearance probability at $\mathbf{E_\nu}$ = 700 MeV as a function of distance in a sterile neutrino model with **Δm^2 = 1.0 eV^2**

- A Near Detector close to the BNB source is a key element in each phase
  - ➡ Sample the beam before the onset of L/E dependent physics
  - ➡ Provide a high statistics constraint on intrinsic event rates

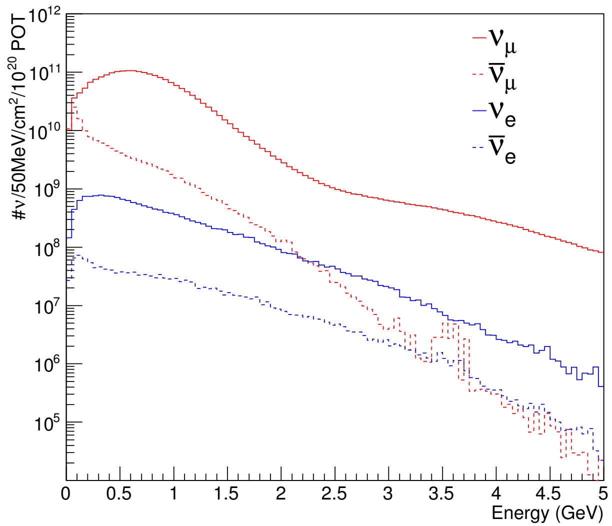


Neutrino beams (I)

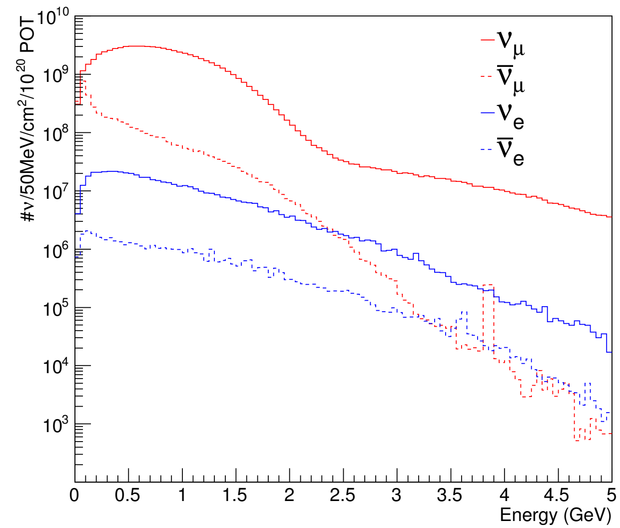
On axis Booster Neutrino Beam fluxes @ different detector locations



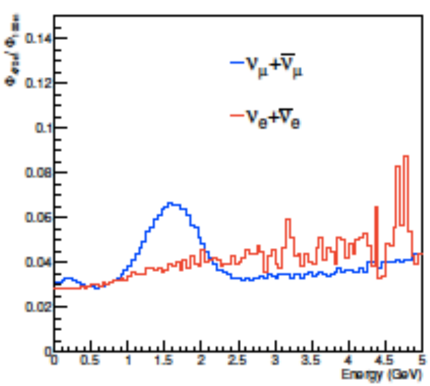
Flux from BNB in nu mode at LAr1-ND (100m)



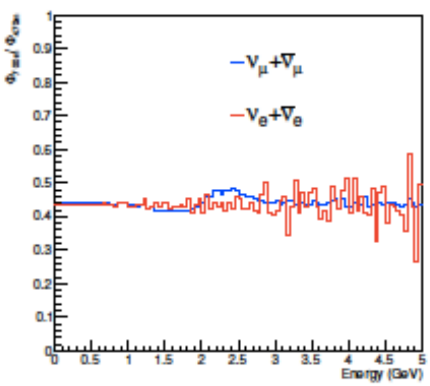
Flux from BNB in nu mode at MicroBooNE (470m)



Ratios of the fluxes at different detector locations.

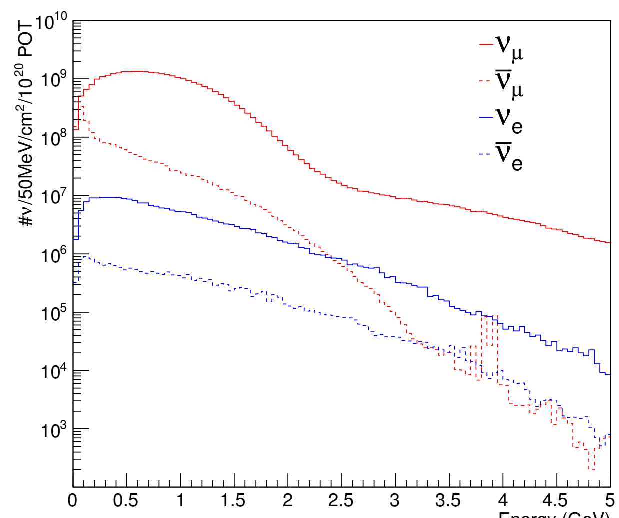


Flux at MicroBooNE vs. flux at LAr1-ND

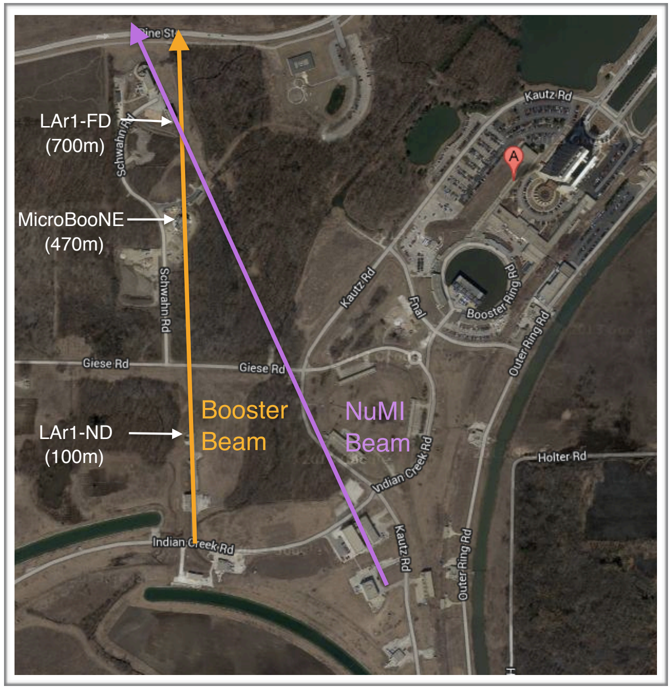


Flux at MicroBooNE vs. flux at LAr1-FD

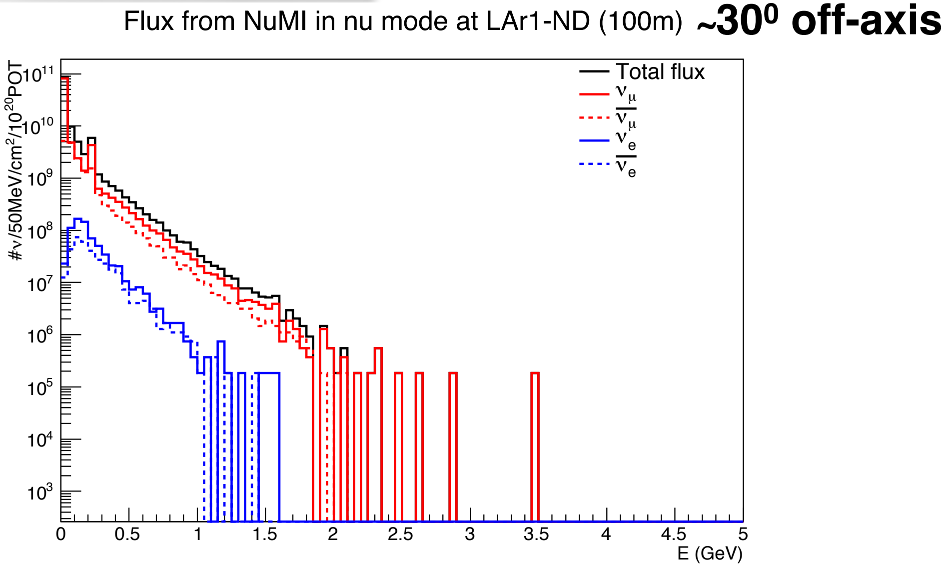
Flux from BNB in nu mode at LAr1-FD (700m)

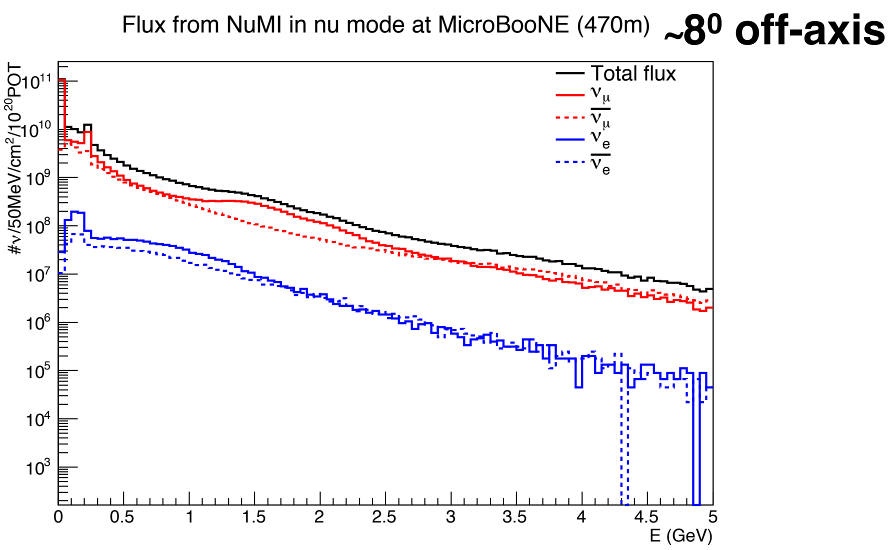


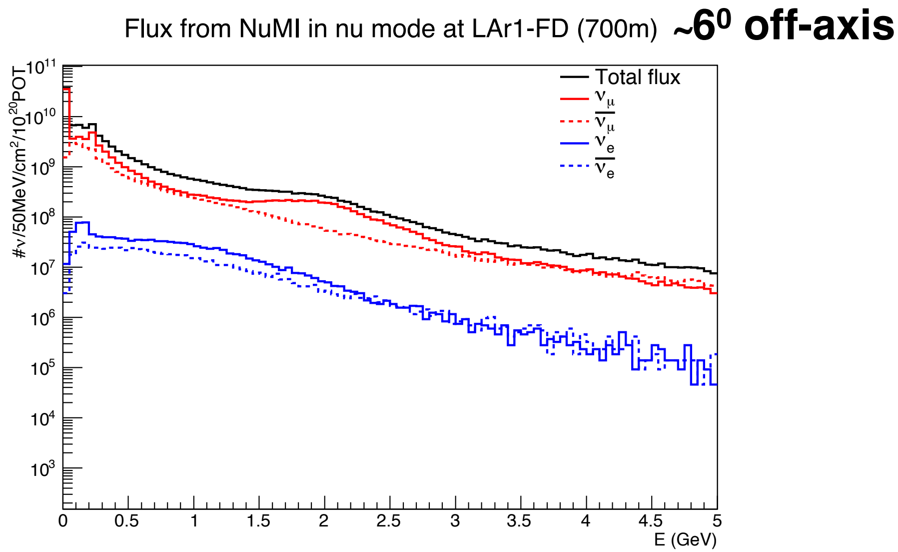
Neutrino beams (II)



Off-axis NuMI fluxes @ different detector locations







LAr1-ND Physics Goals

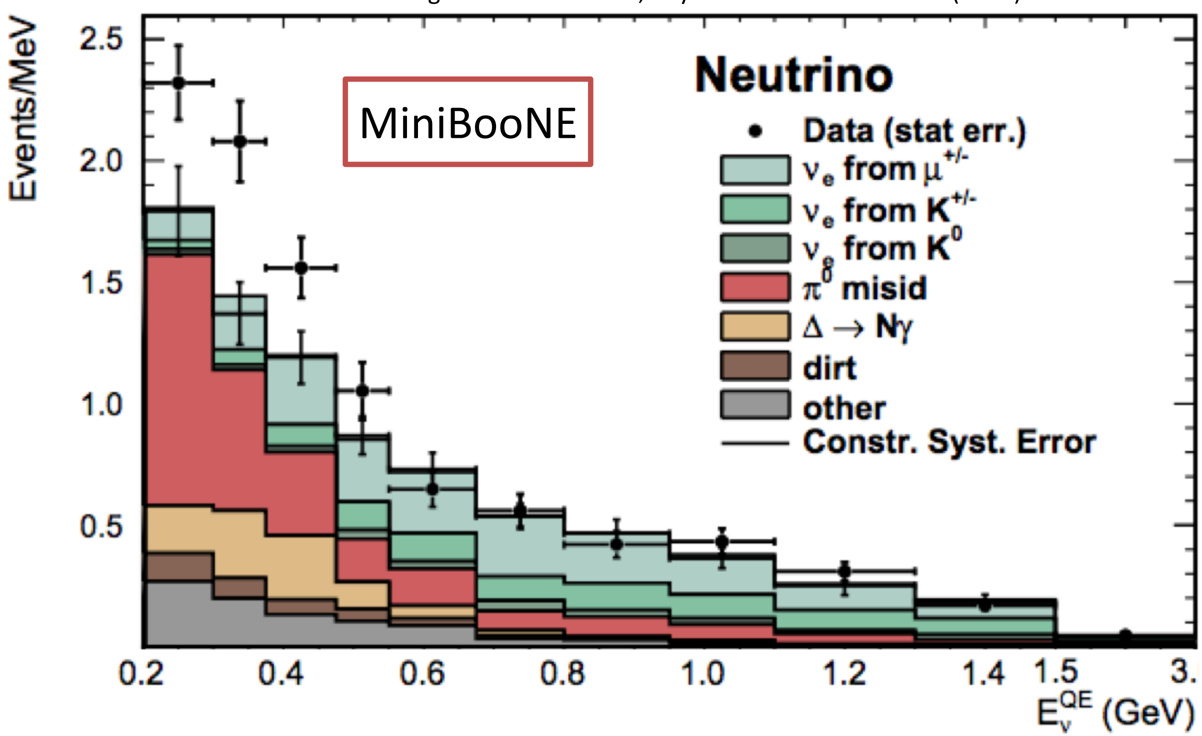
- **MiniBooNE low-energy excess**
  - Directly test the anomalous excess of electron neutrino events reported by MiniBooNE
- **Oscillations: $\nu_\mu \rightarrow \nu_e$ appearance**
  - In combination with MicroBooNE, much improved sensitivity with a near detector (ND)
- **Oscillations: ν_μ disappearance**
  - Only possible with a ND
- **Oscillations: Neutral-current disappearance**
  - Direct test for sterile neutrino content. Only possible with a ND
- **Neutrino-argon interactions**
  - 15x the rate compared to MicroBooNE. ~1M events per year.
  - 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
- **Dark matter search with beam off-target running**
  - Requires future beam off-target running.

Analysis of Booster beam events*

*A large number of neutrino events coming from the NuMI beamline will be observed by the different detectors (see backup slides). These events have not been included yet in the sensitivity studies.

Sensitivity to MiniBooNE Low-Energy ν_e Excess

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



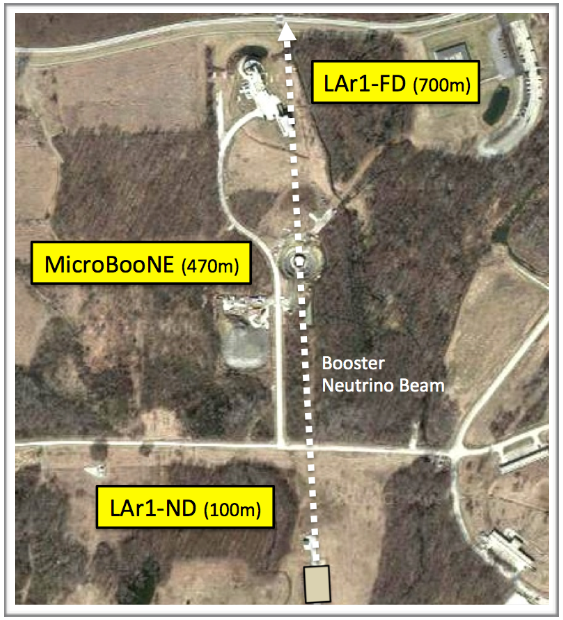
Is the excess of electromagnetic events observed in MiniBooNE due to ν_e or photon final states?

MicroBooNE will determine the nature of the MiniBooNE excess reported at ~500 m.

In either scenario (electrons or photons) LAr1-ND can address the obvious next question:

<u>Does the excess appear over a distance or is it intrinsic to the beam?</u>

Sensitivity to MiniBooNE Low-Energy ν_e Excess



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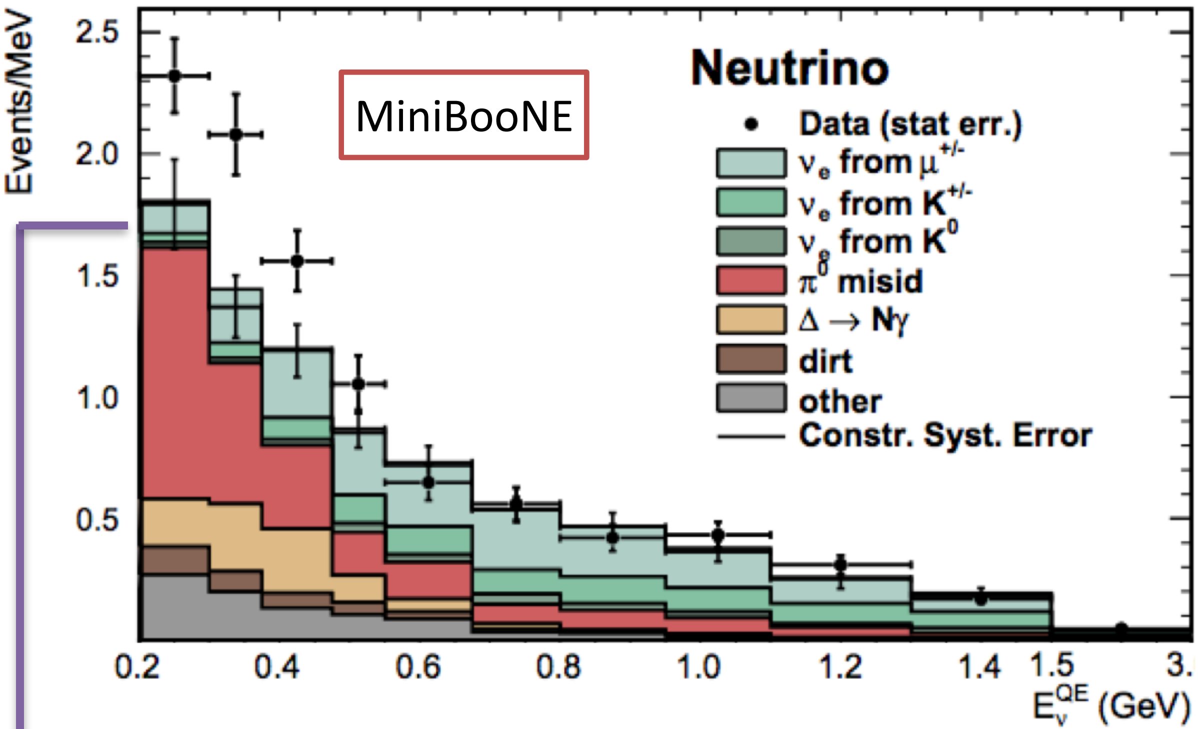
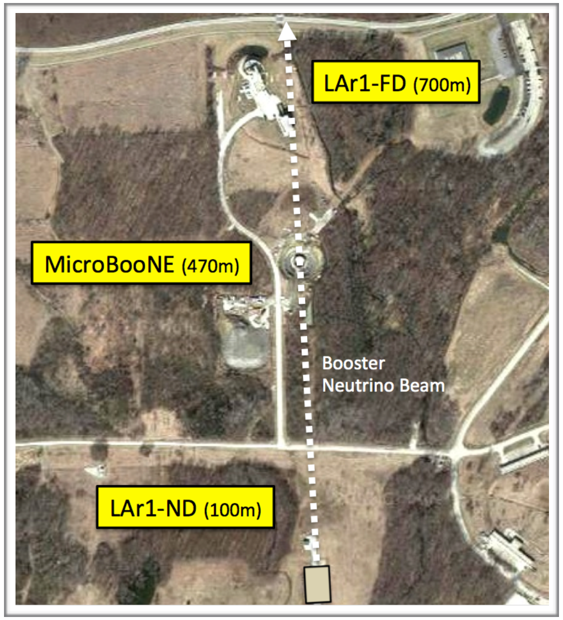


By scaling directly from observed rates in MiniBooNE, MicroBooNE expects to see ~50 background and 50 excess events in 6.6x10^{20} POT run

Sensitivity to MiniBooNE Low-Energy ν_e Excess



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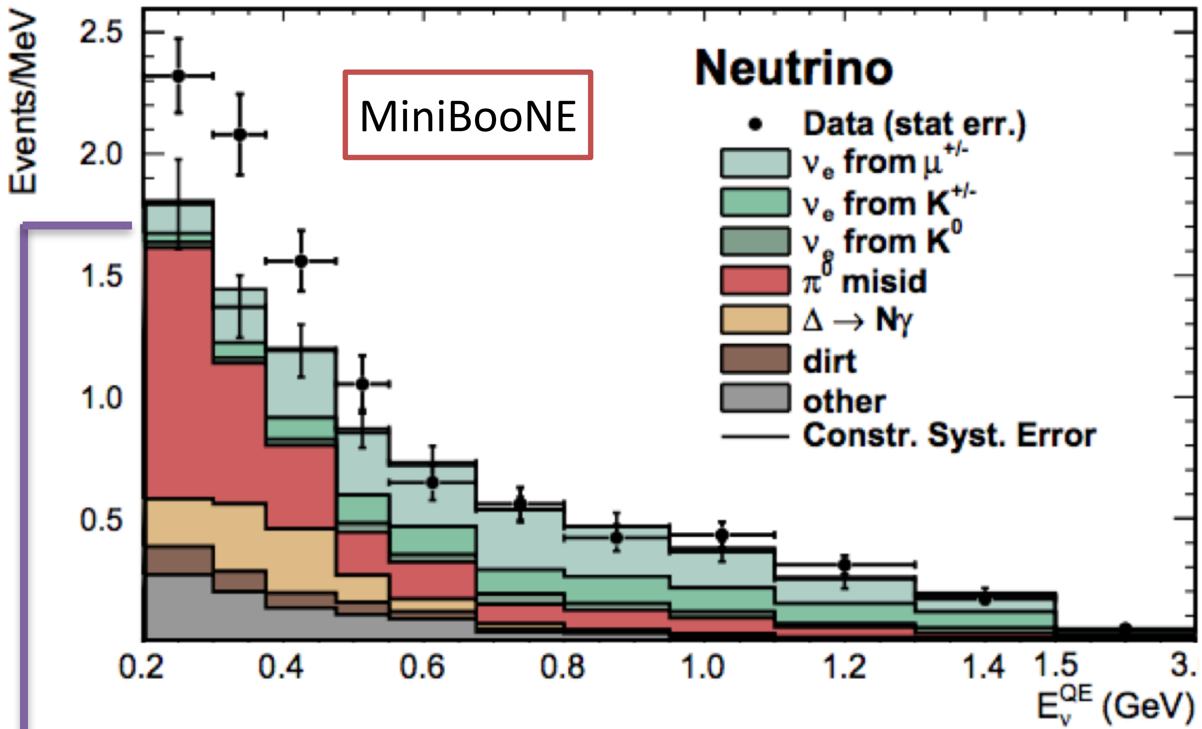


By scaling directly from observed rates in MiniBooNE, MicroBooNE expects to see ~50 background and 50 excess events in 6.6×10^{20} POT run

Assuming NO L/E dependence LAr1-ND would expect to see ~320 background and 300 excess events in 2.2×10^{20} POT run

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

Monte Carlo simulation

To estimate physics sensitivities of the experiment, a full Monte Carlo simulation is used:

1. Beam simulation (verified against the MiniBooNE beam Monte Carlo) —> Booster Neutrino Beam flux in the target hall.
2. Flux propagated *(GSimple package)* to the detectors at 100 m, 470 m, as well as 700 m.
3. Neutrino interactions are simulated using the *GENIE neutrino event generator*.
4. Particles exiting a nucleus after the neutrino interaction are passed on to the *LArSoft framework (Geant4* to propagate in the LAr detector volumes). Geometry descriptions are provided for each detector.
5. Full reconstruction in the LArSoft framework is not applied (yet), but we assume efficiencies based on studies (using the reconstruction tools in the LArSoft framework):
   - For example, we use a 94% rejection rate of single photon background coming from π^0 decays or other sources (using the **dE/dx** tag in the first few centimeters of the electromagnetic shower)
6. *Calorimetric energy reconstruction*: the incoming neutrino energy in CC events is estimated by summing the energy of the lepton and all charged hadronic particles (above observation thresholds) present in the final state.

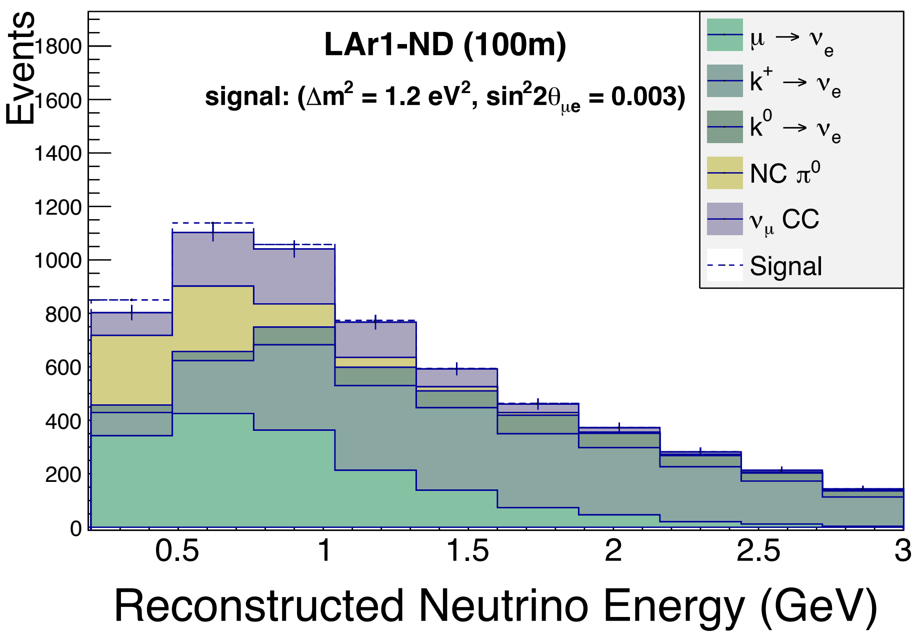
With the *full simulation of the neutrino events* we can accurately model realistic backgrounds for the multiple channels in which we are sensitive to sterile neutrino signals instead of assuming, e.g. flat distributions.

$\nu_\mu \rightarrow \nu_e$ Appearance

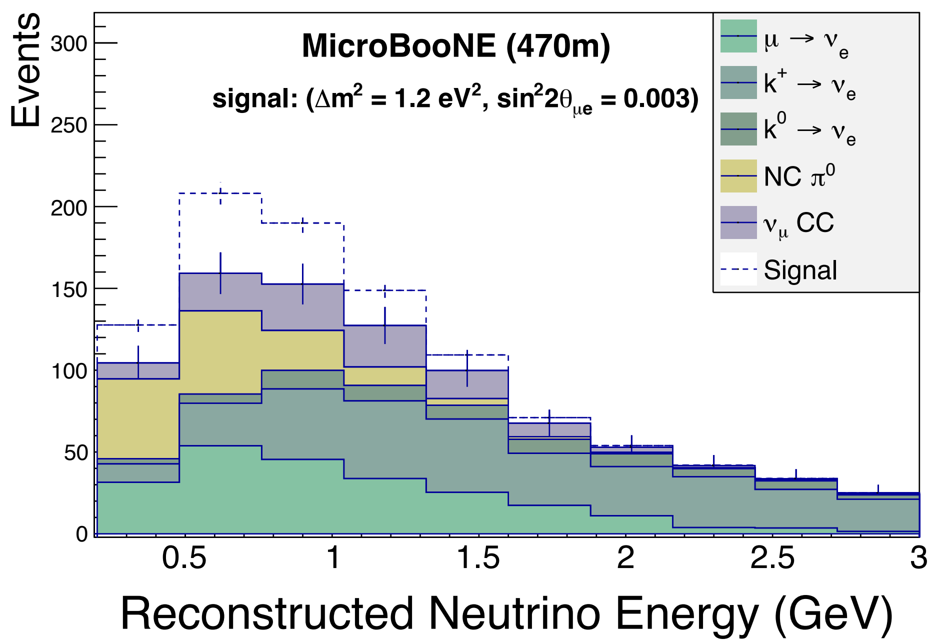
- Testing $\nu_\mu \rightarrow \nu_e$ appearance in the context of a 3 active + 1 sterile neutrino model (3+1)

- The observed electron candidate event rate in LAr1-ND at 100m is used to constrain the expected rate (in the absence of oscillations) in MicroBooNE at 470m

2.2×10^{20} POT exposure for LAr1-ND



6.6×10^{20} POT exposure for MicroBooNE

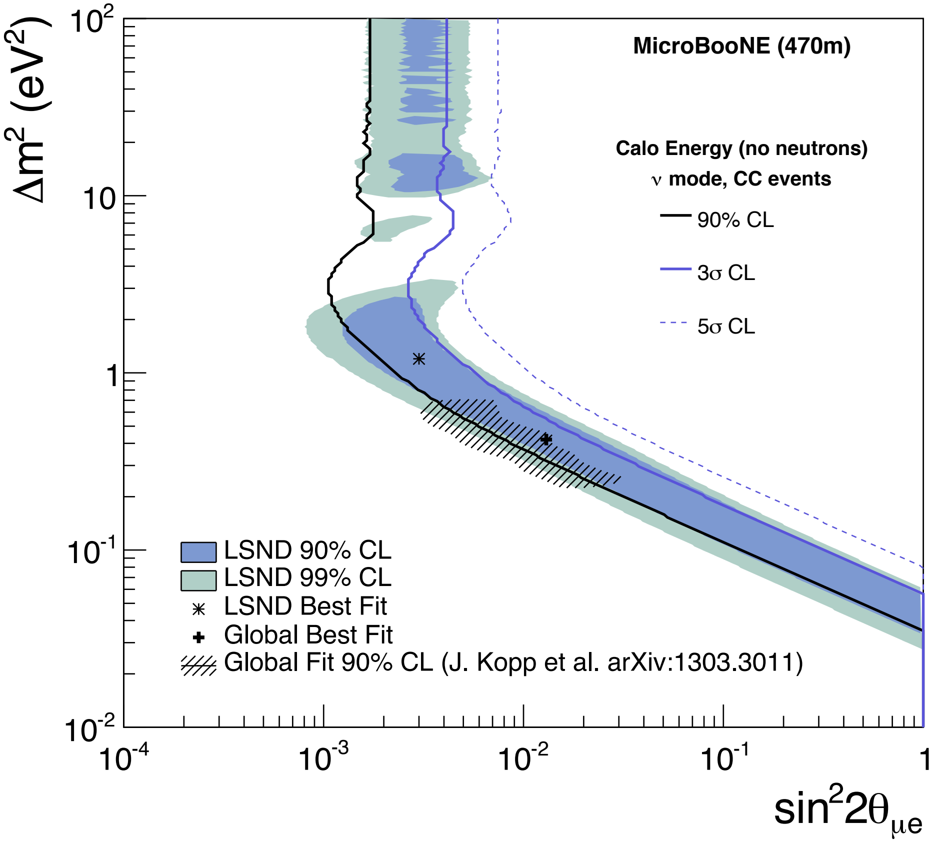


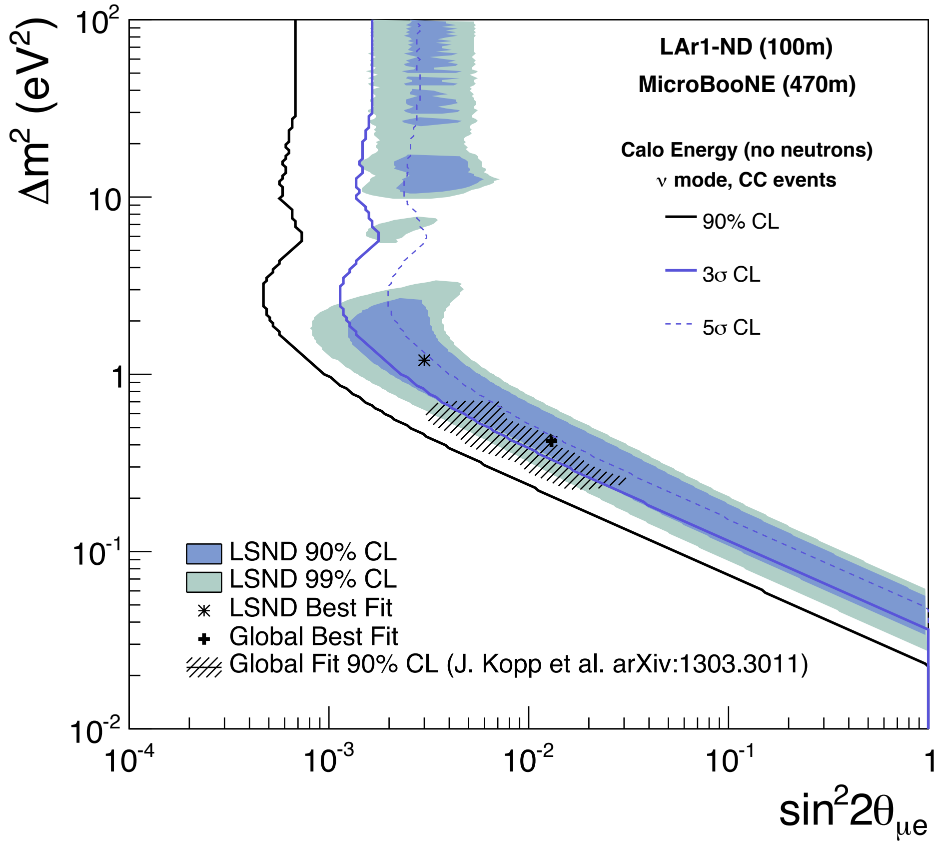
$\nu_\mu \rightarrow \nu_e$ Appearance

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

+ND

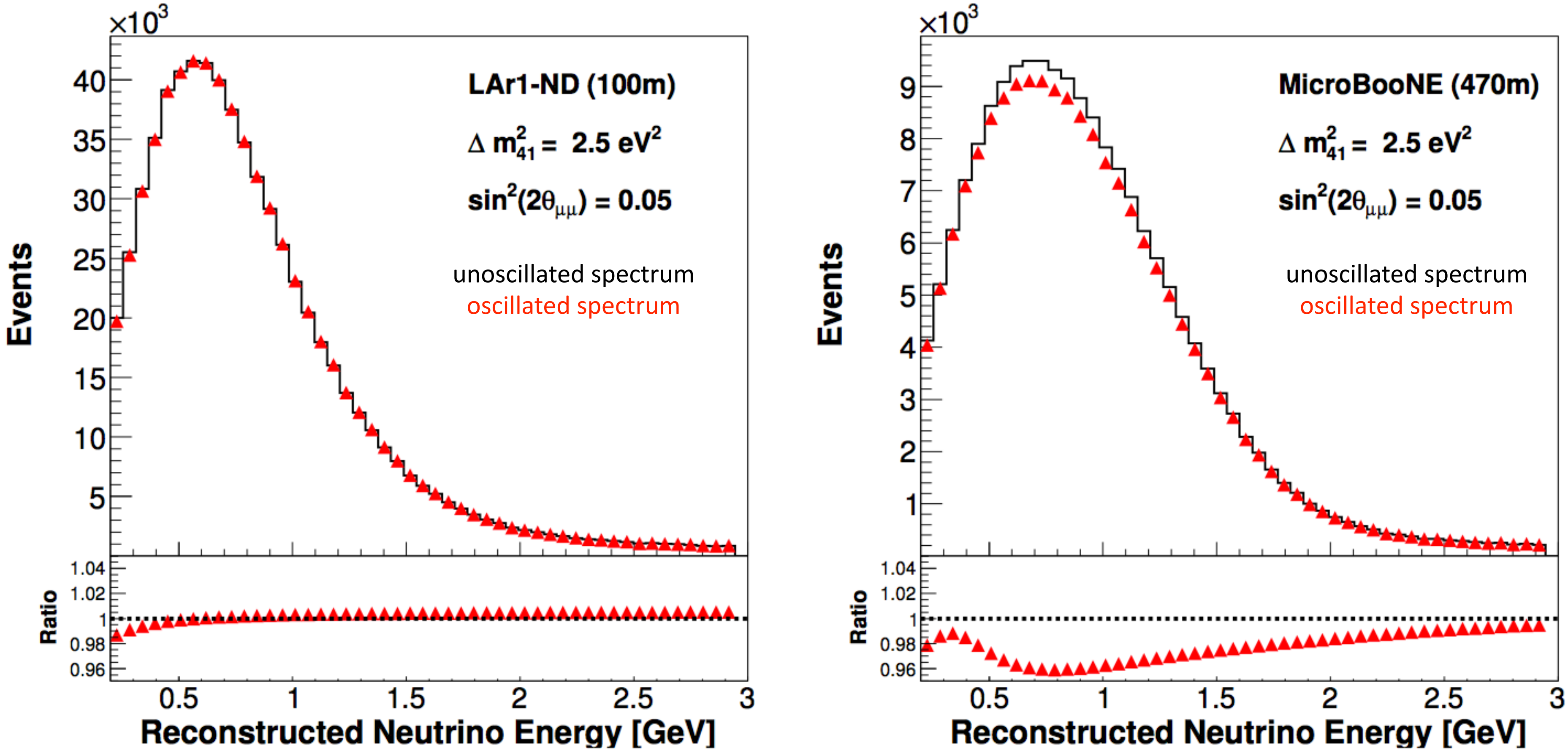
Same MicroBooNE exposure + 2.2x10[20] POT exposure for LAr1-ND to constrain background prediction





ν_μ Disappearance

- Testing ν_μ disappearance only enabled with near detector constraint
  - Flux and cross section errors of 15-20% conceal a disappearance signal in MicroBooNE alone, but using an observed LAr1-ND spectrum to normalize the expected rate at MicroBooNE makes it observable

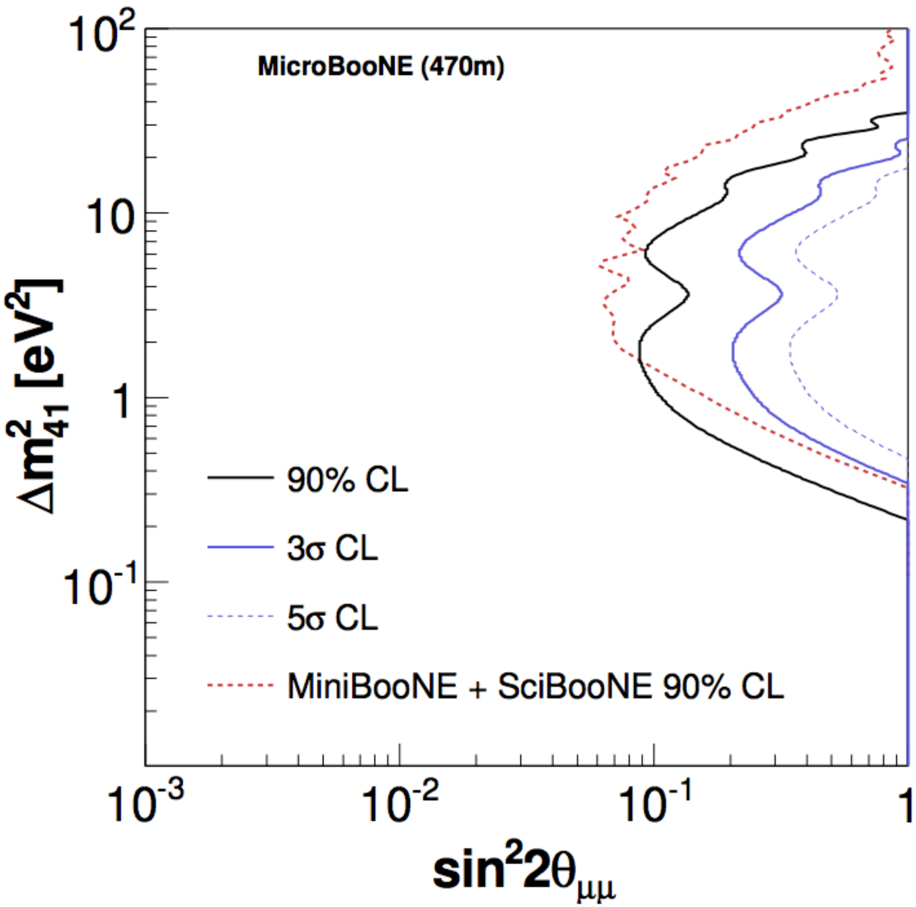


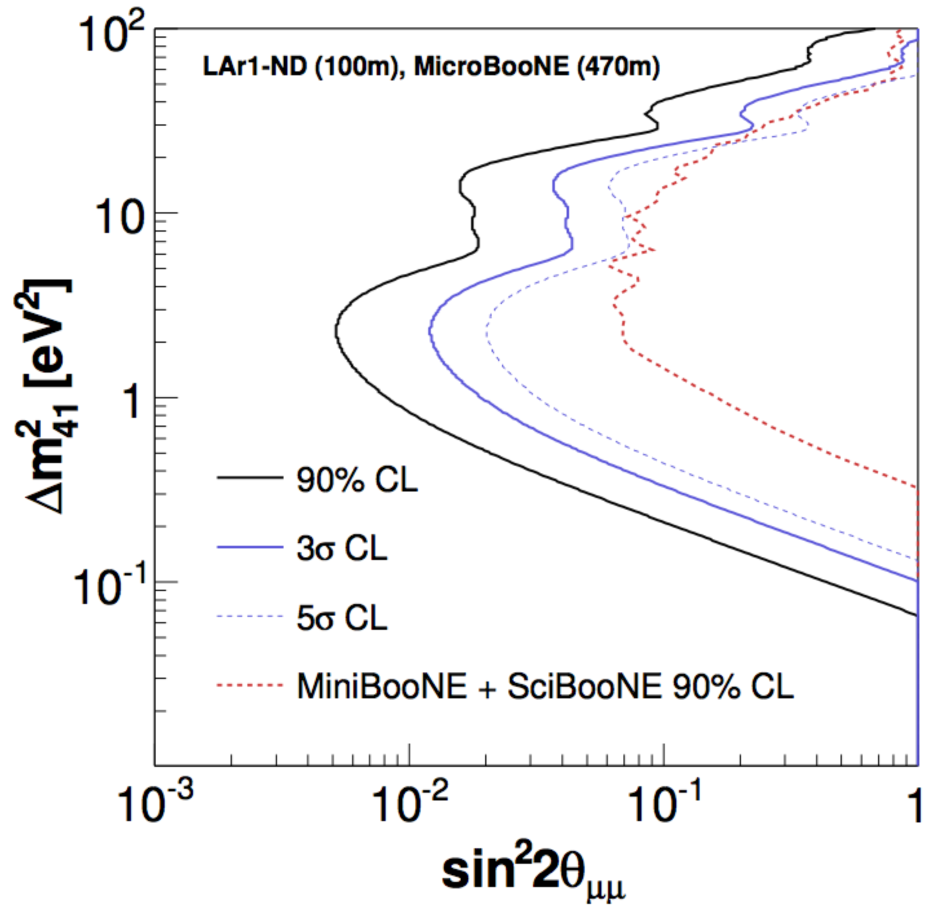
ν_μ Disappearance

6.6×10^{20} POT exposure for MicroBooNE alone, assuming 15% systematic uncertainties on the absolute ν_μ event rate

+ND

Same MicroBooNE exposure + 2.2×10^{20} POT exposure for LAr1-ND to measure unoscillated ν_μ





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

Neutrino-Argon Interactions

GENIE estimated event rates

Process	*2.2x10[20] POT exposure for LAr1-ND*	No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		787,847
CC 0 π	$\nu_\mu N \rightarrow \mu + Np$	535,673
	$\cdot\ \nu_\mu N \rightarrow \mu + 0\text{p}$	119,290
	$\cdot\ \nu_\mu N \rightarrow \mu + 1\text{p}$	305,563
	$\cdot\ \nu_\mu N \rightarrow \mu + 2\text{p}$	54,287
	$\cdot\ \nu_\mu N \rightarrow \mu + \geq 3\text{p}$	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 π	$\nu_\mu N \rightarrow \text{nucleons}$	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
	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	$\nu_\mu n \rightarrow \mu^- \text{p}$	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 great venue to conduct high statistics precision cross section measurements in the 1 GeV energy range

Event rates based on categorization in terms of exclusive experimental topologies

Energy threshold on protons: 21 MeV.
The 0π topologies include any number of neutrons in the event.

total events per ~year

Event rates based on classification by physical process from GENIE Monte Carlo truth information.

Phase-2 Short-Baseline Neutrino Program at FNAL

- LAr1-ND + MicroBooNE already presents a significant extension of the physics program, but LAr1-ND can also be thought of as the next step in the development of a program of short-baseline accelerator-based neutrino physics at Fermilab

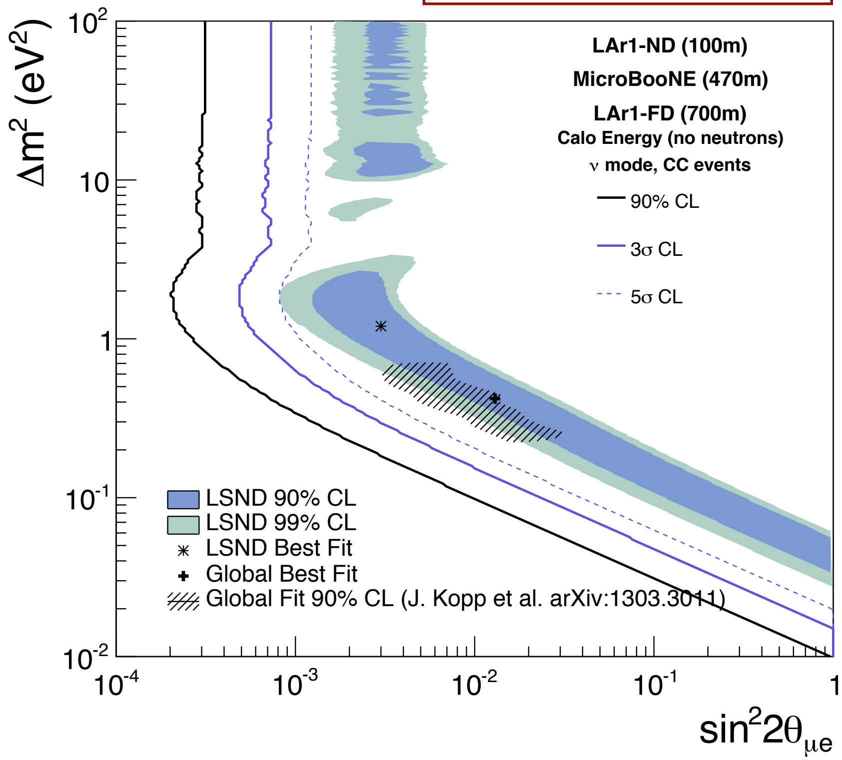
- The addition of a large (kiloton-scale) detector at longer baseline (~700 m) could address oscillations in anti-neutrino mode and make precision measurements of sterile neutrino oscillations if they are discovered

- 5σ level coverage of the null hypothesis for the oscillation parameter space indicated by existing experimental anomalies

- Three detector configuration provides a powerful confirmation of the interpretation of any results as an oscillation signal

- Have calculated sensitivities, more available in backup slides

About 3 yrs neutrino-mode data



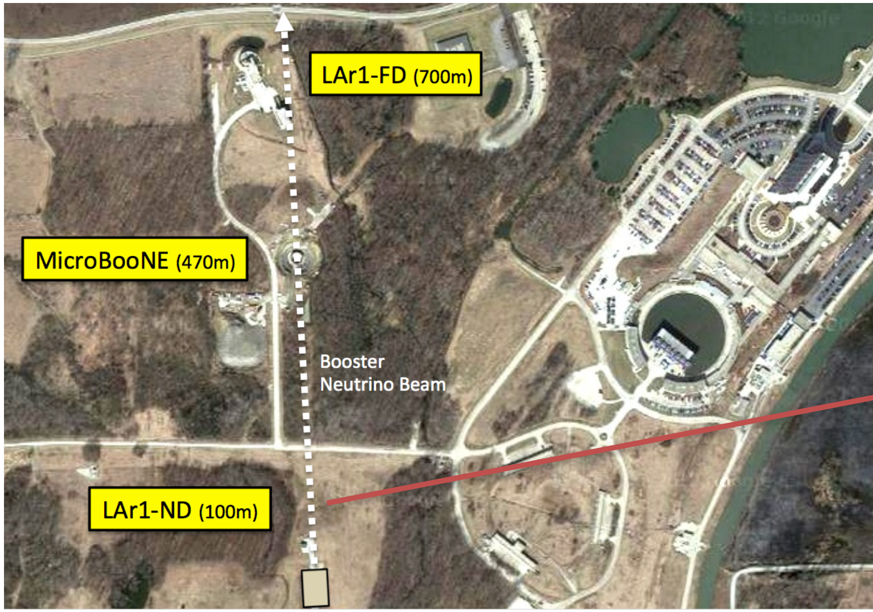
LAr1-ND: Detector Location

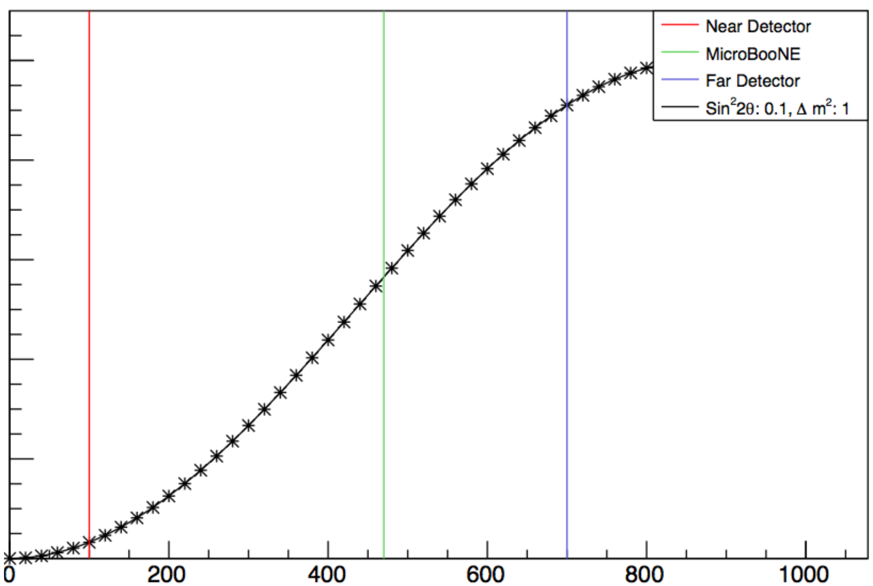
- In choosing a location for the LAr1-ND detector, our strategy was to look into taking advantage of an existing, empty detector hall along the Booster Neutrino Beam, formerly used by the SciBooNE experiment
  - Reduce costs
  - Minimize time to physics in phase-1 to inform phase-2

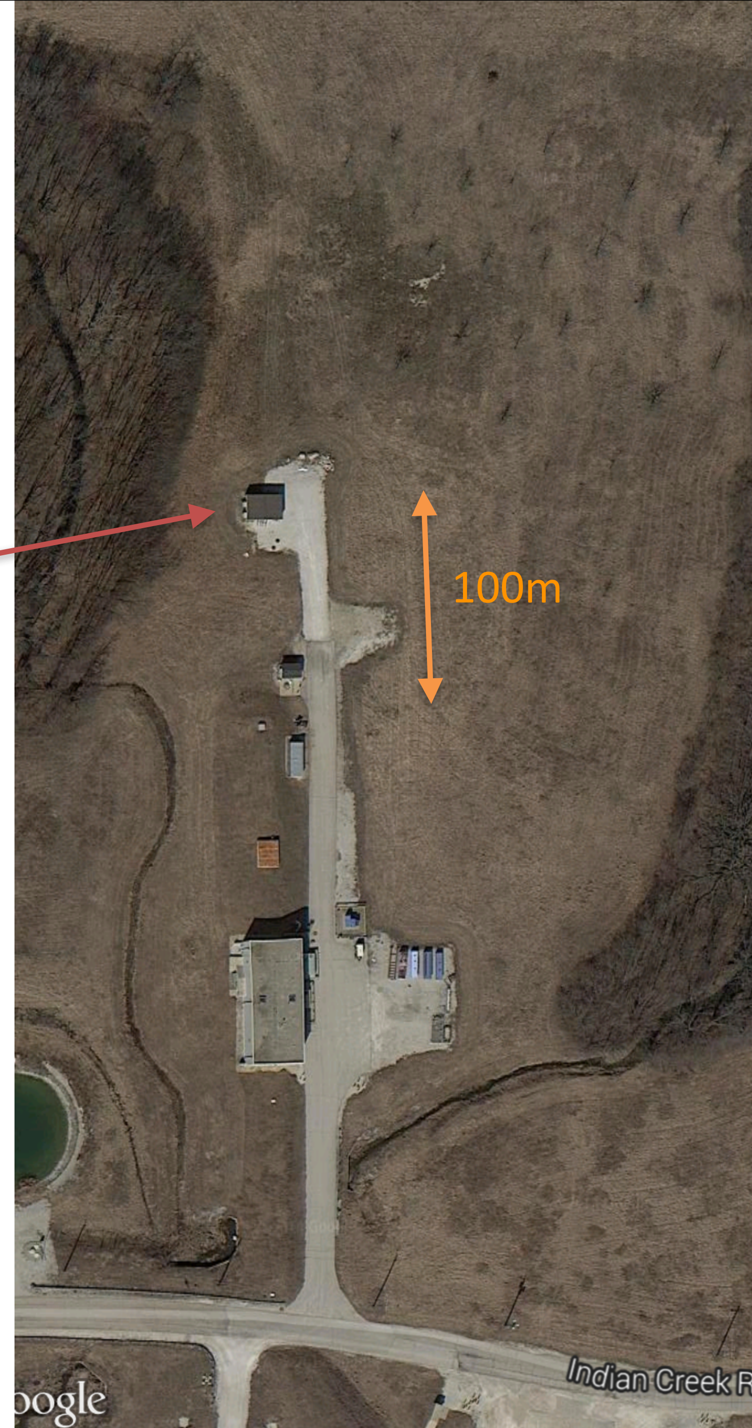
- The "SciBooNE Enclosure" was built on a budget to barely contain the SciBooNE neutrino detector
  - "Concrete elevator shaft"

- This space could be perfect for a membrane cryostat LAr detector built to fit against the concrete walls of this space
  - Dimensions essentially determined

- Given the advantages to cost/schedule, our approach then was to determine, using simulation, if a detector of this mass and configuration could do the physics we are after → Yes.


LAr1-FD (700m)
MicroBooNE (470m)
Booster
Neutrino Beam
LAr1-ND (100m)


Near Detector
MicroBooNE
Far Detector
$Sin^2 2\theta$: 0.1, Δ m^2: 1
0
200
400
600
800
1000

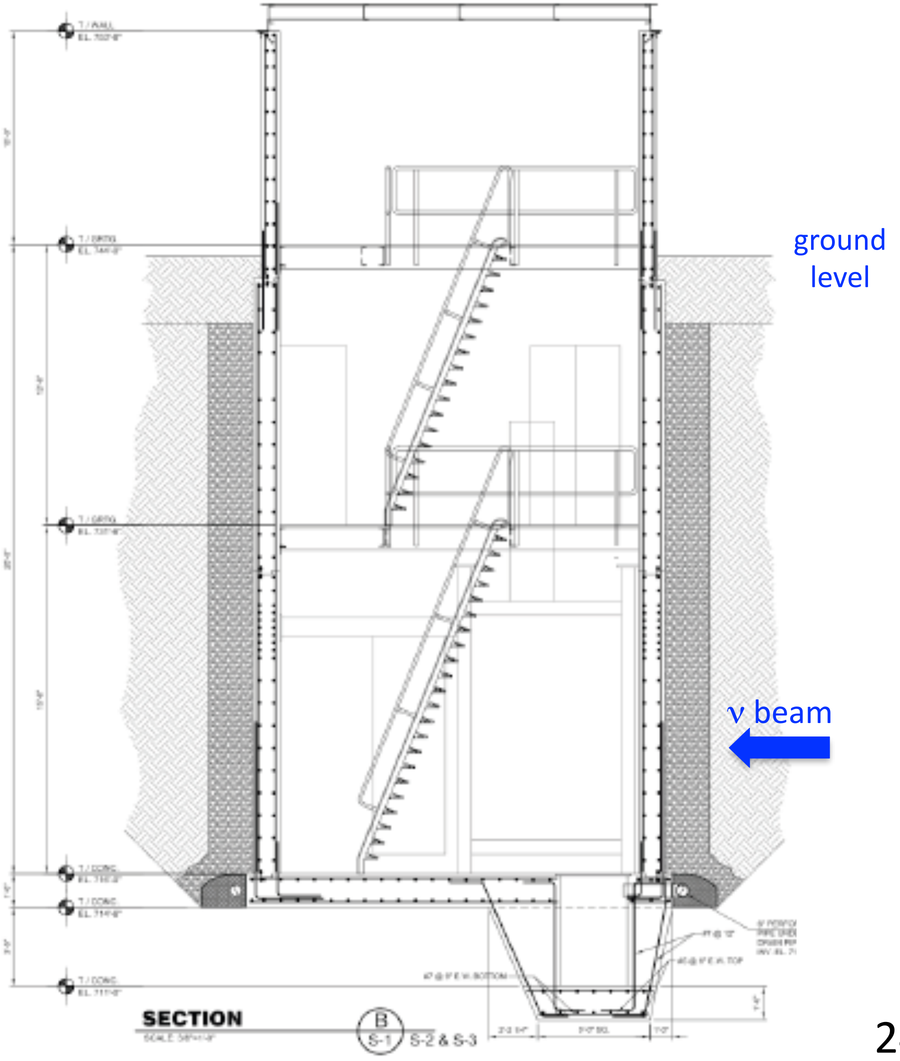

100m
Indian Creek

Detector Location

The SciBooNE experimental hall

- The SciBooNE enclosure is a below grade rectangular concrete structure with interior dimensions:

  Length *(beam direction) = 4.9 m;* **Width** = 7.0 m; **Depth**: floor-grade = 8.5 m, floor-ceiling = 11.6 m



LAr1-ND Detector Overview

- The current conceptual layout for the LAr1-ND detector is based on:
  - Utilizing this existing structure
  - Implementing current technology that builds upon current experience from the T600, MicroBooNE, 35 ton prototype, etc.
  - Utilizing design elements developed for the LBNE Far Detector design

- Still lots of detailed decisions, "value engineering", to be made during the technical design phase to come

- The enclosure is in an isolated area, with nearby surface space for auxiliary enclosures or facilities related to cryogenics, etc

LAr1-ND Detector Overview

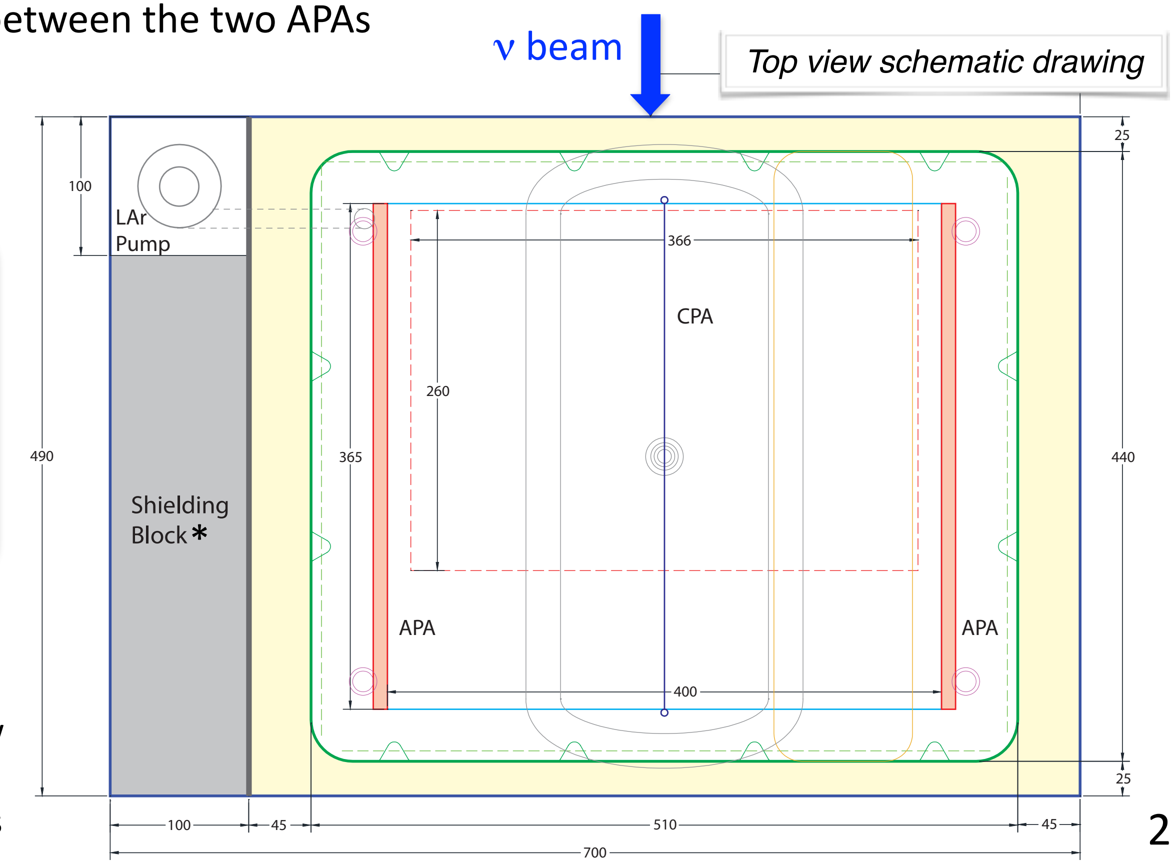
- A foam insulated, corrugated stainless steel membrane cryostat is constructed in the pit, supported by the outer concrete walls of the enclosure, and filling the entire length in the beam direction.

- The interior dimensions of the rectangular cryostat are:
  - 4.4 m long in the neutrino beam direction, 5.1 m wide and 4.8 m tall, amounting to 150 tons total of liquid argon

- A Time Projection Chamber (TPC), located inside the cryostat vessel, consists of two APAs (Anode Plane Assemblies - to read out ionization electron signals) near the walls of the cryostat, and one CPA (Cathode Plane Assembly) centered between the two APAs

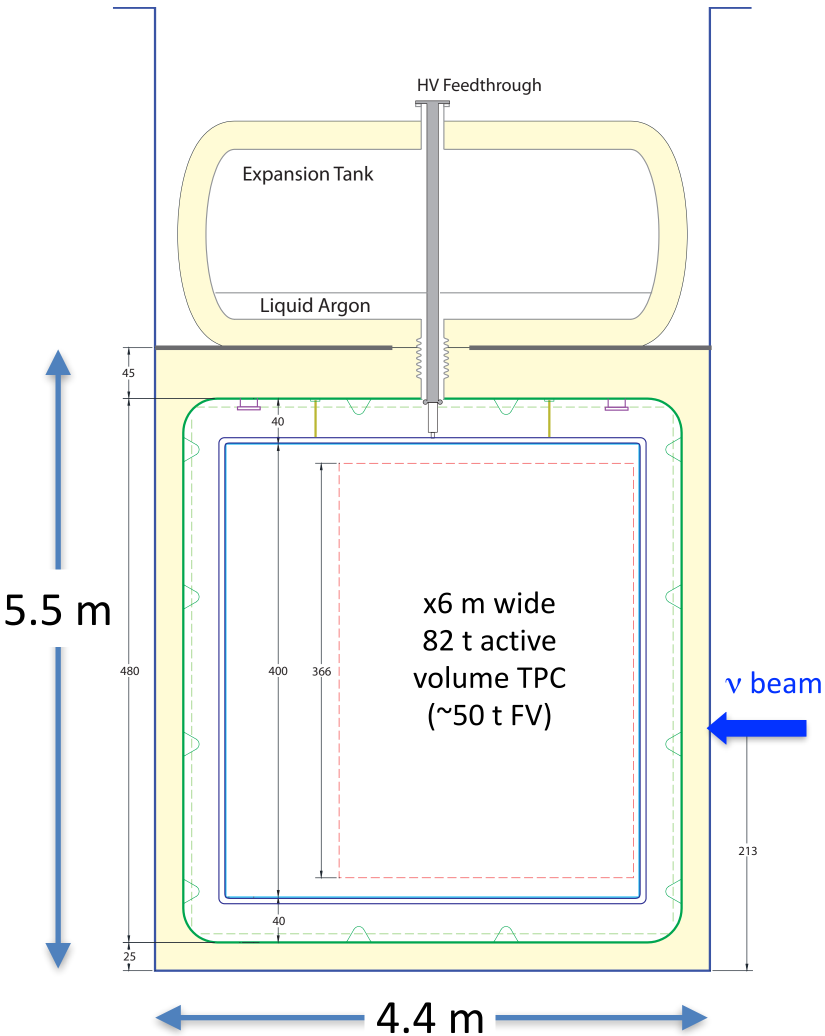
The TPC active volume:

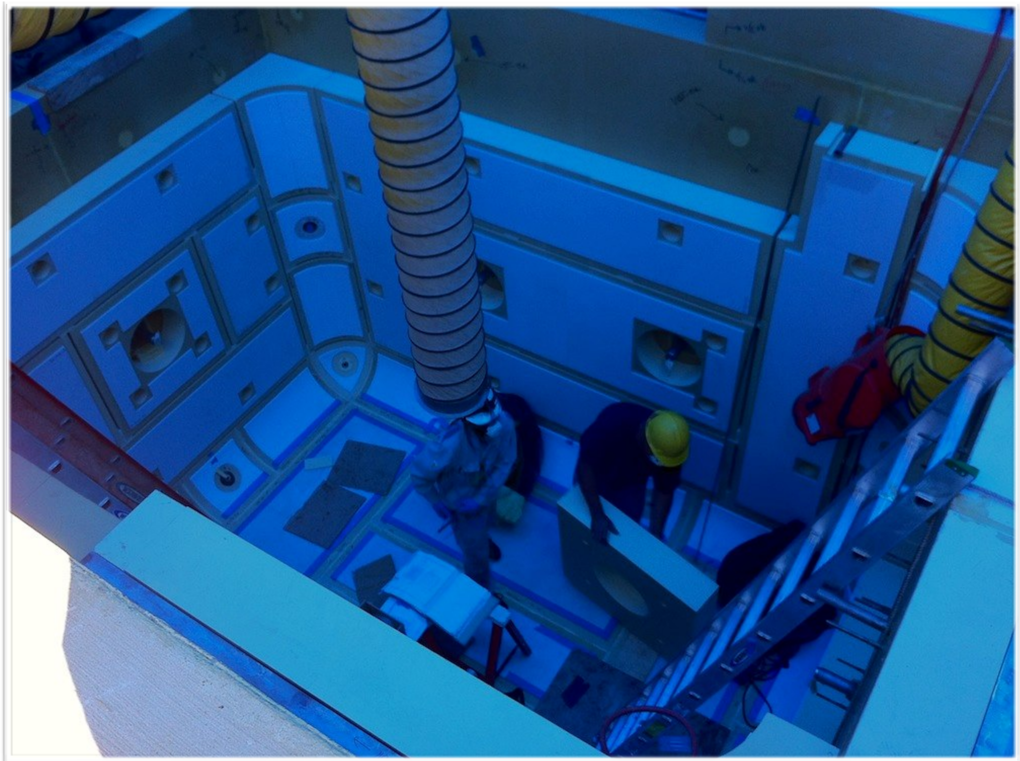
3.65 m *(beam direction)* x
4.0 m *(wide)* x
4.0 m *(tall)*
= 58.4 m^3 (82 tons of argon)



* Shielding blocks are used to narrow the hall by 1 m, to approximately center the detector on the beam axis

LAr1-ND: Membrane Cryostat





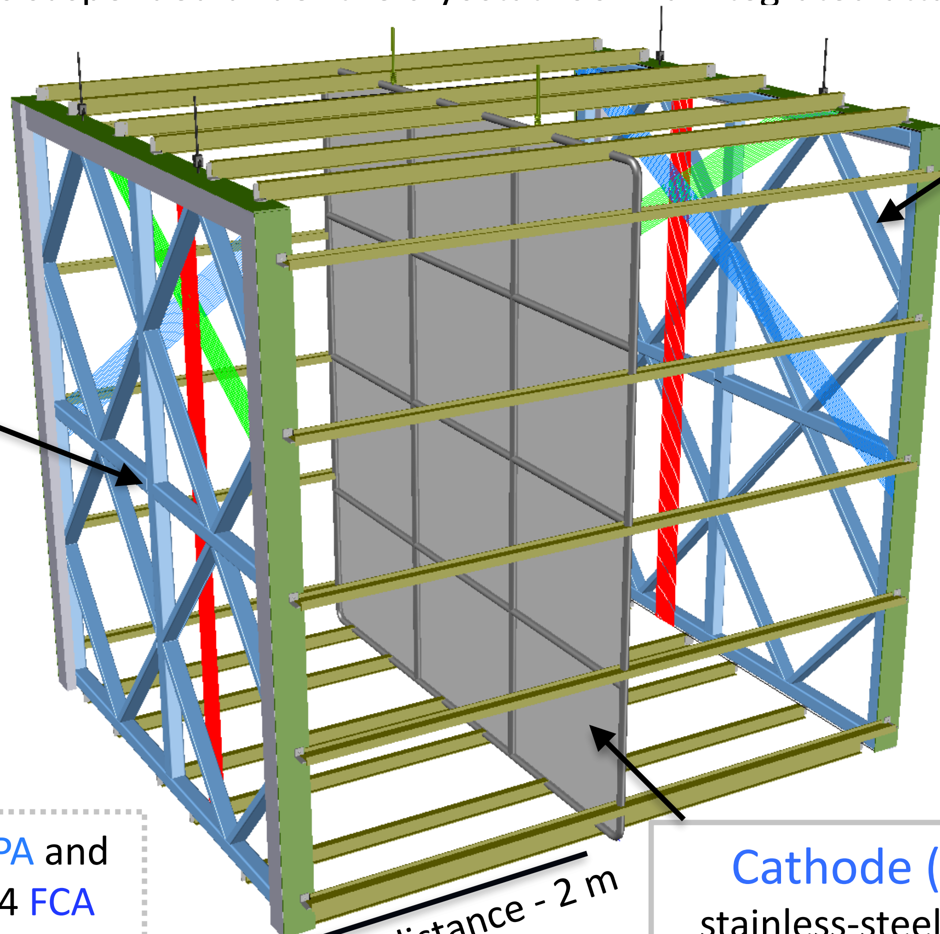
The interior of the 35 ton prototype membrane cryostat during construction at Fermilab

From the information provided by the Fermilab Facilities Engineering Services Section, the walls and floor of the SciBooNE enclosure are capable of withstanding the hydrostatic pressures of the LAr1-ND cryostat

More detail to follow in talk from D. Montanari

LAr1-ND: Time Projection Chamber Layout

The entire TPC structure is suspended under the cryostat roof via integrated attachment points.



Anode (APA)
active area:
3.65 m wide and 4 m tall

Each pair of facing CPA and APA forms an electron-drift region

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

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

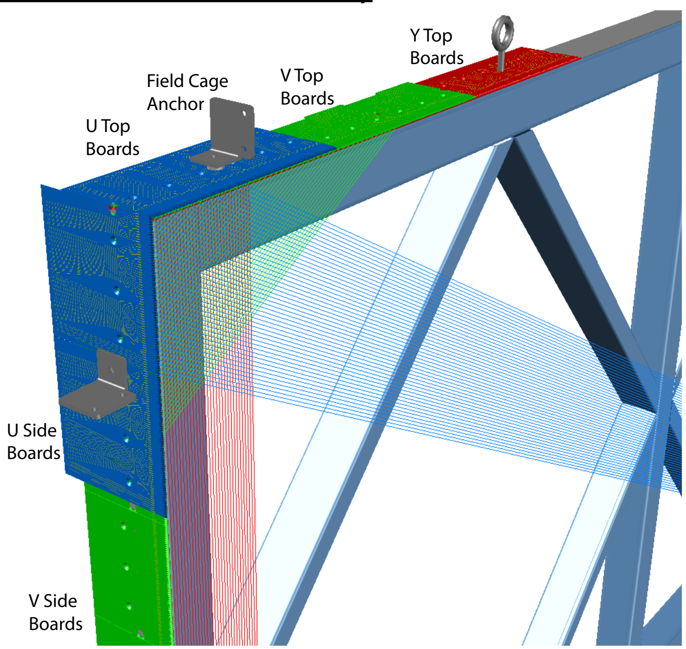
At a 500 V/cm drift field and 2 m drift distance, the cathode plane is biased at -100 kV (< than MicroBooNE HV)

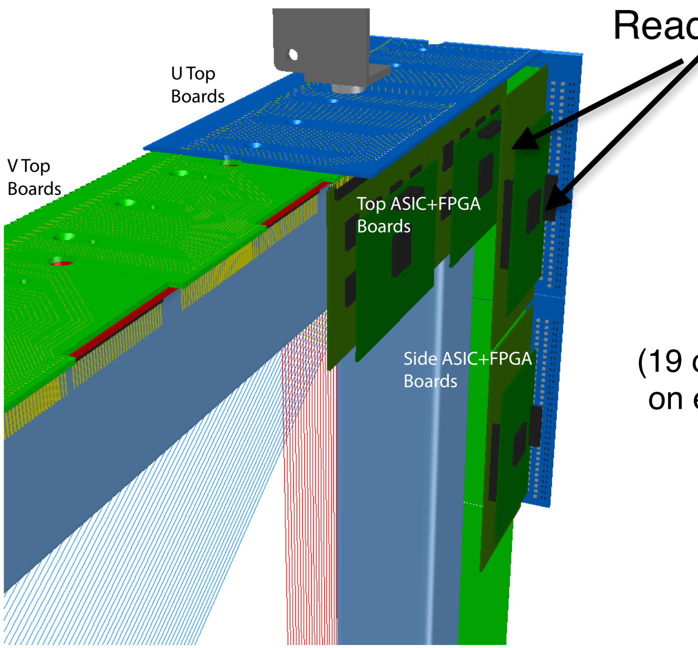
Anode Plane Assembly

- Each APA holds three planes of wires (U, V and Y) on one side. The wire pitch (3 mm) and angles (0^0 and $\pm 60^0$ from vertical) are identical to that of MicroBooNE

Single sided APA: uses the same wire bonding method developed for the LBNE APAs, but <u>without the continuous helical wrapping</u>, to minimize ambiguities in track reconstruction.

Each wire is connected to a front-end readout channel with <u>cold electronics boards</u> at the top and vertical sides of each APA. The <u>total number of readout channels is 4736 per APA (9472 in the entire detector)</u>





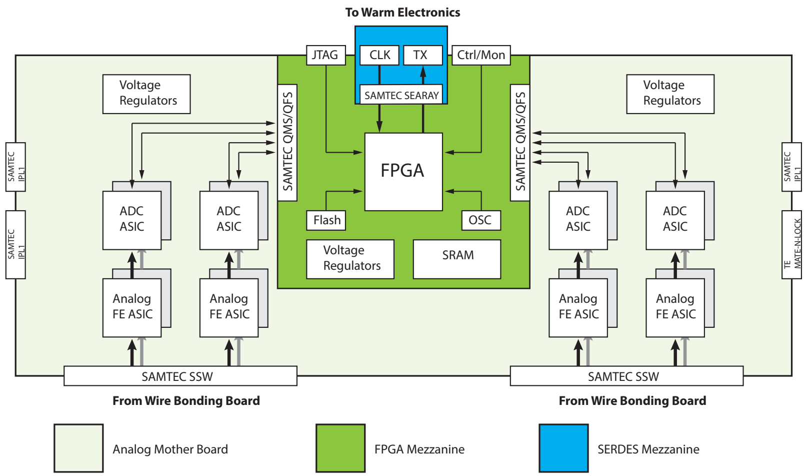
Each APA has
55 front end
mother boards
(19 on top - 128 channels, 18
on each side - 64 channels)

Corner view of an APA. Wires at 0^0 (collection plane) and $\pm 60^0$ from vertical (2 induction planes) are attached to wire bonding boards at the sides and ends of the APA.

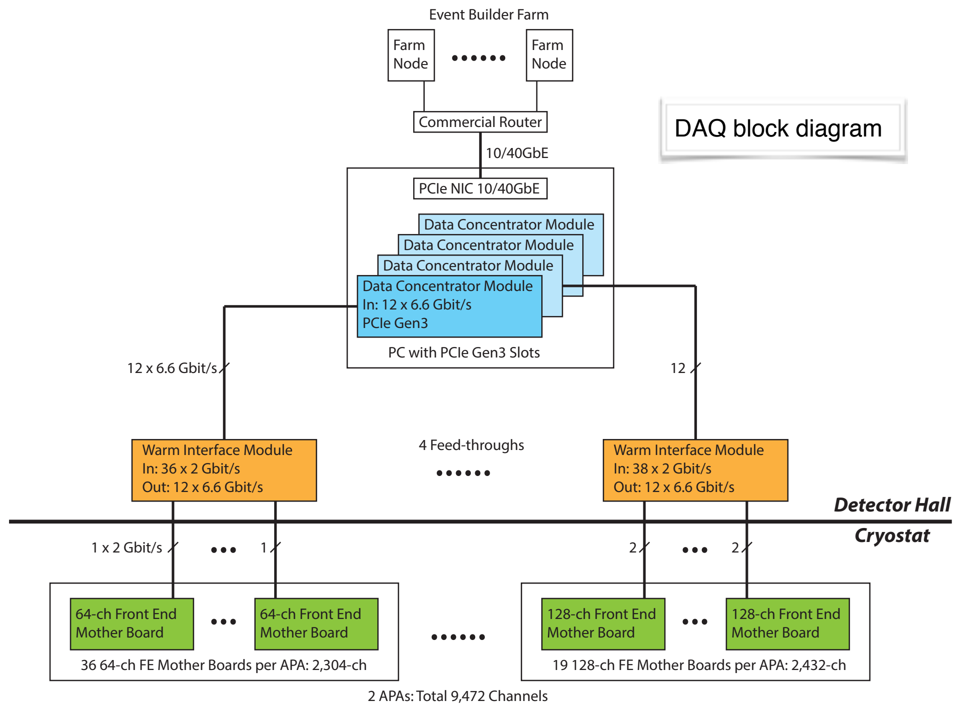
Readout Electronics & DAQ

- ➢ The electronic readout chain is implemented as CMOS ASICs designed for operation in LAr, and commercial FPGAs (multiplexing). *Both analog Front End (FE) ASIC and ADC ASIC have already been developed for LBNE, and analog FE ASIC is being used in MicroBooNE*

- ➢ 8 FE, 8 ADC plus a FPGA comprise a single 128-channel front end mother board



Front End Mother board



DAQ block diagram

- ➢ The FPGA on each motherboard transmit data out of the cryostat through a feedthrough to the DAQ system.

- ➢ The DAQ system is located external to the cryostat vessel, with components in the detector hall and in an on-site control room. It consists of the Warm Interface Module (WIM), timing system, and commodity Data Concentrator Modules (DCM), network switch and computing farm

Trigger - Light Collection

- Detection of scintillation light plays several important roles in LAr TPCs:
  - For a surface detector in a beam, like LAr1-ND, the scintillation light provides a tag of events in-time with the beam pulse, allowing rejection of cosmic rays;
  - The light also provides the T_0 for non-accelerator events (such as supernova events);
  - If a suitable high efficiency light collection system is in use, energy deposited into light can be related to energy deposited into charge for an improved calorimetric reconstruction.

- A compact light-guide-based system has been proposed as Photon Detector (PD) for LBNE *(acrylic bars read out by silicon photomultipliers, SiPMs*). The results of an R&D program show that, while more development is still necessary, the system works properly and is proposed as the basic design for light collection in the LAr1-ND detector

However, the relatively small volume of LAr1-ND provides an excellent test-bed for light collection systems being designed and optimized for LBNE and for studies of the light collection efficiency as a function of the photocathode coverage

LAr1-ND Timeline

Based on experience in constructing LAr TPC detectos, 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

A construction start on the 2015 time scale maximizes the physics potential within the existing Fermilab program, making it possible to run the LAr1-ND detector concurrently with MicroBooNE toward the end of the already planned neutrino-mode running

Conclusions

- LAr1-ND enables the interpretation of a MicroBooNE signal, be it electrons or photons, by providing a high statistics measurement at nearer baseline on a rapid time scale
- LAr1-ND also a critical element even for a future phase with a larger-scale far detector at 700m along the BNB
- LAr1-ND combines timely neutrino physics with experience in LArTPC detector development for teams also working toward next generation experiments
  - LAr1-ND is a collaboration of institutions from the U.S. and Europe with a range of experience with LAr detectors and neutrino physics
  - Discussions concerning specific contributions from collaborating institutions are now on-going
  - CERN, with significant expertise and resources, is an extremely important collaborator for the development of the LAr technology for neutrino physics overall
  - LAr1-ND could be well-suited to serve as a next step in the collaboration of CERN (as it is with others) and the FNAL neutrino physics program

Overflow

The 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]

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[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*

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

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

11 institutions also on MicroBooNE
Nearly all interested in longer term long-baseline FNAL program

*Contact person

Sensitivity to MiniBooNE Low-Energy ν_e Excess

Estimated event rates by direct <u>scaling of MiniBooNE event rates</u>* and accounting for differences in fiducial masses, beam exposures and selection efficiencies between detector technologies

*A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), "Unexplained Excess of Electron-Like Events From a 1 GeV Neutrino Beam." Phys. Rev. Lett. 102 101802 (2009)

Process	200 - 300 MeV (mB)	300 - 475 MeV (mB)	Total (mB)	Scaling (LAr1-ND)	Total (LAr1-ND)
Background fror					
$\mu \to \nu_e$	13.6	44.5	58.1	2.40	139.8
$K^+ \to \nu_e$	3.6	13.8	17.4	2.40	41.9
$K^0 \to \nu_e$	1.6	3.4	5.0	2.40	12.0
Background from ν_μ					
ν_μ CC	9.0	17.4	26.4	1.20	31.8
$\nu_\mu e \to \nu_\mu e$	6.1	4.3	10.4	2.40	25.0
NC π^0	103.5	77.8	181.3	.241	43.6
Dirt	11.5	12.3	23.5	.241	5.7
$\Delta \to N\gamma$	19.5	47.5	67.0	.241	16.1
Other	18.4	7.3	25.7	.241	6.2
Background	187	228	415		**322.1**
Excess	45.2	83.7	128.9	2.40	**310.2**

Backgrounds (including both intrinsic sources of ν_e and single photon final state ν_μ interactions)

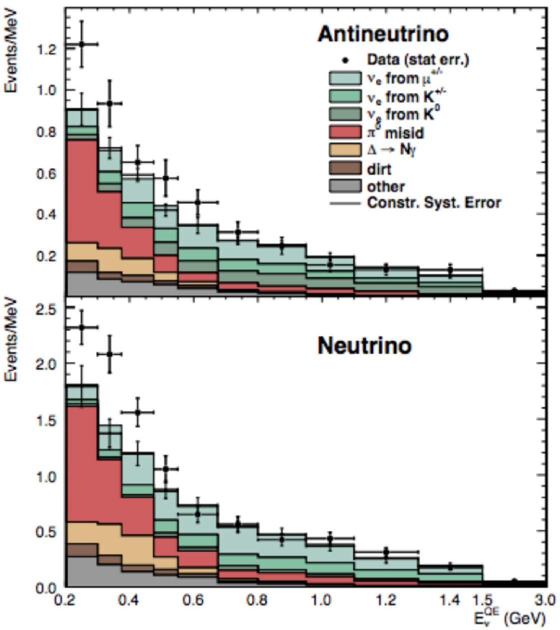
MicroBooNE expects ~50 signal and 50 background events in 6.6×10^{20} POT

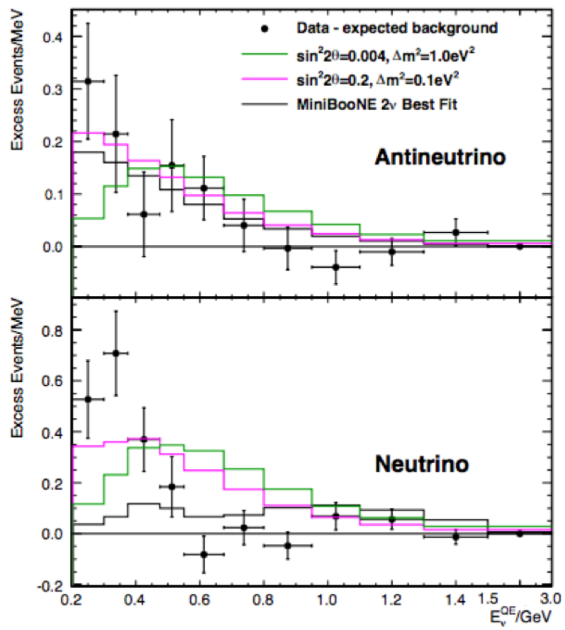
"Signal": scale the excess event counts reported by MiniBooNE *as if they are electrons*

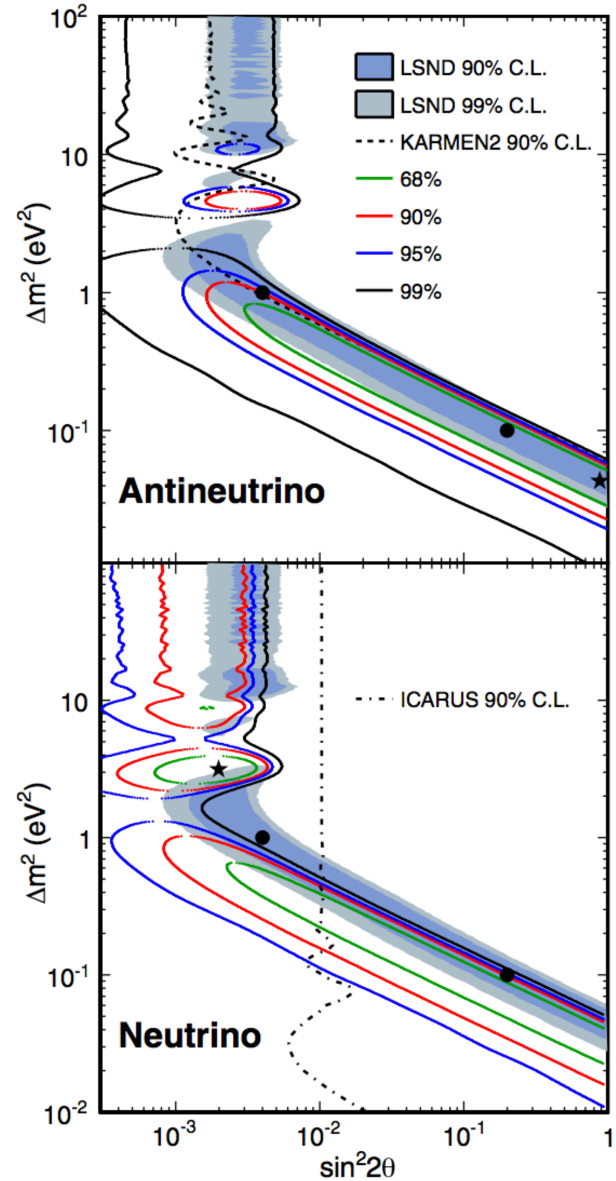
LAr1-ND: 2.2×10^{20} POT exposure
Estimate **>6.5**σ observation of MiniBooNE-like excess

MiniBooNE Excesses

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







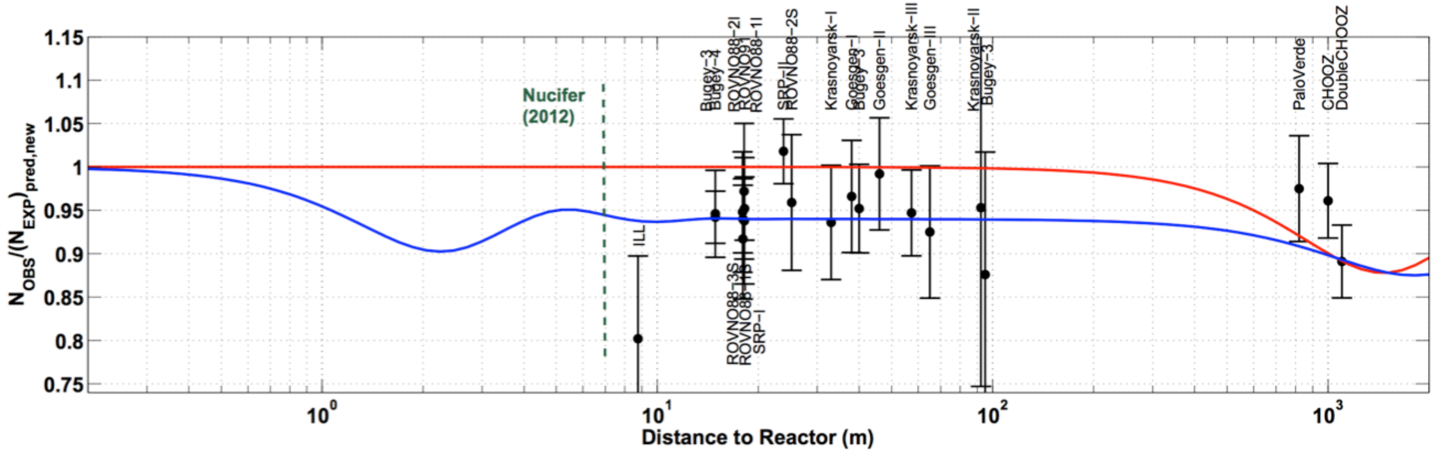


Figure 2.3: *Ratio of the observed to predicted reactor $\bar{\nu}_e$ rate for 19 different reactor neutrino experiments at baselines less that 100 m. The mean average ratio including correlations is* 0.927 ± 0.023*, indicating a 7.3% deficit at short baseline. The curves show fits to the data assuming standard three neutrino oscillations (red) and assuming 3+1 neutrino oscillations including one additional sterile neutrino (blue) [18].*

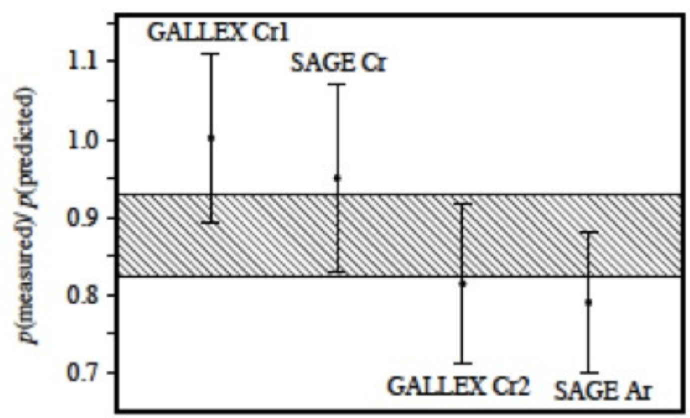


Figure 2.4: *The measured/predicted event ratio for GALLEX and SAGE source calibration data. The average, shown by the shaded band, is 0.86 ± 0.05 [19].*

Appearance Global Fit

J. Kopp et al., “Sterile Neutrino Oscillations: The Global Picture”. hep-ph/1303.3011 (2013).

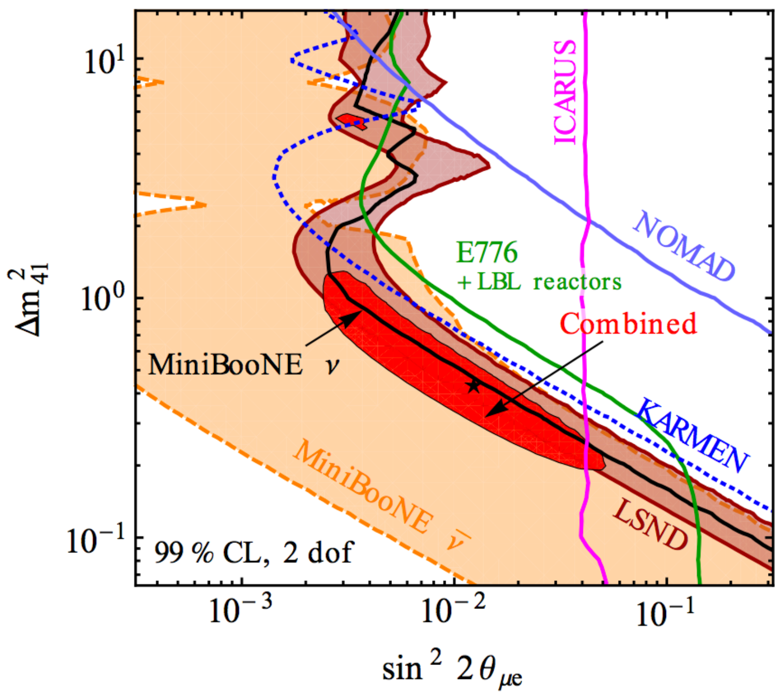
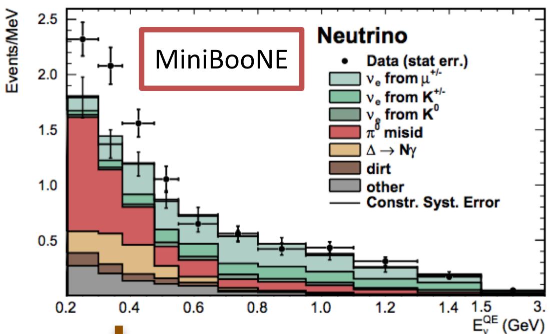
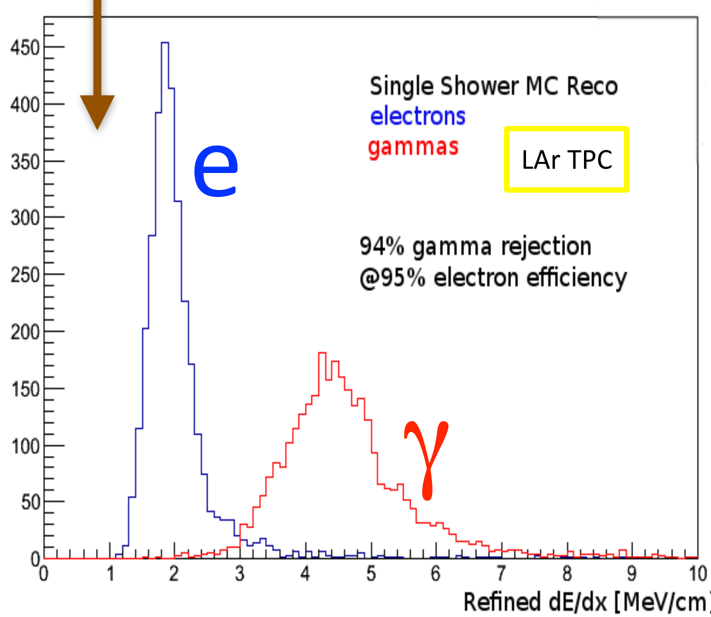


Figure 7. Allowed regions and upper bounds at 99% CL (2 dof) for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance experiments in the 3+1 scheme. We show the regions from LSND and MiniBooNE anti-neutrino data and the bounds from MiniBooNE neutrinos, KARMEN, NOMAD, ICARUS, and E776. The latter is combined with LBL reactor data in order to constrain the oscillations of the $\overset{(-)}{\nu}_e$ backgrounds; this leads to a non-vanishing bound on $\sin^2 2\theta_{\mu e}$ from E776 at low Δm^2_{41}. The red region corresponds to the combination of those data, with the star indicating the best fit point.

MicroBooNE @ ~500m

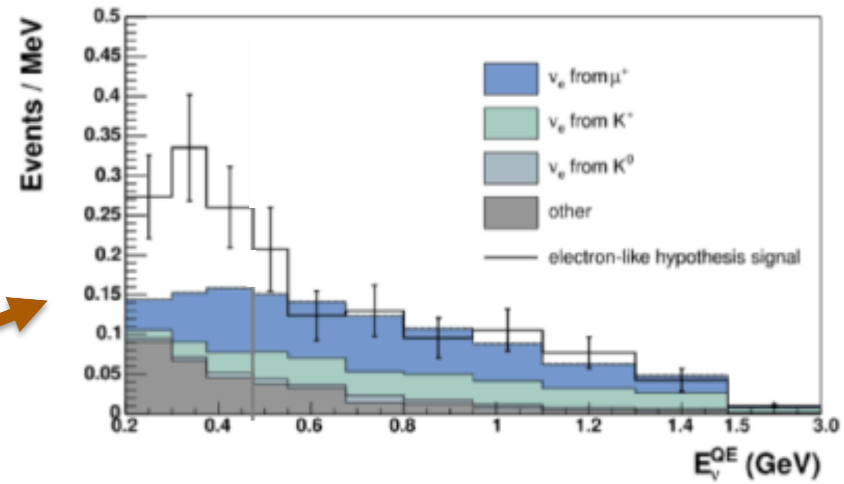




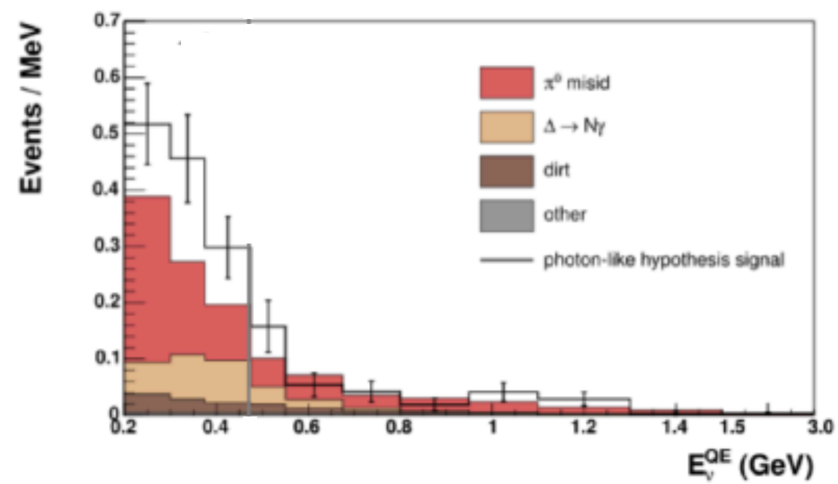
electrons

photons

>5σ stat. significance if all electrons



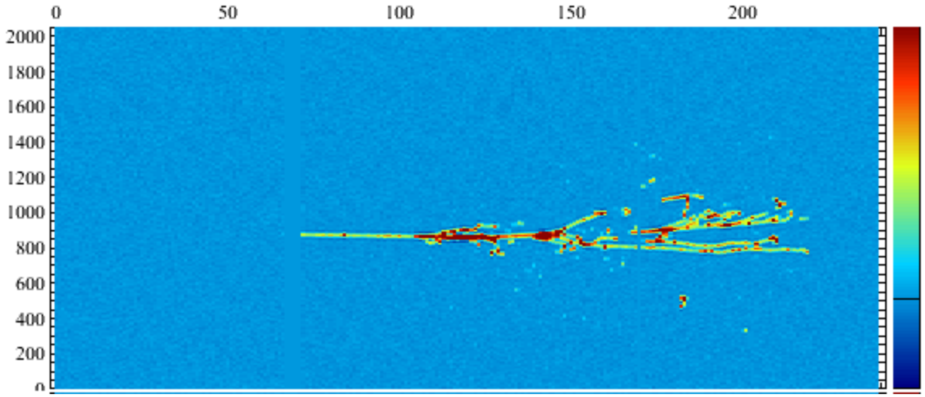
>4σ stat. significance if all photons



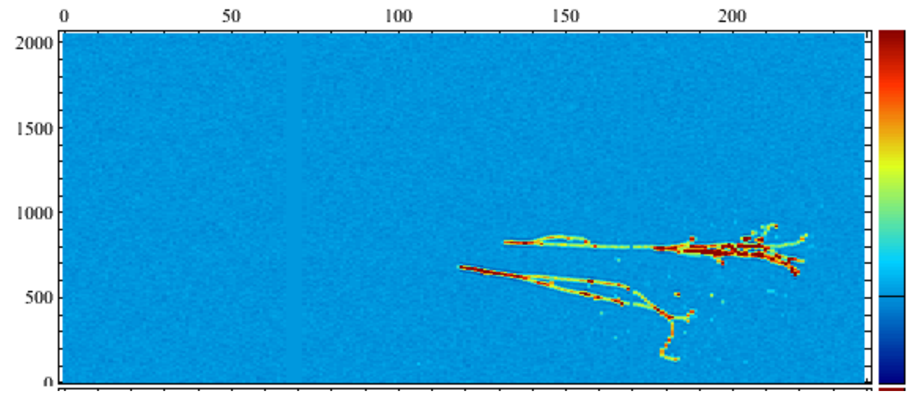
MicroBooNE can investigate a critical piece of the puzzle: **are the excess events seen by MiniBooNE <u>electrons</u> or <u>photons</u>?**

Electron/photon Separation

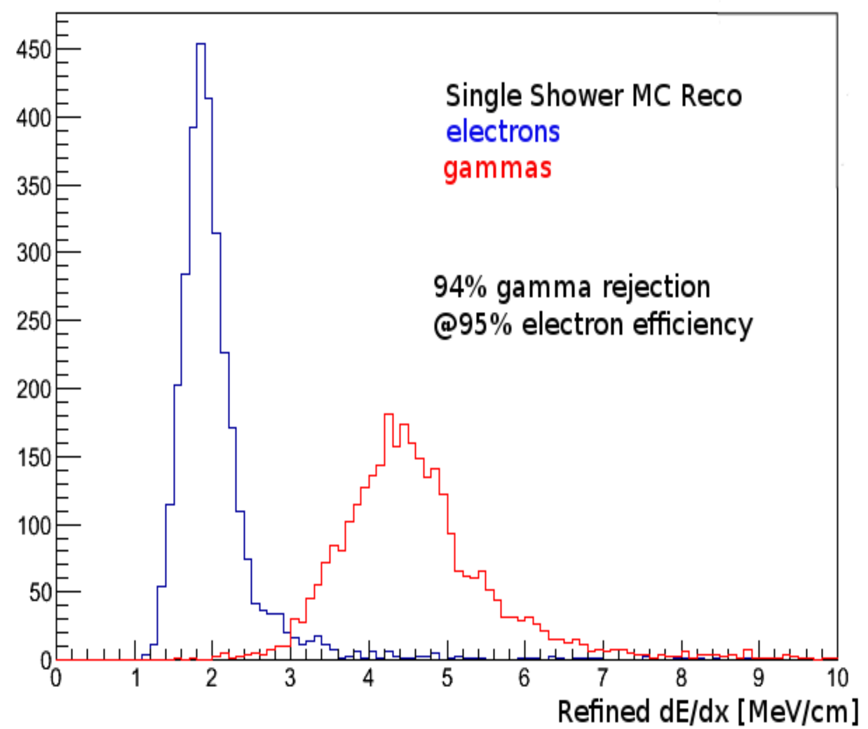
1 GeV electron shower



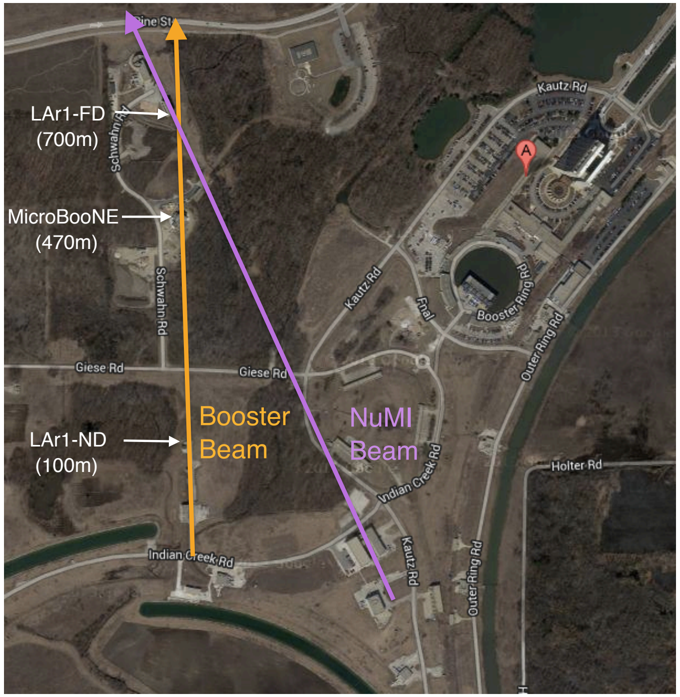
Decay of a 1 GeV π^0 to two photons.



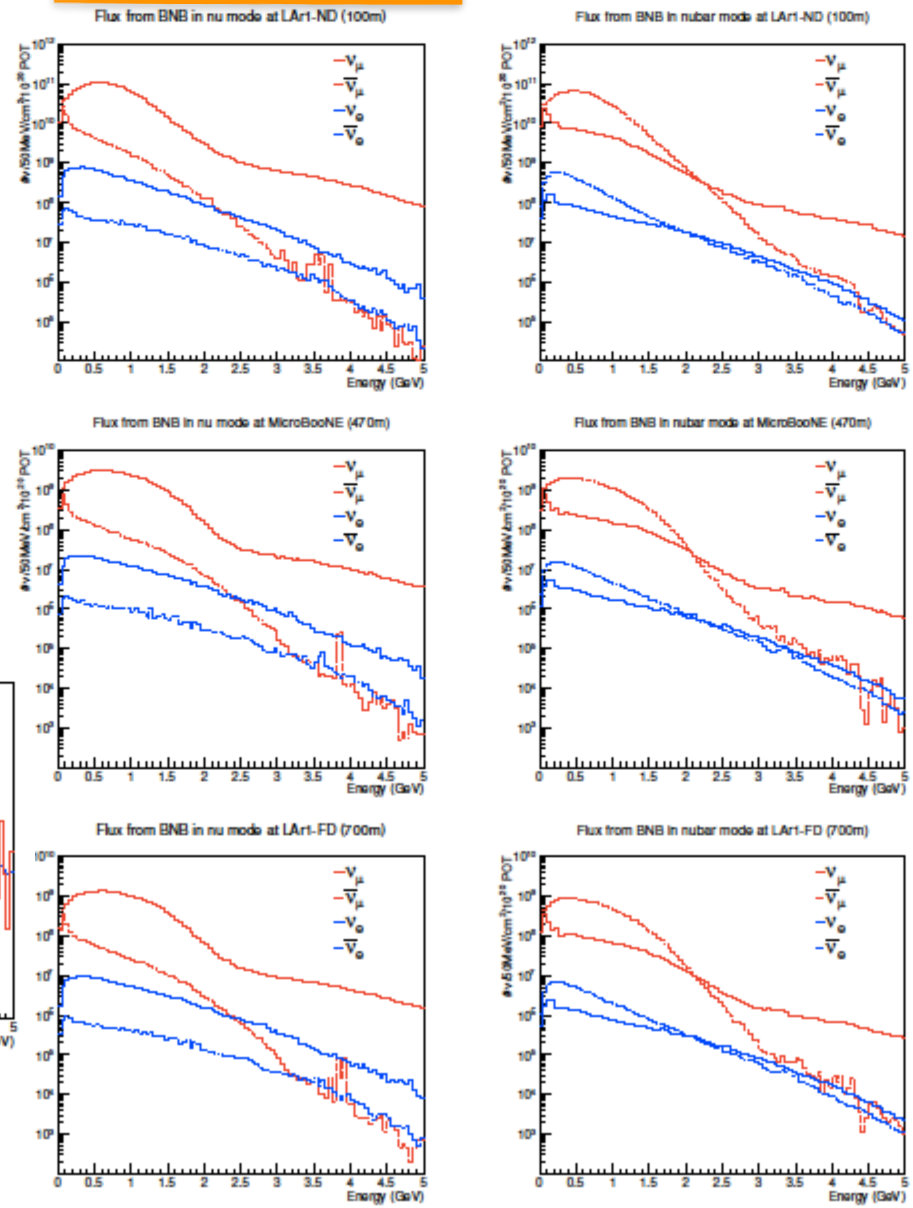
The double mip deposition of converted photons allows even single photons to be identified, significantly reducing backgrounds in searches for ν_e appearance



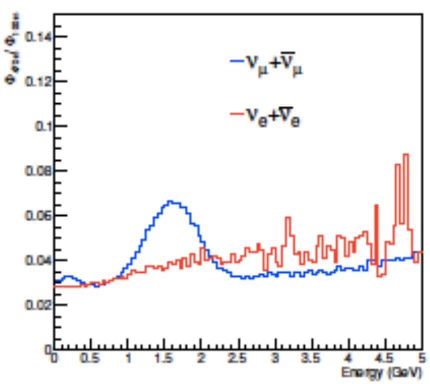
Neutrino beams (I)



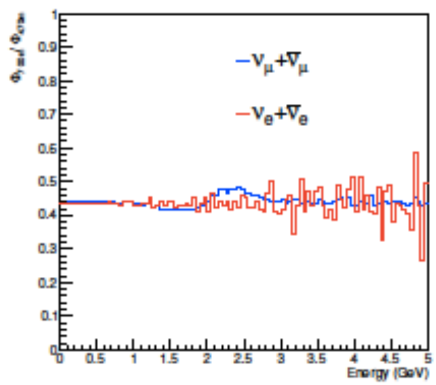
The Booster Neutrino Beam @ different detector locations



Ratios of the fluxes at different detector locations.

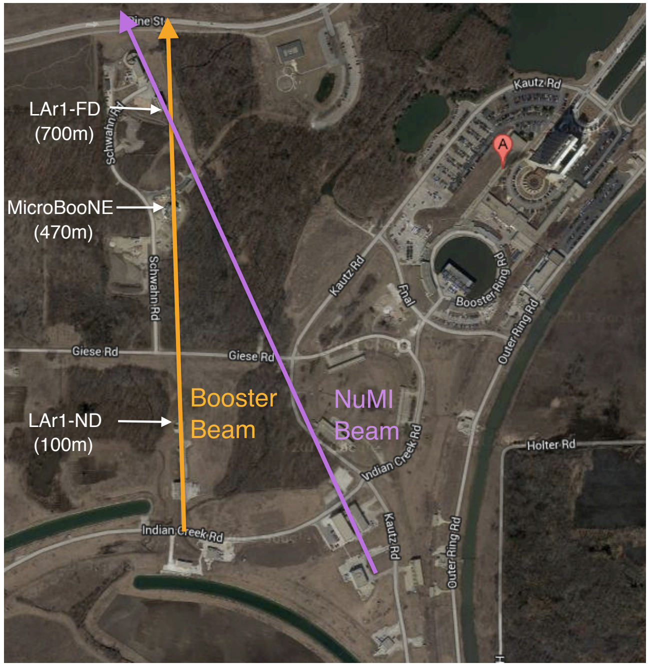


Flux at MicroBooNE vs. flux at LAr1-ND

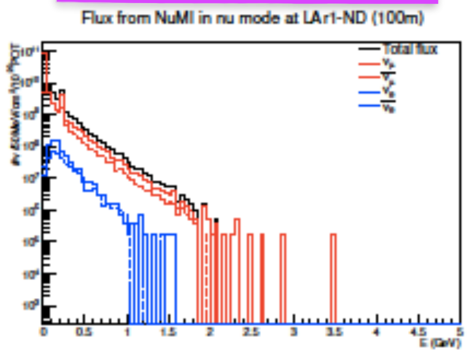


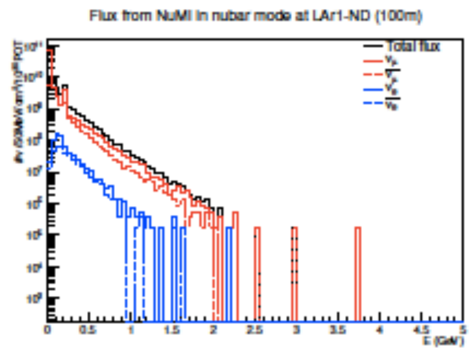
Flux at MicroBooNE vs. flux at LAr1-FD

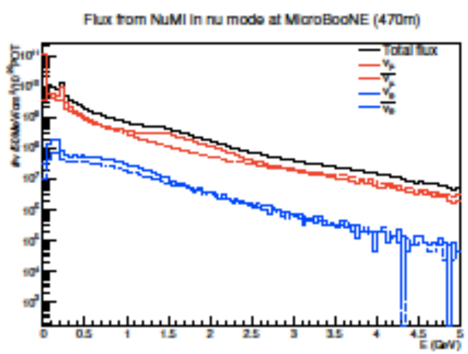
Neutrino beams (II)

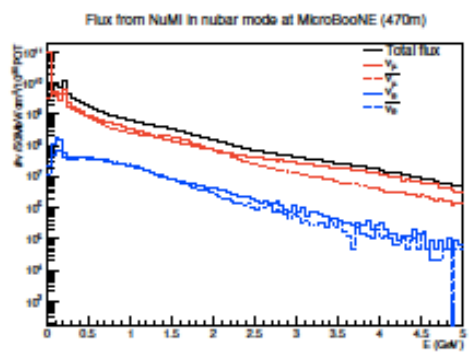


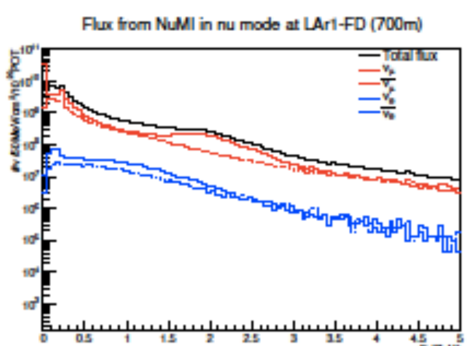
Off-axis NuMI fluxes @ different detector locations

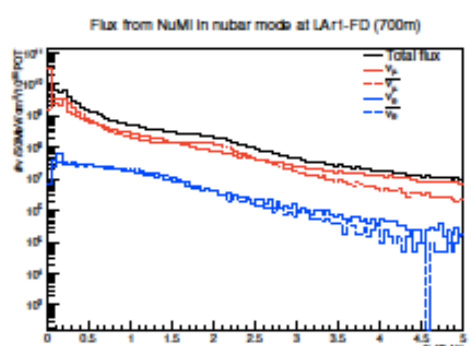






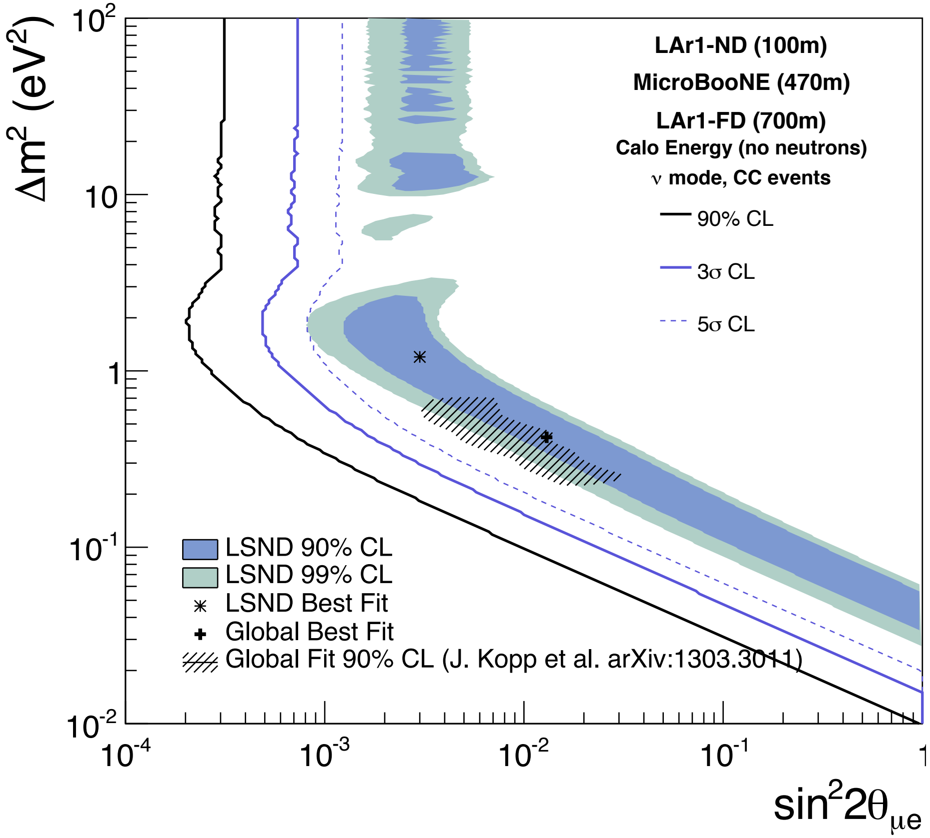




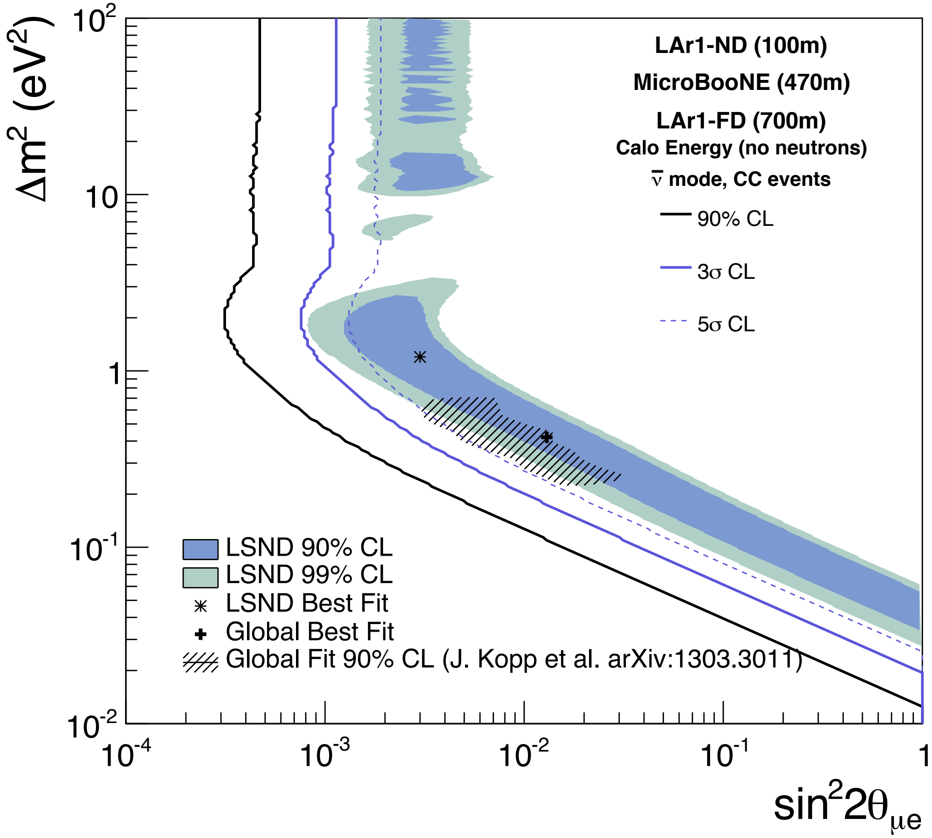


$\nu_\mu \rightarrow \nu_e$ Appearance (3-det)

- LAr1-ND + MicroBooNE + 1 kiloton Far Detector at 700m

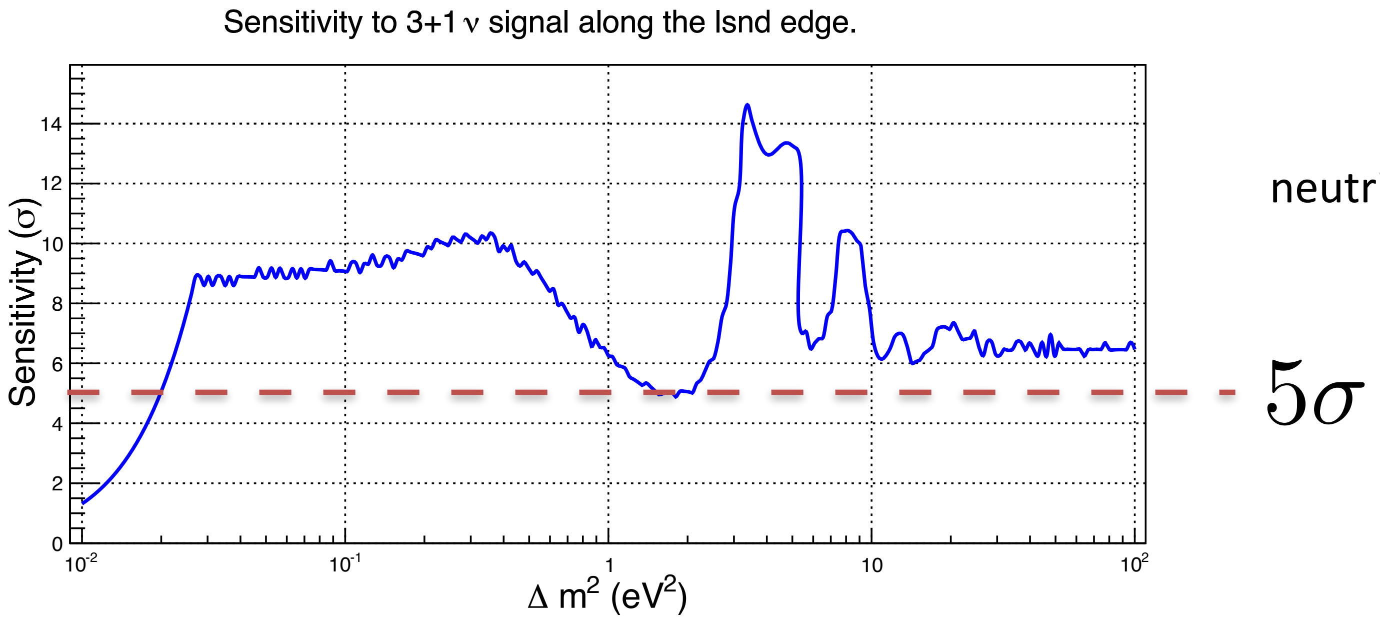


6.6x10^{20} POT exposure
neutrino mode

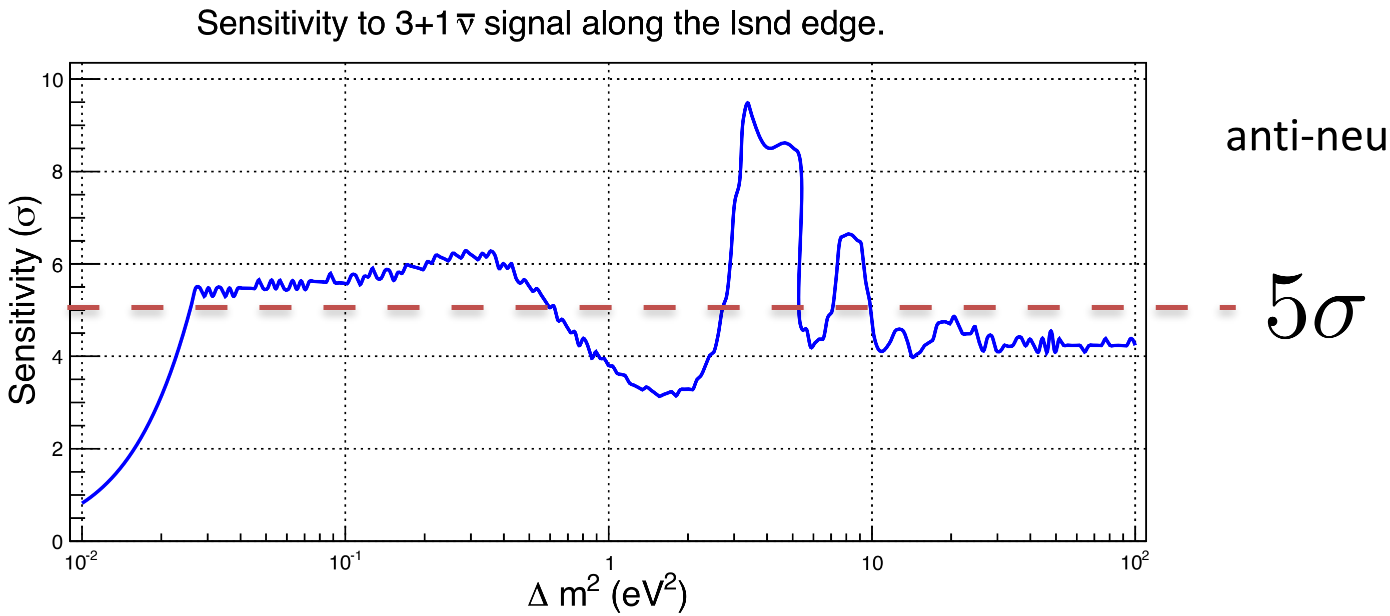


10x10^{20} POT exposure
anti-neutrino mode
(assumes both neutrinos and anti-neutrinos oscillate)

$\nu_\mu \rightarrow \nu_e$ Appearance (3-det)

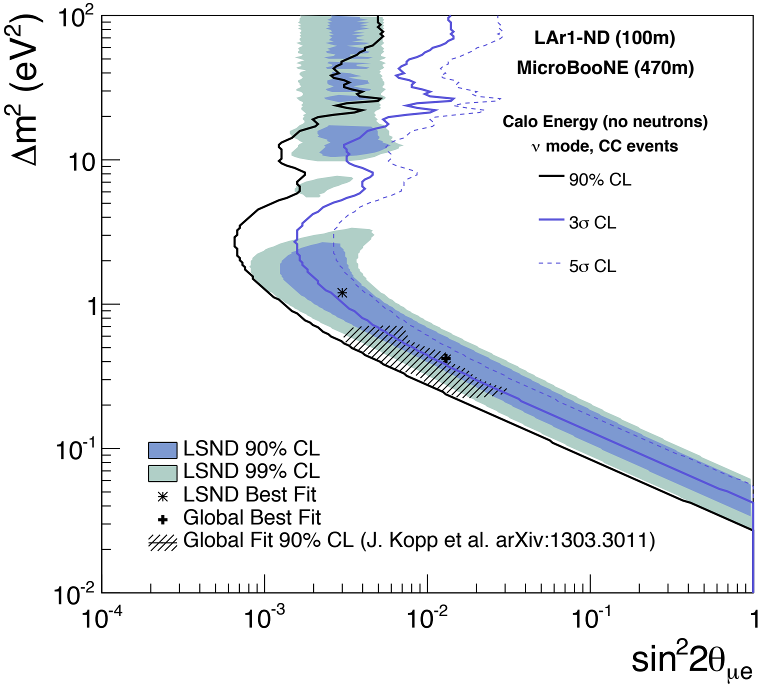


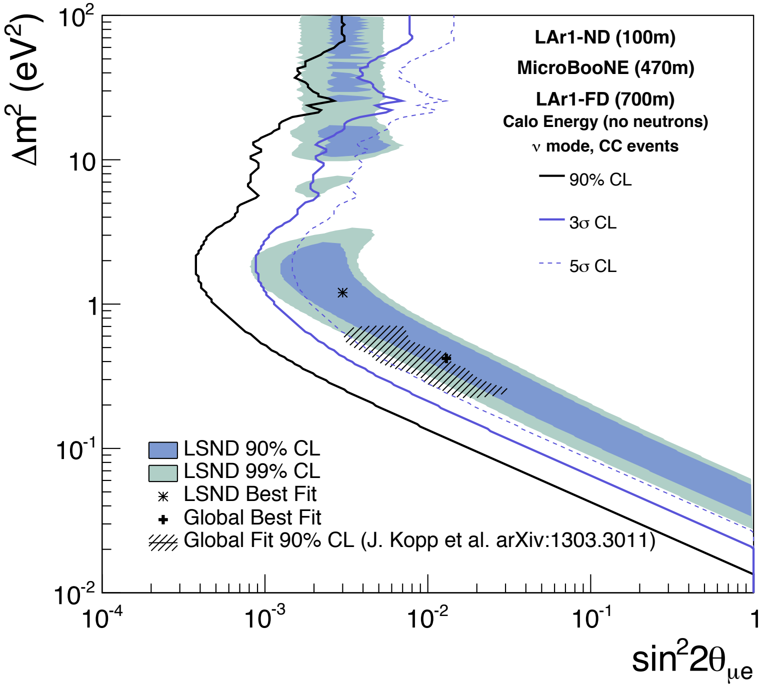
neutrino mode

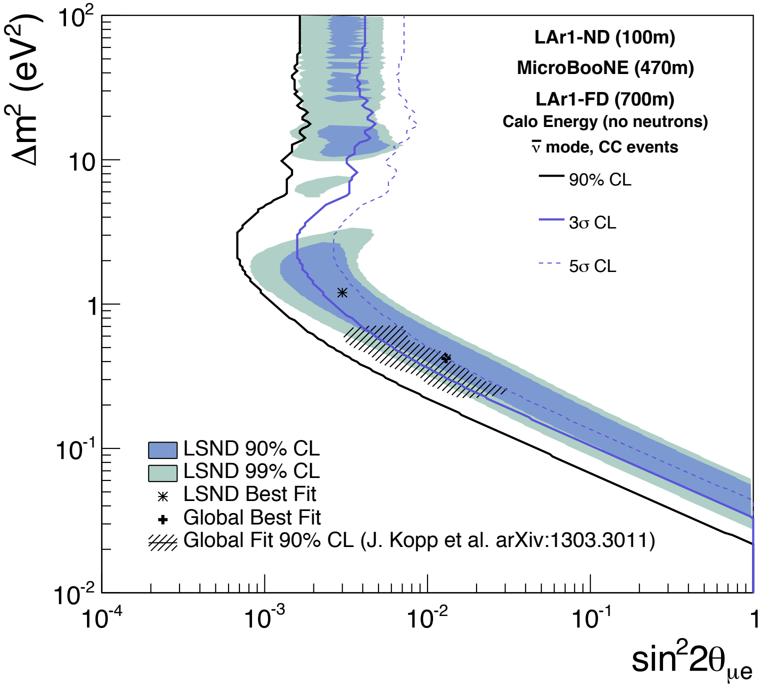


anti-neutrino mode

$\nu_\mu \rightarrow \nu_e$ Appearance (shape only)

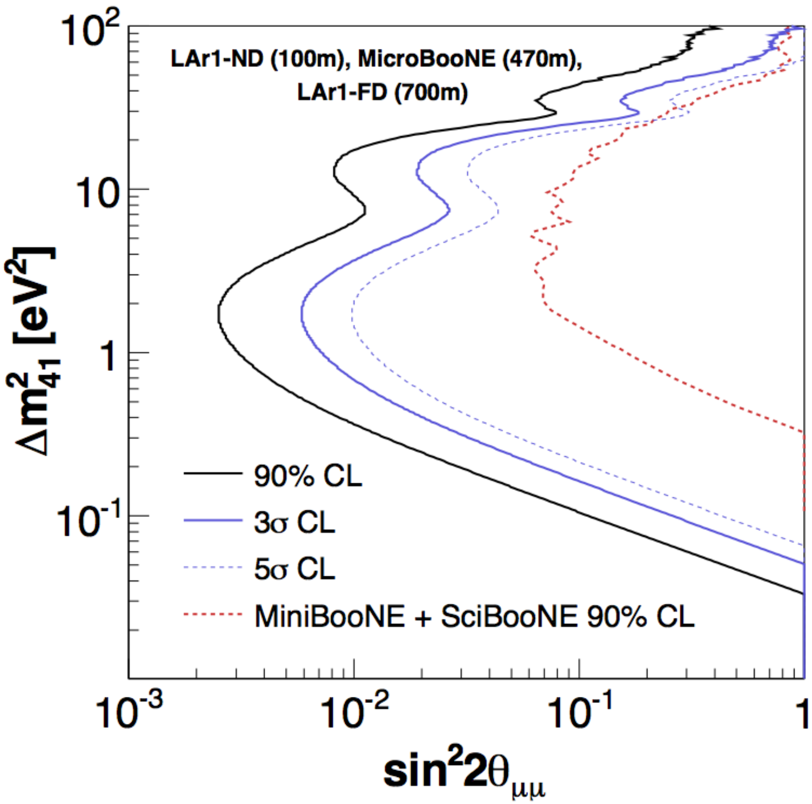




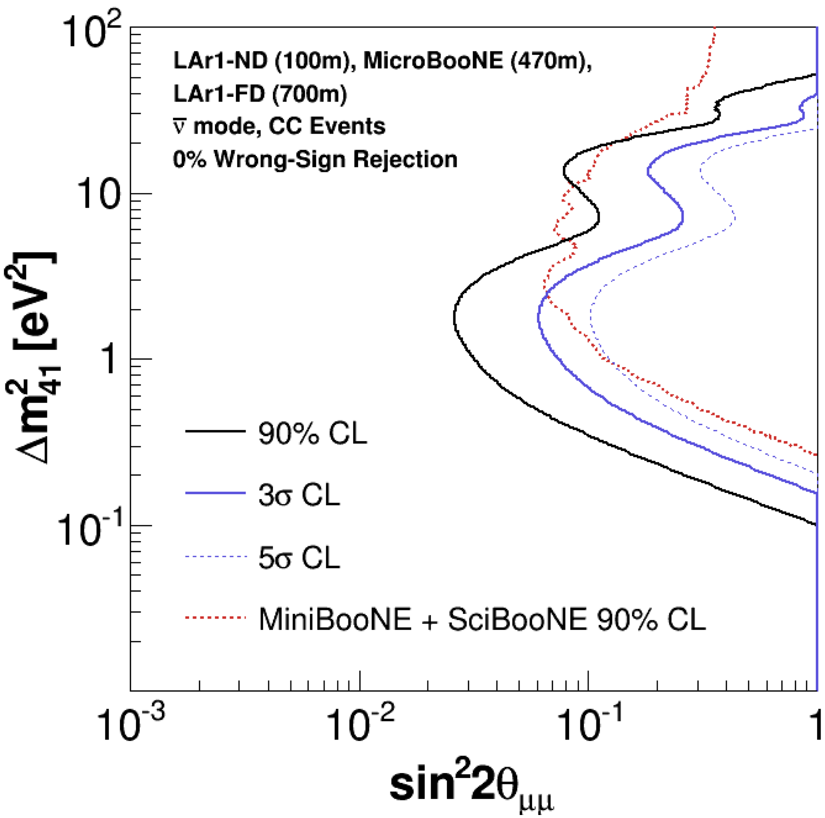


ν_μ Disappearance (3-det)

- LAr1-ND + MicroBooNE + 1 kiloton Far Detector at 700m



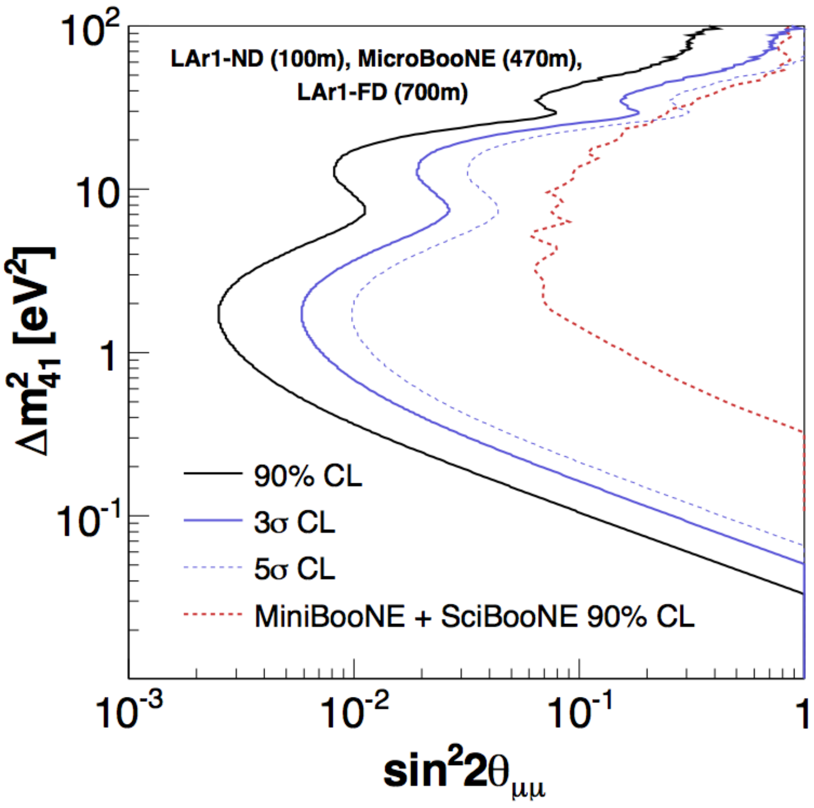
6.6x10^{20} POT exposure
neutrino mode



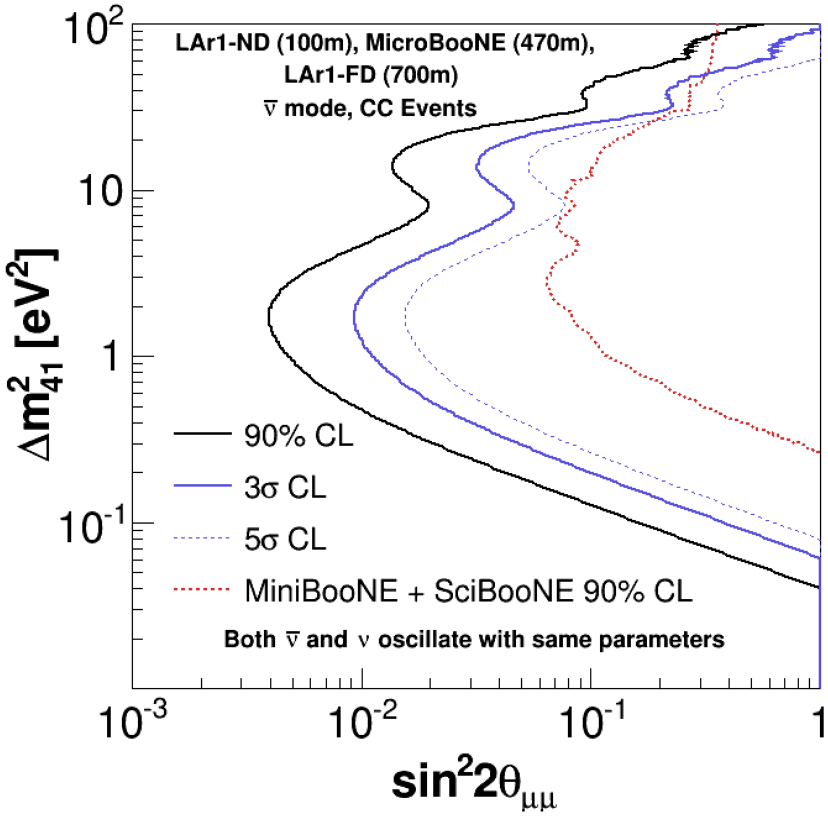
10x10^{20} POT exposure
anti-neutrino mode
(assumes only anti-neutrinos oscillate with WS background)

ν_μ Disappearance (3-det)

❖ LAr1-ND + MicroBooNE + 1 kiloton Far Detector at 700m



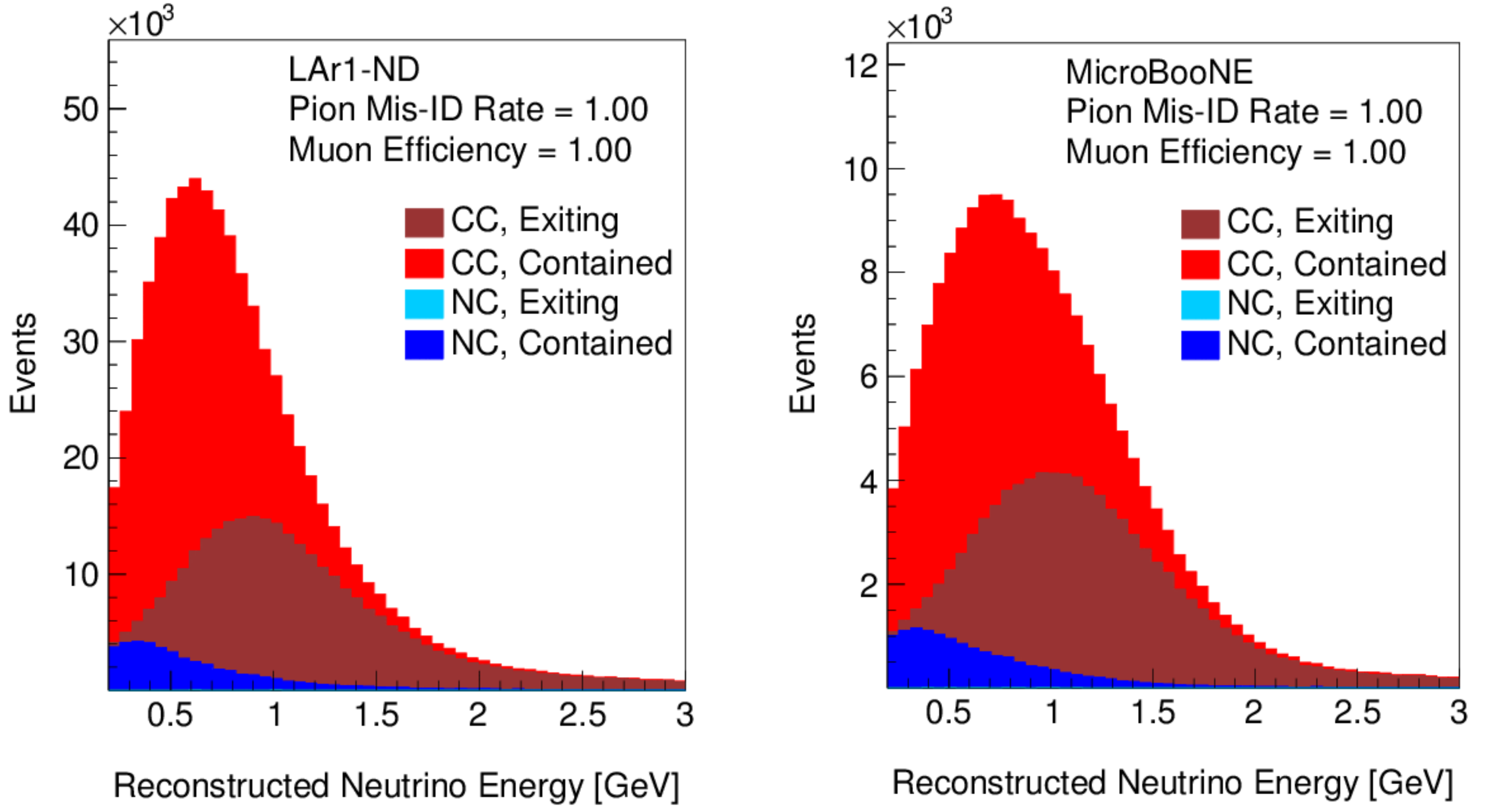
6.6x10[20] POT exposure
neutrino mode



10x10[20] POT exposure
anti-neutrino mode
(assumes both neutrinos and anti-neutrinos oscillate)

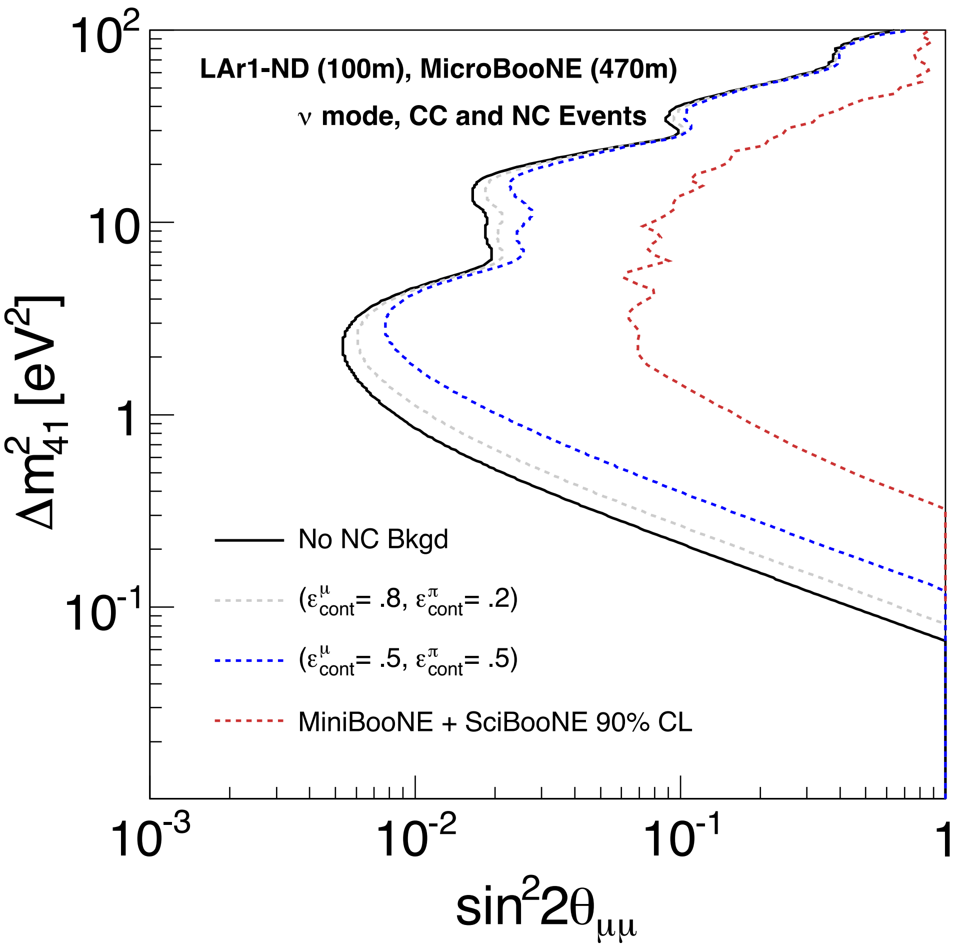
ν_μ Disappearance: Neutral Current Backgrounds

- Charged pions and muons which exit the detector cannot be distinguished
- Contained tracks may be distinguishable, but the precise efficiency/purity is an area of active study
- Plots show total CC and NC-charged-pion rates predicted by simulation



ν_μ Disappearance: Neutral Current Backgrounds

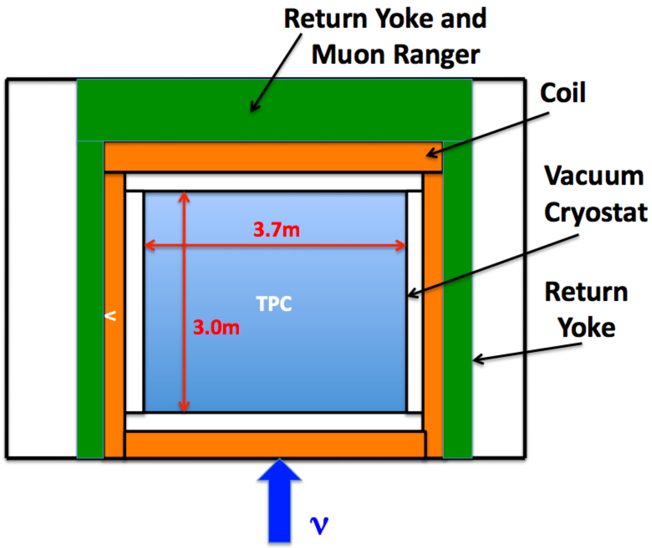
- Plot shows sensitivity for two different efficiency/purity assumptions
- When determining the sensitivity we assume that the NC events do not oscillate
- The uncertainty on the fraction of NC events is set at 30%



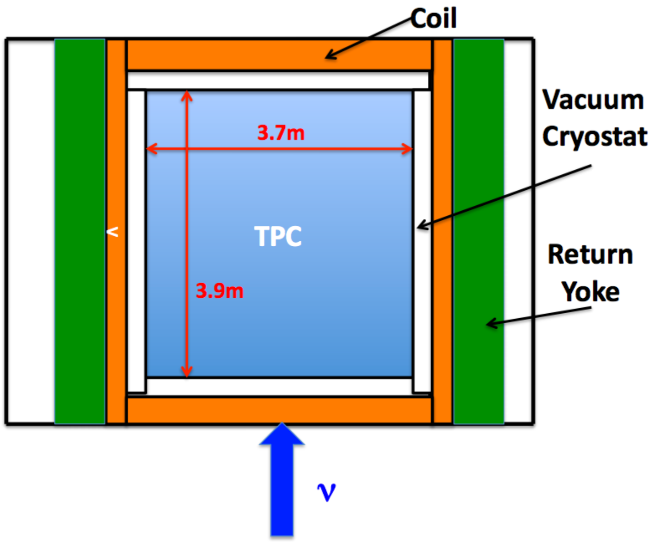
Magnetized LAr1-ND

- Two possible detector designs
  - Configuration A: The return yoke downstream of the neutrino beam and be instrumented with scintillator modules to form a muon spectrometer increasing the detector acceptance and allowing for particle ID for escaping charged pions
  - Configuration B: Compared to (A) there is an extended detector volume but contains no downstream spectrometer

Configuration A

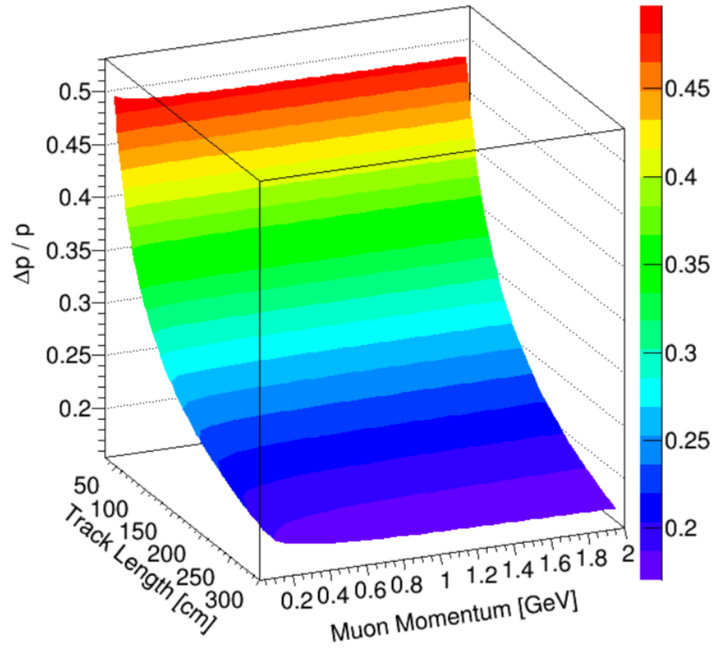


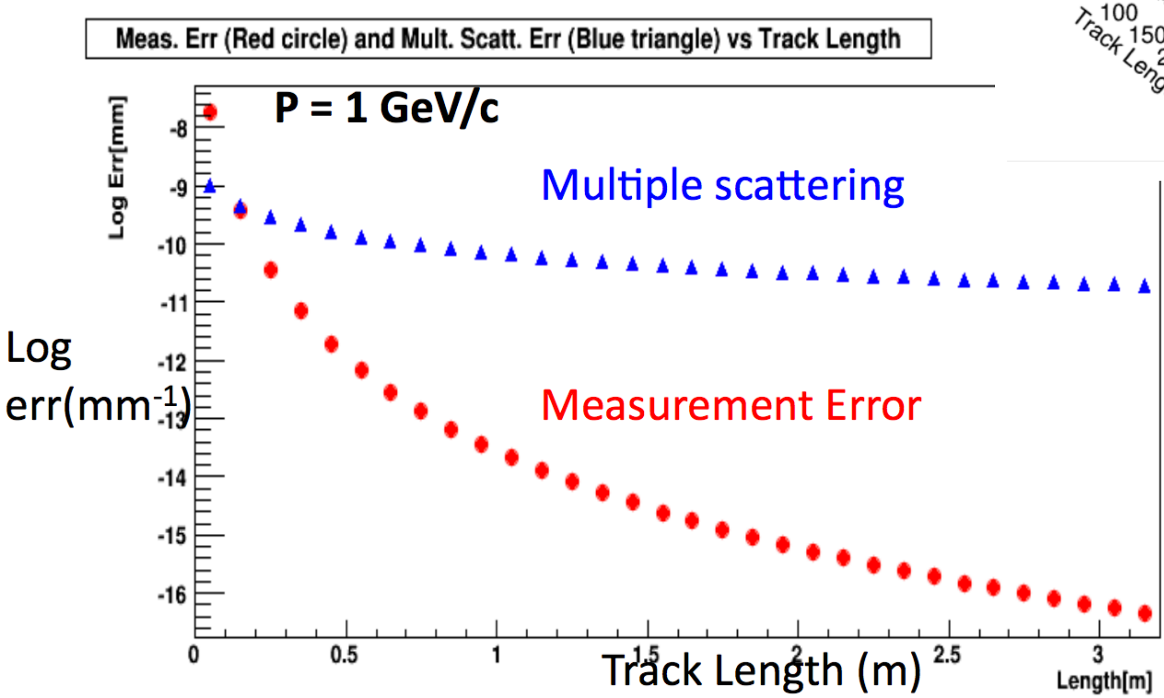
Configuration B



Resolution of Magnetized LAr1-ND

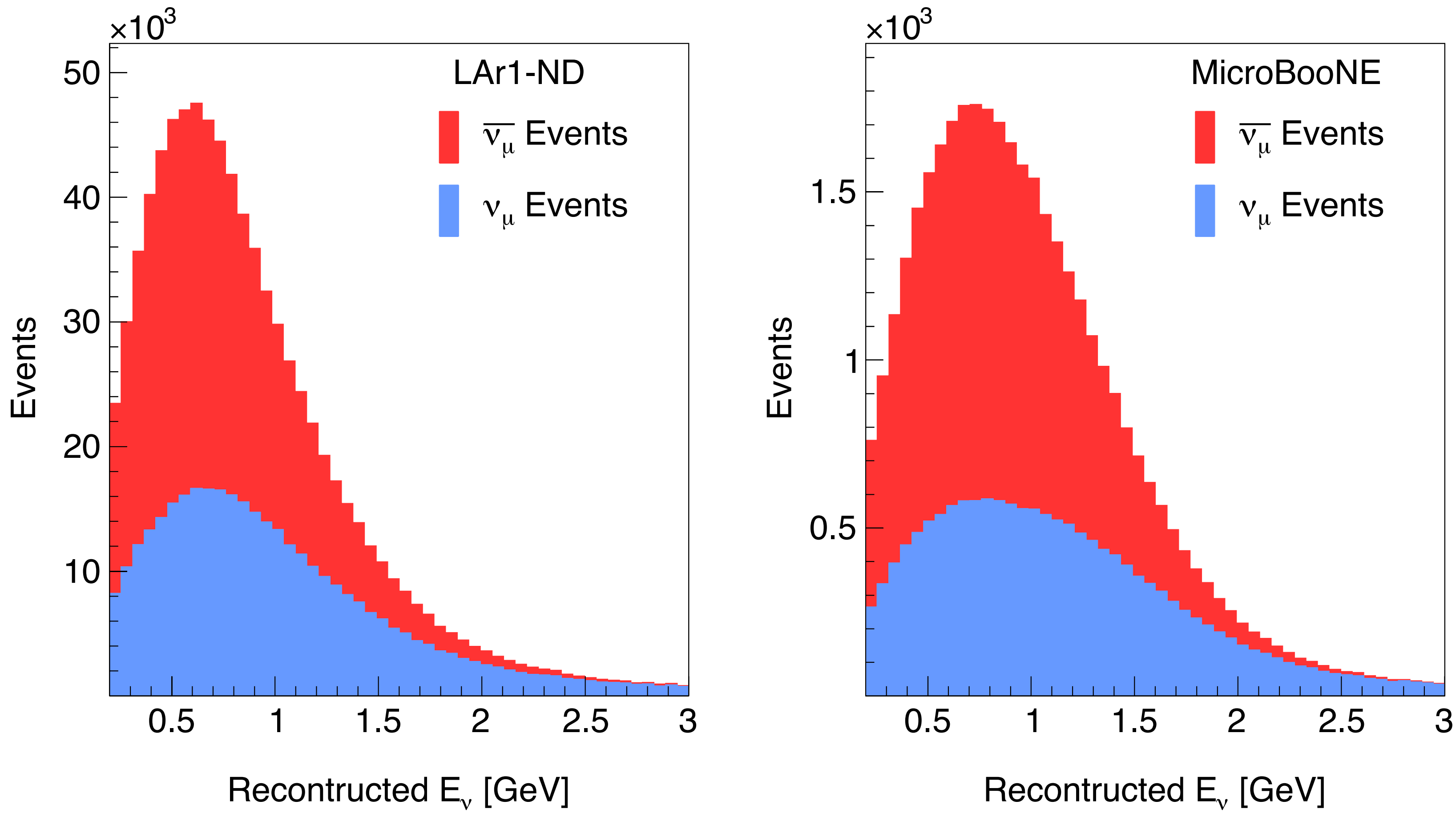
- Use curvature of the track to determine momentum
- Bending in a magnetic field is also a powerful instrument for rejecting wrong-sign backgrounds in antineutrino running





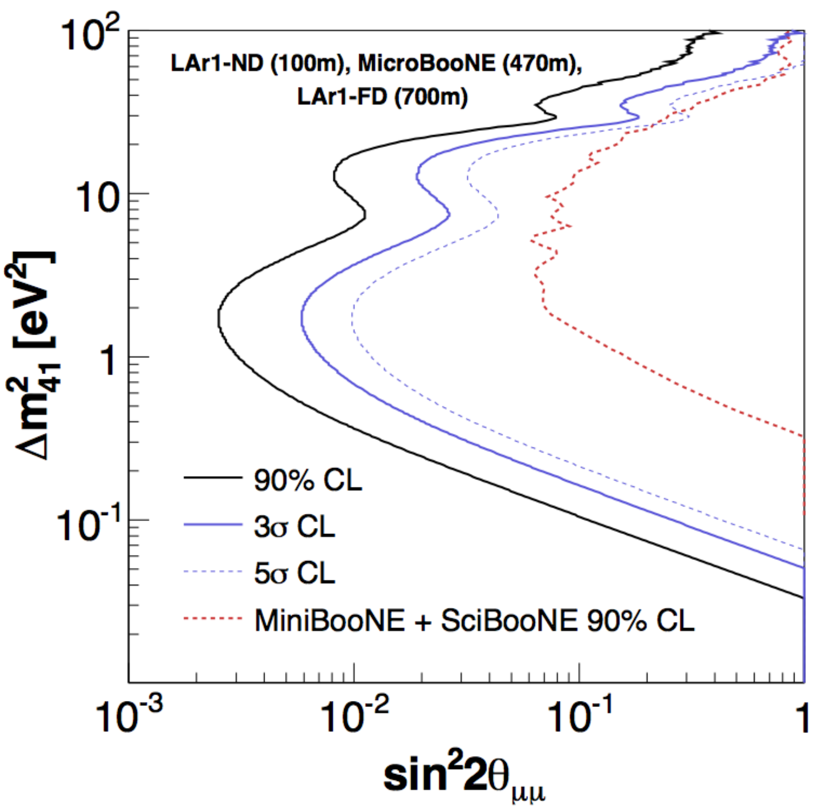
Wrong Sign Contamination

- Charge selection (in antineutrino mode) is one of the main motivating factors for a magnetized detector
  - Neutrino background in the antineutrino beam

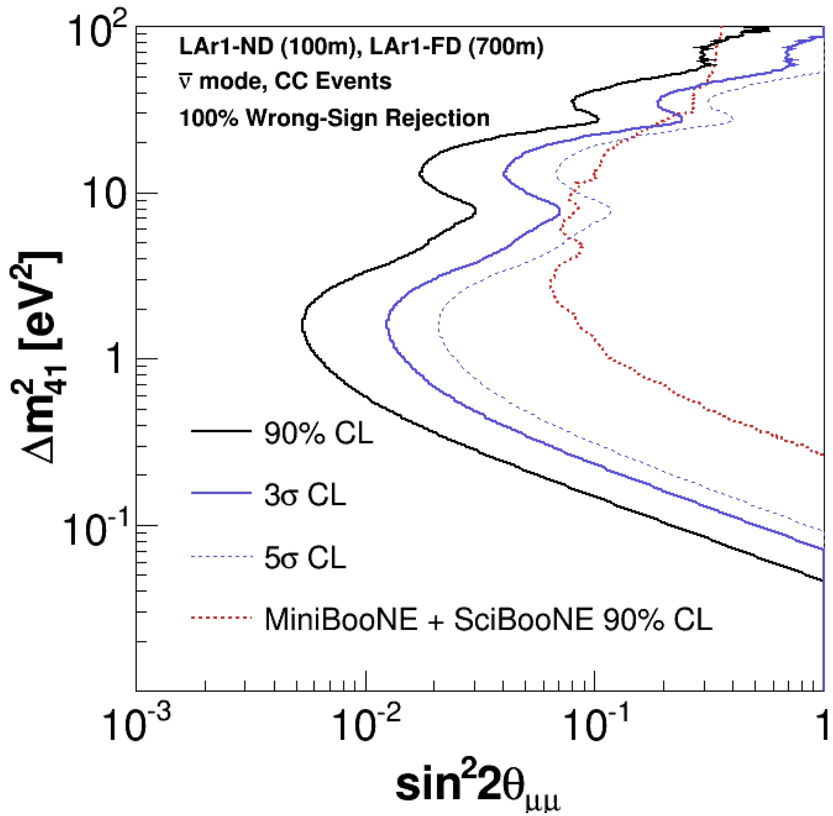


ν_μ Disappearance (3-det)

❖ LAr1-ND + MicroBooNE + 1 kiloton Far Detector at 700m

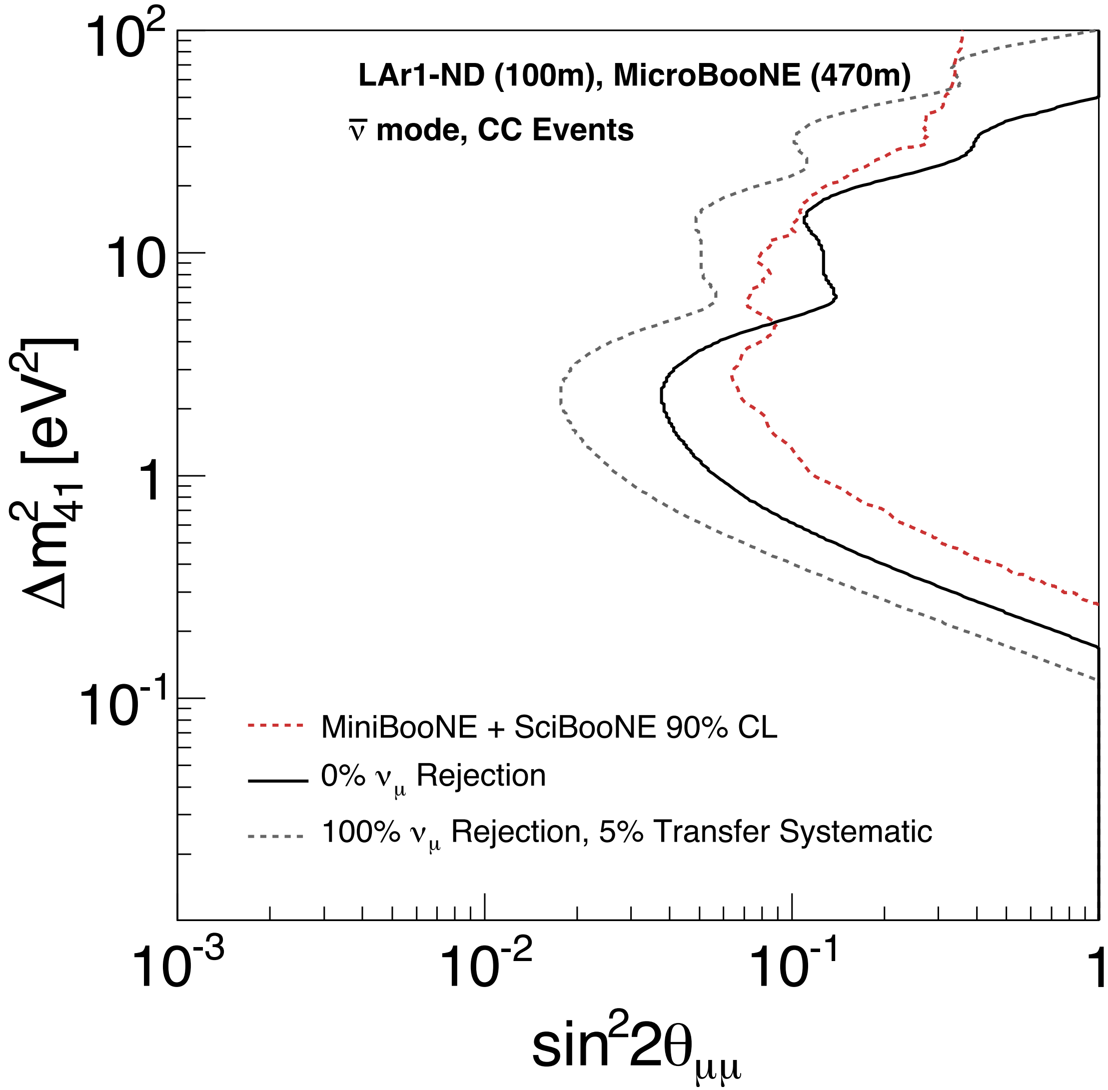


6.6x10^{20} POT exposure
neutrino mode



10x10^{20} POT exposure
anti-neutrino mode
(magnetized detectors)

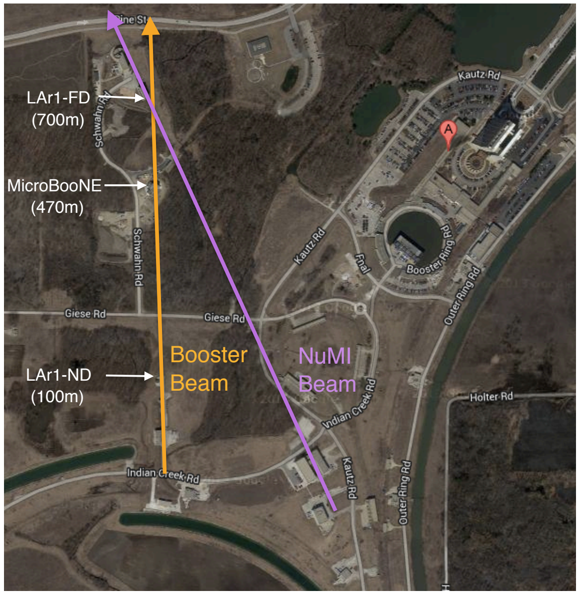
Sensitivity: Antineutrino Disappearance with Magnetized LAr1-ND + MicroBooNE



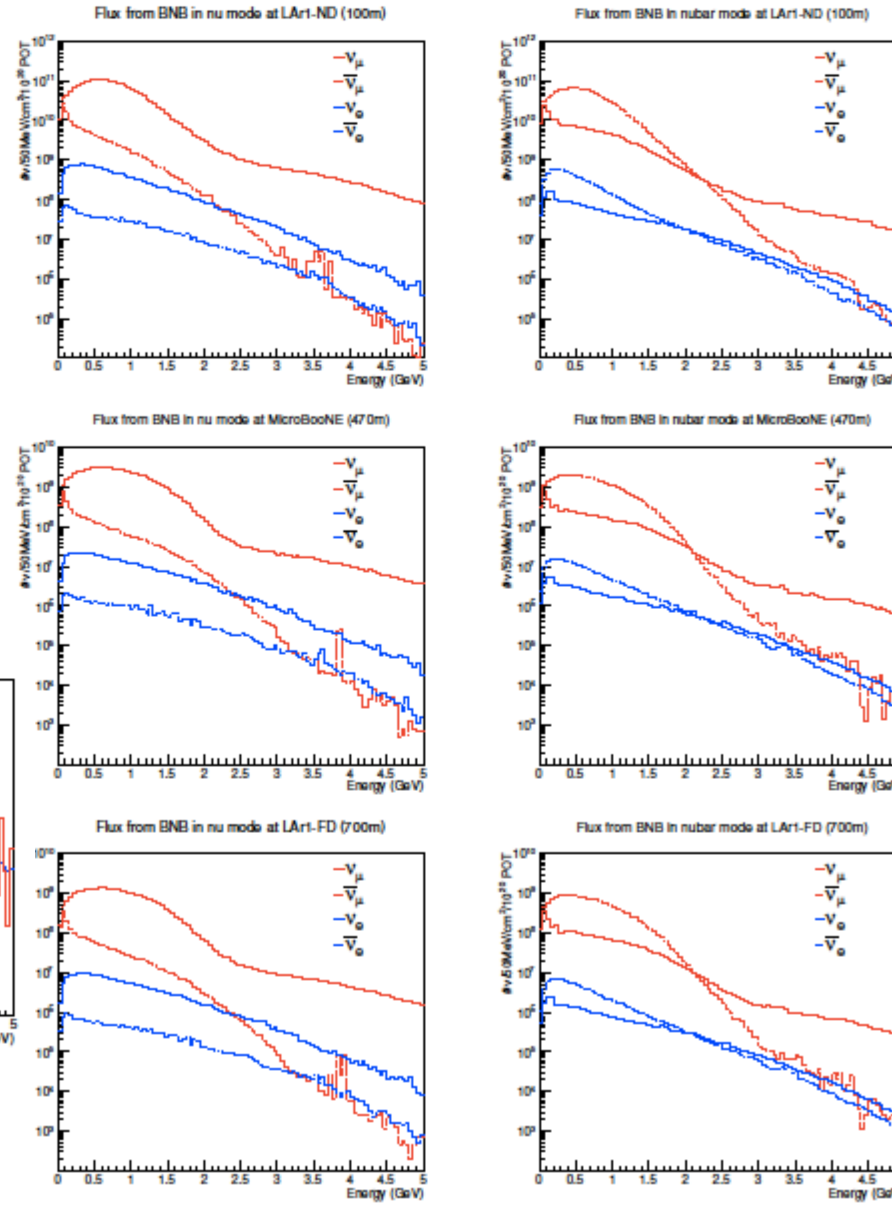
non-magnetized LAr1-ND

magnetized ND constrains neutrino content in uBooNE to 5%

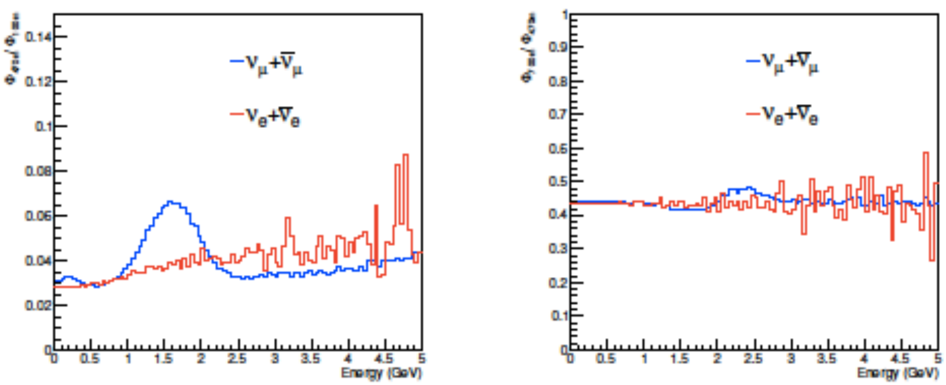
Neutrino beams (I)



The Booster Neutrino Beam @ different detector locations



Ratios of the fluxes at different detector locations.

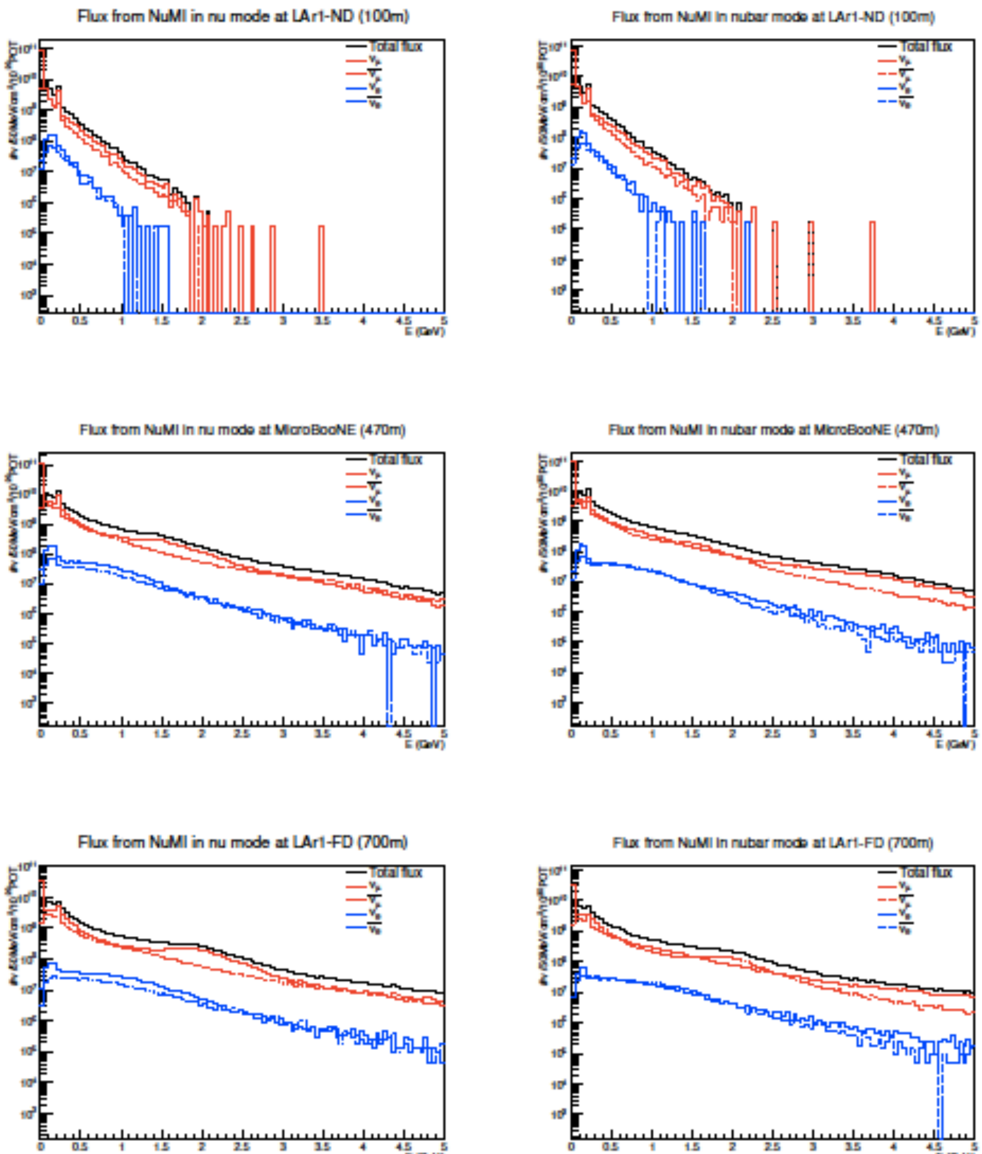


Flux at MicroBooNE vs. flux at LAr1-ND

Flux at MicroBooNE vs. flux at LAr1-FD

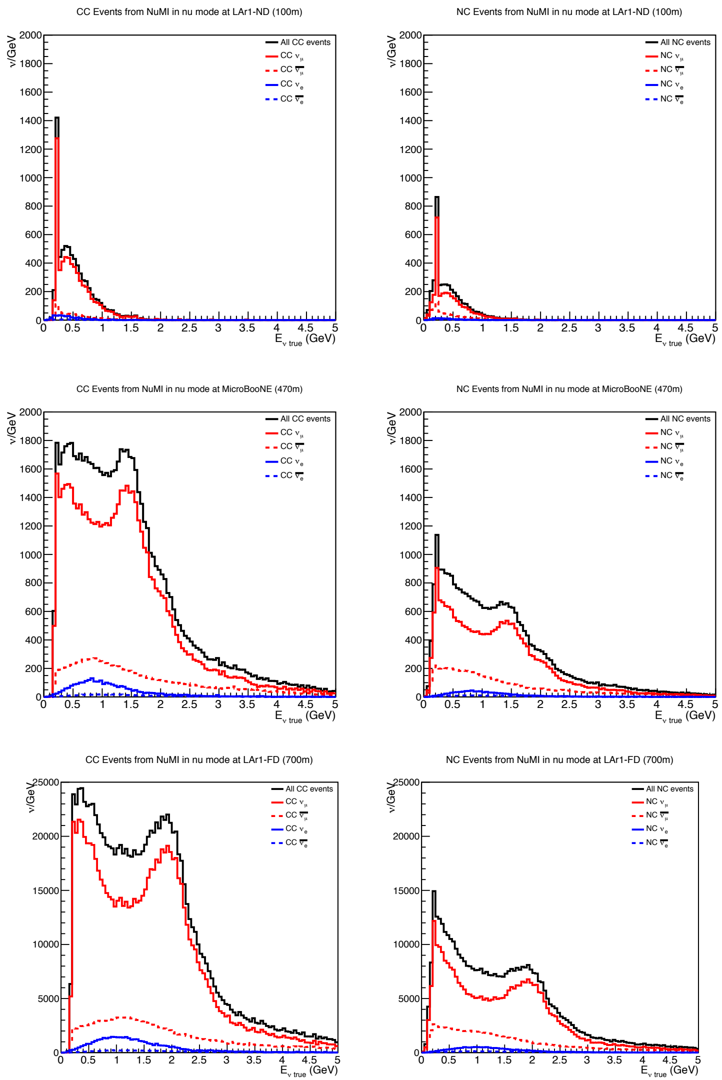
Neutrino beams (II)

Off-axis NuMI fluxes @ different detector locations



NuMI beam events (I)

Neutrino events from NuMI beam in neutrino mode 9×10^{20}POT*



LAr1-ND

Neutrino flavor	All events	CC events	NC events
ν_μ	9,148	6,143	3,005
$\bar{\nu}_\mu$	1,498	720	778
ν_e	430	311	119
$\bar{\nu}_e$	74	41	33
Total	11,150	7,215	3,935

MicroBooNE

Neutrino flavor	All events	CC events	NC events
ν_μ	78,955	56,751	22,204
$\bar{\nu}_\mu$	17,769	10,946	6,823
ν_e	3,834	2,828	1,006
$\bar{\nu}_e$	888	569	319
Total	101,446	71,095	30,351

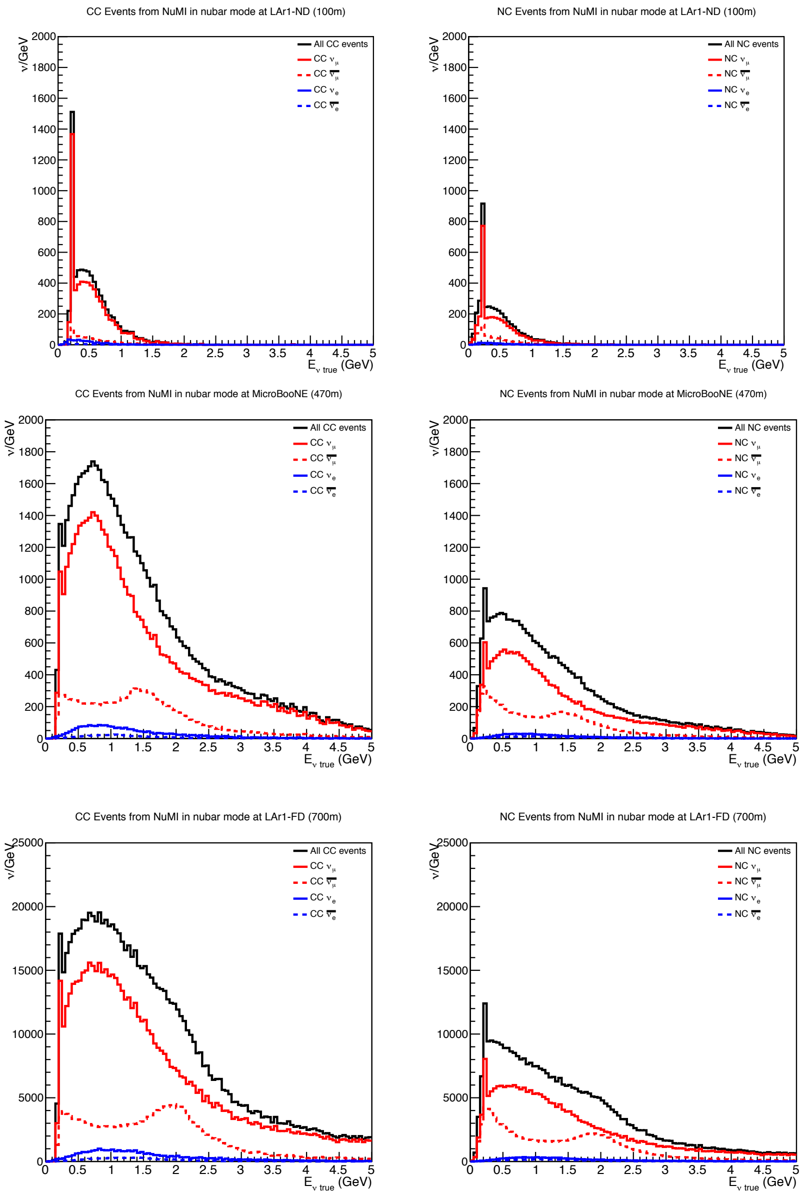
LAr1-FD

Neutrino flavor	All events	CC events	NC events
ν_μ	1,206,770	872,937	333,833
$\bar{\nu}_\mu$	261,104	164,183	96,921
ν_e	58,692	43,405	15,287
$\bar{\nu}_e$	13,325	8,690	4,635
Total	1,539,891	1,089,215	450,677

* it is expected that during the NOvA era the NuMI beam could generate up to 6×10^{20} POT/year

NuMI beam events (II)

Neutrino events from NuMI beam in antineutrino mode 9x10^{20}POT



LAr1-ND

Neutrino flavor	All events	CC events	NC events
ν_μ	9,506	6,388	3,118
$\bar{\nu_\mu}$	1,531	735	796
ν_e	439	319	120
$\bar{\nu_e}$	84	46	38
Total	11,561	7,488	4,073

MicroBooNE

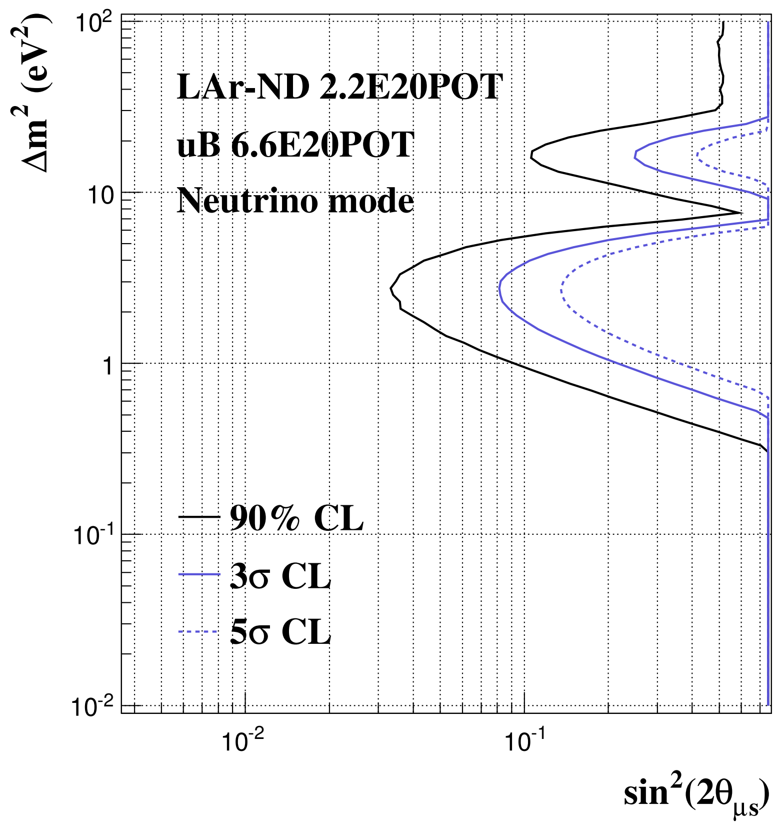
Neutrino flavor	All events	CC events	NC events
ν_μ	67,861	49,060	18,801
$\bar{\nu_\mu}$	19,317	11,783	7,534
ν_e	3,320	2,452	868
$\bar{\nu_e}$	950	600	350
Total	91,449	63,895	27,554

LAr1-FD

Neutrino flavor	All events	CC events	NC events
ν_μ	941,910	684,049	257,861
$\bar{\nu_\mu}$	303,661	189,003	114,659
ν_e	44,662	32,994	11,668
$\bar{\nu_e}$	15,114	9,749	5,364
Total	1,305,347	915,794	389,552

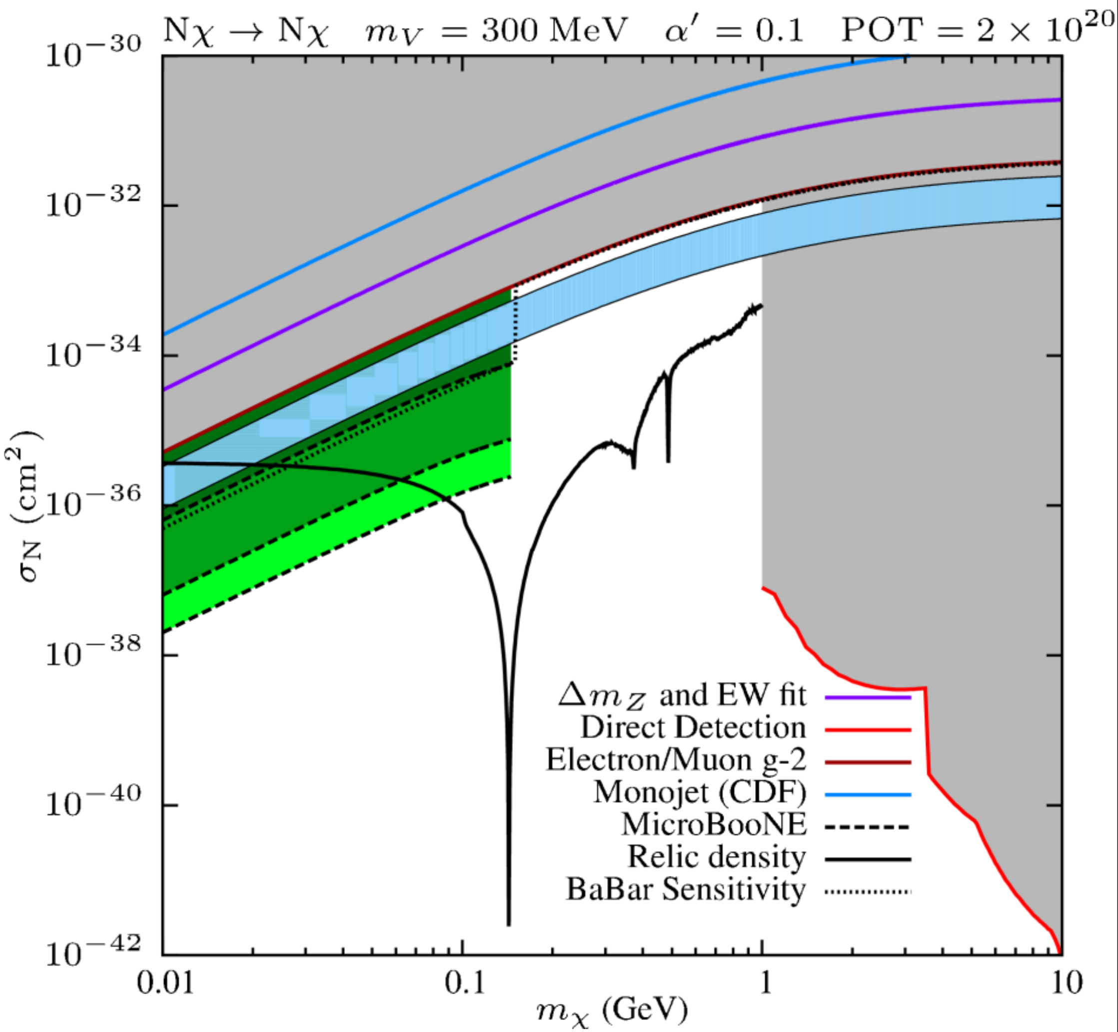
Probing Active to Sterile Oscillations with Neutral-Currents

- A unique probe of sterile neutrino oscillations, directly sensitive to any “sterile" flavor content, is available through neutral-current (NC) neutrino interactions. In this type of search, one looks for an overall depletion of the flavor-summed event rate.
- We have considered the NC π^0 channel, due to its characteristic event topology and kinematics. Unlike other NC channels, the presence of the two photons from the π^0 decay pointing back to a common vertex, with an invariant mass corresponding to $m_{\pi 0}$, provides a powerful discriminant against potential backgrounds.



Dark Matter Searches with Booster Beam Off-Target Running

- Sensitive to anomalous signals in neutral current channel in a beam dump run – ideal to search for low mass dark matter
- LAr ND has many advantages over other BNB experiments– excellent event reconstruction, better background rejection, lower systematics, close proximity to source
- Expected number of excess events (estimated background ~1600 events):
  - 1-10 light green
  - 10-1000 green
  - >1000 dark green



Cryogenic system

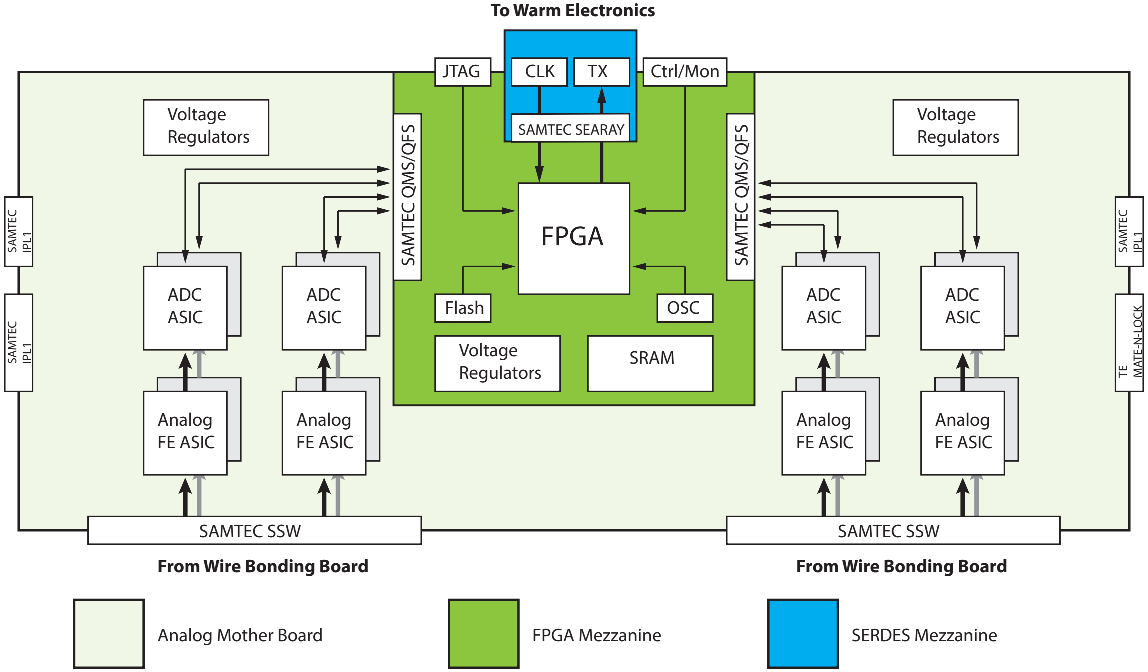
- The cryogenic system design is based on experience with the designs and operation of the systems for LAPD, MicroBooNE and 35 ton.

- The choice of the cryogenic systems layout and location is intended to optimize safety and efficiency. It will:
  - Minimize the risk of personnel injury to any Oxygen Deficiency Hazard (ODH)
  - Minimize heat ingress to the cryogenic system (by minimizing piping length and pump power)
  - Minimize the volume of the argon system external to the cryostat and hence minimize the potential for argon escape or contamination
  - Provide safe access to refrigeration equipment that requires periodic maintenance

- The LN2 cooling system, argon re-condensers, and gas/liquid purifiers will be located in a surface building immediately adjacent to the cryostat pit. The surface facility will include a LAr and LN2 receiving dewars. The cryostat will hold an inventory of 155 tons of liquid argon. The liquid argon purification system will be required only to achieve the initial liquid argon purity. After that the circulation of the argon gas in the expansion tank will maintain the high purity. The purification plant will consist of duty and standby molecular-sieve columns to remove water and an activated copper column to remove oxygen.

The Readout electronics

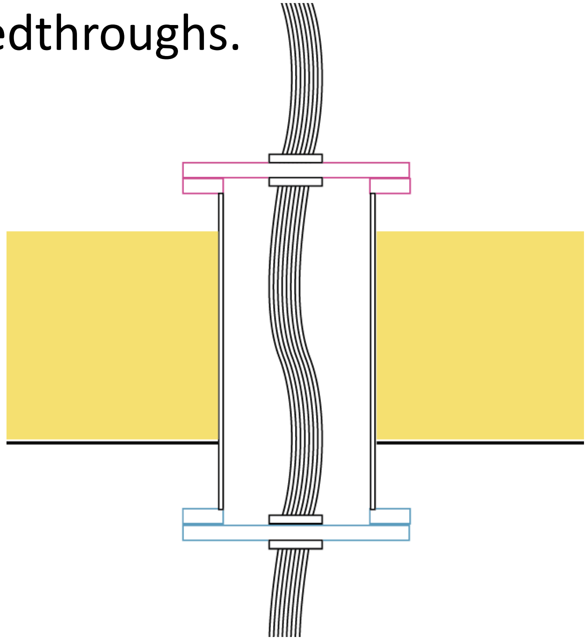
- The electronic readout chain is implemented as CMOS ASICs designed for operation in LAr, and commercial FPGAs tested for cryogenic operation. Both analog Front End (FE) ASIC and ADC ASIC have already been developed for LBNE, and analog FE ASIC is being used in MicroBooNE.
- The Front End electronics chain is composed of:
  - a 16-channel analog FE ASIC providing amplification and shaping,
  - a 16-channel ADC ASIC implemented as a mixed-signal design providing digitization, buffering and the first stage of multiplexing,
  - a FPGA providing the second multiplexing stage, and voltage regulators.
- 8 FE, 8 ADC plus a FPGA comprise a single <u>128-channel front end mother board</u>.



Front End Mother Board

Cold signal feedthroughs

- "Double feedthrough" are used:
  - a cold flange, with all connections to the cold cable inside of the cryostat, is welded to one end of a stainless pipe, and
  - a warm flange, with connections to the warm cables to the DAQ, is welded on the other end of the stainless st. pipe.
  - A set of cables interconnects the two flanges. The space between the two flanges is evacuated. This technique ensures all cables inside the cryostat are at the LAr temperature to minimize outgassing, and the other side of the feedthrough can be exposed to air without worrying about condensation (can be heated if necessary).
- The ATLAS LAr calorimeters used such feedthroughs, with the same pin carriers as the ones on MicroBooNE signal feedthroughs.

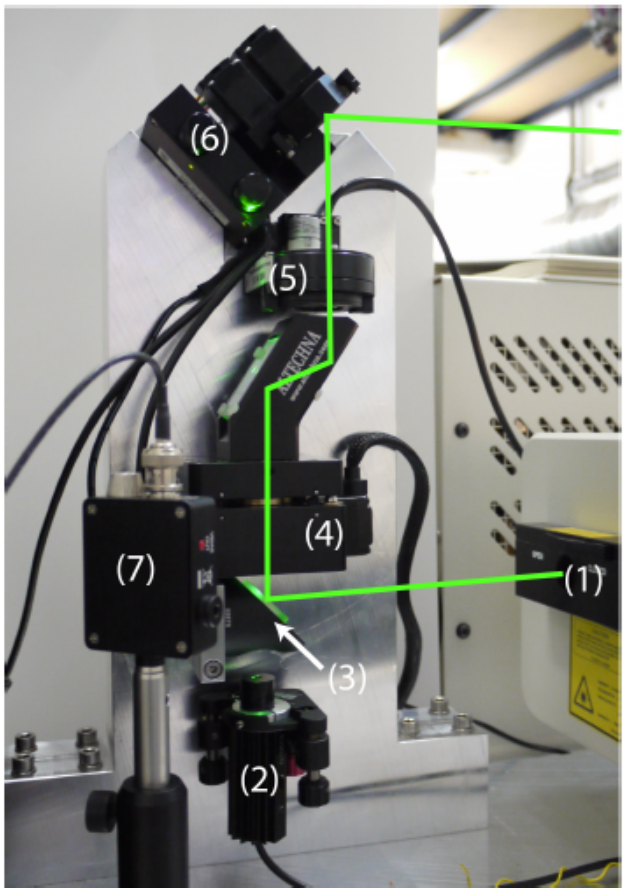


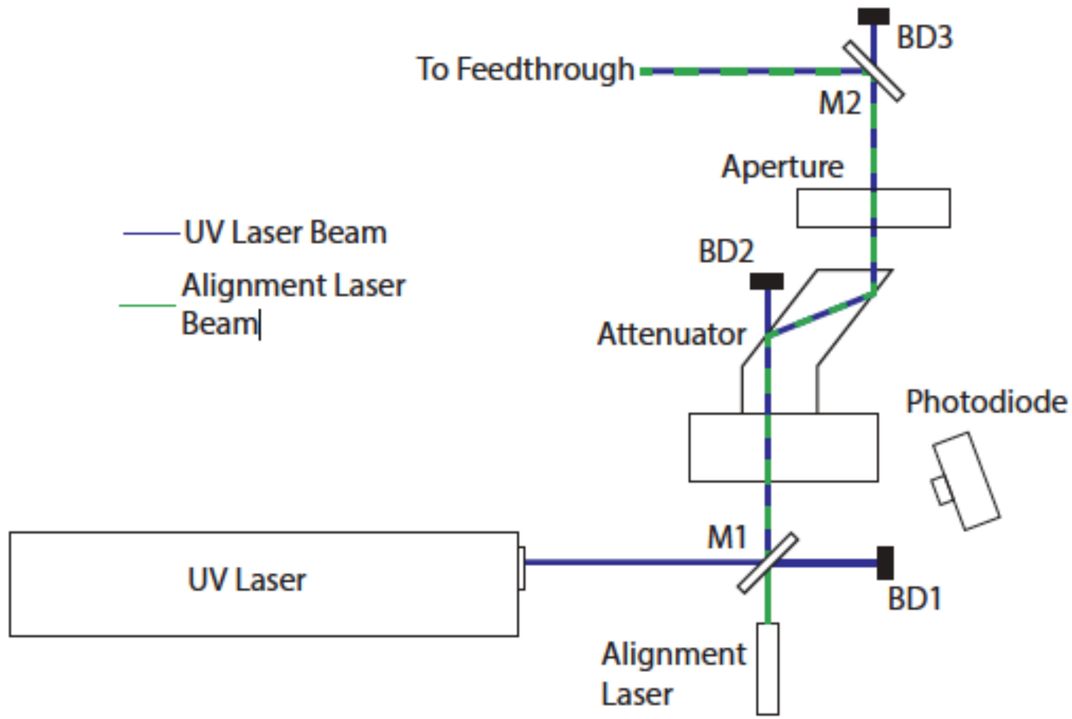
Calibration Laser System

The UV laser calibration system

- Measure electric field distortion by introducing straight ionizing tracks
- Additional tool to measure:
  - Purity
  - Diffusion
  - Recombination

Design of the system allows automatic operation, remote control access to optimize laser beam path and power





(1) UV laser, (2) Alignment laser, (3) Fixed Mirror, (4) Attenuator, (5) Iris, (6) Moveable Mirror, (7) Photo Diode

Cost and Schedule

- Estimates construction costs for LAr1-ND are based on recent experience at Fermilab building related LAr projects including MicroBooNE, the LBNE 35 ton membrane cryostat, and the Liquid Argon Purity Demonstrator (LAPD).
- The total project cost for the detector, modifications to the conventional facilities, and project management is estimated at $13M.

Item	Estimated Cost
1. Enclosure	$0.3M
2. Cryostat	$2.5M
3. Cryogenic System	$3.0M
4. Time Projection Chamber (TPC)	$2.0M
5. Front-end TPC Electronics	$1.5M
6. Light Detection System	$0.5M
7. Readout, Trigger and DAQ	$0.5M
8. Integration and Installation	$1.0M
Total Construction Costs	$11.3M
Project Management at 15%	$1.7M
Project Total	$13M

1. Enclosure: Tasks and costs include what is needed to prepare the enclosure to accommodate a cryogenic detector, including some structural work for an interior wall, mechanical support structures above the detector and an upgrade to the electrical service to the building to support operation of the cryogenics.
2. Cryostat: Costs are based on scaling from the LBNE 35 ton prototype recently built at Fermilab.
3. Cryogenic System: The cryogenic system design is based on experience with the designs and operation of the systems for LAPD, MicroBooNE and 35 ton. Lessons learned and improvements for cost and performance have been incorporated into the estimate.
4. TPC: The design and fabrication of the parts of the TPC, including installation fixtures and all hardware are based on the experience from construction of the MicroBooNE TPC. The estimate includes on-site assembly and installation labor costs.
5. Front-end Electronics: The front-end electronics includes charge collection, amplification and digitization of signals from the TPC. The M&S and design costs are based on experience from the MicroBooNE system.
6. Light Detection System: LAr1-ND will develop an innovative approach to light detection using new ideas that have been initiated in the context of R&D for the LBNE far detector.
7. Readout, Trigger and DAQ: The Readout and Trigger requirements for LAr1-ND are under development. The DAQ system will be based on the system that has been developed for MicroBooNE. Costs are estimated from the M&S and labor costs for the development of the similar systems in MicroBooNE.
8. Integration and Installation: Cost and schedule for assembly and installation are estimated based on experience to date in MicroBooNE.

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

A construction start on the 2015 time scale maximizes the physics potential in Phase-I within the existing Fermilab program by making it possible to run the LAr1-ND detector concurrently with MicroBooNE toward the end of the already planned neutrino-mode running.