Additional Interim Accelerator-Based Neutrino Projects

P5 Face-to-Face Meeting

3 November 2013, Fermilab

David Schmitz, University of Chicago

Intent of this Talk

- The charge for this presentation is suggested by the title:
  - Additional – Not covered in other presentations at this meeting
  - Interim – Not currently running experiments, but proposals and LOIs; to be executed between now and LBNE running in mid-2020's
  - Accelerator-Based Neutrino Projects
- Due to the number of projects to be mentioned, not time for detailed coverage
  - All slides provided by collaborations are included as overflow slides
- Will focus on comparison of major elements and how projects fit into the U.S. accelerator-based neutrino physics program leading to LBNE in the next decade

Project	Estimated Cost*	Detector Technology	Location	Physics / R&D Program
RADAR	$170M	LAr (4.6kt)	Ash River, MN ■	off-axis long-baseline LAr R&D
CHiPs	$100M less with R&D	Water Cherenkov (100 kt)	Wentworth Pit, MN	off-axis long-baseline
LAr1	$80M	LAr (1kt)	Fermilab	short-baseline LAr R&D
OscSNS	$20M	Oil with scintillator (450t)	Oak Ridge	short-baseline
LAr1-ND	$10M	LAr (40t)	Fermilab ■	short-baseline LAr R&D
MiniBooNE+	$0.1M	Oil with scintillator (450t)	Fermilab ■⦿	short-baseline
LArIAT	$1.5M (phase I)	LAr (0.3t)	Fermilab ■⦿	LAr R&D TPC calibration
CAPTAIN	$2.5M	LAr (5t)	LANL, Fermilab ■	LAr R&D Neutron/Neutrino meas.

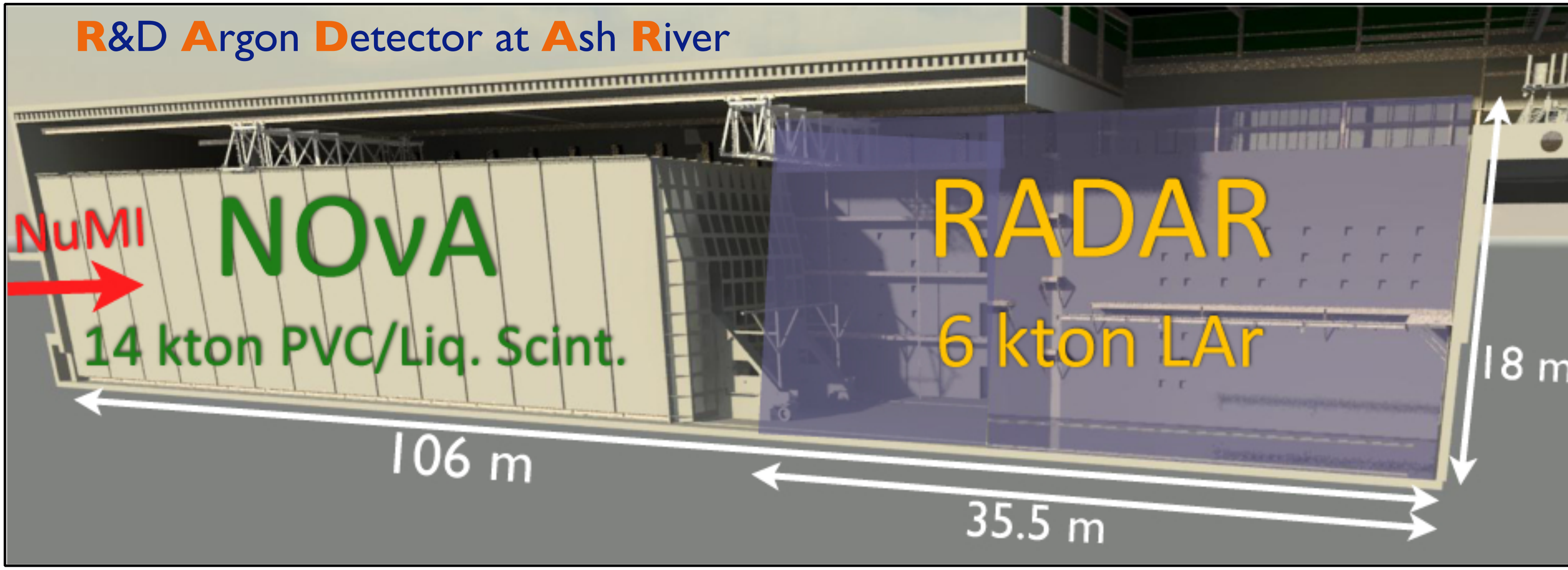
■ existing facility for detector ⦿ existing detector

*These estimates are for rough comparison and may vary in their robustness. For details please see the main proponents of each project.

Status & Documentation

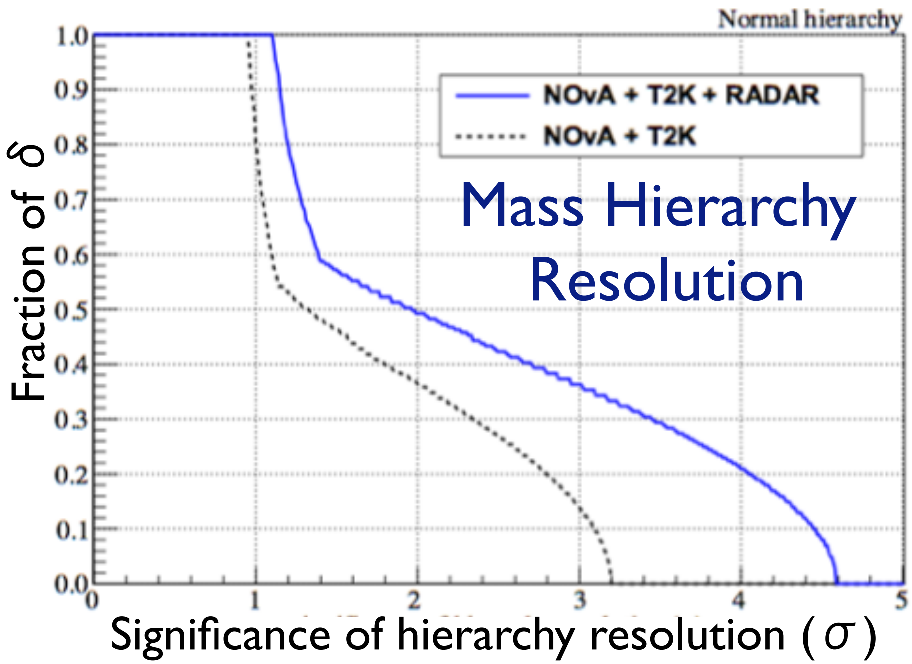
- RADAR
  - Proposal in development
  - Snowmass White Paper: http://arxiv.org/abs/1307.6507
- CHiPs
  - R&D proposal to go to winter 2014 FNAL PAC
  - Snowmass White Paper: http://arxiv.org/abs/1307.5918
- OscSNS
  - Proposal in development
  - Snowmass White Paper: http://arxiv.org/abs/1307.7097
- LAr1
  - LOI Presented to FNAL PAC in June 2012
  - LOI to FNAL: http://www.fnal.gov/directorate/program_planning/June2012Public/P-1030_LAR1_LoI_wAuthors.pdf
- LAr1-ND
  - Proposal to go to winter 2014 FNAL PAC (as phase I of full LAr1 program)
  - Snowmass White Paper: http://arxiv.org/abs/1309.7987
- MiniBooNE+
  - LOI presented to FNAL PAC in October 2012; proposal to go to winter 2014 FNAL PAC
  - Snowmass White Paper: http://arxiv.org/abs/1310.0076
- LArIAT
  - Physics run summer 2014
  - Snowmass White Paper: http://if-neutrino.fnal.gov/whitepapers/lariat.pdf
- CAPTAIN
  - Construction funded through LANL LDRD
  - Snowmass White Paper: http://arxiv.org/abs/1309.1740

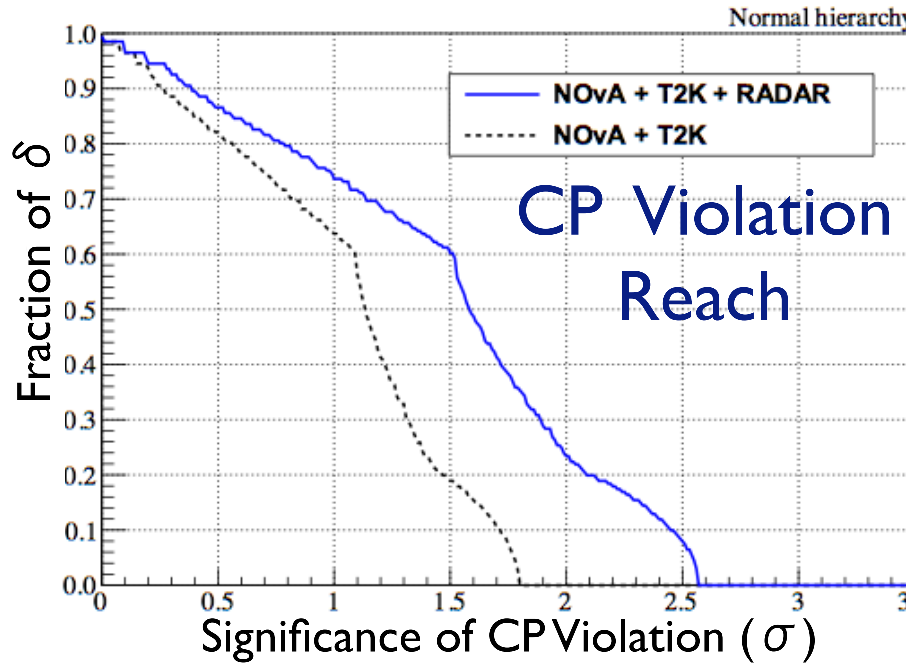
RADAR Concept

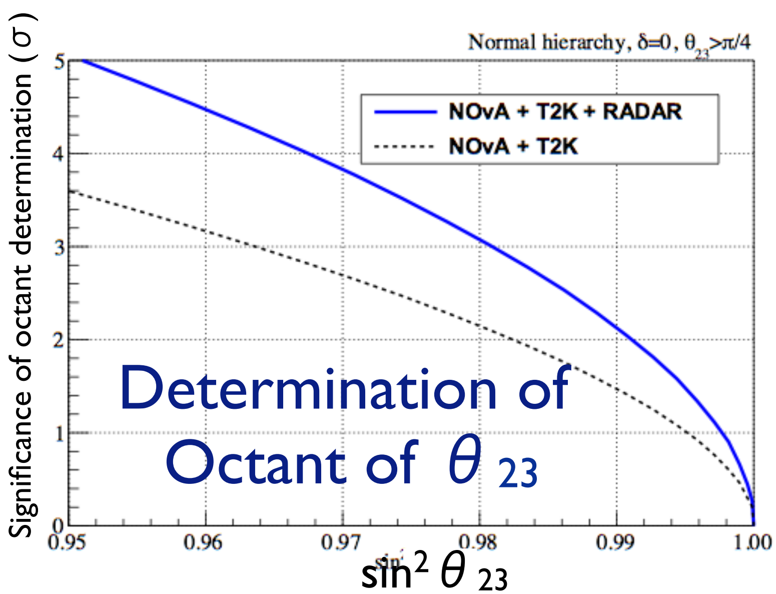


- Exploit the NuMI beam, the most powerful neutrino beam in operation, to help develop LBNE detector technology, while enhancing NuMI's long-baseline physics reach
- Place a 6 kton (4.6 kton fiducial) LAr TPC in assembly area of NOvA's building
  - Space is readily available after 2014, only require extra power
- Use LBNE-like cryostat and detector modules to perform a full-scale test of LBNE's design
  - Reuse RADAR components in LBNE where possible to offset project costs
  - Majority of R&D costs for LBNE are absorbed into RADAR project
- Estimate 60 FTE required in project phase, 40 FTE in operations, 40 FTE in data analysis
  - Expect a large fraction of the LBNE Collaboration to contribute to RADAR

RADAR Science Goals

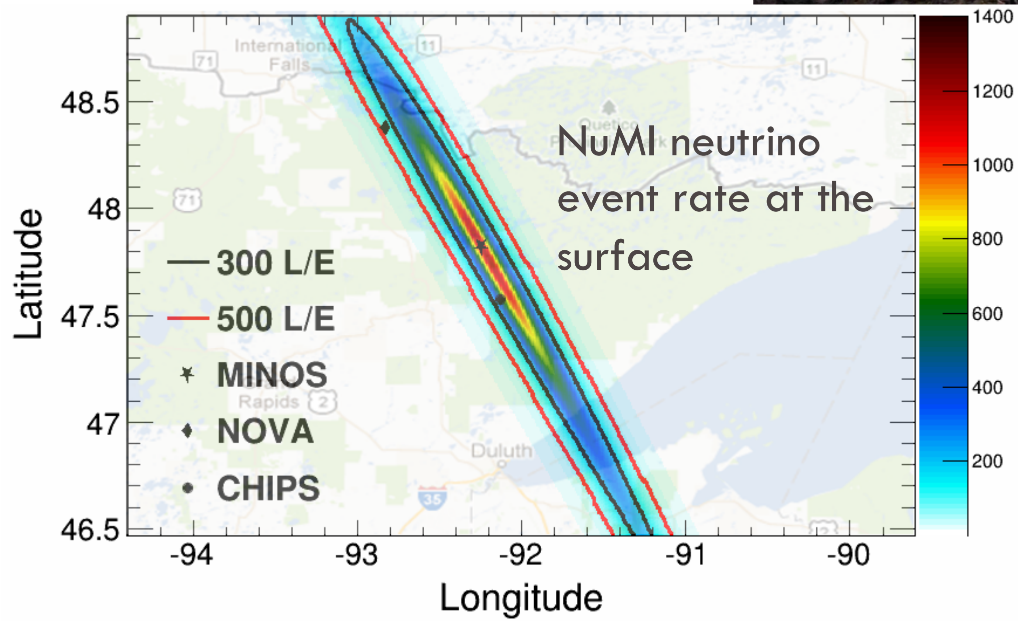


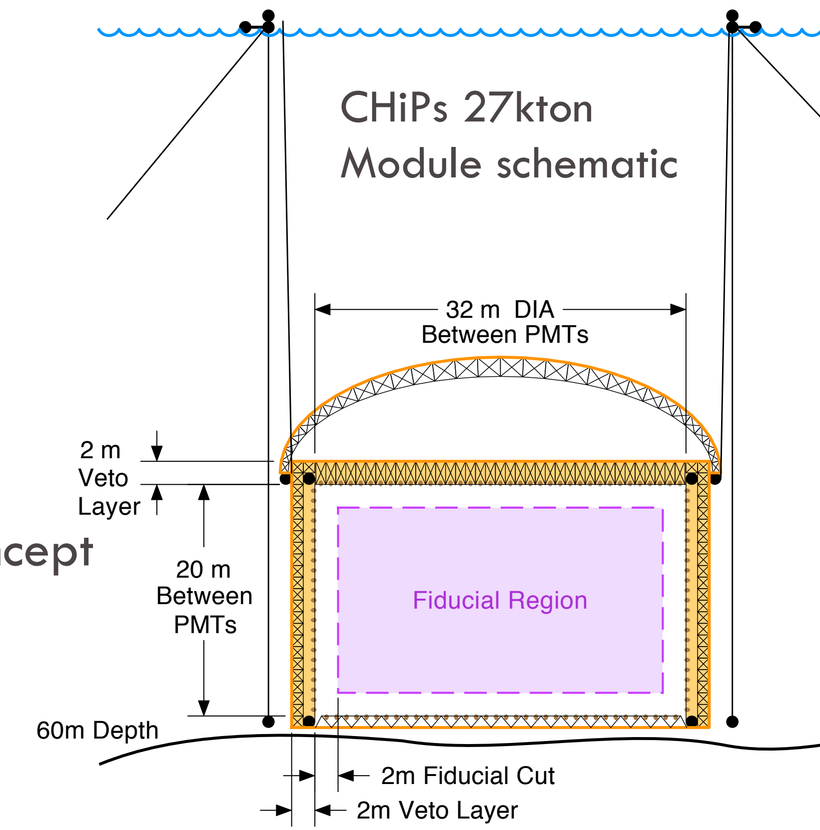




- Assume NuMI operation at 700 kW in medium-energy beam mode
- RADAR runs for 5 years starting in 2019; NOvA runs for 10 years from 2014-2023; T2K completes run during this decade
- Can determine mass hierarchy up to 4.5σ for favorable δ_{CP} values
- CP violation coverage at >2σ for 25% of δ_{CP} values
- Can determine octant of θ_{23} at > 3σ for $\sin_2(2\theta_{23})=0.98$, if $\theta_{23} > \pi/4$

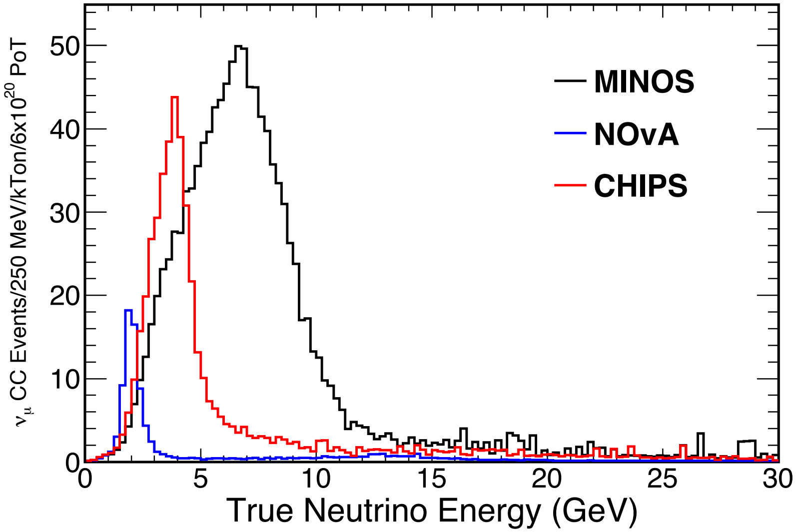
CHiPs Concept

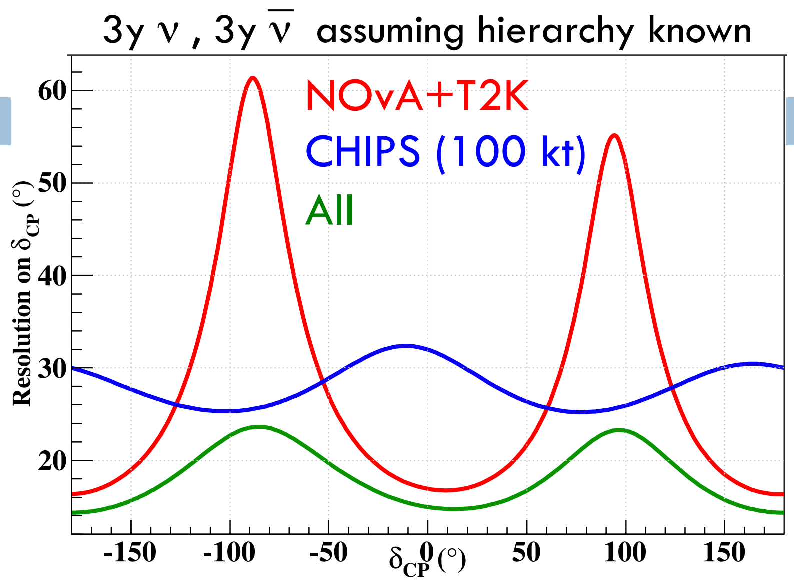


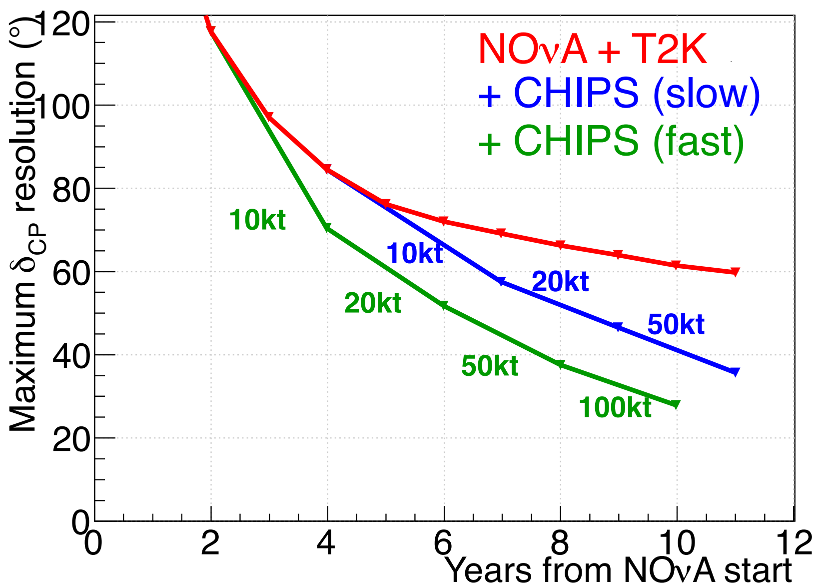


- Affordable, megaton scale Cherenkov detector
- Submerged underwater, following LBNE WC concept
  - No expensive mechanical structure
  - No expensive underground cavern
  - Wentworth Pit—7mrad off-axis in NuMI beam

CHiPs Physics Goals





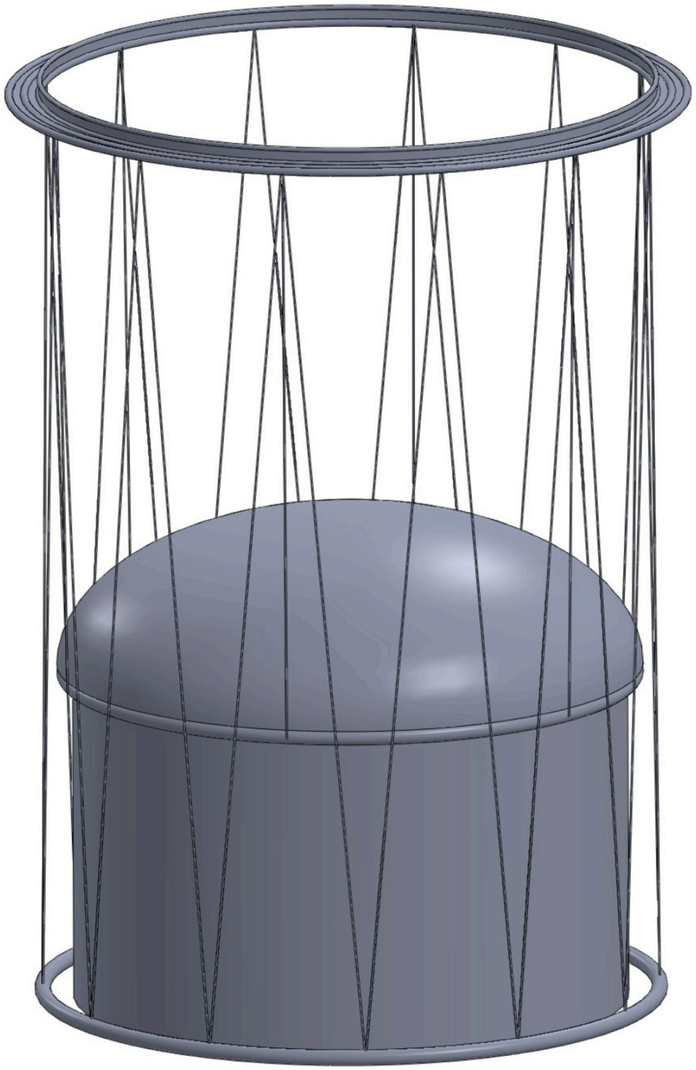


- 100 kt CHiPs detector in NuMI complements the delta CP reach of NOvA + T2K
- Even phased approach contributes to improved resolution on delta CP
- Can be redeployed in off-axis LBNE beam after run in NuMI

CHiPs R&D project

- R&D proposal to FNAL PAC
  - Demonstrate concept
  - Prototype mechanical structure and construction plan
  - Develop full engineering design for full size CHiPs module
  - Reduce cost to ~$300-500K/kton

    (a factor of 3)
- Mine pit currently instrumented with equipment to measure underwater currents

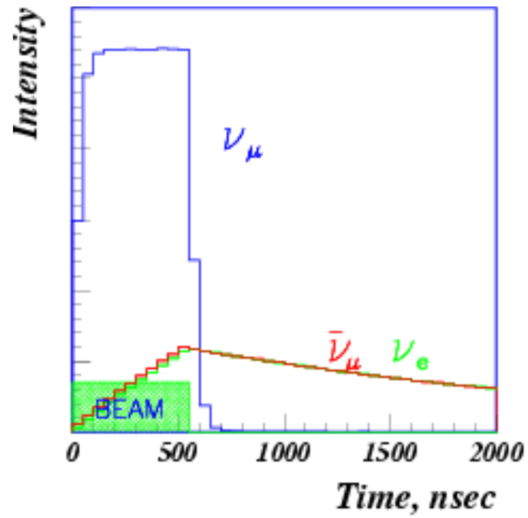


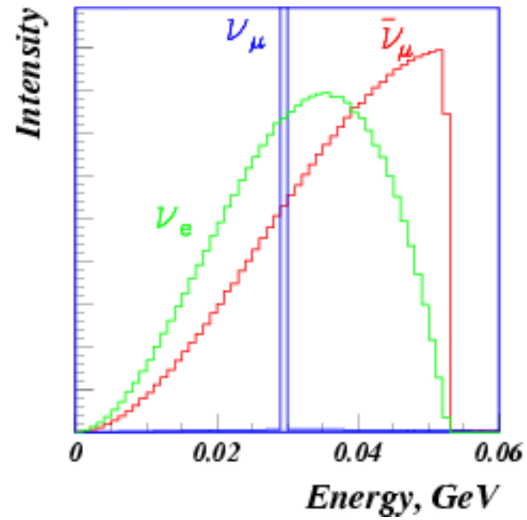
10 kt module in 4-5 years

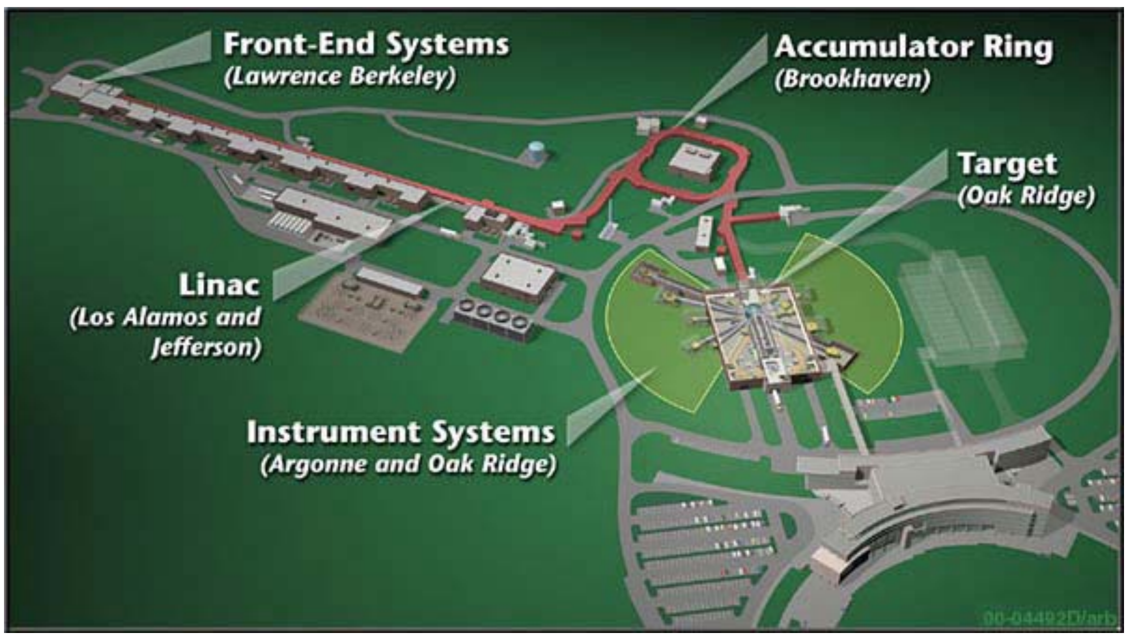
International Collaboration ready to deploy instruments this summer using seed money from Universities, small R&D proposals

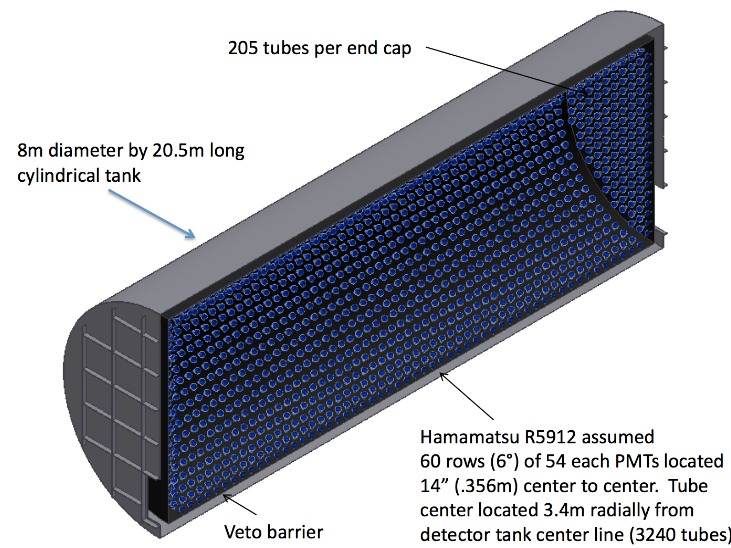
OscSNS

- LSND approach to short baseline oscillation search with larger detector (x5), more flux (x2), and lower duty factor (x1000)
- Spallation neutron source at ORNL
  - ~1GeV protons on Hg target (1.4MW)
  - Free source of neutrinos
  - Well understood flux of neutrinos
- 3y construction beginning in 2015



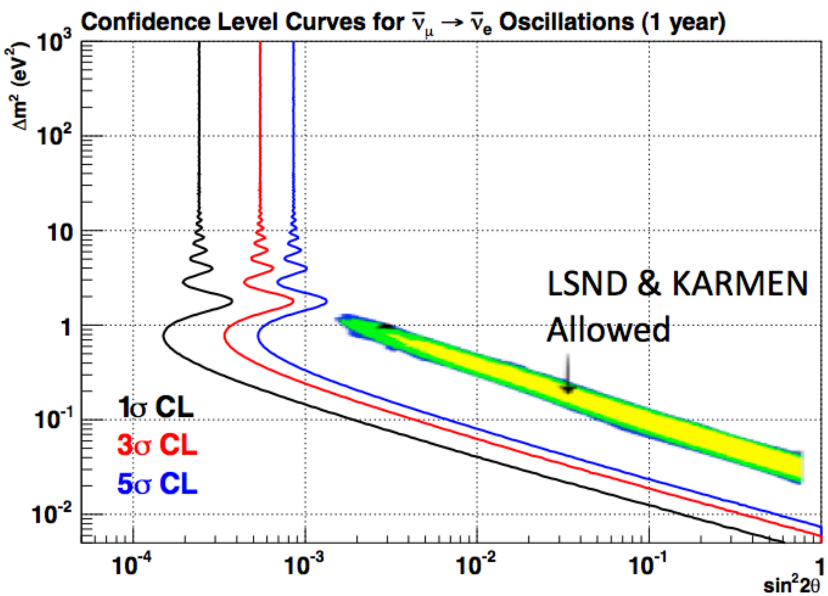


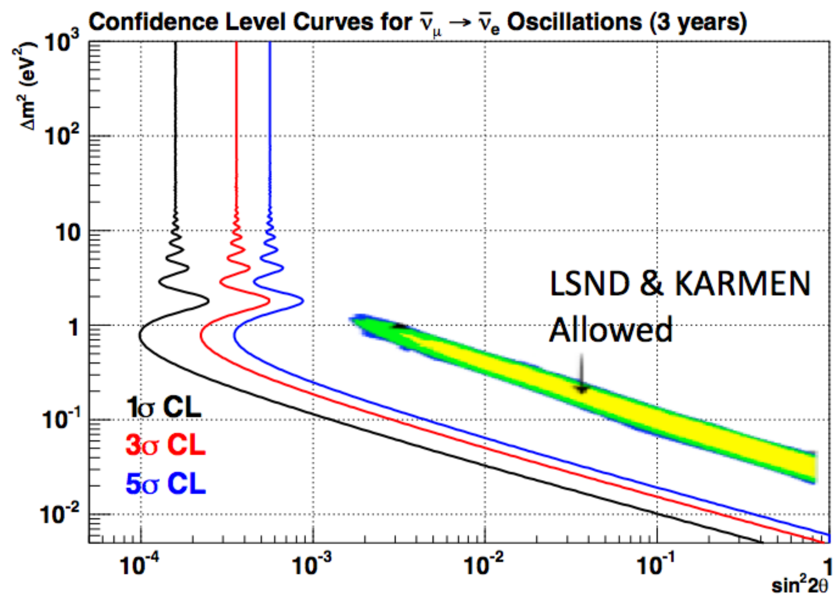




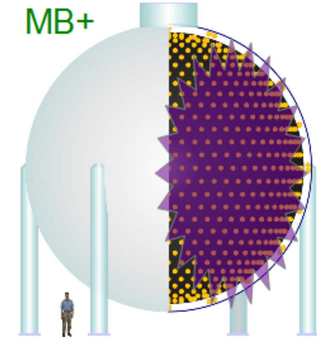
OscSNS Physics Goals

- Prove or disprove existence of sterile neutrinos by observing oscillations in the detector with a NC reaction
- Short baseline $\bar{\nu}_e$ appearance
- Short baseline ν_e and ν_μ disappearance
- Neutrino cross section measurements





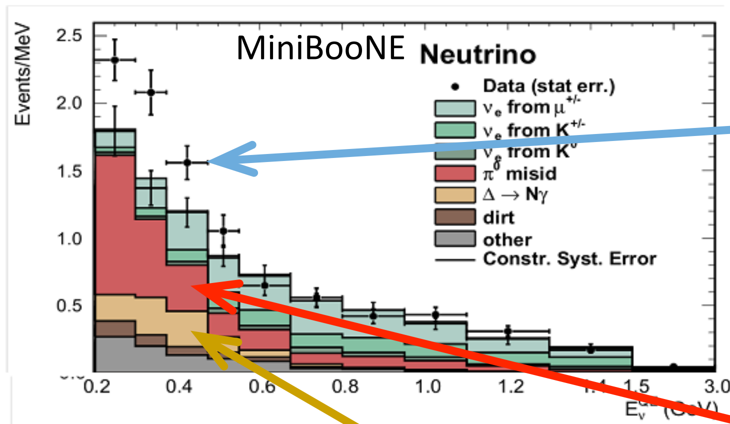
Future running with MiniBooNE: MiniBooNE+

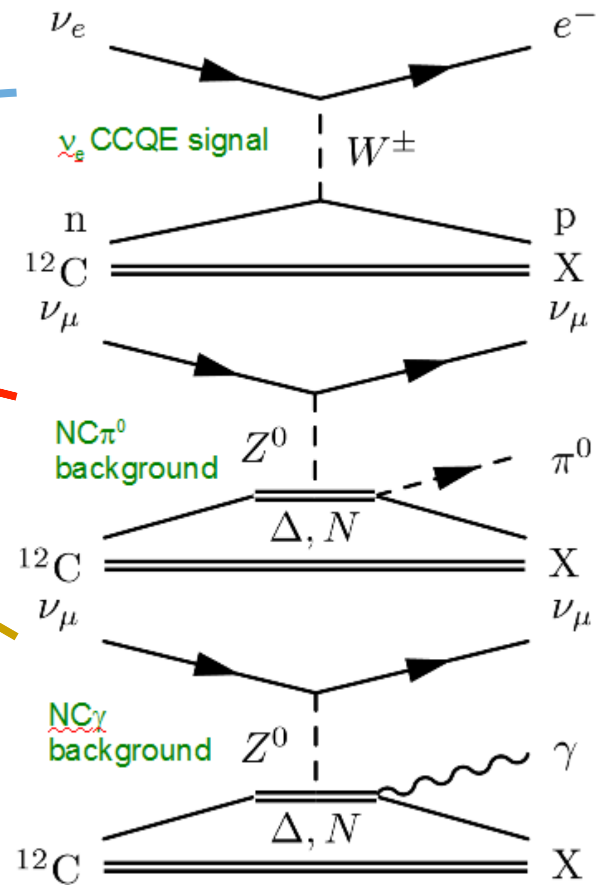


Sterile ν oscillation search via addition of scintillator to MB

Enables discrimination of NC background from CC signal via (2.2 MeV) n-capture signature and nucleon recoil.

- Add 300kg PPO ($75k)
- Calibrate (and test) with ν_μ CCQE, and NCπ^0 channels in ~1 year run
- Can push MB sensitivity to 5σ in ~3 yr run





Other features:

- Measure Δs via NC elastic p to n ratio
- Test E_ν^{QE} energy reconstruction via nucleon recoil measurements
- Search for dark matter from beam dump
- Complementary to MicroBooNE with higher statistics, well-understood large detector in same beam.
- Resource needs minimal: scintillator and repairs (~$100k), lean collaboration

Status:

- PPO funding secured
- Working on proposal for FNAL
- Hope to run 2014 , concurrently with MicroBooNE

R. Tayloe
Indiana U.

A Staged Multi-LArTPC SBL Program at FNAL

LAr1 was originally conceived as a 1 kton fiducial volume far detector for MicroBooNE to address the MiniBooNE antineutrino anomaly.
Recently reconsidering LAr1 as a phased short-baseline program.

Phase 1:

LAr1-ND as Near Detector to MicroBooNE*
Run ~2016-2017
Estimated ~100 collaborators

*MicroBooNE begins running in 2014

Phase 2:

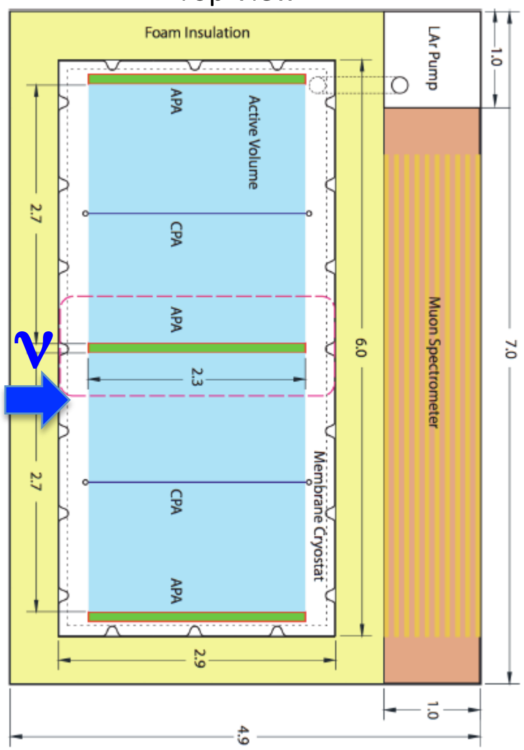
1 kton-scale Far Detector to complete 3 detector configuration
Run ~2020-
Estimated 100-150 collaborators

Overall, the design philosophy of the LAr1(ND) detectors is to serve as a development step toward LBNE both for hardware and software development (as a next step beyond current LAPD, 35 ton etc. prototypes), while functioning as a physics experiment

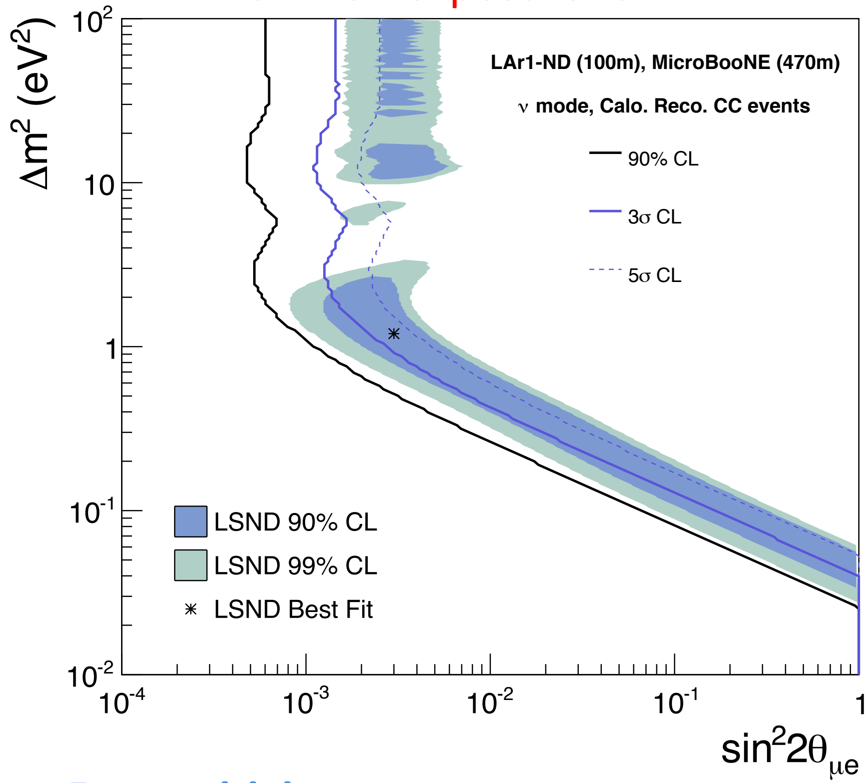
The LAr1 Experimental Program (I)

➢ **Phase I, LAr1-ND:** A modest-scale (40 ton) LArTPC Near Detector in the *existing* enclosure at 100m to run in conjunction with MicroBooNE

Top View



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



While MicroBooNE will definitively address the MiniBooNE excess as electrons or photons in neutrino mode, the combination of LAr1-ND and MicroBooNE will allow for its interpretation as new physics.

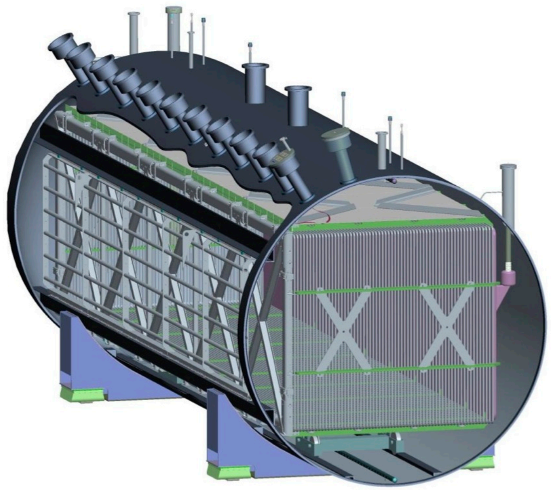
5σ sensitivity to MiniBooNE low-energy excess with 1 year of data

The LAr1 Experimental Program (II)

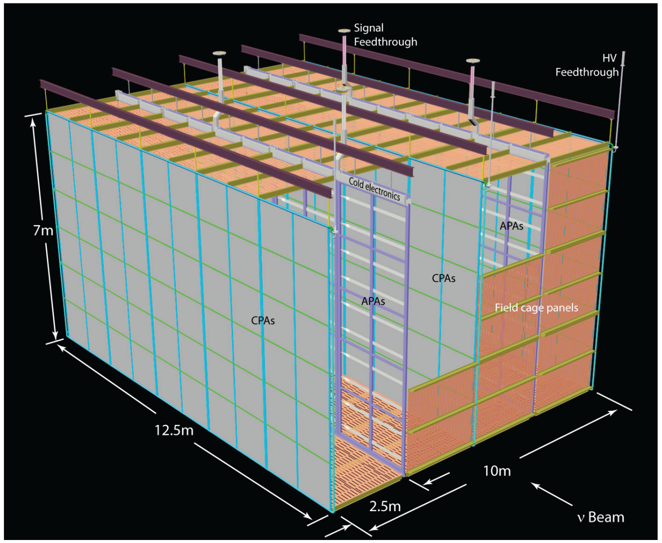
➢ **Phase II, Three LArTPC Detector Configuration:** LAr1-ND serves as a near detector for the full LAr1 program with addition of kton-scale FD

LAr1-ND
(40ton fiducial) at 100 m

MicroBooNE
(61ton fiducial) at 470 m



LAr1-FD Far detector
(1kton fiducial) at 700 m



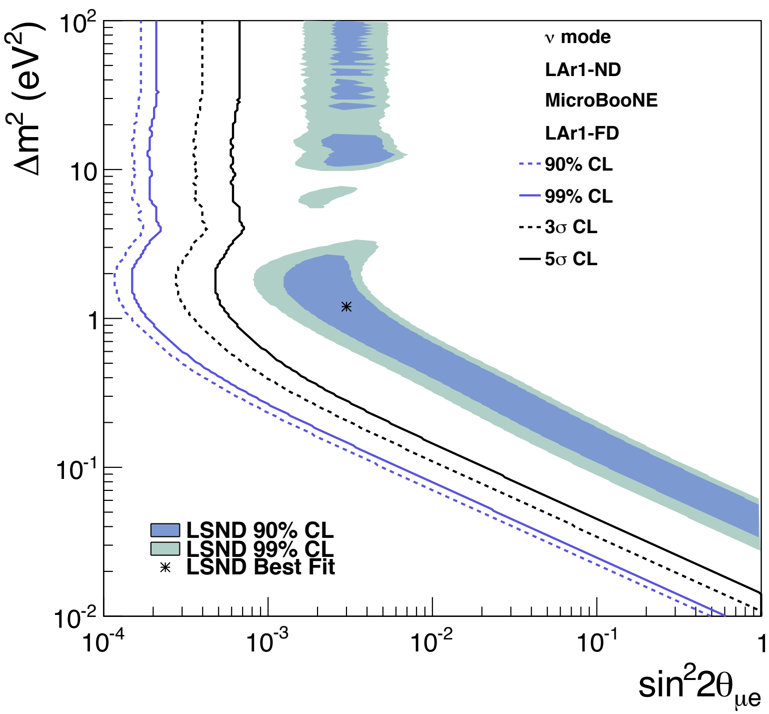
This multiple detector combination would provide a powerful constraint of experimental uncertainties and <u>address in a definitive way</u> whether the observed short-baseline anomalies are due to high Δm^2 neutrino oscillations (sterile neutrinos)

Opportunity to construct a kiloton-scale LBNE prototype on-site at Fermilab

The LAr1 Experimental Program (II)

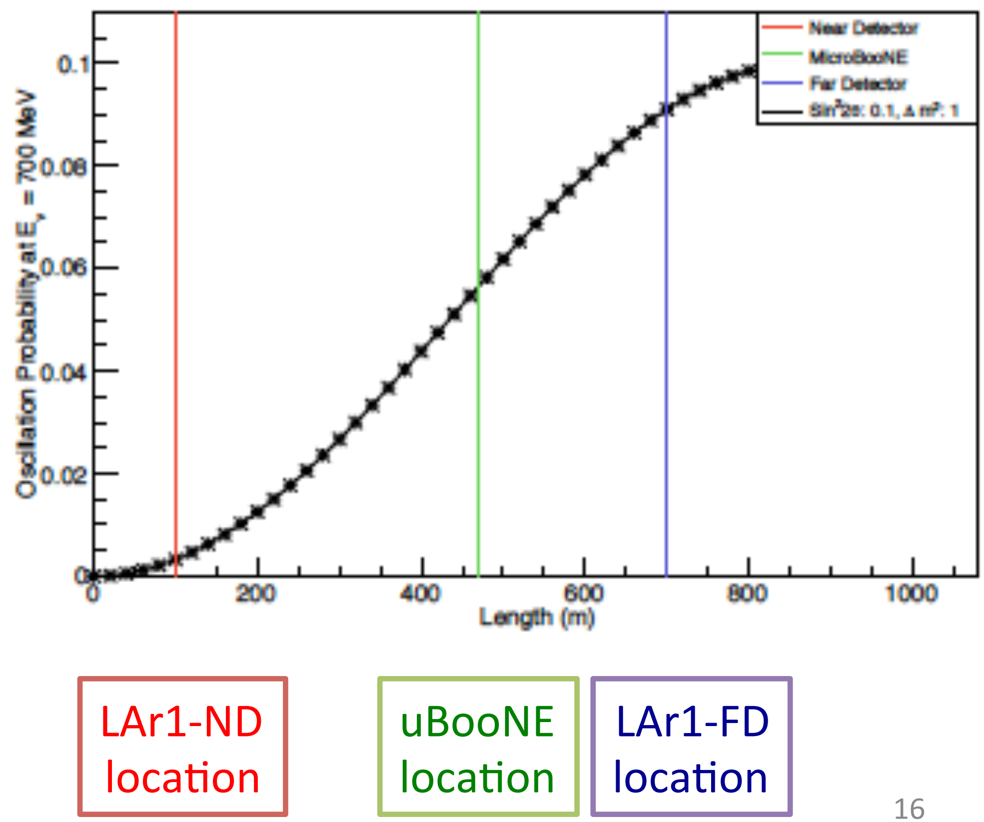
➢ **Phase II, Three LArTPC Detector Configuration:** LAr1-ND serves as a near detector for the full LAr1 program with addition of kton-scale FD

Neutrino mode: 6.6×10^{20} POT exposure



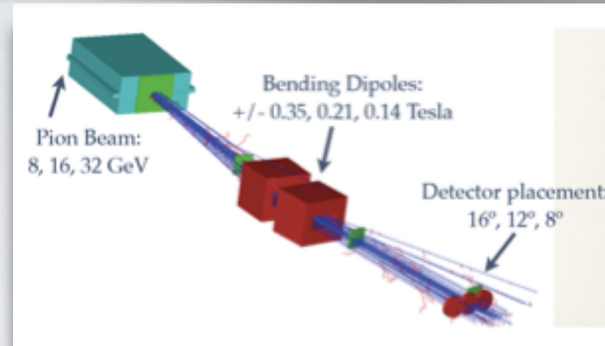
Caveat: Assuming 80% electron identification efficiency and no non-ν_e backgrounds. Full sensitivity studies with LAr1-ND & kton-scale FD are underway to be included as part of LAr1-ND proposal

ν_μ disappearance probability at $\mathbf{E}_\nu$ = 700 MeV as a function of distance in a sterile neutrino model with $\Delta\mathbf{m}^2$ = 1 eV^2 and $\sin^2 2\theta_{\mu\mu}$ = 0.1



LARIAT

Liquid ARgon TPC In A Testbeam (FNAL-T1034)

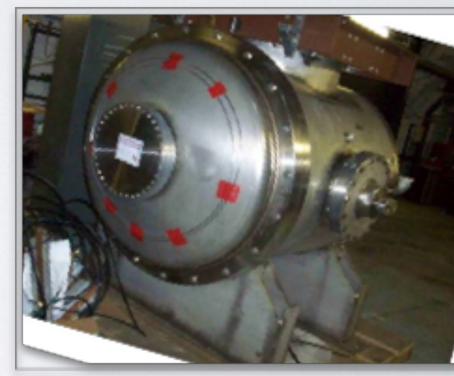


- **THE VISION:**

  LArIAT - a long-term ***Test Beam Facility*** for LArTPC's at FNAL with a new dedicated BEAM LINE [0.2 - 2. GEV], cryogenics & purification plant for LAr and DAQ system for TPC.

- **THE MOTIVATION & THE METHOD:**

  Study in LArTPC of all the particles emerging from ν interactions (in the energy range relevant for μB and LBNE) by means of particles (of known ID, mom. and sign) emerging from the Test Beam in the same energy range.



- **CURRENT STATUS AND SCHEDULE** 1ST RUN: SPRING 2014

  Detector : existing refurbished ArgoNeuT TPC and cryostat ⊕ new high efficiency Scintillation Light System (completed) ⊕ New Cold Electronics and DAQ (in progress)

  Cryogenics/Purification : under construction (delivery by Feb.'14)

  Dedicated beam : commissioning by Jan.'14,

  Beam Counters : tested and ready for installation

- **THE LARIAT COLLABORATION**

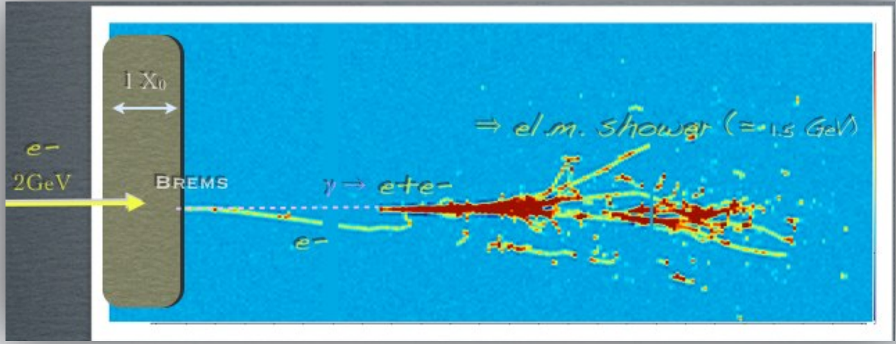
  54 Collaboration members (and 20+ students in summer) from 3 US national labs, 12 US universities and 4 foreign institutions

SCIENCE: LARIAT

ELECTRON VS PHOTON SHOWER DISCRIMINATION

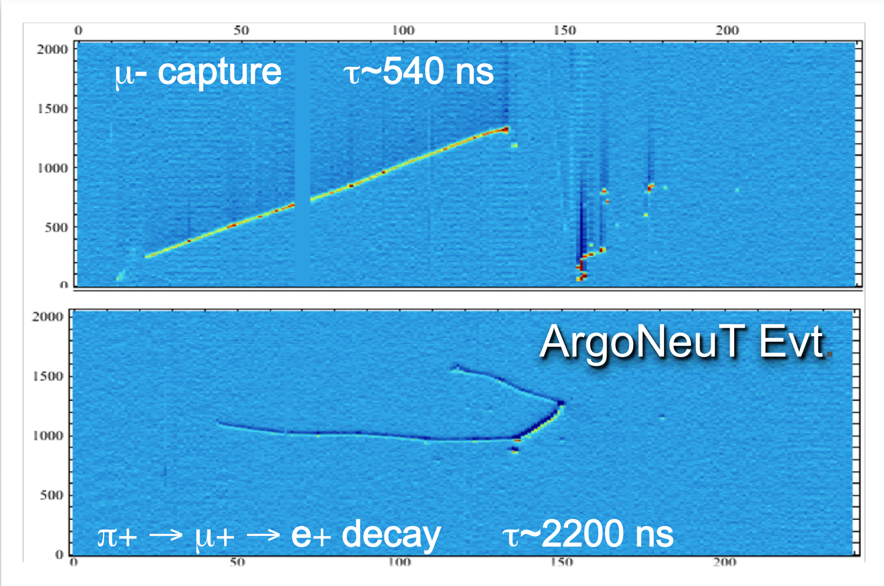
Experimental confirmation for the separation efficiencies (MC determined) - key feature of LArTPC technology

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



MUON SIGN DETERMINATION (W/OUT MAGNETIC FIELD)

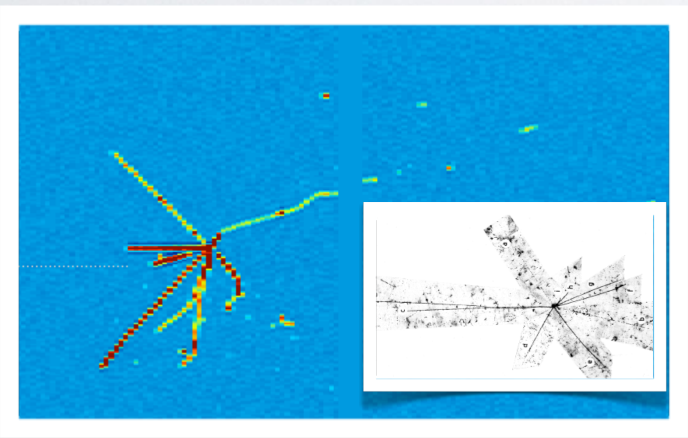
Explore a LArTPC feature never systematically considered (decay vs capture in LAr)



STUDY OF NUCLEAR EFFECTS

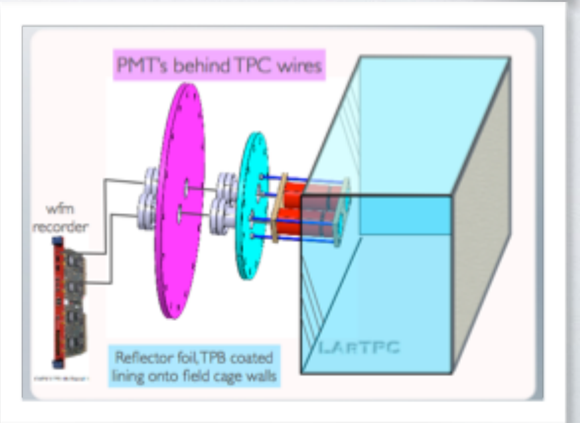
Pion Absorption, π0 from $\pi\pm$ Charge Exchange and Antiproton annihilation (relevant for n-nbar oscillations)

Simulation of Antiproton Star in LAr



DEVELOPMENT OF A NEW CONCEPT IN LAR SCINTILLATION LIGHT COLLECTION

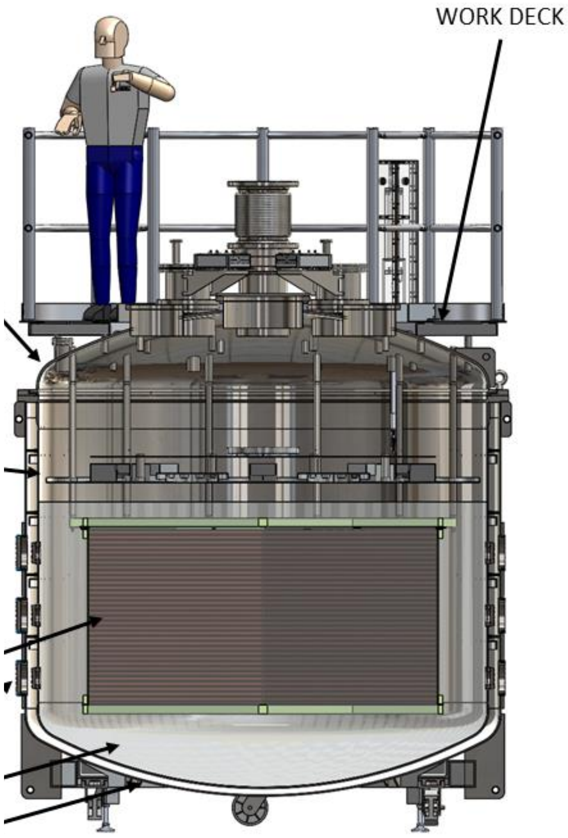
Relate energy deposited to **charge** and **light** for an improved calorimetric energy resolution



CAPTAIN Program

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

- Physics Program via neutron running and neutrino running impacts two LBNE physics missions
  - Low-energy neutrinos – supernova neutrinos
  - Neutron running to measure production of cosmogenic spallation products
  - Medium-energy neutrinos – accelerator and atmospheric neutrinos
  - Neutron running to measure neutron interactions in argon important for total neutrino energy reconstruction
  - CC and NC cross-sections in low and medium energy neutrino running, reconstructed vs. true neutrino energy correlation
- Available for neutrino running from CY 15 – low-energy (stopped pion source – SNS or off-axis BNB), medium-energy (NuMI)
- Collaboration 15 institutions, 53 collaborators – more welcome
- CAPTAIN and LArIAT have related, but complementary missions that impact medium-energy neutrino physics



5 ton active vol. TPC

Summary

- Neutrino community intent on applying U.S. accelerator facilities to answering open questions in neutrino physics
  - Do neutrinos violate CP? What is the neutrino mass hierarchy?
    - Added benefit of multiple LBL detectors
  - Do light sterile neutrinos exist?
    - The right experiment can be definitive on this question, broadening the physics reach of the U.S. program over the next decade
- Also intent on continued development of neutrino detector technologies
  - LArTPC experience particularly valuable to neutrino community working toward LBNE
- A diversity of scale in the projects proposed for the next decade
  - Smaller scale test beam and LAr R&D efforts (on-going)
  - Middle scale short-baseline projects to address sterile neutrinos; detector development
  - Larger scale long-baseline projects to add to global sensitivity to CP and hierarchy

Project	Estimated Cost*	Detector Technology	Location	Physics / R&D Program
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■ existing facility for detector ⊙ existing detector

*These estimates are for rough comparison and may vary in their robustness. For details please see the main proponents of each project.

Overflow

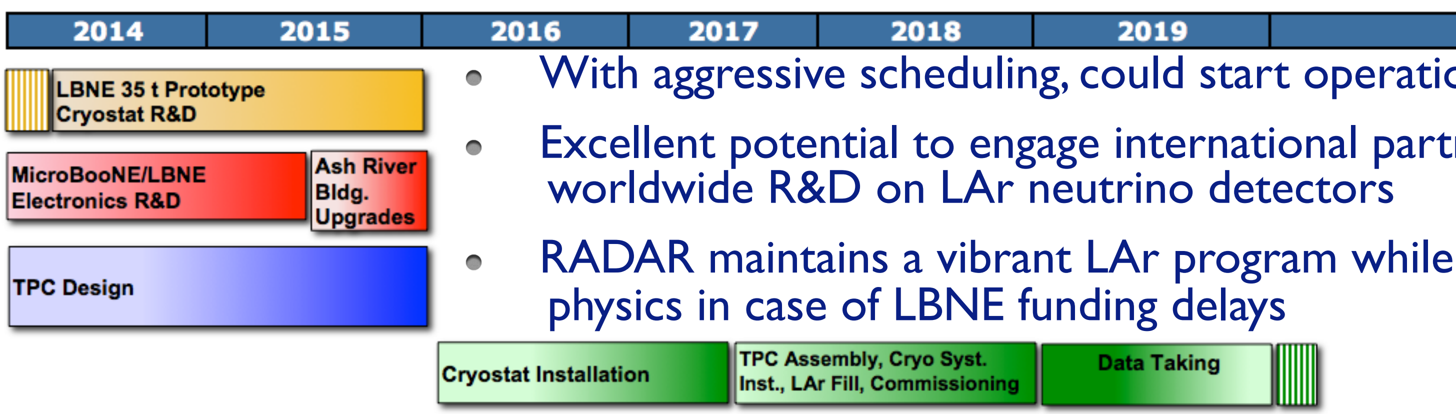
RADAR

RADAR Costs and Timeline

- RADAR cost estimated at ~$170M, including contingency and escalation
- Component reusability in LBNE may offset these costs by $60M
- Estimate 60 FTE required in project phase, 40 FTE in operations, 40 FTE in data analysis
  - Expect a large fraction of the LBNE Collaboration to contribute to RADAR

Project Component	Scaled DIC Cost (×$1M)	Included Scaled Contingency	Recoverable Costs (×$1M)
Ash River Bldg. Enhancements	10.0	50%	0.0
LAr TPC	25.6	49%	25.6
Cryogenics and Cryostat	84.1	32%	25.0
LAr Storage Tank	14.5	50%	0.0
Detector Monitoring and Control	4.6	50%	2.3
LAr Photon Detector	5.0	39%	5.0
Installation and Commissioning	11.2	52%	0.0
Project Management	14.0	16%	0.0
Total Cost	169.0	36%	57.8

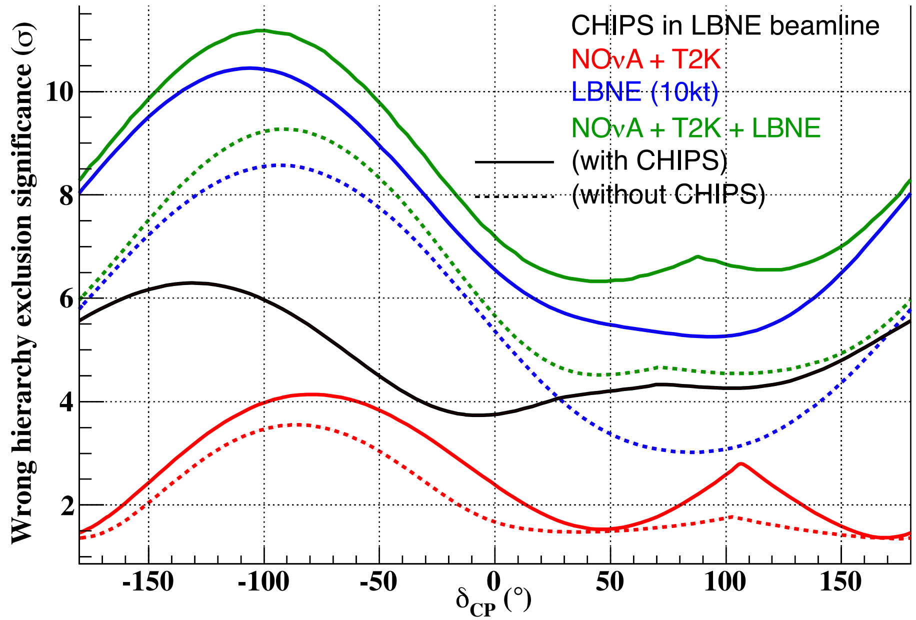
- Costs sourced from LBNE estimates, reviewed by Jim Strait and Bruce Baller

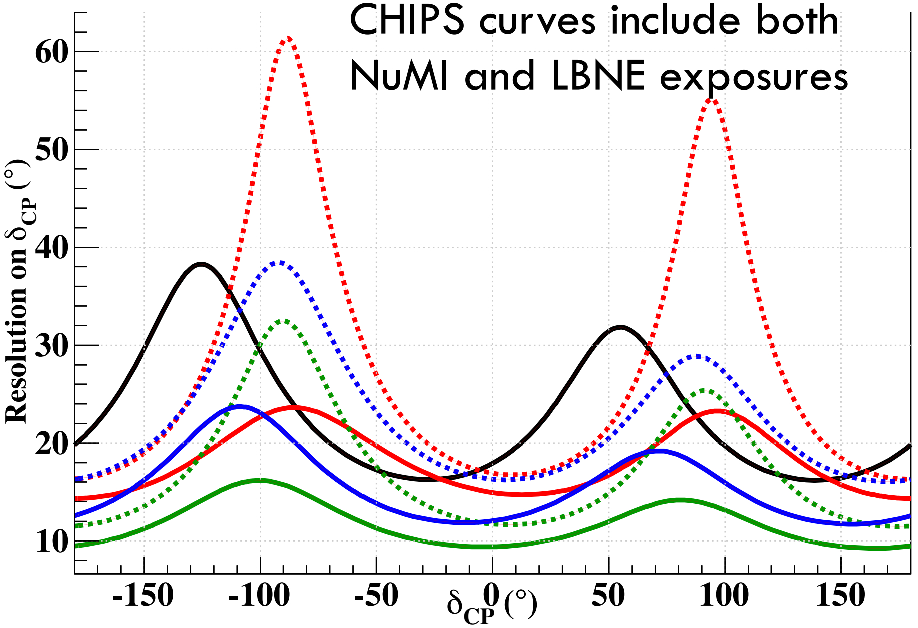


- With aggressive scheduling, could start operations in 2019
- Excellent potential to engage international partners and to serve worldwide R&D on LAr neutrino detectors
- RADAR maintains a vibrant LAr program while delivering leading physics in case of LBNE funding delays

CHiPs

Redeploy in LBNE





- CHiPs in off-axis LBNE at second oscillation peak
  - Disentangle MH vs. CP violating effects
  - More appearance
  - Less feed down from high E NC events in off axis narrow band beam
  - Energy (0.8 GeV) well suited to water Cherenkov
- Pactola Lake in LBNE beam line at 20mrad off axis with L=1300km
- LBNE 35kt+CHIPS+NOvA+T2K gets down to 5-10 degrees—begin to reach NuFact levels

Physics Sensitivity in NuMI

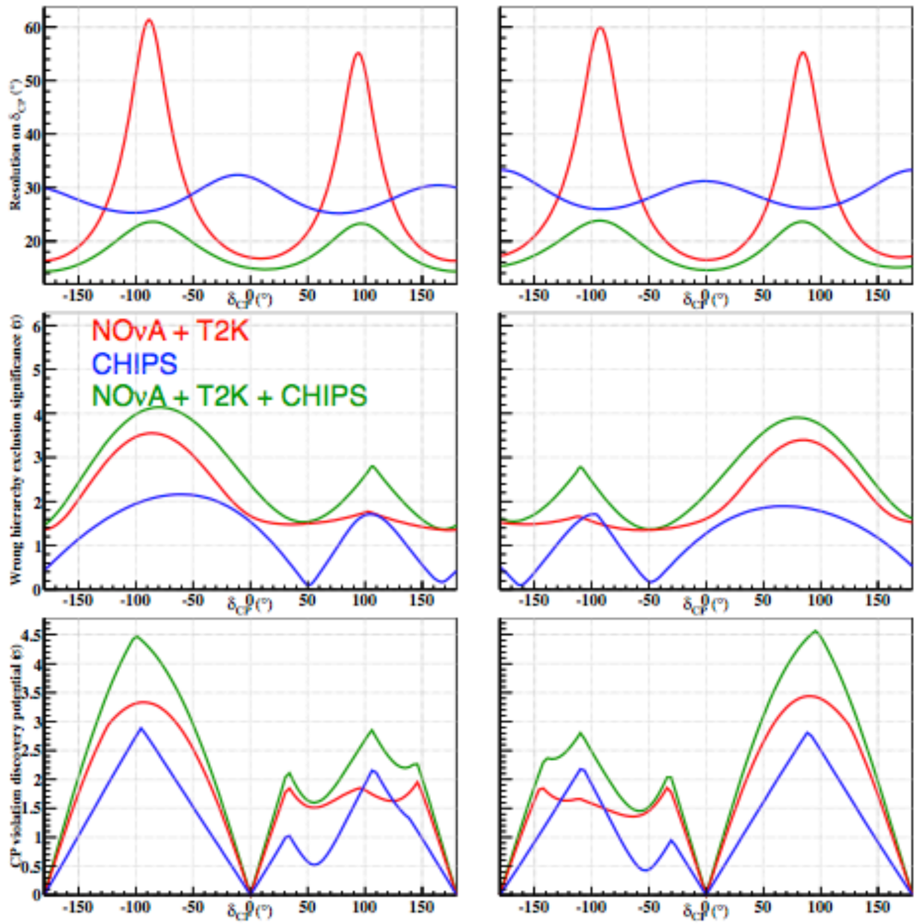


Figure 3: CHIPS physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOνA (5+5y) and T2K(8.8e21 POT), and CHIPS(3+3y). (Top) δ_{CP} resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOνA and T2K, the blue line is CHIPS and the green is the combination.

Physics Sensitivity in LBNE

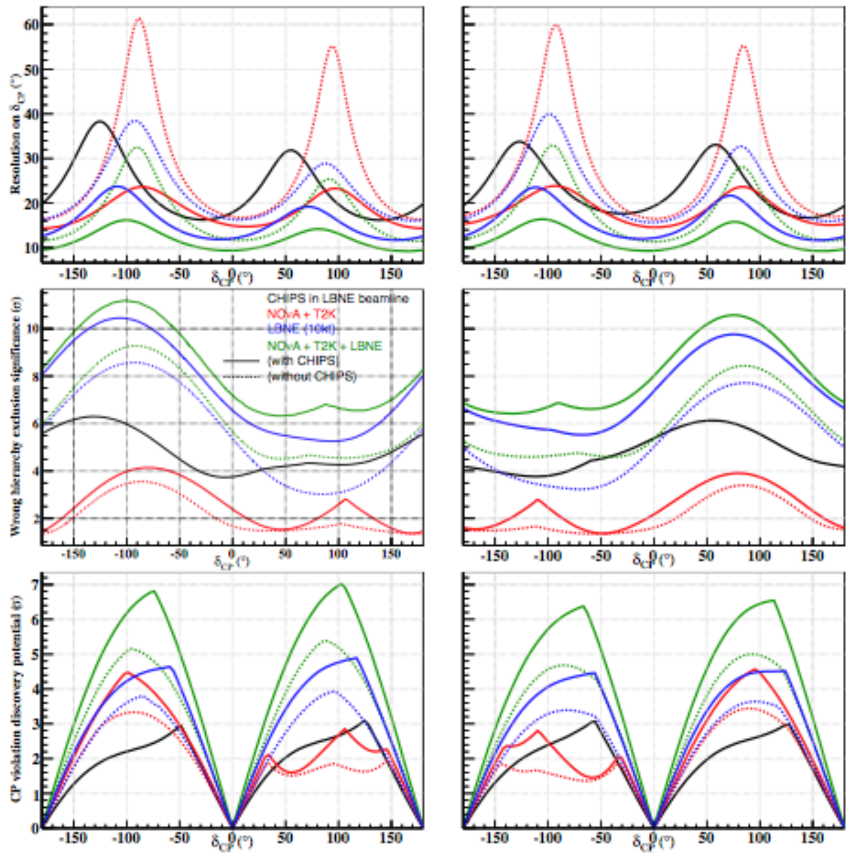
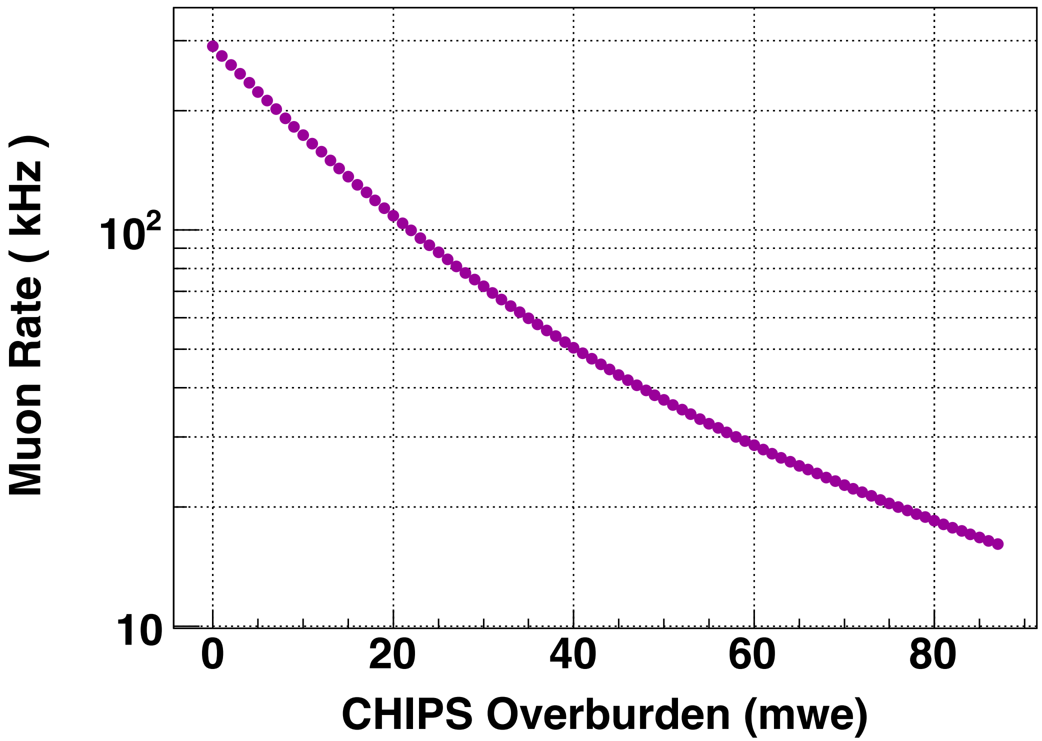


Figure 8: Physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOνA+T2K, 10 kton LAr LBNE, and CHIPS in the LBNE beam at 20 mrad. (Top) δ_{CP} resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOνA and T2K, the blue line is a 10 kton LAr detector on-axis in the LBNE beam, and the green is the combination of those experiments. Solid black line is for CHIPS, from both a NuMI and LBNE run. Dotted lines show each experiment (or combination of experiments) without a CHIPS run. Solid lines show the effect of adding CHIPS to the results.

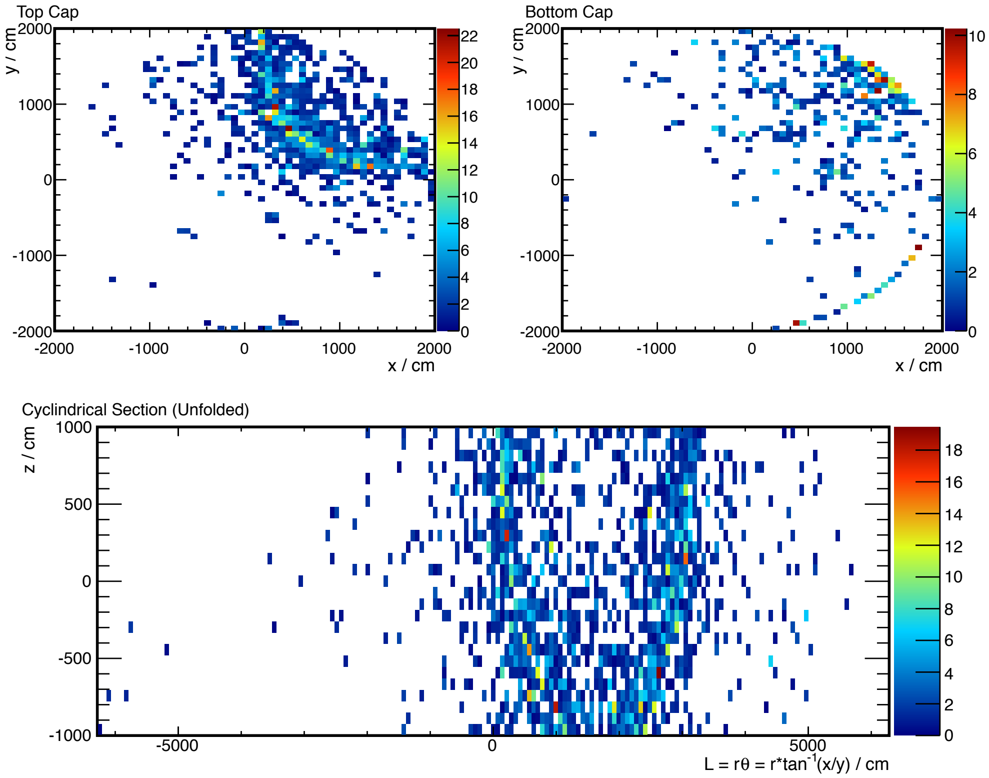
Cosmic Rate

- CHiPs will have a 40m overburden
- Cosmic rate 50kHz



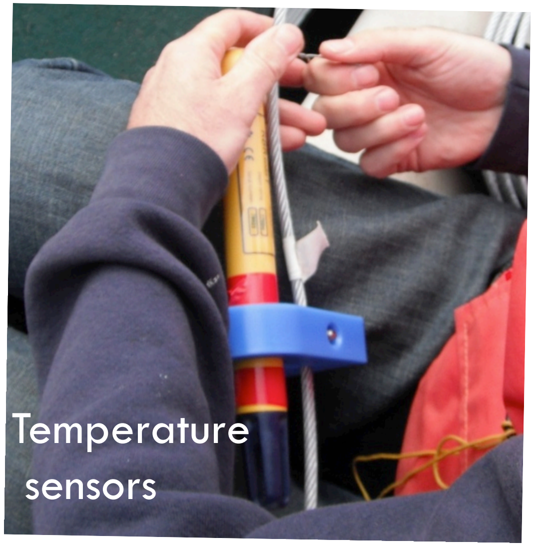
Simulation and Reconstruction

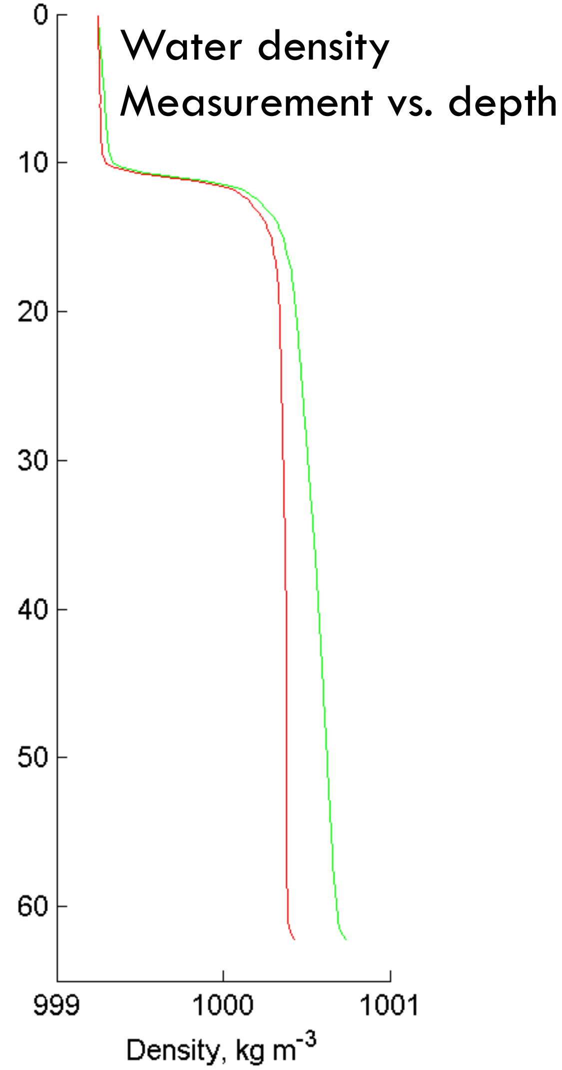
- Full Geant4 detector simulation (WCSim)
- Reconstruction algorithms based on MiniBooNE experience implemented
- Optimize photocathode coverage and layout with full simulation and reconstruction suite



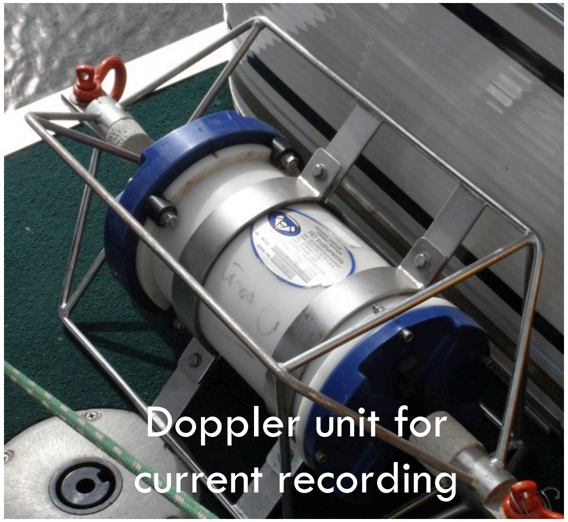
1.6 GeV simulated electron neutrino interaction

Measuring Currents at Depth





400lb MINOS steel Anchor

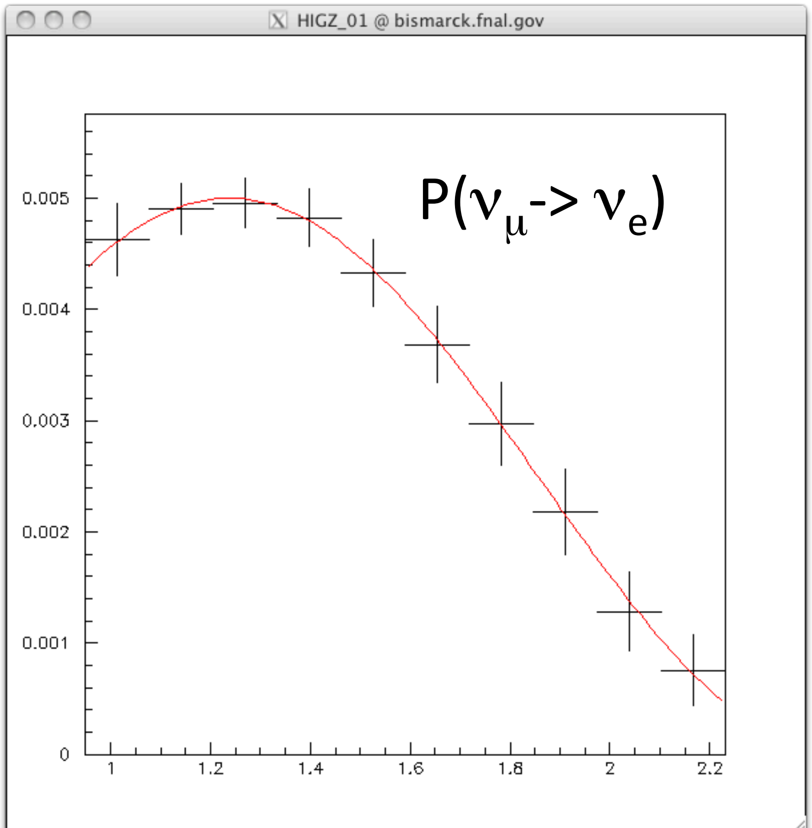


OscSNS

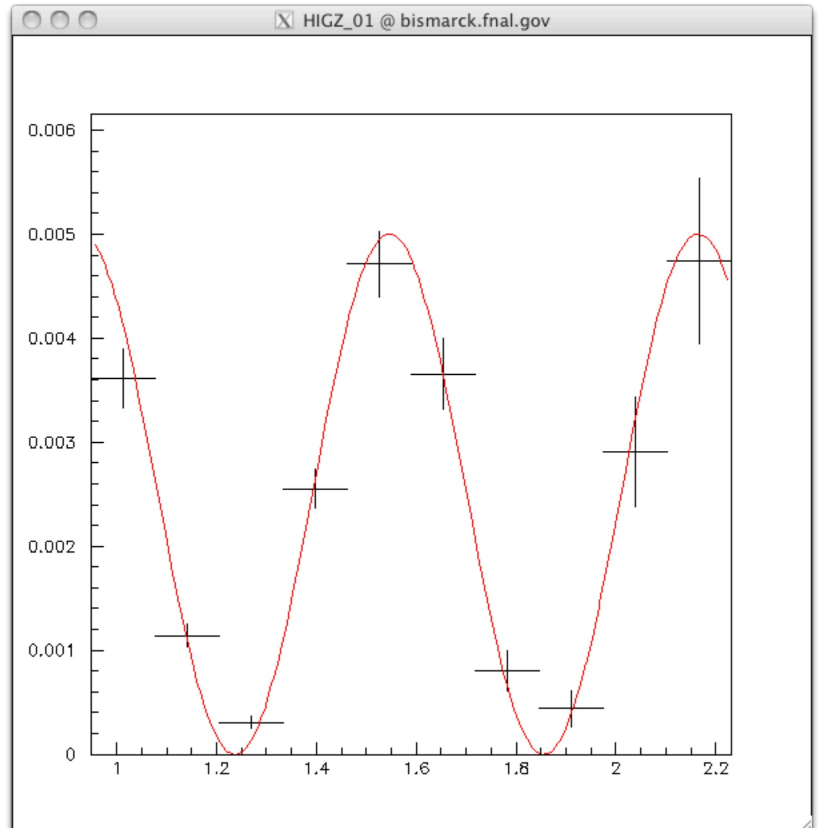
OscSNS Signals

$\bar{\nu}_e$ p -> e+ n

Assuming 10y of data & sin2$2\theta$ = 0.005, Δm2=1 eV2



Assuming 10y of data & sin2$2\theta$ = 0.005, Δm2=4 eV2



L/E (m/MeV)

OscSNS Cost & Schedule

Table 11.1 shows a breakdown of the OscSNS cost estimate, which is based on the MiniBooNE construction costs. The largest component is the civil construction cost of \$5.461M, which has been been estimated by the BWSC company of Knoxville, TN. The total estimated cost of the OscSNS experiment is \$21.852M, including contingency ($\sim$ 54%) and escalation ($\sim$ 5%). The OscSNS construction is assumed to start in the beginning of FY15 and last for 3 years. Expenditures per year are estimated to be \$5896K, \$9048K, and \$6908K in FY15, FY16, and FY17, respectively.

Item	Cost (\$K)	Contingency	Escalation	Total Cost (\$K)
Phototubes	5219	30%	4%	7056
Preamps	53	20%	12%	71
Electronics	665	30%	12%	969
DAQ	50	20%	12%	67
Civil Constr.	5462	100%	0%	10,924
Plumbing	20	20%	8%	26
Oil	1034	20%	2%	1265
Detector Tank	1030	30%	8%	1446
Support	20	30%	8%	28
Total	13,553	54%	5%	21,852

Table 11.1: A breakdown of the OscSNS cost estimate, including contingency and escalation. The OscSNS construction is assumed to start in the beginning of FY15 and last for 3 years.

The OscSNS cost estimate can be reduced by reusing the MiniBooNE oil and PMTs. The use of additional parts from MiniBooNE may also be considered.

LAr1-ND + LAr1

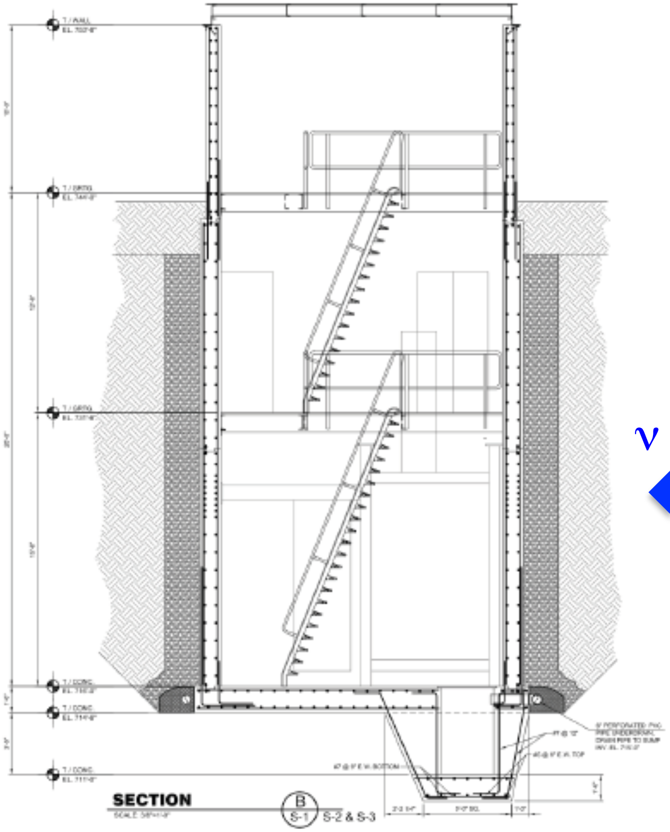
A Staged Multi-LArTPC Program at Fermilab

*LAr1 was originally conceived as a 1 kton fiducial volume far detector for MicroBooNE to address the anti-neutrino MiniBooNE anomaly. Recently reconsidering LAr1 as a **phased short-baseline program.***

- Physics case for LAr1 first described in LoI submitted to FNAL in Summer 2012. The prime motivation for that configuration was strong sensitivity in antineutrinos.
- Since then, we have come to recognize the power of adding a Near Detector to strengthen the sensitivity by providing a high-statistics constraint near the source, before any potential L/E dependent physics turns on
- White Paper submitted to the Snowmass pre-meeting of the Neutrino Subgroup at SLAC in March 2013 (3 detector configuration: Near detector at 100 m + MicroBooNE + 1 kton LArTPC at 700 m)
- Official Snowmass White Paper submitted last week focused on LAr1-ND as a first phase. Brief description of potential to expand into full program with LAr1-FD.
- Intending to submit Proposal for LAr1-ND to FNAL for the January 2014 PAC

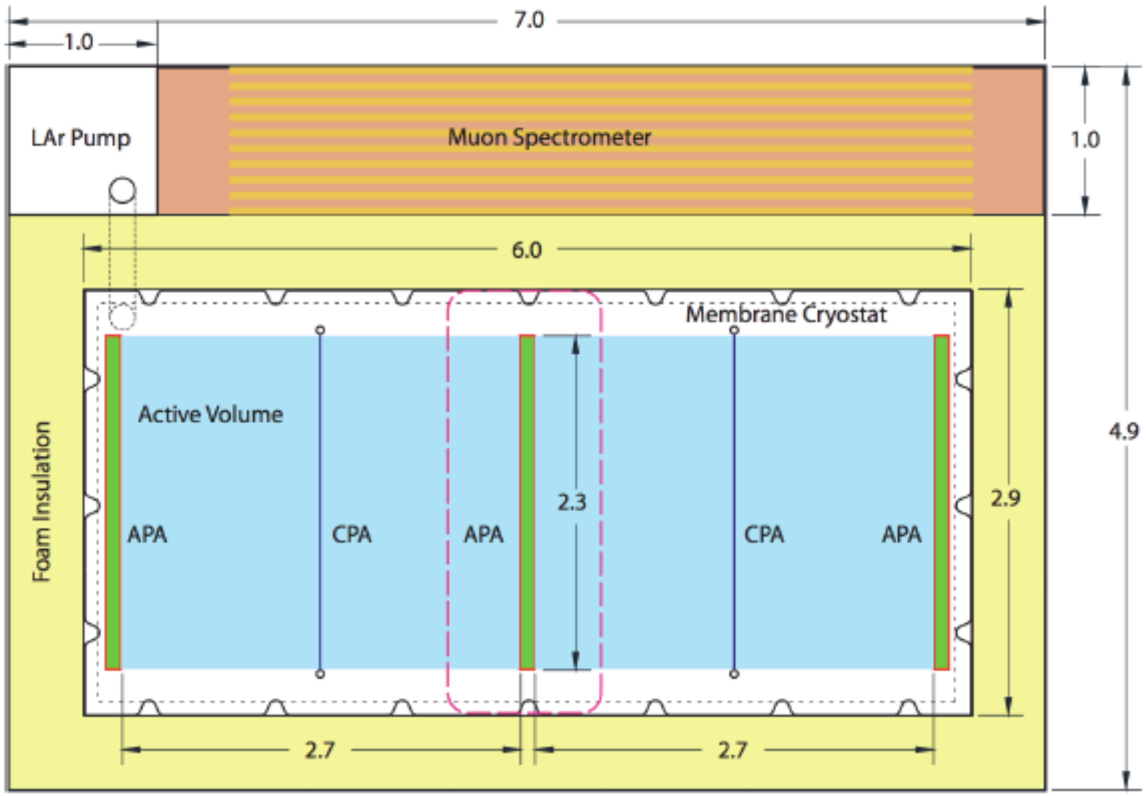
- The enclosure formerly used by the SciBooNE experiment (located on-axis at 100 m from the Booster Neutrino Beam target) is currently empty and provides an ideal location for a <u>membrane cryostat</u> LAr1-ND detector.

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



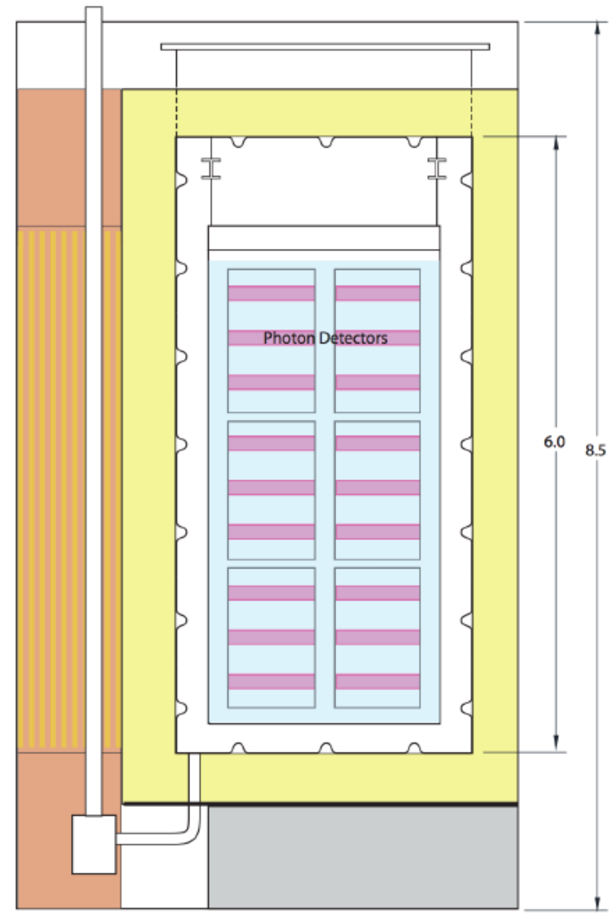
ν beam

Schematic design for the LAr1-ND detector



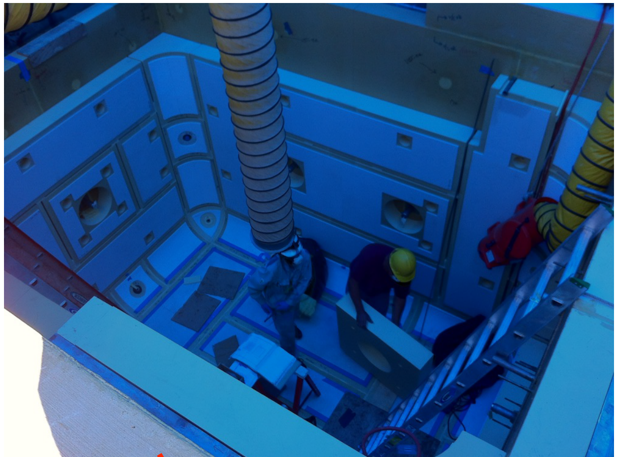
Top view

ν beam



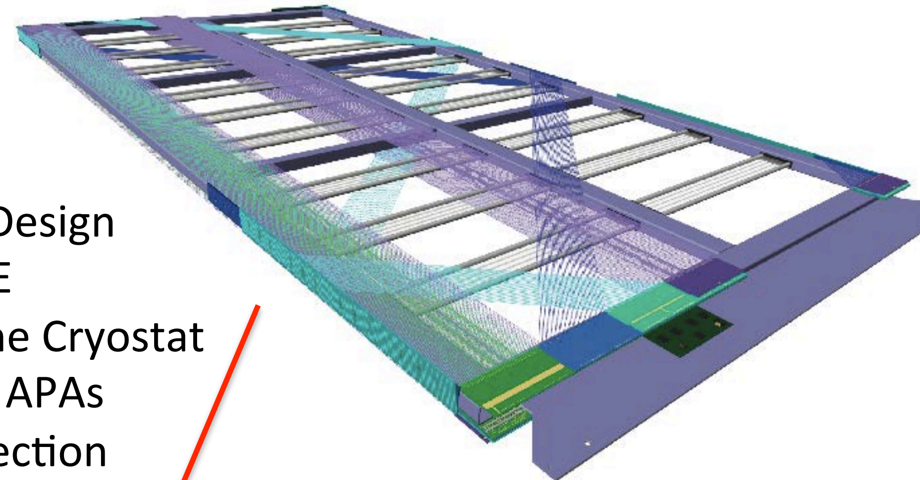
Side view

- A corrugated steel membrane cryostat is built up against three of the outer concrete walls of the enclosure.
- Downstream of the TPC, a 1.0 m space is left for the installation of a Muon Range Detector (1 m thick), positioned inside the pit behind the downstream wall of the membrane cryostat for momentum measurement of neutrino induced muons escaping the LAr volume.



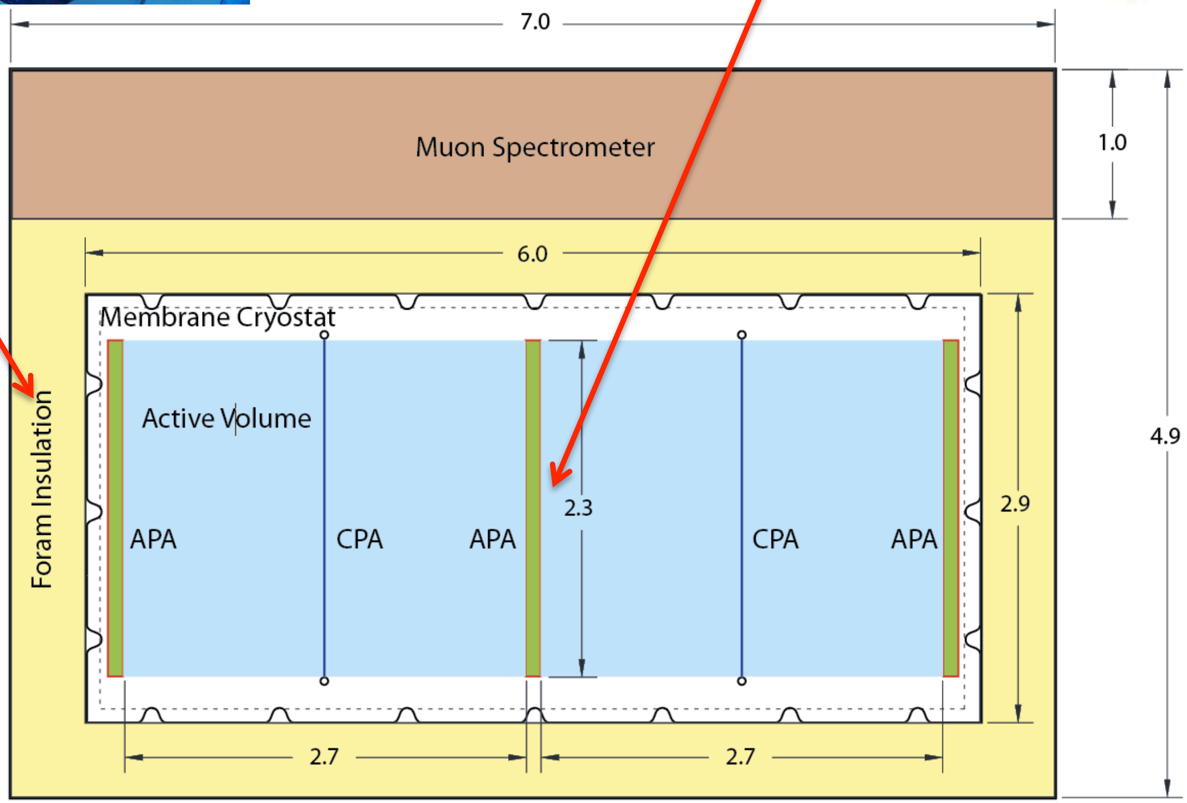
Conceptual Design Follows LBNE

- Membrane Cryostat
- CPAs and APAs
- Light collection



Provide a means to explore innovative designs for LBNE for underground science goals

- TPC design
- Light Collection



LAr1-ND view from above

Total active volume 77 tons of liquid argon (~40 ton fiducial volume)

LAr1-ND Physics Studies

Low-energy excess

- MicroBooNE will determine the nature of the MiniBooNE excess at ~500m. But in either scenario (electrons or photons) LAr1-ND can address the obvious next question of whether the excess appears over a distance or is intrinsic to the beam?

ν_e appearance

- In combination with uB; improved with a ND

ν_μ disappearance

- In combination with uB; only possible with a ND

Neutral-current disappearance

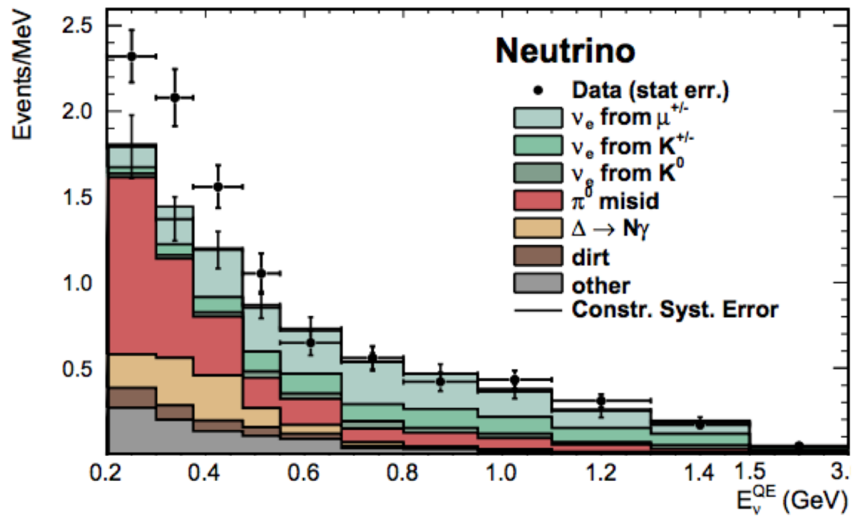
- In combination with uB; only possible with a ND

Neutrino-argon interactions

- About 15x the rate as in uB
- If low-energy excess determined to be Standard Model photon production mechanism, LAr1-ND can make precise measurement of rate and kinematics
  - 100s of events per year instead of 10s of events per year

Sensitivity to MiniBooNE Low-Energy ν_e Excess (I)

Does the anomalous excess of electromagnetic events reported by MiniBooNE, whether electrons or photons, appear over a distance or exist intrinsically in the beam?



Assess the ability of LAr1-ND to test the nature of the MiniBooNE neutrino anomaly in a way independent of any specific oscillation model

Follow the procedure used in the MicroBooNE proposal: scale the event rates observed by MiniBooNE in bins of reconstructed energy

Sensitivity to MiniBooNE Low-Energy ν_e Excess (II)

Estimated event rates in MicroBooNE and LAr1-ND determined by scaling from MiniBooNE event rates* and accounting for differences in fiducial masses, beam exposures and selection efficiencies between the 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)

Background (including both intrinsic sources of ν_e as well as single photon final state ν_μ interactions)

Process	200 - 300 MeV (mB)	300 - 475 MeV (mB)	Total (mB)	Scaling (μB)	Total (μB)	Scaling (LAr1-ND)	Total (LAr1-ND)
Background from intrinsic ν_e							
$\mu \to \nu_e$	13.6	44.5	58.1	.369	21.5	2.40	139.8
$K^+ \to \nu_e$	3.6	13.8	17.4	.369	6.4	2.40	41.9
$K^0 \to \nu_e$	1.6	3.4	5.0	.369	1.8	2.40	12.0
Background from ν_μ misidentification							
ν_μ CC	9.0	17.4	26.4	.185	4.9	1.20	31.8
$\nu_\mu e \to \nu_\mu e$	6.1	4.3	10.4	.369	3.8	2.40	25.0
NC π^0	103.5	77.8	181.3	.037	6.7	.241	43.6
Dirt	11.5	12.3	23.5	.037	0.9	.241	5.7
$\Delta \to N\gamma$	19.5	47.5	67.0	.037	2.5	.241	16.1
Other	18.4	7.3	25.7	.037	0.9	.241	6.2
Background	187	228	415		**49.4**		**322.1**
Excess	45.2	83.7	128.9	.369	**47.6**	2.40	**310.2**

MicroBooNE: 6.6×10^{20} POT exposure

LAr1-ND: 2.2×10^{20} POT exposure

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

Sensitivity to MiniBooNE Low-Energy ν_e Excess (III)

To estimate the significance of a "MiniBooNE-like" signal in LAr1-ND, we apply the fractional systematic uncertainties reported by MiniBooNE. We include an additional 10% uncertainty on the efficiency of the dE/dx cut applied to separate e/γ final states in a LArTPC

Process	Events (μB)	Events (LAr1-ND)	MiniBooNE unc.	dE/dx unc.	Total unc.	Error (μB)	Error (LAr1-ND)
$\mu \to \nu_e$	21.5	139.8	0.26	0.1	0.28	6.0	39.0
$K^+ \to \nu_e$	6.4	41.9	0.22	0.1	0.24	1.55	10.1
$K^0 \to \nu_e$	1.8	12.0	0.38	0.1	0.39	0.73	4.73
ν_μ CC	4.9	31.8	0.26	0.0	0.26	1.27	8.26
$\nu_\mu e \to \nu_\mu e$	3.8	25.0	0.25	0.1	0.27	1.03	6.74
NC π^0	6.7	43.6	0.13	0.1	0.16	1.10	7.16
Dirt	0.9	5.7	0.16	0.1	0.19	0.16	1.07
$\Delta \to N\gamma$	2.5	16.1	0.14	0.1	0.17	0.43	2.77
Other	0.9	6.2	0.25	0.1	0.27	0.26	1.67
Total	49.4	322.1				6.55	42.6

	MicroBooNE	LAr1-ND
Total Events	97	632
"Low-energy Excess"	47.6	310.2
Background	49.4	322.1
Statistical Error	7.0	18.0
Systematic Error	6.6	42.6
Total Error	9.6	46.3
Statistical Significance of Excess	6.8 σ	17.3 σ
Total Significance of Excess	**5.0 σ**	**6.7 σ**

MicroBooNE: 6.6×10^{20} POT exposure

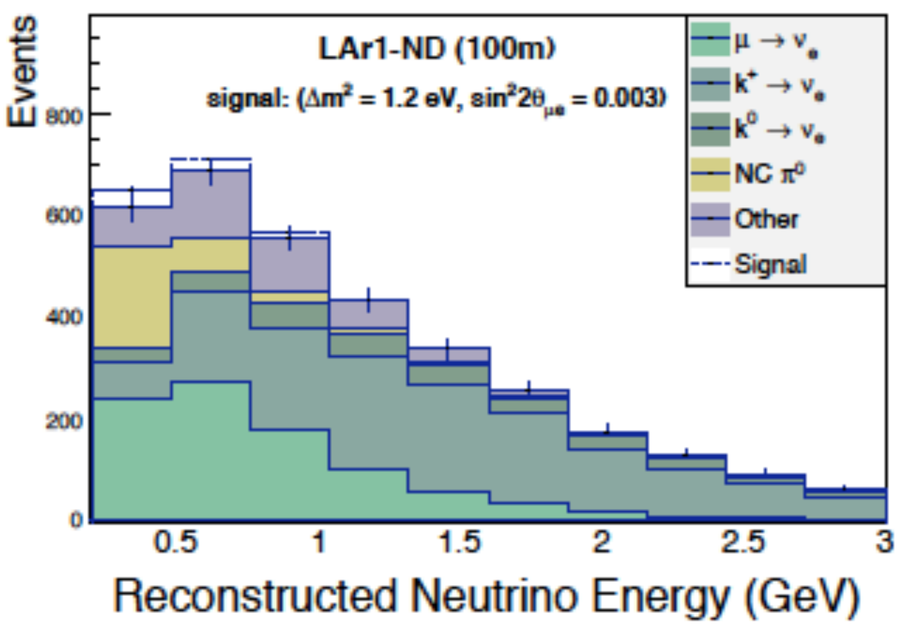
LAr1-ND: 2.2×10^{20} POT exposure

310 signal events expected would correspond to a 6.7σ excess over the expected 322±18.0(stat)±42.6(syst) in LAr1-ND

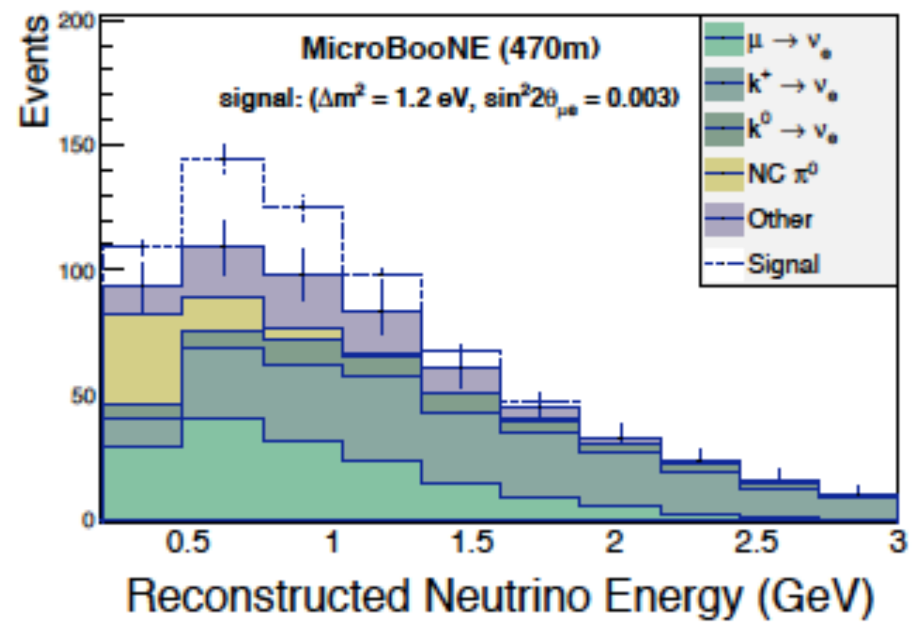
ν_μ -> ν_e Appearance

- Testing a ν_μ -> ν_e appearance scenario in the context of a 3 active+1 sterile neutrino model (3+1)
- The observed electron candidate event rate in LAr1-ND at 100 m is used to predict the expected rate (in the absence of oscillations) in MicroBooNE at 470 m.

2.2x10[20] POT exposure for LAr1



6.6x10[20] POT exposure for MicroBooNE

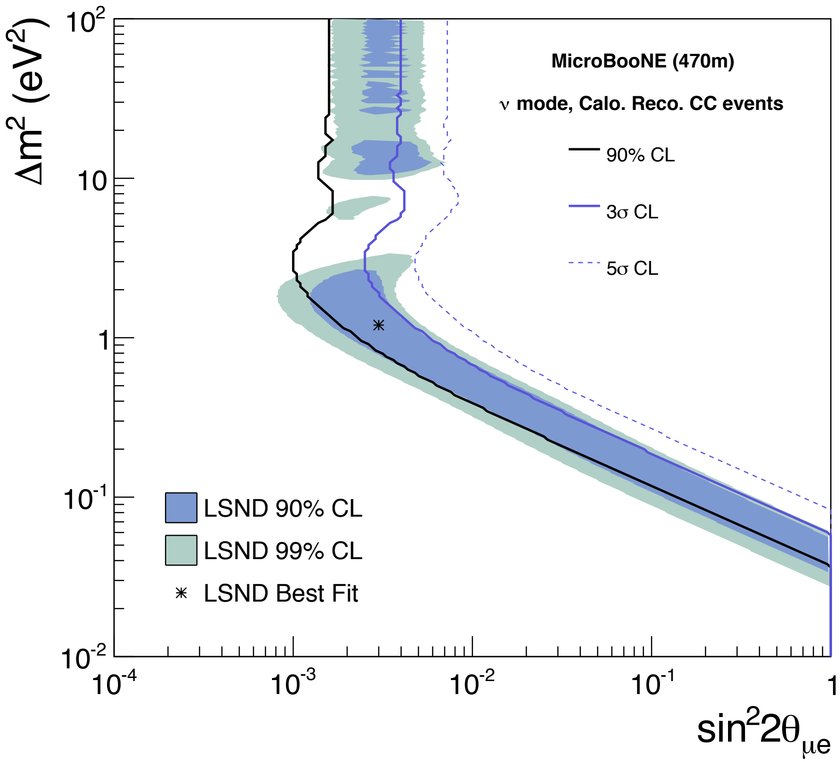


Neutrino energy is estimated by summing the energy of the electron candidate and all charged hadronic particles above observation thresholds

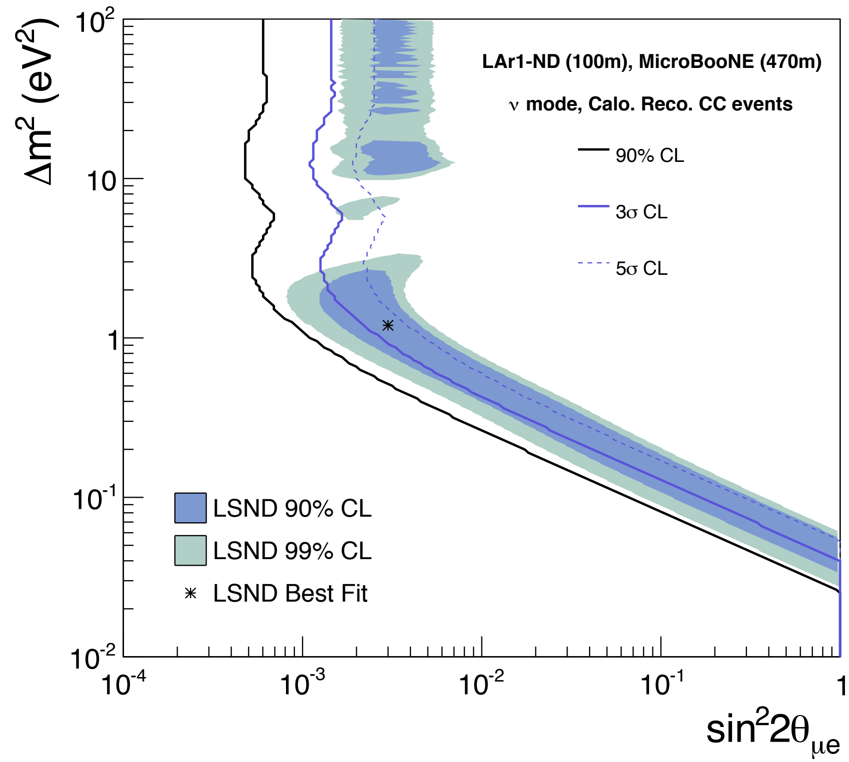
$\nu_\mu \rightarrow \nu_e$ Appearance

- The high statistics event sample in LAr1-ND constrains the expected background event rate in MicroBooNE, reducing the systematic uncertainties on the background

6.6×10^{20} POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on ν_e backgrounds



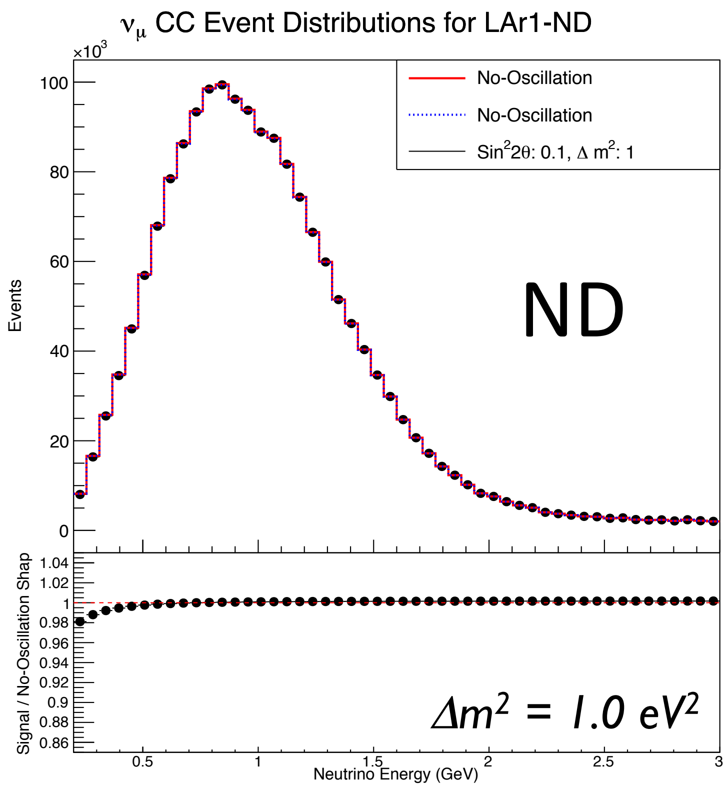
Same MicroBooNE exposure + 2.2×10^{20} POT exposure for LAr1-ND

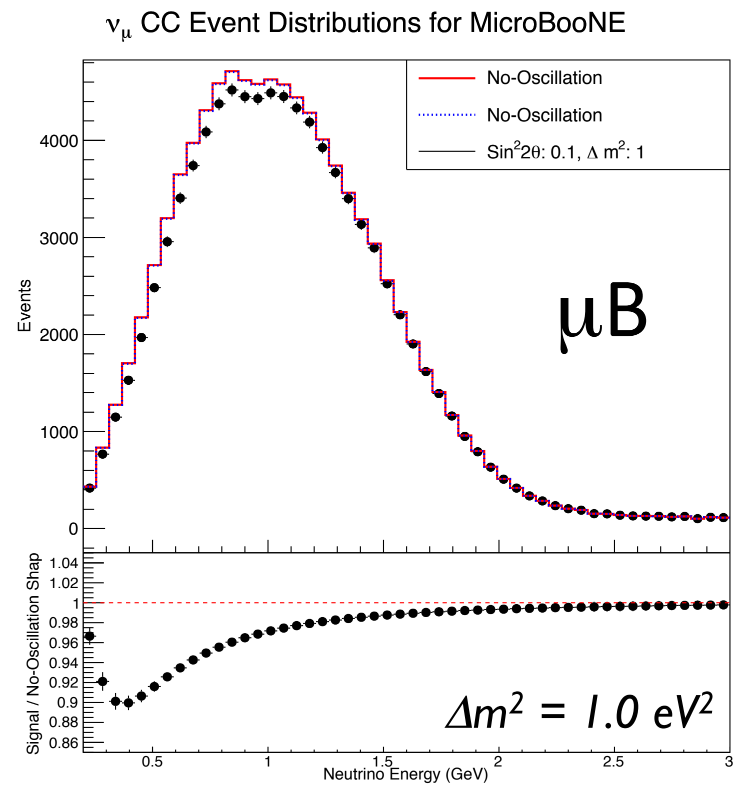


The sensitivity is strengthened through the reduction of systematic errors, covering the LSND best-fit point at ~4σ.

ν_μ Disappearance

- LAr1-ND, by providing a high statistics measurement of the interaction rate in the beam (flux × cross section) before the on-set of any oscillation, enables a search for ν_μ disappearance at the MicroBooNE location



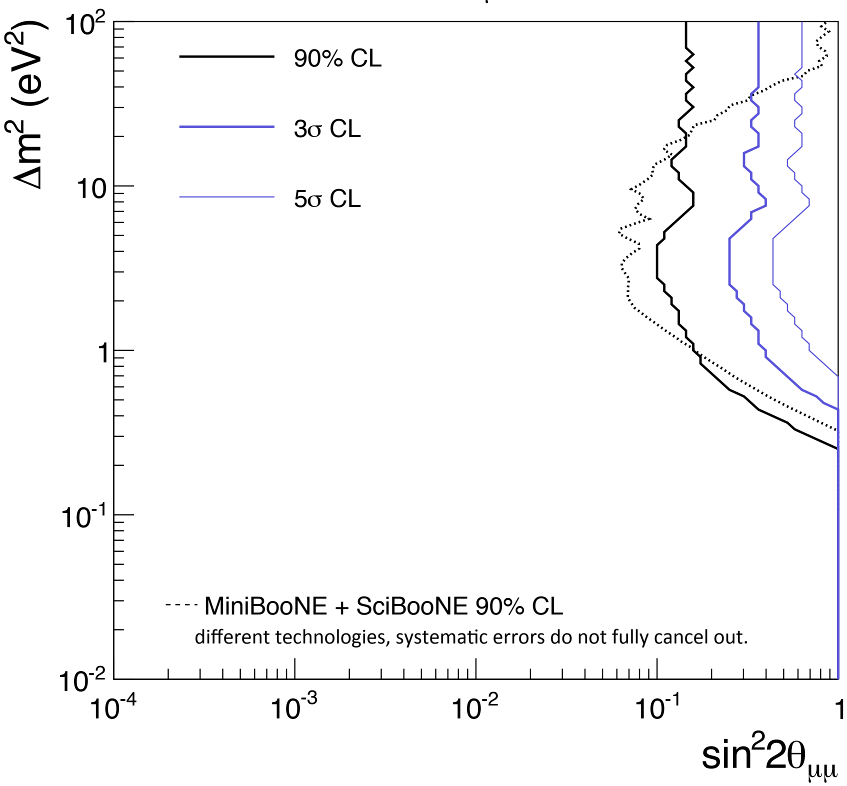


- Due to its near location, the effects of the oscillation are barely noticeable in LAr1-ND.
- At the MicroBooNE location, however, a significant distortion is visible. Flux and cross section errors of 15-20% would hide this signal in MicroBooNE alone, but using the observed LAr1-ND spectrum to normalize the expected rate at MicroBooNE makes it observable.

ν_μ Disappearance

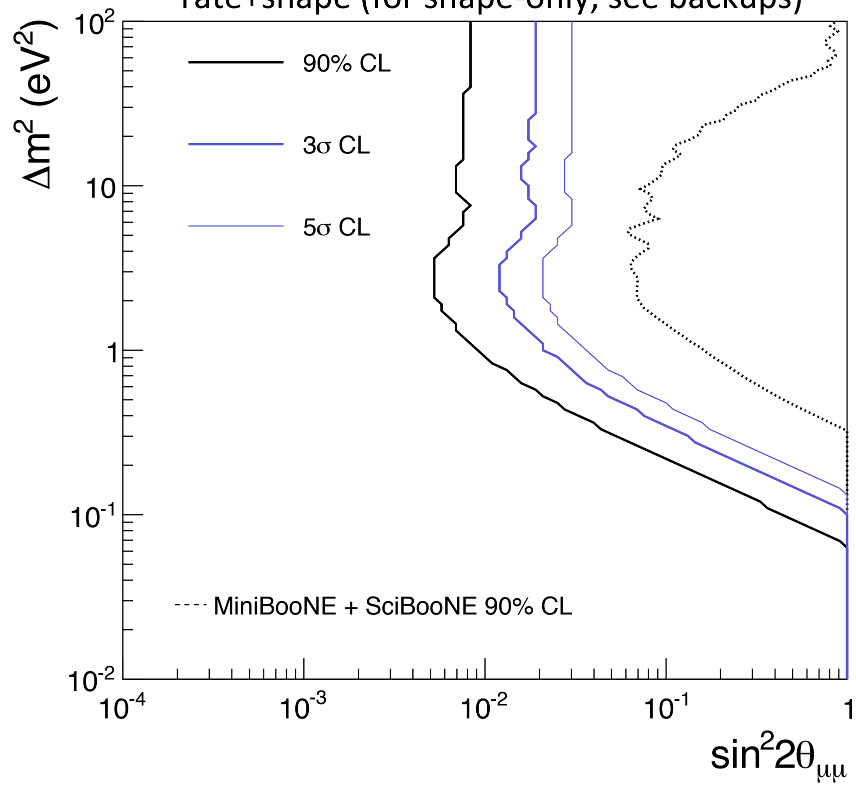
Sensitivity to ν_μ disappearance in neutrino mode

6.6x10[20] POT exposure for MicroBooNE alone, assuming 15% systematic uncertainties on the absolute ν_μ event rate



Same MicroBooNE exposure + 2.2x10[20] POT exposure for LAr1-ND

rate+shape (for shape-only, see backups)



Assuming 100% ν_μ-CC event identification efficiency and no non-ν_μ backgrounds

The systematics in the far detector (MicroBooNE) are taken to be the statistical uncertainties in LAr1-ND

Neutrino Cross Sections

*GENIE estimated event rates**

$2.2x10^{20}$ POT exposure for LAr1-ND

Process		No. Events
	ν_μ Events (By Final State Topology)	
CC Inclusive		449,959
CC 0 π	$\nu_\mu N \to \mu + Np$	307,441
	$\cdot\ \nu_\mu N \to \mu + 0\text{p}$	73,863
	$\cdot\ \nu_\mu N \to \mu + 1\text{p}$	173,830
	$\cdot\ \nu_\mu N \to \mu + 2\text{p}$	29,894
	$\cdot\ \nu_\mu N \to \mu + \geq 3\text{p}$	29,854
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + 1\pi^\pm$	99,446
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 2\pi^\pm$	8,433
CC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	43,048
NC Inclusive		171,869
NC 0 π	$\nu_\mu N \to \text{nucleons}$	118,787
NC 1 $\pi^\pm$	$\nu_\mu N \to \text{nucleons} + 1\pi^\pm$	22,407
NC $\geq 2\pi^\pm$	$\nu_\mu N \to \text{nucleons} + \geq 2\pi^\pm$	2,788
NC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	30,910
	ν_e Events	
CC Inclusive		3,465
NC Inclusive		1,195
Total ν_μ and ν_e Events		626,488
	ν_μ Events (By Physical Process)	
CC QE	$\nu_\mu n \to \mu^- \text{p}$	270,623
CC RES	$\nu_\mu N \to \mu^- N$	124,417
CC DIS	$\nu_\mu N \to \mu^- X$	46,563
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	1,664

← total events per ~year

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

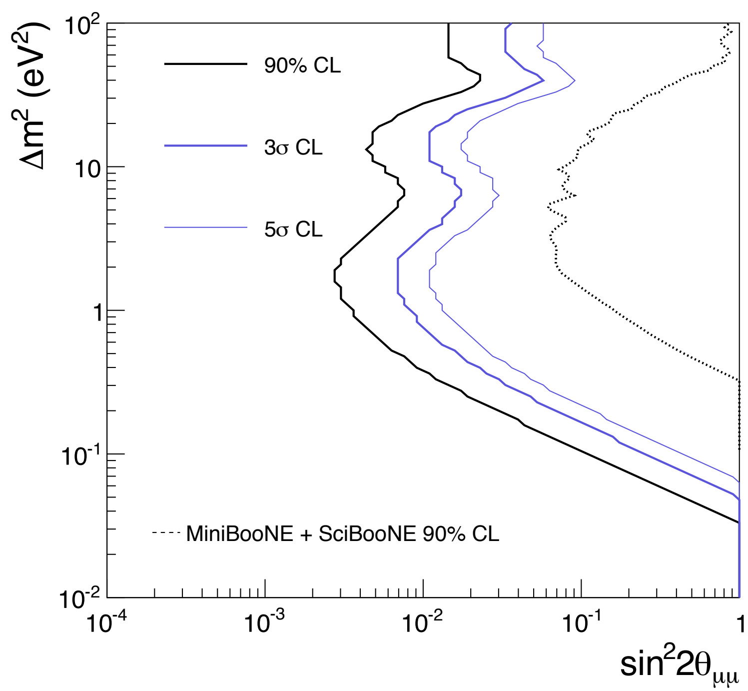
* Energy threshold on protons: 21 MeV. The 0π topologies include any number of neutrons in the event.

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

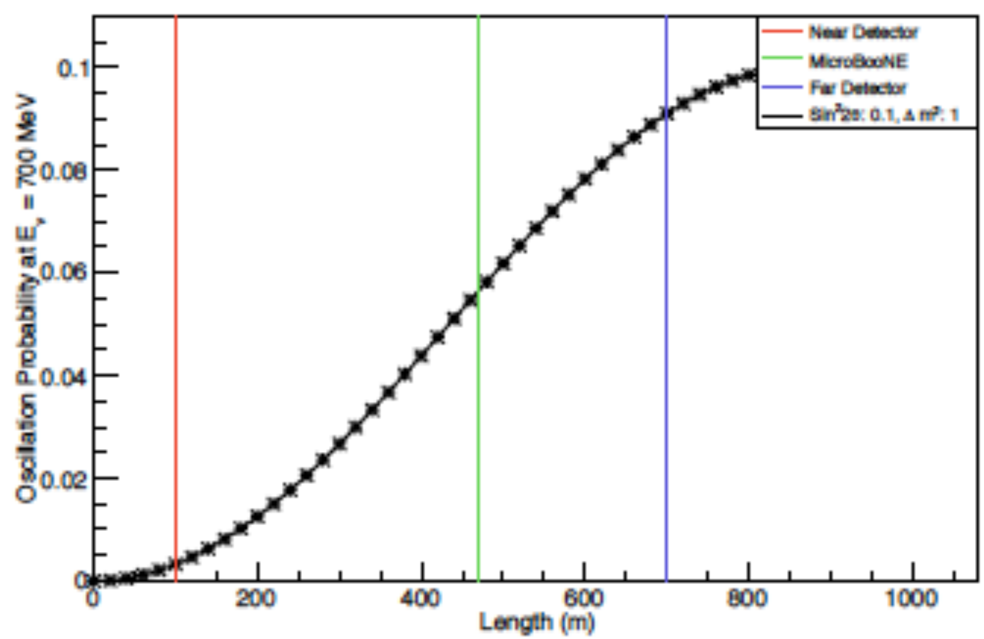
The LAr1 Experimental Program (II)

- **Phase II, Three LArTPC Detector Configuration:** LAr1-ND can serve as a near detector for the full LAr1 program to definitively address neutrino and antineutrino anomalies.

Ex: Sensitivity to ν_μ disappearance with the full 3-detector LAr1 experiment



ν_μ disappearance probability at $\mathbf{E}_\nu$ = 700 MeV as a function of distance in a sterile neutrino model with $\Delta\mathbf{m}^2 = 1\ \mathrm{eV}^2$ and $\sin^2 2\theta_{\mu\mu} = 0.1$



LAr1-ND location

uBooNE location

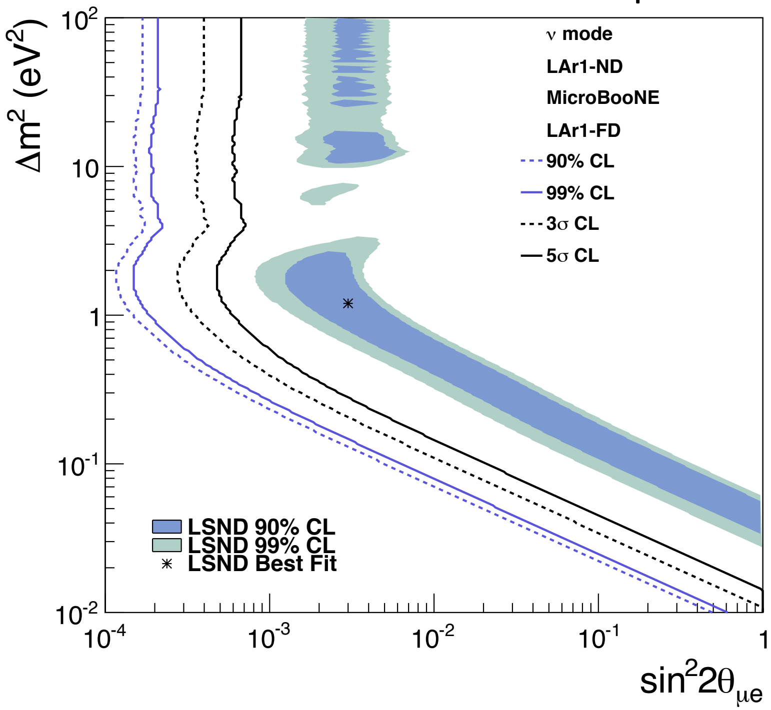
LAr1-FD location

Phase II: Three LArTPC Detector Configuration

- Possible future extension to this experimental program:
  The addition of a 1 kton-scale far detector located at 700 m, LAr1-FD, would provide a powerful opportunity to understand the antineutrino mode anomalies and potentially make precision measurements of oscillations to sterile states in neutrino mode
- Sensitivities to appearance in (anti)-neutrino mode:

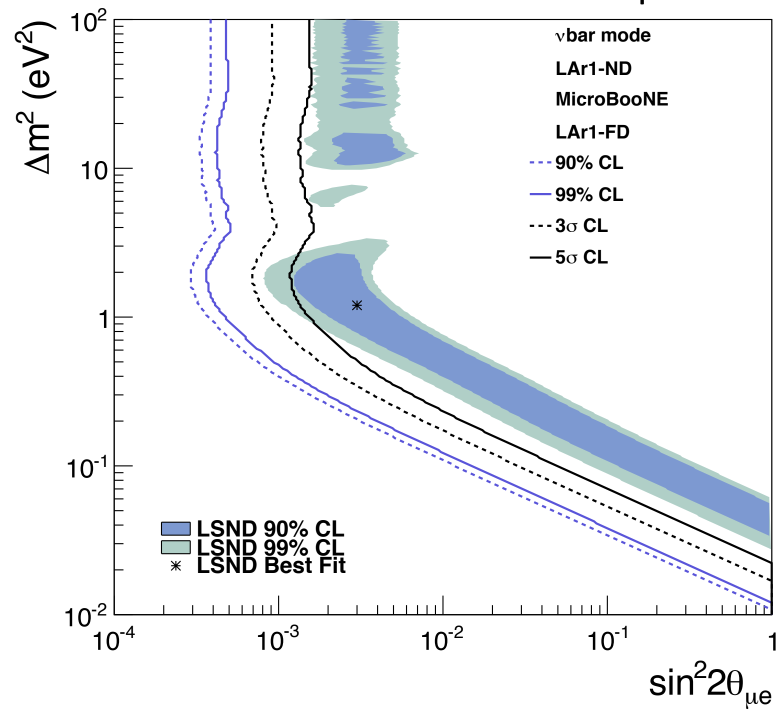
$\nu_\mu \to \nu_e$ Appearance

Neutrino mode: 6.6x10^20 POT exposure



$\bar{\nu}_\mu \to \bar{\nu}_e$ Appearance

Anti-neutrino mode: 10x10^20 POT exposure

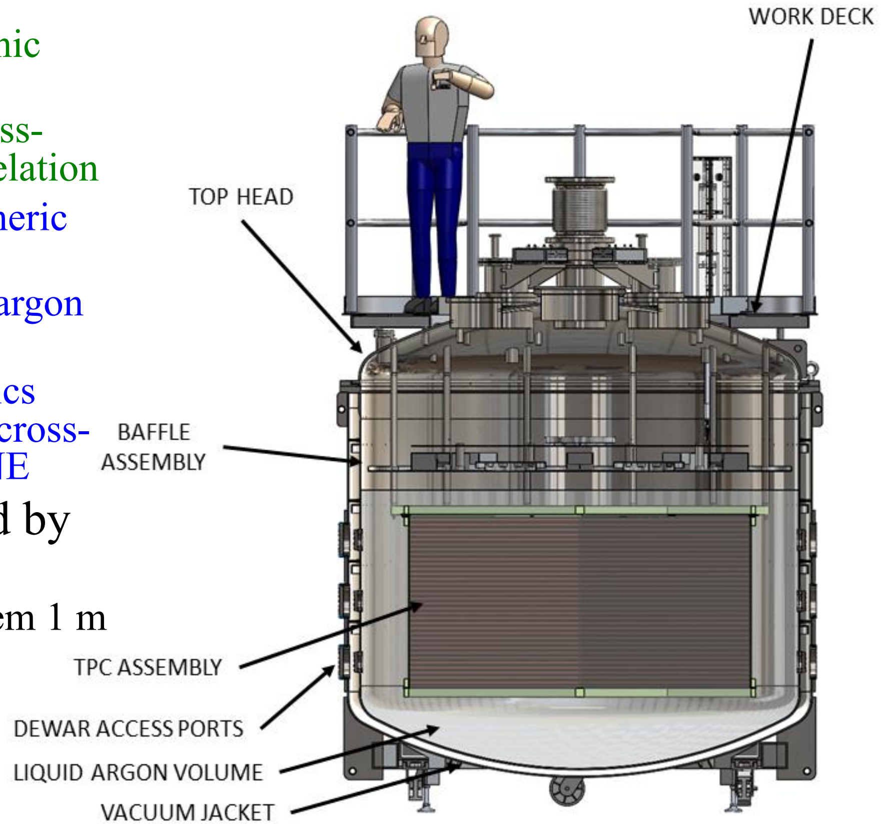


CAPTAIN

The CAPTAIN Program

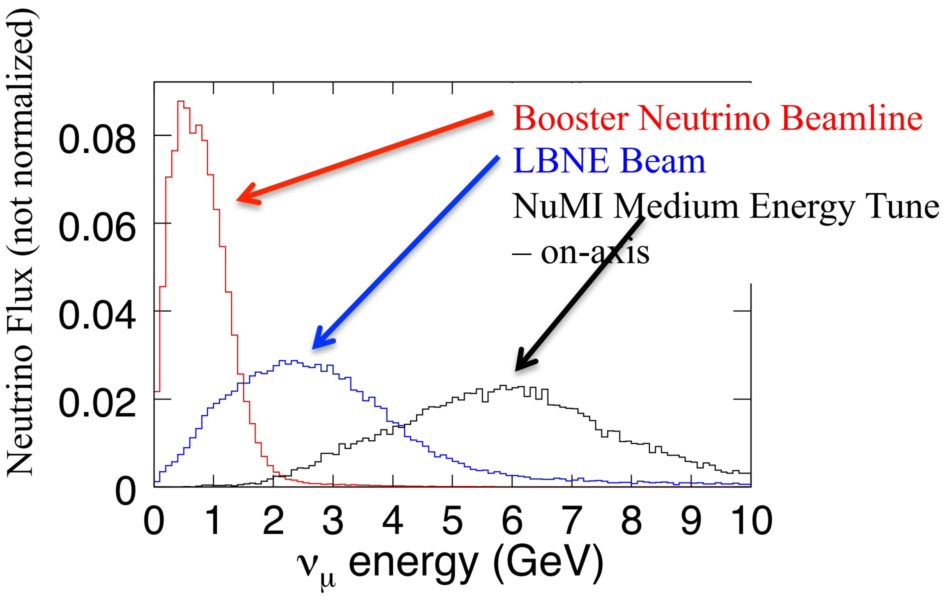
CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

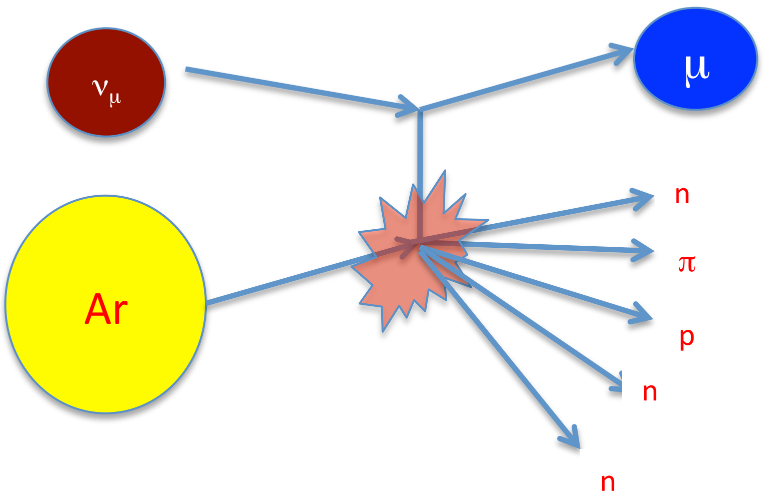
- Physics Program via neutron running and neutrino running impacts two LBNE physics missions
  - Low-energy neutrinos – supernova neutrinos
  - Neutron running to measure production of cosmogenic spallation products
  - Low-energy neutrino running yields CC and NC cross-sections, reconstructed vs. true neutrino energy correlation
  - Medium-energy neutrinos – accelerator and atmospheric neutrinos
  - Neutron running to measure neutron interactions in argon important for total neutrino energy reconstruction
  - Medium-energy neutrino running yields high-statistics event samples in the resonance regime and RR/DIS cross-over energy regime – complementary to MicroBooNE
- Detector – liquid argon TPC (completely funded by LANL LDRD)
  - hexagonal TPC with vertical drift, height and apothem 1 m yields 5 instrumented tons
  - 2000 channels, 3mm pitch
  - indium seal – can be opened and closed
  - same electronics as MicroBooNE
  - designed to operate safely at multiple facilities – ASME U-stamped vessel



CAPTAIN Program

- Detector funded by LANL LDRD program (project ends at end of FY 14)
- Anticipate DOE OHEP support for operation from FY15 – mostly people, minor M&S for shielding (low-energy neutrino running) and cryogenic safety
- Neutron running at LANSCE in autumn of CY 14
- Available for neutrino running from CY 15 – low-energy (stopped pion source – SNS or off-axis BNB), medium-energy (NuMI)
- Collaboration 15 institutions, 53 collaborators – more welcome
- International collaboration not required, but definitely welcome – especially for those considering LBNE participation
- For LBNE, critical to understand:
  - cross-sections and event topologies
  - propagation and reconstruction of charged particles
  - propagation and secondary interactions of neutrons for full neutrino energy reconstruction and background estimation
- CAPTAIN and LArIAT have related, but complementary missions that impact medium-energy neutrino physics
- CAPTAIN whitepaper: arXiv:1309.1740





Supernova Neutrinos in LBNE

- Galactic supernova will produce > 2000 events in the LBNE far detector
- Argon has a large CC electron neutrino cross-section – complementarity with large water detectors
- Large NC cross-section recently identified with ~ 10 MeV gamma-ray
- Supernova environment – neutrino-neutrino scattering is important

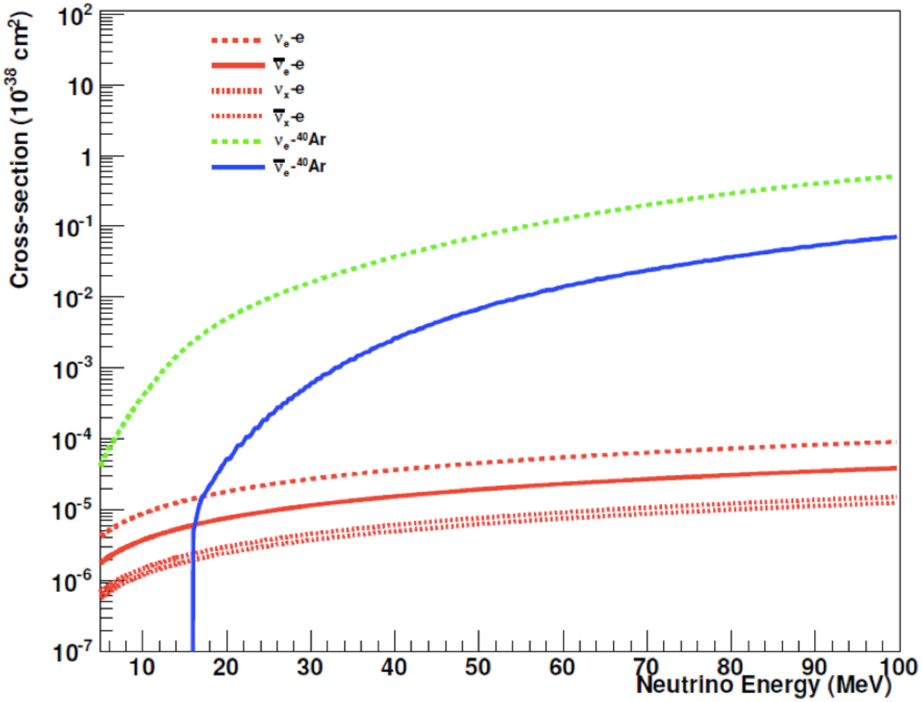
Primary interaction processes for neutrinos from supernova

$$\nu_e +^{40} Ar \rightarrow e^- +^{40} K^*$$

$$\bar{\nu}_e +^{40} Ar \rightarrow e^+ +^{40} Cl^*$$

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$$\nu_x +^{40} Ar \rightarrow^{40} Ar^* + \gamma$$

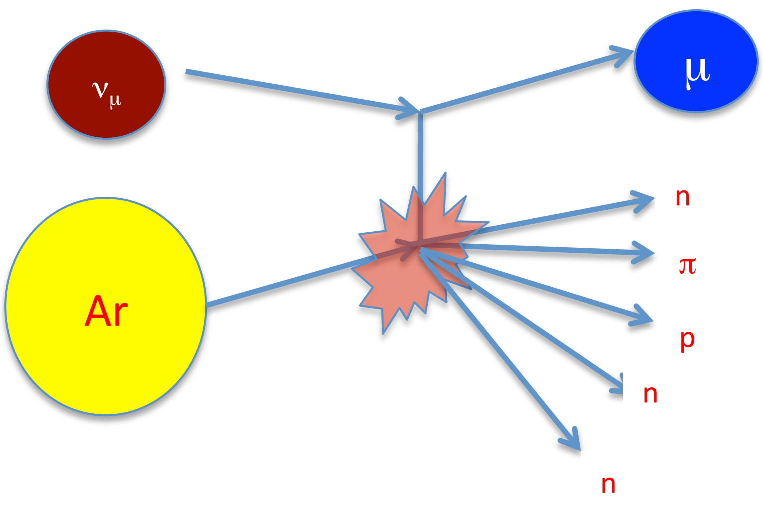


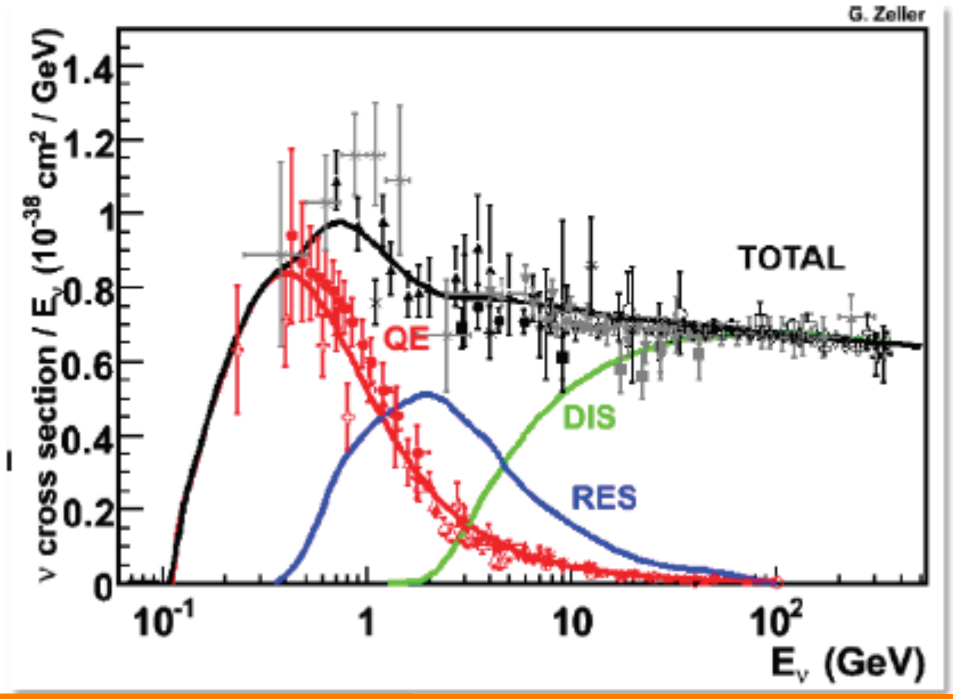
Low-Energy Neutrinos – Experimental Challenges

- Cosmogenic spallation backgrounds not well constrained
  - Spallation of argon from muon-argon photo-nuclear interactions
  - Muon-produced high energy neutrons – subsequent neutron spallation of argon
  - Muon-produced charged pions – subsequent spallation of argon
- Cross-sections have never been measured
  - Absolute cross-sections uncertain
  - Visible energy vs. neutrino energy
- Low energy is challenging for the TPC
  - Relatively poor energy resolution for the TPC at low energies
  - Trigger efficiency not well understood
- Use photon detection system to trigger and improve energy resolution
- A lot of light, but complicated structure
  - Scintillation and Cherenkov radiation
  - Prompt (~6ns) and late(~1.6 μsec) scintillation time constants
  - Scattering length 95 cm
- Anisotropic distribution of photon detectors in a TPC

Medium-Energy Neutrinos

- LBNE does long-baseline physics in resonance regime (1st Oscillation Maximum at ~2.4 GeV) and resonance/DIS cross-over regime
- Atmospheric neutrinos are measured in the same neutrino energy regime
- Neutrino oscillation phenomena depend on mixing angles, masses, matter densities, distance from production to measurement point, neutrino flavor and neutrino energy
- Critical to understand the correlation between true and reconstructed neutrino energy



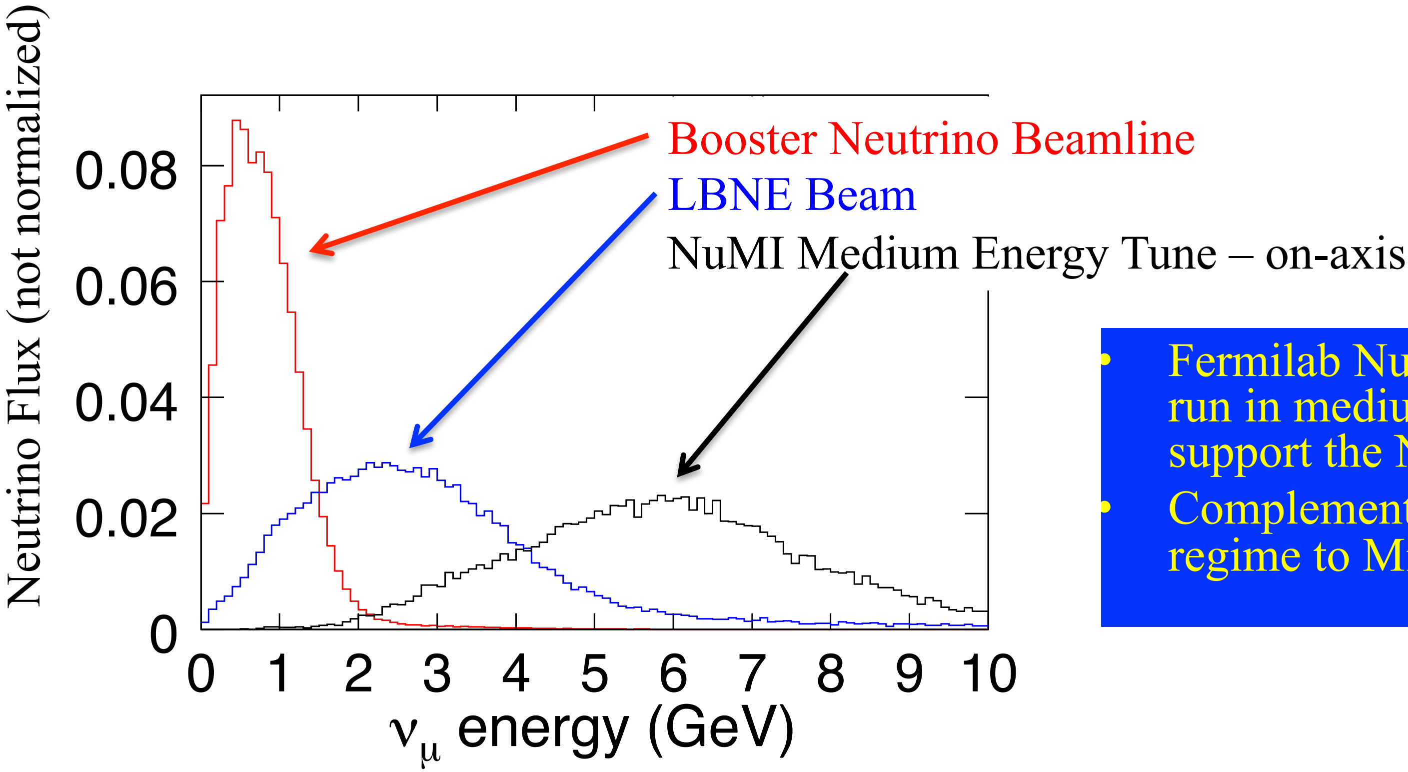


CAPTAIN Physics Program

Neutron Beam
Low-Energy Neutrino Beam
Medium-Energy Neutrino Beam

- Low-energy neutrino physics related
  - Measure neutron production of spallation products
  - Benchmark simulations of spallation production
  - Measure the neutrino CC and NC cross-sections on argon in the same energy regime as supernova neutrinos
  - Measure the correlation between true neutrino energy and visible energy for events of supernova-neutrino energies
- Medium-energy neutrino physics related
  - Measure higher-energy neutron-induced processes that could be backgrounds to ν_e appearance e.g. $^{40}Ar(n,\pi^0)^{40}Ar^{(*)}$
  - Measure neutron interactions and event signatures (e.g. pion production) to allow us to constrain number and energy of emitted neutrons in neutrino interactions
  - Measure inclusive and exclusive channels neutrino CC and NC cross-sections/ event rates in a neutrino beam of appropriate energy
  - Test methodologies of total neutrino energy reconstruction with neutron reconstruction

Neutrino Spectra



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

- 400,000 contained events per year (containing all but lepton)
  - employment of methods for neutron energy reconstruction
  - detailed exploration of threshold region for multi-pion production, kaon production
  - high-statistics data for algorithm development required for LBNE
  - early development of multi-interaction challenge – must solve if wish to usefully employ a near liquid argon TPC

CAPTAIN, LArIAT and medium-energy neutrinos

- Neutrino interactions are not well understood in the resonance and resonance/DIS cross-over region important for LBNE
- Critical to understand:
  - cross-sections and event topologies
  - propagation and reconstruction of charged particles
  - propagation and secondary interactions of neutrons for full neutrino energy reconstruction and background estimation
- CAPTAIN and LArIAT have related, but complementary missions that impact medium-energy neutrino physics

Summary

- The CAPTAIN Detector is a liquid argon time-projection chamber with 5 instrumented tons being constructed at Los Alamos National Laboratory
- CAPTAIN is designed to address scientific questions of importance to two major LBNE missions: low-energy (supernova) neutrinos and medium-energy (long-baseline, atmospheric) neutrinos
- CAPTAIN will address the scientific issues with neutron beam running and neutrino running
- CAPTAIN will be a test-bed for LBNE laser calibration design activities
- CAPTAIN will be available for LBNE R&D activities
- CAPTAIN is complementary to other crucial efforts (MicroBooNE, LArIAT)
- The CAPTAIN science program will:
  - provide near-term scientific opportunities for scientists
  - build the intellectual critical mass of people who will run LBNE when it is built (10 years from now)