Short-Baseline Neutrino Experiments at Fermilab and Role of the Near Detector

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Outline

- LSND experiment
- MiniBooNE experiment
- Short-Baseline Anomalies
- Sterile Neutrinos and Summary of Relevant Results
- Future Short-Baseline Experiments
- LAr Technique
- Short-Baseline Neutrino Program at Fermilab
- SBN R&D Component and P5
- SBND: Short-Baseline Near Detector
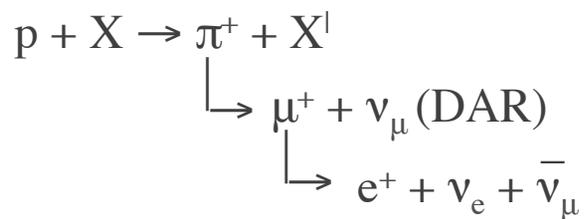- Booster Beamline Optimization
- Summary
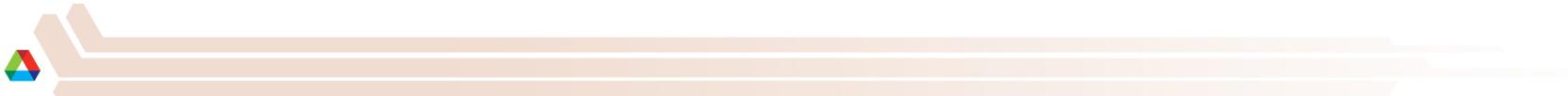
Short-Baseline Results: LSND

- LSND: Los Alamos Liquid Scintillator Neutrino Detector
  -Low energy $\bar{\nu}_\mu$ beam from DAR using LANSCE proton beam at LANL
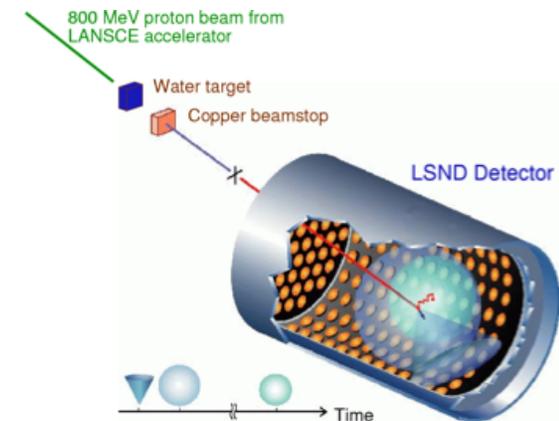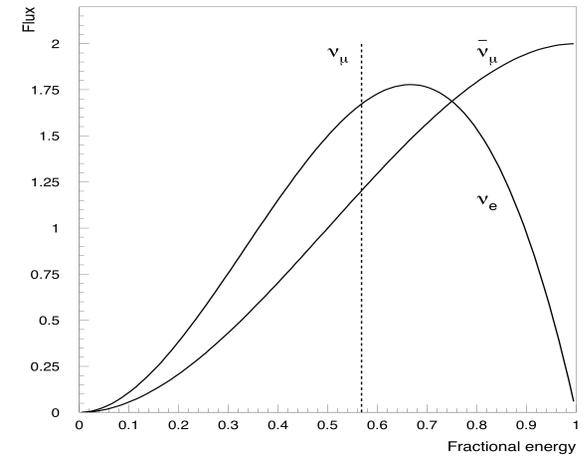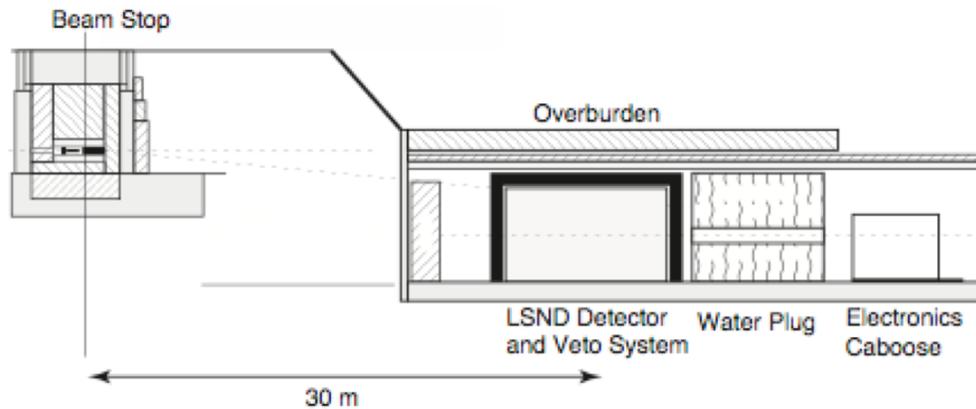
-Used intense proton beam to produce muon anti-neutrinos

$$p + X \rightarrow \pi^+ + X^!$$
$$\quad\quad \hookrightarrow \mu^+ + \nu_\mu \,(DAR)$$
$$\quad\quad\quad\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

-Detection based on IBD reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\quad\quad n + p \rightarrow d + \gamma \,(2.2 \text{ MeV})$$

3
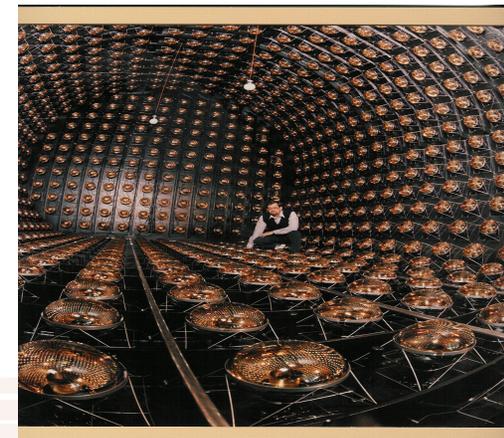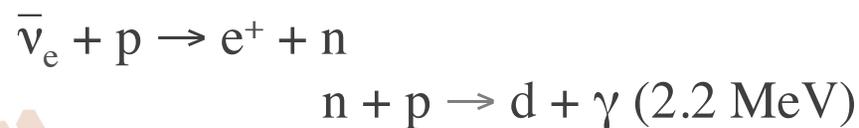
Short-Baseline Results: LSND

- LSND: Los Alamos Liquid Scintillator Neutrino Detector
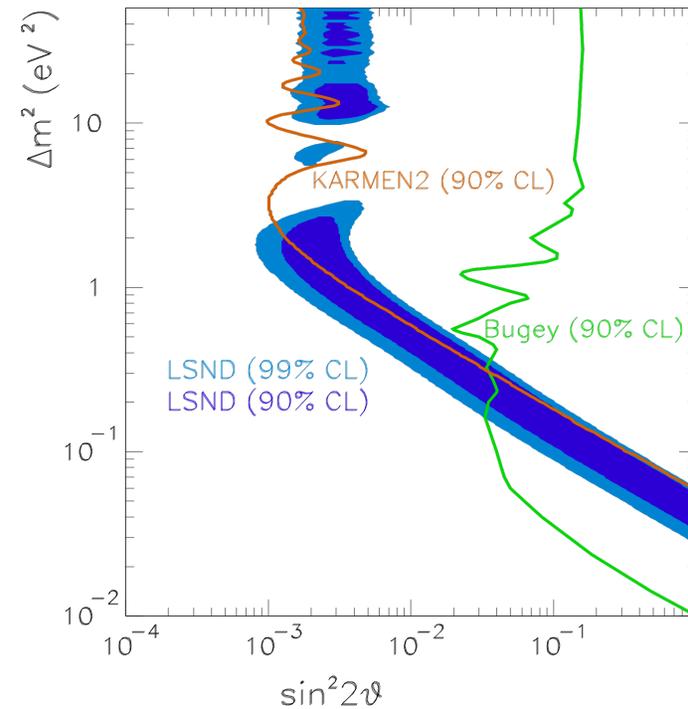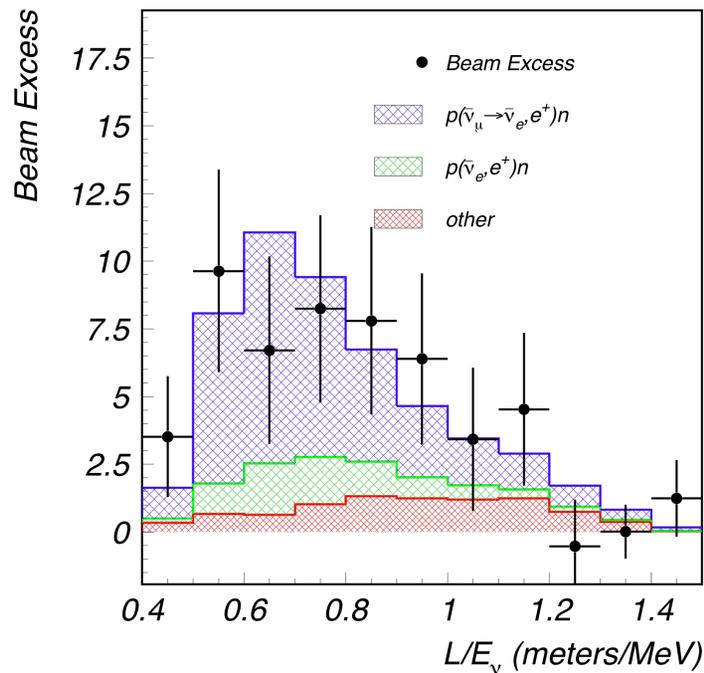
- LSND observed a 3.8σ excess of events above background expectation.
  -if interpreted through neutrino mixing it would be consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, corresponding to $P_{osc} = (0.264 \pm 0.067 \pm 0.045)\%$
  -not consistent with L/E of the three neutrino paradigm i.e. L/E ~ 1 km/GeV

- Could this be evidence of mixing through a sterile sector?

Short-Baseline Results: MiniBooNE

- MiniBooNE Experiment (Mini Booster Neutrino Experiment)

μ^-

p

π^-

$\overline{\nu}_\mu$

π^+

(antineutrino mode)
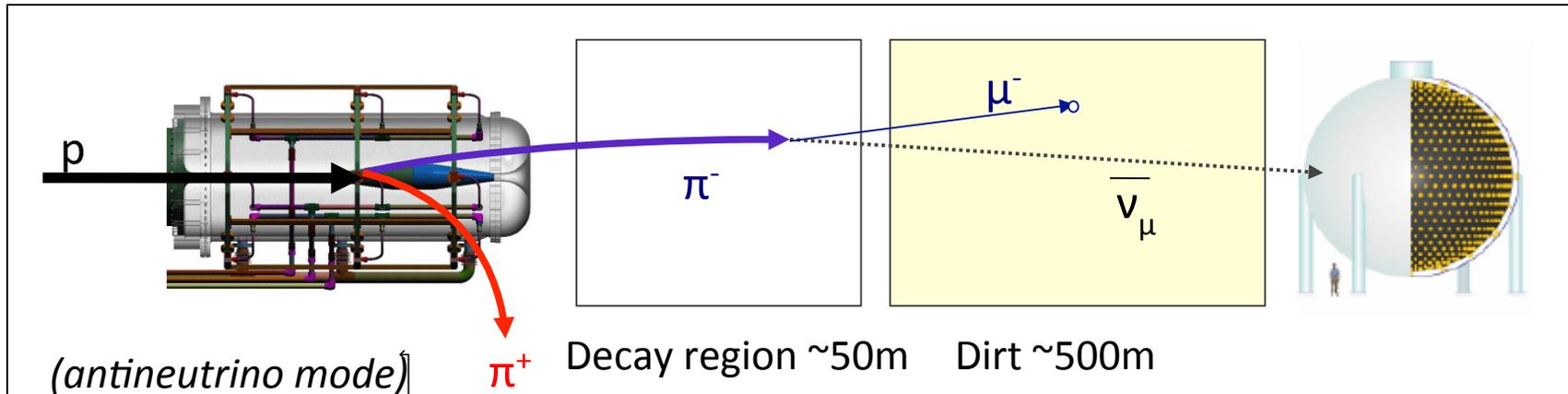
Decay region ~50m   Dirt ~500m

- Similar L/E as LSND for $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p + Be)
  - Horn polarity $\rightarrow$ neutrino or anti-neutrino mode
- 800 ton mineral oil Cherenkov detector

Short-Baseline Results: MiniBooNE

- MiniBooNE Detector Tank

Short-Baseline Results: MiniBooNE

- MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)

11.27x10^{20} POT

MiniBooNE observes an excess of events consistent with $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

6.46x10^{20} POT

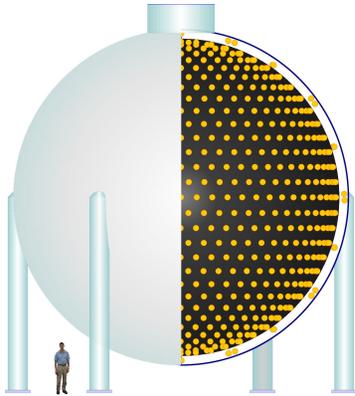Excess events can be electrons or single photons since these are indistinguishable in MiniBooNE's Chrenkov detector

Short-Baseline Results: MiniBooNE

- MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)
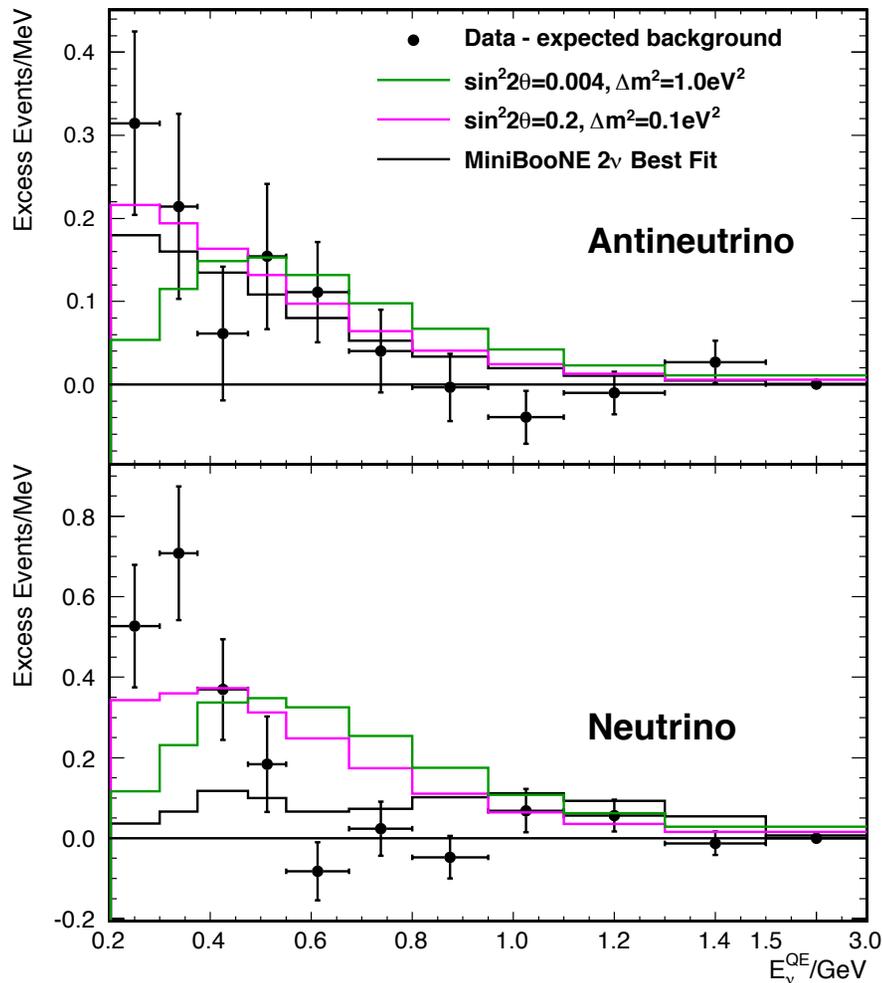
Antineutrino Event Excess
from 200-1250 MeV =
78.4+-20.0+-20.3 (2.8σ)

Neutrino Event Excess from
200-1250 MeV =
162.0+-28.1+-38.7 (3.4σ)

Low energy excess:
- By shape not good fit to
  LSND result
- Is it e or γ?
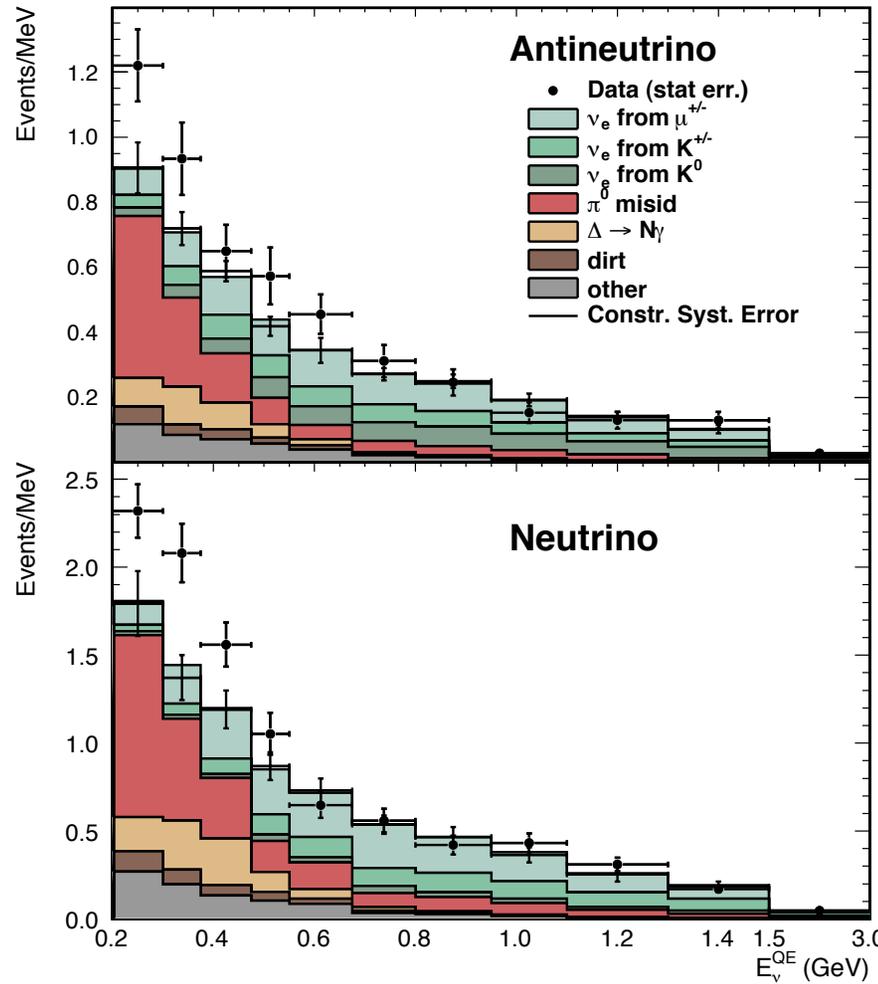
Combined Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

Short-Baseline Results: MiniBooNE

- MiniBooNE Neutrino Oscillation Results
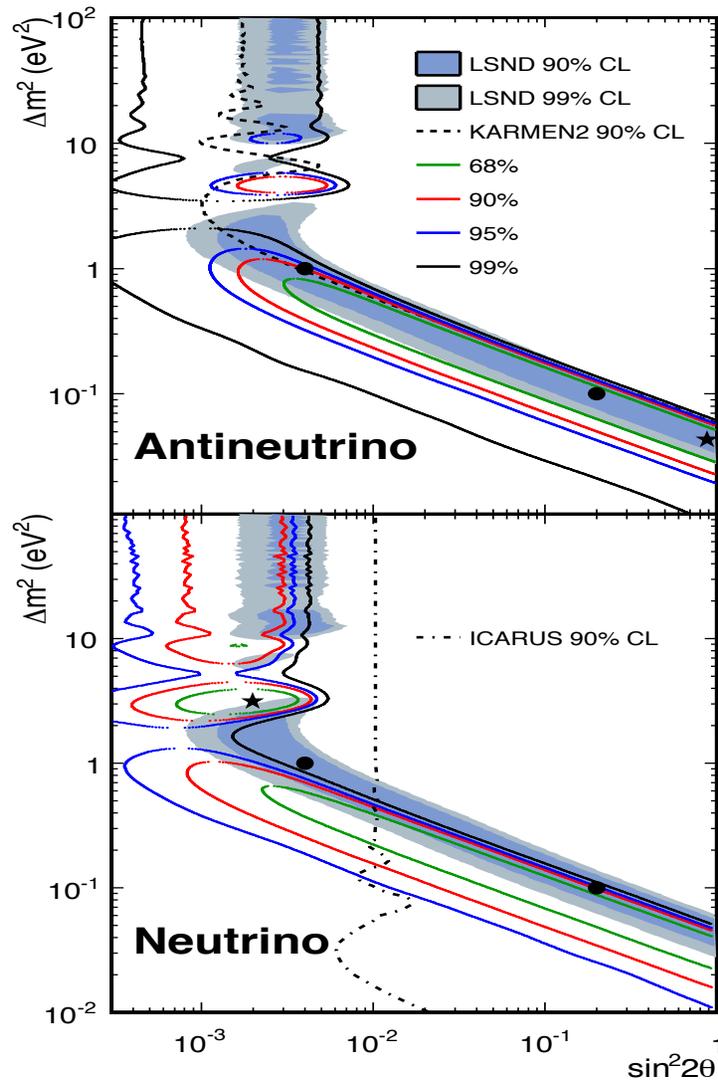
Phys. Rev. Lett. 110, 161801 (2013)

Antineutrino

$P_{bf} = 66\%$, $P_{null} = 5.4\%$
P_{null} relative to $P_{bf} = 0.5\%$

Neutrino

$P_{bf} = 6.1\%$, $P_{null} = 0.5\%$
P_{null} relative to $P_{bf} = 2.0\%$

The black stars show the MiniBooNE best fit points, while the circles show the example values for several oscillation parameter sets.

Short-Baseline Results: MiniBooNE

- Caveats Associated with MiniBooNE Combined Neutrino + Antineutrino Fit
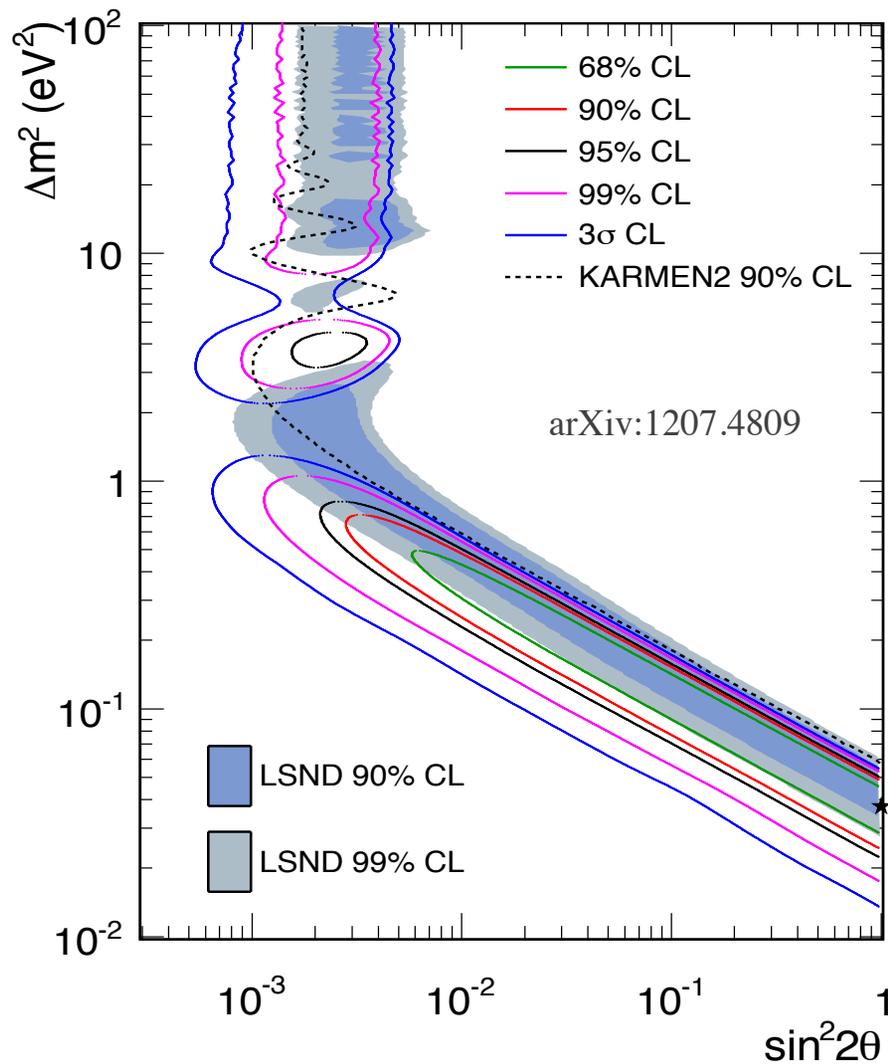
Neutrino energy distortions can affect the oscillation fits:
- N-N interactions
- ν_e & ν_μ disappearance
- 3+N models with CP

$P_{bf} = 6.7\%$, $P_{null} = 0.1\%$
P_{null} relative to $P_{bf} = 0.03\%$

Short-Baseline Results: MiniBooNE

- MiniBooNE L/E Distributions
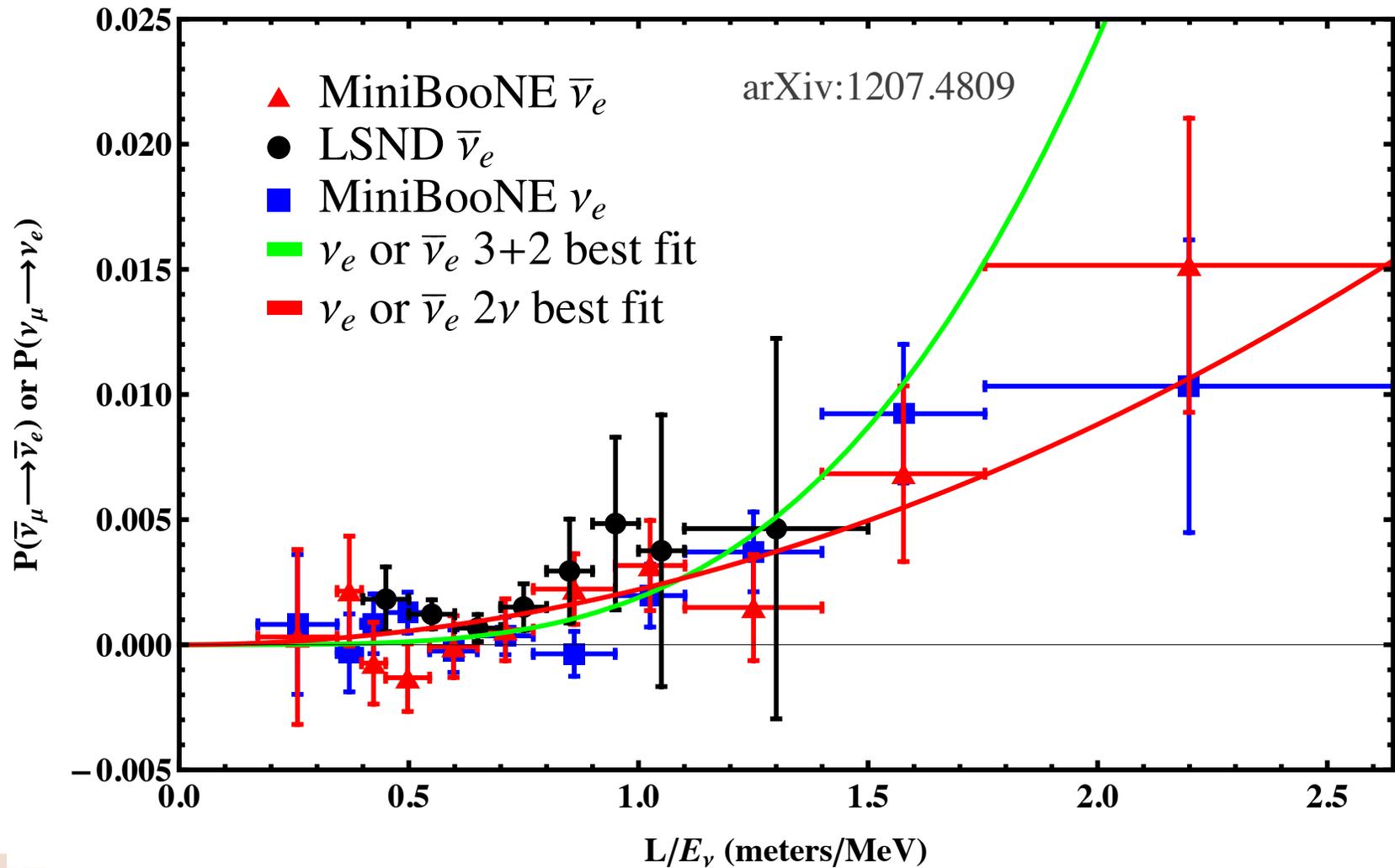
Short-Baseline Neutrino Anomalies

- Radioactive Source Measurements: Gallium Anomaly
  -GALLEX/SAGE: observe fewer events than expected from their calibration measurements,
  -Consistent with ν_e disappearance to sterile neutrinos.

SAGE, Phys. Rev. C 73 (2006) 045805

R=0.86±0.05

Giunti et al.; arXiv:1210.5715
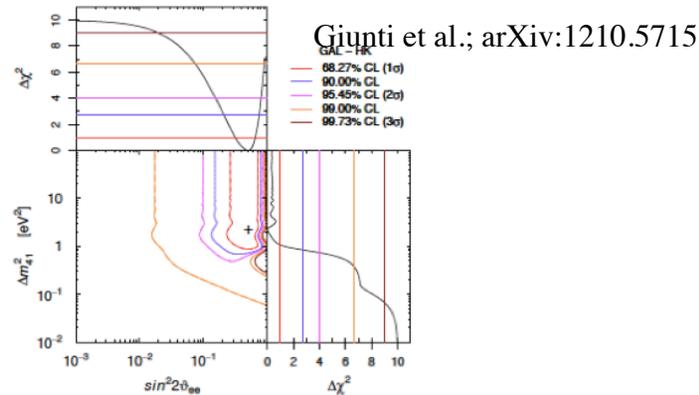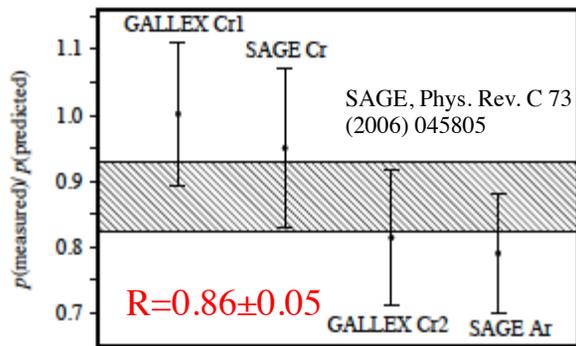
- Reactor Antineutrino Results: Reactor Anomaly
  -Reactor neutrino experiments observe fewer events than expected (in addition to θ_{13} effect)
  -Consistent with ν_e disappearance to sterile neutrinos.
  -What is systematic uncertainty in neutrino flux?
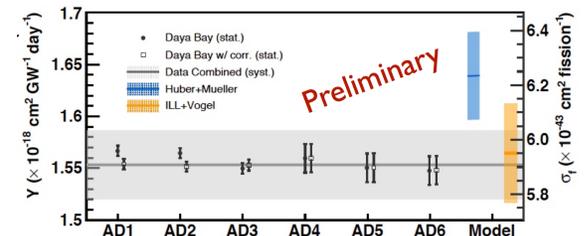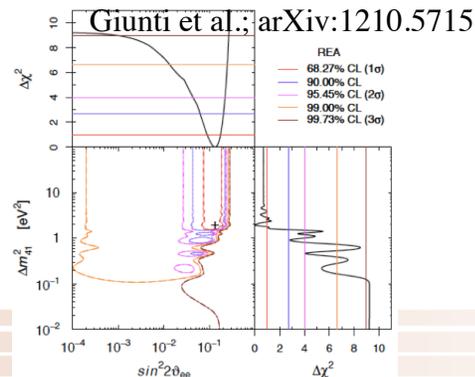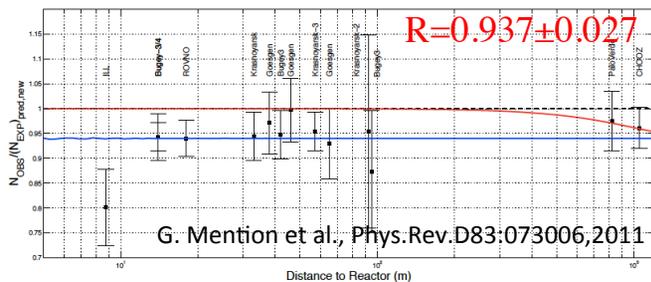
W. Tang, Daya Bay at PPC2015

R=0.937±0.027

G. Mention et al., Phys.Rev.D83:073006,2011

Giunti et al.; arXiv:1210.5715
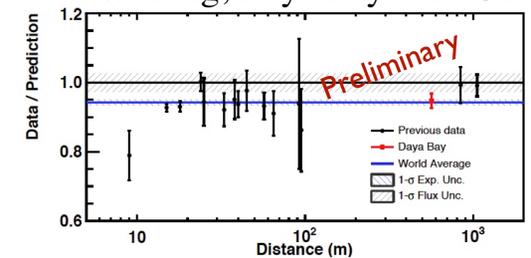
Daya Bay result: R = 0.946 ± 0.022
The World Average: R = 0.942 ± 0.009

12

Sterile 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)

- For comparisons we often work with 3 + 1 models.
  -However, models with a single ν_s don't describe all of the data

3+N Sterile Neutrino Models

ν_5

$\Delta m^2_{51} \sim 0.1\text{-}100 \text{ eV}^2$

ν_4

$\Delta m^2_{41} \sim 0.1\text{-}100 \text{ eV}^2$

ν_3

ν_2

ν_1

$\Delta m^2_{21} = \Delta m^2_{32} = \Delta m^2_{31} = 0$
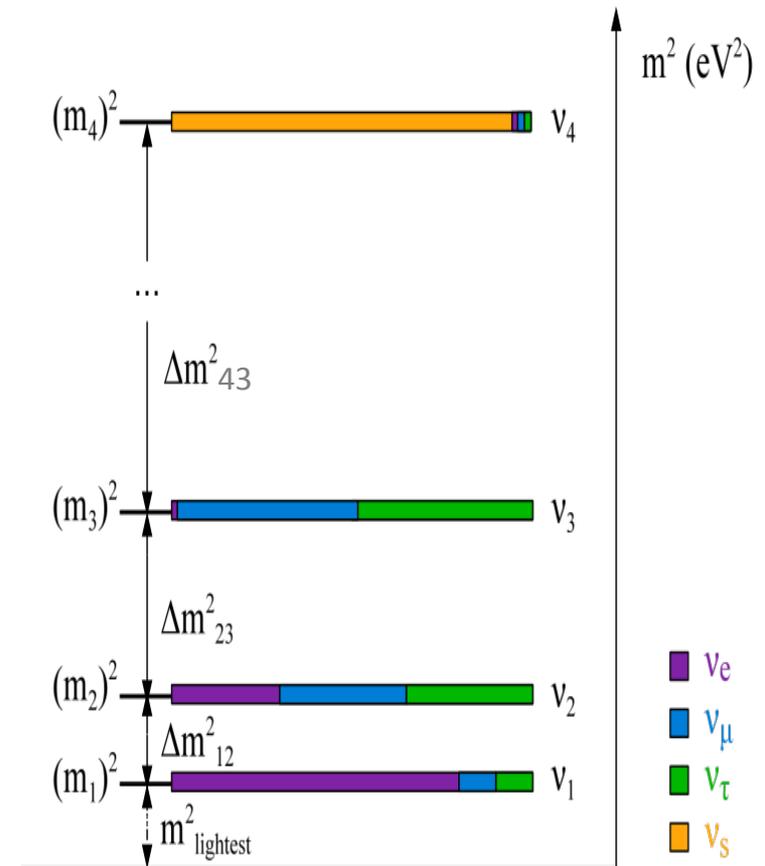
ν_e ν_μ ν_τ ν_s
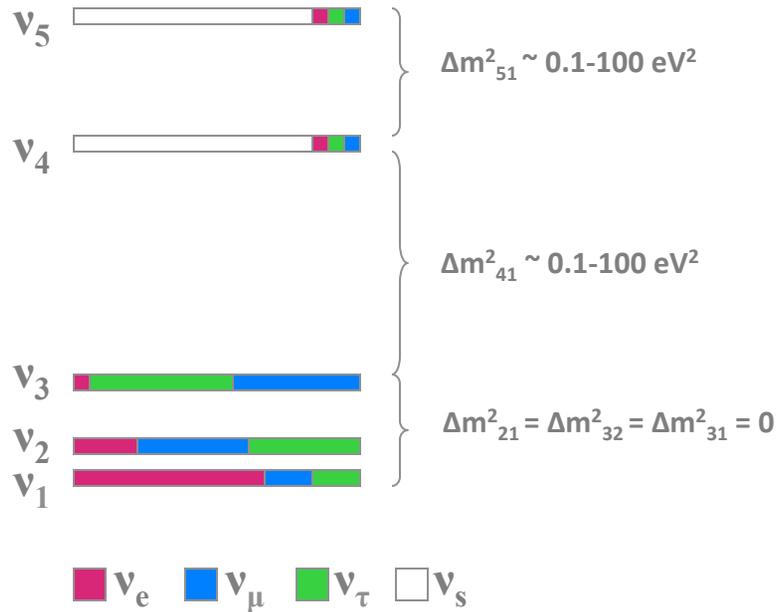
- 3+N models

- Simplified 3+2 Models for $\nu_\mu \rightarrow \nu_e$:
  - -2 independent Δm^2
  - -3 mixing parameters
  - -1 Dirac CP phase

- $N_s > 1$ allows CP violation for short baseline experiments

  - $\overline{\nu}_\mu \rightarrow \overline{\nu}_e \neq \nu_\mu \rightarrow \nu_e$

Note: There are also other, more exotic possibilities

Summary of Experimental Results

- 3+1 model

Giunti et al.

Kopp et al.
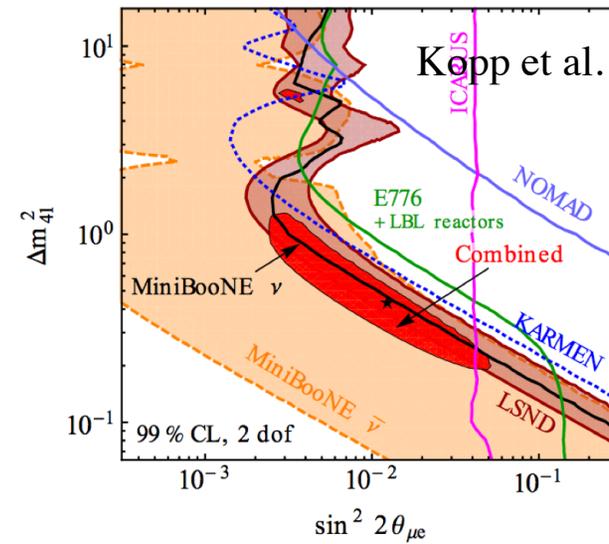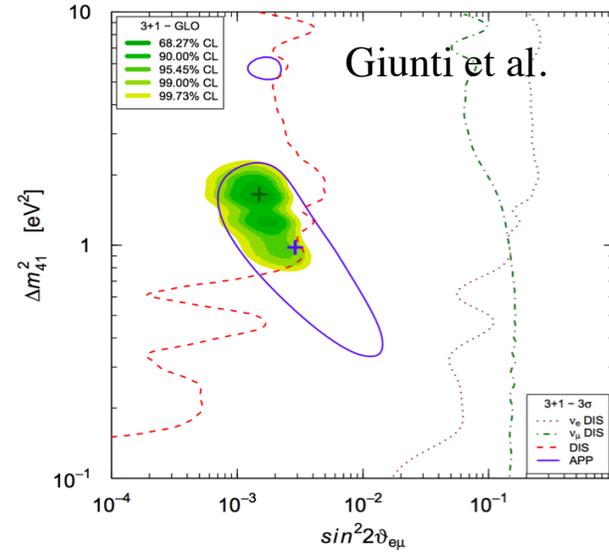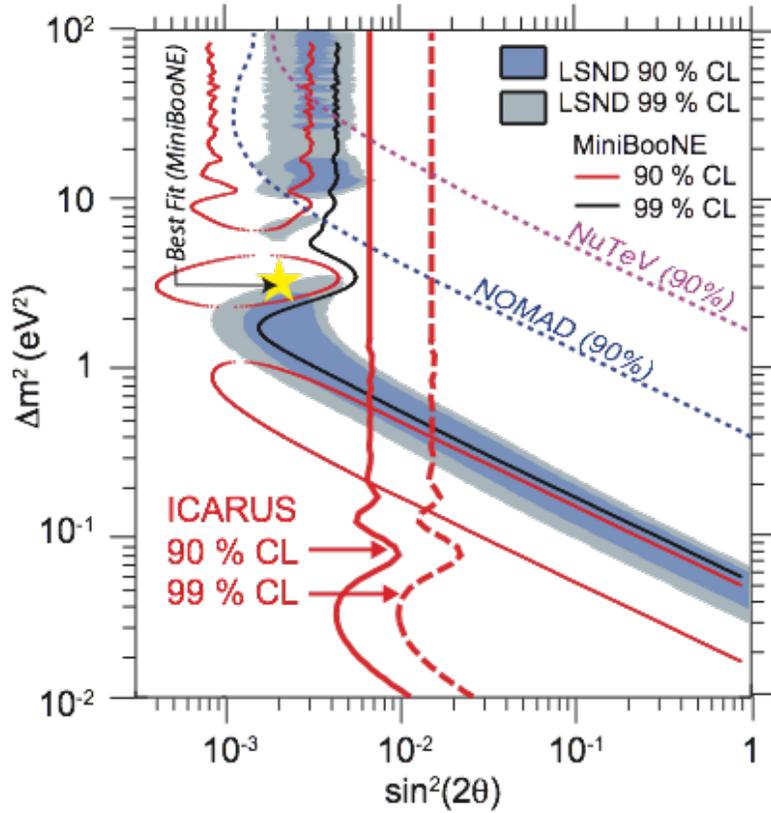
Summary of Experimental Results

- Global 3+N Fits to World Data
  - J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, & J. Spitz, arXiv:1207.4765

3+1 (P=55%)

3+2 (P=69%)
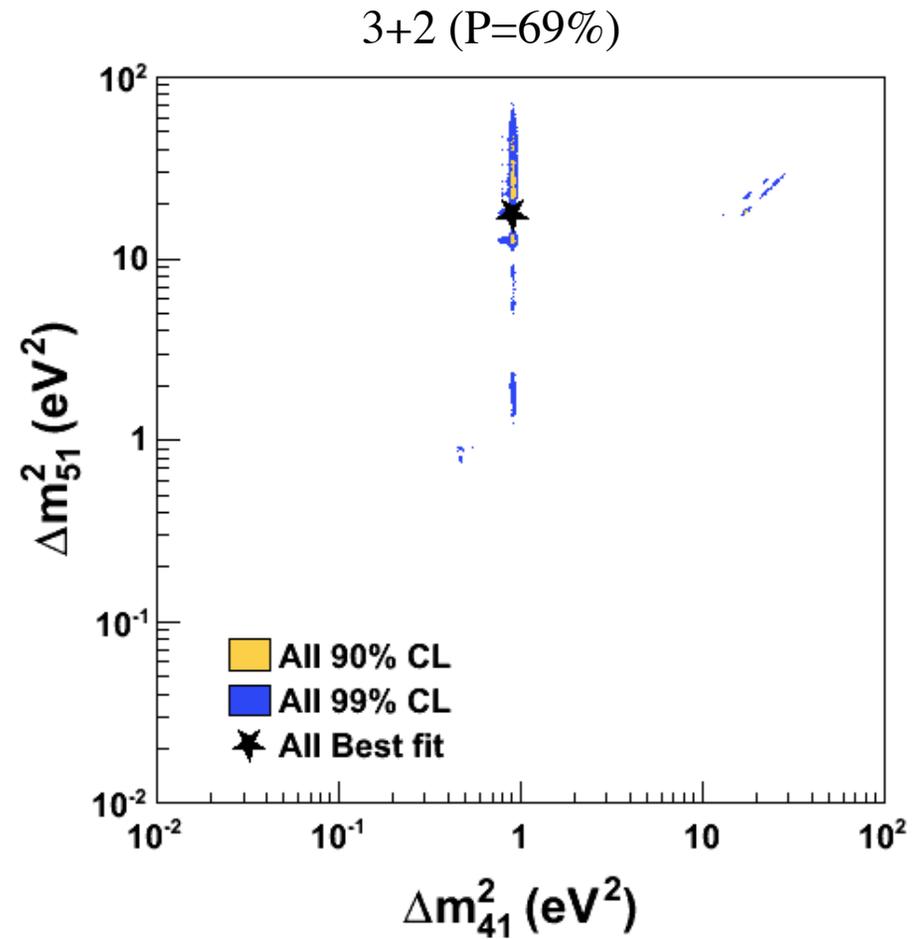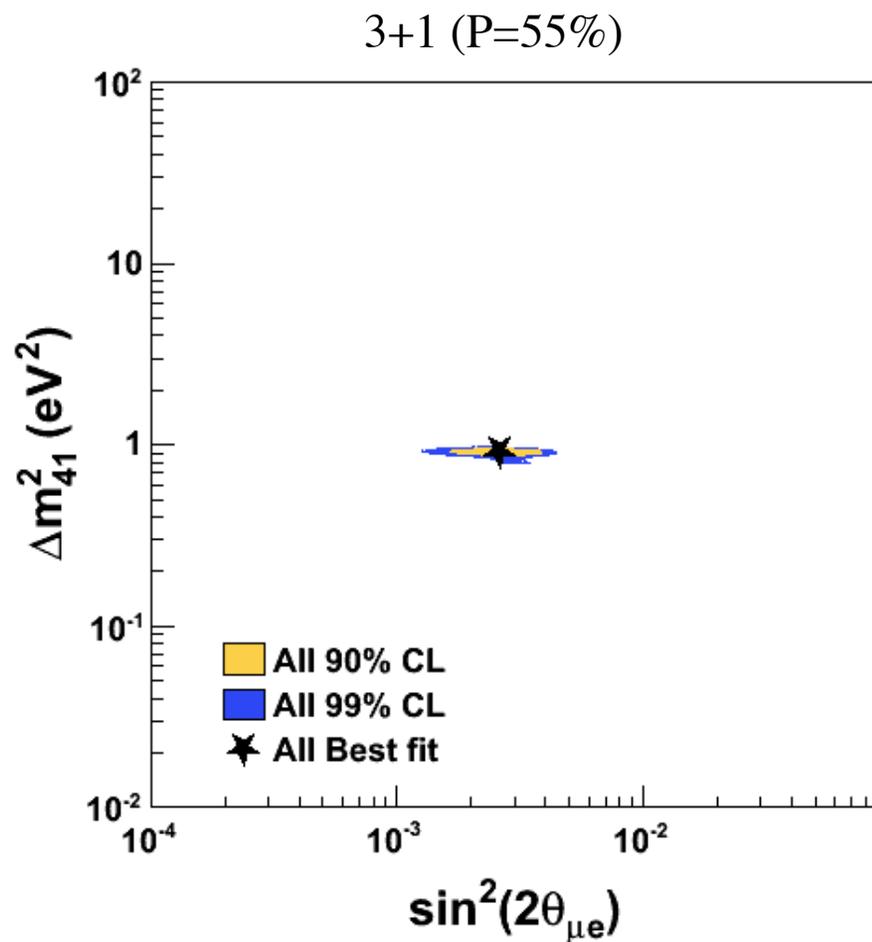
Summary of Experimental Results

- Global 3+2 & 1+3+1 Fits
  -Kopp, Machado, Maltoni, & Schwetz, arXiv:1303.3011
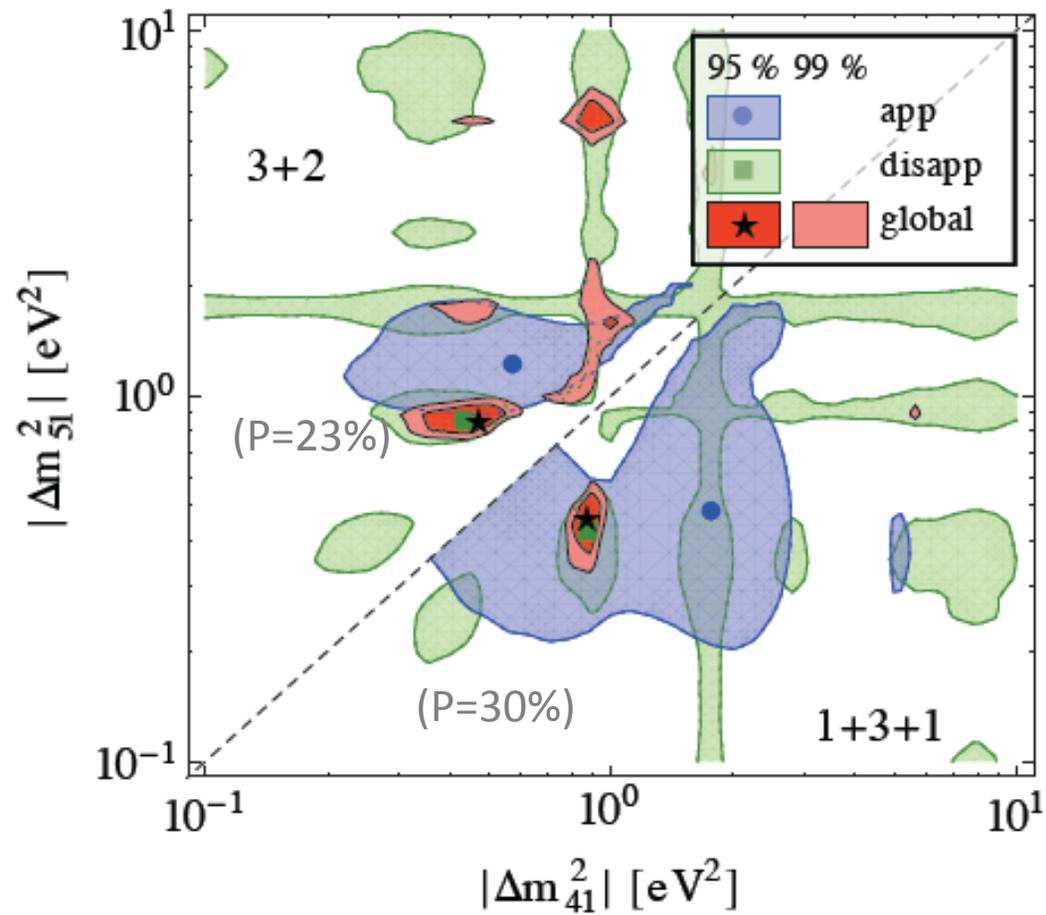
Future Sterile ν Tests

- There is a diverse set of experiments, spanning vastly different energy scales (from ~1 MeV to ~10 TeV), that have been proposed to test the 3+N models & resolve the present anomalies:

- Accelerator ν Experiments: MicroBooNE+SBND+ICARUS, MINOS+, NuStorm , DUNE, OscSNS at ORNL, KPIPE, J-PARC E56, IsoDAR, nuPRISM
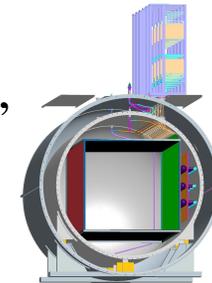
- Reactor anti-ν Experiments: SCRAAM, NUCIFER, PROSPECT
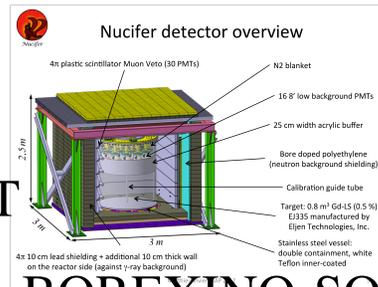
- Radioactive Source ν Experiments: BOREXINO-SOX, KamLAND, Daya Bay, Baksan, LENS

- Atmospheric ν Experiments: IceCube
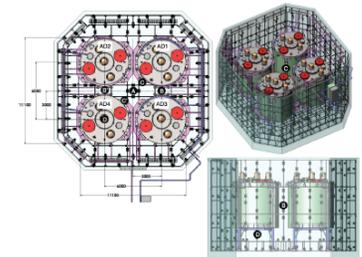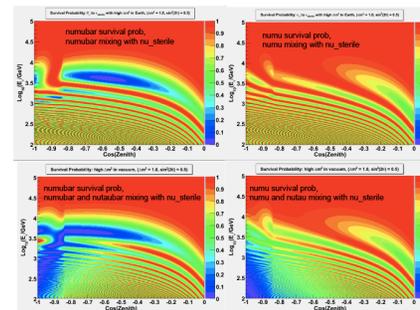
P5 Recommendations

- The Particle Physics Project Prioritization Panel (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP), has completed its report in 2014, a ten-year strategic plan for high energy physics in the U.S.
- P5 recommendations on neutrino program:

Recommendation 12: In collaboration with international partners, develop a coherent **short-** and **long-baseline neutrino program** hosted at Fermilab.

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Recommendation 15: Select and perform in the short term a set of **small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm**. Some of **these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab**.

Historical Development of the Short-Baseline Program

- 2003-13 - 1st gen. BNB experiments: MiniBooNE and SciBooNE

- 2015-18 - 2nd gen. BNB experiment: MicroBooNE => apply liquid argon technology to separate electrons from gammas!

- Jan. 2014 – Two new proposals to Fermilab PAC for next phase at BNB:
  -P-1052: ICARUS@FNAL
  -P-1053: LAr1-ND*

- May 2014 – P5 recommendations

- May 2014 – SBN Taskforce and working groups start developing joint proposal

- Jan. 2015 – Joint proposal presented to PAC, recommends Stage 1 approval

- Feb. 2015 – Director grants Stage 1 approval

  * March 2015: LAr1-ND changed name to Short-Baseline Near Detector (SBND)

Liquid-Argon TPC Technology

- Liquid Argon Time Projection Chamber (TPC) Operation

MIP dE/dx = 2.2 MeV/cm
→ ~ 1fC/mm @ 500 V/cm
→ ~1 MeV/wire
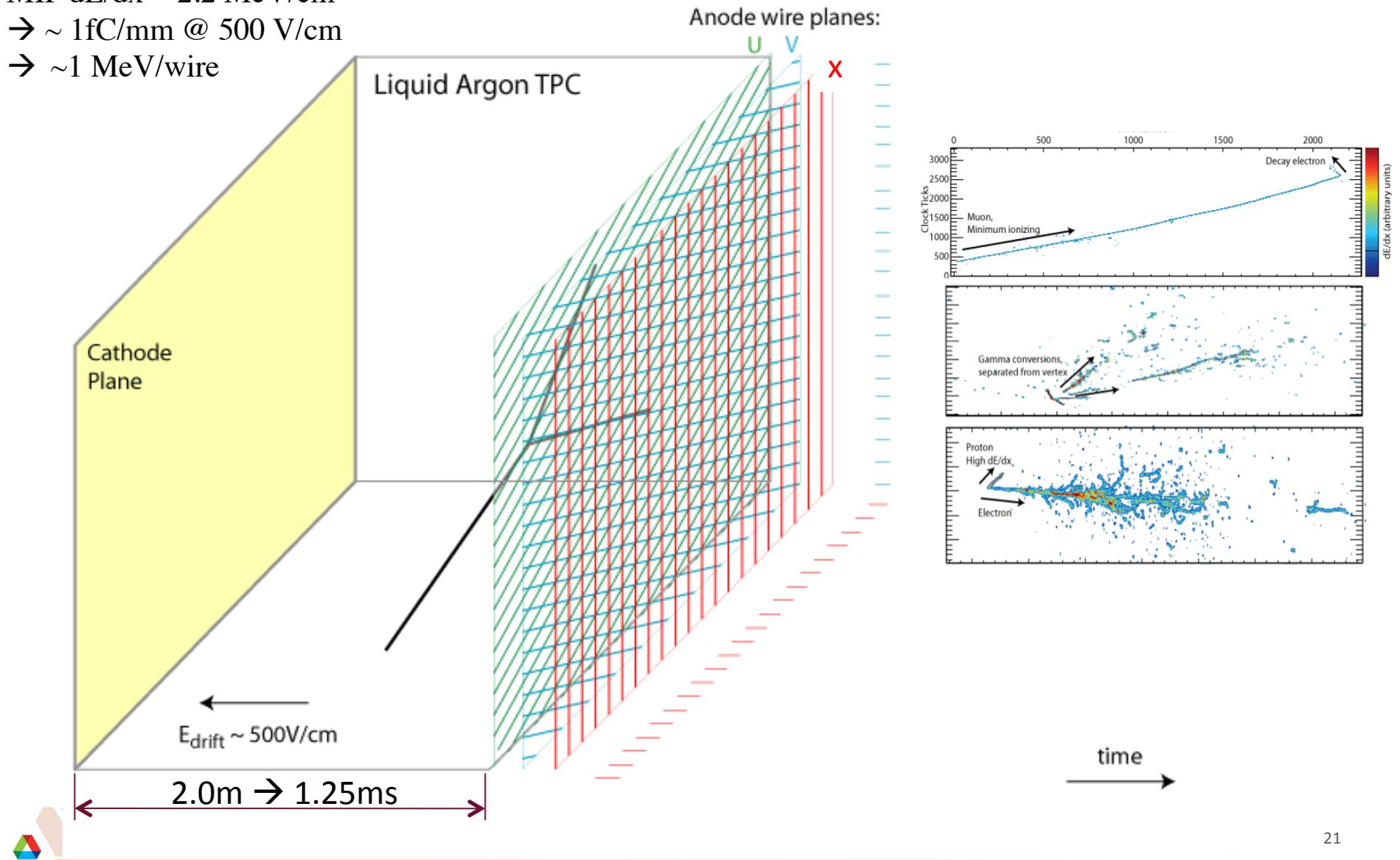
Liquid-Argon TPC Technology

- A new generation of detectors for neutrino oscillation searches (SBN, DUNE) will be based on the liquid argon time projection chamber (LArTPC) technique.
-enables unprecedented capabilities in tracking, particle ID and calorimetric energy reconstruction.

ArgoNeuT

- Neutrino interactions in LAr will produce the final state particles; these particles will ionize the liquid and produce free electrons.
-A field of ~500 V/cm is applied between anode plane assemblies (APAs) and cathode plane assemblies (CPAs).

Single electron shower

γ→e⁺/e⁻ shower

- An APA will consist of three planes (an induction and two collection planes) of closely spaced wires (3-5 mm distance apart) to be used to collect the drifted charge from free electrons.
-The signal induced on the wires is proportional to the amount of energy deposited in the drift region.
-Along with about 9000 electrons released per cm of an ionizing particle track, about 10000 scintillation photons are emitted with a wavelength of 128 nm.

ArgoNeuT Preliminary

Neutrino 2014

dE/dx el vs γ Data
electrons
gammas
γs reco
elecs reco

e

$\gamma \rightarrow e^+e^-$

Average dE/dx [MeV/cm]
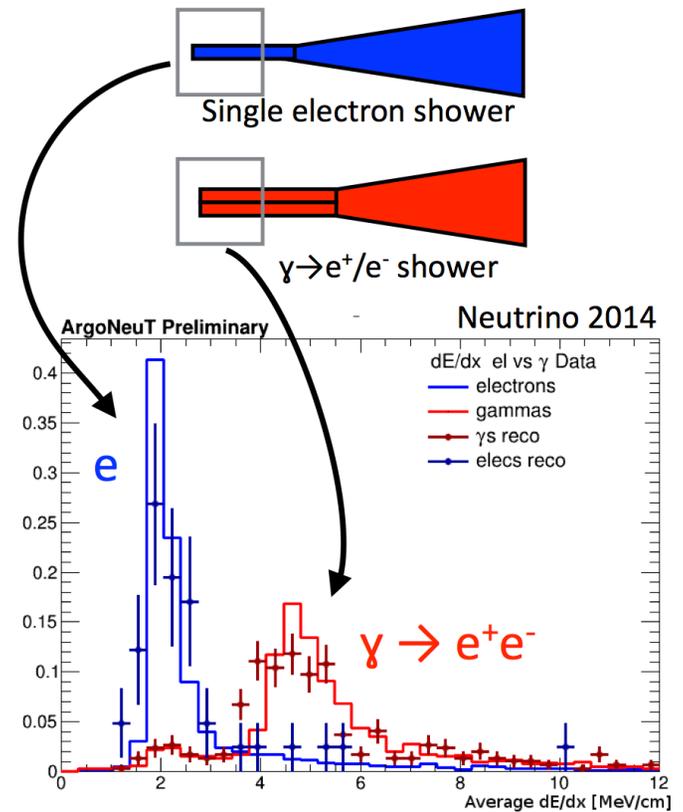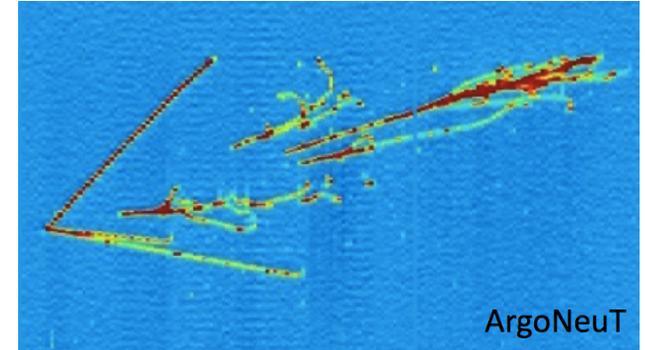
Two Neutrino Beams at Fermilab

Booster ν beam
low energy, short distance
- MiniBooNE
- SciBooNE
- MicroBooNE
- SBND
- ICARUS

ν_μ

ν_μ

NuMI ν beam
high energy,
long distance
- MINOS
- MINERvA
- NOvA

Booster
proton energy: 8 GeV

Main Injector
proton energy: 120 GeV
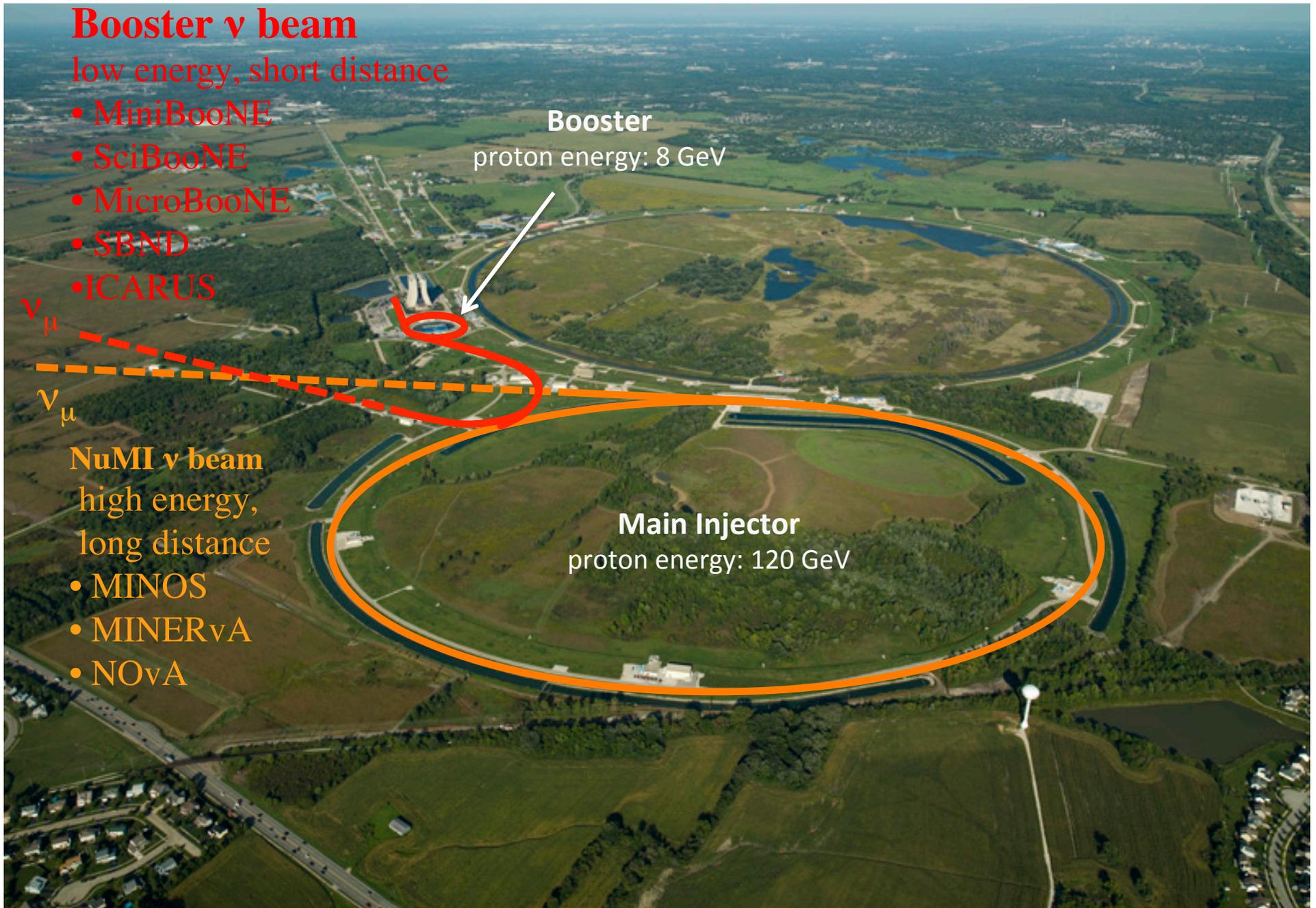
SBN: A Multi-LAr TPC Short-Baseline Program at FNAL
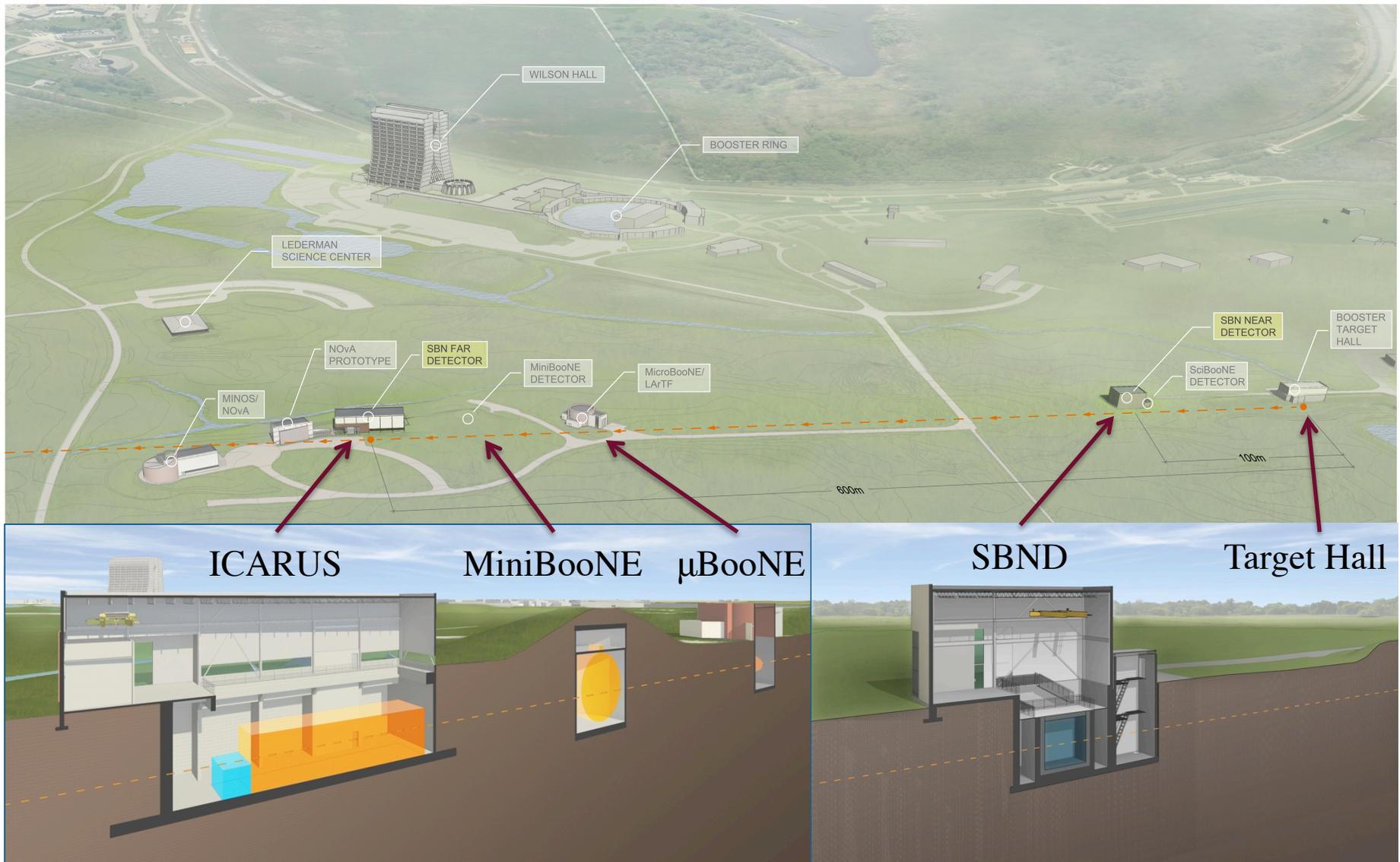
Short-Baseline Neutrino (SBN) Program at Fermilab

- Program Objectives

  -Test Neutrino Anomalies with multiple LAr TPC Detectors at FNAL: is there a new physics (i.e. sterile neutrino)?
  -Use the short-baseline program as R&D platform for DUNE.

- Realization with Near and Far Detectors at Booster beam-line at FNAL

Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
SBND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t

SBN Near Detector: SBND

SBN Far Detector: ICARUS@FNAL

MicroBooNE

Neutrino Energy: 700 MeV

$\Delta m_{41}^2 = 1.2 \ eV^2$

$sin^2(2\theta) = 0.003$

Oscillation Probability [%]

Length of Neutrino Flight [m]
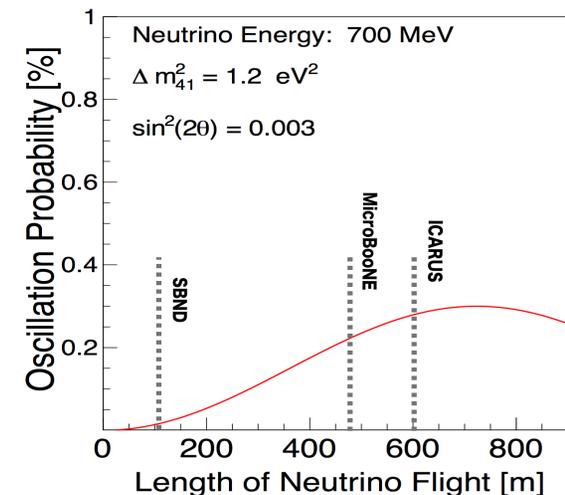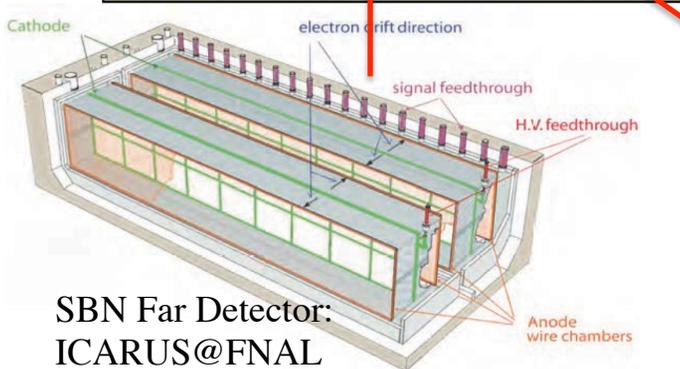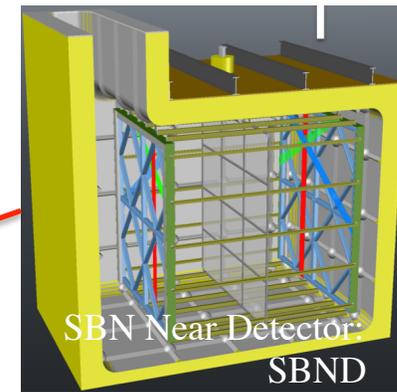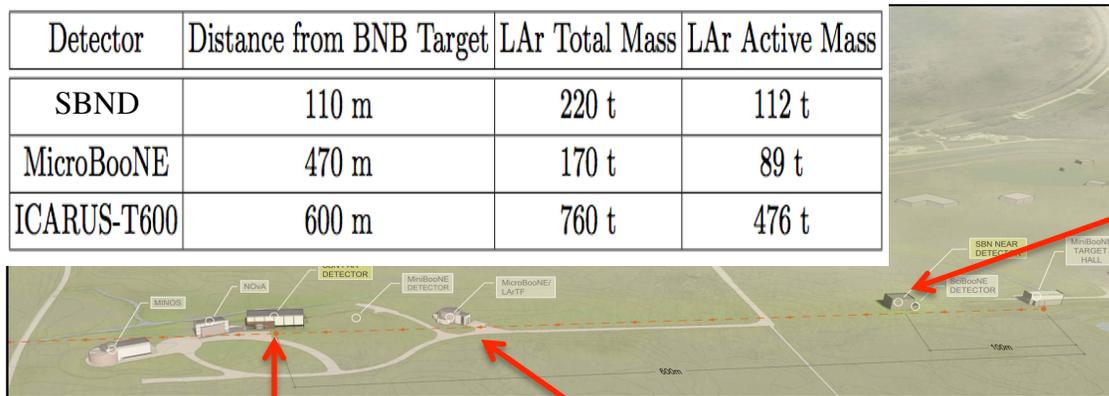
Short-Baseline Neutrino (SBN) Program at BNB

- Centered along the Booster Neutrino Beam (BNB)
- Well understood ν flux with peak at ~700 MeV
  - Hadron production data (HARP experiment @ CERN)
  - 10+ years of study by MiniBooNE and SciBooNE
- Detectors at ~500m yield L/E ~ 1 km/GeV
- Robust target and single horn system: 375 million pulses on last horn
- Beam near surface (~10m):
  - Modest civil construction cost
  - Cosmic backgrounds need to be understood
- Future improvements planned

Flux from BNB in nu mode at SBND (100m)   Flux from BNB in nubar mode at SBND (100m)
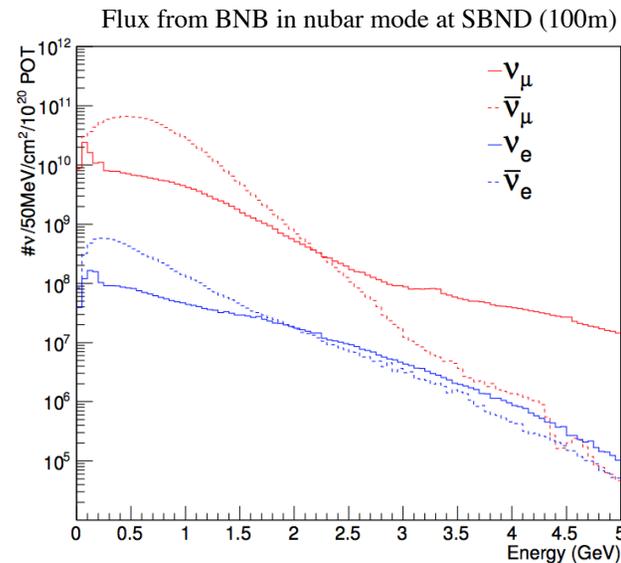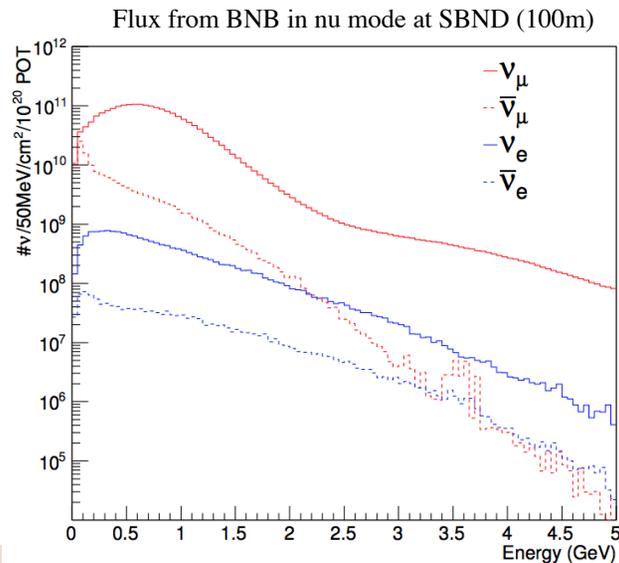
SBN Program Proposal

- A joint proposal by three Short-Baseline Neutrino Collaborations
  - ICARUS-WA104,
  - SBND (formerly known as the LAr1-ND), and
  - MicroBooNE
  - (+ additional contributors)

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam
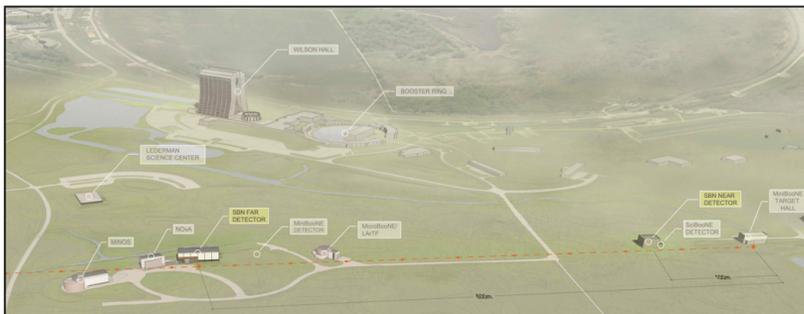
The ICARUS-WA104 Collaboration

M. Antonello[16], B. Baibussinov[31], V. Bellini[5], P. Benetti[32], S. Bertolucci[6], H. Bilokon[15], F. Boffelli[32], M. Bonesini[17], J. Bremer[6], E. Calligarich[32], S. Centro[31], A.G. Cocco[19], A. Dermenev[20], A. Falcone[32], C. Farnese[31], A. Fava[31], A. Ferrari[6], D. Gibin[31], S. Gninenko[20], N. Golubev[20], A. Guglielmi[31], A. Ivashkin[20], M. Kirsanov[20], J. Kisiel[38], U. Kose[6], F. Mammoliti[5], G. Mannocchi[15], A. Menegolli[32], G. Meng[31], D. Mladenov[6], C. Montanari[32], M. Nessi[6], M. Nicoletto[31], F. Noto[6], P. Picchi[15], F. Pietropaolo[31], P. Płoński[42], R. Potenza[5], A. Rappoldi[32], G.L. Raselli[32], M. Rossella[32], C. Rubbia*[,6,11,16], P. Sala[18], A. Scaramelli[18], J. Sobczyk[44], M. Spanu[32], D. Stefan[18], R. Sulej[43], C.M. Sutera[5], M. Torti[32], F. Tortorici[5], F. Varanini[31], S. Ventura[31], C. Vignoli[16], T. Wachala[12], and A. Zani[32]

The LAr1-ND Collaboration

C. Adams[45], C. Andreopoulos[23], A.M. Ankowski[41], J. Asaadi[40], L. Bagby[10], B. Baller[10], N. Barros[33], M. Bass[30], S. Bertolucci[6], M. Bishai[3], A. Bitadze[25], J. Bremer[6], L. Bugel[26], L. Camilleri[9], F. Cavanna[10,a], H. Chen[3], C. Chi[9], E. Church[10,45], D. Cianci[7], G.H. Collin[26], J.M. Conrad[26], G. De Geronimo[3], R. Dharmapalan[1], Z. Djurcic[1], A. Ereditato[2], J. Esquivel[40], J. Evans[25], B.T. Fleming[45], W.M. Foreman[7], J. Freestone[25], T. Gamble[37], G. Garvey[24], V. Genty[9], D. Göldi[2], E. Gramellini[45], H. Greenlee[10], R. Guenette[30], A. Hackenburg[45], R. Hänni[2], J. Ho[7], J. Howell[10], C. James[10], C.M. Jen[41], B.J.P. Jones[26], L.N. Kalousis[41], G. Karagiorgi[25], W. Ketchum[24], J. Klein[33], J. Klinger[37], U. Kose[6], I. Kreslo[2], V.A. Kudryavtsev[37], D. Lissauer[3], P. Lively[22], W.C. Louis[24], M. Lüthi[2], C. Mariani[41], K. Mavrokoridis[23], N. McCauley[23], N. McConkey[37], I. Mercer[22], T. Miao[10], G.B. Mills[24], D. Mladenov[6], D. Montanari[10], J. Moon[26], Z. Moss[26], S. Mufson[14], M. Nessi[6], B. Norris[10], F. Noto[6], J. Nowak[22], S. Pal[37], O. Palamara*[,10,b], J. Pater[25], Z. Pavlovic[10], J. Perkin[37], G. Pulliam[40], X. Qian[3], L. Qiuguang[24], V. Radeka[3], R. Rameika[10], P.N. Ratoff[22], M. Richardson[37], C. Rudolf von Rohr[2], B. Russell[45], D.W. Schmitz*[,7], M.H. Shaevitz[9], B. Sippach[9], M. Soderberg[40], S. Söldner-Rembold[25], J. Spitz[26], N. Spooner[37], T. Strauss[2], A.M. Szelc[45], C.E. Taylor[24], K. Terao[9], M. Thiesse[37], L. Thompson[37], M. Thomson[4], C. Thorn[3], M. Toups[26], C. Touramanis[23], R.G. Van de Water[24], M. Weber[2], D. Whittington[14], T. Wongjirad[26], B. Yu[3], G.P. Zeller[10], and J. Zennamo[7]

The MicroBooNE Collaboration

R. Acciarri[10], C. Adams[45], R. An[13], A.M. Ankowski[41], J. Asaadi[40], L. Bagby[10], B. Baller[10], G. Barr[30], M. Bass[30], M. Bishai[3], A. Blake[4], T. Bolton[21], C. Bromberg[27], L. Bugel[26], L. Camilleri[9], D. Caratelli[9], B. Carls[10], F. Cavanna[10,a], H. Chen[3], E. Church[10,45], G.H. Collin[26], J.M. Conrad[26], M. Convery[39], S. Dytman[34], B. Eberly[39], A. Ereditato[2], J. Esquivel[40], B.T. Fleming*[,45], W.M. Foreman[7], V. Genty[9], D. Göldi[2], S. Gollapinni[21], M. Graham[39], E. Gramellini[45], H. Greenlee[10], R. Grosso[8], R. Guenette[30], A. Hackenburg[45], O. Hen[26], J. Hewes[25], J. Ho[7], G. Horton-Smith[21], C. James[10], C.M. Jen[41], R.A. Johnson[8], B.J.P. Jones[26], J. Joshi[3], H. Jostlein[10], D. Kaleko[9], L.N. Kalousis[41], G. Karagiorgi[25], W. Ketchum[24], B. Kirby[3], M. Kirby[10], T. Kobilarcik[10], I. Kreslo[2], Y. Li[3], B. Littlejohn[13], D. Lissauer[3], S. Lockwitz[10], W.C. Louis[24], M. Lüthi[2], B. Lundberg[10], A. Marchionni[10], C. Mariani[41], J. Marshall[4], K. McDonald[35], V. Meddage[21], T. Miceli[28], G.B. Mills[24], J. Moon[26], M. Mooney[3], M.H. Moulai[26], R. Murrells[25], D. Naples[34], P. Nienaber[36], O. Palamara[10,b], V. Paolone[34], V. Papavassiliou[28], S. Pate[28], Z. Pavlovic[10], S. Pordes[10], G. Pulliam[40], X. Qian[3], J.L. Raaf[10], V. Radeka[3], R. Rameika[10], B. Rebel[10], L. Rochester[39], C. Rudolf von Rohr[2], B. Russell[45], D.W. Schmitz[7], A. Schukraft[10], W. Seligman[9], M.H. Shaevitz[9], M. Soderberg[40], S. Söldner-Rembold[25], J. Spitz[26], J. St. John[8], T. Strauss[2], A.M. Szelc[45], N. Tagg[29], K. Terao[9], M. Thomson[4], C. Thorn[3], M. Toups[26], Y. Tsai[39], T. Usher[39], R. Van de Water[24], M. Weber[2], S. Wolbers[10], T. Wongjirad[26], K. Woodruff[28], M. Xu[13], T. Yang[10], B. Yu[3], G.P. Zeller*[,10], J. Zennamo[7], and C. Zhang[3]

Additional Fermilab Contributors

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SBN Program Proposal

- Presented January 2015 PAC meeting:

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted jointly by ICARUS, MicroBooNE and SBND (LAr1-ND)
arxiv:1503.01520

- Measure ν_e appearance and ν_μ disappearance in one program
- Detailed analysis for program sensitivities (e.g.):
  - Cosmogenic and beam based backgrounds ("Dirt" events)
  - Systematics from flux minimized by use of near detector, cross-section, and dirt systematics.
  - Detector systematics reduced by use of common technology
- To address cosmics from surface operation need: overburden, fast light detection and external cosmic tagger systems
- Technology development for LBNF/DUNE
- Granted Stage 1 approval by Fermilab director in February
- Operate in 2018

SBN ν_e Appearance Sensitivity
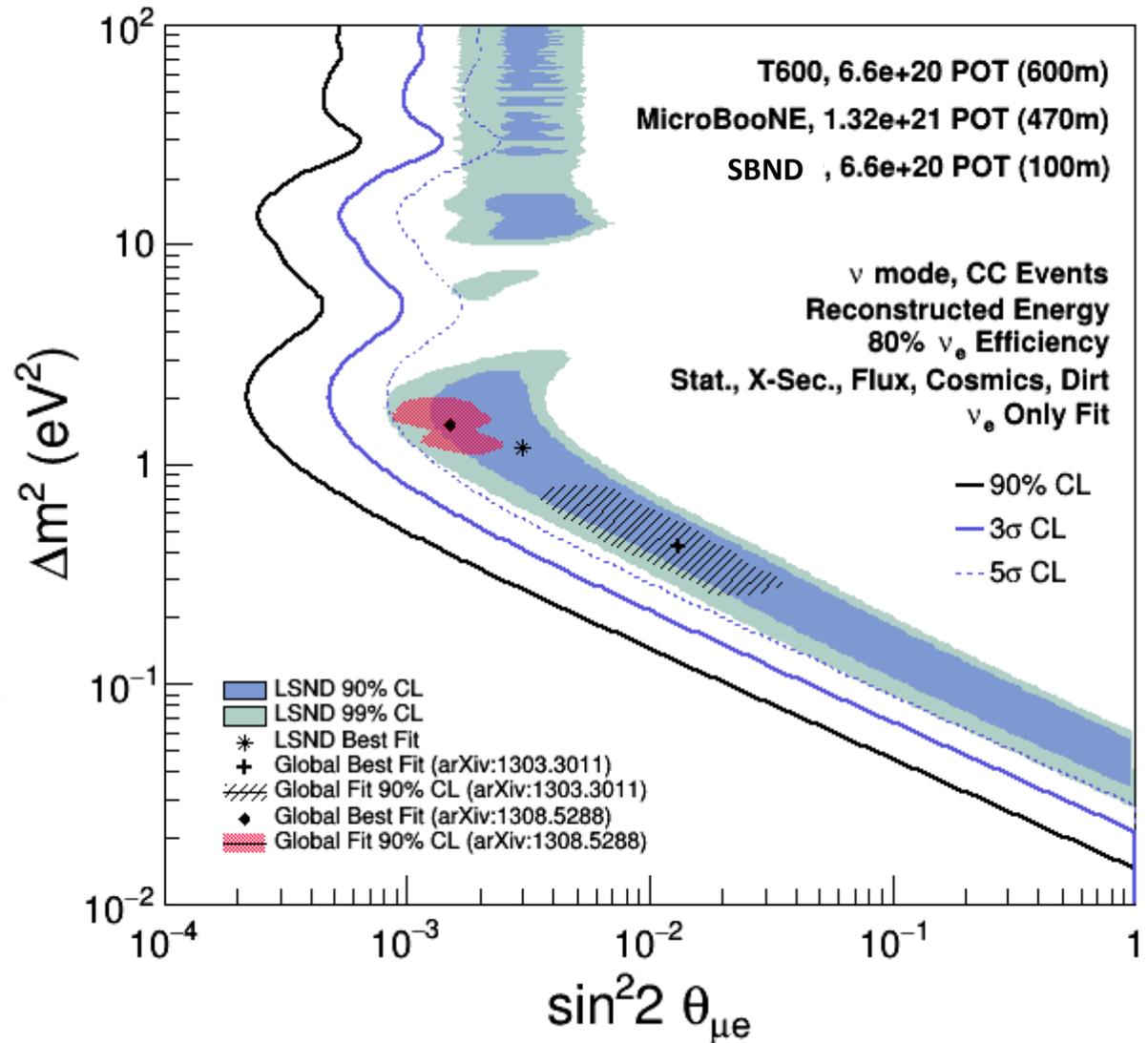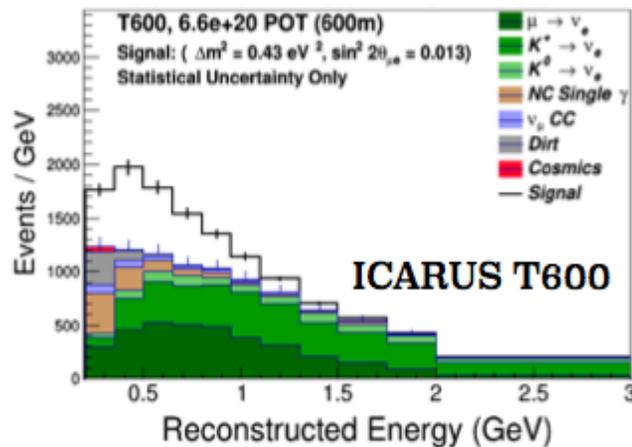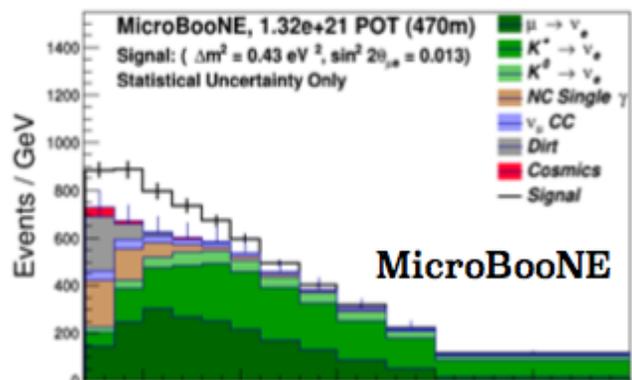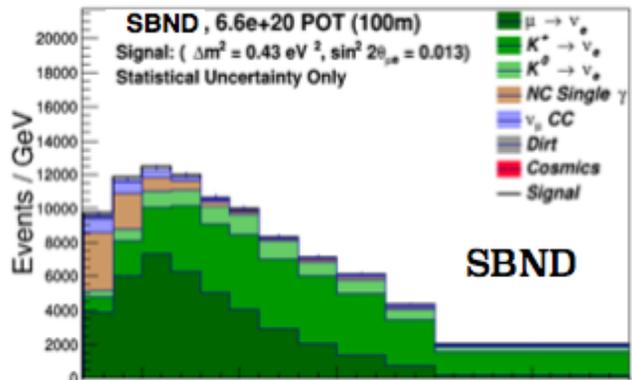
SBN ν_μ Disappearance Sensitivity

Why SB program is more sensitive than MiniBooNE+SciBooNE:
-same detector technology => cancels systematics
-large size => alleviates statistical limitations.
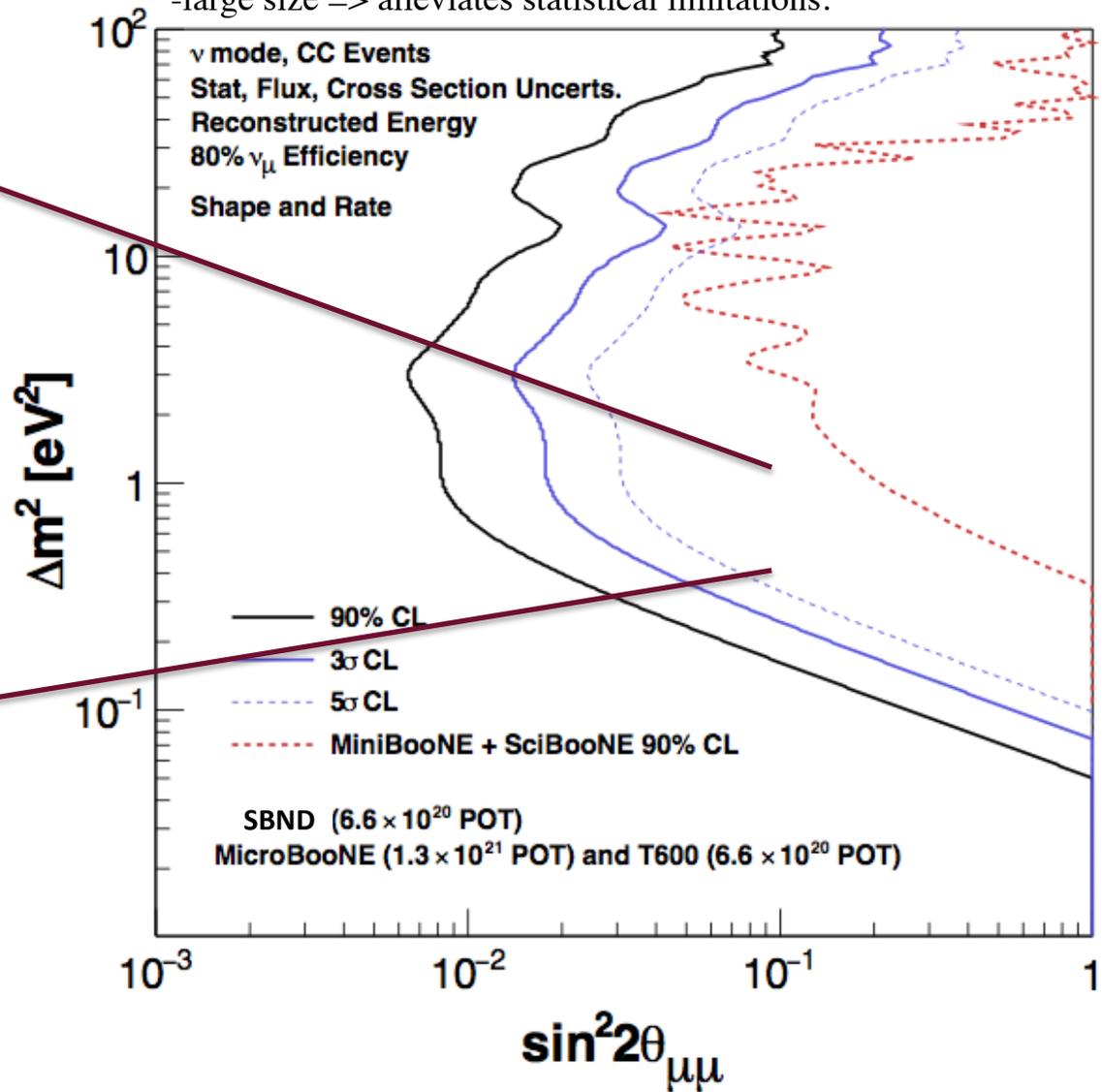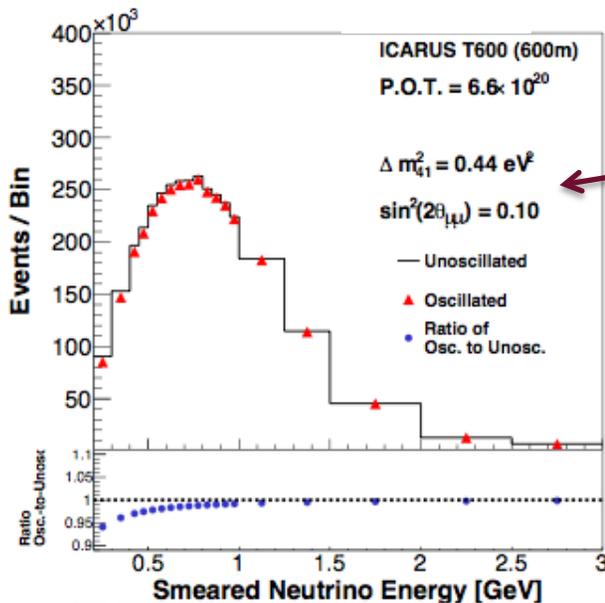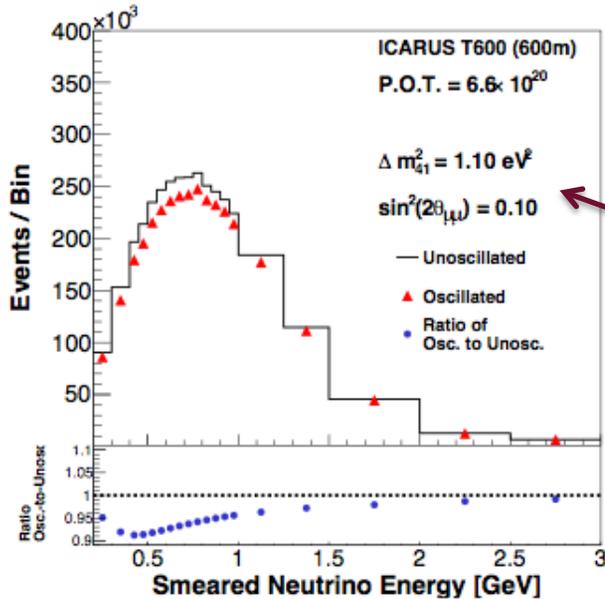
NuMI Neutrinos

- Potential for independent neutrino analysis
  -Events from NuMI beamline will be observed as well

SBN Program
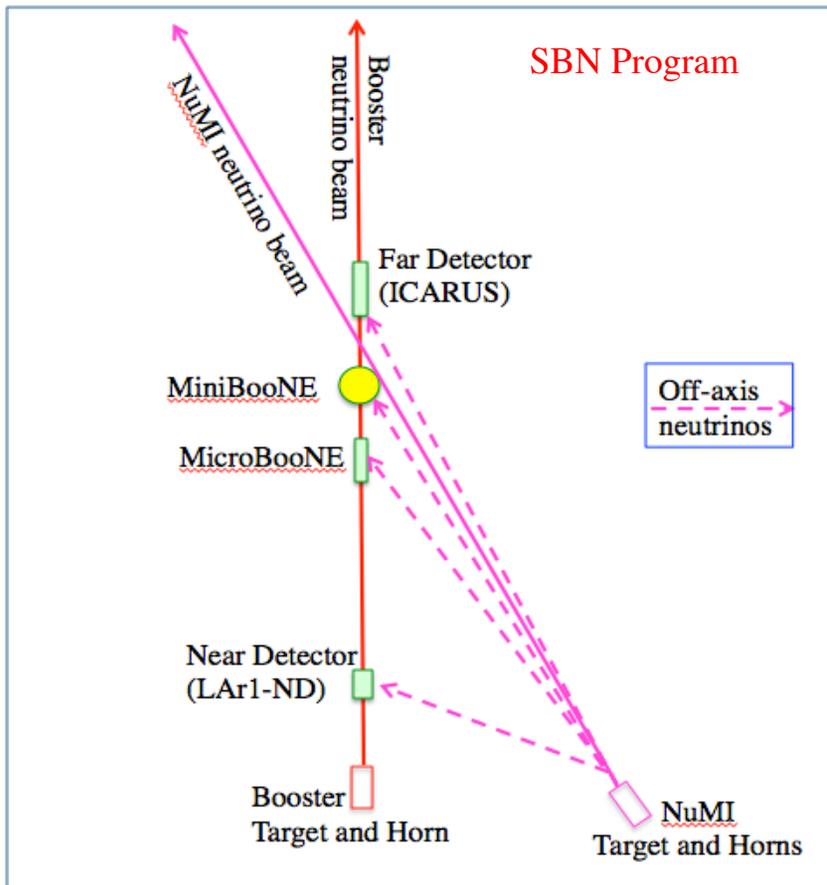
Former NuMI analysis at MiniBooNE
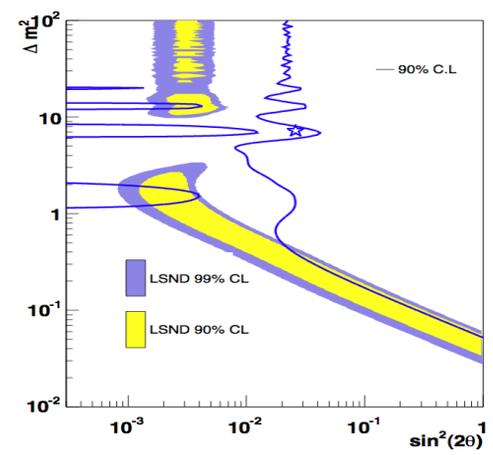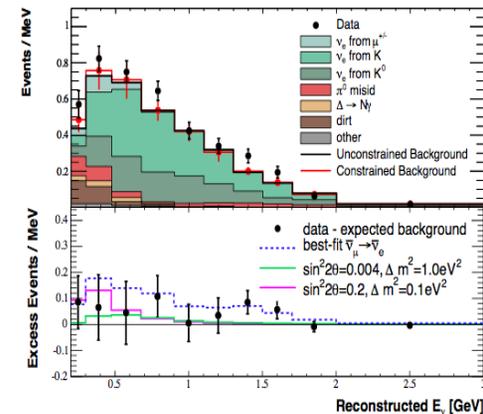
LArTPC Development Path to LBNF/DUNE

- DUNE is considering two options for readout of ionization signals:

  -Single-phase wire-plane readout
  - Ionization signals (collection + induction) read out in liquid volume
  - As used in ICARUS, ArgoNEUT/LArIAT, MicroBooNE, SBND
  - Long-term operation/stability demonstrated by ICARUS T600

  -Dual-phase readout
  - Ionization signals amplified and detected in gaseous argon above the liquid surface
  - Being pioneered by the WA105 collaboration
  - If demonstrated, potential advantages over single-phase approach

- Parallel development: testbeam devices and SBN detectors

  - CERN neutrino platform: R&D activities towards a long-baseline neutrino experiment
  - Fermilab neutrino platform: LAr R&D activities and SBN experiments

LArTPC Development Path to LBNF/DUNE

Single-Phase LArTPCs
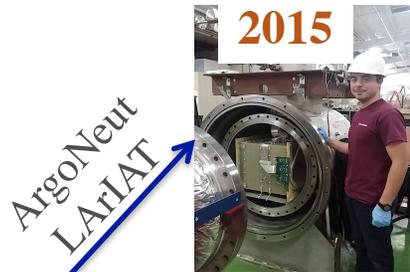
Fermilab and CERN neutrino platforms provide a strong LArTPC development and prototyping program.

2015

ArgoNeut
LArIAT

ICARUS@LNGS

35t Prototype
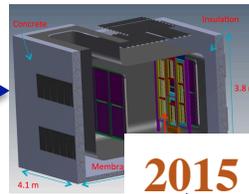
DUNE SP PT @ CERN

DUNE Reference Design

2015

2018

SBN

2015

MicroBooNE

2018

SBND

2018

ICARUS@SBN

2016

WA105: 1x1x3 m^3

2018
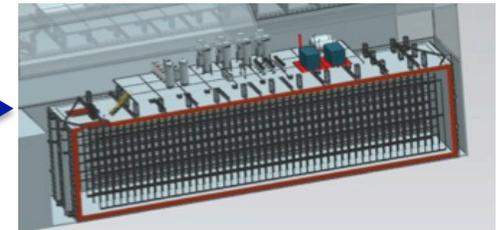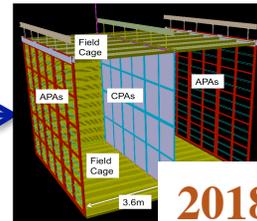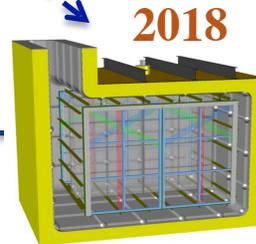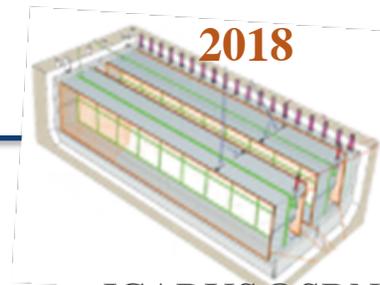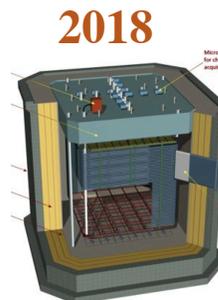
WA105

DUNE Alternative Design

Dual-Phase LArTPCs
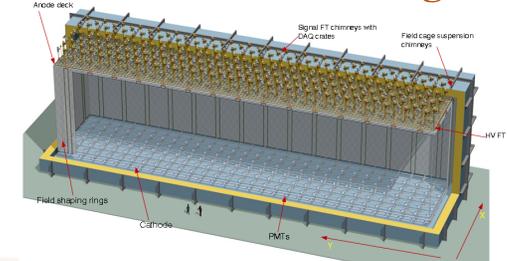
SBN R&D Component for DUNE

- Short baseline program will serve as R&D platform for DUNE
    - Automated event reconstruction
    - Laser and other calibration techniques
    - Photon detector R&D
    - Cold/warm electronics
    - Cold feed-through/understanding of HV breakdown
    - Argon purification
    - Cryogenic liquid processing

The HEP community is engaged in development of a short-baseline neutrino (SBN) program hosted at Fermilab, as a part of the P5 recommendation for a short baseline neutrino portfolio, to operate coherently with the long-baseline program in order to address some of the short-baseline neutrino anomalies and support R&D towards LBNF/DUNE.

SBND (former LAr1-ND)

DUNE

Beam
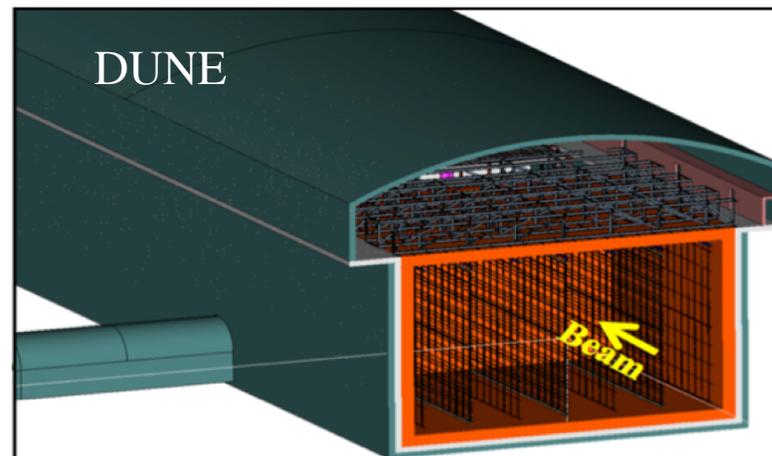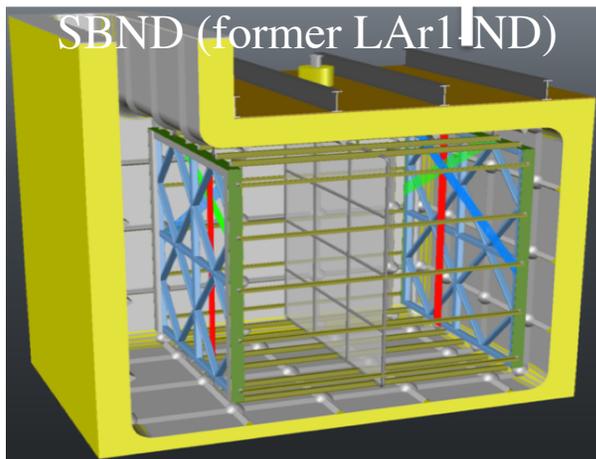
SBN Physics Component for DUNE

- SBN detectors will collect large data sets from the BNB and the NuMI off-axis fluxes

  -SBND: ~1.7M CC interactions per year (~12,000 ν_e)

  -Large complementary samples in MicroBooNE and T600

  -T600: ~100k NuMI off-axis events per year

- Important for DUNE

  -BNB events in the region of DUNE's 2nd osc. maximum;
  -NuMI events at SBN Far Detector cover DUNE's 1st osc. maximum.

- Precision measurements of ν-Ar cross sections are important component in reaching required systematics for DUNE

- Large data sets will require that event reconstruction and analysis become fully automated.
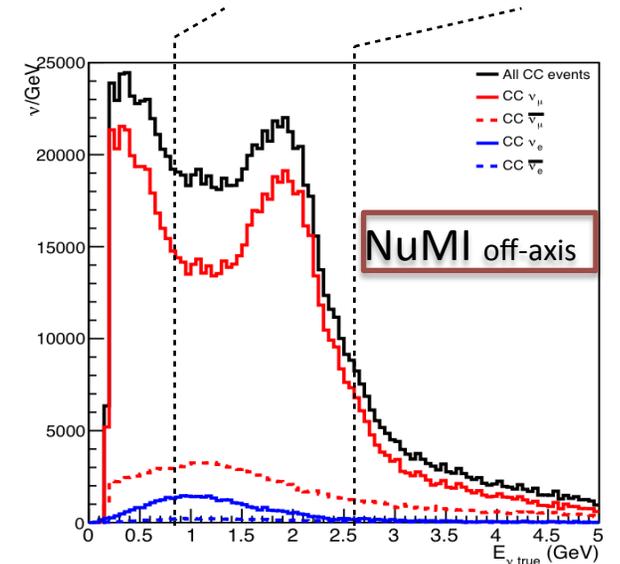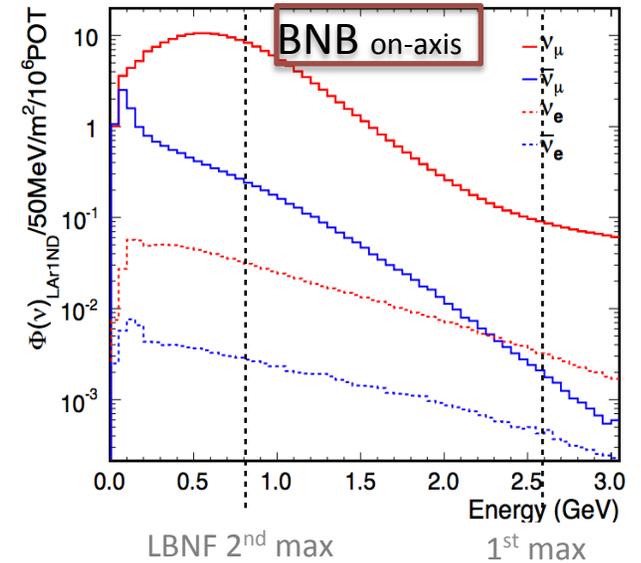
SBND: the Short-Baseline Near Detector

- Detector Development : Build on experience and lessons learned from ICARUS, MicroBooNE, LBNE 35 ton prototype
  -incorporate ideas being discussed for DUNE

- Physics : size and location to provide best control of systematics for ν_e appearance

- Schedule : make decisions in a timely manner to be ready when far detector is ready

- Cost : use multiple funding sources to cover required scope
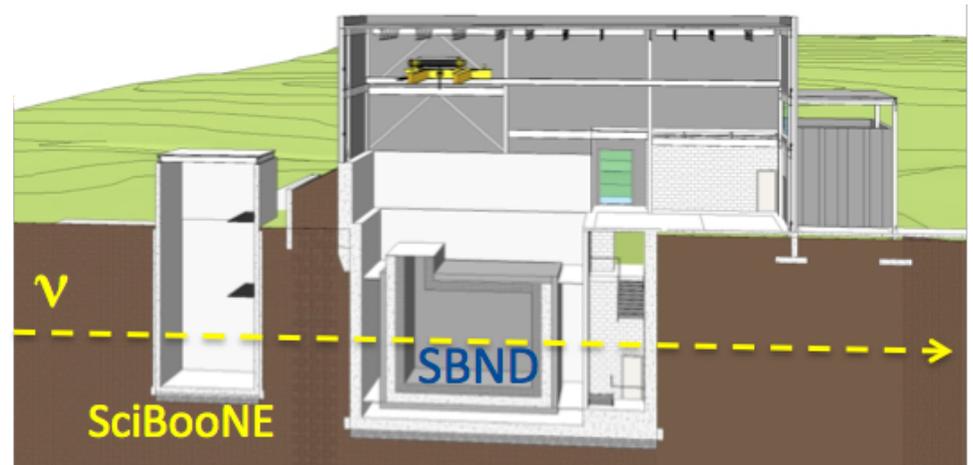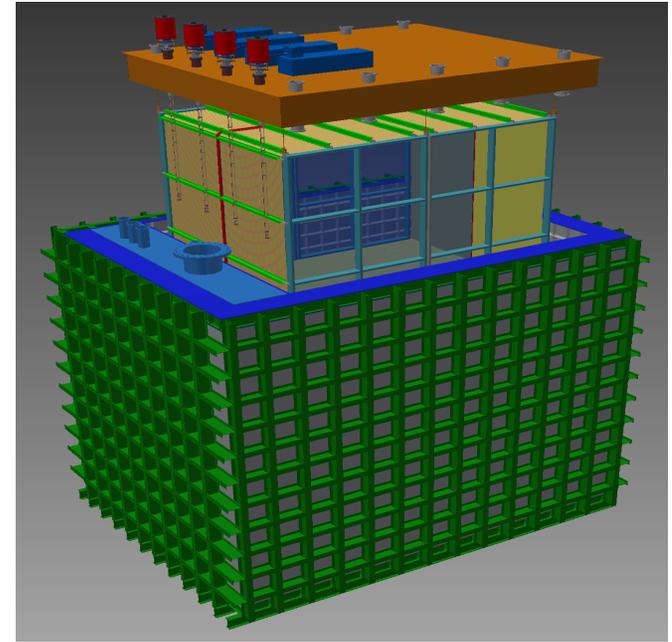
SBND Event Rates

- Rich event sample for study of anomalies and cross-section models
  - Estimated event rates using GENIE (v2.8) in the SBND active volume (112 t) for a 6.6×10^{20} proton-on-target exposure (~3 years) in the Booster Neutrino Beam.

Process		No. Events	Events/ ton	Stat. Uncert.
ν_μ Events (By Final State Topology)				
CC Inclusive		5,212,690	46,542	0.04%
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830	31,713	0.05%
	$\cdot \ \nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	$\cdot \ \nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	$\cdot \ \nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	$\cdot \ \nu_\mu N \to \mu + \geq 3p$	371,347	3,316	0.16%
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to \text{nucleons}$	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to \text{nucleons} + 1\pi^\pm$	260,924	2,330	0.20%
NC $\geq 2\pi^\pm$	$\nu_\mu N \to \text{nucleons} + \geq 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	358,443	3,200	0.17%
ν_e Events				
CC Inclusive		36798	329	0.52%
NC Inclusive		14351	128	0.83%
Total ν_μ and ν_e Events		7,251,948	64,750	
ν_μ Events (By Physical Process)				
CC QE	$\nu_\mu n \to \mu^- p$	3,122,600	27,880	
CC RES	$\nu_\mu N \to \mu^- \pi N$	1,450,410	12,950	
CC DIS	$\nu_\mu N \to \mu^- X$	542,516	4,844	
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	18,881	169	

-cross-sections need to be understood for DUNE physics phase.

SBND Cryostat + TPC

- Membrane cryostat: same as planned for the DUNE far detector
  - Two worldwide vendors serving the LNG industry (IHI-Japan, GTT-France)
- Series of cryostats being jointly developed by CERN and Fermilab
  - DUNE 35t (IHI)
  - WA105-182 dual-phase (50t) (GTT)
  - SBND (GTT through CERN)
  - WA105 dual-phase (GTT)
  - DUNE single-phase for CERN testbeam (GTT)
  - Full size LBNF 10-40kt
- Collaboration between Fermilab and CERN

Plate A: TPC support and detector feedthroughs

TPC

Plate B: Cryogenic Services

SS Inner Membrane

Foam Insulation (60cm)

Steel outer cryostat and support structure
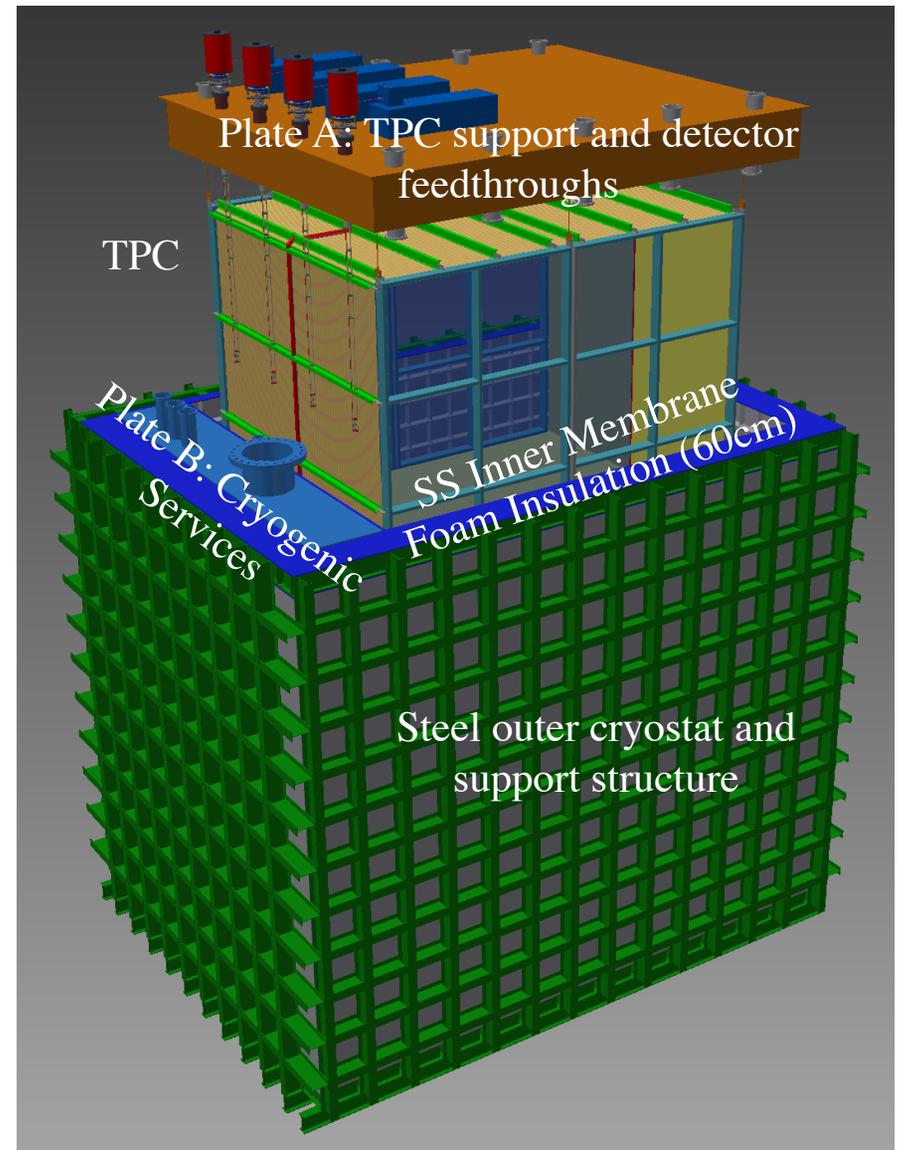
SBND TPC Design

- Started with current DUNE single phase design
- Active volume: 5m (beam) x 4m (width) x 4m (height)
- Central cathode plane assembly (CPA), two anode plane assemblies (APA) on either side w/ 2m drift distance each.
- Single sided APA wire planes joined at edge to reduce readout channels
- Light detectors mounted behind APAs on frames

CPA

4.0m

4.0m

5.0m

APAs

Field Cage
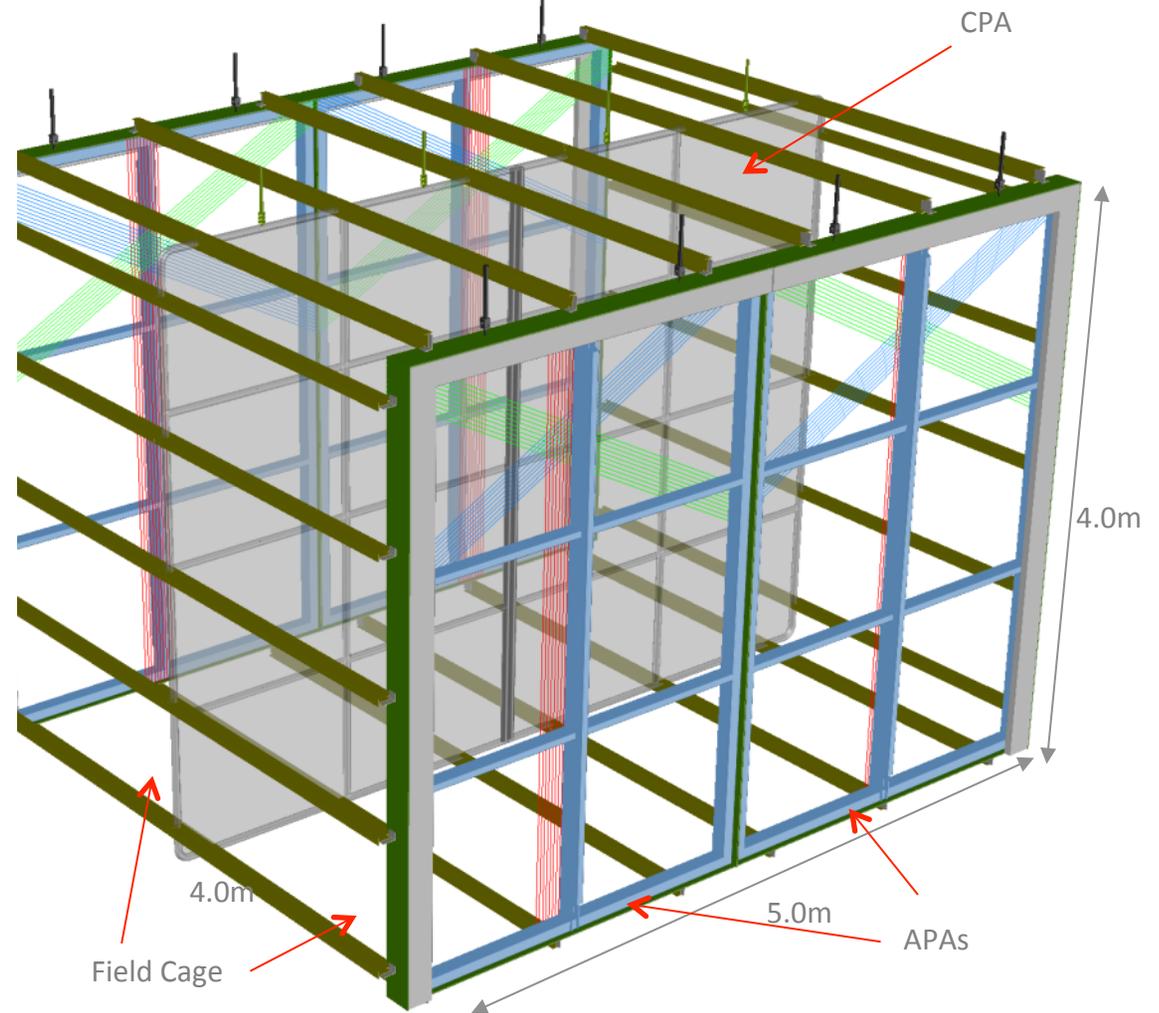
SBND: Anode Plane Assemblies

The SBND APA is a hybrid between that of MicroBooNE and LBNE

Readout boards
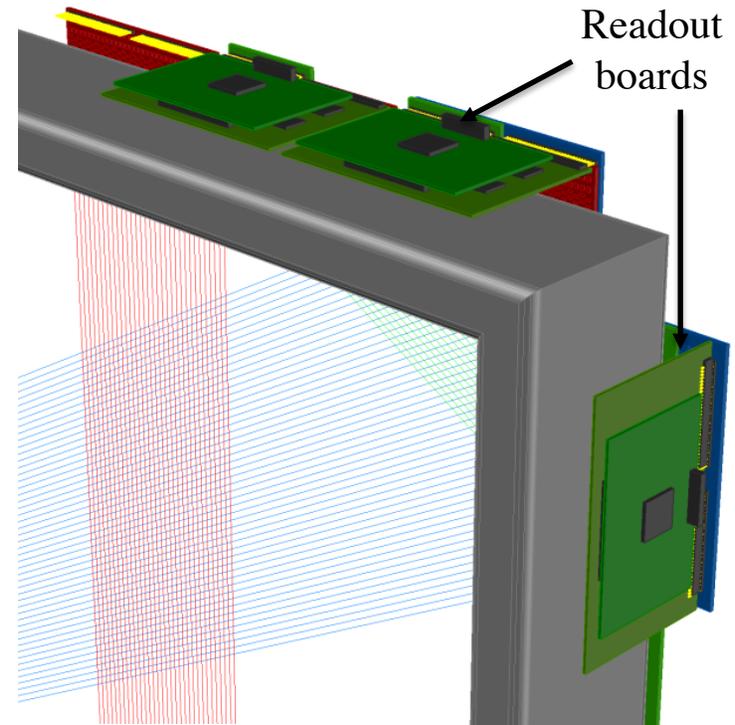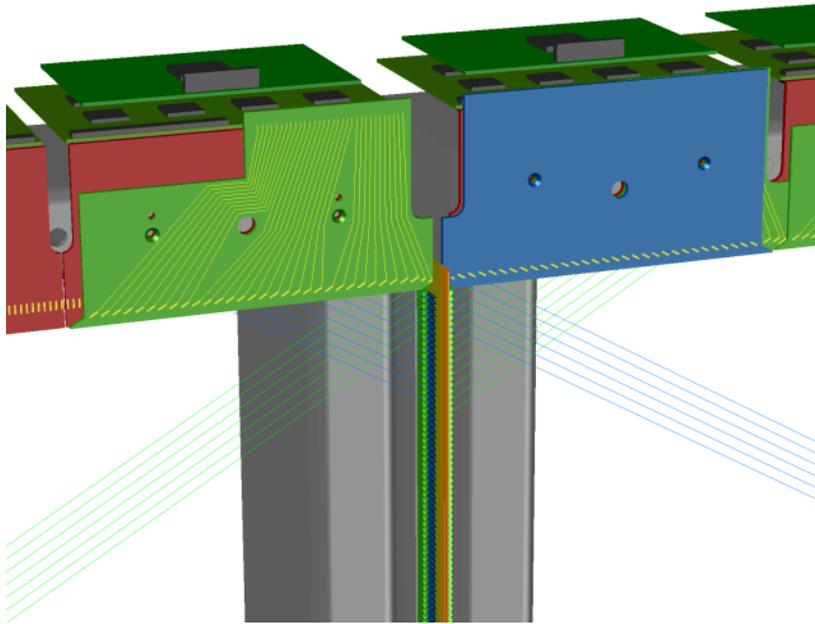
Innovation example: Bias board between adjacent APAs to eliminate dead region

electron drift path

U wire

V wire   Y wire

APA Frame
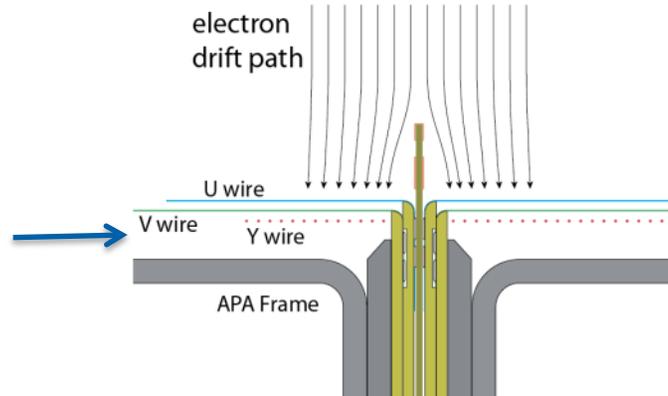
SBND Cold Electronics

- Front-End ASIC & ADC ASIC developed by BNL for LBNE along with FPGA (data sparsification) all in cold

  - MicroBooNE uses cold front-end but warm digitizer

  - DUNE 35 ton prototype uses full cold chain

  - SBND to use next generation based on the 35 ton lessons

  - Synchronize development with DUNE CERN Single-Phase prototype
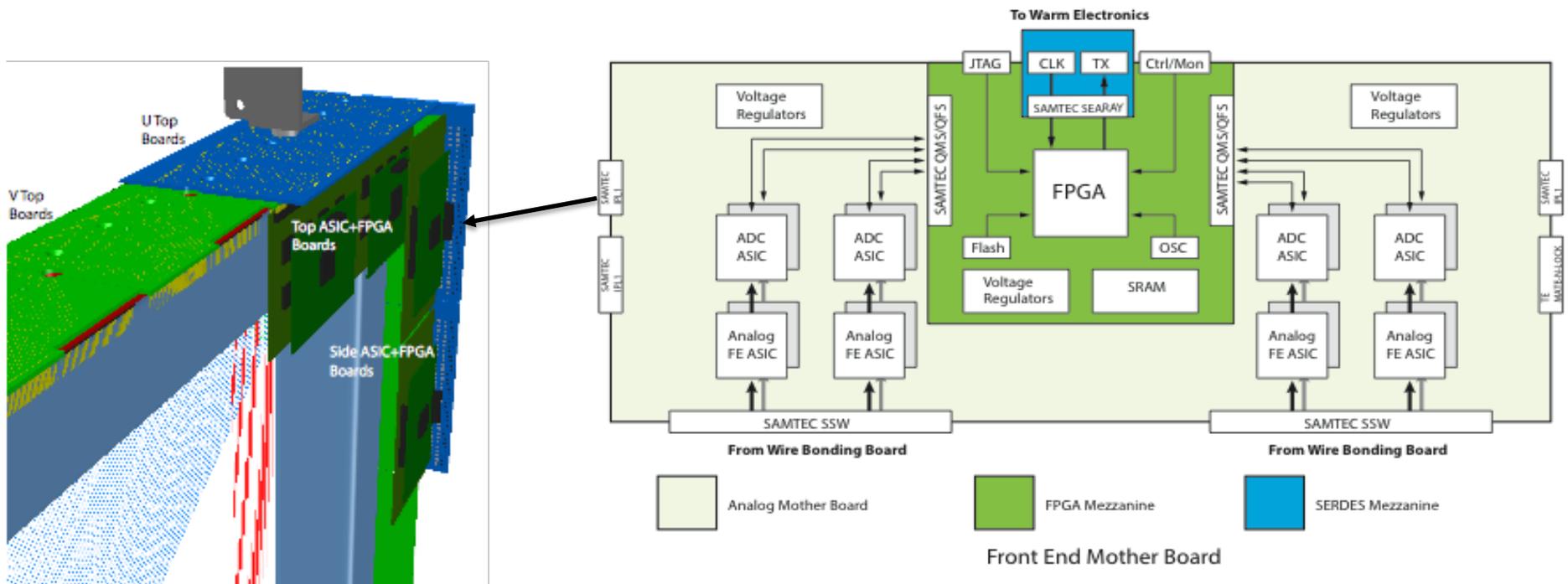
Collaboration on Infrastructure: Cryogenics

- Cryogenics teams for LAr detectors formed at CERN and Fermilab
  - Coordinated efforts on SBN and LBNF
  - Fermilab cryogenics engineer based at CERN for calendar 2015
- Common designs wherever possible across multiple LAr-TPCs, e.g.
  - SBN: LN2 delivery (see right)
  - Cryostat designs for SBND, WA105, DUNE CERN prototype
- LAr purification building on expertise at INFN (T600), CERN (ATLAS), and Fermilab (LAPD/LBNE 35ton, MicroBooNE)
- Cryogenics systems scheduled for delivery to Fermilab in early to mid-2017
- Other collaborative efforts in development: DAQ, cosmic taggers, reco. software

Example: SBN LN2 Delivery Systems
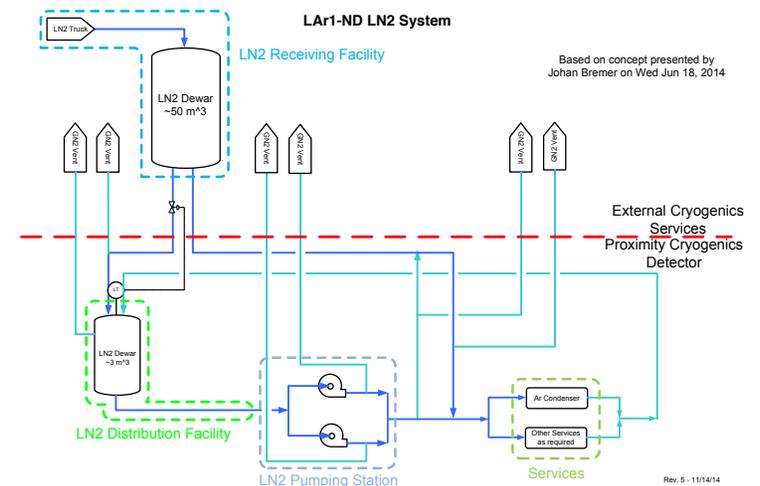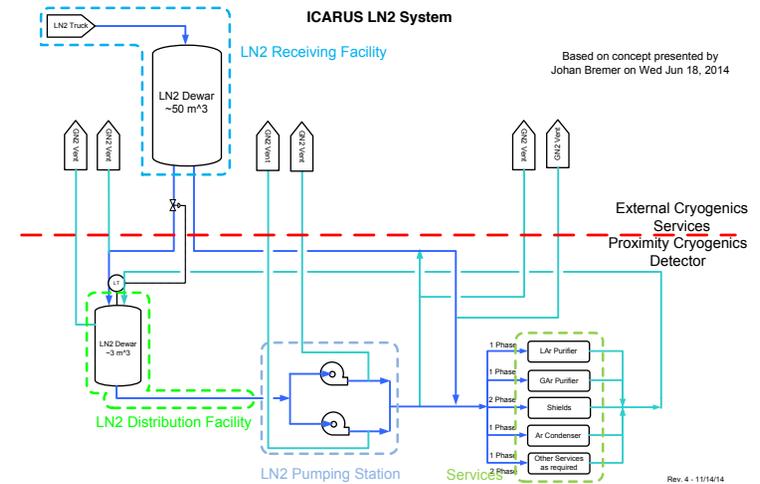
Photon Detector (PD) System

- PD in SBND should trigger on every cosmic muon and neutrino interaction (provide "t0").

- With a good time resolution one could explore correlation between beam spills (Booster RF structure) and events observed in the detector.

- Different PD designs under investigation, with appropriate readout electronics
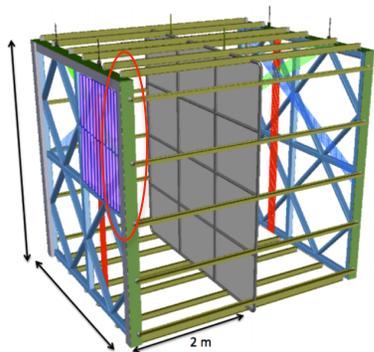
Wave-length shifting acrylic bar system with SiMPs
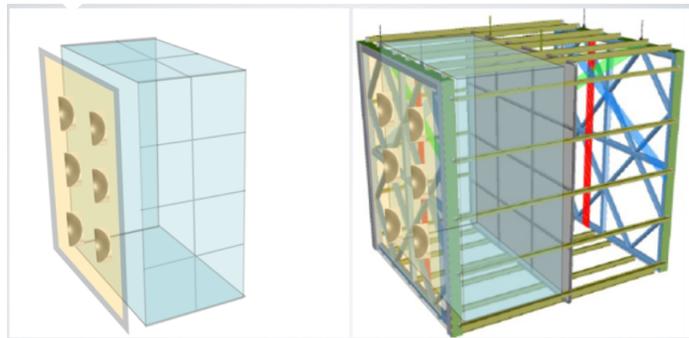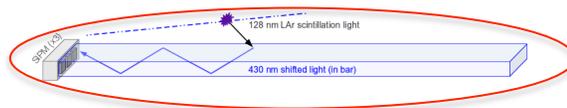
Wave-length shifting reflective foils system with SiMPs and/or PMTs

RWM Wave Form (ADC counts + 31500 0ffset)

Booster RF proton beam buckets
RF peak time resolution
$1\sigma = 1.15$ ns
(FWHM = 2.7 ns)

Train of 81 RF proton buckets in 1.6 μs

MiniBooNE ν_μ CCQE event absolute timing with all 81 bunches overlayed on top of each other
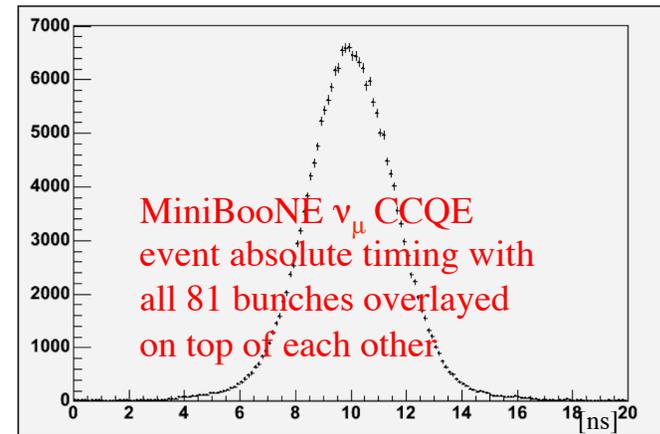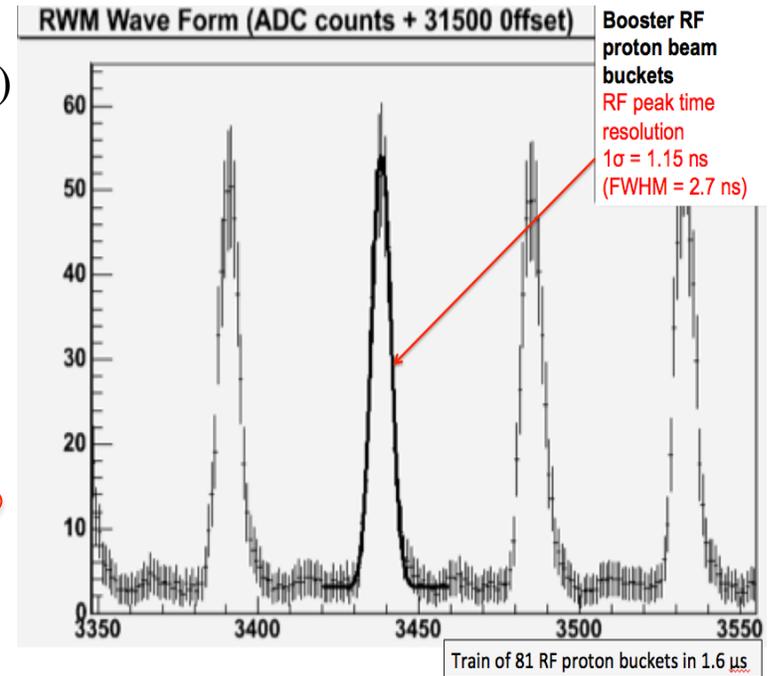
Near Detector Building

- Design started January 2015

- Designed for 3m concrete overburden inside building to mitigate cosmogenic backgrounds for near surface operation

- Timeline:
  - June 2015 - Design complete
  - Aug-Sept 2015 - Construction start
  - Nov 2016 - Beneficial occupancy

ν

SciBooNE
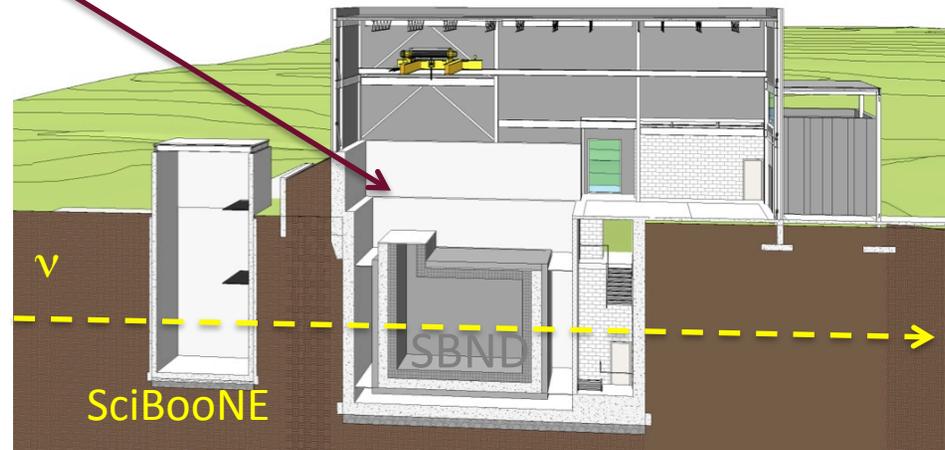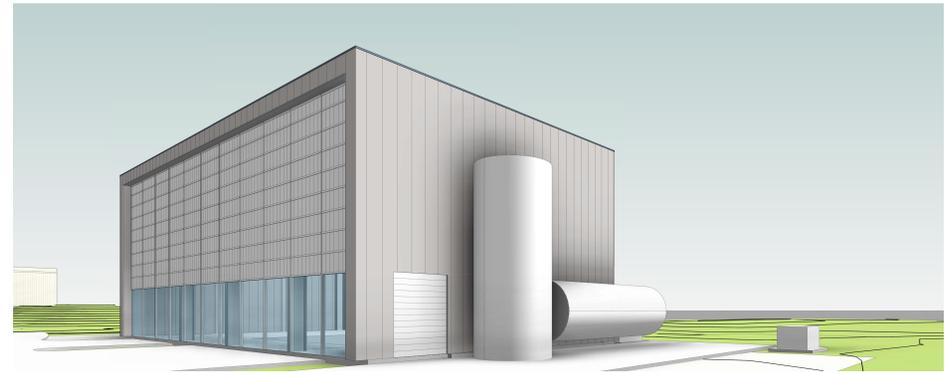
SBND

SBND Impact on LBNF/DUNE Technology

	SBND	LBNE/DUNE (Single Phase)	Comparison
LAr pump	Outside cryostat	Inside cryostat?	Test alternative concept
TPC configuration	CPA in the middle, single sided APAs against the walls	CPAs against the walls, double sided APAs in the middle	Avoid a costly fiducial cut in the center of the active region. The APAs can be placed closer to the cryostat walls to maximize active region in the limited available space.
APA configuration	Single sided, no helical wire wrapping, readout on 3 edges	Double sided, helical wire wrapping on two induction planes, readout on one edge	SBND's APA design avoids the wire wrapping, optionally allowing APA tiling on all 4 sides. The SBND design provides a verified alternative to the LBNE APAs.
APA wire configuration	3 sense wire planes, +/- 60 degree, 3mm wire pitch	3 sense wire planes, +/- 36 degrees, 4.8mm wire pitch	SBND's wire configuration is identical to MicroBooNE and same angles as ICARUS.
Cold Electronics	FE ASIC, ADC ASIC, FPGA	FE ASIC, ADC ASIC, Digital ASIC	SBND may update the FE ASIC chip to include on-chip pulser
Warm Interface Board	FPGA + Optical Transceiver	Optical Transceiver and/or FPGA	SBND will use FPGA to study data compression and trigger algorithm, and keep the capability to stream all data out
Light Collection	Developing multiple technologies	Light guides with WLS coating	Test alternative concepts to improve the low energy sensitivity of DUNE PDs.

SBN Program Timeline

EPOC	EXPT	2015	2016	2017	2018	2019	2020	
NOW	MINOS+	RUN						
NOW	MicroBooNE		RUN 1			RUN - SBN		
NEXT	SBND		BUILD + INSTALL *			RUN - SBN		
NEXT	ICARUS		REFURBISH+INSTALL*			RUN - SBN		
NEXT+	?						decide	????

PROGRESS

MINOS+   MicroBooNE   SBN   5σ

$\sin^2 2\theta_{24}$ sensitivity ~ 0.02 (90%CL) for Δm^2 ~ 0.5 eV^2

MiniBooNE anomaly e or γ determination at 4-5 σ

Increasing sensitivity to LSND anomaly
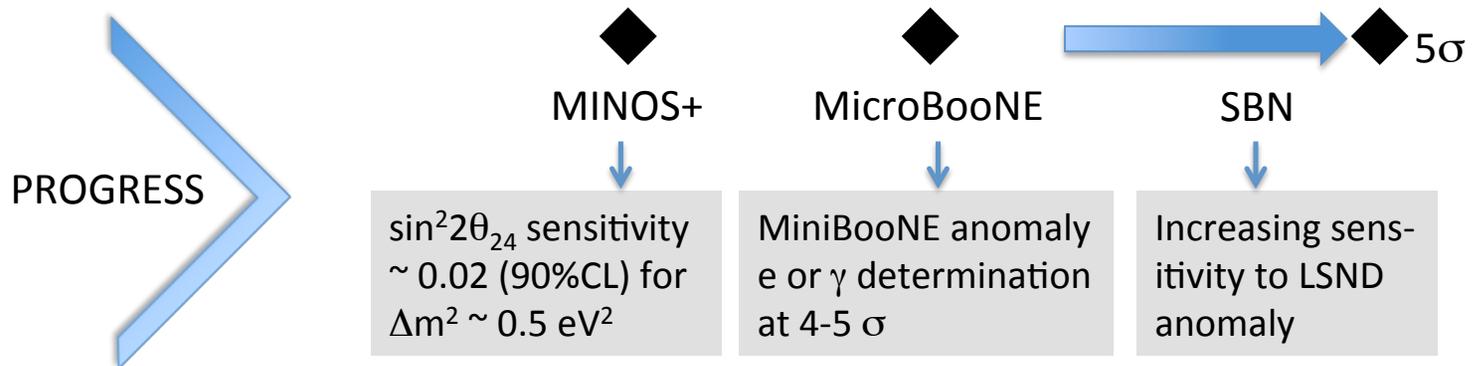
* Important contributions from CERN Neutrino Platform and European funding agencies (INFN, STFC, SNSF)

Source of information: January 2015 Fermilab PAC meeting; presentations & Report:

presented at ICFA Neutrino panel (April 2015), presented at FNAL PAC (June 2015)

46

Booster Neutrino Beamline Improvements

- BNB sterile neutrino search is limited by (Far) detector statistics

  -(Neutrino flux) x (Detector mass)
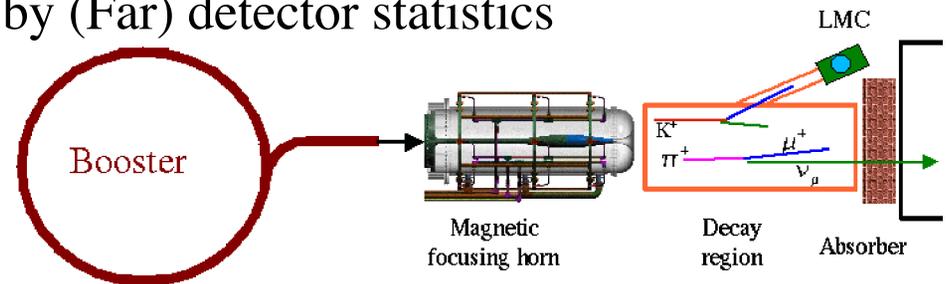
- Increased ν statistics would further increase the program sensitivity

  -Higher ν production efficiency

  -More protons on target

- BNB ν energy distribution optimized for MiniBooNE Cherenkov detector

  -LAr-TPCs more tolerant of high energy tail (distinguish NC π^0 background)

  -Allows for reconsideration of target and horn design

  -First studies in 2014 exploring one horn and two horn designs indicate an

   improvements 30-100% are possible

- Protons on target is limited to 5 Hz average

  -After Proton Improvement Plan could get up to 15 Hz during times when NUMI

   beam (and Muon program) is off

  -Upgraded power supply would permit more opportunistic use of beam pulses

Booster Neutrino Beamline Improvements

Two options span a range of improvements and cost:
  1) Short, improved MiniBooNE-style horn + power supply modifications
  2) New horn, max. length (3.5m) + power supply modifications
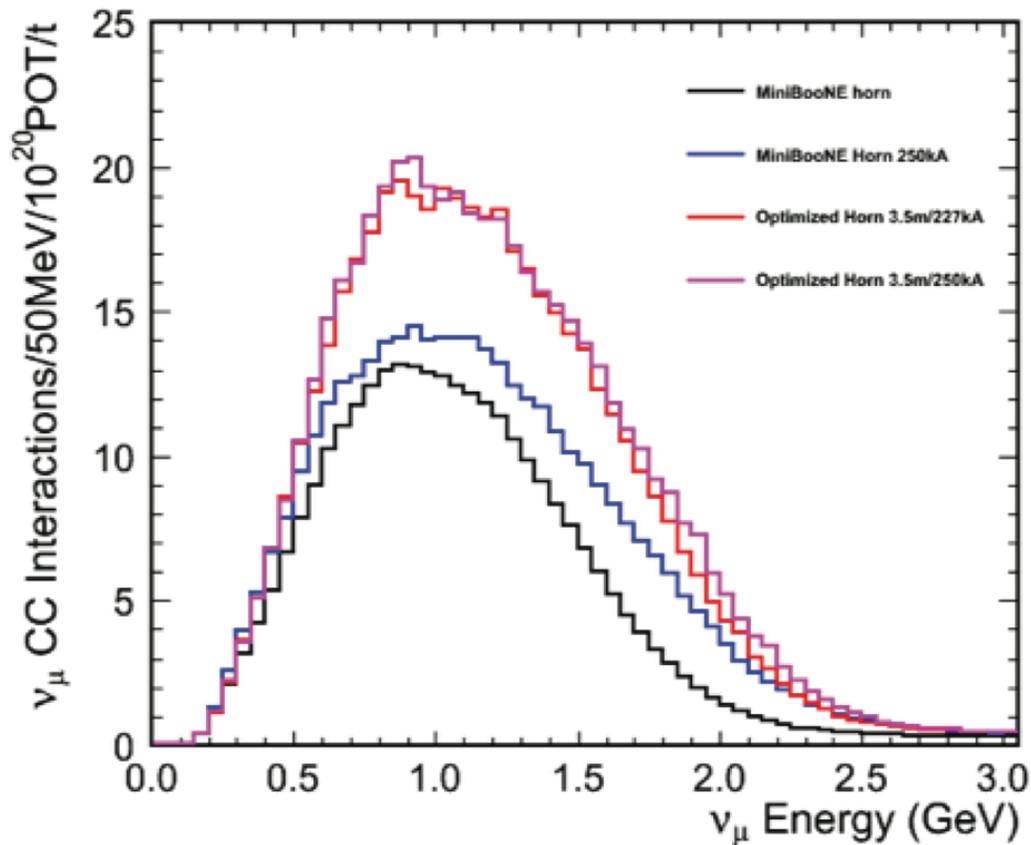
Interaction yield with a 3.5m long horn (option 2) compare to present yield
  -Gives +70% efficiency (not incl. more booster cycles)
  -Plan to complete conceptual design in 2016

Summary

- The SBN physics program of three LAr-TPC detectors at the Booster Neutrino Beam at Fermilab is being developed: it has been approved and it is moving forward quickly.

- Near Detector: SBND
    - Needs to be designed, built, installed and operated => get physics.
    - Needs to incorporate lessons learned as well as new ideas; in particular ones that will inform us how to scale to larger detector mass.
    - Funding available from a variety of sources.

- This new SBN Program will deliver a rich and compelling physics opportunity to resolve a class of experimental anomalies in neutrino physics, and to perform the most sensitive search to date for sterile neutrinos at the eV mass-scale through both appearance and disappearance osc. channels.
    - Using data sets of 6.6e20 protons on target in the SBND and ICARUS T600 detectors plus 13.2e20 P.O.T. in the MicroBooNE detector, $\nu_\mu \rightarrow \nu_e$ search can be performed with ~5 σ sensitivity for the LSND allowed (99% CL) parameter region.

- Important component of the program is liquid argon R&D with goals to advance the technology and build the international community for LBNF at Fermilab.

Backups
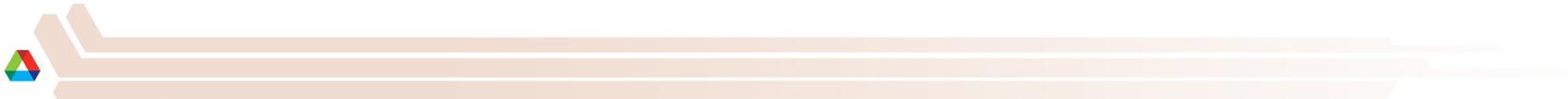
Sterile Neutrino Effects on LBL Experiments

- 3+1 Models Can Have Big Effect on Long-Baseline

* Best fit to T2K data
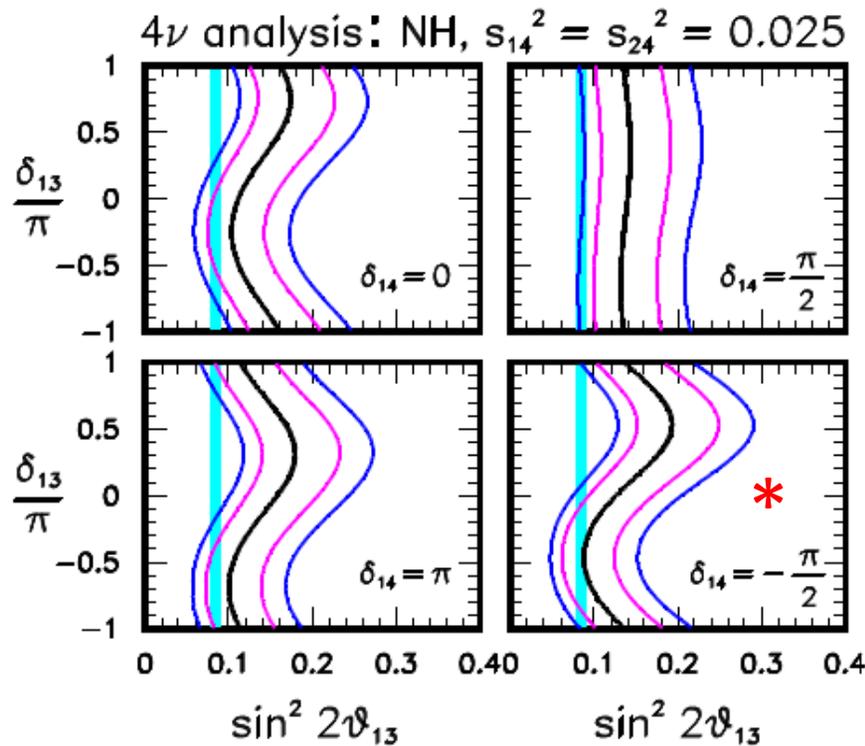
FIG. 3: Regions allowed by T2K for four values of CP-phase δ_{14}. Normal hierarchy is assumed. The mixing angle θ_{23} is marginalized away. The vertical band represents the region allowed by reactor experiments. Confidence levels as in Fig. 2.
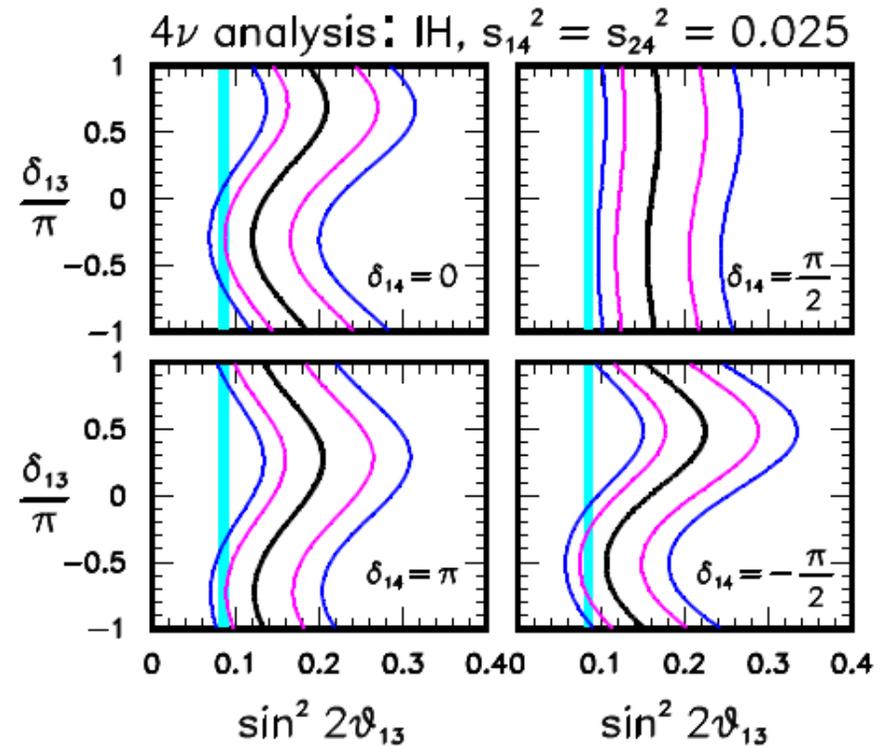
FIG. 4: Regions allowed by T2K for four values of CP-phase δ_{14}. Inverted hierarchy is assumed. The vertical band represents the region allowed by reactor experiments. The mixing angle θ_{23} is marginalized away. Confidence levels as in Fig. 2.

Klop & Palazzo, arXiv:1412.7524

SBND Building Design

SBN Near Detector: SBND
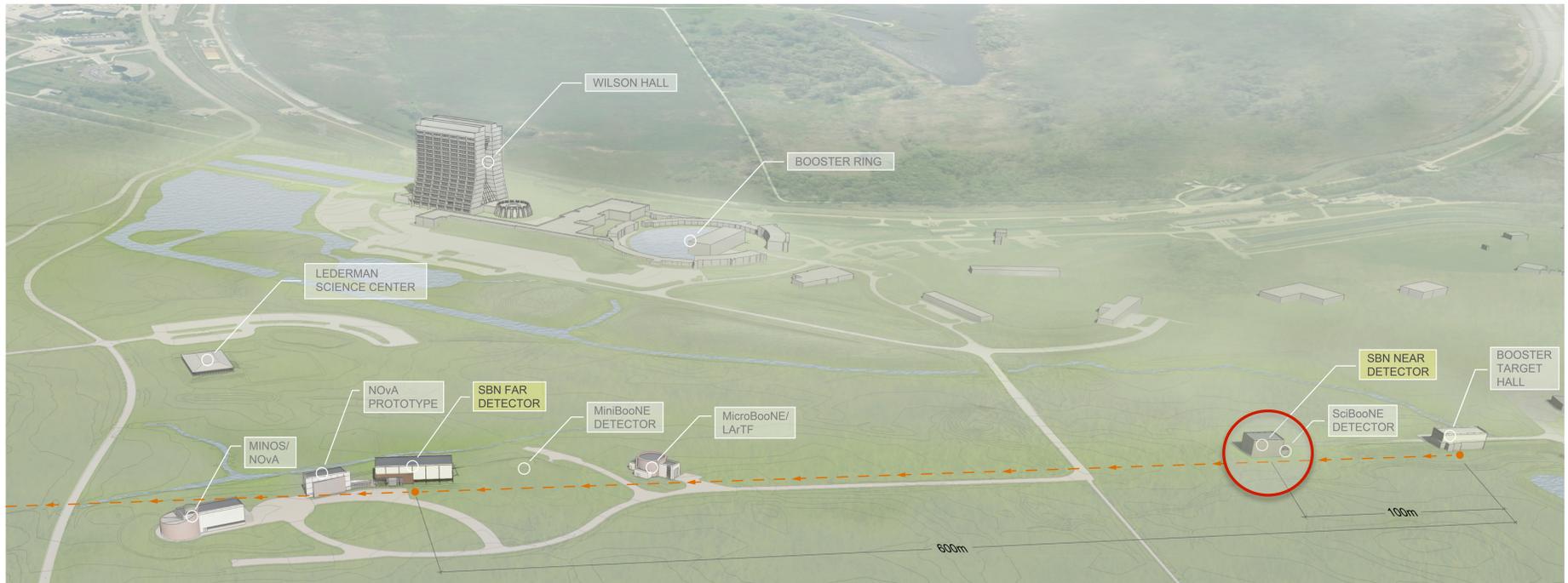
- Build on experience from ICARUS, MicroBooNE, LBNE 35 ton prototype
- Opportunity for prototyping DUNE designs
  - TPC construction techniques (US NSF – STFC)
  - TPC Electronics (US DOE/NSF)
  - Light detection (DOE?)
  - Cryostat technology (CERN-Fermilab)
  - Cryogenics systems (CERN-Fermilab)

  - Laser Calibration (SNSF)
  - Cosmic Tagger System (SNSF)

LBNF/DUNE
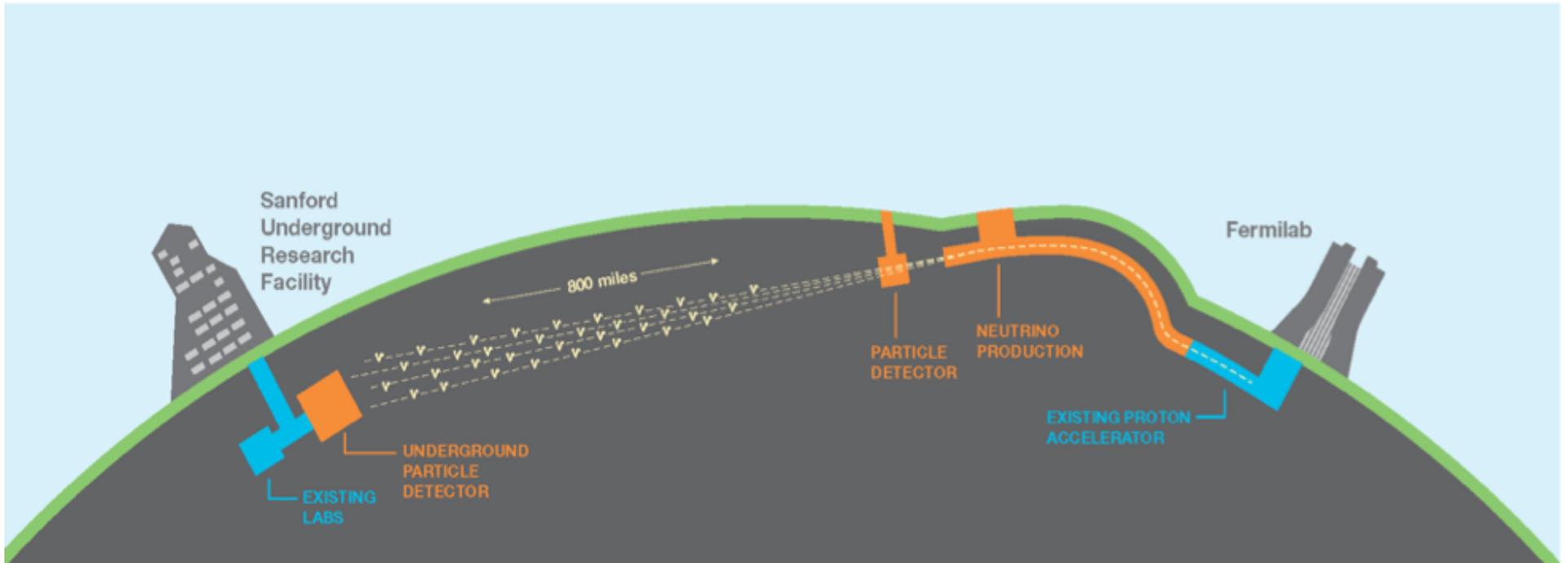
3+N Sterile Neutrino Models

-3+N Models with ν_e Appearance Require Large ν_e & ν_μ disappearance!

-In general, $P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

-Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

-For 3+1 Models (arXiv:1207.4765):

$$P(\nu_\alpha \rightarrow \nu_\beta) \simeq 4|U_{\alpha4}|^2|U_{\beta4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E) ,$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) \simeq 1 - 4(1 - |U_{\alpha4}|^2)|U_{\alpha4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E) .$$

3+N Sterile Neutrino Models

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-In general, $P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

-Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

-For 3+2 Models (arXiv:1207.4765):

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\beta) \simeq & -4|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} \sin^2(1.27\Delta m_{54}^2 L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| + |U_{\alpha 5}||U_{\beta 5}| \cos\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin^2(1.27\Delta m_{41}^2 L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} + |U_{\alpha 5}||U_{\beta 5}|)|U_{\alpha 5}||U_{\beta 5}| \sin^2(1.27\Delta m_{51}^2 L/E) \\
& +2|U_{\beta 5}||U_{\alpha 5}||U_{\beta 4}||U_{\alpha 4}| \sin\phi_{54} \sin(2.53\Delta m_{54}^2 L/E) \\
& +2(|U_{\alpha 5}||U_{\beta 5}| \sin\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin(2.53\Delta m_{41}^2 L/E) \\
& +2(-|U_{\alpha 4}||U_{\beta 4}| \sin\phi_{54})|U_{\alpha 5}||U_{\beta 5}| \sin(2.53\Delta m_{51}^2 L/E) \, ,
\end{aligned}$$

Φ_{54} is the CP phase angle

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\alpha) \simeq & 1 - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2(1.27\Delta m_{54}^2 L/E) \\
& -4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E) \\
& +|U_{\alpha 5}|^2 \sin^2(1.27\Delta m_{51}^2 L/E)) \, .
\end{aligned}$$

3+N Sterile Neutrino Models

-Probability of Neutrino Oscillations

$$P_{ab} = \delta_{ab} - 4\Sigma_i\Sigma_j \, |U_{ai} U^*_{bi} U^*_{aj} U_{bj}| \, \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As #ν increases, the formalism gets rapidly more complicated!

#ν	#Δm_{ij}^2	#θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
4	3	6	3
5	4	10	6
6	5	15	10

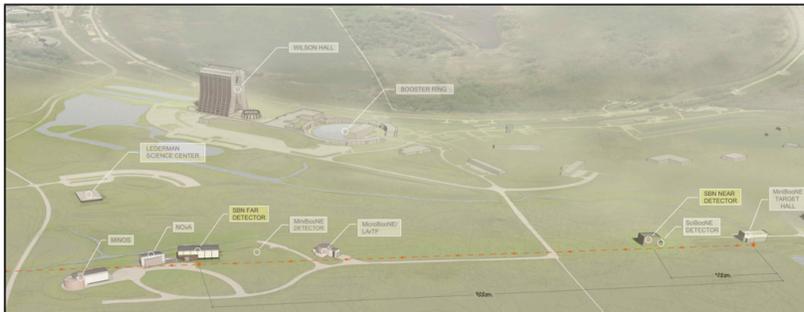Therefore, there needs to be ≥ 3 neutrino mixing for CP Violation!

SBN Program Proposal

In this proposal for the SBN Program, we describe the physics analysis, the conceptual design of the LAr1-ND detector, the design and refurbishment of the T600 detector, the necessary infrastructure required to execute the program, and a possible reconfiguration of the BNB target and horn system to improve its performance for oscillation searches.

**A Proposal for a Three Detector
Short-Baseline Neutrino Oscillation Program
in the Fermilab Booster Neutrino Beam**

The ICARUS-WA104 Collaboration

M. Antonello[16], B. Baibussinov[31], V. Bellini[5], P. Benetti[32], S. Bertolucci[6], H. Bilokon[15], F. Boffelli[32], M. Bonesini[17], J. Bremer[6], E. Calligarich[32], S. Centro[31], A.G. Cocco[19], A. Dermenev[20], A. Falcone[32], C. Farnese[31], A. Fava[6], A. Ferrari[6], D. Gibin[31], S. Gninenko[20], N. Golubev[20], A. Guglielmi[31], A. Ivashkin[20], M. Kirsanov[20], J. Kisiel[38], U. Kose[6], F. Mammoliti[5], G. Mannocchi[15], A. Menegolli[32], G. Meng[31], D. Mladenov[6], C. Montanari[32], M. Nessi[6], M. Nicoletto[31], F. Noto[6], P. Picchi[15], F. Pietropaolo[31], P. Płoński[42], R. Potenza[5], A. Rappoldi[32], G.L. Raselli[32], M. Rossella[32], C. Rubbia*[,6,11,16], P. Sala[18], A. Scaramelli[18], J. Sobczyk[44], M. Spanu[32], D. Stefan[18], R. Sulej[43], C.M. Sutera[5], M. Torti[32], F. Tortorici[5], F. Varanini[31], S. Ventura[31], C. Vignoli[16], T. Wachala[12], and A. Zani[32]

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Impact of Three Detector System
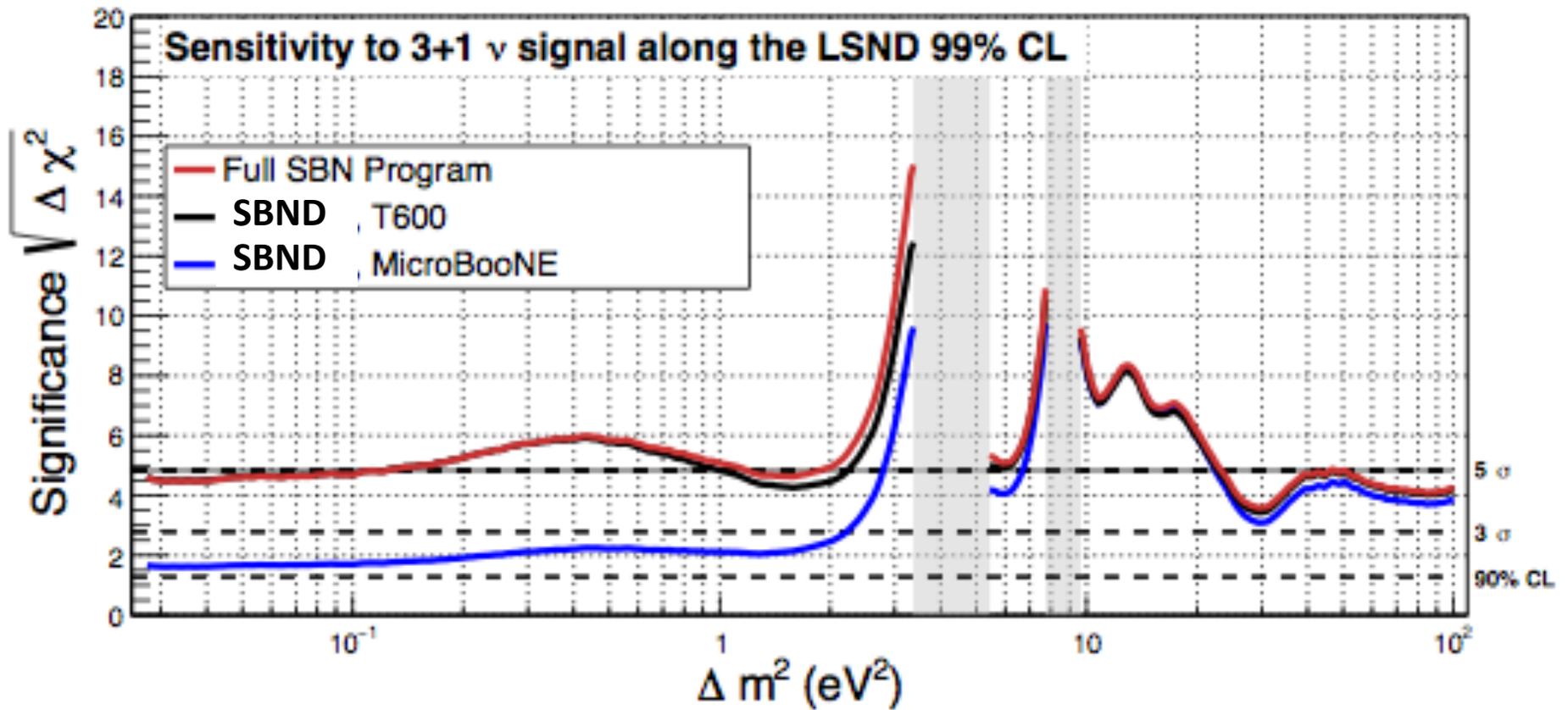
SBN Institutions and Authors

US 22

Russia 1

UK 6

Poland 5

CH 1

CERN

Italy 9
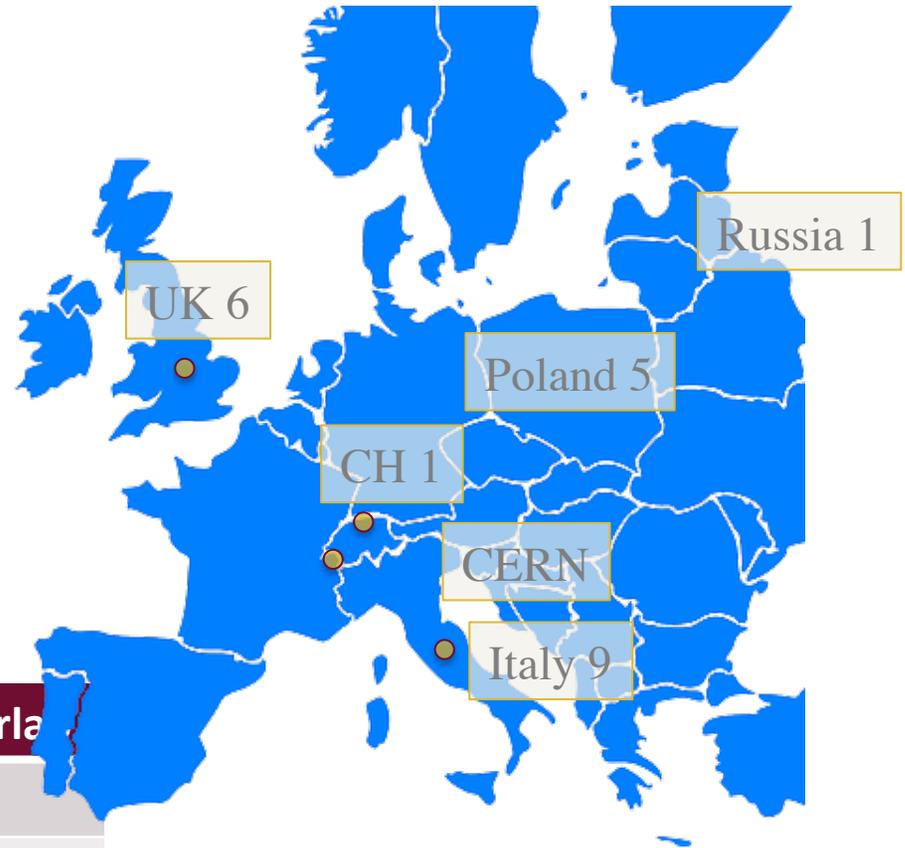
Collaboration	Authors	Overlap
ICARUS	57+n	6
SBND	108	
MicroBooNE	118	59
All SBN (excl overlaps)	**218+**	

Recent addition of 5 U.S. institutions to ICARUS

Institutions	SBN	SBN-DUNE Overlap
US	22+2	20+2
Non-US	23	19

Main SBN Funding Sources
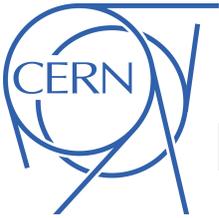
Main International Agreements