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Coherence of Short-Baseline and Long-Baseline Neutrino Programs

Peter Wilson

Fermilab Institutional Review

11 February 2015

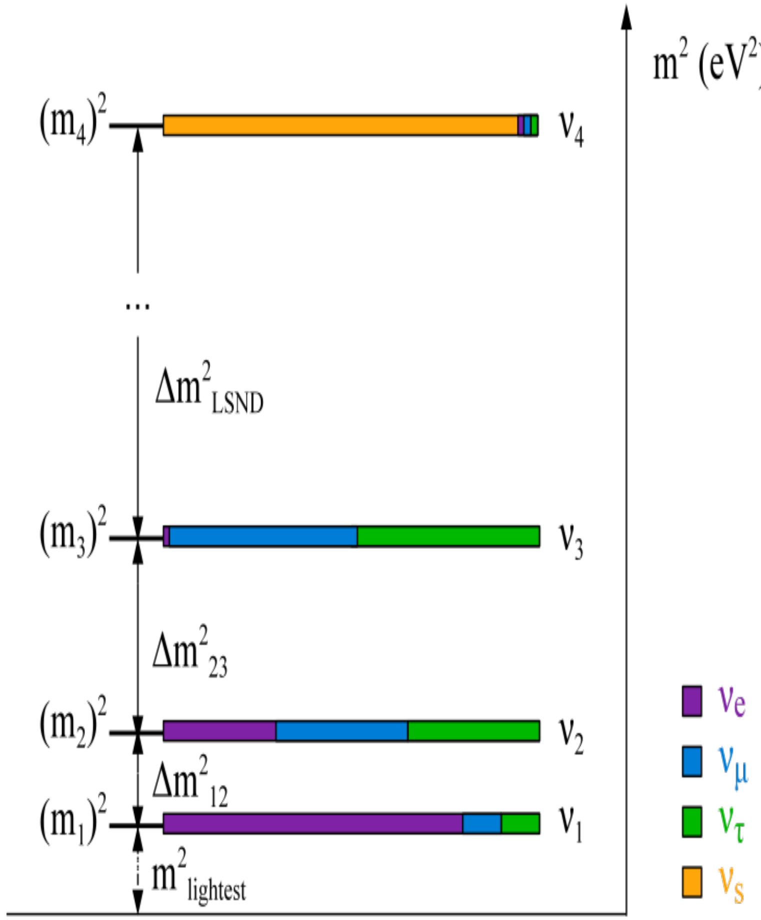
Outline

- Physics
  - Short baseline anomalies and SBN
  - ν-Ar cross sections
- Software and Reconstruction
  - Automated reconstruction
  - Software Tools
- Technology
  - Infrastructure
  - Detector components
- People and collaborations

SBN Science → LBN Science

- A basic goal of ELBNF is to determine if the three neutrino paradigm is a correct description of nature.
- If nature has a sterile neutrino(s) or other new physics causing the short baseline anomalies, it will be critical for interpreting long baseline experiments to understand it (them).
- The SBN program is designed to address these anomalies on a timescale to inform ELBNF

Example: 3+1 Scenario



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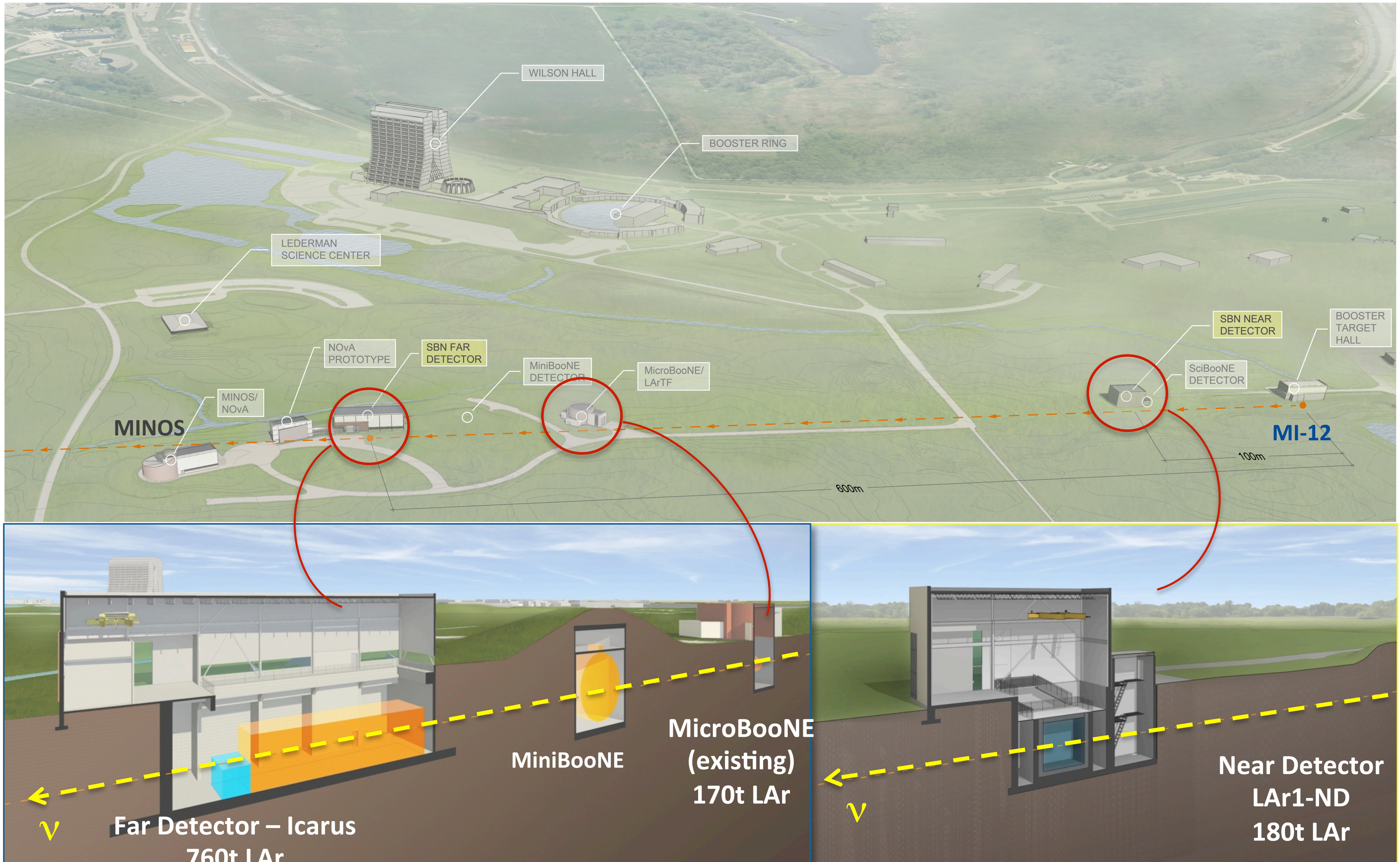
Brief History of Fermilab SBN Program

- Second generation of BNB based experiments about to start:
  - MiniBooNE: 2003-2013(?)
  - SciBooNE: 2007-2008
  - MicroBooNE: follow-up on MiniBooNE anomalies, start data-taking in 2015
- Proposals to address short-baseline anomalies using multiple LAr detectors under consideration for several years (e.g. ICARUS@CERN, LAr1@FNAL)
- At January 2014 Fermilab PAC two new proposals for next phase at BNB:
  - P-1052: ICARUS@FNAL: Updated ICARUS-T600 detector plus new T150 as near detector on the BNB for oscillation searches.
  - P-1053: LAr1-ND: LAr1-ND + MicroBooNE (possibly followed by 1kton scale far detector).
- Soon after, proponents of ICARUS, LAr1-ND, and MicroBooNE, along with representatives from FNAL, INFN and CERN, started working together to develop a plan for a coherent SBN physics program.

SBN Program Layout



The SBN Proposal

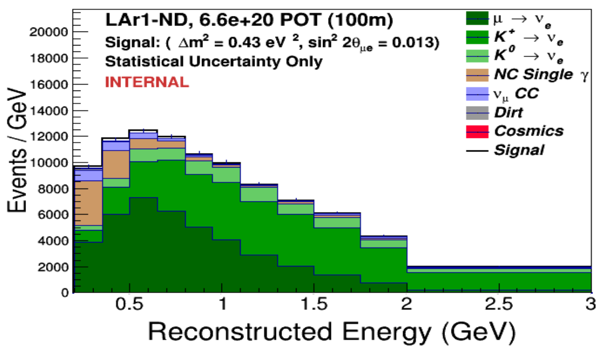
- Returned to the January 2015 PAC meeting with an updated proposal:

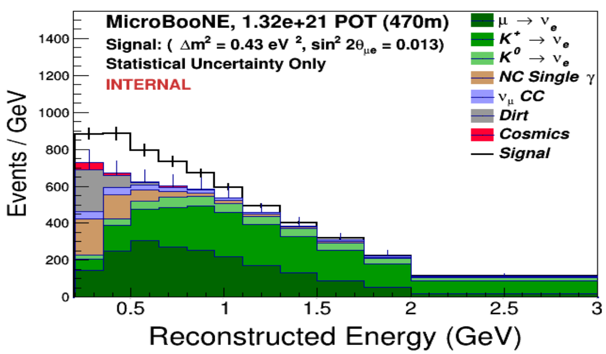
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

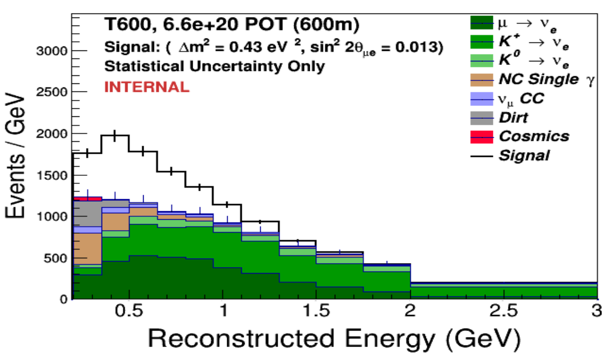
- The SBN program will consist of three LAr-TPC detectors:
  - **ICARUS-T600:** the only large-scale LAr-TPC in the world exposed to a neutrino beam
  - **MicroBooNE:** the largest LAr-TPC built in the US, starting operations in 2015
  - **LAr1-ND:** providing a new opportunity for development on the path to LBNF

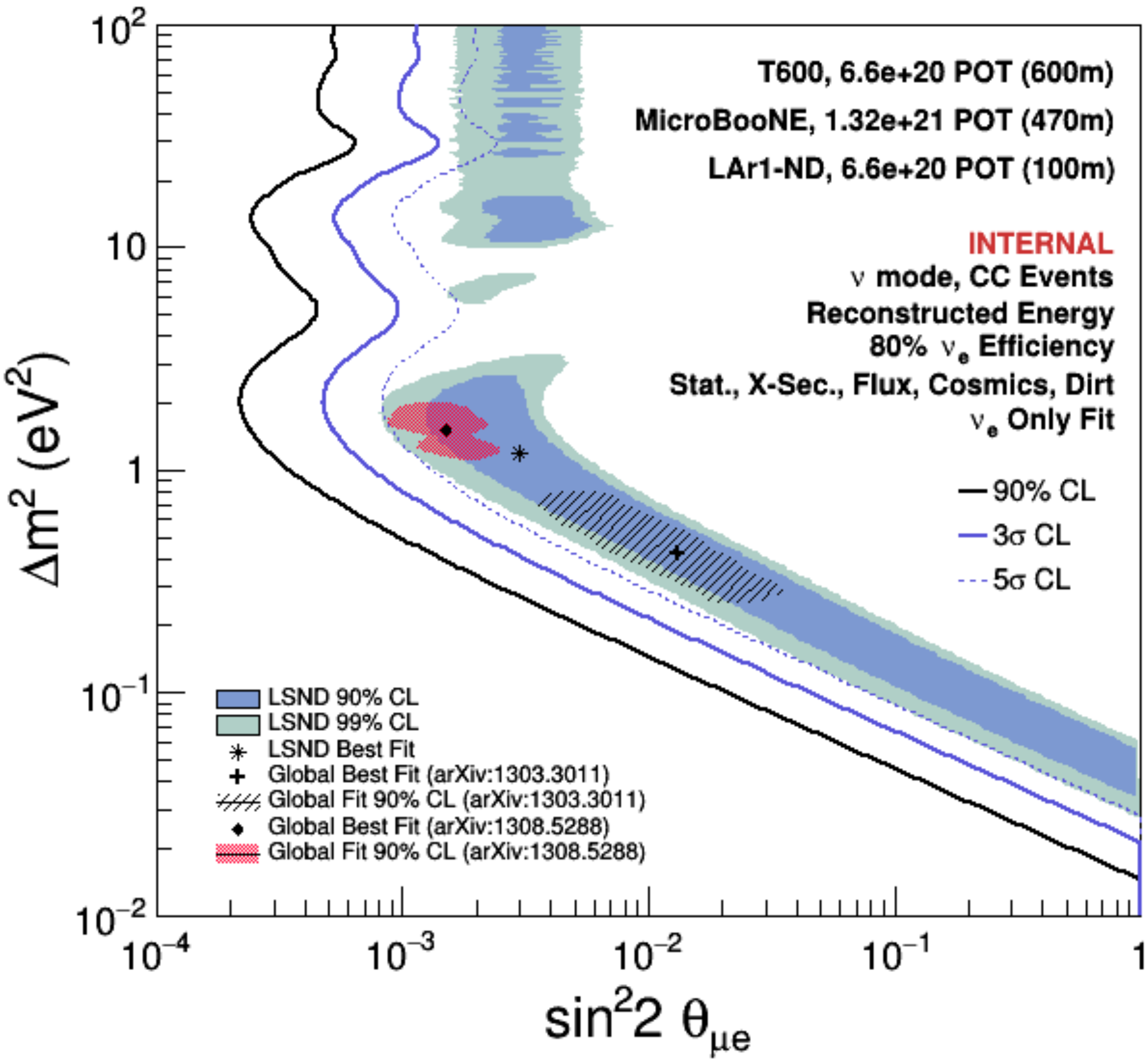
- These three detectors and the international teams of physicists and engineers realizing them represent a significant scientific as well as R&D opportunity toward the future neutrino program.

SBN ν_e Appearance Sensitivity

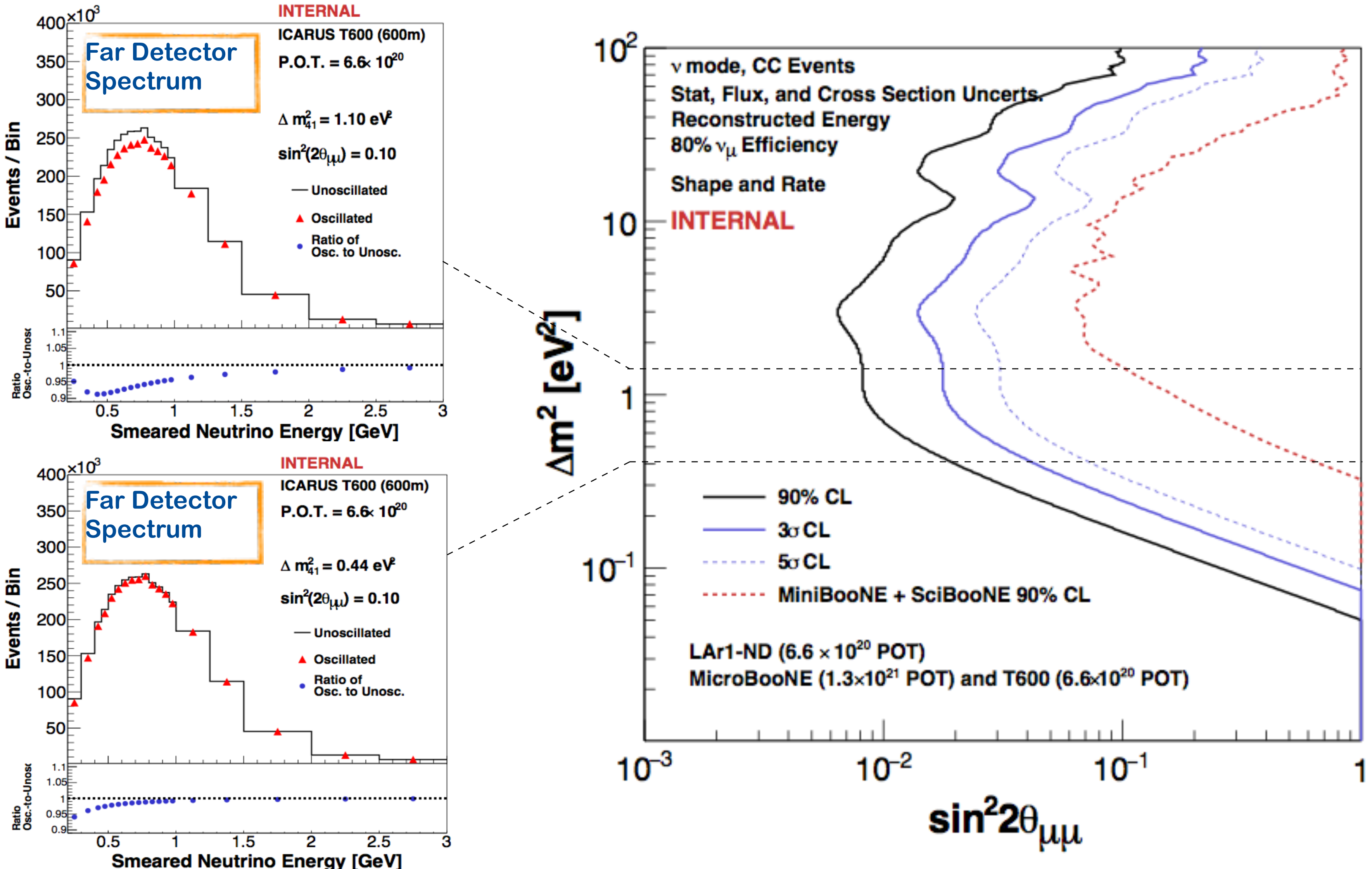








SBN ν_μ Disappearance Sensitivity



ELBNF – Confronting Systematics

To achieve the necessary level of systematic uncertainties for ELBNF, cross-section data will be needed to calibrate MC

Cross-section and nuclear models: Beyond current uncertainties

What is needed for LBNF?
Elizabeth Worcester
WINP 2015

14

- Basic strategy is to compare observables among alternative cross-section and nuclear-interaction models in GENIE
  - Long- and short-range correlations among nucleons
  - Effect of random phase approximations
  - Meson exchange currents
  - 2p-2h effects in CCQE
  - Effective spectral functions
  - Coherent pion production
  - Alternative model of DIS interactions
  - Variation of tunable parameters within existing models

In various stages of implementation in GENIE.

- Comparison with data (MINERvA, NOvA-ND, T2K-ND280, μBooNE, LAr1-ND, T600, …)
- Comparison with alternative generators (NuWro, GiBUU)
- Requires support for and close collaboration among model builders, developers of event generators, cross-section experiments, and ELBNF.

ETW: What is needed for LBNF? WINP, 4 February 2015

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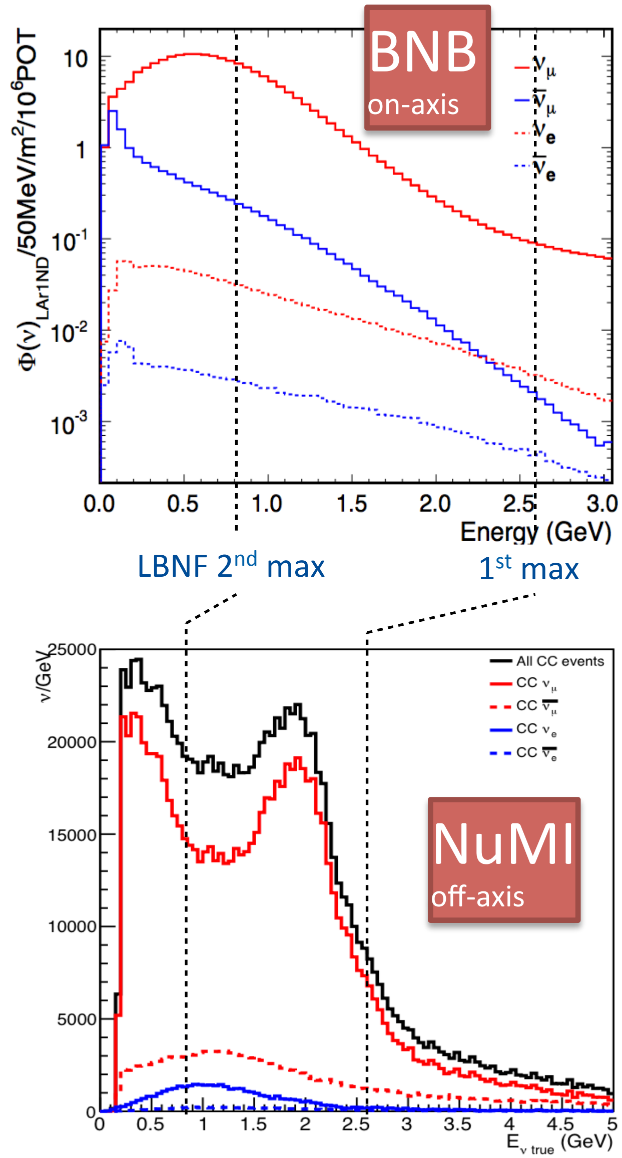
SBN - Neutrino Interaction Physics

- All three SBN detectors will collect large data sets from the BNB that can be used for cross-section measurements:
  - ND: ~1.2M CC interactions per year (~7,000 ν_e)
  - Large complementary samples in MicroBooNE and T600
- T600 and MicroBooNE will see NuMI beam events
  - T600: ~100k NuMI off-axis events per year
- Precision measurements of ν-Ar cross sections are an important component in reaching necessary systematics level for ELBNF



Interaction Measurements for SBN-ND

- Significant sample sizes for many channels with the SBN program
- Example of samples for 3 years data-taking of LAr1-ND →

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 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924	2,330	0.20%
NC $\geq 2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ \geq 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to$ 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	

TABLE I: *Estimated event rates using GENIE (v2.8) in the LAr1-ND active volume (112 t) for a 6.6×10^{20} exposure. In enumerating proton multiplicity, we assume an energy threshold on proton kinetic energy of 21 MeV. The 0π topologies include any number of neutrons in the event.*

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Software and Event Reconstruction

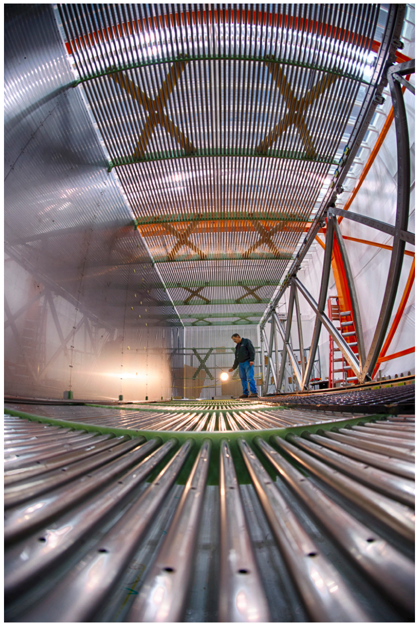
- SBN and ELBNF will both need to confront large data sets requiring event reconstruction and analysis
- These large data sets will require that event reconstruction and analysis become fully automated
  - Current LAr-TPC experiments (e.g. ICARUS and ArgoNeuT) use a combination of automated filtering and hand scanning. This will be too labor intensive for SBN and ELBNF.
  - Precision testing of event reconstruction and identification techniques possible with large SBN data sets
  - This development for SBN physics will have direct impact for LBN in the future
- The LHC experiments produced physics extremely quickly, benefiting significantly from expertise developed at the Tevatron and LEP before them. ELBNF can get to physics faster with the detailed studies of neutrino interactions in argon possible at the SBN
  - Provide both an understanding of the underlying physical processes and develop tools for reconstruction

Software Infrastructure

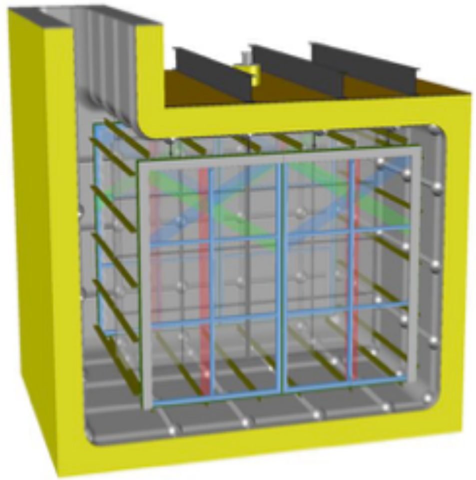
- Software tools development is a critical component of the preparation for ELBNF
- The LArSoft platform supported by Fermilab provides a common base that can be used throughout the world for sharing tools. It is already in use by several LAr-TPC experiments: e.g. LArIAT, MicroBooNE, ELBNF (eg 35t)
- The SBN program provides an opportunity to integrate the experience on reconstruction from the ICARUS collaboration with the more recent expertise from LArIAT and MicroBooNE into the LArSoft environment and hence into the ELBNF.
  - Effort already started within ICARUS-WA104 to use LArSoft
- Continued and enhanced support of LArSoft infrastructure by Fermilab will be essential to the success of the SBN and ELBNF programs.

SBN ⟷ ELBNF Detector Technology

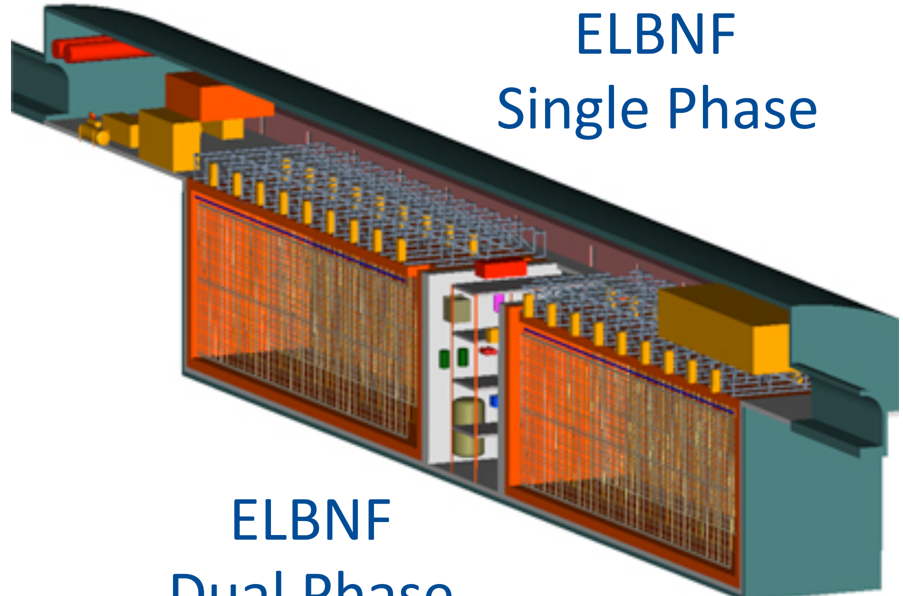
MicroBooNE



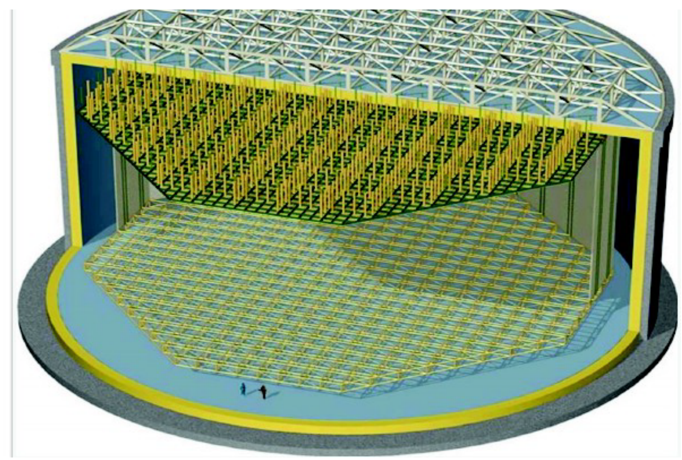
Lar1-ND



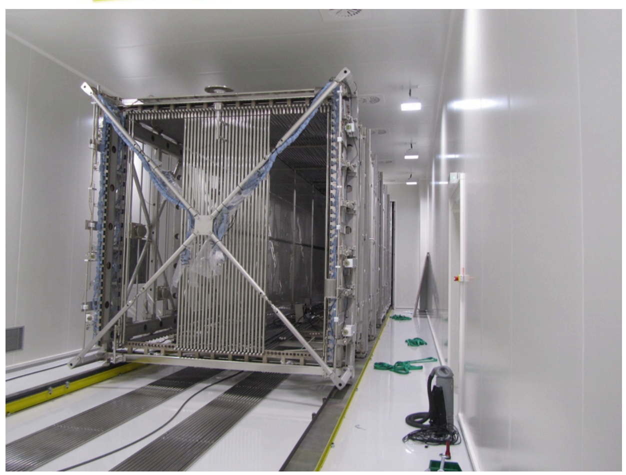
ELBNF
Single Phase



ELBNF
Dual Phase



ICARUS T600



SBN Technology ➔ LBN Technology

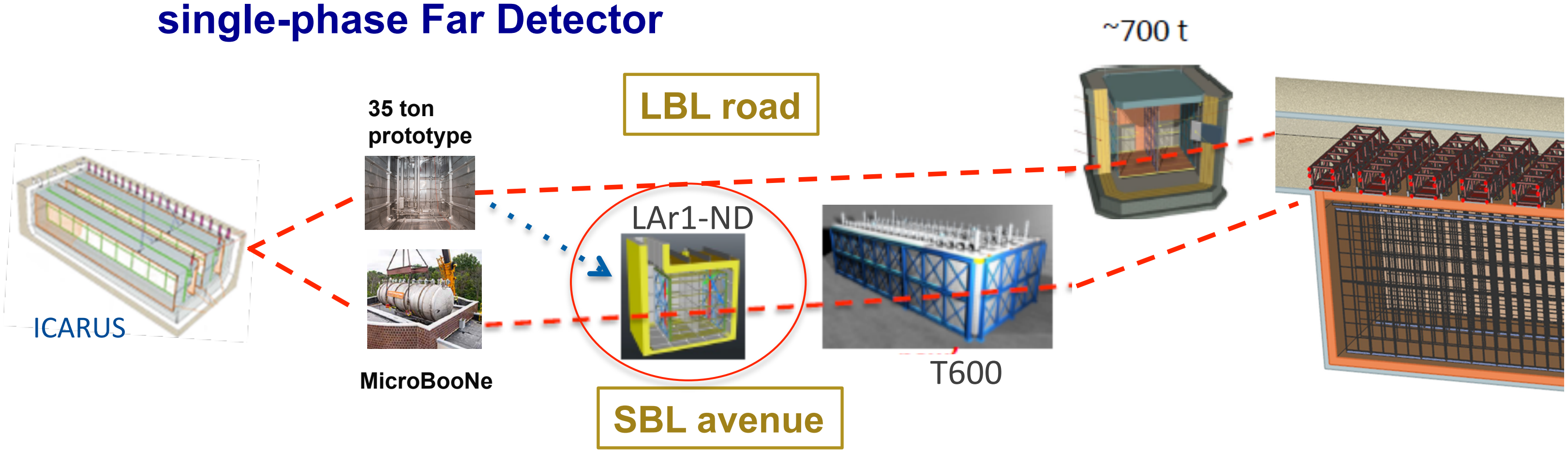
Evolution

Single-Phase Prototype at CERN
Mark Thomson
ELBNF Proto-Collaboration Meeting

★ Goal is to provide option for construction of a 10 kton far detector (~2021) + 30 kton (~2025)

★ Road to 10 kton by 2021 is challenging (& exciting)

- Need a program of single-phase development that minimizes risk
- Builds from strength, e.g. existing experience
  - ICARUS, Argoneut, …
- Now embarking on two development paths towards a "ELBNF"-scale single-phase Far Detector



SBN Technology: MicroBooNE

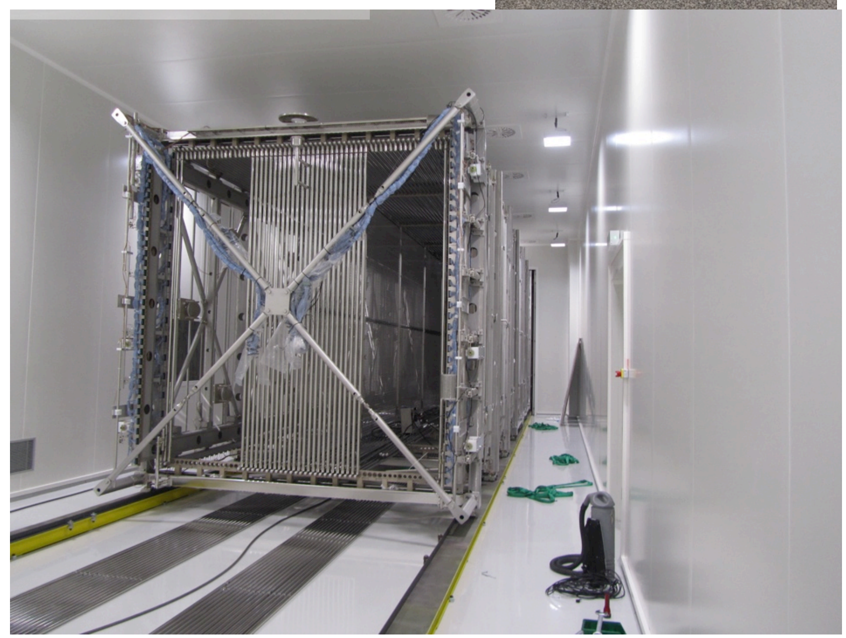
- Detector Installed, operations soon
- MicroBooNE Physics
  - Address MiniBooNE low energy excess: is it electron or photon?
  - Low energy ν-Ar cross-section measurements
- MicroBooNE R&D
  - Argon fill without evacuation
  - Cold front-end (amplifier) electronics
  - Long drift (2.5m)
  - Near surface operation
  - Automated reconstruction

SBN Technology: ICARUS-T600

- Only large scale LAr-TPC operated on a ν beam (CNGS → LNGS).
  - Achieved electron lifetime >15ms
  - Physics program including limits on sterile neutrinos
- For FNAL-SBN, refurbish at CERN w/ new cryostats and electronics, upgraded light detection.
- Further T600 technology development
  - Address lessons learned from LNGS operation
  - Focus on cosmogenic background rejection for surface operation
  - Light detection, external tagger system

Ready to leave LNGS

First T300 in Cleanroom at CERN



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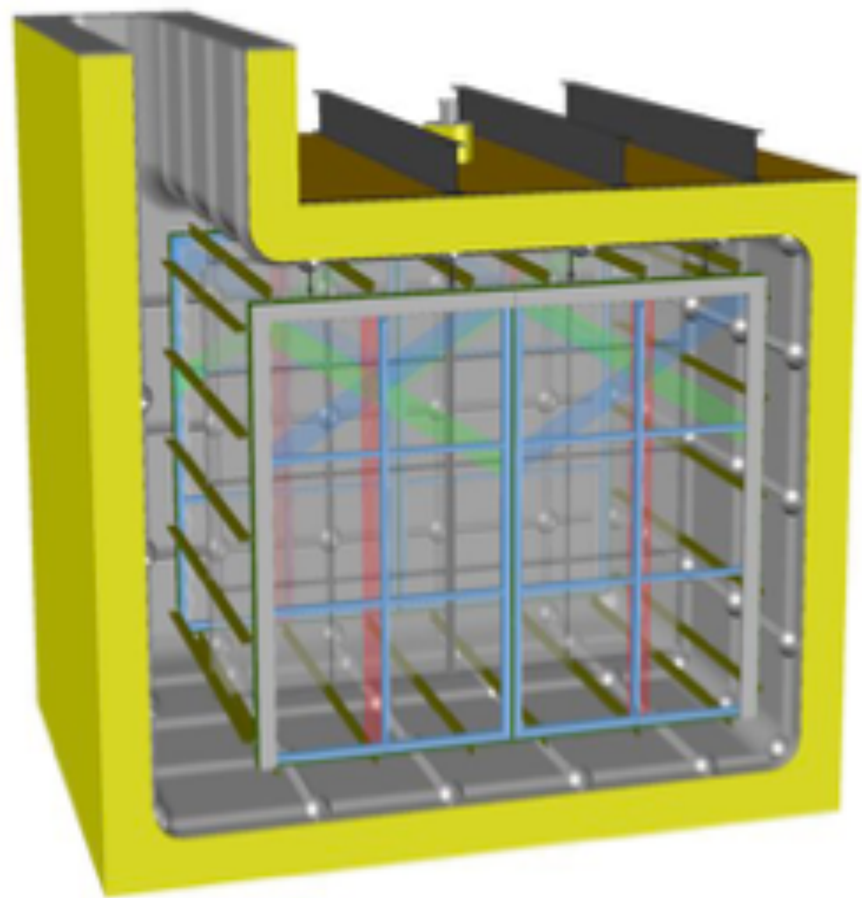
SBN Technology: LAr1-ND

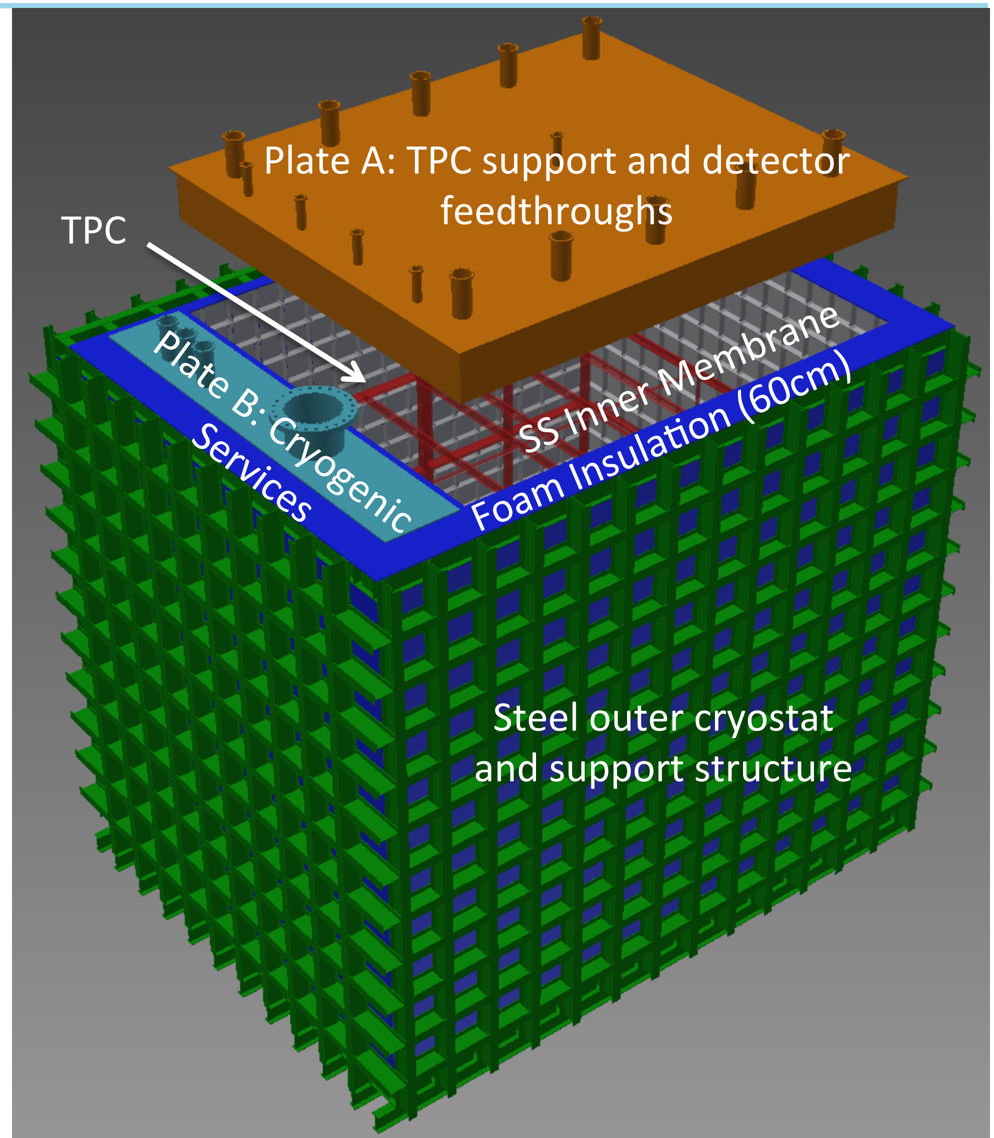
- A new detector, building on experience from ICARUS, MicroBooNE, LBNE 35 ton prototype
- Based on current ELBNF single-phase designs
  - Wherever possible build on lessons learned from 35 ton
- Provides an opportunity for prototyping ELBNF designs
  - Cryostat technology
  - Cryogenics systems
  - TPC construction techniques
  - Electronics
  - Light detection



Membrane cryostat

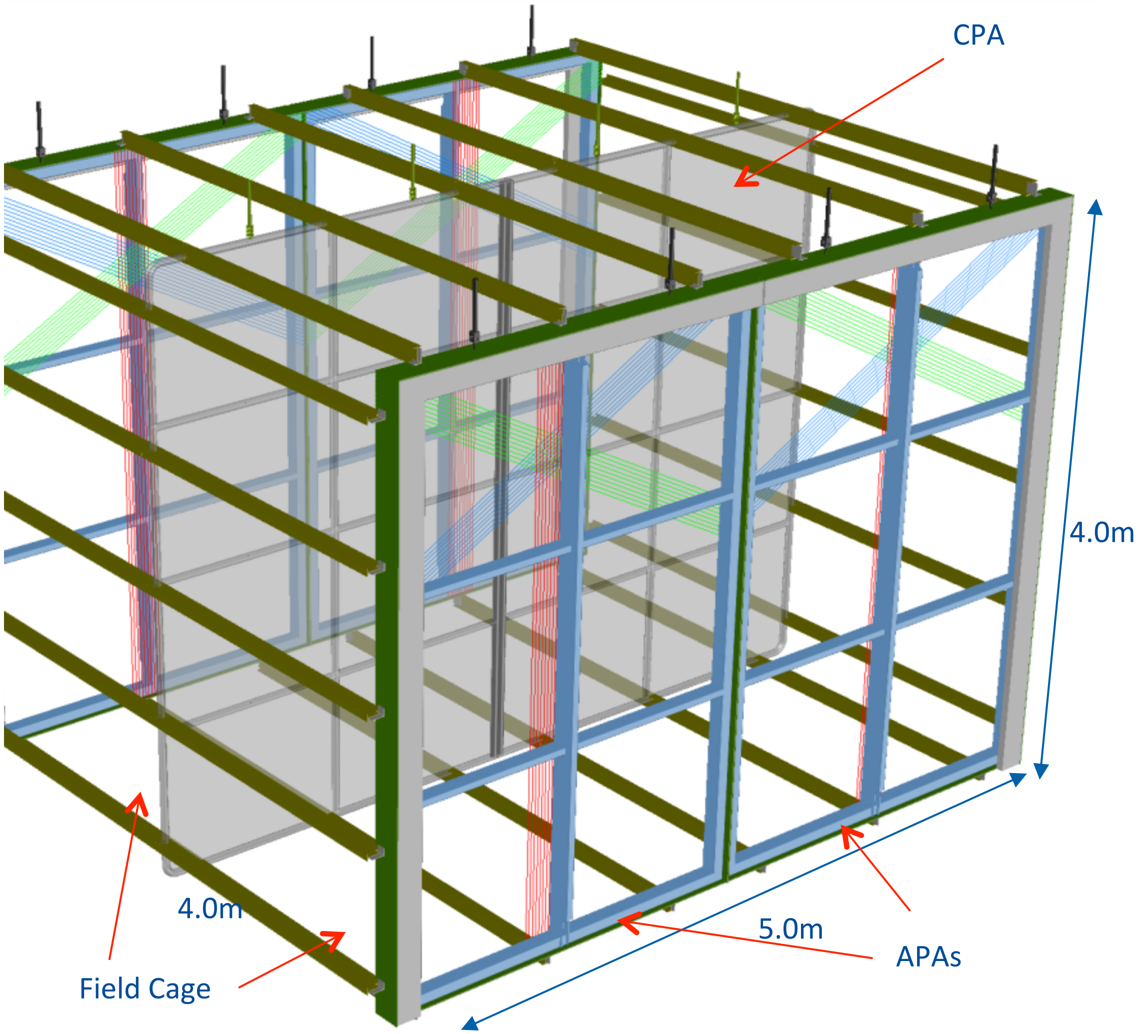
LAr1-ND Cryostat

- Membrane cryostat technology is for planned for the ELBNF far detector
  - Two worldwide vendors serving the LNG industry (IHI-Japan, GTT-France)
- LAr1-ND fits in series of cryostats being developed for LBNF designs
  - LBNE 35t (IHI)
  - WA105 dual-phase (50t) (GTT)
  - LAr1-ND (GTT through CERN)
  - WA105 dual-phase (GTT)
  - LBNF single-phase for CERN testbeam (GTT)
  - Full size LBNF 10-40kt (tbd)
- Collaboration between Fermilab and CERN



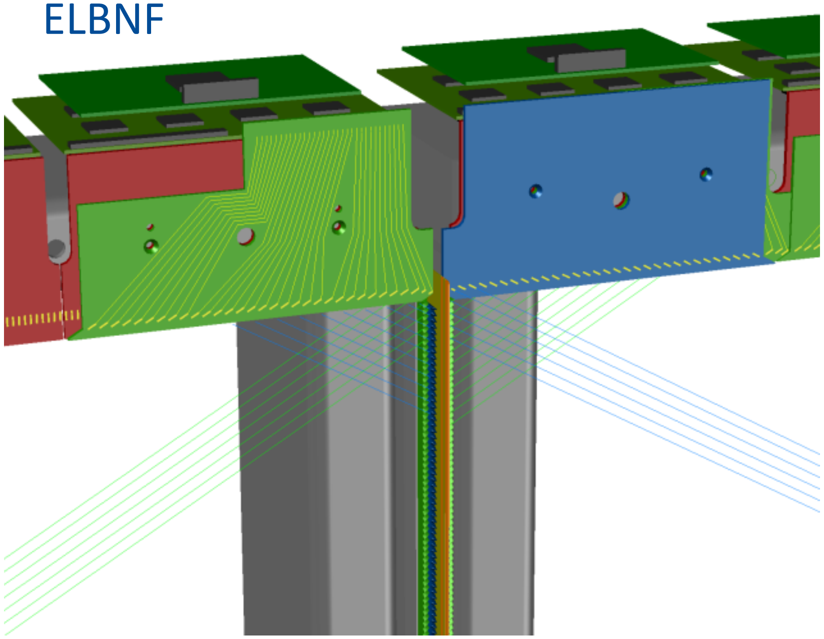
LAr1-ND TPC Design

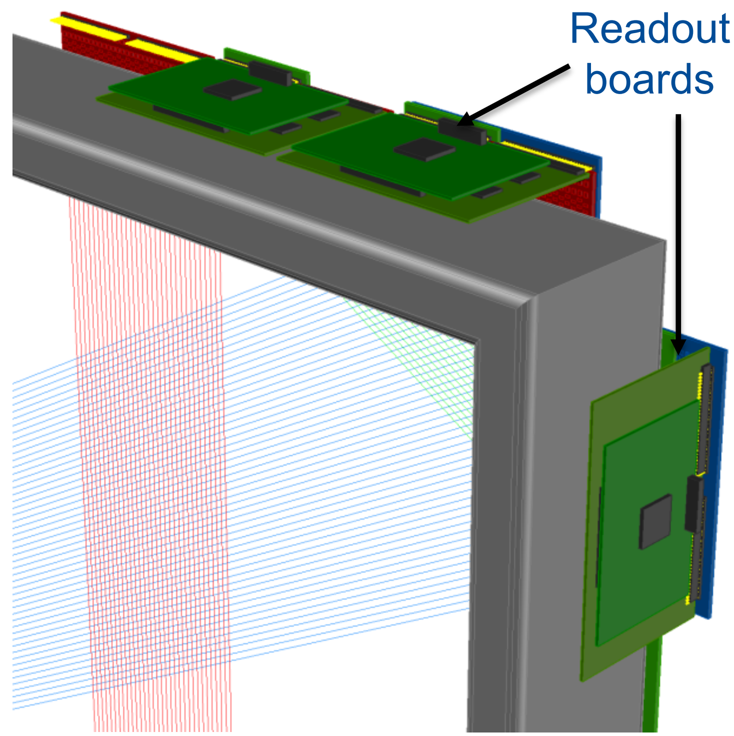
- Based on current ELBNF single phase design
- Active volume: 5m (beam) x 4m (width) x 4m (height)
- Central cathode plane assembly (CPA), two anode plane assemblies (APA) on either side w/ 2m drift distance each.
- Single sided APA wire planes joined at edge to reduce readout channels
- Light detectors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



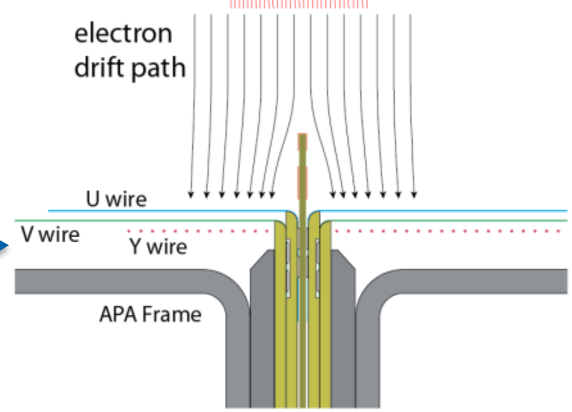
LAr1-ND: Anode Plane Assemblies

The LAr1-ND APA is a hybrid between that of MicroBooNE and LBNE with innovative features that will benefit ELBNF



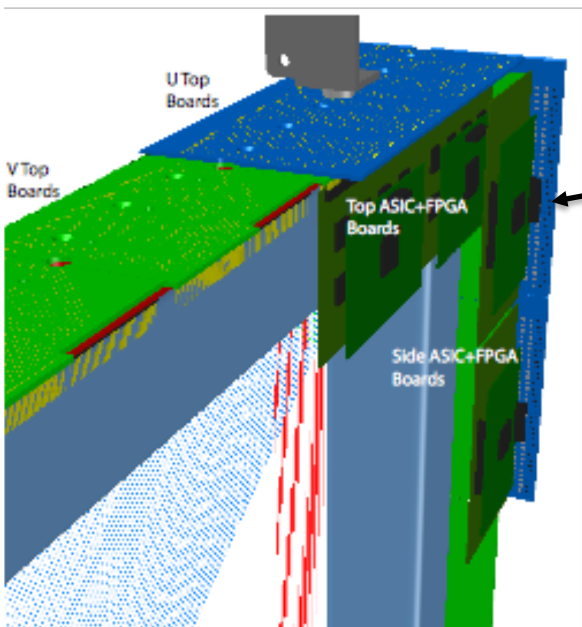


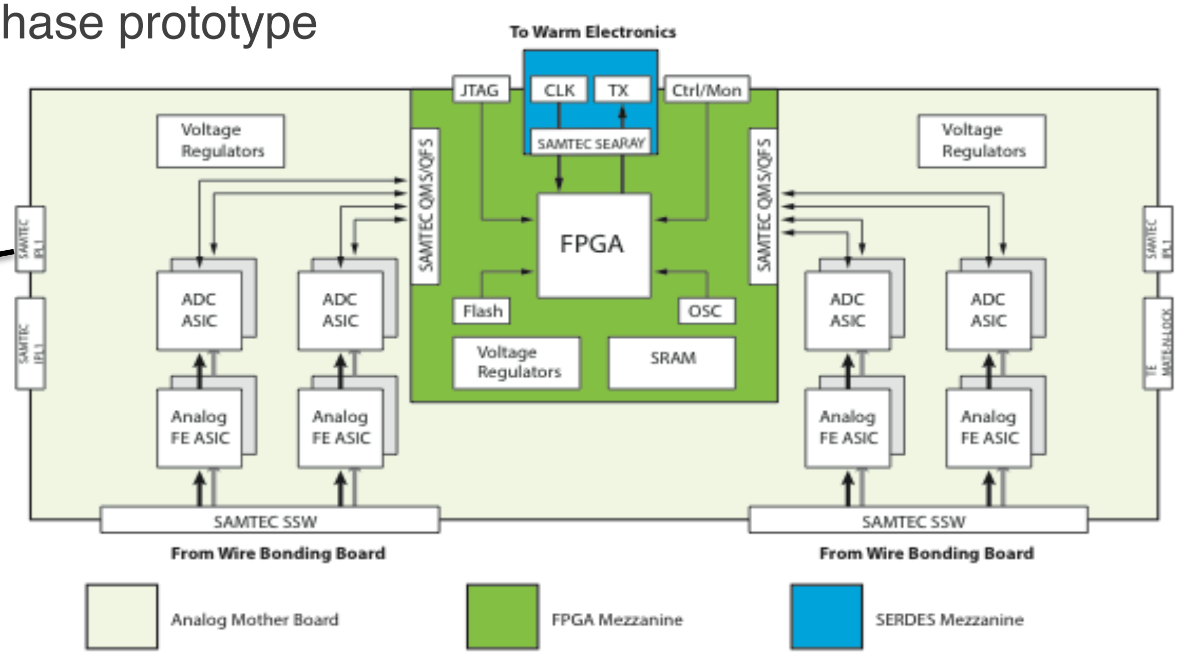
Innovation example: Bias board between adjacent APAs to eliminate dead region



LAr1-ND Cold Electronics

- Front-End ASIC & ADC ASIC developed for LBNE along with FPGA (data sparsification) all in cold
  - MicroBooNE uses cold front-end but warm digitizer
  - LBNE 35 ton prototype uses full chain
  - LAr1-ND to use next generation based on 35 ton lessons
  - Will need to synchronize development with simultaneous development for ELBNF CERN Single-Phase prototype





Front End Mother Board

SBN-ND ⟷ ELBNF Technology Comparison

	LAr1-ND	ELBNF (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	LAr1-ND's APA design avoids the wire wrapping, optionally allowing APA tiling on all 4 sides. The LAr1-ND 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	LAr1-ND's wire configuration is identical to MicroBooNE
Cold Electronics	FE ASIC, ADC ASIC, FPGA	FE ASIC, ADC ASIC, Digital ASIC	LAr1ND may update the FE ASIC chip to include on-chip pulser
Warm Interface Board	FPGA + Optical Transceiver	Optical Transceiver and/or FPGA	LAr1-ND 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 ELBNF PDs.

SBN ⟷ ELBNF Engineering Teams

- SBN design and engineering teams are an integral part of ELBNF single-phase development. Most components of LAr1-ND have been conceived and developed by scientists and engineers working on ELBNF designs:
  - TPC concept from Bo Yu (BNL) who designed the MicroBooNE TPC and LBNE 35 ton prototype
  - TPC detailed design and fabrication is a collaboration between the US consortium behind the MicroBooNE TPC and UK institutes developing TPC construction for ELBNF (eg CERN single phase prototype)
  - Cold electronics designed by BNL Instrumentation Division for ELBNF
  - Baseline light collection based on work by Indiana for the 35 ton prototype
- As SBN enters next stage with technical review of designs, need to explicitly review alignment with ELBNF development
  - Some designs should be the same (test ELBNF design)
  - Some designs should be different due to different requirements OR to test alternate solutions

SBN ⟷ ELBNF Example: LAr Cryogenics Teams

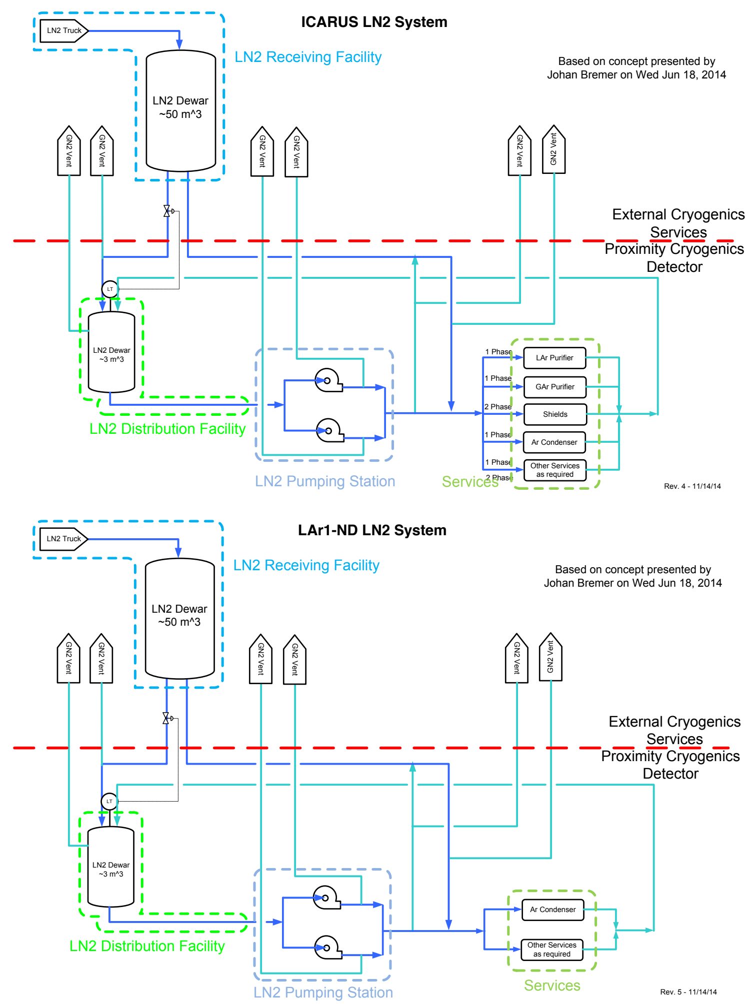
- In 2014, new engineering teams were formed at Fermilab and CERN with the joint mission of development of cryostats and cryogenics for LAr-TPC detectors for SBN, CERN testbeam and ELBNF. Focus on common designs that are scalable.
- Fermilab team initiated in the Particle Physics Division and moved to new Neutrino Division in October 2014.
  - Combination of engineers and designers from AD, PPD, and TD. Additional personnel through new hires and contractors.
  - Decades of experience on LAr (Liquid Argon Purity Demonstrator, LBNE 35 ton, MicroBooNE, LBNF) and LHe: Tevatron cryogenics, SRF teststands etc
- CERN team draws on expertise from ATLAS LAr calorimeter and LHC
  - Just starting to staff up with two new hires posted last week
- One Fermilab engineer stationed at CERN for CY 2015 to jump start collaborative efforts. Expect more exchanges in both directions.

SBN ⟷ ELBNF Example: Cryogenics Infrastructure

- Common designs wherever possible across multiple LAr-TPC. Apply designs to uses at Fermilab and CERN (e.g.):
  – LAr1-ND, WA105 (small and large) , LBNF CERN prototype, LBNF

- Multiple areas of design:
  – Membrane cryostat designs
  – LN2 delivery: SBN near and far detectors working on common solution (see right)
  – Standardize LAr filtration skid design in a scalable way that builds on experience from ICARUS/T600, LAPD/LBNE 35ton, MicroBooNE.

SBN LN2 Delivery Systems



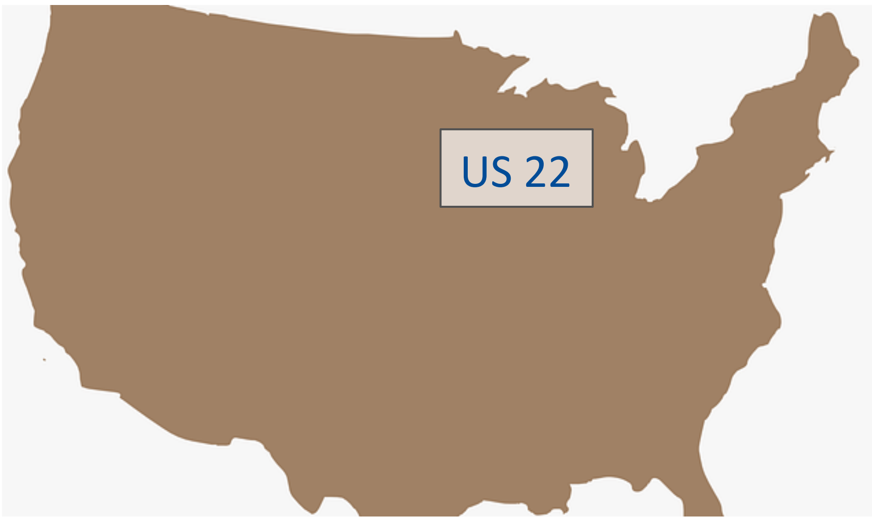
SBN Collaboration Building

- The SBN proposal presented to the PAC in January 2015 is the product of the coordinated effort of three international collaborations. This work has forged a partnership between the leading experts on LAr-TPCs from Europe with the rapidly developing expertise in the US and UK
- Most of the SBN institutions and collaboration members are active on ELBNF or plan to be active on ELBNF.
  - The students and postdocs cutting their teeth on the SBN program will be at the core of ELBNF a decade from now.

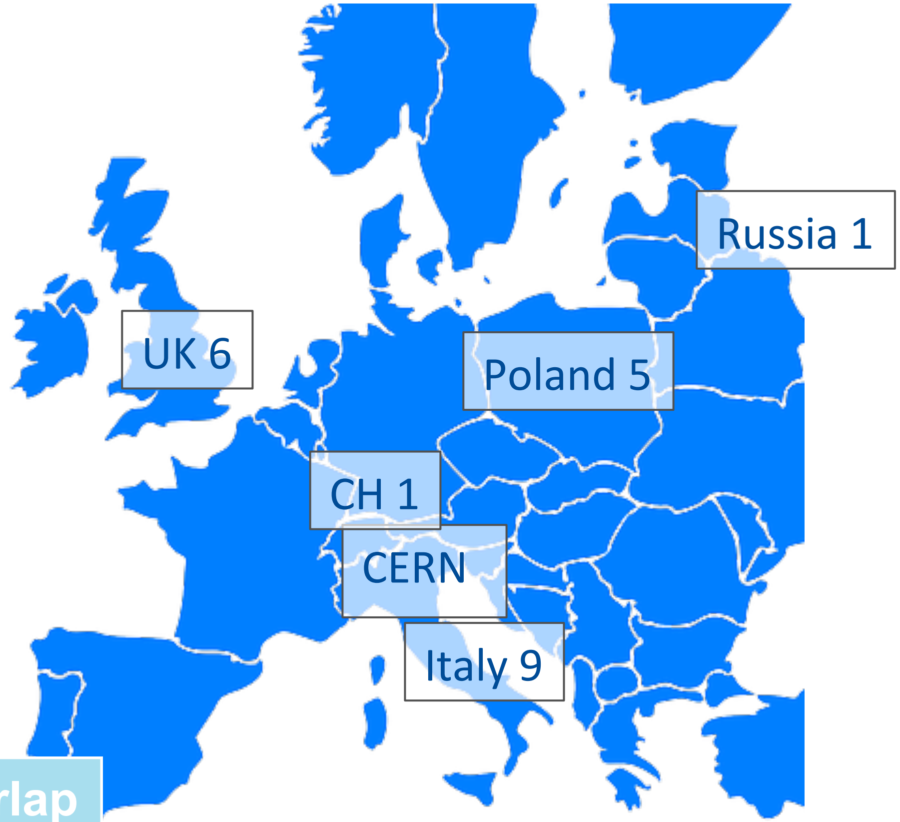
MicroBooNE:
S. Gollapinni (KSU),
D. Caratelli (Columbia),
D. Kaleko (Columbia)

MicroBooNE:
M. Mooney (BNL),
J. Joshi (BNL),
Y. Li (BNL)

SBN Institutions and Authors



More institutions/countries expressing interest



Collaboration	Authors	Overlap
ICARUS-WA104	57	6
LAr1-ND	108	59
MicroBooNE	118	
All SBN (excl overlaps)	**218**	

Institutions	SBN	SBN-ELBNF Overlap
US	22	20
Non-US	23	19

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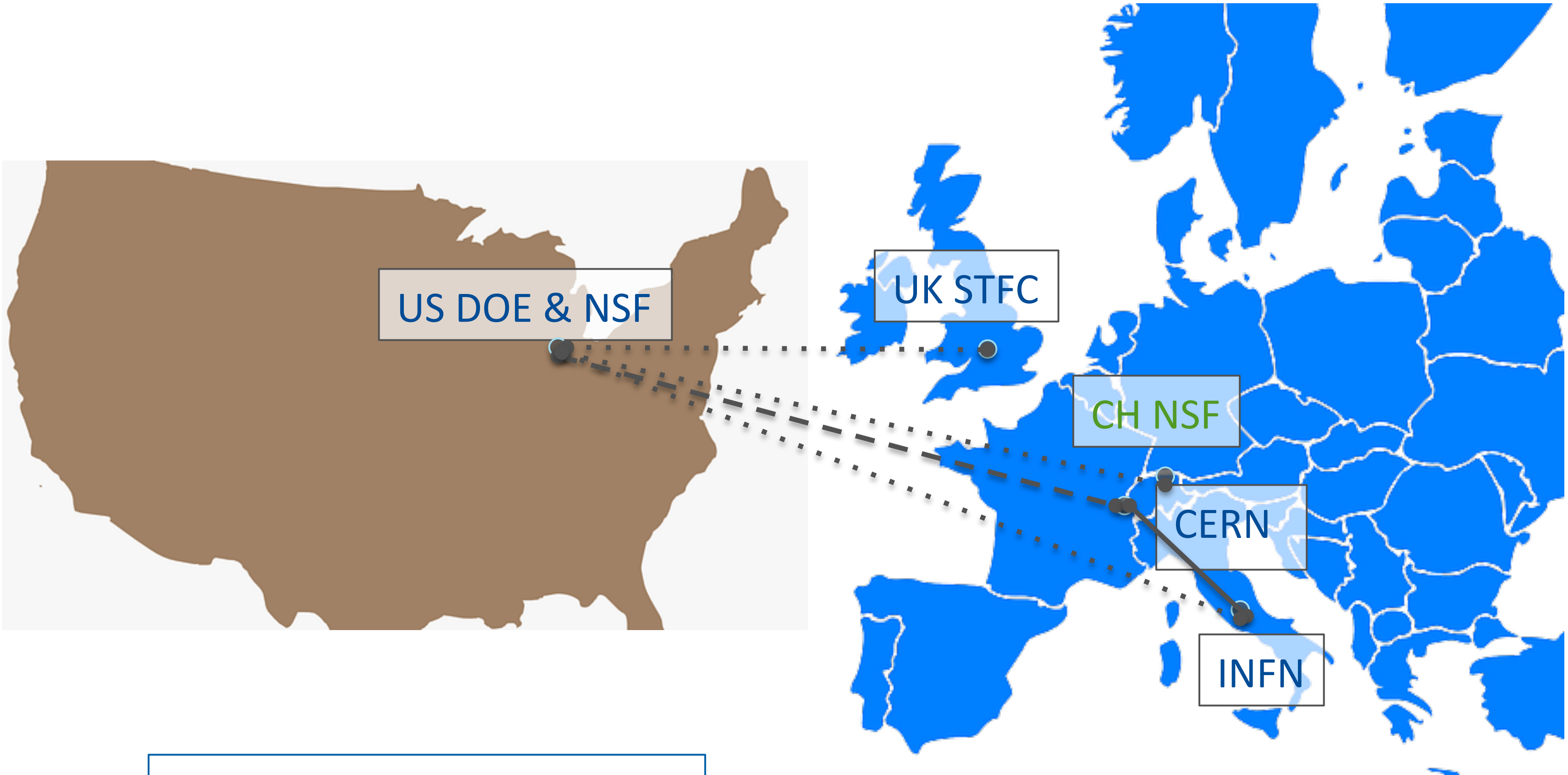
Main SBN Funding Sources



Agreement Status
- Signed
- In discussion
- Discussion to be started

Summary

- The SBN program is a crucial intermediate term part of a coherent neutrino program leading to ELBNF.
- A definitive statement on the LSND and MiniBooNE anomalies and the potential for discovery of a sterile neutrino are an important component of testing the 3 neutrino paradigm that ELBNF is designed to test.
- ELBNF will rely on improved models of ν-nucleon interactions to achieve the necessary level of systematic uncertainty. The SBN program will provide valuable measurements of ν-Ar interactions based on high statistics data samples.
- The large data sets in the three SBN LAr-TPCs will be a testing ground for reconstruction algorithms and automation of reconstruction that will be essential for ELBNF.
- The LAr1-ND detector is being developed by many of the same people who have been developing the ELBNF single-phase design. This will ensure that lessons learned are shared between the two programs.

SBN Proposal Author List

The ICARUS-WA104 Collaboration

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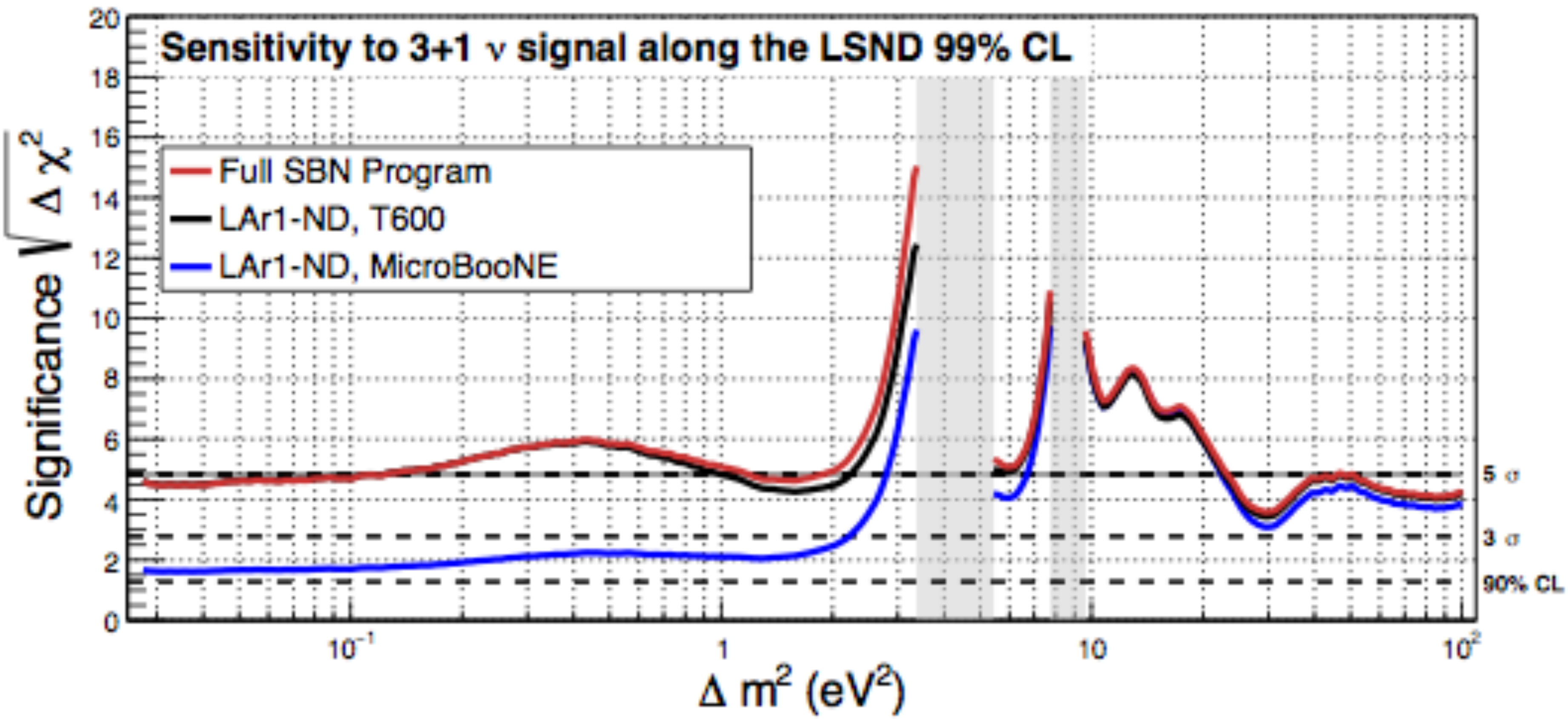
Impact of Three Detector System



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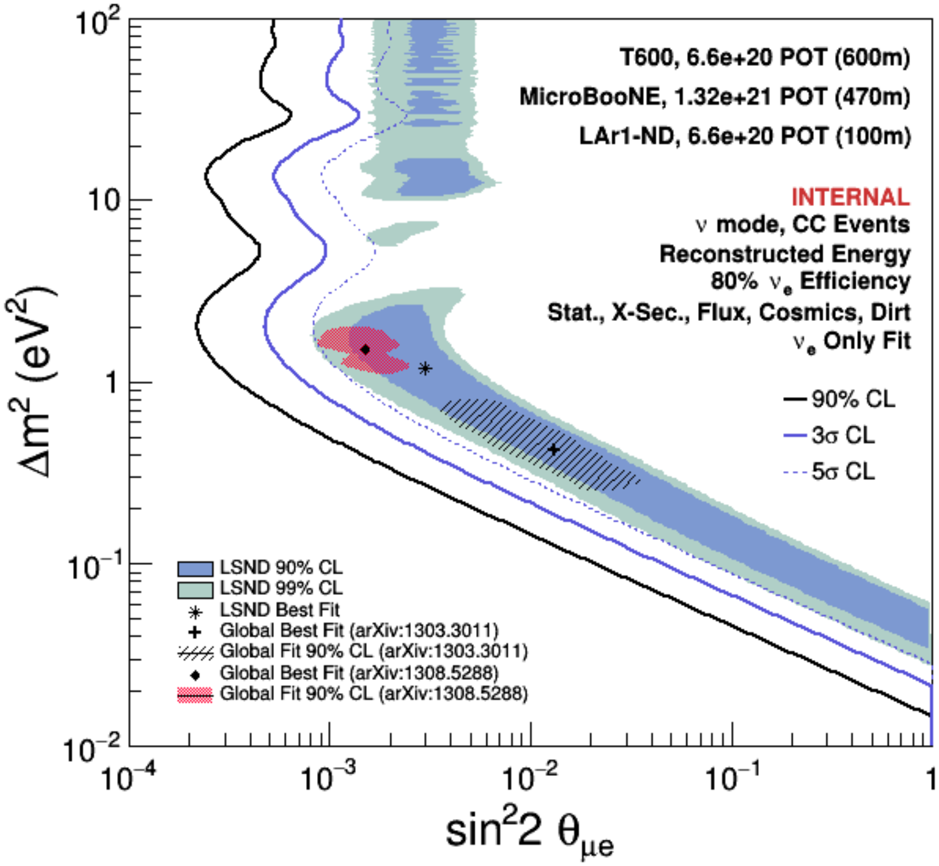
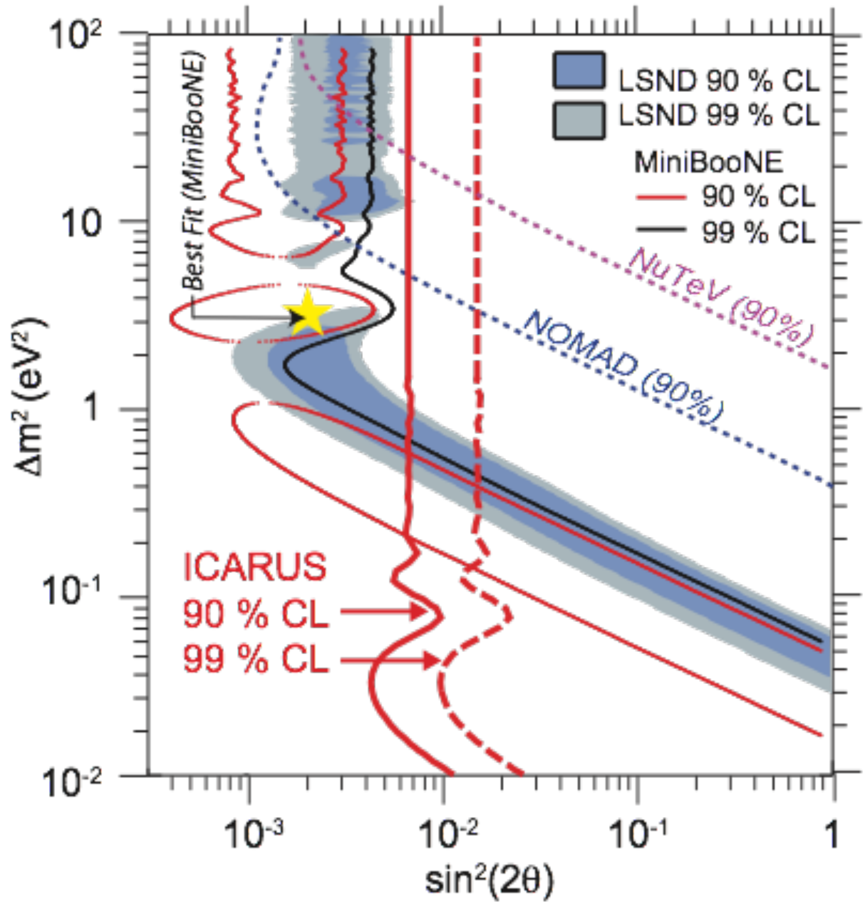
Comparison to MiniBooNE ν Mode





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