Liquid Argon Neutrino Program
Short- and Long-Baseline Neutrino Experiments

Zelimir Djurcic, Maury Goodman

ANL HEP-PHY Neutrino Meeting, April 13, 2015.

P5 Recommendations

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

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**.

Deep Underground Neutrino Experiment (DUNE)

- Long-baseline neutrino experiment DUNE is proposed to consists of
  -an intense neutrino beam originating at Fermilab
  -near detector systems at Fermilab
  -at least ~40 kt liquid argon time-projection chamber (TPC) at Sanford Laboratory at 4850 foot depth – 1300 km from Fermilab

DUNE Science Goals

- LBNE is a comprehensive program to measure neutrino oscillation
- LBNE design follows these priorities:

  -CP violation in neutrino sector

  -CP phase measurement regardless of its value

  -Neutrino mass hierarchy determination

  -Determination of θ_{23} octant and precision parameter measurements

  -Precision tests of 3-flavor neutrino model.

  comprehensive program with beam neutrinos

  -Atmospheric neutrino measurements (confirmation of mass ordering with independent data)

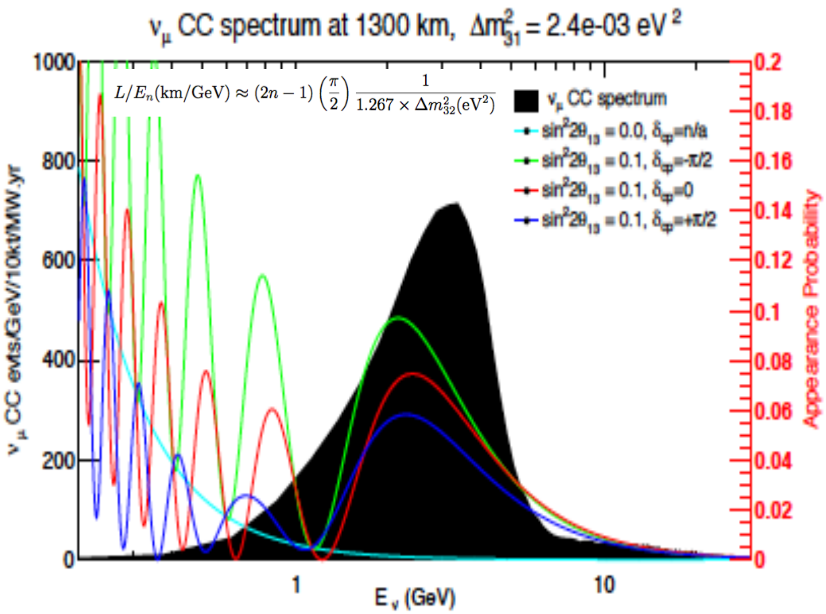
  -Nucleon decay

  -Supernova burst neutrinos

  -A very capable near detector will have a synergistic scientific program of precision neutrino and weak interaction physics.

Experimental Technique

- Produce a pure muon-neutrino beam with energy spectrum matched to oscillation pattern at selected distance.
- Measure spectrum of ν_μ and ν_e at a distant detector.



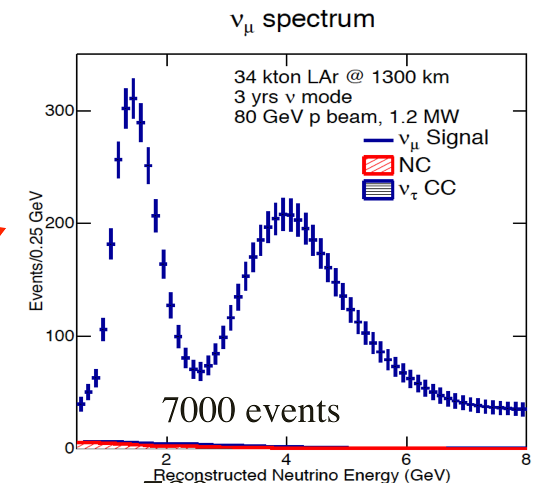
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos \Delta_{32} - \alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin \Delta_{32}$$

$$a = G_F N_e \sqrt{2}$$

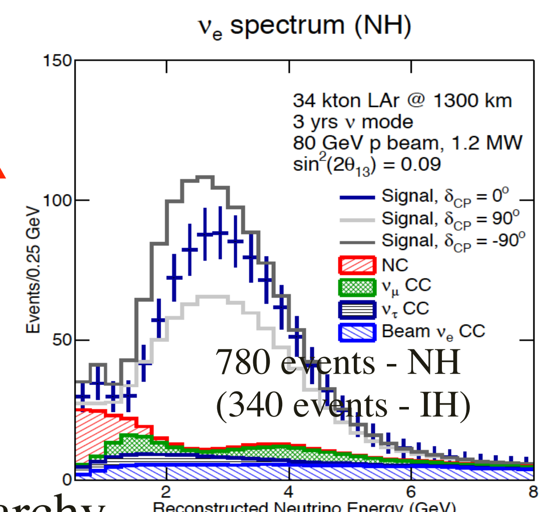
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

ν_μ disappearance

ν_e appearance



$\approx$ 780 ν_e events



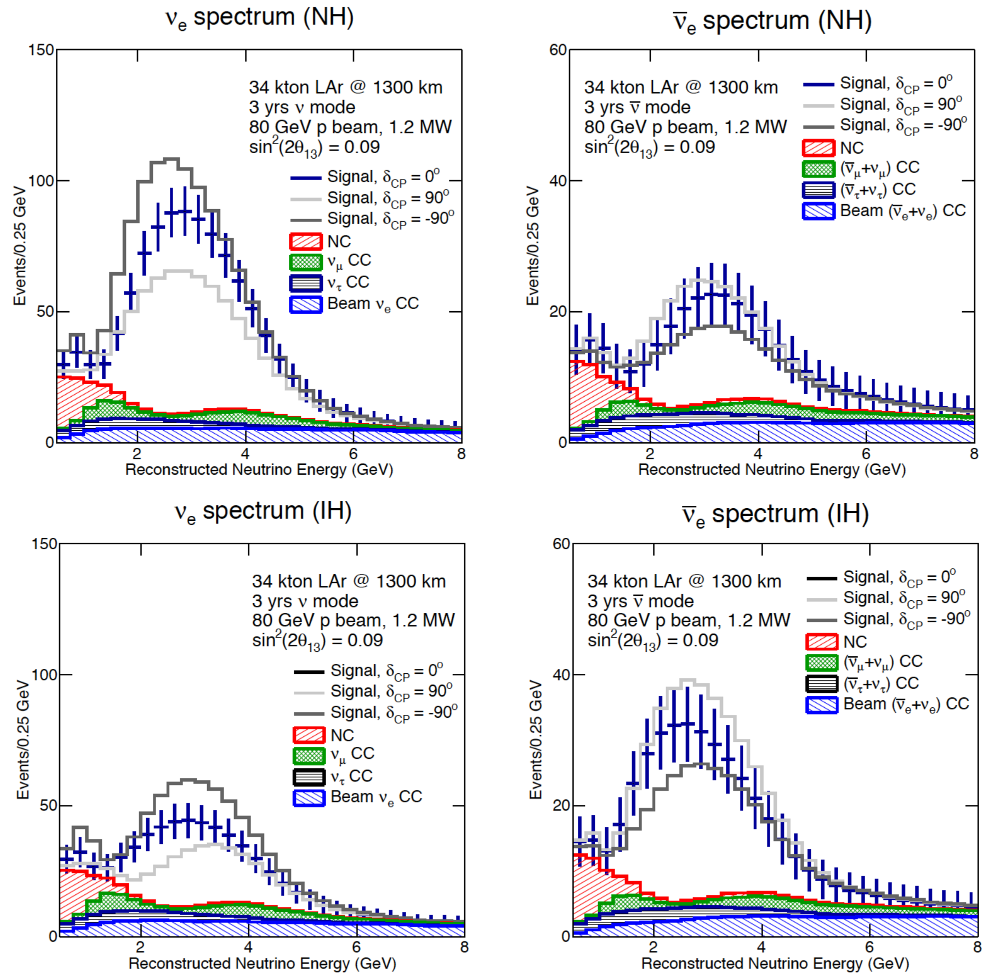
- LBNE is a good choice of beam and distance for sensitivity to CP-violation, CP-phase, neutrino mass hierarchy, and other oscillation parameters within the same experiment.

Event Rates at the Far Detector

GLoBES simulation with global smearing and efficiencies based on ICARUS.

Three years of running each for neutrinos and anti-neutrinos

neutrino running | anti-neutrino running



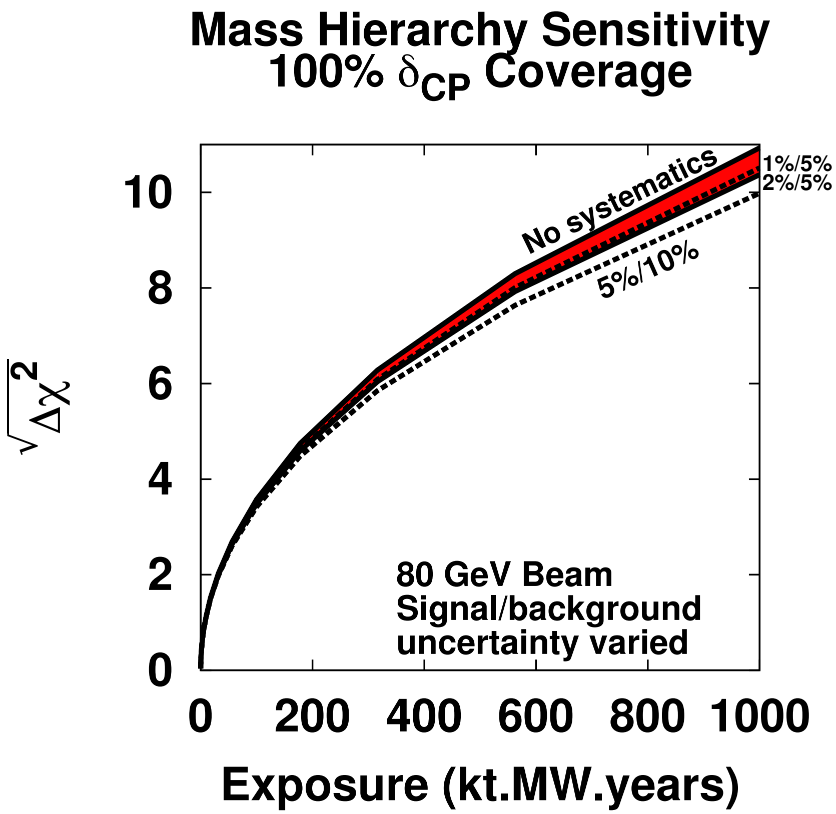
Normal Hierarchy

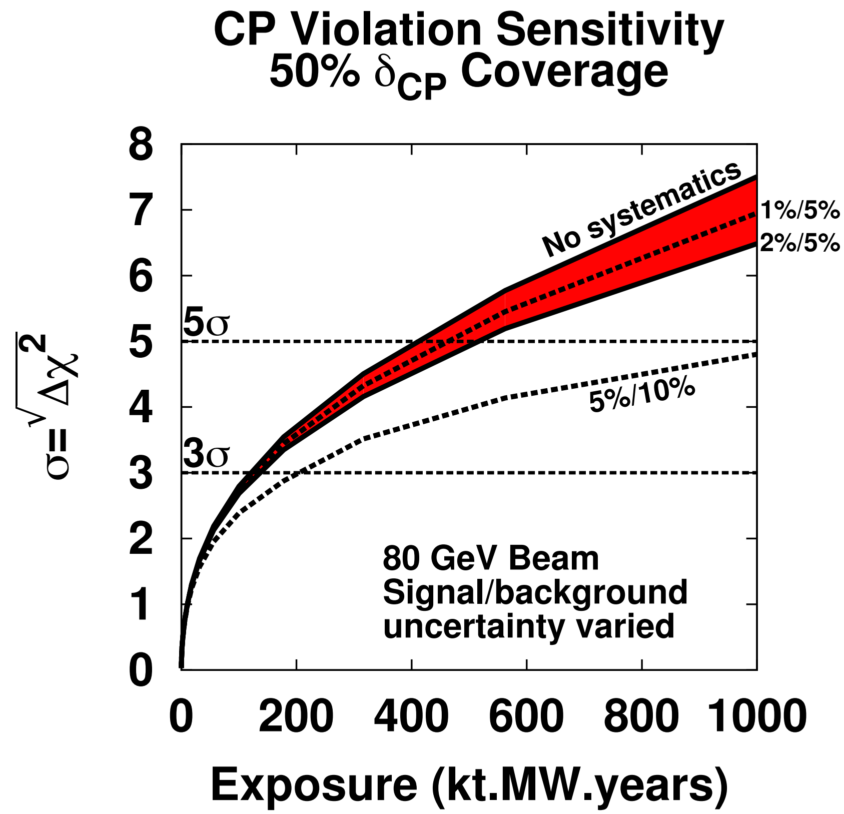
Inverted Hierarchy

Aiming for ~1000 events in neutrinos and ~300 in anti-neutrinos

- In ν_e appearance search aiming at ~1000 events in neutrino run and ~300 events in anti-neutrino run.

Mass Hierarchy and CP Sensitivities

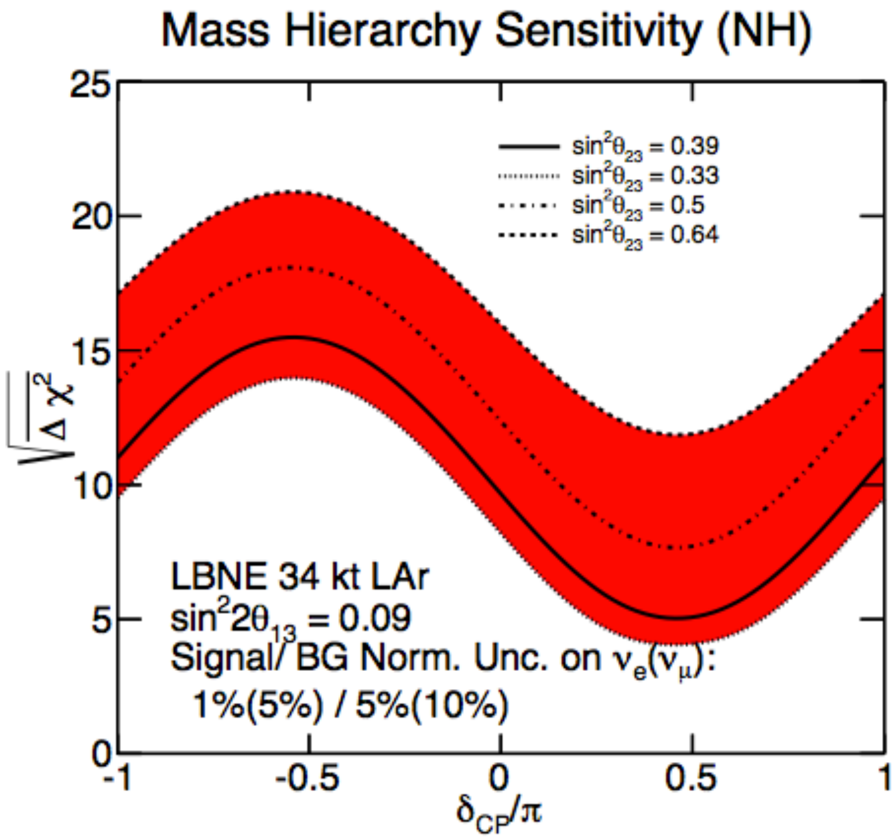


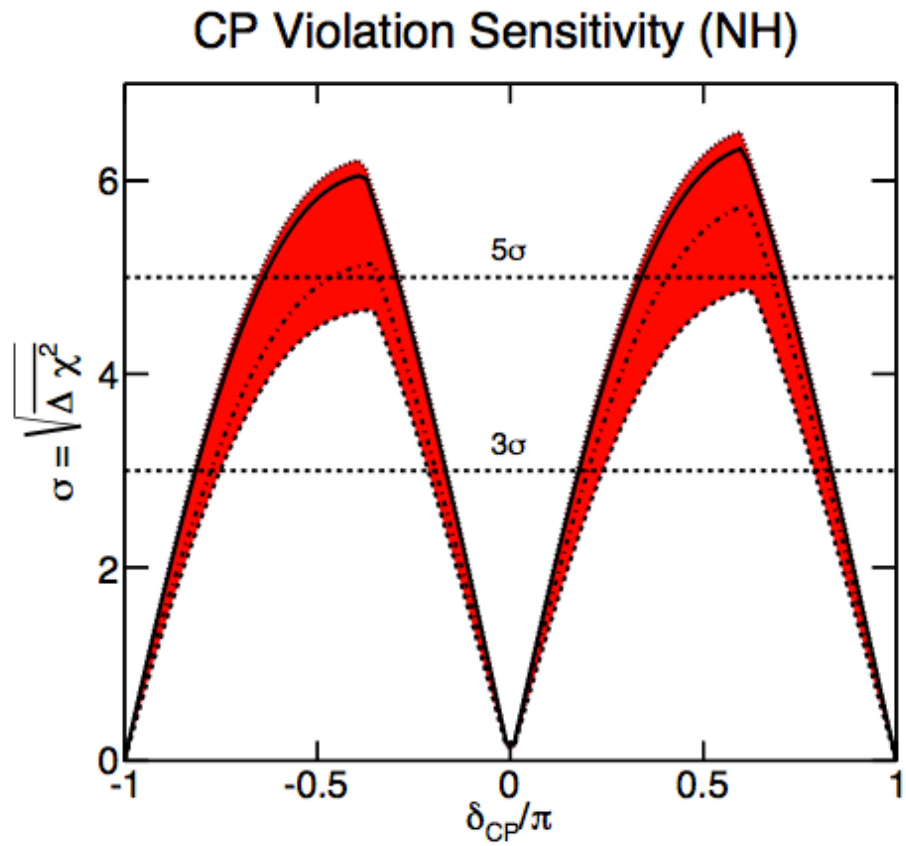


-To get a sense of an expected exposure: for 40 kt FD and 1.2 MW beam it amounts to ~40-50 kt*MW per year.

Mass Hierarchy and CP Sensitivities

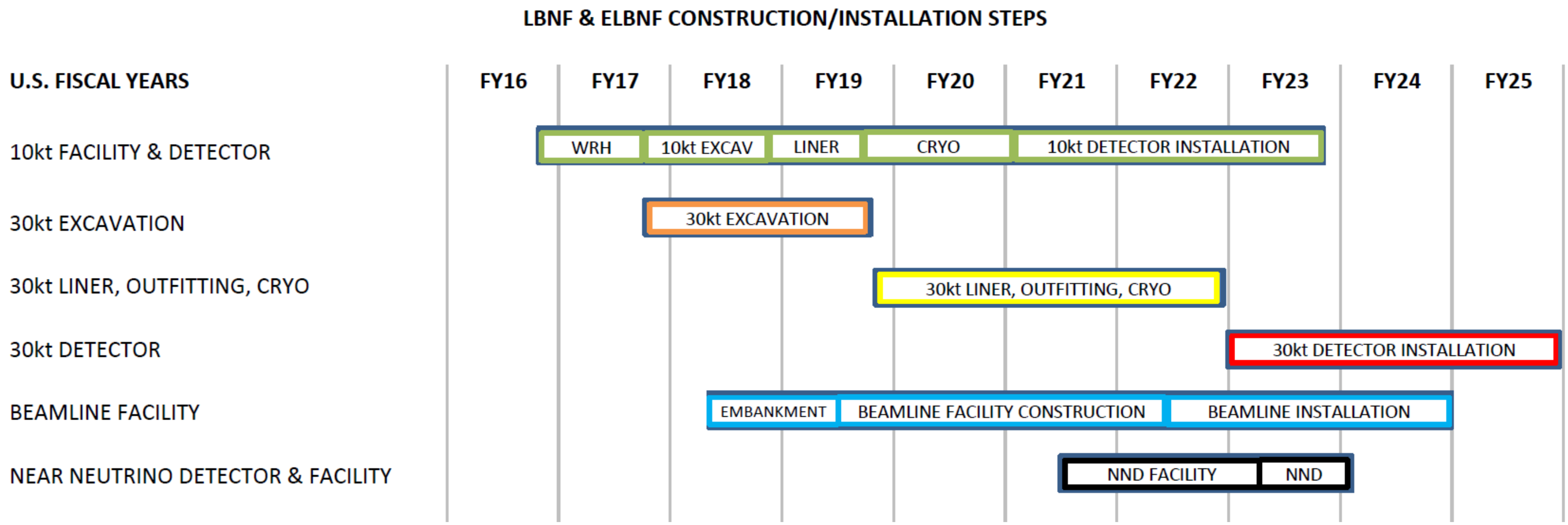
- Exposure: 245 kt.MW.yr = 34 kt x 1.2 MW x (3ν+3ν) years





DUNE Timescale

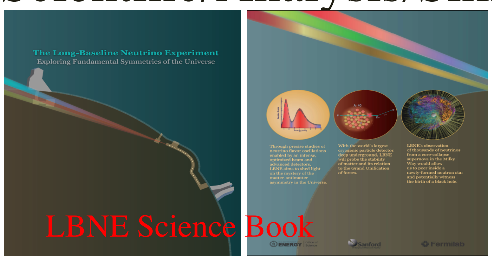
- Showed by Nigel Lockyer at ELBNF proto-colaboration meeting, January 22-23, 2015:



- Expect it to be flushed at DUNE Collaboration meeting later this week (April 16-18)

LBNE to DUNE Transition

- We actively participated in (former) LBNE Collaboration, with roles
  - -Deputy Spokesperson
  - -R&D Coordinator
  - -Data-base manager
  - -Development of photon-detector readout and calibration technique for LBNE LAr prototypes.
  - -Scientific/Analysis/Simulation Contributions.



LBNE Science Book

PHYSICAL REVIEW D **91,** 052015 (2015)

Baseline optimization for the measurement of *CP* violation, mass hierarchy, and θ_{23} octant in a long-baseline neutrino oscillation experiment

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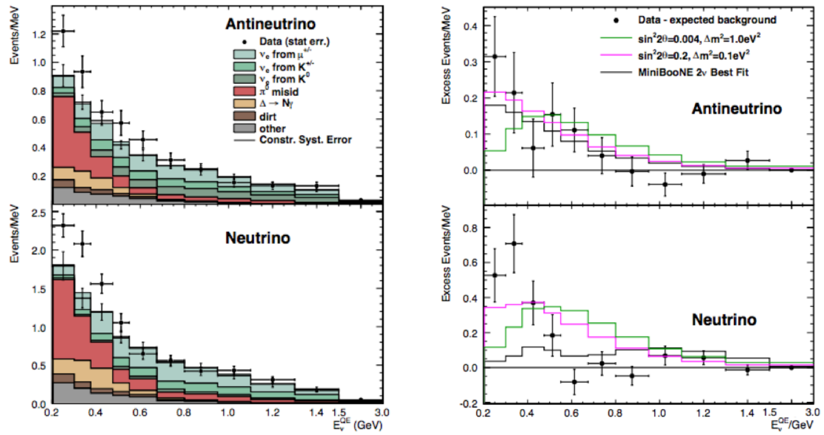
Next-generation long-baseline electron neutrino appearance experiments will seek to discover *CP* violation, determine the mass hierarchy and resolve the θ_{23} octant. In light of the recent precision measurements of θ_{13}, we consider the sensitivity of these measurements in a study to determine the optimal baseline, including practical considerations regarding beam and detector performance. We conclude that a detector at a baseline of at least 1000 km in a wide-band muon neutrino beam is the optimal configuration.

- LBNE Retired in January. New DUNE Collaboration formed. Now looking for new roles. Initial roles:
  - -IB Chair role (Maury Goodman)
  - -Continue development of photon-detector readout and calibration technique
  - -Data analysis from DUNE prototypes (35t detector, etc).
  - -…
- DUNE is a long-term project that is viewed as a major component of national HEP program in next > 10 years.

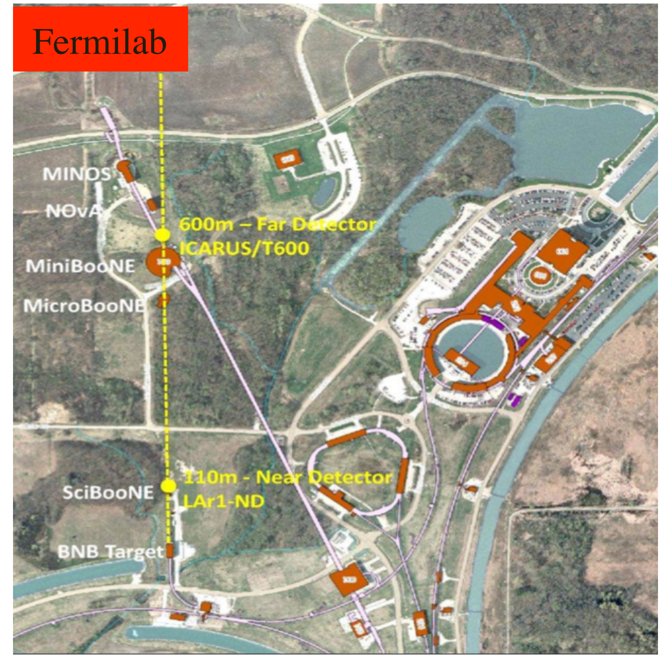
Short-Baseline Neutrino (SBN) Experiments

SBN Goals

- Testing Neutrino Anomalies with Multiple LAr TPC Detectors at Fermilab

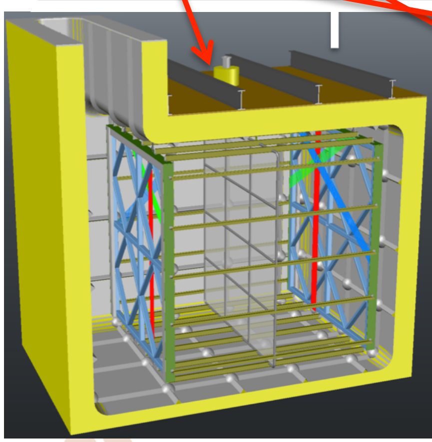


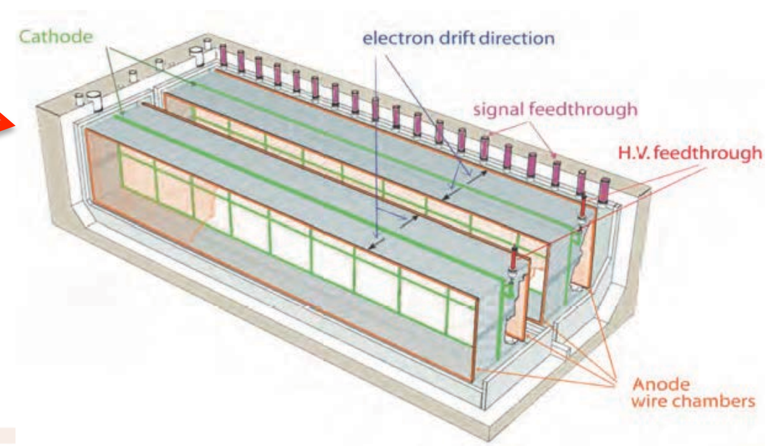
MiniBooNE
νμ ➔νe
sterile neutrino
search results



- SBN is a “triple” experiment at Fermilab Booster beamline

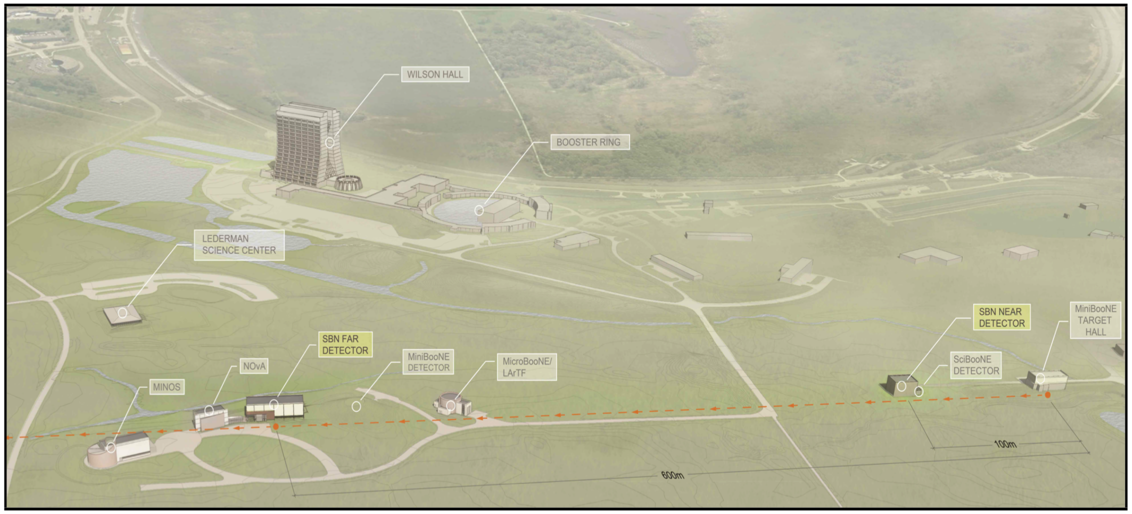
Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t



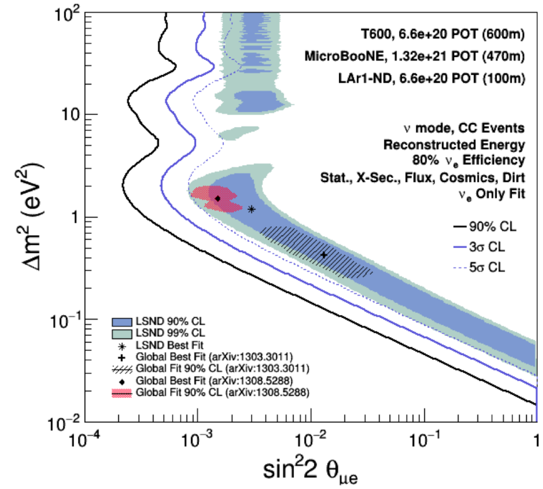


SBN Goals

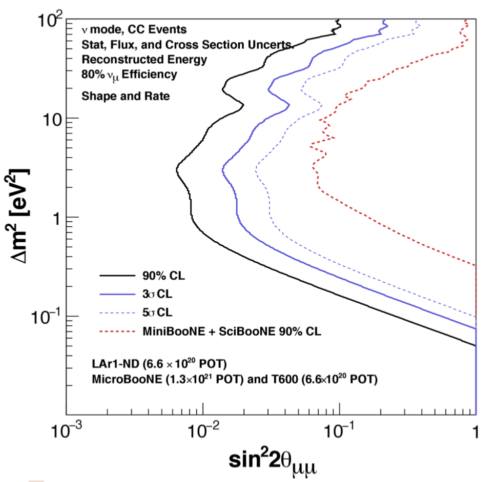
- Short-baseline experiments and SBND



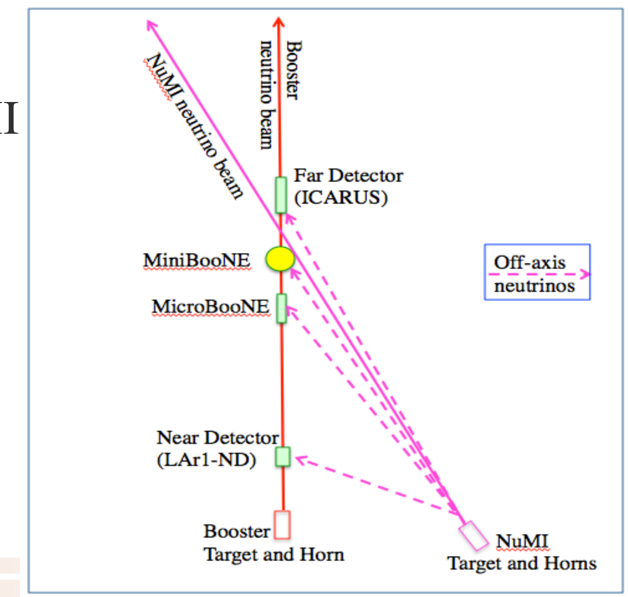
- Sensitivity of the SBN Program to νμ → νe oscillation signals (3+1 model).



- Sensitivity prediction for the SBN program to νμ → νx oscillations



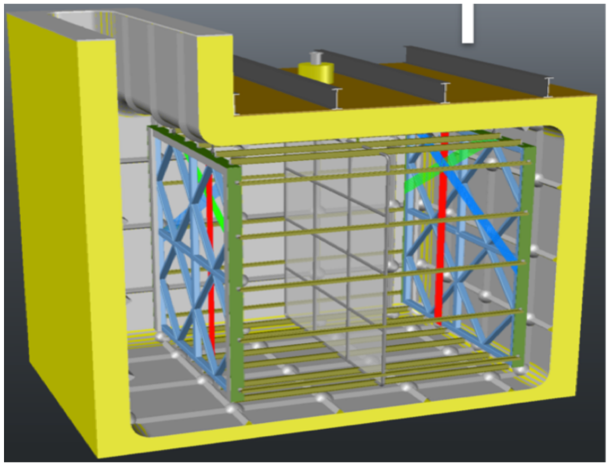
-Events from NuMI beamline will be observed as well



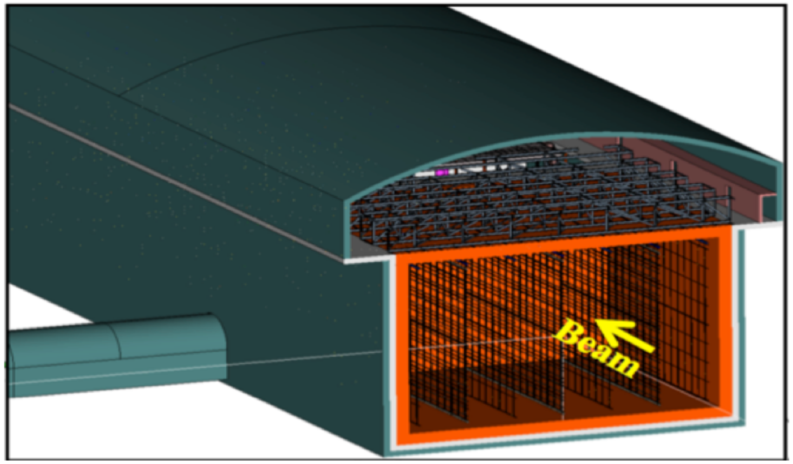
SBN Goals

- Short baseline program will be coordinated to serve as R&D platform for DUNE
  - -Automated event reconstruction
  - -Laser Calibration
  - -Photon detector R&D
  - -TPC readout
  - -Cold/warm electronics
  - -Cold feed-throughs/understanding of HV breakdown
  - -Argon purification
  - -Cryogenic liquid processing
  - -…

SBND



DUNE



- SBND may be viewed as a "neutrino test beam" experiment for DUNE.

SBND Event Rates

- Rich event sample for study of anomalies and cross-section models
  - Estimated event rates using GENIE (v2.8) in the LAr1-ND active volume (112 t) for a 6.6×10^{20} proton-on-target exposure (~3 years) in 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%
	· $\nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	· $\nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	· $\nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	· $\nu_\mu N \to \mu + \geq 3p$	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	

ANL Interest in SBND

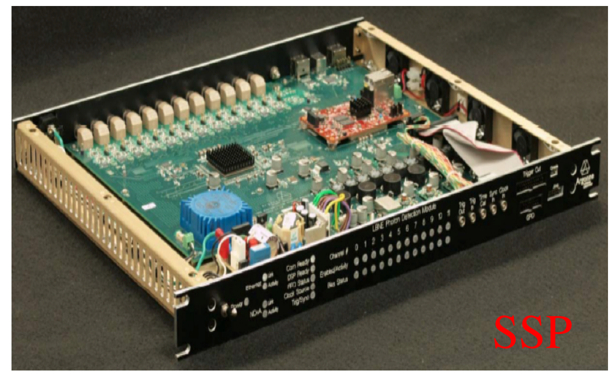
- Use SBN to transition to DUNE (important component of national HEP prohram)
  -Provides opportunity for a Coherent science/technology program
  NOvA->SBN->DUNE. Complementary to JUNO.

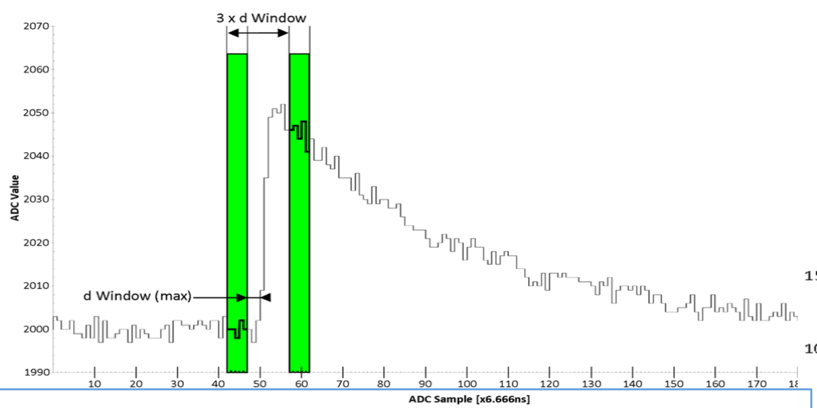
- Opportunities for ANL participation
  - SBND (formerly known as LAr1 ND): possible contributions
    -Photo-detector Readout (leverage off existing design for 35t prototype)
    -RPC as cosmic veto,
    -Leading to optimization of photodetection in ELBNF
    -Neutrino-theory collaboration with PHY on neutrino-Ar cross section.
    -Expertise from participation in MiniBooNE (simulation, data analsysis, sterile neutrino searches).
    -Potential use of ANL HPC (High-Performance Computing).
  - DUNE
    -Computing (database-ATLAS expertise, HPC-ATLAS and Cosmology)
    -Readout Electronics and Photo-detectors (LAPPD and alternatives).
    -Calibration techniques
    -Neutrino cross-section working group (PHY Theory)

- Status: Joined SBND. Participating in ELBNF formation.

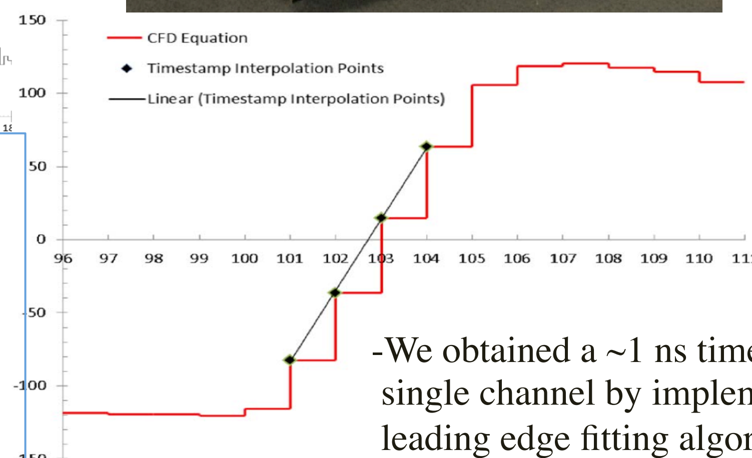
Photon-detector Electronics

- Design and deployment of the front-end electronics (SSP modules)) and calibration system for the photon detector system.
  -These components are being actively developed with our electronics group for tests to be performed with the LBNE 35-ton prototype detector at Fermilab in 2015.
  -The 35-ton photon detector system was developed in a collaboration with university groups where ANL is responsible for the readout electronics.
  -We will use experience gained from these tests as a starting point for future development (SBND, DUNE).





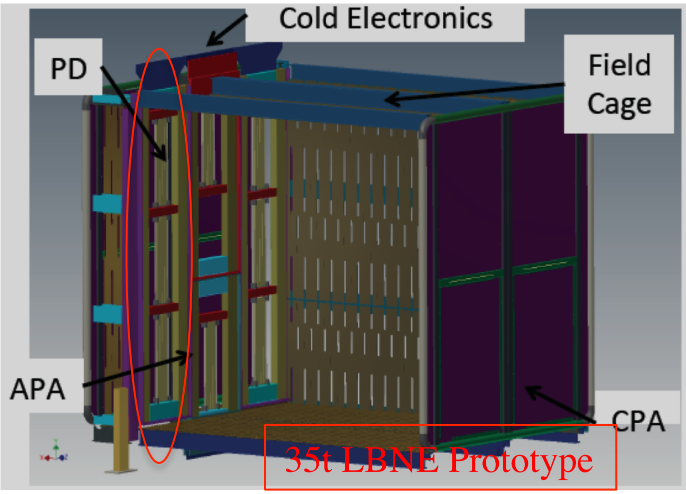
Key SSP (Silicon Photomultiplier Processor) features:
- -single p.e. resolution capable.
- -14 bit dynamic range (1.8 V full range).
- -timing resolution ≤ 2 ns.
- -data buffer length 13 μs: enables late light detection.
- -individual channel voltage biasing.
- -charge injection to calibration.
- -system highly configurable.

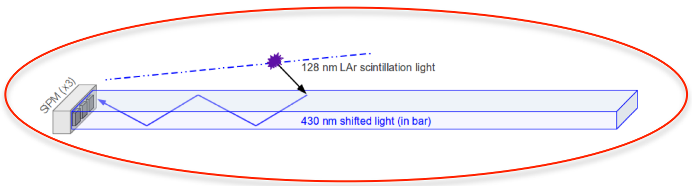


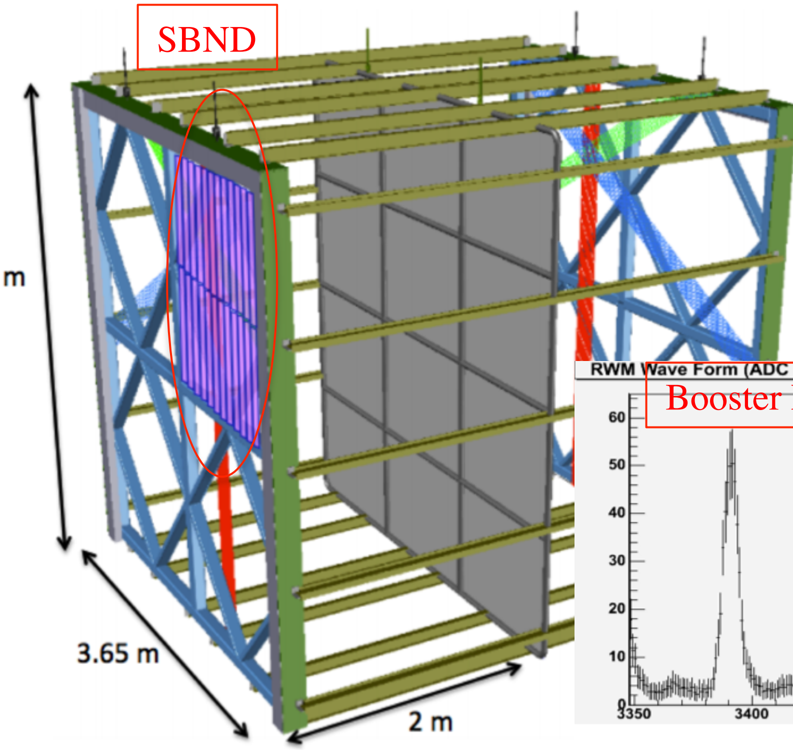
-We obtained a ~1 ns time resolution at single channel by implementing an leading edge fitting algorithm within FPGA.

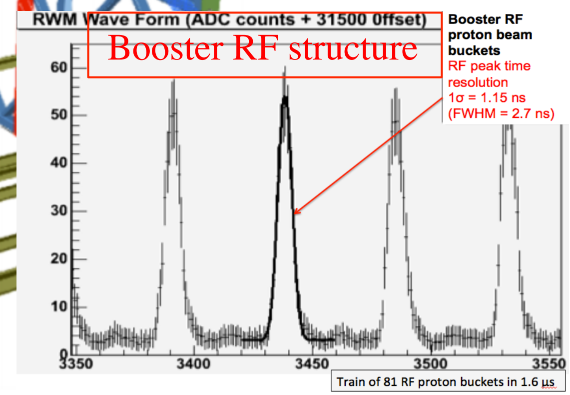
Photon-detector Electronics

-Photon detector in SBND should trigger on every cosmic ray muon and neutrino interaction









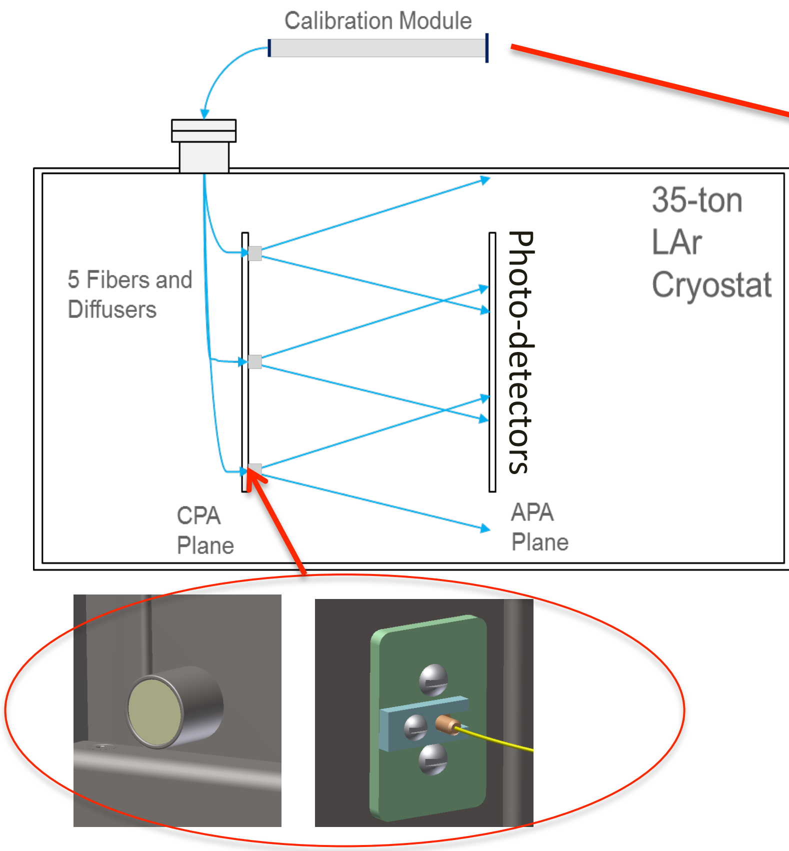
-The readout electronics for the photon detector at LAr1-ND is expected to be capable of observing light pulses at a single photo-electron level which should enable a separation of prompt from delayed components of scintillation light. (pulse-shape discrimination).

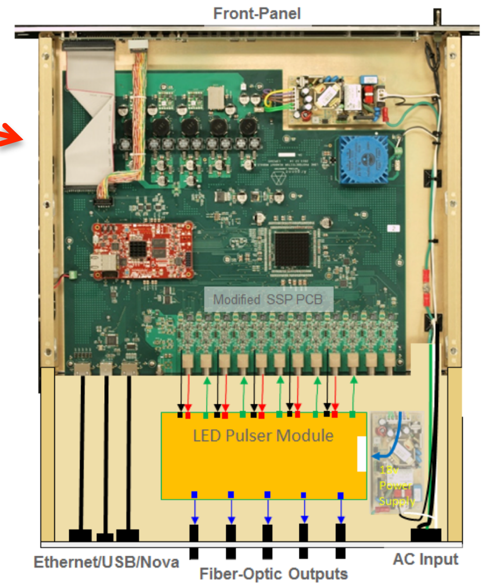
-The photon system system should have a high time resolution (~1 ns) to explore correlation between beam spills (Booster RF structure) and events observed in the detector.

-Interest tied to other efforts at ANL such as development of novel fast photo-sensors (“LAPPD” development) that may have future applications in cryogenic detectors.

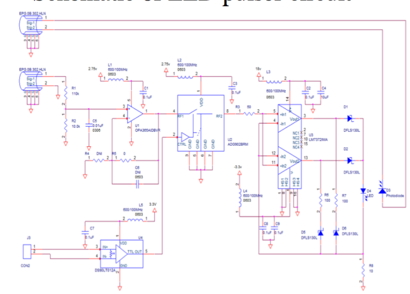
Photon-detector Calibration

- UV light calibration system: transport light from UV LEDs through quartz fiber to the TPC volume; diffuse light to the photon detection system and mimics physics.
  -monitor stability, uniformity and time resolution of the system

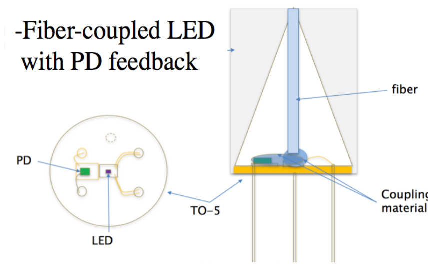




-Schematic of LED pulser circuit



-Fiber-coupled LED with PD feedback



- Other calibration techniques need development
  -Deploying a radioactive source to the TPC
  -Accelerator option (think of it in a connection to JUNO accelerator?)

Physics Contribution

- We have extensive neutrino experience, including work with Soudan 2, MINOS, MiniBooNE, NOvA, Double Chooz and LBNE.
  -We plan to be active in a simulation, reconstruction, and data analysis.
  -We would plan to significantly contribute to analysis of the Booster beam neutrinos, but also to bring in the knowledge and expertise with NuMI beamline.
  -With respect to the sterile neutrino searches we were actively involved in MiniBooNE experiment where he had important roles in the oscillation analysis of Booster beam neutrinos and a leading role in an analysis of NuMI beam neutrinos observed with the MiniBooNE detector.
  -We have worked on the issue of cosmic ray background on NOvA and LBNE, and are interested in specifying the LAr1-ND sensitivity to new physics other than sterile neutrinos.
  -Theory Initiative. We may discuss a potential ANL HEP and ANL PHYSICS experimental theory collaboration that could enhance the SBN program. There may be a strong interest within PHYSIS in the nuclear structure physics and electroweak interactions that are relevant to aspects of neutrino-nucleus scattering.

Other Opportunities

- There could be other opportunities to support the LAr1-ND and the SBN program
  -Other electronics contributions are possible as well, given a very high level of technical expertise within our electronics group.
  -We would explore possibilities to construct other experimental components and the equipment with involvement of our mechanical support group (recently built components of ATLAS, NOvA, CTA, etc).
  -We are discussing a use of ANL RPC detection system for the muon tagging.
  => recently presented to the collaboration; strong interest expressed.
  -We are looking into detector development including the possible use of nanoparticle coatings on phototubes to enhance response, by replacing TPB wavelength-shifter (contacts with ANL CNM, and external contacts).
  -We will consider use of the high-performance computing (HPC) resources at ANL on the software and computing side. These resources (700,000 CPUs available) are suitable for event generation and simulation. Could try it with a photon-detector simulation.