PROCEEDINGS OF SCIENCE

Status of the Short-Baseline Near Detector at Fermilab

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The Short-Baseline Near Detector (SBND) will be one of three liquid Argon Time Projection Chamber (LArTPC) neutrino detectors positioned along the axis of the Booster Neutrino Beam (BNB) at Fermilab, as part of the Short-Baseline Neutrino (SBN) Program. The detector is currently in the construction phase and is anticipated to begin operation in the first half of 2023. SBND is characterized by superb imaging capabilities and will record over a million neutrino interactions per year. Thanks to its unique combination of measurement resolution and statistics, SBND will carry out a rich program of neutrino interaction measurements and novel searches for physics beyond the Standard Model (BSM). It will enable the potential of the overall SBN sterile neutrino program by performing a precise characterization of the unoscillated event rate, and by constraining BNB flux and neutrino-Argon cross-section systematic uncertainties. In this paper, the physics reach, current status, and future prospects of SBND are presented.

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1. SBND in a Nutshell

The Short-Baseline Near Detector (SBND) is one of the three neutrino detectors comprising the Short-Baseline Neutrino (SBN) Program[1], the other two being MicroBooNE and Icarus. The three detectors are exposed to Fermilab's Booster Neutrino Beam (BNB), with SBND being most up-stream one, at 110 m from the beam's target. Figure 1 illustrates the site from an aerial view. The program as a whole is designed to carry out searches for new neutrino physics at short baselines, with distance-over-energy ratio around $L/E \cong 500\,\mathrm{m/GeV}$. SBND's observations will be used to characterize the beam, offering a precise reference from which both neutrino disappearances and appearances searches can be carried out. Beyond this role, SBND will register millions of neutrino interactions per year, an unprecedented rate which will allow a rich neutrino-nucleus scattering physics program at the GeV energy scale.

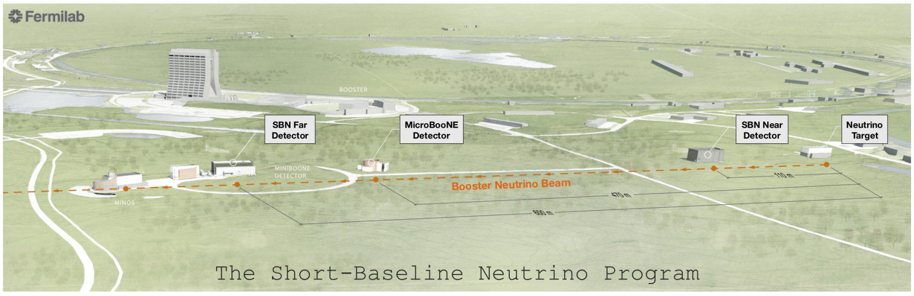


Figure 1: Computer rendering of the Short-Baseline Neutrino experimental area at Fermilab. To the right (south) is the neutrino beam target area where 8 GeV protons from the Booster accelerator hit a beryllium target, producing a neutrino beam of around 1 GeV, traveling toward the left (north). The SBND (at 110 m), MicroBooNE (at 470 m), and Icarus (at 600 m) building locations are indicated. Image credit: Holabird & Root.

To mitigate the systematic uncertainties inherent to the oscillation analysis, all three detectors are built using the same technology, the Liquid Argon Time-Projection Chambers (LArTPCs). These are high granularity imaging detectors with exceptional position and calorimetric resolution. They typically consist of a cathode plane (CPA) and finely instrumented anode plane (APA) immersed in a volume of high-purity liquid argon (impurities kept below 0.1 parts per billion). SBND has two back-to-back TPCs in a single 112 ton active mass of liquid argon, encased in a field cage, with an uniform $500\,\mathrm{V\,cm^{-1}}$ electric field (Fig. 2.a). Neutrino interactions with LAr produces charged particles which both ionizes and excite the argon, leaving ionization tracks and producing prompt scintillation light. While charges drift along the electric field towards the anode plane wires, with a 3 mm pitch[2], the scintillation light is collected by a photon detection system (PDS, seen in Fig. 2.b) comprised of photo multipliers (PMTs) and a novel light sensor called X-ARAPUCA. The combination of charge and light collection allows for the 3-dimensional reconstruction of tracks and events.

In what follows, we present an overview of simulation and physics studies, as well as the installation status at January 2022.

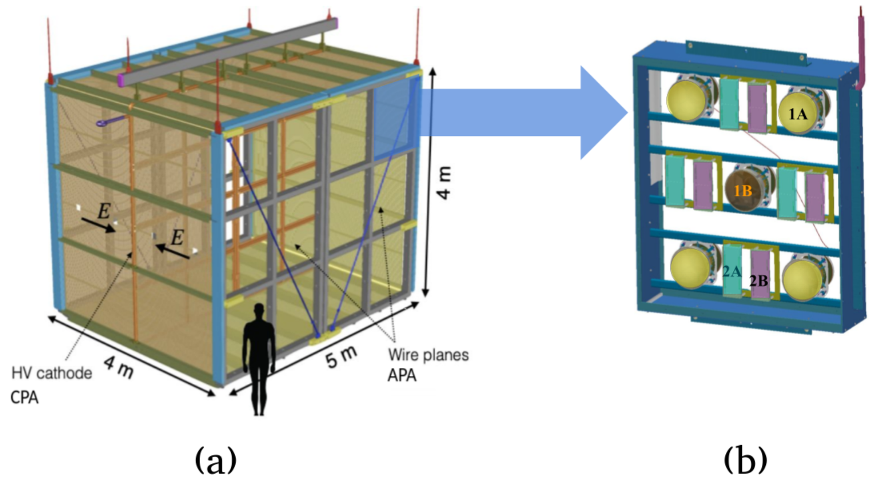


Figure 2: (a) SBND's field cage, with dimensions and electric field direction annotated. The detector is mirror-symmetric around the cathode plane with anode planes on each side, instrumented with wire planes and light sensors. (b) Photon detection box, to be installed on each of the 24 niches in the anode plane, equipped with two types of sensors, **1** PMTs and **2** X-ARAPUCAs, each with two variants, **A** sensitive to direct scintillation light; **B** sensitive to reflected light by the CPA.

2. Physics and Simulation

The BNB is in operation for eighteen years, successfully generating stable beams in both neutrino and anti-neutrino modes. The accumulated expertise from operation and simulations translates to well known fluxes. The BNB simulation was developed by the MiniBooNE collaboration and it relies on p+Be interaction data collected by the HARP experiment at CERN. By using GENIE's models for final-state interactions (FSI) and CORSIKA for cosmic showers, we generate Monte Carlo (MC) samples which are representative even for more exclusive channels. Figure 3 shows three possible interaction, while Fig. 4 shows the relative event rates among charge and neutral current, and the most frequent final state topologies. This latest production corresponds to a total of 6.6×10^6 neutrino interactions, which is expected to be delivered by the BNB along roughly three years of operation. Event selection, reconstruction and background rejection is accomplished with a multi algorithm approach with PANDORA and others developed internally[3], including the use of machine-learning classifiers.

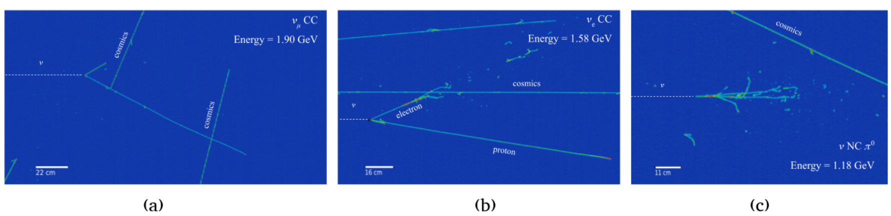
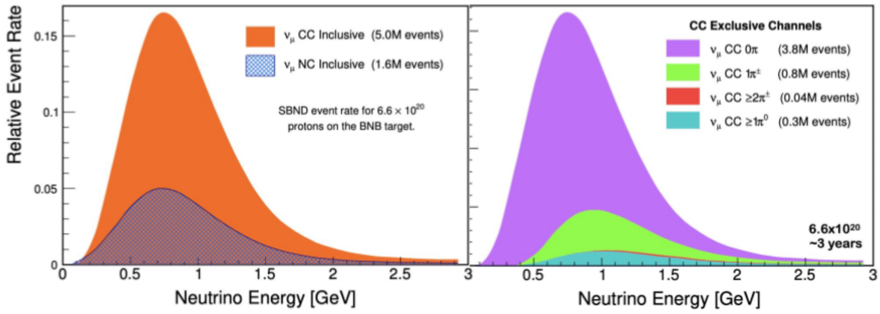


Figure 3: Event viewer showing reconstructed Monte Carlo simulations of BNB neutrinos in three interactions: (a) ν_μ charged current, (b) ν_e charged current and (c) ν neutral current.

SBND has a rich physics program covering Standard measurements and non-Standard searches.

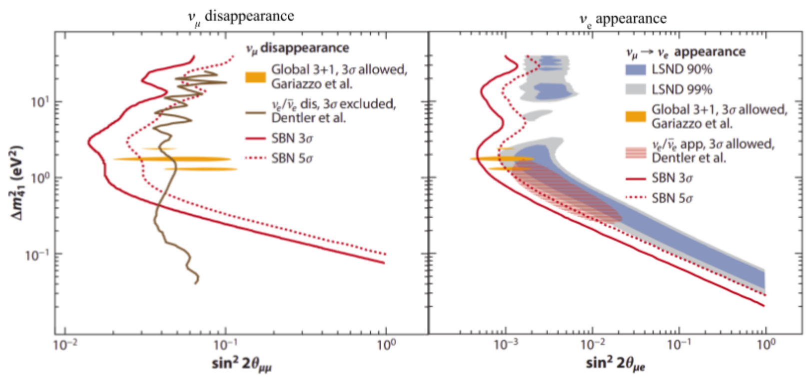
Its high event rate, of about 1 neutrino interaction every 15 s, will allow the observation of still unmeasured channels on argon, such as hyperon production. In particular, the observation of $\nu e \longrightarrow \nu e$ elastic scattering will lead direct measurement of the BNB's neutrino flux, since this process has a well know theoretical cross section. High statistics and precise reconstruction allows for beyond standard model searches.



(a) (b)

Figure 4: Relative event rates from latest MC production: (a) Showing the proportion between charged current (3:4) and neutral current (1:4) events. (b) Breaking down the charged current events over the most frequent final-states topologies, 0π (76%), $1\pi^{\pm}$ (16%), $\geq 1\pi^0$ (6%), and $\geq 2\pi^{\pm}$ (0.8%).

The SBN program is designed to address the short-baseline neutrino anomalies, an excess of events observed by LSND and MiniBooNE. Interpreting these observations as oscillations require the addition of a hypothetical sterile neutrino to the mixing, the so called 3+1 model. SBN will employ three fitting frameworks, which allows for detailed validation and cross-checking. These model fitters are fed with common inputs but are independently developed by different collaborations: SBNFit (by MicroBooNE), CAFAna (by NOνA and DUNE), and VALOR (by T2K). Figure 5 illustrates sensitivity plots for both the ν_μ disappearance and the ν_e appearance channels. SBN will be sensitive to the current Global 3+1 allowed region of the Δm^2_{41}, $\sin^2\theta_{\mu\mu}$, and $\sin^2\theta_{\mu e}$ parameter space.

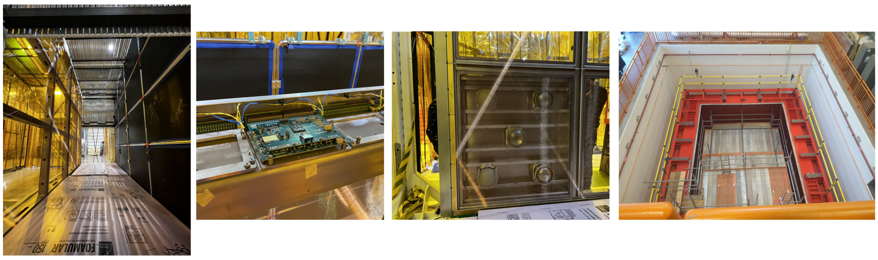


(a) (b)

Figure 5: Sensitivity to the 3+1 neutrino model, showing exclusion curves for three free parameters, Δm^2_{41}, $\sin^2\theta_{\mu\mu}$, and $\sin^2\theta_{\mu e}$, over two channels: (a) ν_μ disappearance and (b) ν_e appearance.

3. Assembling and Installation Status

As of the end of 2021, the SBND detector construction has hit some remarkable milestones. The TPC structure, CPA, APA and Field Cage, are all assembled. Figure 6.a shows the space between the CPA and one of the APAs, seeing from one of the Field Cage's access ports. One of the APAs has already been instrumented with the cold electronics boards (Fig. 6.b) and the Photon Detection Boxes are being test-instated (Fig. 6.c). At the Near Detector building, the cryostat's external structure is in place and ready for installation of the insulation layers and the membrane (Fig. 6.d).



(a) (b) (c) (d)

Figure 6: (a) Interior of SBND's TPC, already assembled, showing the CPA (black covers, on the right of the image) and the APA (still transparent since the photon sensors are not installed). (b) Front-end electronics motherboards (FEMB) being installed on first APA. (c) Test installation of Photon Detection Box. The one seen here does not contain X-ARAPUCAs, only PMTs. (d) Cryostat external structure, seen from the top.

4. Final Remarks

The Short-Baseline Near Detector represents a leap forward in precision neutrino physics. With exceptional reconstruction capabilities, high event rates, and mature analysis tools, the SBND will not only fulfill its role as a reference point for SBN's oscillation analysis but also perform never before seen measurements of neutrino-argon interactions, search for new physics beyond the Standard Model, and even offer feedback to beam physics. The community should expect the first beam-argon events to hit the detector before the middle of 2023.

References

[1] M. Antonello *et al*, *A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam* arXiv:1503.01520 [physics.ins-det] (2015)

[2] R. Acciarri *et al*, *Construction of precision wire readout planes for the Short-Baseline Near Detector (SBND)*, Journal of Instrumentation V. 15, N. 06 (2020).

[3] R. Acciarri *et al*, *Cosmic Ray Background Removal With Deep Neural Networks in SBND*, Frontiers in Artificial Intelligence, V. 4 (2021).

[4] P. A. N. Machado and O. Palamara and D. W. Schmitz, *The Short-Baseline Neutrino Program at Fermilab*, Annual Review of Nuclear and Particle Science, V. 69, N. 1 (2019).