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Status and Plan of ICARUS at Fermilab

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Abstract: ICARUS T600 is an experiment that uses the liquid Argon Time Projection Chamber detector. It took data at the underground Laboratori Nazionali Gran Sasso (LNGS), Italy. After its successful operation in LNGS, the detector was refurbished at CERN and was moved to Fermi National Accelerator Laboratory in the US in 2017. ICARUS T600 will function as the far detector at the Fermilab's Short Baseline Neutrino (SBN) program which utilizes Fermilab's booster beam line with high intensity 8GeV protons for neutrino experiments within the Fermilab campus. The primary goals of ICARUS T600 are addressing the anomalies observed in neutrino measurements and search for sterile neutrinos at low energy regime. The detector is in its final stage of installation, and the commissioning will begin shortly. This report discusses the current status and plan of the experiment for physics data taking, as well as its physics prospects.

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1. Introduction

The discovery and confirmation of neutrino flavor oscillation in late 1990's through much of 2000's confirms that neutrinos have mass, though the exact value of the hierarchy of the masses are unknown. Given that the Standard Model (SM) [1] is built upon the massless neutrino, SM must undergo modifications to better describe neutrinos. These modifications could also lead to a new symmetry in the universe. In addition, in order to better understand the origin of the universe, it is necessary for neutrinos from astrophysical origin, such as electron neutrinos coming from Supernova, relic neutrinos, dark matter, etc. Furthermore, the question of the total number of neutrino species must also be investigated and answered, in particular in light of lingering low energy excess of electron neutrinos observed in LSND and the MiniBooNE experiments.

The ICARUS detector is a liquid argon time projection chamber (LArTPC) detector with 476 tons of active volume. It took data for three years at underground Laboratori Nazionali Gran Sasso (LNGS), Italy. In preparation for data taking at Fermilab's Short Baseline Neutrino (SBN) program, the detector was refurbished at CERN for two years and was moved to Fermilab to function as the far detector in the SBN program.

2. ICARUS at LNGS

ICARUS stands for Imaging Cosmic And Rate Underground Signals [2]. It is the first TPC which uses Liquid Argon as the medium. The LArTPC was invented by Carlo Rubbia in 1977 shortly after the invention of the TPC using high pressure gas. LArTPC is an ideal detector for neutrino physics and nucleon decay given the high density of the liquid argon. In addition, TPC can provide three-dimensional reconstruction with high spatial granularity at the level of mm^3. Since LAr acts as the neutrino interaction target, LArTPC provides a homogeneous detector with full-sampling calorimetry capability. The neutrino interactions also give out the scintillation light which can be used for timing and triggering of the interactions. The ionization electrons can also drift several meters in high purity argon, thus large size detector with high efficiency is possible. Finally, LAr is not only dense but also low cost, enabling kilo-ton (kt) level detectors possible.

To demonstrate the feasibility and to search for sterile neutrinos, large LArTPC was constructed in two separate volumes (T300+T300) and ran for three years in 2010 through 2013

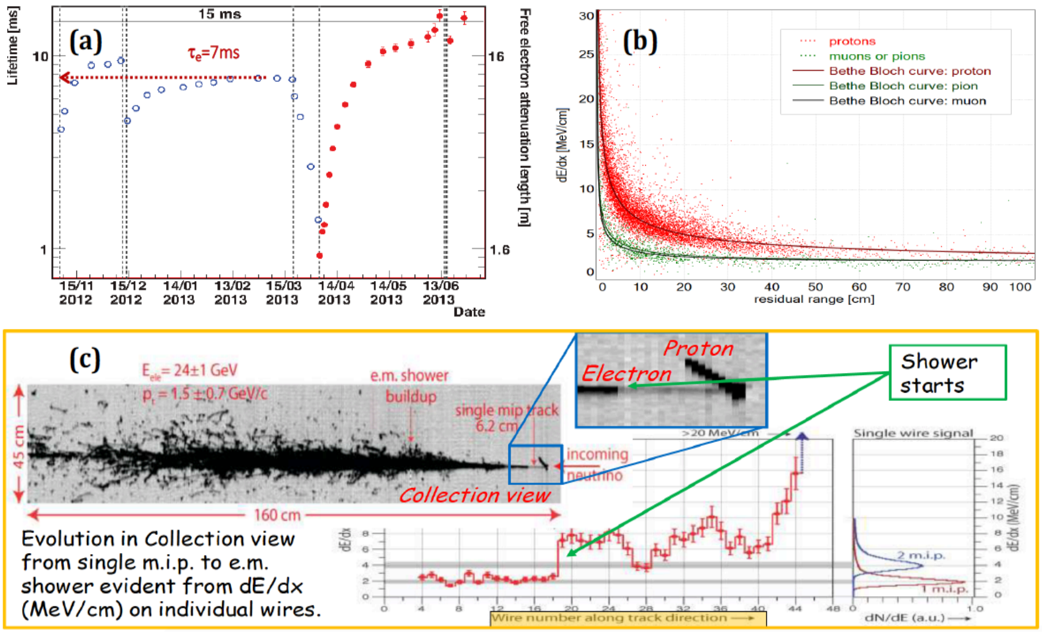

Figure. 1 (a) Electron lifetime as a function of tune (b) dE/dx (MeV/cm) as a function of residual range (cm) (c) Reconstructed image of an electron shower and the corresponding dE/dx evolution which clearly demonstrates the origin of the EM shower was a one mip particle

in LNGS and took data with the CNGS beams and cosmic rays. This three-year run proved the maturity of the LArTPC technology for large scale experiments. High Purity of LAr was accomplished and maintained throughout the entire data taking run. The measured lifetime of the ionization electrons was over 7ms which corresponds to impurity concentration less than 40 ppt [3], clearly demonstrating potential for a large scale detector. Figure 1(a) shows the purity as a function of time. As can be seen, high purity can be reached within two weeks of turning on the filtering system once a stable running condition is reached. Close to the end of the LNGS data taking, LAr purity surpassed 10ms and approached the peak of 15ms just before the shutdown.

An excellent spatial and energy resolution were accomplished as well. dE/dx was accurately measured with the fine $0.02X_0$ sampling, and the particle identification was possible using dE/dx as a function of the range [4]. Figure 1(b) shows dE/dx (MeV/cm) as a function of the residual range. Protons (red) are clearly distinguished from pions and muons (green). The dE/dx curves of these agree very well with the predictions based on Bethe-Bloch formula (solid lines).

The fine granularity energy sampling also enables a high efficiency identification of electro-magnetic particles and allows distinguishing EM shower from a single particles vs those from backgrounds, such as two photons resulting from π^0 decays which is a significant background source for electron neutrino appearance measurements. Top left picture of Fig. 1(c) shows the progression of an EM shower from an electron. Bottom right plot shows the dE/dx measured as a function of the length of the EM shower which clearly demonstrates that the origin of the EM shower was a one MIP particle. The fine granular sampling of ICARUS enables highly efficient identification of electrons resulting from ν_e CC interactions, minimizing systematic uncertainties due to π^0 backgrounds.

3. ICARUS Sterile Neutrino Search Result and Expectation at SBN Program

ICARUS searched for sterile ν oscillations through ν_e appearance in the CNGS beams. Since the L/E of ICARUS at CNGS was 36km/GeV which is much larger than that of the LSND at ~1km/GeV, the sterile-like oscillation is averaged out and cancel out the energy dependence. ICARUS analyzed 2650 ν interactions from 7.9×10^{19} POT. In the absence of anomaly, 8.5 ± 1.1

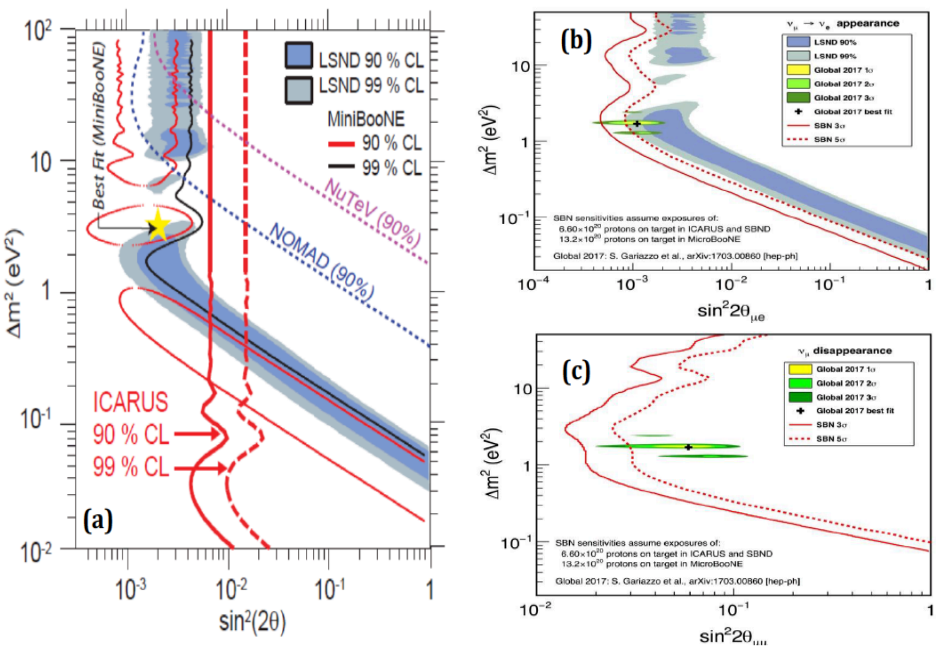

Figure. 2 (a) The exclusion plot from ICARUS LNGS sterile neutrino search in ν_e appearance channel (b) ν_e appearance channel sensitivity reach of the SBN experiments at Fermilab (c) ν_μ disappearance sensitivity reach of the SBN experiments

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background events are expected, predominantly from the intrinsic beam ν_e. The estimated ν_e identification efficiency was 74% with a negligible background from mid-identification, 7 events were observed, consistent with the background expectation. From this null result, a large phase space in Δm^2 vs $\sin^2(2\theta)$ has been excluded [5]. Figure 2(a) shows that most of the LSND allowed region has been excluded, except for small area around $\sin^2(2\theta)$~0.005 and Δm^2 ~1eV^2. Similar result has been obtained by the OPERA experiment with the same CNGS beam but different technique.

Fermilab short baseline neutrino (SBN) program employs high intensity neutrino beams resulting from the high flux 8GeV proton beams out of the Booster. In addition to the high flux neutrino beams, the SBN program consists of two LArTPC detectors, the short baseline near detector (SBND) located 110m and the ICARUS detector which acts as the far detector located 600m downstream of the neutrino target. While the low energy access anomalies have been observed in accelerator experiments (MiniBooNE) and reactor (LSND) neutrino source experiments points to flavor oscillations at Δm^2~1eV^2 range, ν_μ disappearance experiments have not seen similar anomalies. Given this circumstance, with the combination of these two detectors and the high flux neutrino beams, the overall SBN program will be able to provide a definitive clarification on sterile neutrinos through both ν_e appearance and ν_μ disappearance channels at the 5σ level as shown in Fig. 2(b) and (c), respectively.

4. ICARUS at Fermilab SBN Program

After the successful 3 year run at LNGS, the ICARUS detector was transported back to CERN in 2015 for an extensive overhaul in preparation of the data taking at Fermilab's SBN program. Such an overhaul is required since the detector is going to be located on the surface and therefore, high rate (~11kHz) of cosmic ray background is expected. In addition, thanks to the high intensity proton beams from the Fermilab Booster neutrino beam line, the total number of neutrino interactions of the order 10^6 pose additional challenges compared to the quiet underground running environment at LNGS. To prepare the detector for these conditions while maintaining the already achieved performance, several technological improvements have been introduced.

The improvements were, the construction of new cold vessels with a purely passive insulation, renovated LAr cryogenics and purification equipment, improved cathode planarity, upgraded PMT system to precisely ID t_0 of the neutrino interactions in TPC and determine rough event topology rapidly with higher granularity and ns level time resolution, and new faster and higher performance readout electronics. Finally, an extensive cosmic ray tagger (CRT) to correlate residual cosmic ray muons to the TPC signal and a 3m concrete overburden to reduce charged hadron and photon intakes have been introduced.

Specifically, the improved photon detector system employs 90 PMT's per each TPC at 5% coverage with 15pe/MeV responses and provides a sensitivity to low energy events down to ~100MeV, excellent spatial resolution (<50cm), ns timing resolution and an additional means for identification of cosmics via PMT space/time pattern. All the PMT's have been tested at room temperature in a dark room at CERN and illuminated with laser pulse, with a subset of 60 PMT's tested in LAr, which showed consistent behavior to those at LNGS. New TPC readout electronics system uses fully synchronous 12-bit ADC, CAEN A2795 64 channel modules and employs more compact analog and digital electronics in a single flange. These show lower noise at around 1200 e- equivalent which is about 20% S/N improvement compared to LNGS) and shorter shaping time (~1.5ms) with a drastic reduction of undershoot after a large signal at the cold test in 50l TPC at CERN. The signal from the 2nd induction plane keeps bi-polar shape and allows calorimetric measurements in this plane to improve ν_e ID efficiency by ~20%.

5. The ICARUS Timeline

The two ICARUS T300 vessels have been transported from CERN to Fermilab in the summer 2017 after the extensive overhaul. At present, the two vessels have been inserted into the outer shell, and the proximity cryogenics have been completed. The installation of the top cold shield and the top CRT support installation is in progress, and the side CRT installation is in its final stage. The preparation for SBN data analysis is progressing well for day 1 physics. ICARUS team is working together with the SBND team to develop common reconstruction and analysis tools and to ensure understanding detector systematics between them. The full simulation of the detector was performed with the realistic geometry and signals from all sub-detector systems.

All TPC and trigger electronics as well as PMT electronics installation will complete by the end of the summer. This enables the experiment to proceed with cryogenic system commissioning whose completion enables the cooldown and filling. Once the detector is full, the commissioning of CRT, DAQ, trigger and slow control will follow. ICARUS will then take data with cosmic ray, neutrino beams from the Booster and the off-axis neutrino beams from NuMI beam line.

6. Conclusions

After its move to Fermilab in 2018 and the detector construction, the ICARUS detector is ready for detector commissioning with new and improved physics capabilities. Along with the high flux neutrino beams from Fermilab's Booster neutrino beamline, ICARUS will perform more extensive searches for new species of neutrinos and, together with the SBND, will be able to provide definitive answer to the low energy anomaly. Finally, the successful running of ICARUS is a clear demonstration of large scale LArTPC detector.

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