Status and Plans of ICARUS T600

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Outline

• Introduction
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• Physics Potential
• Status and Schedule of ICARUS
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Physics Motivation

• The neutrino sector in the Standard Model needs a fix, so
  – Precision measurements of the oscillation parameters
    • Mixing angles and mass hierarchy
  – Studying the CPV and precisely measuring the CP phase
    • Do neutrinos and anti-neutrinos oscillate the same way?

• These could lead to a new symmetry

• The question of the grand unification
  – Energy scale of the unification and nucleon decay

• Understanding neutrinos of astrophysical origin
  – Supernova, relic neutrinos, dark matter, etc

• And anomalous species of neutrinos (sterile?)
  – Low $E_{\text{ve}}$ deficit anomaly $\Rightarrow$ An indication of new neutrino species?

• These require high statistics samples
  – Large volume and highly capable (near and far!) detectors
  – High intensity neutrino beam facility
Fermilab SBN Campus

L/E$_\nu$ ~ 600 m / 700 MeV ~ $\sigma$(1 m/MeV)

T600 also off-axis on NUMI beam:
Asset for DUNE

ICARUS T600

FBAR DETECTOR:
T600 – 476 ton

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Ready for data end of 2019

MicroBooNE
89 ton

Took data

SBND Under Construction

NEAR DETECTOR:
SBND – 112 ton

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E$_\nu$ = 700 MeV

E$_p$ = 8 GeV

NUMI beam (approximate)
LAr Time Projection Chamber

• First proposed by C. Rubbia in 1977

• LAr-TPCs:
  – Ideal detectors for neutrino physics and nucleon decay:
  – 3D reconstruction with high (mm$^3$) spatial granularity.
  – Homogeneous, full-sampling calorimetry possible
  – Scintillation light for fast signals for timing/triggering.
  – Electrons drift for several meters in high purity LAr
  – LAr dense and low cost → large masses (kt) possible
ICARUS T600 – LNGS Era

- Large scale LAr TPC in two separate volumes (T300+T300) constructed and ran three years in LNGS (2010 – 2013)
- Expected performance observed in CNGS beam and cosmic rays
- Proved the maturity of the technology for large scale experiments
- ICARUS T600 refurbished in 2015 – 2017 at CERN and moved to Fermilab summer 2017
ICARUS LNGS Performance – I

- High LAr purity $\Rightarrow \tau_e > 7\text{ms}$ for whole run
  - Impurity concentration <40ppt
  - Clear demonstration of large scale potential
    - JINST 9 P12006 (2014)

- Excellent spatial and energy resolution
  - Accurate $dE/dx$ measurement w/ fine sampling 0.02$X_0$
  - PID from $dE/dx$ vs range
    - AHEP 260820 (2013)

- Escaping $P_\mu$ multiple Coulomb scattering
  - 15% resolution on stopping muons
    - JINST 12P04010

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\( \nu_e \) CC event separation from NC background with \( \pi^0 \) (\( \gamma \)-initiated showers): crucial for oscillation physics.

- LAr-TPC provides 3 handles:
  - Visual identification of \( \gamma \) conversion gap.
  - Reconstruction of \( \pi^0 \) invariant mass.
  - \( dE/dx \): calorimetric accuracy and fine sampling (0.02 \( X_0 \)) allow measuring \( dE/dx \) on each wire: single MIP corresponds to an electron.

**High E \( \nu_e \) CC interaction at CNGS**

Clear depiction of e shower evolution single mip \( \rightarrow \) shower
ICARUS searched for sterile $\nu$ oscillations through $\nu_e$ appearance in the CNGS beam.
- L/E ~ 36 km/GeV, far from LSND value ~ 1 km/GeV
  $\Rightarrow$ “sterile-like” oscillation was averaged out, canceling energy dependence.
- 7.9x10^{19} pots analyzed (~2650 $\nu$ interactions).
  - Expected ~ 8.5 $\pm$ 1.1 $\nu_e$ bck events in the absence of anomaly (intrinsic beam $\nu_e$ dominant)
- Estimated $\nu_e$ ID efficiency ~74%
  - Negligible background from mis-ID
  - 7 events observed $\Rightarrow$ no evidence of oscillation.
  - Most of LSND allowed region excluded – except for small area around $\sin^22\theta$ ~0.005, $\Delta m^2$~1 eV^2
  - Similar result by OPERA with the same CNGS beam and different detection technique.

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ICARUS Sterile Neutrino Search @ SBN

- SBN experiments can provide a definitive clarification on sterile neutrinos through both $\nu_e$ appearance and $\nu_\mu$ disappearance
  - Some “anomalies” from accelerators (LSND), reactor, neutrino sources, point out to flavor transitions in the $\Delta m^2 \sim 1$ eV$^2$ range
  - However, no evidence of oscillations in $\nu_\mu$ disappearance data (MINOS, IceCube)
  - The 3 SBN experiments w/ the same technology will reduce systematic uncertainties

- Excellent $\nu_e$ ID efficiency $\Rightarrow$ reduced NC background
- ICARUS at $\sim 8^\circ$ off-axis of the NuMI (Neutrinos Main Injector) $\Rightarrow$ LDM search and other opportunities

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ICARUS T600 @ FNAL

• Detector on the surface ➔ large cosmic ray rates (11kHz)
  – Identification of $O(10^6)\nu$ interactions becomes a challenge
• Extensive overhaul at CERN in 2015 – 2017 period
• Several technology improvements were introduced, maintaining the already achieved performance at LNGS run:
  – new cold vessels, with a purely passive insulation;
  – renovated LAr cryogenics/purification equipment;
  – improvement of the cathode planarity;
  – upgrade of the PMT system: higher granularity and ns time resolution;
  – new faster, higher-performance read-out electronics.
• 3 m concrete overburden to reduce charged hadrons/\gamma’s intake
• Cosmic ray tagger to correlate residual $\mu$ with TPC signals.
Light Collection System Upgrade

• In a surface operation, the light collection system will:
  – Generate a trigger signal
  – Precisely ID the $t_0$ of interactions in the TPC
  – Determine rough event topology rapidly

• ICARUS@SBN employs 90 PMTs per TPC (5% coverage, 15 pe/MeV) that provides:
  – Sensitivity to low E events ($\sim 100$ MeV)
  – Good spatial resolution ($\leq 50$ cm)
  – $\approx$ ns timing resolution
  – ID of cosmics via PMT space/time pattern

• Timing/gain equalization w/ laser pulses ($\lambda = 405$ nm, FWHM < 100 ps, $P_{\text{peak}} \sim 400$ mW)
ICARUS PMTs

• All PMT’s tested at room temperature in a dark room at CERN
  – A subset of 60 PMTs tested in LAr for performance comparisons
  – All PMT’s illuminated with laser pulses

• Each PMT characterized at 300K and 87K for gain, dark count rate, peak to valley ratio and the uniformity of the photocathode response
  – The gain reduction at 87K wrt 300K can be compensated by a ~ 150V increase in PS voltage

JINST 13, P10030 (2018)
TPC Readout Electronics Upgrade

- New TPC readout electronics
  - Reside outside the cryostat → accessible
  - Serial 12-bit ADC, fully synchronous
  - CAEN A2795 64-chan modules
  - More compact layout: both analog+digital electronics in a single flange
  - Extensively tested on a 50ℓ TPC @ CERN

- Lower noise ~ 1200 e⁻ equivalent (~20% S/N improvement w.r.t. LNGS)

- Shorter shaping time (~ 1.5 μs all planes) and drastic reduction of undershoot after large signal.

- Induction plane 2 signal keeps bipolar shape → allows calorimetric measurement in this plane, to improve νₑ ID efficiency by ~20%.
ICARUS In Its Home at FNAL

The 2nd T300 being Inserted

Various top infrastructure installed

Electronics Installed

Remaining roof infrastructure installed
Finishing the Installation

- Top cold shields and top CRT support installation in progress
- Installation of proximity cryogenics completed.
- Leak tightness tests completed.
- Vacuum phase began June 5th!
- Side CRT installation ongoing
Recent Readout Electronics Test

- All FT flanges and the mini-crates w/ the TPC read-out electronics (576 channels + optical links) installed
- Full readout chain tested in April/May 2019 for all mini-crates:
  - Check readout continuity and set baseline for noise monitoring
  - Measured noise on random triggers and test pulses
  - Noise RMS ~1700 e⁻, not too far from ~1200 e⁻ measured in CERN 50-liter setup
    - Grounding conditions still far from optimal
- The successful tests demonstrate good performance of the full electronics

![Example of test pulse signal](image)
The Cosmic Ray Tagger (CRT)

- Surrounds the cryostat with two layers of plastic scintillators: 1100 m²
- Tags incident cosmic or beam-induced muons with high efficiency (>95%)
- Provides spatial and timing coordinates of the track entry point
- Reconstructed CRT hits matched to activities in the TPC
- Few ns time resolution allows measuring direction of incoming/outgoing particle propagation via time of flight

**Top:** ~ 400 m² roof + angled parts
- Will catch ~80% cosmic
- 2 strip layers (X+Y)
- SiPM readout

**Middle:** ~ 500 m² 4 sides
- Old MINOS veto modules
- Parallel strips
- SiPM readout

**Bottom:** ~ 200 m²
- Already installed
- D-Chooz veto modules
- 2 parallel layers
- PMT readout
Preparation for SBN Analyses

- Understanding of detector systematics and their correlation across ND – FD essential for SBN
- Common reconstruction tools and oscillation analysis fundamental.
- ICARUS sharing of algorithms and tools and x-check between reconstruction approaches.
- Full simulation performed with realistic geometry and signals from all sub-detectors (TPC, PMT, CRT).

![Graphs showing angle between simulated/reconstructed direction of EM shower in TPC and deconvolution hit finding.](image)
ICARUS @ FNAL Plans

- TPC/TRG electronics and PMT electronics installation to be completed and tested by summer 2019
- After cryogenics commissioning, cool down and filling
- ICARUS T600 should be full and operational in Q4 of 2019
- Commissioning of CRT, DAQ, trigger and slow controls will follow.
- Commissioning with cosmics and neutrino beam to begin by the end of this year.

We are here!
Conclusions!

- The successful 3-year run of ICARUS-T600 at LNGS a clear proof of the maturity of LAr-TPC technology for large-scale $\nu$ experiments.
- ICARUS significantly constrained the allowed phase space for LSND-like anomaly via $\nu_e$ appearance in the CNGS beam.
- The SBN project at FNAL to clarify the sterile $\nu$ puzzle through both appearance and disappearance channels with 3 LAr-TPCs.
- After an extensive overhaul, ICARUS at final stage of installation as the SBN FD at FNAL $\Rightarrow$ SBN data taking expected in early 2020 followed by ND in 2021.
- ICARUS will see the first neutrinos early 2020!
The ICARUS (Imaging Cosmic And Rare Underground Signals) Collaboration at SBN

• The full list of the Collaboration https://icarus.fnal.gov/collaboration

Spokesperson: C. Rubbia, INFN GSSI
more than 90 collaboration members

International Partner

Many thanks for the major contributions to the Far Detector cryogenics and cosmic ray tagger from our partners at CERN, INFN-Bologna, INFN-Lecce, INFN-Milano, INFN-Napoli, INFN-Genoa, INFN-LNS.