Sterile searches with Liquid Argon at FNAL

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OUTLINE

• The “sterile neutrino puzzle”.
• Sterile neutrino searches at FNAL with SBN program.
• Features of the Liquid Argon TPC detection technique.
• ICARUS T600 and the other SBN detectors.
• Present status and timeline.
• Conclusions.
The puzzling picture of short baseline $\nu$ oscillations

- Three independent classes of anomalous experimental results are not fitting into the “standard” landscape of 3-flavour $\nu$ mixing:
  - **Disappearance** in anti-$\nu_e$ events detected from near-by nuclear reactors ($R = 0.938 \pm 0.023$ ratio between observed and predicted event rates);
  - **Disappearance** in $\nu_e$ events from Mega-Curie k-capture calibration sources in solar $\nu$ experiments ($R = 0.86 \pm 0.05$);
  - **Appearance** of $\nu_e$/anti-$\nu_e$ in $\nu_\mu$/anti-$\nu_\mu$ beams at particle accelerators, with $3.4 \sigma$ (MiniBooNE) / $3.8 \sigma$ (LSND) evidence for oscillations.

- Each of these measurements lacks the significance to claim a discovery, but together they point to the possible existence of non standard heavier “sterile” neutrino state(s) driving oscillations at small distances: $\Delta m^2_{\text{SBL}} \approx 1 \text{ eV}^2$, relatively small $\sin^2(2\theta_{\text{new}})$.  

\[
\begin{align*}
\Delta m^2_{\text{SBL}} & \sim 1 \text{ eV}^2 \\
\Delta m^2_{\text{ATM}} & \sim 2.5 \times 10^{-3} \text{ eV}^2 \\
\Delta m^2_{\text{SOL}} & \sim 7.4 \times 10^{-5} \text{ eV}^2
\end{align*}
\]
Global analysis of SBL data

Global fits in the framework of mixing schemes with ≥ 1 sterile vs suffer from a tension between appearance & disappearance SBL ν oscillation experiments.

Neutrino 2016 by C. Giunti : 0.8 < Δm²_{41} < 2 eV² (3σ) → No oscillation disfavored at 6.6 σ

New constr. expected from latest Minos+ results

Data from CMB exps., large scale structure and Lyman-α forest observation, naively bind for 3 massless + 1 massive sterile ν to m_s<0.26 eV at 95% CL and should effectively exclude sterile ν as explanation of LSND anomaly.

If LSND results will be confirmed, a critical review of cosmological measurement framework should be necessary.

JHEP 1305 (2013) 050 by Kopp et al.: There is no globally allowed region in this paper!

ArXiv:1607.00011 by G.H Collin et al.: (Δm²_{41})_{b.f.} = 1.75 eV² ; sin²(2θ_{μe}) = 0.002
ICARUS searched for $\nu_e$ excess related to LSND-like anomaly on the CNGS $\nu$ beam ($\sim$1% intrinsic $\nu_e$ contamination, L/E $\nu$ $\sim$36.5 m/MeV).

Analysis on $7.23 \times 10^{19}$ pot event sample. No excess was observed: 7 $\nu_e$ events compared to $8.5 \pm 1.1$ as expected in absence of LSND signal. This provided the limit on the oscillation probability

$$P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 7.60 \times 10^{-3} \text{ at } 90 \text{ (99) } \% \text{ C.L.}$$

ICARUS result (confirmed by OPERA) indicates a very narrow region ($\Delta m^2 \sim 0.5 \text{ eV}^2$, $\sin^2 2\theta \sim 0.005$) where all experimental results can be accommodated at 90% CL.
SBN Sterile neutrino search at FNAL Booster $\nu$ Beamline

- An ultimate experiment with multiple LAr-TPCs exposed to FNAL Booster $\nu$ Beam (BNB) is in preparation as definitive answer to the "sterile neutrino puzzle".

- The experiment will exploit 3 LAr-TPCs exposed to $\sim 0.8$ GeV FNAL Booster Neutrino Beam (BNB) at different distances from target: SBND (112 t active mass), MicroBooNE (89 t) and ICARUS (476 t) at 110, 470, and 600 m;

- The SBN program is expected to definitely clarify LSND/MiniBooNE, reactor and solar exp. calibration radioactive sources anomalies by precisely/independently measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance, mutually related through

$$\sin^2(2\theta_{\mu e}) \leq \frac{1}{4}\sin^2(2\theta_{\mu x}) \sin^2(2\theta_{e x})$$

- In absence of "anomalies" the 3 detector signals should be a close copy of each other for all experimental signatures. A disappearance signal from $<1\%$ intrinsic beam $\nu_e$ (if confirmed by reactors) may reduce the superimposed LSND $\nu_e$ signal: the two effects can be disentangled by changing horn/decay tunnel length to modify the $\nu$ spectrum.
The Three LArTPC SBN Program

\[ \langle L_\nu \rangle \sim \frac{600 \text{ m}}{700 \text{ MeV}} \sim \mathcal{O}(1 \text{ km/GeV}) \]

![Diagram of the SBN program with various detectors and distances marked.](image_url)
The SBN Collaborations – Institutions (July 2016)

ICARUS
Argonne National Lab, USA
Brookhaven National Lab, USA
CERN, Switzerland
Colorado State University, USA
Fermi National Lab, USA
INFN and University, Catania, Italy
INFN GSSI, L'Aquila, Italy
INFN LNGS, Assergi (AQ), Italy
INFN Sez. di Milano Bicocca, Milano, Italy
INFN Sez. di Napoli, Napoli, Italy
INFN and University, Padova, Italy
INFN and University, Pavia, Italy
H. Niewodniczanski Inst. of Nucl. Phys.,
Polish Acad. of Science, Krakow, Poland
Institute for Nuclear Research (INR),
Institute of Physics, University of Silesia,
Katowice, Poland
Inst. for Radio-Electronics, University of
Technology, Warsaw, Poland
Los Alamos National Lab, USA
Nat. Centre for Nucl. Research, Warsaw,
Poland
University of Pittsburgh, USA
Russian Academy of Science, Moscow,
Russia
SLAC, USA
Texas University at Arlington, USA

MicroBooNE
University of Bern, Switzerland
Brookhaven National Lab, USA
University of Cambridge, UK
University of Chicago, USA
University of Cincinnati, USA
Columbia University, USA
Fermi National Lab, USA
Illinois Institute of Technology, USA
Kansas State University, USA
Lancaster University, UK
Los Alamos National Lab, USA
University of Manchester, UK
MIT, USA
University of Michigan, USA
New Mexico State University, USA
Oregon State University, USA
Otterbein University, USA
University of Oxford, UK
University of Pittsburgh, USA
Pacific Northwest Nat. Laboratory, USA
Princeton University, USA
Saint Mary's University of Minnesota, USA
SLAC, USA
Syracuse University, USA
University of Texas at Arlington, USA
Tubitak Space Tech. Research Inst., Turkey
Virginia Tech, USA
Yale University, USA

SBND
Argonne National Lab, USA
University of Bern, Switzerland
Brookhaven National Lab, USA
University of Cambridge, UK
University of Michigan, USA
Univ. of Campinas – UNICAMP, Brazil
CERN, Switzerland
University of Chicago, USA
Columbia University, USA
Federal Univ. of ABC – UFABC, Brazil
Federal Univ. of Alfenas – UFAL, Brazil
Fermi National Laboratory, USA
Illinois Institute of Technology, USA
Indiana University, USA
Kansas State University, USA
Lancaster University, UK
University of Liverpool, UK
Los Alamos National Lab, USA
University of Manchester, UK
University of Michigan, USA
MIT, USA
University of Oxford, UK
Pacific Northwest National Lab, USA
University of Pennsylvania, USA
University of Puerto Rico
University of Sheffield, UK
Syracuse University, USA
University of Texas, Arlington, USA
University College London, UK
Virginia Tech, USA
Yale University, USA

27 US + 26 non-US Institutions
νμ → νe appearance sensitivity

- **Electron neutrino CC interactions**
  - $π^- → μ → ν_e$
  - $K^+ → ν_e$
  - $K^0 → ν_e$
  - Sample appearance signal

- **Photon-induced e.m. shower backgrounds**
  - NC misIDs
  - $ν_μ$ CC misIDs
  - "Dirt" Backgrounds: beam-related but out-of-detector interactions
  - Cosmogenic photon sources

Example for $\sin^2(2θ)=0.013$
$Δm^2=0.43\ eV^2$

The LSND 99% C.L. region will be covered at $\sim 5\ σ$ level in 3 years of data taking with positive focusing of the BNB ($\sim 6.6 \times 10^{20}$ pot).
**ν_μ** disappearance sensitivity

Example for \( \sin^2(2\theta) = 0.1; \Delta m^2 = 1.1 \text{ eV}^2 \)

The high event rates/correlations between 3 LAr-TPC's will allow extending sensitivity by one order of magnitude beyond present limits.

However for \( \Delta m^2 < 0.5 \text{ eV}^2 \), ν_μ disappearance at 600 m will be limited at lowest ν energy bins 0.2-0.4 GeV. In order to amplify the effect, one ICARUS T300 module might be moved to 1500 m distance at a later stage.

Example for \( \sin^2(2\theta) = 0.1; \Delta m^2 = 0.44 \text{ eV}^2 \)
Liquid Argon TPC detection technique

- Liquid Argon Time Projection Chamber (LAr-TPC) detectors are very well suited for the experimental study of Neutrino Physics, combining a massive and homogeneous target with excellent tracking and calorimetric capabilities.

- Originally proposed by C. Rubbia in 1977 [CERN-EP/77-08], the LAr-TPC technology has been taken to full maturity with the ICARUS T600 detector installed in Gran Sasso INFN Laboratory.

**Ionization electrons:** ~6000 e⁻/mm are produced by a m.i.p. interacting particle within $E=500\text{V/cm}$. This charge is drifted by $E$ toward planes of wires where it induces an electrical signal recorded by electronics. A 3D image is reconstructed by combining the information from wires and the drift time ($\sim 1.5\text{mm}/\mu\text{s}$).

**Scintillation light:** ~5000 $\gamma$/mm ($E=500\text{V/cm}$) are produced by a m.i.p. interacting particle. The light is characterized by $\lambda = 128\text{ nm}$ and two decay time ($\sim 6\text{ ns}$ and $1.8\mu\text{s}$).
ICARUS T600

- 760 t of LAr, 476 t active mass.
- Located at 600 m from the source, will contribute to SBN as far detector.
- ICARUS will also collect ~2 GeV neutrinos from NuMI Off-Axis beam: Accurate determination of cross-sections in LAr;

- 4 TPC with 1.5 m drift and 3 wire planes (0, +/- 60°) with 3 mm pitch. 360 8” PMTs coated with TPB to convert VUV photons to visible light.
- Operated underground at LNGS in 2010 ÷ 2012 with CNGS ν beam.
- Overhauling at CERN (WA104 project).
- Ready for transport to FNAL in early 2017.

ICARUS T600 is also a technological milestone towards future larger LAr-TPCs, as the DUNE project in US.
Important LAr-TPC features have been demonstrated by ICARUS T600 during the LNGS run:

- **Very long e⁻ mobility**: Level of electronegative impurities in LAr can be kept exceptionally low to ensure \( \sim m \) long drift path of ionization e⁻ with very small attenuation \( \tau_{\text{ele}} > 15 \text{ ms} (\sim 20 \text{ p.p.t. } [O_2 \text{ eq.}]). \)

- **Excellent tracking device and calorimeter**: total energy reconstruction by charge integration - excellent accuracy for contained events; momentum of not contained \( \mu \) determined via Multiple Coulomb Scattering \( \Delta p/p \sim 15\% \) in 0.4–4 GeV/c range; measurement of local energy deposition \( dE/dx: e/\gamma \) remarkable separation \( (0.02 \times X_0 \text{ sampling, } X_0 = 14 \text{ cm, particle identification by } dE/dx \text{ vs range}) \).

**Low energy electrons**  
Electromag. showers  
Hadron shower (pure LAr)  
\( \sigma(E)/E = 11%/\sqrt{E}\text{(MeV)} + 2\% \quad \sigma(E)/E = 3%/\sqrt{E}\text{(GeV)} \quad \sigma(E)/E \approx 30%/\sqrt{E}\text{(GeV)} \)
Key features of LAr imaging: $\nu_e$ identification in LAr-TPC

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual $\nu_e$-events with high efficiency.

- The evolution of the actual $dE/dx$ from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.
Atmospheric neutrinos

- Study of LNGS atmospheric neutrinos deep underground is being performed on the available 0.73 kt x year exposure.
- Despite the small statistics of atmospheric events with respect to the FNAL BNB \( \nu \) beam on shallow depth, they represent a relevant test-bench to qualify the automatic \( \nu \) identification algorithm under development in view of operations at FNAL.

**Downgoing, quasi-elastic \( \nu_e \) CC event, deposited energy: \( \sim 240 \text{ MeV} \)**

- 2.1 MeV/cm dE/dx on first wires \( \Rightarrow \) 1 m.i.p. particle
- Short proton track

*Atmospheric neutrinos cover the energy range of BNB neutrinos at FNAL!*
T600 Overhauling at CERN (WA104)

- T600 detector has been moved to CERN for overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/long baseline neutrino experiments (WA104 project).
- The activities are progressing, introducing technology developments while maintaining the already achieved performance:
  - New cold vessels, with a purely passive insulation;
  - Improvement of the cathode planarity
  - Renovated cryogenics/LAr purification equipment;
  - Upgrade of the light collection system: 360 8” PMTs behind the wire planes to precisely localize the collected events in ~1 ms drift window; a fast response - high time resolution, ~1 ns precision, is required.
  - New faster, higher performance read-out electronics.
Upgrade of the light collection system

- A total of 400 R5912-MOD PMTs, which include 10% of spare samples, were produced by Hamamatsu and delivered to CERN.

- Each PMT have been equipped with a customized cryogenic base. The biasing of dynodes is obtained through a passive resistive voltage divider, directly mounted on the PMT flying-leads. Divider components were selected for operation at cryogenic temperature.

- All PMTs have been tested at room temperature and 60 units directly in a LAr bath to evaluate the behaviour at cryogenic temperature of gain, linearity, and dark counts.

- All the tested PMTs are compliant with the requirements for installation in the T600.

- All PMTs have been coated by evaporation with ~200µg/cm² of TPB to detect the λ=128nm scintillation.
New mechanical supports for the PMT installation were designed. Each device is set inside a wire shielding cage which prevents the induction of PMT pulses on the facing collection planes.

All PMTs for the first T300 module have been installed, internal cabling is progressing.
Adoption of serial ADCs (12 bits, one per channel) in place of the multiplexed ones used in T600 at LNGS, very compact, allowing for hosting both analogue and digital electronics directly on the proprietary flanges.

The main advantage is the *synchronous* sampling of all channels (400 ns sampling time) of the whole detector: relevant to slightly improve the $\mu$ momentum measurement by MCS, $\Delta p/p$ from 15% to 12%.

Throughput of read-out system improved up to 10 Hz.

Prototype boards are under test at INFN-LNL and CERN.
Cosmogenic interactions of all kinds depositing more than 100 MeV will occur in the T600 fiducial volume at ~11 kHz: during 1 ms drift time, ~12 uncorrelated cosmic rays are expected.

Moreover, γ’s associated with cosmic µ’s represent a serious background for the νₑ appearance search since electrons generated in LAr via Compton scattering/pair production can mimic a νₑ CC genuine signal.

Mitigation strategy:
- 3m of concrete overburden;
- External cosmic-ray trackers;
- Internal photo-detection system by exploiting the BNB bunched structure (2 ns every 19 ns).
Near and Intermediate SBN Detectors

- **Short-Baseline Near Detector (SBND)**
  - 260 t of LAr, 112 t active mass.
  - Located at 110 m from the source, it will characterize the neutrino beam before the onset of oscillations.
  - Membrane cryostat.
  - 4 TPCs with 2 m drift and 3 wire planes (0, +/- 60) 3mm pitch. 120 8” PMTs coated with TPB.

- **MicroBooNE** *(see A. Furmanski presentation at this workshop)*
  - 170 t of LAr, 87 t active mass.
  - Located at 470 m from the source, it is presently addressing the MiniBooNE low energy excess and will contribute to SBN as intermediate detector.
  - 1 TPC with 2.5 m drift and 3 wire planes with 3 mm pitch. 32 8” PMTs coated with TPB.
SBN Program Timeline

- **MicroBooNE:**
  - Running now addressing the MiniBooNE anomaly and will continue as intermediate detector in SBN.

- **ICARUS:**
  - Overhauling of T600 almost completed and ready for transport in early 2017;
  - Civil construction of far sites and buildings are rapidly progressing at FNAL;
  - Installation and commissioning at FNAL in 2017 to start asap with ν data taking.

- **SBND:**
  - Begin of TPC assembly at FNAL in 2017, install into cryostat in 2018;
  - Civil construction of near sites and buildings is also progressing;
  - Begin commissioning into 2018.
Conclusions

- Fifty years after their introduction by B. Pontecorvo, sterile neutrinos are still an open question in particle physics.
- After twenty years the LSND anomaly, suggesting their existence at ~eV scale is still surviving direct experimental tests.
- The superior detection capabilities of LAr-TPC technology have been demonstrated by ICARUS T600 during the LNGS run.
- A definitive answer to the “sterile neutrino puzzle” is soon expected from the SBN program in preparation at FNAL: 3 LAr-TPC detectors (SBND, MicroBooNE and ICARUS-T600) exposed to Booster neutrino beam.
- The SBN Program, beyond its physics scope, serves also as a platform in view of the Long-Baseline Program DUNE, representing a technological milestone and taking data from the NuMI Off-Axis ν beam.
Thank you!