ICARUS: perspective for Sterile Neutrinos search at FermiLab

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Neutrino masses and oscillations represent today a main experimental evidence of physics beyond SM. Being the only elementary fermions whose basic properties are still largely unknown, $\nu$s are naturally one of the main priorities to complete our knowledge of SM.

The incredible smallness of $\nu$ masses compared to other elementary fermions points to some specific scenario awaiting to be elucidated.
Neutrino oscillations established a coherent picture with mixing of physical $\nu_e, \nu_\mu, \nu_\tau$ with small mass difference. There are however a number of "anomalies" which, if confirmed, could hint at additional 4th non standard sterile $\nu$ driving oscillations at small distance with $\Delta m^2_{\text{new}} \sim 1 \text{ eV}^2$:

- **Observation of $\nu_e$ excess (1)** from $\nu_\mu$ in LSND (3.8 $\sigma$ effect) and MiniBooNE expts at accelerators;

- **Anti-$\nu_e$ event signal (2)** from near-by nuclear reactors where observed to predicted event rate is $R=0.938 \pm 0.023$ and (3) from Mega-Curie $k$-capture calibration sources in solar $\nu_e$ expts, $R=0.86 \pm 0.05$;

Data from CMB expts, large scale structure and Lyman-$\alpha$ forest observation, naively bind for 3 massless + 1 massive sterile $\nu$ to $m_s<0.26 \text{ eV}$ at 95% CL and should effectively exclude sterile neutrino as explanation of LSND anomaly.

If LSND notwithstanding confirmed experimentally, cosmological data will have been proven wrong calling for a re-examine of this entire framework!
Cherenkov radiation detection has been so far one of key choices for exploring \( \nu_s \) with \( Kt \) mass water/ice detectors. Unfortunately these detectors don’t permit to identify unambiguously each ionizing track of complex events produced by \( \nu_s \).

As an alternative, Liquid Argon Imaging technology LAr-TPC, effectively an electronic bubble-chamber, was originally proposed by C. Rubbia in 1977 [CERN-EP/77-08].

With the continuing efforts of ICARUS Coll. and INFN support, LAr-TPC technology has been taken to full maturity with the T600 detector, 0.76 Kt mass ultrapure liquid argon installed in Gran Sasso INFN Lab.

ICARUS T600 is also a technological milestone towards future larger LAr-TPCs, tens of kt as the DUNE project in US.
ICARUS T600, 0.47 Kt LAr active mass, concluded in 2013 a very successful 3 years long run at CNGS ν beam collecting $8.6 \times 10^{19}$ pot event stat with a detector live time > 93%.

At the same time ICARUS recorded cosmics for a total 0.73 kty exposure.

2650 CNGS ν events selected ~ 3.4 ν/10^{17} pot in ~agreement with expects
A key feature of LAr imaging: very long $e^-$ mobility

- Level of $e^-$-negative impurities in LAr must be kept exceptionally low to ensure $\sim$m long drift path of ionization $e^-$ signal without attenuation;
- New industrial/lab purification methods developed to continuously filter and re-circulate both liquid (100 m$^3$/day) and gas (2.5 m$^3$/hour) argon;
- Electron lifetime measured during ICARUS run at LNGS with cosmic $\mu$'s: $\tau_{\text{ele}} > 7$ ms ($\sim$40 p.p.t [O2] eq) $\rightarrow$ 12% max. charge attenuation on 1.5 m drift.

New not-immersed pump on East cryostat since April 4th, 2013: $\tau_{\text{ele}} > 15$ ms!

ICARUS demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors with $\sim$5 m drift as required for LBNF/DUNE project.
ICARUS LAr-TPC performance

- **Tracking device**: precise ~mm$^3$ resolution, 3D event topology, accurate ionization measurement;

- **Global calorimeter**: total energy reconstruction by charge integration- excellent accuracy for contained events; momentum of non 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 $X_0$ sampling, $X_0= 14$ cm, particle id. by $dE/dx$ vs range):
  - Low energy electrons: $\sigma(E)/E = 11%/\sqrt{E$(MeV)$}+2\%$
  - Electromagnetic showers: $\sigma(E)/E = 3%/\sqrt{E$(GeV)$}$
  - Hadron shower (pure LAr): $\sigma(E)/E \approx 30%/\sqrt{E$(GeV)$}$
• An essential tool to measure the momentum of non-contained $\mu$s.

• Algorithm validated on stopping $\mu$s, $L_\mu > 2.5m$ ($3\lambda_I$ in LAr) produced in CNGS vs interactions upstream of T600 and stopping/decaying inside the detector, by comparing $p_{MCS}$ with the corresponding calorimetric $p_{CAL}$.

Some deviations for $p > 3.5$ GeV/c induced by non-perfect planarity of TPC cathode

\[ \Delta p/p \approx 15\% \text{ in 0.4-4 GeV/c momentum range of interest for short/long base-line experiments} \]
$E_k = 102 \pm 10\text{ MeV}$

$E_k = 685 \pm 25\text{ MeV}$

$\pi^0$ reconstruction:
$p_{\pi^0} = 912 \pm 26\text{ MeV/c}$
$m_{\pi^0} = 127 \pm 19\text{ MeV/c}^2$
$\theta = 28.0 \pm 2.5^\circ$

Three “handles” to separate e/γ:
• Invariant mass of $\pi^0$
• dE/dx: single vs. double m.i.p.
• Photon conversion separated from primary vertex

$M_{\gamma\gamma}: 133.8 \pm 4.4 \pm 4\text{ MeV/c}^2$

Crucial for NC rejection in νe-physics

Conversion distances: 6.9 cm, 2.3 cm
CNGS $\nu_e$ CC identification in ICARUS LAr-TPC

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

The evolution of the actual $\text{d}E/\text{d}x$ from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.

$E_{\text{ele}} = 24 \pm 1 \text{ GeV}$

$p_t = 1.5 \pm 0.7 \text{ GeV/c}$

- $\text{d}E/\text{d}x$ vs wire number along track direction
- Single $\text{M.I.P}$
Other CNGS $\nu_e$ interactions

Run 11731 Event 4278:

Double M.I.P
Single M.I.P

Zoomed Induction 2

Run 11319 Event 2862:

Scheme of 3D reconstruction

Collection

$E_{\nu_e} = 6.3 \pm 1.5$ GeV
$P_{\nu_e} = 3.5 \pm 0.9$ GeV/c

$E_{\text{ele}} = 6.4 \pm 0.3$ GeV
$P_{\text{ele}} = 1.2 \pm 0.2$ GeV/c

e.m. shower

incoming neutrino
ICARUS searched for $\nu_e$ excess related to $L/E_\nu \sim 1$ m/MeV LSND anomaly on CNGS $\nu_\mu$ beam (~1% intrinsic $\nu_e$) in 10-30 GeV $E_\nu$ range at 732 km distance;

At CNGS $L/E_\nu \sim 36.5$ m/MeV: LSND-like oscillation signal averages to $\sin^2(1.27\Delta m^2_{\text{new}} L/E) \sim 1/2$. Compared to MINOS and T2K, ICARUS operates in a $L/E_\nu$ range where contributions from standard oscillations not yet too relevant.

No excess observed in $7.93 \times 10^{19}$ pot sample: 7$\nu_e$ events compared to $8.5 \pm 1.1$ expected in absence of LSND-like effect providing 90% CL limit $P(\nu_\mu \rightarrow \nu_e) \leq 3.86 \times 10^{-3}$. The 2650 recorded $\nu$ events allow searching for possible oscillations also in disappearance, provided the initial $\nu$ flux at CERN from the associated $\mu$ measurements.

ICARUS and OPERA restrict allowed parameter to a narrow region $\Delta m^2 \sim 0.5$ eV$^2$, $\sin^2 2\theta \sim 0.005$ where all the experimental results can be coherently accommodated at 90% C.L.

Need for a definitive experiment on sterile $\nu$s to clarify all the reported anomalies.
Towards automatic neutrino search: atmospheric $\nu$

- Recorded cosmic events are being filtered by an automatic algorithm rejecting passing muons and selecting events with a multi-prong interaction vertex topology ($\geq 2$ charged particles, $\sim 30\%$ of $\nu$CC) to identify atmospheric $\nu$ candidates;

- A drastic reduction to $0.5\%$ of events undergoing the next visual scanning has been achieved for multi-prong event topology;

- New algorithms looking for clusterized energy deposition maintaining low the fraction of events needing visual scanning and improving the efficiency up to $70\%$ for $\nu$eCC are under validation;

- 3 $\mu$-like, 2 $e$-like within a sample of 12 observed atm. $\nu$ candidates have been identified so far in $25\%$ of collected statistics ($10\pm2$ multi-prong events are expected)
The first observed „LAr TPC” atmospheric $\nu_e$ CC event

- Quasi-elastic $\nu e$CC with $E_{\text{Dep}}=2.12$ GeV
- Clear primary electron initiated (single m.i.p.) shower (2 GeV);
- 115 MeV proton identified by $dE/dx$

Automatic search for $\nu e$CC in GeV range feasible
A second atmospheric $\nu_e$ CC event: low energy

Downward-going, quasi elastic event: deposited energy: 240 MeV!

- $dE/dx$ measured on first wires (2.1 MeV/cm) corresponds to a m.i.p. particle
- One short proton track recognized.
- Automatic search for $\nu e$CC in sub GeV range is feasible too

Atmospheric neutrinos cover the energy range of BNB neutrinos at FNAL!
Deposited energy ~ 1.9 GeV
Electron deposited energy ~ 1.7 GeV;
\( \text{dE/dx} \) measured on few wires (2 MeV/cm) corresponds to a m.i.p. particle
Very clearly seen in Induction projection;
- Deposited energy ~ 440 MeV
- Electron deposited energy ~ 270 MeV;
- Very clearly seen in Induction projection;

*To be fully studied*
SBN 0.8 GeV $\nu$ FNAL Booster: 3 LAr-TPCs as definitive answer to sterile neutrino puzzle

T600 - shallow depth - will be protected from cosmic neutrals by 3 m overburden.
The experiment will exploit 3 LAr-TPCs exposed to ~0.8 GeV FNAL Booster neutrino beam at different distances from target: SBND (82 t active mass), MicroBooNE (89 t) and ICARUS (476 t) at 100, 470, and 600 m;

The SBN is expected to definitely clarify LSND/MiniBooNE, Gallex, reactor and radioactive source and anomalies by precisely/independently measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance, mutually related through

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

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 $\nu_e$ (if confirmed by reactors) may result in a reducing the superimposed LSND $\nu_e$ signal: two effects can be disentangled by changing horn/decay tunnel length to modify the $\nu$ spectrum;

During SBN operations, ICARUS will also collect ~2GeV neutrinos from NUMI Off-Axis beam. This will be an asset for DUNE-LBNF long-baseline project:

- Accurate determination of cross-sections in LAr;
- Study of all CC/NC channels to realize algorithms improving $\nu$ identification.
The ICARUS/WA104 Collaboration

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Brookhaven National Laboratory (BNL), USA
CERN, Geneva, Switzerland
Colorado State University, USA
Fermi National Laboratory (FNAL), USA
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Pittsburgh University, USA
Russian Academy of Science, Moscow, Russia
SLAC, Stanford, CA, USA
Texas University, Arlington, USA
The LSND 99%CL region is covered at ~5σ
\[ \Delta m^2 = 1.1 \text{ eV}^2 \quad \sin^2 2\theta = 0.1 \]

- High event rate/correlation between the 3 LAr-TPCs allows extending sensitivity by one order of magnitude beyond present limit.

- $\nu_\mu$ disappearance limited to 0.2-0.4 GeV; lowest $\nu$ energy bins for $\Delta m^2 < 0.5 \text{ eV}^2$.

- To amplify the effect, an ICARUS T300 module may be moved at a later stage to 1.5 km distance from target.
Facing a new situation: the LAr-TPC near the surface

- At shallow depth ~12 cosmic $\mu$s will occur in T600 in 1 ms drift window readout at each triggering event: reconstructing track positions along the drift requires to associate to each element of TPC image the proper timing w.r.t. trigger.

- Moreover, $\gamma$'s associated with cosmic $\mu$'s represent a serious background for the $\nu_e$ appearance search since electrons generated in LAr via Compton scattering/pair production can mimic a $\nu_e$ CC genuine signal.

- A large $4\pi$ Cosmic Rays Tagger of plastic scintillators surrounding the LAr volume, combined with timing information from internal scintillation light detectors, will unambiguously identify all cosmics entering the detector.

**Automatic tools to efficiently select, identify and reconstruct $\nu$ events among the millions events triggered by cosmics (to be compared with ~ 3000 $\nu$ events collected at CNGS run) are mandatory!**
ICARUS/WA104 at CERN: overhauling of the T600

- 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: “Improving the ICARUS T600 Liquid Argon Time Projection Chamber (LAr TPC) in order to prepare for its operation at shallow depths” (WA104 project).

- The activities are progressing, introducing technology developments while maintaining the already achieved performance:
  - New cold vessels, with a purely passive insulation;
  - Renovated cryogenics/LAr purification equipment;
  - Upgrade of the light collection system: 360 8” PMTs behind the wire planes (~5 % photo-cathode coverage) to precisely localize the collected events in ~ 1.5 ms window; a fast response - high time resolution, ~1 ns precision, is required to exploit the 2ns/19 ns bunched beam structure for the rejection of cosmics.
  - New faster, higher performance read-out electronics

- The detector is expected to be transferred to FNAL before end 2016 for installation, commissioning and start of data taking with ν beam
According to schedule, the two T300 modules will be ready for shipment to the US by the end of 2016, which is compatible with the foreseen beneficial occupancy of the Far Detector building in beginning 2017.
New Al cold vessels and new purely passive insulation

Dedicated tool for assembly of stiffening of frames at CERN.

- Purely passive insulation with membrane for LNG transport ships. Expected heat loss through insulation: ≈ 6.6 kW (10-15 W/m²).
A new, higher-performance, compact design read-out electronics

- One 12 bits ADCs per channel in place of multiplexed (8x) 10 bit ADCs.
- 400 ns sampling *synchronous* for whole detector, improving event reconstruction, i.e. pm from MCS.
- The digital part is contained in a *single high performance* FPGA in each board, handling signal filtering and related ADC.
- Both analogue/digital electronics hosted directly on the flange feed-throughs.

- **128 induction wires (325 mm)**
  - Drift velocity: 1.5 mm/μs
  - Pulse-height ~400 e/#
  - Drift time (180 μs, 4 μs/#)
  - Collection signal (on a single wires)
  - Induction signal (on a single wire)

- **180 μs (280 mm)**
  - Drift velocity 1.5 mm/μs
  - Collection
  - Induction
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;
- ICARUS T600 experiment, the first large 760 t of highly purified LAr, has successfully completed a 3-years physics program at LNGS recording neutrino interactions from CNGS ν beam and from cosmic rays and demonstrating the superior detection capabilities of LAr-TPC technology. Analysis of the CNGS events provided new stringent constraints on sterile νs indicating a narrow parameter region where all existing experimental results are in agreement.
- A definitive answer on sterile νs is soon expected from the SBN experiment in preparation at FNAL: 3 LAr-TPC’s - SBND, MicroBooNE and ICARUS-T600 exposed to Booster neutrino beam. ICARUS will be moved to FNAL at the end of the present overhauling at CERN
- ICARUS will also record NUMI Off-Axis neutrinos providing a significant amount of data in the energy range of interest for next DUNE/ LBNF Long Baseline experiment

THANK YOU