ICARUS Status and plans



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On behalf of the ICARUS Collaboration

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The ICARUS Collaboration

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The ICARUS T600 at LNGS Laboratory

- The ICARUS experiment completed 3 years of data taking on June 26th, 2013, collecting 8.6 10¹⁹ protons on target with detector live time > 93%.
- Continuous underground operation has proven that the LAr-TPC detection technique is well understood and suited for next generation experiments.
- Cosmic rays data have been collected to study atmospheric v



- Decommissioning of ICARUS started at the end of June 2013. T600 was emptied during summer and gradually brought to room temperature
- The cryogenic plant, including cryo-coolers, and the readout electronic have been dismounted opening the access to cryostats for the extraction of the TPC chambers. All the material will be sent to CERN for the foreseen overhauling.

T600 data analysis

- The analysis of the collected data is progressing along several paths.
- Three new results will be described:
 - > Updated search for anomalous $v_{\mu} \rightarrow v_{e}$ transitions in CNGS beam;
 - determination of muon momentum by multiple scattering;
 - Improvements of the LAr purity.
- The present effort is mainly devoted to:
 - > Search for the v_{μ} disappearance anomaly in the CNGS beam;
 - Study of the cosmic events sample in view of the search for atmospheric neutrino interactions.
- The more complete study of the actual nature of the CNGS events and the study of other data is continuing on a longer time schedule.
- Development of software automatic tools for reconstruction is also progressing.

Search for anomalous LSND v_e events in CNGS beam

- The CNGS facility delivered an almost pure v_μ beam in 10-30 GeV E_ν range (beam associated v_e ~1%) at a distance L=732 km from target.
- There are differences w.r.t. LSND exp.
 - L/E_v ~1 m/MeV at LSND, but
 L/E_v ≈36.5 m/MeV at CNGS
 - LSND -like short distance signal averages to $\sin^2(1.27\Delta m_{new}^2 L/E) \sim 1/2$ and $\langle P \rangle_{\nu\mu \rightarrow \nu e} \sim 1/2 \sin^2(2\theta_{new})$
- When compared to other long baseline results (MINOS and T2K) ICARUS operates in a L/E, region in which contributions from standard v oscillations [mostly sin(θ_{13})] are not yet too relevant.
- Unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



Search for v_e events in CNGS beam

- v_e CC event candidates are visually selected with vertex inside fiducial volume (for shower id.) : > 5 cm from TPC walls and 50 cm downstream
- Energy selection: <30 GeV</p>
 - > 50% reduction on intrinsic beam v_e
- only 15% signal events rejected
 v_µ CC events identified by L > 2.5 m long track without hadronic interactions
- The "Electron signature" requires:

- e.m. shower buildup $E_{ele} = 11 \text{ GeV}$ $p_t = 1.0 \text{ GeV/c}$ $V_e \text{ MC event}$
- A charged track from primary vertex, m.i.p. on 8 wires, subsequently building up into a shower; very dense sampling: every 0.02 X₀;
 Isolation (150 mrad) from other ionizing tracks near the vertex in at least one of the TPC views.
- Electron efficiency has been studied with events from a MC (FLUKA) reproducing in every detail the signals from wire planes: $\eta = 0.74 \pm 0.05$ (0.65±0.06 for intrinsic v_e beam due to harder spectrum).

- New statistics w.r.t. the previously published result in Eur. Phys. J.
 C73:2599 2013 and based on 1995 v interactions (6.0 10¹⁹ pot).
- An additional sample of 455 v interactions, corresponding to 1.2 10^{19} pot: the analysis presented here refers to 2450 v events and 7.23 10^{19} pot out of the fully collected statistics of 8.6 10^{19} pot.
- Expected number of v_e events:
 - \nearrow 7.0 \pm 0.9 due to the intrinsic v_e beam contamination
 - 2.9 ± 0.7 due to θ_{13} oscillations, sin²(θ_{13}) = 0.0242 ± 0.0026
- > 1.6 \pm 0.1 from $v_{\mu} \rightarrow v_{\tau}$ oscillations with subsequent *e* production Total number of expected events: 11.5 \pm 1.2
- Expected number of electron events, corrected for detection efficiency: 7.9 ± 1.0 (syst.only)
- 2 additional electron neutrino events identified: now 6 v_e events
- In all the 6 electron neutrino identified events the single electron shower is opposite to hadronic component in the transverse plane.

The new ICARUS result with 2450 v interactions

- Event with a clear electron signature found in the sample of 2450 ν interactions (7.23 10^{19} pot).
- 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.



Event with a clearly identified electron signature



ICARUS result on the search of the LSND-anomaly

- 6 v_e events have been observed in agreement with the expected 7.9 ± 1.0 due to conventional sources (the probability to observe ≤ 6 v_e events is ~33%).
- Weighting for the efficiency, ICARUS limits on the number of events due to LSND anomaly are:
 5.2 (90 % C.L.) and 10.3 (99 % C.L.).
 These provide the limit
- These provide the limits on the oscillation probability:

P(
$$v_{\mu} \rightarrow v_{e}$$
) ≤3.85 × 10⁻³ (90 % C.L.)
P($v_{\mu} \rightarrow v_{e}$) ≤7.60 × 10⁻³ (99 % C.L.)



Neutrino

LSND-like exclusion from the ICARUS experiment



ICARUS result strongly limits the window of parameters for the LSND anomaly to a very narrow region ($\Delta m^2 \approx 0.5 \, eV^2$ and $sin^2 2\theta \approx 0.005$) for which there is an overall agreement (90% CL) of

- the present ICARUS limit
- the limits of KARMEN
- the positive signals of LSND and MiniBooNE

Measurement of muon momentum via multiple scattering

In absence of a magnetic field, the initial muon momentum can be determined through the reconstruction of multiple Coulomb Scattering (MS) in LAr



The RMS of θ deflection depends on p , on the spatial resolution σ and $\theta_{RMS} \div \frac{13.6MeV}{p} \sqrt{\frac{l}{X_o} \oplus \frac{\sigma}{l^{3/2}}}$ on the segmentation L_{seg}

The method has been tested in T600 on ~1000 stopping muon sample from CNGS v interactions in the upstream rock, comparing the initial momentum measured by p^{MS} with the corresponding calorimetric determination p^{CAL} .

Muon momentum reconstructed by calorimetric measurement for the stopping muon sample

This energy range (0.5-4 GeV) is appropriate to proposed short / long baseline experiment at FNAL

Determination of muon momentum by multiple scattering

- Stopping muons have been visually selected amongst all the neutrino events recorded in coincidence with the CNGS beam spill.
 - > μ -identification : L μ ≥ 2.5 m (~ three hadronic interaction lengths) and the absence of nuclear interactions along the track.
 - No other activity in the event
- Automatic 3D track reconstruction (visually validated); only collection view has been used for multiple scattering analysis.
- Identification/removal of δ rays before proceeding to p fit:
 - Multiple hits on the same wire
 - > charge of the hit (noise, large δ rays)
- Momentum extracted from measurement of deflection angle θ and from χ^2 of the fit: $\begin{cases} \theta_{MS} \propto \sqrt{L_{seg}}/p \leftarrow MS \text{ angle} \\ \theta_{det} \propto L_{seg}^{-3/2} \leftarrow \frac{detector}{resolution} \end{cases}$
- Cut the easy part: multiple scattering is measured on the first 4 m for stopping tracks L > 5 m: p_{MS} is compared with the momentum from spscalorimetry.

Beam-associated stopping long muons

Stopping μ track length: > 5 m Used length: 4m





Resolution ~16% in the energy rage of interest for future experiments

Some bias appears for larger momenta High precision measurement, in strong competition with the measurement error: $\theta_{MS} \approx 10$ mrad for a 10 GeV muon over a 1 X₀ track segment,

Measured uncertainty on single hit \rightarrow average 0.73 mm, $\rightarrow \approx 8 \text{ mrad over 1 } X_0$ Slide# : 14

ICARUS T600 LAr purity

- The LAr TPC performance strongly depends on LAr purity, since impurities reduce the drifting electrons lifetime attenuating the signal
- A detailed offline analysis with a robust algorithm and large μ statistics has been performed to measure very small signal attenuation along the drift:
 - \blacktriangleright Accurate identification/removal of δ and e.m. activity associated to μ ;
 - A 10% truncated mean is applied to signals of single tracks to remove under/over fluctuations;
 - $\ge 1/\tau_{ele}$ is used as estimation of the signal attenuation.
- Cross check with muons from CNGS v interacting in the upstream rock: <dE/dx> is correctly reconstructed as a constant along the drift coordinate



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ICARUS T600 LAr purity offline analysis: new results

- ICARUS has operated with $\tau_{ele} > 7 \text{ ms}$ (~40 p.p. trillion $[O_2]_{eq}$) corresponding to a 12% maximum charge attenuation at longest drift distance! New pump has been installed
- on East cryostat since April 4th, 2013: and still rising!
 - A remarkable purity has been achieved on ~1 kt scale detector, to be compared with \approx 1ms longest electron drift time, approaching the LAr lifetime of $\tau_{ele} \approx$ 21 ms previously observed with a ~100 litres prototype.

τ_{ele} exceeding 12 ms



ICARUS has demonstrated the effectiveness of the single phase LAr-TPC technique, paving the way to huge detectors/~5 m drift as required for LBNE project

Search for v disappearance

- Poor information available for v_{μ} disappearance, although they may eventually present the same effect as Reactor and Gallium anomalies.
- T600@LNGS can explore ν_{μ} disappearance with $~\approx$ 2000 neutrino interactions using the CNGS muon monitors as reference.
- Ongoing studies to estimate all relevant quantities and their systematics
- Beam calculation: production and focusing
- Proton beam monitors : recalibrated to 2% by CERN team
- Muon monitors: new field map, calibration checks ongoing
- Uncertainties on neutrino cross sections
- Spill by spill corrections for (small) horn/reflector instabilities
- Trigger system efficiency (see later)
- Selection efficiency & possible contamination from interactions in inactive materials: data and MC scanning ongoing SPSC



Horn/reflector current

2000

1000

0

0.31

0.315

0.32

0.325

0.33

0.335

0.34

0.345

Charge/pot

- The measured current in the CNGS Horns varies slightly
- Between the two spills of the same extraction
- From time to time
- Variations are seen in the muon monitors
- Corrections to event rate needed
- During a short period in 2011, currents lower than nominal were set due to hardware problems
- Check of the simulation and basis for the corrections to event rate



0.35

Horn/reflector current

- Nominal currents: Horn 150kA, reflector 180 kA
 - Two short periods with Horn 120, reflector 180 Horn 120, reflector 150
- Same conditions in MC
- Agreement within stats



Signal in 1st muon pit and neutrino rate relative to nominal current conditions



Systematics on neutrino cross sections



CNGS PMT trigger performance

- The main ICARUS CNGS trigger exploited the coincidence of PMT sum signal in each TPC with a 60 μs gate in correspondence of the proton spill extraction.
- A complementary trigger system based on wire signals (S-Daedalus) was implemented progressively during the run.
- PMT trigger efficiency was measured on samples of 2012 cosmic muons tracks at least 4 cm long triggered independently by S-Daedalus.



full PMT trigger efficiency for E_{dep} > 300 MeV in both T600 modules
 Packet-loss of "Early Warning" p extraction: 1.8% (2011) and 3.8% (2012).
 CNGS gate opening inefficiency: <0.1% due to spills at wrong predicted time.

Trigger manager system: dead-time ~ 2% in 2011 and < 0.1% in 2012.

2012 run: S-Daedalus trigger for CNGS events

- The S-Daedalus CNGS trigger was fired by TPC signal in Collection view in correspondence of each CNGS gate in absence of the PMT trigger signal.
- Performance was validated on $10^4 v_e CC$, v NC and $v_\mu CC$ Monte Carlo events. Distance of interaction vertex > 15 (5) cm from the upstream(downstream) borders of the active detector volume and 1.5 cm in the other directions.



A full efficiency down to ~ 0.3 GeV deposited energy is reached with the minimal requirement of 4 cm occupancy in one TPC (inefficiencies for CNGS events with E_{dep} < 300 MeV are limited to tracks travelling along the Collection wires direction)

Overall CNGS trigger efficiency: 2011

- The 2011 CNGS run was performed with a similar PMT trigger layout but without PMT waveform recording and improved electronics introduced to increase le scintillation light collection.
- The CNGS trigger performance has been determined by analyzing:
 - > Cosmic rays triggered by the coincidence of PMT sum signals in 2 adjacent chambers: no difference in cosmic ray spectrum between 2011 and 2012 was observed for E_{dep} > 1 GeV. This result is extendable to CNGS run, taking into account the uniformity of the PMT response with respect to event direction.
 - > CNGS spill standalone trigger: 100% (~99.4%) efficiency of 2011 PMT trigger for CNGS v interactions (μ from v interacting in surrounding rock) was measured with an independent CNGS spill standalone trigger on a limited event sample ($\approx 10^{19}$ pot)
 - > Neutrino interaction rate: agreement of the average rate of recorded v events between 2011 (3.4 \pm 0.1 per 10¹⁷ pot) and 2012 (3.5 \pm 0.1 per 10¹⁷ pot).

 \implies 100% efficiency for $E_{dep} > 1 \, GeV$

arXiv: 1405.7591 [ins-det] Submitted to JINST

Cosmic muons



- Prepare for the atmospheric v search
- Automatic 3D reco of cosmic μ
- Quality checks of the detector
- Control sample: MC with all detector effects (dead pmts, missing crates..) BUT assuming ϕ symmetry
- Data show evidence of mountain structure (being included in MC)



First applications of automatic reconstruction to real data



(color the same but there are 2 diff. violet clusters)

Collection

- Automatic tools: a must for the future of LAr
- 3D reco is ready, but needs 2D "objects"
- 2D "Segmentation" algorithm developed on MC
 - Test on CNGS events

REAL CNGS neutrino event

SPSC

Application of automatic reconstruction to rock muons

- Automatic reconstruction was applied to muons from external interactions, as practical application and as check of the algorithm: a total of almost 2000 events processed.
- A subset of 400 events have been scrutinized to investigate the causes for inefficiencies.
- Out of these, 31 events not reconstructed due to missing signals from some of the electronic crates (simple patches are under development): can be recovered
- and 36, that is less than 10% of the sample, for bad hit identification or ambiguities in the reconstruction.
- first "massive" application encouraging
- Work is in progress to further improve the performance (technical changes in hit finding etc)
- Full iterative coupling of the 2D segmentation and the 3D reconstruction to resolve ambiguities in the identification of tracks stage : ongoing.

What's next?

TPC Extraction & Transport

Stirling units and associated pipes/valves.. stored in containers ready for transport.

Activities dedicated to cryostat dismantling and opening started.

The wire chamber containers have been designed and ordered
 Procedures for the transport contracts well advanced



Hall B Virtual Top View



Both the OPERA barrack and the WArP clean room need to be removed to allow for the extraction of the TPCs

Next step: T600 at CERN

Bldg. 185 is being adapted to host the assembly of the TPCs in the new cold vessels.



The first of the two TPC transports is expected by September





Conclusions

ICARUS T600 detector has successfully completed the CNGS-2 experiment conclusively demonstrating that LAr-TPC is a leading technology for future short/long baseline accelerator driven neutrino physics.

- The accurate analysis of the CNGS events and the identification of 6 ve events provide no evidence of oscillation into sterile neutrinos in ICARUS L/E interval.
- The global fit of all SBL data + ICARUS limits the window of parameters for a possible LSND anomaly to a very narrow region around 0.5 eV².
- Muon p measurement by Multiple Scattering is achieved with ≈ 16% resolution in the momentum range of interest for future LAr TPCs.
- A remarkable LAr purity, exceeding 12 ms, has been measured opening the way for future large TPC detectors.
- Decommissioning procedures are advanced, preparing for transport and overhauling at CERN





e/ γ separation and π^0 reconstruction in ICARUS



Unique feature of LAr to distinguish e from γ and reconstruct π^{0} \Rightarrow Estimated bkg. from π^{0} in NC and v_{μ} CC: negligible