Neutrino Flavour Appearance at LNGS: Results and Perspectives

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Muon Flux
3.0 \(10^{-4}\) \(\mu m^{-2} s^{-1}\)

Neutron Flux
2.92 \(10^{-6}\) n cm\(^{-2}\) s\(^{-1}\) (0-1 keV)
0.86 \(10^{-6}\) n cm\(^{-2}\) s\(^{-1}\) (> 1 keV)

Depth: 1400 m (3800 m w.e.)
Surface: 17800 m\(^2\)
Volume: 180000 m\(^3\)

Rn in air: 20-80 Bq/m\(^3\)
ISO 14001
Ventilation: 1 Lab volume/3 h
Electrical power: 1300 kW
Access: horizontal
Research activities:

- Dark matter searches
- Neutrino physics
- Nuclear Astrophysics
- Associate Sciences:
  Environmental Radioactivity for Earth Sciences, Geophysics, Fundamental Physics, Biology
Neutrino Physics: open questions

- Solar, atmospheric, accelerator and reactor neutrino experiments show that the usual three active neutrinos have mass and that flavour mixing concerns the leptonic sector;
- Massive neutrinos are the only experimental evidence of phenomena beyond the SM of particle physics;
- The main goals of neutrino physics for the next decades:
  1. The determination of the neutrino mass hierarchy and the assessment and measurement of CP violation in the leptonic sector
     New scenarios opened by the recent measurements and the relative large value of $\theta_{13}$
  2. The discrimination of the Dirac/Majorana nature of neutrinos,
  3. Beyond 3 $\nu$ ??
- Neutrinos from cosmos are very important messengers for our comprehension of the stars and of the Universe evolution.
Basic neutrino properties
- $0\nu DBD$

Solar neutrinos (Borexino)
- $^7\text{Be}$ the main target
- $^8\text{B}$, $\text{pep}$ first evidence, $\text{CNO}$ limit, and possibly pp

Geo anti-neutrinos (Borexino)

SuperNova neutrinos
- LVD, Borexino and ICARUS
- LVD and Borexino are in the SNEWS network

Cern Neutrino Gran Sasso neutrinos
OPER A and ICARUS
CNGS beam:
CERN Neutrino to Gran Sasso

High Energy $\nu_\mu$ beam $\approx 17$ GeV:
optimized for $\nu_\tau$ CC interactions

Goal: prove definitely the neutrino oscillations in appearance mode

Project INFN-CERN: approved in 1999, started in 2006
$\nu_\mu$ beam produced at CERN and detected at LNGS
Experimental halls designed in the CERN direction

OPERA running since 2006
ICARUS running since 2010
• Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations by looking at the appearance of $\nu_\tau$ in a pure $\nu_\mu$ beam
• Search for the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations for $\Theta_{13}$ measurement
The direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations by looking at the appearance of $\nu_\tau$ implies opposite requirements to the detector:

- Large mass [O(kton)] due to small neutrino $\sigma \rightarrow$ lead target
- High granularity [1$\mu$] for clear identification of the “kink signal” and background rejection $\rightarrow$ nuclear emulsions
**OPERA Hybrid detector:**

- **Emulsion Cloud Chamber BRICKS**: Nuclear emulsion interleaved with lead plates
- Electronic detectors for trigger and pre-selection of candidate bricks and for time resolution to emulsions
- Magnet spectrometers for muon ID and momentum/charge measurement

**Hybrid target structure:**

- ECC brick
- Pb
- 1 mm
- Emulsion layers
- Electronic trackers
- Interface films (CS)
- Changeable Sheet thickness 3mm
### OPERA

<table>
<thead>
<tr>
<th>Counts for 22.5x10^{19} pot</th>
<th>Signal $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>New J. Phys. 14 (2012) 033017</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Proton On Target POT</th>
<th>Number of Neutrino Interactions</th>
<th>Integrated POT / Proposal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$1.78 \times 10^{19}$</td>
<td>1698</td>
<td>7.9%</td>
</tr>
<tr>
<td>2009</td>
<td>$3.52 \times 10^{19}$</td>
<td>3557</td>
<td>23.6%</td>
</tr>
<tr>
<td>2010</td>
<td>$4.04 \times 10^{19}$</td>
<td>3912</td>
<td>41.5%</td>
</tr>
<tr>
<td>2011</td>
<td>$4.84 \times 10^{19}$</td>
<td>4210</td>
<td>63.0%</td>
</tr>
<tr>
<td>2012</td>
<td>(~$4.7 \times 10^{19}$)</td>
<td>(~4050)</td>
<td>(~84%)</td>
</tr>
</tbody>
</table>

**Expected total POT after 2012 Run: $18.9 \times 10^{19}$**
In 2010 at LNGS the first evidence of direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode. Event found in the decay search of 2008 and 2009 Physics Runs (Phys. Lett. B 691 (2010) 138)
Neutrino Oscillations: OPERA

In 2012 the second $\nu_\tau$ candidate. Event taken on April 2011

Topology and reconstruction

$2000 \mu$m
OPERA second $\nu_\tau$ candidate: Layout of the event

Interaction Vertex in Lead plate with one Nuclear fragment

Decay point in Plastic Base No Nuclear fragment Flight length 1.54mm

Secondary Interaction in Emulsion With four Nuclear fragments
# Momentum measurement and particle identification of event tracks

<table>
<thead>
<tr>
<th>Track#</th>
<th>Momentum (1σ interval) [ GeV/c]</th>
<th>Particle ID</th>
<th>Method / Comments</th>
</tr>
</thead>
</table>
| Primary | 2.8 (2.1-3.5)                   | Hadron      | • Momentum-Range Consistency Check  
Stops after 2 brick walls. Imcompatible with muon (26÷44 brick walls) |
| d1     | 6.6 (5.2 - 8.6)                 | Hadron      | • Momentum-Range Consistency Check |
| d2     | 1.3 (1.1 -1.5)                  | Hadron      | • Momentum-Range Consistency Check |
| d3     | 2.0 (1.4 - 2.9)                 | Hadron      | Interaction in the Brick @ 1.3cm downstream |

Independent momentum measurements carried out in two labs
Satisfying the criteria for $\nu_\tau \rightarrow \tau \rightarrow 3\text{hadron decay}$
## OPERA status of the $\nu_\tau$ candidate search

<table>
<thead>
<tr>
<th>Years</th>
<th>Status</th>
<th># of events for Decay search</th>
<th>Expected $\nu_\tau$ (Preliminary)</th>
<th>Observed $\nu_\tau$ candidate events</th>
<th>Expected BG for $\nu_\tau$ (Preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-2009</td>
<td>Finished</td>
<td>2783</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2010-2011</td>
<td>In analysis</td>
<td>1343</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Started</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4126</td>
<td>2.1</td>
<td>2</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Neutrino Oscillations: OPERA $\nu_e$ search

Systematic $\nu_e$ search in $0\mu$ located events (NC-like) 2008 and 2009 Runs (5.3*10^{19} pot)

- Extrapolate primary tracks to CS
- Search for shower hints on CS
- If shower hints, open additional volume

$E_\nu = 15.6$ GeV
Event energy distribution

Expected events: oscillated $\nu_e$ 1.5, beam $\nu_e$ 19.2

Observed $\nu_e$: 19 events

After low-energy selection ($E_\nu < 20\text{GeV}$)

Expected events: oscillated $\nu_e$ 1.1, beam $\nu_e$ 3.7

Observed $\nu_e$: 4 events
OPERA $\nu_\mu \rightarrow \nu_\text{e}$ oscillation result

$\Delta m_{23}^2 = 2.45 \times 10^{-3}$
$\sin^2 \theta_{23} = 0.51$

1) Statistics will be Increased $\times 3$
2) Improvement of the efficiency
ICARUS T600 @ LNGS

Two identical modules
3.6 x 3.9 x 19.6 ≈ 275 m³ each
Liquid Ar active mass: ≈ 476 t

Conceived as a Multi-purpose detector: atmospheric, solar (>8 Mev), supernovae neutrinos, nucleon decay searches in “exotic” channels, CNGS beam

The most important Milestone towards a multi-kton LAr detector with unique imaging capability, and spatial/calorimetric resolutions

CNGS neutrino events

- 2012 detector live-time > 93%
- May 10th ÷ 24th 2012: timing measurement with bunched beam.
- 2010-2011 data sample (3.3 10¹⁹ pot)
  1091 neutrino interaction analyzed.
The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and e/π0 separation allow “to see” events in a new way.

The detector is collecting “bubble chamber like” CNGS events since October 2010: for \(10^{20}\) pot (expected until November 2012)
- CC event expected \(\approx\) 2800 ev
- NC event expected \(\approx\) 900 ev
- Muons from upstream GS rock \(\approx\) 12000 ev (\(\approx\) 8200 on TPC front face)
- Intrinsic beam \(v_e\) CC \(\approx\) 26 ev
- \(v_\mu\) => \(vt\) detecting \(\tau\) decay with kinematical criteria (\(\sim\) 2 event \(\tau\)-\(\rightarrow\)e).
- Search for sterile neutrinos in LSND parameter space, with e-like CC events excess at \(E > 10\text{GeV}\) (0 – 55 events CC depending on \(\theta\), max calculated for \(\Delta m^2 = 0.2\ \text{eV}^2\), \(\sin^2(2\theta) = 0.04\), bottom corner of exclusion)

The T600 is also collecting simultaneously “self triggered” events:
- \(\approx\) 100 ev/year of atmospheric \(v\) CC interactions.
- Proton decay with \(3 \times 10^{32}\) nucleons, zero bkg. in some of the channels.
The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and $e/\pi Z$ separation allow “to see” events in a new way.

The detector is collecting “bubble chamber like” CNGS events: for $10^{20}$ pot (beam until November 2012)

See Rubbia’s talk (Arxive 1209.0122)

- Search for sterile neutrinos in LSND parameter space, with $e$-like $CC$ events excess at $E > 10 GeV$ (0 - 55 events $CC$ depending on $\theta$, max calculated for $\Delta m^2 = 0.2 eV^2$, $\sin^2(2\theta)=0.04$, bottom corner of exclusion)

- The T600 is also collecting simultaneously “self triggered” events:
  - $\approx 100$ ev/year of atmospheric $\nu CC$ interactions.
  - Proton decay with $3 \times 10^{32}$ nucleons, zero bkg. in some of the channels.
Progress on data analysis in 2012

✓ CNGS events analysis ➔ ongoing
✓ Cosmic-ray analysis ➔ automatic reconstruction of deposited energy in agreement with expectations
✓ Development / optimization of analysis tools in terms of performance, calibrations and event reconstruction.

Progresses in:
• 3D reconstruction, leading to better performance especially for horizontal tracks
• Muon momentum measurement by M.S. under refinement
• Particle Identification Algorithm
• Automatic reconstruction: vertex finding, clustering, track finding
• Developments on tools for Calorimetric reconstruction
Cosmic Rays: \(\sim 130\) cosmic events/h

- Coincidence of PMT sum signals of two adjacent chambers (50% cathode transparency). Signal threshold \(\sim 100\) (200) phe West (East) cryostat
- CR data automatically filtered:
  - Skip fake triggers
  - Find "good" muons for purity
  - First reconstruction
- Exposure: 0.25 kton*year in 2011, expected total \(\sim 0.6\) kton*year by the end of 2012.

Good agreement of energy spectrum with MC expectation is found (MC simulation includes light collection and trigger conditions).

April-July 2012: 0.13 kton*year sample

Since March 2012 an additional trigger based on charge deposition on TPC wires is active to push forward the trigger performance at low energy (Super-Daedalus).
3D and calorimetric reco: real decaying kaon

REAL EXAMPLE FROM CNGS EVENT
Important for nucleon decay channels with K in final state

Corresponding PID patterns

Good PID performances

Improved 3D reco
Reconstruction in CNGS event

π⁰ - showers identified by
- 2γ conversion separated from primary vertex
- Reconstruction of γγ invariant mass
- Ionization in the first segment of showers (1 mip or 2 mips)

Mean: $133.8 \pm 4.4\text{(stat)} \pm 4\text{ (syst)}$ MeV/c²
σ = 20.5 MeV
Question marks:

1. Besides the $0\nu{\text{DBD}}$ search, will LNGS continue to play a significant role in the neutrino physics sector???
2. Will be there any space available in the future for new experiments ??
3. What about future experiments on the search for sterile neutrinos, LBL or atmospheric neutrinos ??
A proposal for a short baseline sterile neutrino search experiment in the Borexino detector has been submitted to the LNGS SC in April 2012

ν⁵¹Cr Source under the detector

Antiν¹⁴⁴Ce-¹⁴⁴Pr inside the detector

The proposal ICARUS -NESSiE:
Large mass LAr-TPC, now running @LNGS, moved to CERN
Complemented with magnetic spectrometers for the charge determination
 spacesss @ LNGS

Currently at underground Laboratory:
Since the end of the CNGS program (2013-2015), and before next decade, large underground space could be made available:
- the entire Hall B (110 m long, 17K m$^3$)
- there may be additional 40 m in Hall C

LNGS may host in future new detectors for neutrino physics searches. Enough underground space for:

1. $\approx (7-10)$ Kt Liquid Argon TPC detector

2. $\approx 100$ Kt magnetized iron scintillator detector
   See “Monolith” (13 x 14.5 x 30 m$^3$=34Kt)

For CPV and mass hierarchy with LBL and/or atmospheric $\nu$
New halls in the present site can hardly be excavated

LNGS-B proposal:
A shallow depth (1.2 Km w.e.) new laboratory
- 2 possible sites, 7-12 Km off axis CNGS
- Out of the protected area of the Gran Sasso Park
- Any presence of significant Uwater
- Contributions from Regional funds may be possible
NEW LABORATORY SECTION

Courtesy of Prof. Ing. Roberto Guercio - University of Rome “La Sapienza”
Towards a new Liquid Argon Imaging Chamber for the MODULAr project

The MODULAR detector

- Each gap is a scaled-up version of ICARUS (x 2.66^3):
  - 8 X 8 m^2 LAr cross section and about 60 m length
  - Two gaps within a same cryogenic volume: 10'740 ton
  - 4 m drift (2.66 ms), E_{drift} = 0.5 kV/cm, H.V.: -200 kV
  - 3-D imaging like ICARUS, 6 mm pitch (~50000 chs)
  - PM's will extract the trigger and timing LAr signal.

Courtesy of C. Rubbia
Daya Bay and RENO have recently observed a large $\theta_{13}$ neutrino mixing angle which confirms the early results from T2K, Double-Chooz and MINOS, as well as from global neutrino data analyses. This finding offers an unprecedented opportunity to study the leptonic mixing matrix with artificial neutrino beams, addressing the major challenges in this field, as the occurrence of CP violation in the leptonic sector, the determination of the neutrino mass hierarchy and the measurement of $\theta_{23}$.

The meeting will evaluate the experimental perspectives of such a “large $\theta_{13}$” scenario. The talks and discussions will target the opportunities offered by the existing and new facilities and in particular by the long-baseline experiments.

A principal aim was to clarify which type of neutrino beams, detectors and which laboratories are best suited to investigate the neutrino properties, in order to outline a realistic European roadmap for the next decade.
There is a possibility that the neutrino mass pattern might be measured in less than a decade with a significance of $\approx 3\sigma$ by a combination of the presently running experiments (T2K, MINOS, Double Chooz, Daya Bay, RENO) or going to take data (Nova). However, none of them guarantees a safe coverage of the CP-violation parameter space, especially for conservative assumptions on the performances of the facilities.

An ultimate answer well beyond $3\sigma$ for any value of CP phase requires a dedicated facility.

Many proposals on the floor:
HyperK, LBNE, LAGUNA-LBNO, PINGU, Daya Bay II

Besides the reactor experiments, the exploitation of matter effects remains the most promising approach to determine mass hierarchy.

The CERN-LNGS baseline is not well suited in this context.
ICAL@INO could also be able to determine mass hierarchy before 2025 irrespective to the CP value with a significance of $\approx 3\sigma$ under optimistic assumptions on the calorimeter resolutions.

At LNGS a $\approx 100$ Kt magnetized iron scintillator detector could be envisaged. However a significantly better granularity than ICAL@INO would be necessary to reach conclusive ($>3\sigma$) sensitivities on the mass pattern.
The assessment of CP violation and the precise measurement of $\delta$ is still a major challenge even in presence of the relative large value of $\theta_{13}$:

Three new projects on the floor: LAGUNA-LBNO, LBNE/LAr, Hyper-K

It’s well known that baselines in the approximate range of 1000 Km are well suited for CP violation

LNGS offer a baseline of 730Km for Superbeams from CERN and of 1500Km for a neutrino factory (RAL-LNGS)

The CERN-LNGS baseline hypothesis has been deeply analyzed during the NUTURN 2012 workshop @LNGS
Considered beams from CERN

- **off-axis** configurations: the SPS at 400 GeV
- **on-axis** configurations: a 50 GeV machine

Why? Using a 400 GeV p-driver it is difficult to efficiently populate the low energy region (see for example hep-ph/0609106v1)

We will show results as a function (MW Mt $10^7$s) thus allowing to "read" the combination of mass and beam needed to get a certain coverage.

Anyway we set some reasonable **benchmarks** to allow an easier "reading" of the plots:

- SPS at 400 GeV
  - $1.2 \times 10^{20}$ pot/year = 2.7 nominal CNGS ~ 770 kW + variable mass
  - Same pot/year as in the MODULAR study
- 50 GeV machine (as assumed in the context of LAGUNA):
  - $0.77 \rightarrow 2.4$ MW + 10 kt mass (could fit in existing LNGS)

We use a run sharing of: 5 years of $\nu$ + 5 years of anti-$\nu$
CPV coverage (off-axis 7 km 400 GeV)

5% systematic error on flux normalization 5ν + 5ν̄bar years

CP coverage at 3σ (%), 5+5 y, err.sys. = 0.05 OFFAXIS7

- Normal (known)
- Inverted (known)
- Normal (unknown)
- Inverted (unknown)

Benchmarks (vertical lines)
- 20 kt ⊗ 0.77 MW ⊗ 10 y ⇒ 5-10 %
- 30 kt ⊗ 0.77 MW ⊗ 10 y ⇒ 15-25 %
- 100 kt ⊗ 0.77 MW ⊗ 10 y ⇒ 40-50 %

• CPV: for each δ value claim 3σ discovery if the CP conserving cases (δ = 0, π) can be excluded (for both hypotheses on MH, unless it is assumed known)
CPV coverage (on-axis 50 GeV)

5% systematic error on flux normalization

5 ν + 5 ν̄ years

CP coverage at 3 σ (%), 5+5 y, err.sys. = 0.05 ONAXIS

Normal (known)
Inverted (known)
Normal (unknown)
Inverted (unknown)

Benchmarks (vertical lines):

10 kt ⊗ 0.77 MW ⊗ 10 y ⇒ 0 %
10 kt ⊗ 1.0 MW ⊗ 10 y ⇒ 0 %
10 kt ⊗ 2.4 MW ⊗ 10 y ⇒ 30-40 %

 Courtesy of Longhin
Comparison 2290 Km, 50 GeV p-driver ↔ 730 Km, 50 GeV p-driver

Courtesy of Longhin
Conclusions on LNGS perspectives

- After the end of the CNGS program (2013-2015), large underground space could be made available @LNGS

- LNGS-B: a shallow depth new laboratory can be envisaged

- New proposals on the floor:
  1. Search for sterile neutrino with Borexino
  2. Search for CPV with Modular

- A possible scenario CERN-LNGS-B, dedicated high power proton driver (2.4MW) and a very large LAr detector are worth further studies for CP violation