OPERA results on neutrino oscillations, cosmic rays and neutrino velocity
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2. The OPERA project and the CNGS

3. Data taking and results on neutrino oscillations

4. Cosmic-ray data and analysis

5. Neutrino velocity
   • Baseline measurements & Geodesy (➡ M. Crespi, A. Mazzoni)
   • Clock synchronization & timing
   • Data analysis and “the unexpected result”
   • The Day After: digesting the feedback from the scientific community

6. Conclusions and outlook
Why physicists care so much about **neutrinos**?

**Neutrino Physics**

**Past decades:**
- Key particles to understand “radioactivity” and build-up the electroweak theory
- Basic building-blocks of matter, 3 “lepton flavours” detected
- Not quite “elementary”, they MIX and thus they have (tiny) mass (**Neutrino Oscillations**)  

**Present issues:**
- Unique probes of fundamental processes (“beyond the Standard Model”)
- Messengers of the deep-inside stars (and planets) and early-stage collapsing objects (e.g. supernovae); relics of the primordial universe (Solar model, Astrophysics, Geoneutrinos, Cosmology, dark matter?)
- Properties still unknown: all mixing parameters, mass, mass hierarchy, Dirac/Majorana nature, CP-violation, any “sterile” partner…

**Electromagnetic radiation (including “visible light”)**

**Atoms**
- Nuclei
- Protons, Neutrons

**Radioactivity**
Natural neutrino sources...

Supernova Neutrinos (~10 MeV)
Relic “Big-Bang” Neutrinos (250 meV)
Nuclear reactors

Reactors = only source of a pure anti-neutrino beam, pure electron-flavor beam!
Anti-neutrinos are emitted by the radioactive fissile products when they disintegrate via beta decay (~few MeV Energy)

Accelerators

Main process: $\pi, K \rightarrow \mu + \nu_\mu$
$\nu_e$ contamination from muon decay & K
...A price to pay to “enjoy” neutrinos: HUGE detectors needed!...

...e.g. ν mixing & “oscillations”

OPERA: first direct detection of neutrino oscillations in ντ appearance mode following the Super-Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams.

The **PMNS** 3-flavor oscillation formalism predicts:

\[
P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(\Delta m^2_{23} L/4E)
\]

Requirements:

1) ~”pure” νμ beam, 2) long baseline, 3) high neutrino energy, 4) high beam intensity, 5) detect short lived τ’s
Oscillation Project with Emulsion tRacking Apparatus

Provide a direct evidence of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation
look for $\nu_\tau$ appearance in a pure $\nu_\mu$ beam

“hybrid” detector with ECC target

beam: CNGS

<table>
<thead>
<tr>
<th>$\langle E_\nu \rangle$</th>
<th>17 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\nu_\mu + \bar{\nu}<em>\mu)/\nu</em>\mu$</td>
<td>0.87%</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu / \nu</em>\mu$</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>negligible</td>
</tr>
</tbody>
</table>

At the given distance (732 Km), $\nu_\mu$ flux optimized to maximize the $\nu_\tau$ charged current interactions
$<L/E> = 43$ Km/GeV

$\nu_\mu$ oscillation

$\nu_\tau$ decay “kink”

$\nu_\mu$ $\rightarrow$ $\nu_\tau$, $\tau^-$ $\rightarrow$ $\mu^-$, $h^-$, $e^-$

Hybrid technique: tracking apparatus with “many” Emulsion Cloud Chamber target units

- Long-baseline, flavour oscillation: small fraction of $\nu_\tau$:
  Far-away source, low flux, weak interaction:
  → large target mass required (as usual for $\nu$s ...)

- CC interactions of $\nu_\tau$ tagged by the $\tau$ decay ($c = 87 \mu$m):
  → need high spatial resolution & lepton Id
  (background rejection, including charm production and decay)

Hybrid technique: tracking apparatus with “many” Emulsion Cloud Chamber target units

$CNGS < E_{\nu_\mu} > 17$ GeV ($\nu_\mu + \bar{\nu}_\mu$)

$\frac{\bar{\nu}_\mu}{\nu_\mu} = 2.1%$

$\nu_\tau$ prompt negligible

At the given distance (732 Km), $\nu_\mu$ flux optimized to maximize the $\nu_\tau$ charged current interactions
$<L/E> = 43$ Km/GeV

$\Delta m^2 = 3 \times 10^{-3} eV^2$

$P_{\nu_\mu} \sigma_{CC}$ (arbitrary units)

$\nu_\mu$ oscillation

$\nu_\tau$ decay “kink”

$\nu_\mu \rightarrow \nu_\tau$, $\tau^- \rightarrow \mu^-$, $h^-$, $e^-$

$\tau^- :$ $\mu^-$, $\nu_\tau$, $\bar{\nu}_\mu$ (17.4%)
$e^-$, $\nu_\tau$, $\bar{\nu}_e$ (17.8%)
$h^-$, $\nu_\tau$, $n\pi^0$ (49.5%)
$\pi^0$, $\pi^-$, $\pi^-$, $\nu_\tau$, $n\pi^0$ (14.5%)

Kink

Multiprong

Dept. Of Physics – Sapienza University
The OPERA Collaboration
160 physicists, 30 institutions, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
LNGS Assergi
Bari
Bologna
LNF Frascati
L’Aquila
Naples
Padova
Rome
Salerno

Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

http://operaweb.lngs.infn.it/scientists/?lang=en
Detector overview

Modular, Hybrid Detector:
Two supermodules, each consisting of
- **Target Section** (total target mass: 1.25 kton)
  31 Target Tracker modules (scintillator strips) & Walls of target units *(ECC bricks)*
- **Magnetic Spectrometer** (XPC, RPC, Drift tubes)
  - Upstream: VETO (glass RPC)
  - Both sides: Brick Manipulation System (BMS)
- Data Taking:
  1. LNGS DAQ: ethernet nodes + time stamp
  2. Emulsion scanning [Europe and Japan]
     ... & several facilities for brick & emulsion film handling

Hall C
Gran Sasso Lab

CNGS beam

SM1

SM2

Veto

Target tracker Spectrometer

BMS
Extract brick and CS, scan CS. Confirm the event in the brick. Develop brick: ship to scanning labs.

A “hybrid”, complex experiment...

12.5x10.2 cm², 8 cm thick, 8.4 kg, 10 X₀ (94% Pb)

~ 9x10⁶ Emulsion films in OPERA, and as many Pb sheets...

150,000 Bricks in OPERA (“brick”= ECC target unit)
Most of them are $\nu_\mu$ induced “charged current” (CC) or “neutral current (NC) events

$\nu \rightarrow \mu^-$

$W^+$

$d \rightarrow u$

$u \rightarrow u$

$\nu \rightarrow \nu$

$Z^0$

$d \rightarrow d$

$u \rightarrow u$

...but a few $\nu_e$ and some rare $\nu_\tau$ may be hidden inside each event: catch them!

Event classification: “with muon/ muonless”
Lepton flavour unveiled (CC only!) after emulsion plate scanning and measurements ...

Example 1: a muon-neutrino, with a short-lived “charmed” particle produced
Lepton flavour unveiled (CC only!) after *emulsion plate scanning and measurements* ...

*Example 2: an electron-neutrino identified by its “e.m. showering”*
Lepton flavour unveiled (CC only!) after *emulsion plate scanning and measurements* ... 

Example 3: “the” tau-neutrino event caught by its decay topology and... the many checks done


Dept. Of Physics – Sapienza University
### Status of CNGS data taking: “protons on target” (p.o.t.)

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam days</th>
<th># p.o.t.*</th>
<th>SPS eff.</th>
<th>Events in the bricks</th>
<th>Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td></td>
<td>0.082 x 10^{19}</td>
<td></td>
<td>38</td>
<td>commissioning</td>
</tr>
<tr>
<td>2008</td>
<td>123</td>
<td>1.78 x 10^{19}</td>
<td>61%</td>
<td>1698</td>
<td>Physics runs</td>
</tr>
<tr>
<td>2009</td>
<td>155</td>
<td>3.52 x 10^{19}</td>
<td>70%</td>
<td>3693</td>
<td>Physics runs</td>
</tr>
<tr>
<td>2010</td>
<td>187</td>
<td>4.04 x 10^{19}</td>
<td>81%</td>
<td>4248</td>
<td>Physics runs</td>
</tr>
</tbody>
</table>

+ **2011 run in good progress**

(4.55 x 10^{19} p.o.t. as of October 10th)

...hope same performance in **2012**

(\sim 2 x 10^{20} p.o.t., overall, 20,000 events in the bricks)
**Status of the oscillation analysis**

Analysis of 2008-2009 runs ~ completed
arXiv-1107.2594v1 – submitted

<table>
<thead>
<tr>
<th></th>
<th>0mu</th>
<th>1mu</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events predicted by the electronic detector</td>
<td>1503</td>
<td>3752</td>
<td>5255</td>
</tr>
<tr>
<td>Interactions located in ECC</td>
<td>519</td>
<td>2280</td>
<td>2799</td>
</tr>
<tr>
<td>Located in dead material</td>
<td>54</td>
<td>245</td>
<td>299</td>
</tr>
<tr>
<td>Decay search performed</td>
<td>494</td>
<td>2244</td>
<td>2738</td>
</tr>
</tbody>
</table>

**Charm events as a control sample (data versus MC)**

<table>
<thead>
<tr>
<th>Topology</th>
<th>Observed events</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charm</td>
<td>Background</td>
</tr>
<tr>
<td>Charged 1-prong</td>
<td>13</td>
<td>15.9</td>
</tr>
<tr>
<td>Neutral 2-prong</td>
<td>18</td>
<td>15.7</td>
</tr>
<tr>
<td>Charged 3-prong</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>Neutral 4-prong</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td>39</td>
<td>39.1±7.5</td>
</tr>
</tbody>
</table>
Status of the oscillation analysis

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Number of signal events expected for 22.5 × 10^{19} p.o.t.</th>
<th>Analysed sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau \to \mu)</td>
<td>1.79</td>
<td>0.39</td>
</tr>
<tr>
<td>(\tau \to e)</td>
<td>2.89</td>
<td>0.63</td>
</tr>
<tr>
<td>(\tau \to h)</td>
<td>2.25</td>
<td>0.49</td>
</tr>
<tr>
<td>(\tau \to 3h)</td>
<td>0.71</td>
<td>0.15</td>
</tr>
<tr>
<td>Total</td>
<td>7.63</td>
<td>1.65</td>
</tr>
</tbody>
</table>

One \(\nu_\tau\) candidate observed in the \(\tau \to h\) channel

\leftrightarrow Expected signal events

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Number of background events for: 22.5 × 10^{19} p.o.t.</th>
<th>Analysed sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charm Hadron Muon Total</td>
<td>Charm Hadron Muon Total</td>
</tr>
<tr>
<td>(\tau \to \mu)</td>
<td>0.025 0.00 0.07 0.09±0.04</td>
<td>0.00 0.00 0.02 0.02±0.01</td>
</tr>
<tr>
<td>(\tau \to e)</td>
<td>0.22 0 0 0.22±0.05</td>
<td>0.05 0 0 0.05±0.01</td>
</tr>
<tr>
<td>(\tau \to h)</td>
<td>0.14 0.11 0 0.24±0.06</td>
<td>0.03 0.02 0 0.05±0.01</td>
</tr>
<tr>
<td>(\tau \to 3h)</td>
<td>0.18 0 0 0.18±0.04</td>
<td>0.04 0 0 0.04±0.01</td>
</tr>
<tr>
<td>Total</td>
<td>0.55 0.11 0.07 0.73±0.15</td>
<td>0.12 0.02 0.02 0.16±0.03</td>
</tr>
</tbody>
</table>

Background re-evaluated

Sept. 2011 update (+1000 ev, 2010 run): 52 charm candidates, 20 \(\nu_e\) candidates, 1 \(\nu_\tau\) candidate

Speed-up of tau search with “wise cuts” & electron-neutrino study in progress
Cosmic-ray Data in OPERA (muons reaching the underground detector)


Preliminary analysis of new data recently released
1454057 $\mu$ collected during
2008-2009-2010 CNGS runs
 corresponding to 407.1 days of livetime

Presented by M. Sioli at the TAUP 2011 Conference
Cosmic-ray Data in OPERA

\[ R_{\mu} \text{ measurements with } E_{\mu} \cos \theta^* > 1 \text{ TeV} \]

Drop observed after \( \pi/K \) rise. Speculation on the possible physical nature:
- Sudden change in the n/p ratio in the all-nucleon spectrum?
- Strong scaling violation in the forward fragmentation region for \( \pi/K \) mesons?
- Upraise of a new muon component?
Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

We profited from the collaboration of individuals and groups that worked with us for the various metrology measurements reported here:

CERN: CNGS, Survey, Timing and PS groups

The geodesy group of the Università Sapienza of Rome

The Swiss Institute of Metrology (METAS)

The German Institute of Metrology (PTB)

T. Adam et al. [OPERA Collaboration]
“Measurement of the neutrino velocity with the OPERA detector in the CNGS beam
ArXiv:1109.4897 [hep-ex]
Past experimental results

FNAL experiment (Phys. Rev. Lett. 43 (1979) 1361)

high energy (E_ν > 30 GeV) short baseline experiment. Tested deviations down to |ν-c|/c ≤ 4×10^{-5} (comparison of muon-neutrino and muon velocities).

SN1987A (see e.g. Phys. Lett. B 201 (1988) 353)

electron (anti) neutrinos, 10 MeV range, 168’000 light years baseline.
|ν-c|/c ≤ 2×10^{-9}.
Performed with observation of neutrino and light arrival time.

MINOS (Phys. Rev. D 76 072005 2007)

muon neutrinos, 730 km baseline, E_ν peaking at ~3 GeV with a tail extending above 100 GeV.
(ν-c)/c = 5.1 ± 2.9×10^{-5} (1.8 σ).
**Principle of the neutrino velocity measurement**

Definition of neutrino velocity:

ratio of precisely measured baseline and time of flight

**Time of flight measurement:**

- tagging of neutrino production time
- tagging of neutrino interaction time by a far detector
- accurate determination of the baseline (geodesy)
- expected small effects: long baseline required
- adequate level of systematic errors reached
Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

\[ |T_{\text{OPERA}} - (T_{\text{Kicker}} + \text{TOFc})| < 20 \mu s \]

Synchronisation with standard GPS systems \(\sim 100\) ns (inadequate for our purposes)
Real time detection of neutrino interactions in target and in the rock surrounding OPERA
Geodesy at LNGS (➔ M. Crespi, A. Mazzoni)
Combination with CERN geodesy

CERN – LNGS measurements (different periods) combined in the ETRF2000 European Global system, accounting for earth dynamics (collaboration with CERN survey group)

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS1</td>
<td>4579518.745</td>
<td>1108193.650</td>
<td>4285874.215</td>
</tr>
<tr>
<td>GPS2</td>
<td>4579537.618</td>
<td>1108238.881</td>
<td>4285843.959</td>
</tr>
<tr>
<td>GPS3</td>
<td>4585824.371</td>
<td>1102829.275</td>
<td>4280651.125</td>
</tr>
<tr>
<td>GPS4</td>
<td>4585839.629</td>
<td>1102751.612</td>
<td>4280651.236</td>
</tr>
</tbody>
</table>

LNGS benchmarks in ETRF2000

Cross-check: simultaneous CERN-LNGS measurement of GPS benchmarks, June 2011

Resulting distance (BCT – OPERA reference frame)

\[(731278.0 \pm 0.2) \text{ m}\]
CNGS-OPERA synchronization

CERN

XLi GPS

GMT

CNGS

LNGS

ESAT 2000 GPS

PolaRx2e

Cs

Cs

PolaRx2e

Common View Mode

Common View Mode

DAQ Time Comparison (CTRI)

At CERN Every second

DAQ Time Comparison (CTRI)

At OPERA Every second

 Corrections

New system installed in 2008
Standard GPS receivers \(\sim 100\) ns accuracy:

- CERN Symmetricom XLI (source of General Machine Timing)
- LNGS: ESAT 2000

2008: installation of a twin high accuracy system calibrated by METAS (Swiss metrology institute)
- Septentrio GPS PolaRx2e + Symmetricom Cs-4000

PolaRx2e:

- Frequency reference from Cs clock
- Internal time tagging of 1PPS with respect to individual satellite observations
- Offline common-view analysis in CGGTTS format
- Use ionosphere free P3 code

Standard technique for high accuracy time transfer

Permanent time link (\(\sim 1\) ns) between reference points at CERN and OPERA
GPS common-view mode

Standard GPS operation:
resolves $x, y, z, t$ with $\geq 4$ satellite observations

Common-view mode (the same satellite for the two sites, for each comparison):

$x, y, z$ known from former dedicated measurements: determine time differences of local clocks (both sites) w.r.t. the satellite, by offline data exchange

$730 \text{ km} \ll 20000 \text{ km}$ (satellite height) $\rightarrow$ similar paths in ionosphere
Result: TOF time-link correction (event by event)
CERN-OPERA inter-calibration cross-check

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt

High accuracy/stability portable time-transfer setup @ CERN and LNGS

GTR50 GPS receiver, thermalised, external Cs frequency source, embedded Time Interval Counter

Correction to the time-link:
\[ t_{\text{CERN}} - t_{\text{OPERA}} = (2.3 \pm 0.9) \text{ ns} \]
THE STARTER: the CNGS neutrino beam

- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5 μs extractions (by kicker magnet) separated by 50 ms
- Beam intensity: $2.4 \times 10^{13}$ proton/extraction
- ~ pure muon neutrino beam ($<E> = 17$ GeV) travelling through the Earth’s crust
Proton spill shape

Reminiscence of the Continuous Turn extraction from PS (5 turns)
SPS circumference = 11 x PS circumference: SPS ring filled at 10/11
Shapes varying with time and both extractions

→ Precise accounting with WFD waveforms:
more accurate than: e.g. average neutrino distribution in a near detector
Proton pulse digitization:
- Acqiris DP110 1GS/s waveform digitizer (WFD)
- WFD triggered by a replica of the kicker signal
- Waveforms UTC-stamped and stored in CNGS database for offline analysis

Proton timing by Beam Current Transformer
- Fast BCT 400344 (~ 400 MHz)

2010 calibration with Cs clock
Typical waveform (2011)

Fourier analysis

200 MHz

(zoom)

(zoom)

5 ns
CNGS events selection

OPERA data: narrow peaks of the order of the spill width (10.5 µs)

Negligible cosmic-ray background: $O(10^{-4})$
Measurement of the neutrino event time distribution

Typical neutrino event time distributions in 2008 w.r.t kicker magnet trigger pulse:
1) Not flat
2) Different timing
   → Need to precisely measure the protons spills for first and second extraction
Neutrino event-time distribution PDF

- Each event is associated to its proton spill waveform
- The “parent” proton is unknown within the 10.5 μs extraction time

→ normalized waveform sum: PDF of predicted time distribution of neutrino events
→ compare to OPERA detected neutrino events

\[ \text{PDF} \]

Different timing w.r.t. kicker magnet signal
Time calibration techniques

• **Portable Cs-4000:**
  Comparison: time-tags vs 1PPS signal (Cs clock) at the start- and end-point of a timing chain

• **Double path fibers measurement:**
  by swapping Tx and Rx component of the opto-chain

### Portable Cs-4000

Comparison: time-tags vs 1PPS signal (Cs clock) at the start- and end-point of a timing chain.

#### Start

- **CS 1PPS**

#### End

- **CS 1PPS**

### Double Path Fibers Measurement

- **Start**
  - \( T_A \) ?
  - Optical fiber
  - \( T_B \) ?

- **End**
  - Measure \( T_A - T_B \)
  - \( T_A T_B \)

- **Start**
  - Measure \( T_A + T_B \)
  - Optical fiber
  - \( T_B \) ?

- **End**

---

Dept. Of Physics – Sapienza University
Continuous two-way measurement of UTC delay at CERN (variations w.r.t. nominal)
BCT calibration (1)

Dedicated beam experiment:

BCT plus two pick-ups (~1 ns) with LHC beam (12 bunches, 50 ns spacing)

\[ \Delta t_{\text{BCT}} = t_4 - t_3 = (580 \pm 5) \text{ ns} \]

\( t_3 \) : derived by \( t_1 - t_2 \) measurement and survey
result: signals comparison after $\Delta_{\text{BCT}}$ compensation
**Unknown neutrino production point:**

1) accurate UTC time-stamp of protons  
2) relativistic parent mesons (full FLUKA simulation)

\[ \Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c} \left( \frac{1}{\beta} - 1 \right) \approx \frac{z}{c} \frac{1}{2\gamma^2} \]

\[ \langle \Delta t \rangle = 1.4 \times 10^{-2} \text{ ns} \]
(+) → delays increasing $\delta t$
(-) → delays decreasing $\delta t$
The Target Tracker (TT)

- pre-location of neutrino interactions and **event timing**
- Extruded plastic scintillator strips (2.6 cm width)
- Light collections with WLS fibres
- Fibres read out at either side with multi-anode 64 pixels PMTs (H7546)

**Read out by 1 Front-End DAQ board per side**
Trigger-less, asynchronous Front-End nodes (1200); Gigabit Ethernet network
Clock distribution system (10 ns UTC event time-stamp granularity)

Mezzanine DAQ card common to all sub-detectors Front End nodes: CPU (embedded LINUX), Memory, FPGA, clock receiver and ethernet
Scintillator, WLS fibers, PMT, analog FE chip (ROC) up to FPGA trigger input

UV laser excitation:
→ delay from photo-cathode to FPGA input: 50.2 ± 2.3 ns

Average event time response: 59.6 ± 3.8 ns (sys)

(including position and p.h. dependence, ROC time-walk, DAQ quantization effects accounted by simulations)
<table>
<thead>
<tr>
<th>Item</th>
<th>Result</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN UTC distribution (GMT)</td>
<td>10085 ± 2 ns</td>
<td>• Portable Cs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Two-ways</td>
</tr>
<tr>
<td>WFD trigger</td>
<td>30 ± 1 ns</td>
<td>Scope</td>
</tr>
<tr>
<td>BTC delay</td>
<td>580 ± 5 ns</td>
<td>• Portable Cs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dedicated beam experiment</td>
</tr>
<tr>
<td>LNGS UTC distribution (fibers)</td>
<td>40996 ± 1 ns</td>
<td>• Two-ways</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Portable Cs</td>
</tr>
<tr>
<td>OPERA master clock distribution</td>
<td>4262.9 ± 1 ns</td>
<td>• Two-ways</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Portable Cs</td>
</tr>
<tr>
<td>FPGA latency, quantization curve</td>
<td>24.5 ± 1 ns</td>
<td>Scope vs DAQ delay scan (0.5 ns steps)</td>
</tr>
<tr>
<td>Target Tracker delay (Photocathode to FPGA)</td>
<td>50.2 ± 2.3 ns</td>
<td>UV picosecond laser</td>
</tr>
<tr>
<td>Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)</td>
<td>9.4 ± 3 ns</td>
<td>UV laser, time walk and photon arrival time parametrizations, full detector simulation</td>
</tr>
<tr>
<td>CERN-LNGS intercalibration</td>
<td>2.3 ± 1.7 ns</td>
<td>• METAS PolaRx calibration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• PTB direct measurement</td>
</tr>
</tbody>
</table>
Summary of the principle for the TOF measurement

Measure $\delta t = \text{TOF}_c - \text{TOF}_\nu$
Event selection (earliest TT hit of the event as “stop”)

Statistics: 2009-2010-2011 CNGS runs (~$10^{20}$ pot)

Internal events:
Same selection procedure as for oscillation searches: **7586 events**

External events:
Rock interaction $\rightarrow$ require muon 3D track: **8525 events**
(Timing checked with full simulation, 2 ns systematic uncertainty by adding external events)

Data/MC agree for 1st hit timing (within systematics)
"INTERNAL" and "EXTERNAL" OPERA EVENTS

- $\nu_\mu$ CC
- NC

- $\mu$ from external interaction
Event time corrections

Time-link correction (blue points)

Correction due to the earliest hit position

average correction: 140 cm (4.7 ns)
Analysis method

For each neutrino event in OPERA → proton extraction waveform

Sum up and normalise: → PDF w(t) → separate likelihood for each extraction

\[ L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \quad k=1,2 \text{ extractions} \]

Maximised versus \( \delta t \):

\( \delta t = \text{TOF}_c - \text{TOF}_\nu \)

Positive (negative) \( \delta t \) → neutrinos arrive earlier (later) than light

Statistical error evaluated from log likelihood curves
“Blind “ analysis

Analysis deliberately conducted by referring to the obsolete timing of 2006:

1) Wrong baseline, referred to an upstream BCT in the SPS, ignoring accurate geodesy
2) Ignoring TT and DAQ time response in OPERA
3) Using old GPS inter-calibration prior to the time-link
4) Ignoring the BCT and WFD delays
5) Ignoring UTC calibrations at CERN

→ Resulting $\delta t$ by construction much larger than individual calibration contributions $\sim 1000$ ns
→ “Box” opened once all correction contributions reached satisfactory accuracy
Data vs PDF: before and after likelihood result

\[(\text{BLIND}) \delta t = \text{TOF}_c - \text{TOF}_v = (1048.5 \pm 6.9) \text{ ns (stat)}\]

\[\chi^2 / \text{ndof} :\]

first extraction: 1.06
second extraction: 1.12
Zoom on the extractions leading and trailing edges

First extraction
$\delta t=1048.5$ ns

Second extraction
$\delta t=1048.5$ ns

Events/50 ns

(ns)

Events/50 ns

(ns)
Analysis cross-checks

1) Coherence among CNGS runs/extractions

2) No hint for e.g. day-night or seasonal effects:

|d-n|: $(17.1 \pm 15.5)$ ns

|(spring+fall) – summer|: $(11.3 \pm 14.3)$ ns

3) Internal vs external events:

All events: $\delta t$ (blind) = $TOF_c - TOF_\nu$ = $(1048.5 \pm 6.9 \text{ (stat.)})$ ns

Internal events only: $(1047.4 \pm 11.2 \text{ (stat.)})$ ns
### Opening the box

**Timing and baseline corrections**

<table>
<thead>
<tr>
<th>Blind 2006</th>
<th>Final analysis</th>
<th>Correction (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (ns)</td>
<td>2440079.6</td>
<td>2439280.9</td>
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<tr>
<td>Correction baseline</td>
<td></td>
<td>-798.7</td>
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<tr>
<td>CNGS DELAYS:</td>
<td></td>
<td></td>
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<tr>
<td>UTC calibration (ns)</td>
<td>10092.2</td>
<td>10085</td>
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<tr>
<td>Correction UTC</td>
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<td>-7.2</td>
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<td>WFD (ns)</td>
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<td>Correction WFD</td>
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<td>BCT (ns)</td>
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<tr>
<td>Correction BCT</td>
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<td>-580</td>
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<tr>
<td>OPERA DELAYS:</td>
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<td></td>
</tr>
<tr>
<td>TT response (ns)</td>
<td>0</td>
<td>59.6</td>
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<tr>
<td>FPGA (ns)</td>
<td>0</td>
<td>-24.5</td>
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<tr>
<td>DAQ clock (ns)</td>
<td>-4245.2</td>
<td>-4262.9</td>
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<tr>
<td>Correction TT+FPGA+DAQ</td>
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<td>17.4</td>
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<tr>
<td>GPS synchronization (ns)</td>
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</tr>
<tr>
<td>Time-link (ns)</td>
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<tr>
<td>Correction GPS</td>
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<td>350.7</td>
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<tr>
<td>Total</td>
<td></td>
<td>-987.8</td>
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</table>

**Systematic uncertainties**

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (20 cm)</td>
<td>0.67</td>
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<tr>
<td>Decay point</td>
<td>0.2</td>
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<tr>
<td>Interaction point</td>
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<tr>
<td>UTC delay</td>
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<tr>
<td>LNGS fibres</td>
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<tr>
<td>DAQ clock transmission</td>
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<tr>
<td>FPGA calibration</td>
<td>1</td>
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<tr>
<td>FWD trigger delay</td>
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<tr>
<td>CNGS-OPERA GPS synchronization</td>
<td>1.7</td>
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<tr>
<td>MC simulation (TT timing)</td>
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<tr>
<td>TT time response</td>
<td>2.3</td>
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<tr>
<td>BCT calibration</td>
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<tr>
<td>Total uncertainty (in quadrature)</td>
<td>7.4</td>
</tr>
</tbody>
</table>
Results

For CNGS $\nu_\mu$ beam, $<E> = 17$ GeV:

$$\delta t = \text{TOF}_c - \text{TOF}_\nu =$$

$$(1048.5 \pm 6.9 \text{ (stat.)}) \text{ ns} - 987.8 \text{ ns} = (60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)}) \text{ ns}$$

relative difference of neutrino velocity w.r.t. $c$:

$$(\nu - c)/c = \delta t / (\text{TOF}_c - \delta t) = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$$

$(730085 \text{ m used as neutrino baseline from parent mesons average decay point})$

$6.0 \sigma \text{ significance}$
Study of the energy dependence

- Only internal muon-neutrino CC events used for energy measurement (5489 events)

\[ E = E_\mu + E_{\text{had}} \]

- Full MC simulation: no energy bias in detector time response (<1 ns)
  → systematic errors cancel out

\[ \delta t = \text{TOF}_c - \text{TOF}_\nu = (60.3 \pm 13.1 \text{ (stat.)} \pm 7.4 \text{ (sys.)}) \text{ ns for } \langle E_\nu \rangle = 28.1 \text{ GeV} \]

(result limited to events with measured energy)
No clues for energy dependence within the present sensitivity in the energy domain explored by the measurement.
Conclusions (1)

• The OPERA detector at LNGS in the CERN CNGS muon neutrino beam has allowed the most sensitive terrestrial measurement of the neutrino velocity over a baseline of about 730 km.

• The measurement profited of the large statistics accumulated by OPERA (~16000 events), of a dedicated upgrade of the CNGS and OPERA timing systems, of an accurate geodesy campaign and of a series of calibration measurements conducted with different and complementary techniques.

• The analysis of data from the 2009, 2010 and 2011 CNGS runs was carried out to measure the neutrino time of flight. For CNGS muon neutrinos travelling through the Earth’s crust with an average energy of 17 GeV the results of the analysis indicate an early neutrino arrival time with respect to the one computed by assuming the speed of light:

\[
\delta t = \text{TOF}_c - \text{TOF}_\nu = (60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)}) \text{ ns}
\]

• We cannot explain the observed effect in terms of known systematic uncertainties. Therefore, the measurement indicates a neutrino velocity higher than the speed of light:

\[
\frac{(v-c)}{c} = \frac{\delta t}{\text{TOF}_c - \delta t} = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}
\]

with an overall significance of 6.0 σ.
Conclusions (2)

• A possible $\delta t$ energy dependence was also investigated. In the energy domain covered by the CNGS beam and within the statistical accuracy of the measurement we do not observe any significant effect.

• Despite the large significance of the measurement reported here and the stability of the analysis, the potentially great impact of the result motivates the continuation of our studies in order to identify any still unknown systematic effect.

• We do not attempt any theoretical or phenomenological interpretation of the results.
Results scrutinized worldwide by the scientific community

Apart from “skepticism” and “irony”, many valuable hints to improve/clarify the issue

Questions about geodesy, time synchronization, calibration methods ~answered

Main concern (and crucial point): rely on BCT timing and the corresponding reference PDF. Further analysis in progress

The “anomaly” till now survived, but unknown systematics could still be there

Interesting experimental follow-up envisaged by MINOS, T2K, and CNGS itself (e.g. Pulsed beam operation, muon pit monitoring, OPERA checks with RPC etc.)

I do not feel allowed to “hope it is true” or “do not believe by prejudice”: mostly I’m CURIOUS to see the outcome, and I’ll stick to the experimental protocol [do (accurate) measurements, estimate systematics and statistical errors, and make results PUBLIC]
More news to follow ….

Thank you for coming!