Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

Giulia Brunetti
LHEP – Bern University
On behalf of the OPERA Collaboration
<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>IIHE-ULB Brussels</td>
</tr>
<tr>
<td>Croatia</td>
<td>IRB Zagreb</td>
</tr>
<tr>
<td>France</td>
<td>LAPP Annecy, IPNL Lyon, IPHC Strasbourg</td>
</tr>
<tr>
<td>Germany</td>
<td>Hamburg</td>
</tr>
<tr>
<td>Israel</td>
<td>Technion Haifa</td>
</tr>
<tr>
<td>Italy</td>
<td>LNGS Assergi, Bari, Bologna, LNF Frascati, L’Aquila, Naples, Padova, Rome, Salerno</td>
</tr>
<tr>
<td>Korea</td>
<td>Jinju</td>
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<tr>
<td>Russia</td>
<td>INR RAS Moscow, LPI RAS Moscow, ITEP Moscow, SINP MSU Moscow, JINR Dubna</td>
</tr>
<tr>
<td>Japan</td>
<td>Aichi, Toho, Kobe, Nagoya, Utsunomiya</td>
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<tr>
<td>Switzerland</td>
<td>Bern, ETH Zurich</td>
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<tr>
<td>Turkey</td>
<td>METU Ankara</td>
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</tbody>
</table>

The OPERA Collaboration
160 physicists, 30 institutions, 11 countries

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

blind analysis: “box” opened after adequate level of systematic errors was reached
Past experimental results

FNAL experiment \((\text{Phys. Rev. Lett. 43 (1979) 1361})\)

high energy \((E_\nu > 30 \text{ GeV})\) short baseline experiment. Tested deviations down to \(|v-c|/c \leq 4 \times 10^{-5}\) (comparison of muon-neutrino and muon velocities).

SN1987A (see e.g. \text{Phys. Lett. B 201 (1988) 353})

electron (anti) neutrinos, 10 MeV range, 168’000 light years baseline. 

\(|v-c|/c \leq 2 \times 10^{-9}\).

Performed with observation of neutrino and light arrival time.

MINOS \((\text{Phys. Rev. D 76 072005 2007})\)

muon neutrinos, 730 km baseline, \(E_\nu\) peaking at \(~3 \text{ GeV}\) with a tail extending above 100 GeV.

\((v-c)/c = 5.1 \pm 2.9 \times 10^{-5} \text{ (1.8 } \sigma)\).
THE DESIGN OF THE OPERA EXPERIMENT

ECC BRICKS + ELECTRONIC DETECTORS FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATION STUDIES

$\nu_\mu$ beam

ECC brick

1 mm

$\nu_\tau$

emulsion layers

interface films (CS)

electronics trackers

Pb

$\tau$
THE IMPLEMENTATION OF THE PRINCIPLE

Target area

Muon spectrometer

G. Brunetti - AEC - 07/12/2011

G. Brunetti - EPFL 28.11.2011
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)
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
“INTERNAL” and “EXTERNAL” OPERA EVENTS

νμ CC

μ from external interaction

NC
The LNGS underground physics laboratory

CERN

LNGS

730 km

1400 m

CNGS

OPERA
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
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 ~100 ns (inadequate for our purposes)
Real time detection of neutrino interactions in target and in the rock surrounding OPERA
CNGS events selection

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

Negligible cosmic-ray background: $O(10^{-4})$

Selection procedure kept unchanged since first events in 2006
OPERA sensitivity

- High neutrino energy - high statistics ~15000 events
- Precise measurement of neutrino time distribution at CERN through proton waveforms
- Sophisticated timing system: ~1 ns CNGS-OPERA synchronisation
- Accurate calibrations of CNGS and OPERA timing chains: ~1 ns level
- Measurement of baseline by global geodesy: 20 cm accuracy over 730 km

→ Result: ~10 ns overall accuracy on TOF with similar stat. and sys. errors
Typical neutrino event time distributions in 2008 w.r.t kicker magnet trigger pulse:

1) Not flat
2) Different timing for first and second extraction

→ Need to precisely measure the protons spills
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)
Typical waveform (2011)

Fourier analysis

200 MHz

(zoom)

5 ns

(zoom)
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
GPS clocks at LNGS w.r.t. Cs clock:

1) Large oscillations
2) Uncertainties on CERN-OPERA synchronisation

→ Need accurate time synchronisation system

Collaboration with CERN timing team since 2003

Major upgrade in 2008
CNGS-OPERA synchronization

New system installed in 2008
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 km $<<$ 20000 km (satellite height) $\rightarrow$ similar paths in ionosphere

Standard technique for high accuracy time transfer

Permanent time link (~1 ns) between reference points at CERN and OPERA
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:

\[ t_{\text{CERN}} - t_{\text{OPERA}} = (2.3 \pm 0.9) \text{ ns} \]
Geodesy at LNGS

Dedicated measurements at LNGS: July-Sept. 2010 (Rome Sapienza Geodesy group)

2 new GPS benchmarks on each side of the 10 km highway tunnel

GPS measurements ported underground to OPERA
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>
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<tr>
<td>GPS3</td>
<td>4585824.371</td>
<td>1102829.275</td>
<td>4280651.125</td>
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<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)

\[(731278.0 \pm 0.2) \text{ m}\]
The GPS distance scale is cross-checked with the ones of other space geodesy techniques:
- VLBI: Signals from Quasars
- SLR: Optical and near-infrared signals

Overall the scale consistency of the ETRF is at level of 1 part per $10^{-9}$
Monitor continent drift and important geological events (e.g. 2009 earthquake)
Geodesy: Tidal effects

Tidal effects were automatically compensated in the GPS measurements by the analysis software → measurements at different epochs directly comparable.

The effects can go up to a max of ~2 cm.

→ Integration of the effects by the same software on the 3 periods of data taking in order to precisely evaluate the average effect (negligible)
Timing, General relativity, composition of movements in non inertial frames

• Schwartzshild geodesics
  - Earth’s gravitational effect: $10^{-8}$
  - Non inertial effects due to the Moon, Sun and Milky Way: extra-suppression wrt to the previous one of $10^{-3}$, $10^{-6}$ and $10^{-15}$, respectively
  - Local red-shift correction to the clocks: $10^{-13}$

• Frame dragging effect: negligible

• Sagnac effect due to the Earth rotation non negligible: see next slide
Sagnac effect

It accounts for the displacement of the OPERA detector point during the neutrino TOF due to the Earth rotation.

Note that neutrinos move from NW (CERN) to SE (LNGS) and the Earth rotates towards E.

Therefore the Earth rotation causes an increase of the distance wrt the geometric distance computed in ETRF.

It amounts to 66 cm, i.e. to a TOF of 2.2 ns.
Summary of the principle for the TOF measurement

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

G. Brunetti - EPFL 28.11.2011
G. Brunetti - AEC - 07/12/2011
Continuous two-way measurement of UTC delay at CERN (variations w.r.t. nominal)

± 0.4 ns

July 2011

Technical stop (no data)
(+) → delays increasing $\delta t$
(-) → delays decreasing $\delta t$
## Delay calibrations summary

<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>
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
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

$$\delta t = \text{TOF}_c - \text{TOF}_\nu = (1043.4 \pm 7.8) \text{ ns (stat)}$$

$$\chi^2 / \text{ndof} :$$

first extraction: 1.1  
second extraction: 1.0
Zoom on the extractions leading and trailing edges

Fitting separately different parts of the WF the result does not change
Check of the PDF and neutrino time distributions

- Kolmogorov-Smirnov test
  - 1st extraction: Prob=61.4%
  - 2nd extraction: Prob=99.0%

- Anderson-Darling test
  - 1st extraction: Prob=38%
  - 2nd extraction: Prob=51%

Residual of the data point wrt to the PDF
1) Coherence among CNGS runs/extractions

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

|d-n|: (16.4 ± 15.8) ns

|(spring+fall) – summer|: (15.6 ± 15.0) ns
Analysis cross-check (II)

3) Internal vs external events:

All events: $\delta t \text{ (blind)} = \text{TOF}_c - \text{TOF}_\nu = (1043.4 \pm 7.8 \text{ (stat.)})$ ns

Internal events only: $(1045.1 \pm 11.3 \text{ (stat.)})$ ns

4) Intensity Dependence

The absolute difference between the two bins is $(6.8 \pm 16.6)$ ns
Opening the box

timing and baseline corrections

<table>
<thead>
<tr>
<th>Blind 2006</th>
<th>Final analysis</th>
<th>Correction (ns)</th>
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</thead>
<tbody>
<tr>
<td>Baseline (ns)</td>
<td>2440079.6</td>
<td>2439280.9</td>
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<tr>
<td>Earth rotation (ns)</td>
<td>2.2</td>
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<tr>
<td>Correction baseline</td>
<td>-796.5</td>
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<tr>
<td>CNGS DELAYS :</td>
<td></td>
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<tr>
<td>UTC calibration (ns)</td>
<td>10092.2</td>
<td>10085</td>
</tr>
<tr>
<td>Correction UTC</td>
<td>-7.2</td>
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<tr>
<td>WFD (ns)</td>
<td>0</td>
<td>30</td>
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<tr>
<td>Correction WFD</td>
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<tr>
<td>BCT (ns)</td>
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<td>-580</td>
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<tr>
<td>Correction BCT</td>
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<td>OPERA DELAYS :</td>
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<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>
</tr>
<tr>
<td>Correction TT+FPGA+DAQ</td>
<td>17.4</td>
<td></td>
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<td>GPS synchronization (ns)</td>
<td>-353</td>
<td>0</td>
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<tr>
<td>Time-link (ns)</td>
<td>0</td>
<td>-2.3</td>
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<tr>
<td>Correction GPS</td>
<td>350.7</td>
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<tr>
<td>Total</td>
<td>-985.6</td>
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</table>

systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>ns</th>
<th>Error distribution</th>
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</thead>
<tbody>
<tr>
<td>Baseline (20 cm)</td>
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<td>Gaussian</td>
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<tr>
<td>Decay point</td>
<td>0.2</td>
<td>Exponential (1 side)</td>
</tr>
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<td>Interaction point</td>
<td>2.0</td>
<td>Flat (1 side)</td>
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<tr>
<td>UTC delay</td>
<td>2.0</td>
<td>Gaussian</td>
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<tr>
<td>LNGS fibres</td>
<td>1.0</td>
<td>Gaussian</td>
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<tr>
<td>DAQ clock transmission</td>
<td>1.0</td>
<td>Gaussian</td>
</tr>
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<td>FPGA calibration</td>
<td>1.0</td>
<td>Gaussian</td>
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<tr>
<td>FWD trigger delay</td>
<td>1.0</td>
<td>Gaussian</td>
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<td>CNGS-OPERA GPS synchronisation</td>
<td>1.7</td>
<td>Gaussian</td>
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<tr>
<td>MC simulation for TT timing</td>
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<td>Gaussian</td>
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<tr>
<td>TT time response</td>
<td>2.3</td>
<td>Gaussian</td>
</tr>
<tr>
<td>BCT calibration</td>
<td>5.0</td>
<td>Gaussian</td>
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</table>

Total systematic uncertainty | -5.9, +8.3 |
Results

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

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

$$(1043.4 \pm 7.8 \text{ (stat.)}) \text{ ns} - 985.6 \text{ ns} = (57.8 \pm 7.8 \text{ (stat.)})^{+8.3}_{-5.9} \text{(sys.)} \text{ ns}$$

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

$$\frac{\nu-c}{c} = \frac{\delta t}{\text{TOF}_c - \delta t} = (2.37 \pm 0.32 \text{ (stat.)})^{+0.34}_{-0.24} \text{(sys.)} \times 10^{-5}$$

(730085 m used as neutrino baseline from parent mesons average decay point)

$6.2 \sigma$ significance
Single wave-form analysis

For each neutrino event in OPERA → proton extraction waveform

Likelihood built by associating each neutrino interaction to its waveform instead of using the global PDF

\[
L(\delta t) = \prod_j w_j(t_j + \delta t)
\]

(BLIND) \(\delta t = \text{TOF}_c - \text{TOF}_\nu = (1040.1 \pm 5.0)\) ns (stat)

A systematic error of 4.4 ns is attributed to this result by comparing different filtering conditions and treatment of the waveform baselines.

It adds up to the systematic uncertainty quoted before

\[
\delta t = (54.5 \pm 5.0\) (stat.)^{+9.6}_{-7.2}\) (sys.)\) ns
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)
  \[ \delta t = \text{TOF}_c - \text{TOF}_v = (61.1 \pm 13.2 \text{ (stat.)} +7.3_{-6.9} \text{ (sys.)}) \text{ ns for } \langle E_\nu \rangle = 28.2 \text{ GeV} \]
  (result limited to events with measured energy)
Energy dependence

• The data have been split in two energy bins

• Bin 1 with \( \langle E_\nu \rangle = 13.8 \text{ GeV} \)
  – \( \delta t = (54.7 \pm 18.4 \text{ (stat.)} \, ^{+7.3}_{-6.9}(\text{sys.})) \text{ ns} \)

• Bin 2 with \( \langle E_\nu \rangle = 40.7 \text{ GeV} \)
  – \( \delta t = (68.1 \pm 19.1 \text{ (stat.)} \, ^{+7.3}_{-6.9}(\text{sys.})) \text{ ns} \)

No clues for energy dependence within the present sensitivity in the energy domain explored by the measurement
Short-bunch wide-spacing neutrino beam

4x10^{16} pot accumulated
Proton bunch-length 3ns
35 beam-related events
20 events selected
Results with the bunched-beam

\[ \delta t = (62.1 \pm 3.7 \text{ (stat.)}) \]

The systematic uncertainties are equal or smaller than those affecting the result with the nominal CNGS beam.

These result excludes biases affecting the PDF based analysis.
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 (~15000 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:

\[
\delta t = \text{TOF}_c - \text{TOF}_v = (57.8 \pm 7.8 \text{ (stat.)} ^{+8.3}_{-5.9} \text{ (sys.)}) \text{ ns}
\]

- 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:

\[
\frac{(\nu-c)}{c} = \frac{\delta t}{\text{TOF}_c - \delta t} = (2.37 \pm 0.32 \text{ (stat.)} ^{+0.34}_{-0.24} \text{ (sys.)}) \times 10^{-5}
\]

with an overall significance of 6.2 \(\sigma\).

- A likelihood built by associating each neutrino interaction to its waveform instead of using the global PDF gives \(\delta t = (54.5 \pm 5.0 \text{ (stat.)} ^{+9.6}_{-7.2} \text{ (sys.)}) \text{ ns}\).
• A dedicated CNGS beam was generated by a purposely setup SPS proton beam. It consisted of a single extraction including four bunches about 3 ns long (FWHM) separated by 524 ns. 20 events were retained, leading to a value of $\delta t$ measured from the average of the distribution of $(62.1 \pm 3.7)$ ns, in agreement with the value of $(57.8 \pm 7.8)$ ns obtained with the main analysis.

• 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.
Thank you for your attention