Do neutrinos travel faster than light ?

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A short explanation of the recent results by OPERA
Based mostly on arXiv:1109.4897[hep-ex]

Did neutrinos travel faster than light?

Outline

1. The experiment and its main purpose
2. How the speed of neutrinos was measured
   - Distance measurement
   - Time measurement
   - The analysis
   - Some cross-checks
3. Testing the result

Aim of OPERA: measuring neutrino oscillations

OPERA: first direct detection of neutrino oscillations in appearance mode

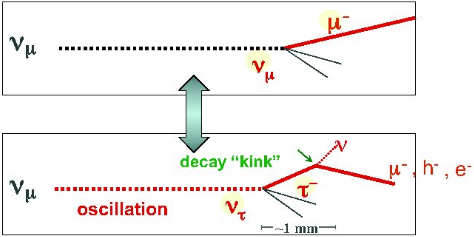
following the Super- Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams. Important, missing tile in the oscillation picture.

The PMNS 3-flavor oscillation formalism predicts:

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

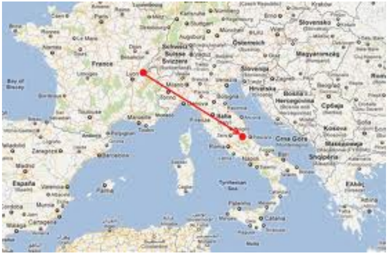
Requirements:

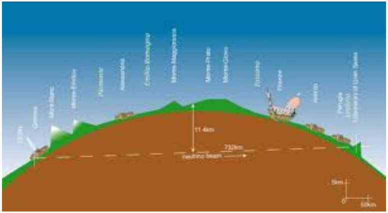
1) long baseline, 2) high neutrino energy, 3) high beam intensity, 4) detect short lived τ's



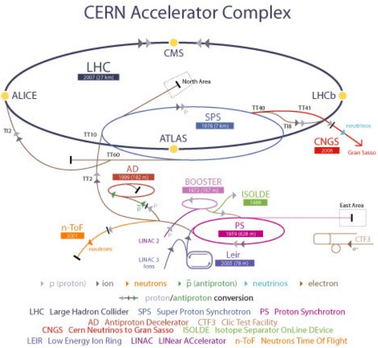
plus 3-prong decay modes

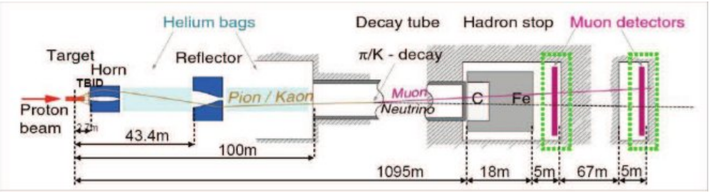
The long baseline experiment



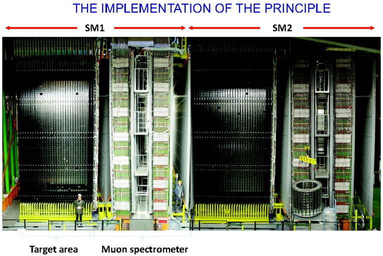


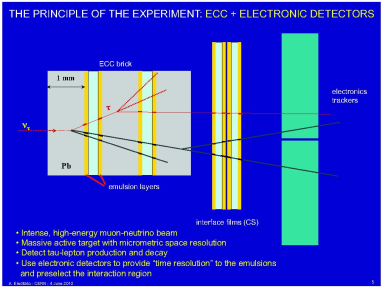
The source


CERN Accelerator Complex
CMS
LHC
2007 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
neutrons
LINAC 2
LINAC 3
Ions
Leir
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
neutrinos
electron
proton/antiproton conversion
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight


Helium bags
Decay tube
Hadron stop
Muon detectors
Target
Horn
TBID
Reflector
π/K - decay
Pion / Kaon
Muon
Neutrino
C
Fe
Proton
beam
2.7m
43.4m
100m
1095m
18m
5m
67m
5m

The detector





Outline

Speed of neutrinos: schematic

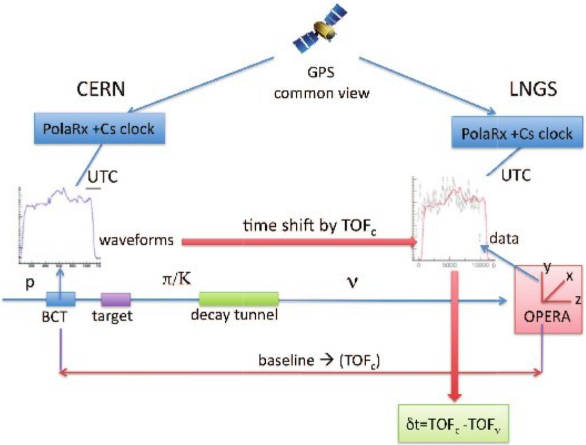


Fig. 5: Schematic of the time of flight measurement.

Outline

Accuracy of distance measurement

- GPS + surveying inside tunnel
- Claimed accuracy: 20 cm

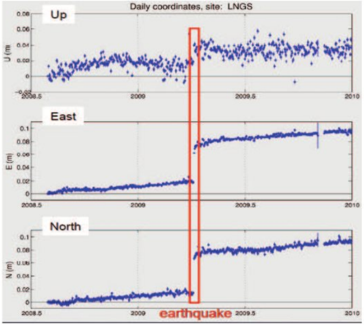


Fig. 7: Monitoring of the PolaRx2e GPS antenna position at LNGS, showing the slow earth crust drift and the fault displacement due to the 2009 earthquake in the L'Aquila region. Units for the horizontal (vertical) axis are years (meters).

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Proton beam pulse shape at CERN

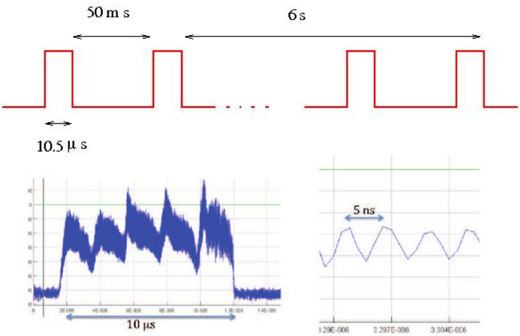


Fig. 4: Example of a proton extraction waveform measured with the BCT detector BFCTI400344. The five-peak structure reflects the continuous PS turn extraction mechanism. A zoom of the waveform (right plot) allows resolving the 200 MHz SPS radiofrequency.

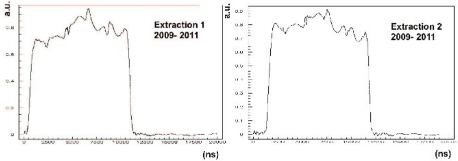


Fig. 9: Summed proton waveforms of the OPERA events corresponding to the two SPS extractions for the 2009, 2010 and 2011 data samples.

Time delays at CERN

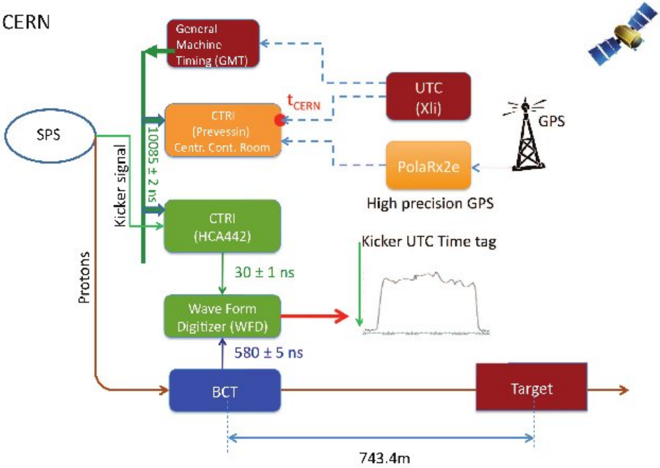


Fig. 3: Schematic of the CERN SPS/CNGS timing system. Green boxes indicate detector time-response. Orange boxes refer to elements of the CNGS-OPERA synchronisation system. Details on the various elements are given in Section 6.

Time delays at Gran Sasso

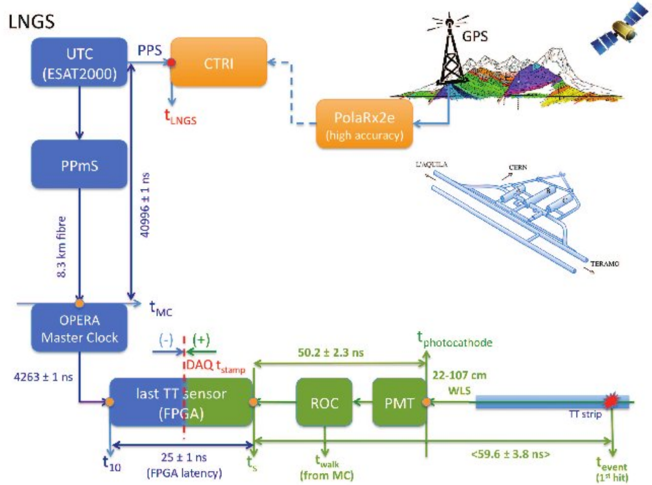
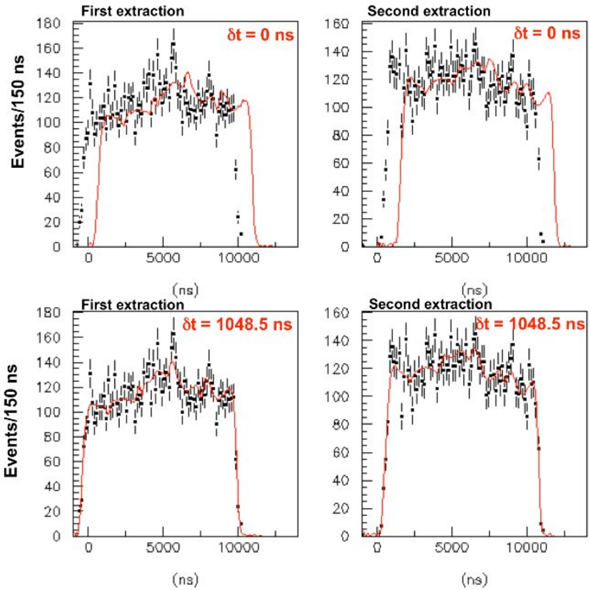


Fig. 6: Schematic of the OPERA timing system at LNGS. Blue delays include elements of the time-stamp distribution; increasing delays decrease the value of δt. Green delays indicate detector time-response; increasing delays increase the value of δt. Orange boxes refer to elements of the CNGS-OPERA synchronisation system.

Outline

Blind analysis: add an unspecified delay



The edge shapes

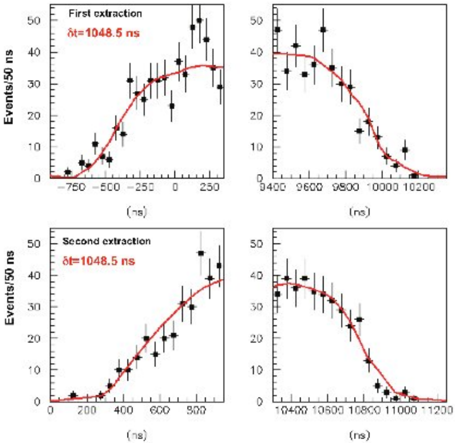


Fig. 12: Zoom of the leading (left plots) and trailing edges (right plots) of the measured neutrino interaction time distributions (data points) and the proton PDF (red line) for the two SPS extractions after correcting for δt (blind).

The final (maximum likelihood) fit

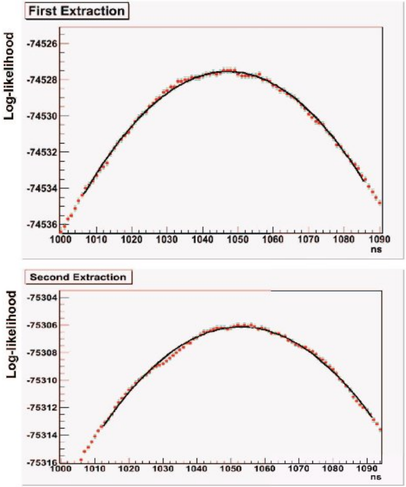


Fig. 8: Log-likelihood distributions for both extractions as a function of δt, shown close to the maximum and fitted with a parabolic shape for the determination of the central value and of its uncertainty.

Actual delay

Table 1: Summary of the time delay values used in the blind analysis and those corresponding to the final analysis.

	Blind 2006	Final analysis	Correction (ns)
Baseline (ns)	2440079.6	2439280.9	
Correction baseline			-798.7
CNGS DELAYS :			
UTC calibration (ns)	10092.2	10085	
Correction UTC			-7.2
WFD (ns)	0	30	
Correction WFD			30
BCT (ns)	0	-580	
Correction BCT			-580
OPERA DELAYS :			
TT response (ns)	0	59.6	
FPGA (ns)	0	-24.5	
DAQ clock (ns)	-4245.2	-4262.9	
Correction TT+FPGA+DAQ			17.4
GPS syncronization (ns)	-353	0	
Time-link (ns)	0	-2.3	
Correction GPS			350.7
Total			**-987.8**

Estimated sources of error

Table 2: Contribution to the overall systematic uncertainty on the measurement of δt.

Systematic uncertainties	**ns**
Baseline (20 cm)	0.67
Decay point	0.2
Interaction point	2.0
UTC delay	2.0
LNGS fibres	1.0
DAQ clock transmission	1.0
FPGA calibration	1.0
FWD trigger delay	1
CNGS-OPERA GPS synchronisation	1.7
MC simulation for TT timing	3.0
TT time response	2.3
BCT calibration	5.0
Total sys. uncertainty (in quadrature)	**7.4**

Outline

Stability across time

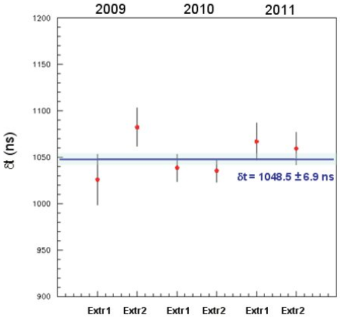
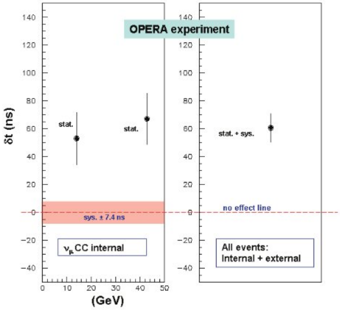


Fig. 10: Results of the maximum likelihood analysis for δt corresponding to the two SPS extractions for the 2009, 2010 and 2011 data samples.

- Day-night: 17.1 ± 15.5 ns
- Spring vs Fall: 11.3 ± 14.5 ns

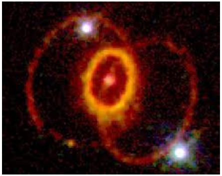
Stability across energies

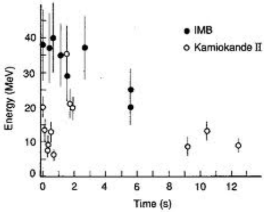


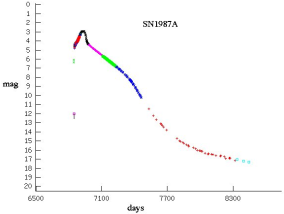
- $\delta t =$ 1948.5 ns - 987.8 ns = $(60.7 \pm 6.9[stat] \pm 7.4[sys])$ ns
- $\frac{v-c}{c} = (2.48 \pm 0.28 \pm 0.30) \times 10^{-5}$

Outline

SN1987A: 23 Feb 1987



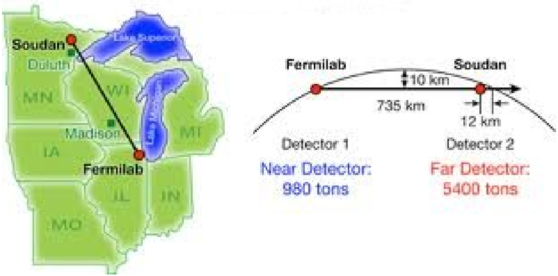




- Neutrino arrived only 3 hours earlier
  (We know they left a few hours earlier, so OK).
- $|c - v|/c < 2 \times 10^{-9}$
- If OPERA measurement is true, they should have arrived 4 years earlier.

Other long baseline neutrino experiments

T2K



MINOS

Older measurements by MINOS

- $(v - c)/c = (5.1 \pm 2.9) \times 10^{-5}$ (at 3 GeV)

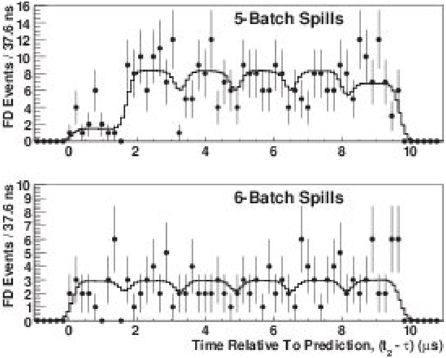


FIG. 2: Time distribution of FD events relative to prediction after fitting the time-of-flight. The top plot shows events in 5-batch spills, the bottom 6-batch spills. The normalized expectation curves $P_2^5(t)$ and $P_2^6(t)$ are shown as the solid lines.

Where can MINOS improve their errors?

	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND Antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD Antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
	Total (Sum in quadrature)	64 ns

TABLE II: Sources of uncertainty in ν relative time measurement.

The future

- OPERA: Recheck for systematic errors.
  - Tidal effects due to the moon
  - Beam profile: beam at CERN vs at Gran Sasso
  - Maybe some more not yet thought of
- MINOS: a new measurement

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Maybe this has already happened in someone's reference frame.