New results of the OPERA long-baseline experiment in the CNGS neutrino beam

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on behalf of the OPERA Collaboration

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The OPERA Collaboration

11 countries, 30 Institutes, ~160 researchers

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi edu.
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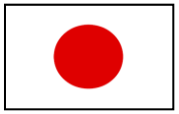
Utsunomiya



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

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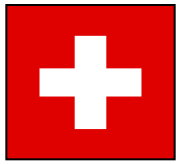


Turkey
METU Ankara

Outline

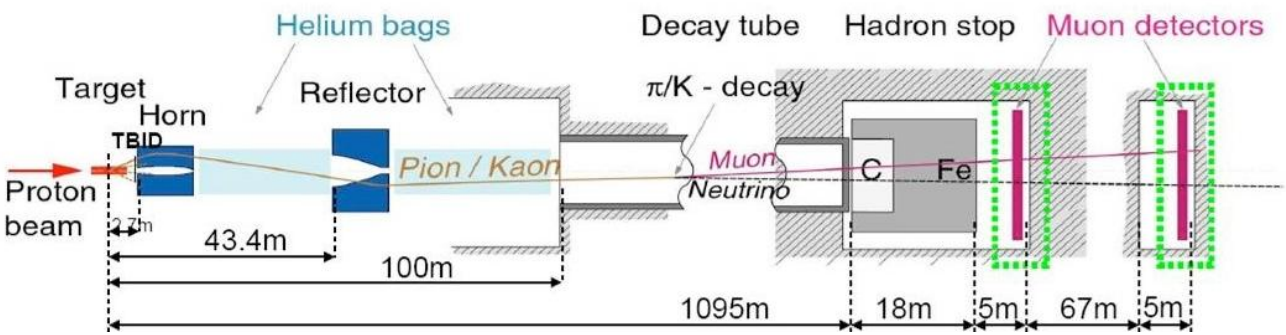
- Introduction
- Beam configurations
- OPERA sub-detectors used for ν velocity
- Working principle of the measurement
- The two unaccounted systematic errors
- Data analysis
  - Statistical analysis (2009-2011 data)
  - 2011 bunched-beam analysis
  - 2012 bunched-beam analysis
- Conclusions

Introduction

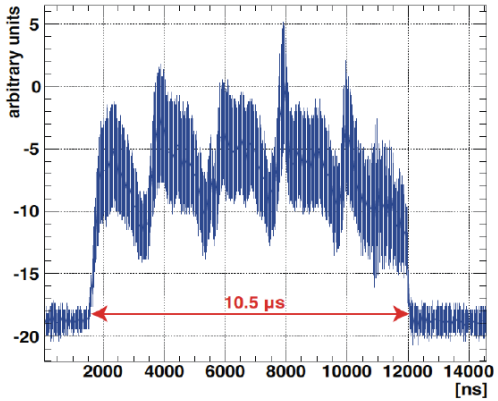
- The OPERA detector was primarily conceived and constructed to unambiguously prove neutrino oscillations in appearance mode (see M. De Serio's talk)
- It has an hybrid structure: passive detectors (nuclear emulsions) for micrometric reconstruction of tau decays and electronic detectors to complement and guide the kinematical recontruction
- Electronic detectors were also used to perform stand-alone non-oscillation studies, among them: cosmic ray studies and neutrino velocity measurement
- The latter produced an astonishing result in Sep 2011, an anticipation of the nutrino ToF w.r.t. the one computed assuming the speed of light
- An intense and successful period to unravel the anomaly followed

The CNGS neutrino beam

- Conventional (~300 kW) neutrino beam production
  - 400 GeV/c protons on a beryllium target followed by coupled magnetic lenses (horn/reflector)
  - ~1 km decay pipe, hadron stopper, downstream muon stations

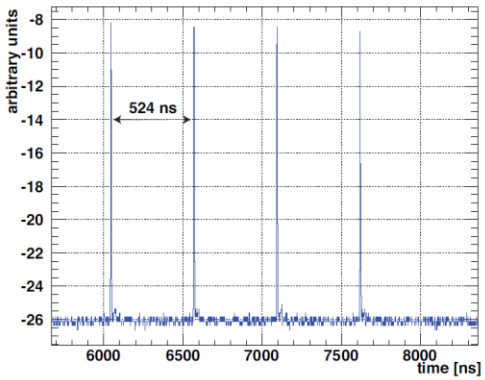


- CNGS "standard" beam
  - Used for oscillation studies and "statistical" ν velocity measurement
  - 2 fast extractions (10.5 μs long) per SPS cycle (6 s) separated by 50 ms
  - ~2×10^{13} pot/extraction, ~4.5×10^{19} pot/year

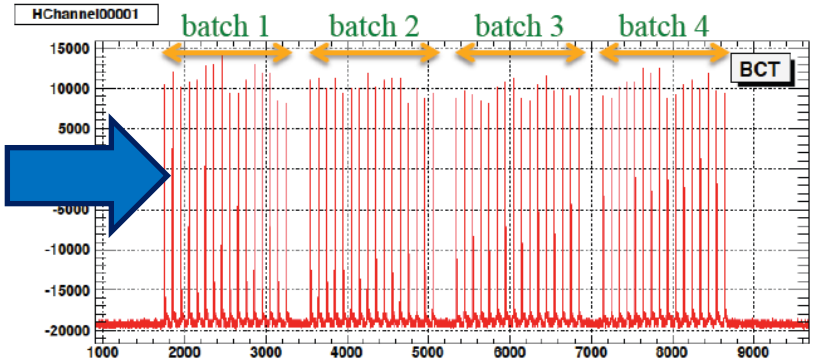


The CNGS bunched-beams

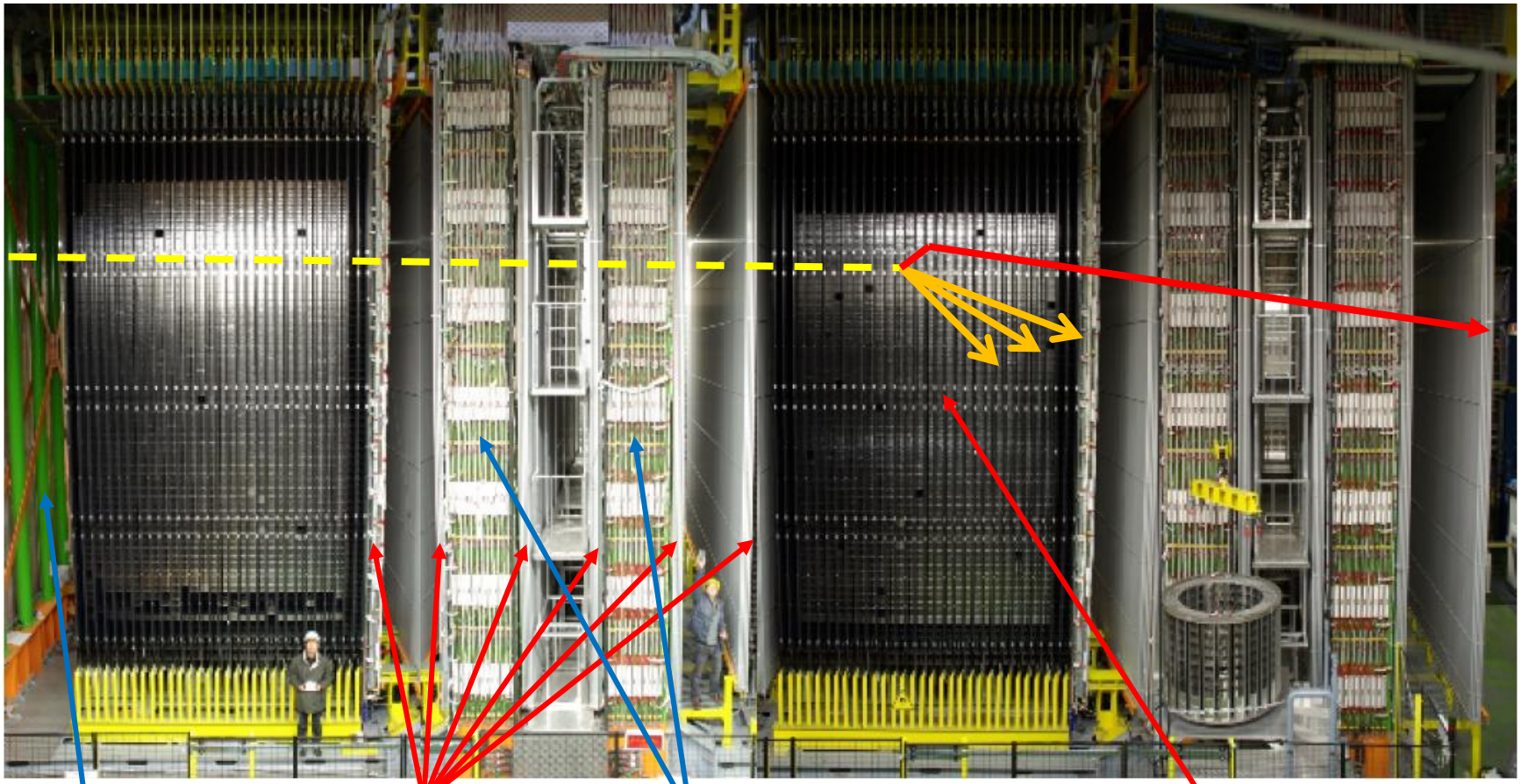
- CNGS short bunched beam in Nov 2011
  - Designed for ν velocity measurement (validation of statistical procedure)
  - Oct 22-Nov 6, 2011 (~4×10^{16} pot in total)
  - 1 extraction/cycle (13.2 s long)
  - 4 bunches/extraction (524 ns separation)
  - Bunch width σ ~ 3 ns



- CNGS short bunched beams in May 2012
  - Designed for ν velocity measurement (final assessment)
  - May 10-24, 2012 (~2×10^{17} pot in total)
  - 1 extraction/cycle (13.2 s long)
  - 4 batches/extraction (300 ns separation)
  - 16 bunches/batch (100 ns separation)
  - Bunch width σ = 1.8 ns



The OPERA detector



Veto plane (RPC)

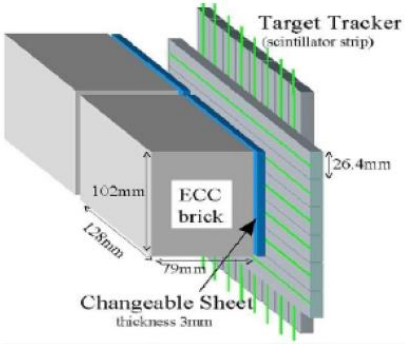
High Precision Tracker
(6 drift tube stations)

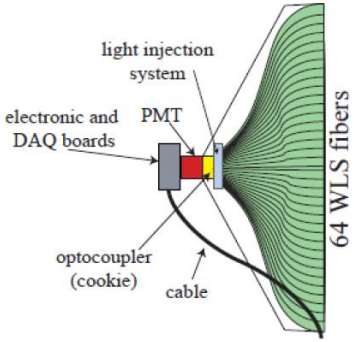
Instrumented dipole magnet
(22 RPC planes in total)

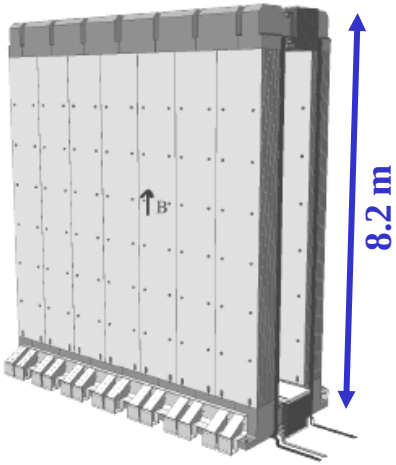
Bricks (lead + emulsions)
and Target Tracker
(plastic scintillators)

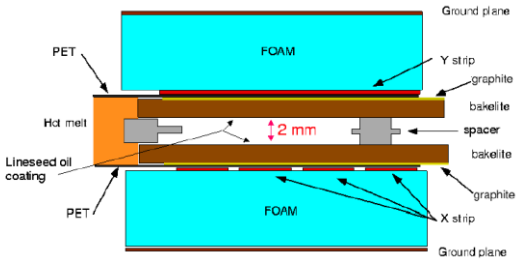
Sub-detectors used for ν velocity

- Neutrino velocity was measured exploiting two electronic detector sub-systems: plastic scintillators ("Target Tracker") and bakelite RPCs
- Target Tracker:
  - 31 walls/supermodule
  - 256×256 strips/wall, vertical and horizontal
  - Each strip: 686×1.1×2.6 cm^3
  - Readout: WLS + multianode PMT (at both sides)
- Bakelite RPCs:
  - 22 RPC planes/spectrometer
  - 21 RPC pads/plane
  - Each pad: 291×113 cm^2

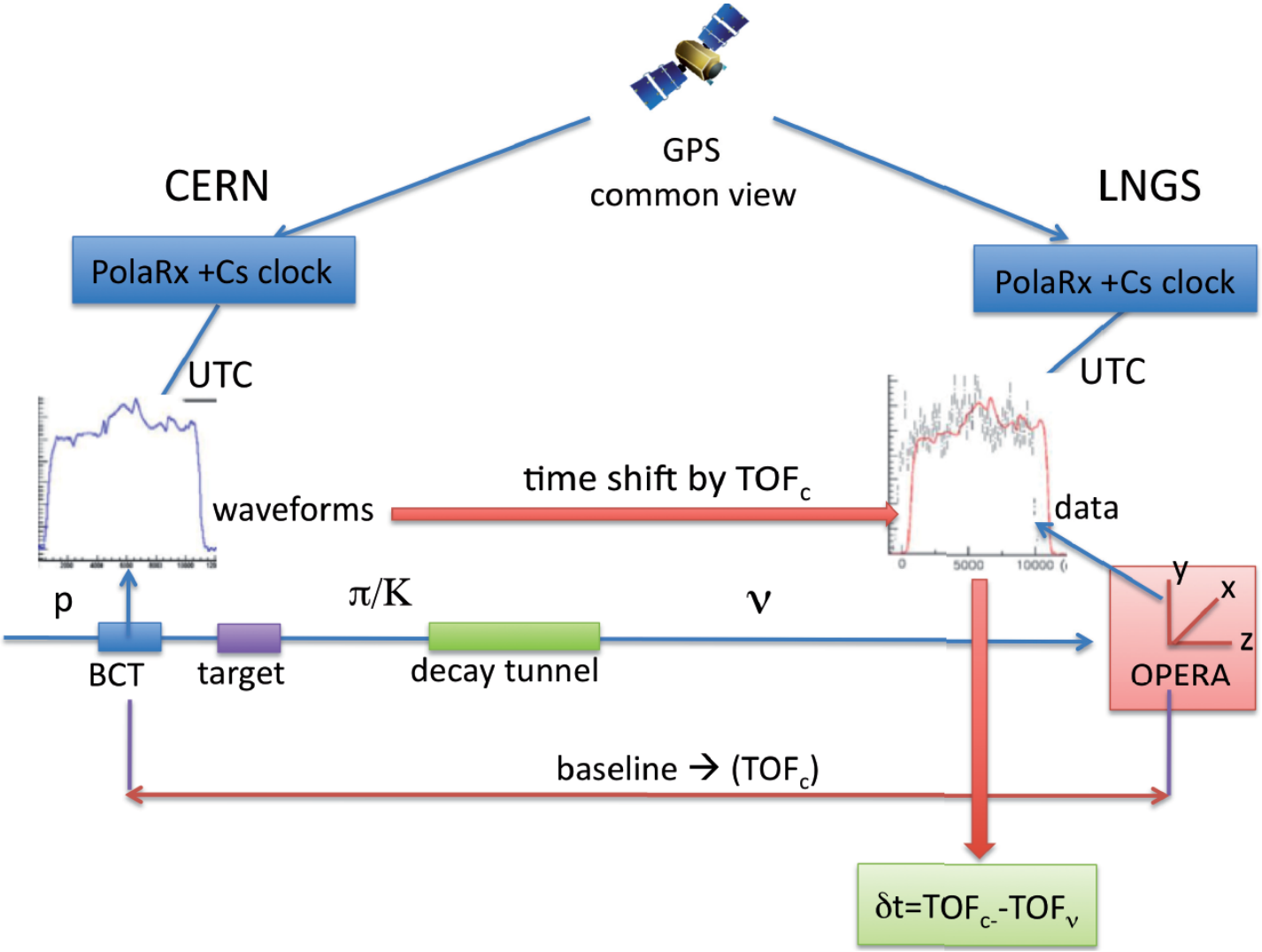








Syncronization, working principle



Calibration of time delays

Item	Result	Method
CERN UTC distribution (GMT)	10077* ± 2 ns	• Portable Cs • Two-ways
WFD trigger	26* ± 1 ns	Scope
BTC delay	580 ± 5 ns	• Portable Cs • Dedicated beam experiment
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement
LNGS UTC distribution (fibers)	40996 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	4262.9 ± 1 ns	• Two-ways • Portable Cs
FPGA latency, quantization curve	24.5 ± 1 ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	50.2 ± 2.3 ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	9.4 ± 3 ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation

* from 2011

±5.5 ns (CERN)

±4.2 ns (OPERA)

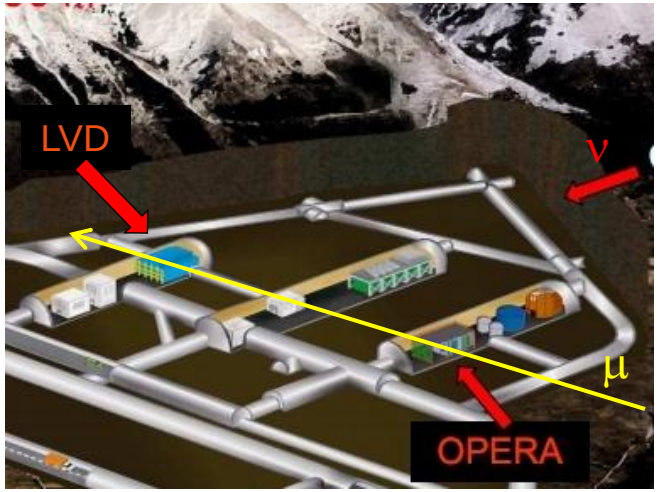
The two (unaccounted) systematic errors

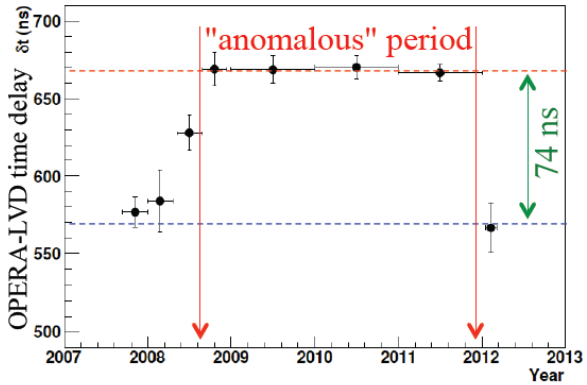
- Time delay of the 8.3 km optical fiber from external to internal Labs
  - Measurements during winter shutdown different from the previous ones: 74 ns to increase the neutrino anticipation (dominant effect)
  - Explanation of the mismatch: fiber not properly connected to the OPERA Master Clock
- Internal Master Clock frequency:
  - Difference w.r.t. nominal frequency $\Delta f/f = 1.24\times10^{-7}$
  - Introduce an artificial delay depending on the position of the events within the DAQ cycle
- Data have to be properly corrected for the two effects
- Details and corrected results presented on the 28th of March at the Gran Sasso Workshop:

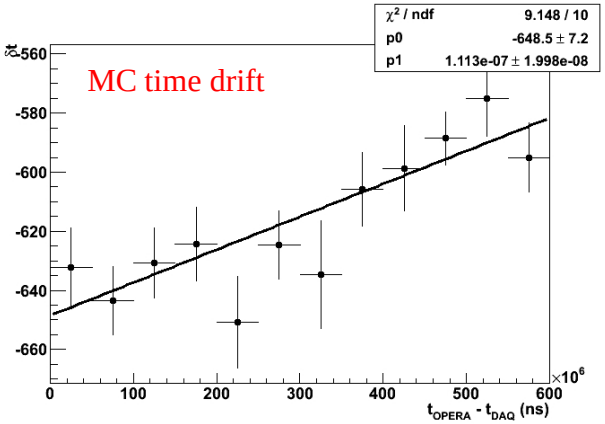
  http://agenda.infn.it/materialDisplay.py?materialId=slides&confId=4896

An independent cross-check

- The two effects were also found using coincident cosmic muon events between OPERA and LVD
  - Detector timing system intercalibration
- Despite its an indirect method, it provided valuable information. Within the statistical accuracy of the procedure:
  - The cable connection problem was there since the beginning, in a stable way
  - The clock drift problem was there since the beginning, in a stable way

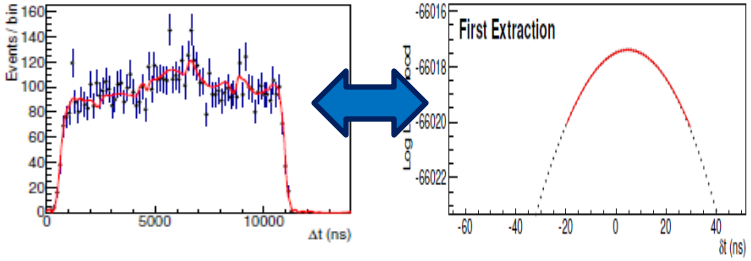






Statistical analysis (re-evaluated result)

- For each OPERA event take the BCT waveform of the corresponding extraction
- Selection criteria:
  - CERN-LNGS timelink ok
  - WFD ok
  - Well identified muon
  - No isolated earliest hits
- 15223 events selected (2009+2010+2011):
  - 7235 internal events
  - 7988 external events
- WFD and neutrino time distribution analyzed with a ML approach



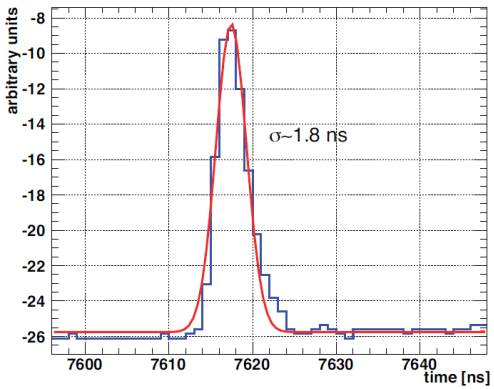
Differential searches
- No day/night effect
- No seasonal effect
- No energy dependence
- No beam intensity effect
- Compatibility ν/ν-bar

$$\delta t = TOF_c - TOF_\nu = (6.5 \pm 7.4(stat)^{+9.2}_{-6.8}(syst))ns$$

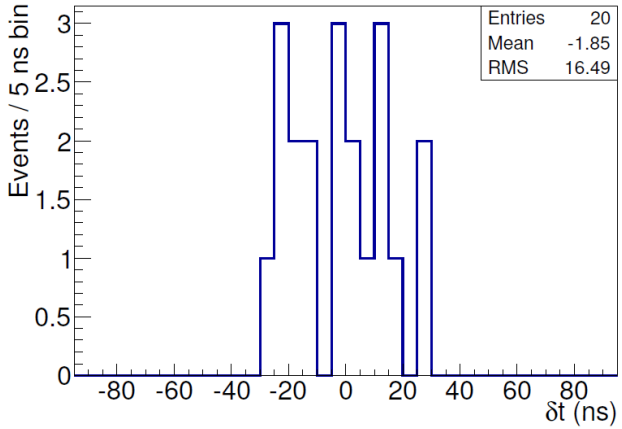
$$\frac{v-c}{c} = \frac{\delta t}{TOF_c^{'} - \delta t} = (2.7 \pm 3.1(stat)^{+3.8}_{-2.8}(syst)) \times 10^{-6}$$

Nov 2011 Bunched Beam

- Mainly designed for OPERA to exclude the statistical procedure as the dominant source of systematic error
- Now for each OPERA event take the "centroid" of the corresponding BCT WF (unambiguous association)
- Results from both TT and RPC sub-detectors
  - Cross-check of systematics related to detector calibrations (<u>but DAQ in common</u>)

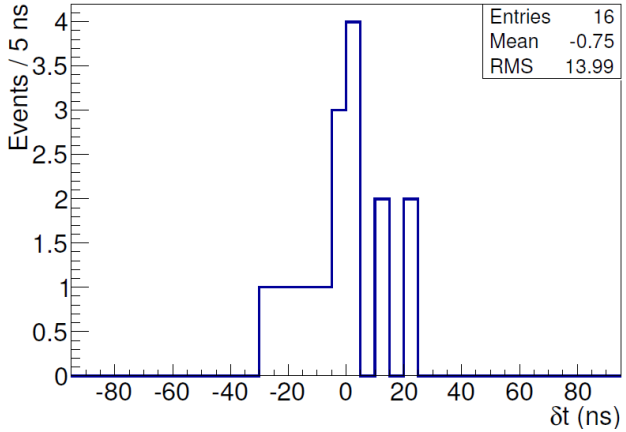


TT: 20 events selected



(1.9 ± 3.7) ns

RPC: 16 events selected

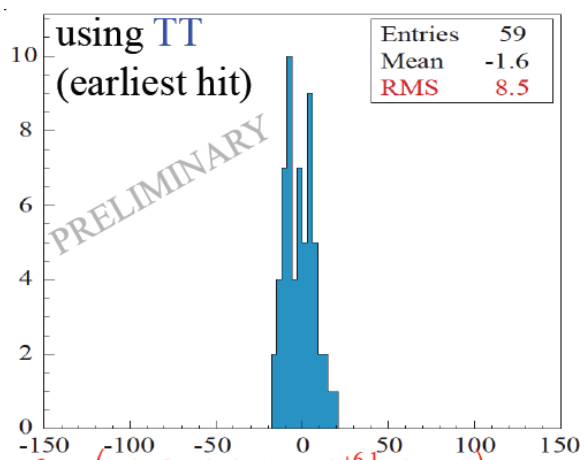


$\delta t = (-0.8 \pm 3.5\ (stat.) \pm 7\ (sys.))\ ns$

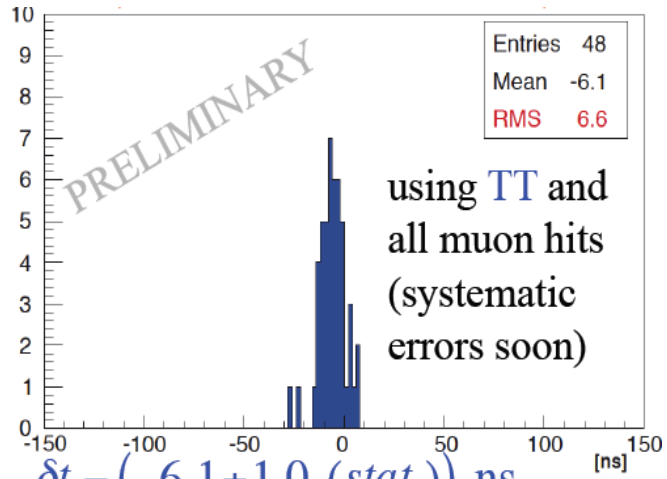
Dispersions are dominated by a ±25 ns jitter due to the GPS signal tagging by the OPERA Master Clock

May 2012 Bunched Beam

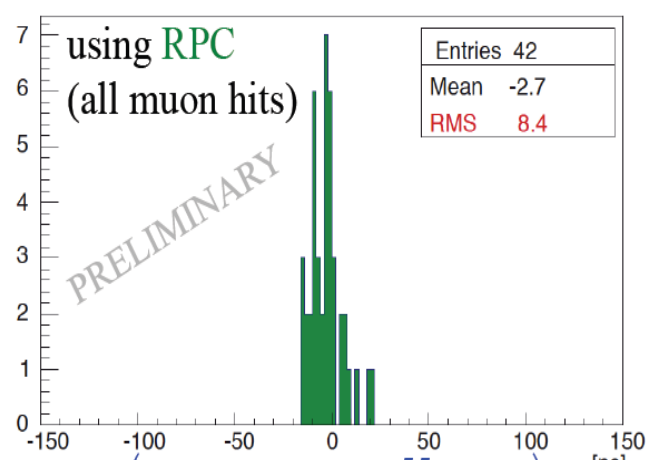
- Mainly designed to finally assess the neutrino velocity issue by all the involved LNGS experiments (Borexino, ICARUS, LVD, OPERA)
- New calibrations:
  - CERN: Time delay related to BCT: (583.7±1) ns
  - CERN & LNGS: White Rabbit system for continuous time delay monitoring
  - OPERA: Master Clock equipped with a TDC to improve the GPS signal latching



$\delta t = \left(-1.6 \pm 1.1\ (stat.)^{+6.1}_{-3.7}\ (sys.)\right)$ ns



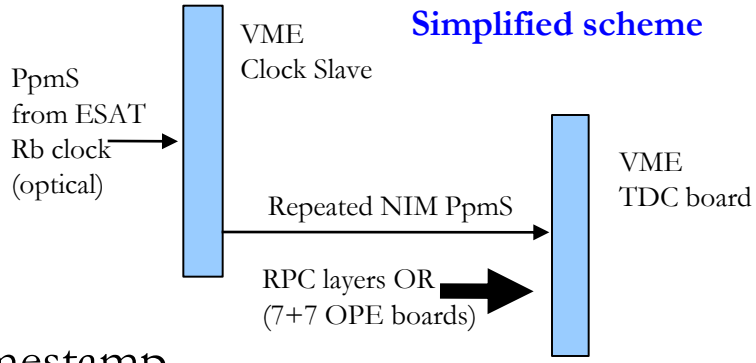
$\delta t = \left(-6.1 \pm 1.0\ (stat.)\right)$ ns

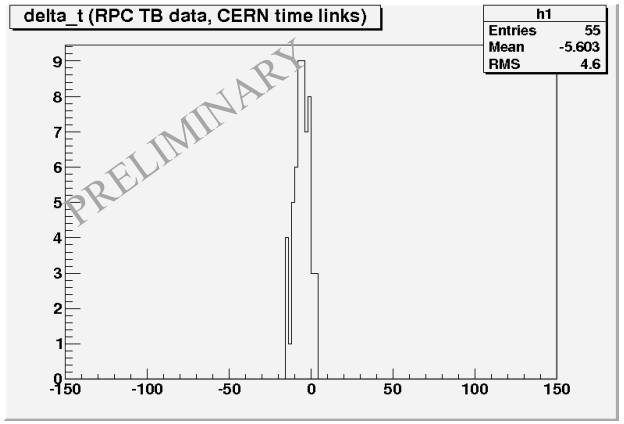


$\delta t = \left(-2.7 \pm 1.3\ (stat.)^{+7.7}_{-7.4}\ (sys.)\right)$ ns

Independent timing system

- An independent timing system was used in parallel exploiting "Timing Boards" installed on RPC detectors
- An independent optical fibre feeds a VME module to decode the PPmS signal coming from the external GPS clock
  - This provides the "ms" part of the event timestamp
- The sub-ms component is given by a TDC counter (up to 1 ns)





Result:

$$\delta t = (-5.6 \pm 0.6(stat)^{+6.5}_{-5.1}(syst))ns$$

Dominant systematic error on the streamer formation time (5 ns)

Conclusions

- OPERA understood the source of the anomaly announced last year and corrected the result accordingly
- All the neutrino velocity measurments performed by OPERA – using different beam configurations and different sub-detectors – are in agreement with the speed of light
  - Statistical analysis with TT and RPC
  - Bunched beam analysis with TT and RPC
  - RPC analysis with and independent timing system
- A combination of all the different (but correlated) experimental results is in progress
- Results are going to be published soon