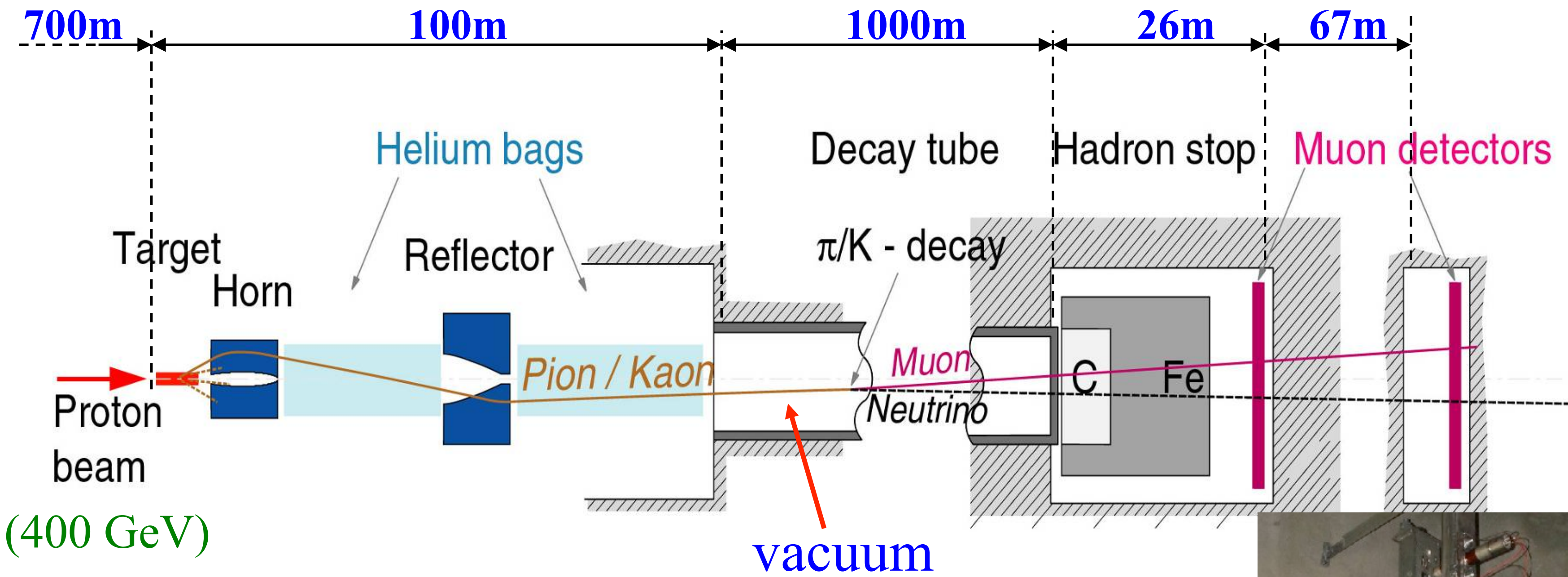
The neutrino velocity measurement by OPERA experiment

Marcos Dracos
IPHC, Université de Strasbourg, CNRS/IN2P3
(on behalf of OPERA Collaboration)

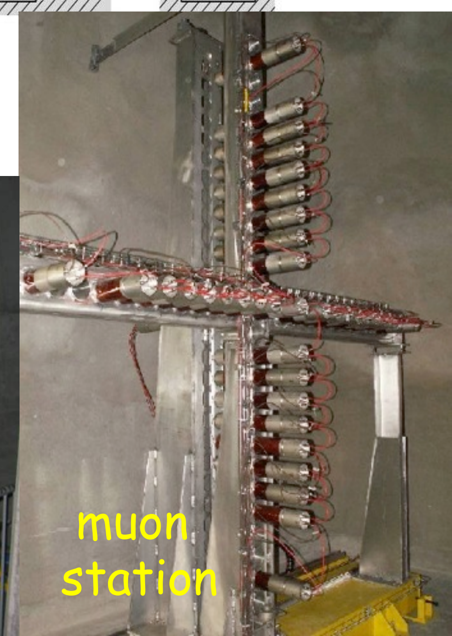
CNGS layout (CERN Neutrino beam to Gran Sasso)



target

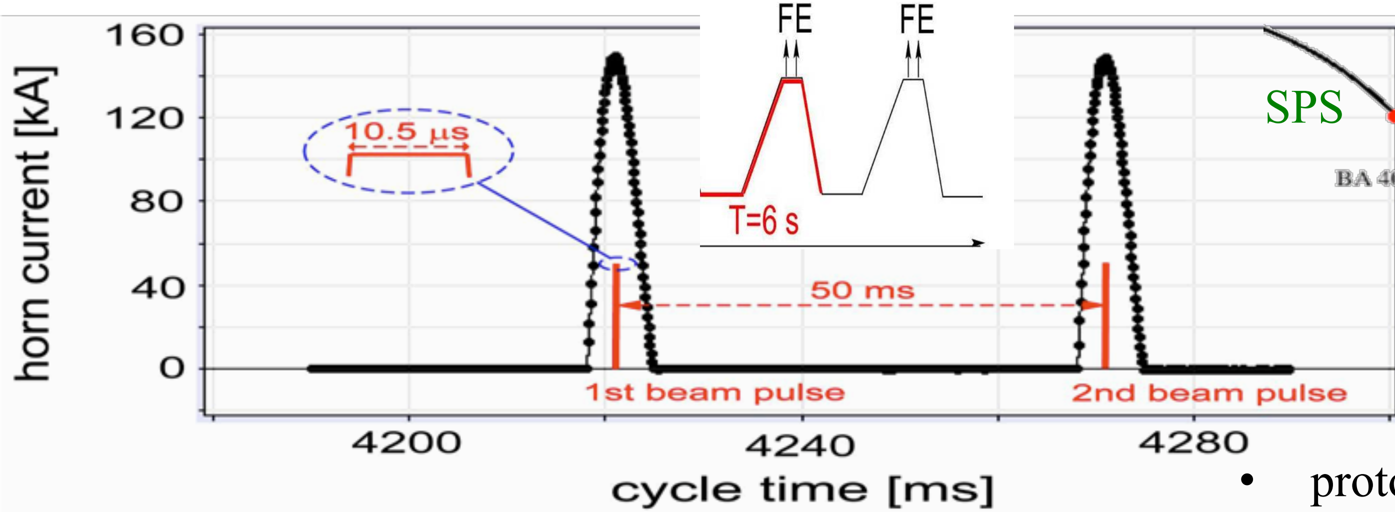
horn

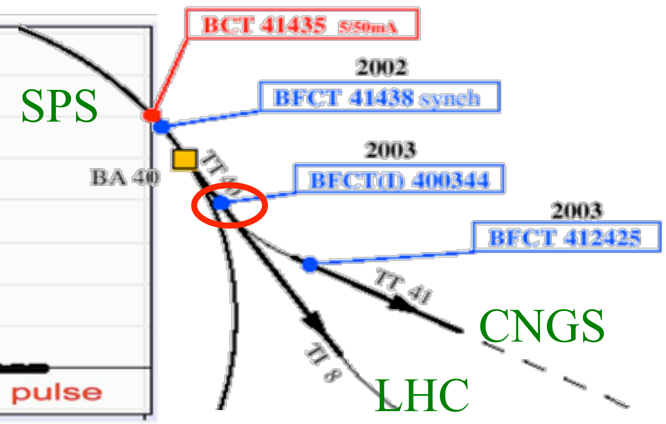
end of the decay tunnel



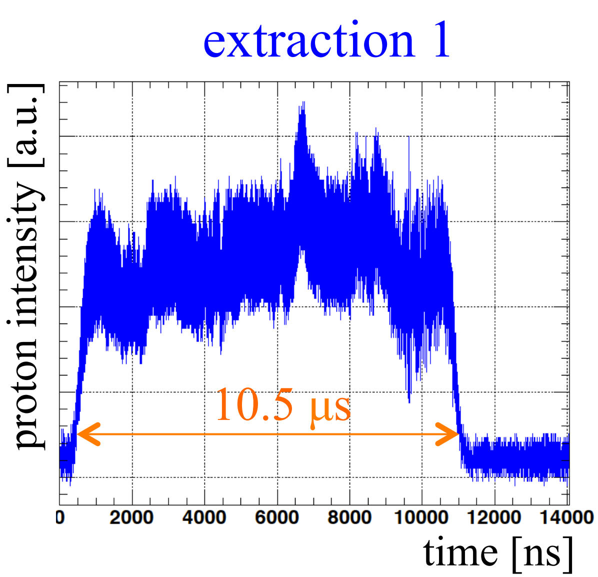
muon station

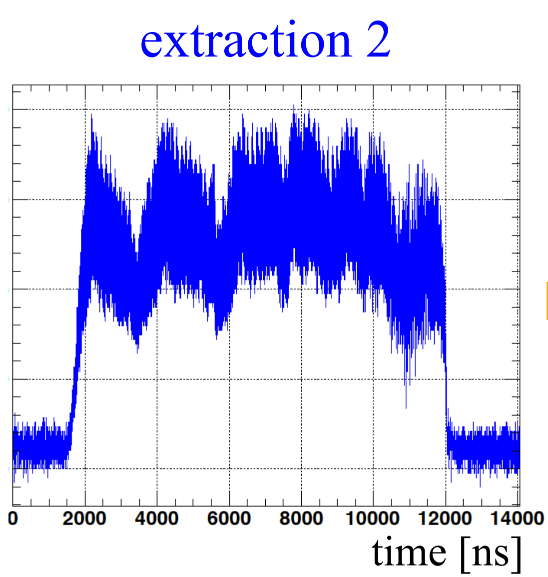
Proton Beam and horn parameters





- proton energy: 400 GeV
- intensity/extraction: ~$2x10^{13}$ p
- p.o.t./year: ~$4.5x10^{19}$

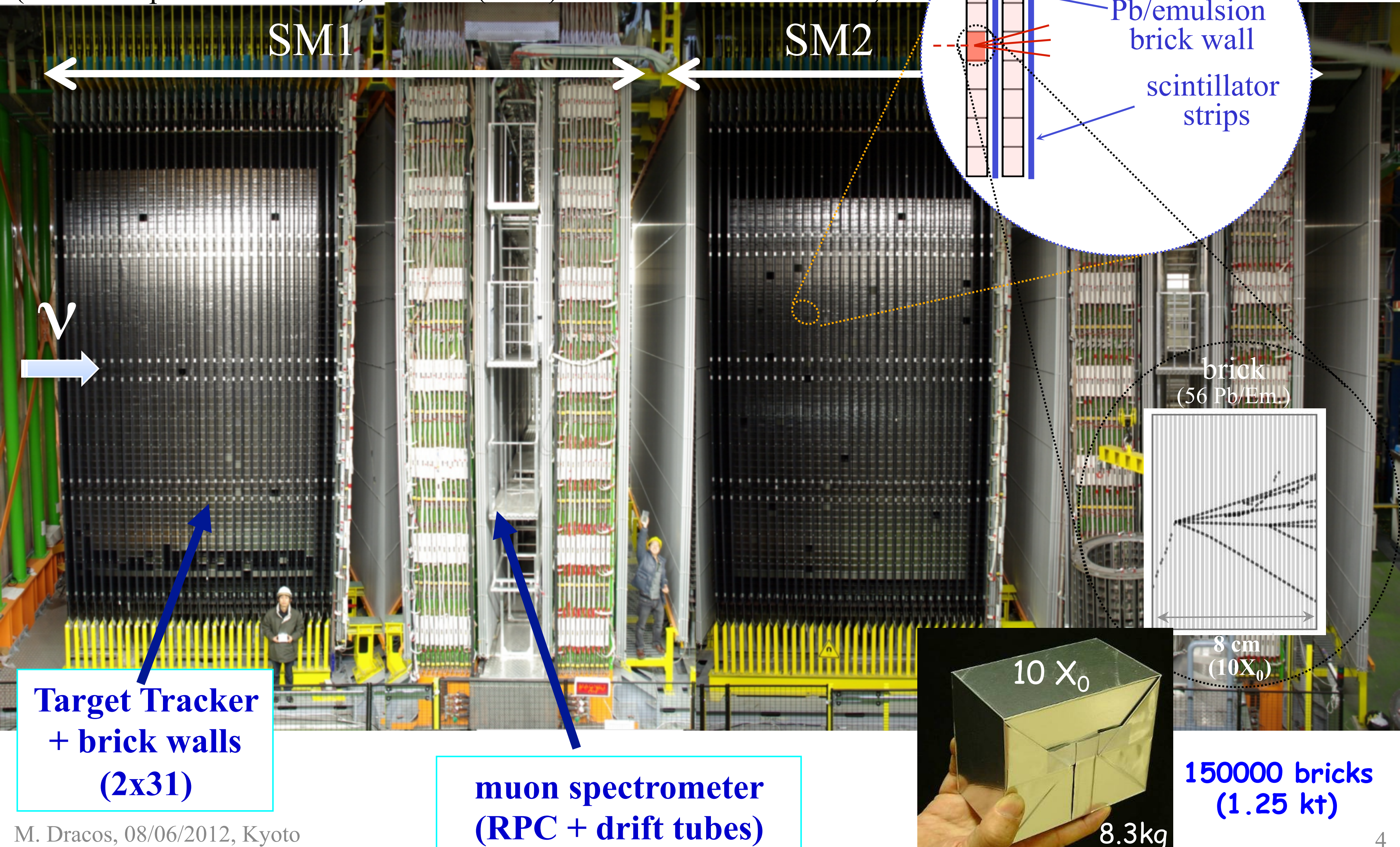




- measure the neutrino velocity statistically by reconstructing the proton waveforms
- the shape of the 2 extractions is not the same
- treat each extraction separately

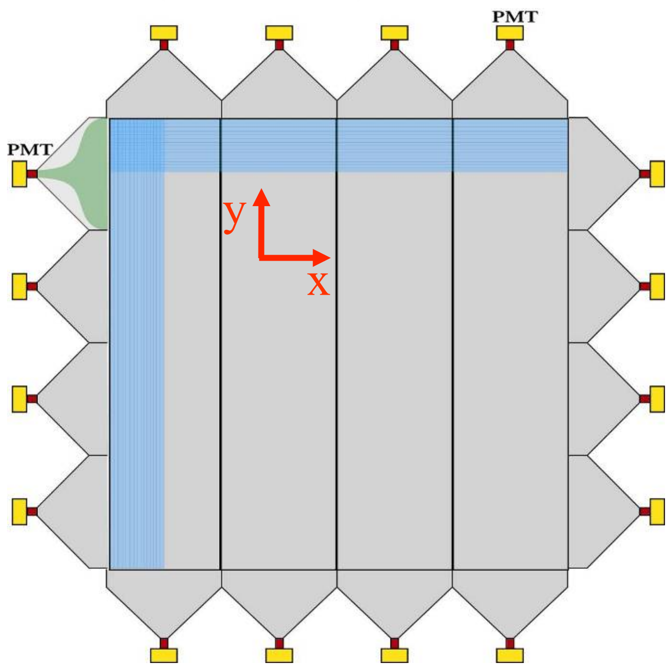
The OPERA detector

(full description in JINST 4, P04018 (2009) and Nakamura-san's talk)



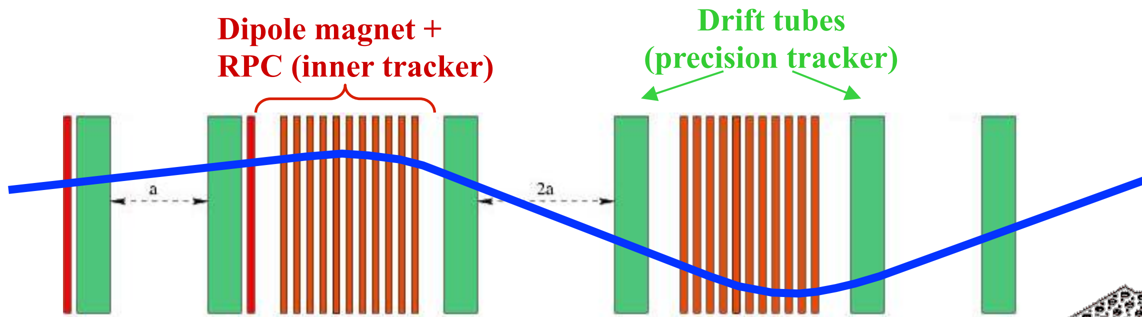
The Electronic Detectors

Target Tracker: plastic scintillator strips (26.4 mm), σ~8 mm

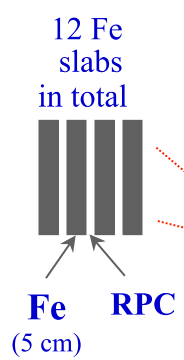


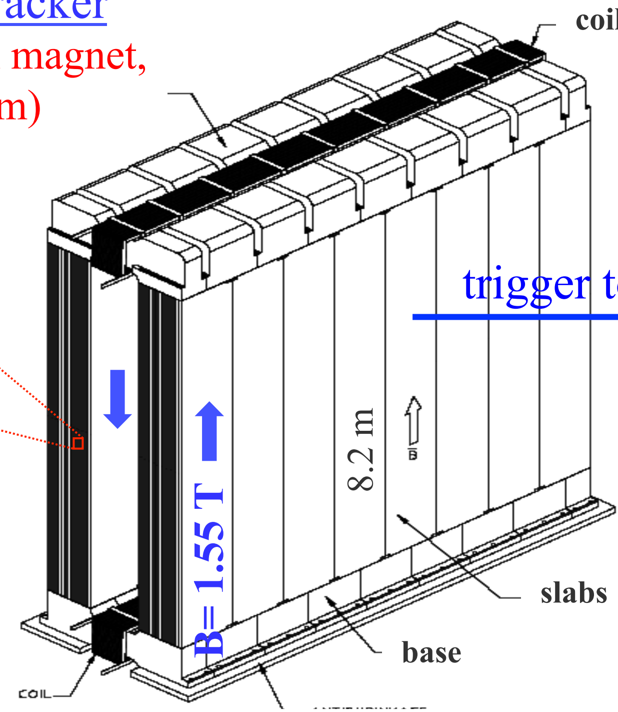
62 walls (496 modules)
7.5x7.5 m^2 Hamamatsu multianode PMT's (64 channels)

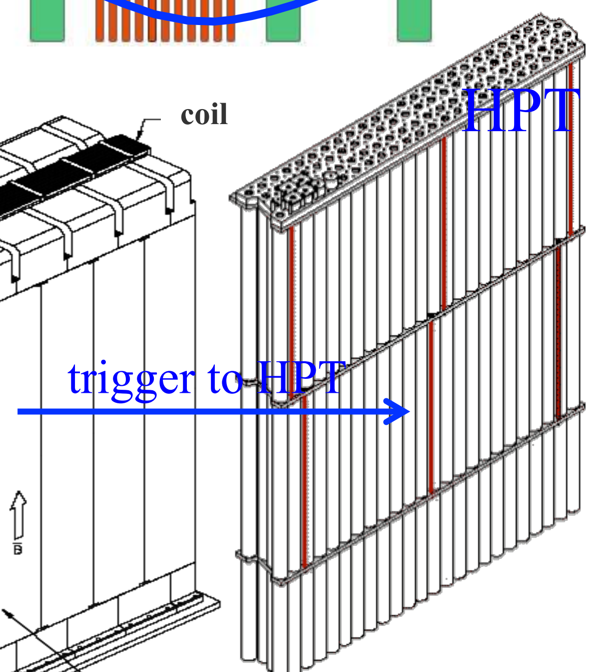
The spectrometers



Inner tracker
(RPC in magnet, σ~13 mm)

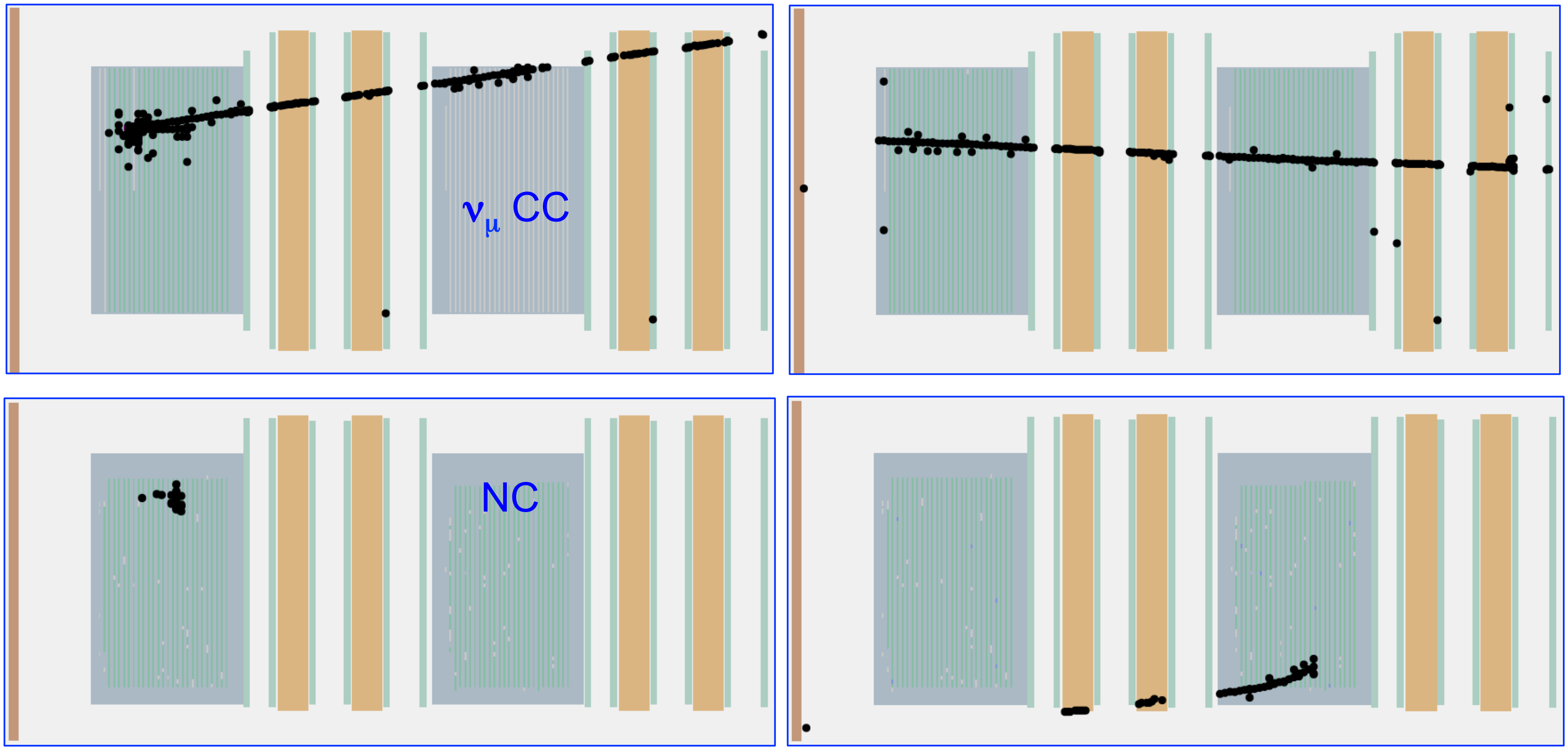






Precision tracker
Tube: vertical, ∅=38 mm, length=8m
σ<0.5 mm

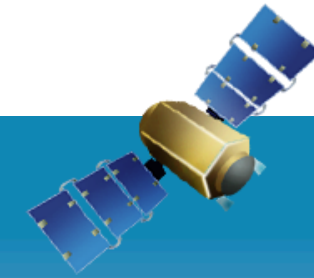
"internal" and "external" events



interactions inside the detector

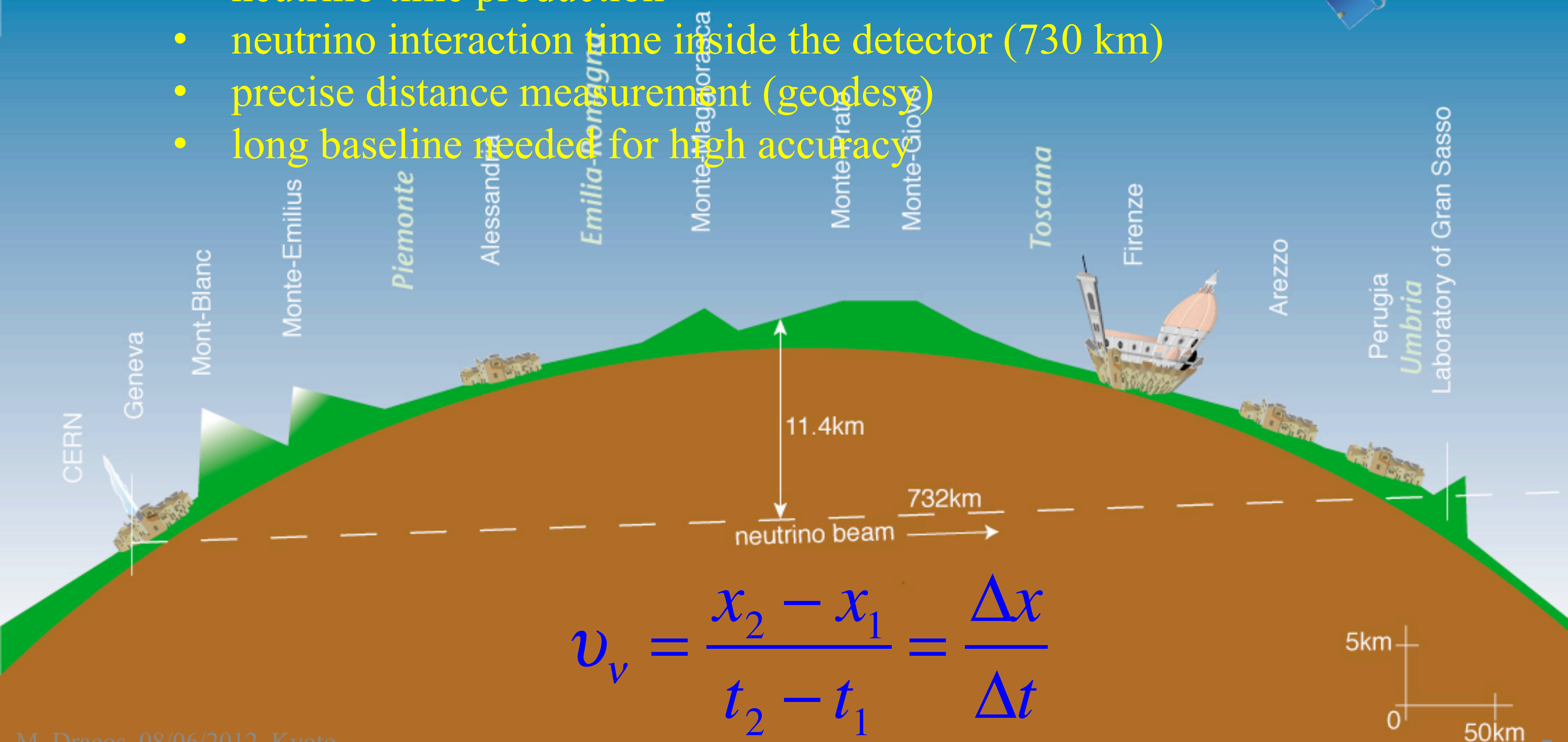
μ from neutrino interactions outside the detector

The neutrino velocity measurement using the CNGS neutrino beam and OPERA detector



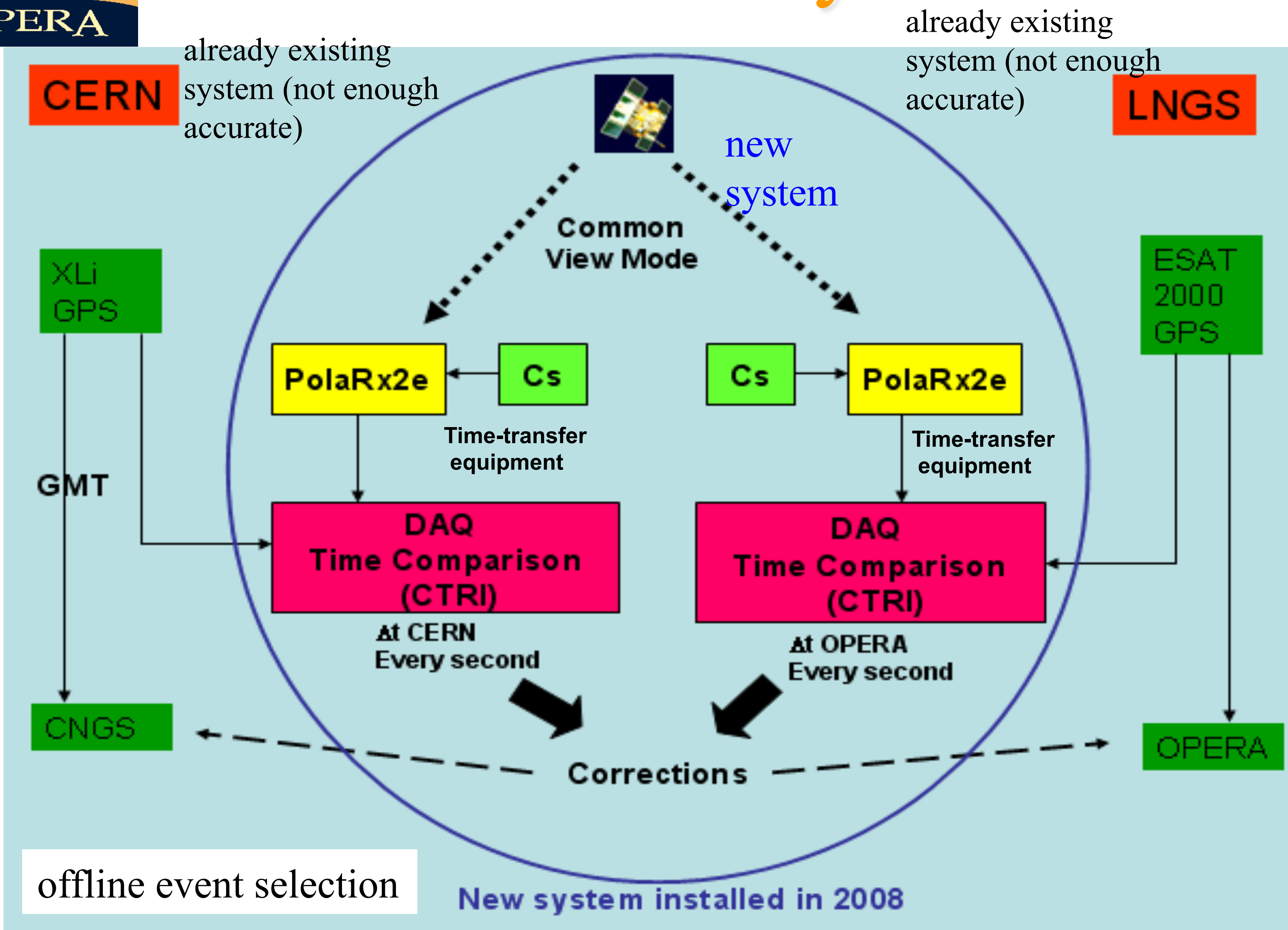
Neutrino time of flight (TOF) measurement:

- neutrino time production
- neutrino interaction time inside the detector (730 km)
- precise distance measurement (geodesy)
- long baseline needed for high accuracy



$$\upsilon_\nu = \frac{x_2 - x_1}{t_2 - t_1} = \frac{\Delta x}{\Delta t}$$

CNGS-OPERA Synchronisation

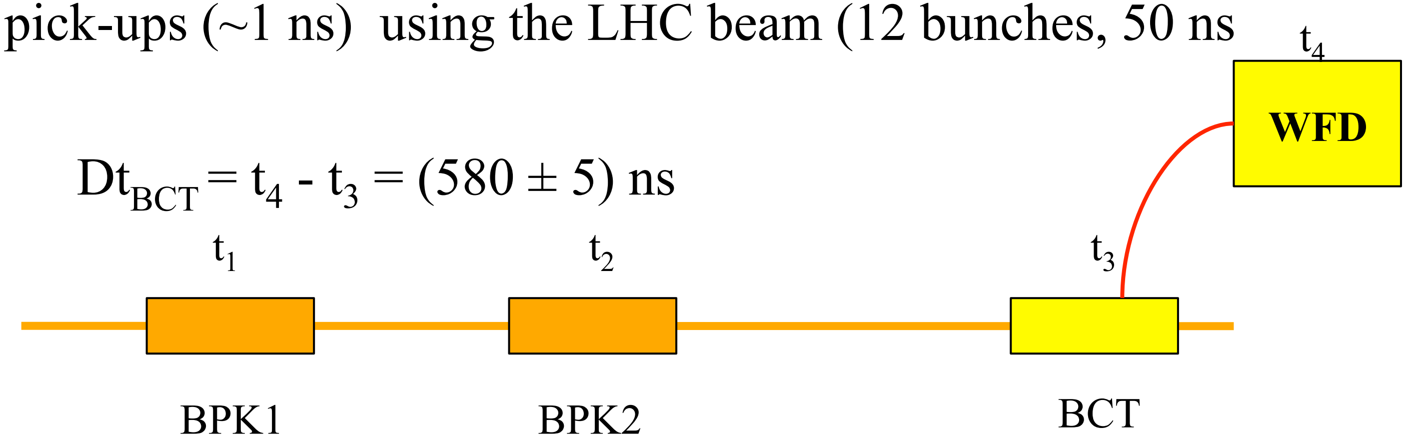


BCT Calibration

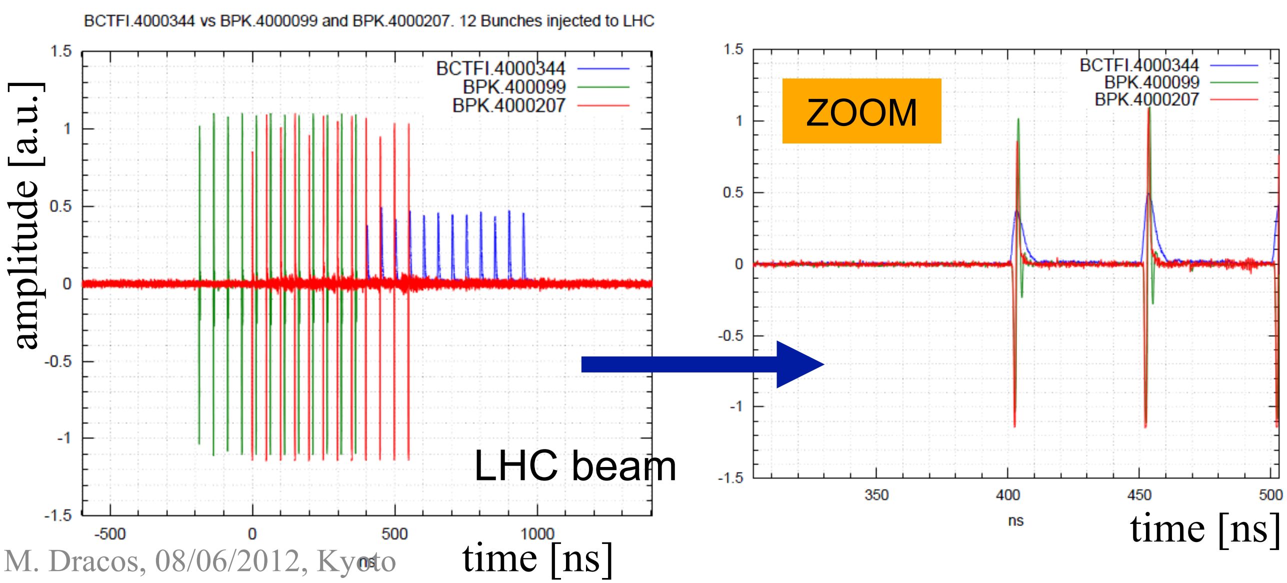
Dedicated beam experiment:

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

$Dt_{BCT} = t_4 - t_3 = (580 \pm 5)$ ns



t_3 : derived by $t_1 - t_2$ measurement and survey



result: signal comparison after Δ_{BCT} compensation

Summary of the calibration 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

±5.5 ns (CERN)

±4.2 ns (OPERA)

*from 2011 on

Distance (BCT–OPERA) = (731278.0 ± 0.2) m

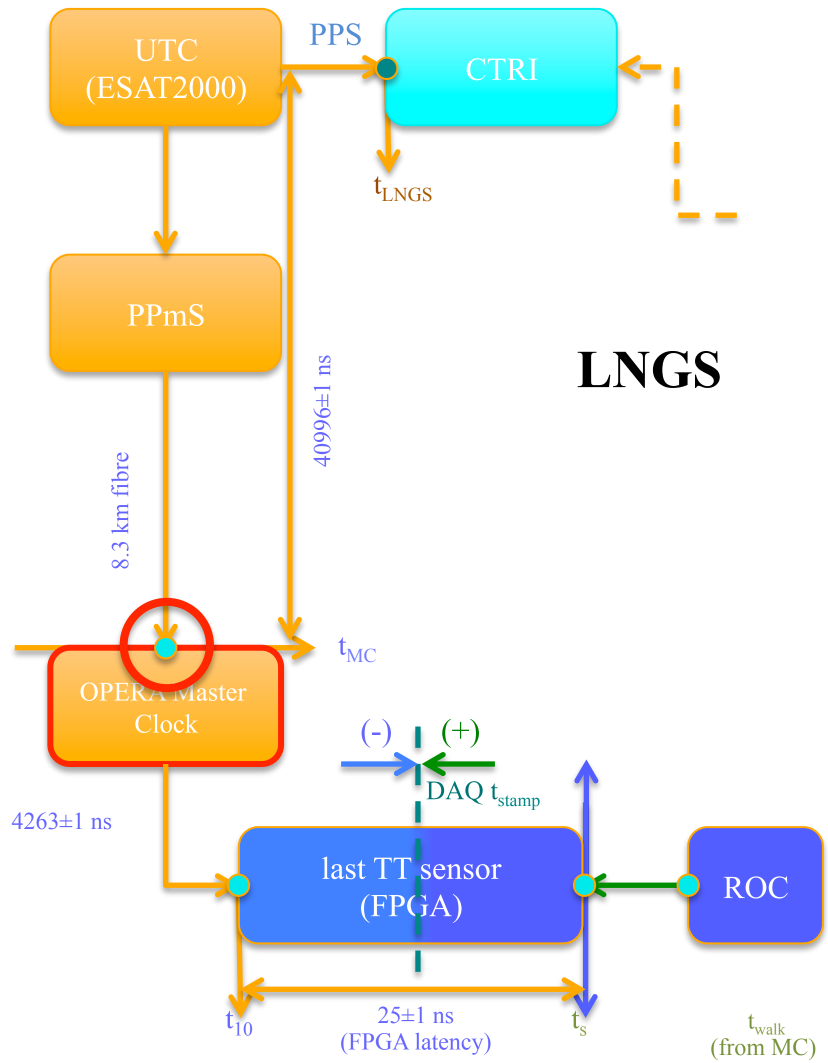
The 2 problems found after the announcement of the first result in September 2011

T. Adam et al. [arXiv:1109.4897]

New cross-checks during the Winter shutdown

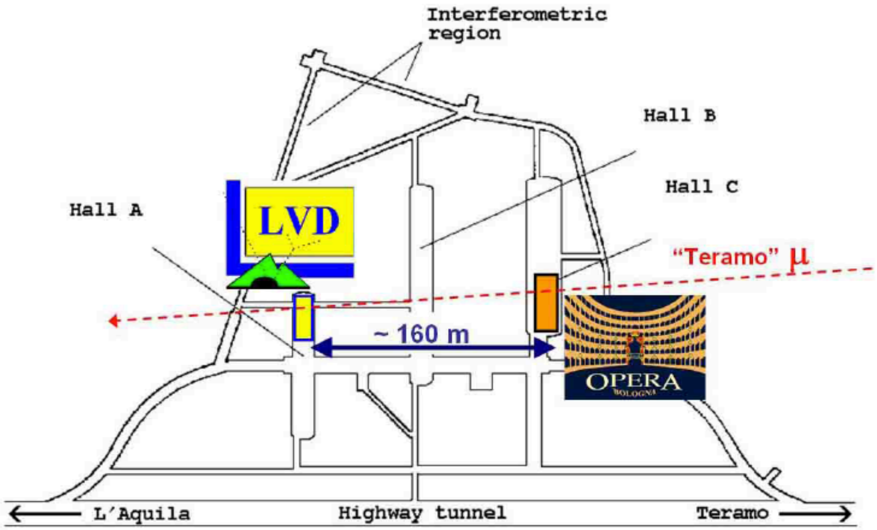
Test of the delay of 8.3 km long optical fiber and of the DAQ internal delays

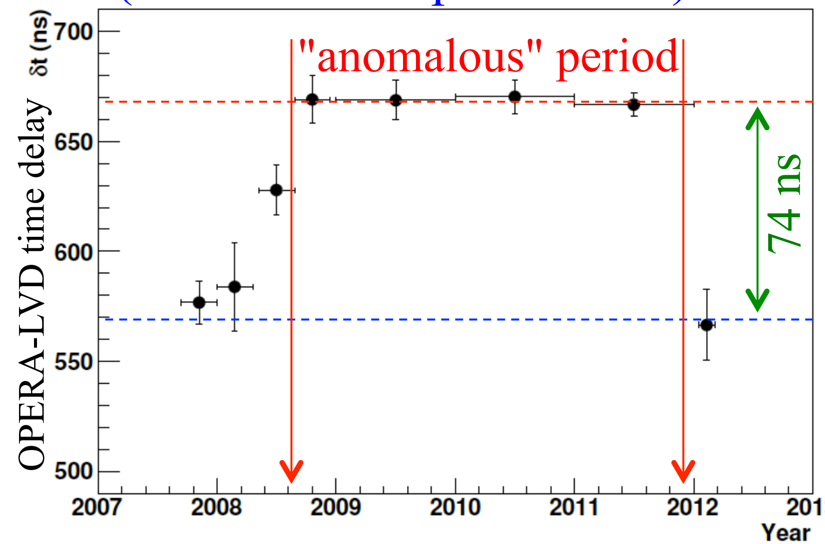
- dedicated campaign Dec11-Feb12
- Two identified issues:
  - Faulty connection of the optical fibre to the Master Clock artificially increasing the neutrino anticipation by ~74 ns.
  - Internal Master Clock frequency off by $\Delta f/f = 1.24\times10^{-7}$ (124 ns/s) artificially decreasing the neutrino anticipation by ~15 ns
    (DAQ time bin 10 ns→9.99999877 ns).
  - Time when "anomalous" conditions occurred during data taking and stability of these conditions subjected to "a special investigation"

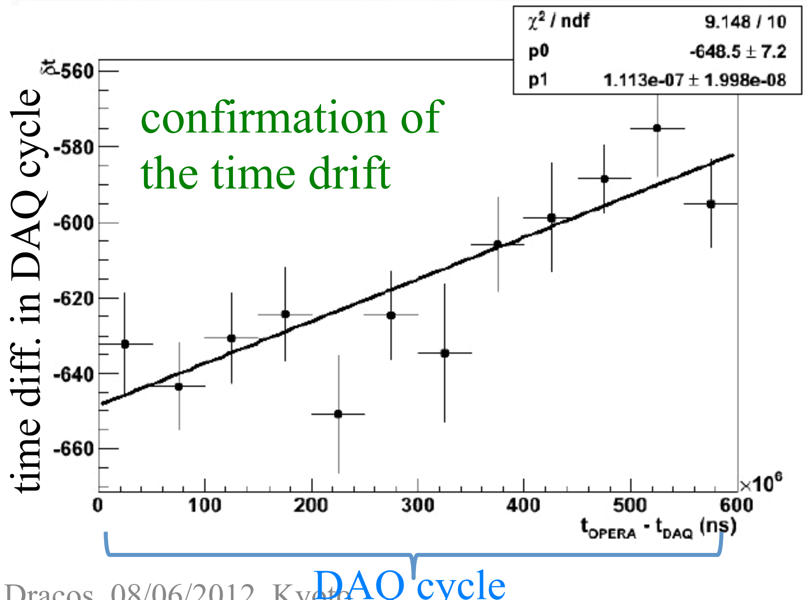


How stable were the "anomalous" conditions? (joint OPERA-LVD analysis)

Coincidences using horizontal cosmic muons (submitted for publication)







- The fiber problem started in 2008 and lasted up to end 2011 when it has been well connected to the OPERA Master Clock (considered data period: 2009-2011).
- "wrong" oscillator frequency was present all the time.
- New systematic errors on the above parameters have been extracted.

After new cross-checks

"The OPERA Collaboration, by continuing its campaign of verifications on the neutrino velocity measurement, has identified two issues that could significantly affect the reported result. The first one is linked to the oscillator used to produce the events time-stamps in between the GPS synchronizations. The second point is related to the connection of the optical fibre bringing the external GPS signal to the OPERA master clock.

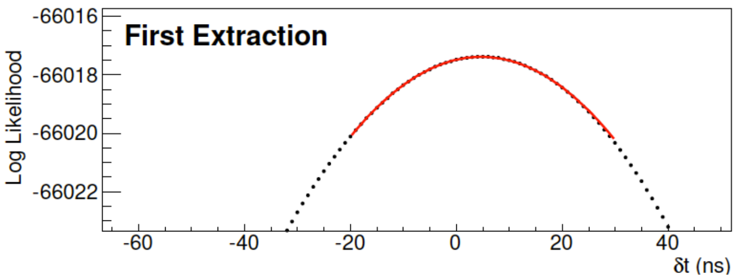
These two issues can modify the neutrino time of flight in opposite directions. While continuing our investigations, in order to unambiguously quantify the effect on the observed result, the Collaboration is looking forward to performing a new measurement of the neutrino velocity as soon as a new bunched beam will be available in 2012. An extensive report on the above mentioned verifications and results will be shortly made available to the scientific committees and agencies."

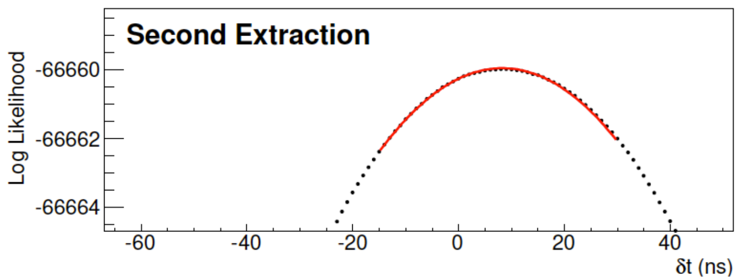
23rd of February 2012

The following 2011 results have been corrected according to the new measured parameters and new systematic errors have been evaluated.

Analysis method and new result

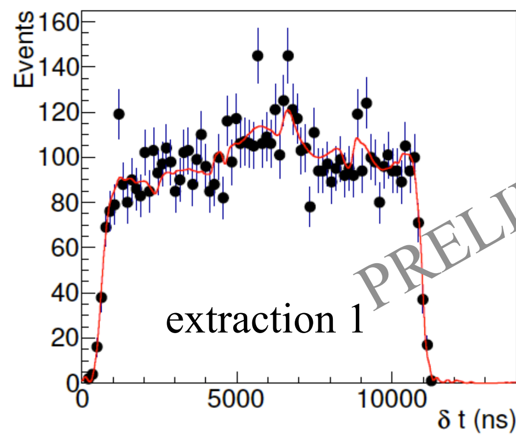
- For each neutrino event in OPERA → proton waveform of the corresponding extraction
- Sum up and normalise: → PDF w(t) → separate likelihood for each extraction

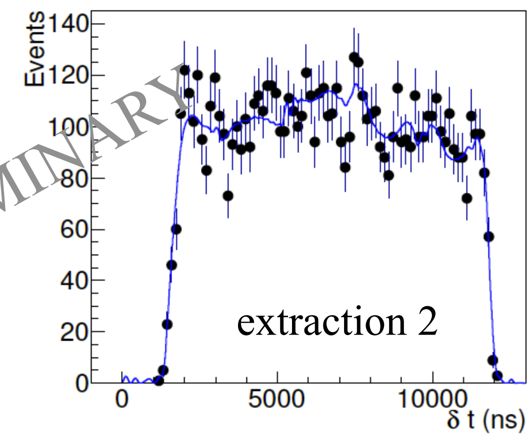




$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \quad k = 1,2 \text{ extractions}$$

- maximisation by varying $\delta t = TOF_c - TOF_\nu$
- statistical error evaluated from the log likelihood curves





- no seasonal effect,
- no day/night effect,
- no energy dependence,
- no beam intensity effect,
- no difference between, internal and external events.

(considered distance 730085 m)

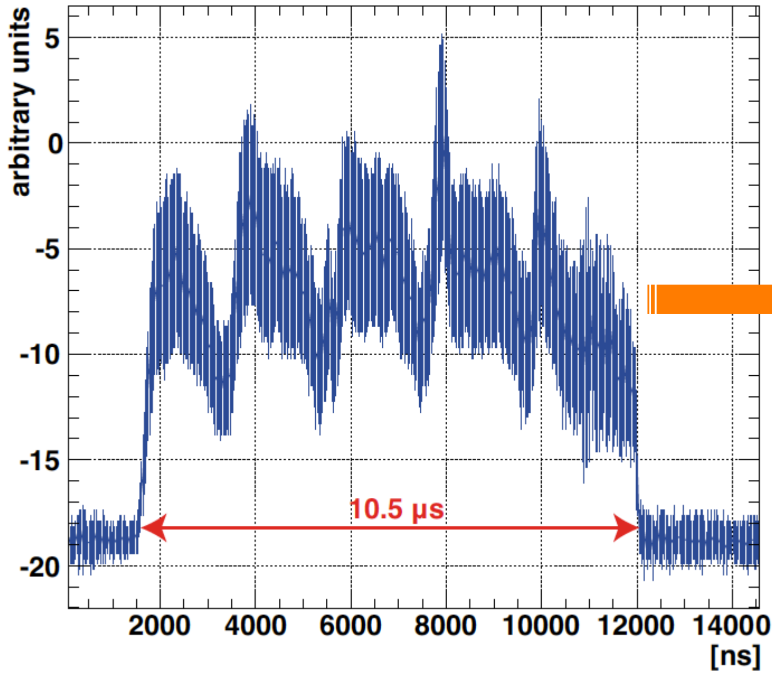
$$\delta t = TOF_c - TOF_\nu = \left(6.5 \pm 7.4\ (stat.)^{+9.2}_{-6.8}\ (sys.)\right) \text{ ns}$$

$$\frac{v-c}{c} = \frac{\delta t}{TOF'_c - \delta t} = (2.7 \pm 3.1\ (\text{stat.})^{+3.8}_{-2.8}\ (\text{sys.})) \times 10^{-6}$$

(positive δt means neutrino anticipation)

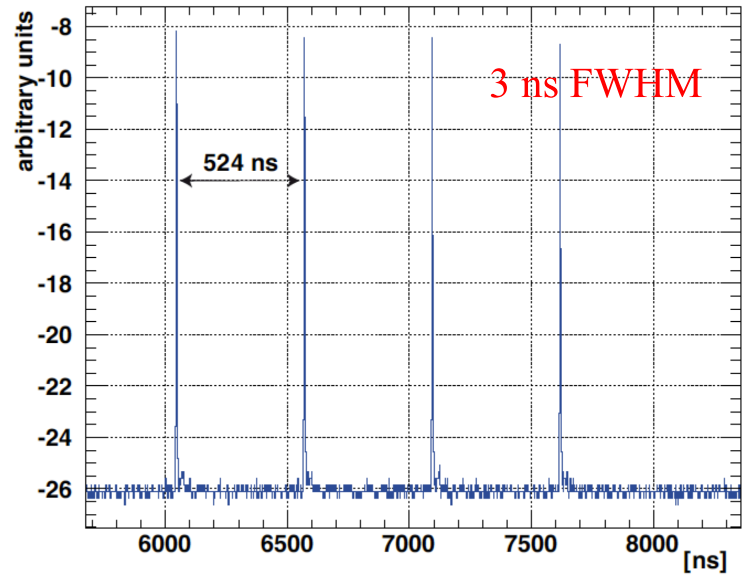
Test with a short-bunch wide-spacing proton beam

2009-2011



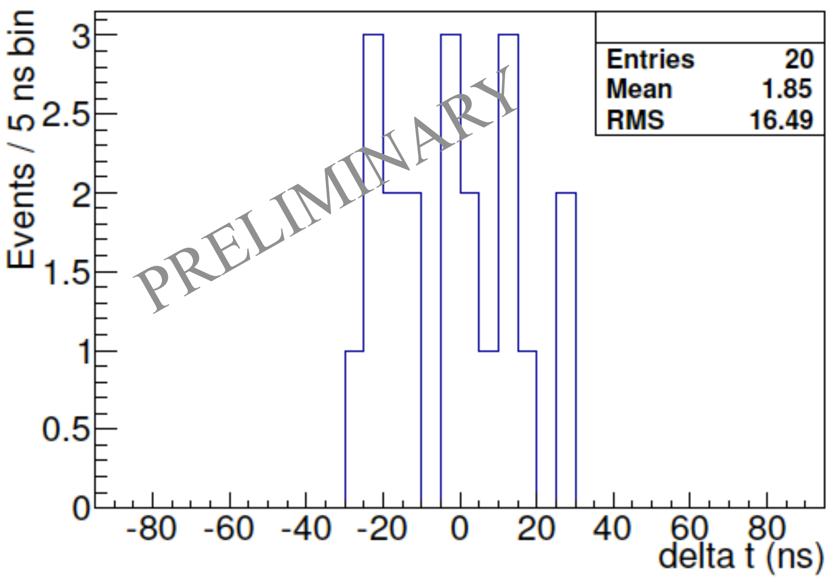
- statistical method for TOF_ν extraction
- ~10^{20} pot
- 7235 internal events
- 7988 external events

October 22 to November 6 (2011)



- TOF_ν for each detected neutrino
- 4×10^{16} pot
- 6 internal events
- 14 external events
- events evenly distributed in the four bunches of the extraction
- mode not compatible with OPERA oscillation program.

Test with a short-bunch wide-spacing proton beam



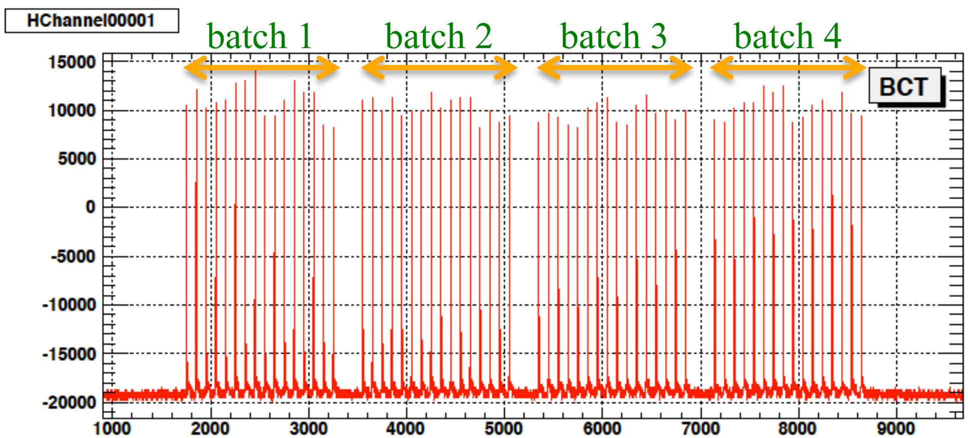
- with TT
- 20 events
- δt=1.9±3.7 ns (same syst. errors)

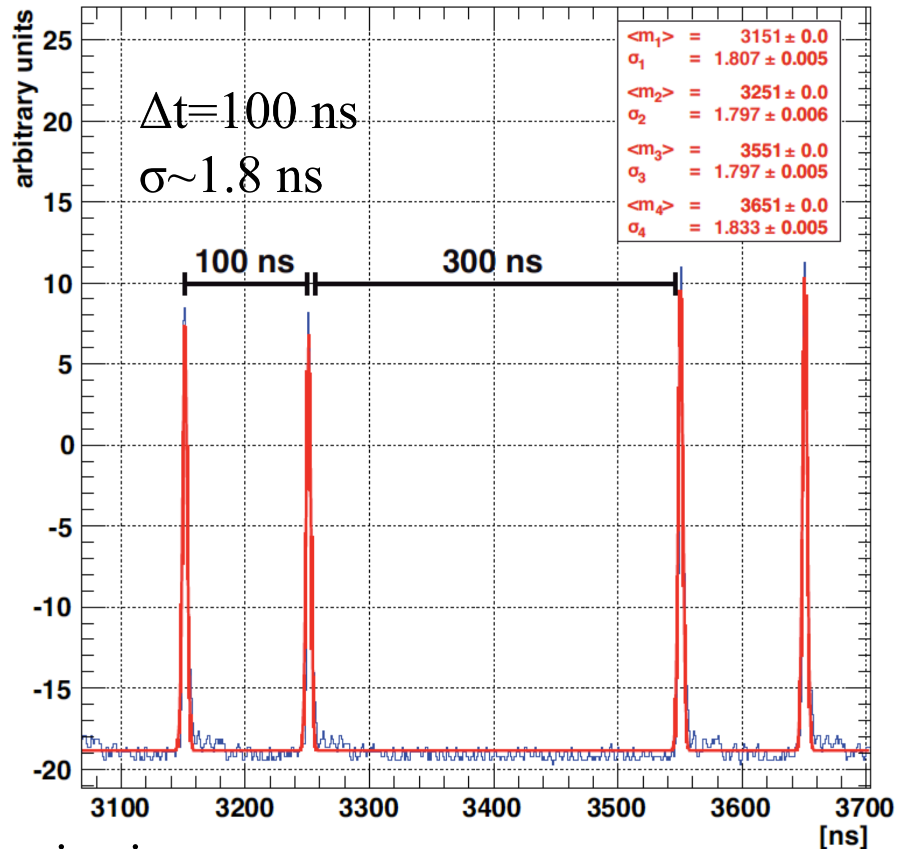
- In agreement with the previous value (6.5±7.4 ns)
- Excludes possible biases affecting the statistical analysis based on the proton PDF.
- Indicates the absence of significant biases due to:
  - the cumulative response of the beam line to long proton pulses
  - pulse duration effects in the BCT response.

T. Adam et al. [arXiv:1109.4897] soon revised and resubmitted to JHEP

New measurements with a short-bunch narrow-spacing proton beam (2012)

10 to 24 May 2012





- 1 extraction per CNGS cycle
- 4 batches per extraction
- 16 bunches per batch
- p.o.t.: ~2 x 10^{17} (2 weeks)
- CERN White Rabbit system for delay monitoring
- **improved OPERA timing system (including both TT and RPC)**
- **106 on time events (external + contained)**

New calibration delays

Item	Result	Method
CERN UTC distribution (GMT)	10077.8 ± 1 ns	• Portable Cs • Two-ways
WFD trigger	26.6 ± 1 ns	Scope
BTC delay	583.7 ± 1 ns	• Portable Cs • Dedicated beam experiment
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement
LNGS UTC distribution (fibers)	41067 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	7046 ± 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

±1.8 ns (CERN)

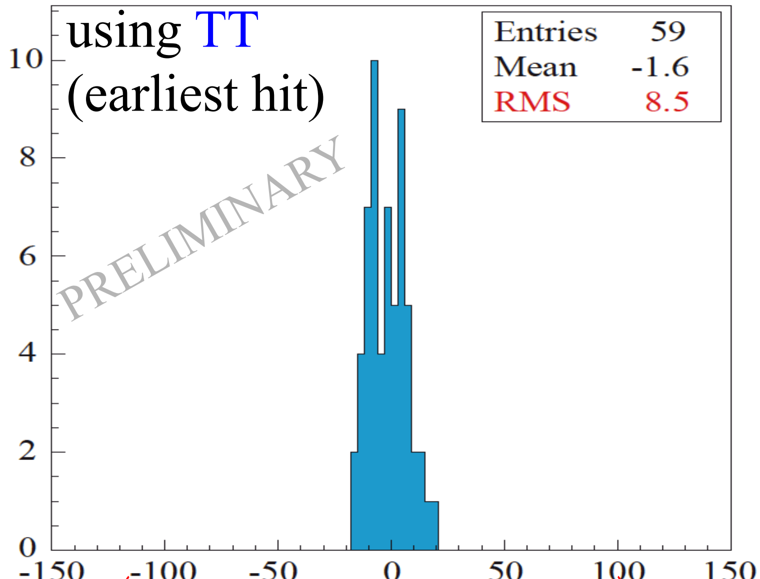
±4.2 ns (OPERA)

PRELIMINARY

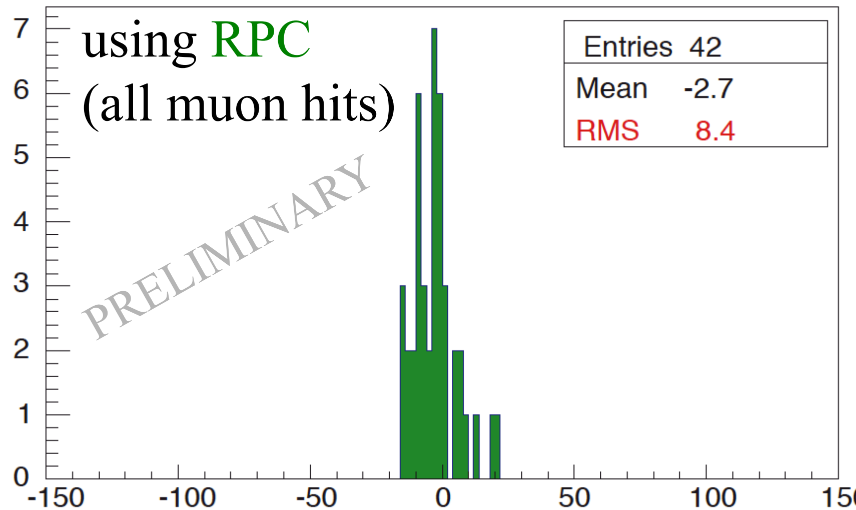
Distance (BCT–OPERA) = (731278.0 ± 0.2) m

New OPERA preliminary results

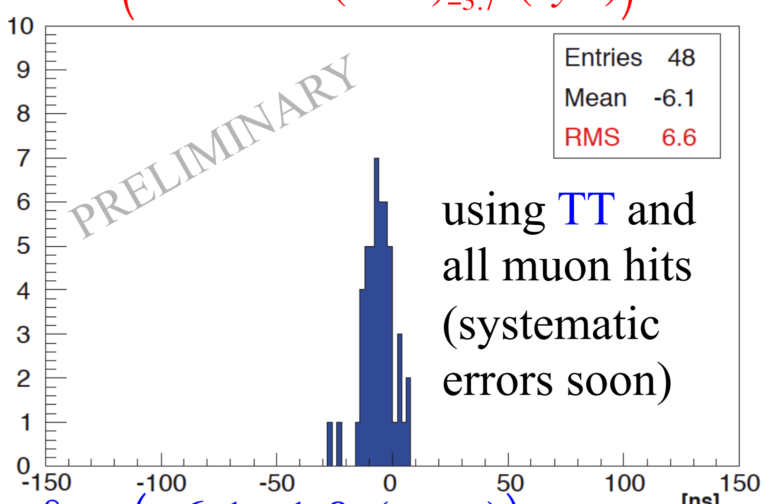
(with new BCT values)



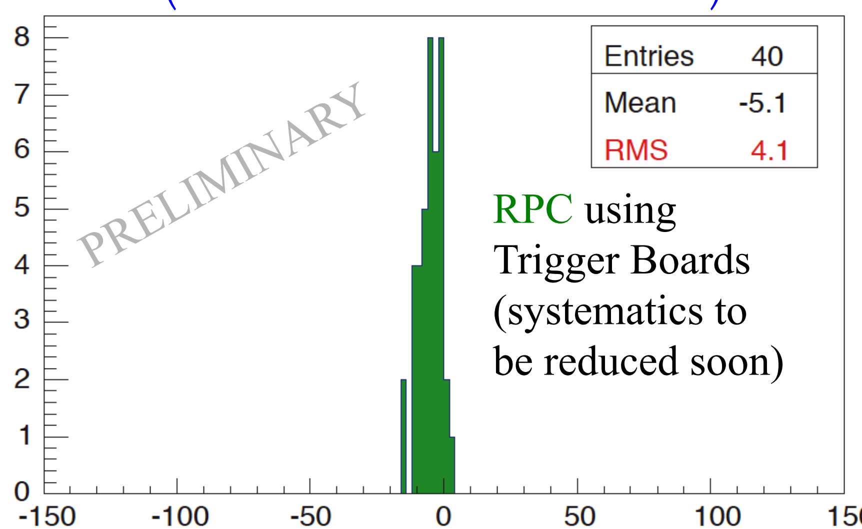
$$\delta t = \left(-1.6 \pm 1.1\ (stat.)^{+6.1}_{-3.7}\ (sys.)\right)\ \text{ns}$$



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



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



$$\delta t = \left(-5.1 \pm 0.6\ (stat.)^{+6.5}_{-5.1}\ (sys.)\right)\ \text{ns}$$

Conclusions

- OPERA has updated the already announced result.
- The two issues found affecting the previous analysis have been understood and new systematic errors have been evaluated.
- A new short-bunch narrow-spacing proton beam run has just finished.
- The new preliminary result from 2012 data is:

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

$$\frac{v-c}{c} = \frac{\delta t}{TOF_c - \delta t} = (-0.7 \pm 0.5\ (\text{stat.})^{+2.5}_{-1.5}\ (\text{sys.})) \times 10^{-6}$$

compatible with the 2011 revised results.

- Results to be published soon.

Thank you