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

Antonio Ereditato

University of Bern

On behalf of the OPERA Collaboration

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

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

Principle of the neutrino velocity measurement

Definition of neutrino velocity:

ratio of precisely measured baseline and time of flight

Time of flight measurement:

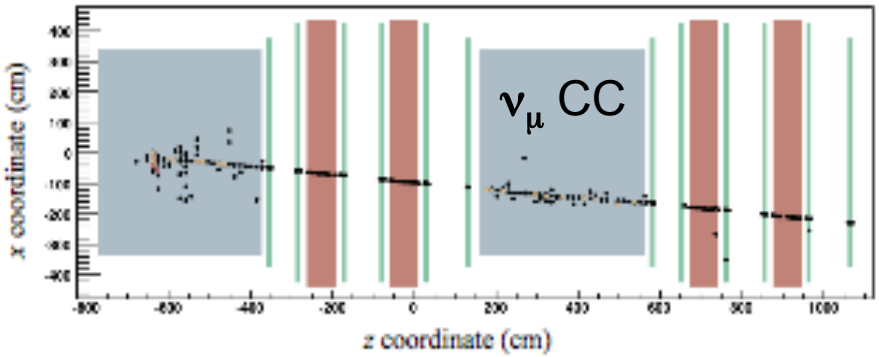
tagging of neutrino production time
tagging of neutrino interaction time by a far detector

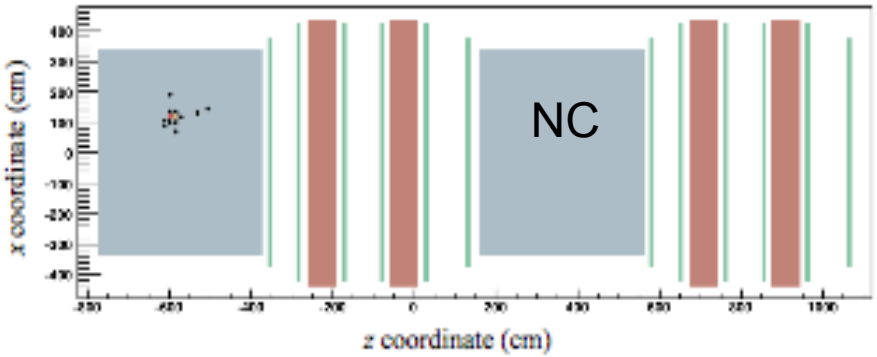
accurate determination of the baseline (geodesy)

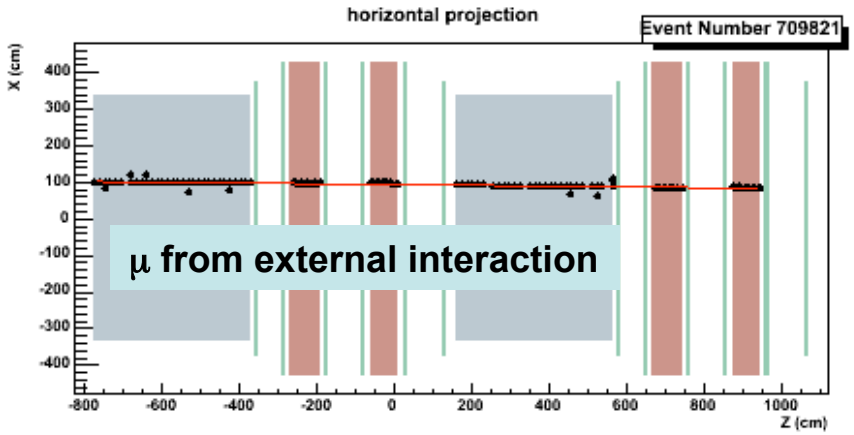
expected small effects: long baseline required

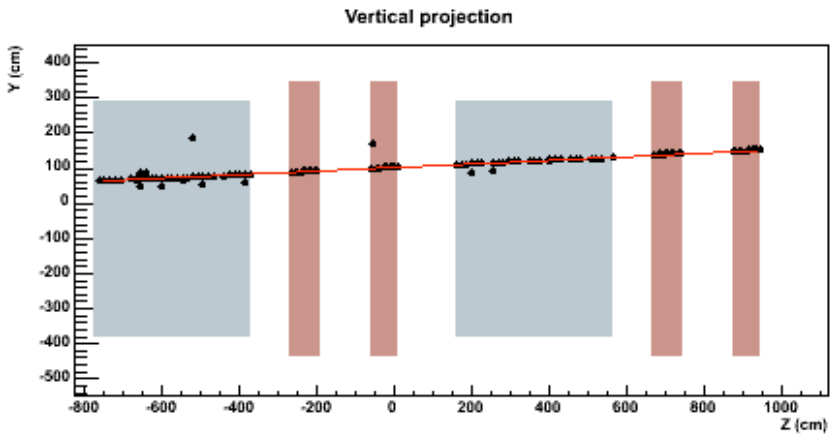
blind analysis: “box” opened after adequate level of systematic errors was reached

“INTERNAL” and “EXTERNAL” OPERA EVENTS

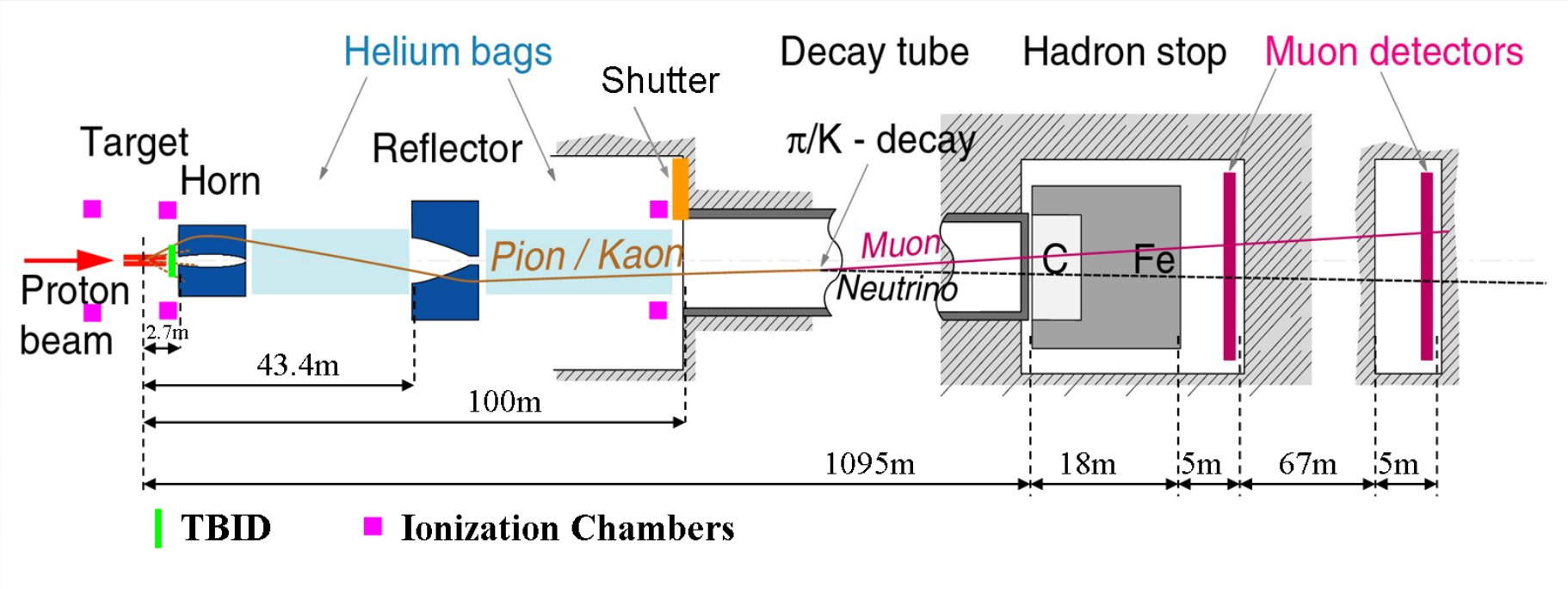








THE CNGS neutrino beam



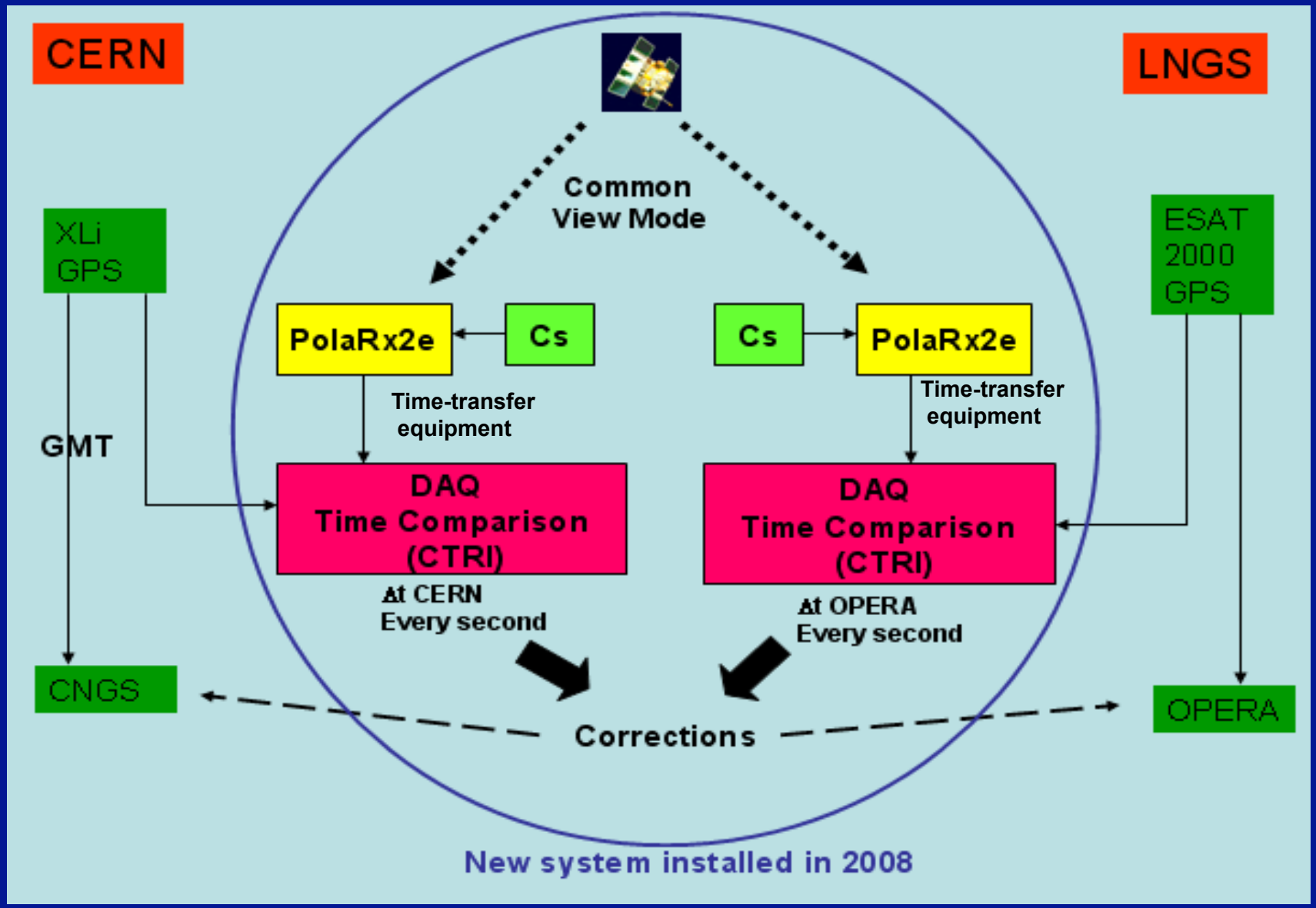
- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5 μs extractions (by kicker magnet) separated by 50 ms
- Beam intensity: 2.4 x10^{13} proton/extraction
- ~ pure muon neutrino beam (<E> = 17 GeV) travelling through the Earth's crust

OPERA sensitivity

- High neutrino energy - high statistics ~16000 events
- Sophisticated timing system: ~1 ns CNGS-OPERA synchronisation
- Accurate calibrations of CNGS and OPERA timing chains: ~ 1 ns level
- Precise measurement of neutrino time distribution at CERN through proton waveforms
- 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

CNGS-OPERA synchronization



GPS common-view mode

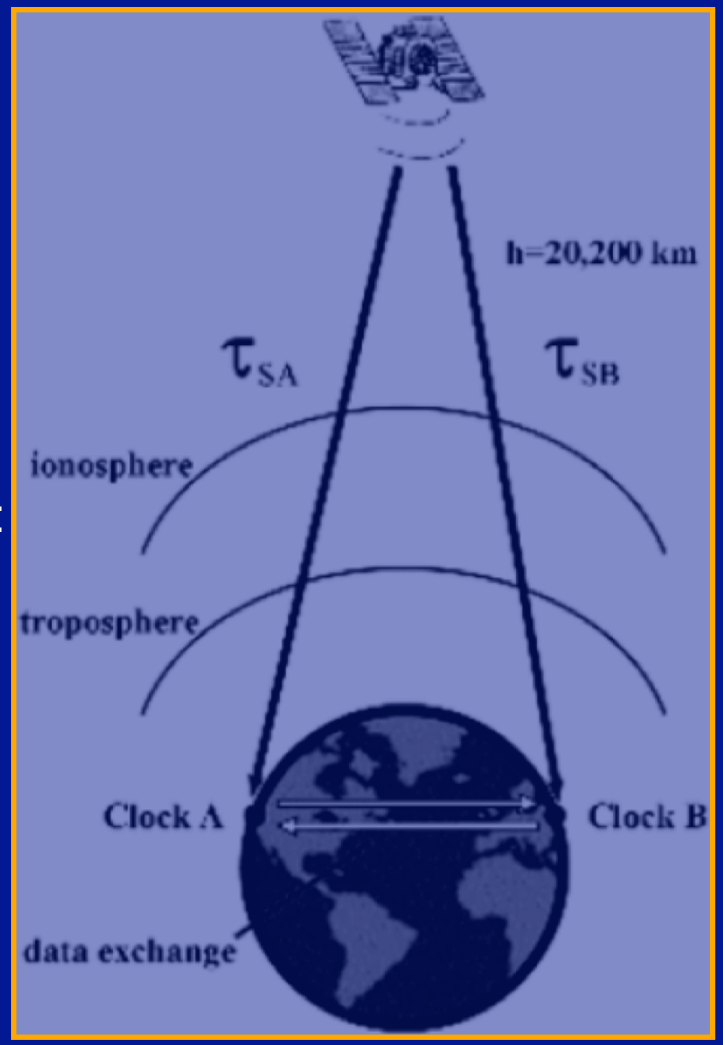
Standard GPS operation:

resolves x, y, z, t with ≥ 4 satellite observations

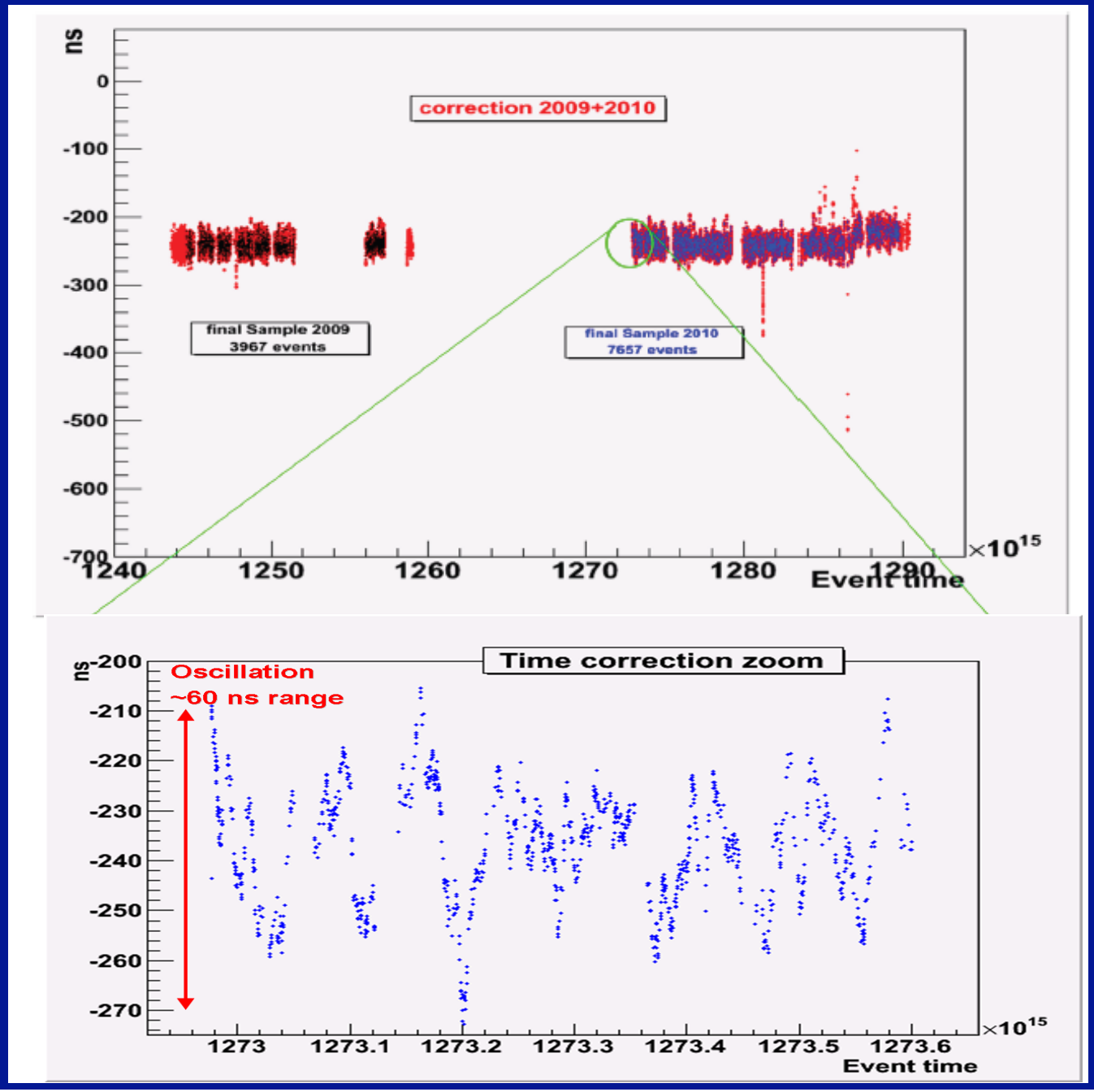
Common-view mode (the same satellite for the two sites, for each comparison):

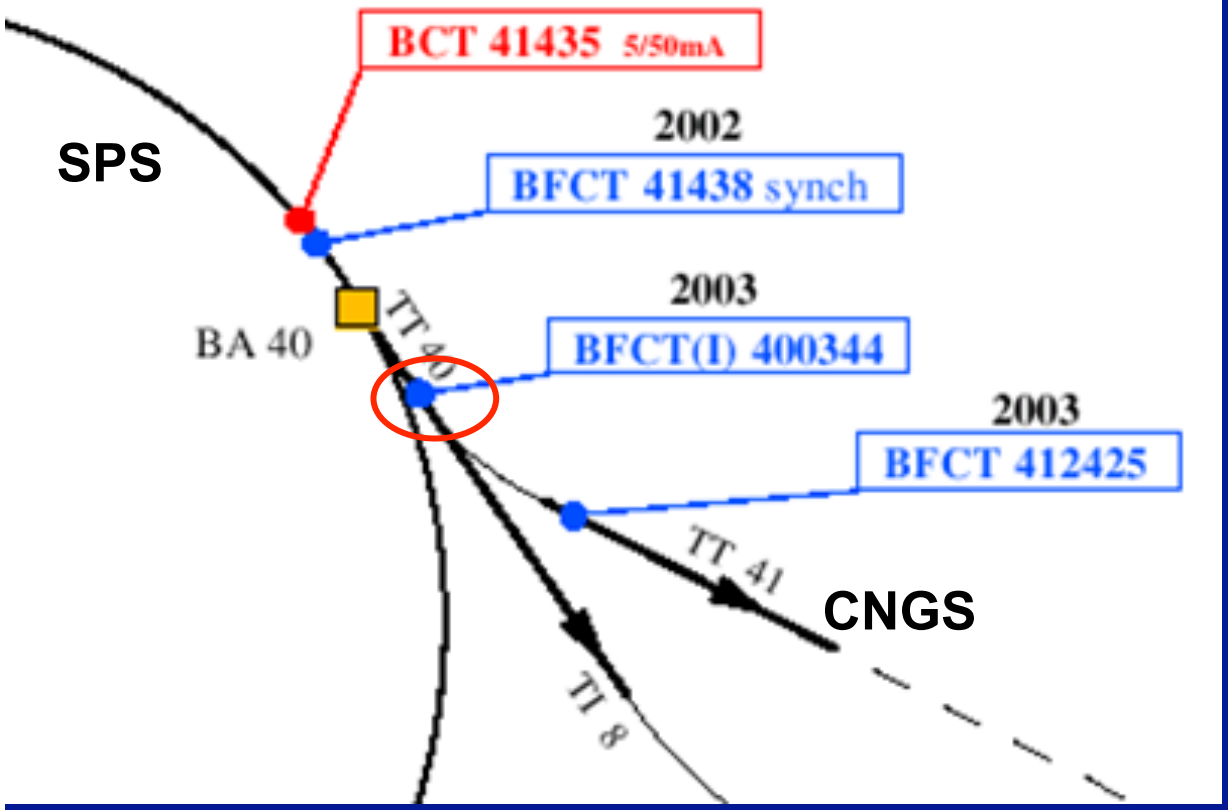
x, y, z known from former dedicated measurements: determine time differences of local clocks (both sites) w.r.t. the satellite, by offline data exchange

730 km << 20000 km (satellite height) → similar paths in ionosphere



Result: TOF time-link correction (event by event)





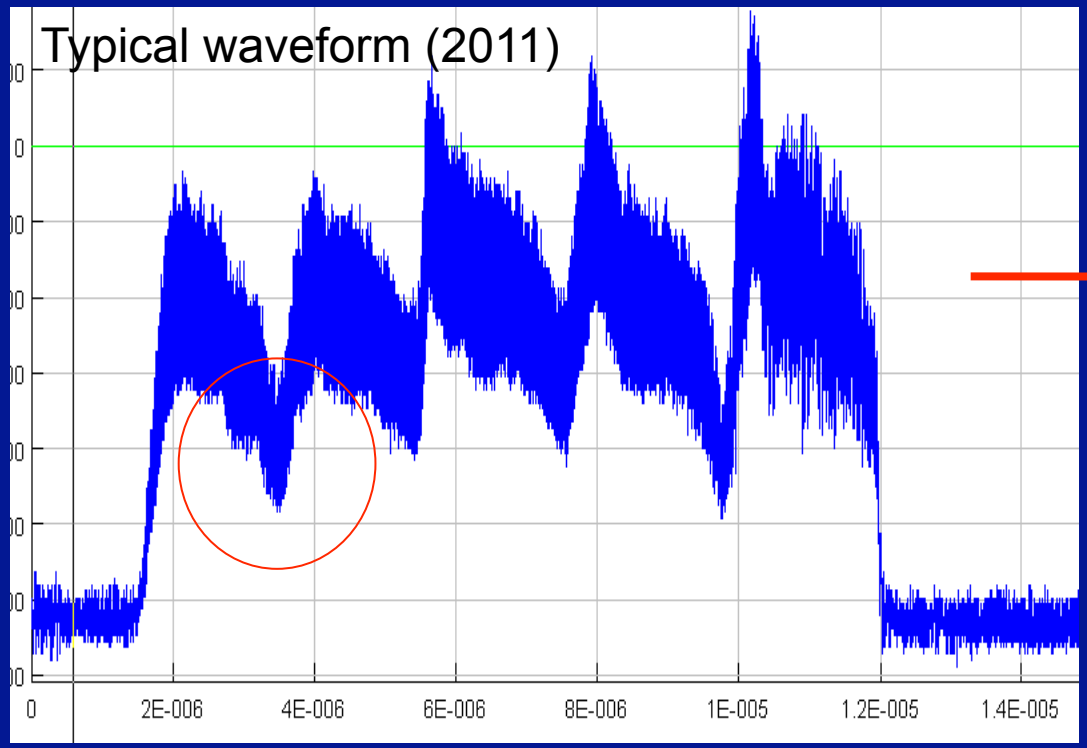
Proton timing by Beam Current Transformer

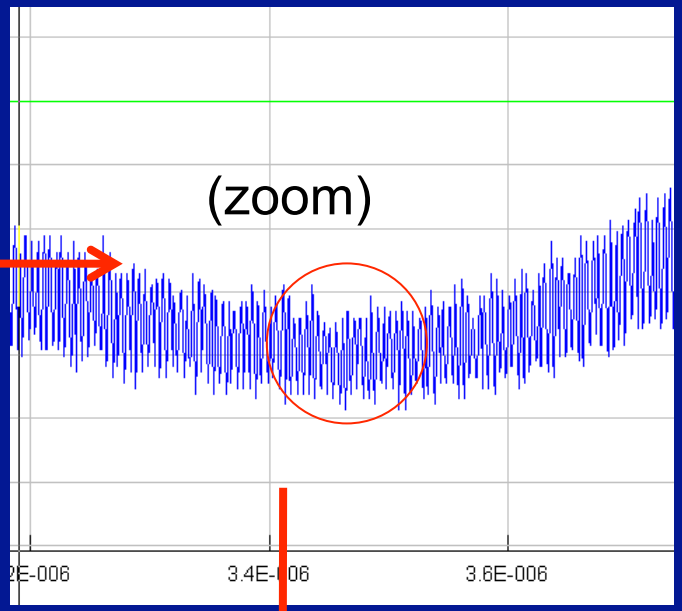
Fast BCT 400344
(~ 400 MHz)

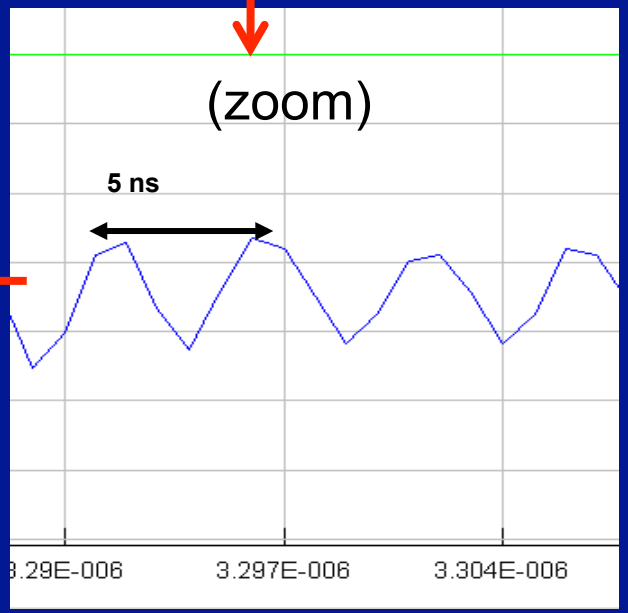
Proton pulse digitization:

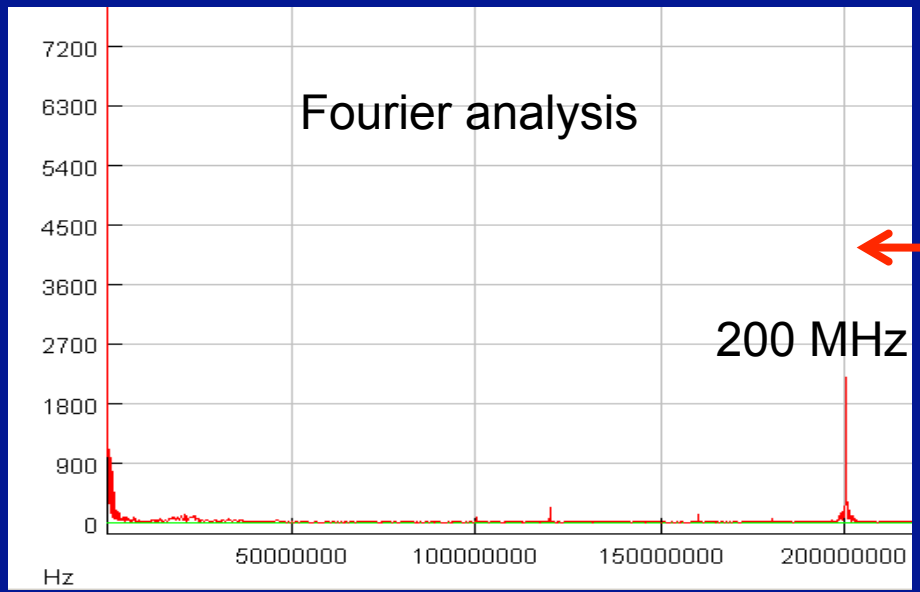
- Acqiris DP110 1GS/s waveform digitizer (WFD)
- WFD triggered by a replica of the kicker signal
- Waveforms UTC-stamped and stored in CNGS database for offline analysis

2010 calibration with Cs clock


Typical waveform (2011)
0
2E-006
4E-006
6E-006
8E-006
1E-005
1.2E-005
1.4E-005


(zoom)
3.4E-006
3.6E-006


(zoom)
5 ns
3.297E-006
3.304E-006

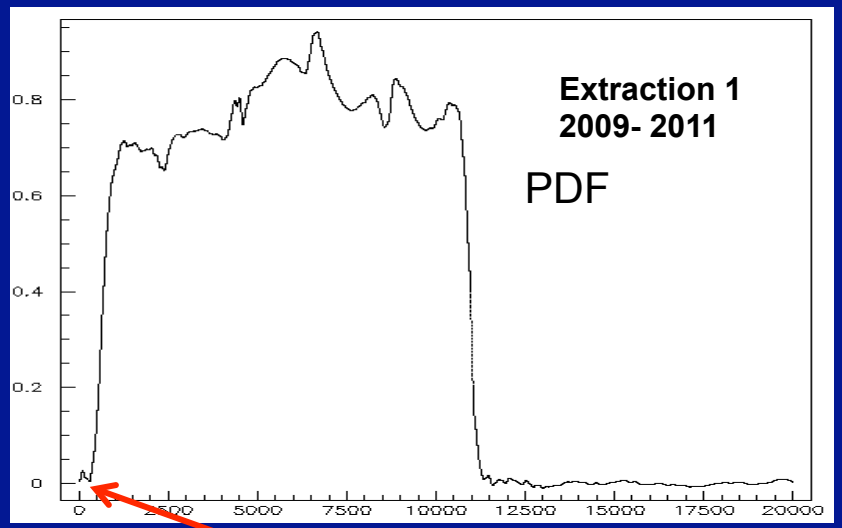

Fourier analysis
200 MHz
7200
6300
5400
4500
3600
2700
1800
900
0
50000000
100000000
150000000
200000000
Hz

Neutrino event-time distribution PDF

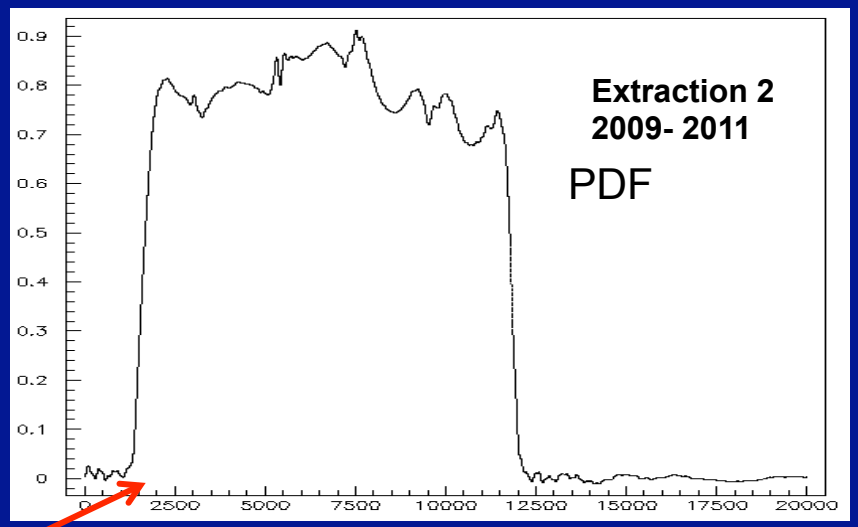
- Each event is associated to its proton spill waveform
- The "parent" proton is unknown within the 10.5 μs extraction time

→ normalized waveform sum: PDF of predicted time distribution of neutrino events

→ compare to OPERA detected neutrino events



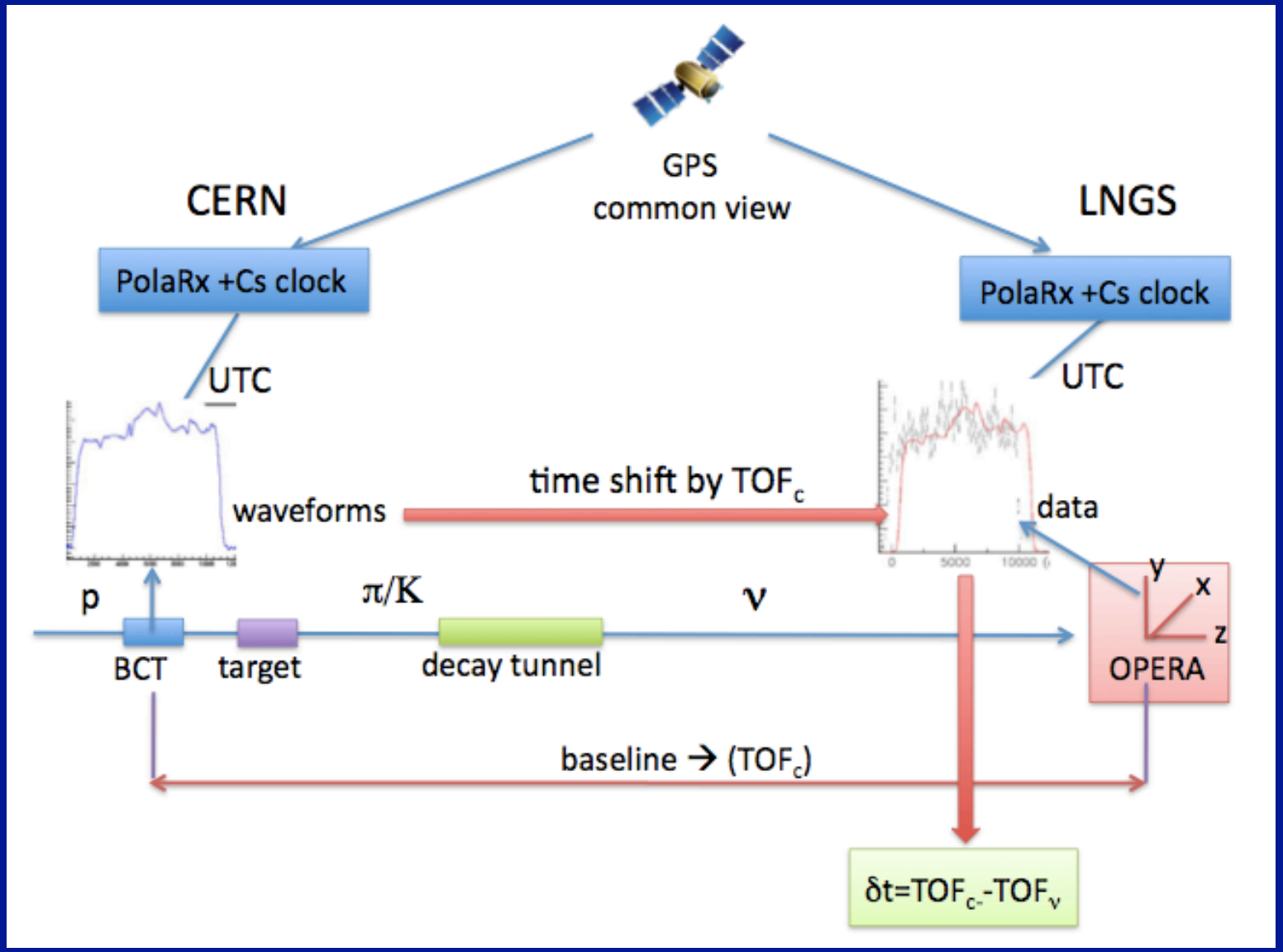
(ns)



(ns)

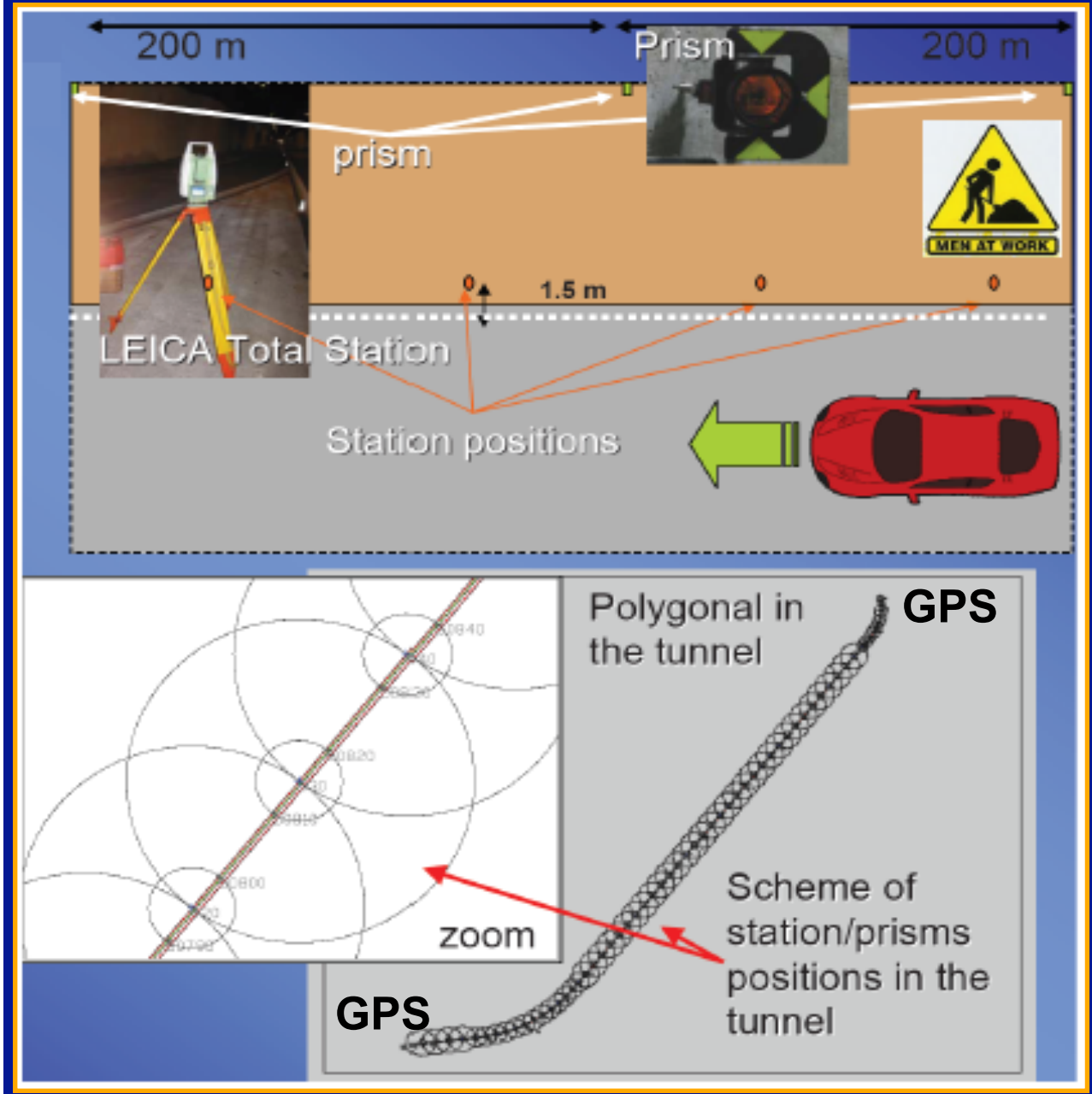
different timing w.r.t. kicker magnet signal

Summary of the principle for the TOF measurement



Measure $\delta t = TOF_c - TOF_\nu$

Geodesy at LNGS



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

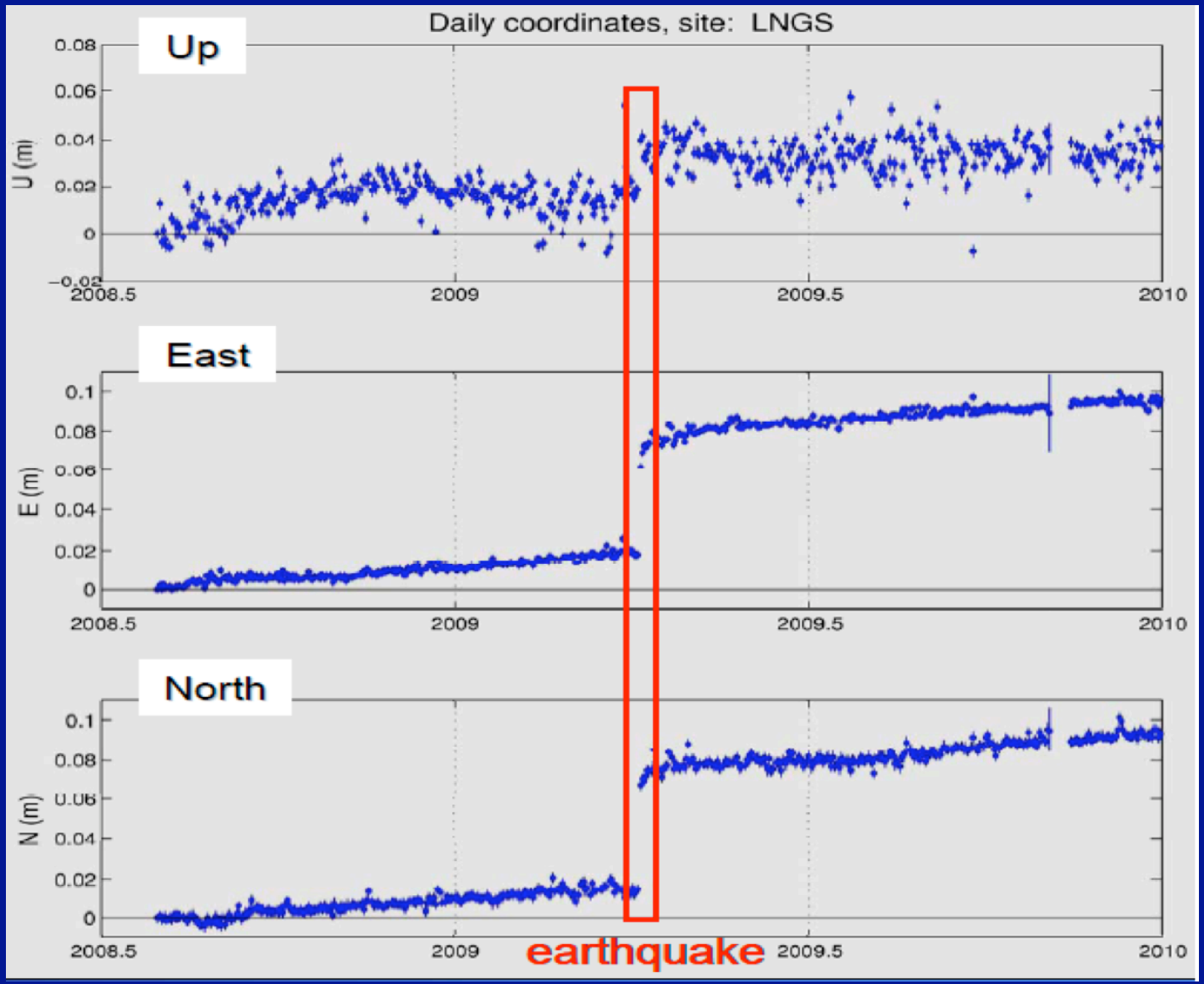
2 new GPS benchmarks on each side of the 10 km highway tunnel

GPS measurements ported underground to OPERA

Resulting distance (BCT–OPERA reference frame)

(731278.0 ± 0.2) m

LNGS position monitoring



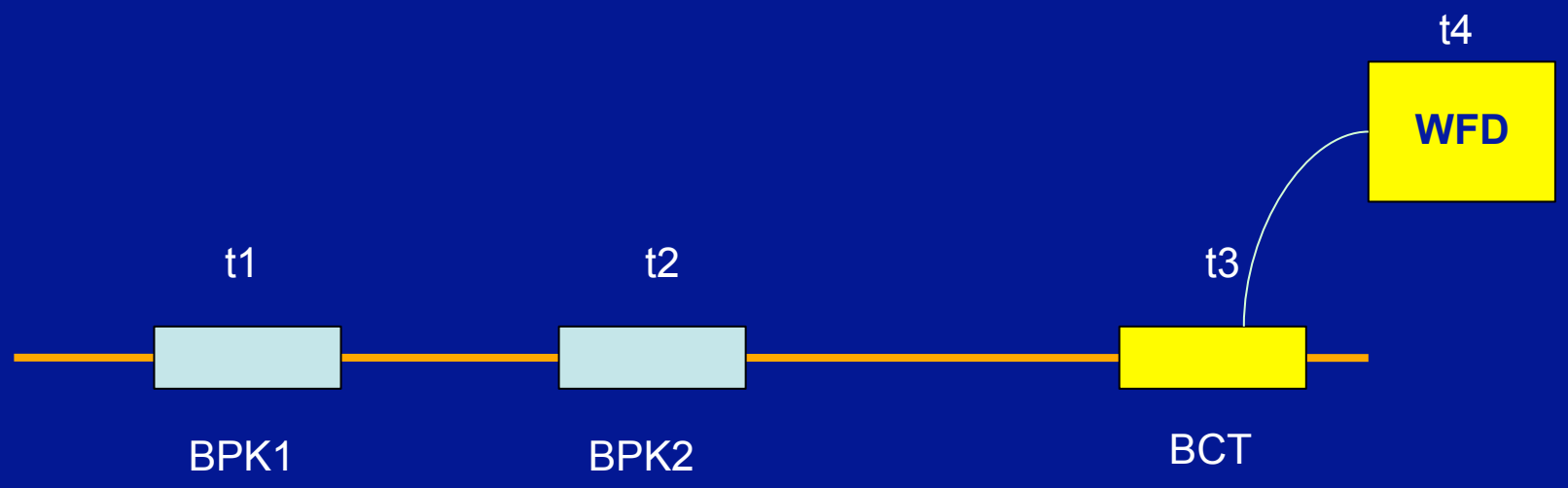
Monitor continent drift and important geological events (e.g. 2009 earthquake)

BCT calibration (1)

Dedicated beam experiment:

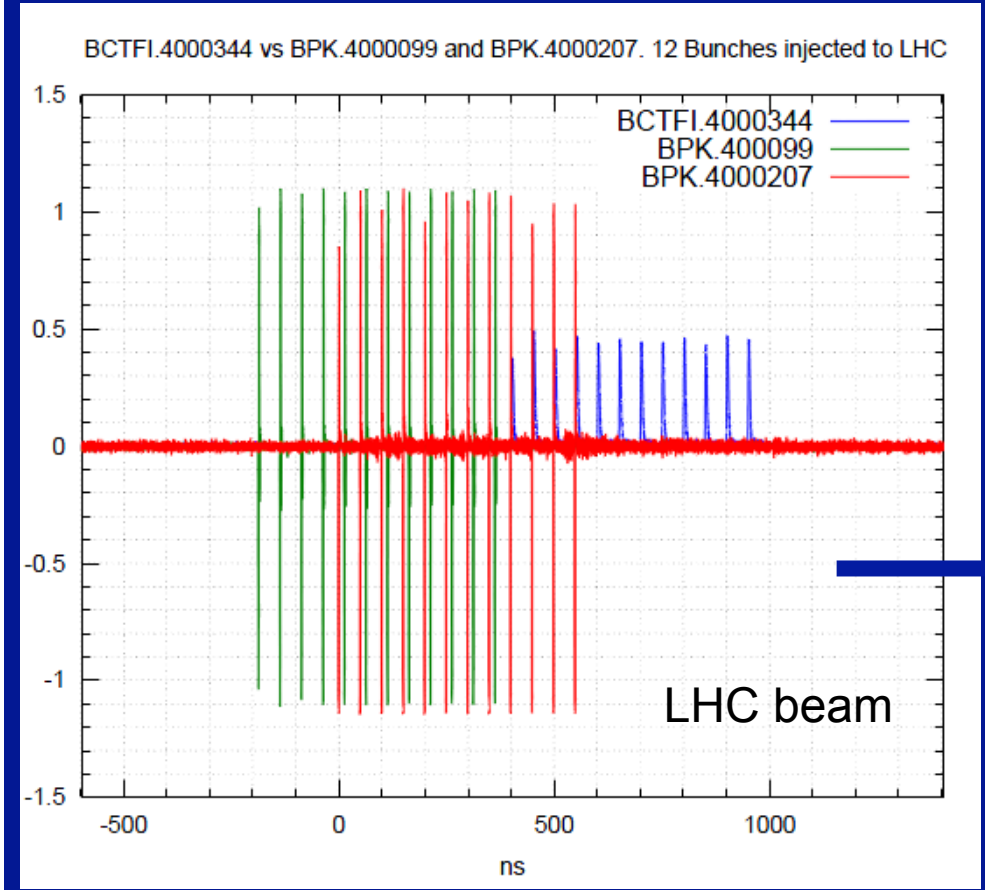
BCT plus two pick-ups (~1 ns) with LHC beam (12 bunches, 50 ns spacing)

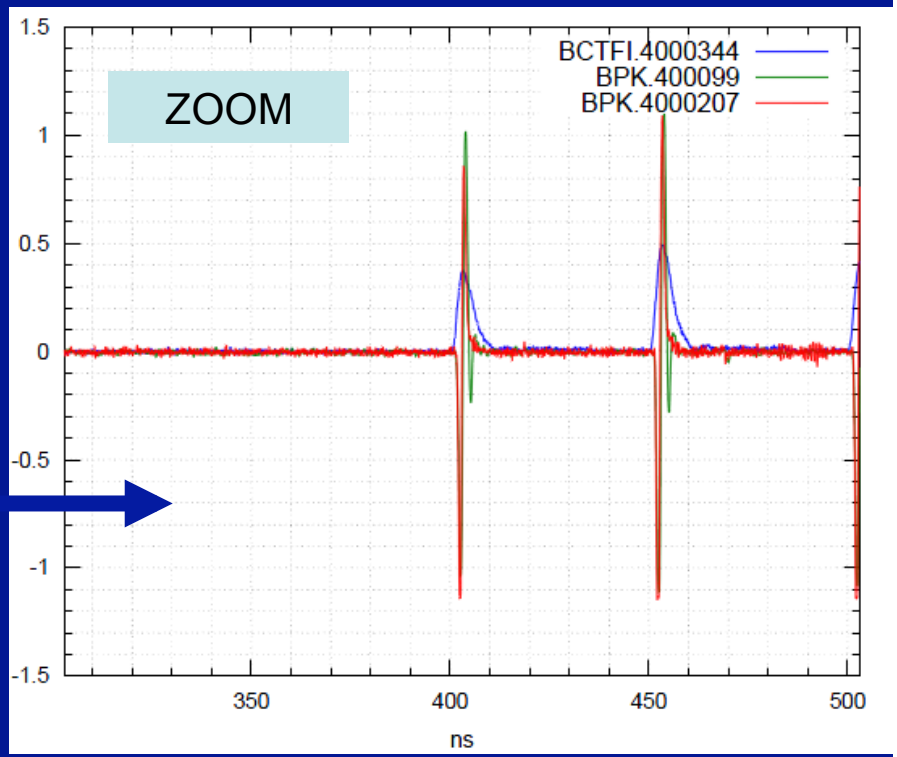
$$\Delta t_{BCT} = t4 - t3 = (580 \pm 5)\ \text{ns}$$



t3 : derived by t1 - t2 measurement and survey

BCT calibration (2)



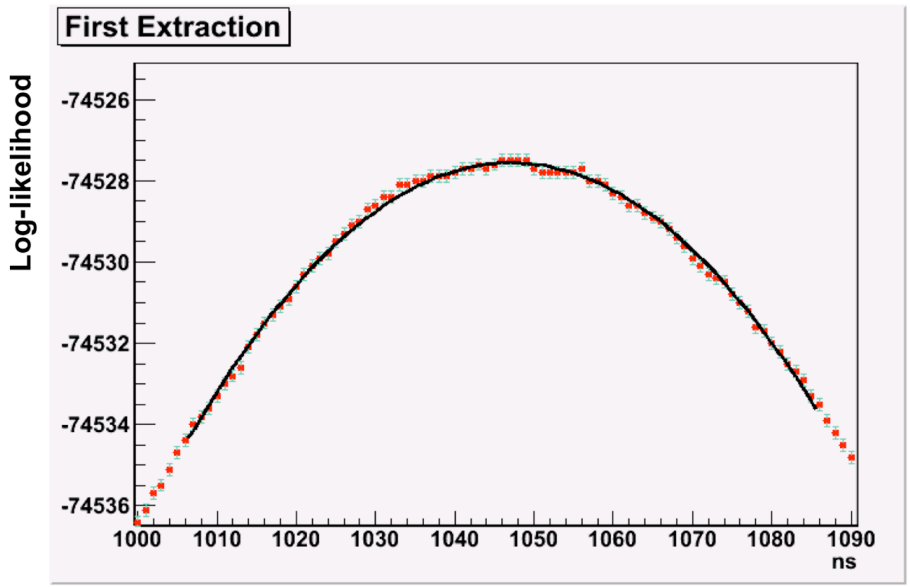


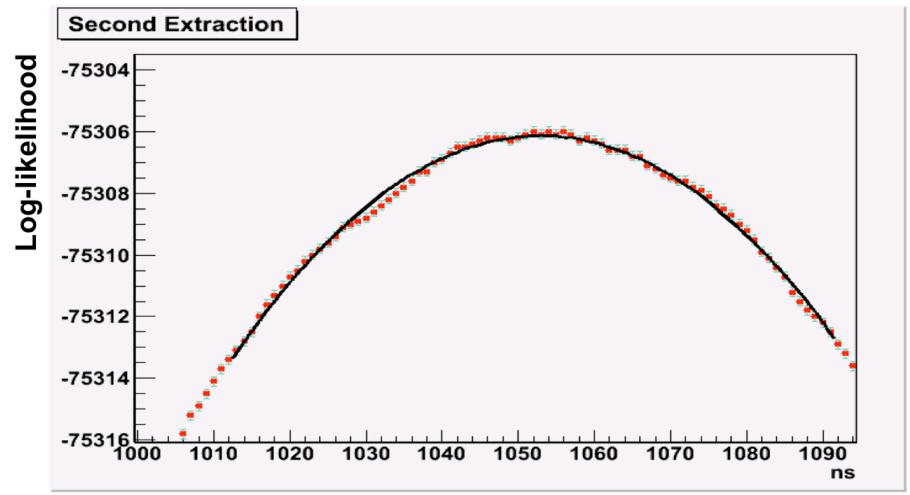
result: signals comparison after Δ_{BCT} compensation

Analysis method

For each neutrino event in OPERA → proton extraction waveform

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





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

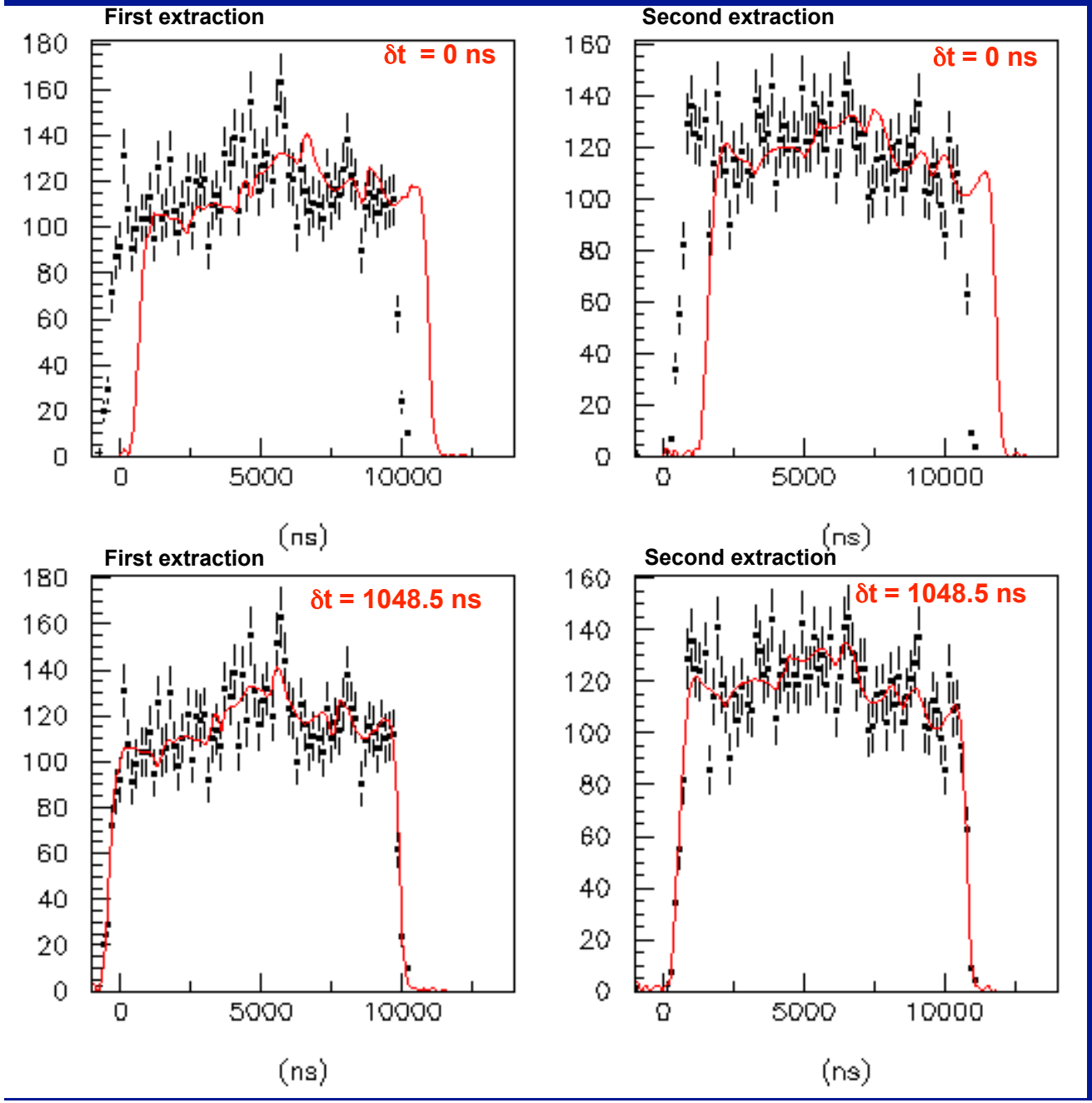
Maximised versus δt:

$\delta t = TOF_c - TOF_\nu$

Positive (negative) δt → neutrinos arrive earlier (later) than light

statistical error evaluated from log likelihood curves

Data vs PDF: before and after likelihood result



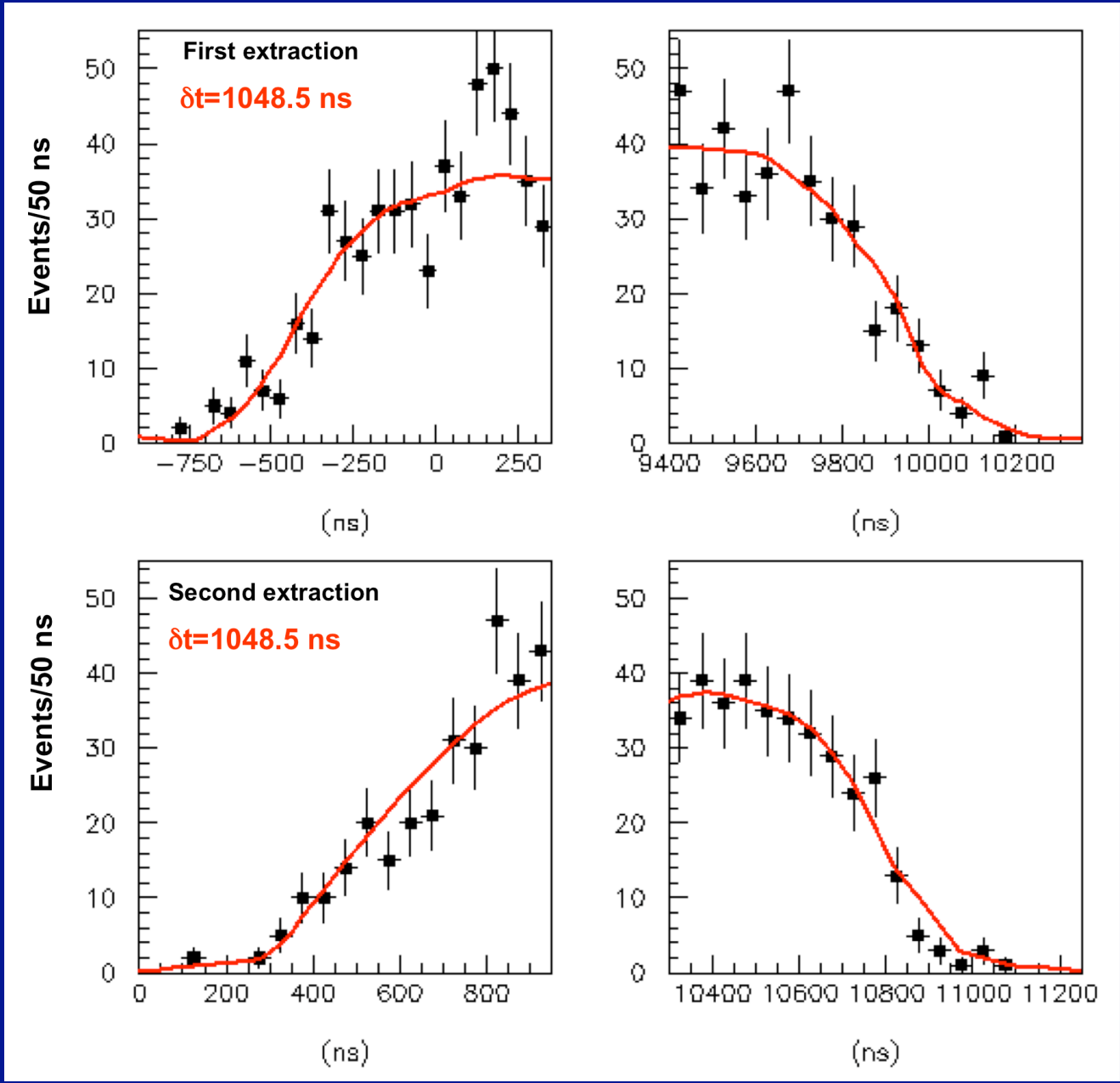
(BLIND) $\delta t = TOF_c - TOF_\nu =$

(1048.5 ± 6.9) ns (stat)

χ^2 / ndof :

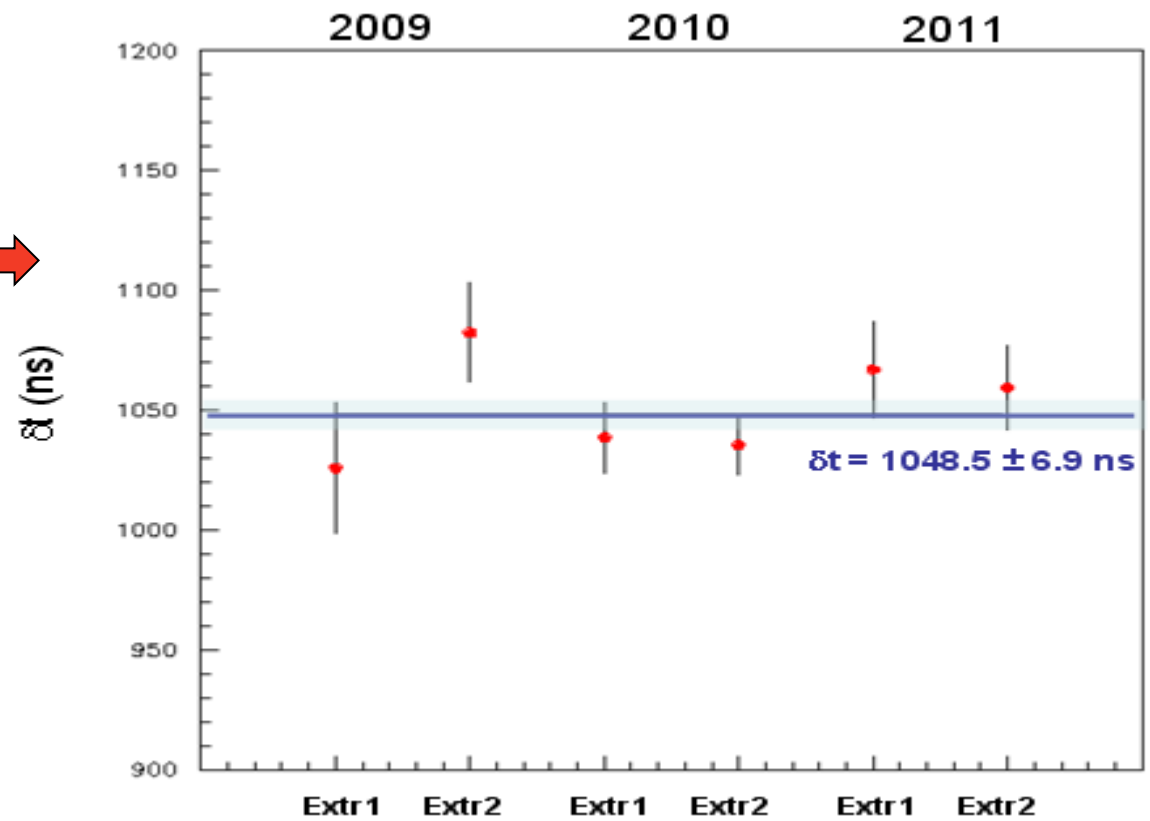
first extraction: 1.06
second extraction: 1.12

Zoom on the extractions leading and trailing edges



Analysis cross-checks

1) Coherence among CNGS runs/extractions



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

|d-n|: (17.1 ± 15.5) ns

|(spring+fall) – summer|: (11.3 ± 14.3) ns

3) Internal vs external events:

All events: δt (blind) = TOF_c -TOF_ν = (1048.5 ± 6.9 (stat.)) ns

Internal events only: (1047.4 ± 11.2 (stat.)) ns

Opening the box

timing and baseline corrections

	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**

systematic uncertainties

Systematic uncertainties	**ns**
Baseline (20 cm)	0.67
Decay point	0.2
Interaction point	2
UTC delay	2
LNGS fibres	1
DAQ clock transmission	1
FPGA calibration	1
FWD trigger delay	1
CNGS-OPERA GPS synchronization	1.7
MC simulation (TT timing)	3
TT time response	2.3
BCT calibration	5
Total uncertainty (in quadrature)	**7.4**

Results

For CNGS ν_μ beam, <E> = 17 GeV:

$\delta t = TOF_c - TOF_\nu =$

(1048.5 ± 6.9 (stat.)) ns – 987.8 ns = (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns

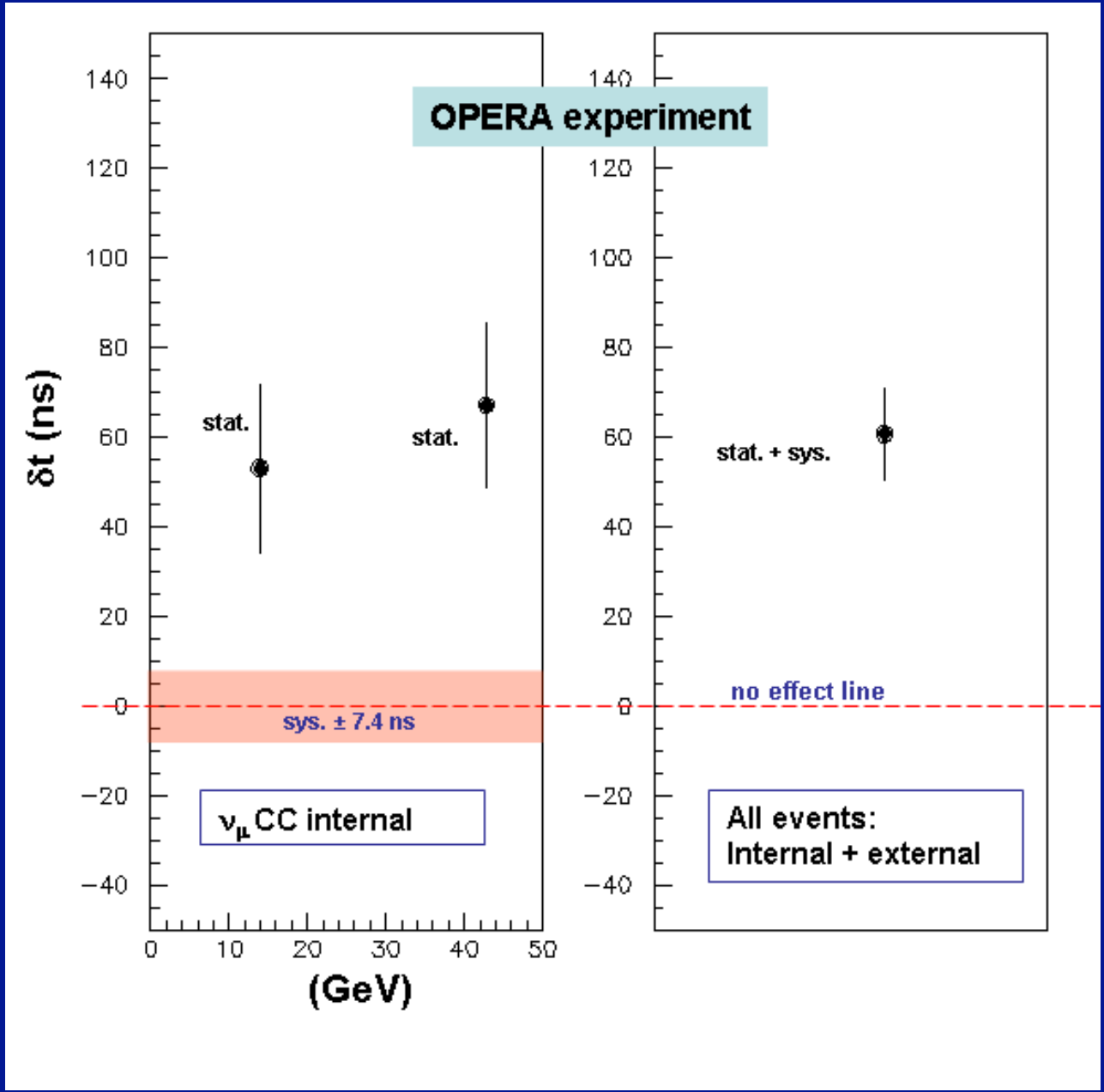
relative difference of neutrino velocity w.r.t. *c:*

$(v-c)/c = \delta t / (TOF_c - \delta t) = (2.49 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$

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

6.0 σ significance

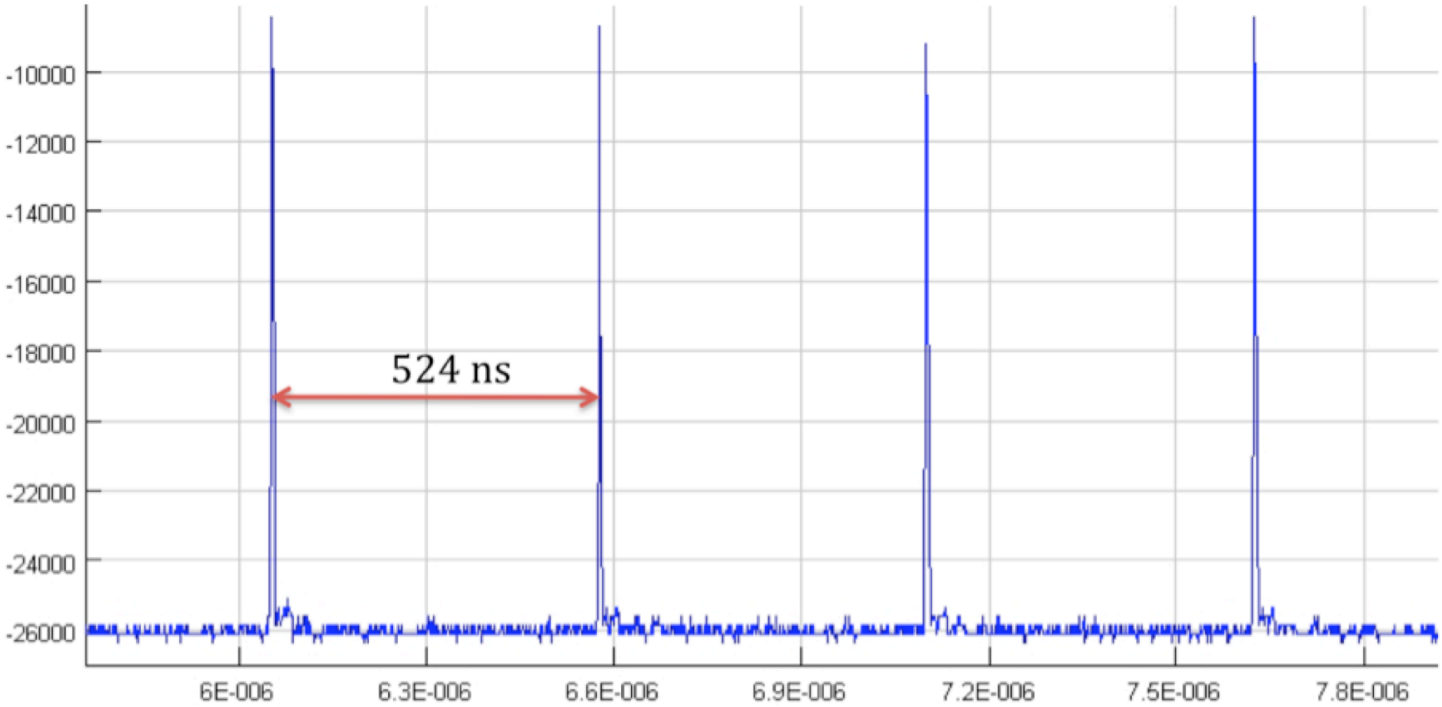
No clues for energy dependence within the present sensitivity in the energy domain explored by the measurement



Recent news

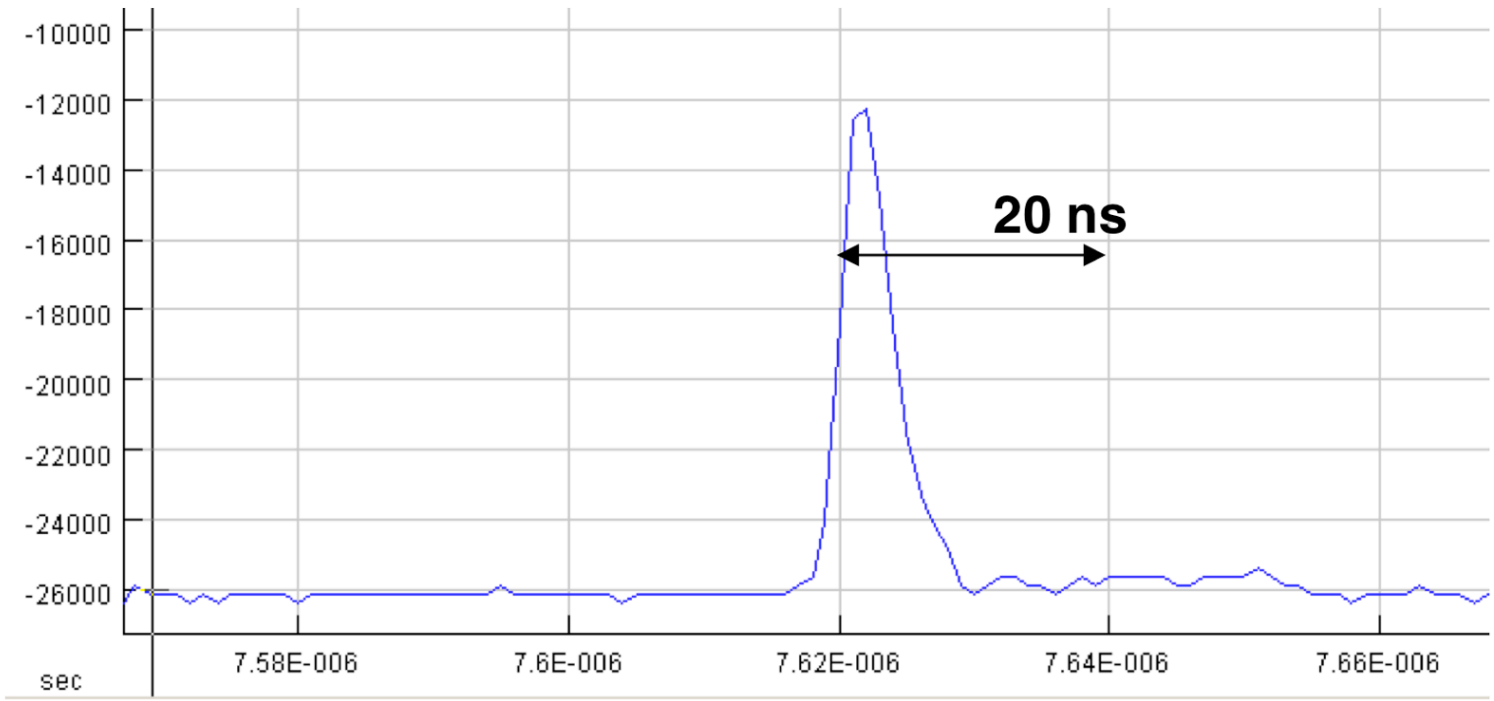
- After 23 November we got a large response from the community (and not only…)
- We worked to make various parts of the preprint more clear and readable
- We also worked to account for “second order” effects, to further check issues raised by colleagues, and to perform additional independent analyses.
- Last but not least, in collaboration with CERN, we worked on a test made with a bunched CNGS beam (see below)
- All that will be included in the forthcoming journal publication
- Our studies will continue and further measurements will be conducted: measure muons in the pit (diamond detector being installed), more bunched beam next year, new metrology campaigns, more statistics, etc.

CNGS bunched beam



Average intensity: ~10^{12} proton/extraction

(~100 times less than the normal operation integrated intensity)



Results to be published soon…

Thank you for your attention