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

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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

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 (Phys. Rev. Lett. 43 (1979) 1361)

high energy (E_ν > 30 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. Phys. Lett. B 201 (1988) 353)

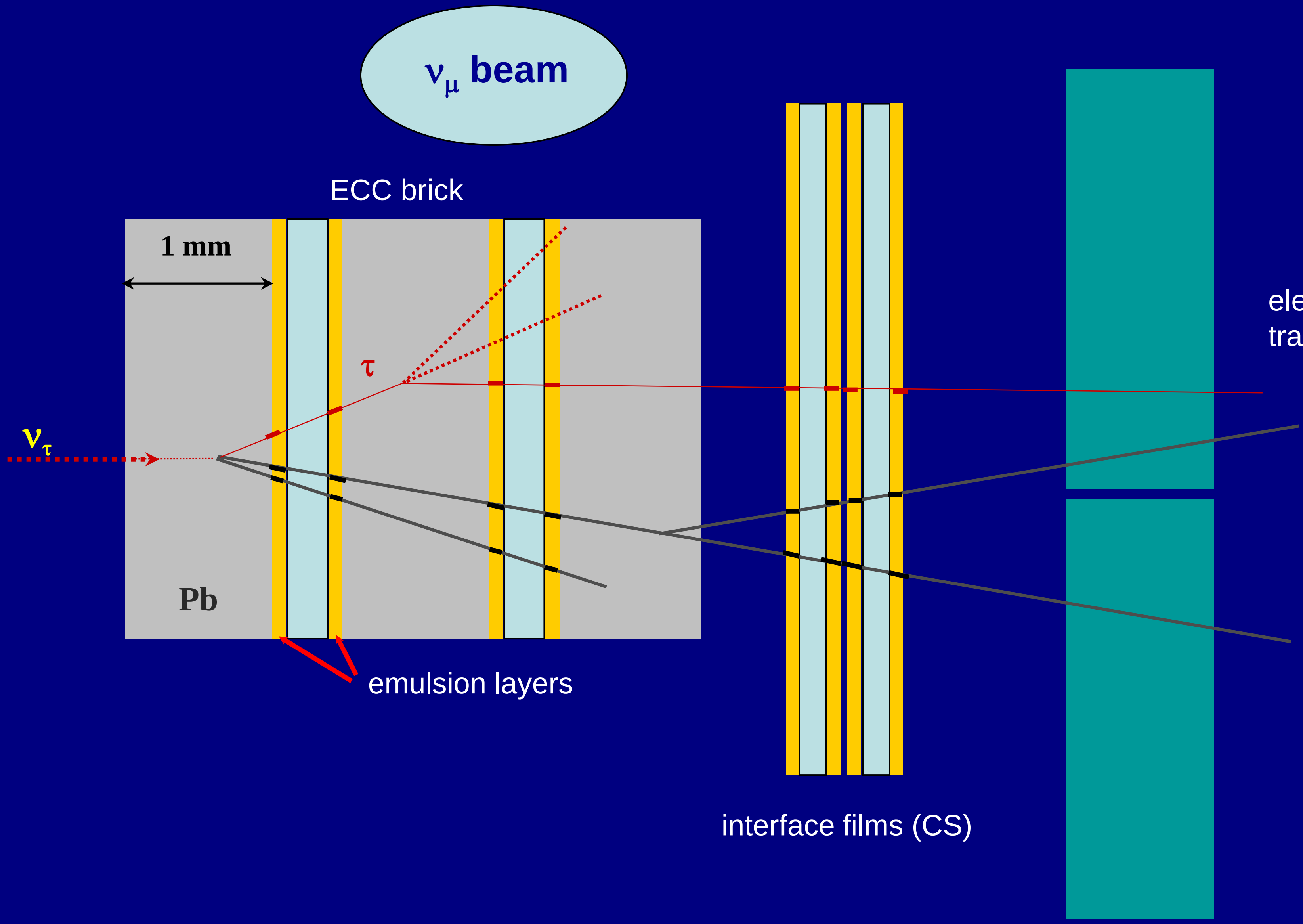
electron (anti) neutrinos, 10 MeV range, 168'000 light years baseline.
$|v-c|/c \leq 2 \times 10^{-9}$.
Performed with observation of neutrino and light arrival time.

MINOS (Phys. Rev. D 76 072005 2007)

muon neutrinos, 730 km baseline, E_ν peaking at ~3 GeV with a tail extending above 100 GeV.
$(v-c)/c = 5.1 \pm 2.9 \times 10^{-5}$ (1.8 σ).

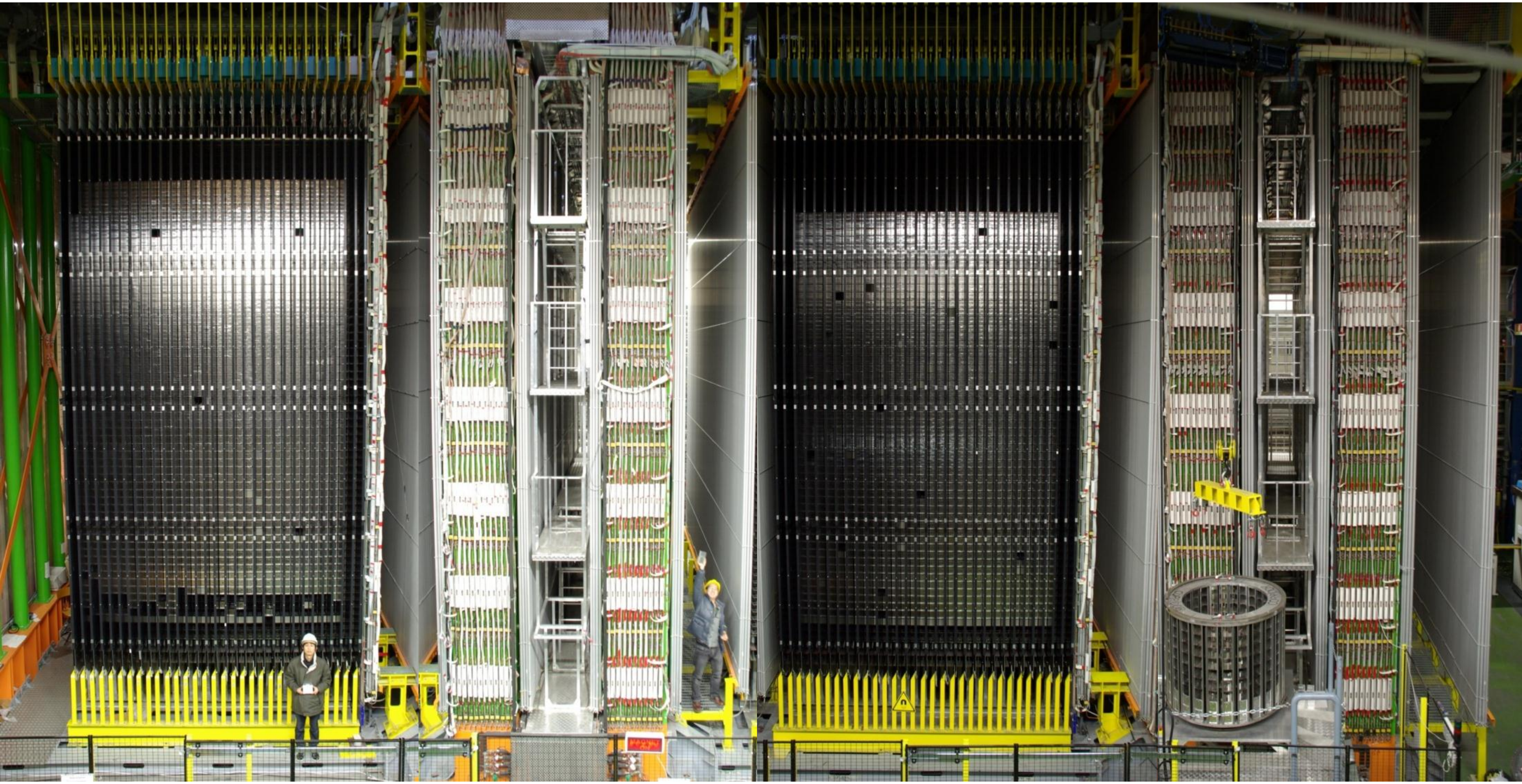
THE DESIGN OF THE OPERA EXPERIMENT

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



THE IMPLEMENTATION OF THE PRINCIPLE

SM1 SM2



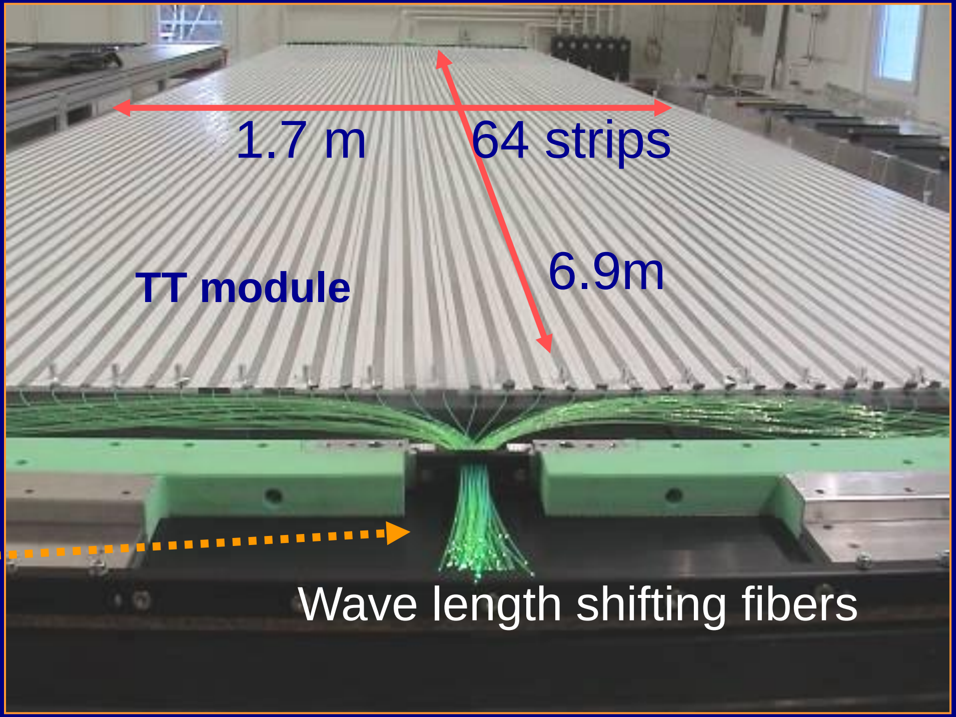
Target area Muon spectrometer

The Target Tracker (TT)

pre-location of neutrino interactions and event timing

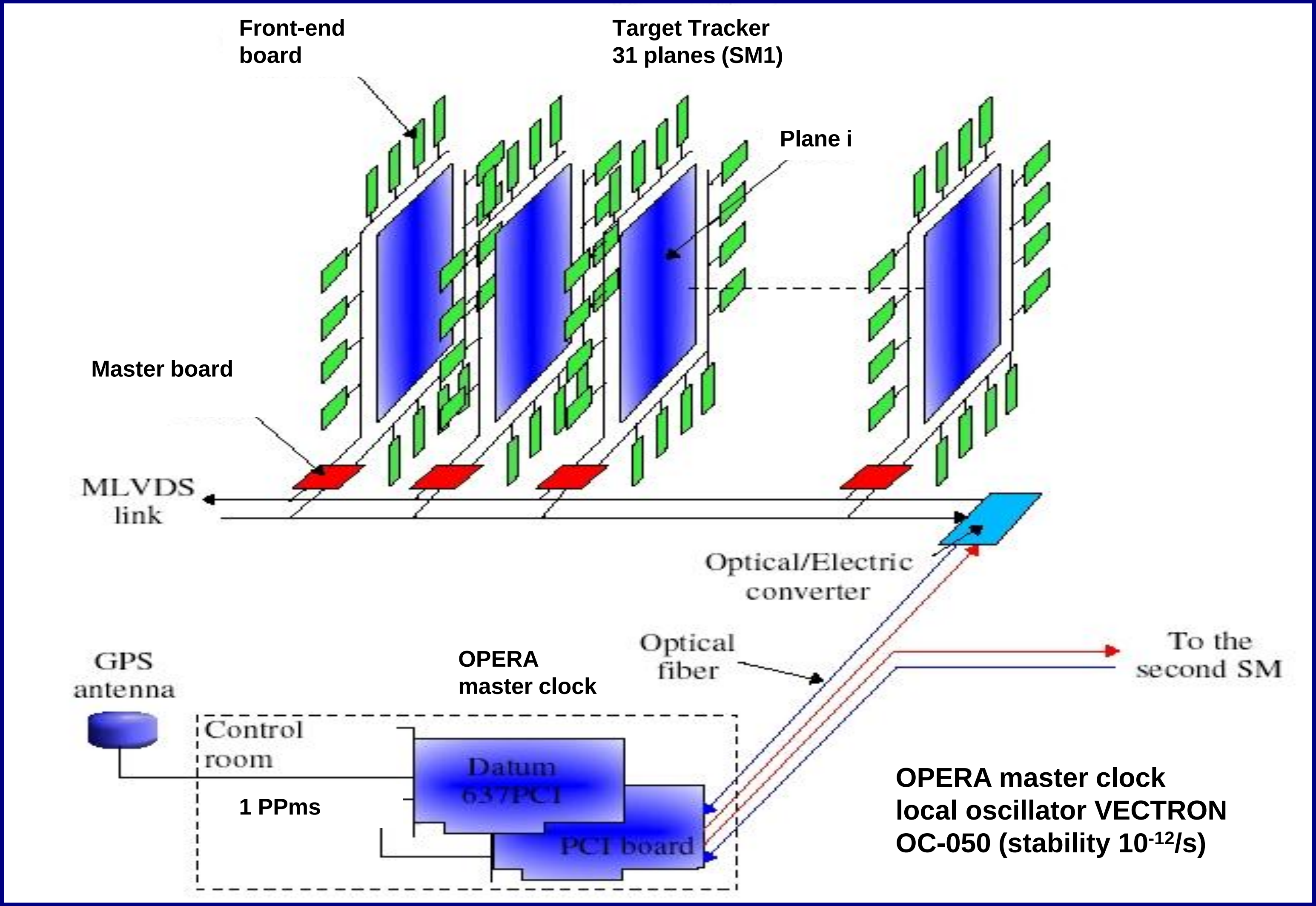
- Extruded plastic scintillator strips (2.6 cm width)
- Light collections with WLS fibres
- Fibres read out at either side with multi-anode 64 pixels PMTs (H7546)

H7546



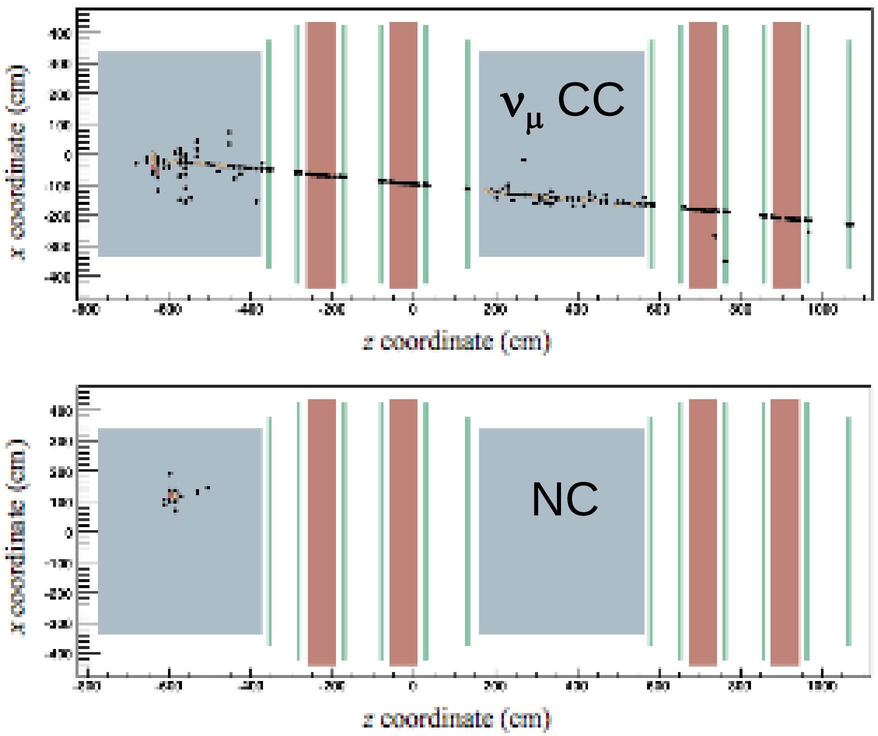
Read out by 1 Front-End DAQ board per side

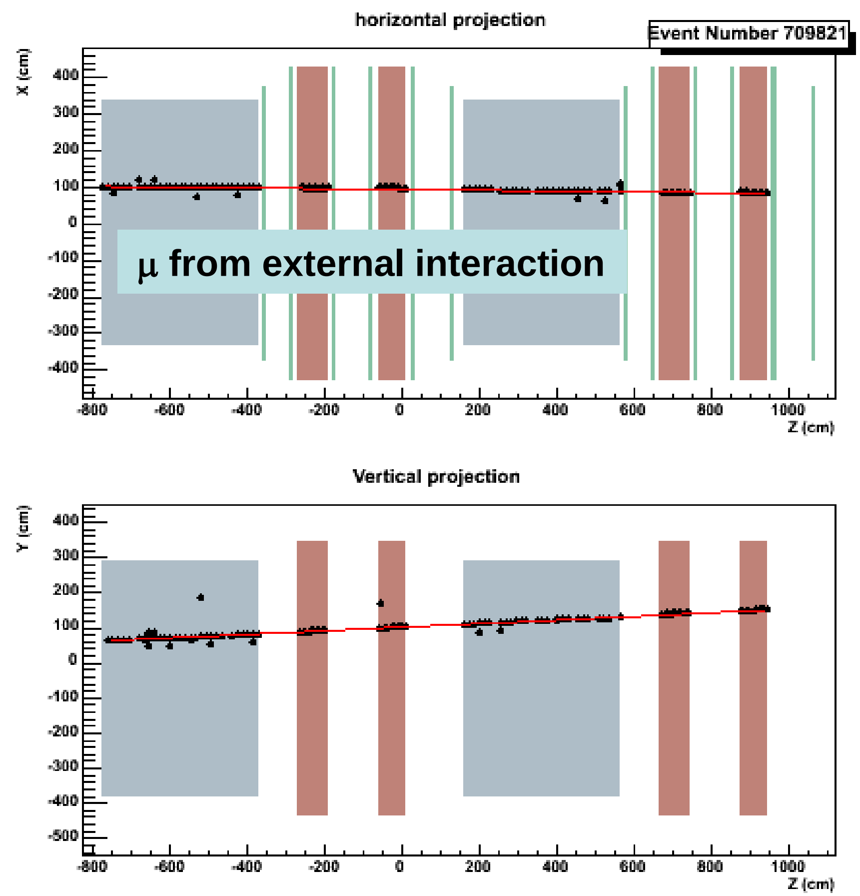
Clock distribution system



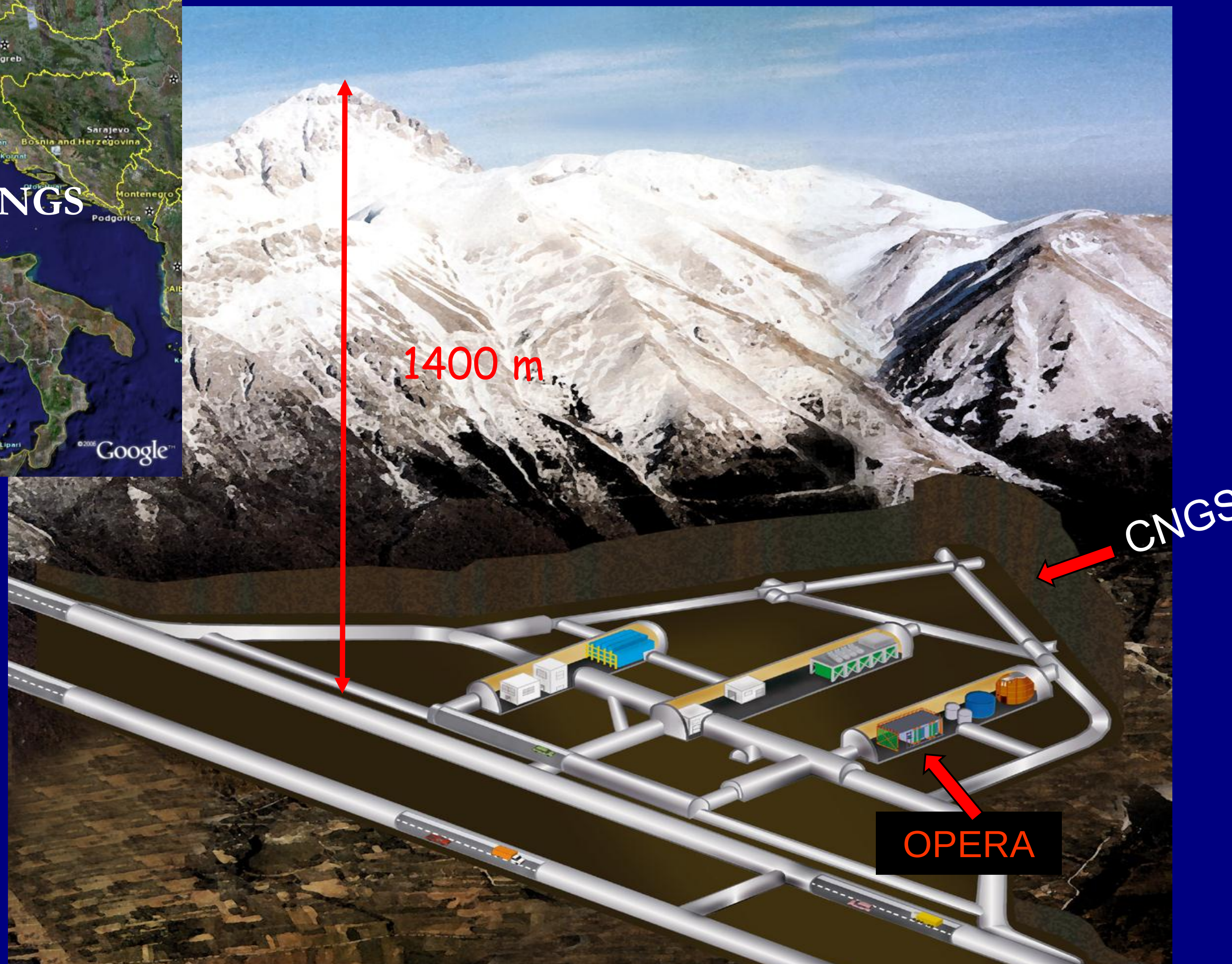
Mezzanine DAQ card common to all sub-detectors Front End nodes: CPU (embedded LINUX), Memory, FPGA, clock receiver and ethernet

“INTERNAL” and “EXTERNAL” OPERA EVENTS

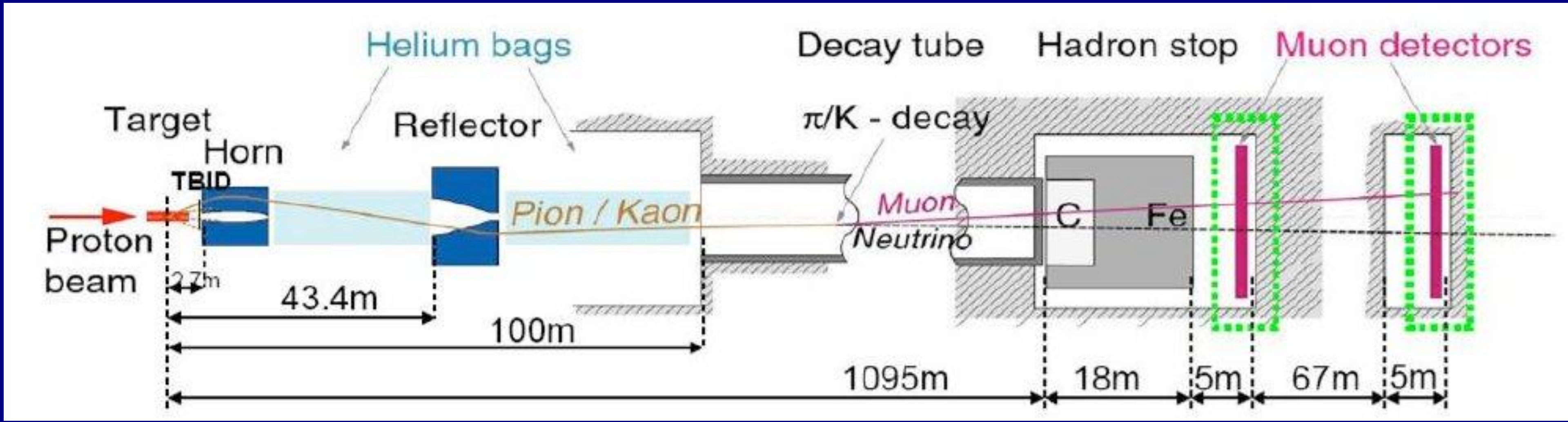




The LNGS underground physics laboratory

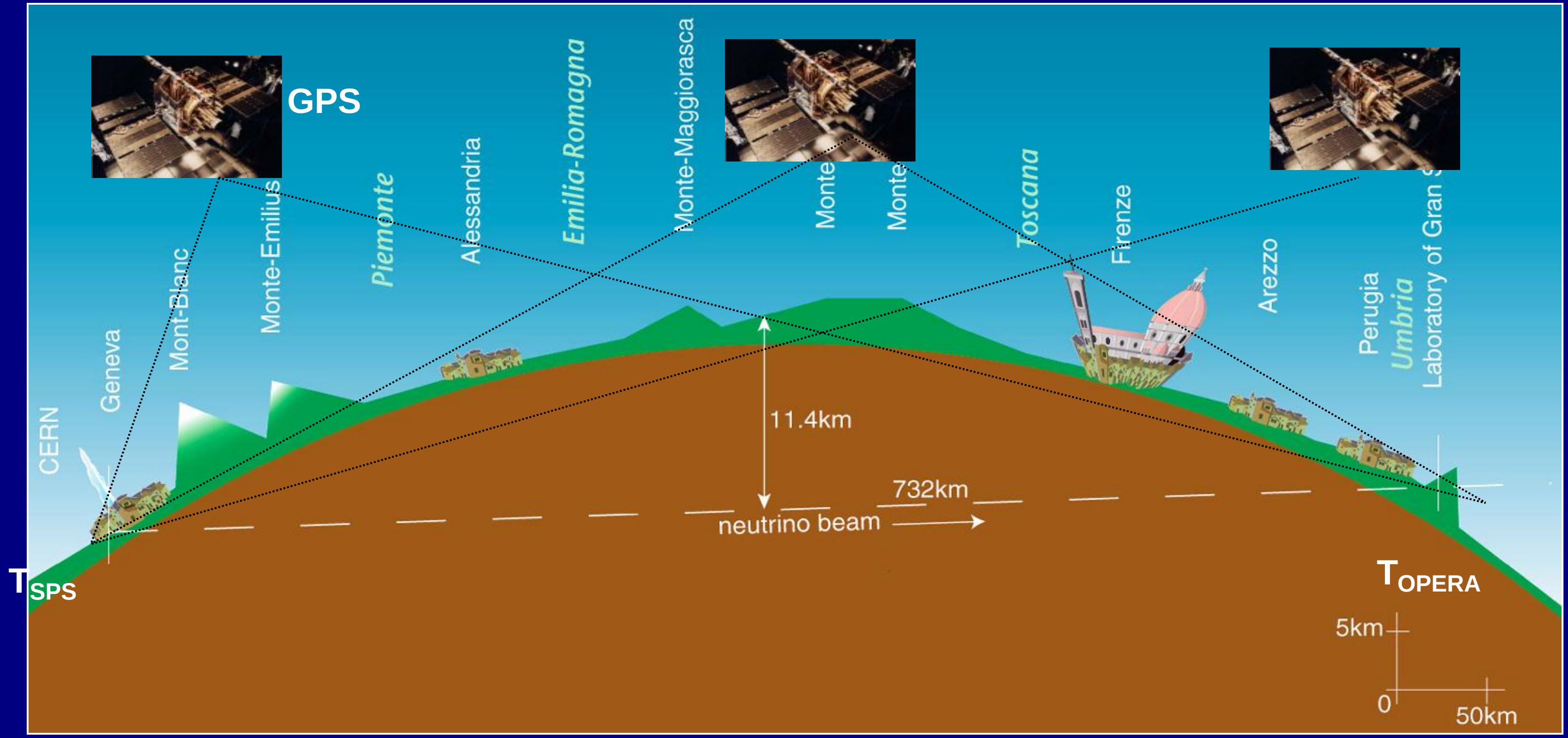


THE CNGS neutrino beam



- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5 μs extractions (by kicker magnet) separated by 50 ms
- Beam intensity: 2.4×10^{13} proton/extraction
- ~ pure muon neutrino beam (<E> = 17 GeV) travelling through the Earth’s crust

CNGS events selection



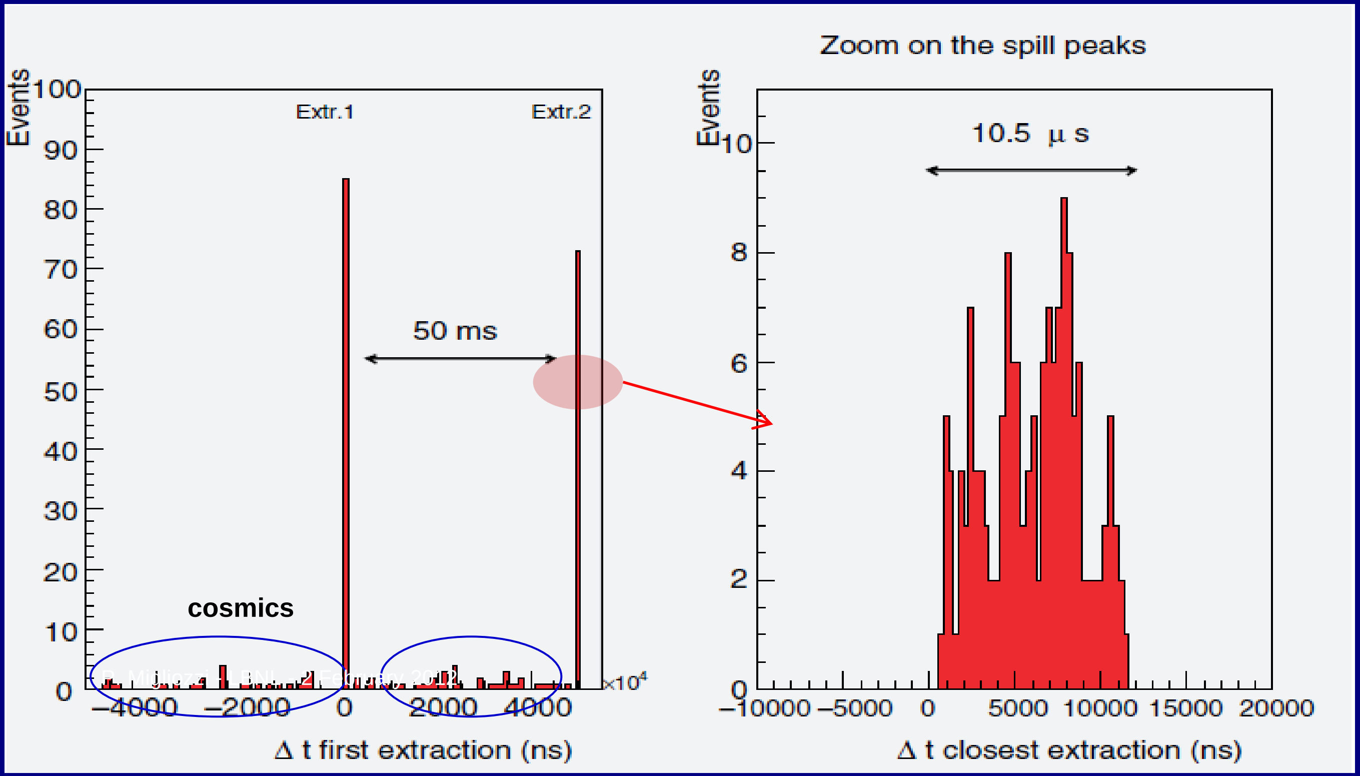
Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

$$|T_{OPERA} - (T_{Kicker} + TOFc)| < 20\ \mu s$$

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})

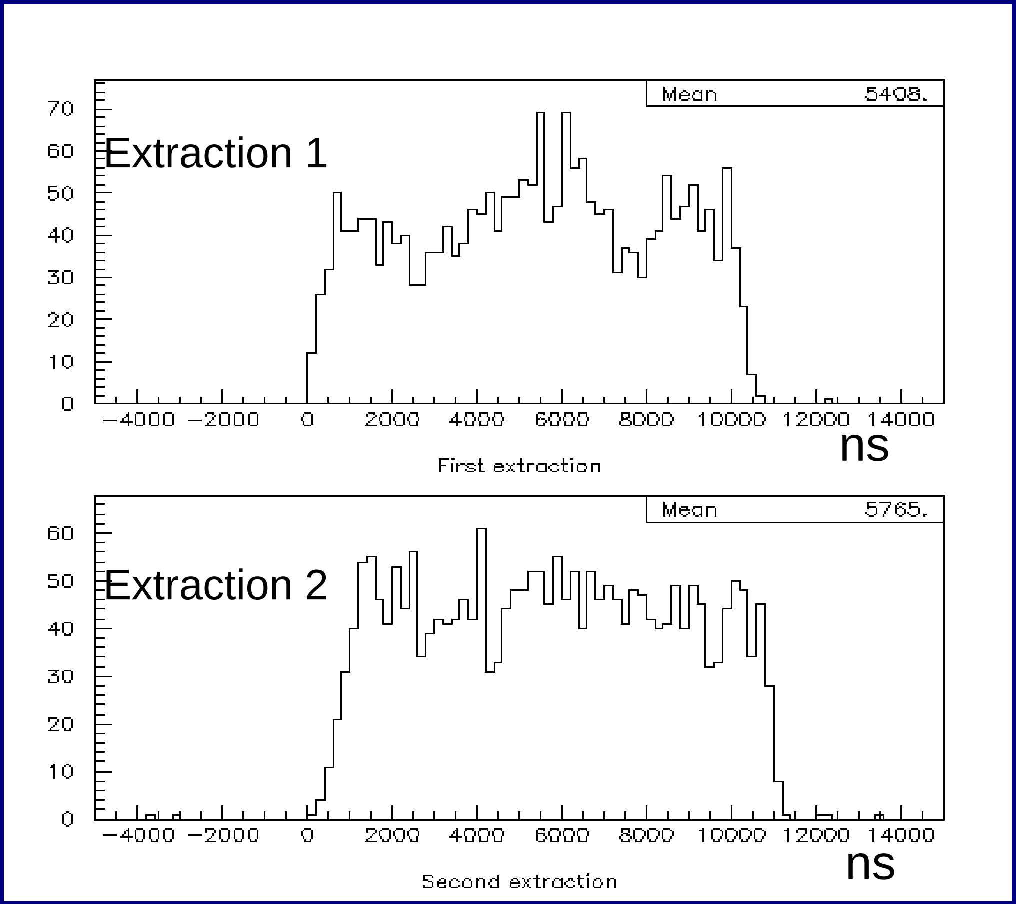
Selection procedure kept unchanged since first events in 2006

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

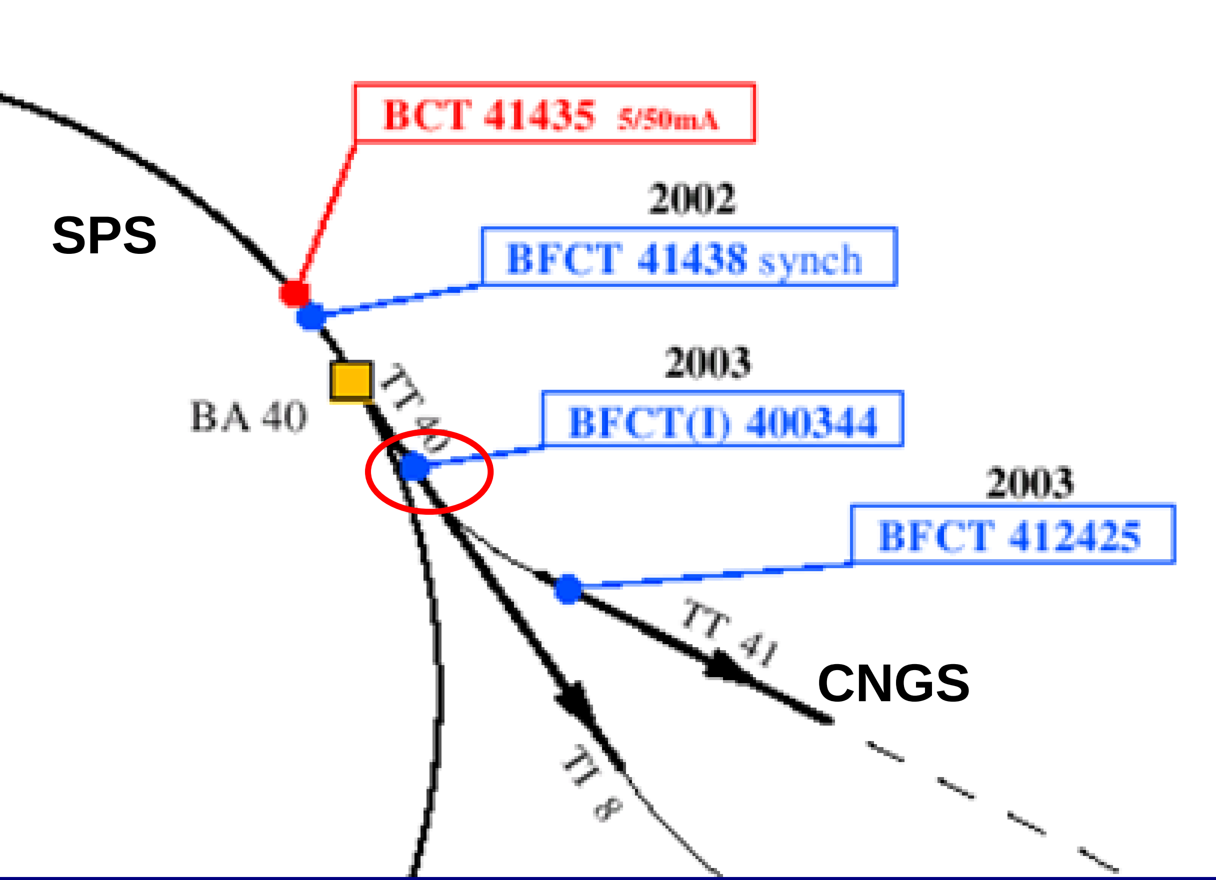
Measurement of the neutrino event time distribution



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 timing by Beam Current Transformer

Fast BCT 400344
(~ 400 MHz)

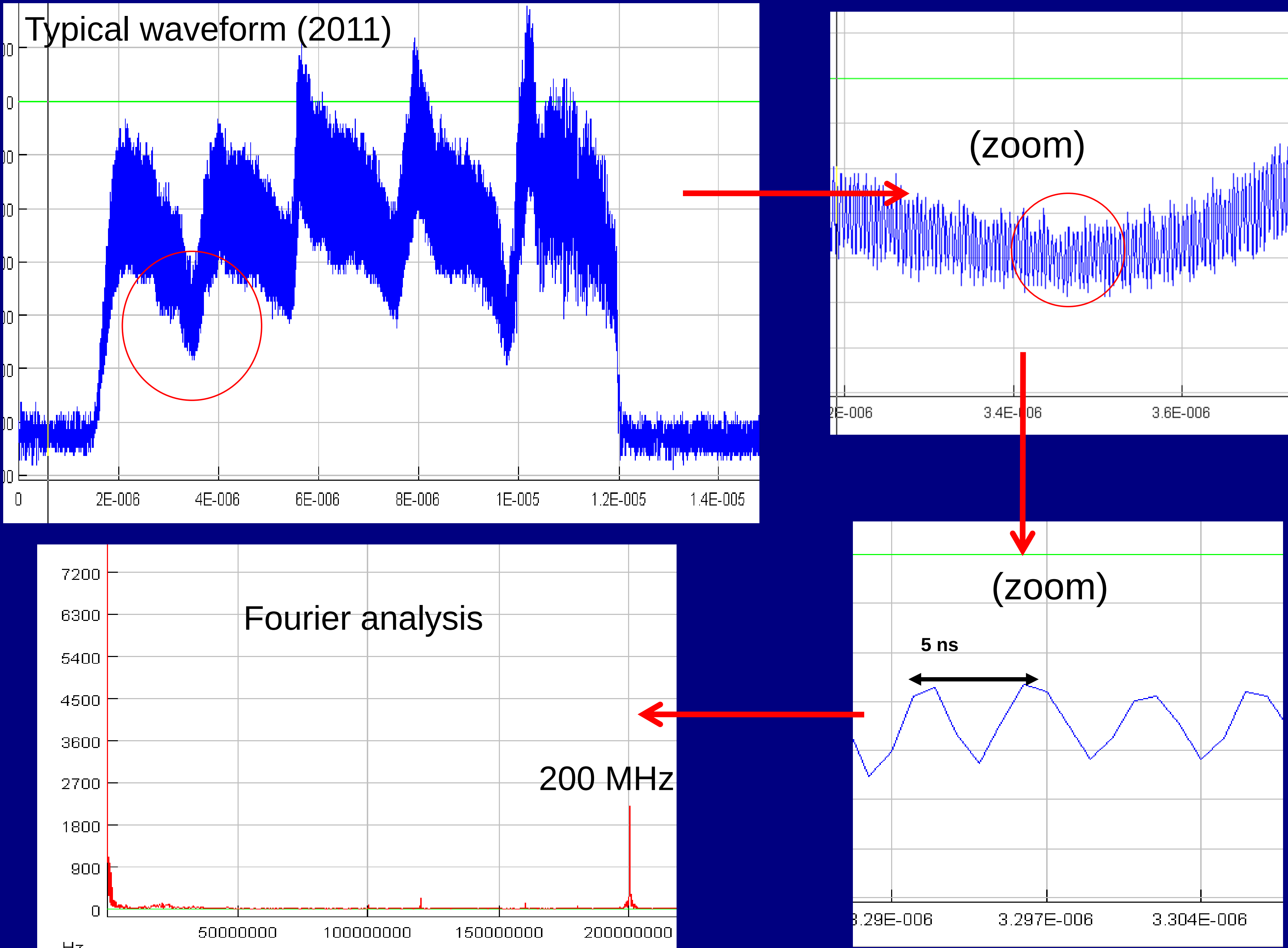
Proton pulse digitization:

• 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



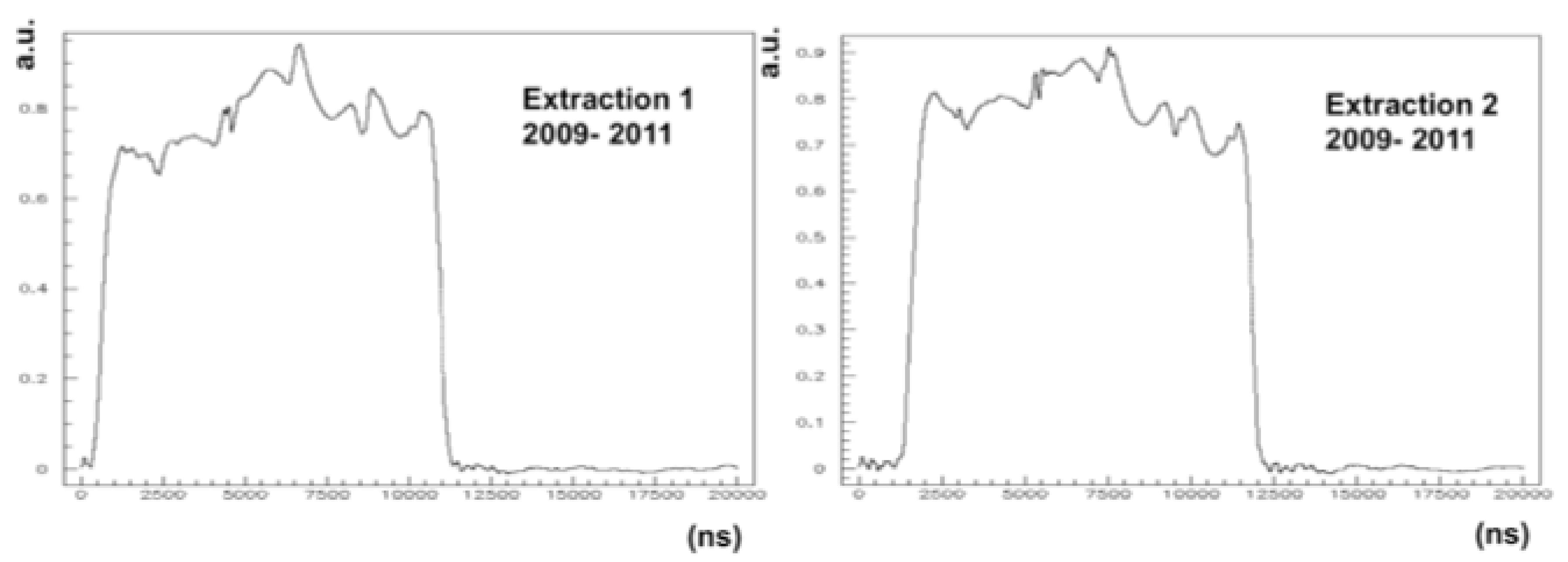
Typical waveform (2011)
0
2E-006
4E-006
6E-006
8E-006
1E-005
1.2E-005
1.4E-005
(zoom)
3.4E-006
3.6E-006
(zoom)
5 ns
3.297E-006
3.304E-006
Fourier analysis
7200
6300
5400
4500
3600
2700
1800
900
0
200 MHz
50000000
100000000
150000000
200000000
Hz

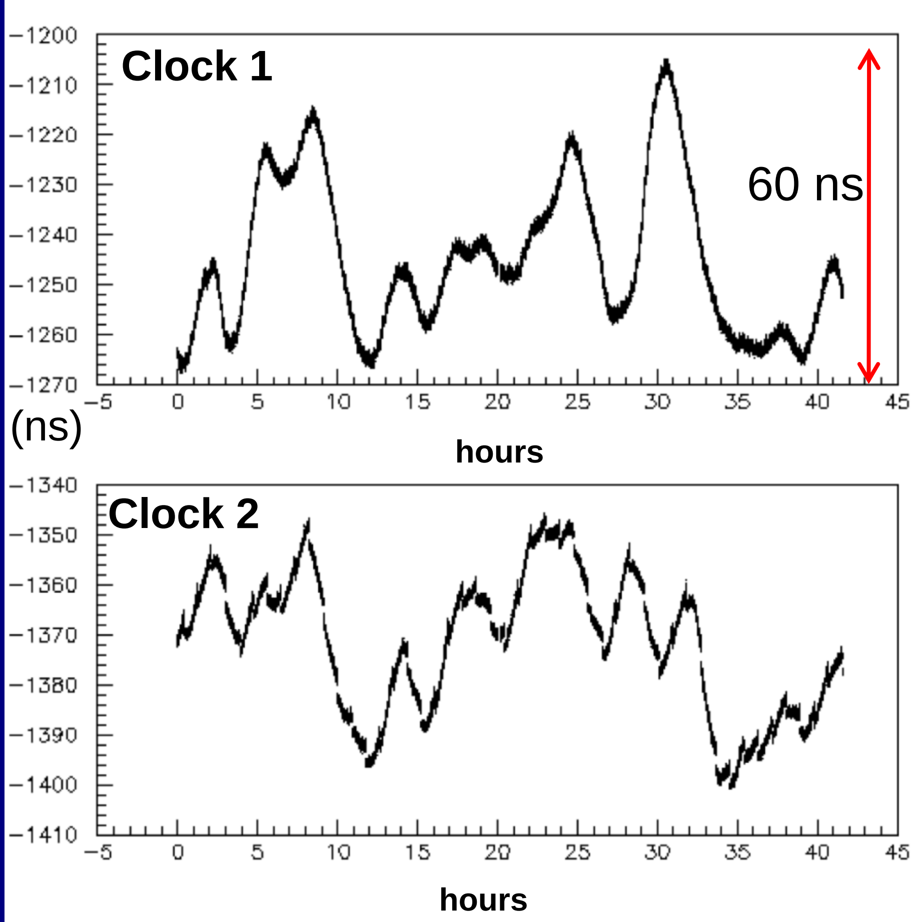
Neutrino event-time distribution PDF

- 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





GPS clocks at LNGS w.r.t. Cs clock:

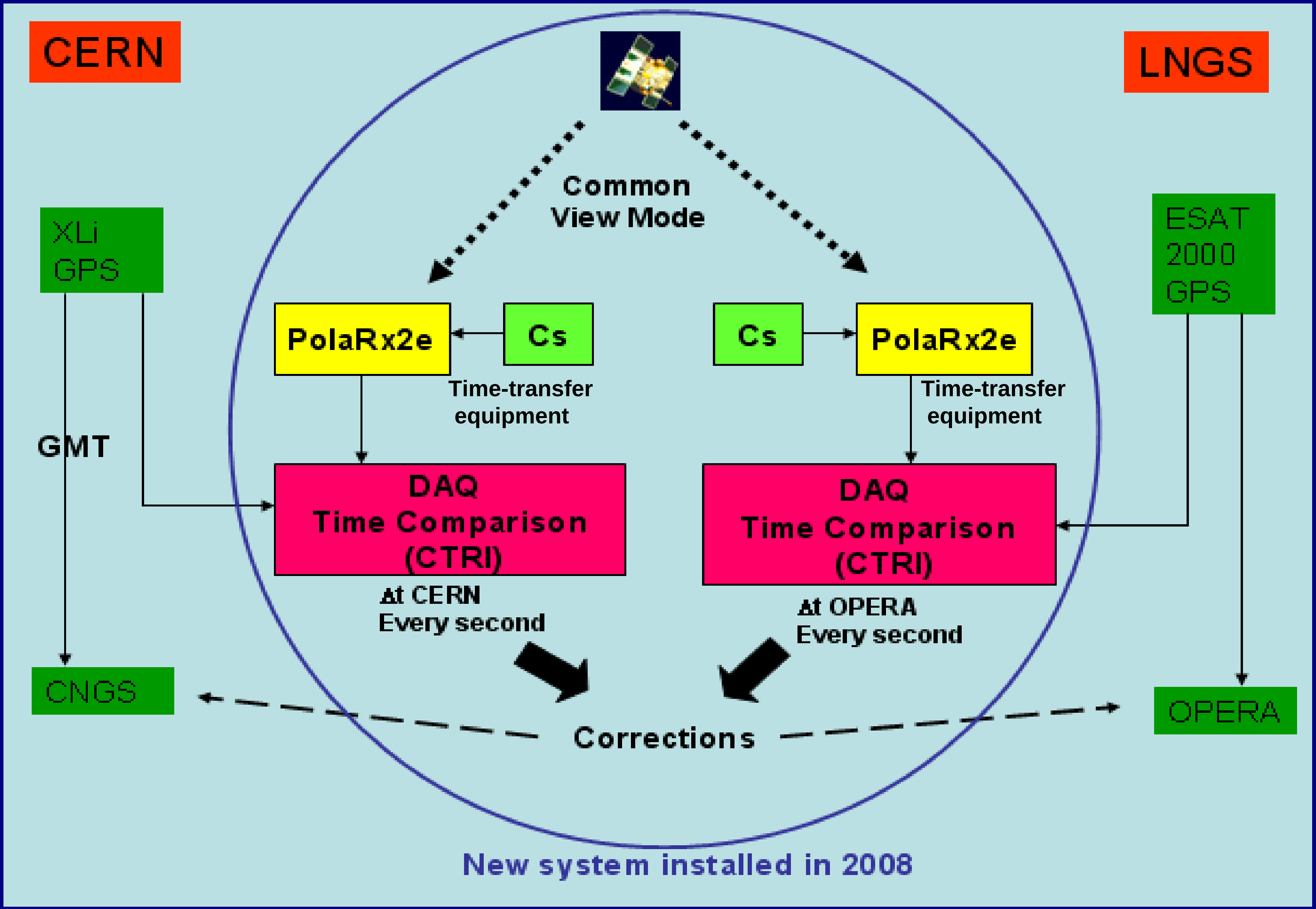
1) Large oscillations
2) Uncertainties on CERN-OPERA synchronisation

→ Need accurate time synchronisation system

Collaboration with CERN timing team since 2003

Major upgrade in 2008

CNGS-OPERA synchronization




PolaRx2e
Cs 4000
CERN


LNGS
ESAT 2000
PolaRx2e
Cs 4000

GPS common-view mode

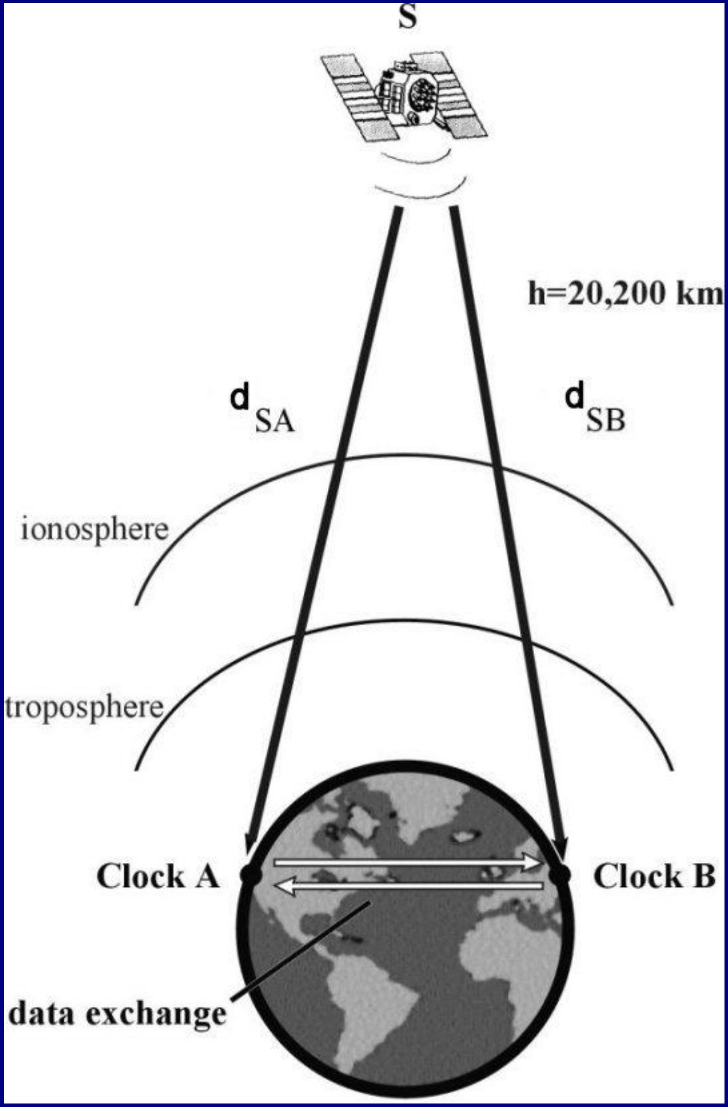
Standard GPS operation:

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

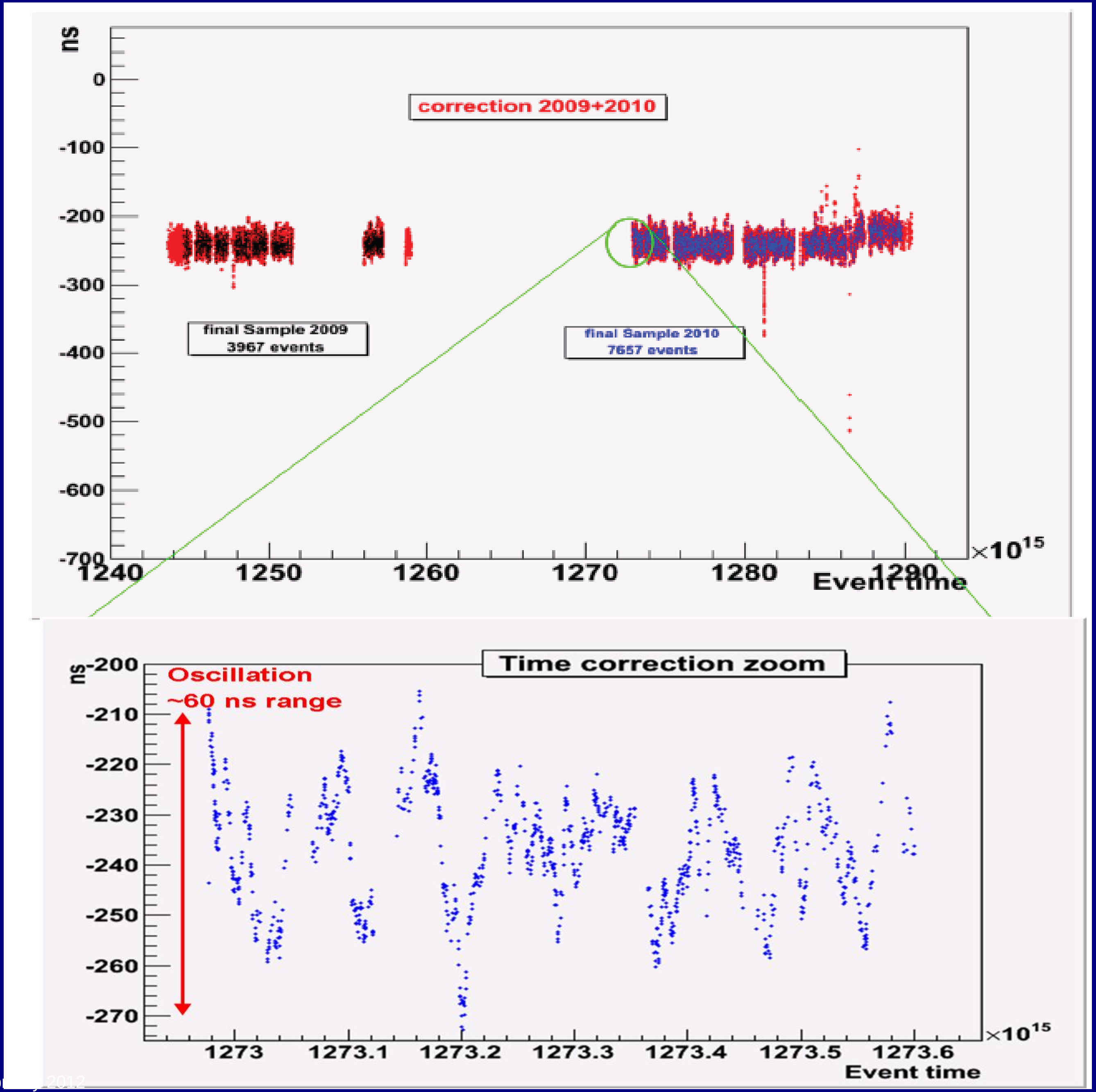
730 km << 20000 km (satellite height) → similar paths in ionosphere



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)

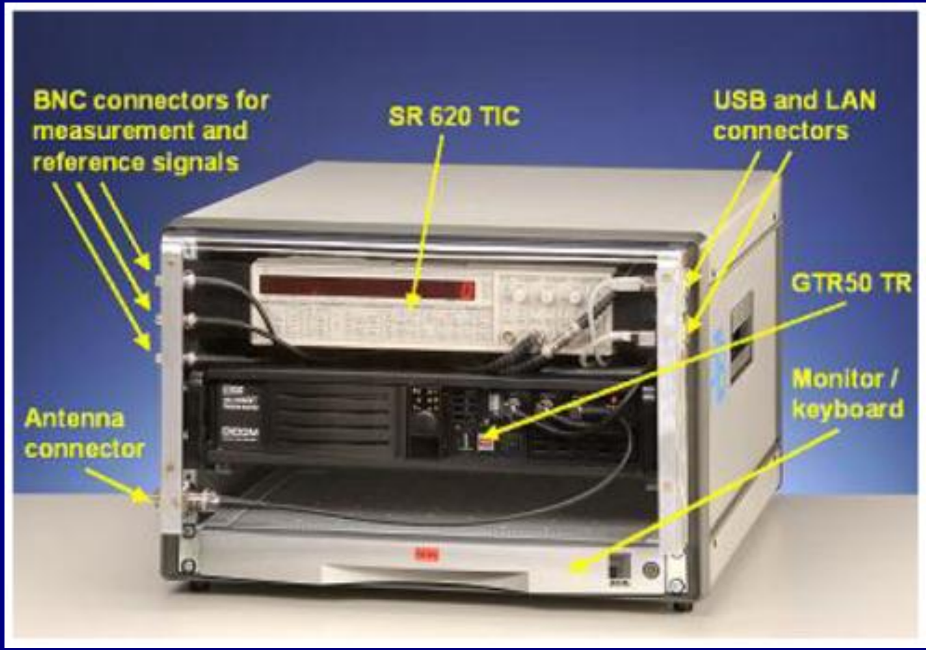


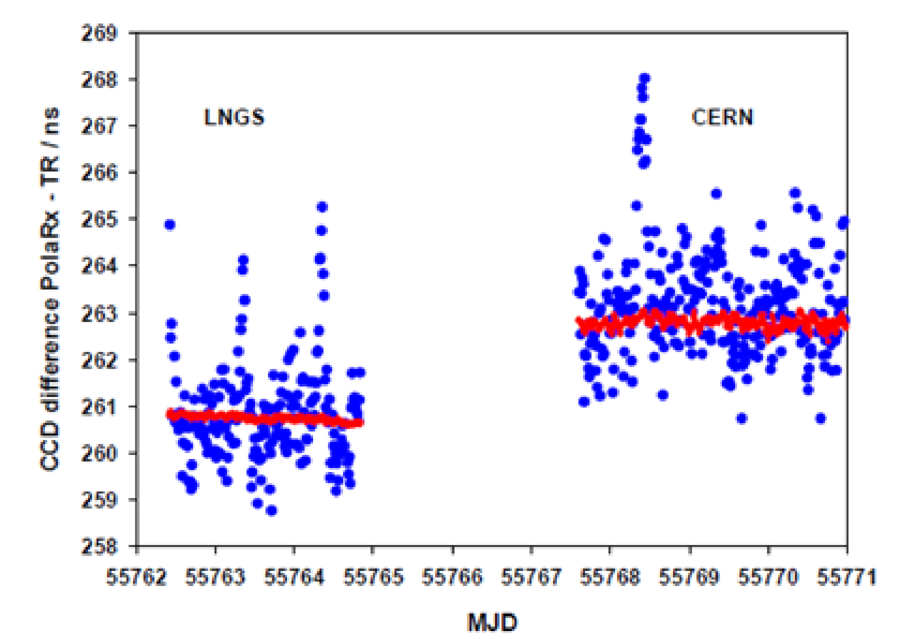
CERN-OPERA inter-calibration cross-check

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

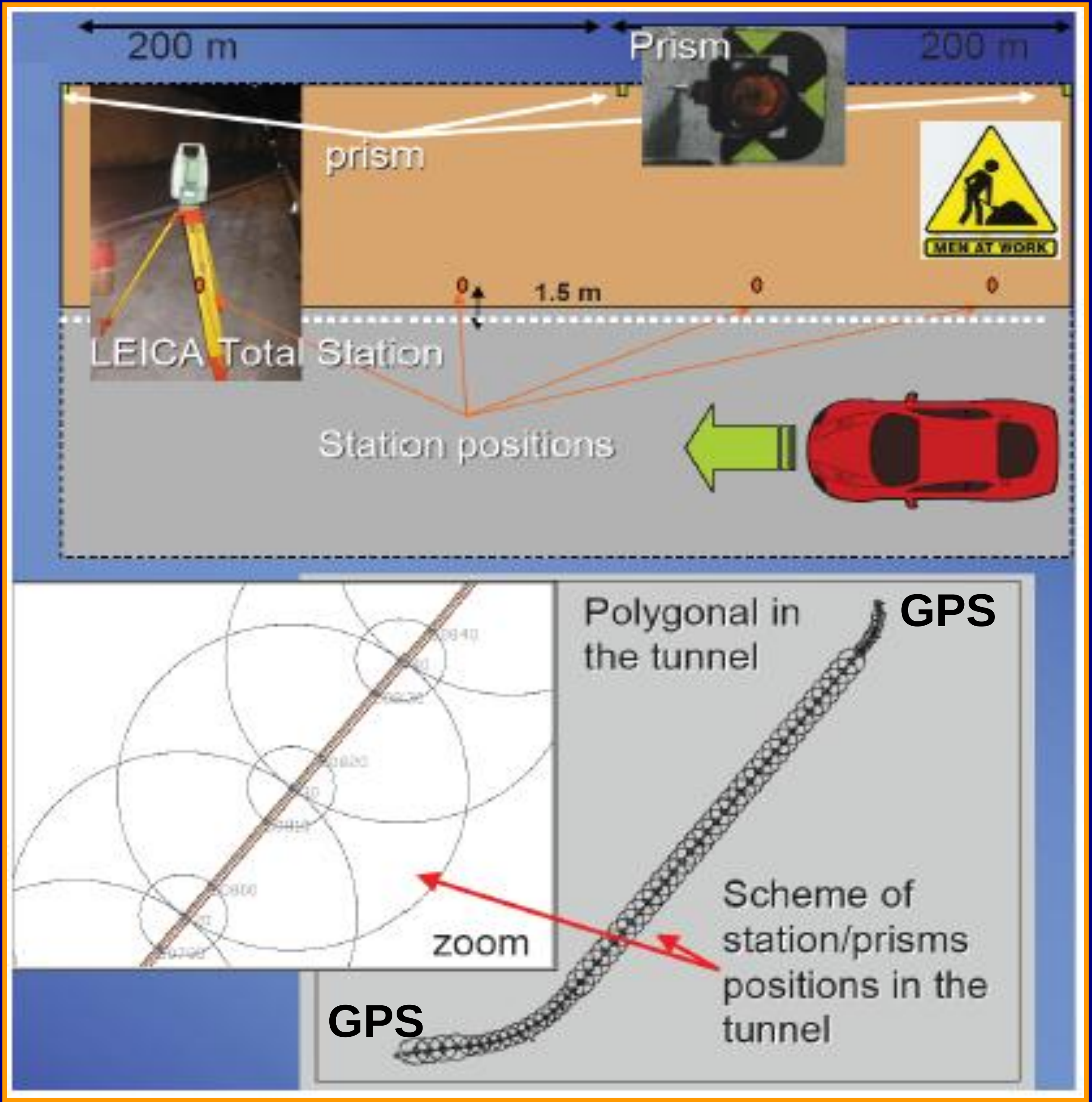




Correction to the time-link:

$t_{CERN} - t_{OPERA} = (2.3 \pm 0.9)$ 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)

Benchmark	X (m)	Y (m)	Z (m)
GPS1	4579518.745	1108193.650	4285874.215
GPS2	4579537.618	1108238.881	4285843.959
GPS3	4585824.371	1102829.275	4280651.125
GPS4	4585839.629	1102751.612	4280651.236

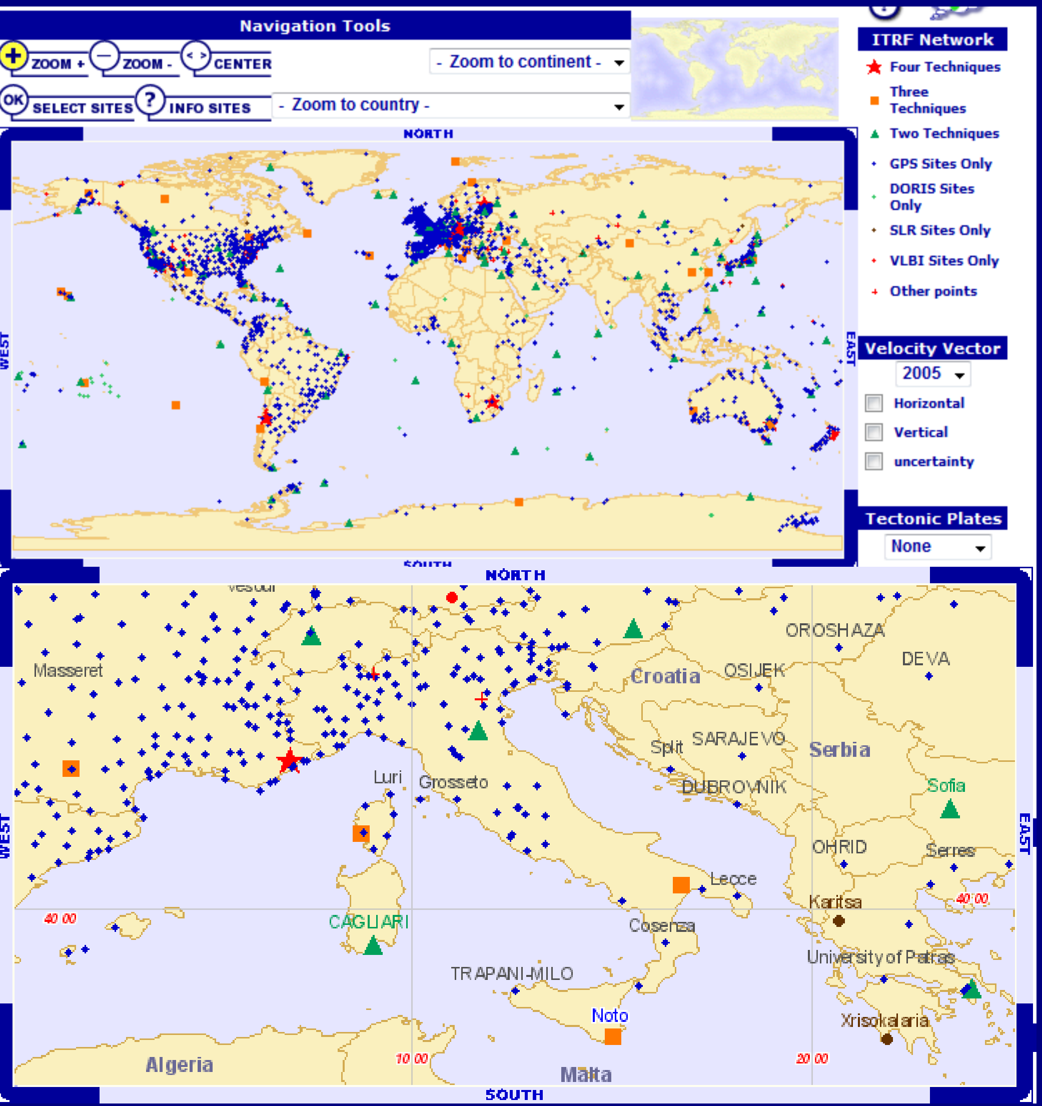
LNGS benchmarks
In ETRF2000

Cross-check: simultaneous CERN-LNGS measurement of GPS benchmarks, June 2011

Resulting distance (BCT – OPERA reference frame)

(731278.0 ± 0.2) m

GPS scale

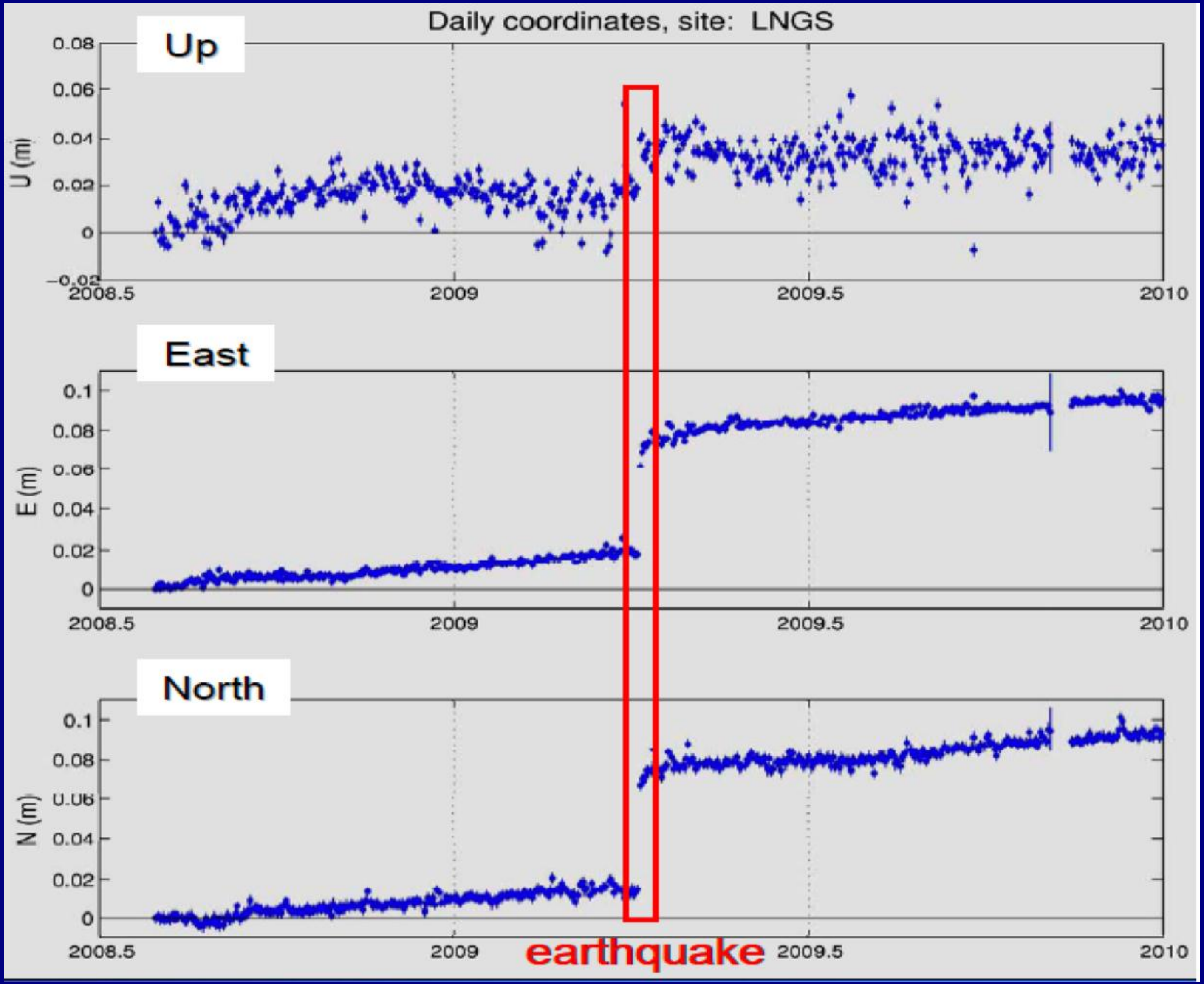


The GPS distance scale is cross-checked with the ones of other space geodesy techniques

- VLBI: Signals from Quasars
- SLR: Satellite Laser Ranging

Overall the scale consistency ofthe ETRF is at level of 1 part per 10^{-9}

LNGS position monitoring



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

Geodesy: Tidal effects

Tidal effect 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)

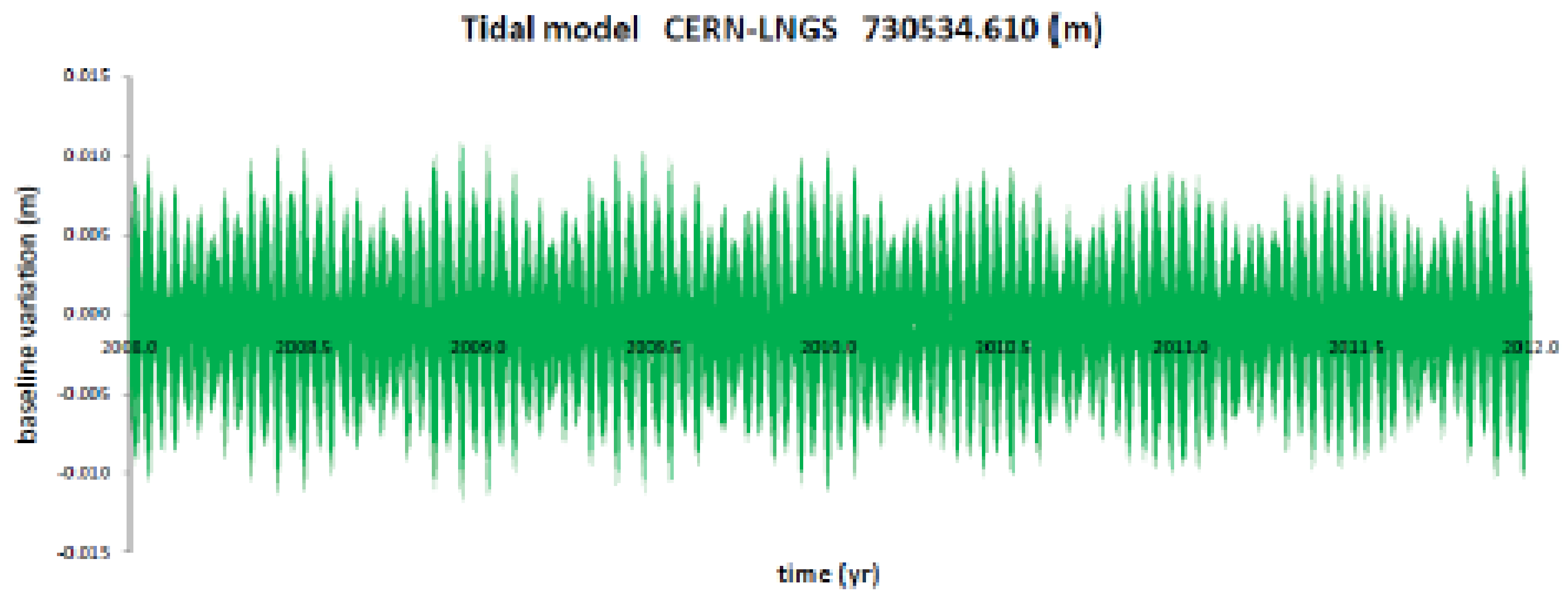


Figure 6: Tidal variations of the baseline CERN-LNGS

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

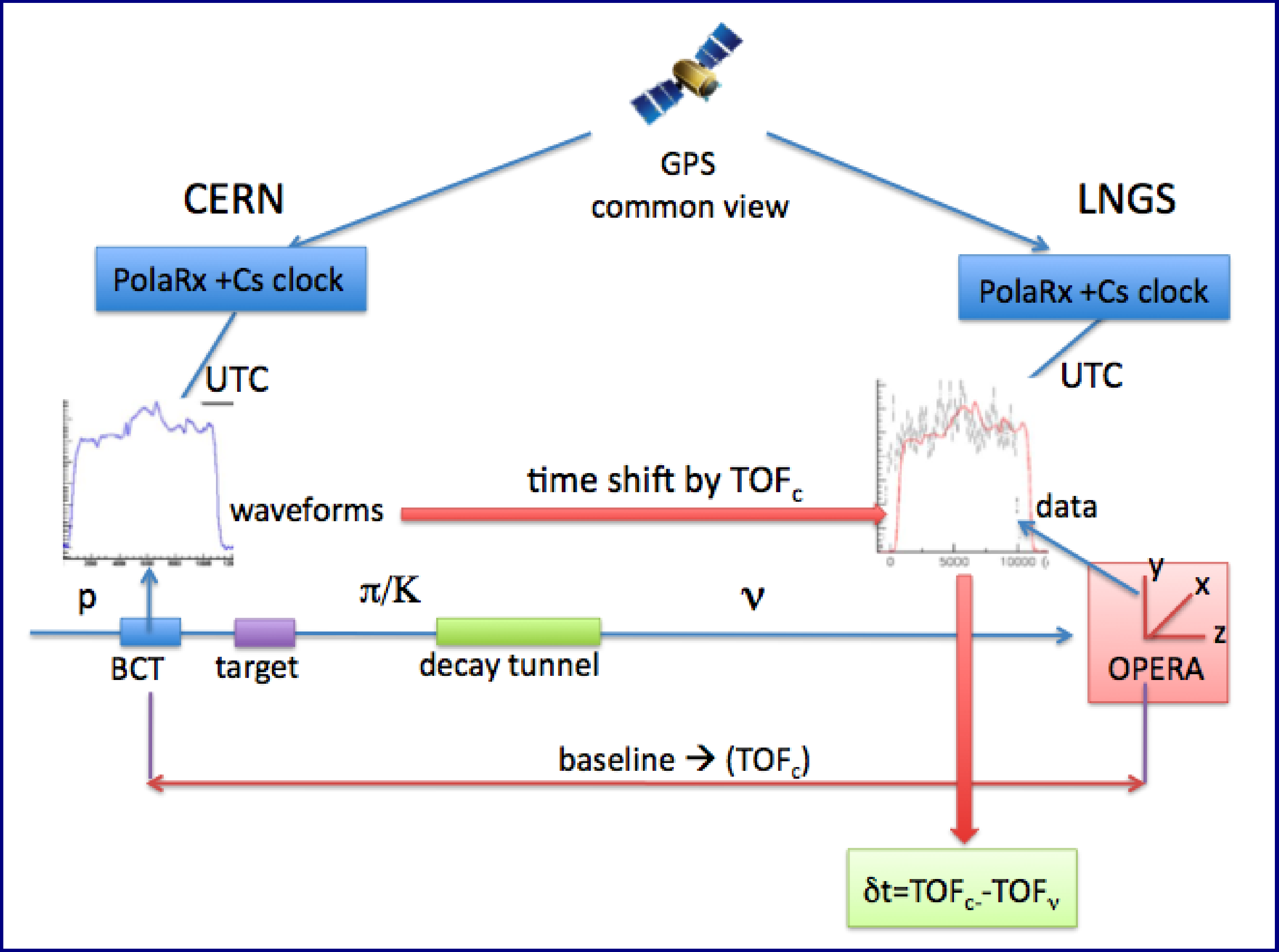
It accounts for the displacement of the OPERA detector point during the neutrino TOF due to the Earth rotation

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

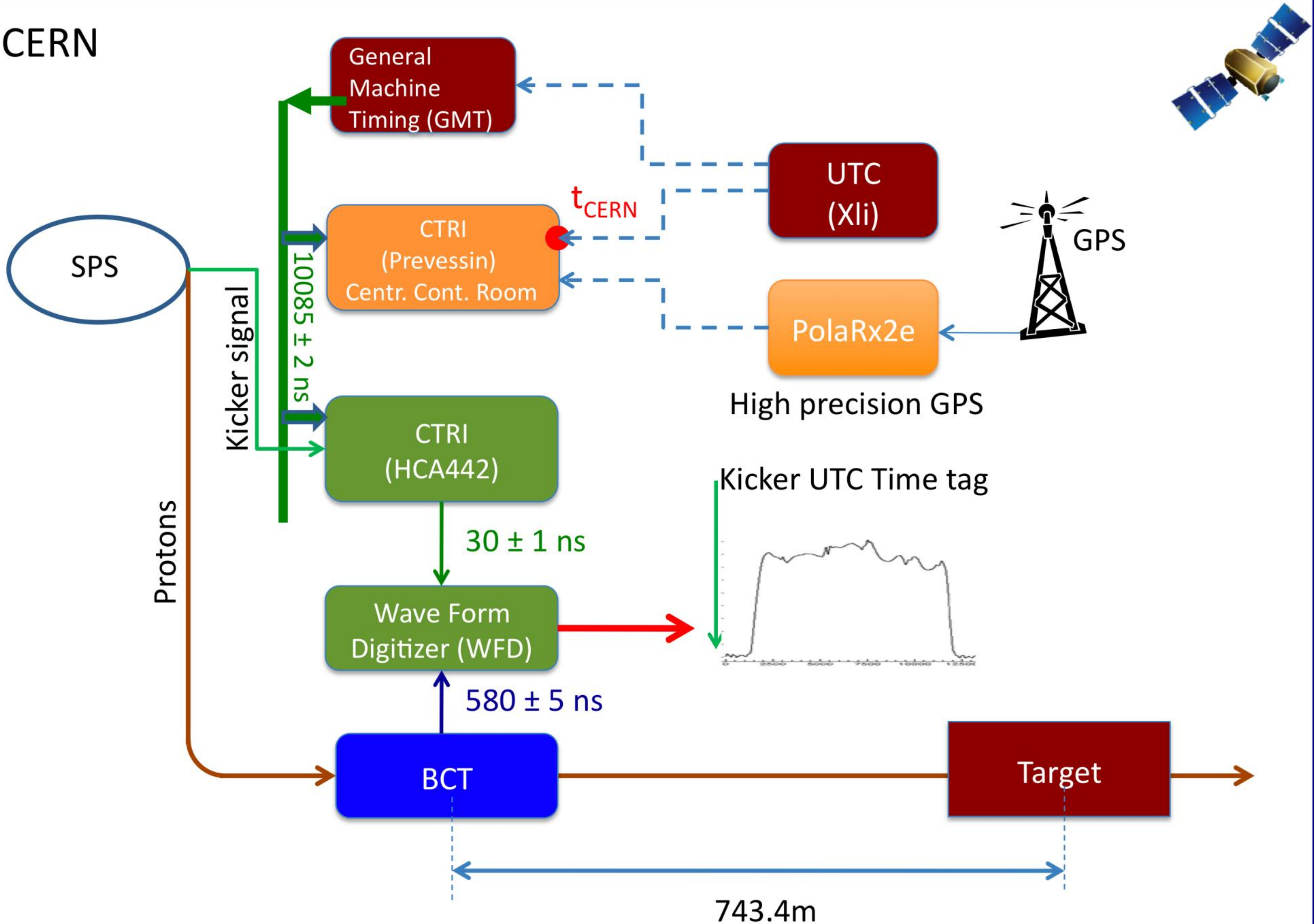
It amounts to 66 cm, i.e. to a TOF of 2.2 ns

Summary of the principle for the TOF measurement



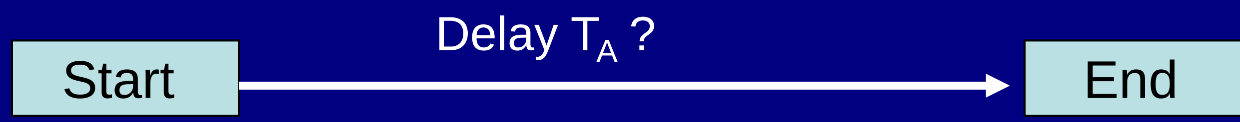
Measure $\delta t = TOF_c - TOF_\nu$

CERN



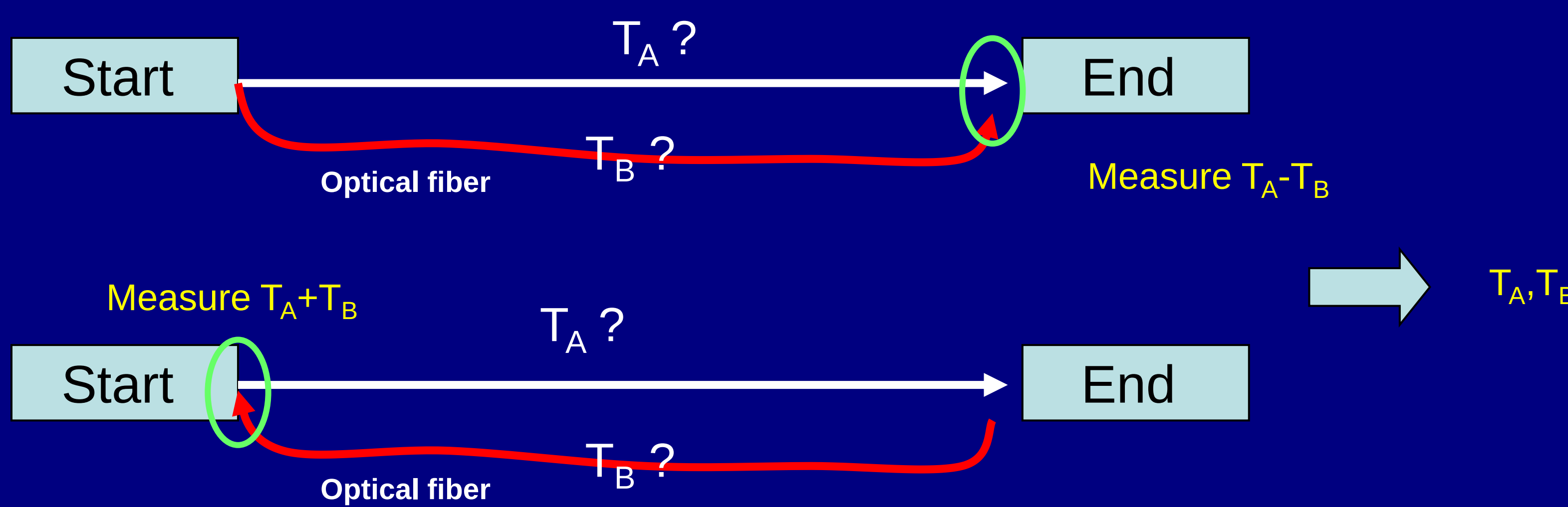
General Machine Timing (GMT)
UTC (Xli)
t_{CERN}
CTRI (Prevessin) Centr. Cont. Room
PolaRx2e
GPS
High precision GPS
SPS
Kicker signal
10085 ± 2 ns
CTRI (HCA442)
Kicker UTC Time tag
Protons
30 ± 1 ns
Wave Form Digitizer (WFD)
580 ± 5 ns
BCT
Target
743.4m

Time calibration techniques

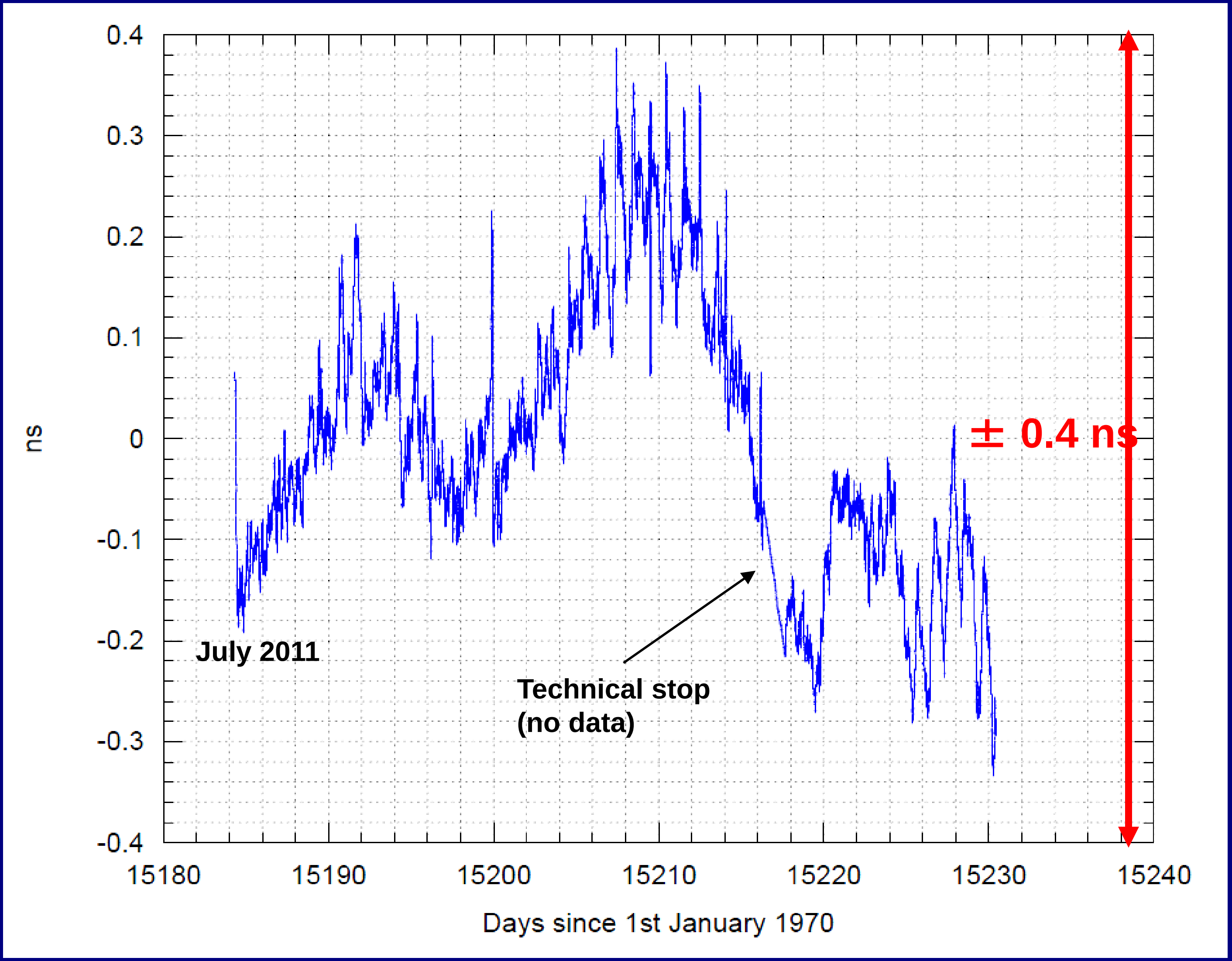


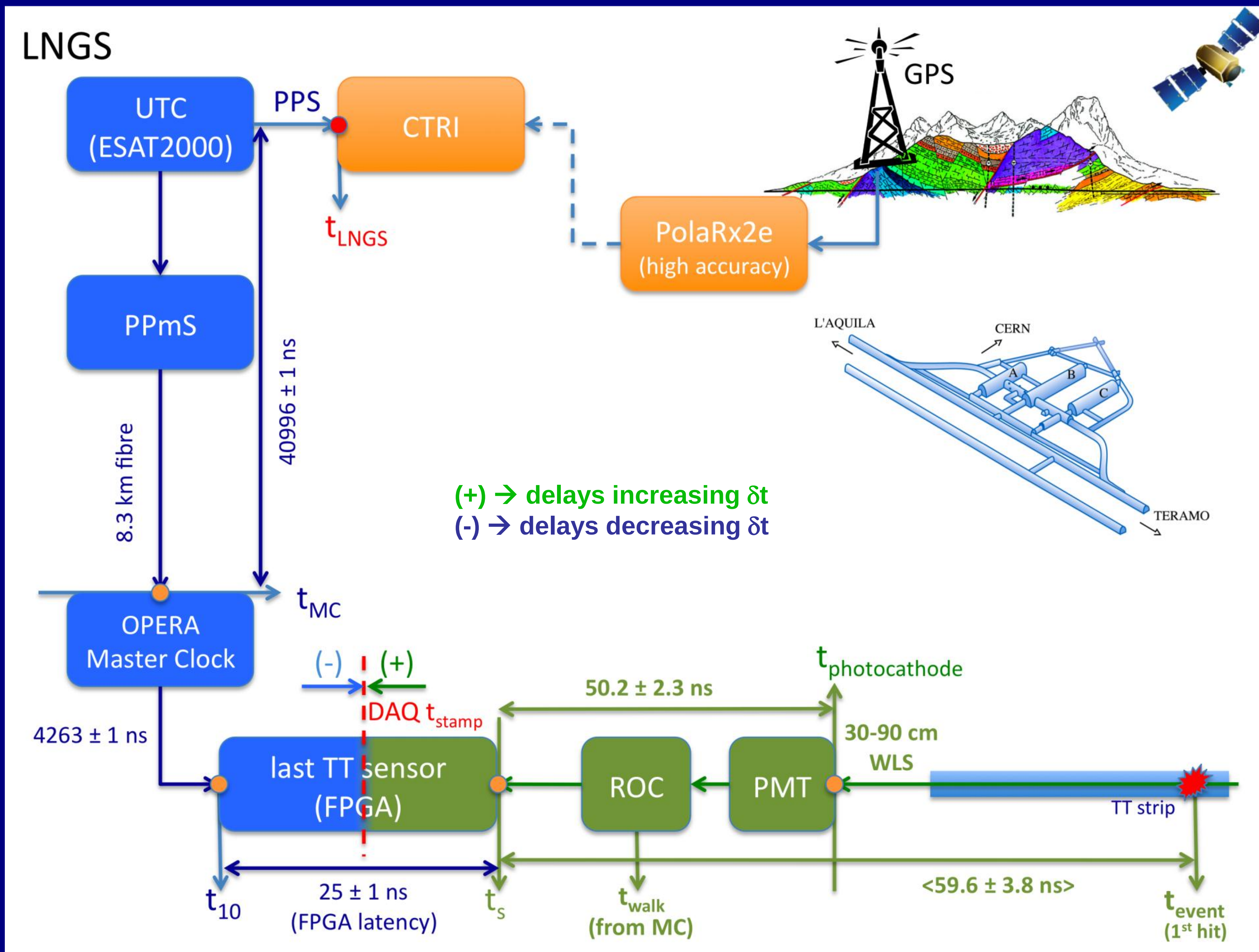
• Portable Cs-4000:
Comparison: time-tags vs 1PPS signal (Cs clock) at the start- and end-point of a timing chain

• Double path fibers measurement:
by swapping Tx and Rx component of the opto-chain



Continuous two-way measurement of UTC delay at CERN (variations w.r.t. nominal)




LNGS
UTC (ESAT2000)
PPS
CTRI
t_{LNGS}
GPS
PolaRx2e (high accuracy)
L'AQUILA
CERN
A
B
C
TERAMO
PPmS
40996 ± 1 ns
8.3 km fibre
(+) → delays increasing δt
(-) → delays decreasing δt
t_{MC}
OPERA Master Clock
(-)
(+)
DAQ t_{stamp}
$t_{photocathode}$
50.2 ± 2.3 ns
4263 ± 1 ns
30-90 cm WLS
last TT sensor (FPGA)
ROC
PMT
TT strip
t_{10}
25 ± 1 ns (FPGA latency)
t_s
t_{walk} (from MC)
<59.6 ± 3.8 ns>
t_{event} (1st hit)

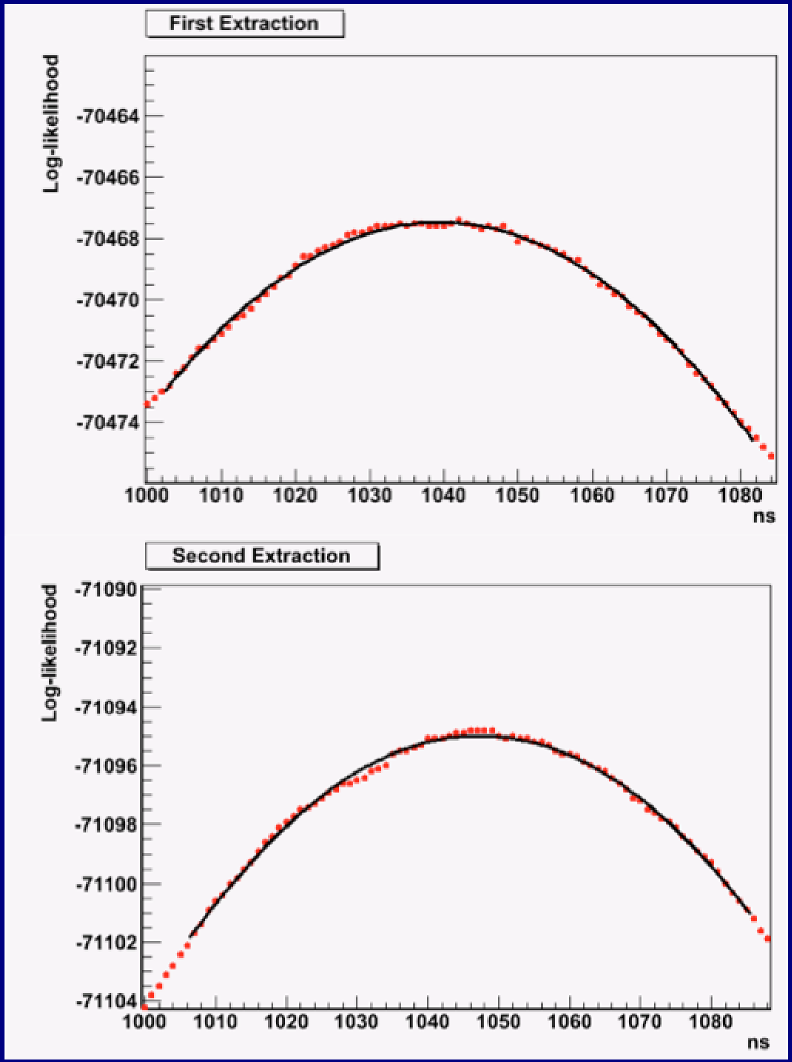
Delay calibrations summary

Item	Result	Method
CERN UTC distribution (GMT)	10085 ± 2 ns	• Portable Cs • Two-ways
WFD trigger	30 ± 1 ns	Scope
BTC delay	580 ± 5 ns	• Portable Cs • Dedicated beam experiment
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
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement

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

Blind analysis

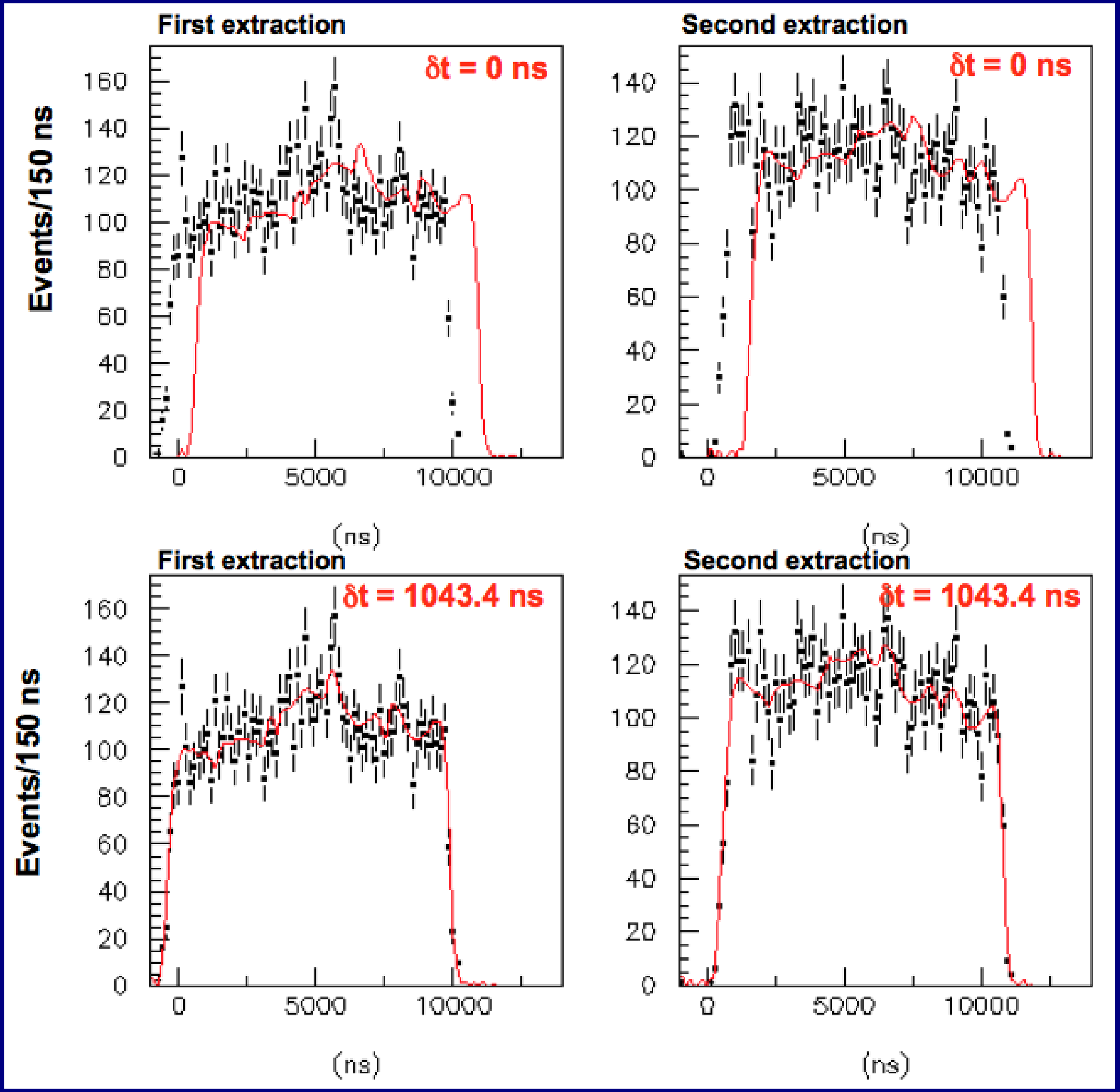
Analysis deliberately conducted by referring to the obsolete timing of 2006:

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 δt by construction much larger than individual calibration contributions ~ 1000 ns**

→ **"Box" opened once all correction contributions reached satisfactory accuracy**

Data vs PDF: before and after likelihood result



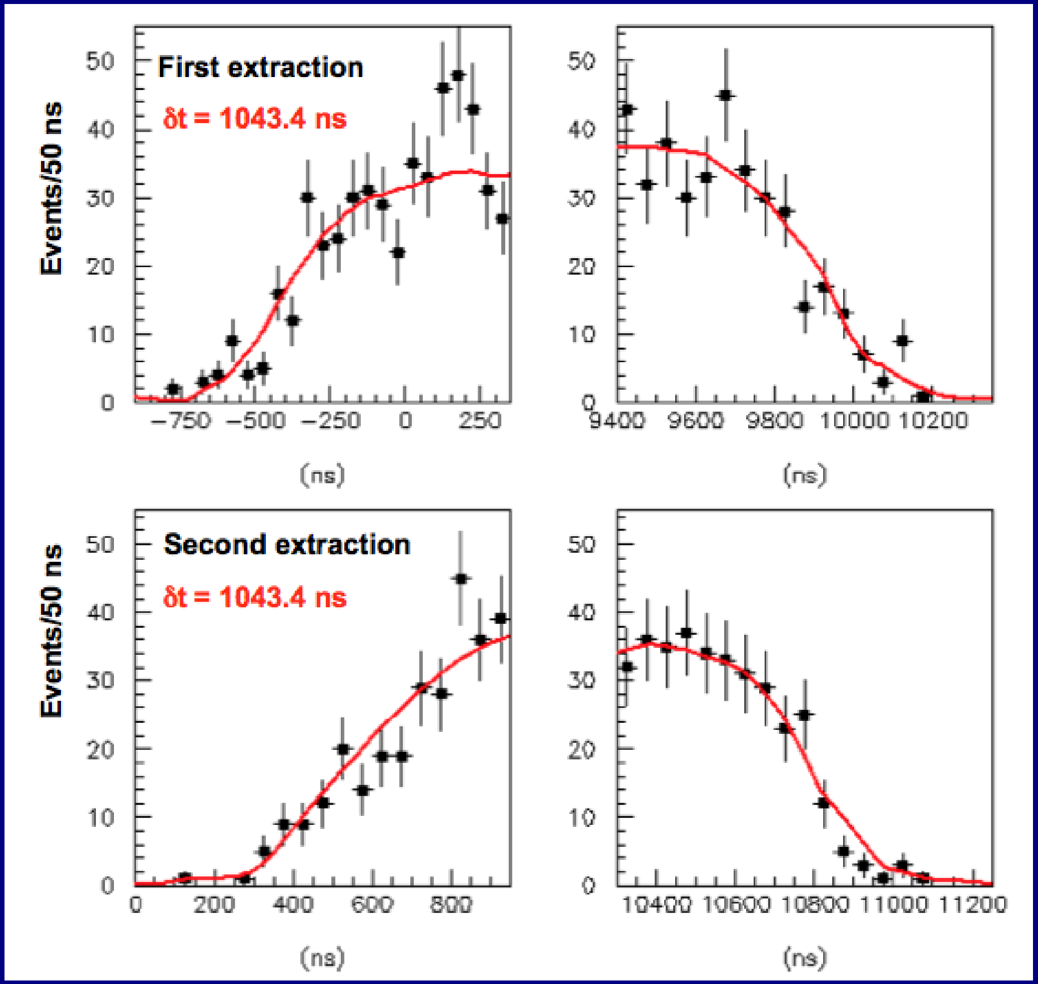
(BLIND) $\delta t = TOF_c - TOF_\nu$ =

(1043.4 ± 7.8) ns (stat)

χ^2 / ndof :

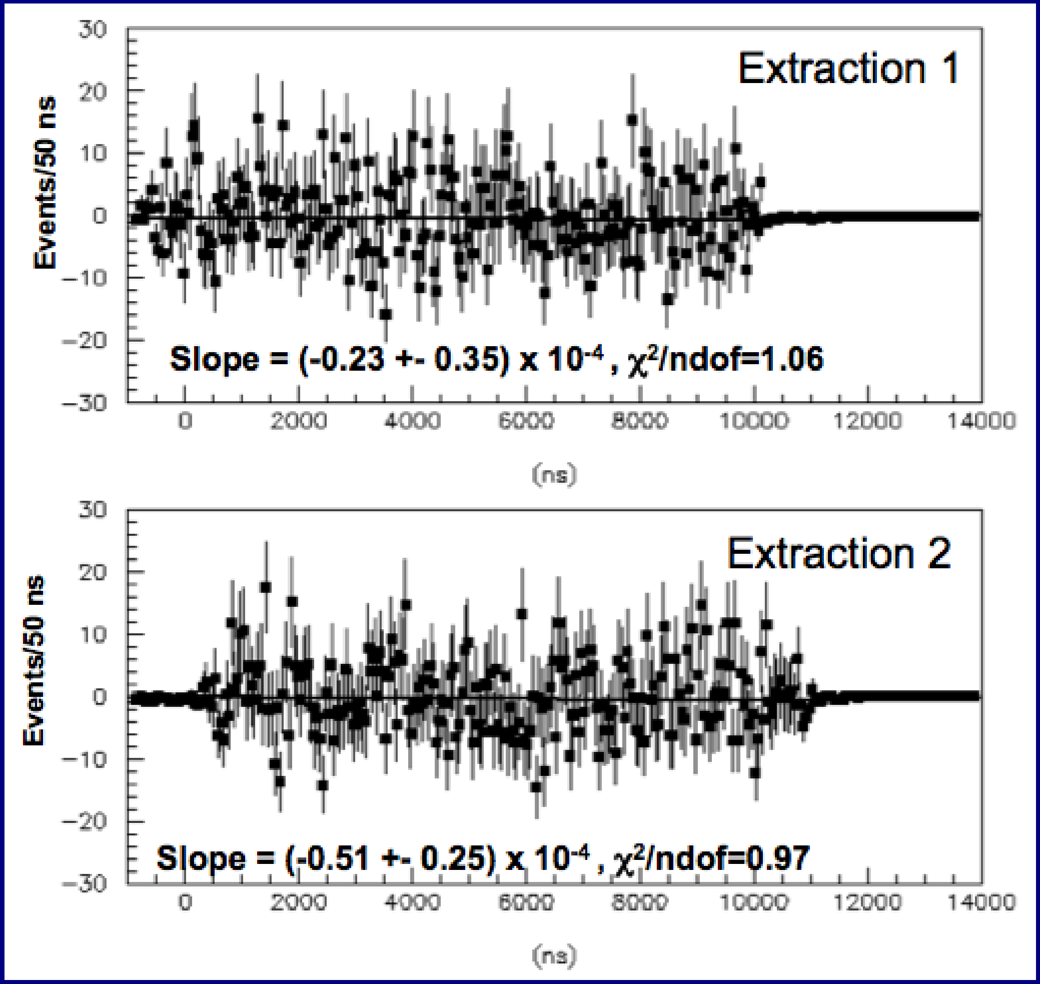
first extraction: 1.1
second extraction: 1.0

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



Residual of the data point wrt to the PDF

- Kolmogorov-Smirnov test
  - 1st extraction: Prob=61.4%
  - 2nd extraction: Prob=99:0%
- Anderson-Darling test
  - 1st extraction: Prob=38%
  - 2nd extraction: Prob=51%

Analysis cross-checks (I)

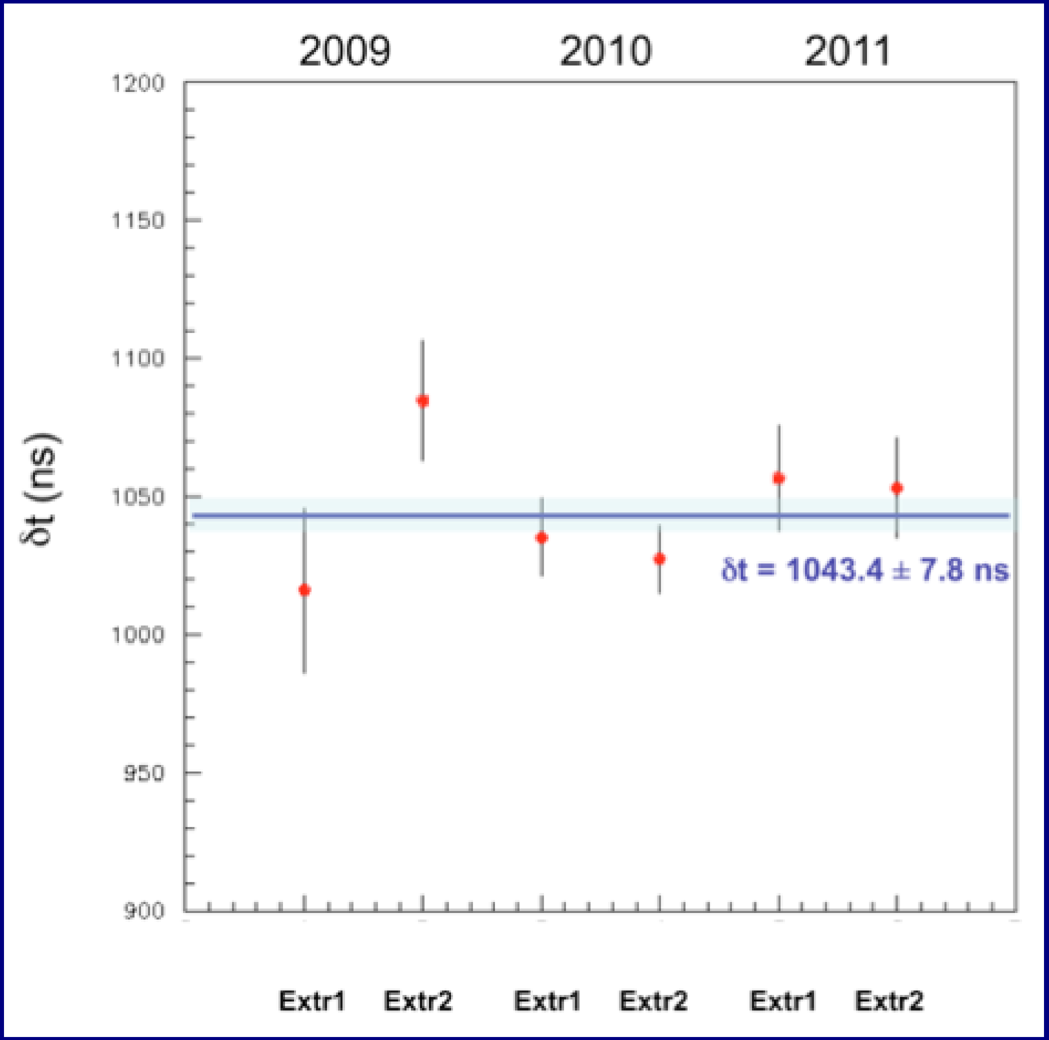
1) Coherence among CNGS runs/extractions

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

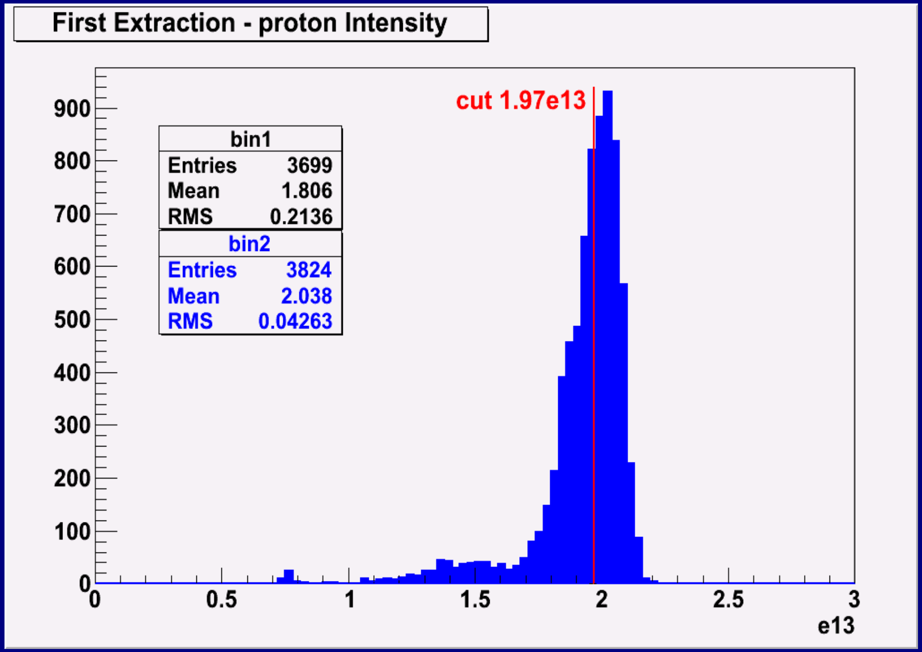
3) Internal vs external events:



All events: δt (blind) = TOF_c -TOF_ν = (1043.4 ± 7.8 (stat.)) ns

Internal events only: (1045.1 ± 11.3 (stat.)) ns

Analysis cross-check (II)



The absolute difference between the two bins is

(6.8±16.6) ns

Opening the box

timing and baseline corrections

	Blind 2006	Final analysis	Correction (ns)
Baseline (ns)	2440079.6	2439280.9	
Earth rotation (ns)		2.2	
Correction baseline			-796.5
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			**-985.6**

systematic uncertainties

Systematic uncertainties	ns	Error distribution
Baseline (20 cm)	0.67	Gaussian
Decay point	0.2	Exponential (1 side)
Interaction point	2.0	Flat (1 side)
UTC delay	2.0	Gaussian
LNGS fibres	1.0	Gaussian
DAQ clock transmission	1.0	Gaussian
FPGA calibration	1.0	Gaussian
FWD trigger delay	1.0	Gaussian
CNGS-OPERA GPS synchronisation	1.7	Gaussian
MC simulation for TT timing	3.0	Gaussian
TT time response	2.3	Gaussian
BCT calibration	5.0	Gaussian
Total systematic uncertainty	**-5.9, +8.3**	

Results

For CNGS ν_μ beam, <E> = 17 GeV:

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

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

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

$(v-c)/c = \delta t/(TOF_c - \delta t) = (2.37 \pm 0.32\ (\text{stat.})\ ^{+0.34}_{-0.24}(\text{sys.})) \times 10^{-5}$

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

6.2 σ 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

$$L(\delta t) = \prod_j w_j (t_j + \delta t)$$

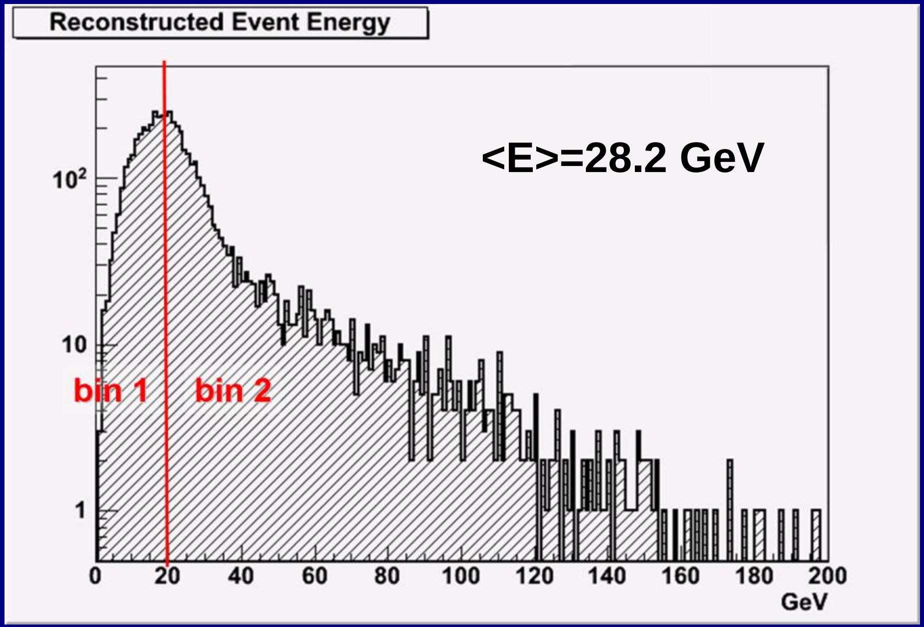
(BLIND) $\delta t = TOF_c - TOF_\nu = (1040.1 \pm 5.0)$ ns (stat)

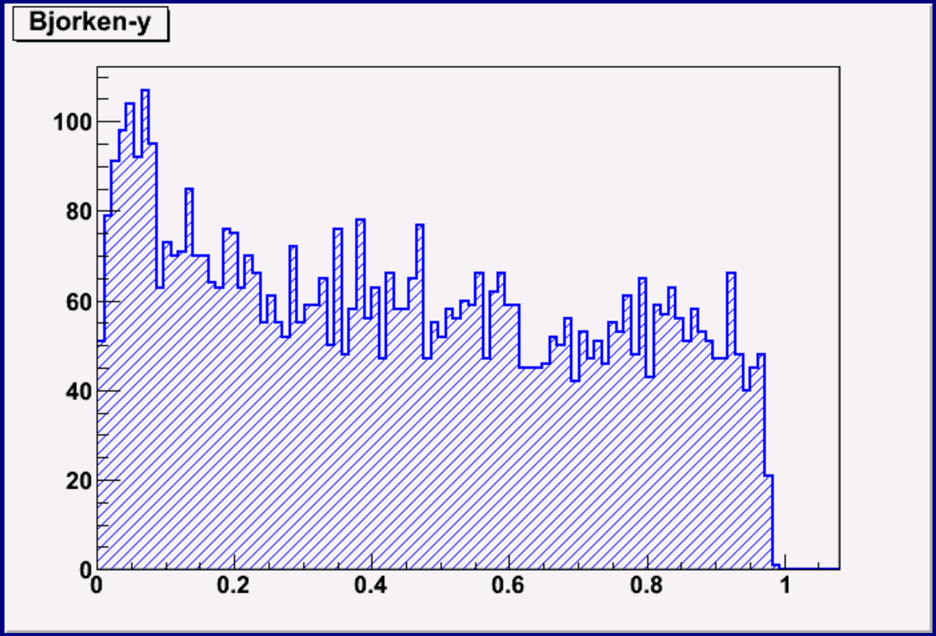
A systematic error of 4.4 ns is attributed to this result by comparing different filtering conditions and treatment of the waveform baselines

It adds up to the systematic uncertainty quoted before

$\delta t = (54.5 \pm 5.0 \text{ (stat.) } {}^{+9.6}_{-7.2} \text{(sys.)})$ ns

Study of the energy dependence





- Only internal muon-neutrino CC events used for energy measurement (5489 events)

$$(E = E_\mu + E_{had})$$

- Full MC simulation: no energy bias in detector time response (<1 ns)
→ systematic errors cancel out

$$\delta t = TOF_c - TOF_\nu = (61.1 \pm 13.2\ (\text{stat.})\ ^{+7.3}_{-6.9}(\text{sys.}))\ \text{ns for } \langle E_\nu \rangle = 28.2\ \text{GeV}$$

(result limited to events with measured energy)

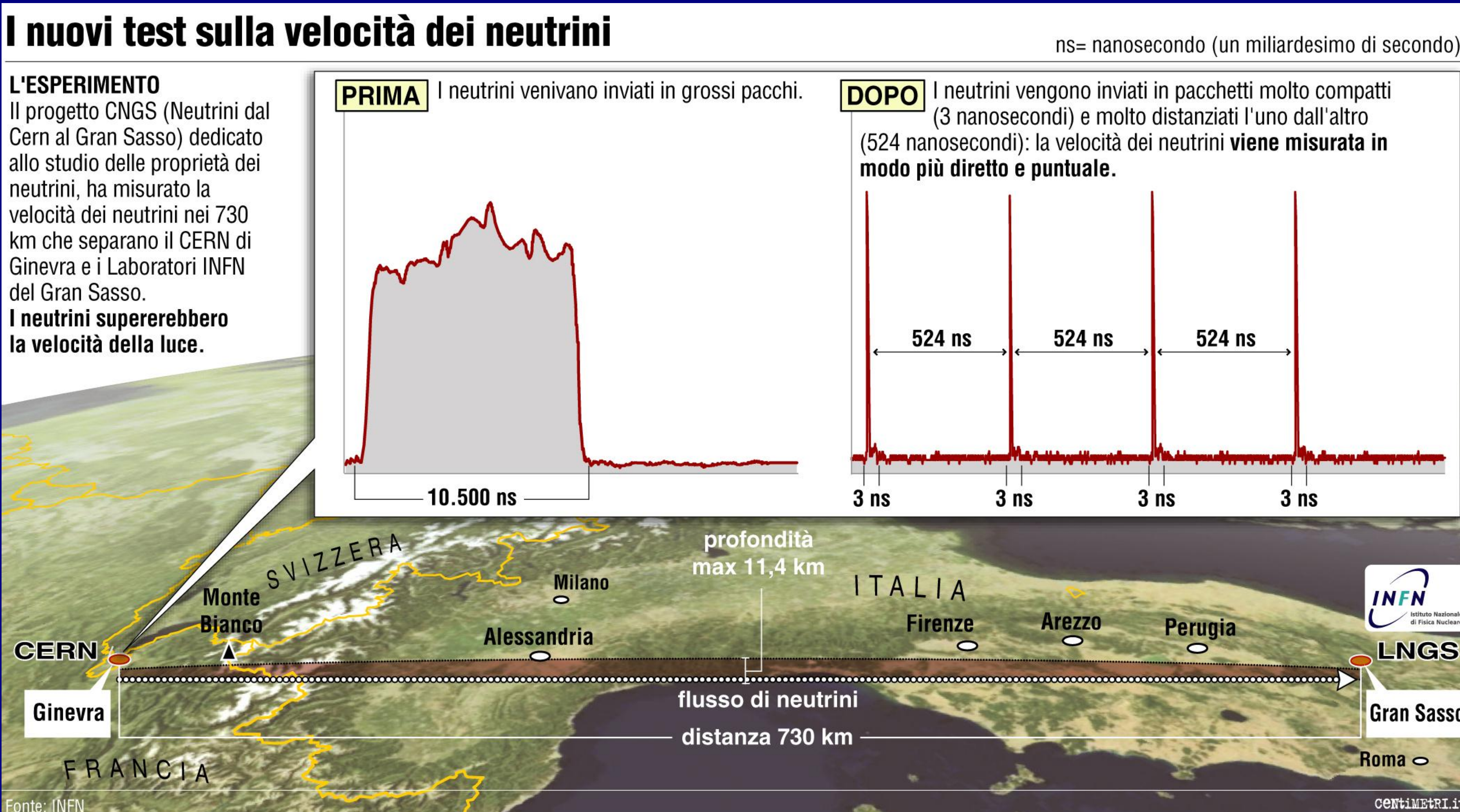
Energy dependence

- The data have been split in two energy bins

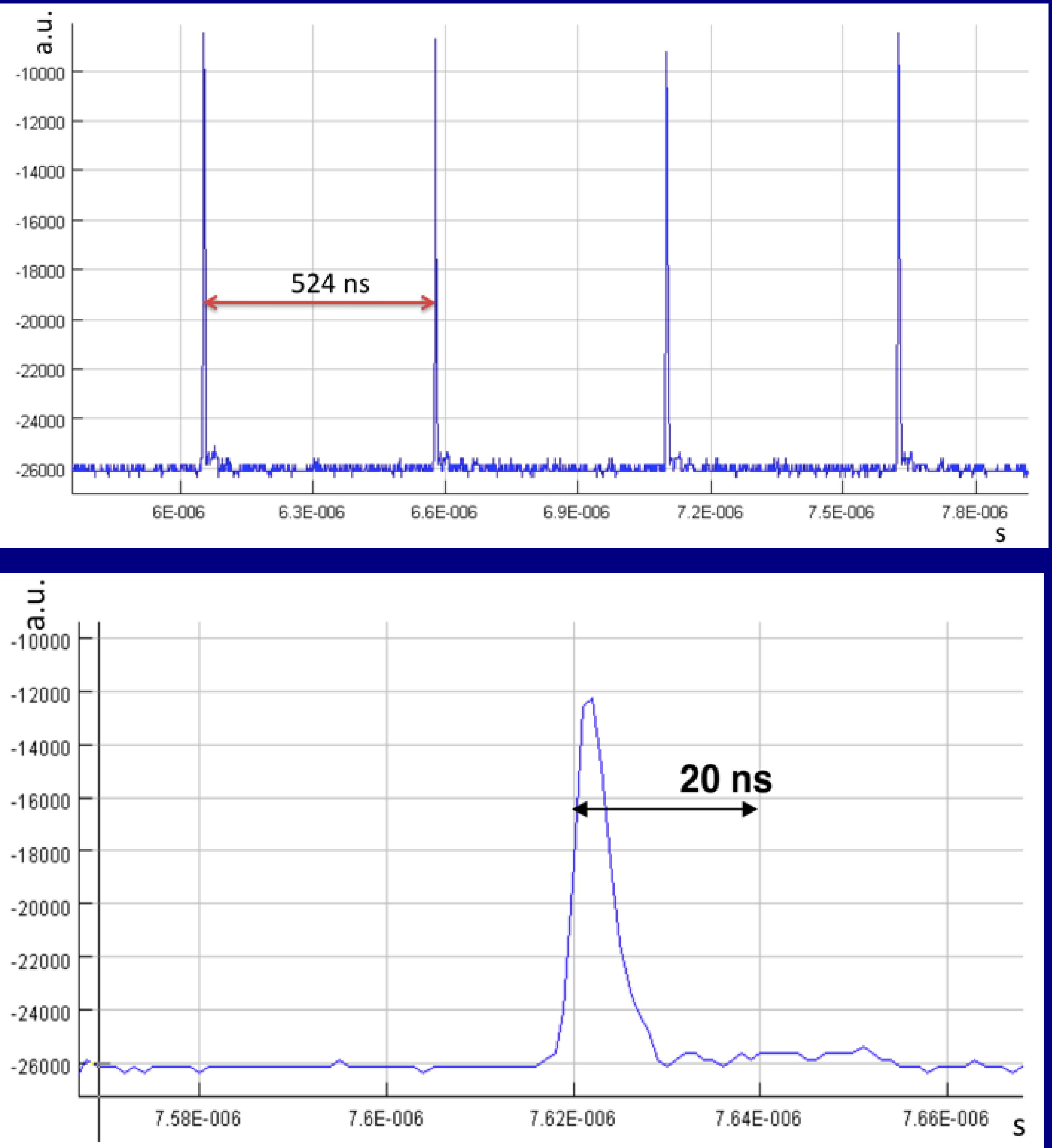
- Bin 1 with $\langle E_v \rangle = 13.8$ GeV
  - $\delta t = (54.7 \pm 18.4\ (\text{stat.})\ ^{+7.3}_{-6.9}(\text{sys.}))$ ns

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

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


I nuovi test sulla velocità dei neutrini
ns= nanosecondo (un miliardesimo di secondo)
L'ESPERIMENTO
Il progetto CNGS (Neutrini dal Cern al Gran Sasso) dedicato allo studio delle proprietà dei neutrini, ha misurato la velocità dei neutrini nei 730 km che separano il CERN di Ginevra e i Laboratori INFN del Gran Sasso.
I neutrini supererebbero la velocità della luce.
PRIMA
I neutrini venivano inviati in grossi pacchi.
10.500 ns
DOPO
I neutrini vengono inviati in pacchetti molto compatti (3 nanosecondi) e molto distanziati l'uno dall'altro (524 nanosecondi): la velocità dei neutrini viene misurata in modo più diretto e puntuale.
524 ns
524 ns
524 ns
3 ns
3 ns
3 ns
3 ns
profondità max 11,4 km
SVIZZERA
ITALIA
FRANCIA
Monte Bianco
Milano
Alessandria
Firenze
Arezzo
Perugia
CERN
LNGS
Ginevra
Gran Sasso
flusso di neutrini
distanza 730 km
Roma
INFN Istituto Nazionale di Fisica Nucleare
Fonte: INFN
centimetri.it

Short-bunch wide-spacing neutrino beam



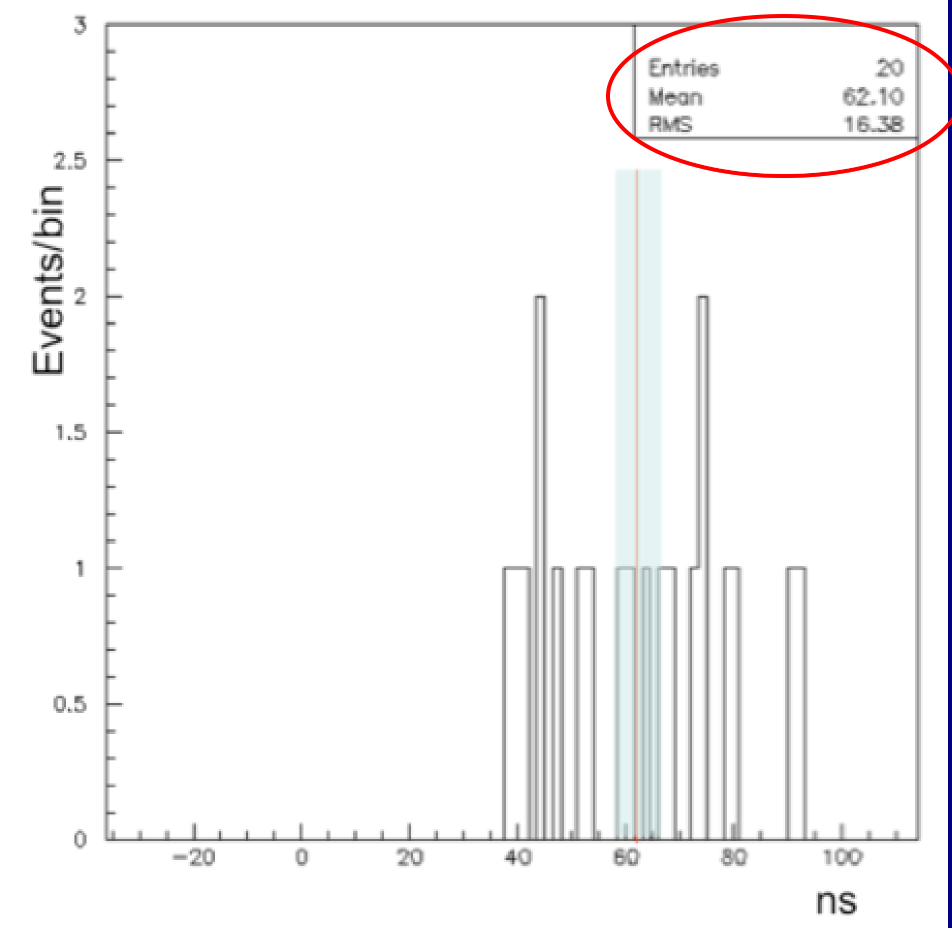
4×10^{16} pot accumulated

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:

$$\delta t = TOF_c - TOF_\nu = (57.8 \pm 7.8\ (\text{stat.})\ ^{+8.3}_{-5.9}\ (\text{sys.}))\ \text{ns}$$

• 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:

$$(v-c)/c = \delta t / (TOF_c - \delta t) = (2.37 \pm 0.32\ (\text{stat.})\ ^{+0.34}_{-0.24}\ (\text{sys.})) \times 10^{-5}$$

with an overall significance of 6.2 σ.

• A likelihood built by associating each neutrino interaction to its waveform instead of using the global PDF gives $\delta t = (54.5 \pm 5.0\ (\text{stat.})\ ^{+9.6}_{-7.2} (\text{sys.}))\ \text{ns}$

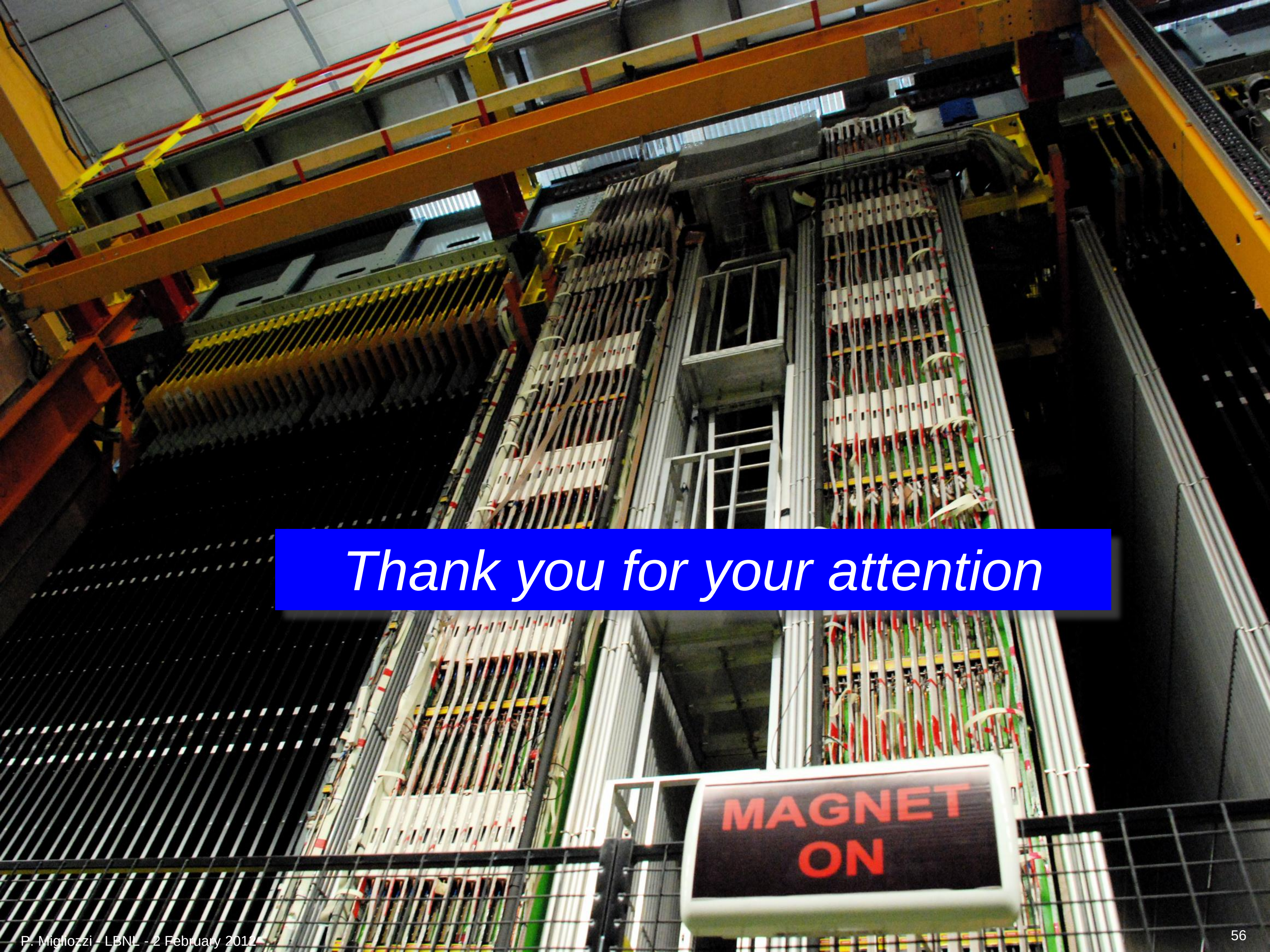
Conclusions (2)

• 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 dt measured from the average of the distribution of (62.1 ± 3.7) ns, in agreement with the value of (57.8 ± 7.8) ns obtained with the main analysis.

•A possible δt 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