



# *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



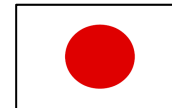
## Italy

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 ( $E_\nu > 30$  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.  
 $|v-c|/c \leq 2 \times 10^{-9}$ .

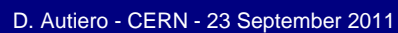
Performed with observation of neutrino and light arrival time.

MINOS (Phys. Rev. D 76 072005 2007)

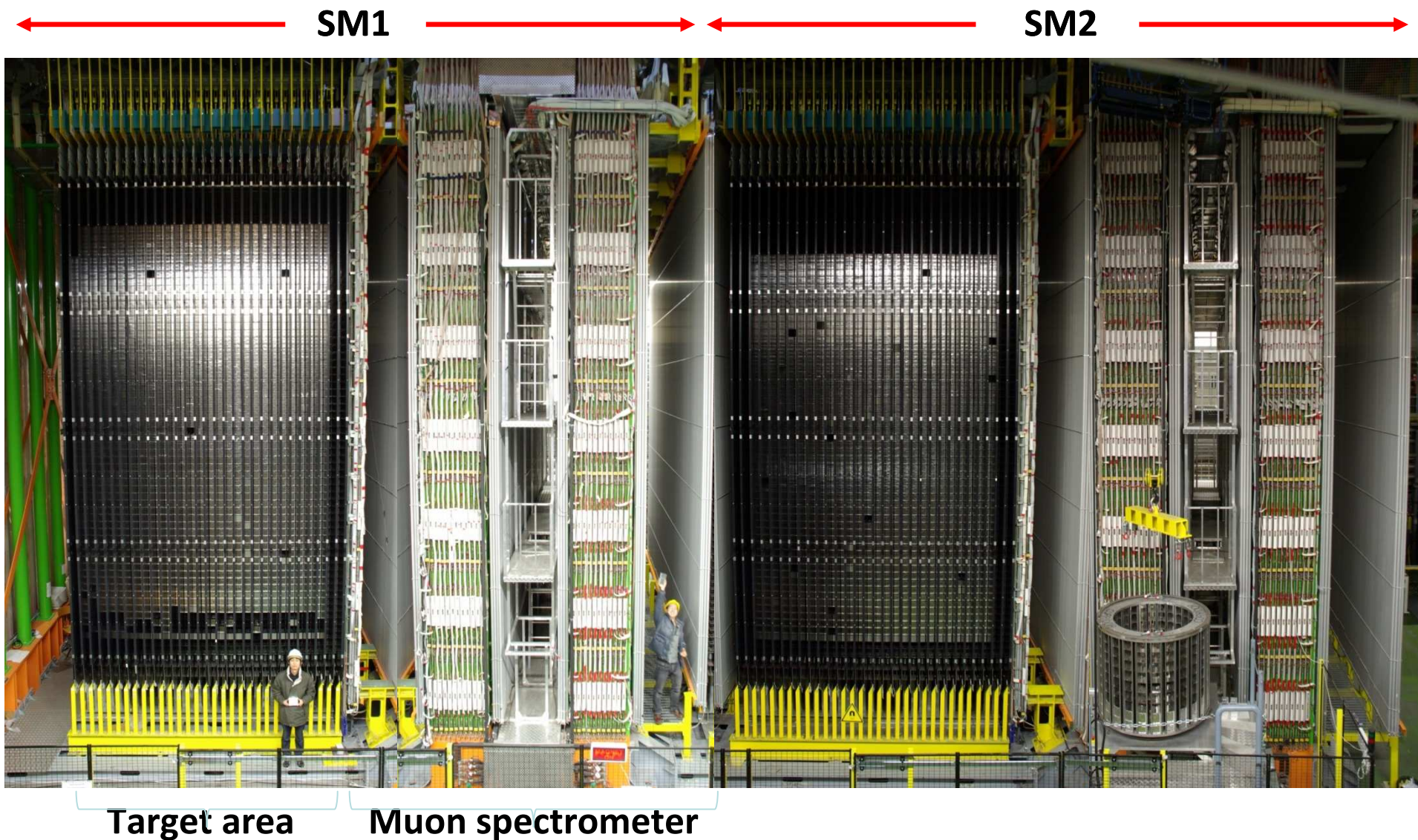
muon neutrinos, 730 km baseline,  $E_\nu$  peaking at  $\sim 3$  GeV with a tail extending above 100 GeV.

$(v-c)/c = 5.1 \pm 2.9 \times 10^{-5}$  (1.8  $\sigma$ ).

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



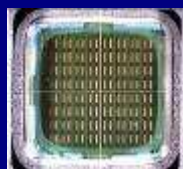
# THE IMPLEMENTATION OF THE PRINCIPLE



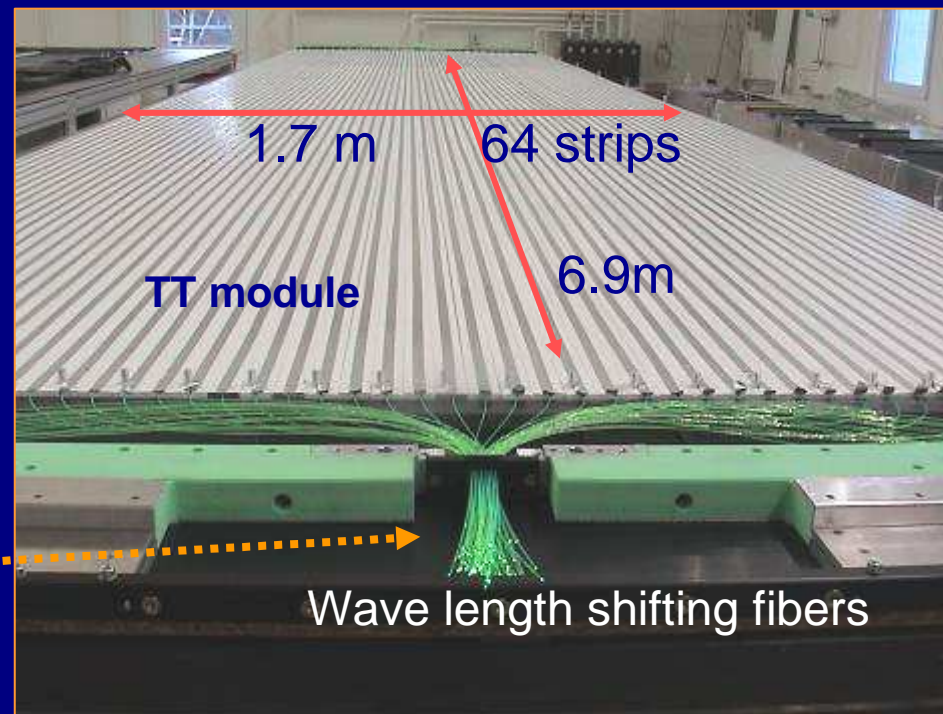
# The Target Tracker (TT)

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)



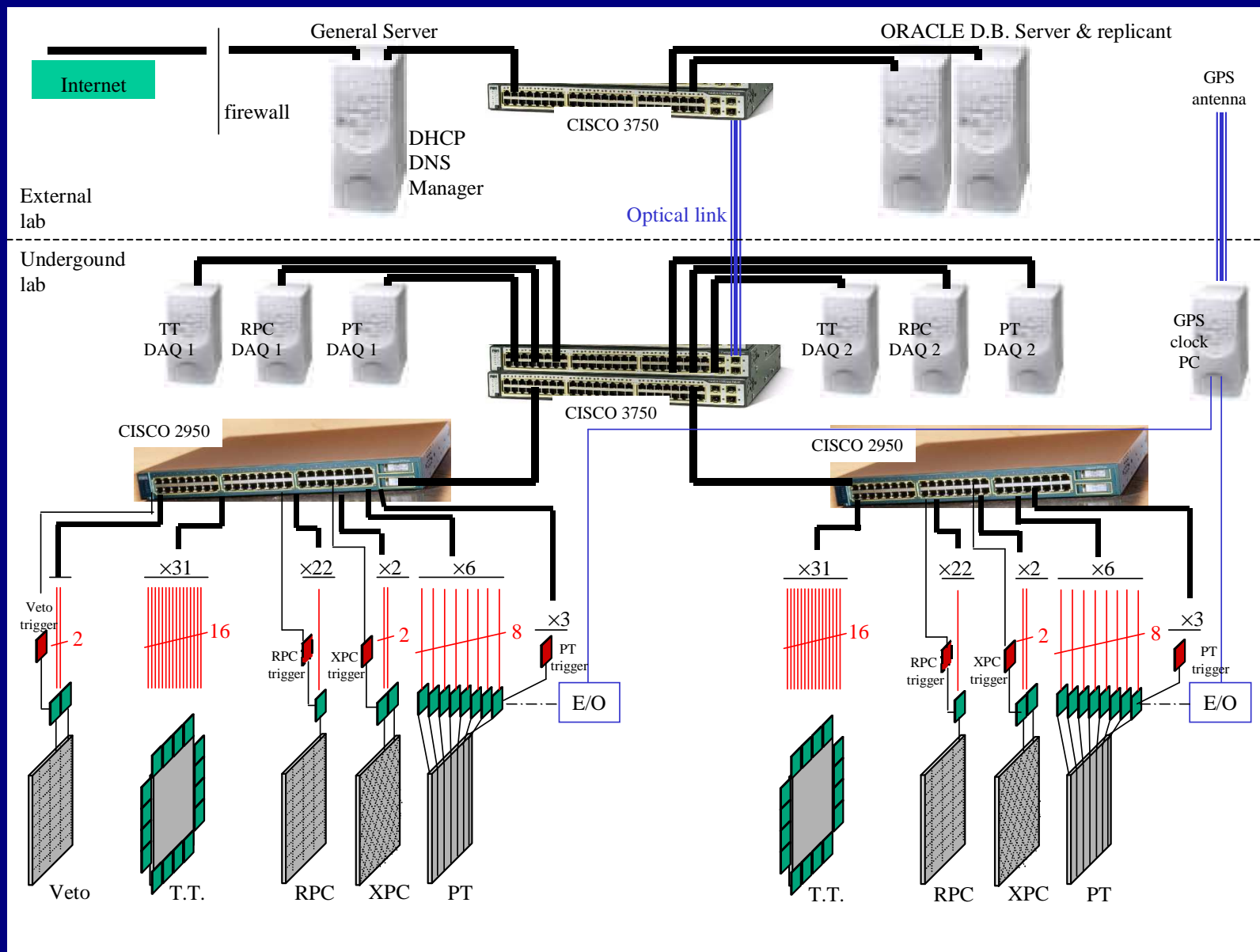
H7546



Read out by 1 Front-End DAQ board per side

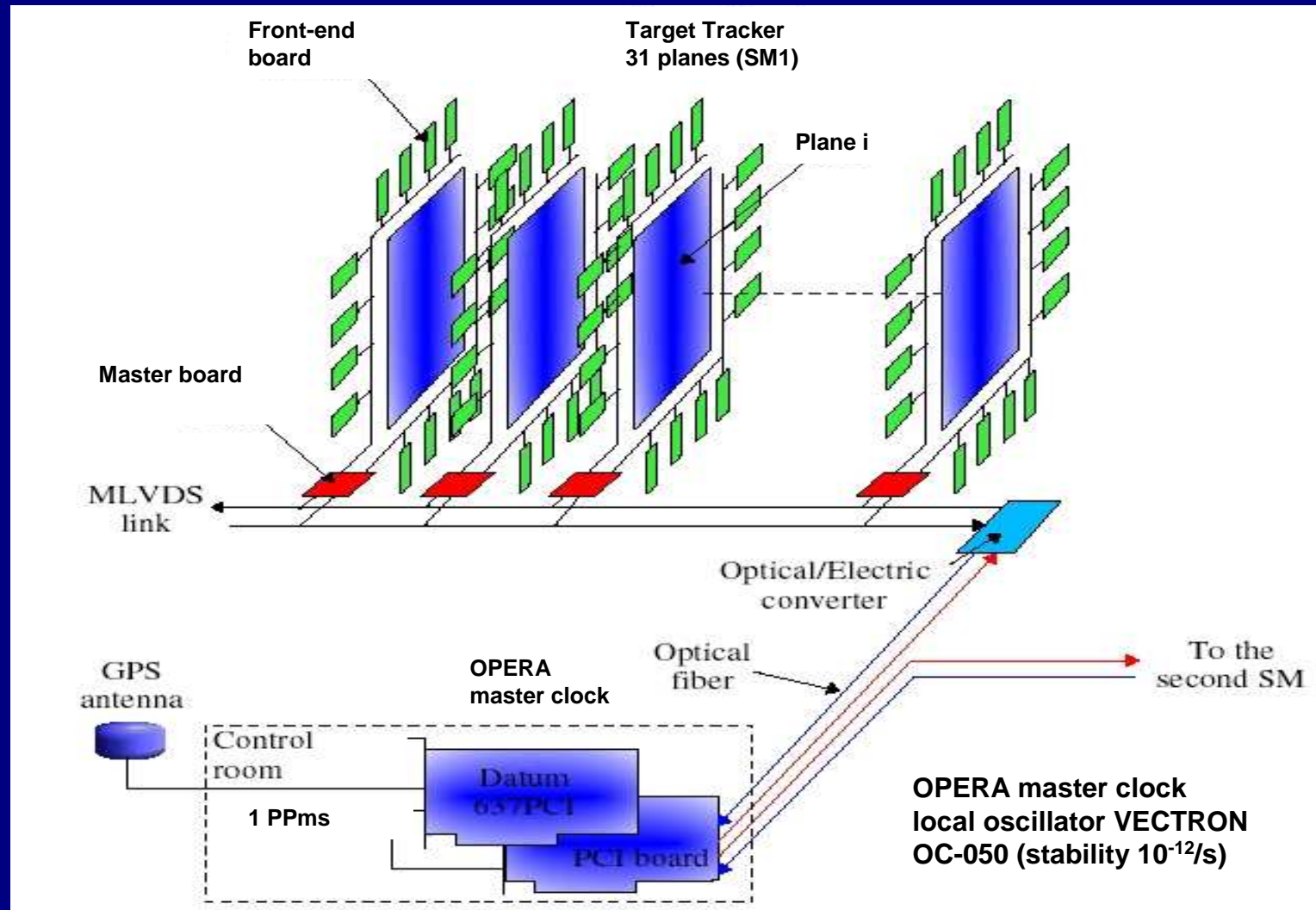


# OPERA readout scheme



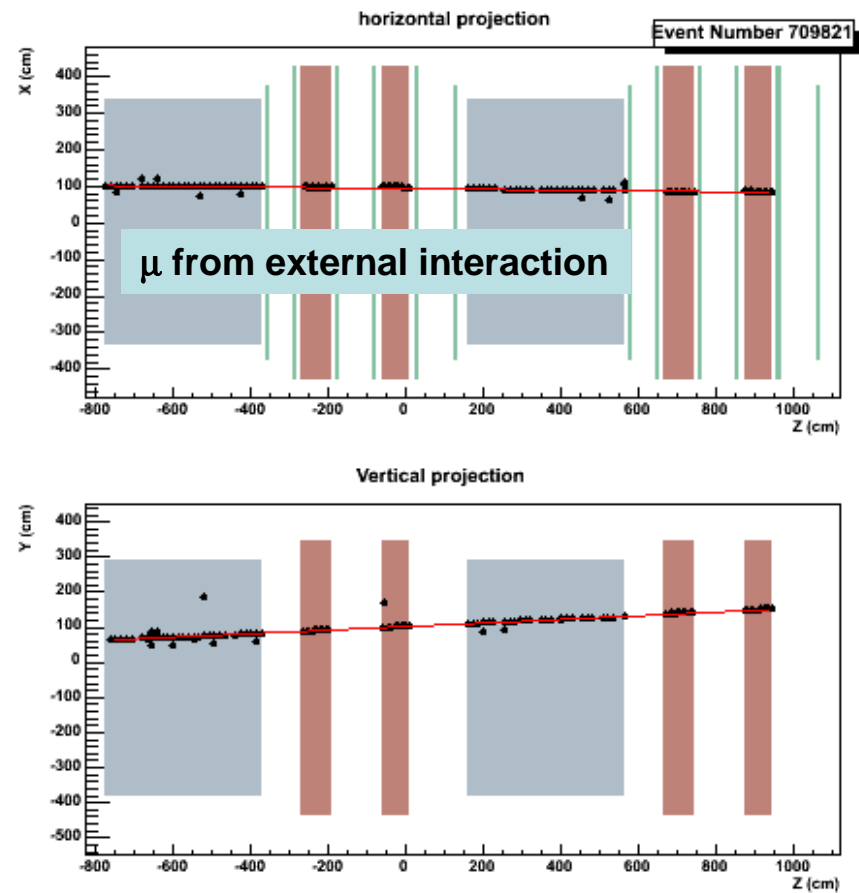
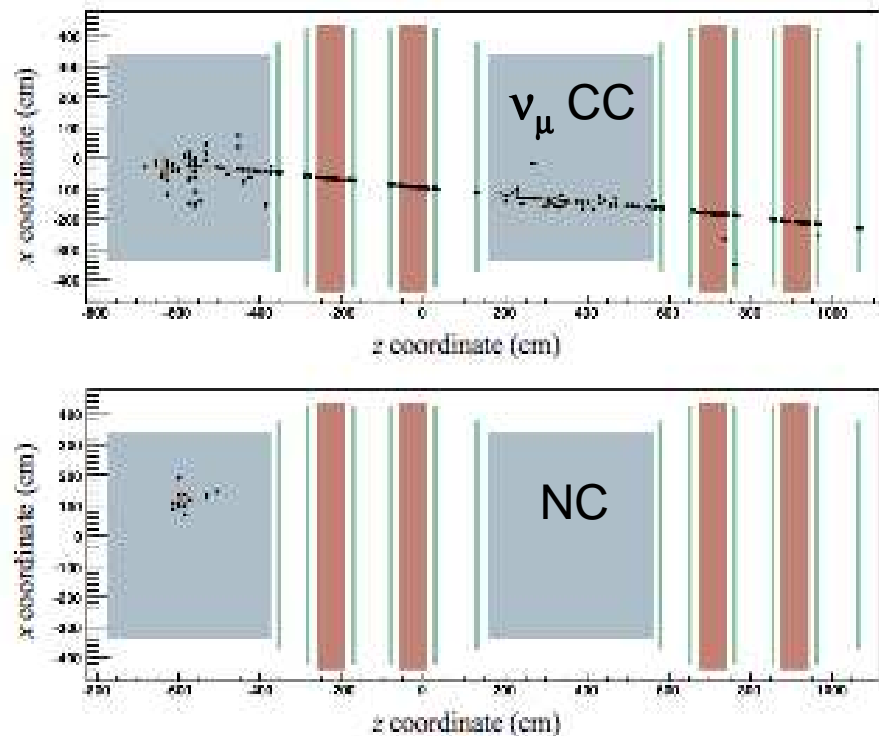
Trigger-less, asynchronous Front-End nodes (1200); Gigabit Ethernet network

## Clock distribution system (10 ns UTC event time-stamp granularity)

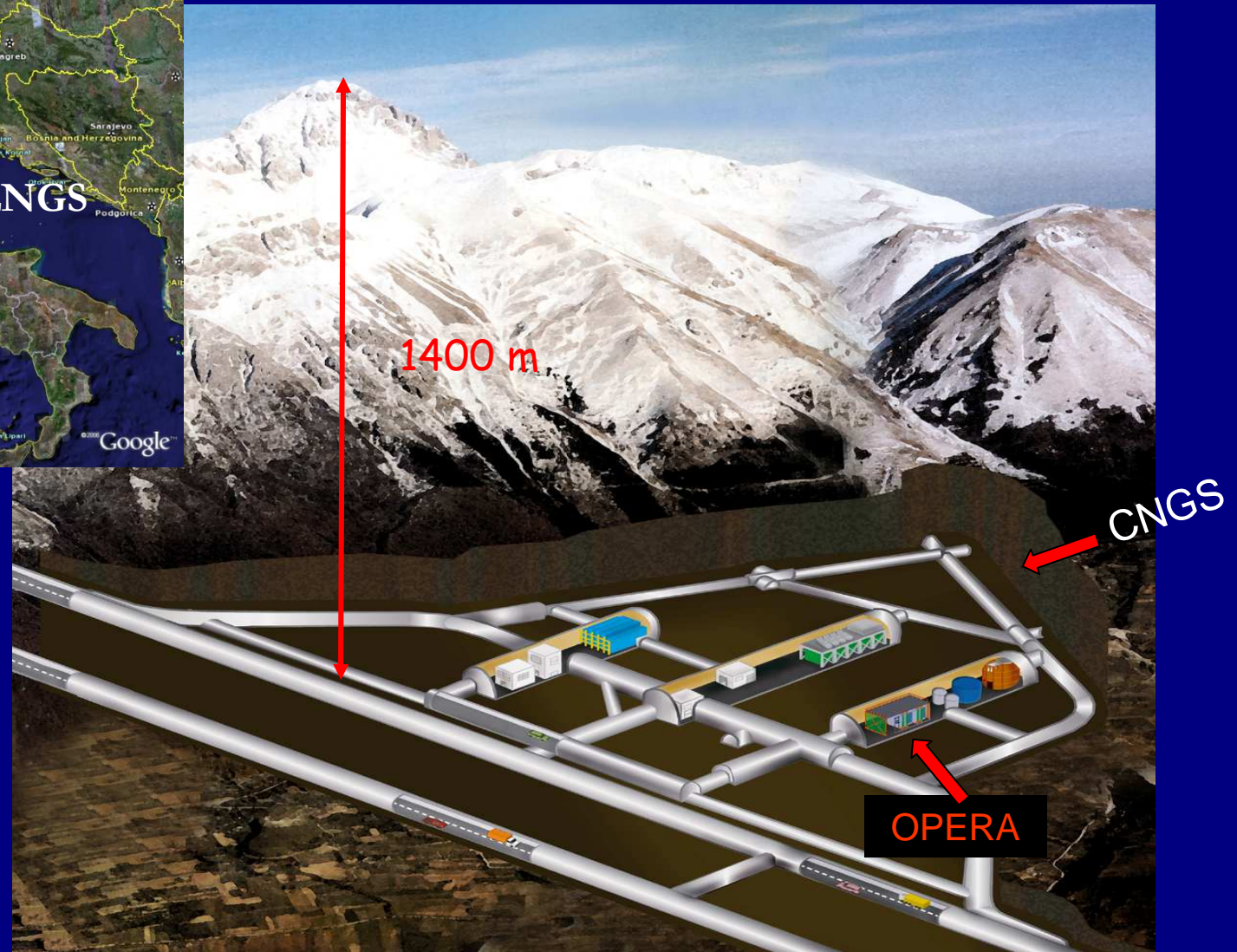


**Mezzanine DAQ card** common to all sub-detectors Front End nodes:  
CPU (embedded LINUX), Memory, FPGA, clock receiver and ethernet

# “INTERNAL” and “EXTERNAL” OPERA EVENTS

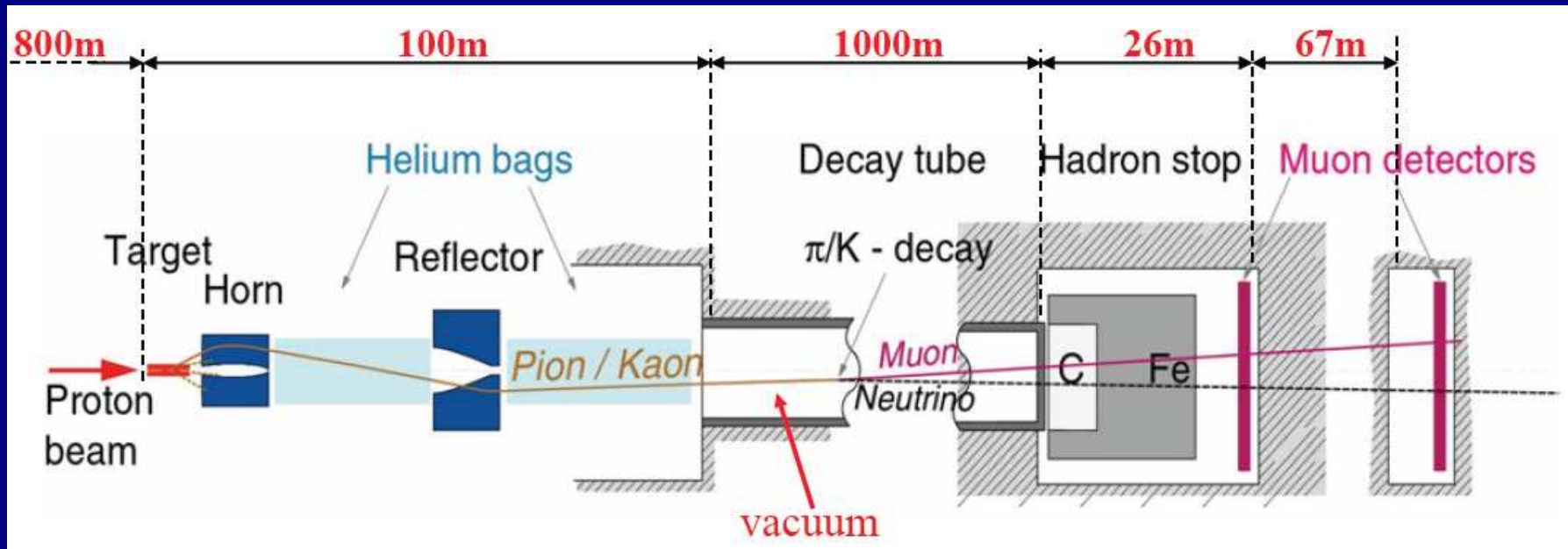


# The LNGS underground physics laboratory



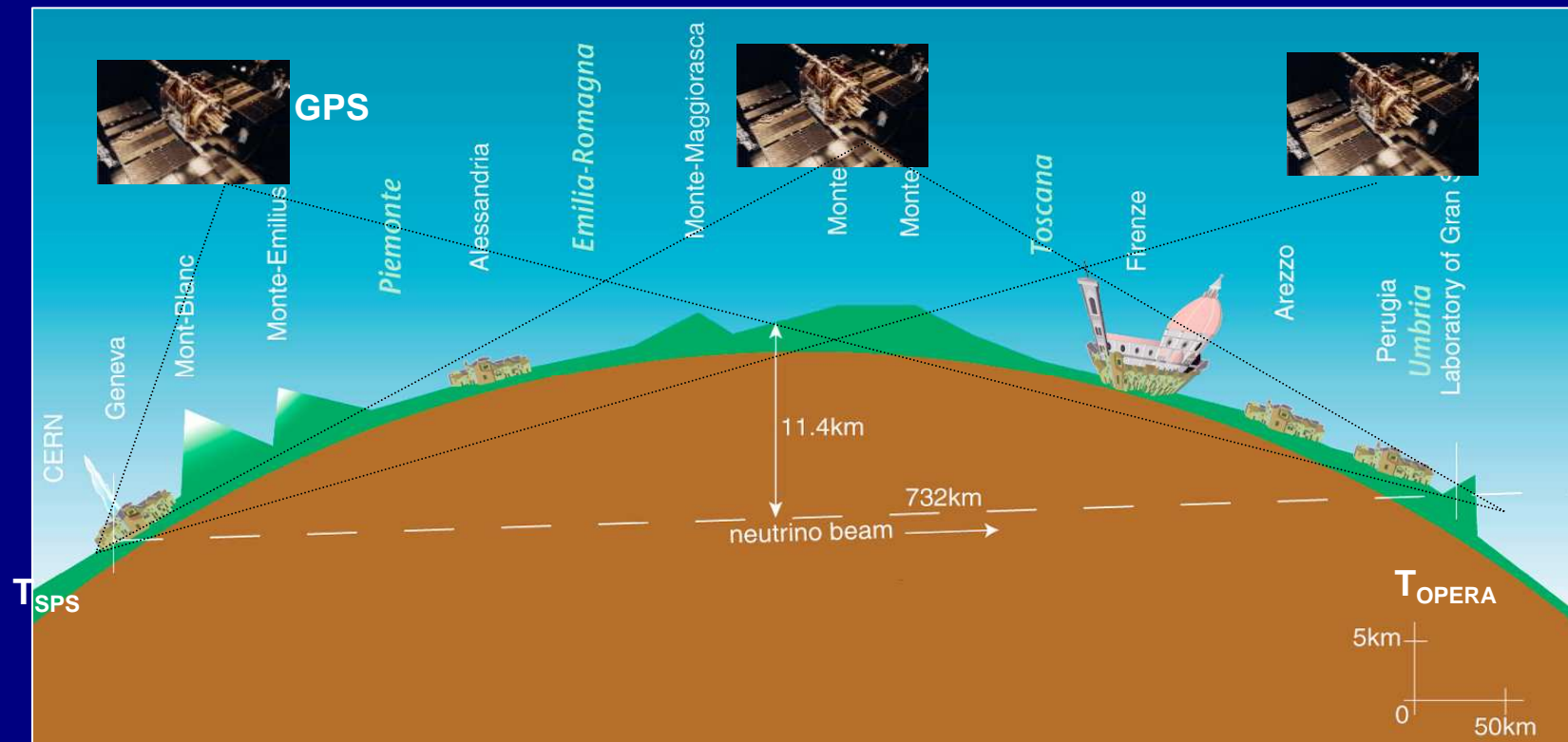


# THE CNGS neutrino beam



- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5  $\mu$ s extractions (by kicker magnet) separated by 50 ms
- Beam intensity:  $2.4 \cdot 10^{13}$  proton/extraction
- ~ pure muon neutrino beam ( $\langle E \rangle = 17$  GeV) travelling through the Earth's crust

# CNGS events selection



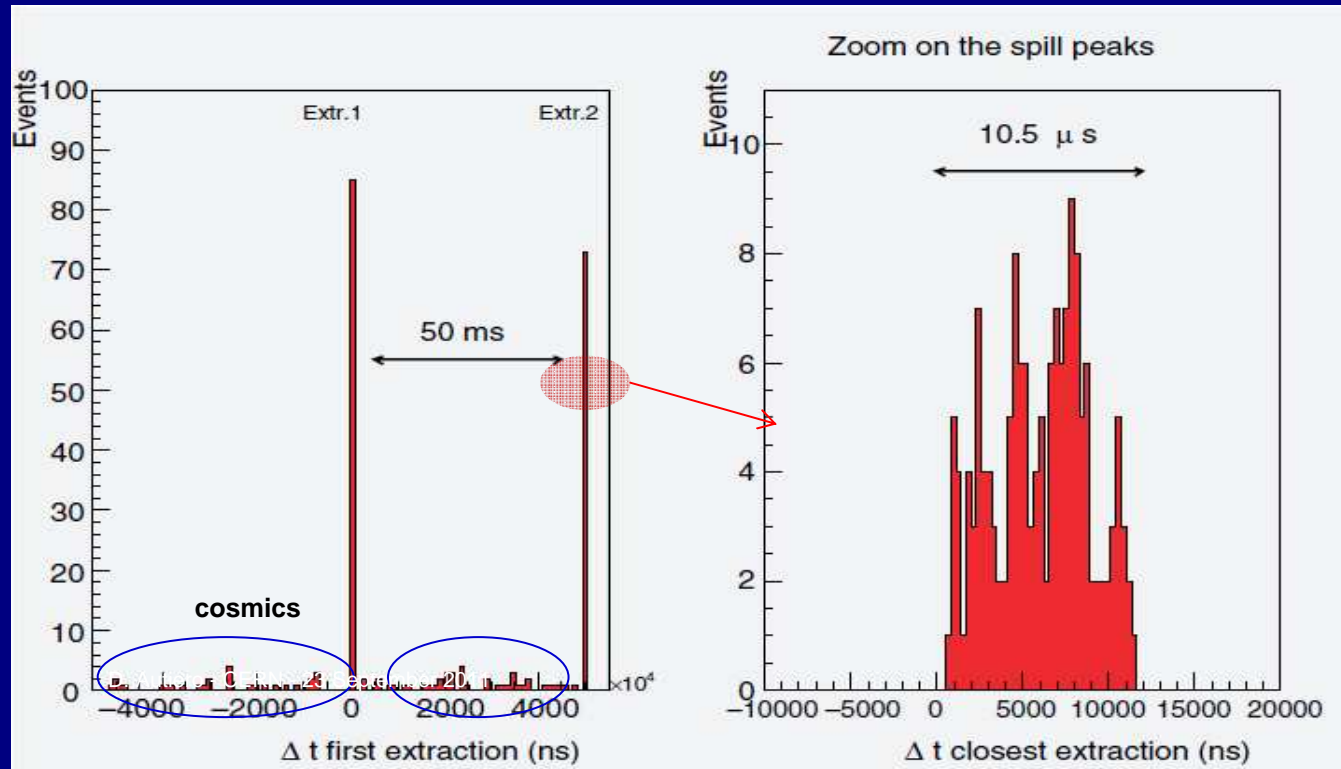
Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

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

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

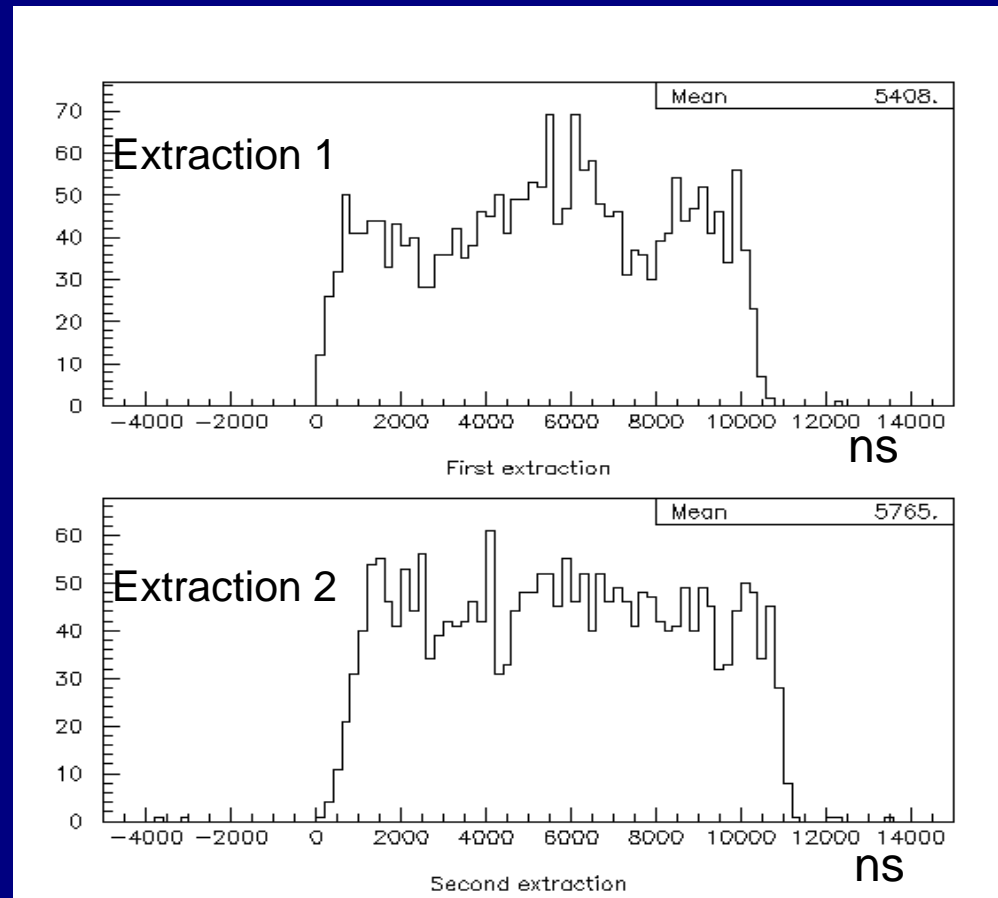


OPERA data: narrow peaks of the order of the spill width (10.5  $\mu$ s)

Negligible cosmic-ray background:  $O(10^{-4})$

Selection procedure kept unchanged since first events in 2006

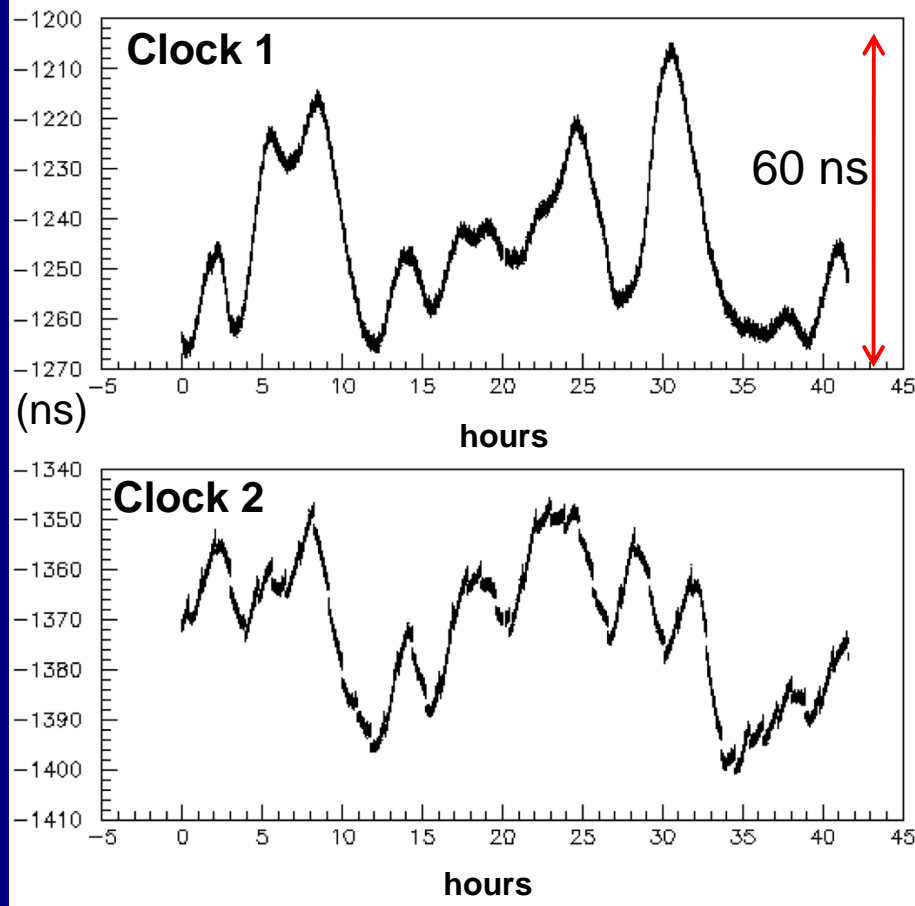
# From CNGS event selection to neutrino velocity measurement



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



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

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

→ Need accurate time synchronisation system

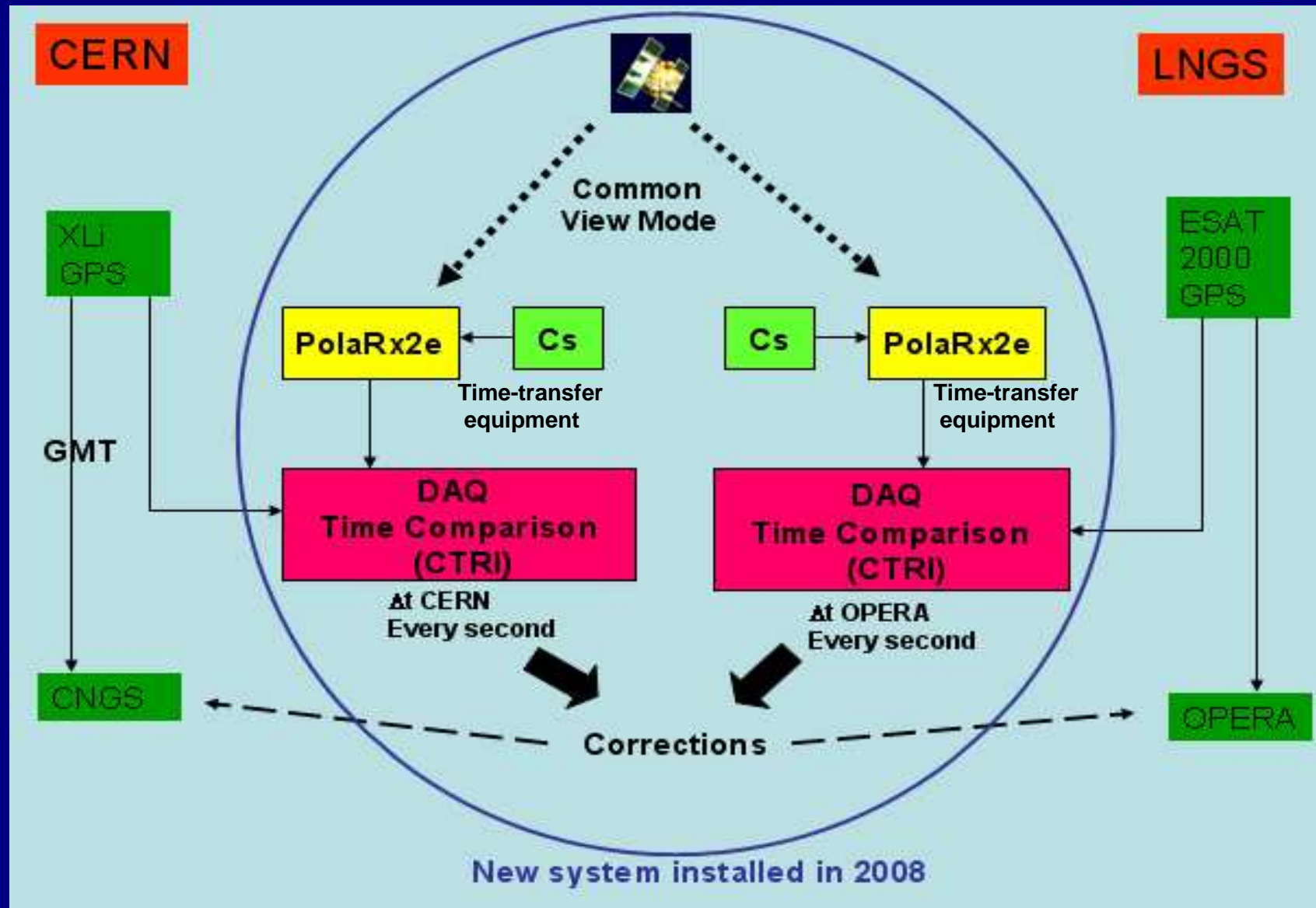
Collaboration with CERN timing team since 2003

Major upgrade in 2008

## 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



Standard GPS receivers ~100 ns accuracy:

CERN **Symmetricon** XLi (source of General Machine Timing)

LNGS: ESAT 2000

2008: installation of a twin high accuracy system calibrated by METAS (Swiss metrology institute) **Septentrio** GPS PolaRx2e + **Symmetricon** Cs-4000

### PolaRx2e:

- frequency reference from Cs clock
- internal time tagging of 1PPS with respect to individual satellite observations
- offline common-view analysis in CGGTTS format
- use ionosphere free P3 code

Standard technique for high accuracy time transfer

Permanent time link (~1 ns) between reference points at CERN and OPERA





D. Autiero - CERN - 23 September 2011



## GPS common-view mode

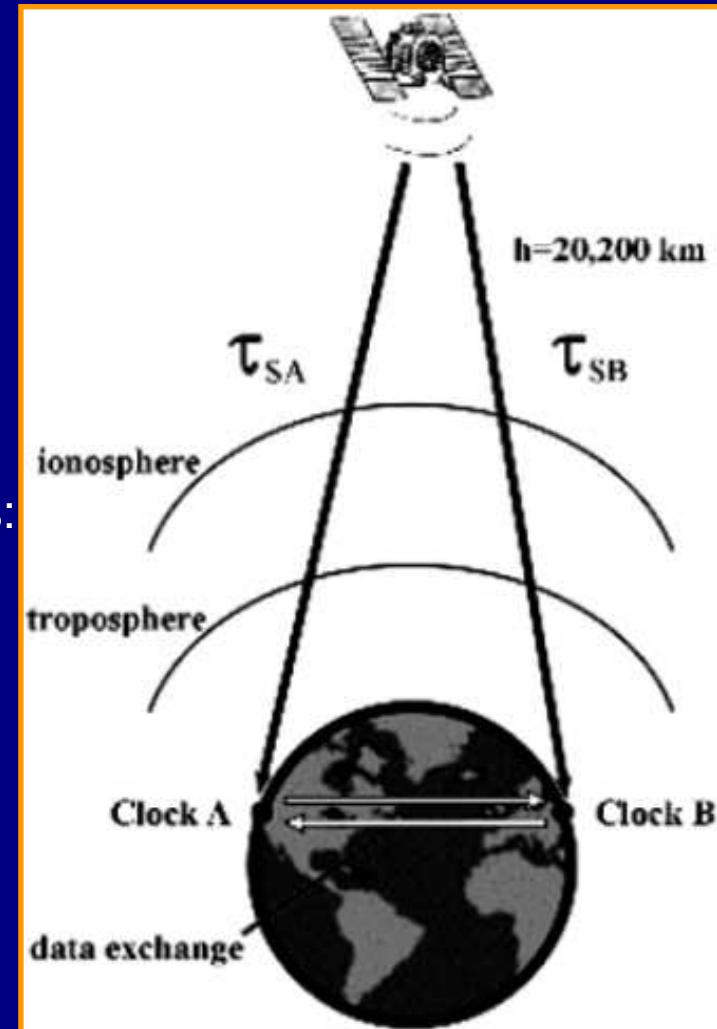
### Standard GPS operation:

resolves  $x, y, z, t$  with  $\geq 4$  satellite observations

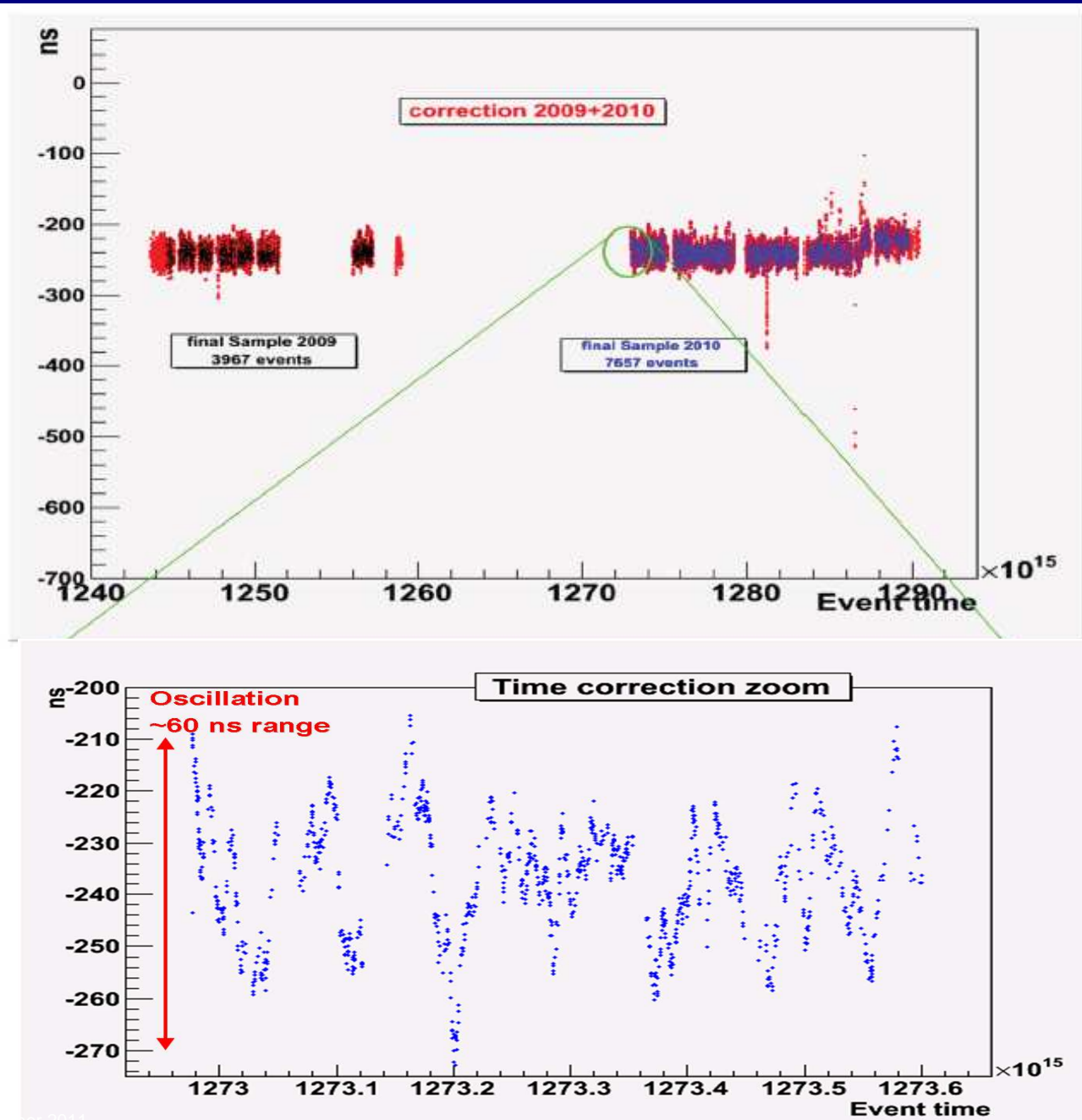
### Common-view mode (the same satellite for the two sites, for each comparison):

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

$730 \text{ km} \ll 20000 \text{ km}$  (satellite height)  $\rightarrow$  similar paths in ionosphere



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



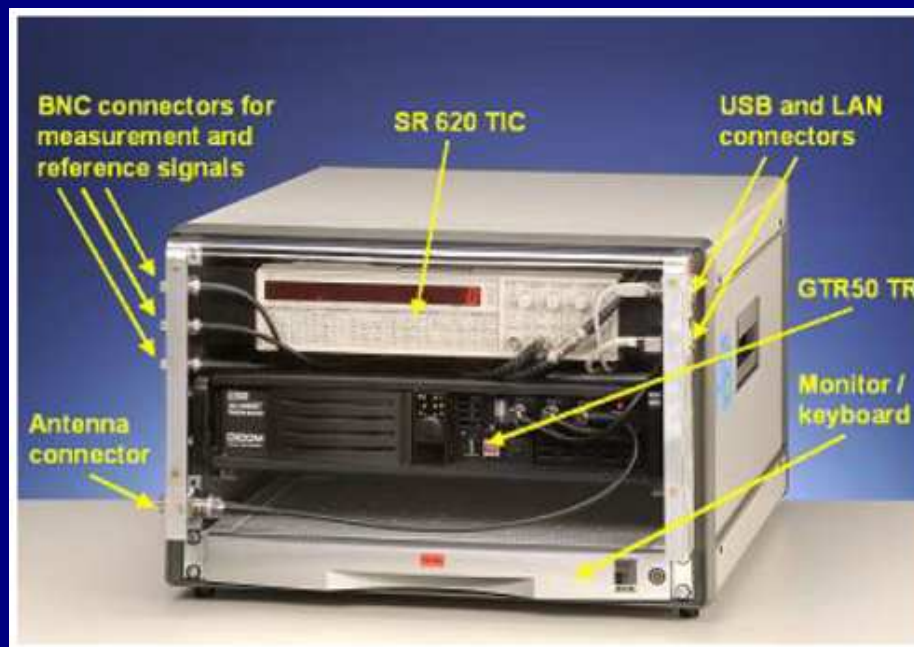
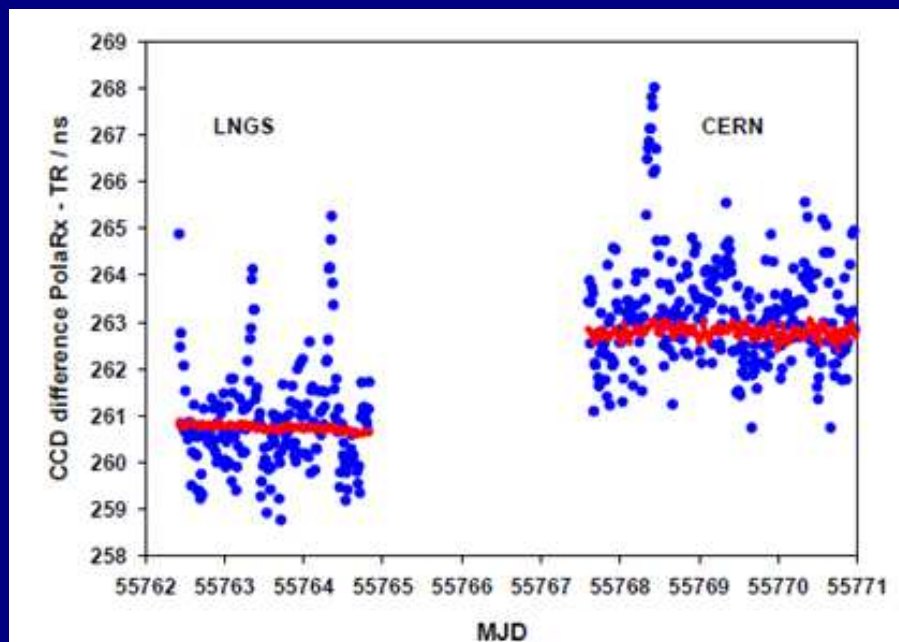


# CERN-OPERA inter-calibration cross-check

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

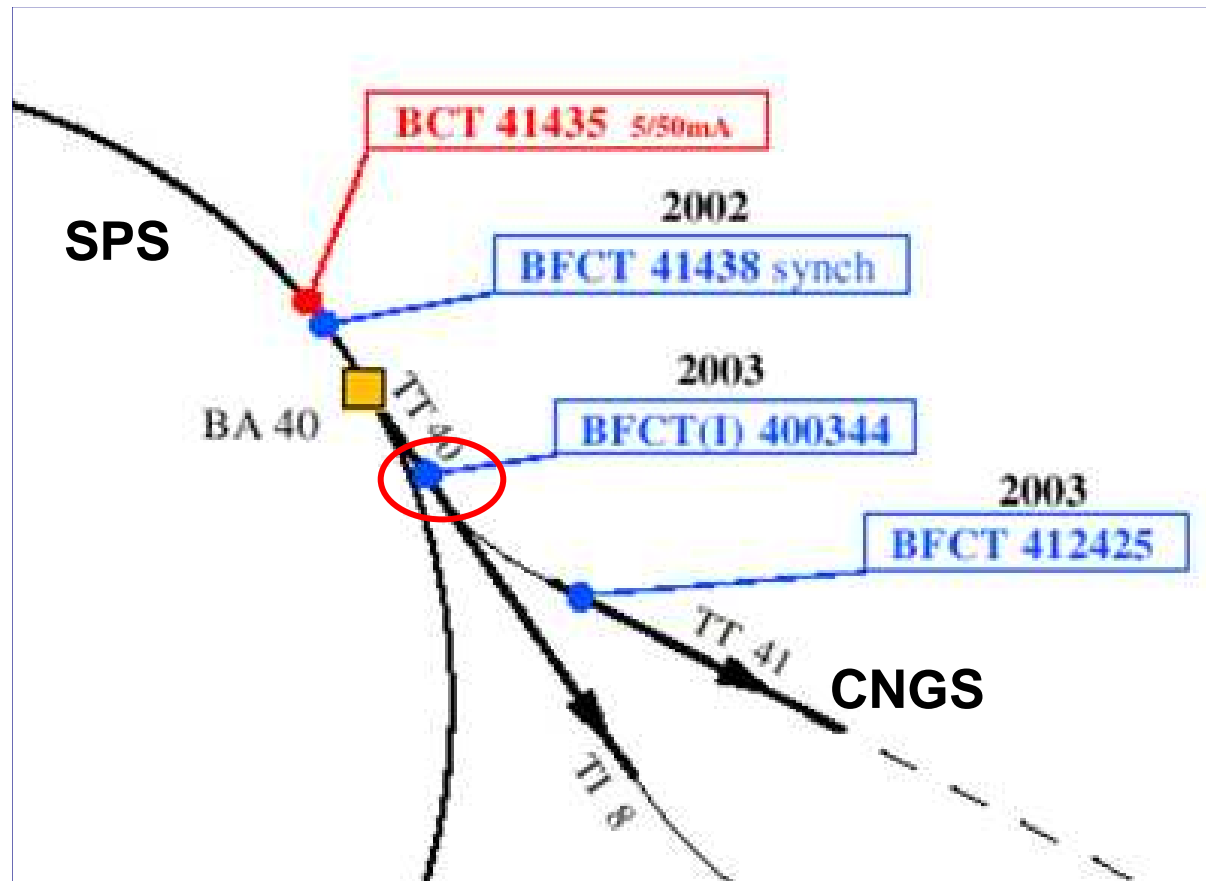


Correction to the time-link:

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

# Proton timing by Beam Current Transformer

Fast BCT 400344  
(~ 400 MHz)



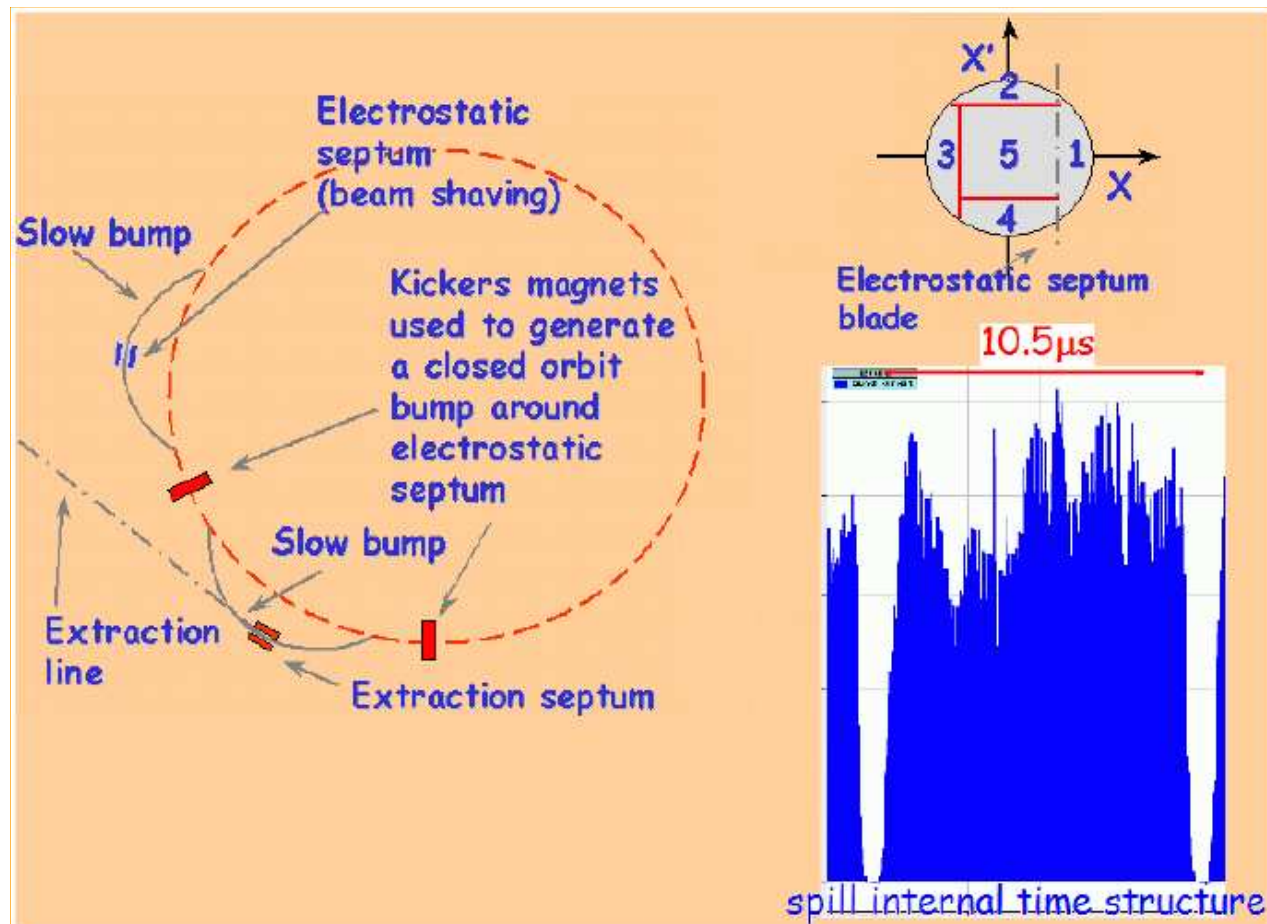
## Proton pulse digitization:

- 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

## Proton spill shape



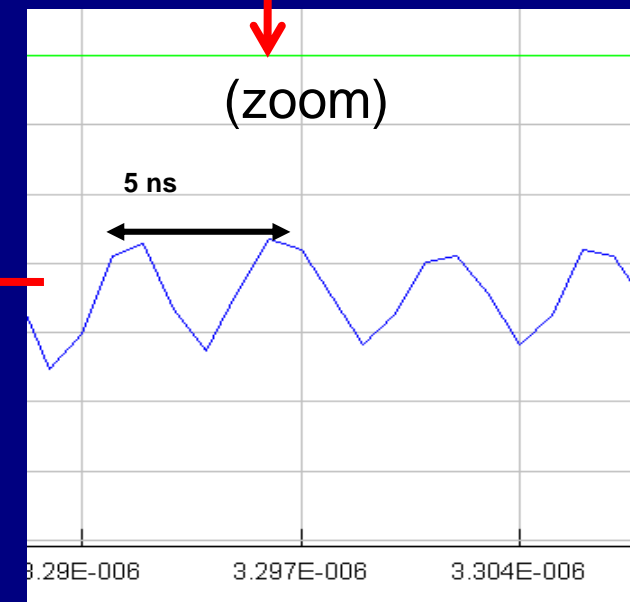
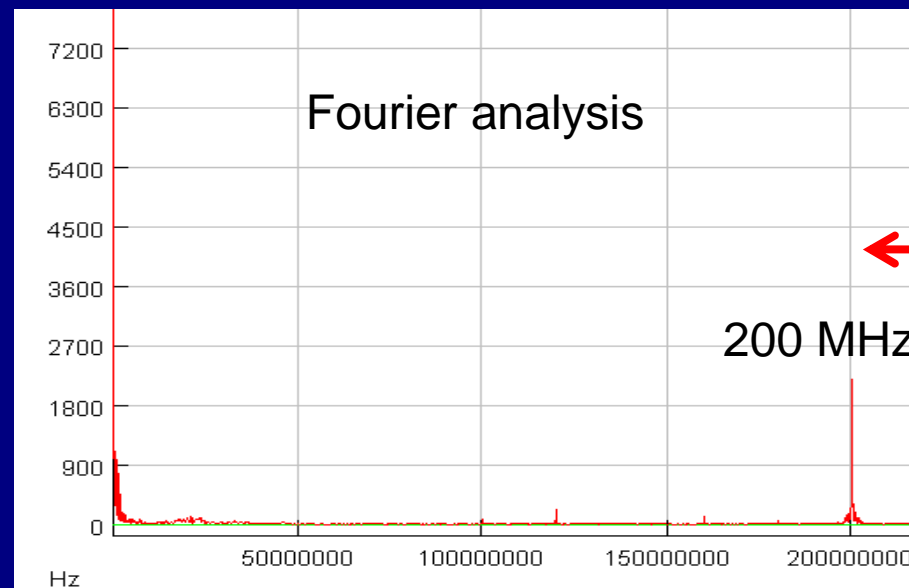
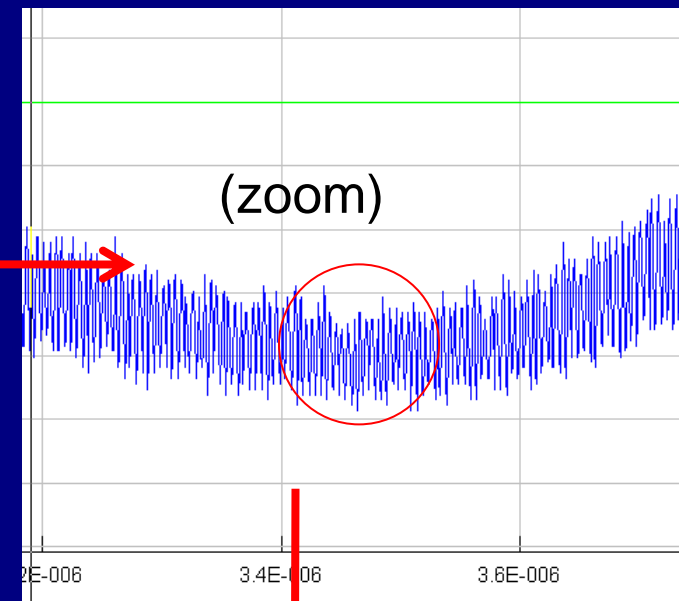
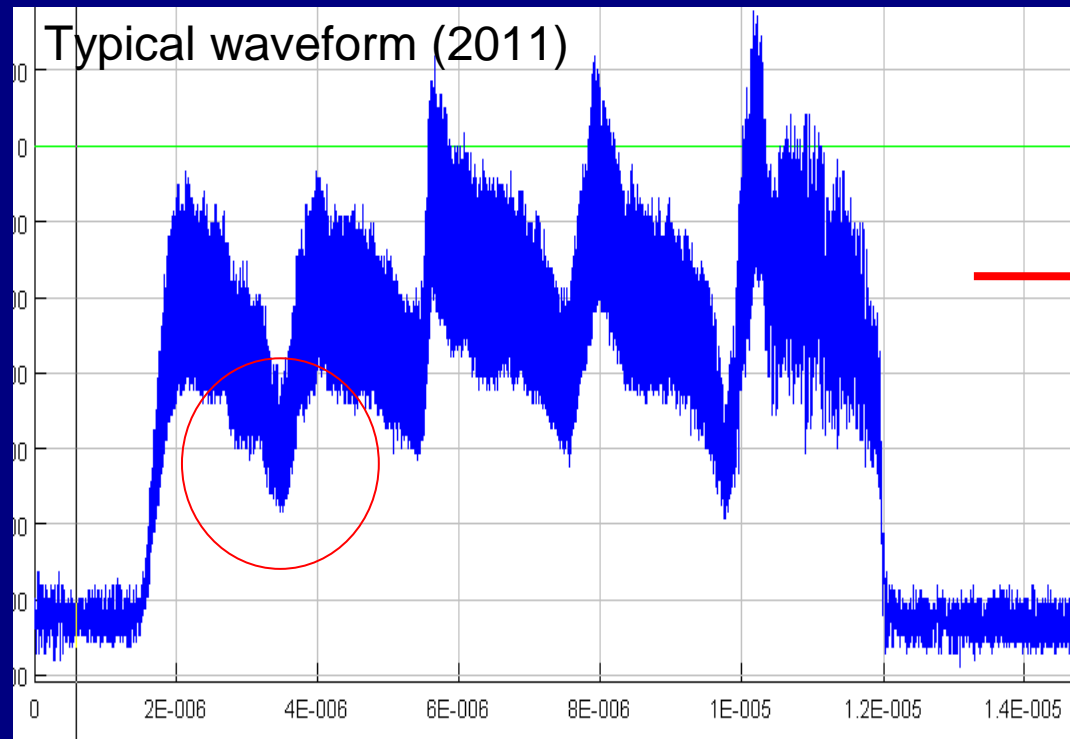
Reminiscence of the Continuous Turn extraction from PS (5 turns)

SPS circumference = 11 x PS circumference: SPS ring filled at 10/11

Shapes varying with time and both extractions

→ Precise accounting with WFD waveforms:

more accurate than: e.g. average neutrino distribution in a near detector

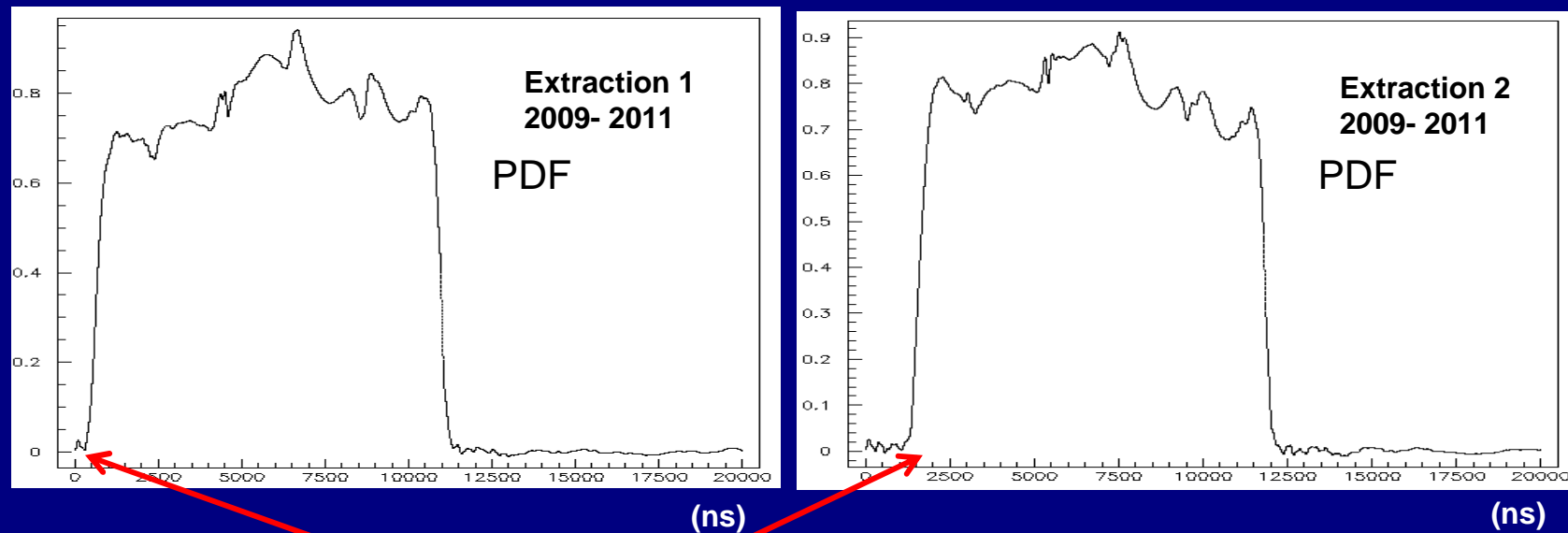


# Neutrino event-time distribution PDF

- Each event is associated to its proton spill waveform
- The “parent” proton is unknown within the 10.5  $\mu\text{s}$  extraction time

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

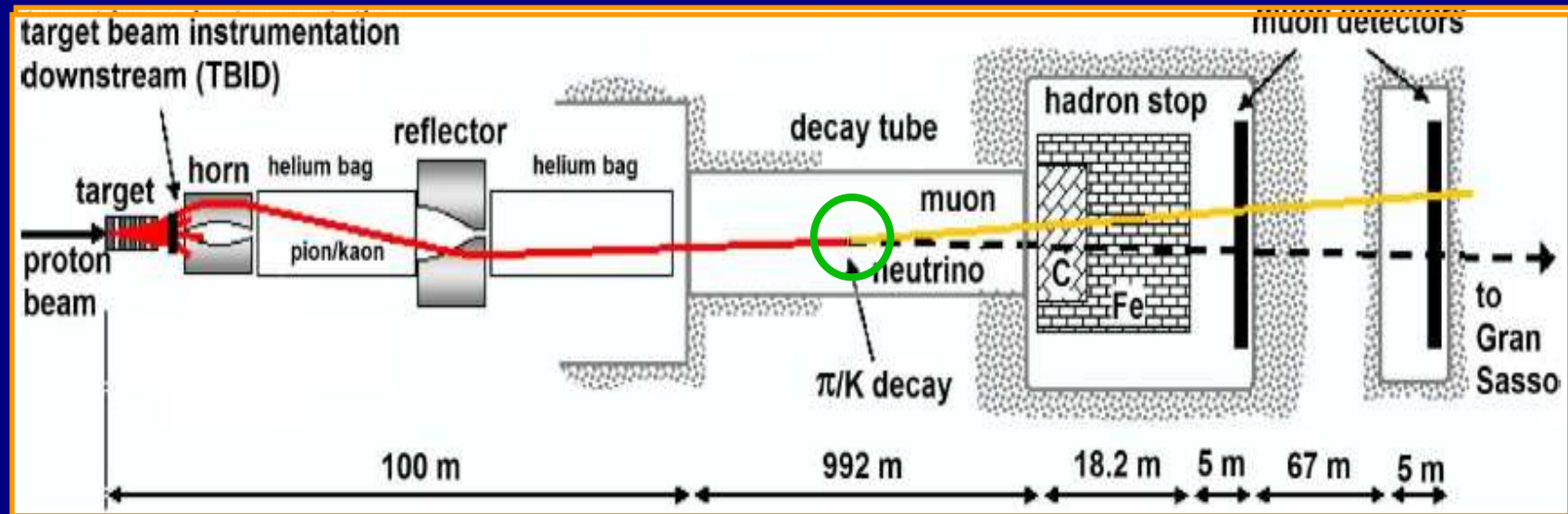
→ compare to OPERA **detected** neutrino events



**different timing w.r.t. kicker magnet signal**



# Neutrino production point



Unknown neutrino production point:

- 1) accurate UTC time-stamp of protons
- 2) relativistic parent mesons (full FLUKA simulation)

$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c} \left( \frac{1}{\beta} - 1 \right) \approx \frac{z}{c} \frac{1}{2\gamma^2}$$

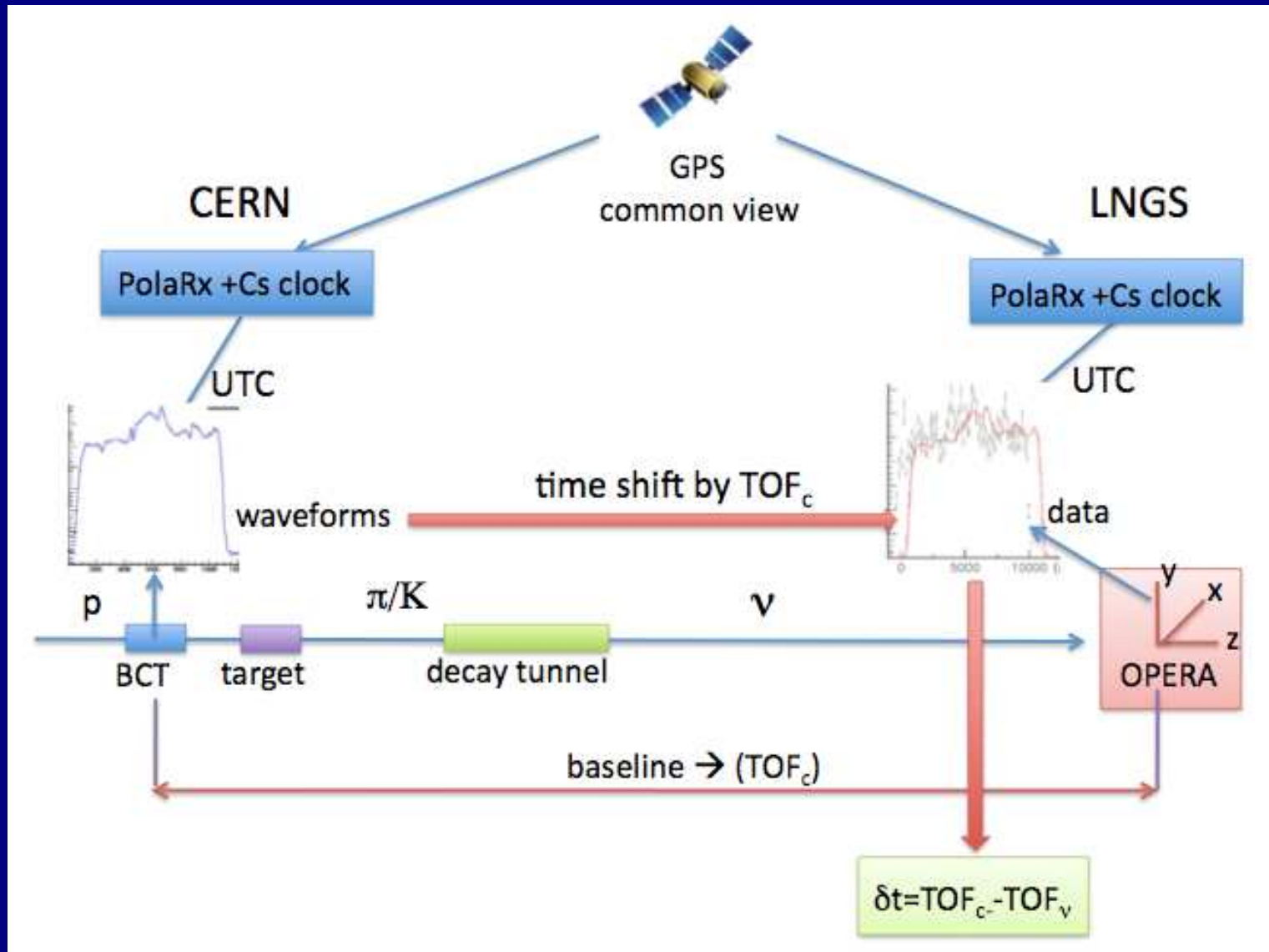
$TOF_c$  = assuming  $c$  from BCT to OPERA (2439280.9 ns)

$TOF_{true}$  = accounting for speed of mesons down to decay point

$$\Delta t = TOF_{true} - TOF_c$$

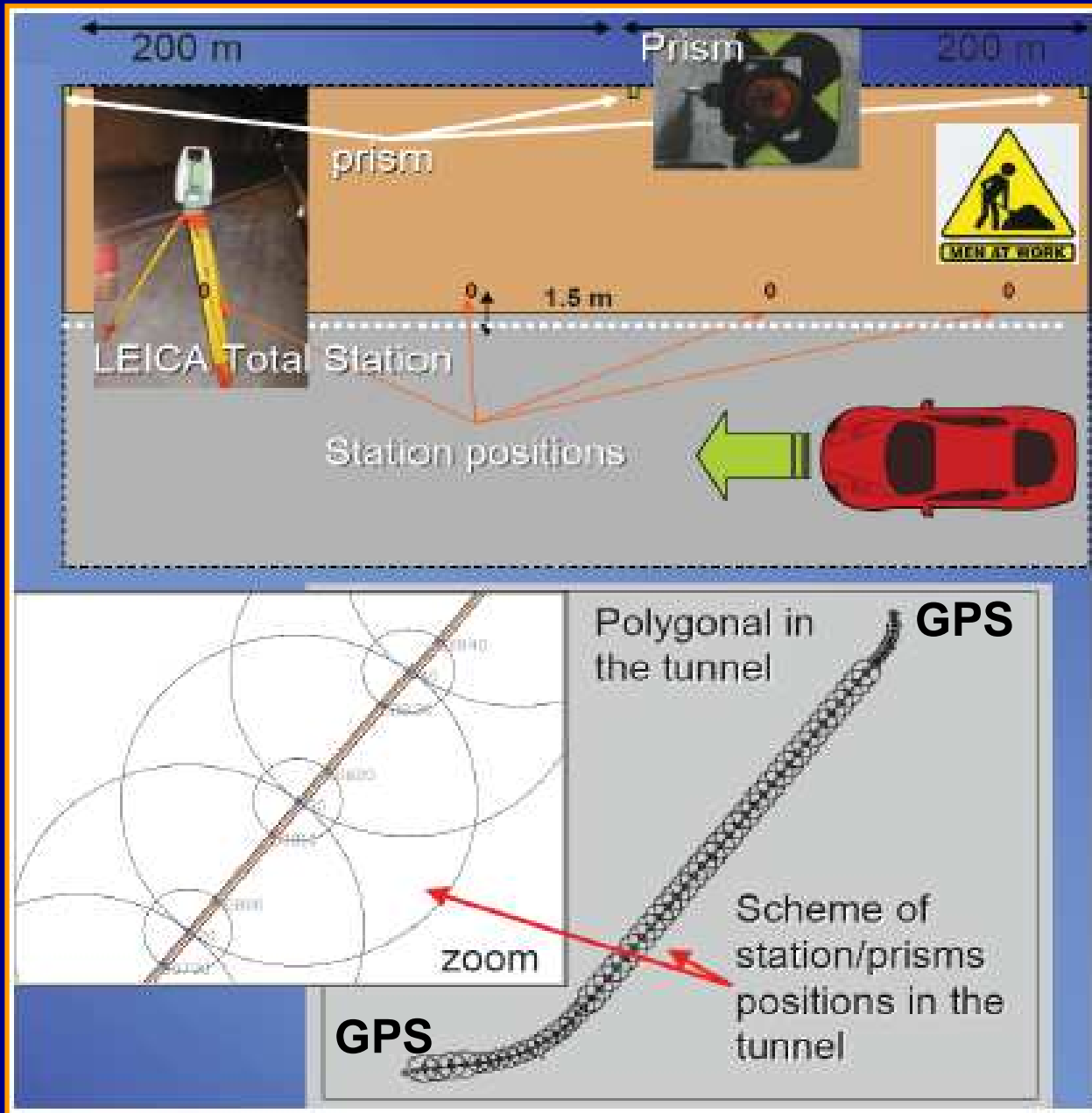
$$\langle \Delta t \rangle = 1.4 \times 10^{-2} \text{ ns}$$

# Summary of the principle for the TOF measurement



Measure  $\delta t = TOF_c - TOF_v$

# 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)

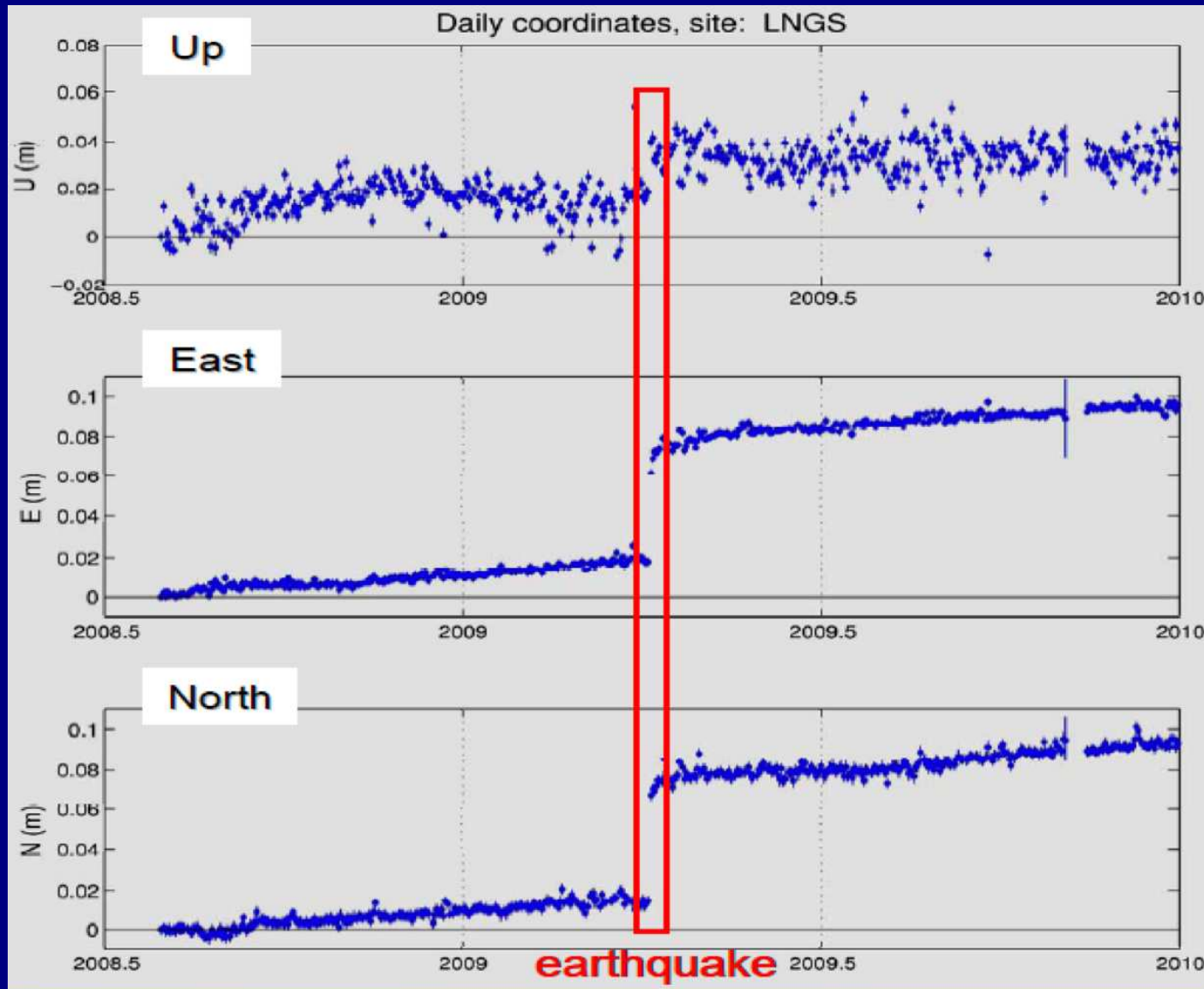
Benchmark	X (m)	Y (m)	Z (m)
GPS1	4579518.745	1108193.650	4285874.215
GPS2	4579537.618	1108238.881	4285843.959
GPS3	4585824.371	1102829.275	4280651.125
GPS4	4585839.629	1102751.612	4280651.236

LNGS benchmarks  
In ETRF2000

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

**Resulting distance (BCT – OPERA reference frame)**  
 **$(731278.0 \pm 0.2) \text{ m}$**

# LNGS position monitoring



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

# Time calibration techniques



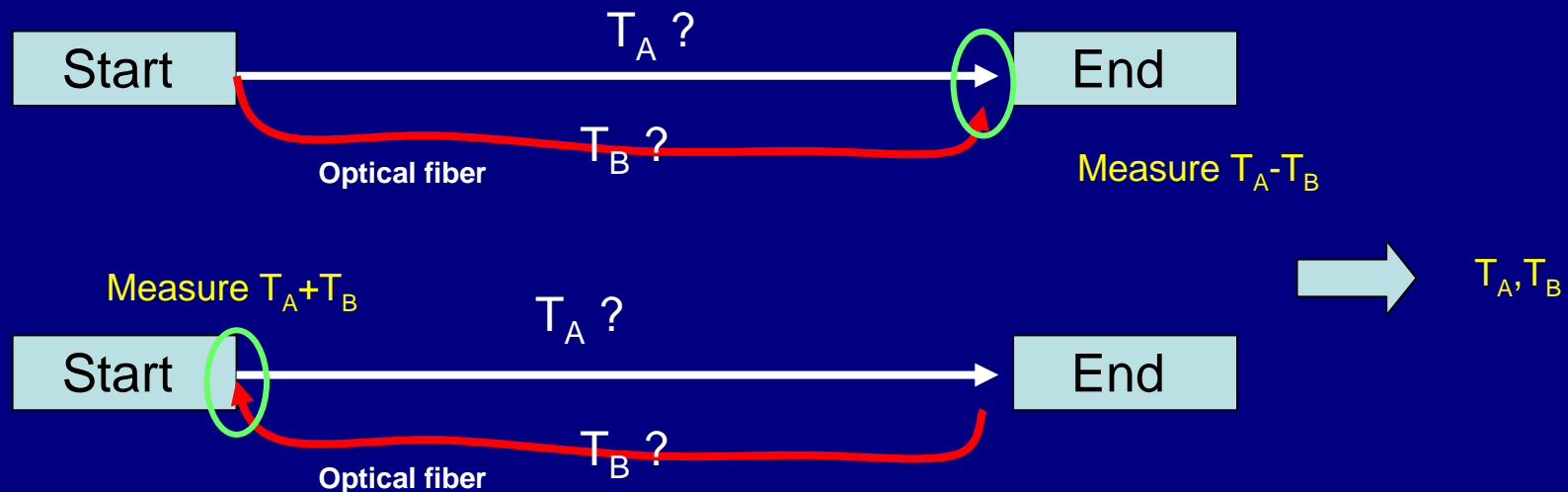
- **Portable Cs-4000:**

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

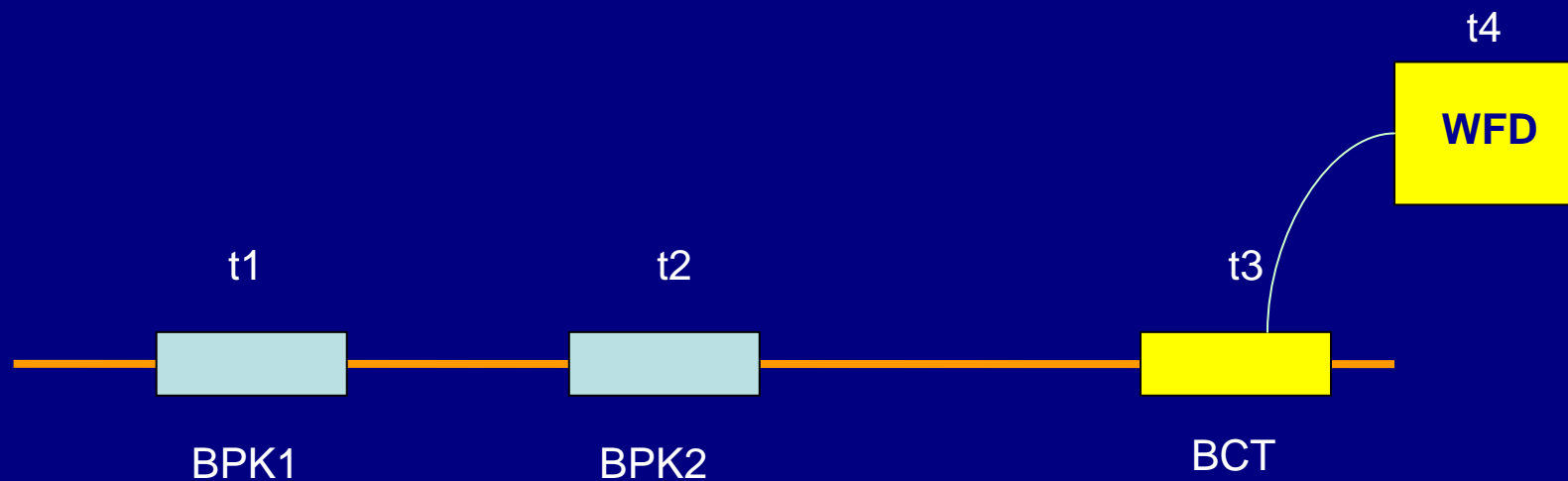


# BCT calibration (1)

Dedicated beam experiment:

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

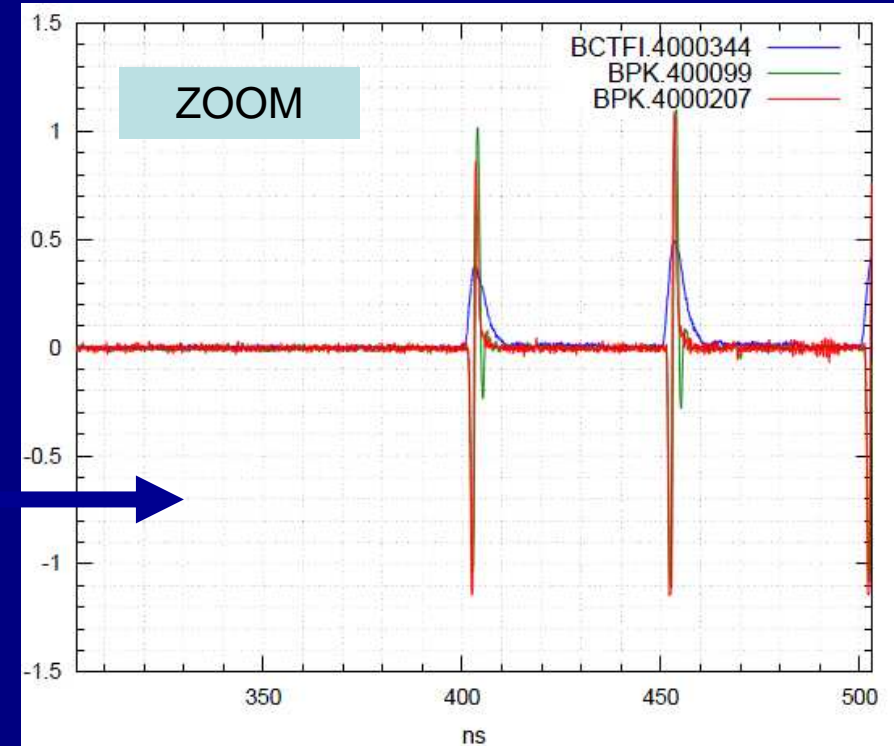
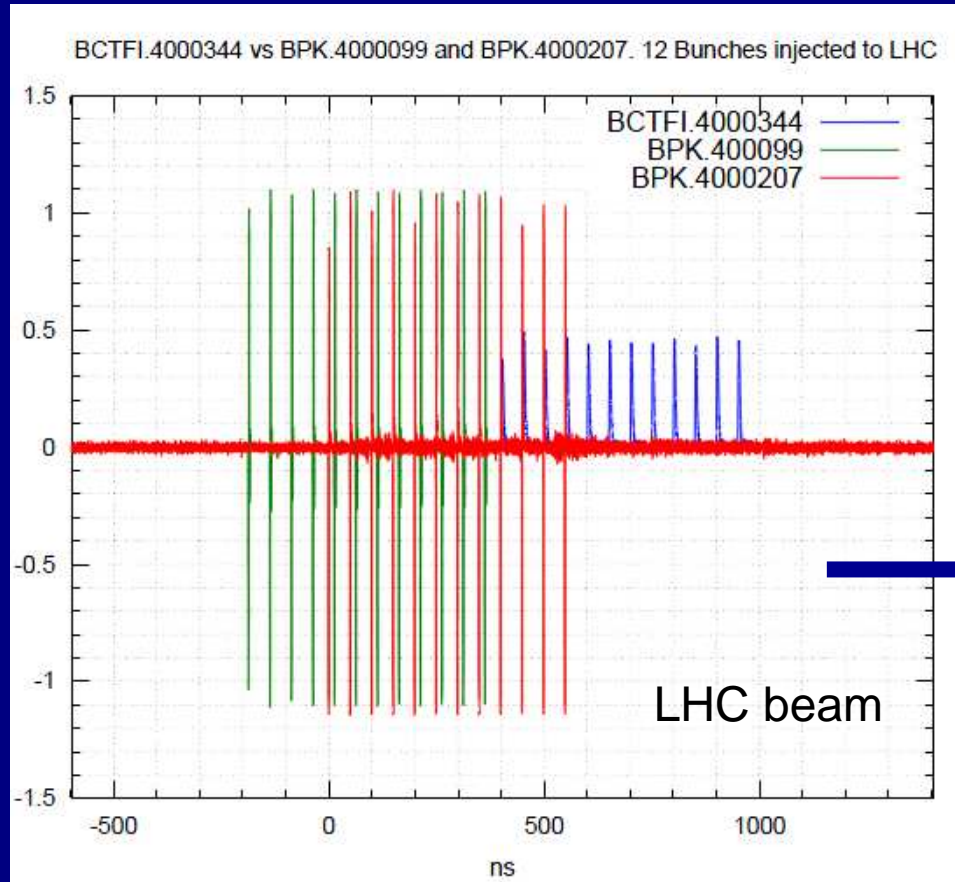
$$\Delta t_{\text{BCT}} = t4 - t3 = (580 \pm 5) \text{ ns}$$



t3 : derived by t1 - t2 measurement and survey



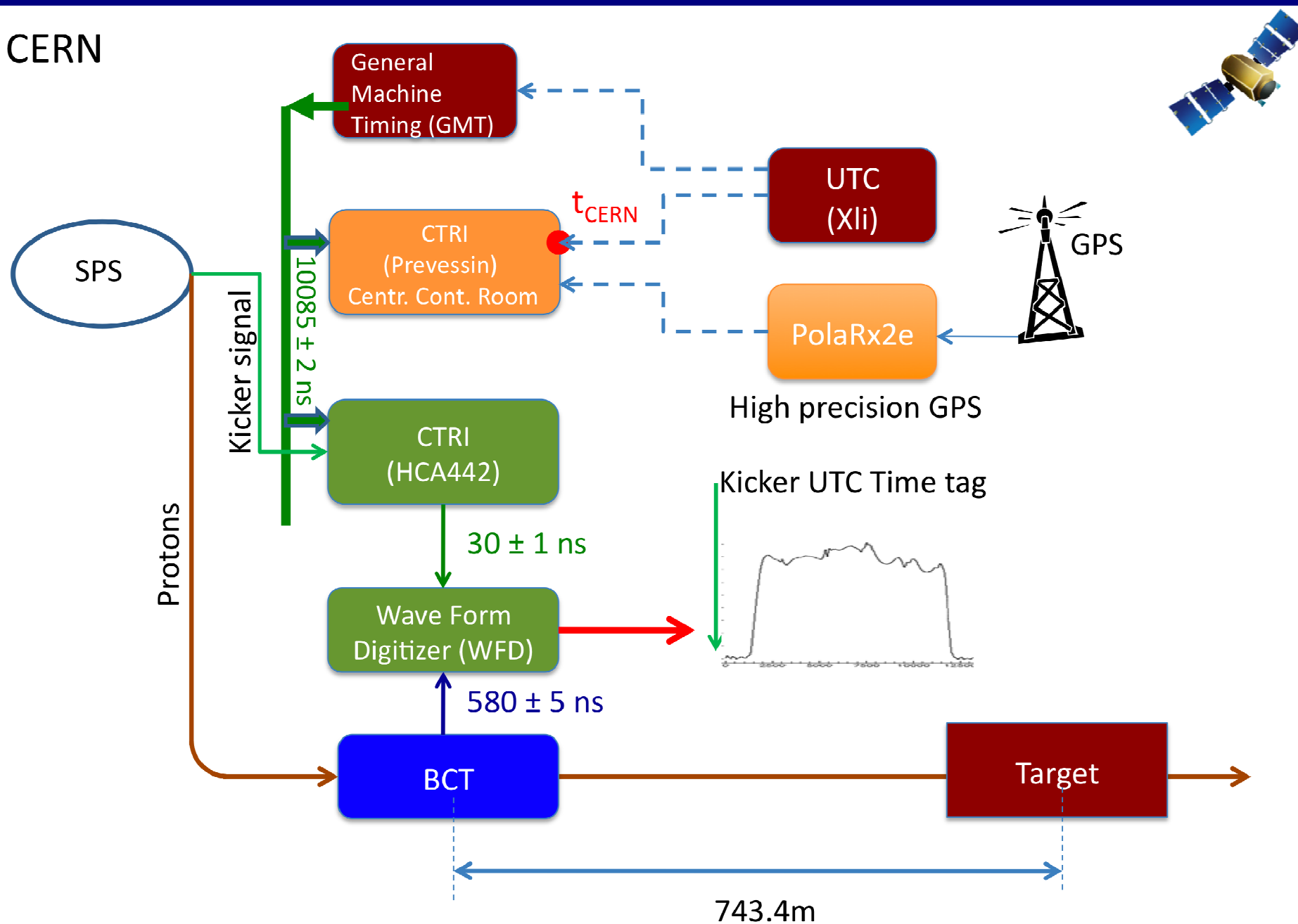
## BCT calibration (2)



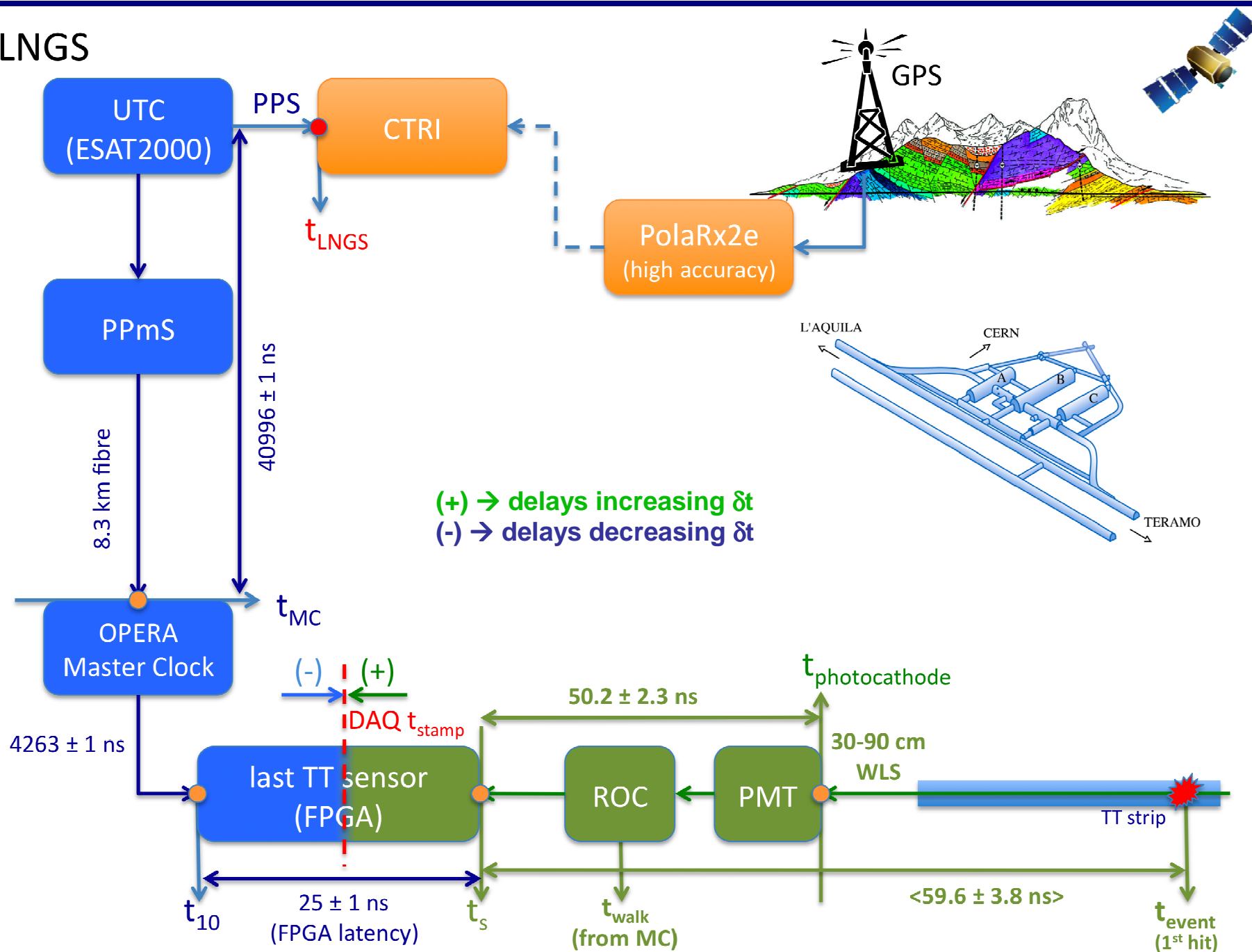
result: signals comparison after  $\Delta_{\text{BCT}}$  compensation



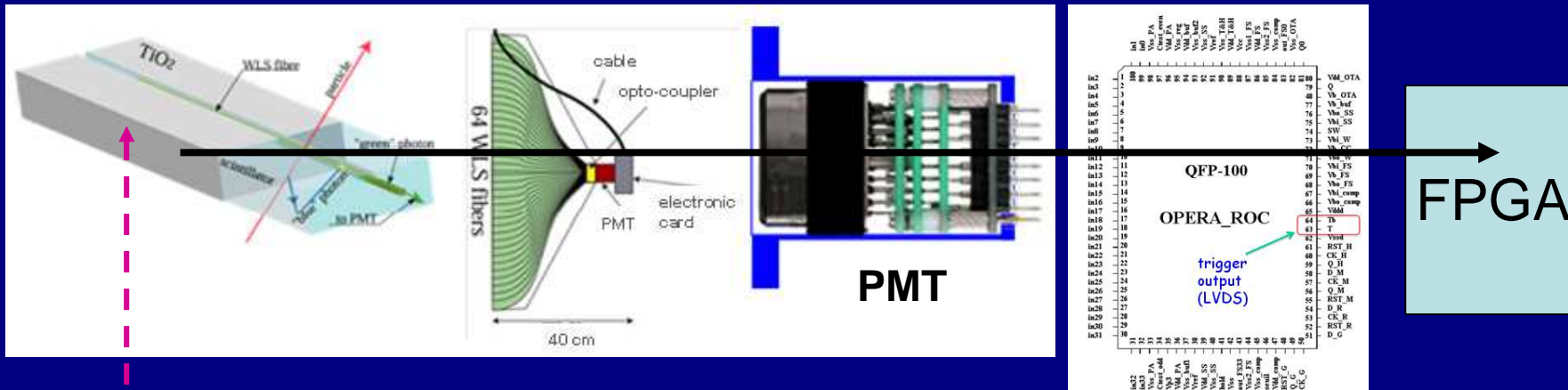
CERN



# LNGS



# TT time response measurement



Scintillator, WLS fibers, PMT, analog FE chip (ROC) up to FPGA trigger input

UV laser excitation:

→ delay from photo-cathode to FPGA input:  $50.2 \pm 2.3$  ns

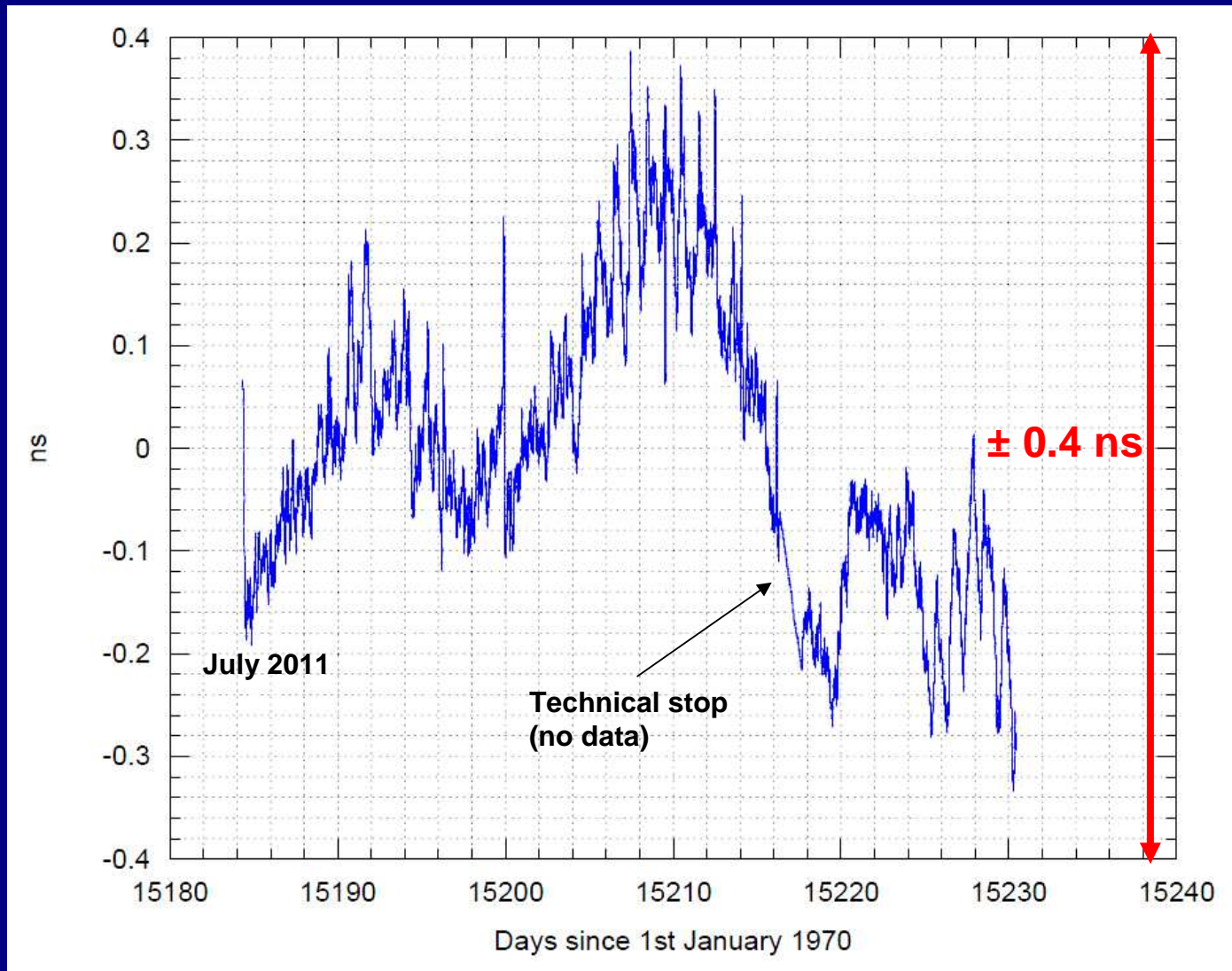
Average event time response:  $59.6 \pm 3.8$  ns (sys)

(including position and p.h. dependence, ROC time-walk, DAQ quantization effects accounted by simulations)

## Delay calibrations summary

Item	Result	Method
CERN UTC distribution (GMT)	$10085 \pm 2$ ns	<ul style="list-style-type: none"> <li>• Portable Cs</li> <li>• Two-ways</li> </ul>
WFD trigger	$30 \pm 1$ ns	Scope
BTC delay	$580 \pm 5$ ns	<ul style="list-style-type: none"> <li>• Portable Cs</li> <li>• Dedicated beam experiment</li> </ul>
LNGS UTC distribution (fibers)	$40996 \pm 1$ ns	<ul style="list-style-type: none"> <li>• Two-ways</li> <li>• Portable Cs</li> </ul>
OPERA master clock distribution	$4262.9 \pm 1$ ns	<ul style="list-style-type: none"> <li>• Two-ways</li> <li>• Portable Cs</li> </ul>
FPGA latency, quantization curve	$24.5 \pm 1$ ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	$50.2 \pm 2.3$ ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	$9.4 \pm 3$ ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation
CERN-LNGS intercalibration	$2.3 \pm 1.7$ ns	<ul style="list-style-type: none"> <li>• METAS PolaRx calibration</li> <li>• PTB direct measurement</li> </ul>

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



# Event selection (earliest TT hit of the event as “stop”)

Statistics: 2009-2010-2011 CNGS runs ( $\sim 10^{20}$  pot)

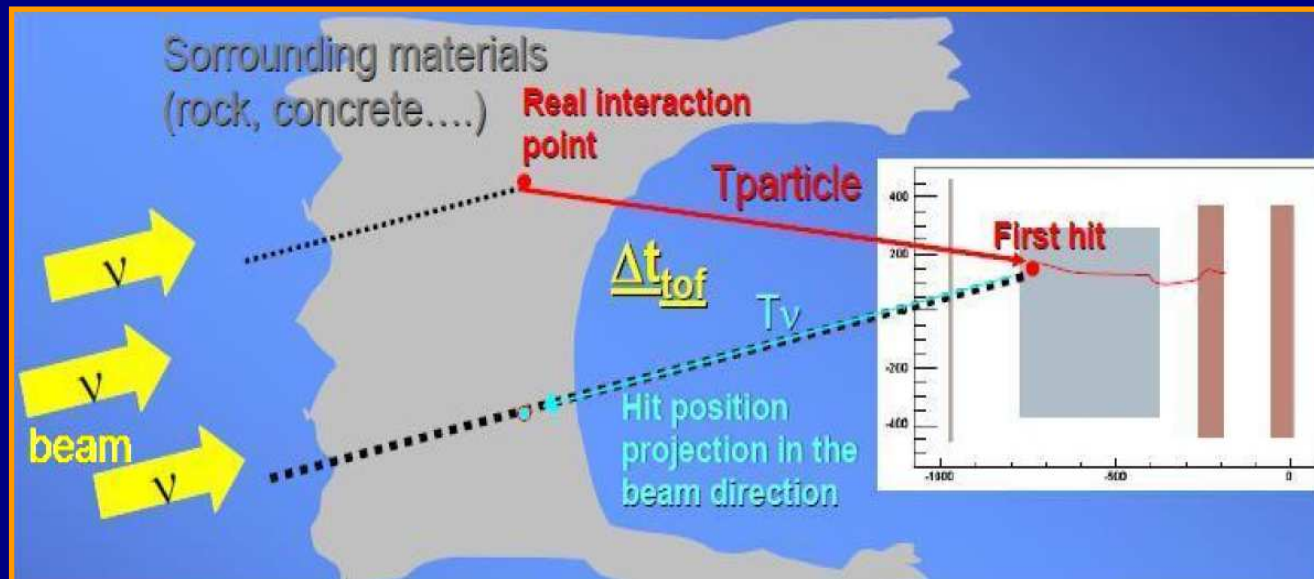
Internal events:

Same selection procedure as for oscillation searches: **7586 events**

External events:

Rock interaction  $\rightarrow$  require muon 3D track: **8525 events**

(Timing checked with full simulation, 2 ns systematic uncertainty by adding external events)

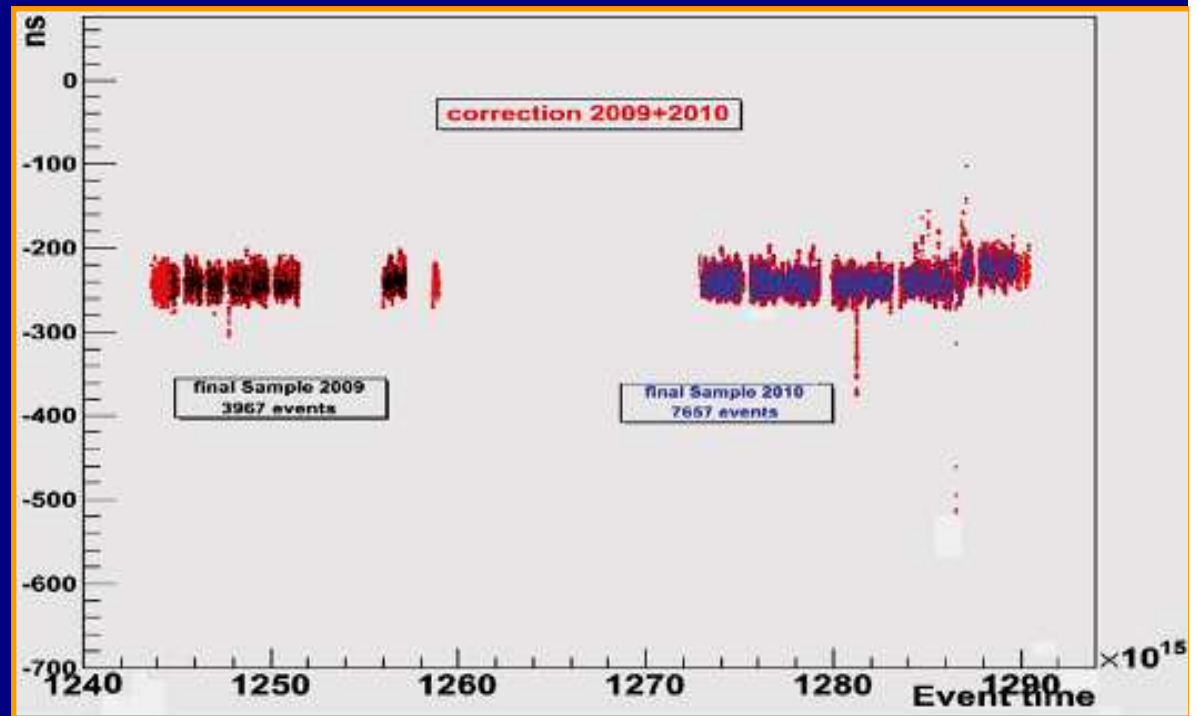


Data/MC agree for 1<sup>st</sup> hit timing (within systematics)



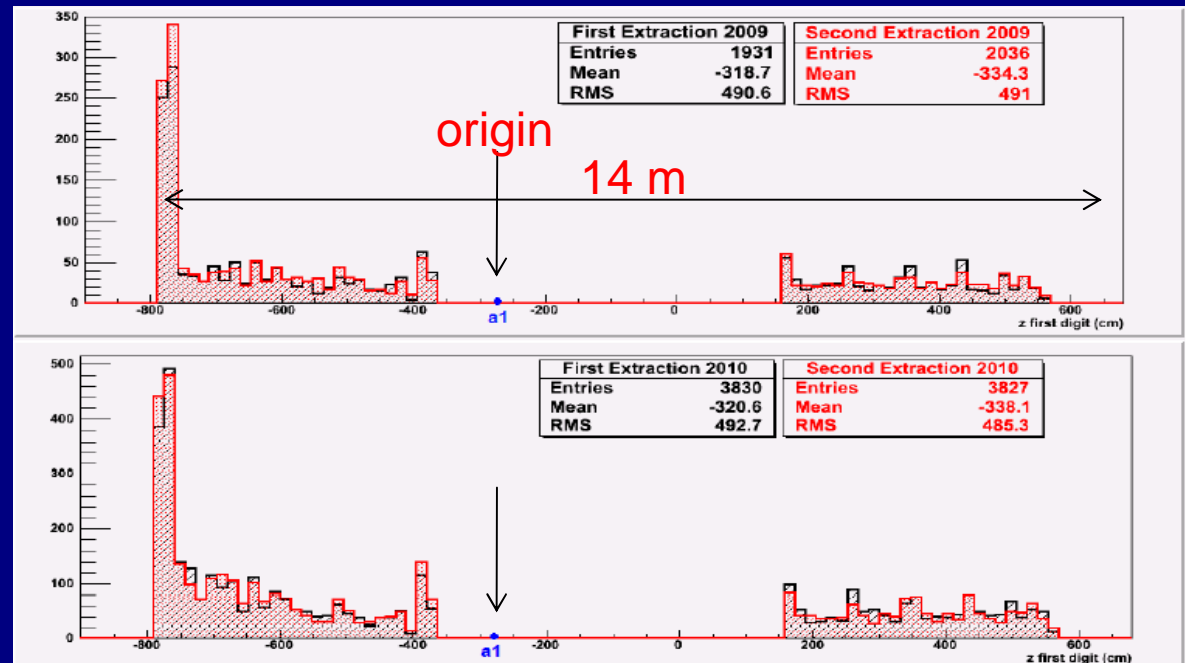
# Event time corrections

Time-link correction (blue points)



Correction due to the earliest hit position

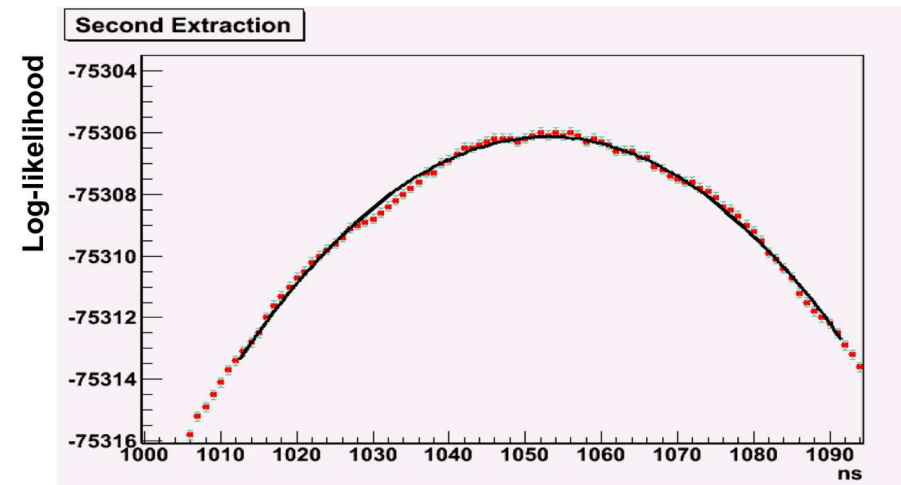
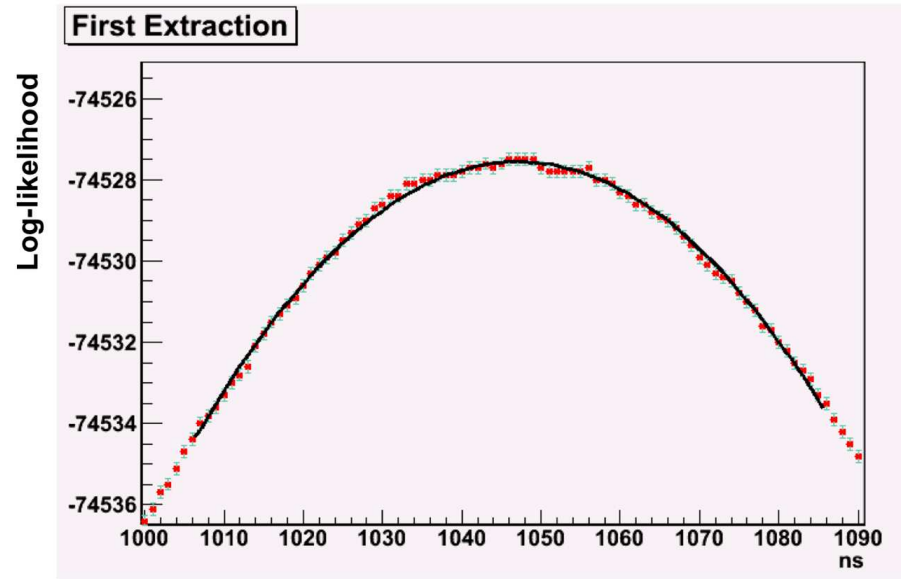
average correction: 140 cm  
(4.7 ns)



# Analysis method

For each neutrino event in OPERA → proton extraction waveform

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



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

Maximised versus  $\delta t$ :

$$\delta t = \text{TOF}_c - \text{TOF}_v$$

Positive (negative)  $\delta t$  → neutrinos arrive earlier (later) than light

statistical error evaluated from log likelihood curves

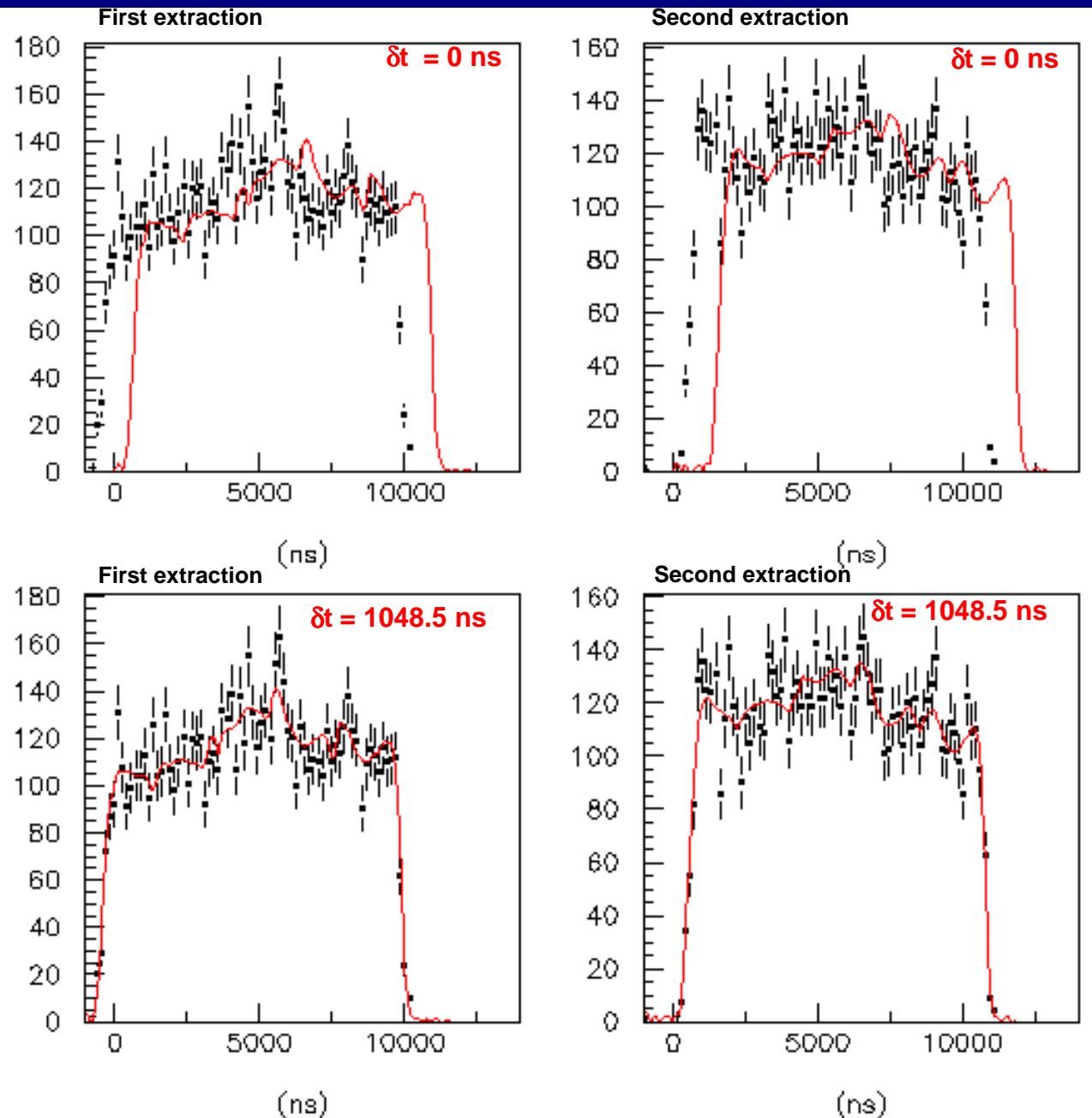
# Blind analysis

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  $\delta t$  by construction much larger than individual calibration contributions  $\sim 1000$  ns
- “Box” opened once all correction contributions reached satisfactory accuracy

# Data vs PDF: before and after likelihood result

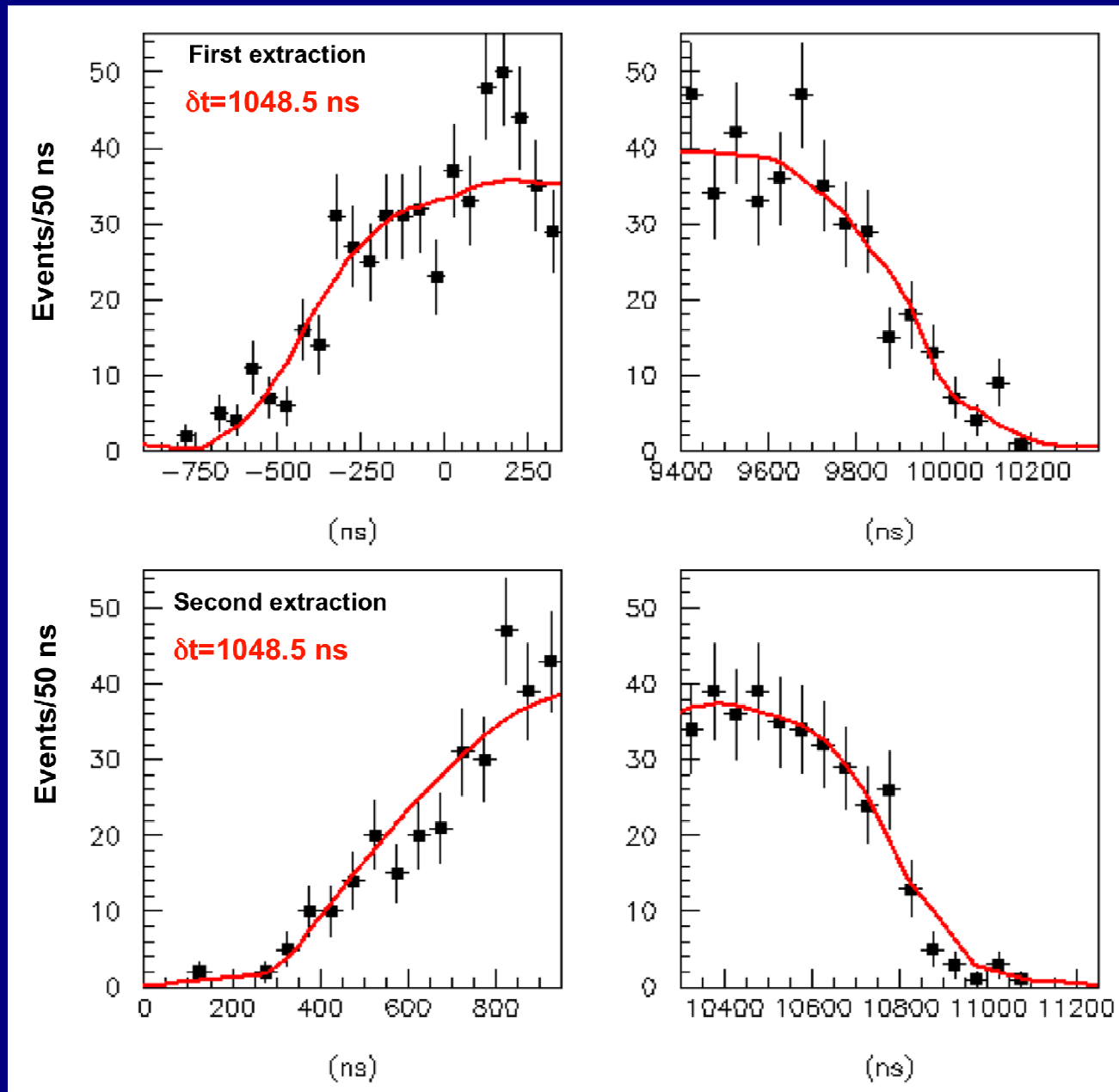


(BLIND)  $\delta t = \text{TOF}_c - \text{TOF}_v =$   
(1048.5  $\pm$  6.9) ns (stat)

$\chi^2 / \text{ndof}$  :

first extraction: 1.06  
second extraction: 1.12

## Zoom on the extractions leading and trailing edges



## Analysis cross-checks

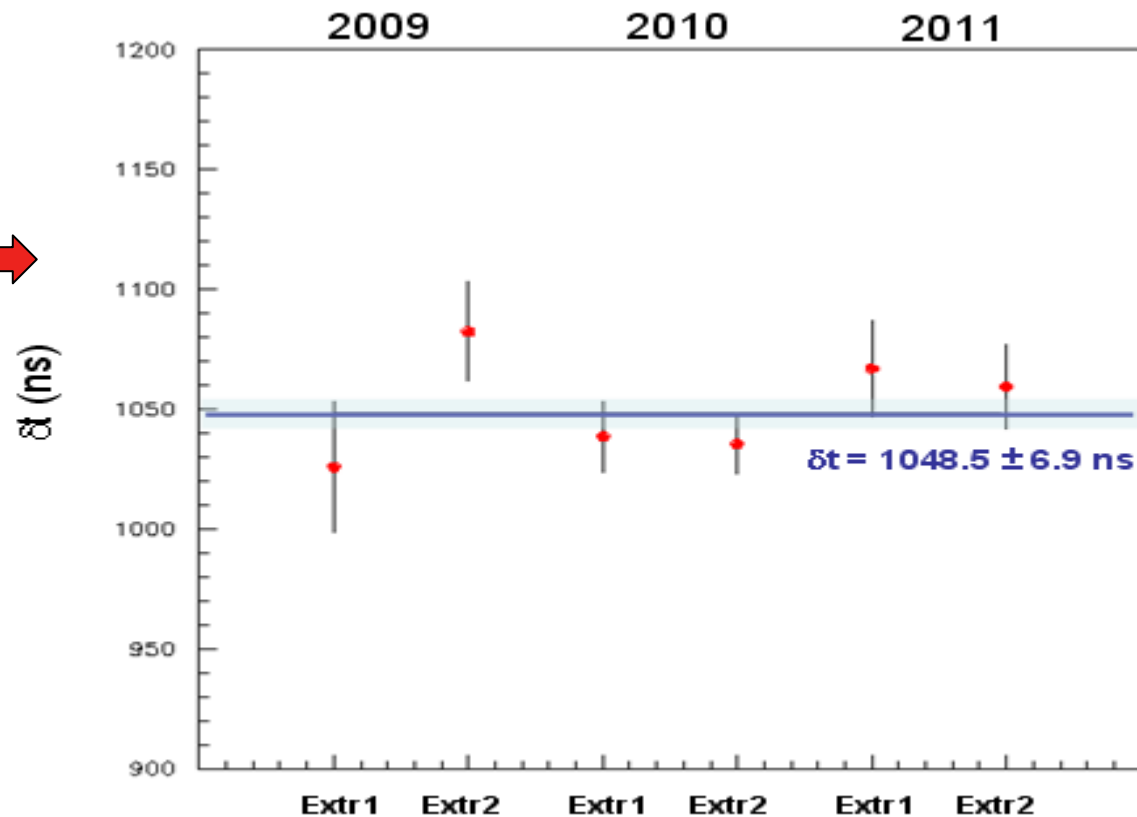
1) Coherence among  
CNGS  
runs/extractions



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

|d-n|:  $(17.1 \pm 15.5)$  ns

|(spring+fall) – summer|:  
 $(11.3 \pm 14.3)$  ns



3) Internal vs external events:

All events:  $\delta t$  (blind) =  $\text{TOF}_c - \text{TOF}_v = (1048.5 \pm 6.9 \text{ (stat.)})$  ns

Internal events only:  $(1047.4 \pm 11.2 \text{ (stat.)})$  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 synchronization (ns)	-353	0	
Time-link (ns)	0	-2.3	
Correction GPS			350.7
<b>Total</b>			<b>-987.8</b>

## 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
<b>Total uncertainty (in quadrature)</b>	<b>7.4</b>

# Results

For CNGS  $\nu_\mu$  beam,  $\langle E \rangle = 17$  GeV:

$$\delta t = \text{TOF}_c - \text{TOF}_\nu =$$

$$(1048.5 \pm 6.9 \text{ (stat.)}) \text{ ns} - 987.8 \text{ ns} = (60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)}) \text{ ns}$$

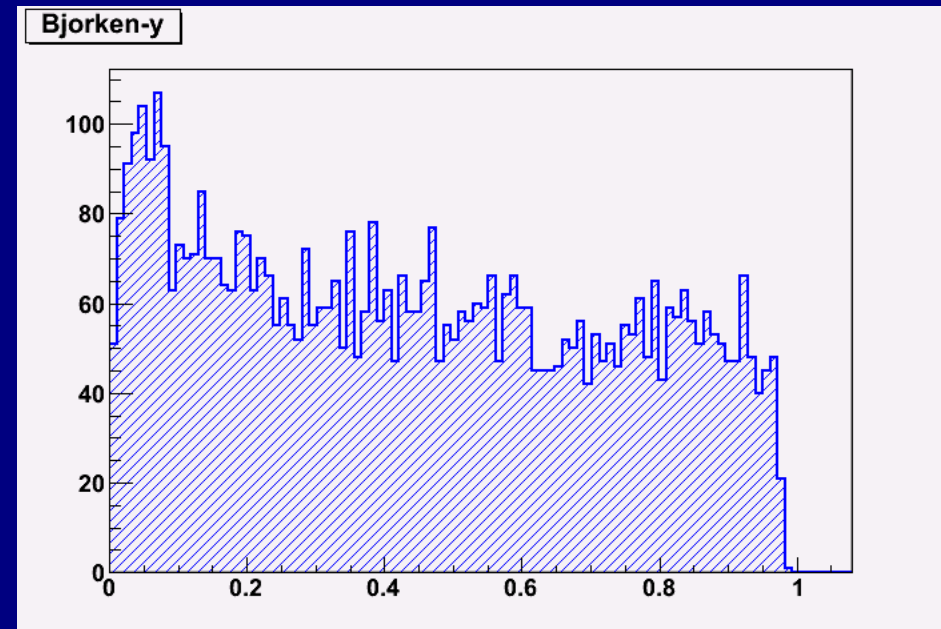
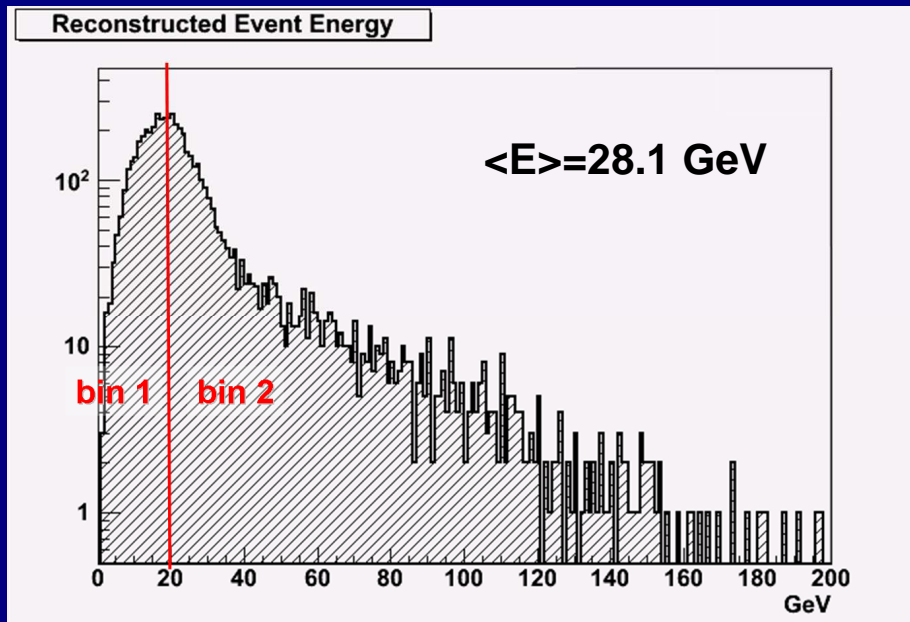
relative difference of neutrino velocity w.r.t.  $c$ :

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

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

6.0  $\sigma$  significance

# Study of the energy dependence



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

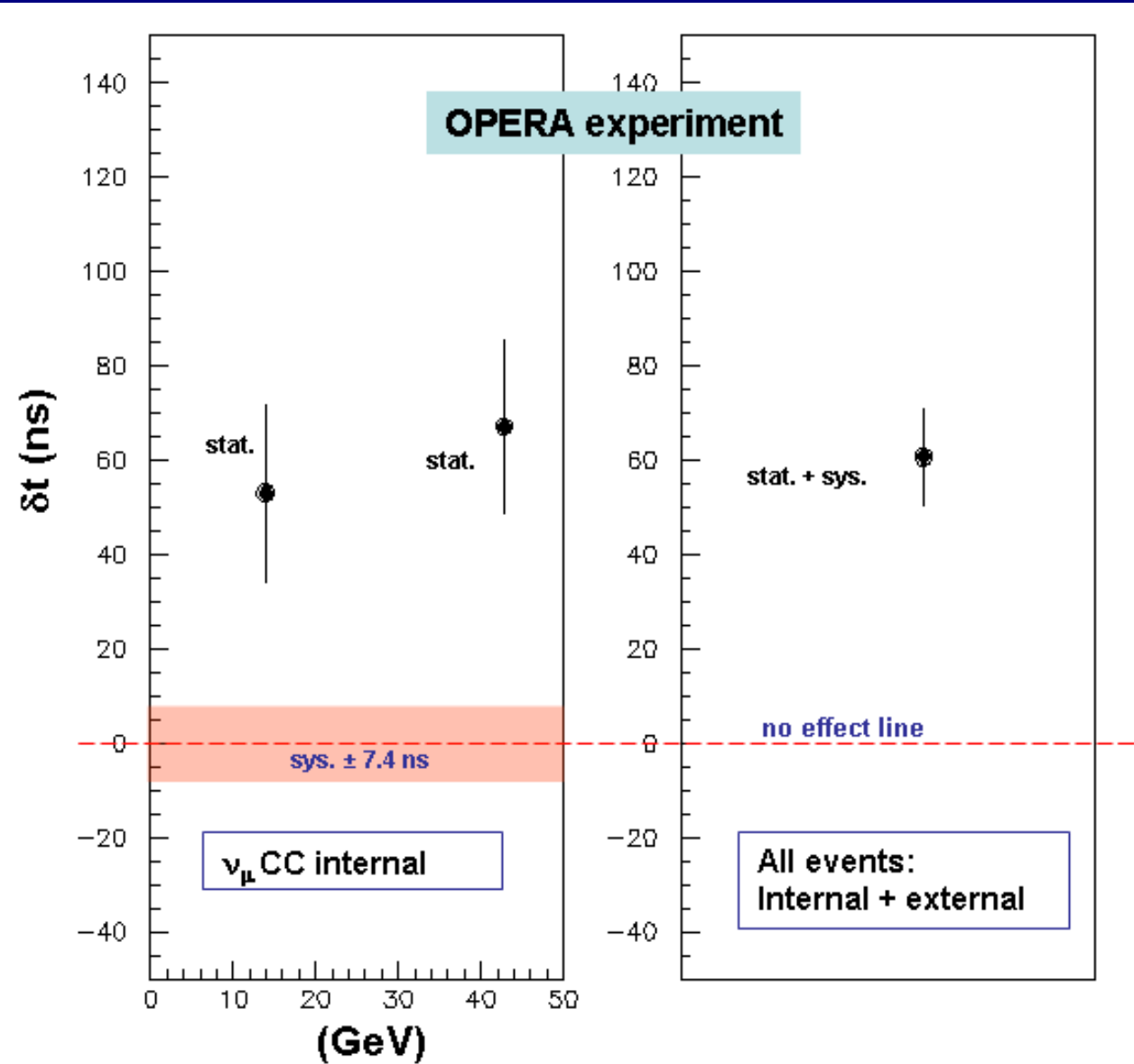
$$(E = E_{\mu} + E_{\text{had}})$$

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

$$\delta t = \text{TOF}_c - \text{TOF}_v = (60.3 \pm 13.1 \text{ (stat.)} \pm 7.4 \text{ (sys.)}) \text{ ns for } \langle E_v \rangle = 28.1 \text{ GeV}$$

(result limited to events with measured energy)

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



# 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 (~16000 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:

$$\delta t = \text{TOF}_c - \text{TOF}_v = (60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)}) \text{ ns}$$

- 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:

$$(v-c)/c = \delta t / (\text{TOF}_c - \delta t) = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$$

with an overall significance of  $6.0 \sigma$ .

## Conclusions (2)

- A possible  $\delta t$  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*