Frontiers in Diagnostics Technologies

LNF Frascati, 29 November 2011

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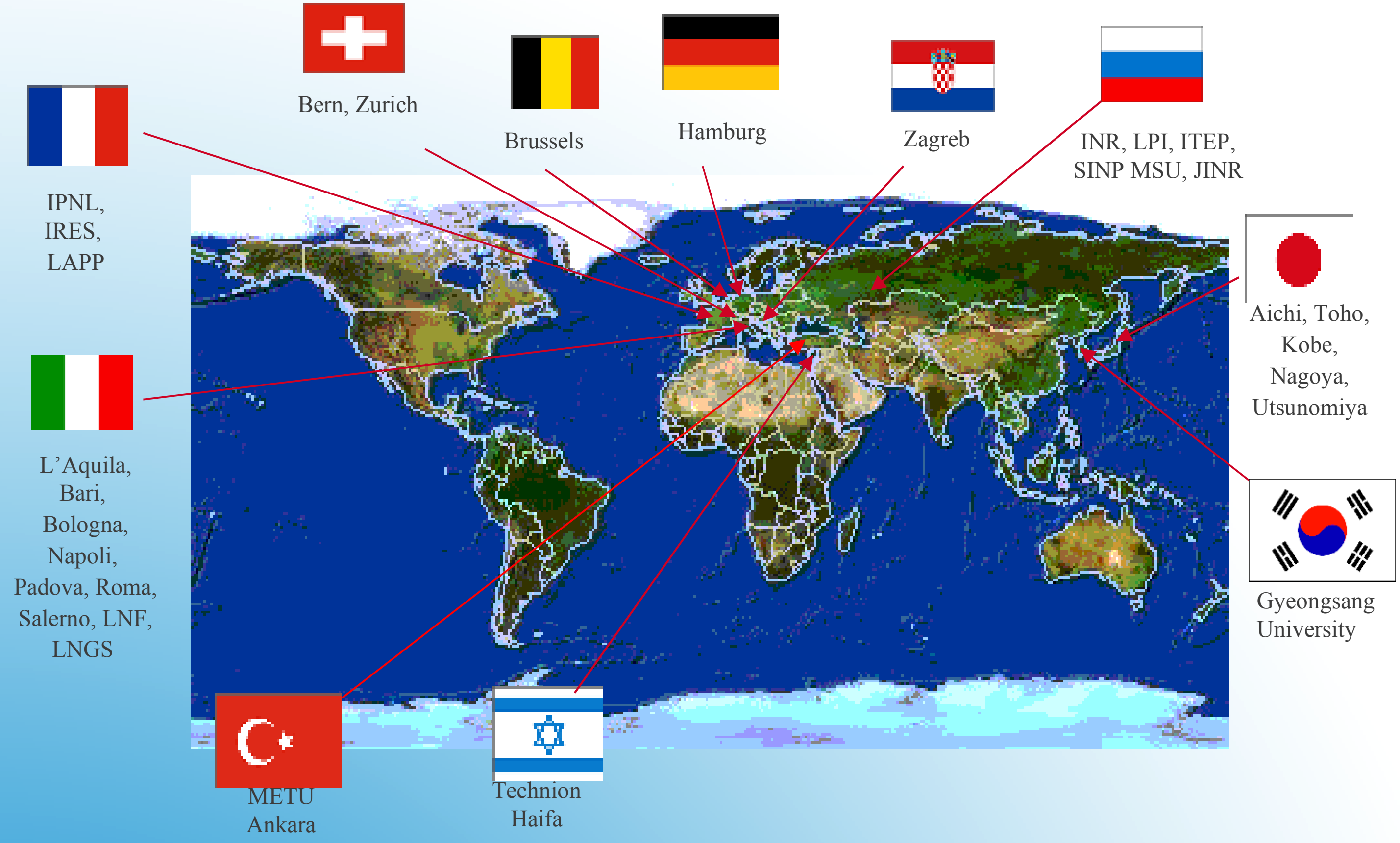
INFN Frascati

On behalf of the OPERA Collaboration

Measurement of the neutrino velocity

OPERA Coll.

- 11 countries
- 30 institutions
- 160 physicists



Collaborators

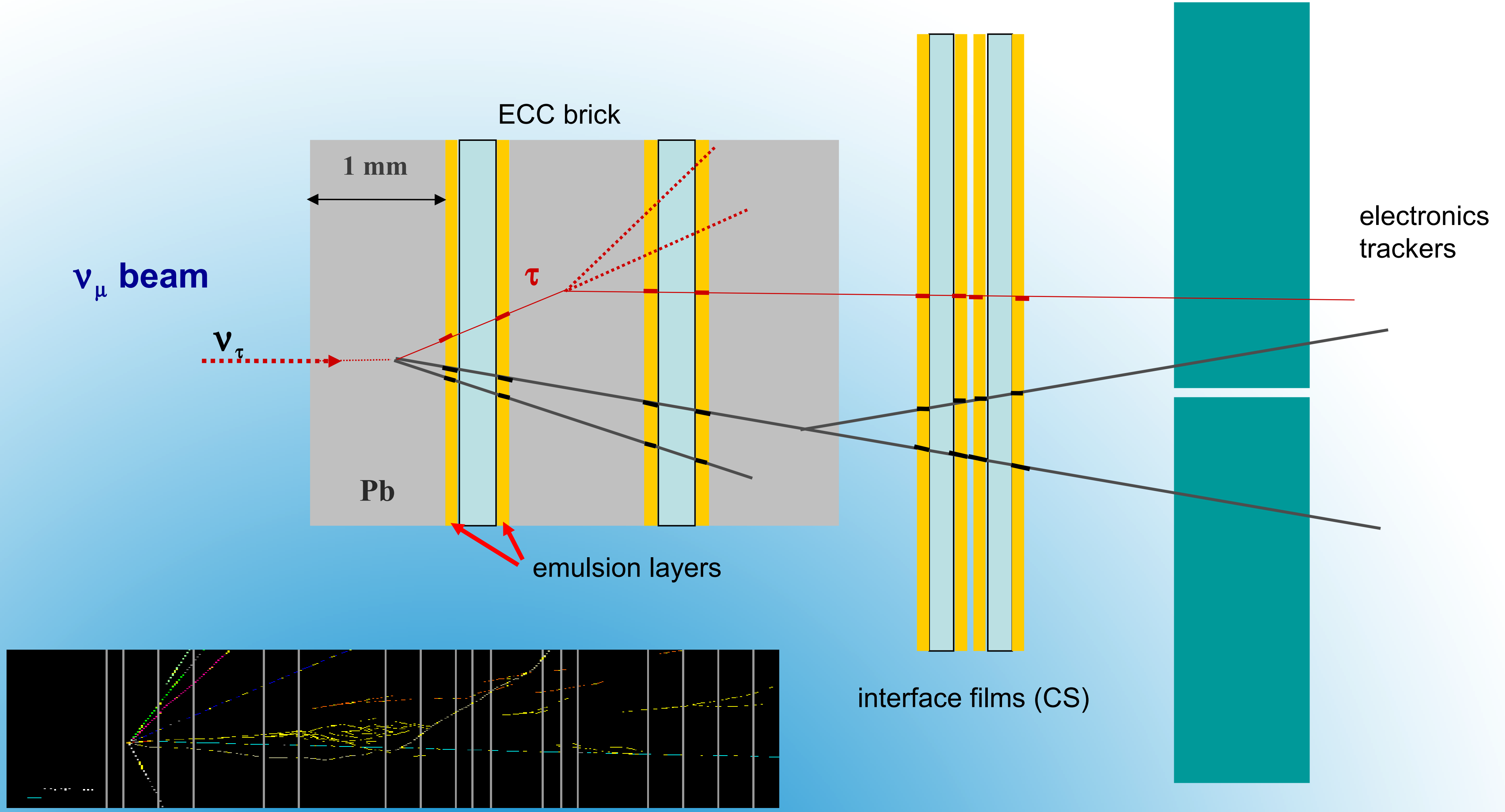
- CERN groups: CNGS beam, survey, timing and PS
- Geodesy group of the Università Sapienza of Rome
- Swiss Institute of Metrology (METAS)
- German Institute of Metrology (PTB)

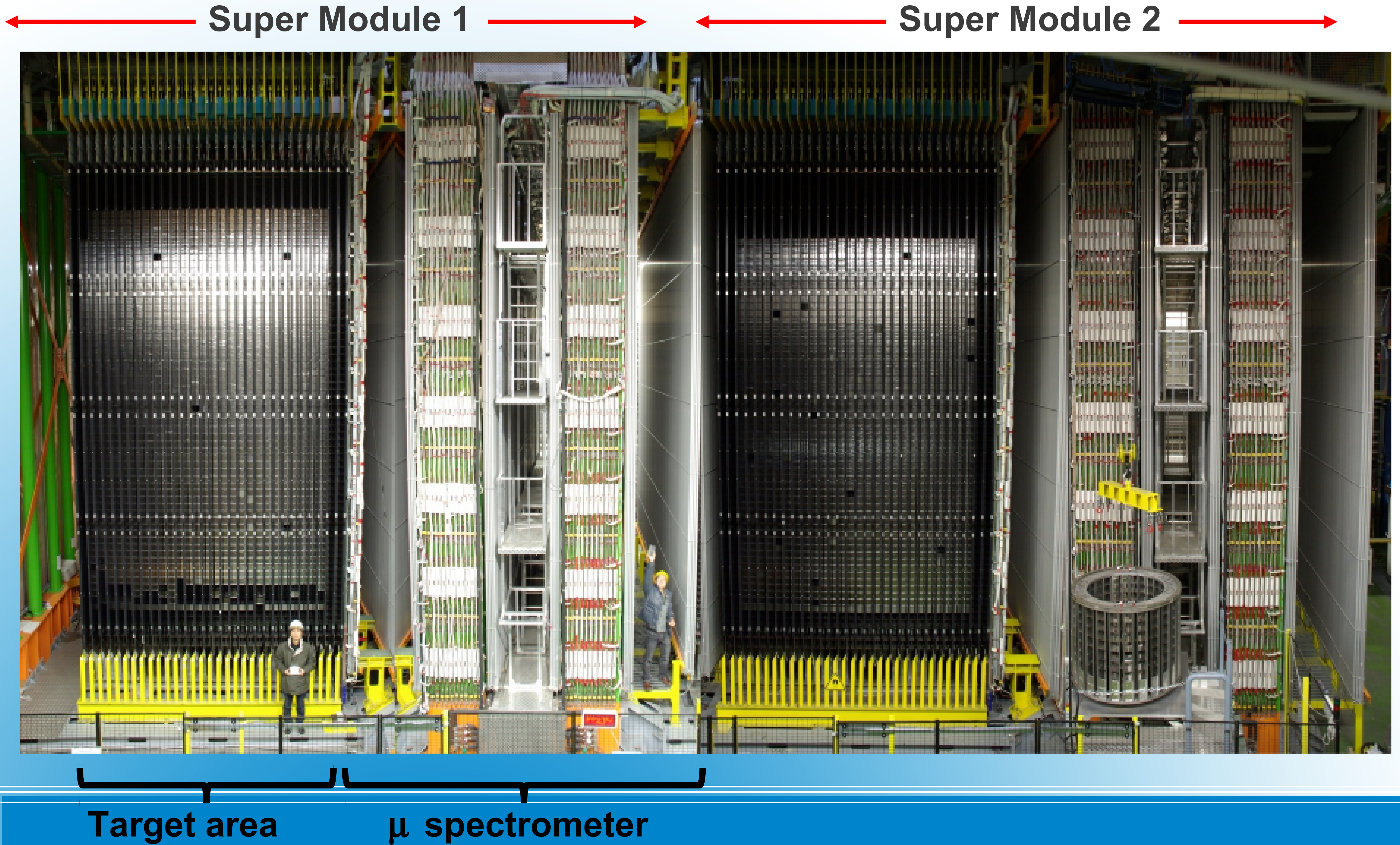
http://arxiv.org/pdf/1109.4897v2

OPERA and collaborating groups

Design of the OPERA experiment

ECC bricks + electronic detectors for $\nu_\mu \rightarrow \nu_\tau$ oscillation (appearance of ν_τ)

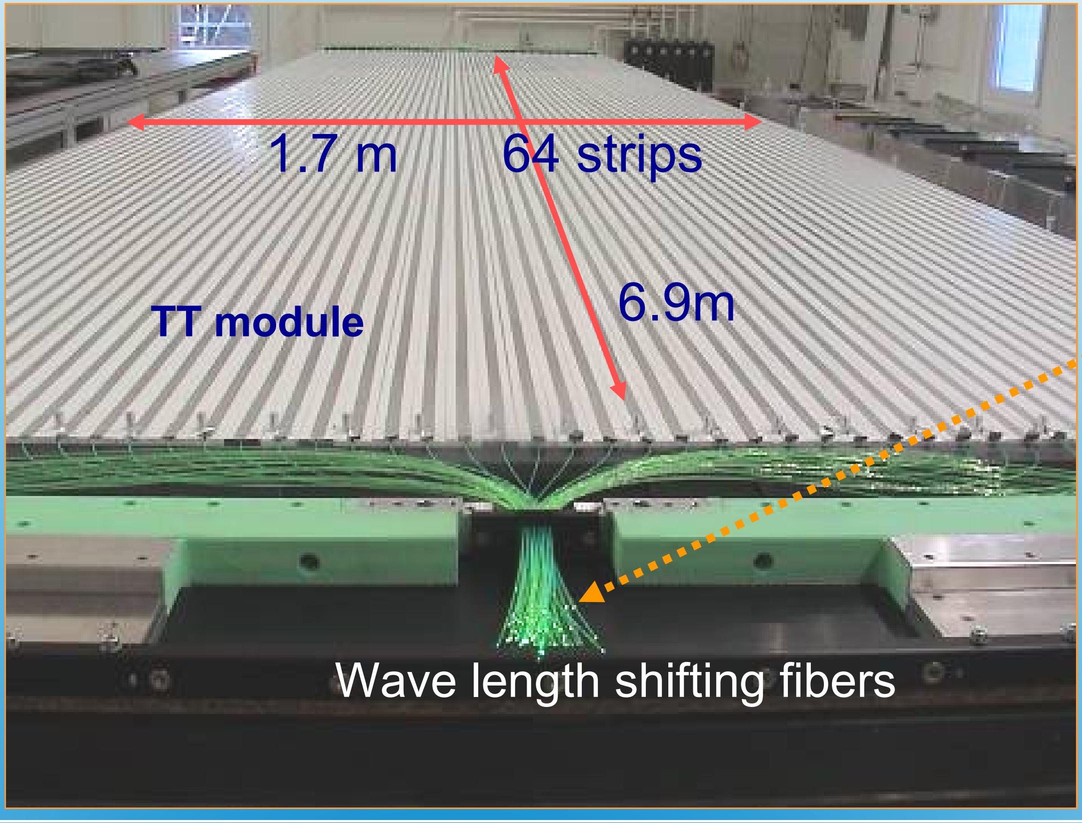


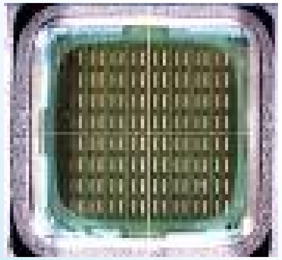


Implementation: the apparatus

Tasks: location of the ECC containing the ν interactions and event timing

- extruded plastic scintillator strips (2.6 cm width)
- light collections with wave length shifting fibers (WLS)
- fibers read-out at either side with multi-anode 64 pixels PMTs (H7546)





H7546
photomultiplier

one front-end DAQ board per side

The target tracker

- FNAL experiment (Phys. Rev. Lett. 43 (1979) 1361)

  ν_μ (E_ν > 30 GeV) short baseline experiment.

  $|v-c|/c \leq 4 \cdot 10^{-5}$ (comparison of ν_μ and μ velocities).

- Supernova SN1987A (e.g. Phys. Lett. B 201 (1988) 353)

  electron (anti) ν, E ~ 10 MeV, 168.000 light years baseline.

  $|v-c|/c \leq 2 \cdot 10^{-9}$ (ν and light arrival time).

- MINOS (Phys. Rev. D 76 072005 2007)

  ν_μ , E_ν ~ 3 GeV with a tail above 100 GeV. 730 km baseline.

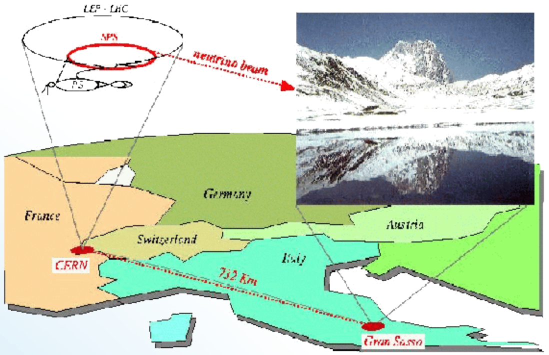
  $(v-c)/c = (5.1 \pm 2.9)\ 10^{-5}$,1.8 σ, (ν_μ at near and far site)

Previous ν–velocity measurements

Time of flight (TOF) + baseline

→ “velocity”

CERN to Gran Sasso Neutrino Beam

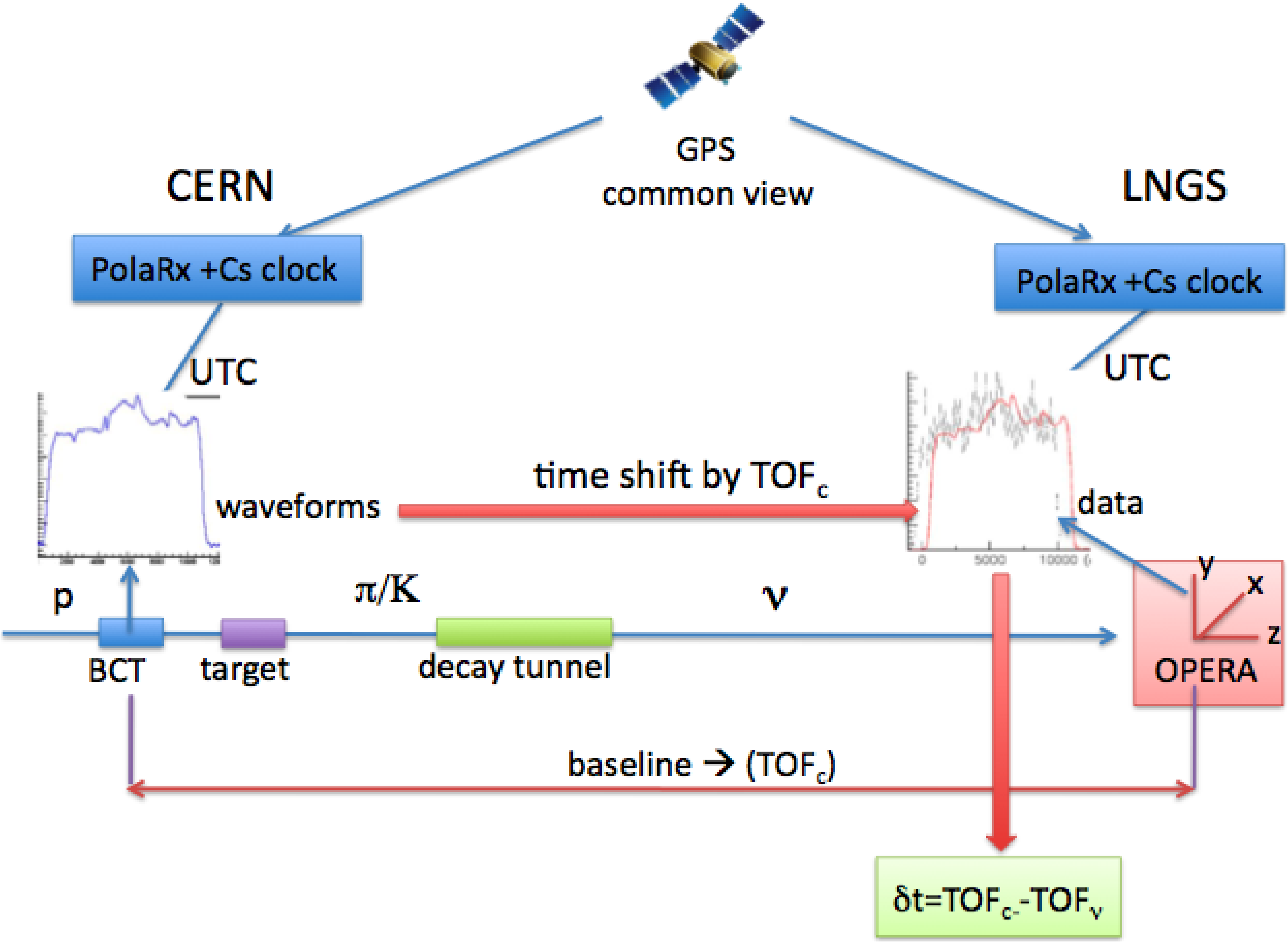


- Key ingredients:
  - Sophisticated timing system: CNGS-OPERA synchronization at ~1ns
  - Accurate calibrations of the timing chains at CERN and OPERA
  - Precise measurement of the ν time distribution at CERN through proton waveforms
  - High ν energy - high statistics (~ 15k events)
  - Measurement of the baseline by geodesy: 20 cm accuracy over 730 Km

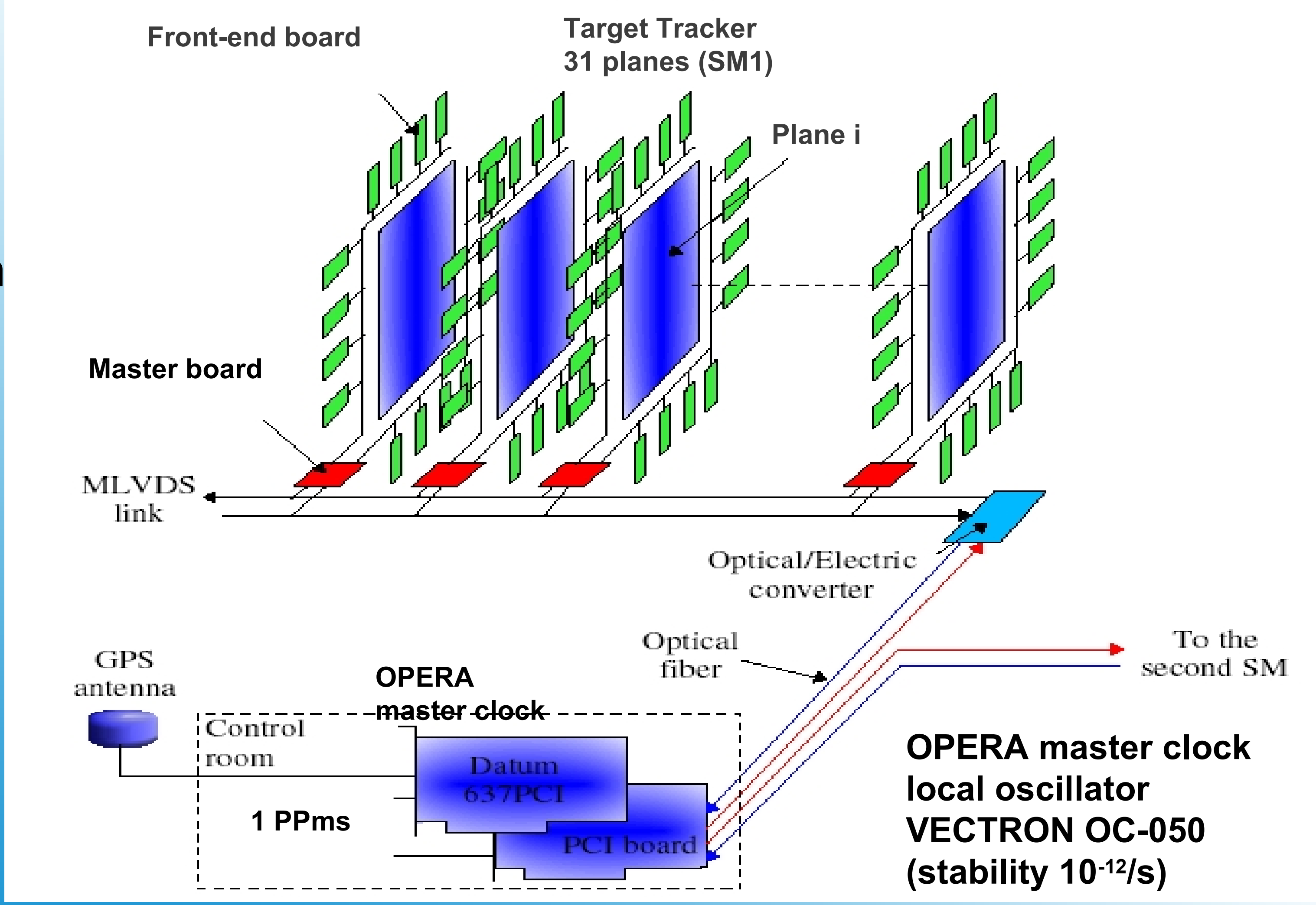
Achieved ~ 10 ns overall accuracy on ν TOF

similar syst. and stat. errors

Principle of the measurement


GPS
common view
CERN
LNGS
PolaRx +Cs clock
PolaRx +Cs clock
UTC
UTC
time shift by TOF_c
waveforms
data
p
π/K
ν
BCT
target
decay tunnel
OPERA
y
x
z
baseline → (TOF_c)
$\delta t = TOF_c - TOF_\nu$

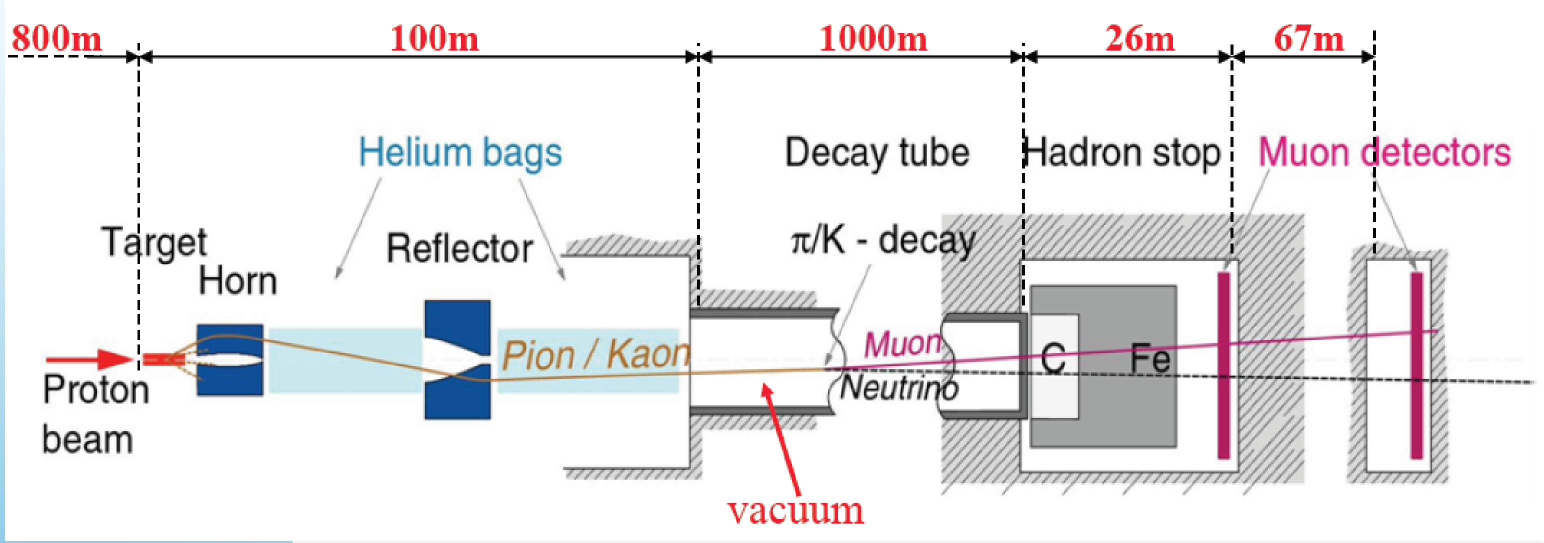
- 1200 asynchronous FE-nodes
- Gigabit ethernet network
- “trigger-less” system
- for each FE node mezzanine card: CPU (embedded Linux), memory, FPGA, clock receiver
- 10 ns UTC event time stamp granularity



OPERA master clock local oscillator VECTRON OC-050 (stability 10^{-12}/s)

OPERA read-out system and clock distribution

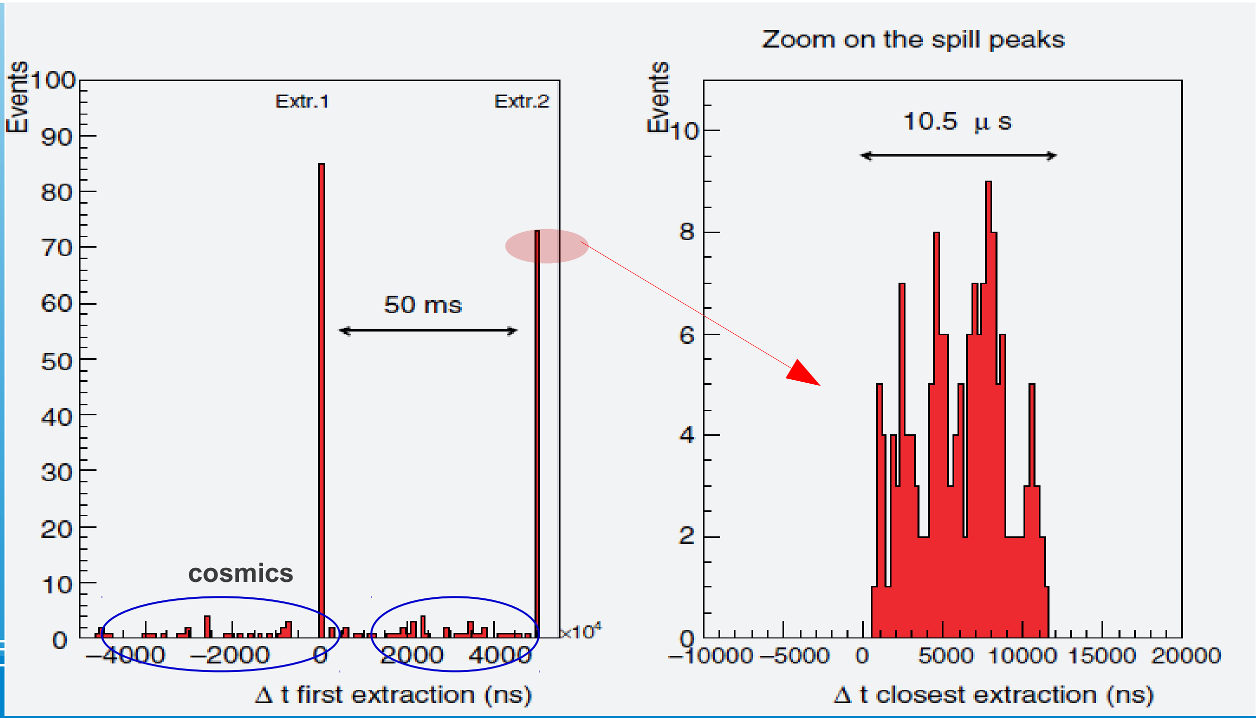
- SPS p: 400 GeV/c
- 6 s cycle
- ~ pure ν_μ
- $<E_\nu>$ = 17 GeV traveling through the Earth's crust



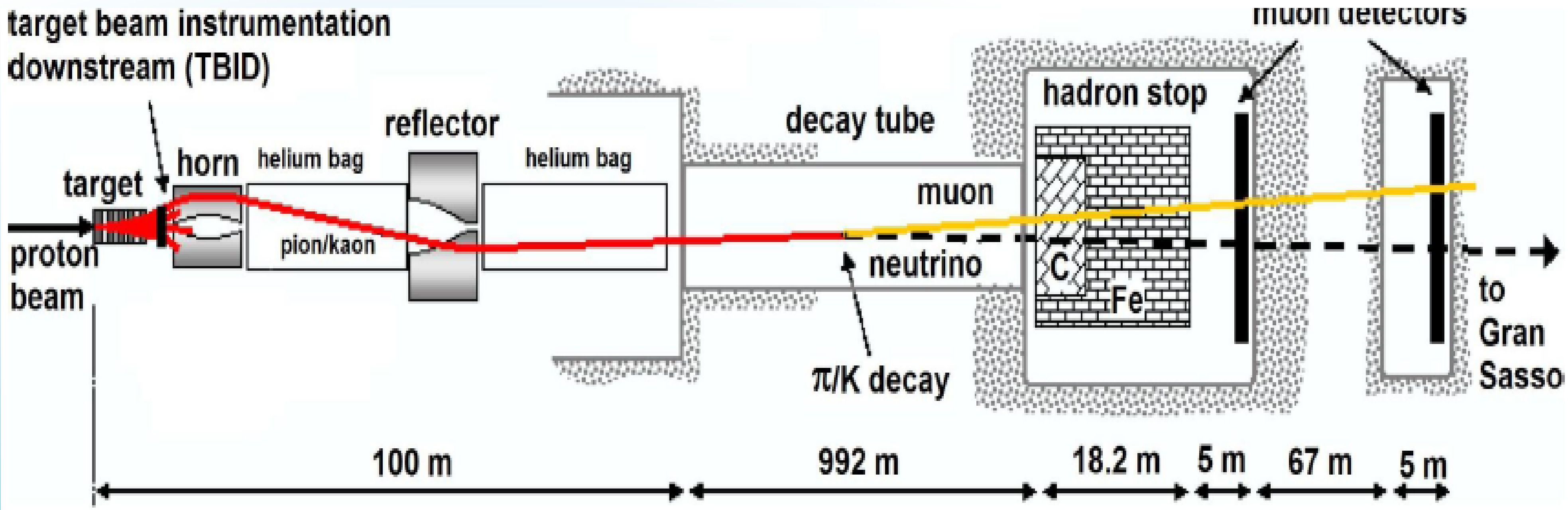
- Two 10.5 µs extractions (by kicker magnet) separated by 50 ms

$2.4 \cdot 10^{13}$ protons/extraction

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



The CNGS neutrino beam



- ν production point is not known but:
  - accurate UTC time-stamp of protons
  - relativistic parent mesons

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

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

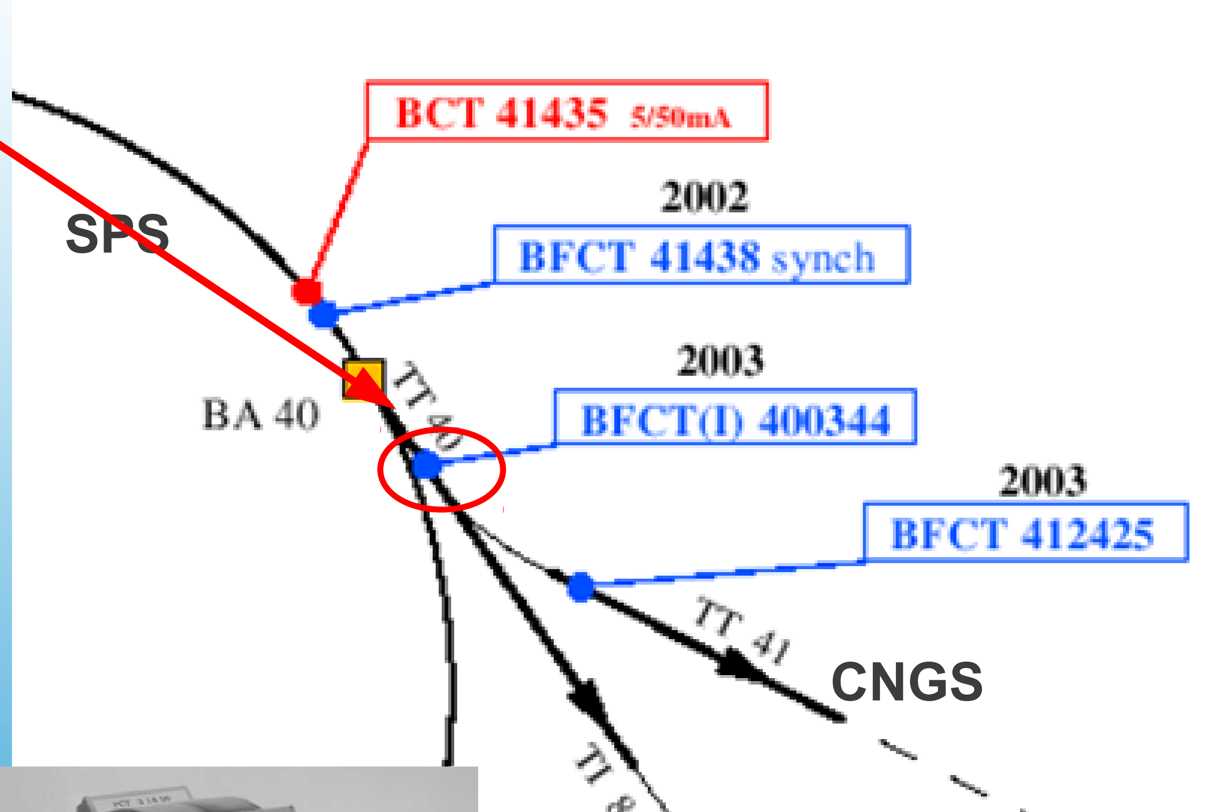
$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c}\left(\frac{1}{\beta} - 1\right) \approx \frac{z}{c}\frac{1}{2\gamma^2}$$

$\langle \Delta t \rangle = TOF_{true} - TOF_c =$ 14 ps   full FLUKA simulation

Neutrino production point

Fast Beam Current Transformer
("BCT", id 400344)
400 MHz bandwidth

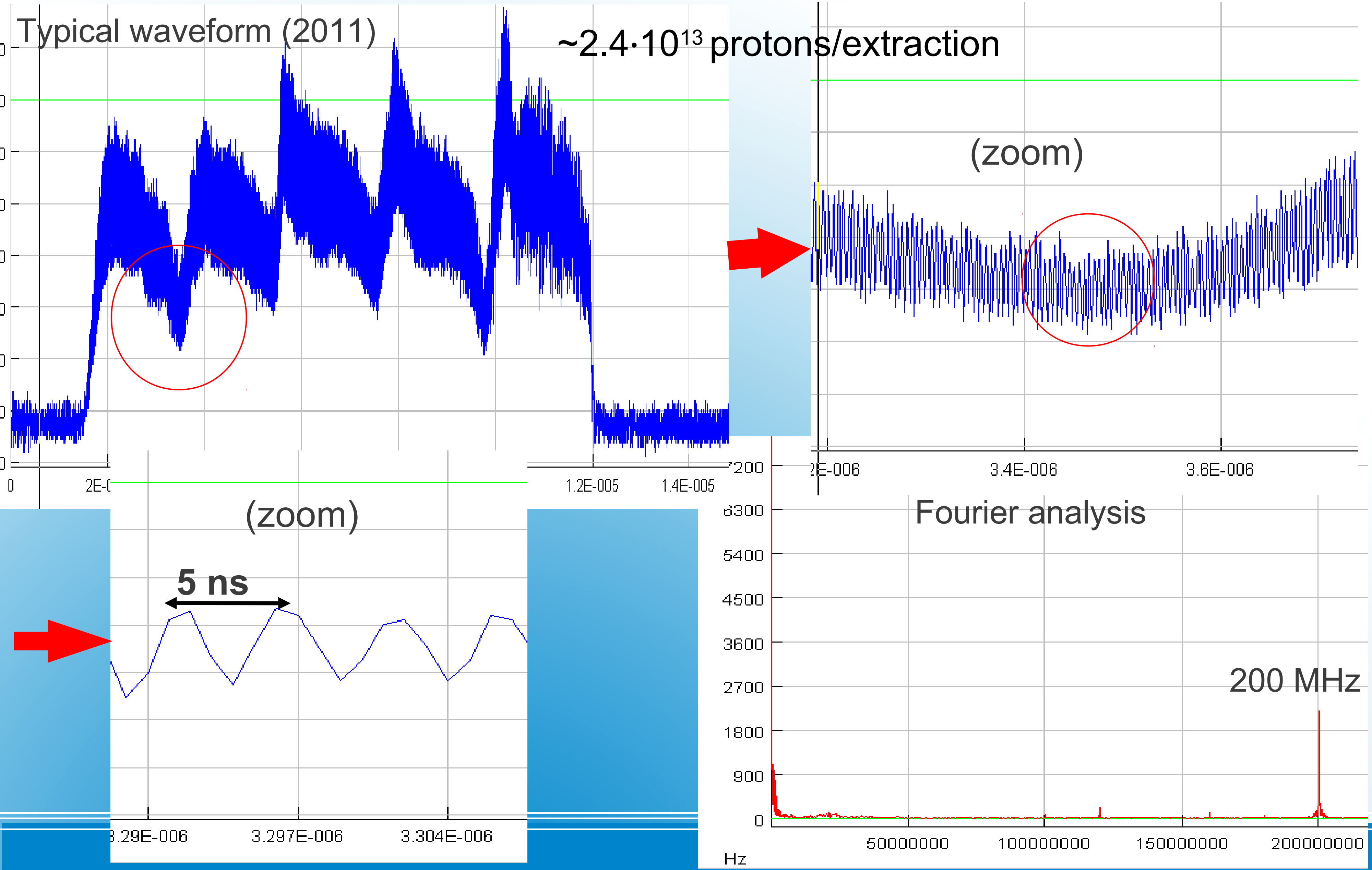
- Proton pulse digitized by a 1GS/s waveform digitizer ("WFD", Acqiris DP110)
- WFD triggered by a replica of the kicker signal
- Waveforms are UTC time-stamped and stored in CNGS database for offline analysis



2010 calibration with Cs clock

12

Accurate p timing

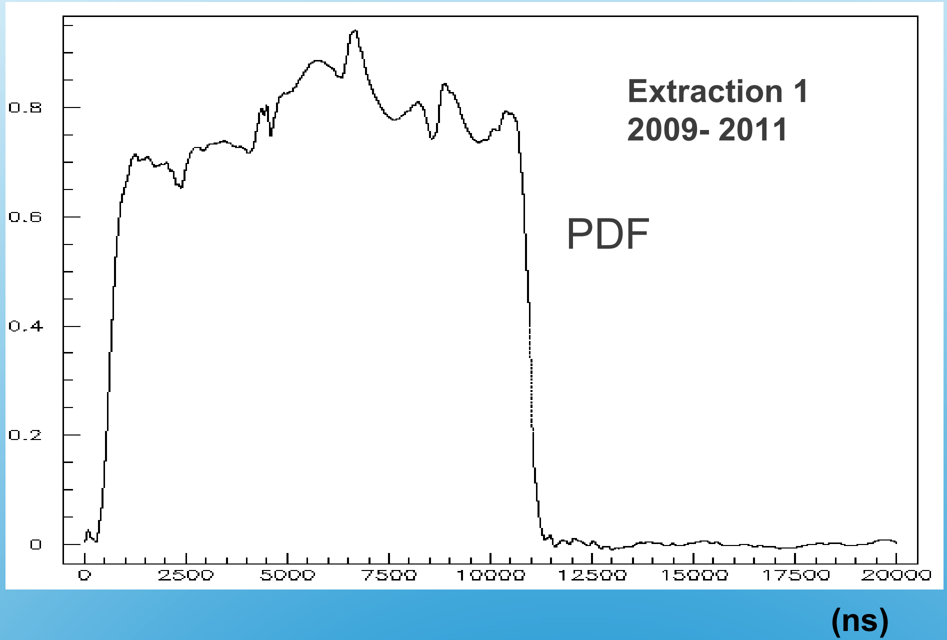


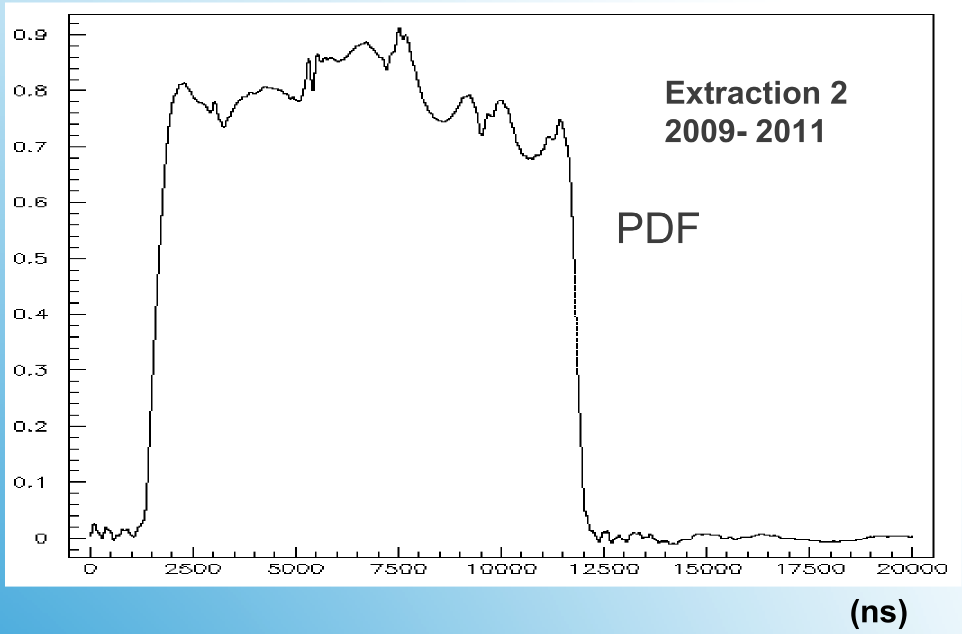
Single proton wave-form example

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

→ normalize each waveform and sum:

Average Probability Density Function (PDF) of the predicted t-distribution of ν events





Another approach:

→ normalize each waveform and use a different PDF for each ν event

Neutrino event-time PDF

LNGS

Rome La Sapienza
Geodesy group

Dedicated measurements:
July-Sept. 2010

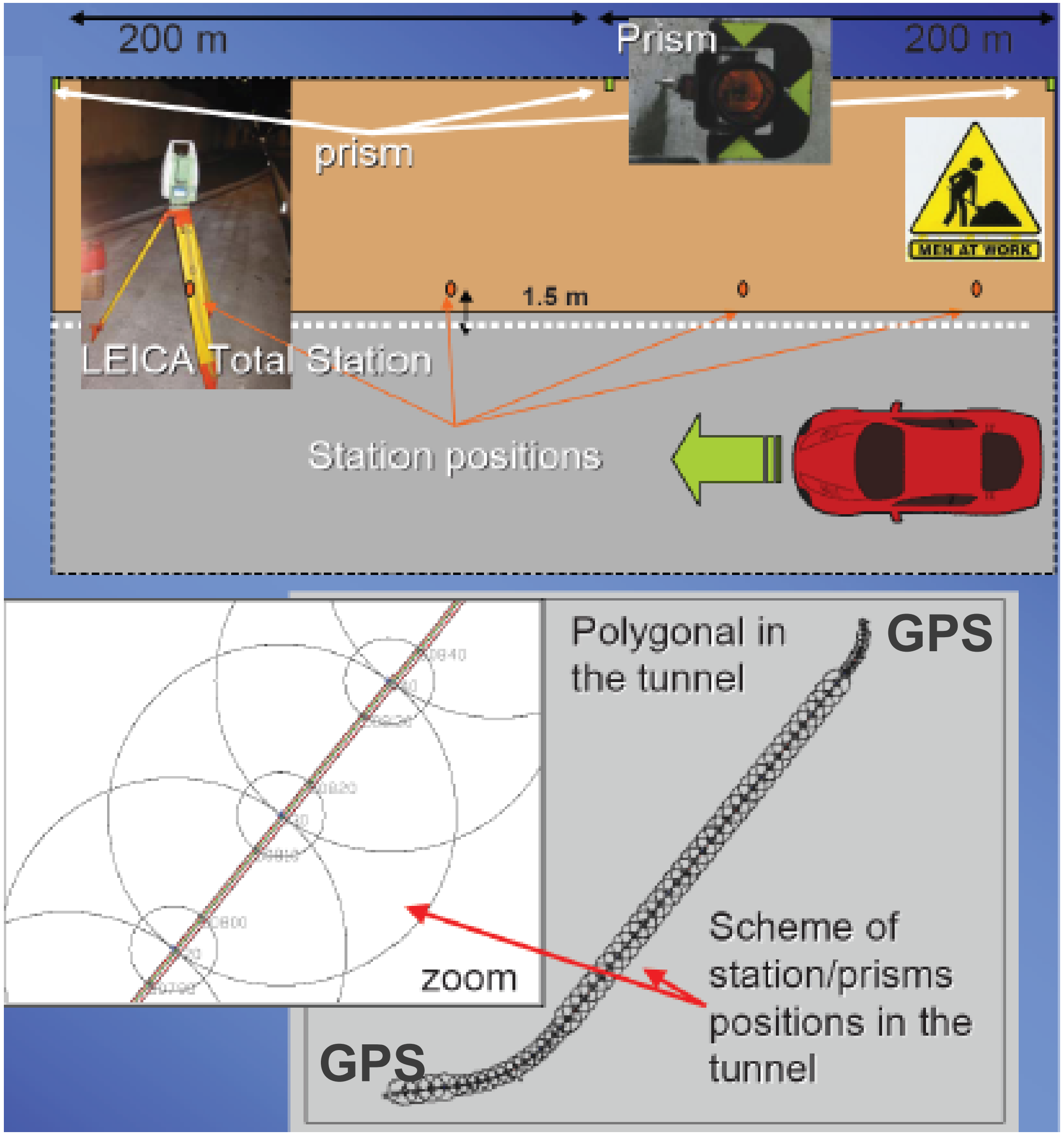
2 new GPS benchmarks on each side of the 10 km highway tunnel

GPS measurements ported underground to OPERA

CERN survey group

CERN measurements (taken in different periods) combined in the ETRF2000 European Global system, accounting for earth dynamics

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



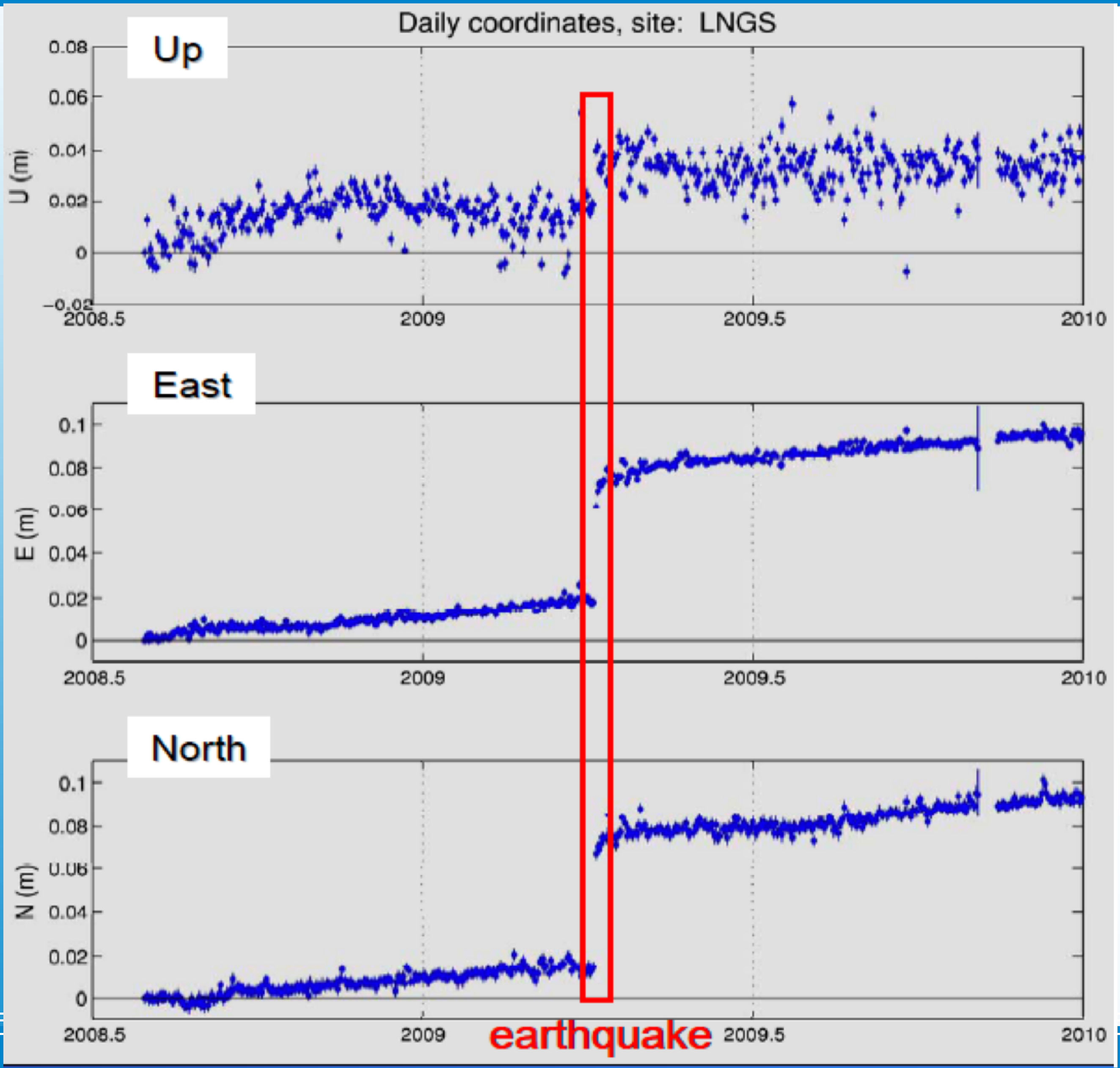
Geodesy

Distance (BCT - OPERA reference frame) =

(731278.0 ± 0.2) m

Long and short time scale phenomena visible:

→ continental drift
→ 2009 L'Aquila earthquake



LNGS position monitoring

GPS common view mode

GPS standard operation

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

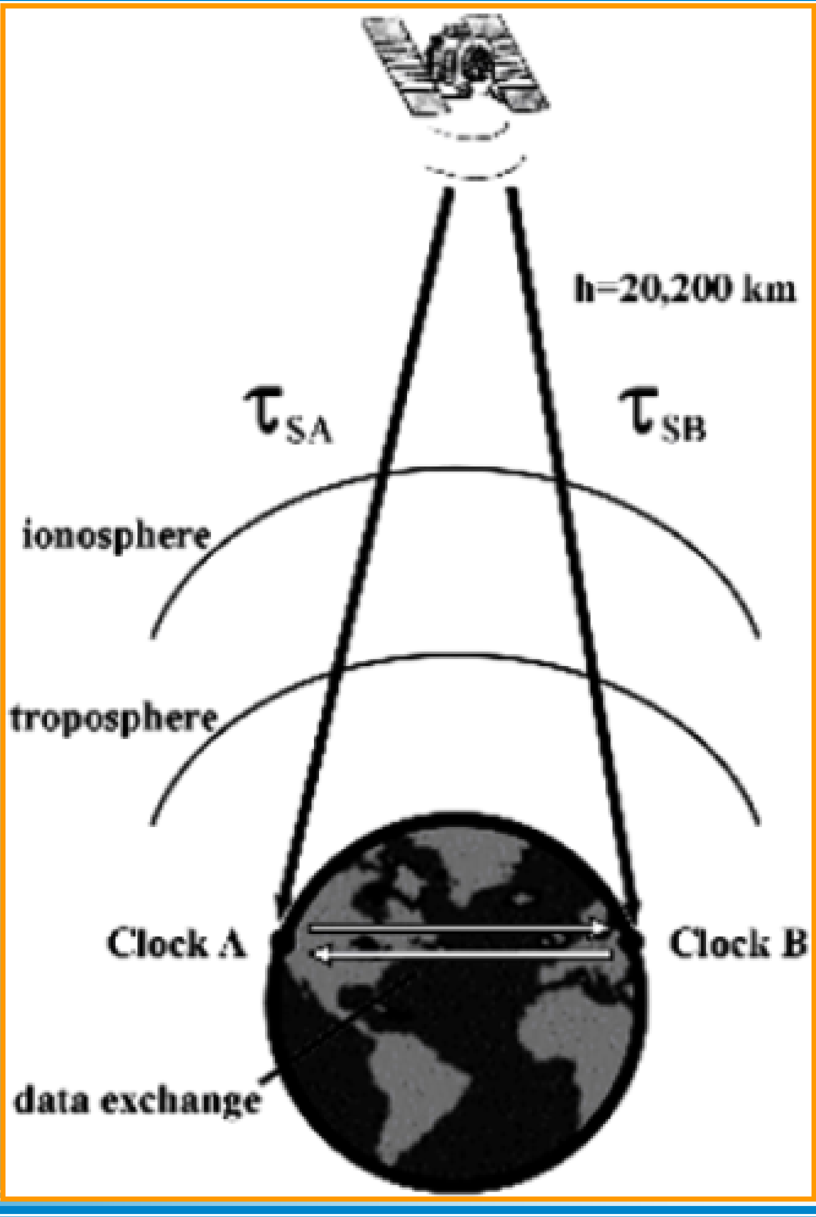
GPS “common-view” mode

same satellite visible from two sites

Knowing (x, y, z) of the sites from former dedicated measurements → determine time differences of local clocks w.r.t. the satellite, by off-line data exchange

Advantage: 730 km << 20000 km (satellite height) → similar paths in ionosphere → error cancellation

Standard technique for high accuracy t-transfer
Permanent time link (~1 ns) between reference points at CERN and OPERA



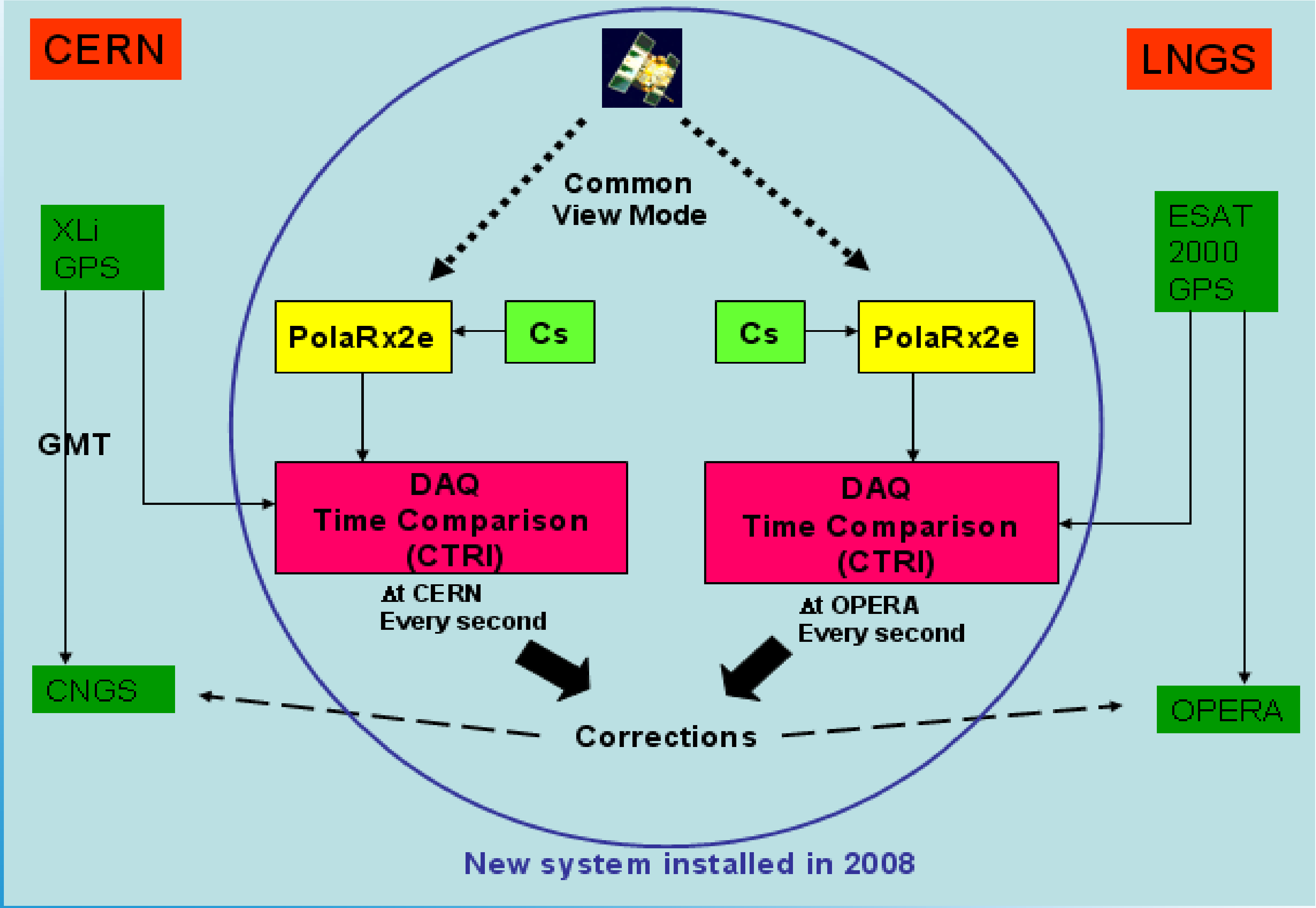
Standard GPS receivers have ~100 ns accuracy:

- XLi (CERN)
- ESAT 2000 (LNGS)

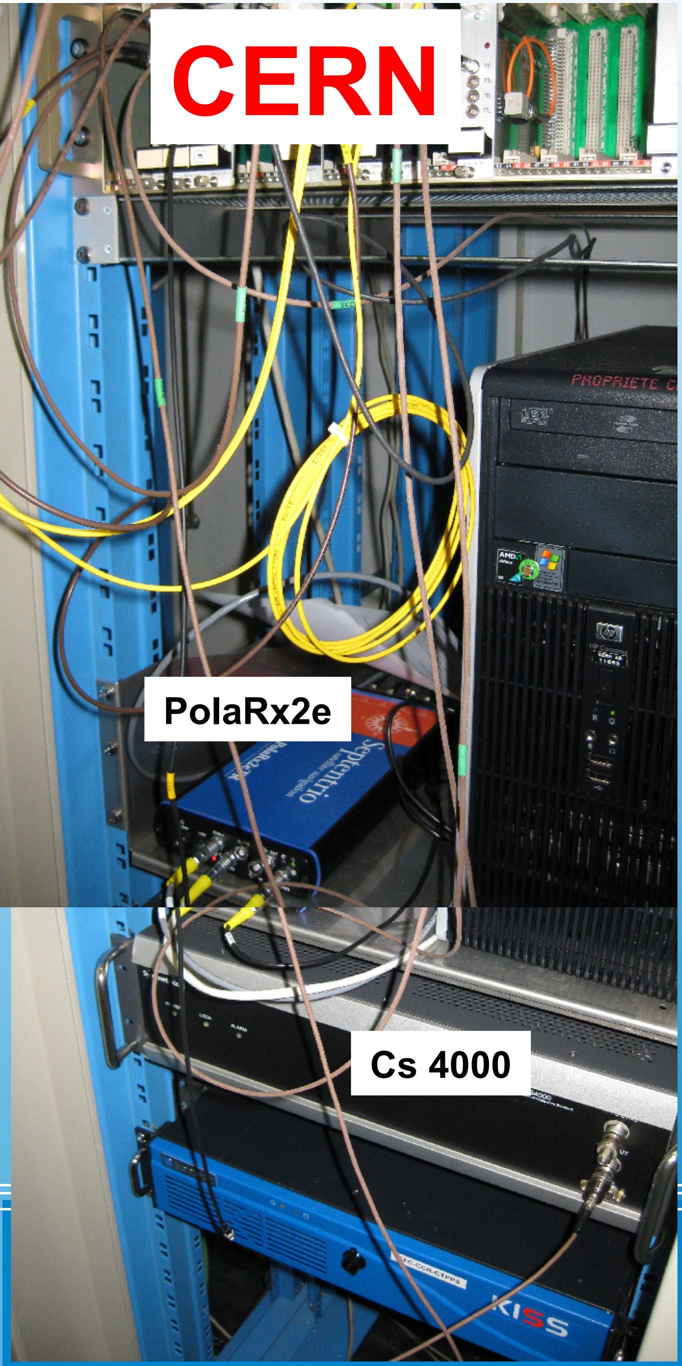
2008: installation of a twin high accuracy system calibrated by METAS (Swiss metrology institute)

- PolaRx2e GPS receiver
- Cs-clock

at CERN and LNGS

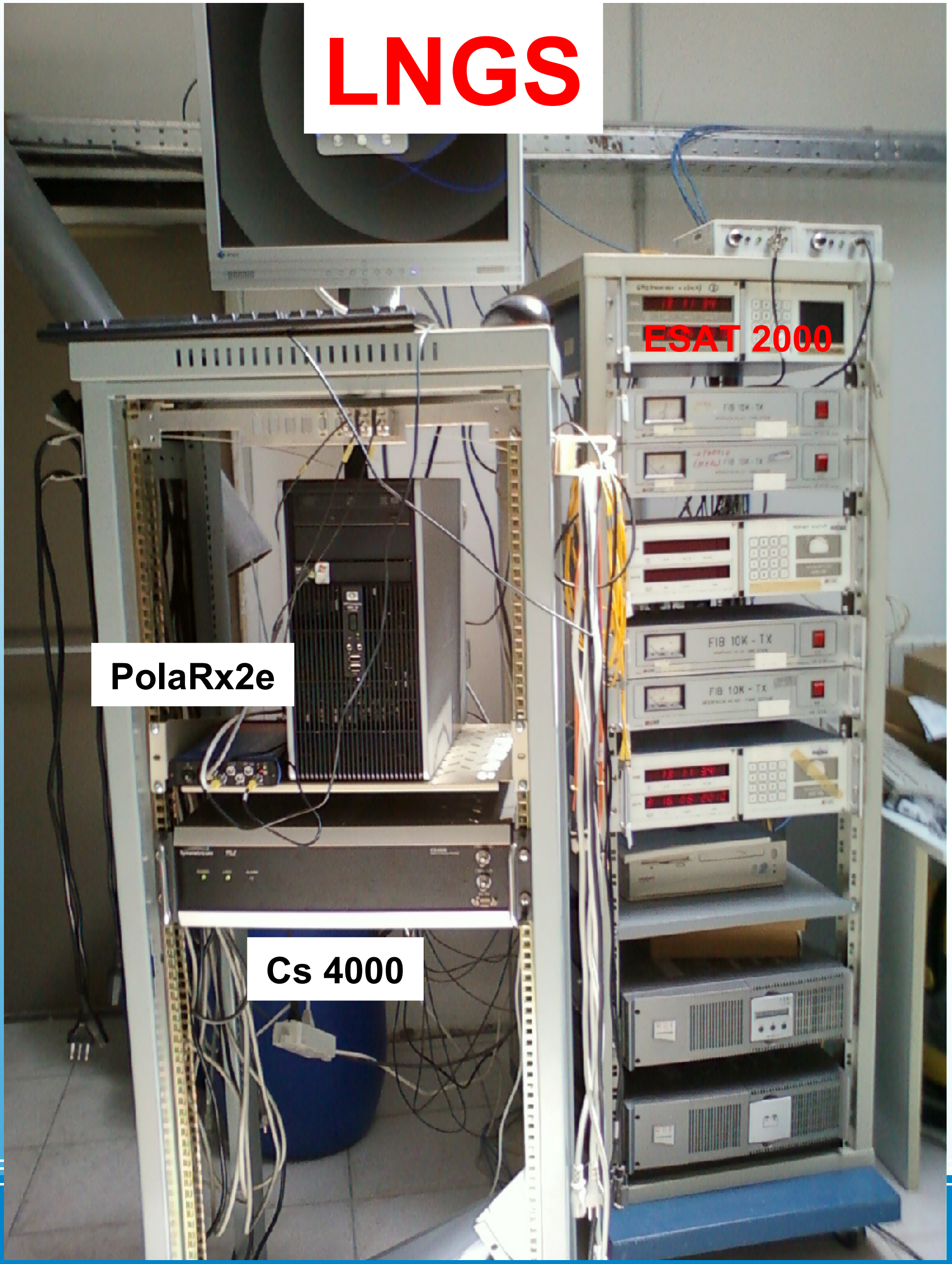


CNGS OPERA synchronization



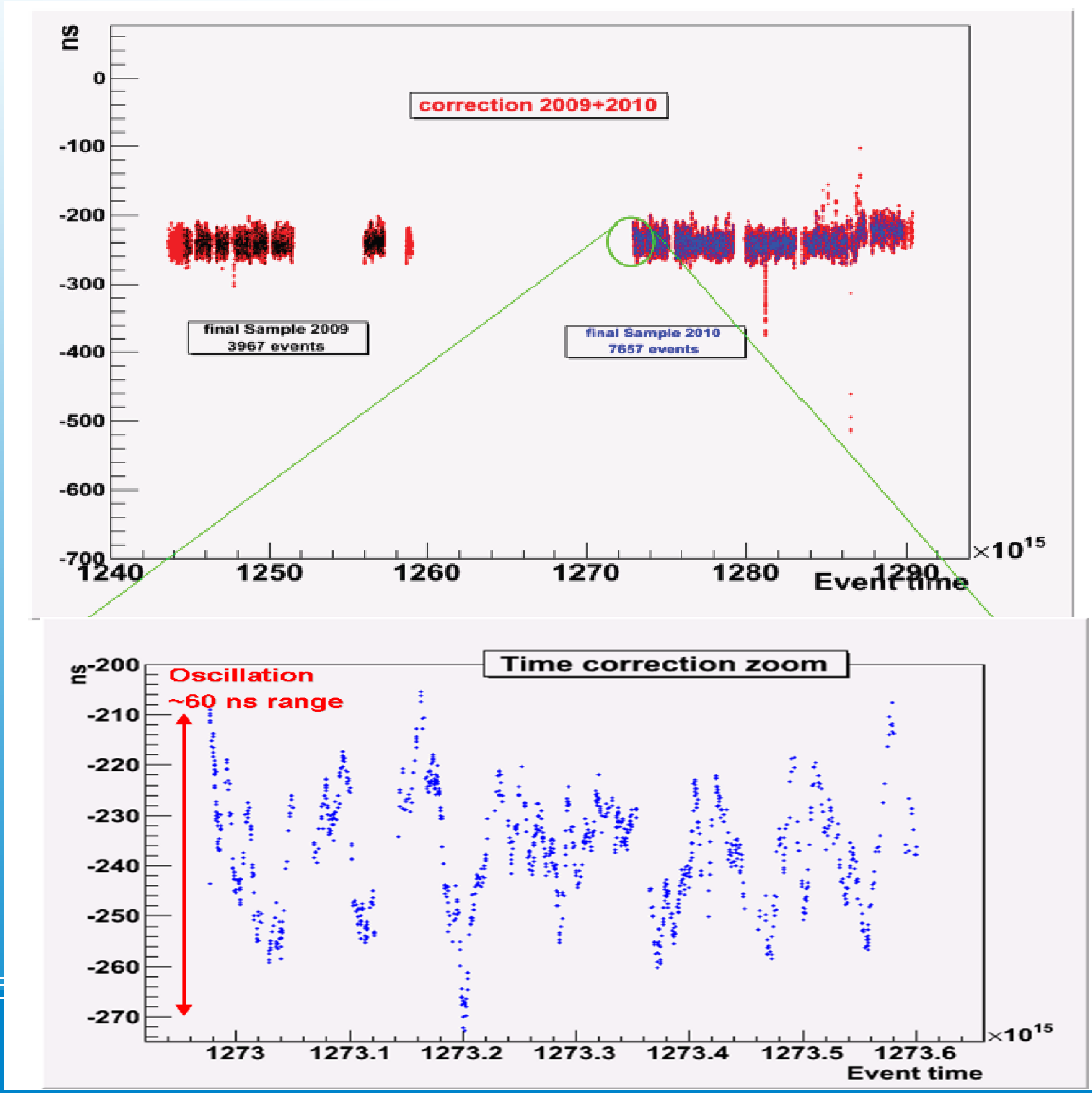
PolaRx2e :
GPS receiver for time-transfer applications:

- frequency reference from Cs clock (Cs-4000)
- internal time tagging of 1PPS with respect to individual satellite observations
- off-line common-view analysis in CGGTTS format
- use ionosphere-free code (P3)



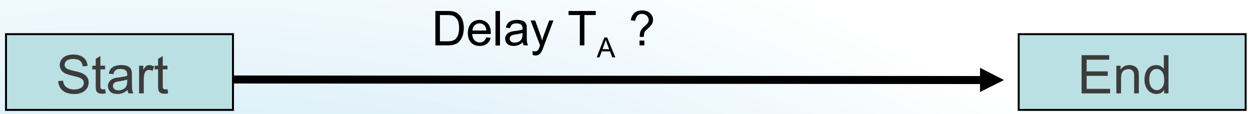
Twin synchronization devices

Event-by-event correction
From the GPS common
view mode operations

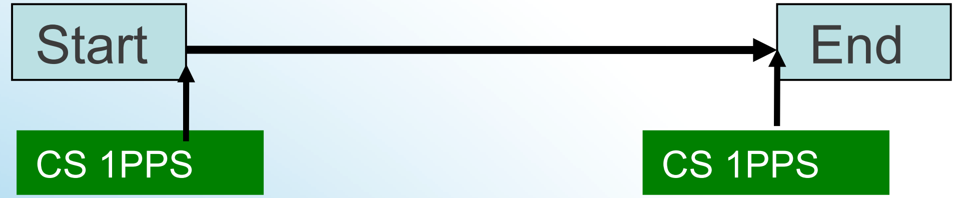


Result: TOF timelink correction

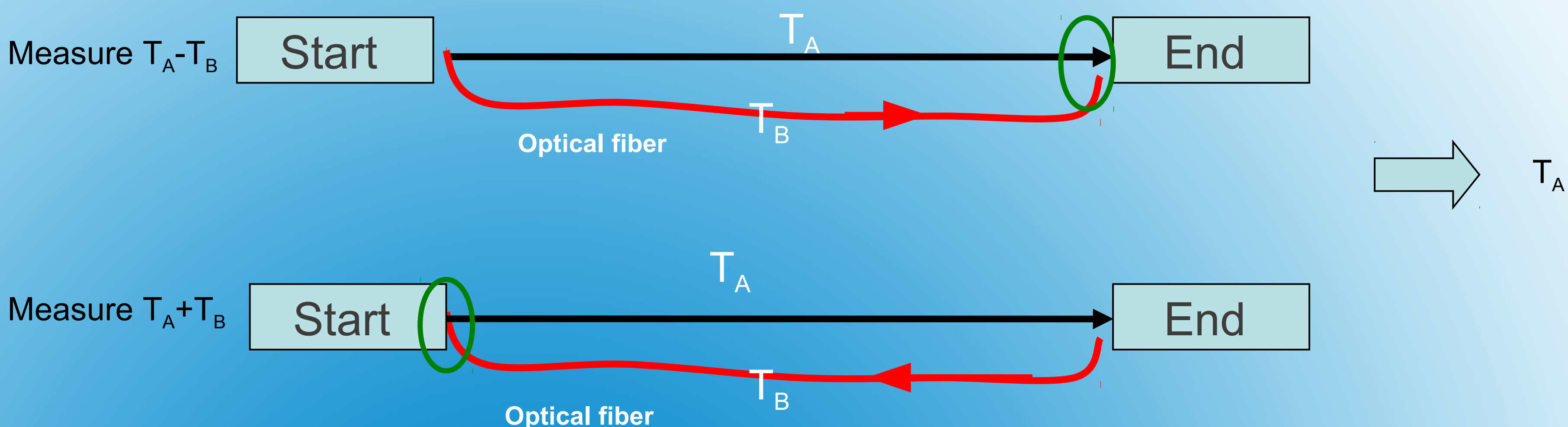
Time calibration techniques

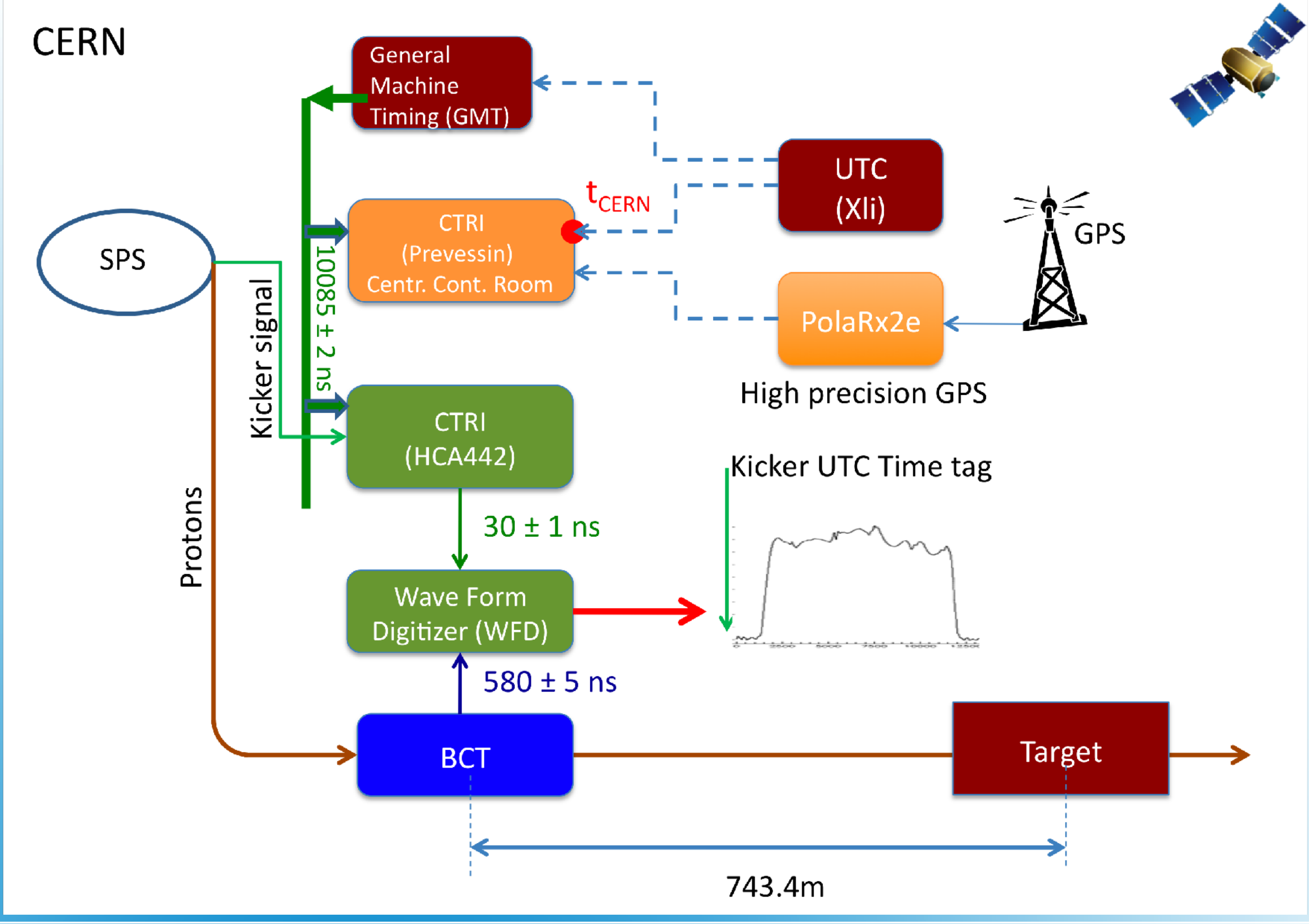


- Portable Cs-4000:
Comparison: time-tags vs 1PPS signal (Cs clock) at the start- and end-point of a timing chain



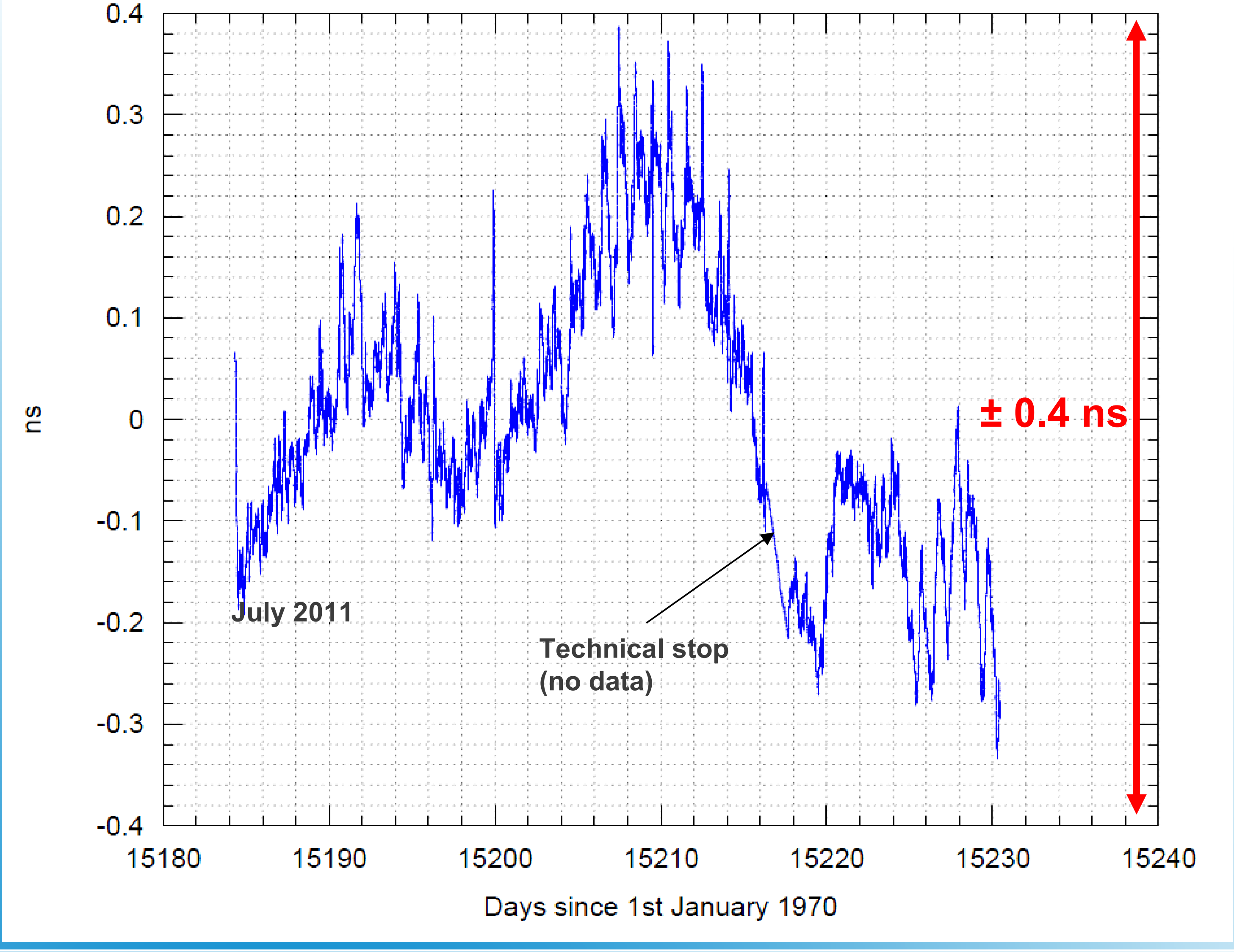
- Double path fibers measurement:
by swapping transmitter and receiver component of the opto-chain





Delay calibrations: CERN side

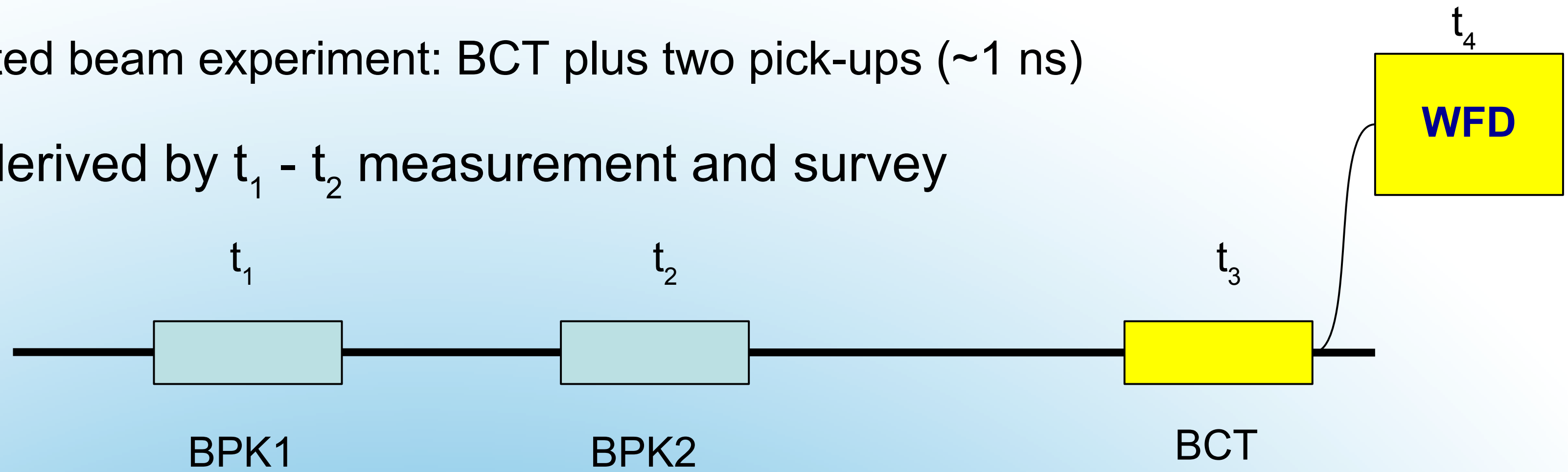
variations w.r.t. nominal



Continuous two-way measurement of UTC delay at CERN

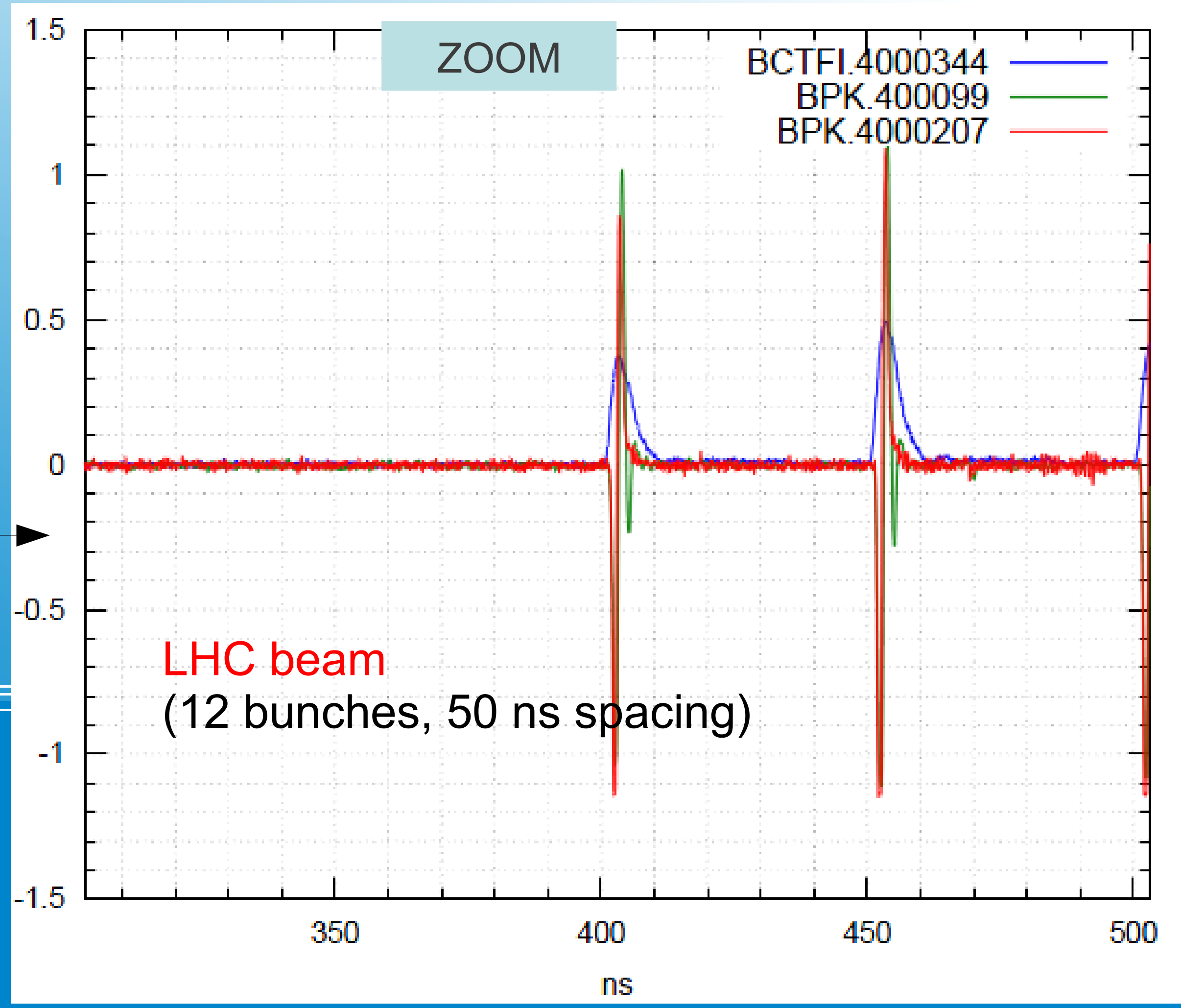
Dedicated beam experiment: BCT plus two pick-ups (~1 ns)

t_3 : derived by t_1 - t_2 measurement and survey

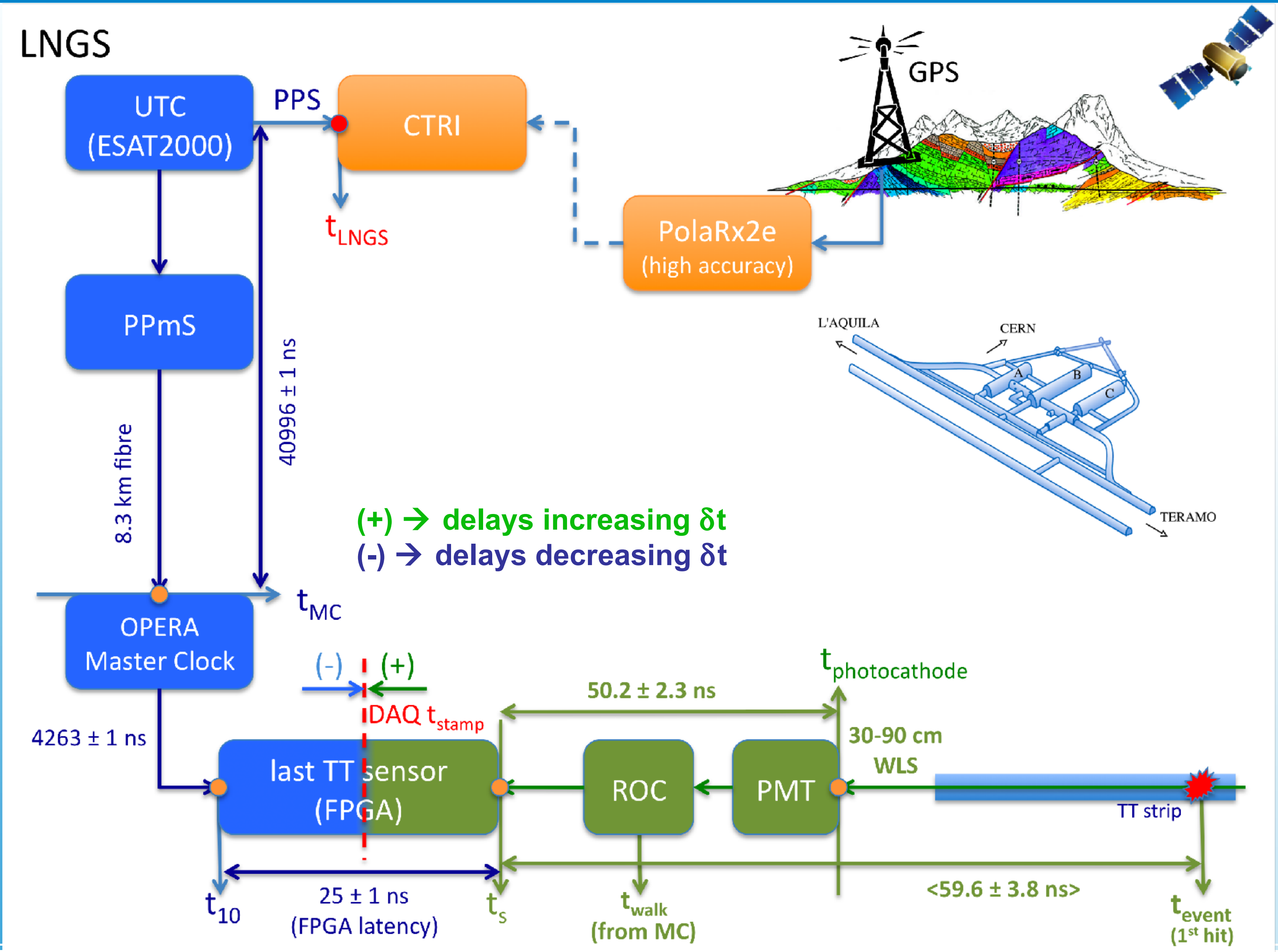


$\Delta t_{BCT} = t_4 - t_3 = (580 \pm 5)$ ns

result: signals comparison after Δ_{BCT} compensation



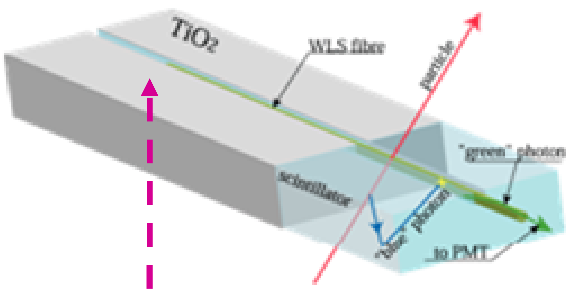
BCT calibration

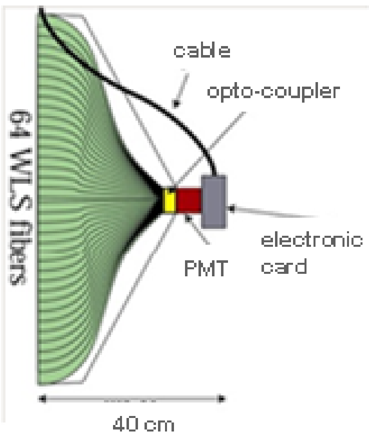


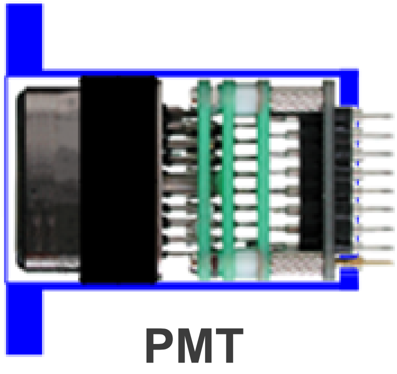
Delay calibrations: LNGS side

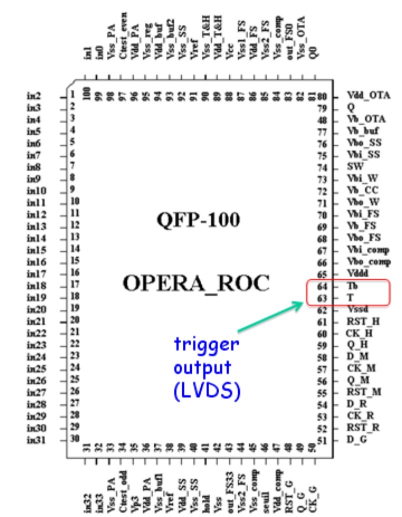
signal

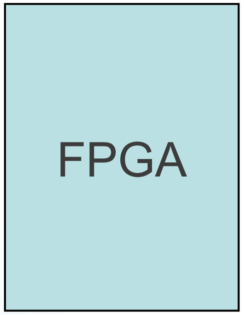
Scintillator + WLS fibers PMT analog Front End chip (ROC) FPGA











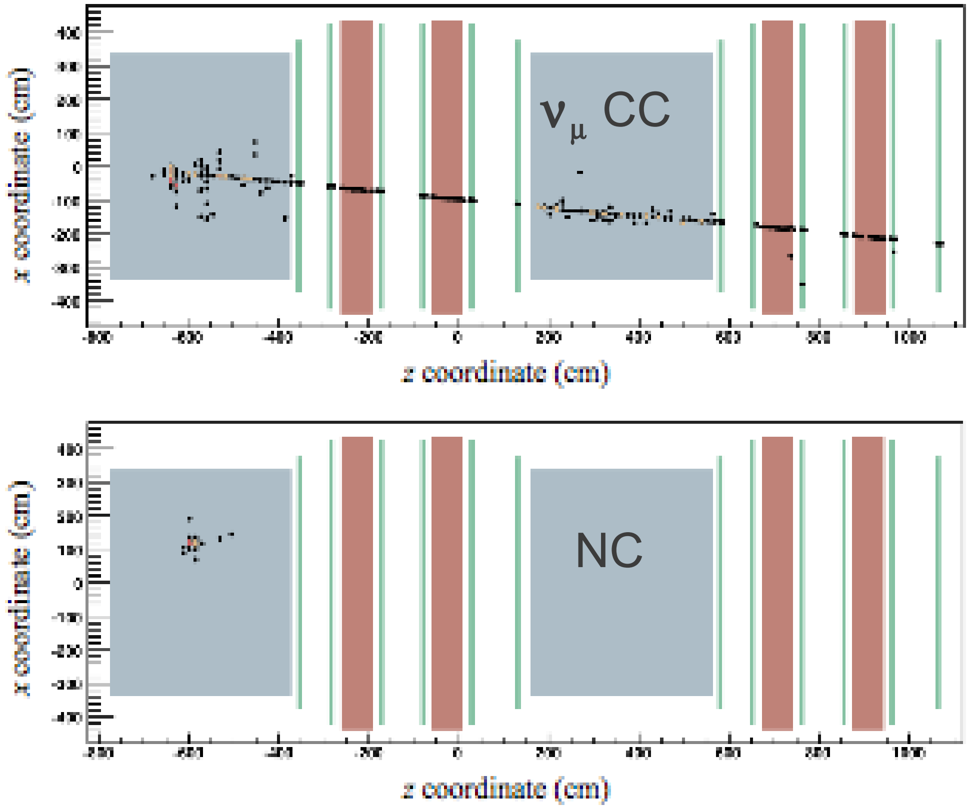
picosecond UV laser excitation:

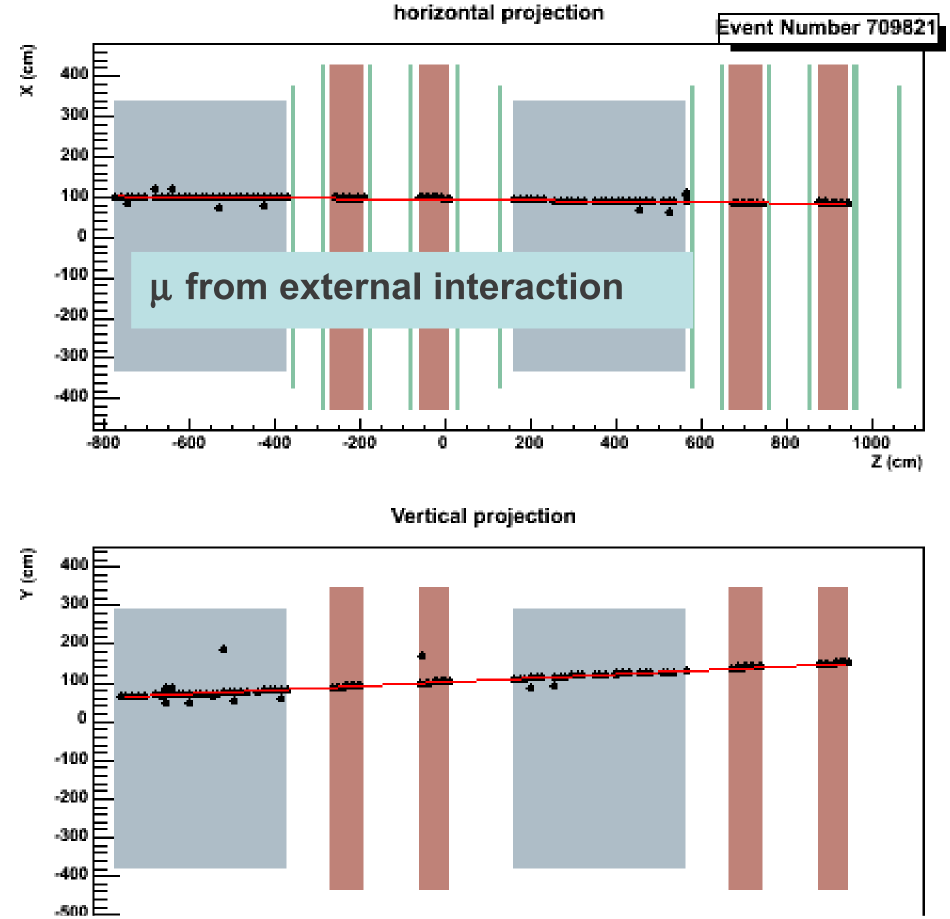
→ delay from photo-cathode to FPGA input: (50.2 ± 2.3) ns

→ average event time response: (59.6 ± 3.8 (sys.)) ns

including event position, pulse height dependence, ROC time-walk, DAQ quantization effects with simulations

TT time response measurement





First TT hit used as "stop"
and translated in time to a common reference point (assuming c)
Internal/External: 7235/7988 events with 2009-2010-2011 CNGS runs (~10^{20} pot)
External events timing checked with full simulation → 2 ns systematic uncertainty

Internal and external events

$\delta t = TOF_c - TOF_\nu$

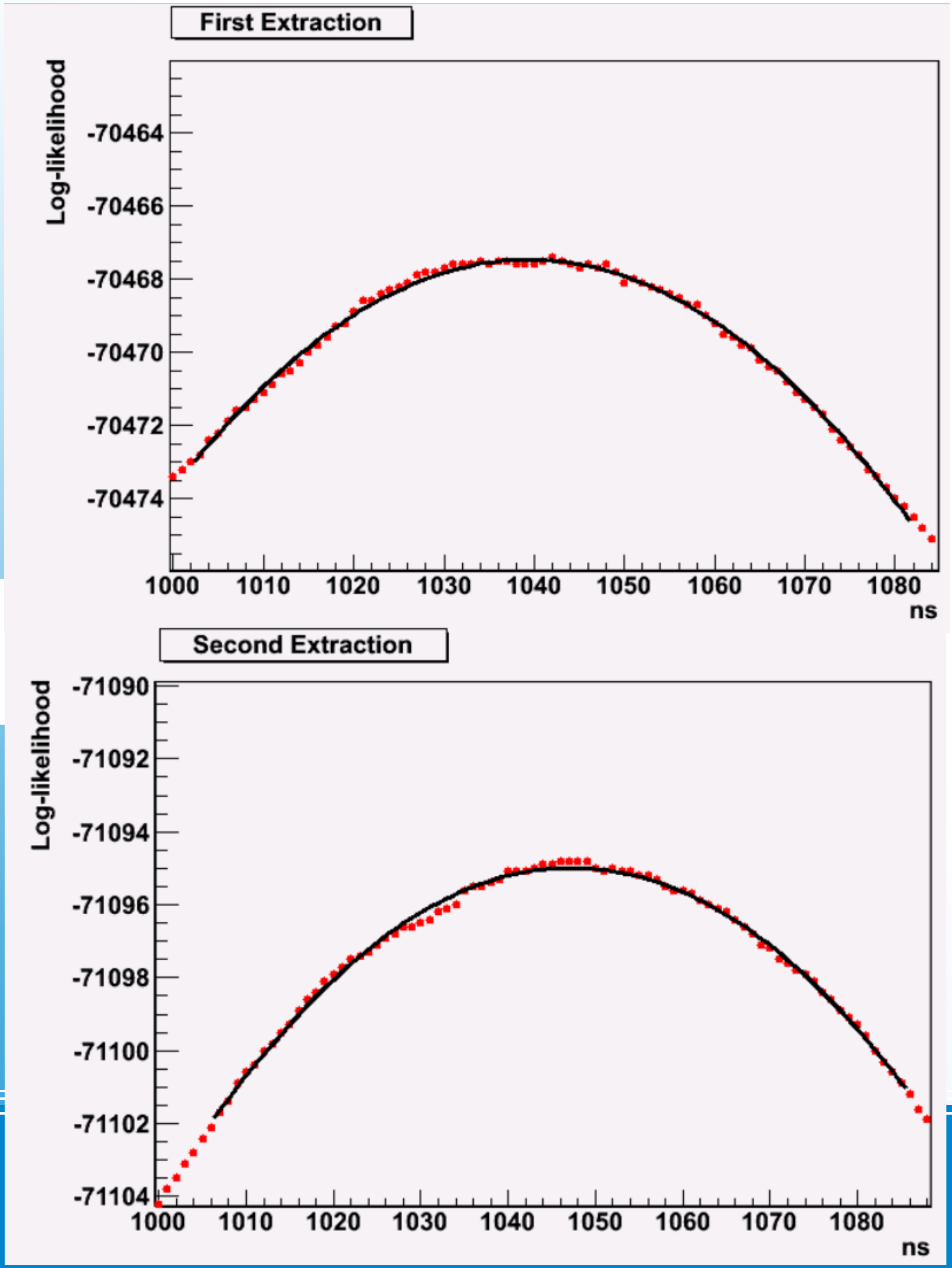
positive (negative) δt →
ν arrives earlier (later) than light

Unbinned Log-Likelihood maximised over δt:

$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k)$$

k=1,2 extractions

Statistical error evaluated from log likelihood curves

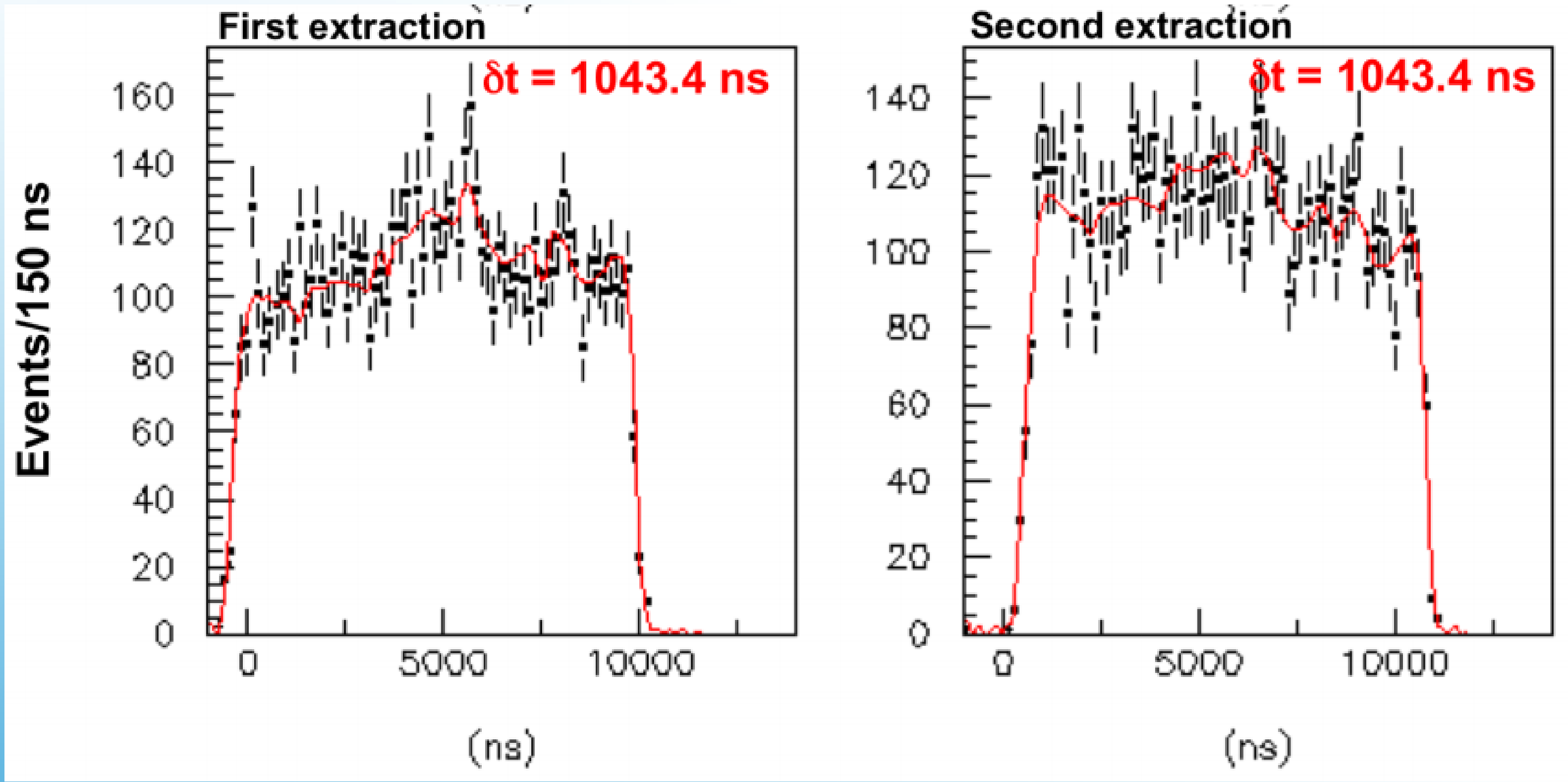


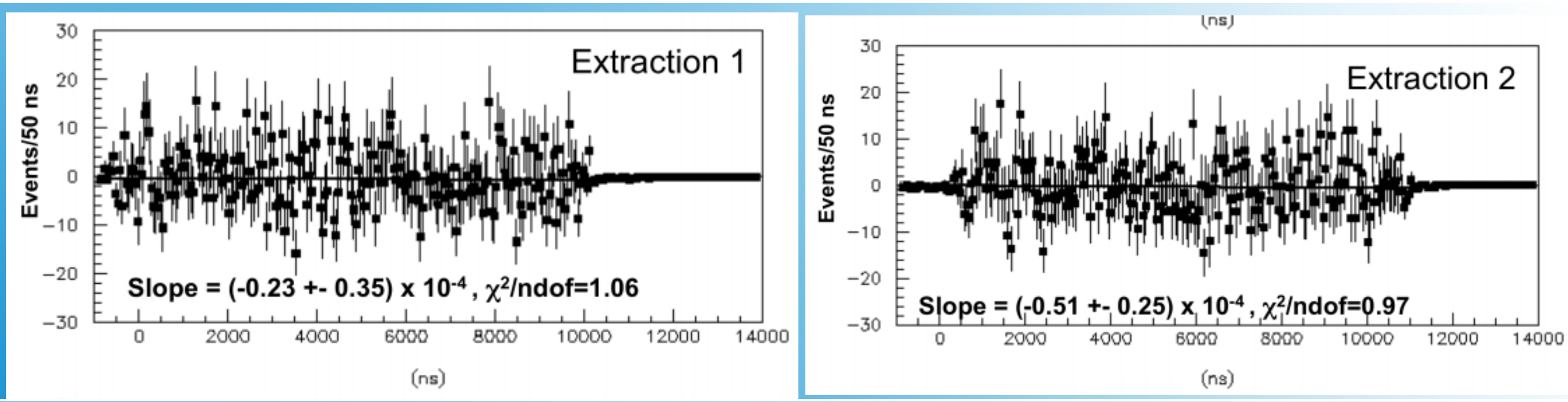
Analysis method

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

Resulting δt ~1000 ns by construction >> individual calibration contributions

"Box" opened once all correction contributions reached satisfactory accuracy



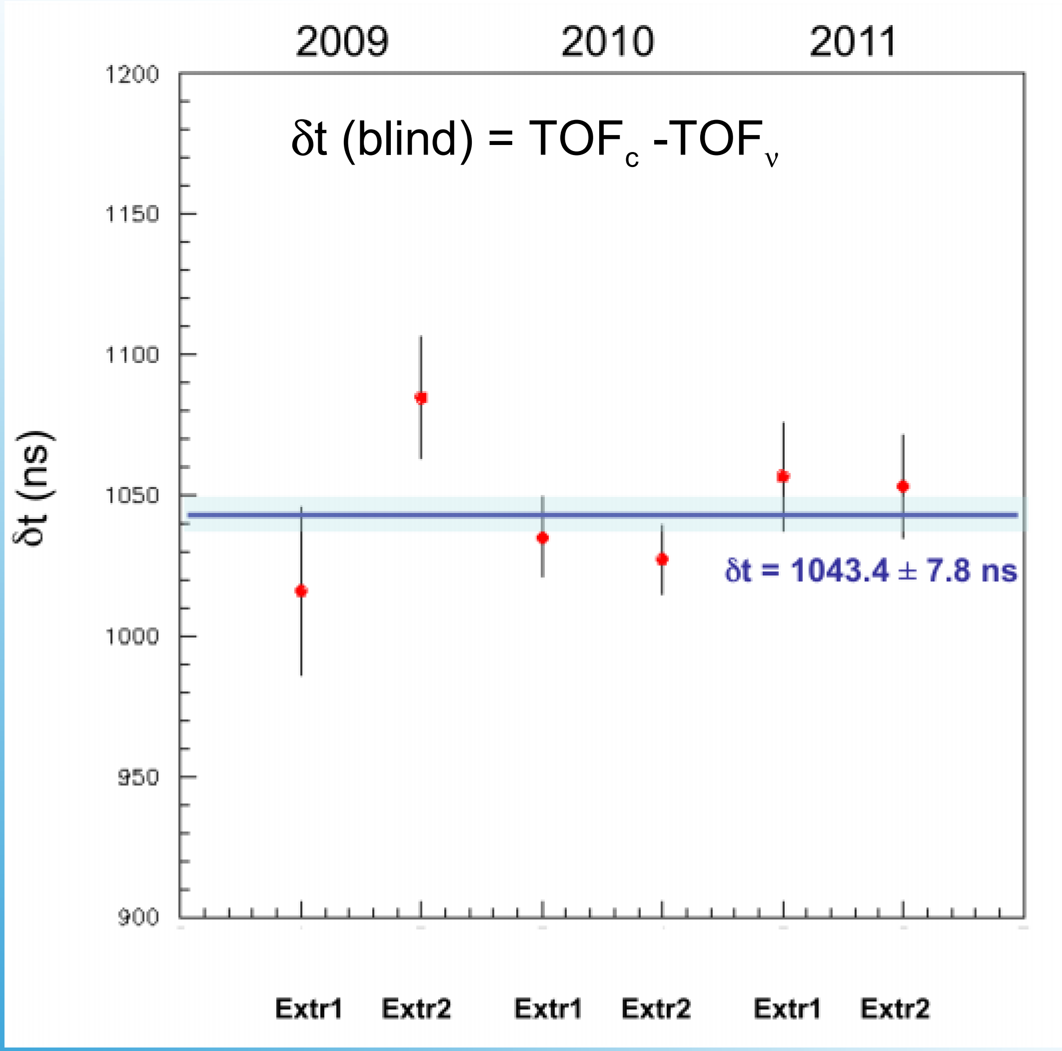


Blind analysis

$\delta t = TOF_c - TOF_\nu = (1043.4 \pm 7.8(\text{stat.}))$ ns

χ^2 / ndof : 1.06 (1st extr) and 0.97 (2nd extr.)

1) Coherence among CNGS runs/extractions



2) No hint for day-night

|day-night| = 16.4 ± 15.8 ns

3) or seasonal effects:
|(spring+fall) - summer|: 15.6 ± 15.0 ns

4) Internal vs external events:

All: 1043.4 ± 7.8 ns
Internal: 1045.1 ± 11.3 ns

Cross-checks

Timing and baseline corrections

	Blind analysis (ns) 2006	Final analysis (ns) 2011	Correction (ns)
Baseline	2440079.6	2439280.9	
Earth rotation		2.2	
Correction baseline			-796.5
CNGS delays:			
UTC calibration	10092.2	10085.0	
Correction UTC			-7.2
WFD	0	30	
Correction WFD			30
BCT	0	-580	
Correction BCT			-580
OPERA Delays:			
TT response	0	59.6	
FPGA	0	-24.5	
DAQ clock	-4245.2	-4262.9	
Correction OPERA			17.4
GPS Corrections:			
Synchronisation	-353	0	
Time-link	0	-2.3	
Correction GPS			350.7
Total correction			**-985.6**

Systematic uncertainties

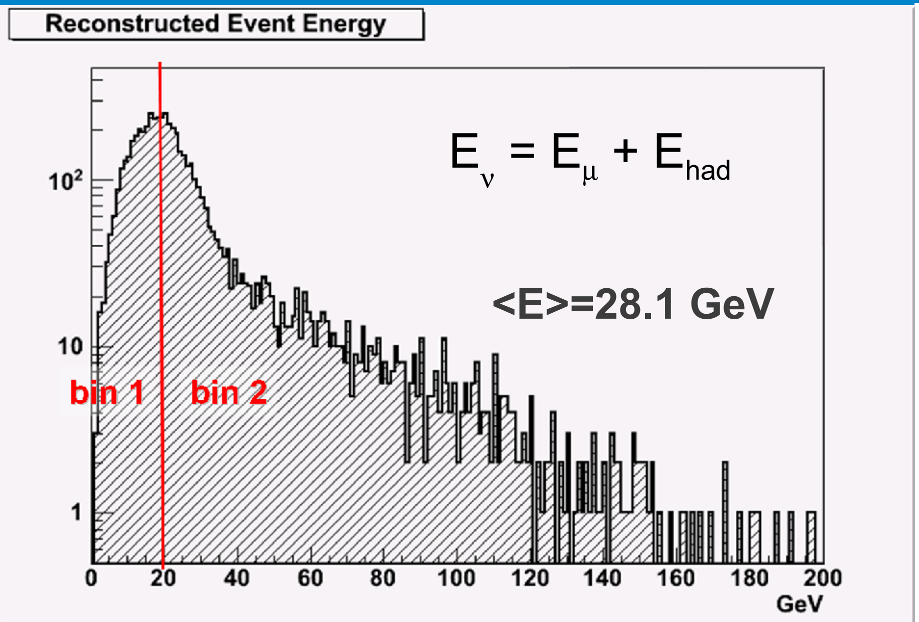
Systematic uncertainties	**ns**	**Error distribution**
Baseline (20 cm)	0.67	Gaussian
Decay point	0.2	Exponential (1 side)
Interaction point	2.0	Flat (1 side)
UTC delay	2.0	Gaussian
LNGS fibres	1.0	Gaussian
DAQ clock transmission	1.0	Gaussian
FPGA calibration	1.0	Gaussian
FWD trigger delay	1.0	Gaussian
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**	

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

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

(L=730085 m taking parent mesons average decay point)

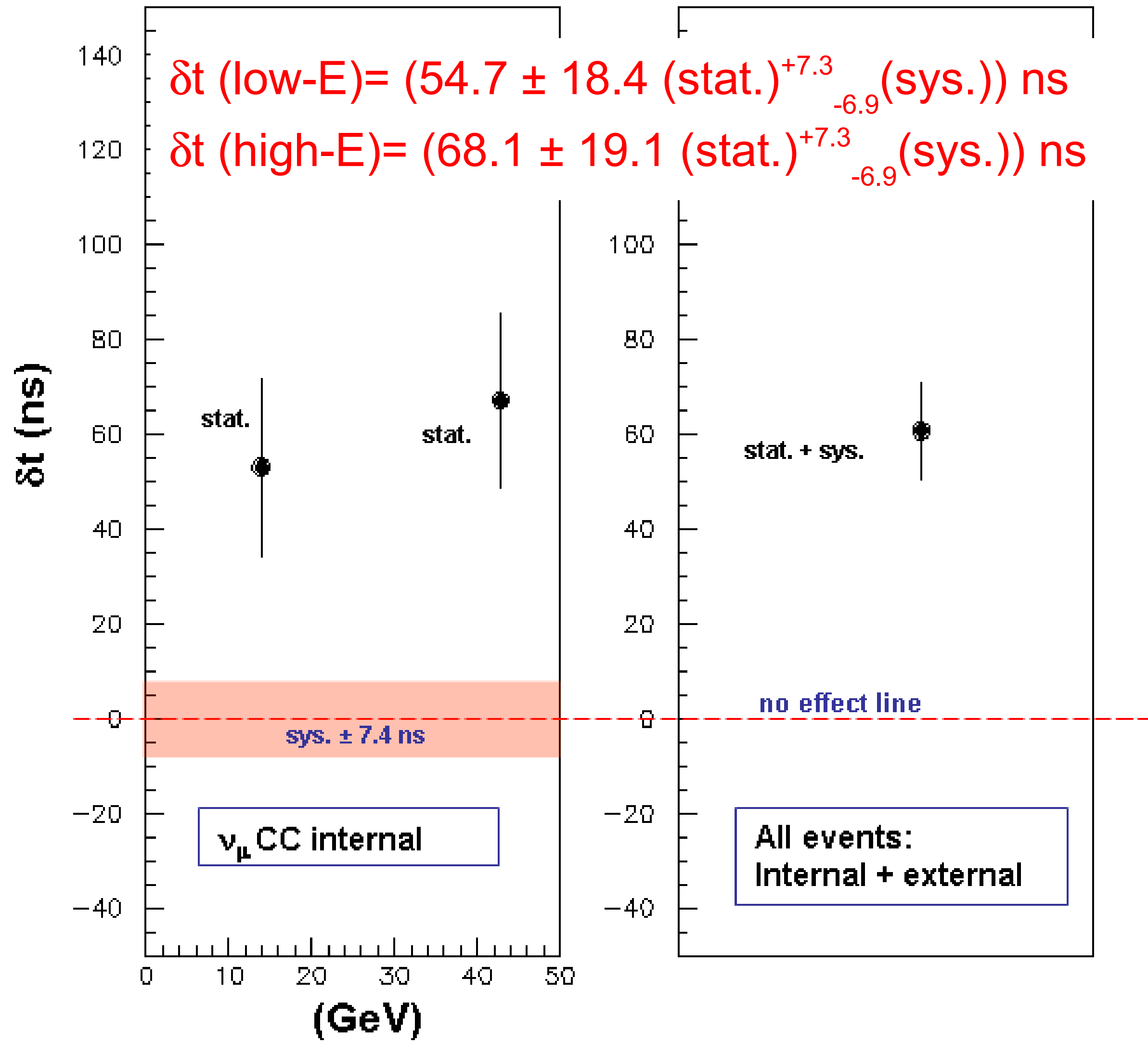
Opening the box: result



Only internal muon-neutrino CC events used (5199 events)

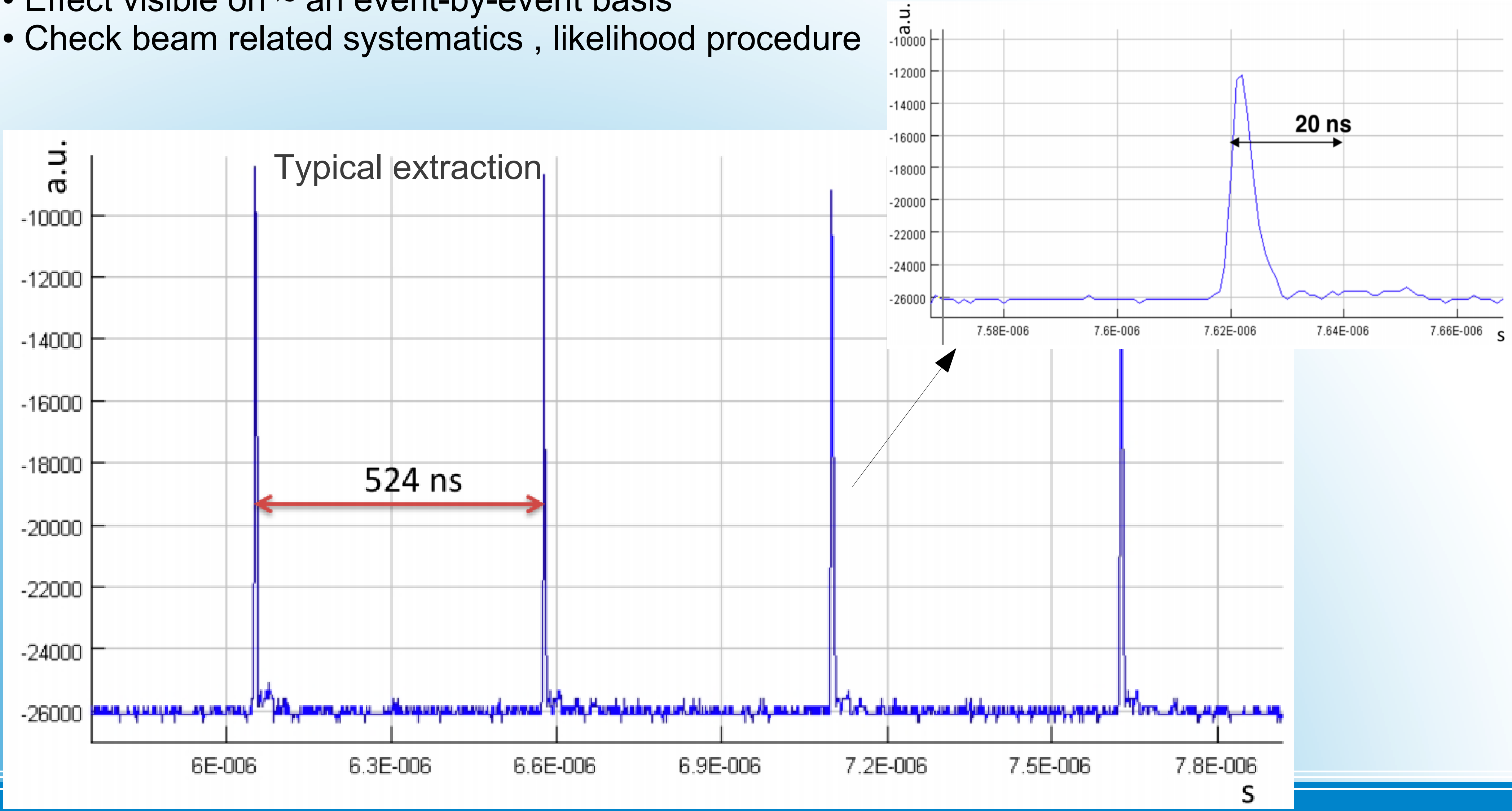
$\delta t = (61.1 \pm 13.2\ (\text{stat.})^{+7.3}_{-6.9}(\text{sys.}))$ ns

No indication for energy dependence within the present sensitivity in the explored energy domain



Energy dependence

- Width of few ns: uncertainty on time of the parent proton strongly reduced
- Effect visible on ~ an event-by-event basis
- Check beam related systematics , likelihood procedure



Nov 2011: bunched-beam test

Bunched-beam result

$\delta t = (62.1 \pm 3.7)$ ns

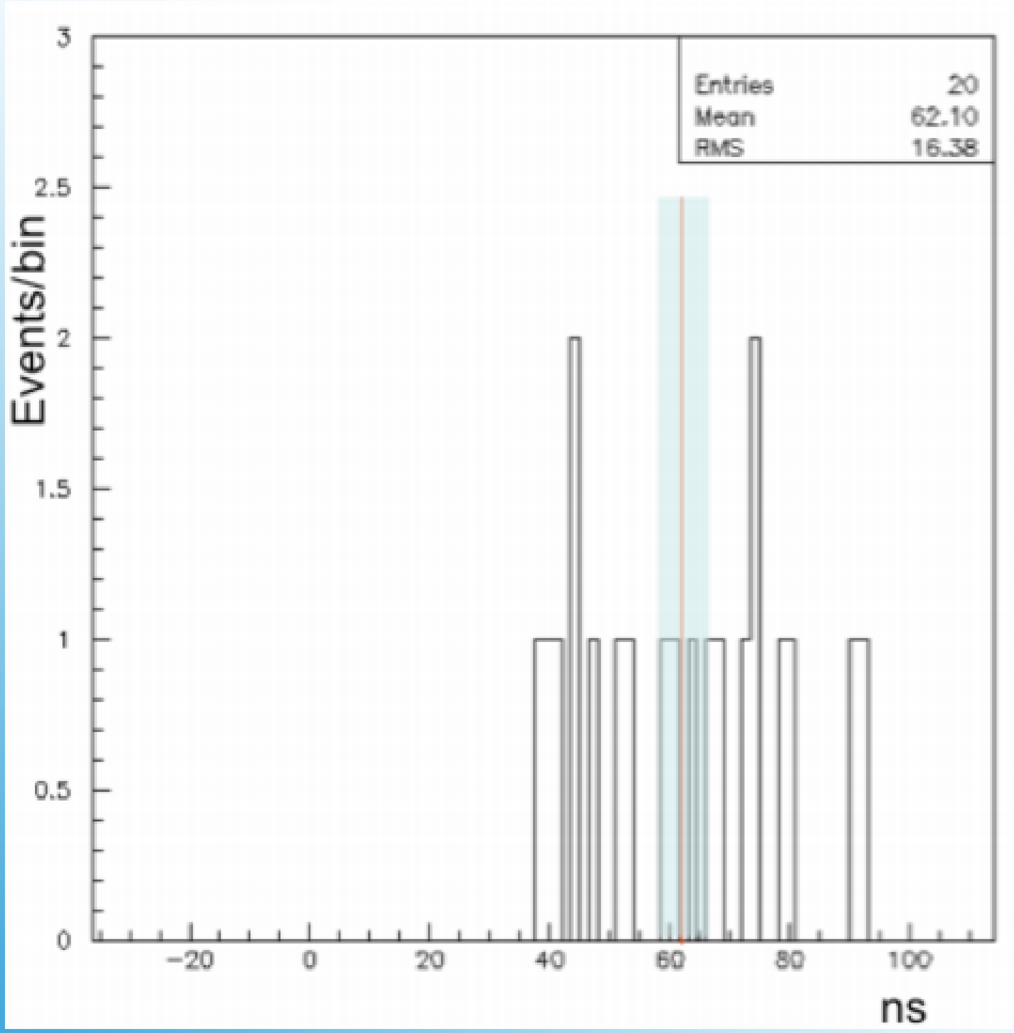
with original beam timing : 57.8 ± 7.8 ns

Main contributions to the RMS (16.4 ns):

- TT response (7.3 ns)
- DAQ time granularity (10 ns full width)
- ± 25 ns flat jitter

– The dominant ± 25 ns term is related to the tagging of the GPS signal by the 20 MHz OPERA master clock (RMS = 50 ns/$\sqrt{12}$ = 14.4 ns).

The statistical accuracy on the average δt is already as small as 3.7 ns with only 20 events (collected in 15 days).



• Large statistics (15k events, 2009-2011), dedicated upgrade of the CNGS and OPERA timing systems, accurate geodesy campaign and of a series of calibration measurements conducted with different and complementary techniques: the most sensitive terrestrial measurement of the neutrino velocity over a 730 km baseline.

• The analysis indicates an early neutrino arrival time with respect to the one computed by assuming the speed of light:

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

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

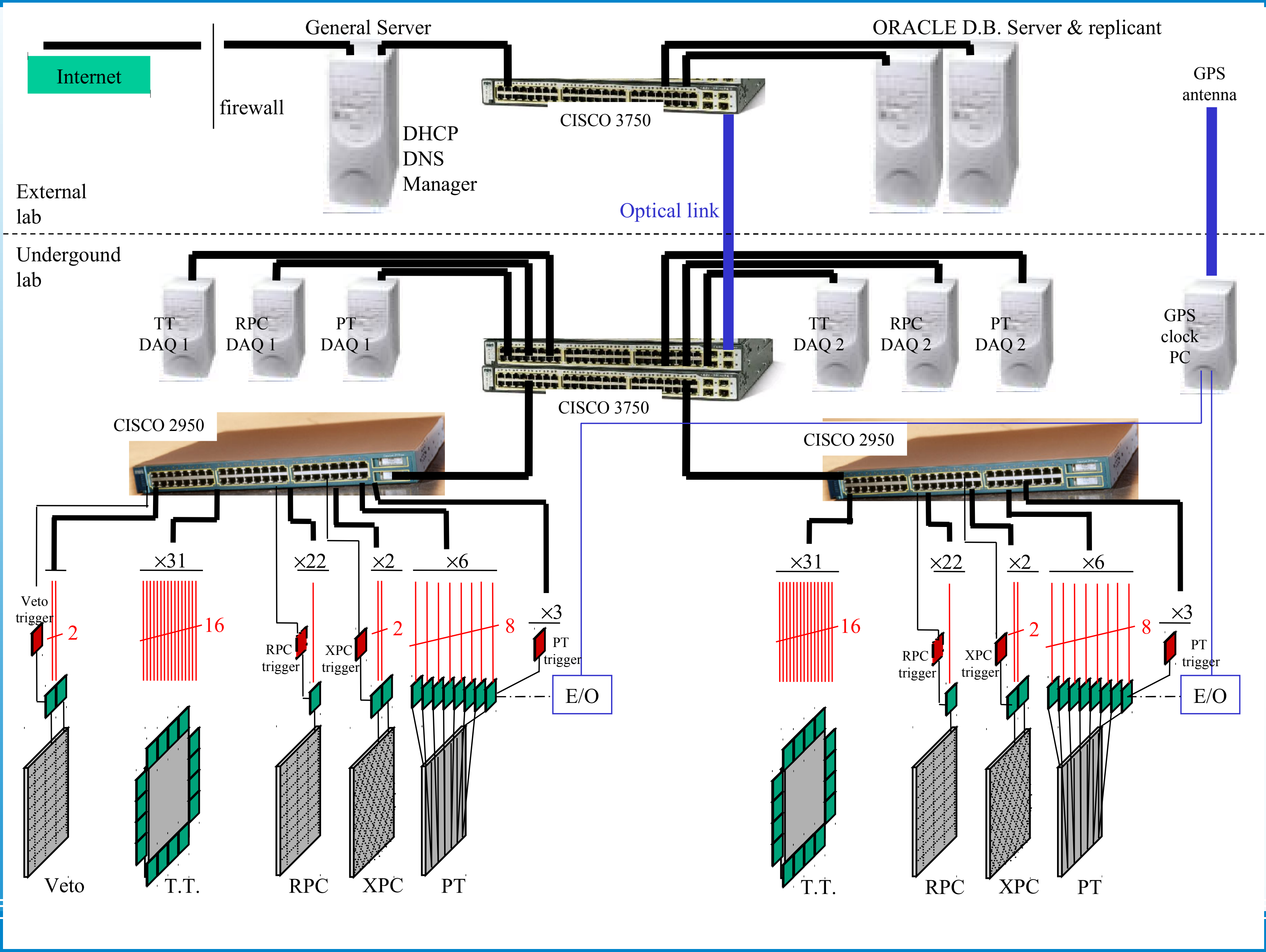
• Energy dependence: no significant effect observed.

• Despite the large significance of the measurement (6.2 σ) and the robustness 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.

Conclusions

Back-up slides

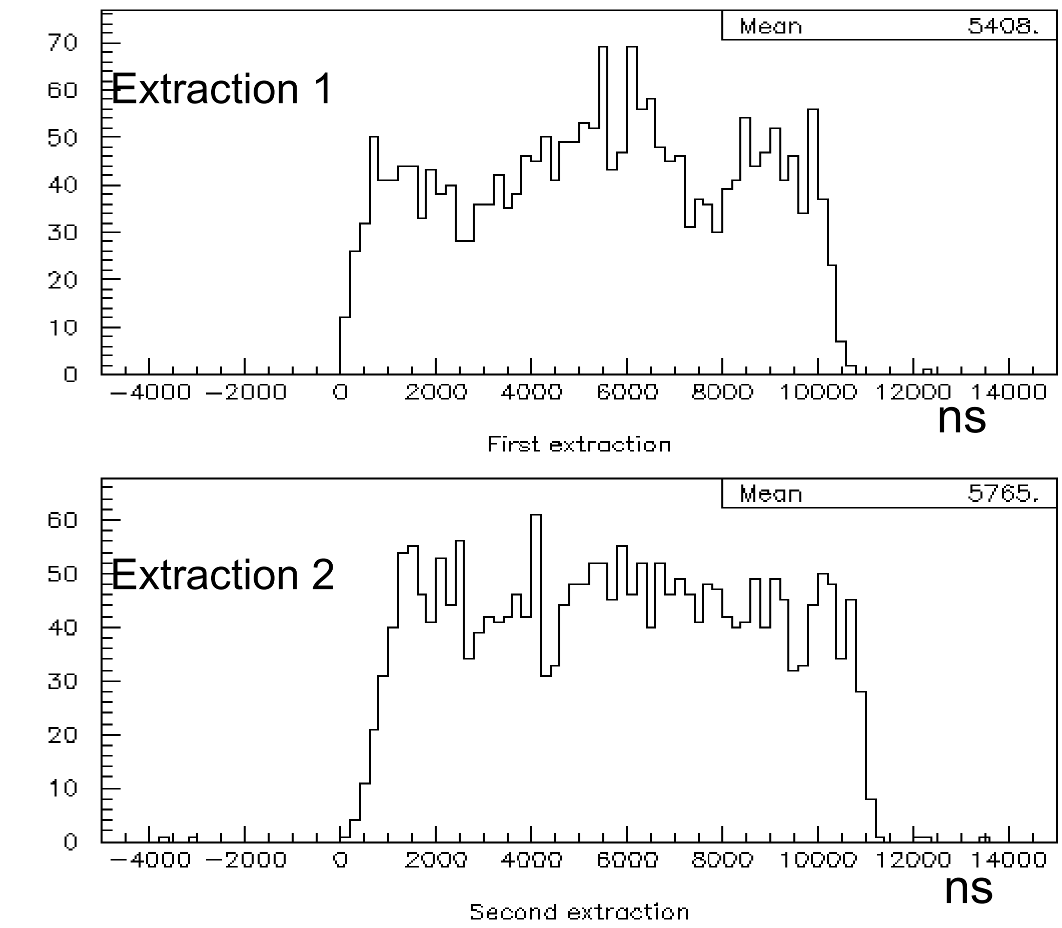
- Trigger-less
- 1200 asynchronous FE nodes
- Gigabit ethernet network



OPERA read-out scheme

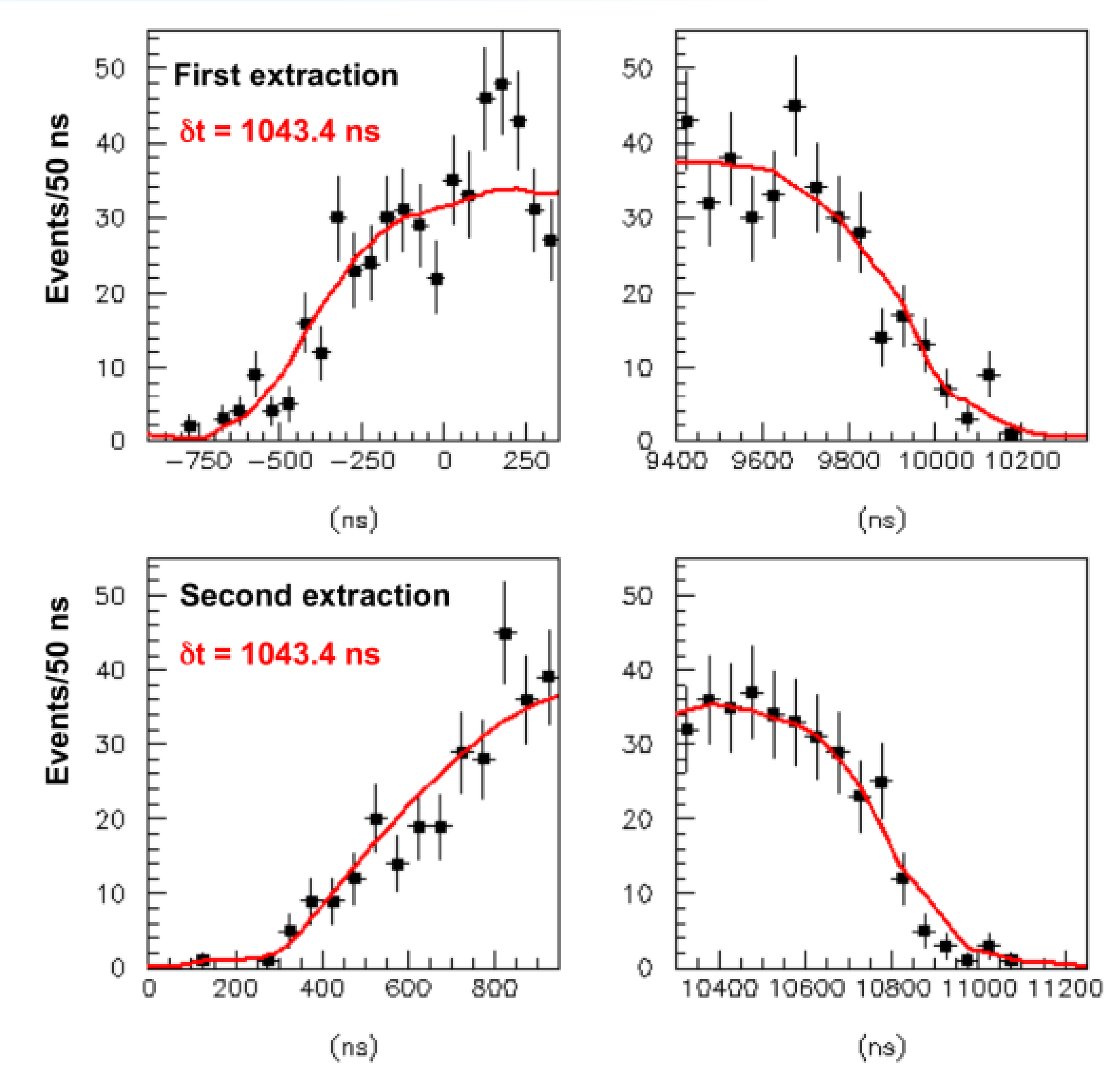
Typical neutrino event time distributions w.r.t kicker magnet trigger pulse =>

- Not flat
- Different timing for the two extractions

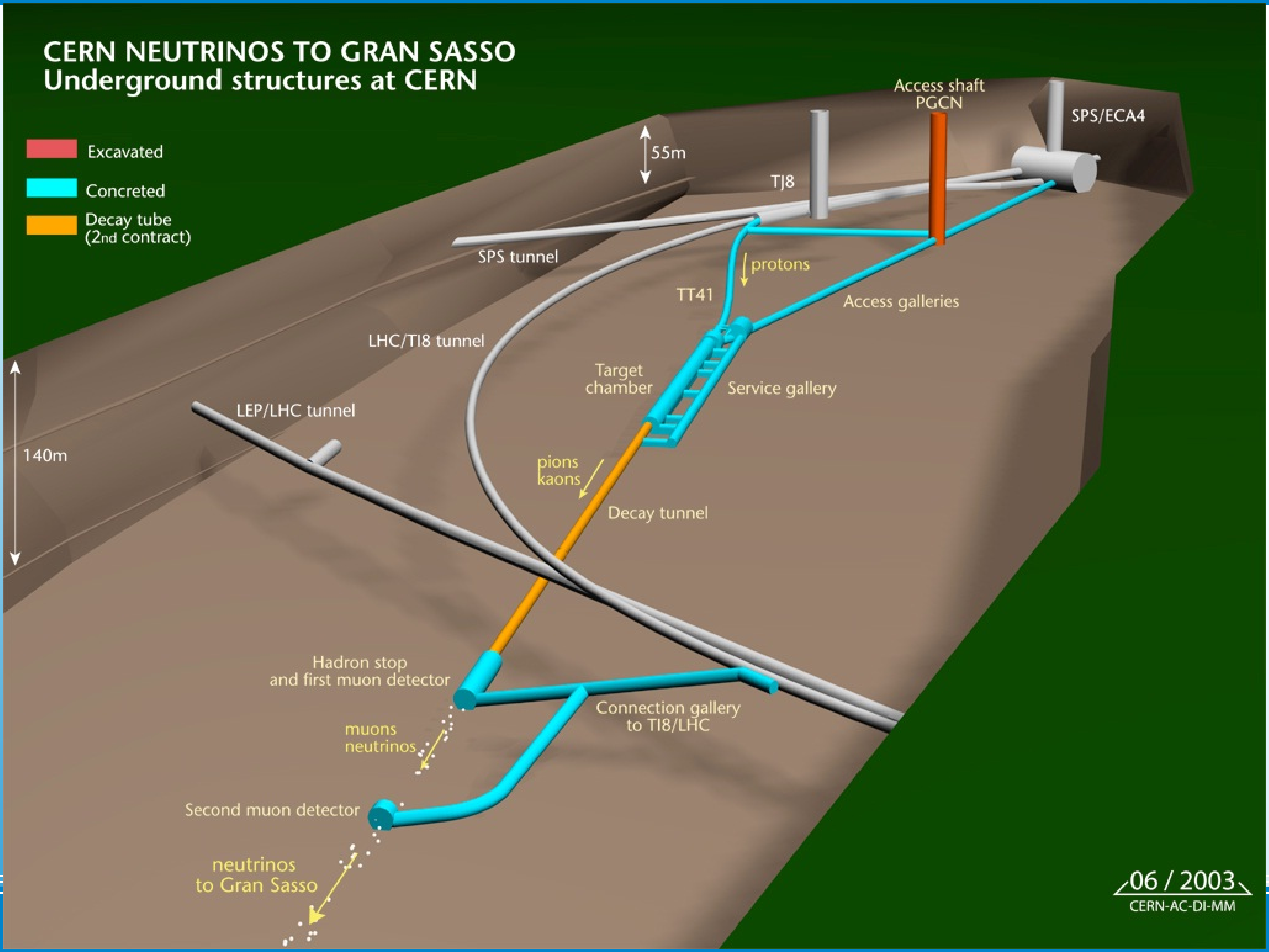


→ Need to measure precisely the proton spills

From selection to the velocity measurement



Edge regions


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
140m
Access shaft
PGCN
SPS/ECA4
TJ8
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM

CNGS

CERN-LNGS measurements (different periods) combined in the ETRF2000 European Global system, accounting for earth dynamics (collaboration with CERN survey group)

LNGS benchmarks
In ETRF2000

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

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

Distance (BCT - OPERA reference frame) = (731278.0 ± 0.2) m

Combination with CERN geodesy

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

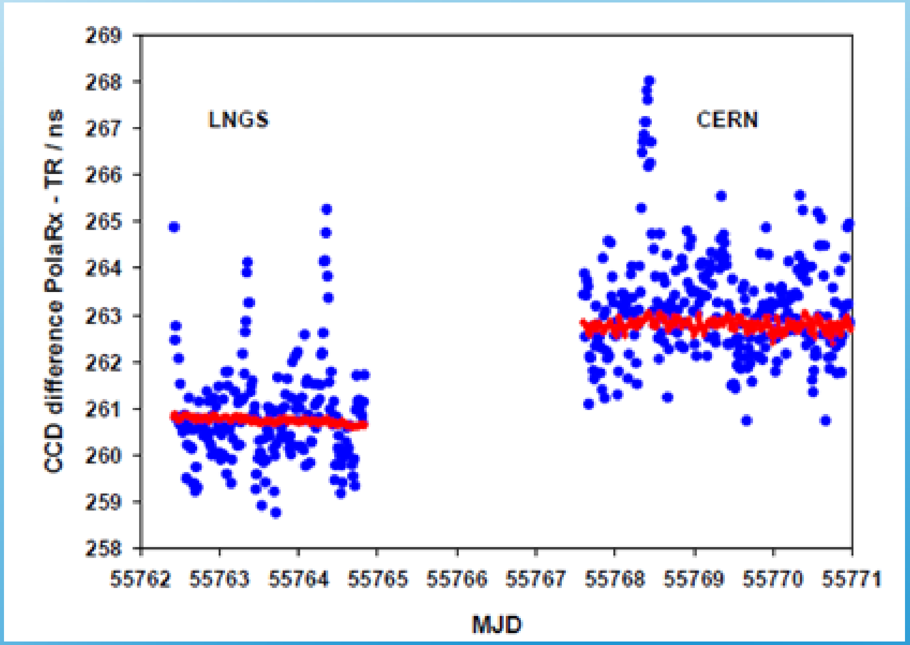
$$\delta t = (54.5 \pm 5.0\ (\text{stat.})\ {}^{+9.6}_{-7.2}\ (\text{sys.}))\ \text{ns}$$

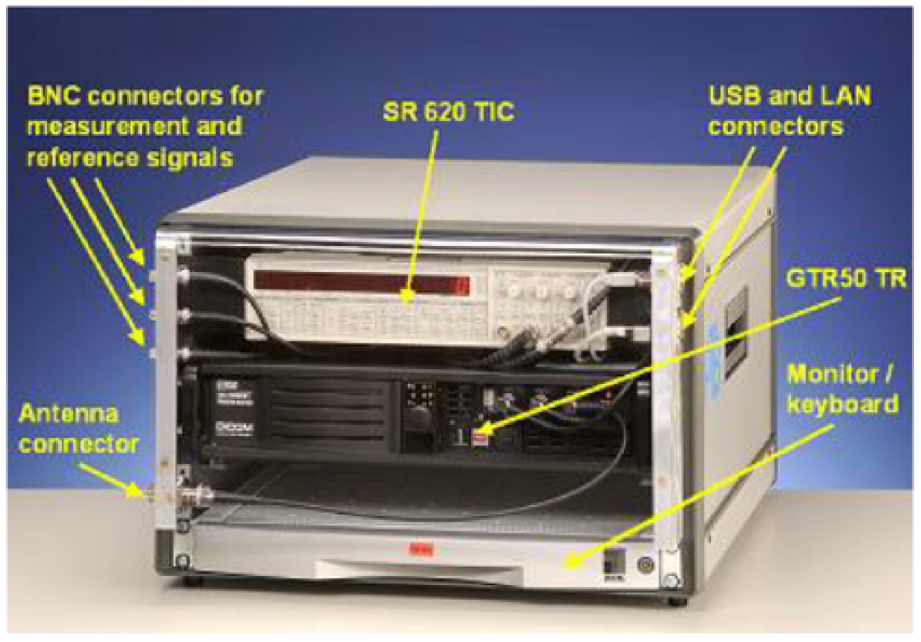
Event-by-event PDFs

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





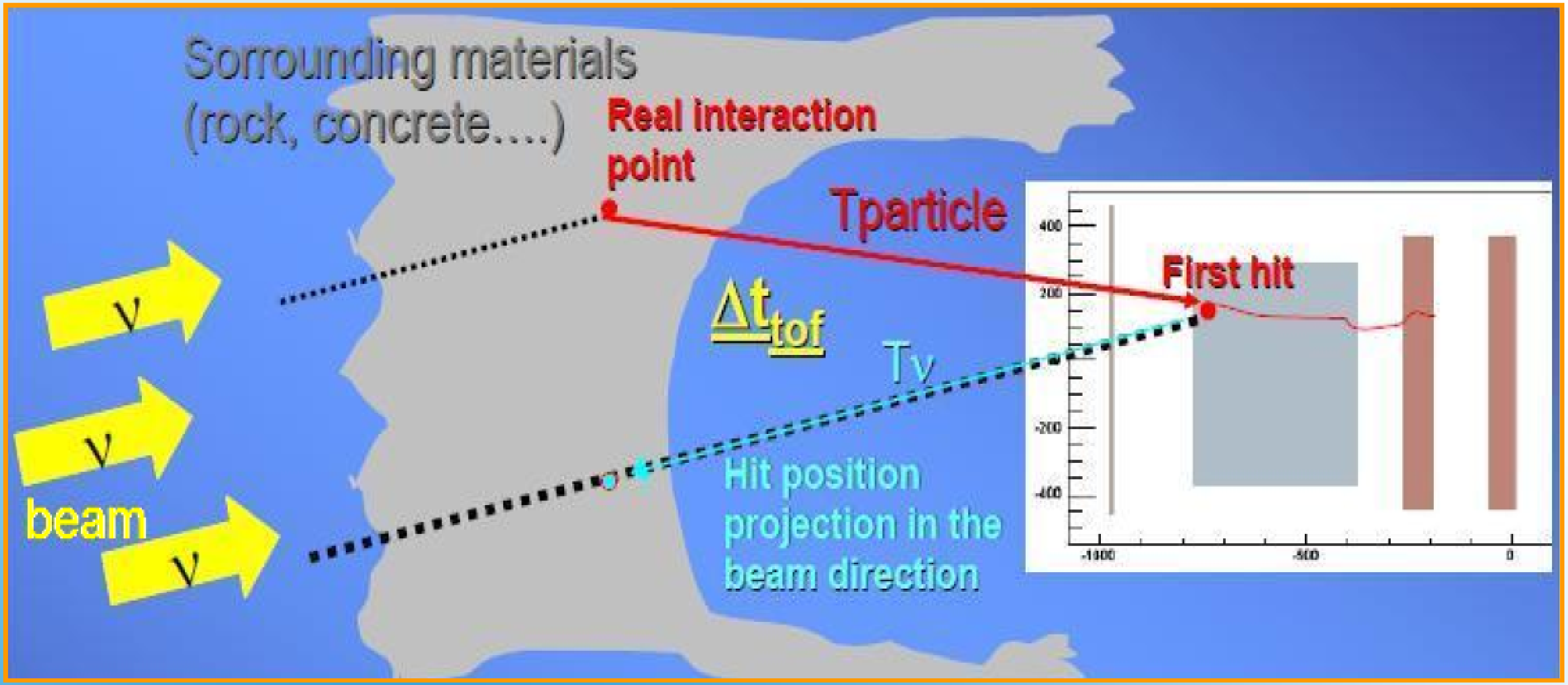
Correction to the time-link:

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

CERN-OPERA intercalibration cross check

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

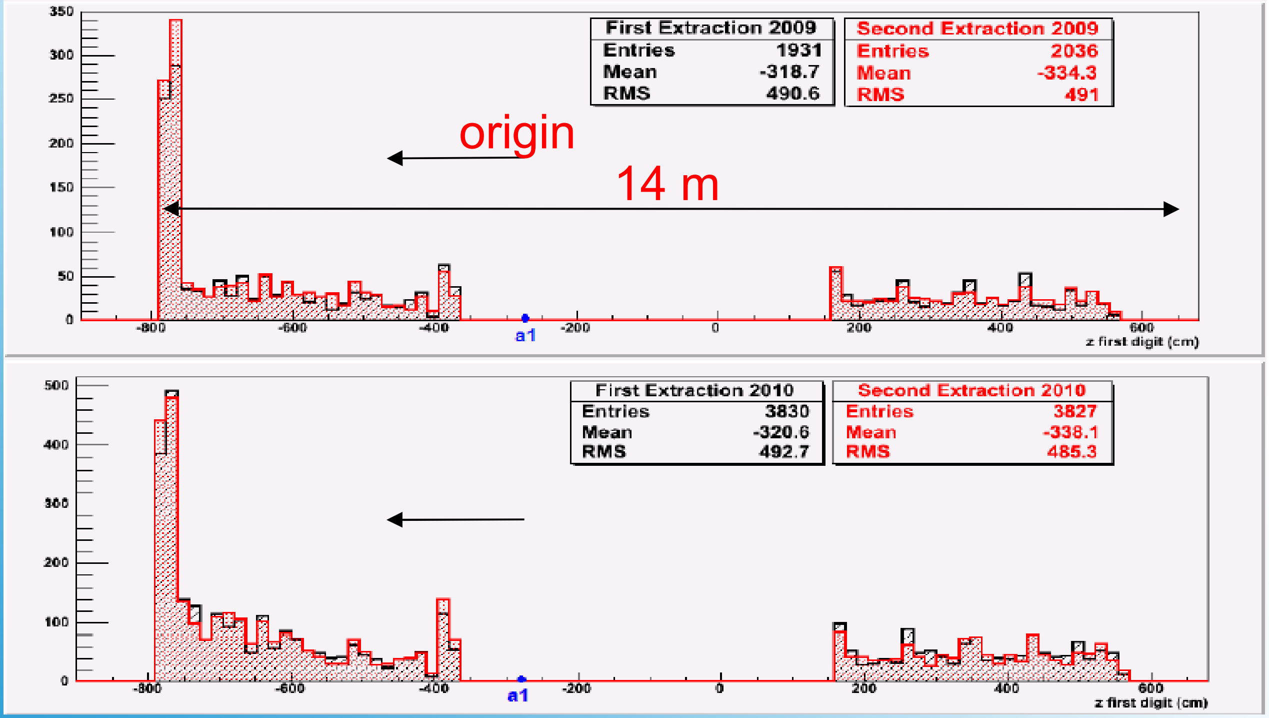
Delay calibrations summary



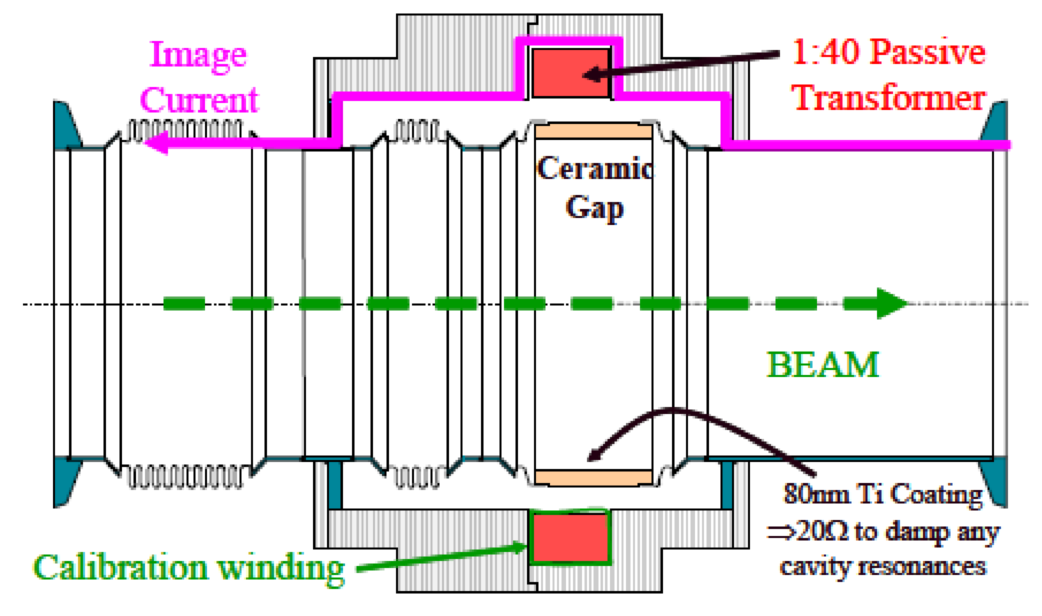
External events

Correction due to the earliest hit position

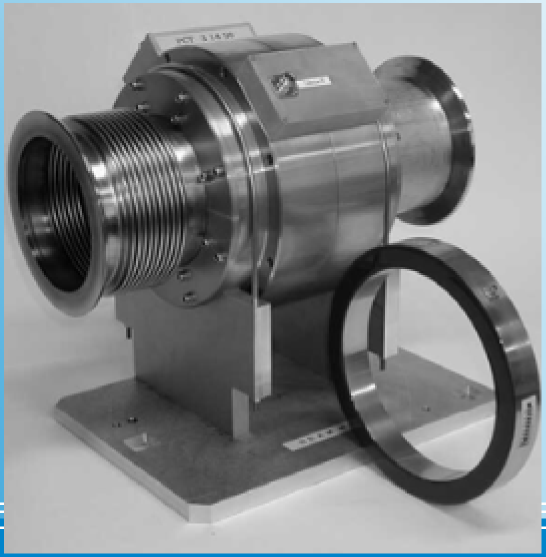
Average correction: 140 cm (4.7 ns)



Z correction



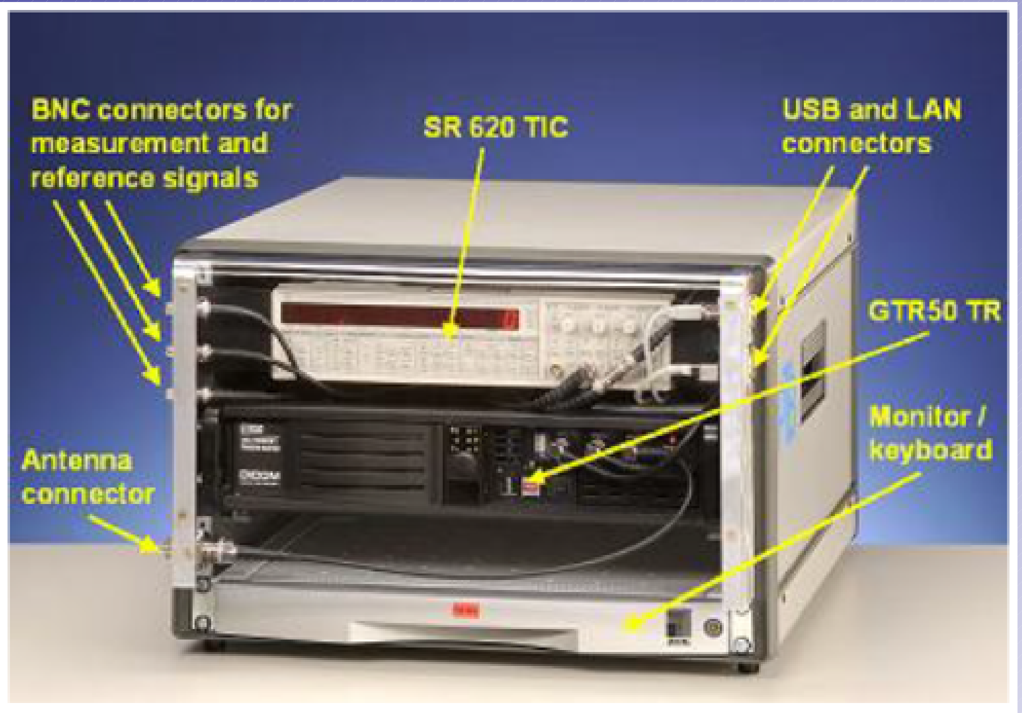
Raw BCT signal used, no integration
<1% linearity
Large bandwidth 400 MHz
Low droop <0.1%/µs



Fast beam current transformer

CERN-OPERA inter-calibration cross-check

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt



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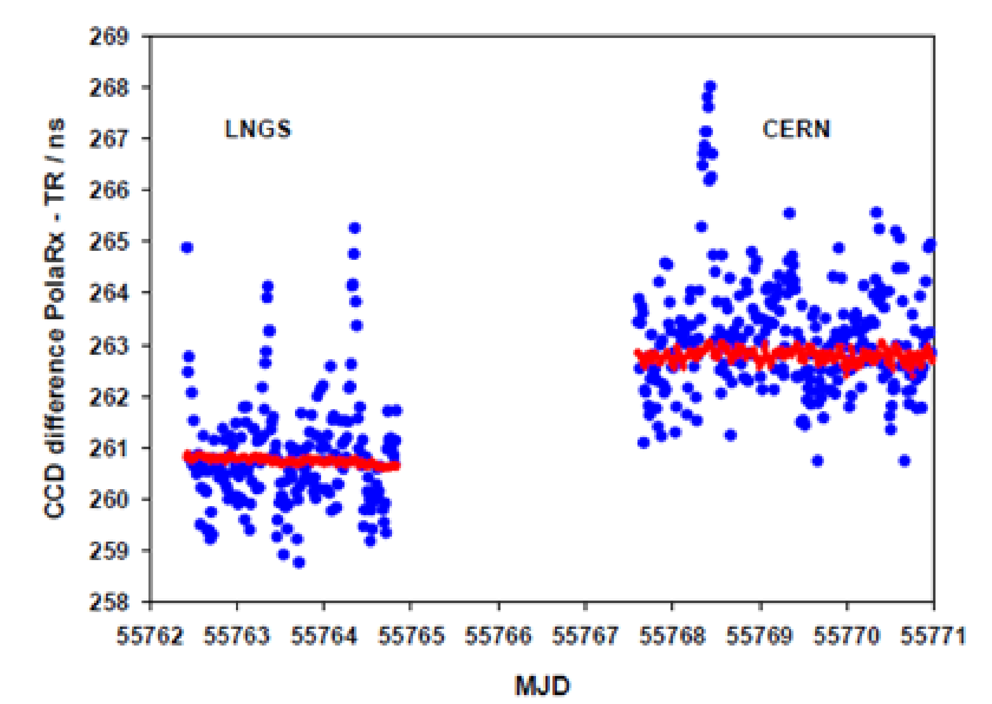

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