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

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On behalf of the OPERA Collaboration

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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 Edu
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)

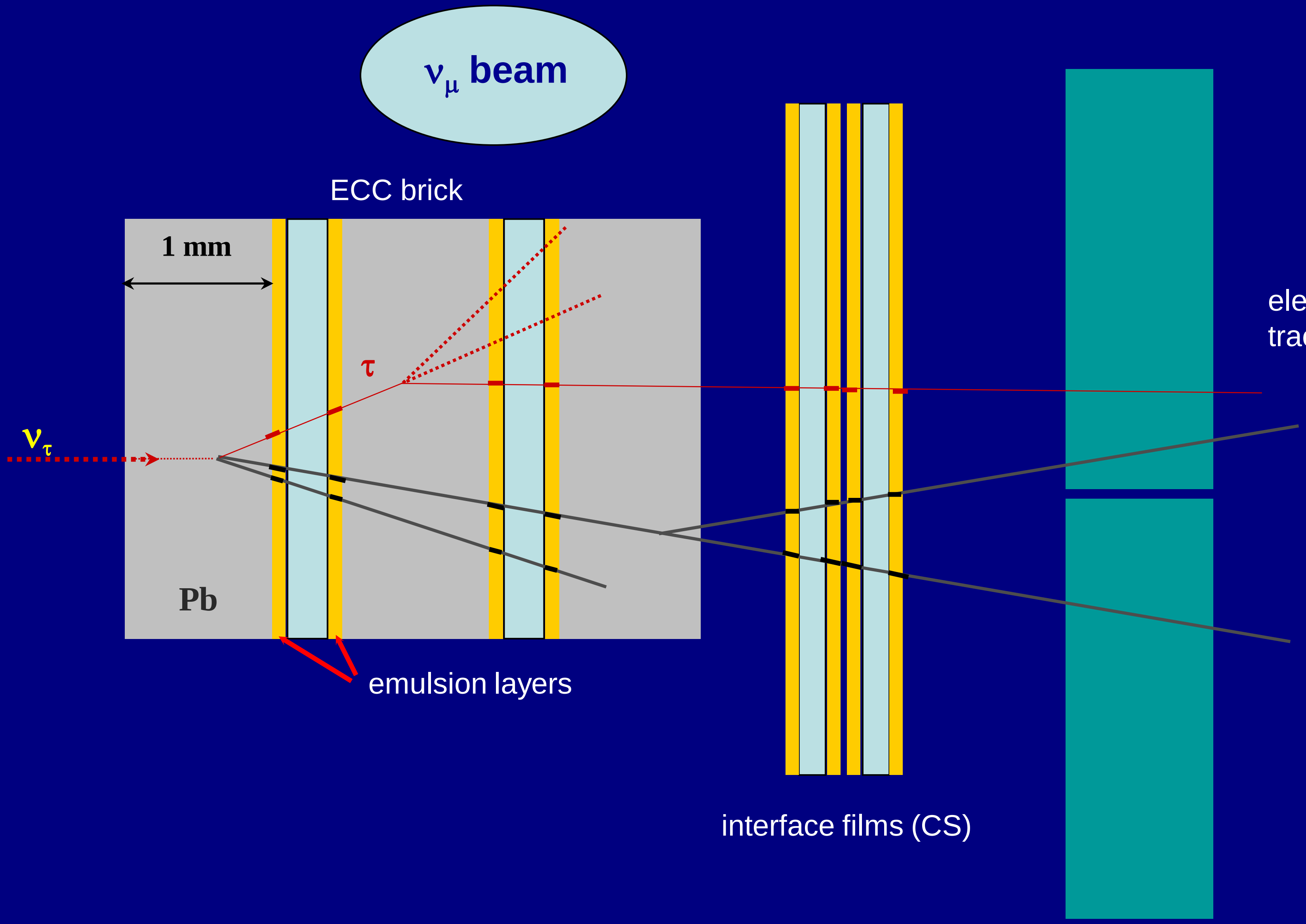
electron (anti) neutrinos, 10 MeV range, 168'000 light years baseline.
$|v-c|/c \leq 2 \times 10^{-9}$.
Performed with observation of neutrino and light arrival time.

MINOS (Phys. Rev. D 76 072005 2007)

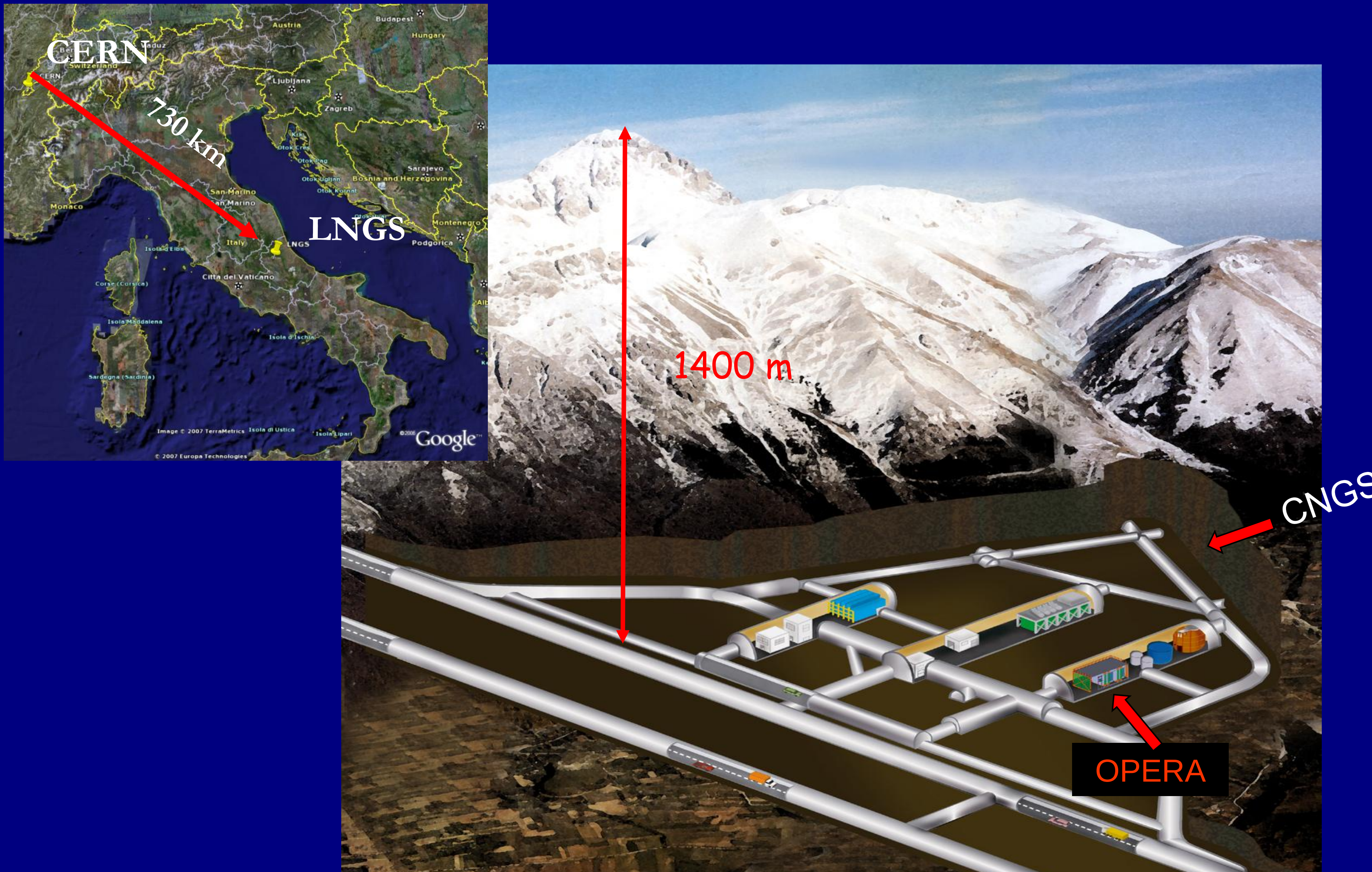
muon neutrinos, 730 km baseline, E_ν peaking at ~3 GeV with a tail extending above 100 GeV.
$(v-c)/c = 5.1 \pm 2.9 \times 10^{-5}$ (1.8 σ).

THE DESIGN OF THE OPERA EXPERIMENT

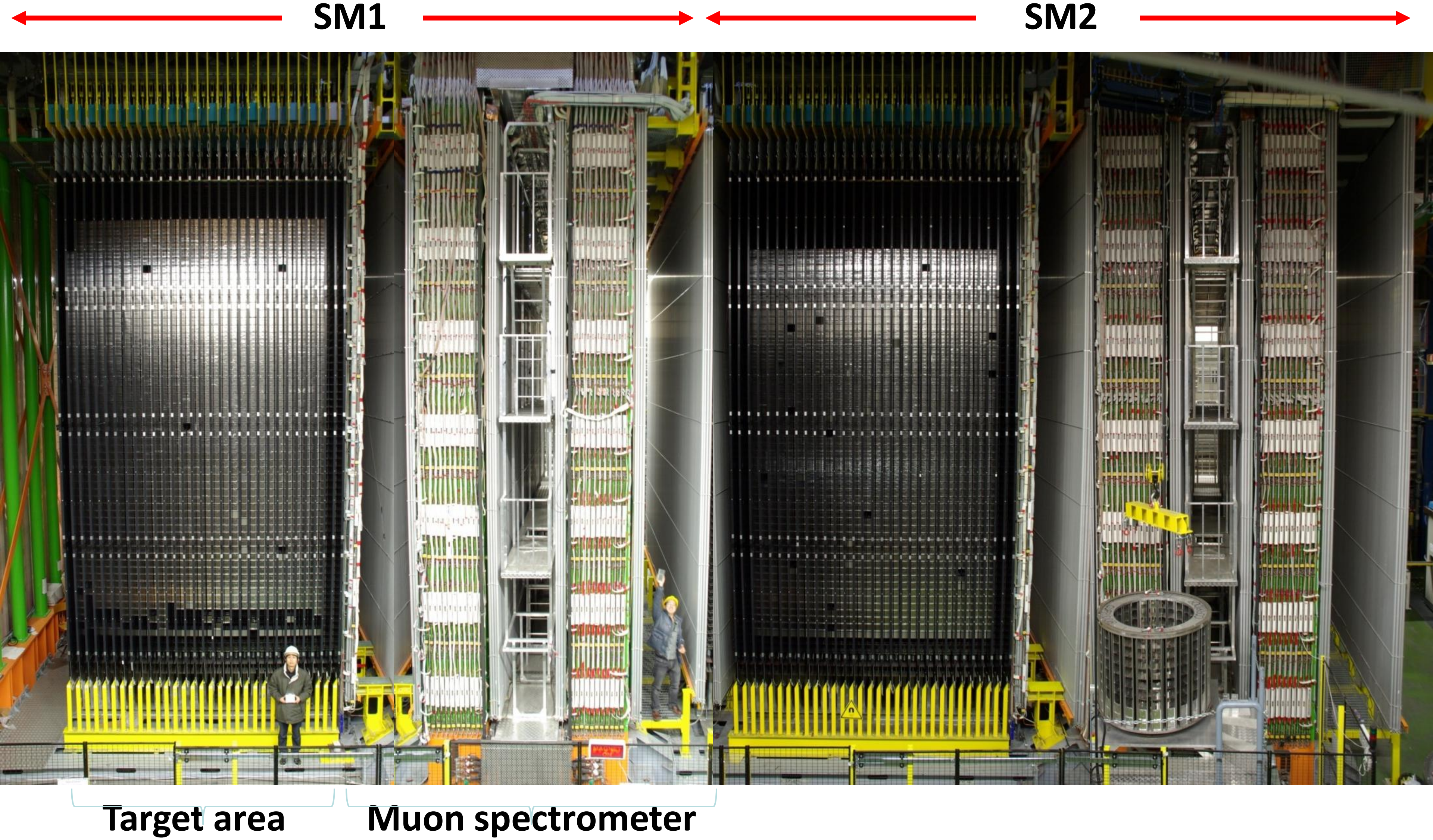
ECC BRICKS + ELECTRONIC DETECTORS FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATION STUDIES



The LNGS underground physics laboratory



THE IMPLEMENTATION OF THE PRINCIPLE

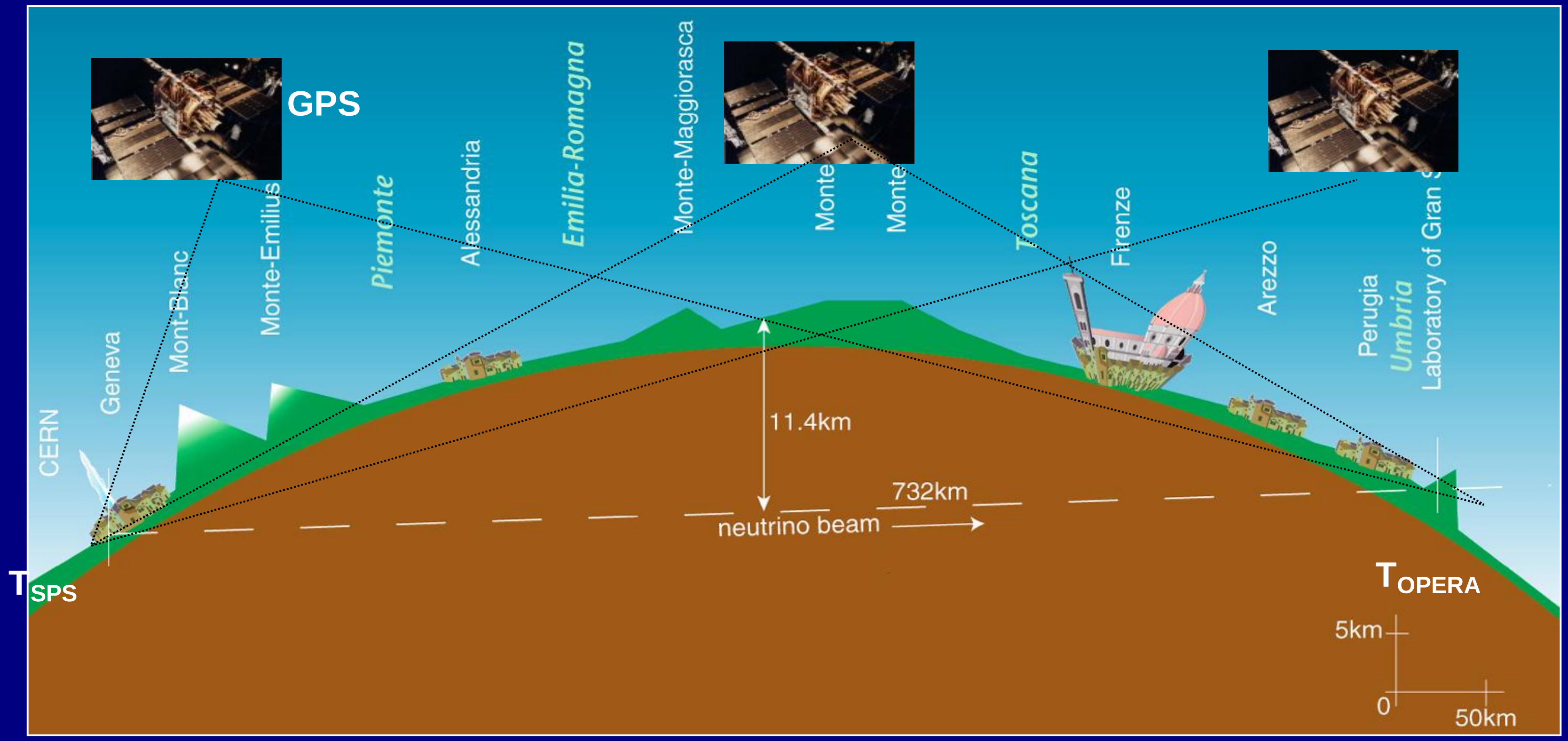


OPERA sensitivity

- 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 events selection

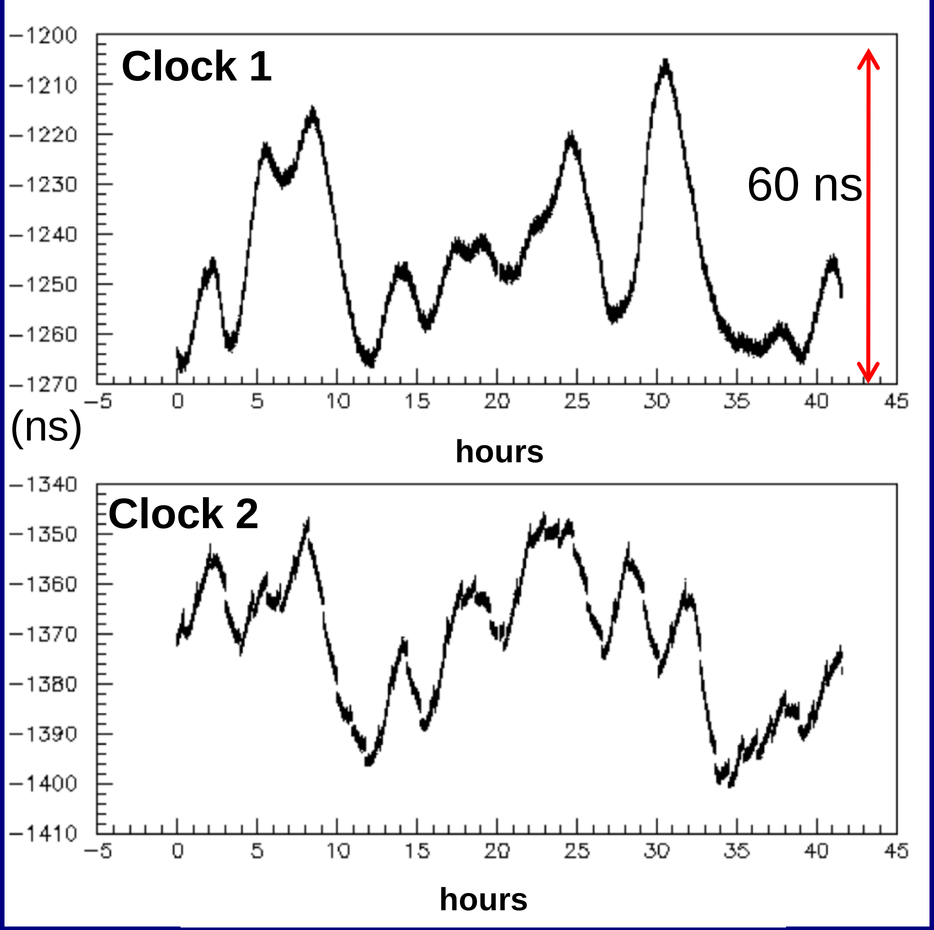


Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

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

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



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

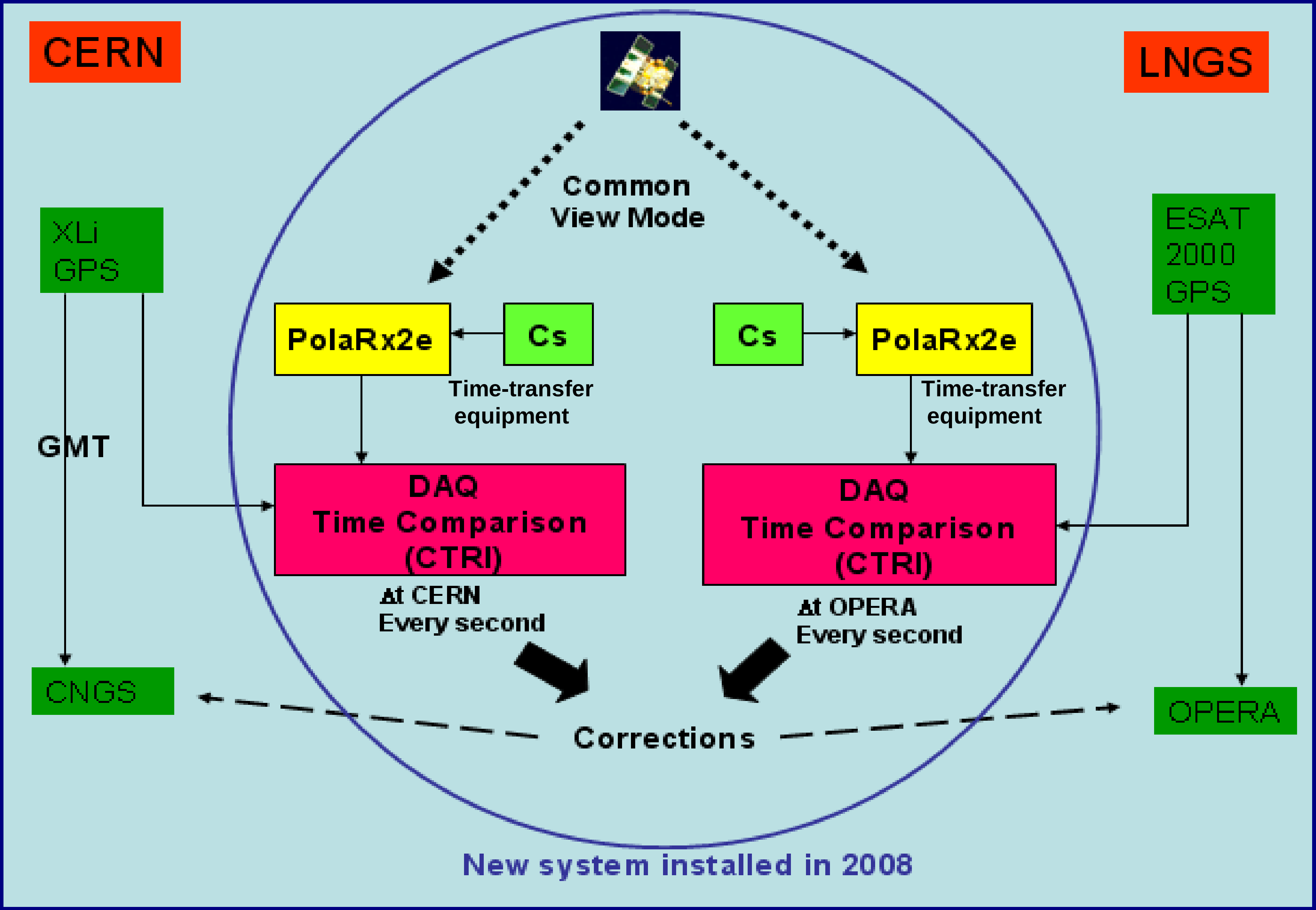
1) Large oscillations
2) Uncertainties on CERN-OPERA synchronisation

→ 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

Standard GPS receivers ~100 ns accuracy:

CERN Symmetricom 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 + Symmetricom 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

GPS common-view mode

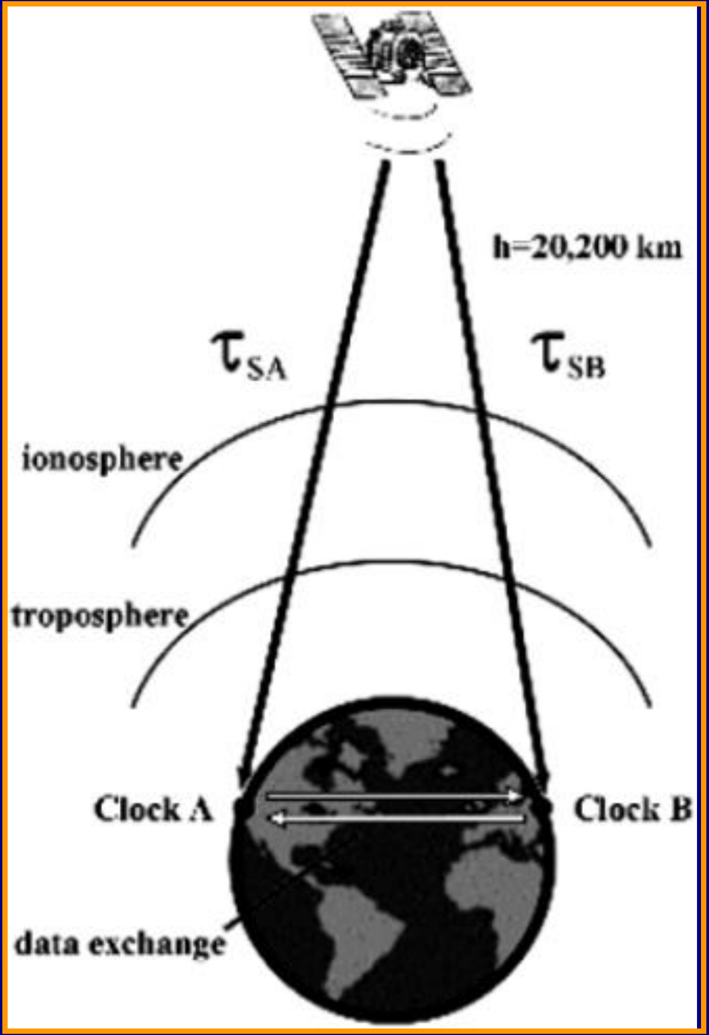
Standard GPS operation:

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

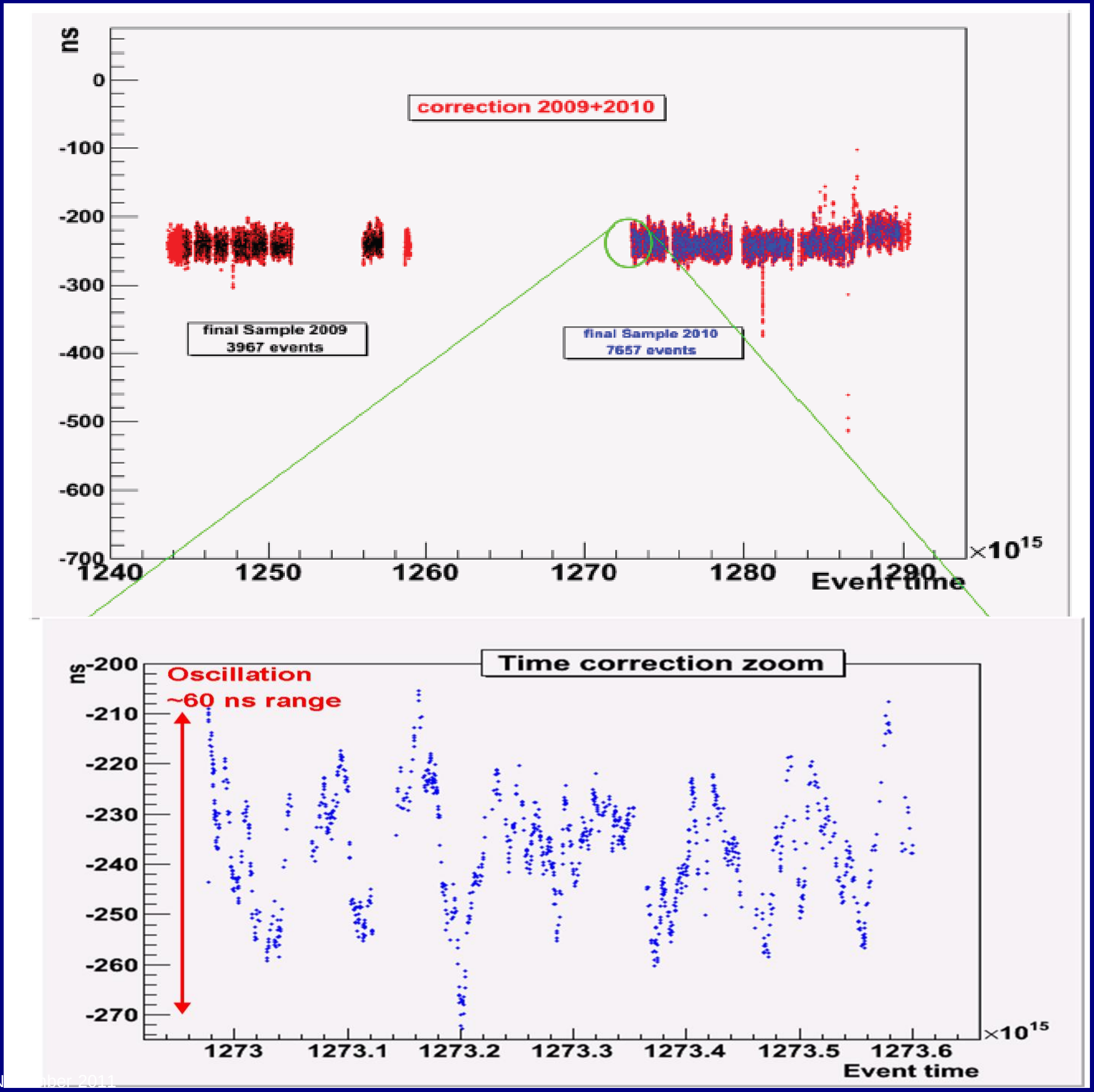
Common-view mode (the same satellite for the two sites, for each comparison):

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

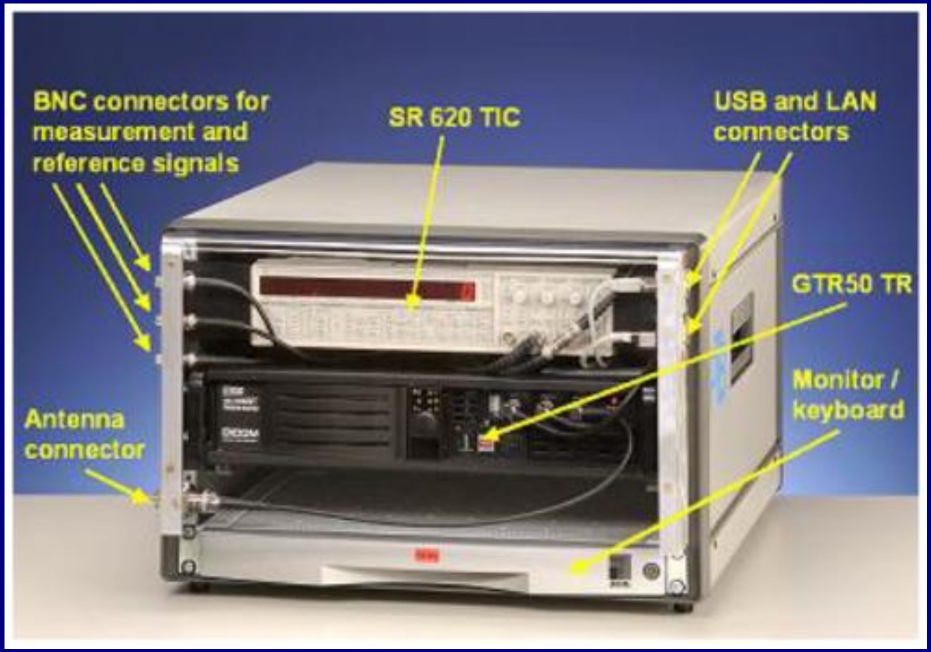


Result: TOF time-link correction (event by event)



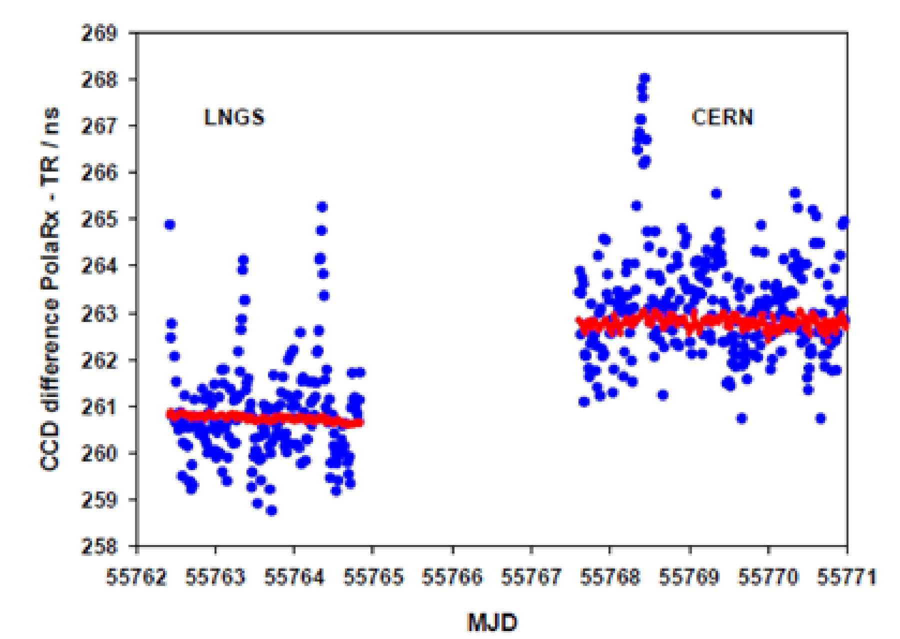
CERN-OPERA inter-calibration cross-check

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt



High accuracy/stability portable time-transfer setup @ CERN and LNGS

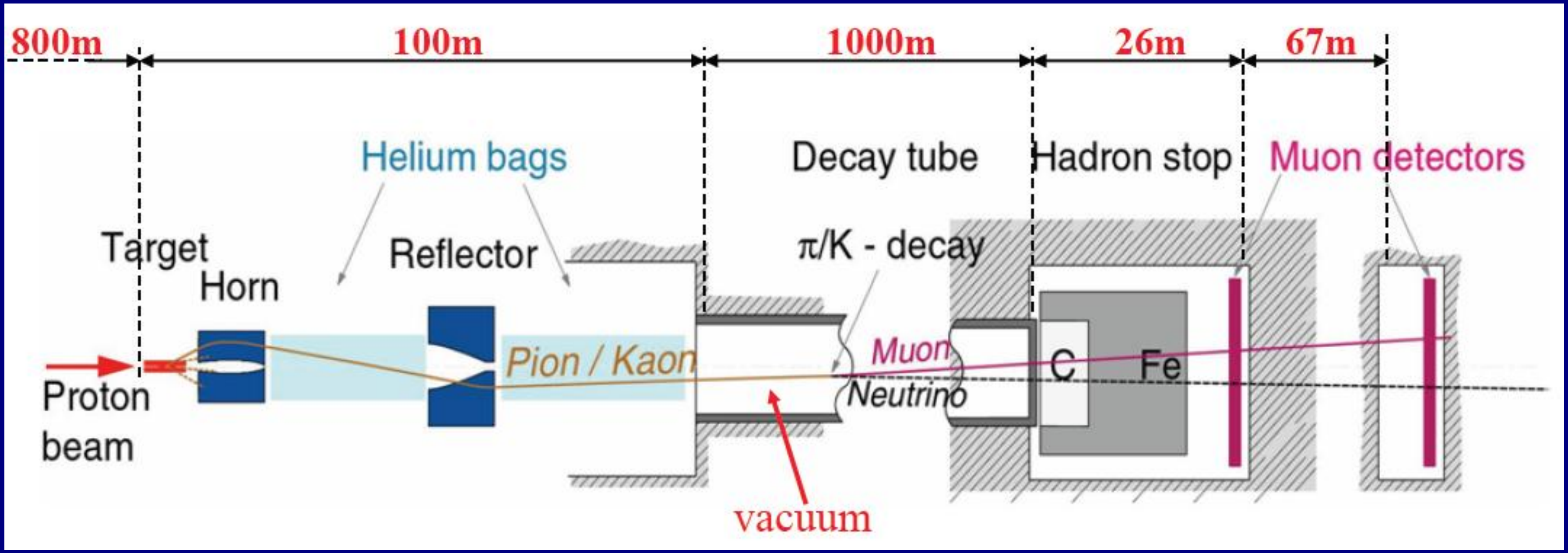
GTR50 GPS receiver, thermalised, external Cs frequency source, embedded Time Interval Counter



Correction to the time-link:

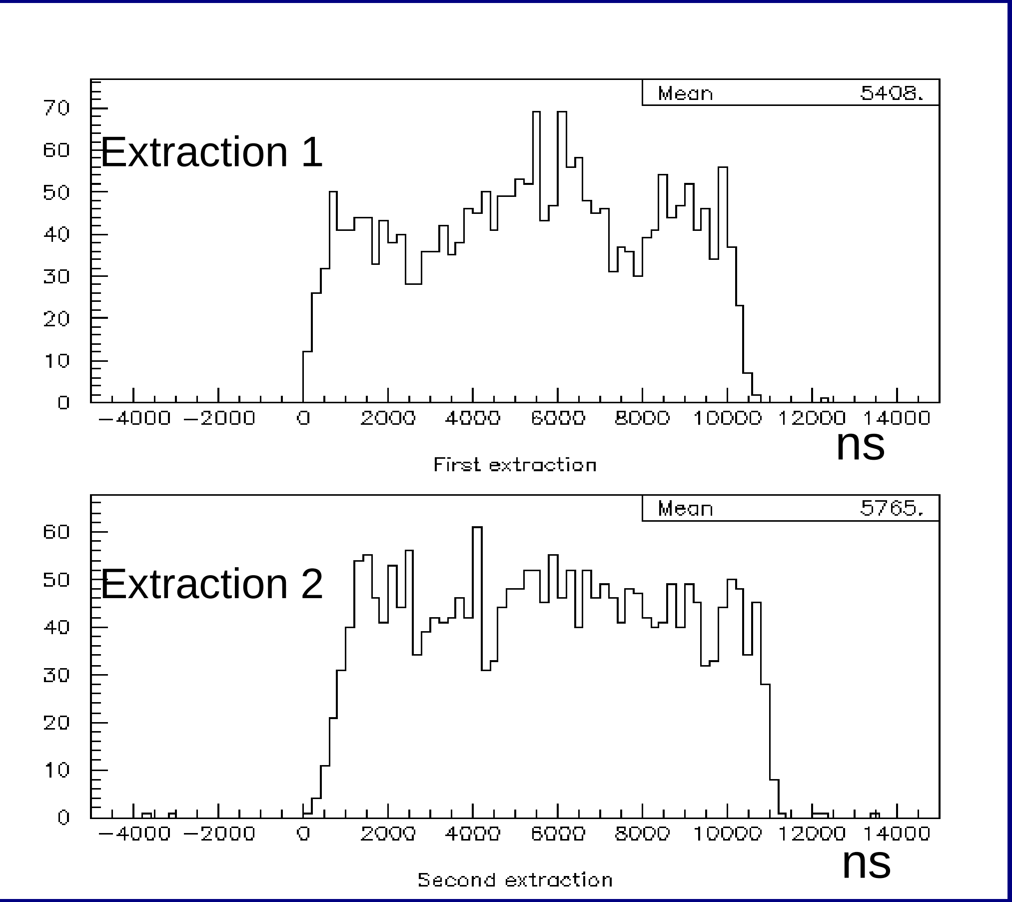
$t_{CERN} - t_{OPERA} = (2.3 \pm 0.9)$ ns

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

From CNGS event selection to neutrino velocity measurement

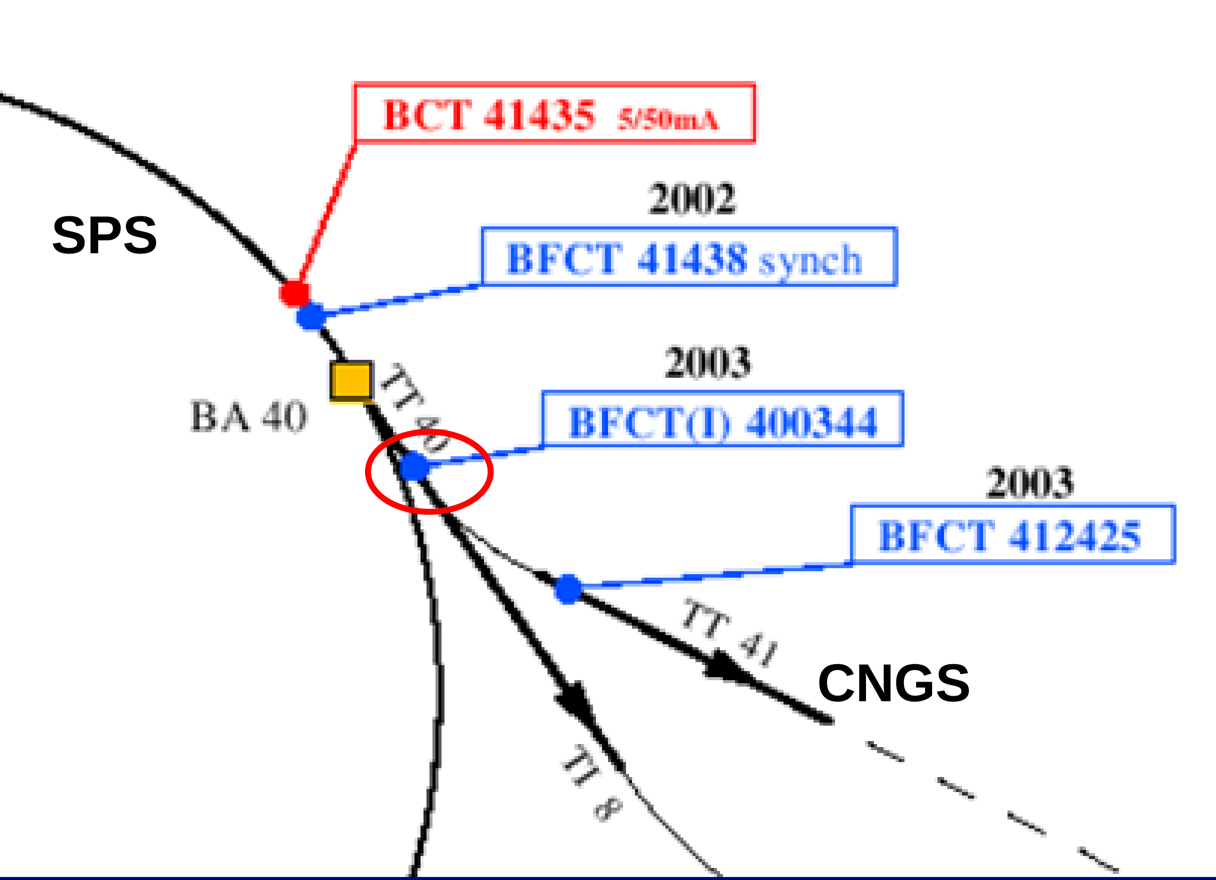


Typical neutrino event time distributions in 2008 w.r.t kicker magnet trigger pulse:

1) Not flat
2) Different timing for first and second extraction

→ Need to precisely measure the protons spills

Proton timing by Beam Current Transformer

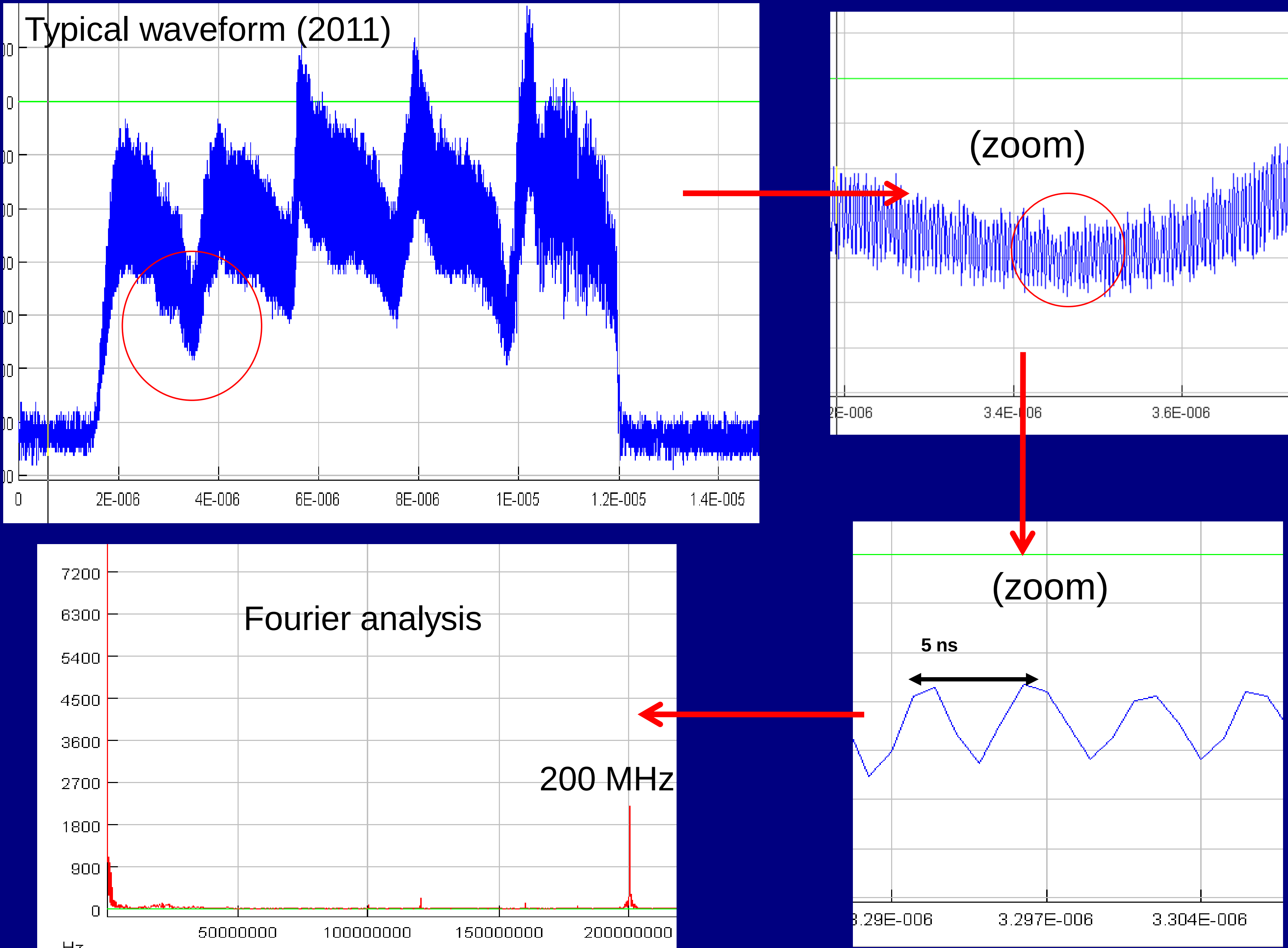


Fast BCT 400344
(~ 400 MHz)

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

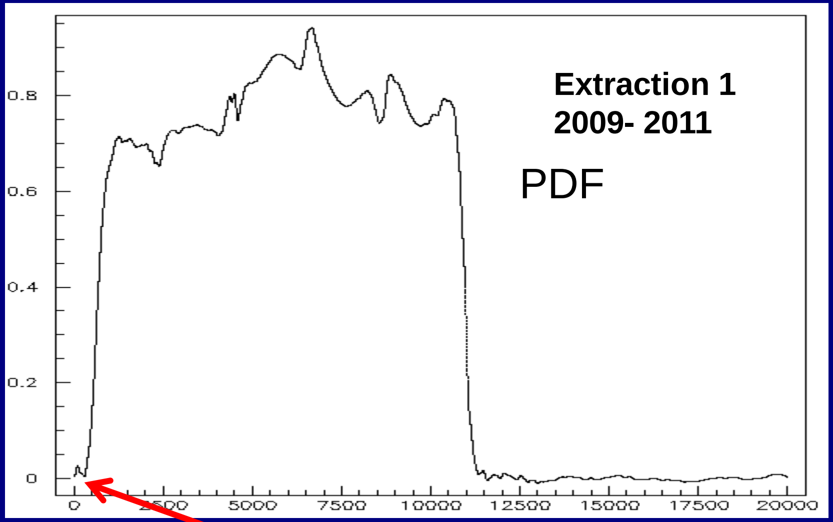

Typical waveform (2011)
0
2E-006
4E-006
6E-006
8E-006
1E-005
1.2E-005
1.4E-005
(zoom)
3.4E-006
3.6E-006
(zoom)
5 ns
3.297E-006
3.304E-006
Fourier analysis
200 MHz
7200
6300
5400
4500
3600
2700
1800
900
0
50000000
100000000
150000000
200000000
Hz

Neutrino event-time distribution PDF

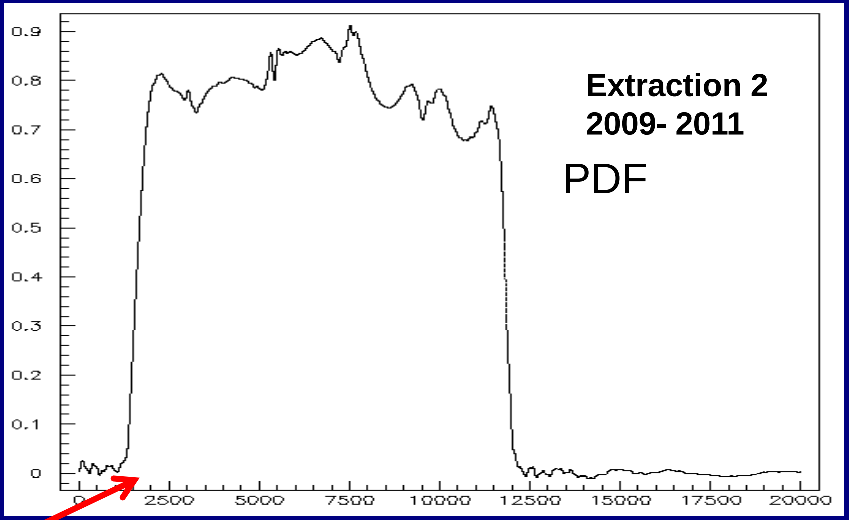
- Each event is associated to its proton spill waveform
- The “parent” proton is unknown within the 10.5 μs extraction time

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

→ compare to OPERA detected neutrino events

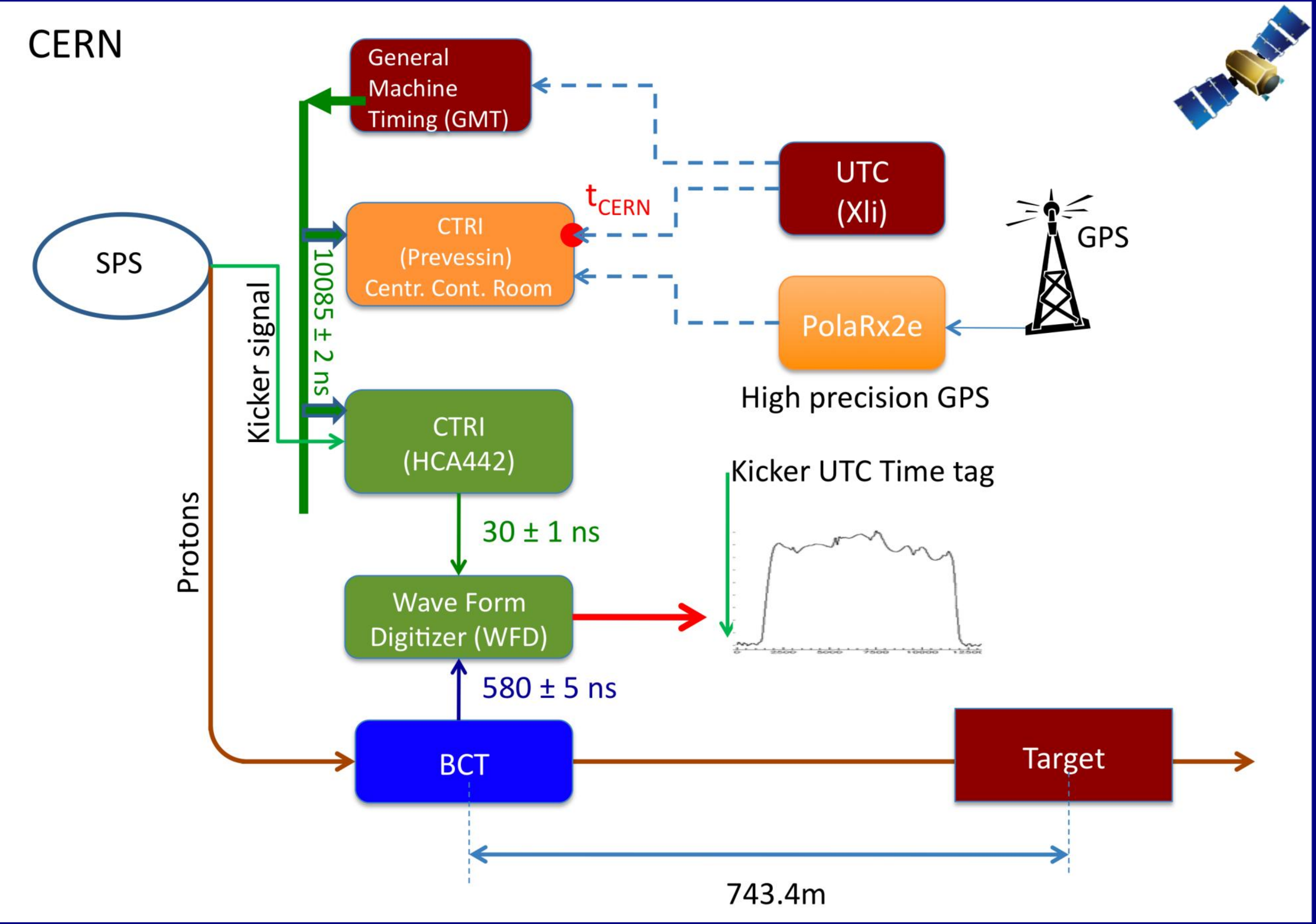


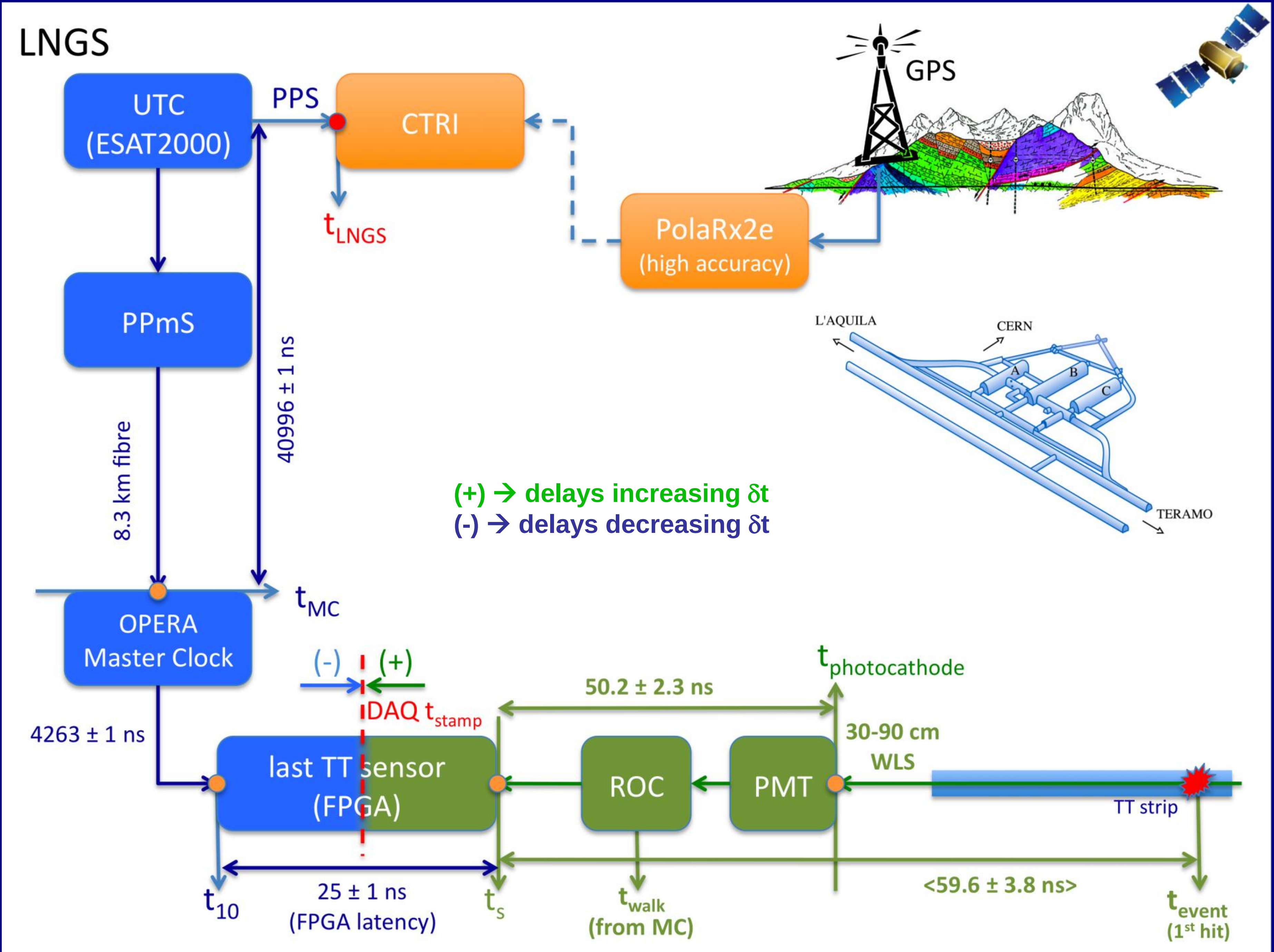
(ns)



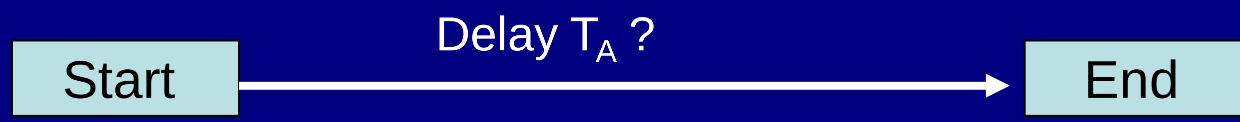
(ns)

different timing w.r.t. kicker magnet signal


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

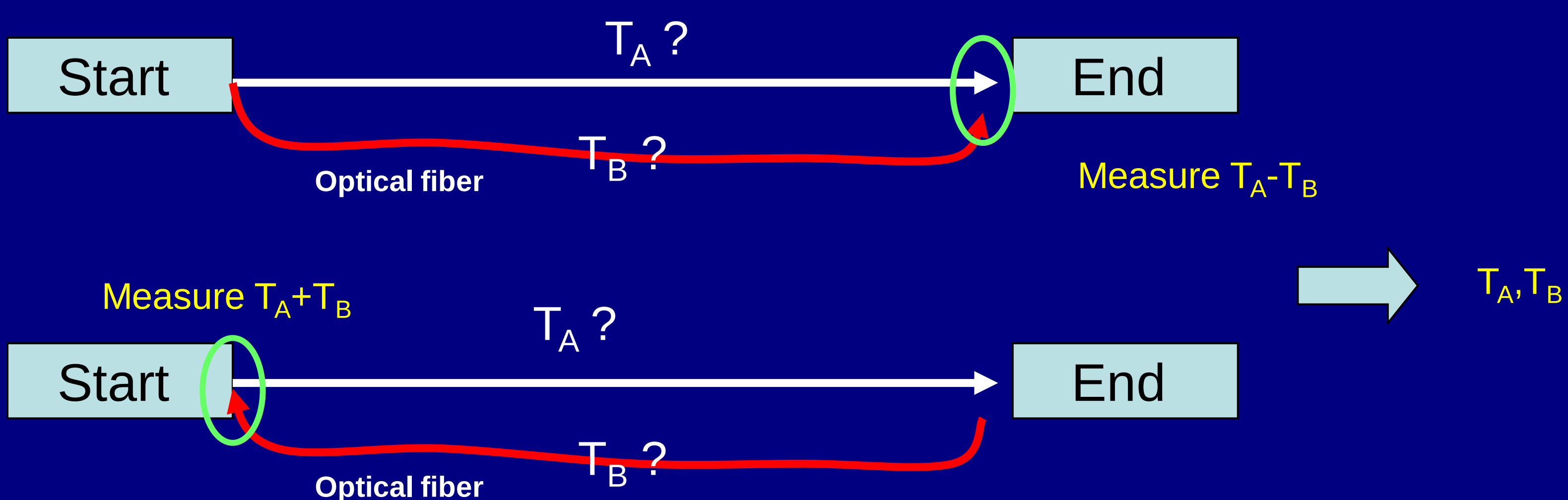

LNGS
UTC
(ESAT2000)
PPS
CTRI
GPS
t_{LNGS}
PolaRx2e
(high accuracy)
PPmS
L'AQUILA
CERN
A
B
C
TERAMO
8.3 km fibre
40996 ± 1 ns
(+) → delays increasing δt
(-) → delays decreasing δt
t_{MC}
OPERA
Master Clock
(-)
(+)
DAQ t_{stamp}
$t_{photocathode}$
50.2 ± 2.3 ns
4263 ± 1 ns
30-90 cm
WLS
last TT sensor
(FPGA)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

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

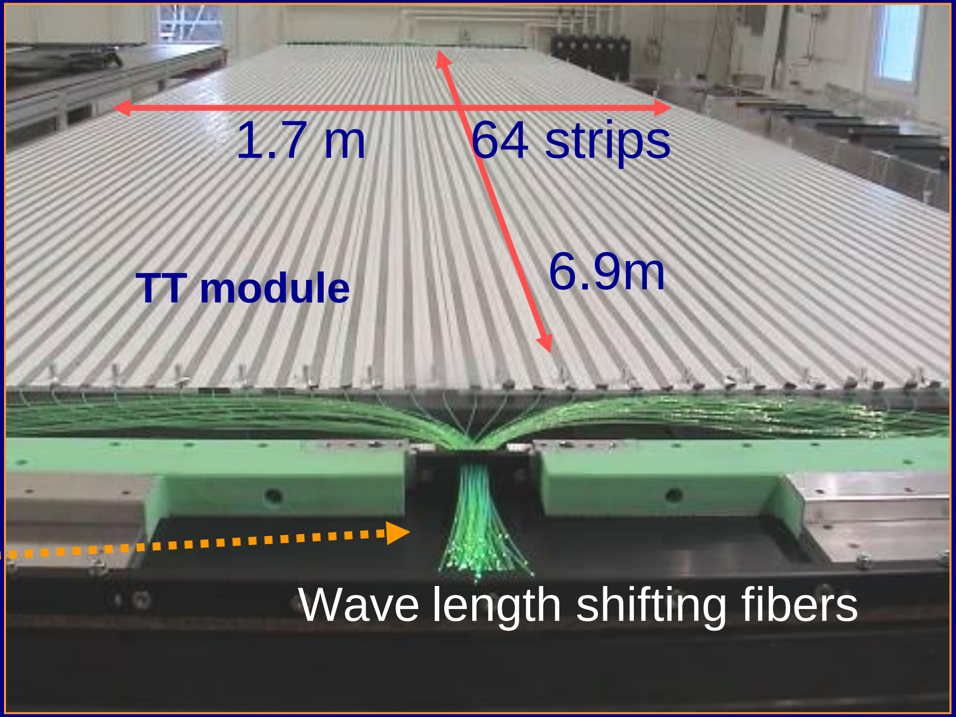


The Target Tracker (TT)

pre-location of neutrino interactions and event timing

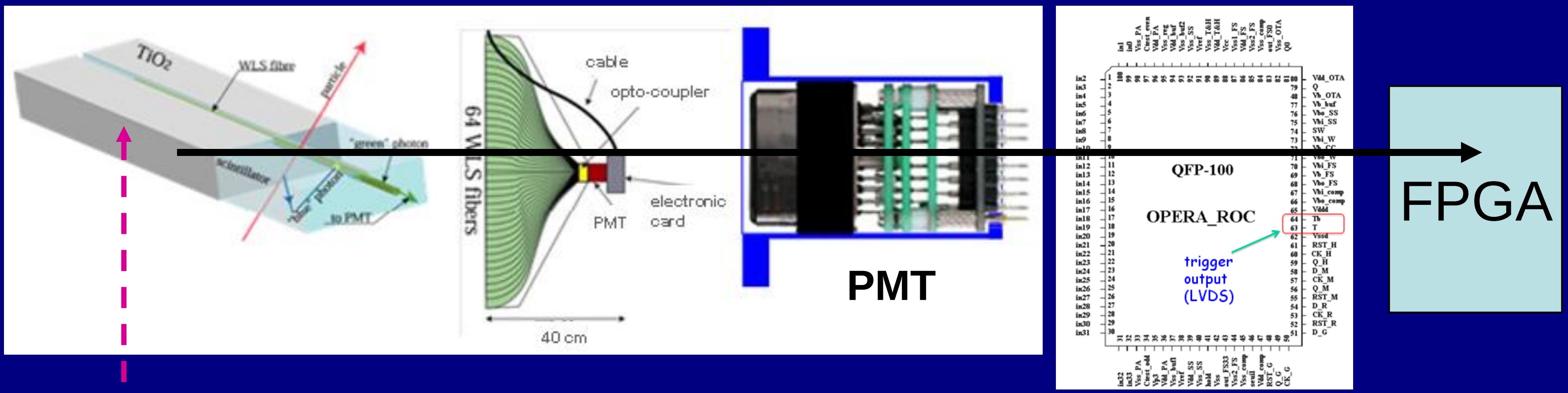
- Extruded plastic scintillator strips (2.6 cm width)
- Light collections with WLS fibres
- Fibres read out at either side with multi-anode 64 pixels PMTs (H7546)

H7546



Read out by 1 Front-End DAQ board per side

TT time response measurement



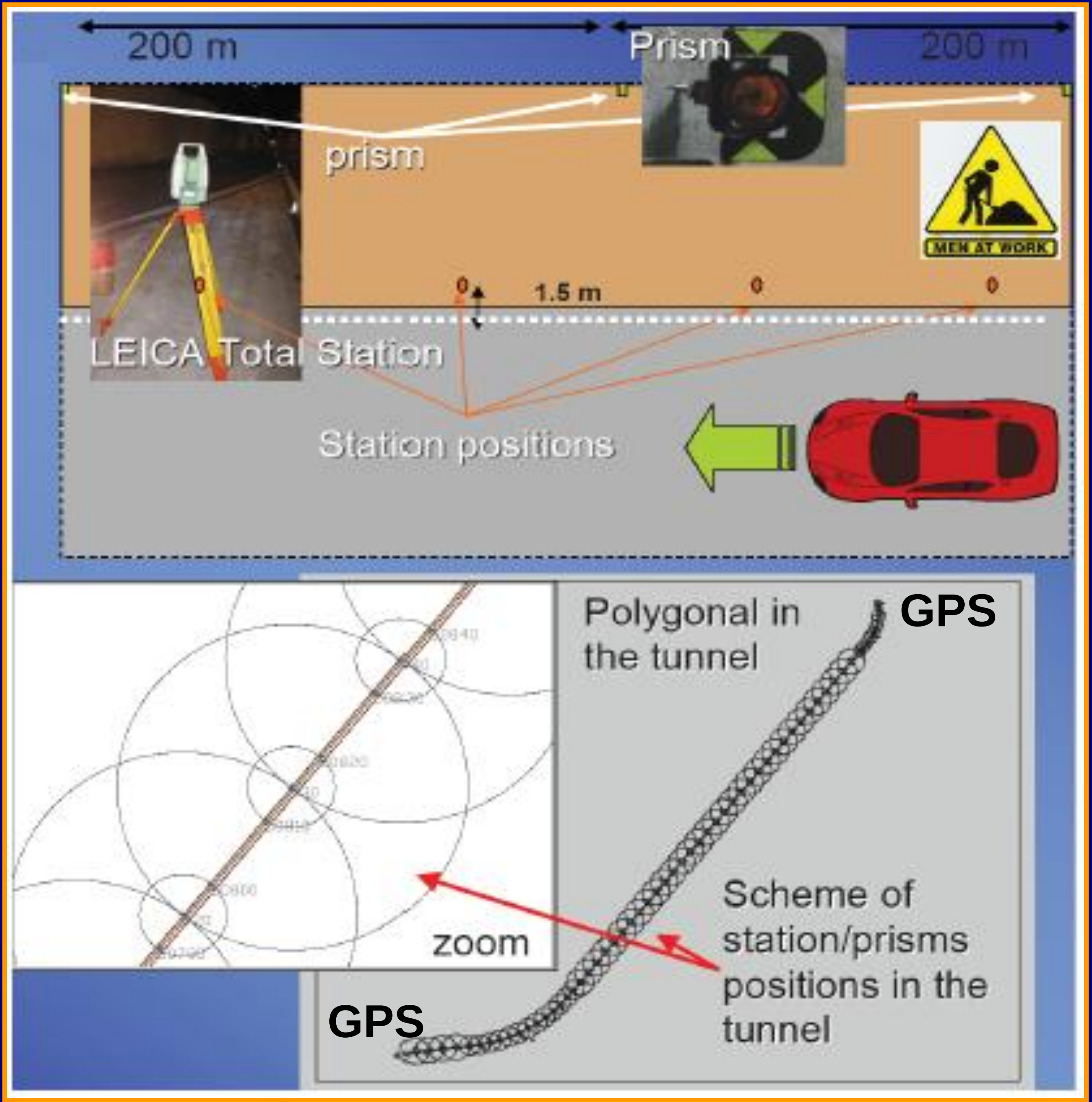
Scintillator, WLS fibers, PMT, analog FE chip (ROC) up to FPGA trigger input

UV laser excitation:
→ delay from photo-cathode to FPGA input: 50.2 ± 2.3 ns

Average event time response: 59.6 ± 3.8 ns (sys)

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

Geodesy at LNGS

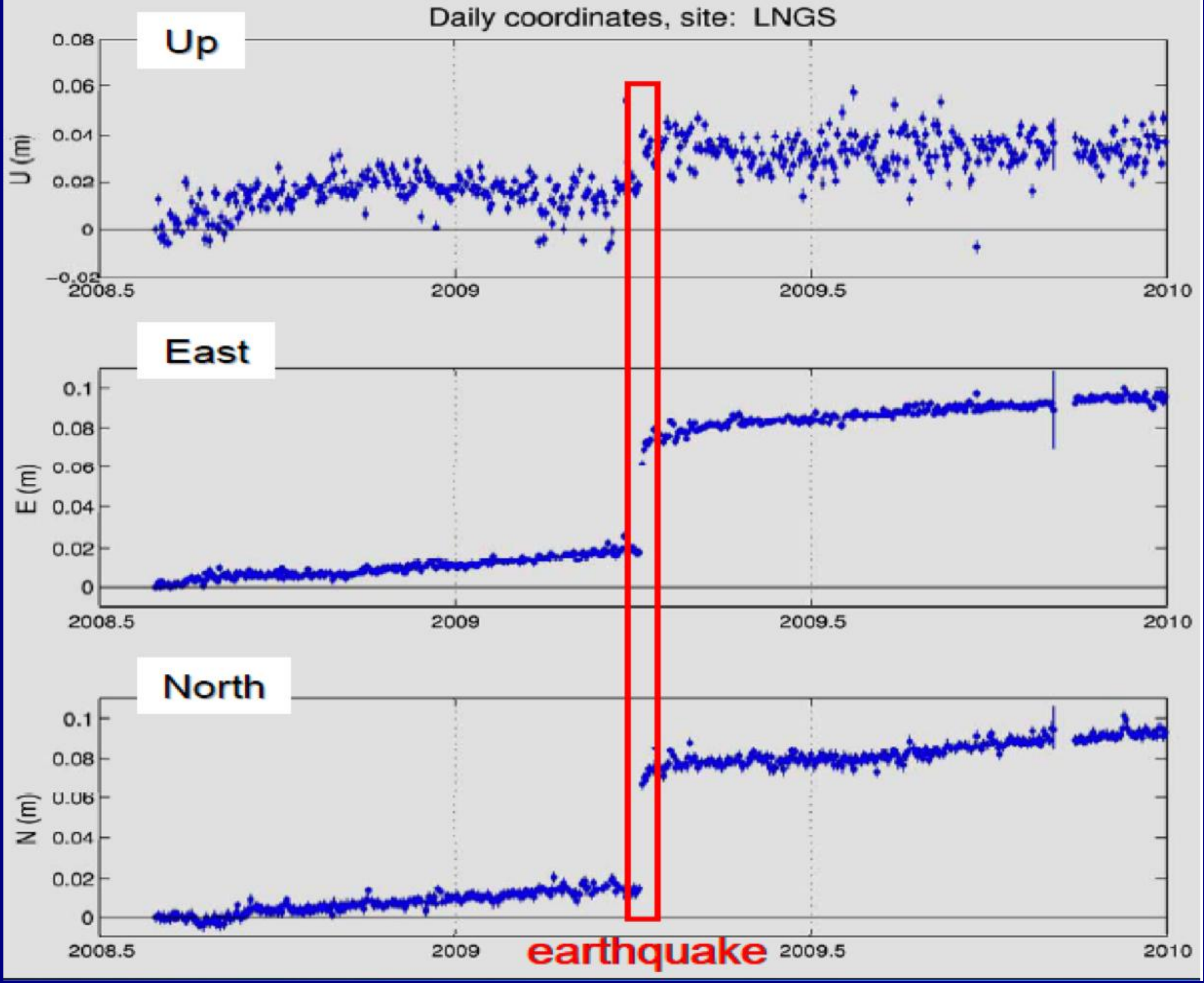


Dedicated measurements at LNGS: July-Sept. 2010 (Rome Sapienza Geodesy group)

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

GPS measurements ported underground to OPERA

LNGS position monitoring



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

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

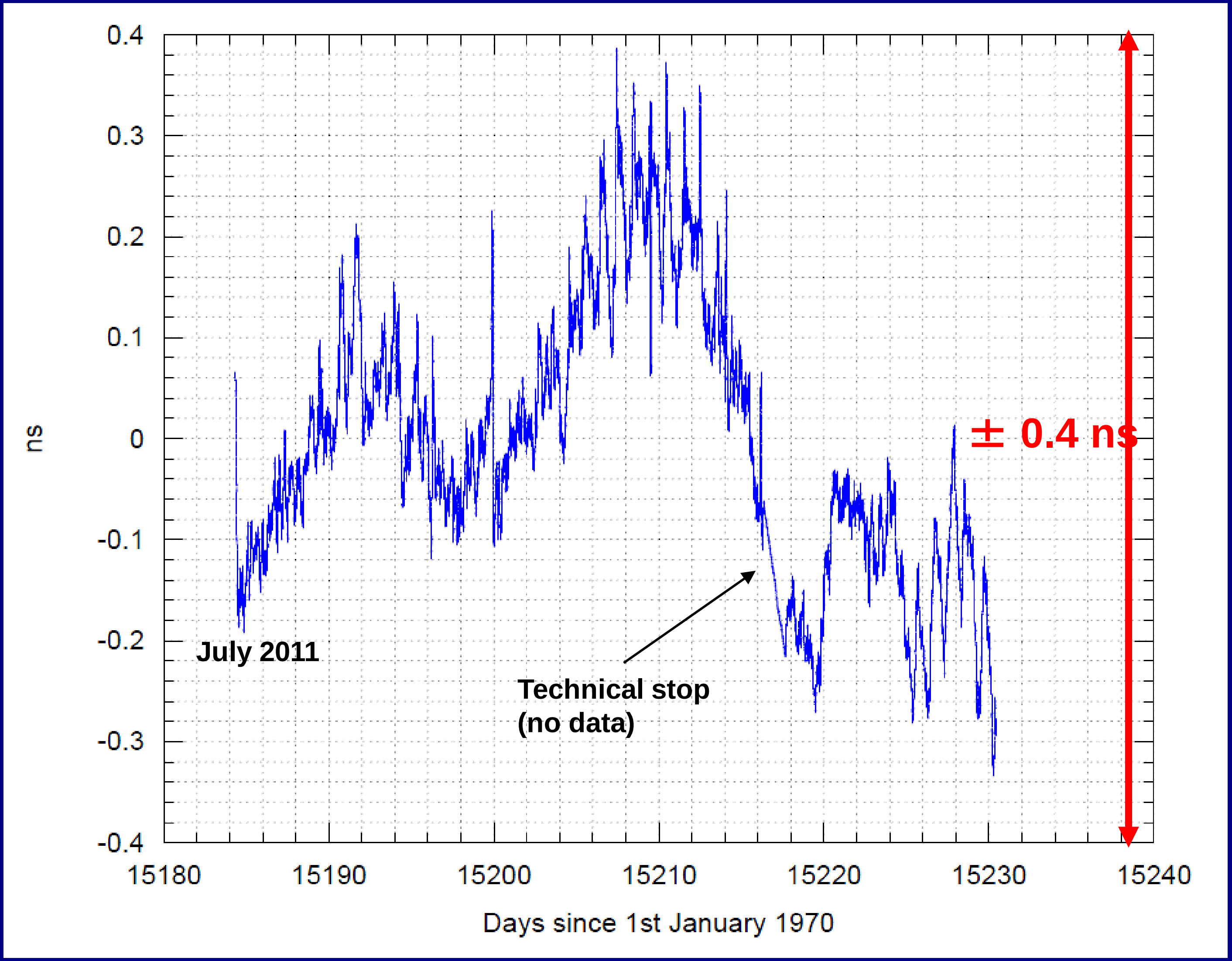
Cross-check: simultaneous CERN-LNGS measurement of GPS benchmarks, June 2011

Resulting distance (BCT – OPERA reference frame)
(731278.0 ± 0.2) m

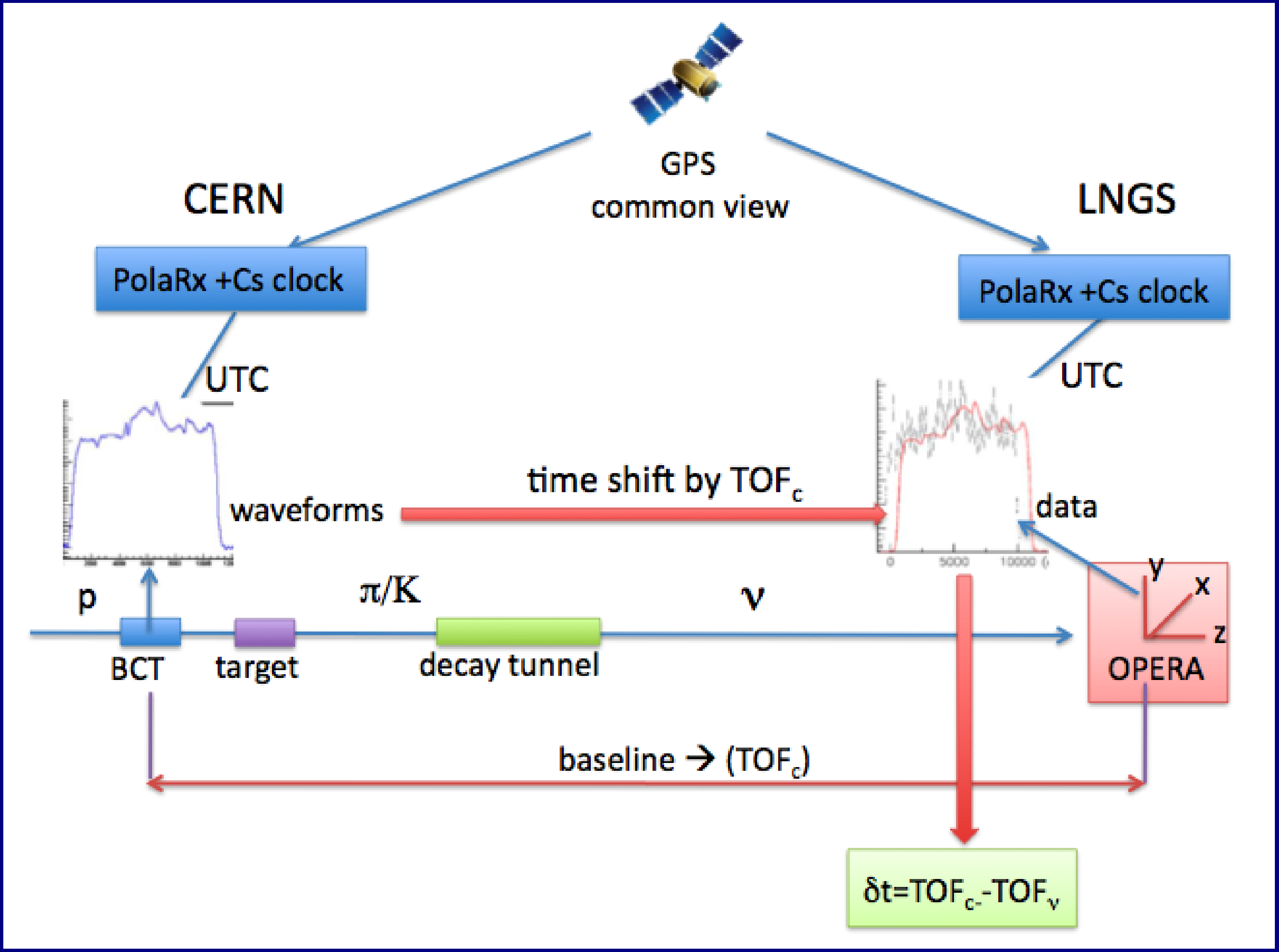
Delay calibrations summary

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

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



Summary of the principle for the TOF measurement



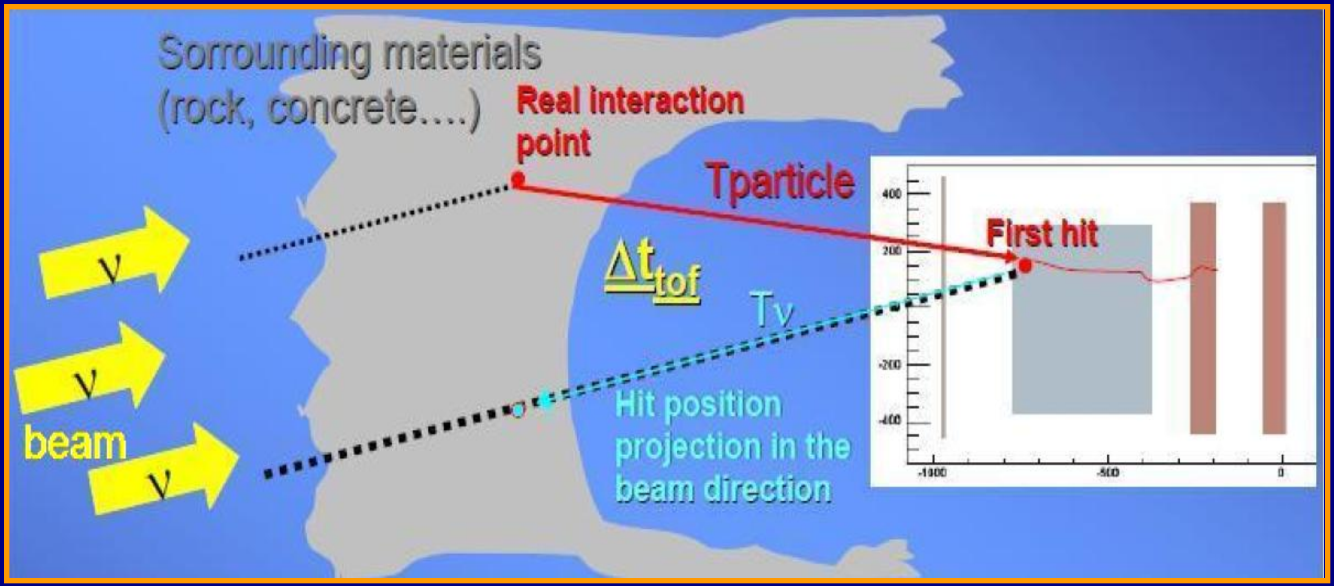
$$\text{Measure } \delta t = TOF_c - TOF_\nu$$

Event selection (earliest TT hit of the event as "stop")

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

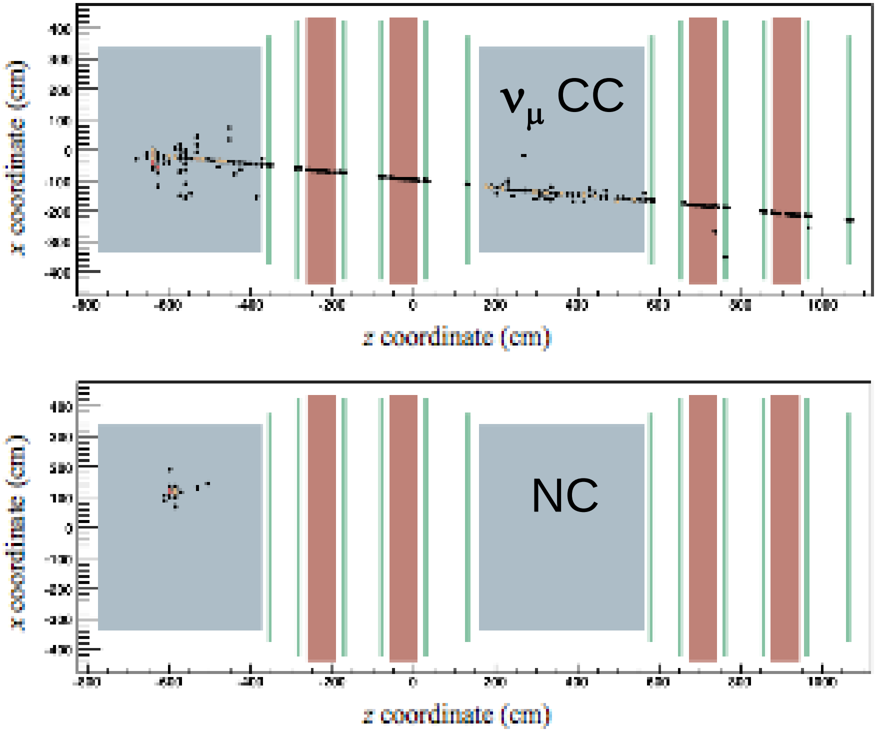
Internal events:
Same selection procedure as for oscillation searches: 7586 events

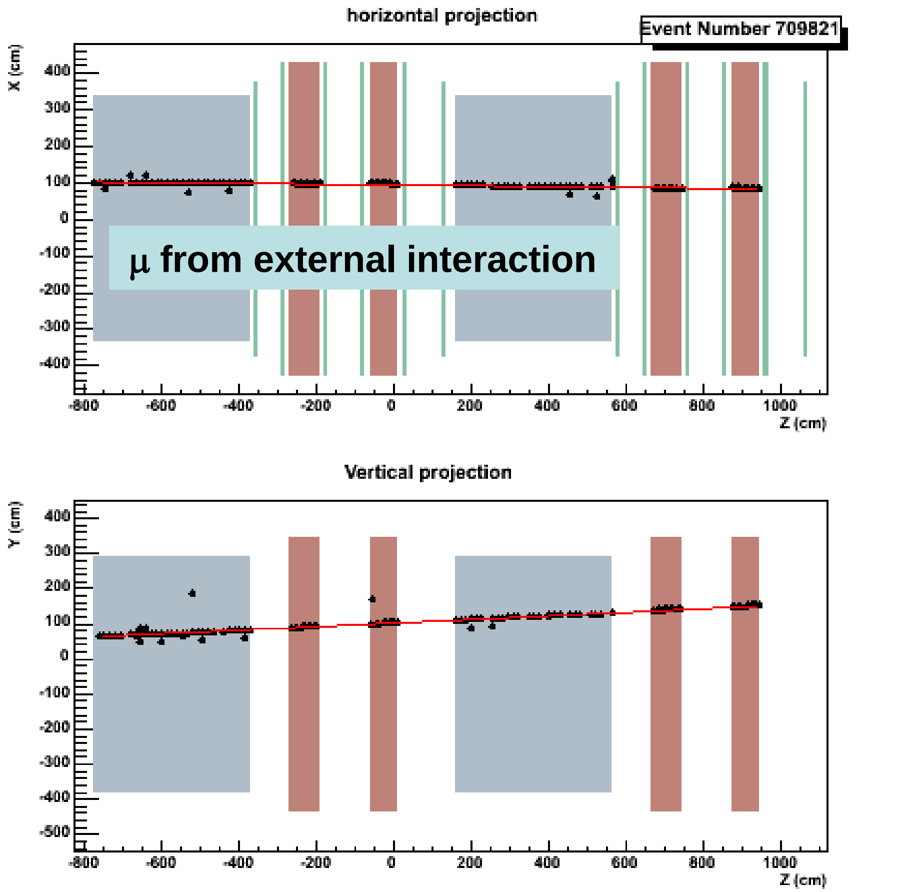
External events:
Rock interaction → require muon 3D track: 8525 events
(Timing checked with full simulation, 2 ns systematic uncertainty by adding external events)



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

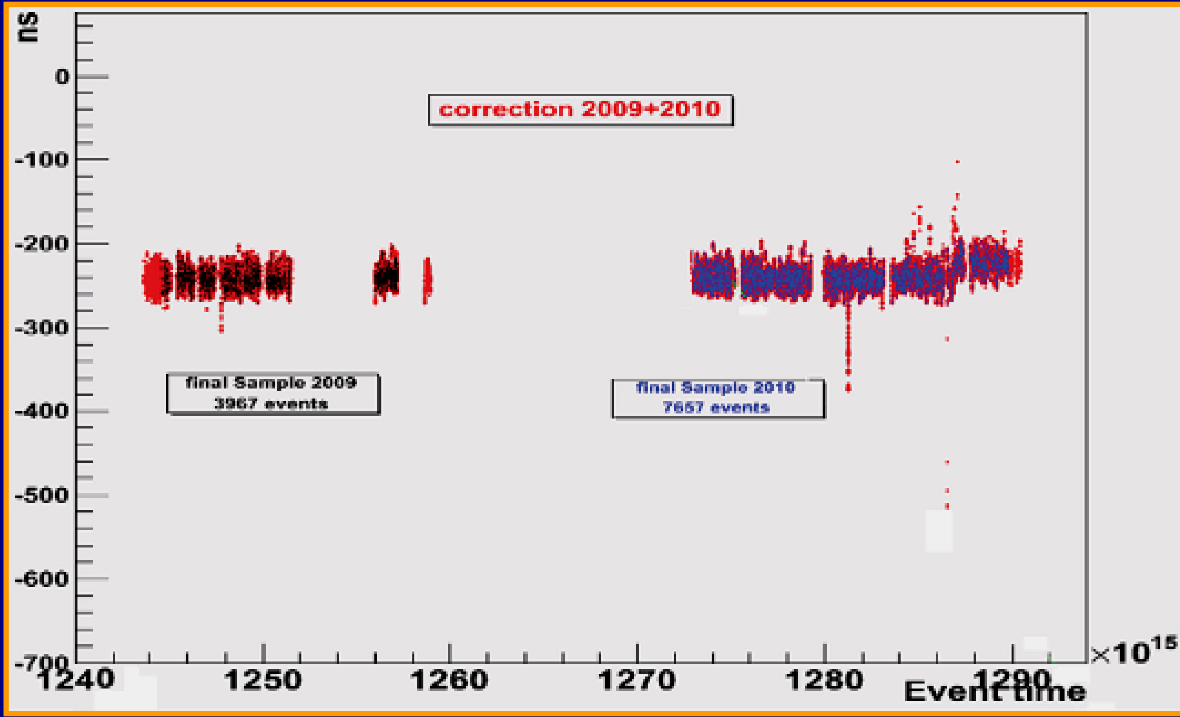
"INTERNAL" and "EXTERNAL" OPERA EVENTS

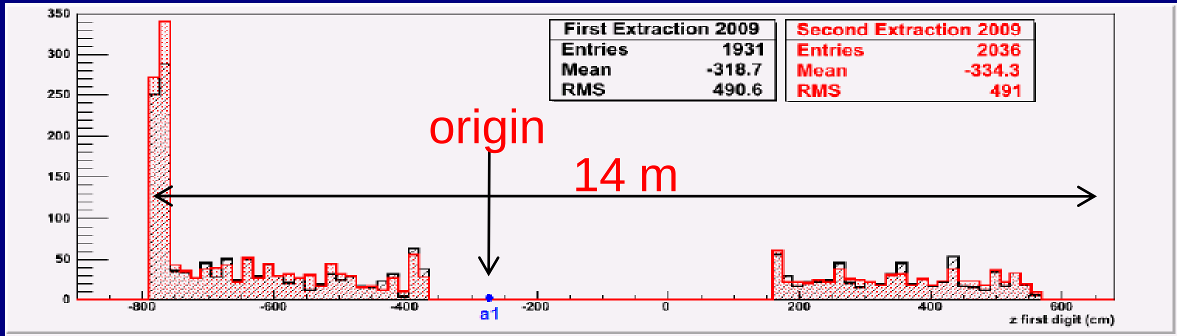


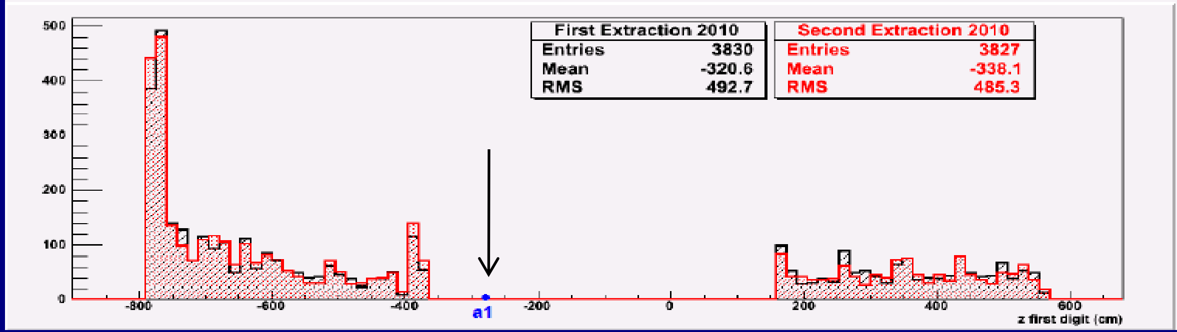


Event time corrections

Time-link correction (blue points)







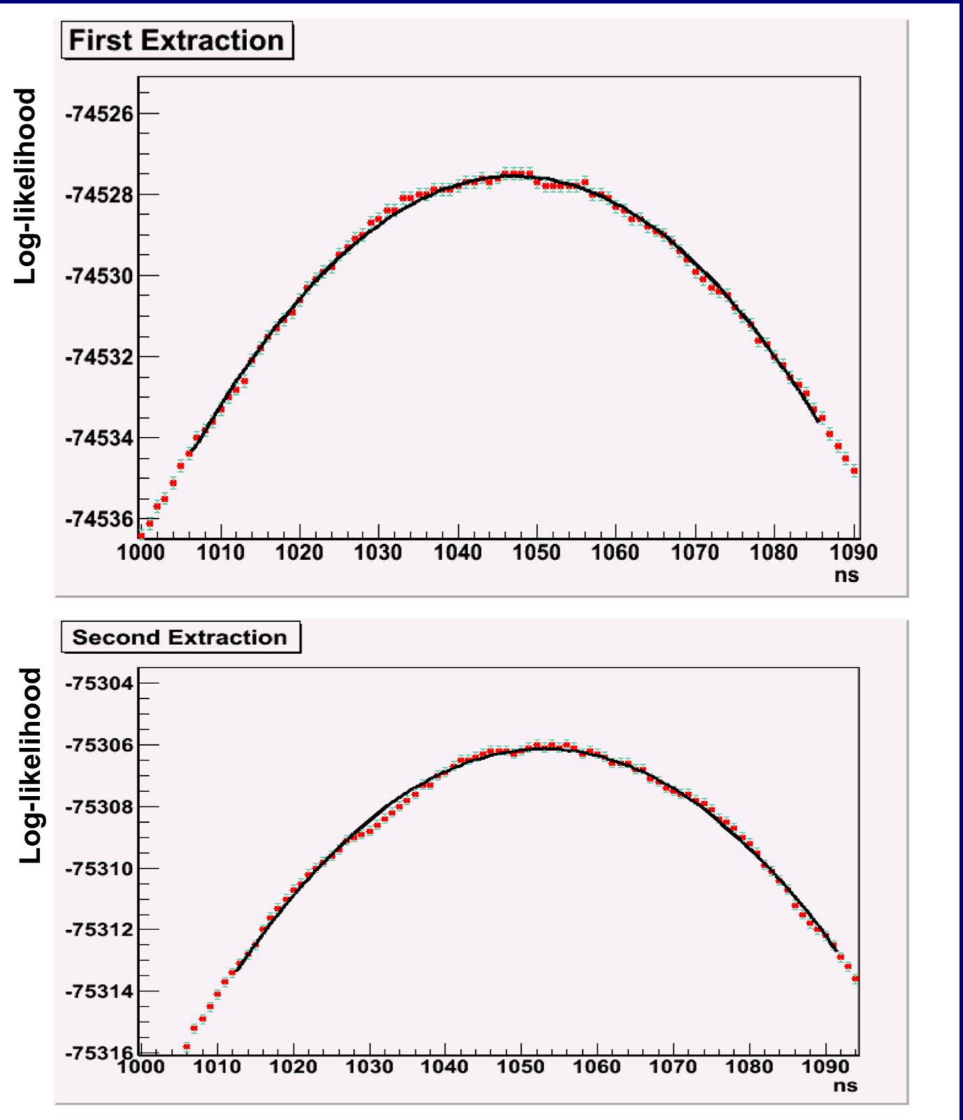
Correction due to the earliest hit position

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



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

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

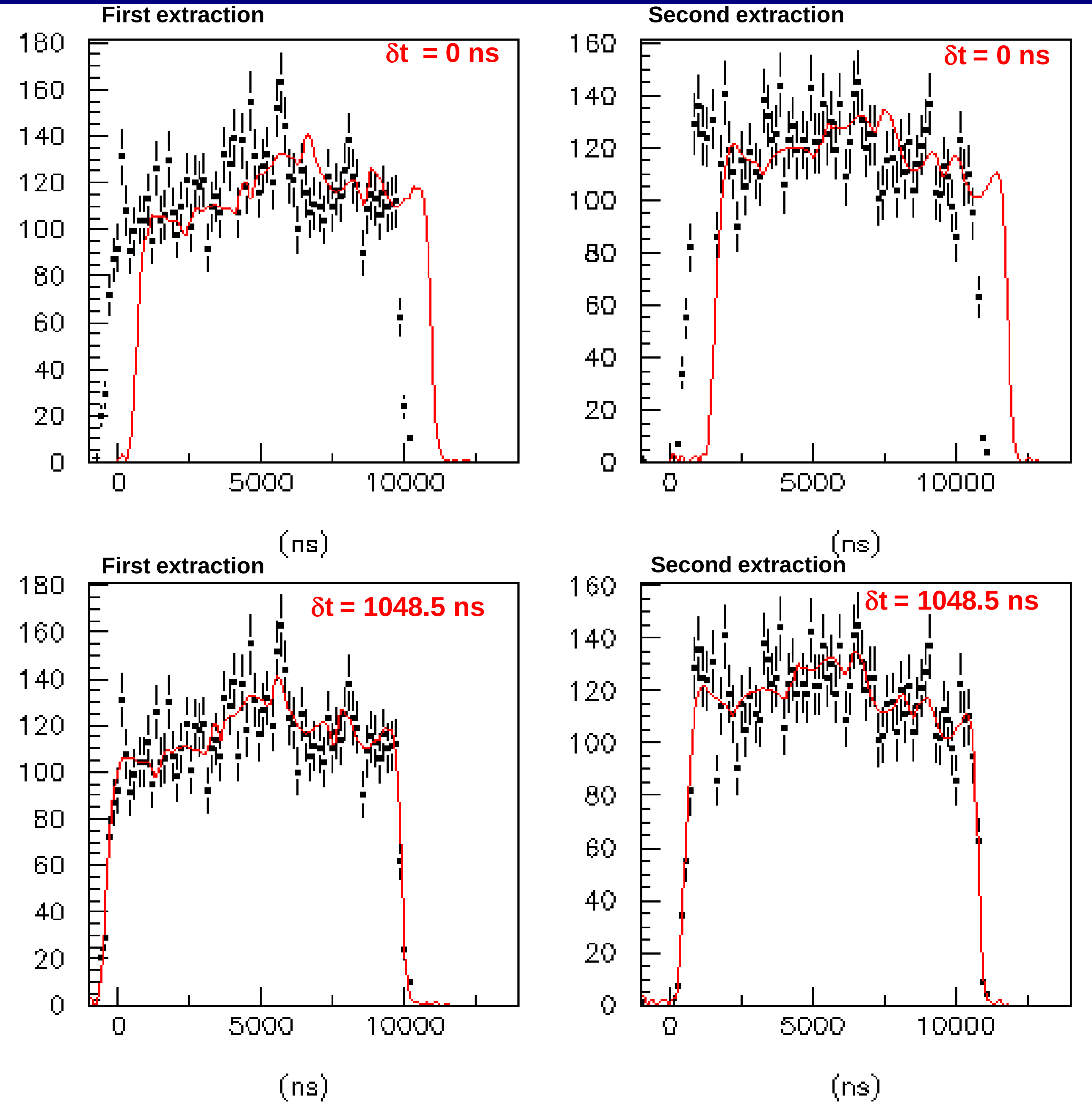
4) Ignoring the BCT and WFD delays

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

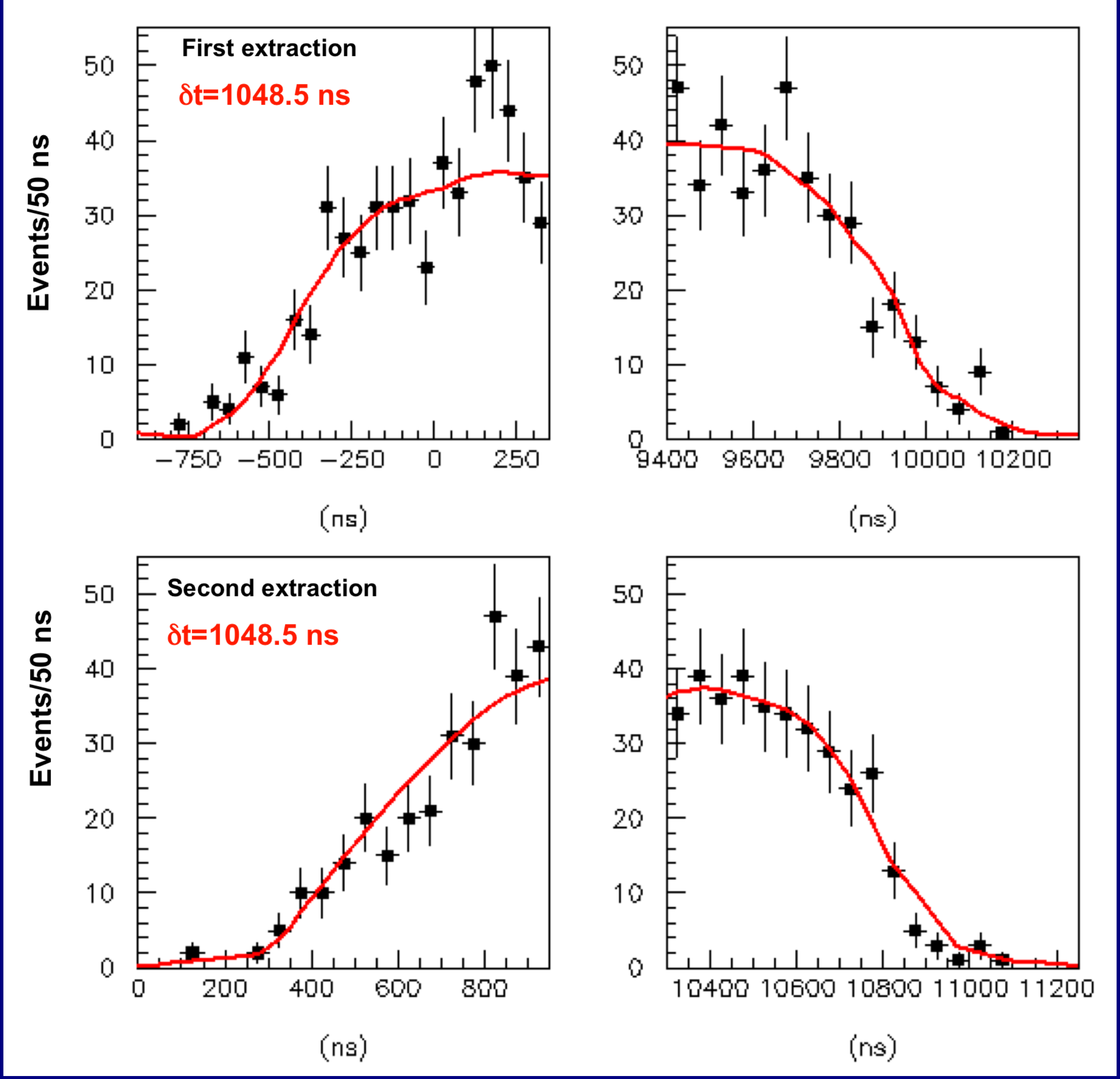
(1048.5 ± 6.9) ns (stat)

χ^2 / ndof :

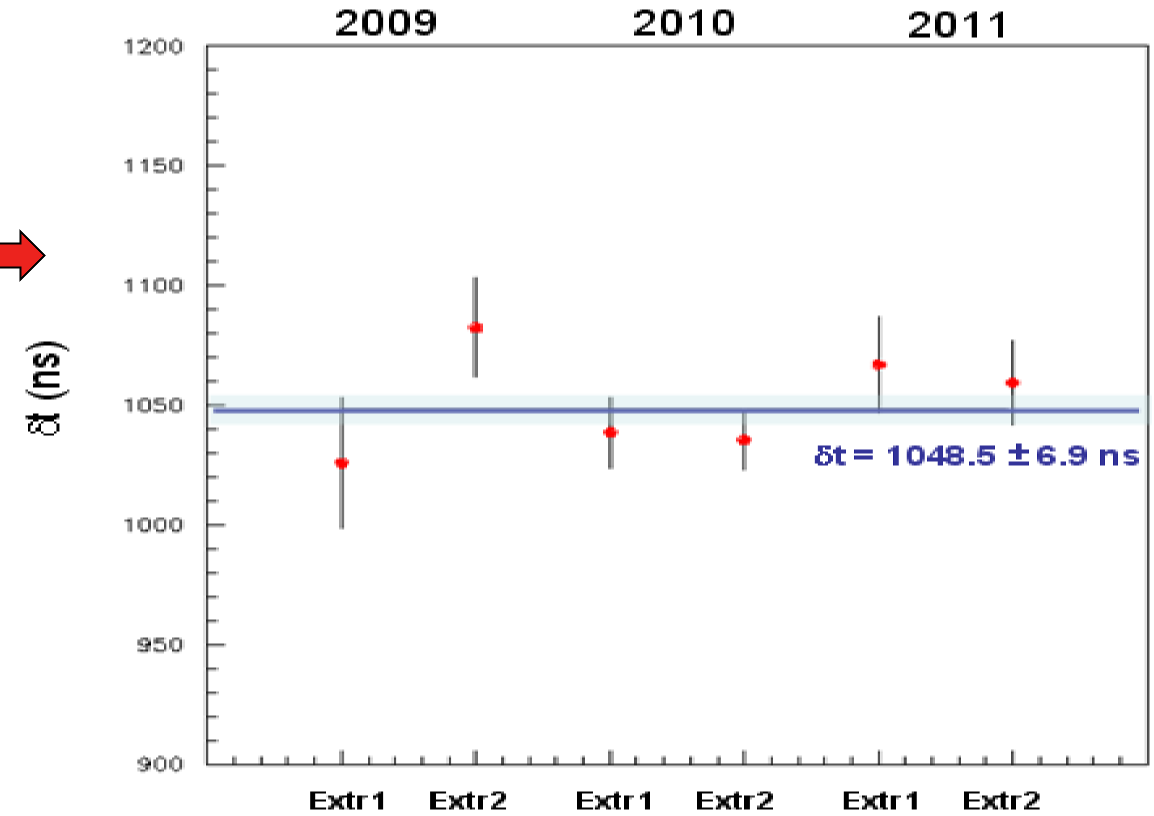
first extraction: 1.06

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 $\pm$ 15.5) ns

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

3) Internal vs external events:

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

Internal events only: (1047.4 $\pm$ 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

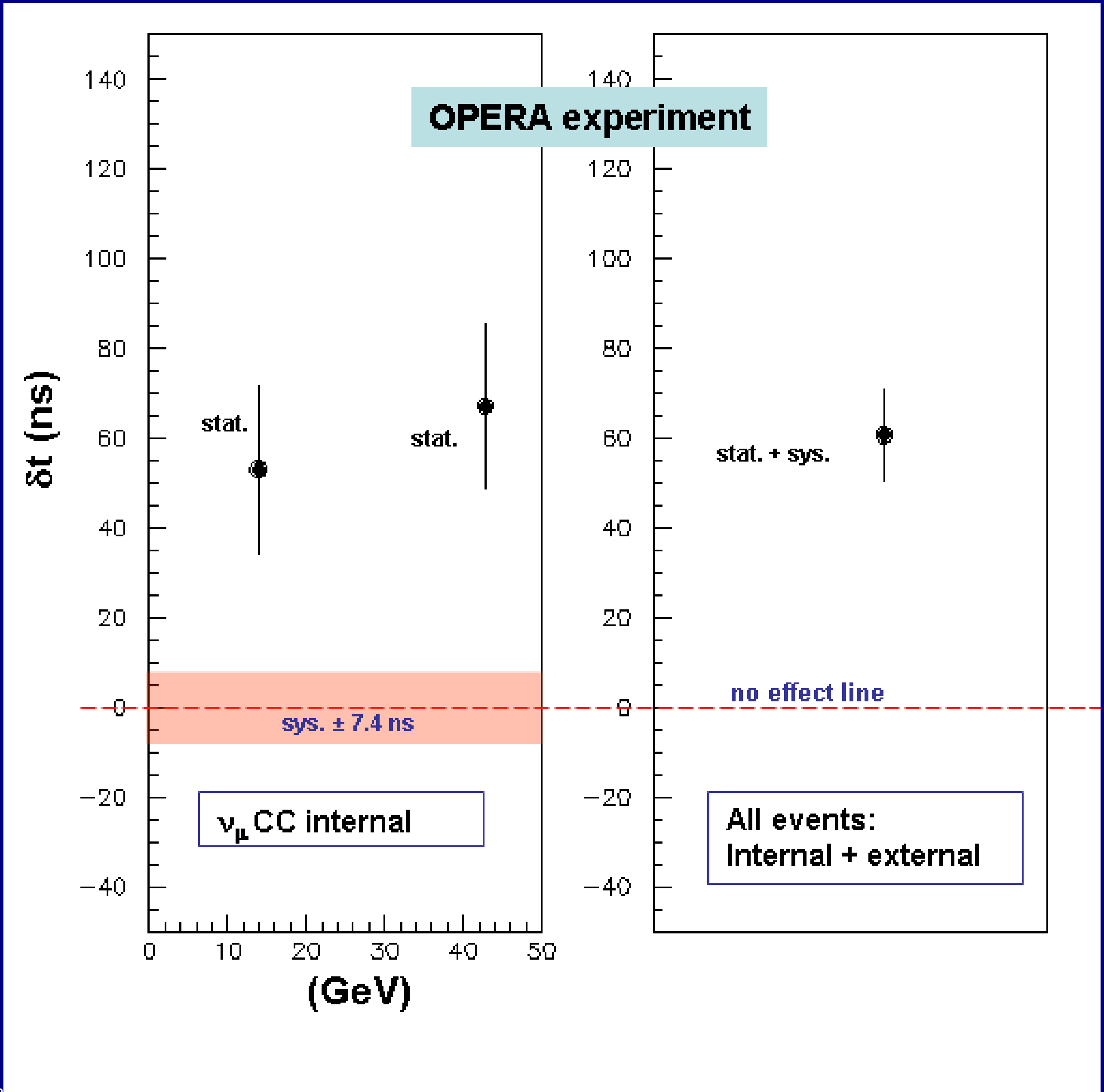
relative difference of neutrino velocity w.r.t. *c:*

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

(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



Small systematic effects: neutrinos beam line related

Setting up of the CNGS horns during the yearly CNGS beam start-up

J.-M. Cravero, E. Gschwendtner and I. Koszar

L. Bruno and I. Efthymiopoulos

CNGS target explained

- Target: $\mathbf{13 \;\; 10}\,\boldsymbol{cm}$ long graphite rods of $\mathbf{4\text{-}5}\,\boldsymbol{mm}\,\varnothing$

  Accuracy to the target centre: 50 (90) $\boldsymbol{\mu m}$ RMS horizontally (vertically)

  Spot size stability: $\mathbf{10^{-3}}$
- $\boldsymbol{T}$ increase during $\mathbf{10.5}\,\boldsymbol{\mu s}$ ejection: ~ $\mathbf{300}\,\boldsymbol{K}$

  $\Rightarrow$ density reduction: $\mathbf{0.3\%} \Rightarrow$ negligible effect on $\boldsymbol{\nu}$ timing and yield
- Horn and reflector magnets pulses in beam line: $\mathbf{100}\,\boldsymbol{ms}$ centered on $\mathbf{10.5}\,\boldsymbol{\mu s}$ ejection

  Pulse timing without effect on neutrino timing

http://operaweb.lngs.infn.it:2080/Opera/publicnotes/note137.pdf

http://operaweb.lngs.infn.it:2080/Opera/publicnotes/note138.pdf

Small systematic effects: special and general relativity

Special and General Relativity corrections to the OPERA neutrino velocity measurement.

E. Kiritsisa and F. Nittib

- Sagnac effect caused by Earth rotation around its axis:

  increase of TOFc and δt by 2.2 ns.
- Earth revolution around the Sun and solar system in the Milky Way:

  negligible
- Gravitational fields of Moon, Sun and Milky Way and the Earth frame-dragging:

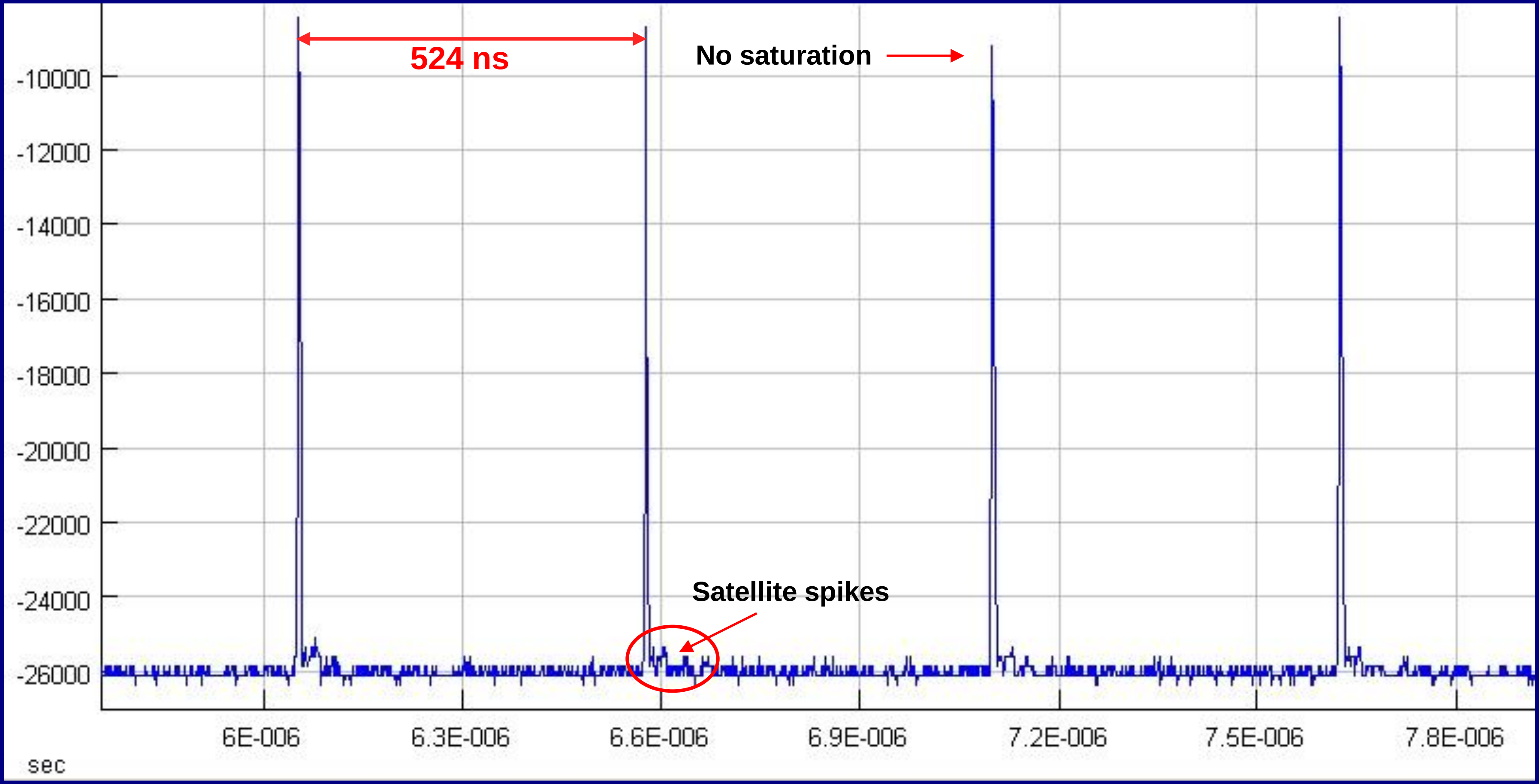
  negligible.
- Relative effect of the Earth gravitational field on the Schwartzschild geodesic:

  10^{-8}.
- Gravitational red-shift due different CERN and LNGS altitudes:

  10^{-13} on clocks synchronisation.

http://operaweb.lngs.infn.it:2080/Opera/publicnotes/note136.pdf

First CNGS bunched beam test 22/10/2011-6/11/2011



Bunched beam test
- 1 extraction/cycle
- 4 bunches/extraction separated by ~524 ns,
- ~3 ns bunches
- Typical intensity $1.05 \times {}^{12}$ pot/extraction

Standard CNGS beam

2 extractions/cycle

extractions separated by 50 ms

10.5 μs extractions

$2.4 \times {}^{13}$ pot/extraction

Number of CNGS cycles depends on other users (LHC filling …)

We expect 1.4 events/day !!

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:

$$\delta t = TOF_c - TOF_\nu = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))\ \text{ns}$$

• 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:

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

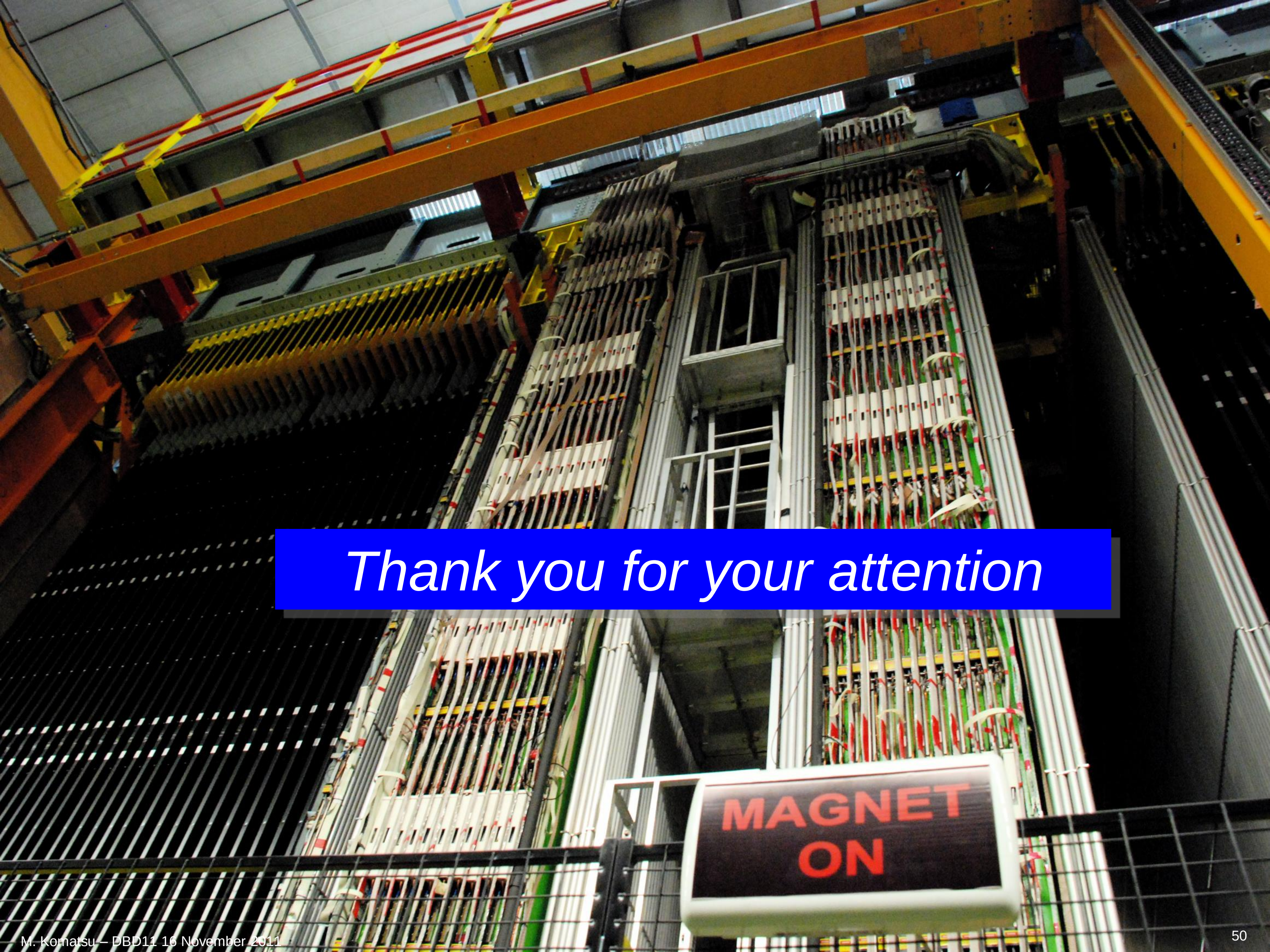
with an overall significance of 6.0 σ.

Conclusions (2)

• 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.

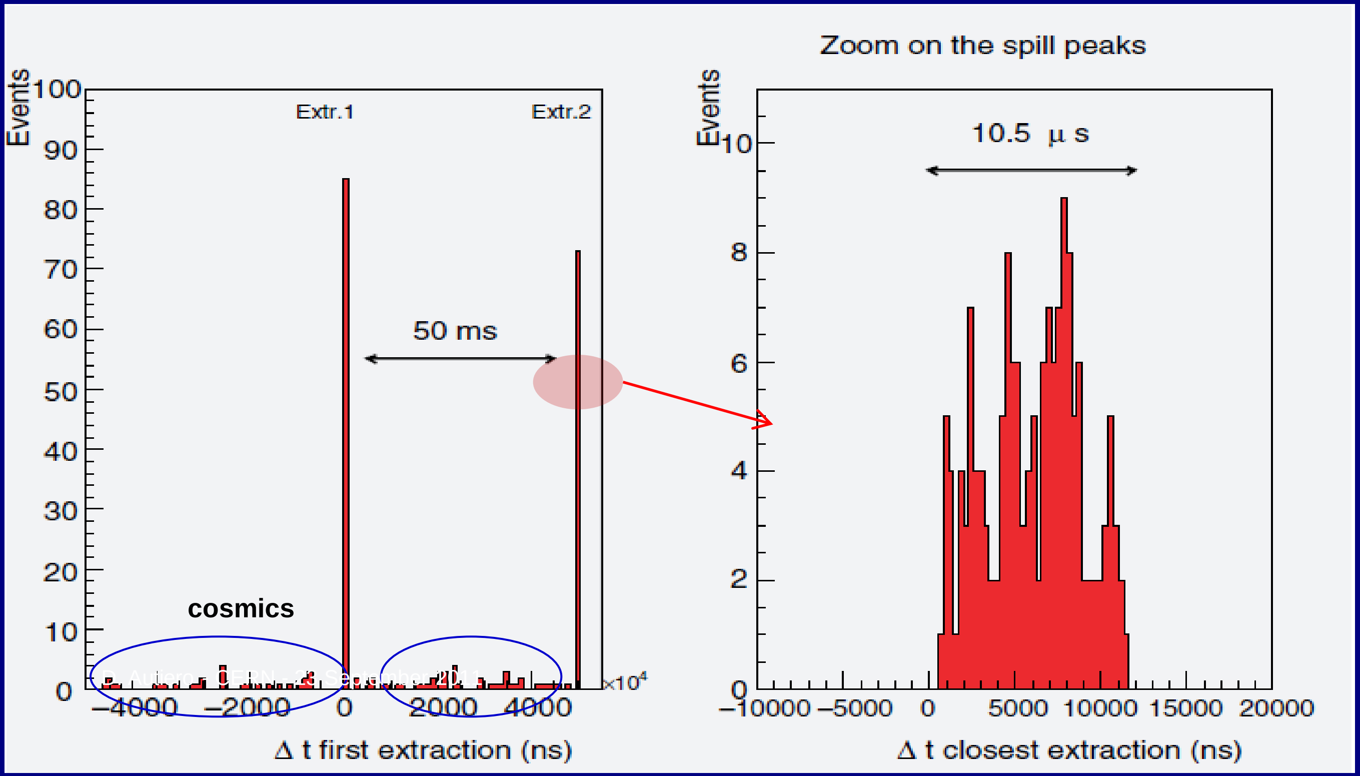
• Despite the large significance of the measurement reported here and the stability of the analysis, the potentially great impact of the result motivates the continuation of our studies in order to identify any still unknown systematic effect.

• We do not attempt any theoretical or phenomenological interpretation of the results.



Thank you for your attention

CNGS events selection

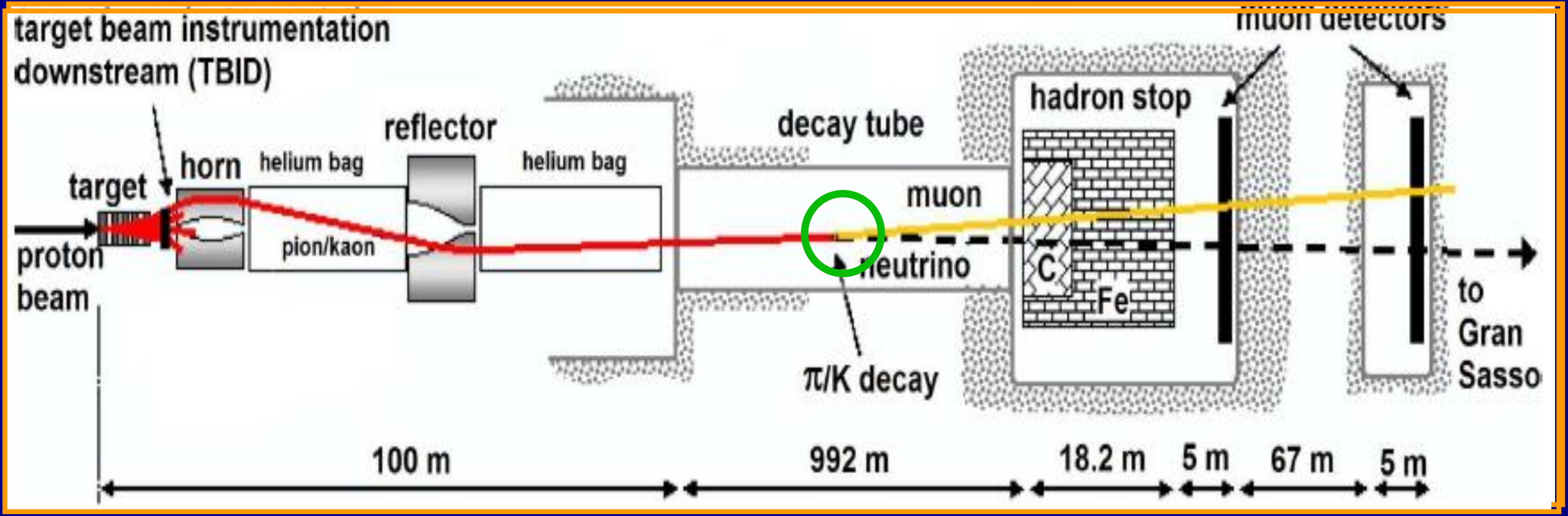


OPERA data: narrow peaks of the order of the spill width (10.5 μs)

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

Selection procedure kept unchanged since first events in 2006

Neutrino production point



Unknown neutrino production point:

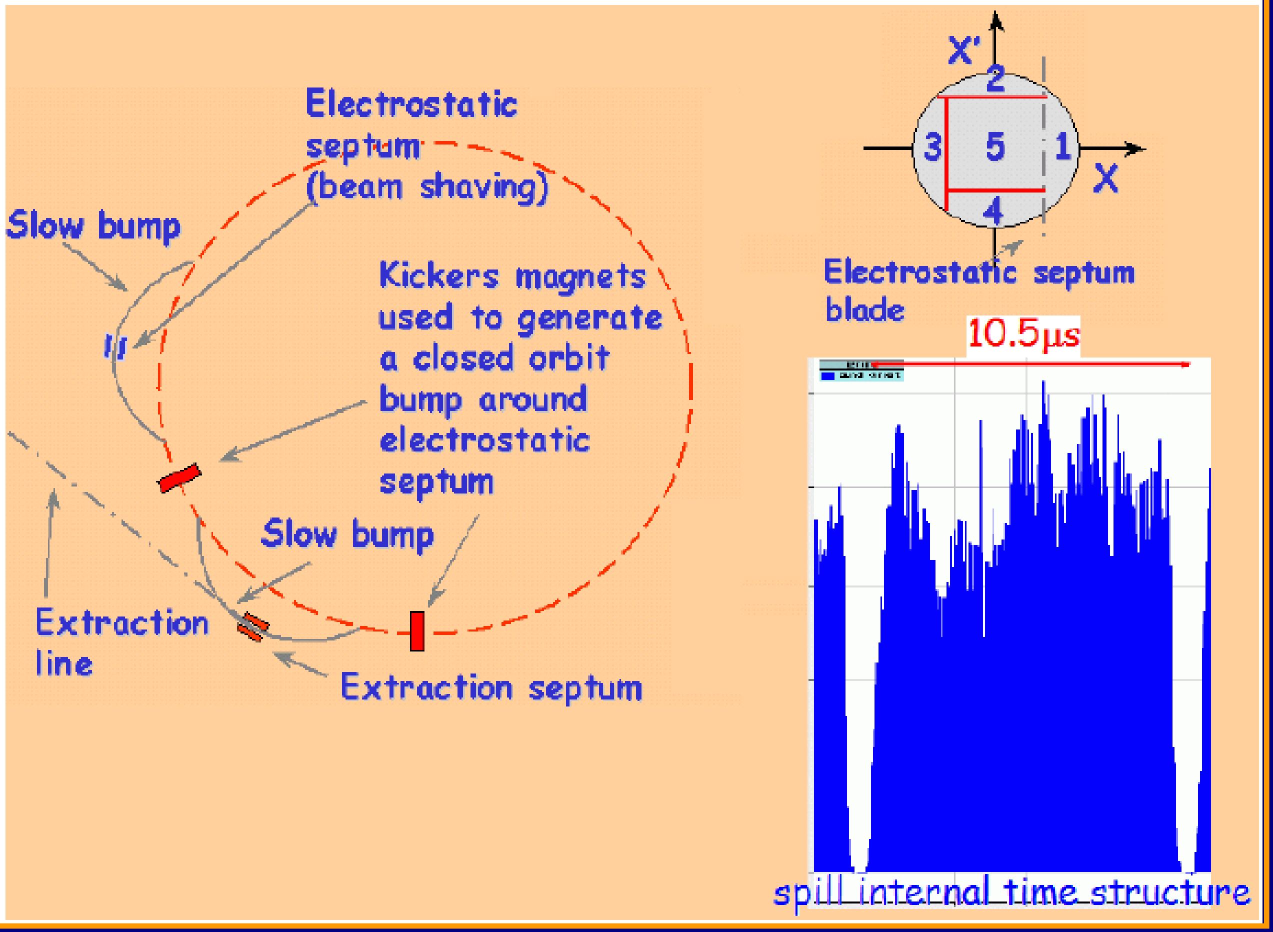
$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c}\left(\frac{1}{\beta} - 1\right) \approx \frac{z}{c}\frac{1}{2\gamma^2}$$

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

TOF_c = assuming *c* from BCT to OPERA (2439280.9 ns)
TOF_{true} = accounting for speed of mesons down to decay point
$\Delta t = TOF_{true} - TOF_c$

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

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:

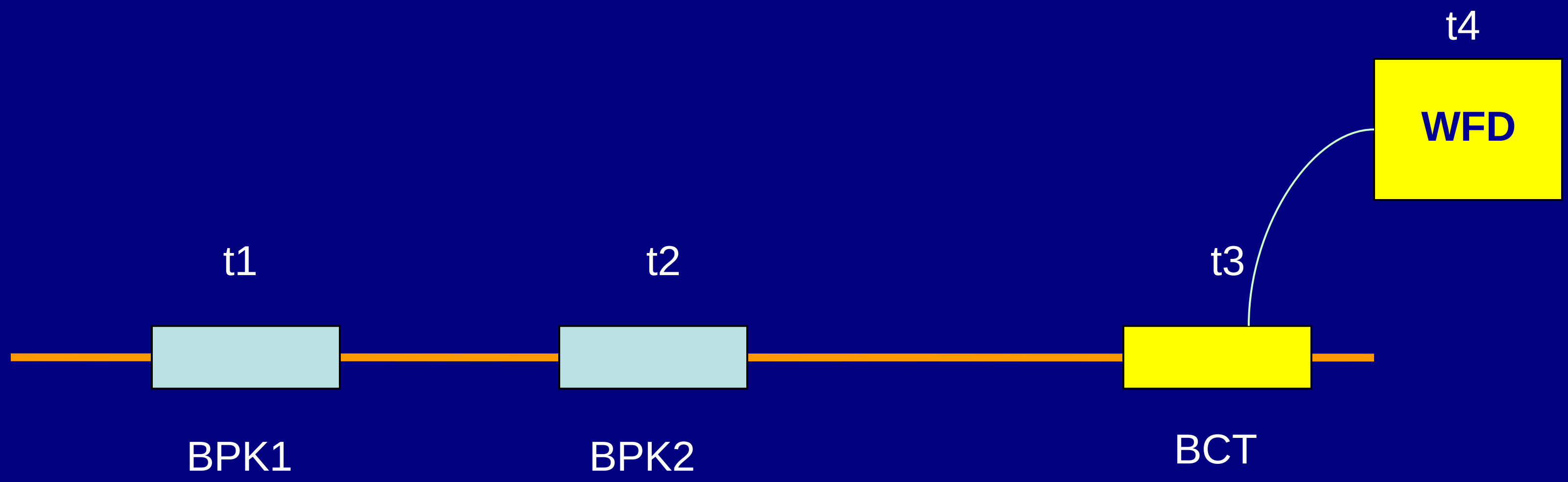
more accurate than: *e.g.* average neutrino distribution in a near detector

BCT calibration (1)

Dedicated beam experiment:

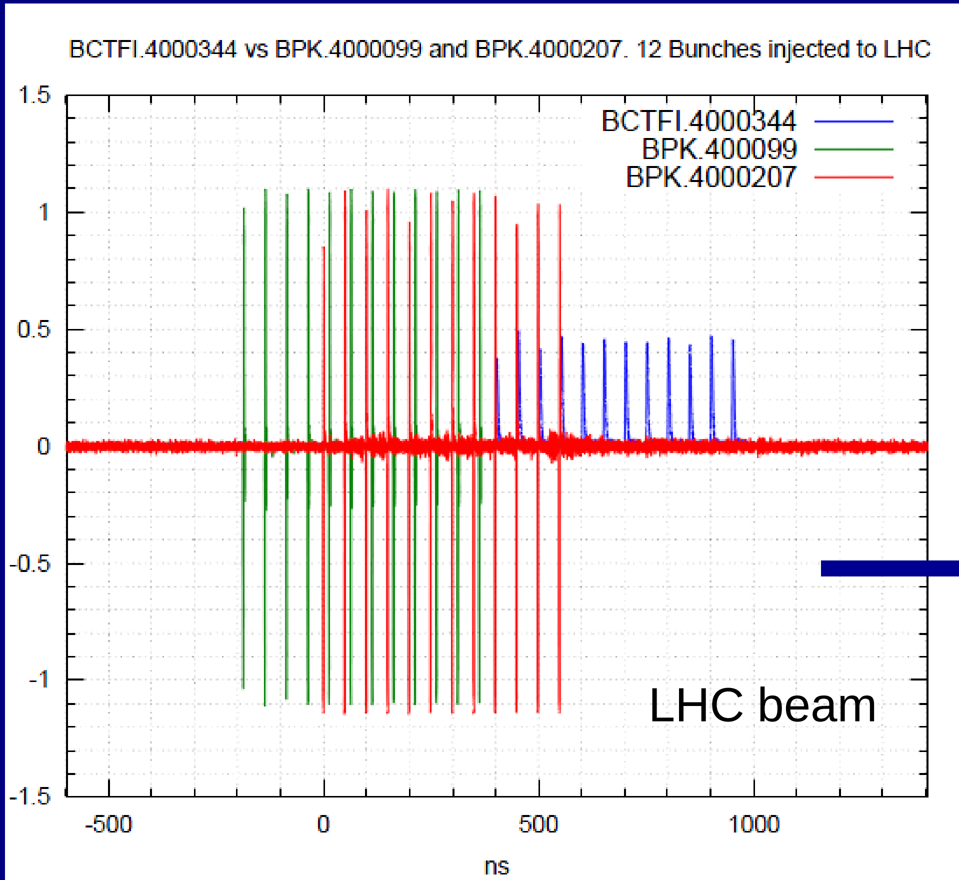
BCT plus two pick-ups (~1 ns) with LHC beam (12 bunches, 50 ns spacing)

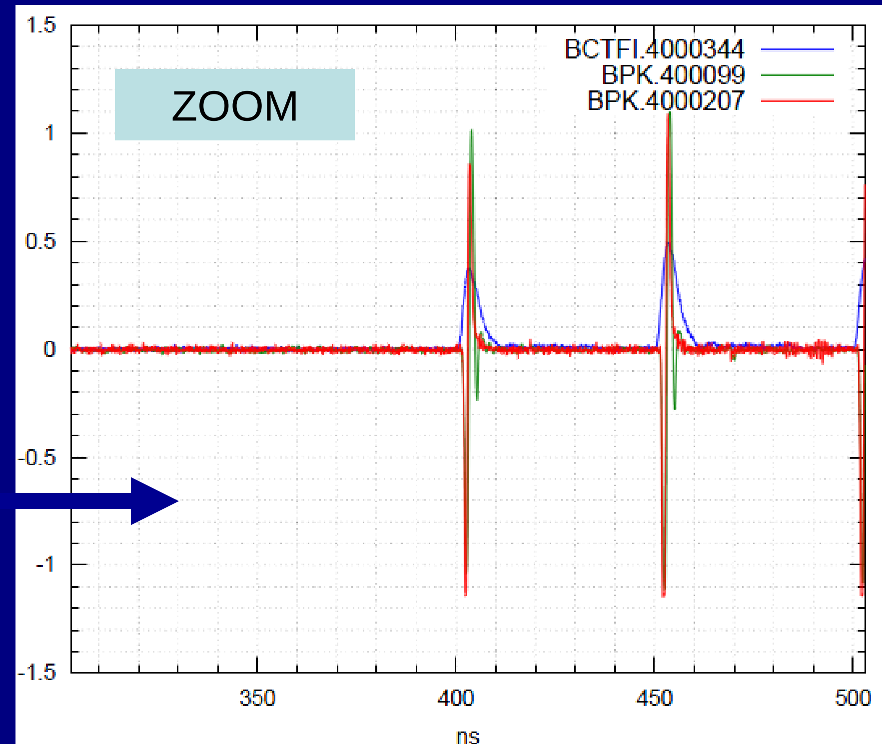
$$\Delta t_{BCT} = t4 - t3 = (580 \pm 5)\ \text{ns}$$



t3 : derived by t1 - t2 measurement and survey

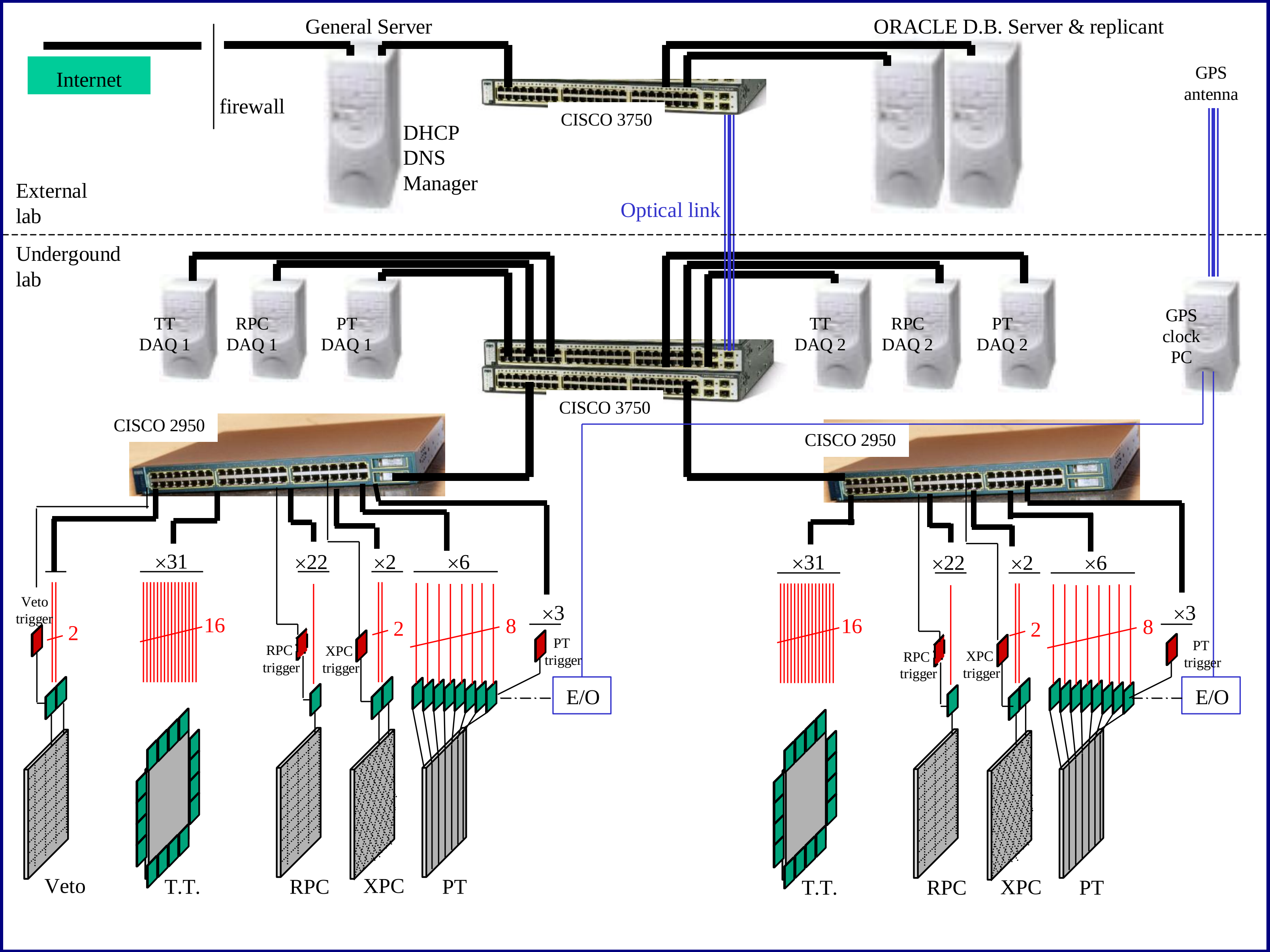
BCT calibration (2)





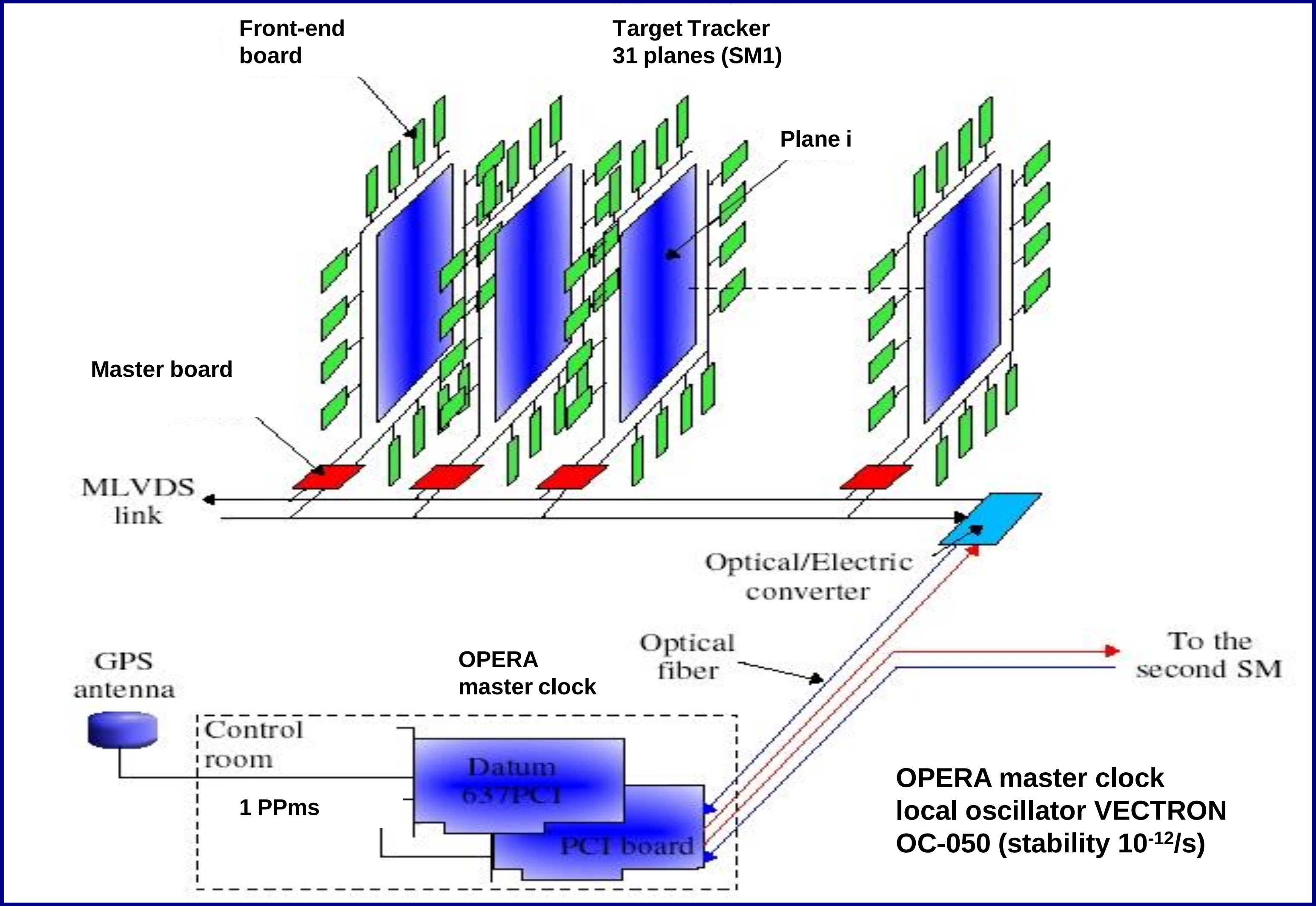
result: signals comparison after Δ_{BCT} compensation

OPERA readout scheme



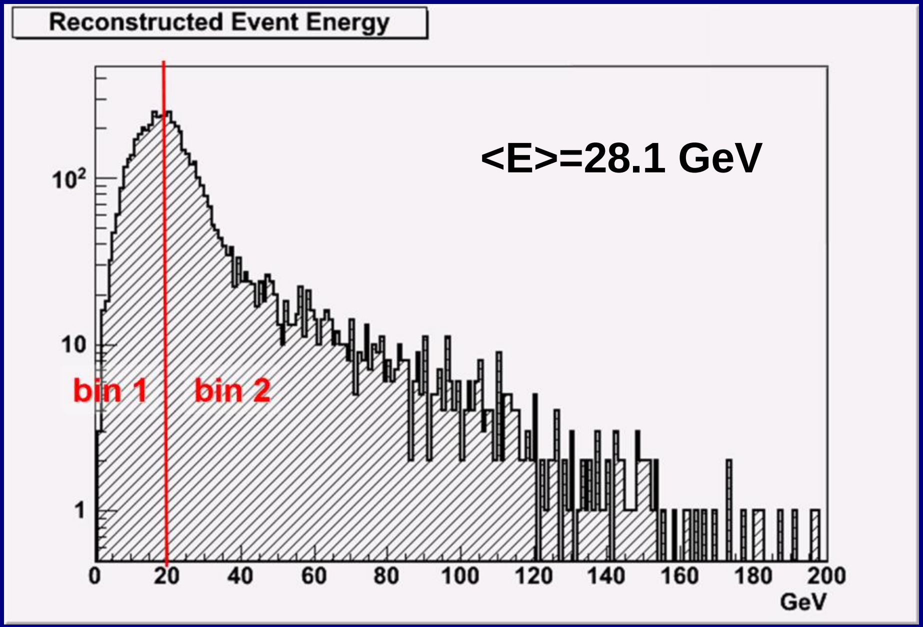
Trigger-less, asynchronous Front-End nodes (1200); Gigabit Ethernet network

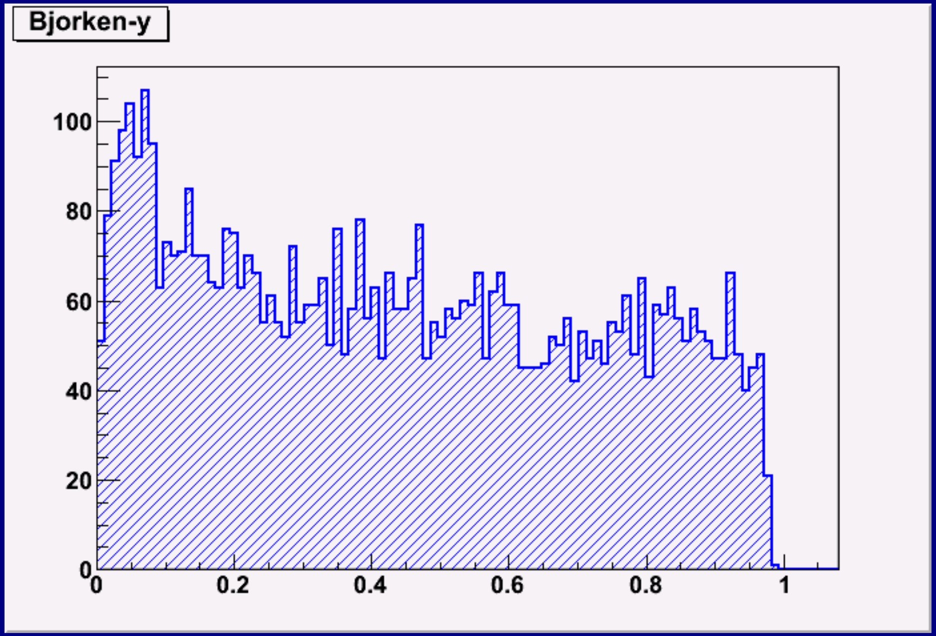
Clock distribution system (10 ns UTC event time-stamp granularity)



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

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

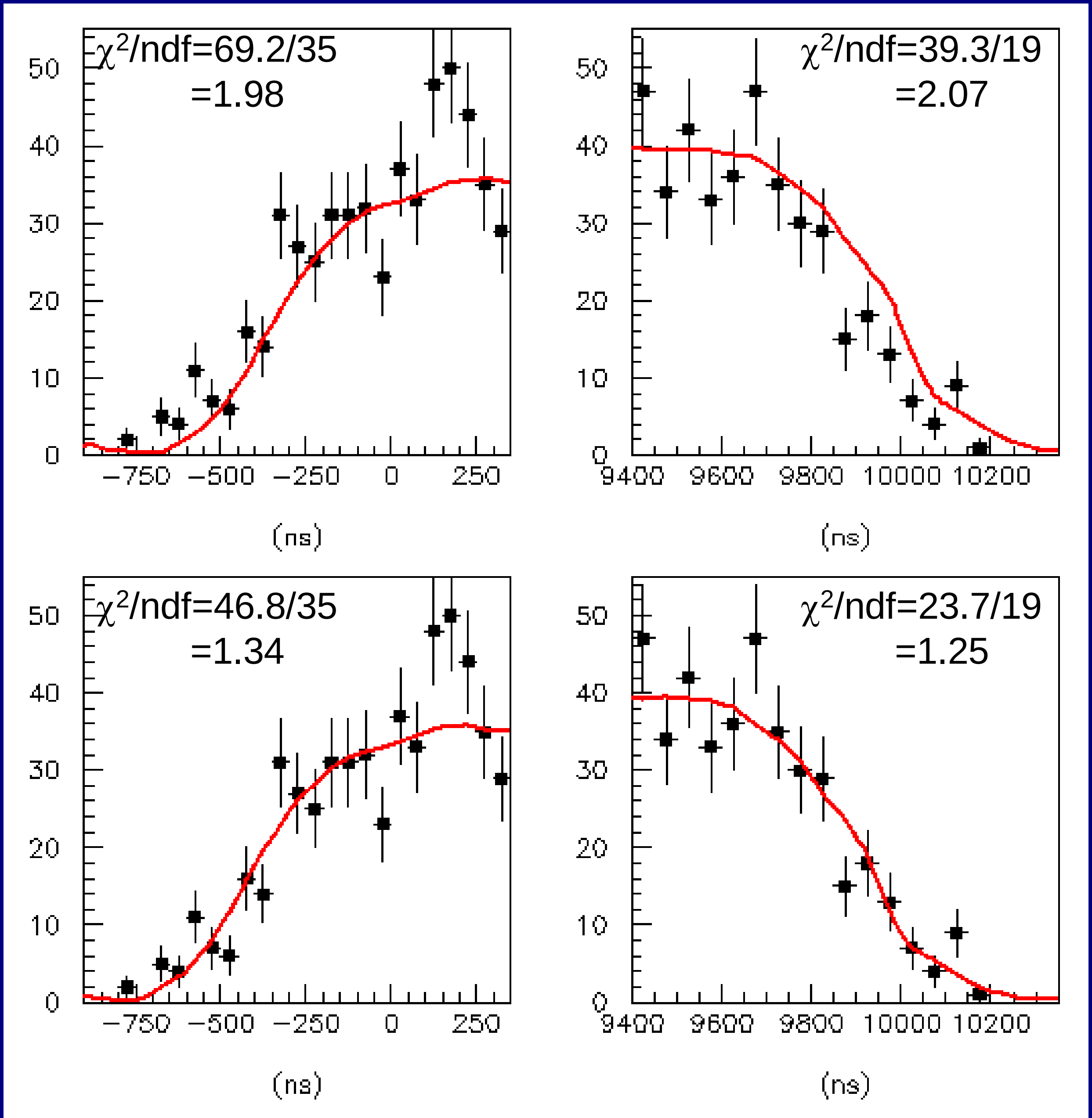
$\delta t = TOF_c - TOF_{\nu} = (60.3 \pm 13.1\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ ns for $\langle E_{\nu} \rangle = 28.1$ GeV
(result limited to events with measured energy)

Zoom on the extractions leading and trailing edges

Extraction 1

$\delta t = 0$ ns

$\delta t = 60.7$ ns

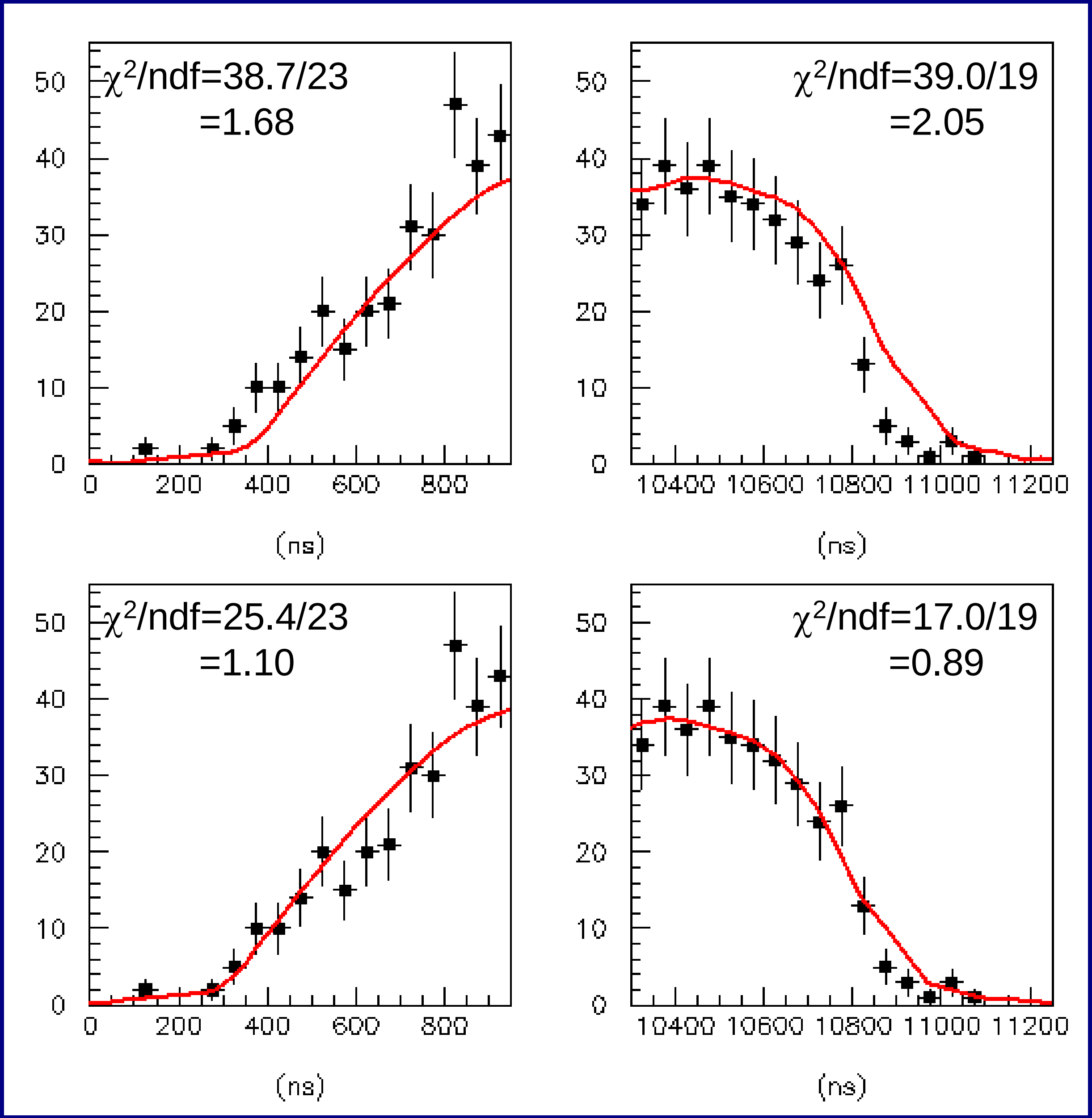


Zoom on the extractions leading and trailing edges

Extraction 2

$\delta t = 0$ ns

$\delta t = 60.7$ ns



Portable Cs clock calibrations (1) Time tagging

Start time tagging device

UTC distribution

End time tagging device

1PPS

Time-stamp
xx ns

Time-stamp
yy ns

1PPS

Δ = yy -xx

UTC propagation delay

Portable Cs clock calibrations (2) Delay measurement

Start

Signal propagation

End

Signal output

Oscilloscope

Δ_1

1PPS

Signal output

Oscilloscope

Δ_2

1PPS

$$\Delta = \Delta_2 - \Delta_1$$

Propagation delay

Time calibrations at CERN/CNGS

Equipment:

CTRI_1 (general purpose timing receiver, 0.1 ns accuracy) logging at the CCR the PolaRx2e 1PPs vs XLi 1PPS

CTRI_2 performing at HCA4 the kicker trigger time stamp and sending a delayed replica of the trigger to the WFD

WFD digitizing proton extractions measured by the BCT

The two CTRI get the UTC distributed by GMT

→Distribution delay measured by injecting the 1PPS output from a portable Cs-4000 in the two CTRI and by performing a two path fiber measurement: 10085 +- 2ns

Delay between the kicker signal at CTRI_2 and at the WFD: 30 +- 1 ns, determined with oscilloscope measurements

Delay between the instant protons pass in the BCT and the one the signal arrives at the WFD

→ measured with the Cs 1PPS injection in its calibration input and with a dedicated experiment: 580 +- 5 ns

Time calibrations at LNGS/OPERA:

Equipments:

- ESAT receiver + High accuracy GPS in the external laboratory + logging CTRI
- OPERA master clock card
- OPERA F.E. nodes
- Target Tracker (time response)

❖ The OPERA master clock card receives a signal from the ESAT every ms via 8.3 Km monomodal fiber

→ Calibration vs the CTRI input (40996 +-1 ns) with two ways fiber measurement (spare fiber) and travelling Cs

❖ The master clock card signal is propagated to the DAQ F.E. nodes (4263 +- 1 ns)

→ Calibration with two ways fibres measurement and with travelling CS

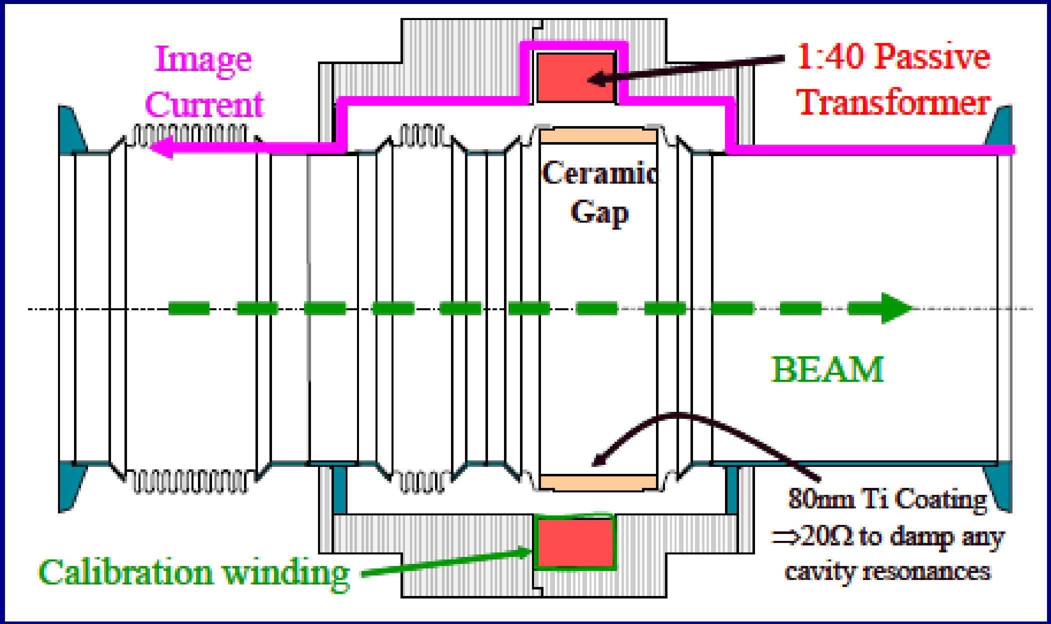
❖ FPGA latency on the F.E. in interpreting the clock signal as T0 for detector triggers (24.5 +-1 ns) measured by comparing DAQ output with oscilloscope measurements

❖ TT time response (scintillator, WLS fibers, PM, trigger chip, trigger delay, DAQ quantization, 59.6 ns):

→ Set of experimental measurements injecting ps UV laser ligth in the scintillator at various distances, parametrization of photons arrival rime distributions and discriminator time walk.

→ Simulation based on experimental measurement to account for position and pulse heigh dependence (RMS 7.4 ns)

Fast Beam Current Transformer



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

Analysis cross-checks

MC simulation:

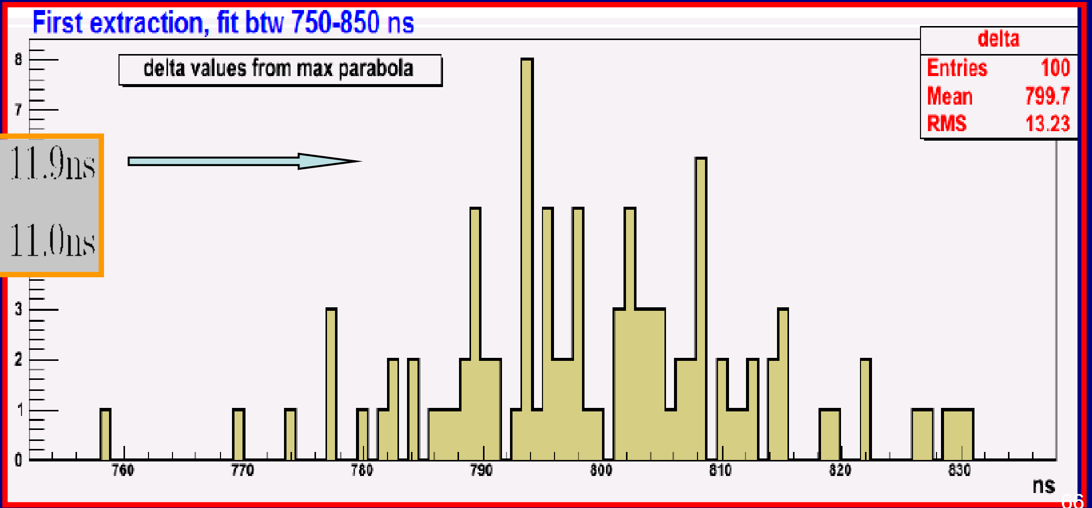
Generation of events from experimental PDF → ensemble of 100 data sets simulated (7000 OPERA neutrino interactions/data set)

Simulated data shifted in time by a constant quantity faking a time of flight deviation.

Applying same maximum likelihood procedure as for real data.

✓Average of the results of simulated experiments well reproducing the time shift applied to the simulation.
✓Average statistical error extracted from the likelihood analysis also reproducing the RMS distribution of the mean values.

First extraction	$\langle\delta\rangle$	799.7 ns (rms	13.2)	$\langle\sigma\rangle = 11.9$ns
Second extraction	$\langle\delta\rangle$	800.3 ns (rms	10.1)	$\langle\sigma\rangle = 11.0$ns



Muon Monitors

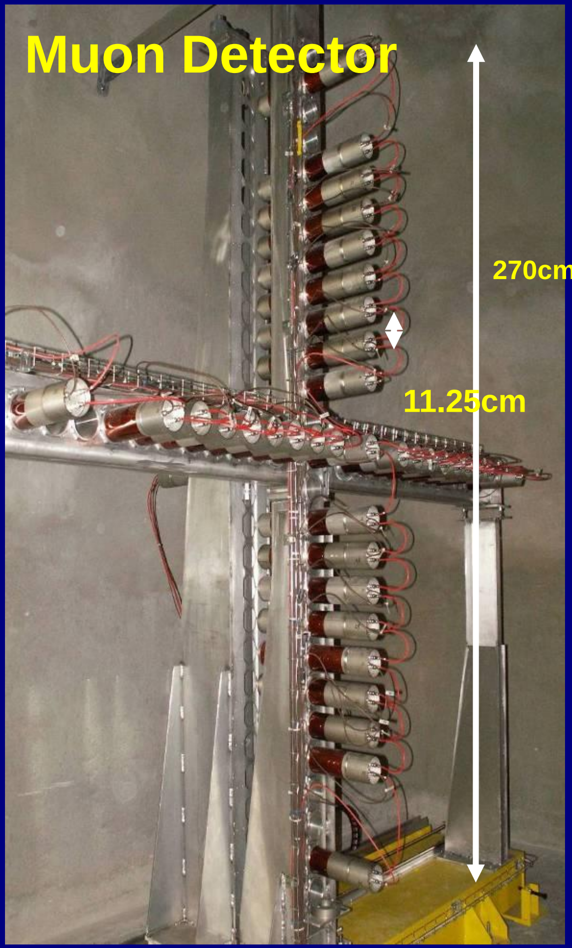
Very sensitive to any beam changes! → Online feedback on quality of neutrino beam

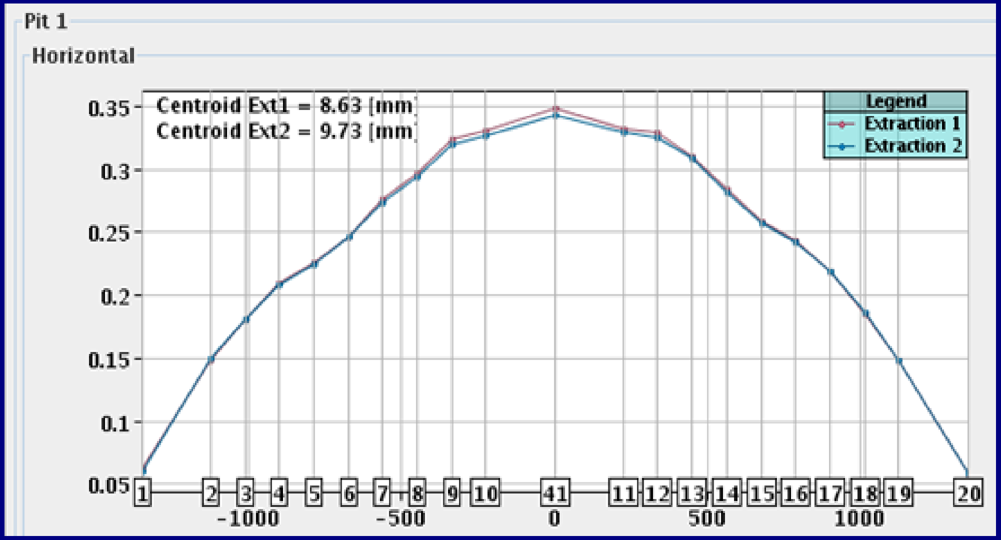
- Offset of **target vs horn** at 0.1mm level
  - Target table motorized
  - Horn and reflector tables not

→ Muon Profiles Pit 1

- Offset of **beam vs target** at 0.05mm level

→ Muon Profiles Pit 2



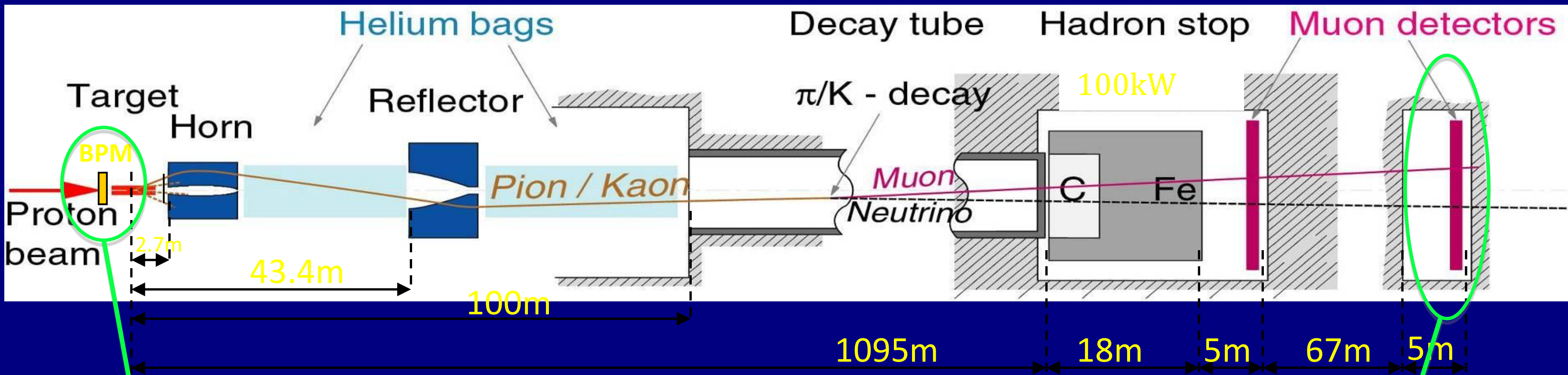


Centroid = $\sum(Q_i * d_i) / \sum(Q_i)$

Q_i is the number of charges/pot in the i-th detector,

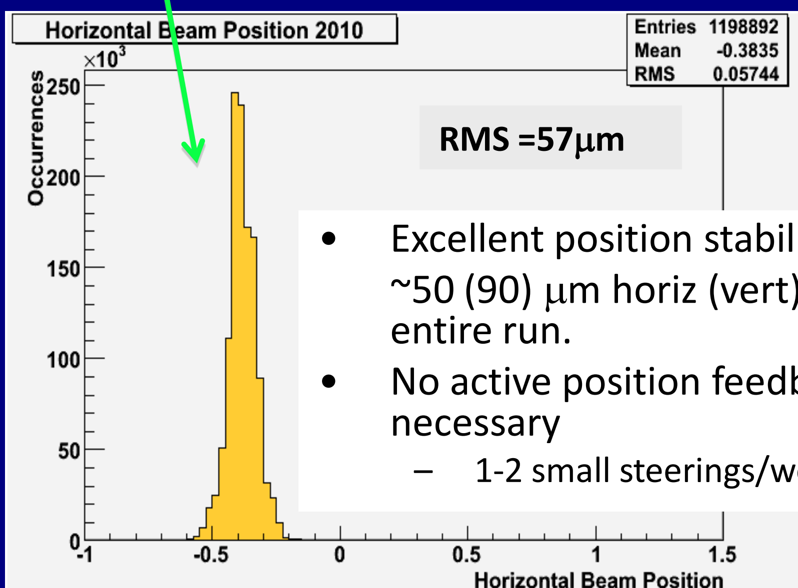
d_i is the position of the i-th detector.

Beam Stability



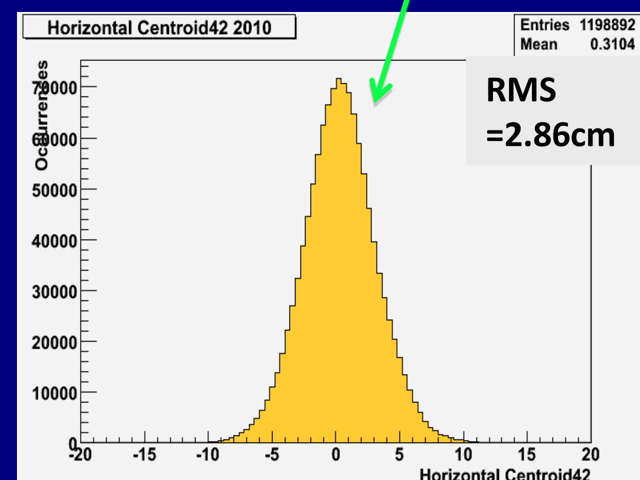
→ Beam position on target

→ Position stability of muon beam in 2[nd] pit is ~2-3cm rms



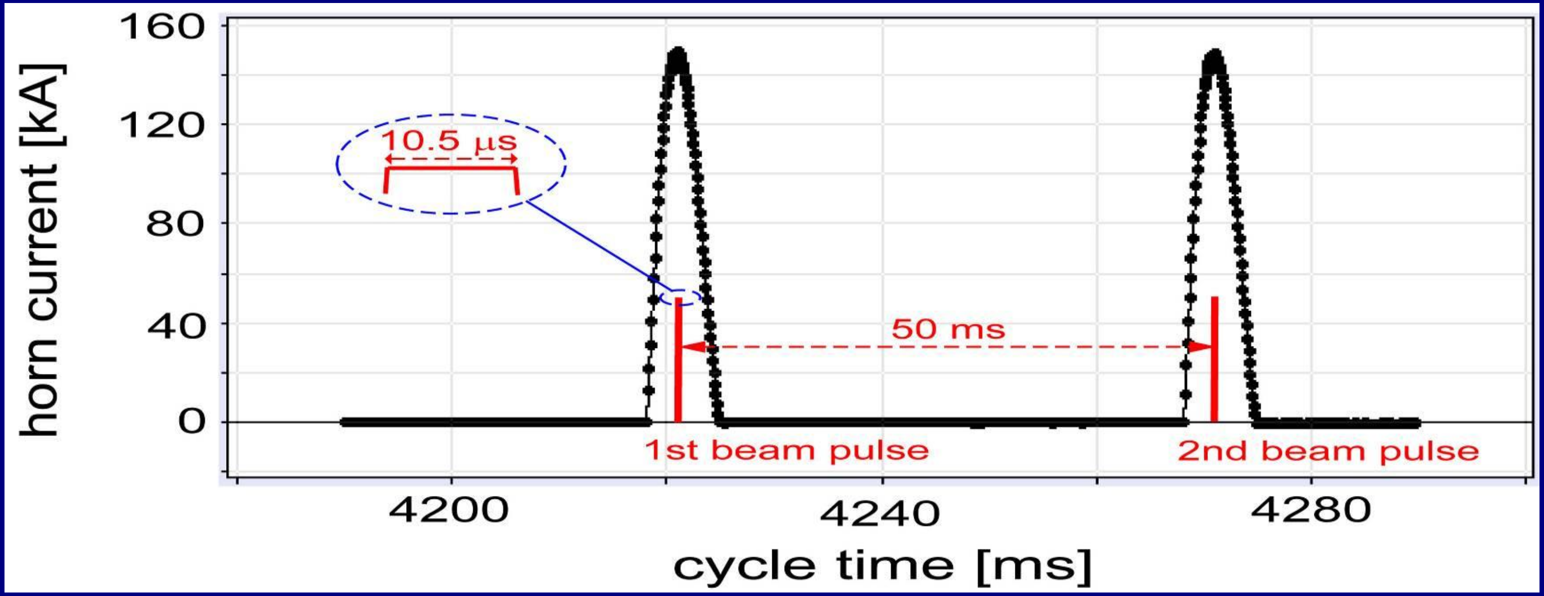
- Excellent position stability; ~50 (90) µm horiz (vert) over entire run.
- No active position feedback is necessary
  - 1-2 small steerings/week only

Horizontal beam position on target



Horizontal centroid

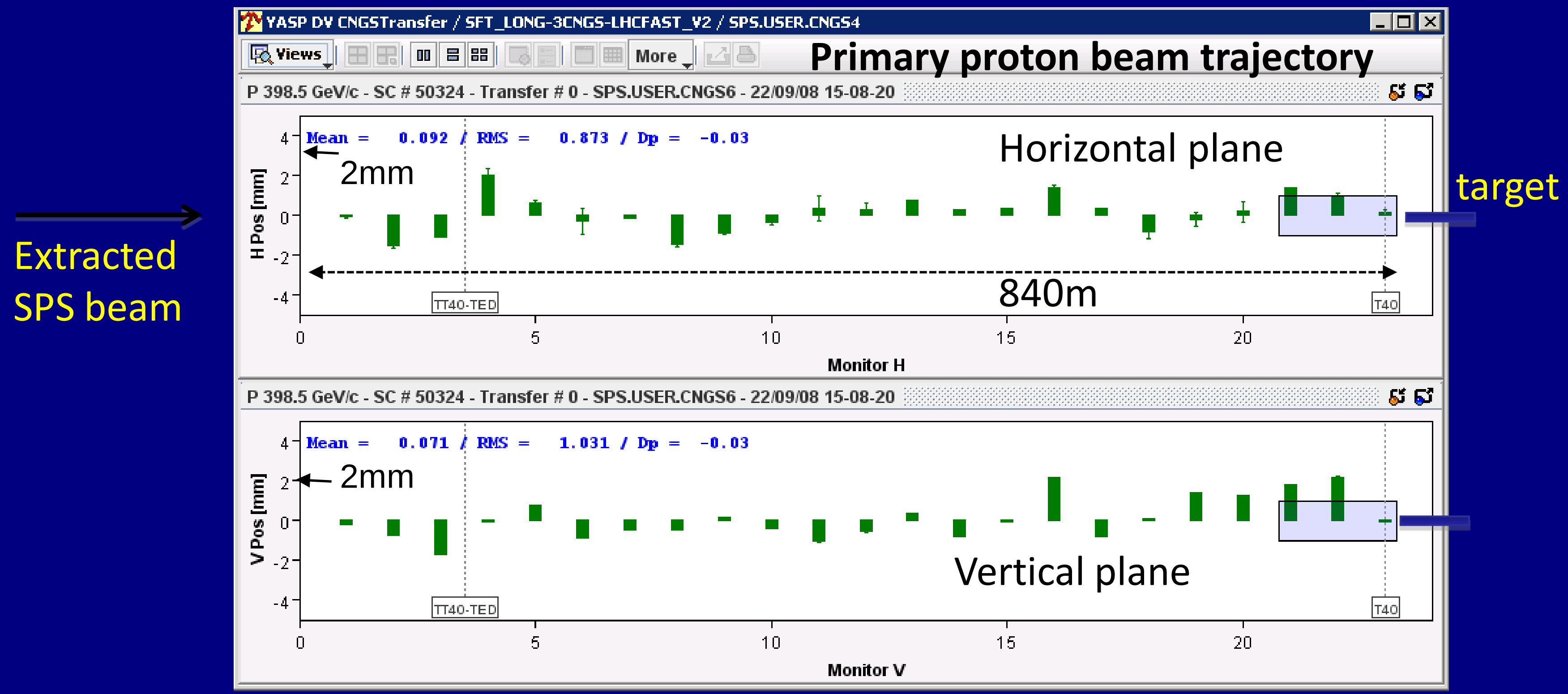
Horn/Reflector Power System



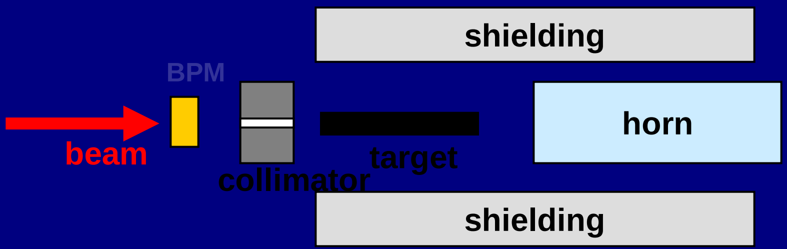
	Unit	HORN	REFLECTOR
Load Peak current	kA	150	180
Pulse duration	ms	6.5	9.8
Transformer ratio		16	32
Primary peak current	A	9375	5646
Charging voltage	V	6300	5800
Water flow for delta T=5C	l/min	75	48
Pressure	bar	1.2	1.2

CNGS Primary Beam

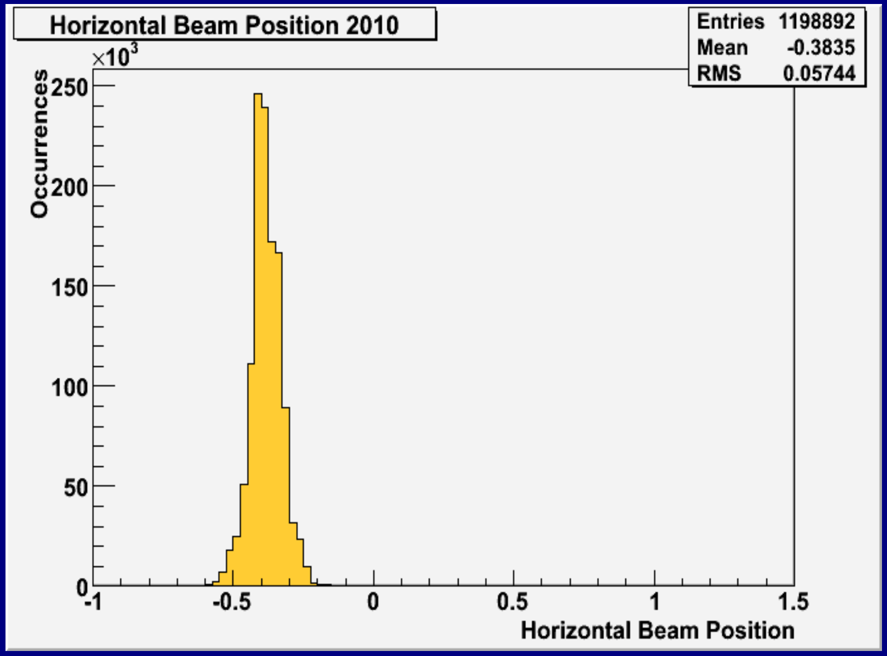
- Extraction interlock modified to accommodate the simultaneous operation of LHC and CNGS
  - Good performance, no incidents
- No extraction and transfer line losses
- Trajectory tolerance: 4mm, last monitors to +/-2mm and +/- 0.5mm (last 2 monitors)
  - Largest excursion just exceed 2mm

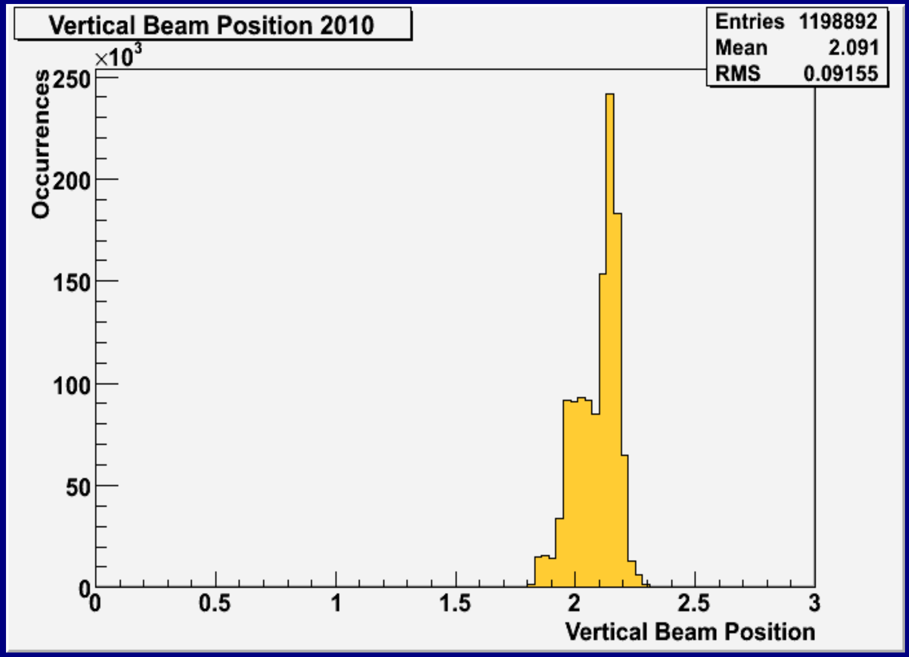


Beam Position on Target



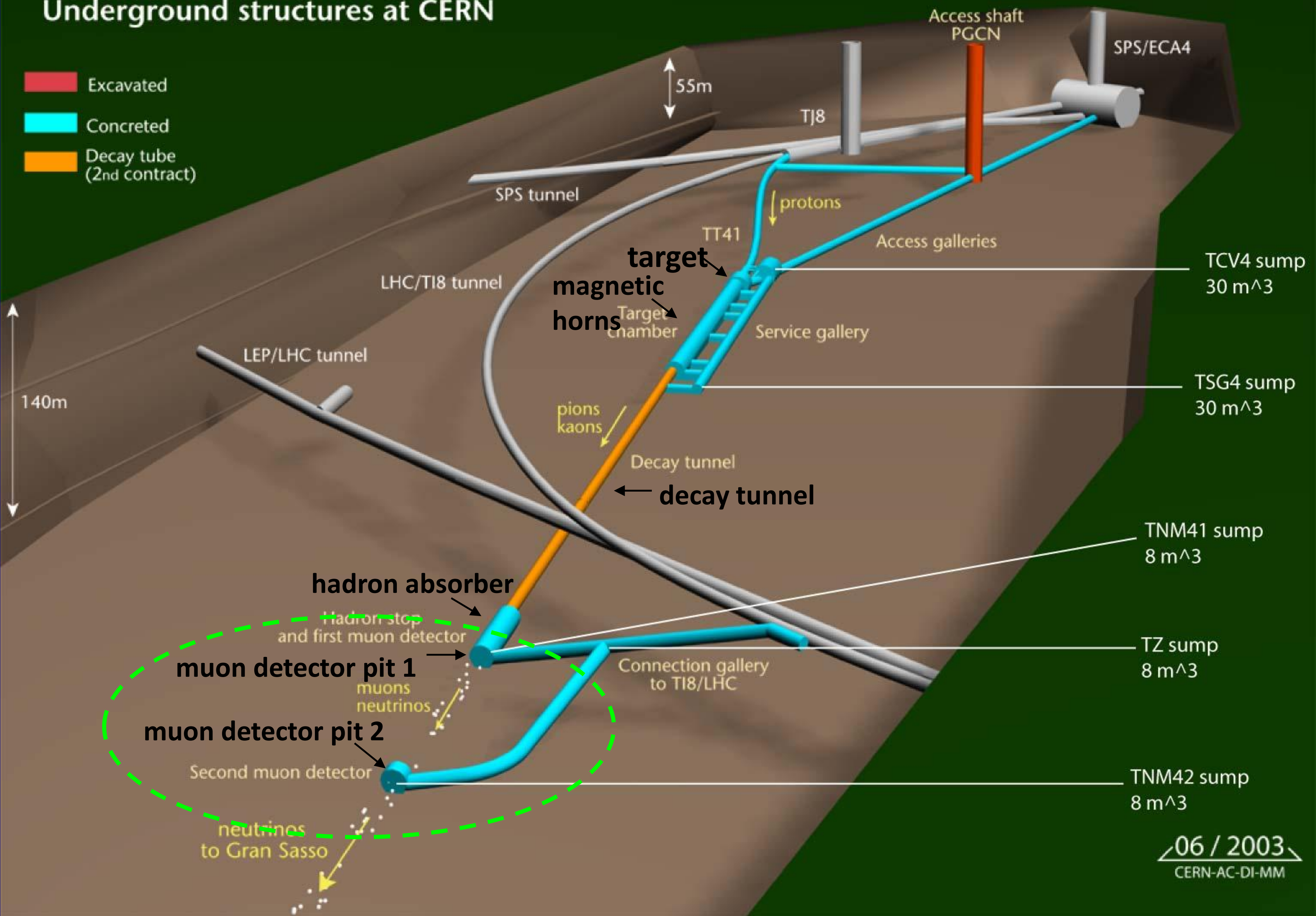
- Excellent position stability; ~50 (90) μm horiz (vert) over entire run.
- No active position feedback is necessary
  - 1-2 small steerings/week only





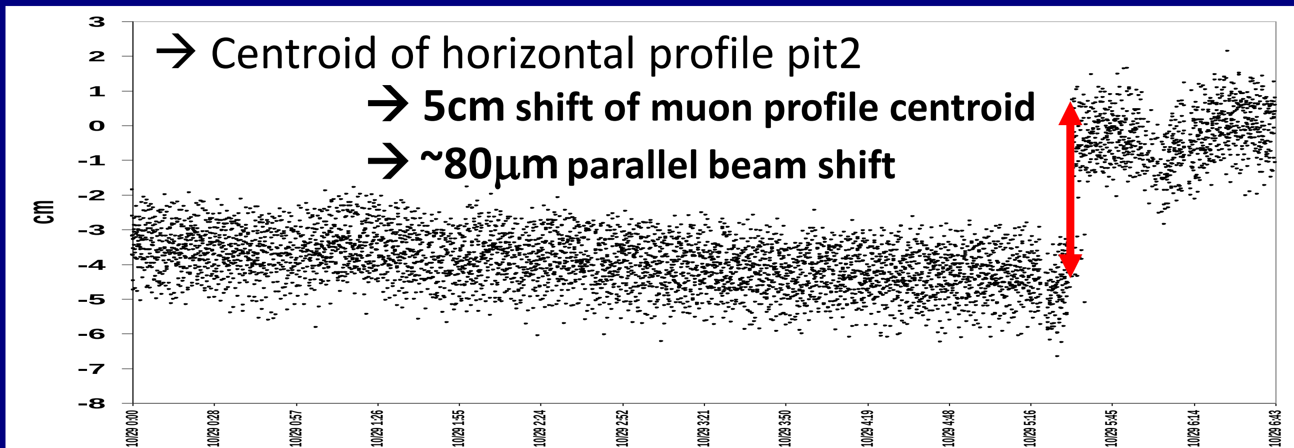
Horizontal and vertical beam position on the last Beam Position Monitor in front of the target

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

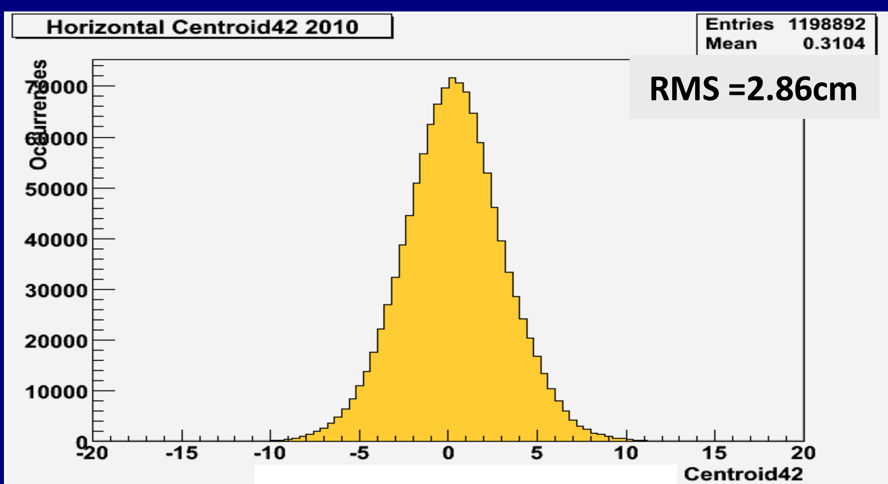


Beam Stability Seen on Muon Monitors

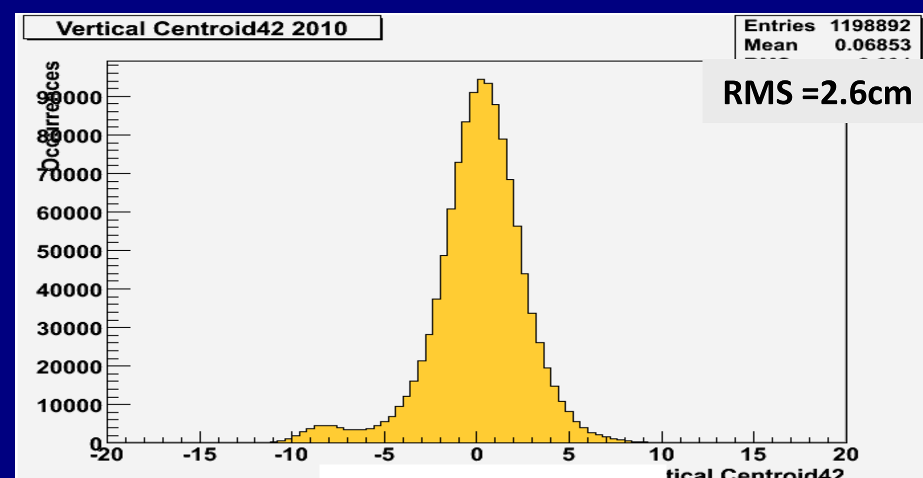
- Beam position correlated to beam position on target.
  - Parallel displacement of primary beam on T40



→ Position stability of muon beam in pit 2 is ~2-3cm rms

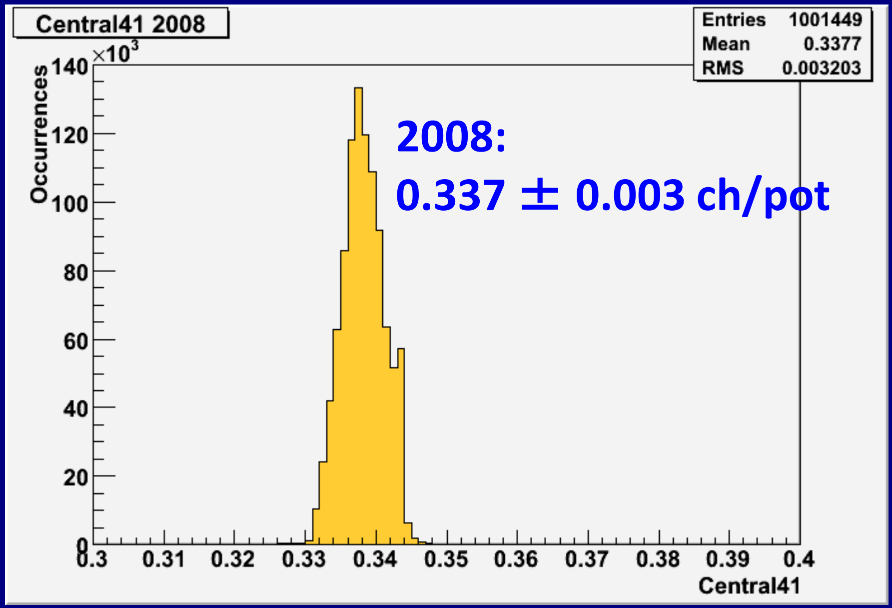


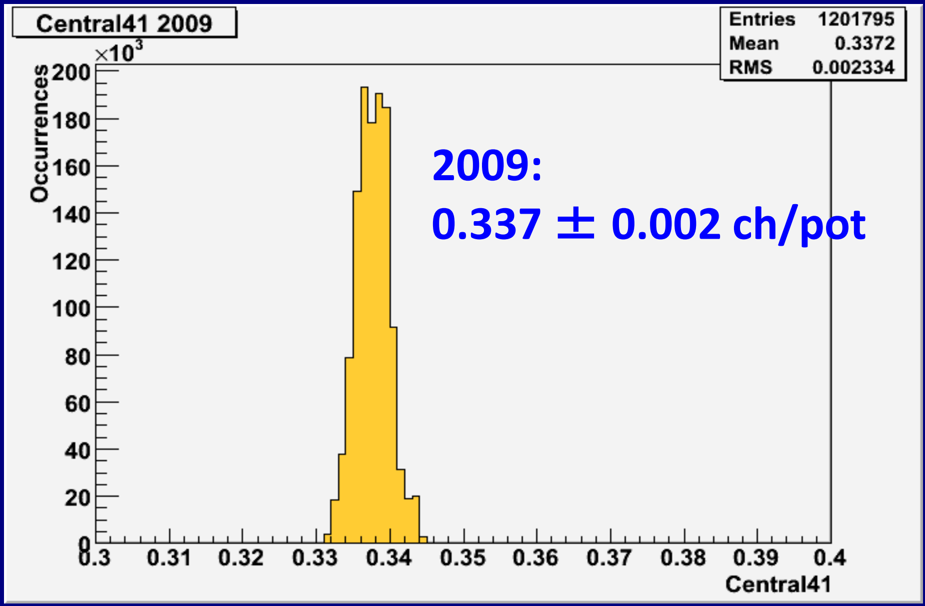
Horizontal centroid

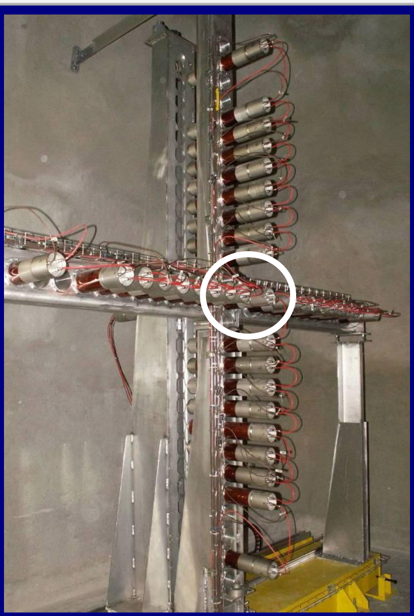


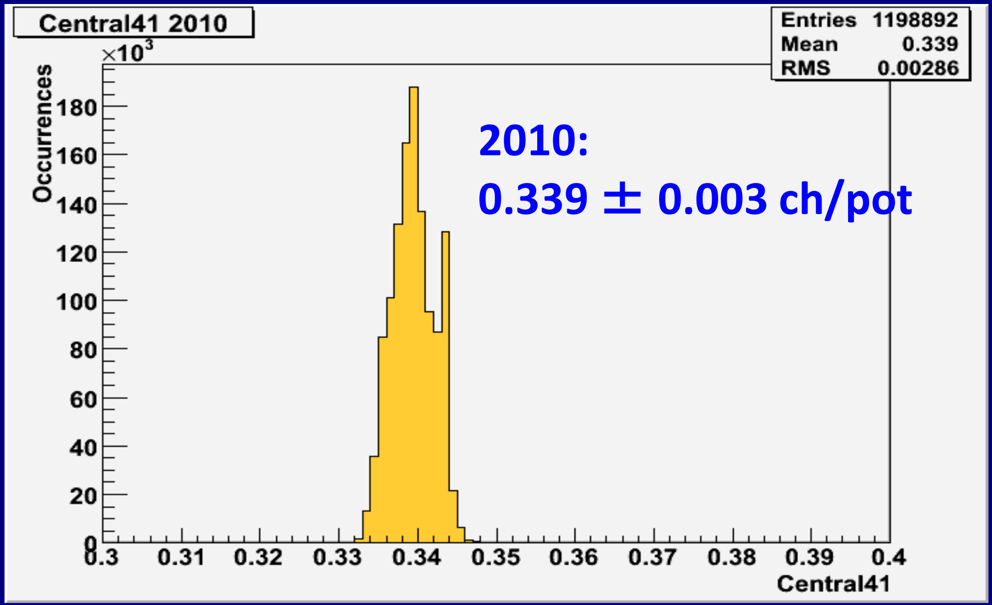
Vertical centroid

Central Muon Detector Stability, 1st Pit

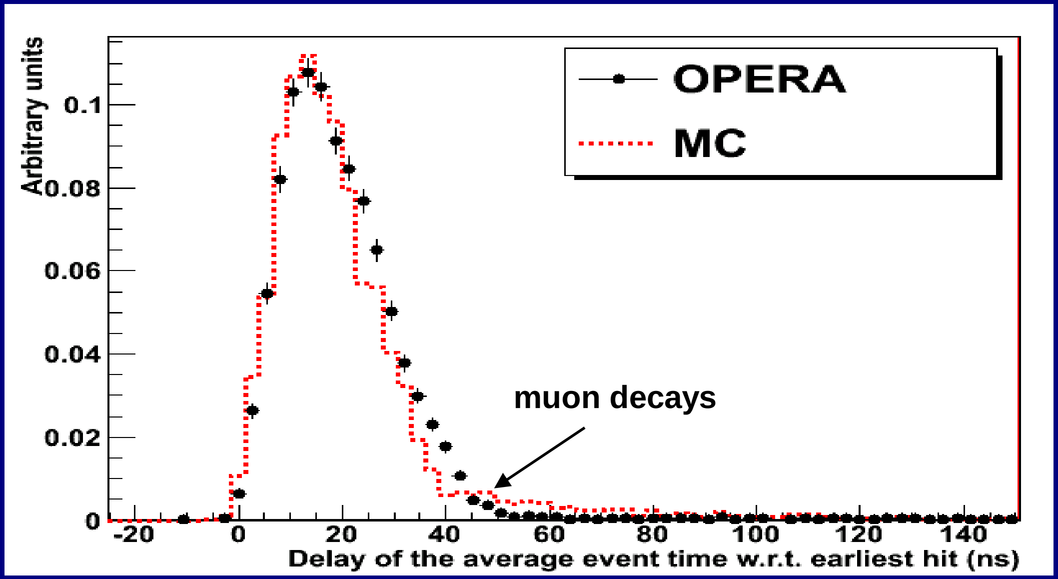




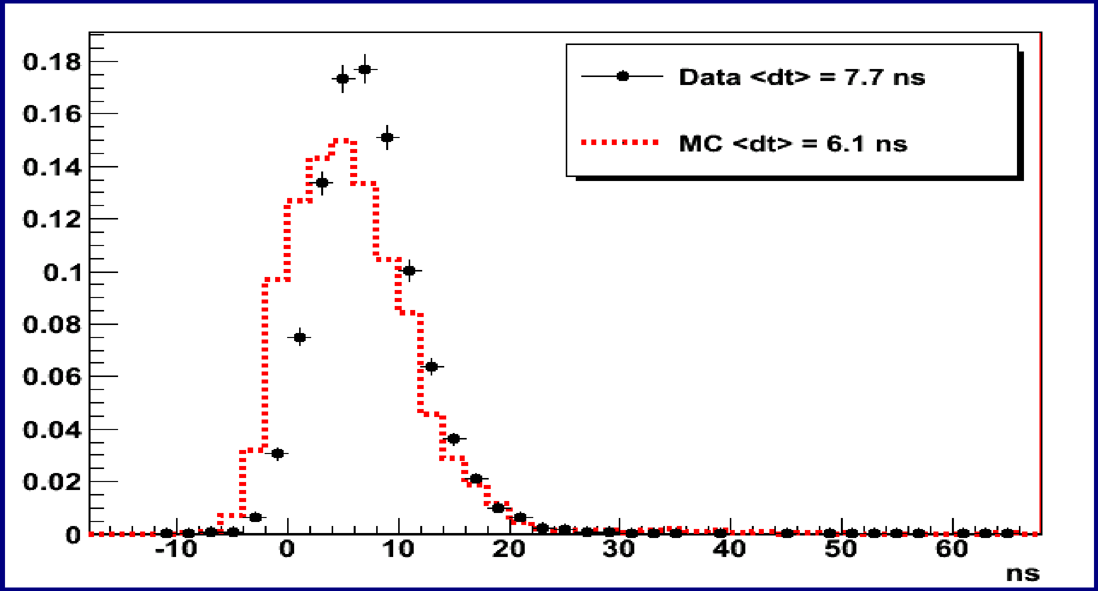




Data/MC agreement for earliest hit timing



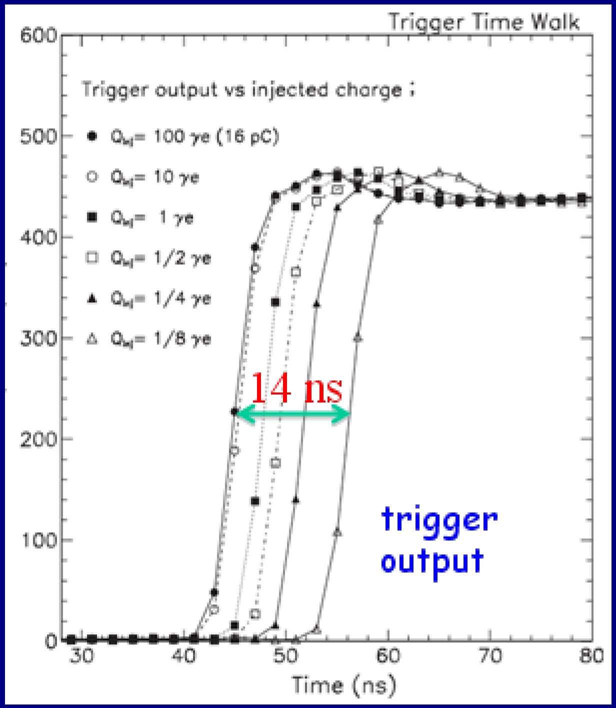
DATA vs MC
Earliest hit vs average event time (z corrected)



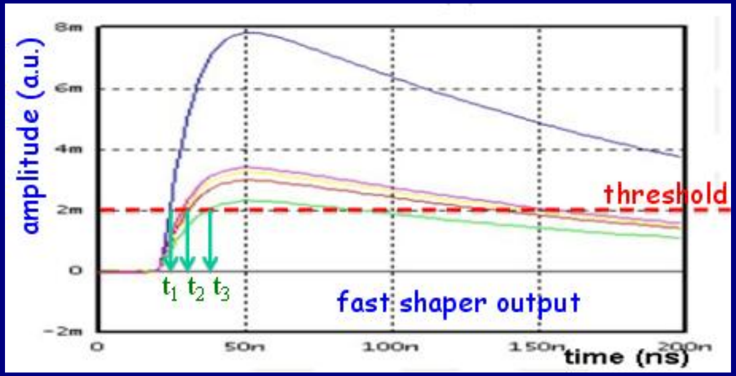
DATA vs MC
Earliest hit vs average muon track time
(z corrected)

Target Tracker simulation

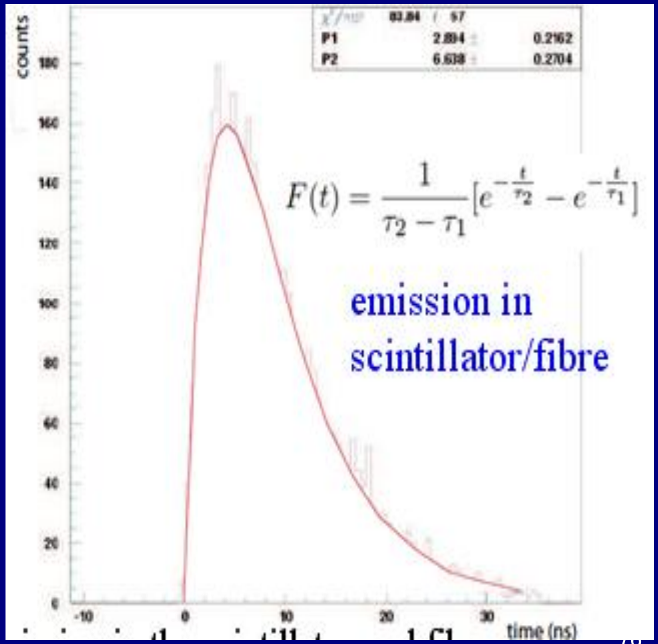
Full GEANT simulation of detector response with detailed geometry and time response parametrization from experimental measurements



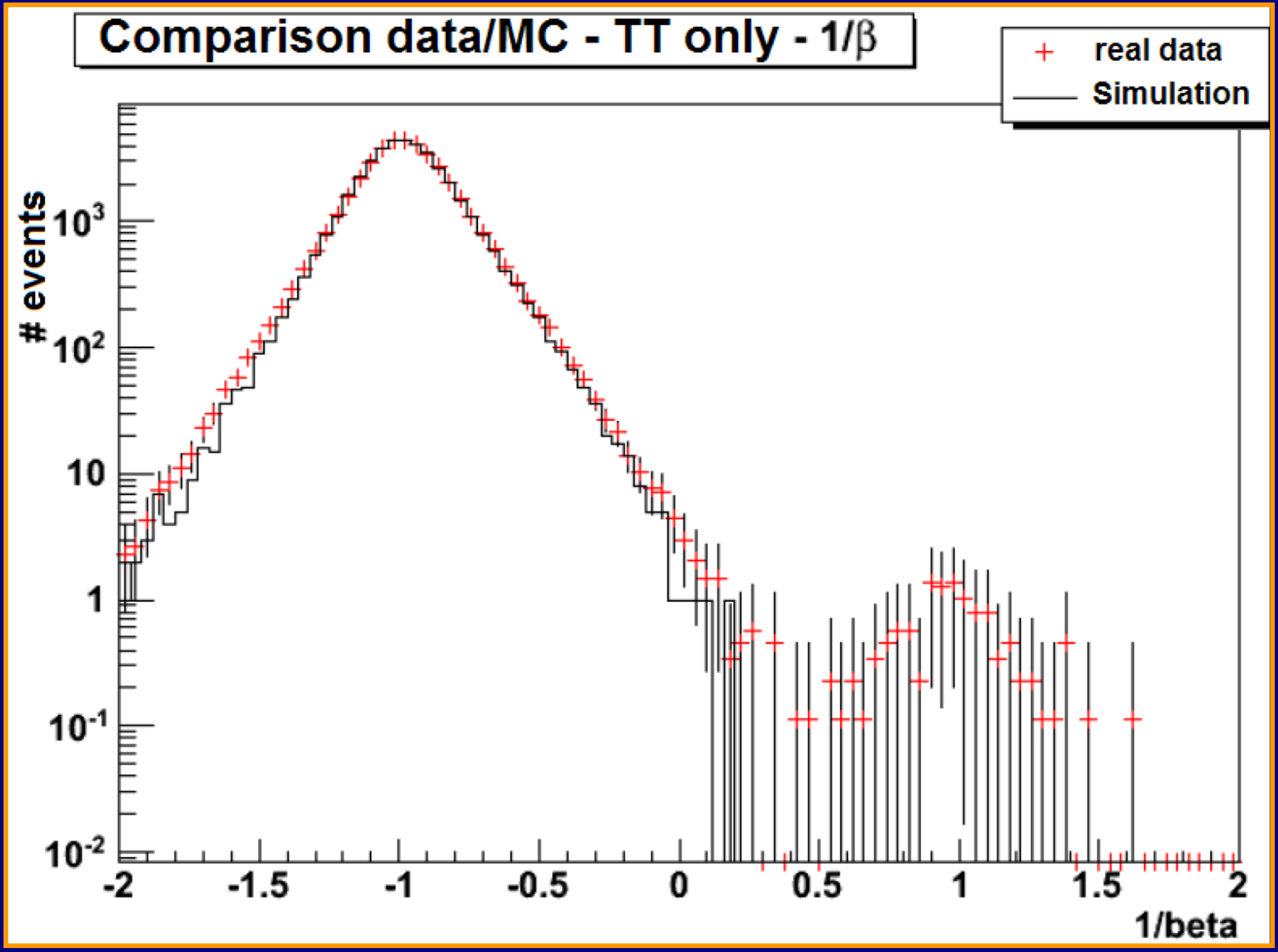
Trigger threshold time walk



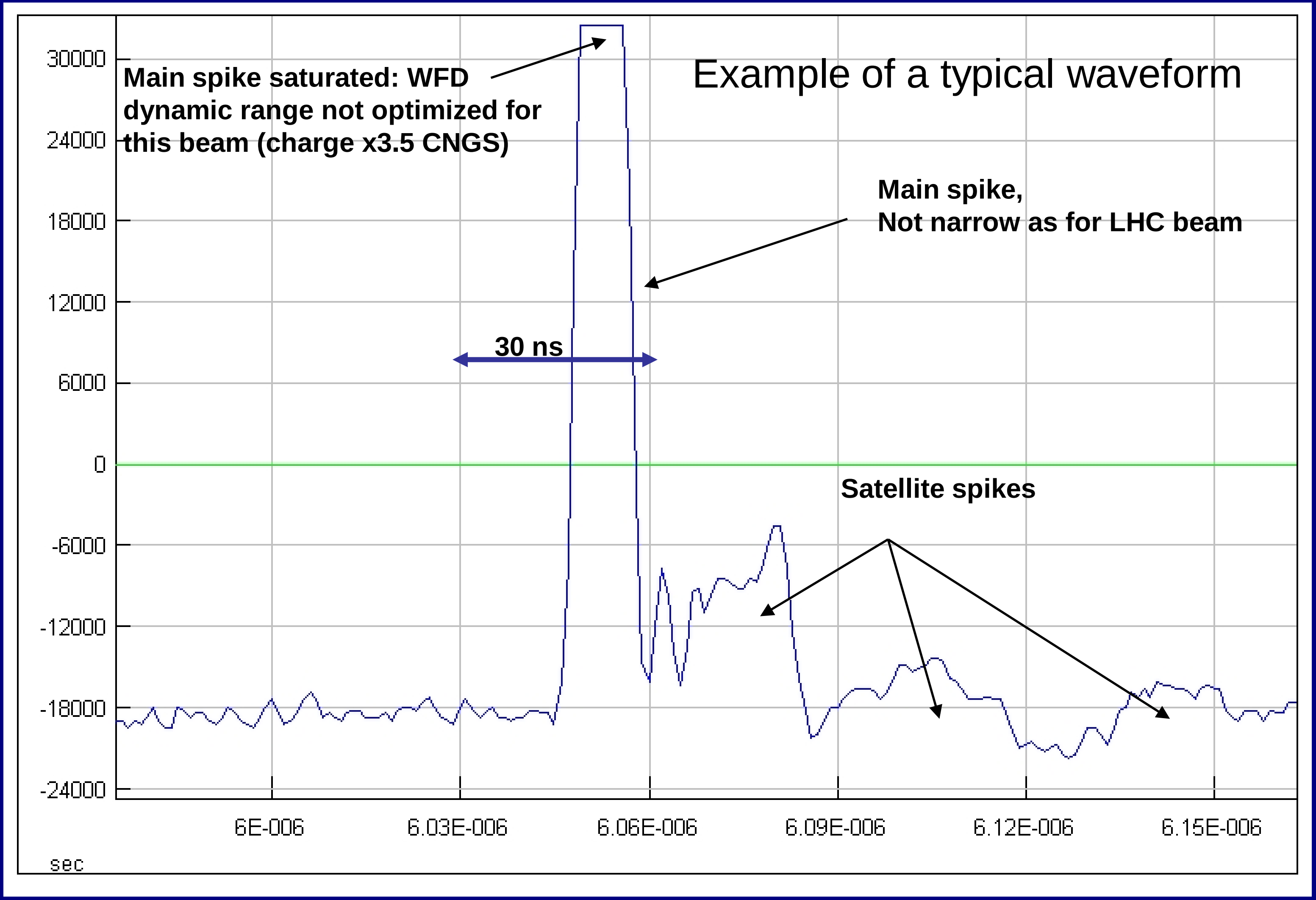
Arrival time distributions of photons on the phototcatode



Simulation extensively validated on the atmospheric neutrinos and C.R. analysis (upward going muons)



First CNGS bunched beam test made available much earlier than anticipated: start 21/10/2011 end 6/11/2011



Can we compare v_ν to c given that ν have mass and travel through matter ?

Mass effect

$m_{\nu_e}^{eff} < 2eV$ from T_e spectrum in Tritium β-decay experiments

$$< E_\nu >= 17GeV \quad \Rightarrow \quad 1 - \frac{v_\nu}{c} < 10^{-19}$$

Effect of index of refraction in the Earth crust (SM Weak Interactions)

$$n = 1 + \frac{V}{E} \approx 1 + 10^{-23}$$

Both effects are unmeasurable by many orders of magnitute

Small systematic effects: Tides

Effect smaller then $\pm 1\ cm$

Effect on LEP ring: $1\,mm$ on $26.7\,km \Rightarrow 2.7\,cm$ on $730\,km$