Новые результаты эксперимента “OPERA"

доклад на Совете НИИЯФ и ОЯФ физического фак-та МГУ

28 октября 2011 года

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НИИЯФ МГУ

22 сентября

http://arxiv.org/ftp/arxiv/papers/1109/1109.4897.pdf

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

Abstract

The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light (v-*c*)/*c* = (2.48 ± 0.28 (stat.) ±0.30 (sys.))×10-5.

As usual, I am sending you this CERN press release before we issue it to the media.
Unusually this time, however, I feel that it needs a few words of introduction.
The OPERA collaboration has measured the time of flight of neutrinos sent from CERN to Gran Sasso, along with the distance they cover. These measurements appear to show that the neutrinos are travelling faster than light. When a collaboration makes a surprising observation such as this and is unable to account for it, the ethics of Science demand that the results be made available to a wider community, to seek scrutiny and to encourage independent experiments. That's why when the spokesperson of the OPERA collaboration asked me whether they could hold a seminar here, I said yes.
Given the potential impact of such a measurement, I felt it important for CERN formally to make its position clear. That's the reason for the cautiously worded statement we're sending to the media today.

23.09.2011 Rolf Heuer, CERN DG

23 сентября - семинар в CERN
26 сентября – семинар в Гран-Сассо
семинар в KEK
Дубна, ИЯИ РАН, ФИАН, ИТЭФ, МИАН, ГАИШ

Настоящий доклад использует материалы семинара D. Autiero - CERN - 23 September 2011


OPERA

The OPERA Collaboration
160 physicists, 30 institutions, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
LNGS Assergi
Bari
Bologna
LNF Frascati
L'Aquila
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

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

We profited from the collaboration of individuals and groups that worked with us for the various metrology measurements reported here:

CERN: CNGS, Survey, Timing and PS groups

The geodesy group of the Università Sapienza of Rome

The Swiss Institute of Metrology (METAS)

The German Institute of Metrology (PTB)

Principle of the neutrino velocity measurement

Definition of neutrino velocity:

ratio of precisely measured baseline and time of flight

Time of flight measurement:

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

accurate determination of the baseline (geodesy)

expected small effects: long baseline required

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

Past experimental results

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

high energy (E_ν > 30 GeV) short baseline experiment. Tested deviations down to $|v-c|/c \leq 4\times10^{-5}$ (comparison of muon-neutrino and muon velocities).

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

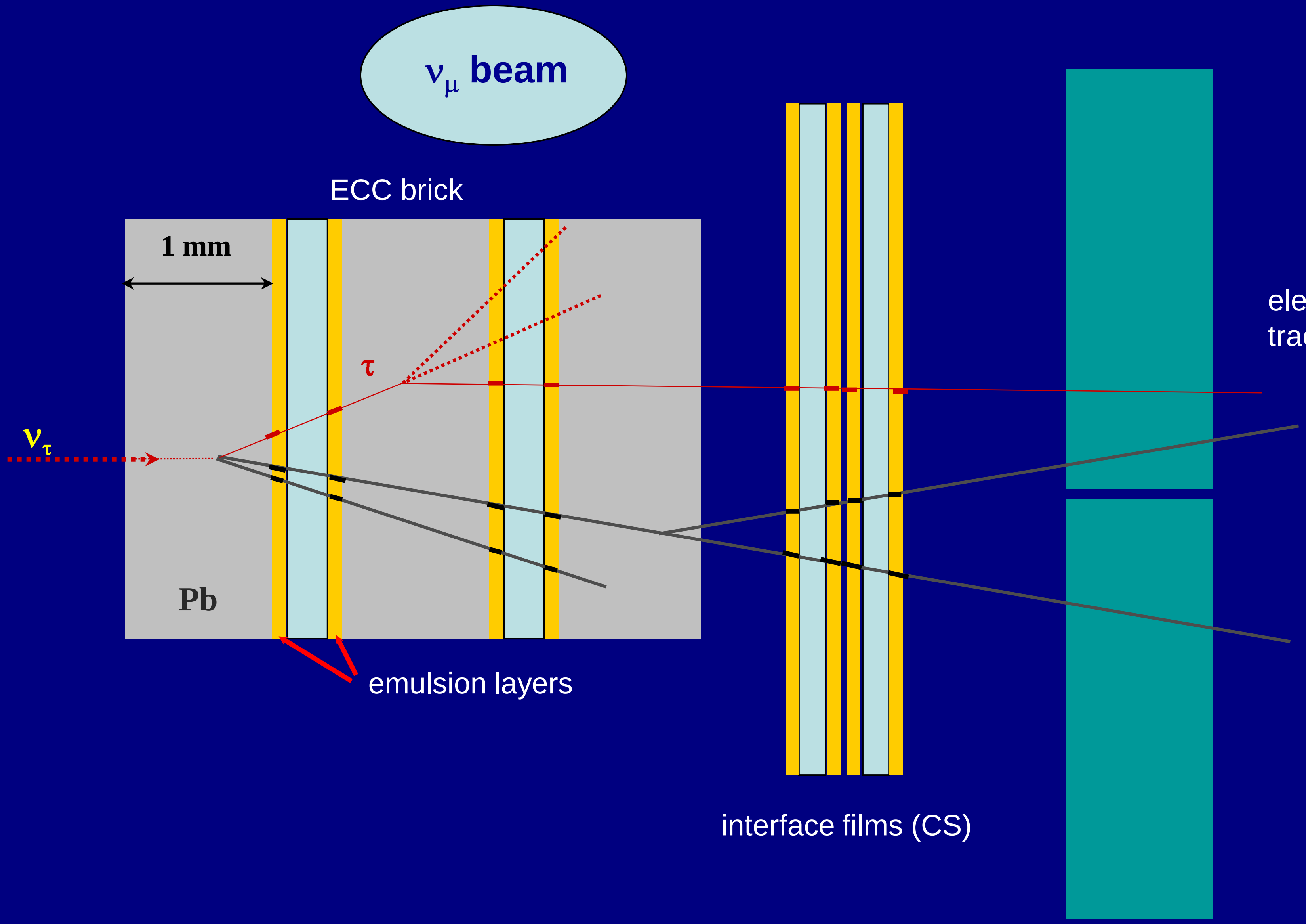
electron (anti) neutrinos, 10 MeV range, 168'000 light years baseline.
$|v-c|/c \leq 2\times10^{-9}$.
Performed with observation of neutrino and light arrival time.

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.
$(v-c)/c = 5.1 \pm 2.9\times10^{-5}$ (1.8 σ).

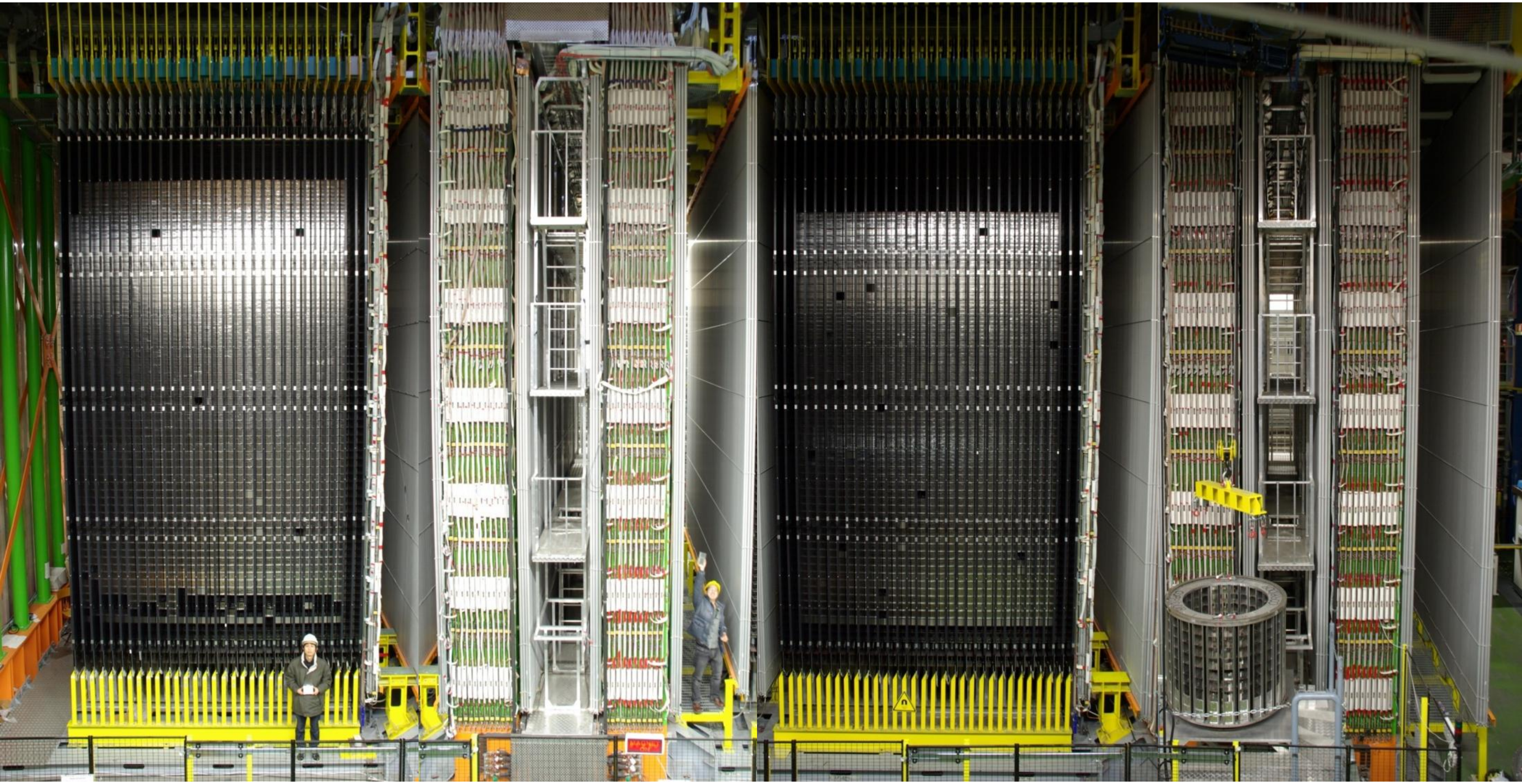
THE DESIGN OF THE OPERA EXPERIMENT

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



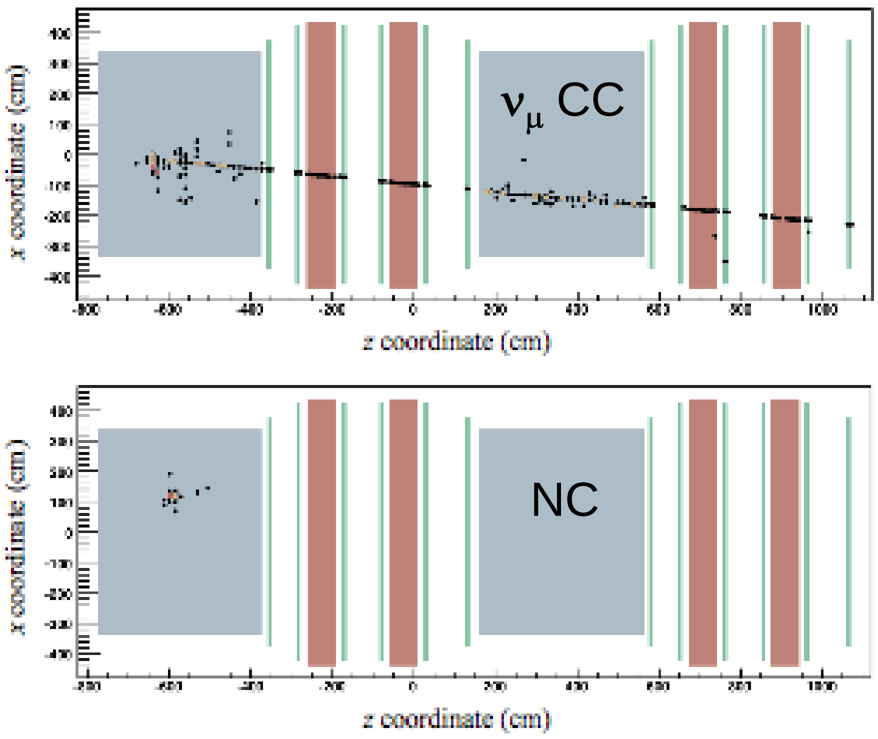
THE IMPLEMENTATION OF THE PRINCIPLE

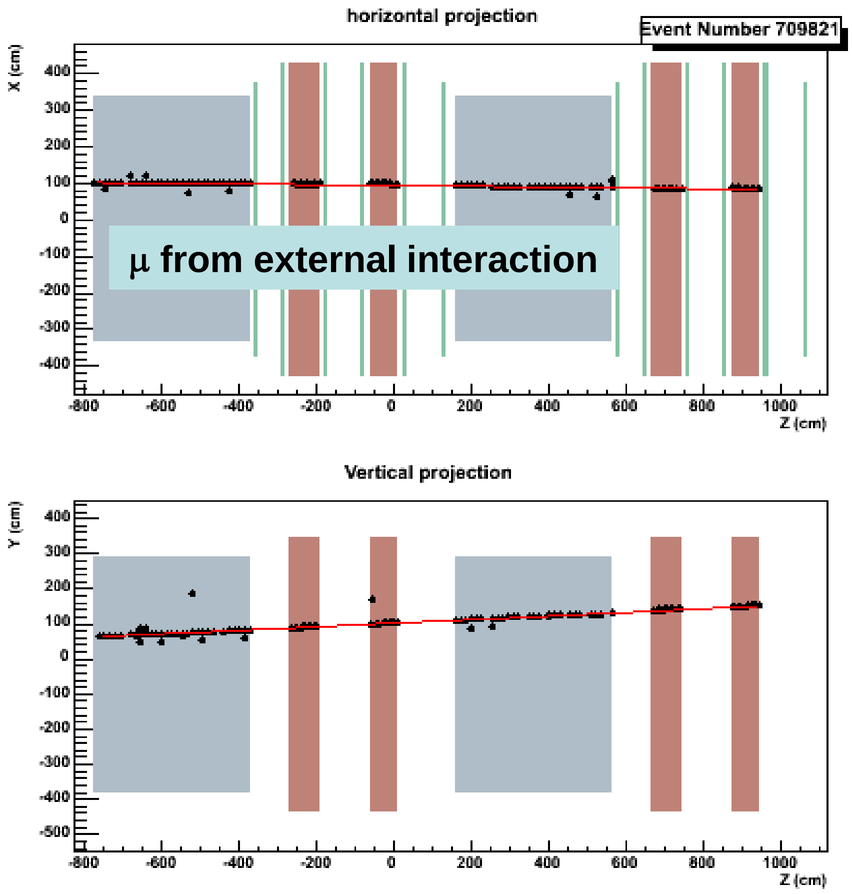
SM1 SM2



Target area Muon spectrometer

“INTERNAL” and “EXTERNAL” OPERA EVENTS





The LNGS underground physics laboratory

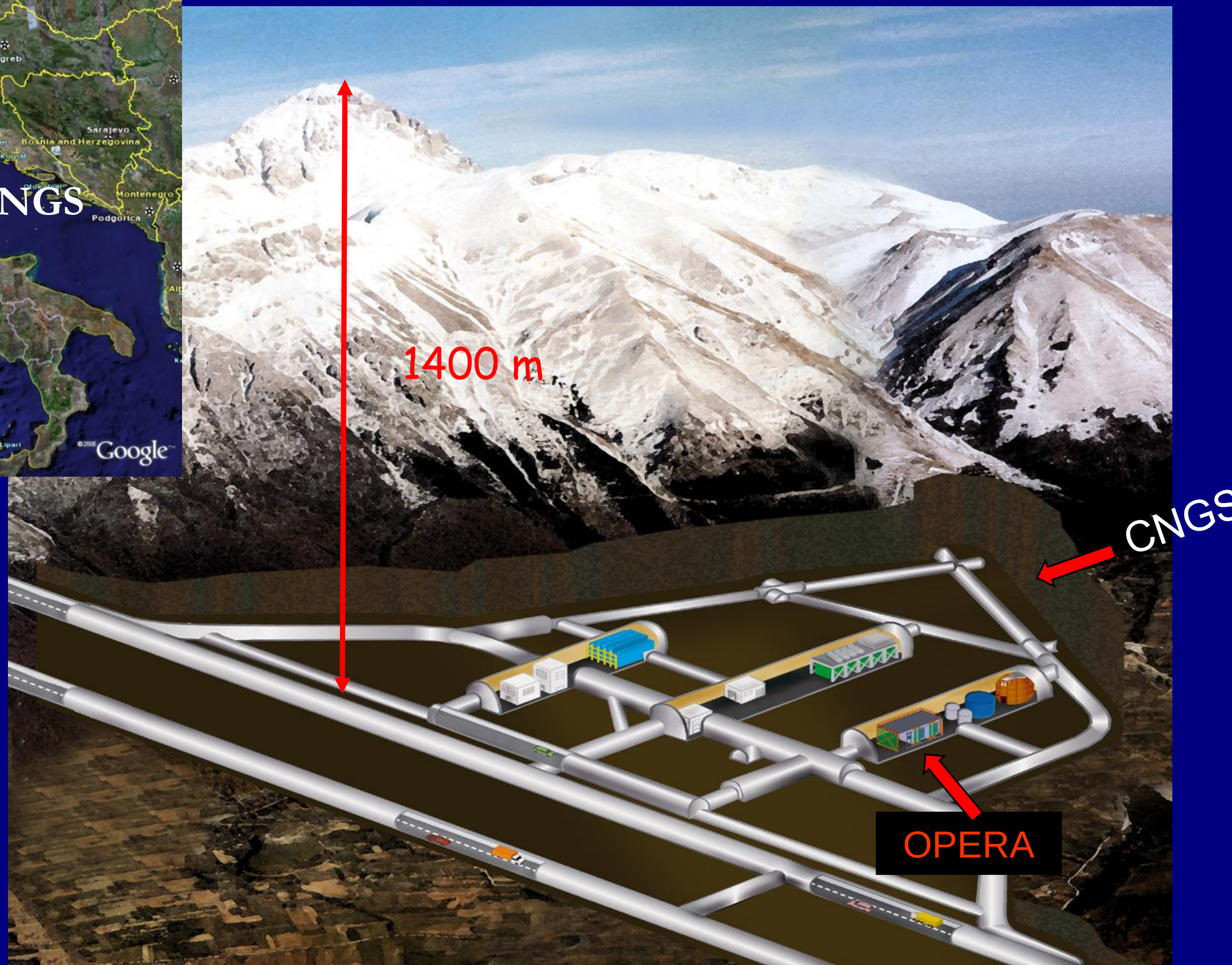
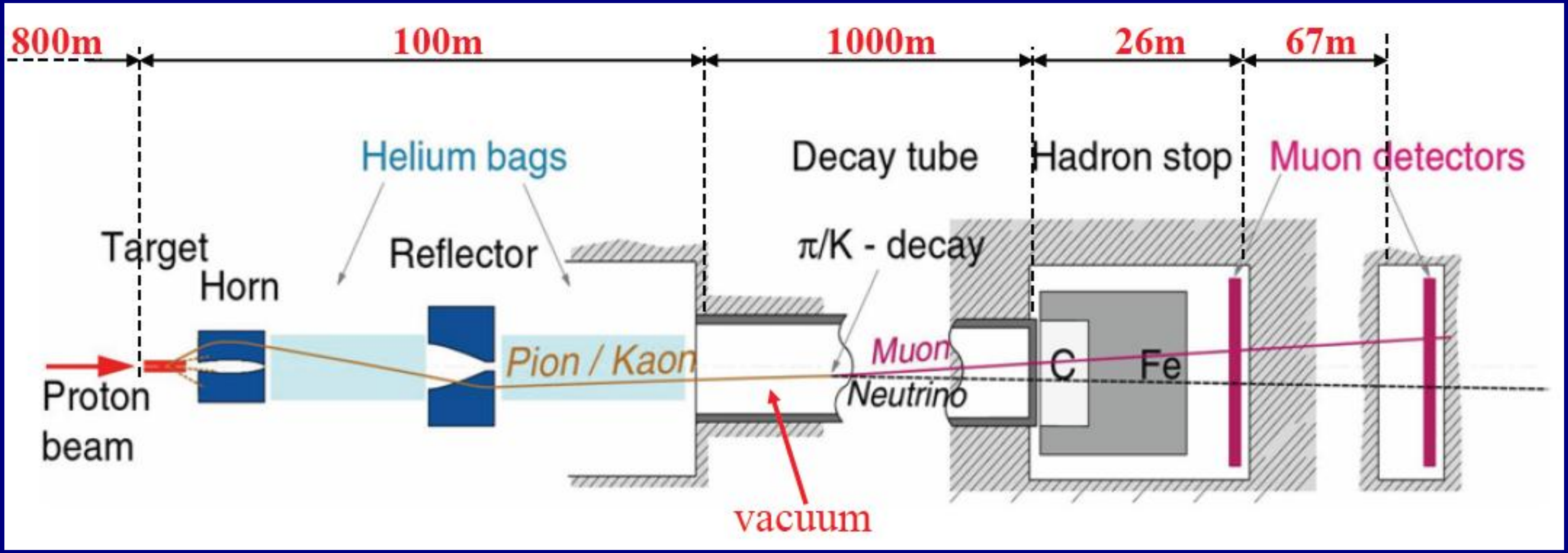


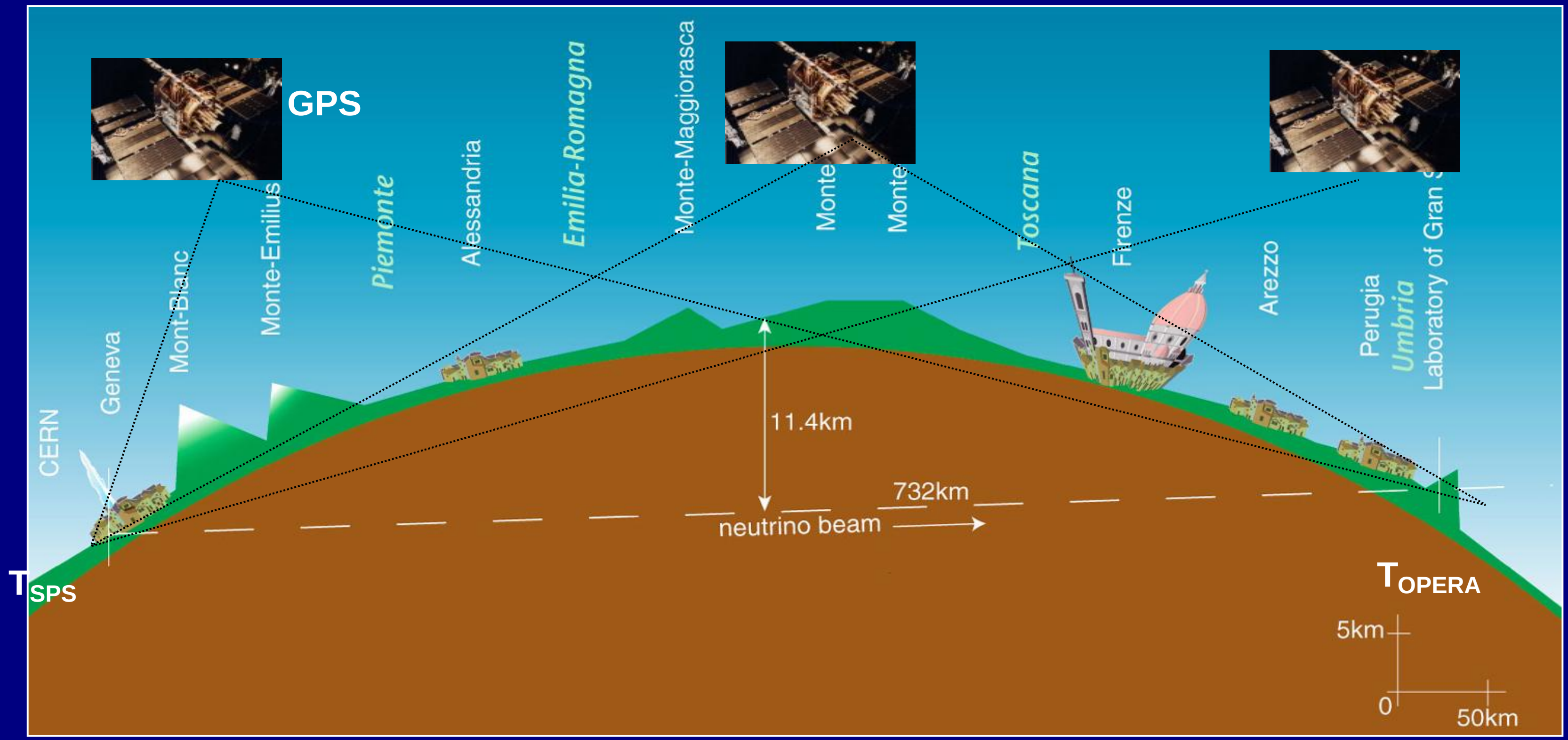
Fig. 1: Artistic view of the SPS/CNGS layout

THE CNGS neutrino beam



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

CNGS events selection



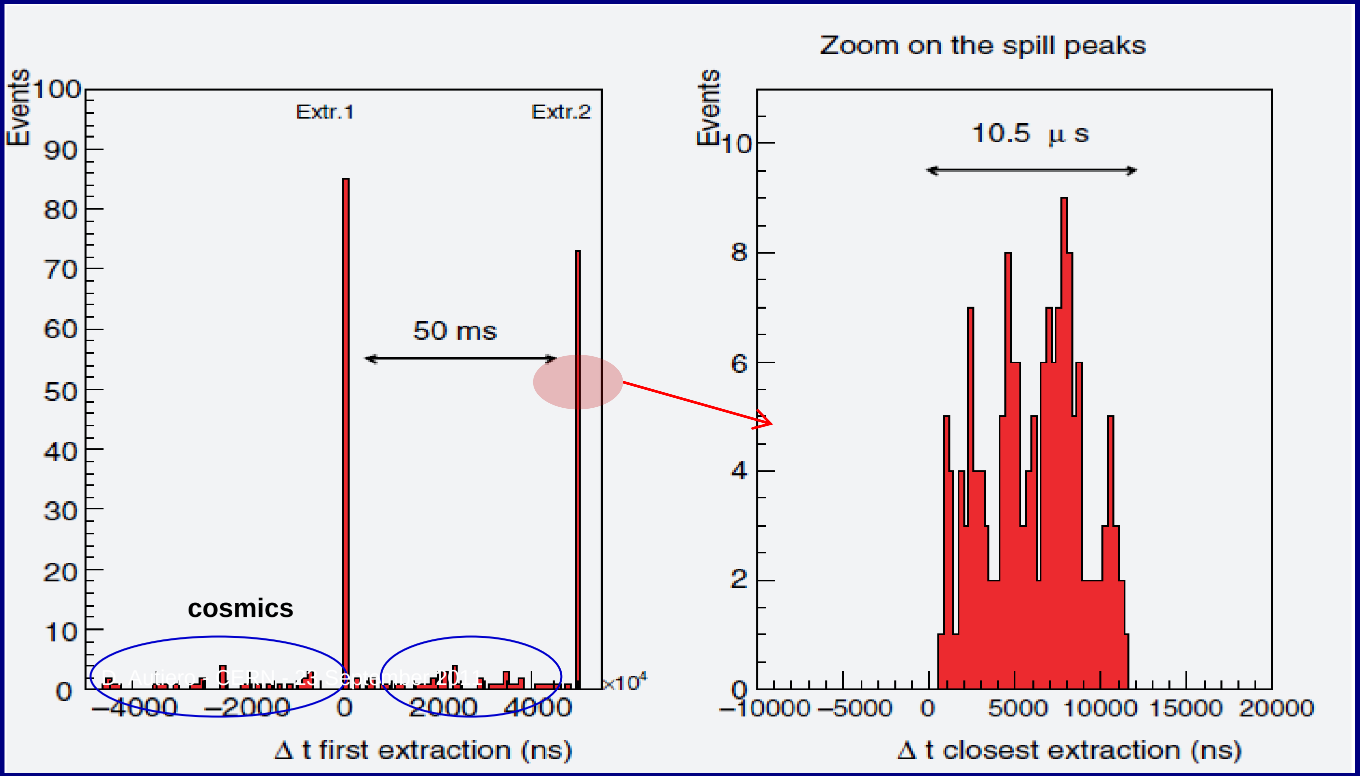
Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

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

Synchronisation with standard GPS systems ~100 ns (inadequate for our purposes)

Real time detection of neutrino interactions in target and in the rock surrounding OPERA

CNGS events selection



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

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

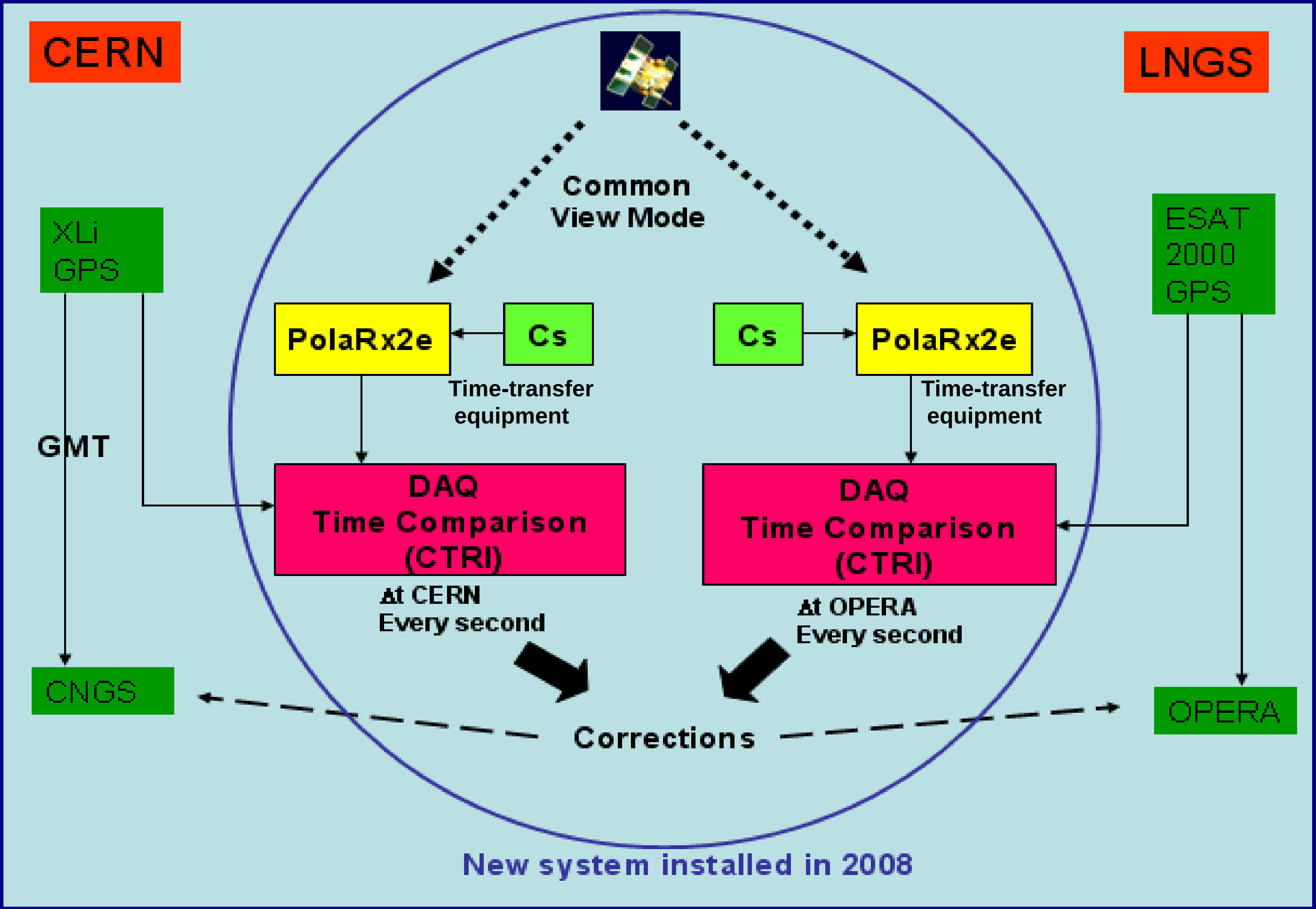
Selection procedure kept unchanged since first events in 2006

OPERA sensitivity

- High neutrino energy - high statistics ~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 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


PolaRx2e
Cs 4000
CERN


LNGS
ESAT 2000
PolaRx2e
Cs 4000

GPS common-view mode

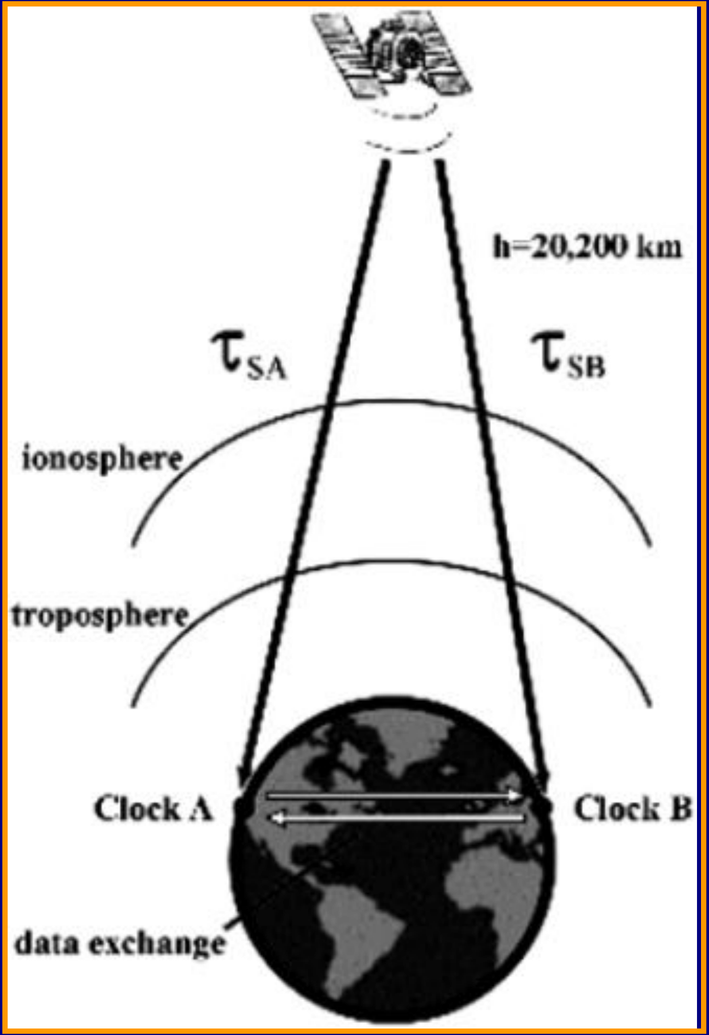
Standard GPS operation:

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

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

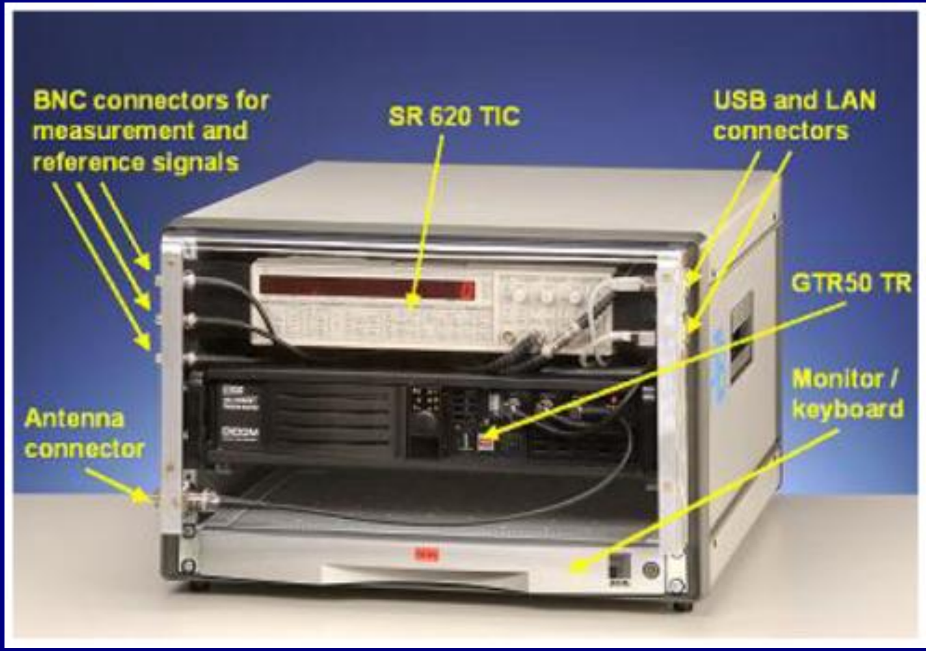
x, y, z known from former dedicated measurements: determine time differences of local clocks (both sites) w.r.t. the satellite, by offline data exchange

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



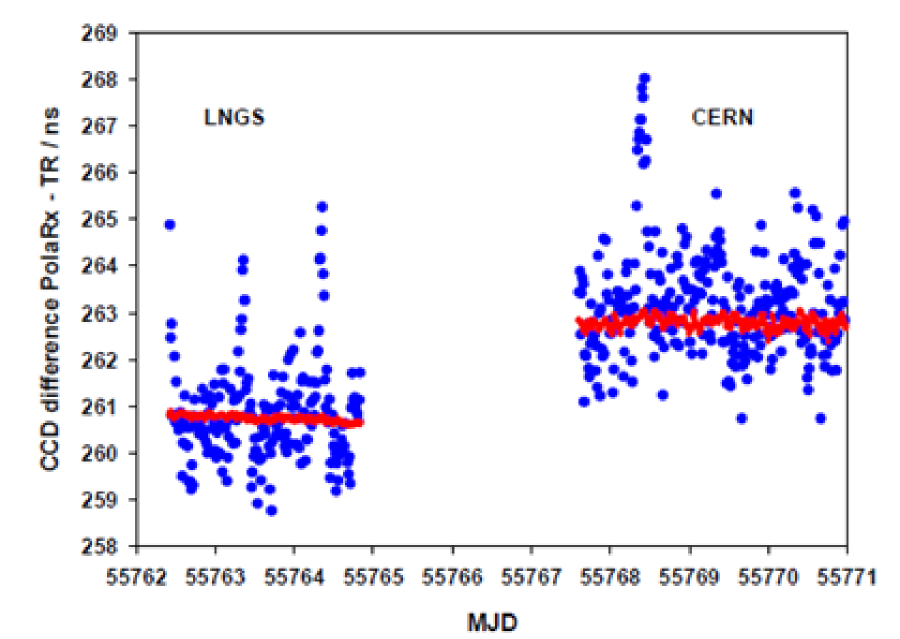
CERN-OPERA inter-calibration cross-check

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt



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

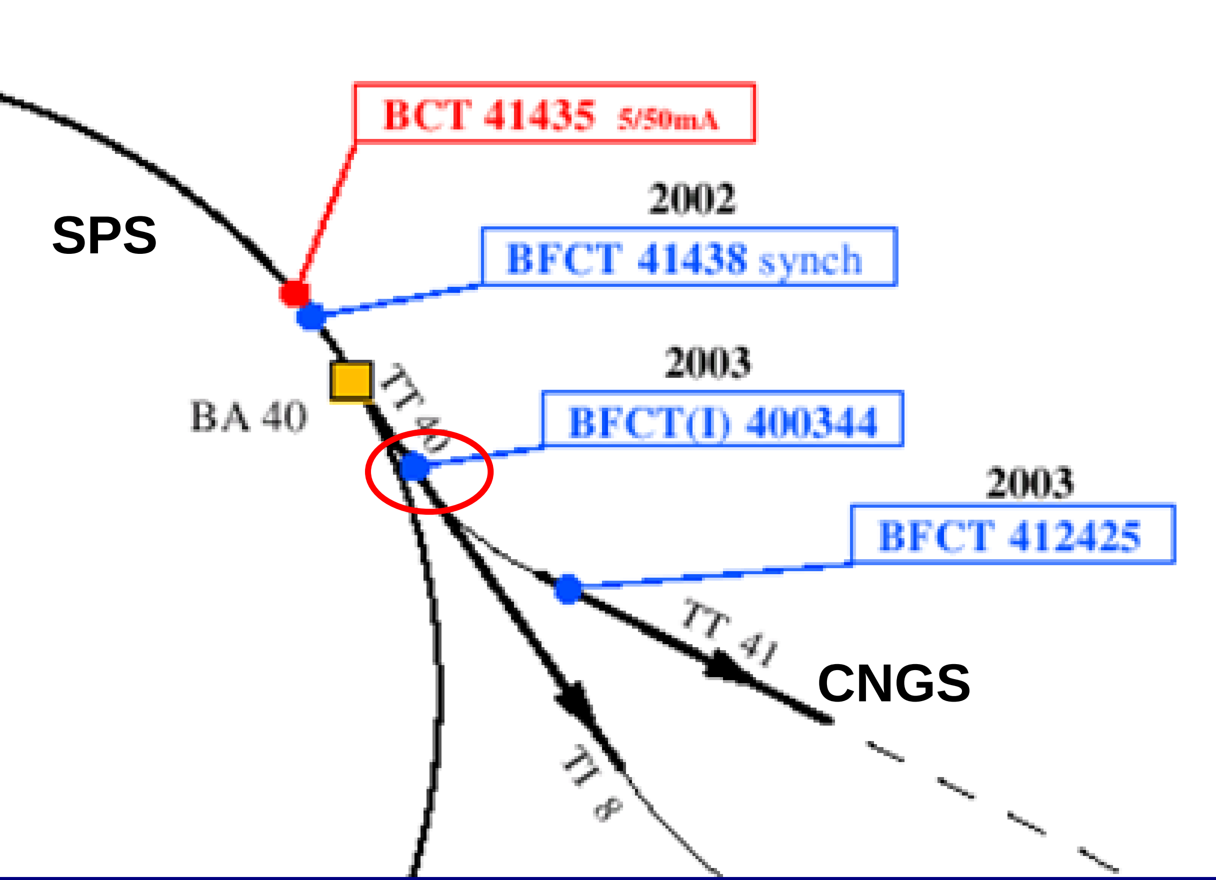
GTR50 GPS receiver, thermalised, external Cs frequency source, embedded Time Interval Counter



Correction to the time-link:

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

Proton timing by Beam Current Transformer

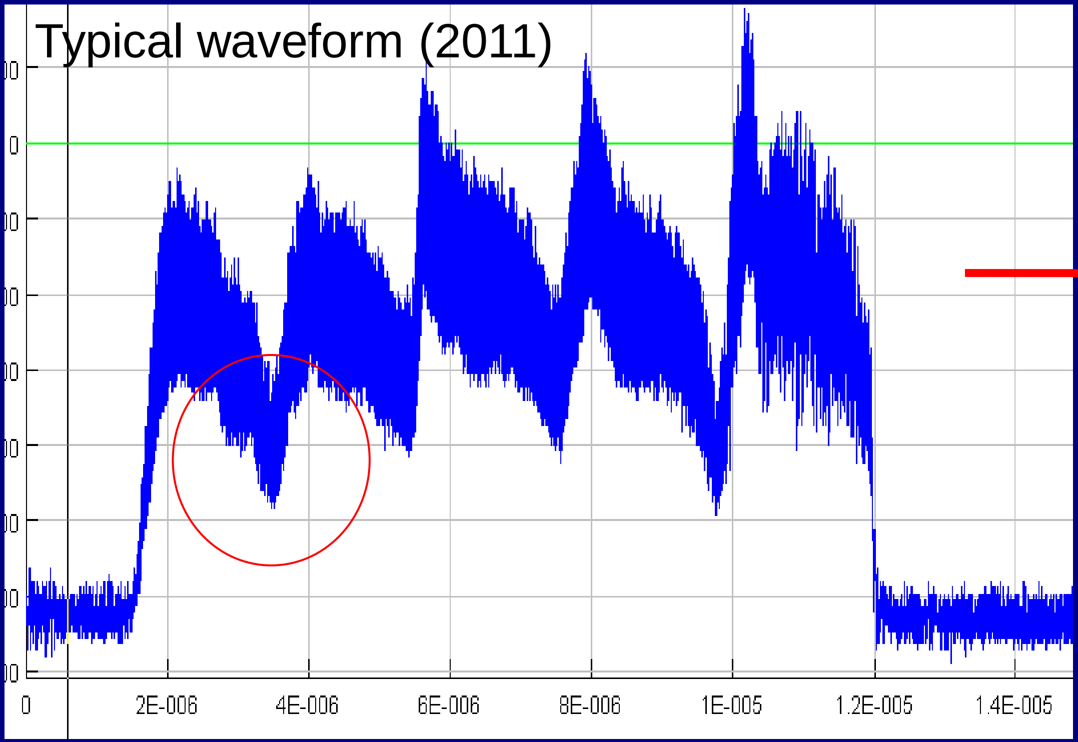


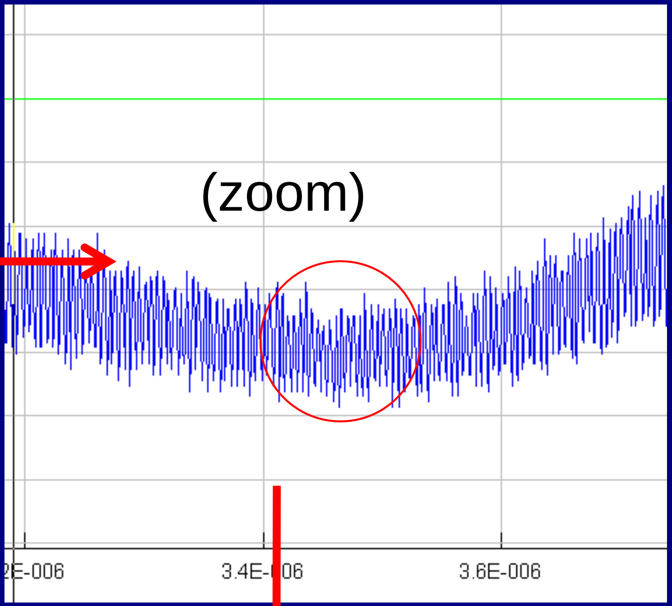
Fast BCT 400344
(~ 400 MHz)

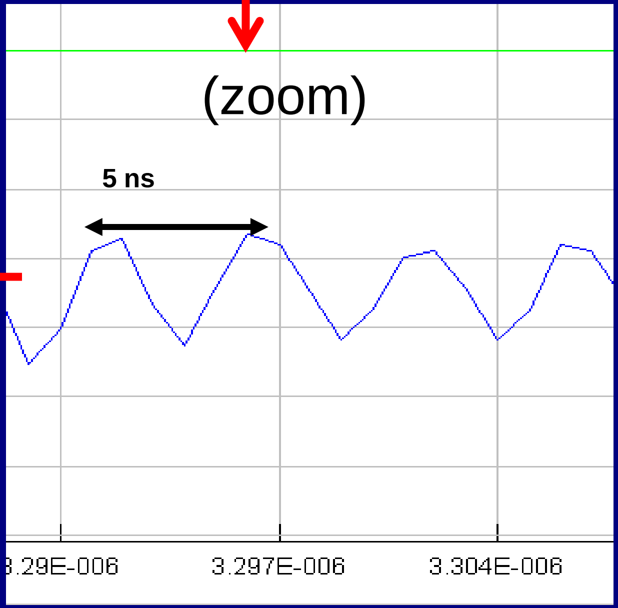
Proton pulse digitization:

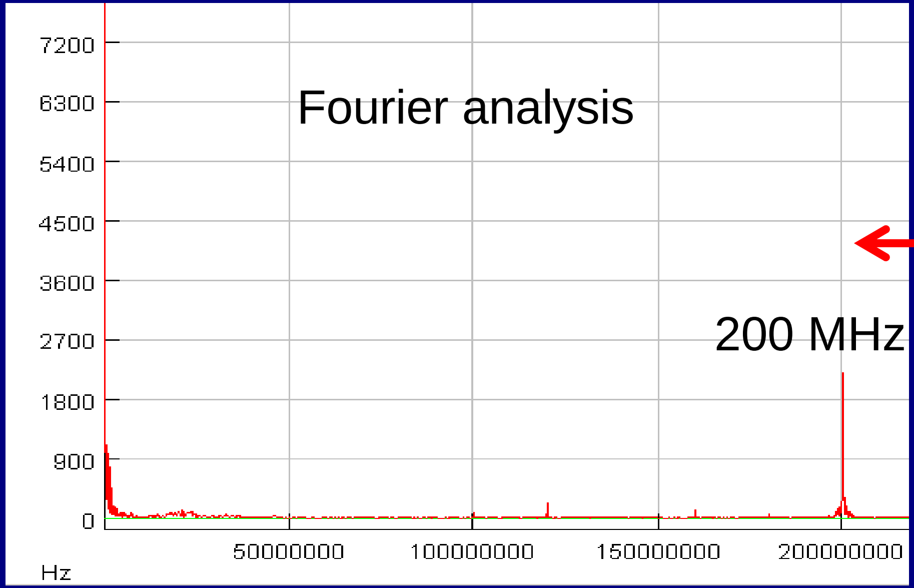
- Acqiris DP110 1GS/s waveform digitizer (WFD)
- WFD triggered by a replica of the kicker signal
- Waveforms UTC-stamped and stored in CNGS database for offline analysis

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

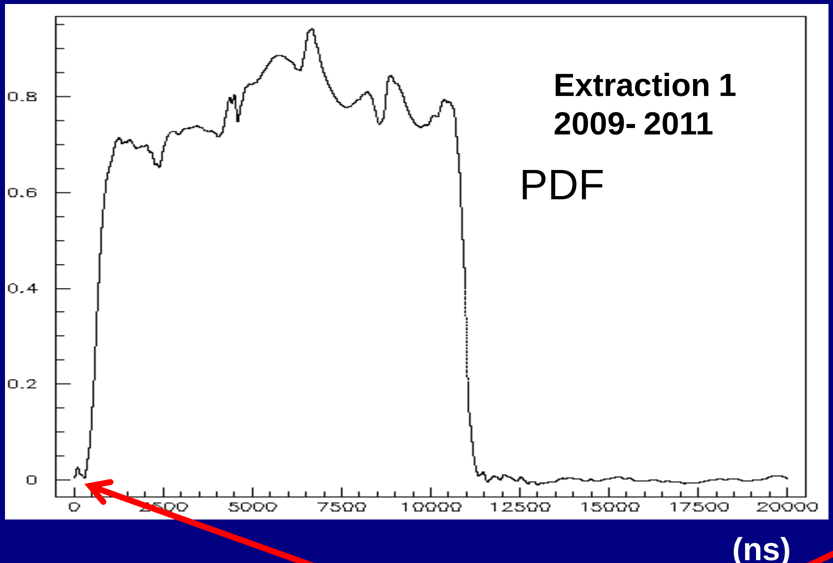

Fourier analysis
200 MHz
7200
6300
5400
4500
3600
2700
1800
900
0
50000000
100000000
150000000
200000000
Hz

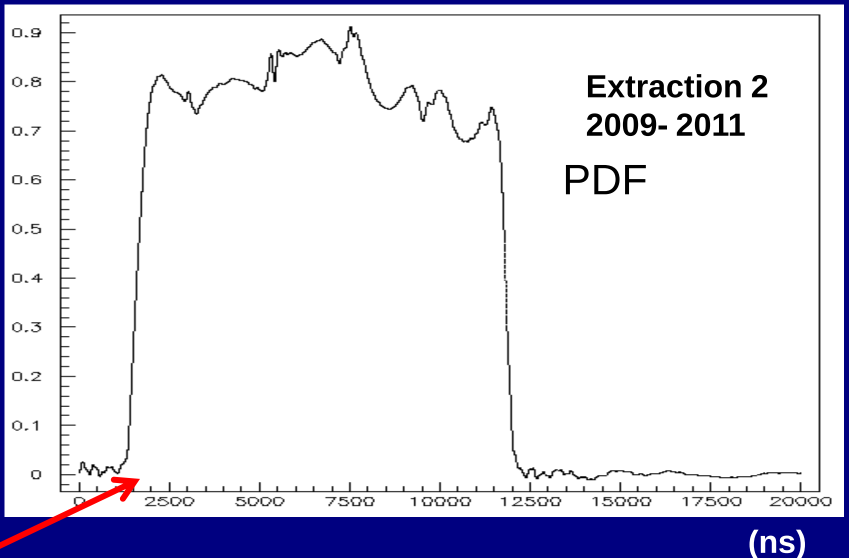
Neutrino event-time distribution PDF

- 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

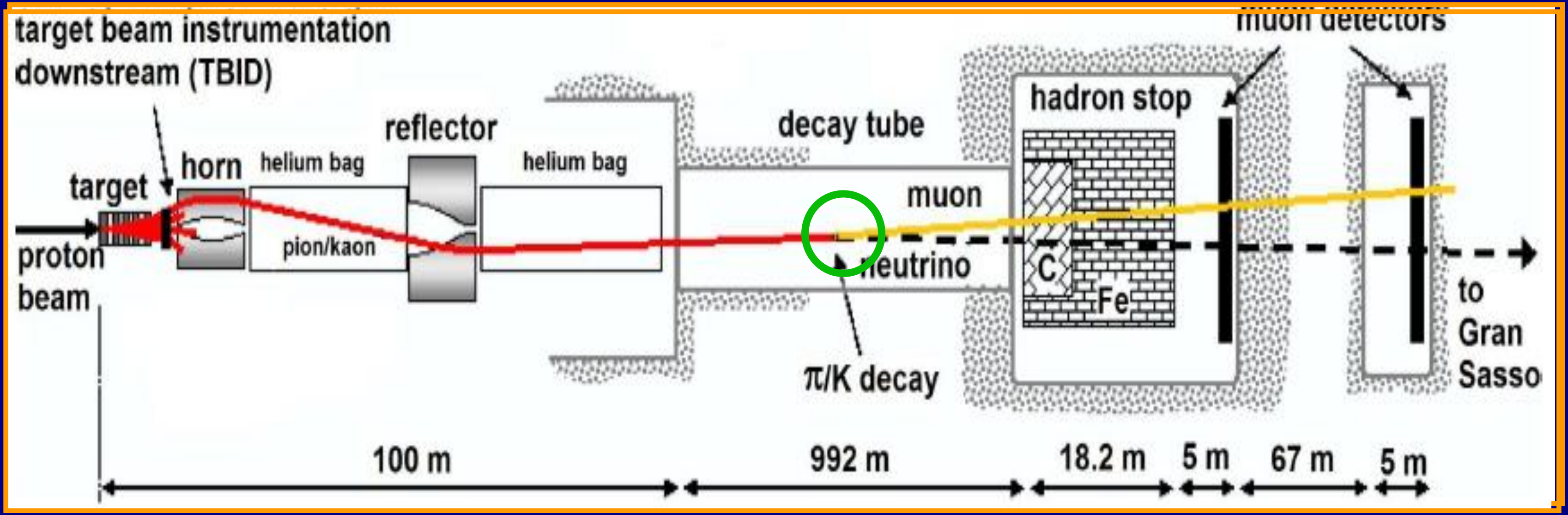
→ compare to OPERA detected neutrino events





different timing w.r.t. kicker magnet signal

Neutrino production point



Unknown neutrino production point:

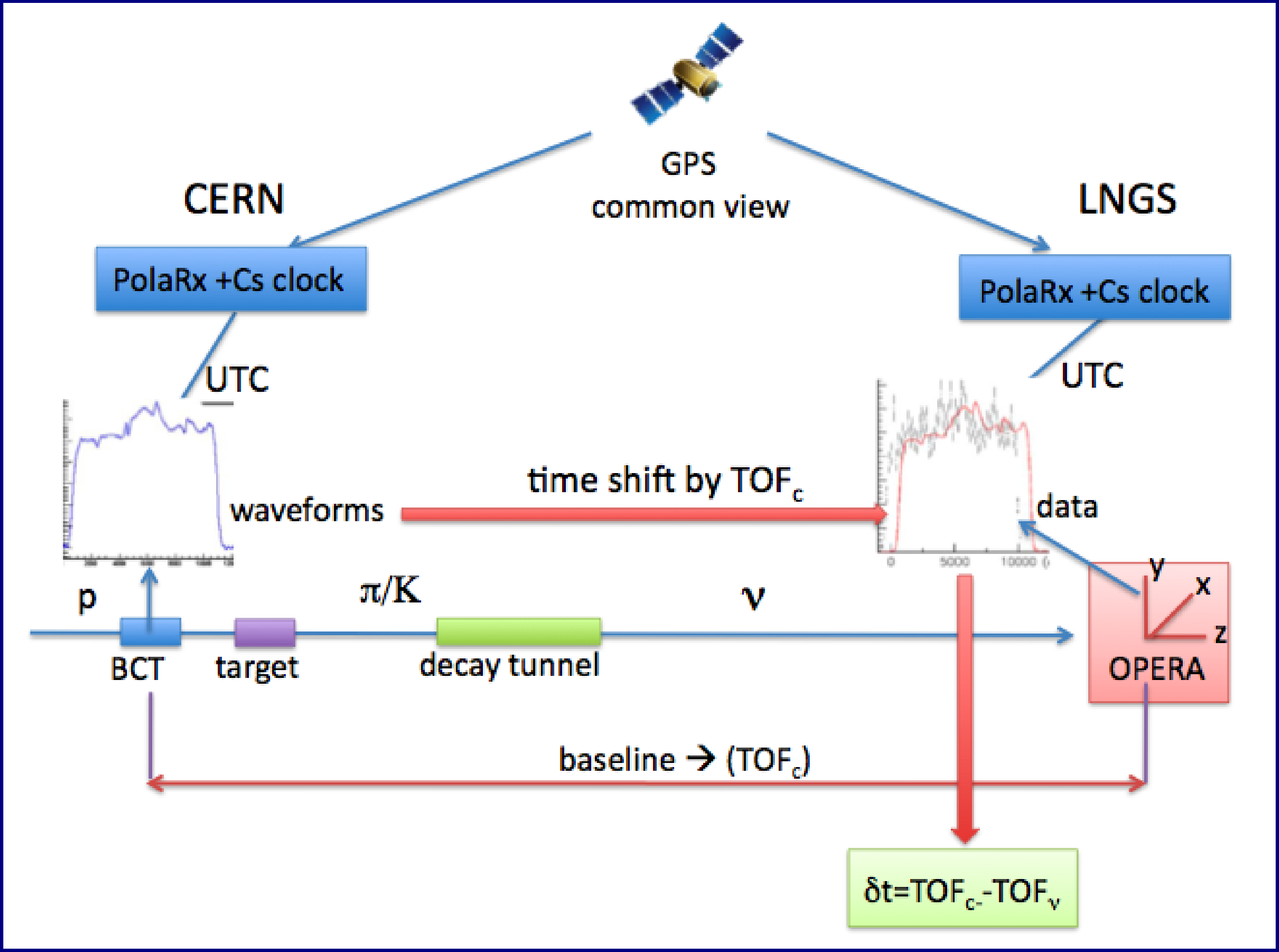
$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c}\left(\frac{1}{\beta} - 1\right) \approx \frac{z}{c}\frac{1}{2\gamma^2}$$

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

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

Summary of the principle for the TOF measurement



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

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)

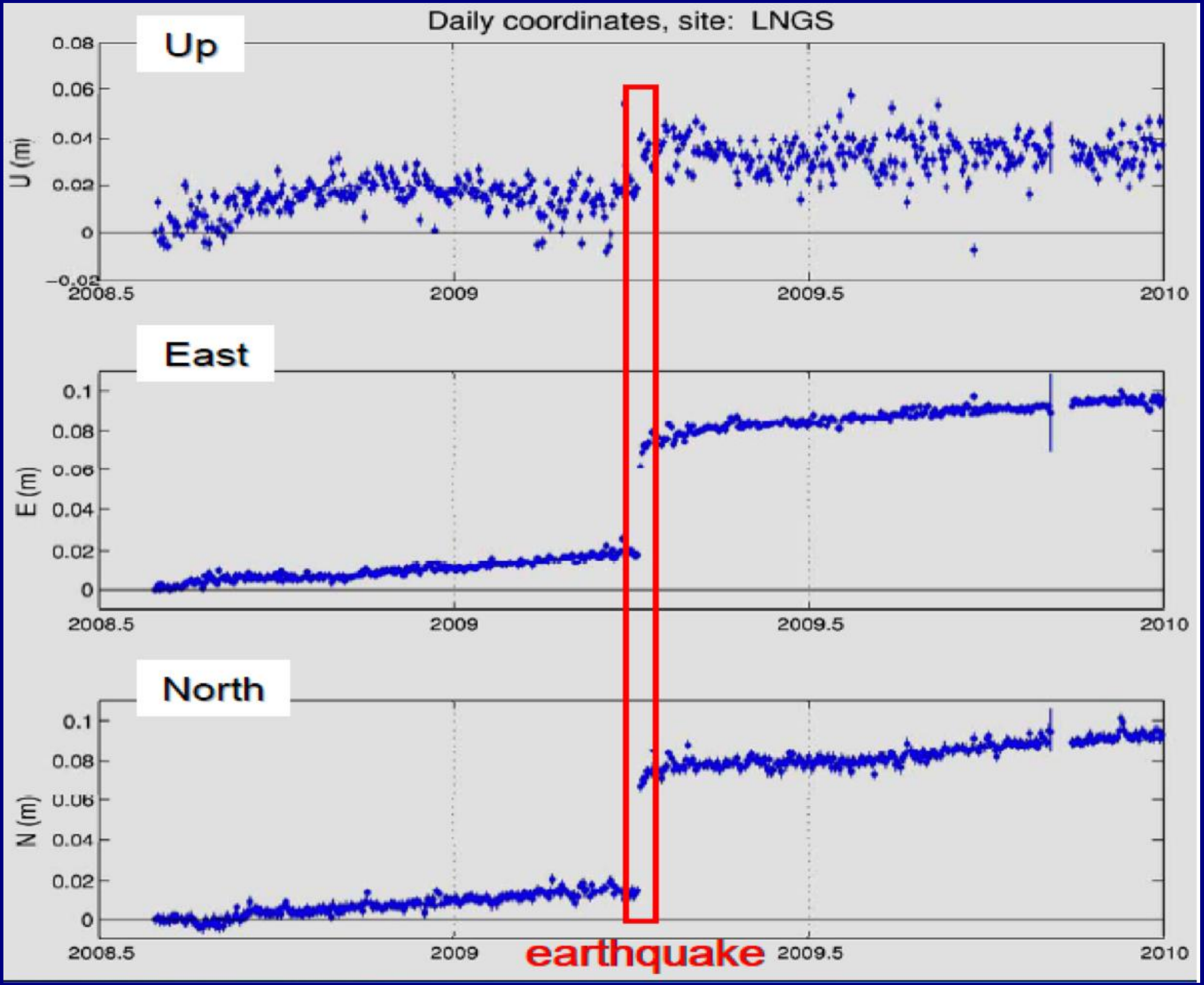
Benchmark	X (m)	Y (m)	Z (m)
GPS1	4579518.745	1108193.650	4285874.215
GPS2	4579537.618	1108238.881	4285843.959
GPS3	4585824.371	1102829.275	4280651.125
GPS4	4585839.629	1102751.612	4280651.236

LNGS benchmarks
In ETRF2000

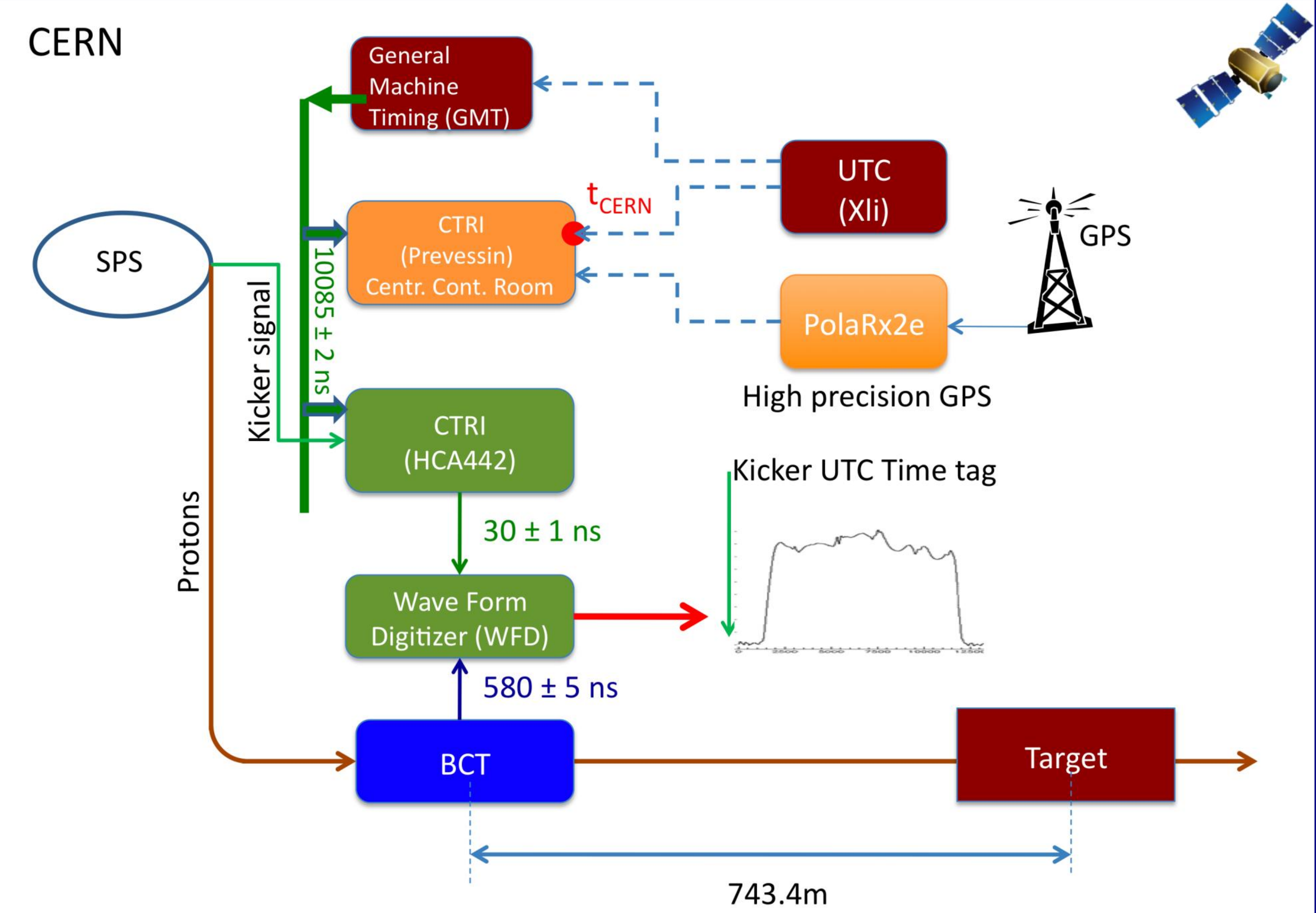
Cross-check: simultaneous CERN-LNGS measurement of GPS benchmarks, June 2011

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

LNGS position monitoring

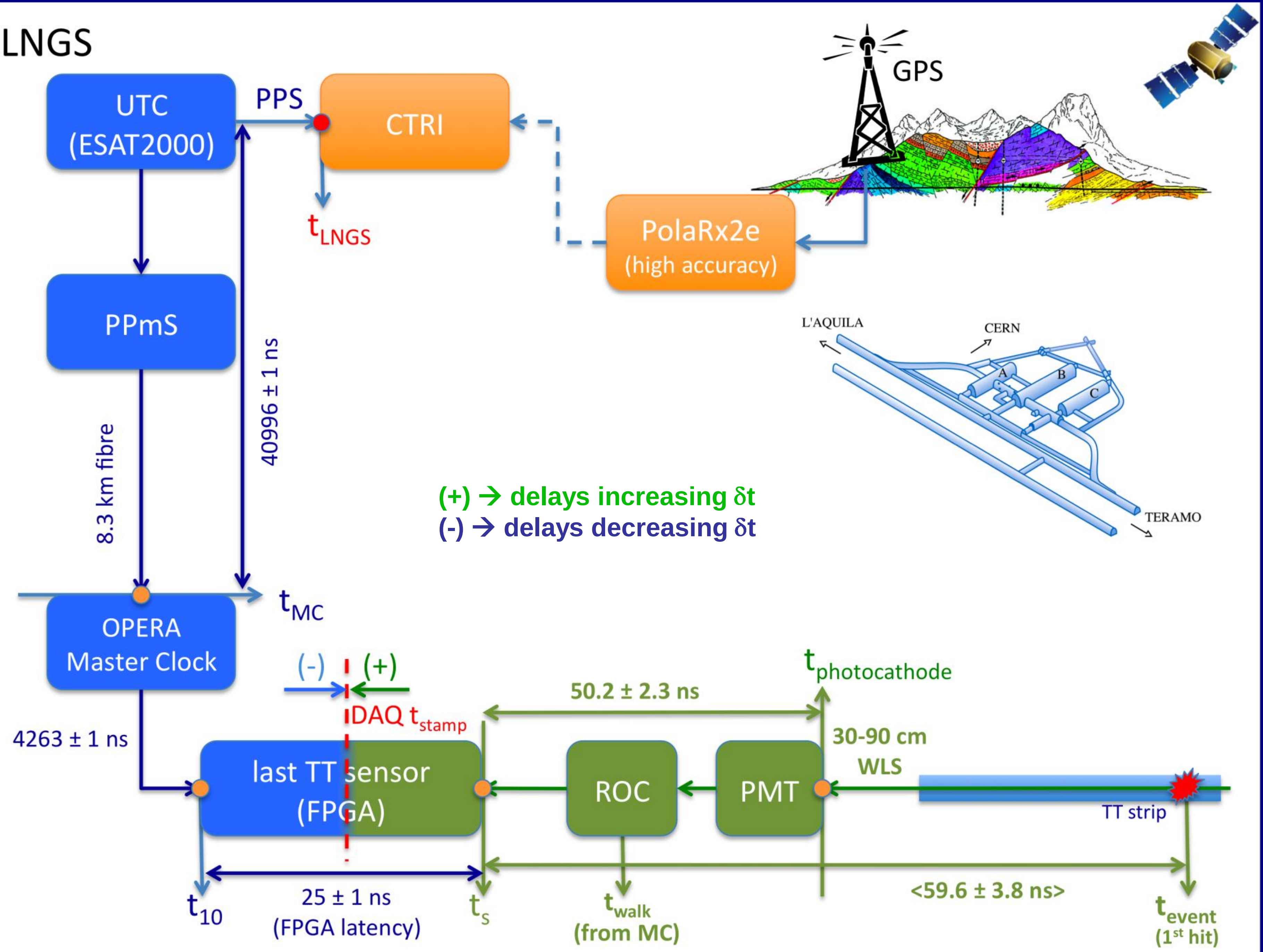


Monitor continent drift and important geological events (e.g. 2009 earthquake)



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

LNGS

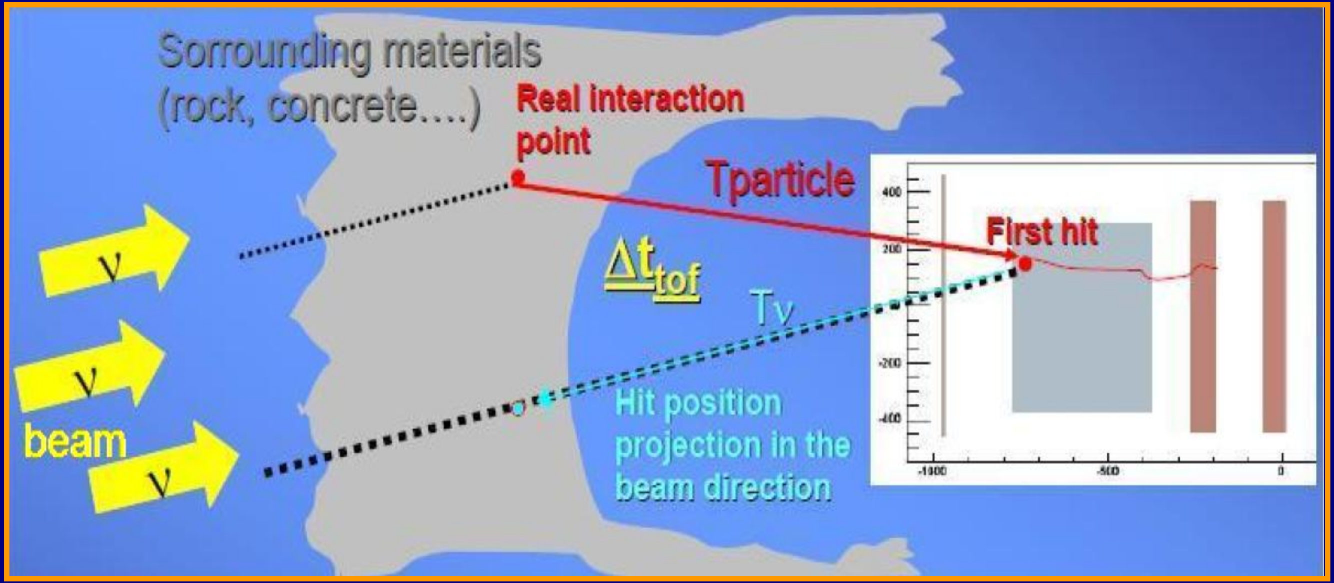

UTC
(ESAT2000)
PPS
CTRI
t_{LNGS}
GPS
PolaRx2e
(high accuracy)
PPmS
8.3 km fibre
40996 ± 1 ns
L'AQUILA
CERN
A
B
C
TERAMO
(+) → delays increasing δt
(-) → delays decreasing δt
OPERA
Master Clock
t_{MC}
(-)
(+)
DAQ t_{stamp}
$t_{photocathode}$
50.2 ± 2.3 ns
30-90 cm
WLS
4263 ± 1 ns
last TT sensor
(FPGA)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

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)

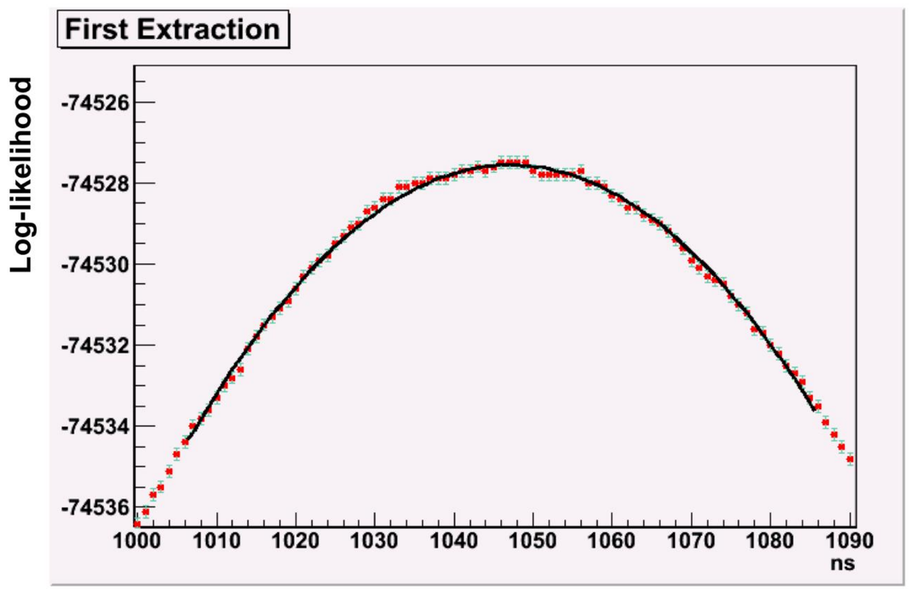


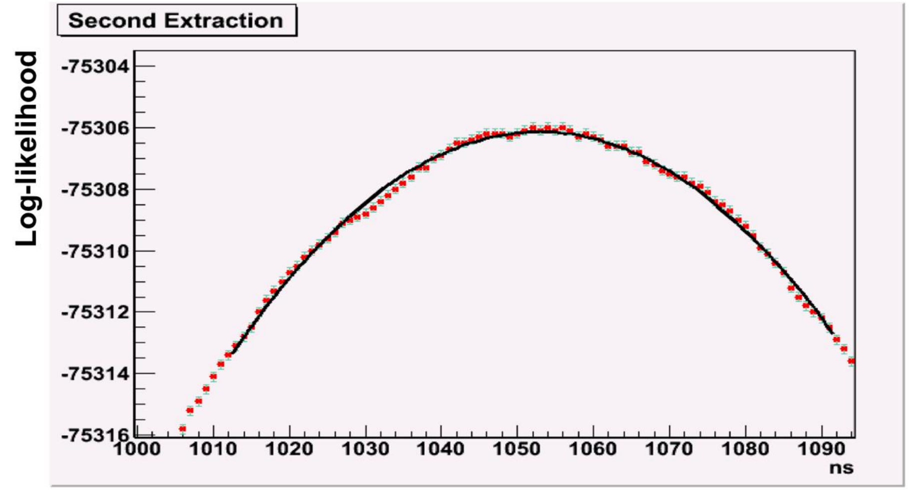
Data/MC agree for 1st hit timing (within systematics)

Analysis method

For each neutrino event in OPERA → proton extraction waveform

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





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

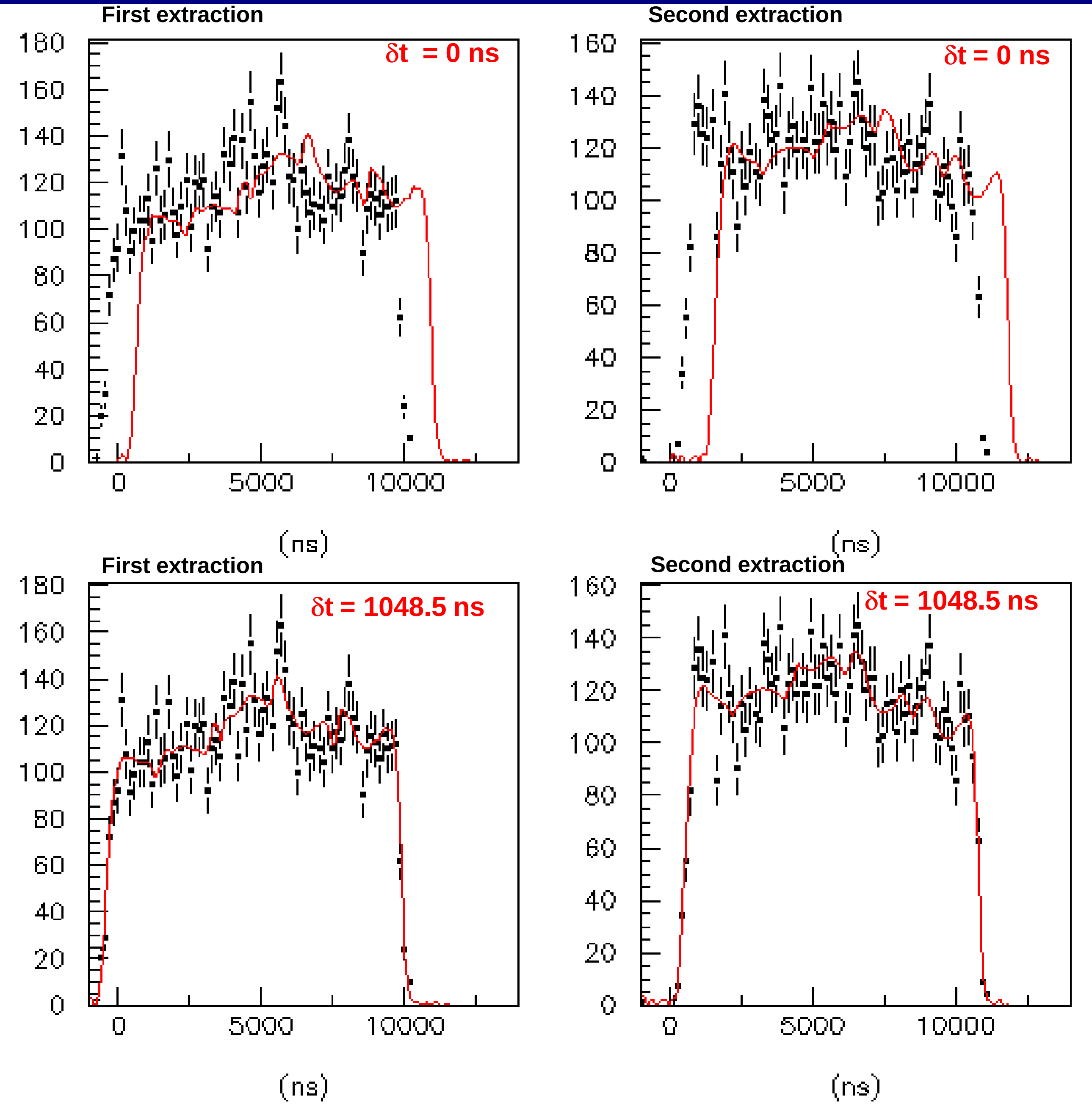
Maximised versus δt:

$\delta t = TOF_c - TOF_\nu$

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

statistical error evaluated from log likelihood curves

Data vs PDF: before and after likelihood result



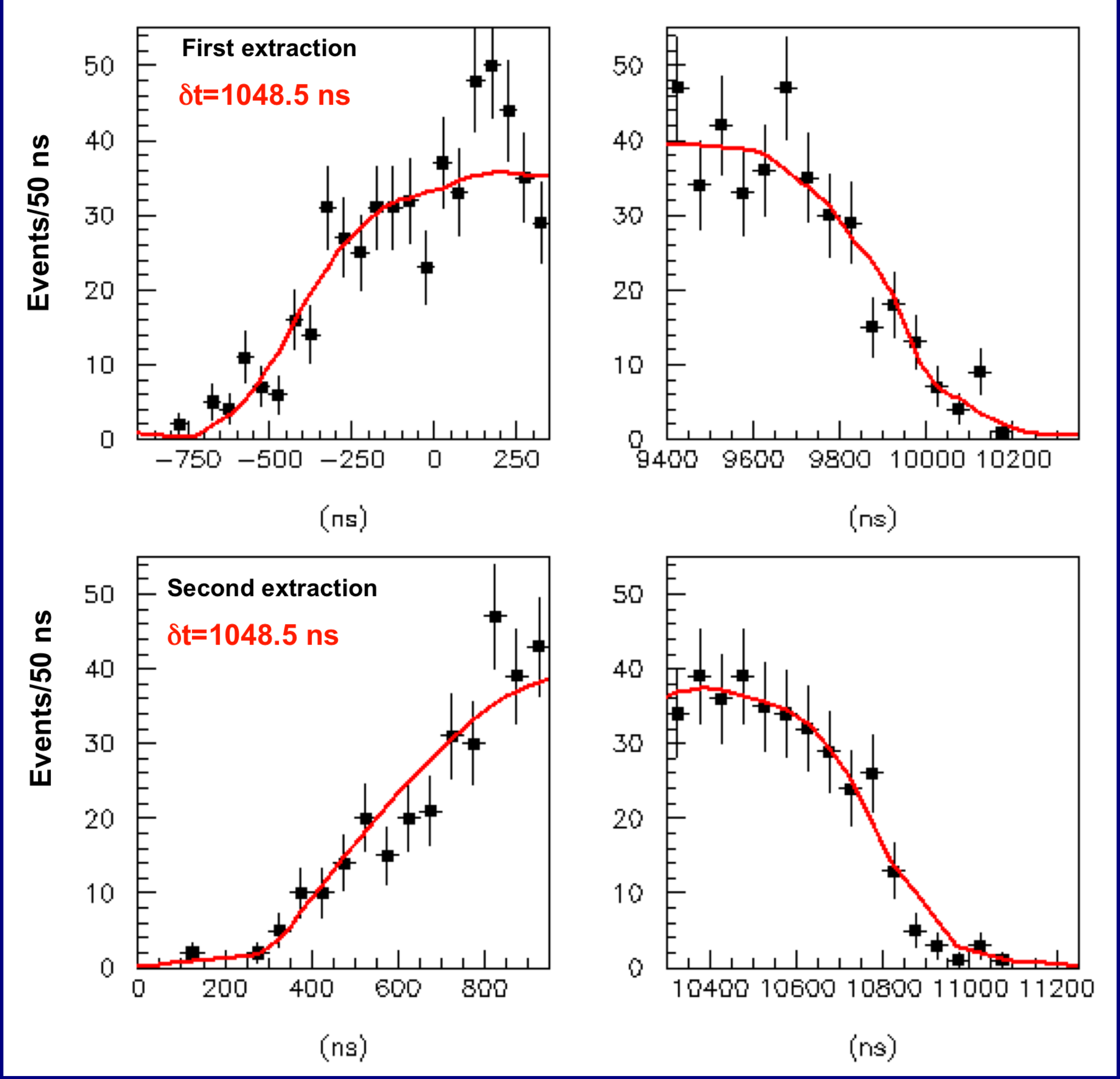
(BLIND) $\delta t = TOF_c - TOF_\nu$ =

(1048.5 ± 6.9) ns (stat)

χ^2 / ndof :

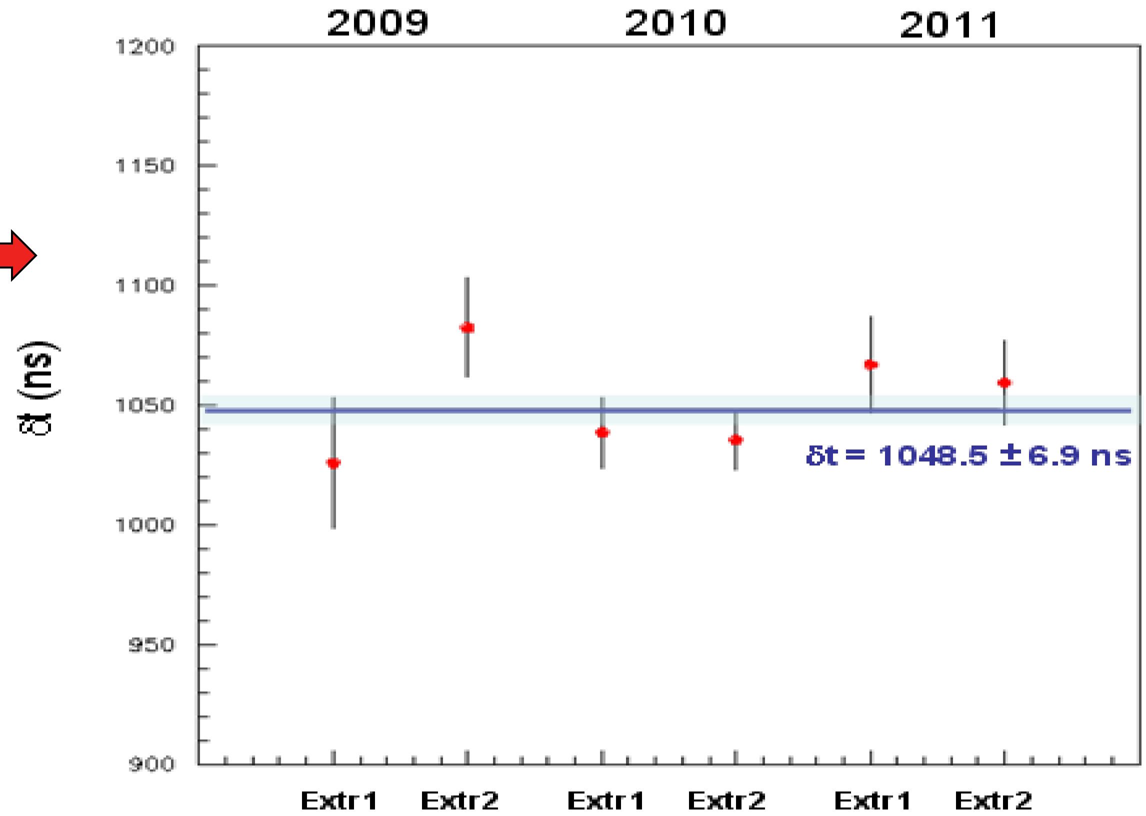
first extraction: 1.06
second extraction: 1.12

Zoom on the extractions leading and trailing edges



Analysis cross-checks

1) Coherence among CNGS runs/extractions



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

|d-n|: (17.1 ± 15.5) ns

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

3) Internal vs external events:

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

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

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**

Study of the energy dependence

Results

For CNGS ν_μ beam, <E> = 17 GeV:

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

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

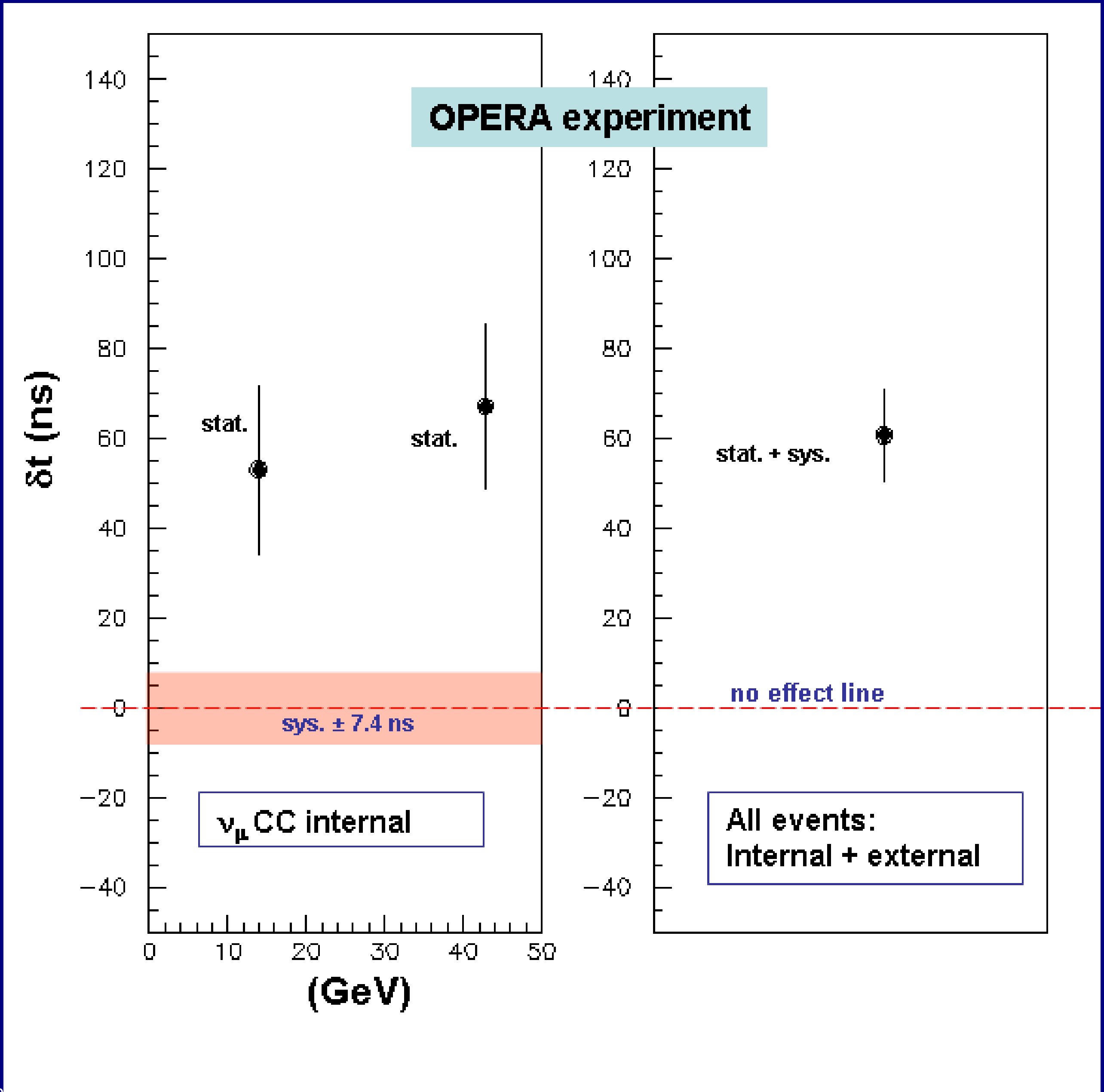
relative difference of neutrino velocity w.r.t. *c:*

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

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

6.0 σ significance

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



ВЫВОДЫ

- Детектор OPERA в LNGS с использованием пучка мюонных нейтрино CERN CNGS позволил провести наиболее чувствительные земные измерения скорости нейтрино на базе 730км.
- Измерения основывались на большой статистике, полученной в эксперименте OPERA, (~16000 событий), выполненной специально для этих измерений модернизации систем измерения времени CNGS и OPERA, специальных геодезических измерениях и серии калибровочных экспериментов, проведенных с использованием различных дополнительных методов.
- Для измерения времени пролета (TOF) нейтрино были проанализированы данные сеансов 2009, 2010 и 2011 гг.. Результаты анализа для мюонных нейтрино из пучка CNGS со средней энергией 17 ГэВ, проходящих сквозь толщу Земли, показали ранний приход нейтрино по сравнению с рассчитанным в предположении скорости нейтрино, равной скорости света:

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

ВЫВОДЫ (2)

- Мы не можем объяснить этот эффект известными до сих пор систематическими ошибоками. Поэтому мы полагаем, что наш измерения указывают на то, что скорость нейтрино превышает скорость света:

$$(v\text{-}c)/c = \delta t / (TOF_c - \delta t) = (2.48 \pm 0.28(stat.) \pm 0.30\ (sys.)) X10^{-5}$$

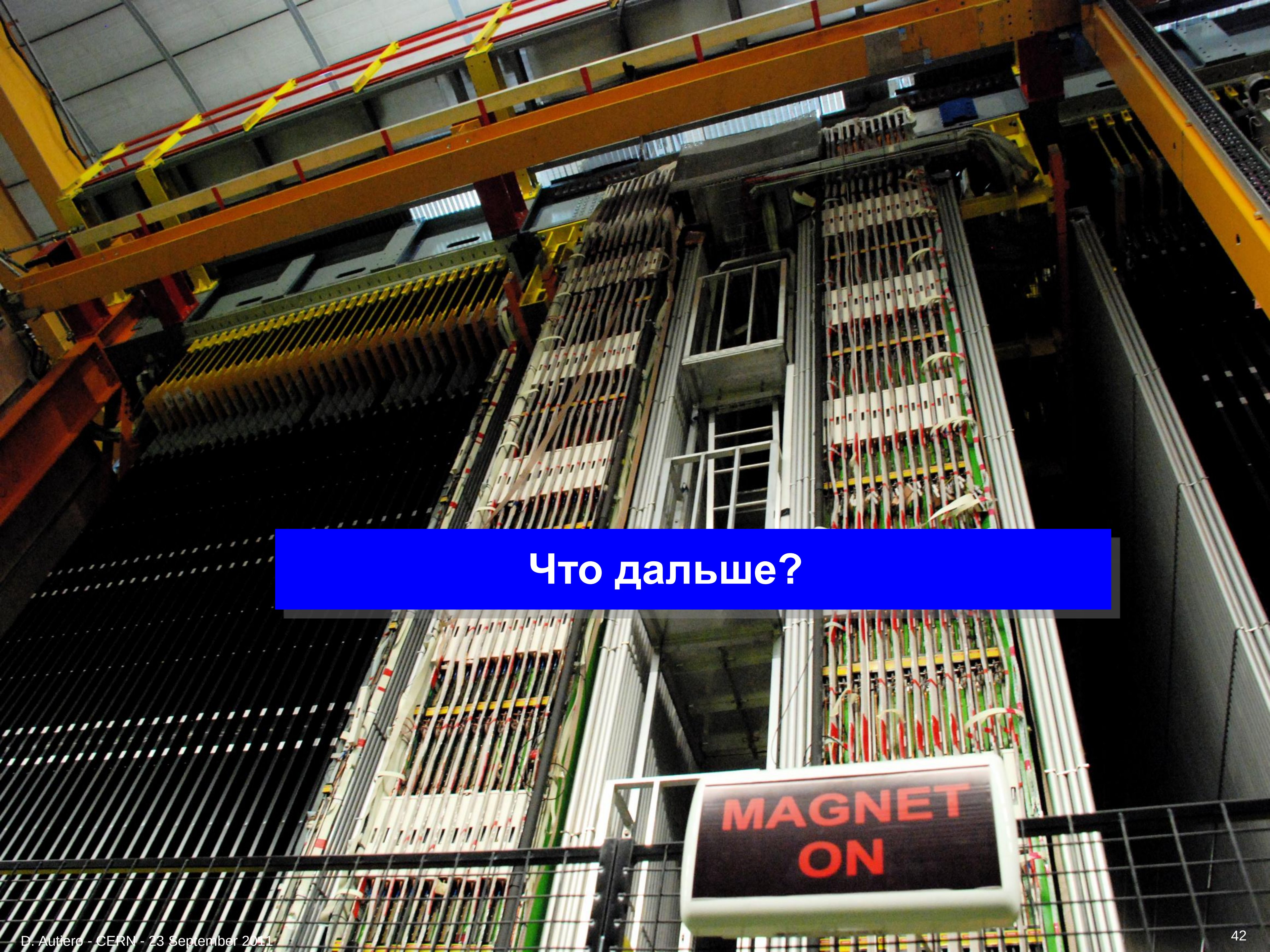
На уровне достоверности 6.0 σ .

- Исследовалась также возможная зависимость δ **t** от энергии. В энергетическом диапазоне CNGS и в пределах статистической точности измерений мы не наблюдаем значительного эффект

- Несмотря на большое значение выполненных измерений и их стабильность, возможное сильное влияние результатов побуждает нас к продолжению исследований для того, чтобы найти до сих пор возможно неизвестные систематические эффекты.

- Мы не даем теоретическую или феноменологическую интерпретацию результатов.

Что дальше?



Если отбросить ажиотаж в средствах массовой информации, то пока прошел только семинар, целью которого было обратить внимание коллег на неожиданный результат, привлечь к нему внимание научного мира и стимулировать проведение независимых экспериментов, не прекращая проверок собственных данных так же, как и поиска объяснений наблюдаемого эффекта.

Семинар в ЦЕРНе и публикация препринта вызвали поток предложений возможных проверок, которые внимательно изучаются коллаборацией ОПЕРА.

Интенсивная проверка результатов внутри OPERA

Nuvel Working Group

Analysis
All general discussions about analysis

Simulation
All general discussions about simulation

Theory
All discussions about theory (low priority in this forum)

Target Tracker
All discussion about everything concerning the TT (delays, length of cables, TT DAQ...)

Fit of waveforms
All discussion about maximum likelihood fit or any other fitting method

Proton Waveforms and BCT
All discussion about proton waveforms and BCT

GPS Synchronisation
All discussion about GPS synchronization

Timing at LNGS
All discussion about timing at LNGS

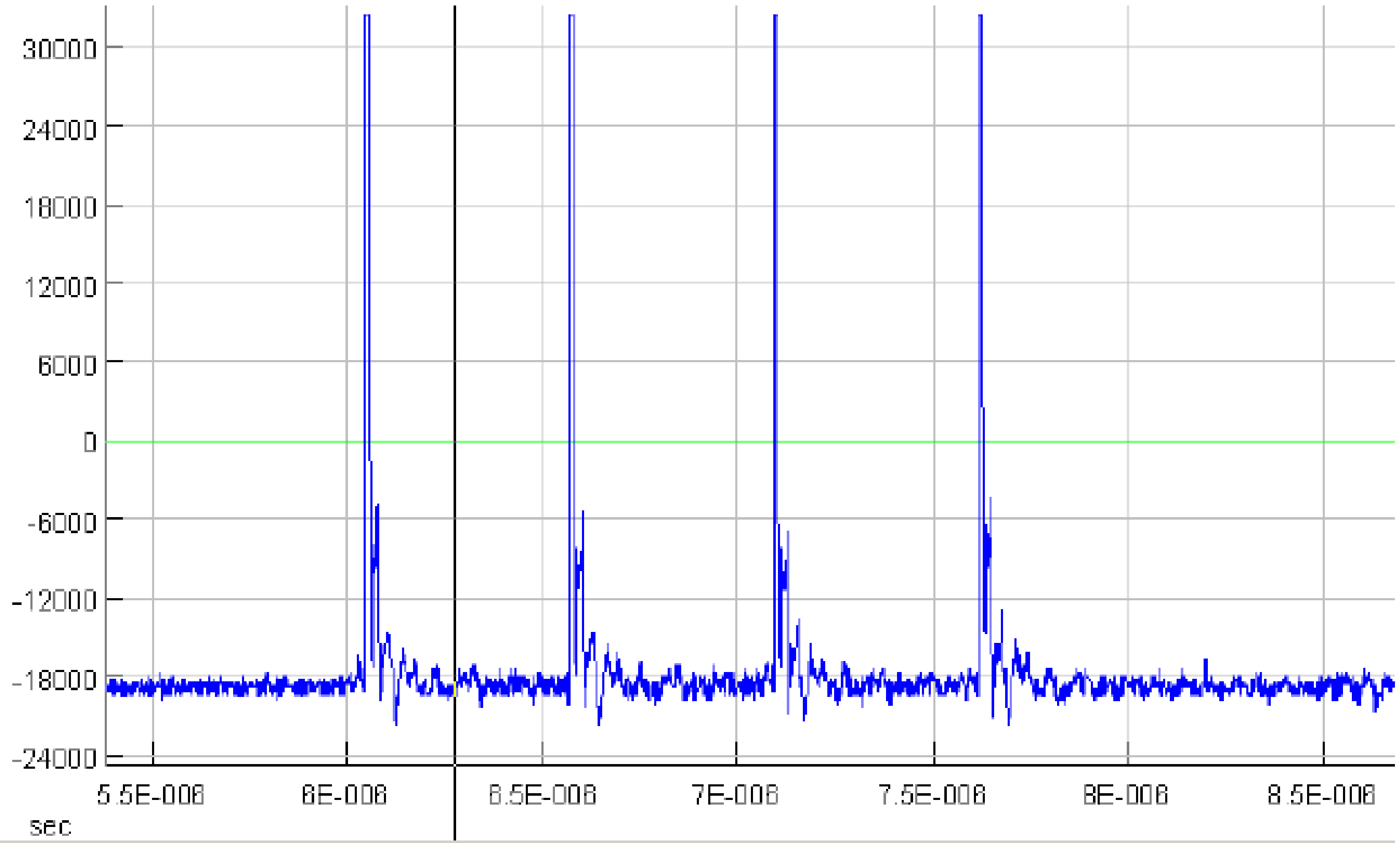
Timing at CERN
All discussion about timing at CERN

Geodesy
For all geodesy questions

Модификация пучка в CERN

4 Bunches/Extraction separated by ~524 ns, bunches of ~3 ns
Typical intensity 1.05^{E}12 pot/extraction

Example of a typical waveform



Другие эксперименты

Borexino

Borexino is installed in the same LNGS underground hall (Hall C), about 20 metres upstream of the OPERA experiment with respect to the neutrino flight direction from CERN. The volume of the Borexino detector is larger than that of OPERA, and Borexino is able to collect a larger number of events produced by CERN neutrinos.

The main goal of the Borexino experiment is the study of solar neutrinos and geoneutrinos. At present, the experiment is not equipped with the special timing devices required to measure the neutrino time-of-flight from CERN with the accuracy required to cross-check the OPERA results, which would be possible only by installing new timing devices.

After preliminary discussions, the Borexino Collaboration has expressed interest in performing an independent measurement to cross-check the result from OPERA. However, the discussion has barely started and is still ongoing. A decision has not been yet been made.

In an optimistic scenario, the Collaboration could be in a position to collect data by the start of the beam run in February 2012, but this depends on the successful implementation of necessary improvements, which cannot be fully evaluated at this time.

LVD

The LVD Collaboration has a great interest in the issue raised by the recent OPERA measurement. The experiment, designed to detect gravitational stellar collapses, can also detect neutrinos from the CERN beam. However, the Collaboration has to evaluate carefully if it can contribute a significant result with their detector as it is, or if it has to change, modify or add some detector parts.

T2K

Based on an initial assessment of the experiment's current capability, T2K cannot make any definitive statement to verify the OPERA measurement of the speed of neutrino. The Collaboration will assess the possibility of improving their experimental sensitivity in order to cross-check the OPERA anomaly in the future. Such a measurement with an improved system, however, could take a while to achieve.

MINOS

MINOS

The MINOS Collaboration is planning to improve its measurement of the neutrino time-of-flight since its last result in 2007, with better-controlled systematics and about 10 times more data. The first update should be in about 6 months. There will be a further improvement (which was already planned) for the MINOS+ experiment, starting in 2013, which will take very high statistics, and higher energy data. This should give a total error of 5-10 ns on the final measurement.

Проведение этих экспериментов даст окончательный ответ на вопрос:

Может ли скорость нейтрино быть больше скорости света?