Superluminal anomaly in OPERA experiment

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UCSB, 10/27/2011

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Sunčani i atmosferski neutrini

- Super KamiokaNDE (Japan 1996-) observes atmospheric neutrino flux as a function of azimuthal angle and energy -> indirect indication of neutrino oscillations
- SNO (Sudburry neutrino Oscillation, Canada 1999-2006) measured total neutrino flux (all flavors). Conclusion was that where v_e account for 35% of the flux – in concordance with SSM
- ... exhaustive list of neutrino experiments is long !

Man-made eksperimenti

- **Nomad** (CERN 1994-1999), CHORUS (CERN 1993-1997) L=900m. Oscillations not found, LSND result excluded

- K2K (KEK to Kamioka, Japan 1999-) L=250km measured dissapearance of ν_μ neutrinos from the beam (disappearance type experiment)
  Δm^2_{23}= (2.8±0.13) 10^{-3} eV^2/c^4 @ 90%CL

- KamLAND (53 nucl. reactors, Japan 2002-) <L>=180km
  Δm^2_{12}= (7.59±0.21) 10^{-5} eV^2/c^4 & $\tan^2(\theta_{12})$ = (0.47±0.06)

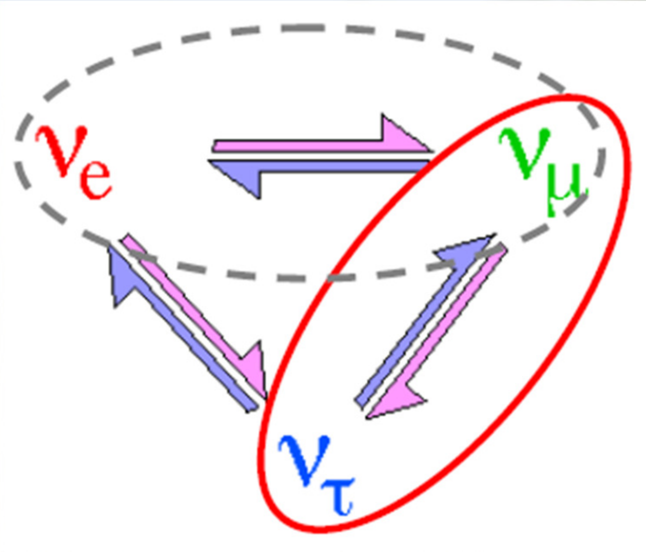
- MINOS (USA 2005-) L=735km (disappearance type)
  Δm^2_{23}= (2.43±0.13) 10^{-3} eV^2/c^4 & $\sin^2(2\theta_{23})$ > 0.90 @ 90%CL

- **OPERA** (Italy 2006-) looks for direct observations of tau neutrino from oscillation process $\nu_\mu \rightarrow \nu_\tau$ L=732km (appearance type)

Oscillation Project with Emulsion tRacking Apparatus (OPERA)

• direct search for oscillations $\nu_\mu \to \nu_\tau$ in Δm^2 range compatible with atmnospheric measurements, by observation of ν_τ in almost pure ν_μ beam.

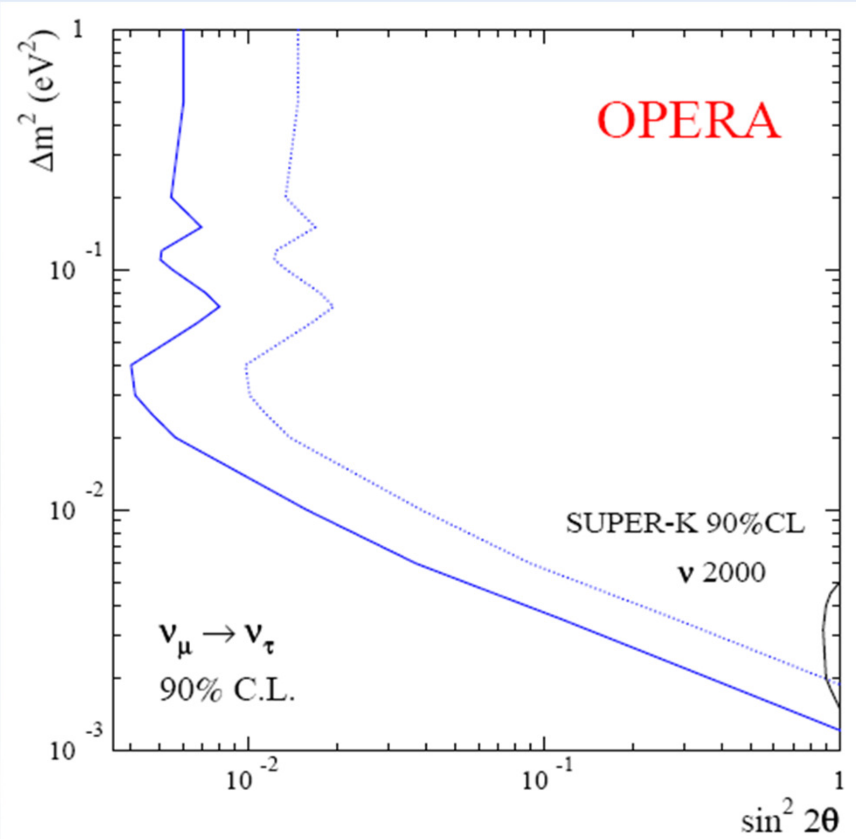
• search for $\nu_\mu \to \nu_e$ oscillations and setting tighter limits on θ_{13}



• for atmospheric neutrinos (Super-K):

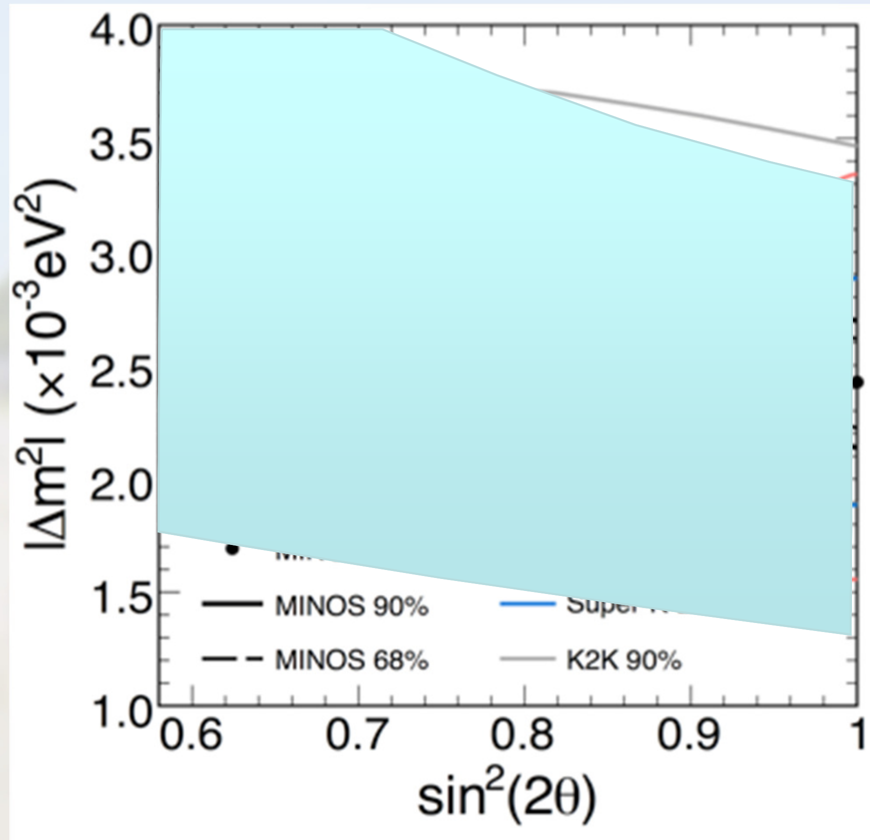
$1.4\times10^{-3} < \Delta m^2_{23} < 3.3\times10^{-3}$ eV^2
$0.9 < \sin^2 2\theta_{23}$ @ 90% C.L.

in case of a negative result



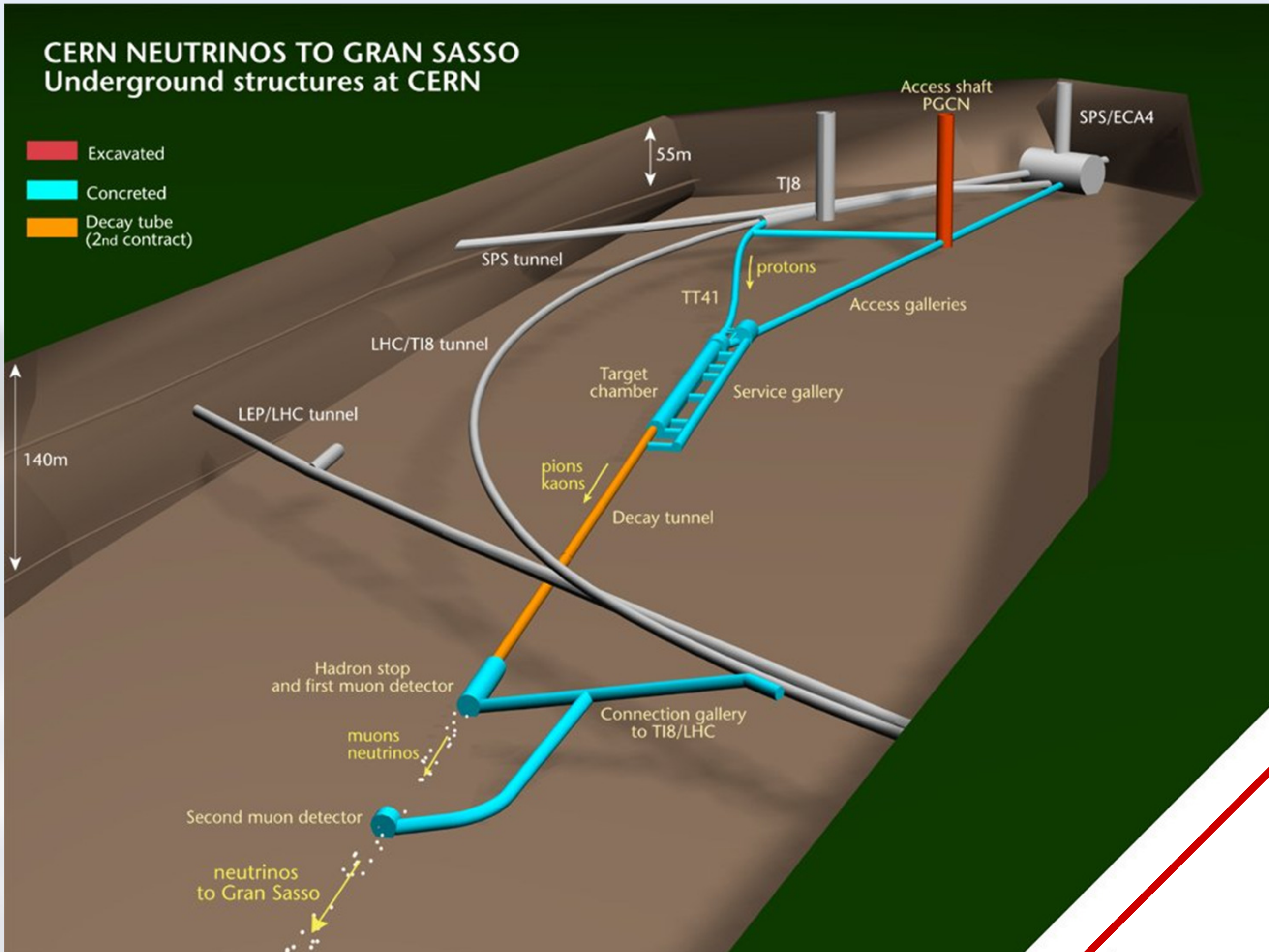
Sensitivity of OPERA after 2 and 5 years of data collection

Detection of tau neutrinos on OPERA sets more stringent limit on Δm^2_{23}



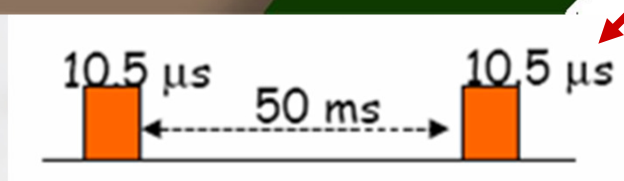
in case of positive result

CNGS – neutrino beam at CERN

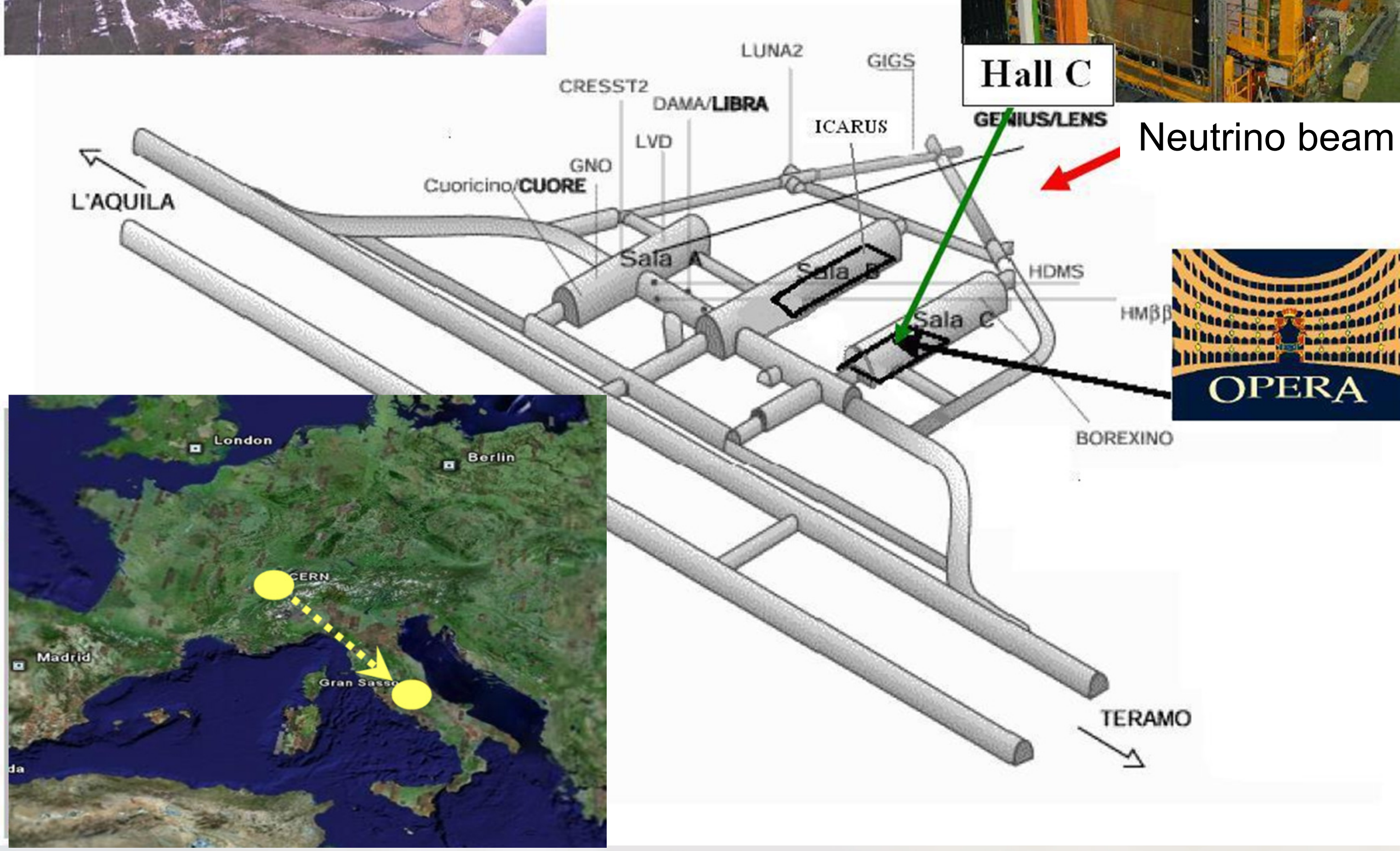


Ciklus 6 s

2 ekstrakcije/ciklusu svaka od po 10.5 us separirane 50 ms

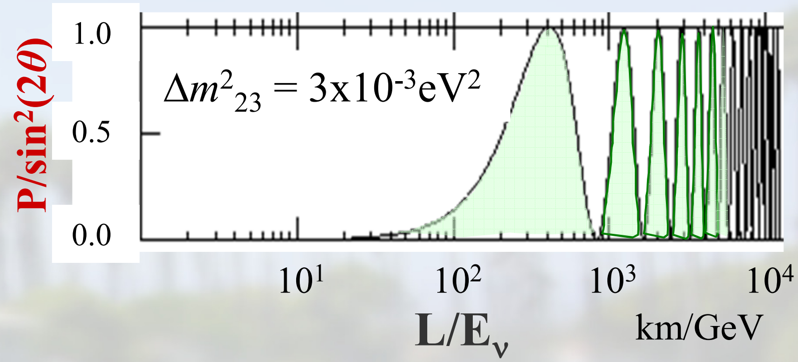


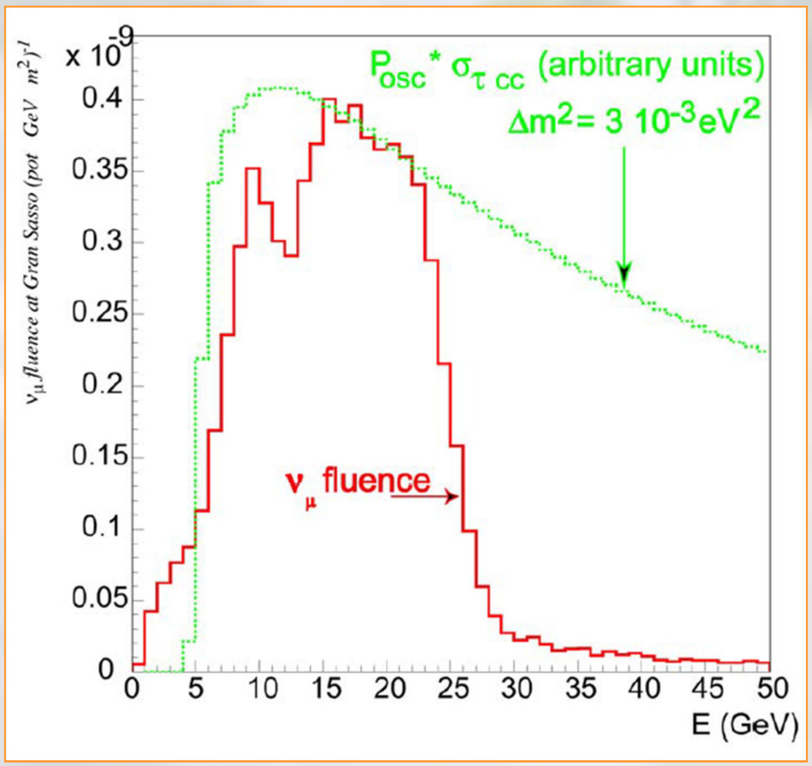
LNGS


Hall C
Neutrino beam
L'AQUILA
CRESST2
DAMA/LIBRA
LUNA2
GIGS
ICARUS
GENIUS/LENS
LVD
GNO
Cuoricino/CUORE
Sala A
Sala B
Sala C
HDMS
HMββ
OPERA
BOREXINO
TERAMO
London
Berlin
CERN
Madrid
Gran Sasso

Search for ν_τ in the beam of ν_μ

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \, \sin^2\left(\frac{1.27 \Delta m^2 L}{E_\nu}\right)$$

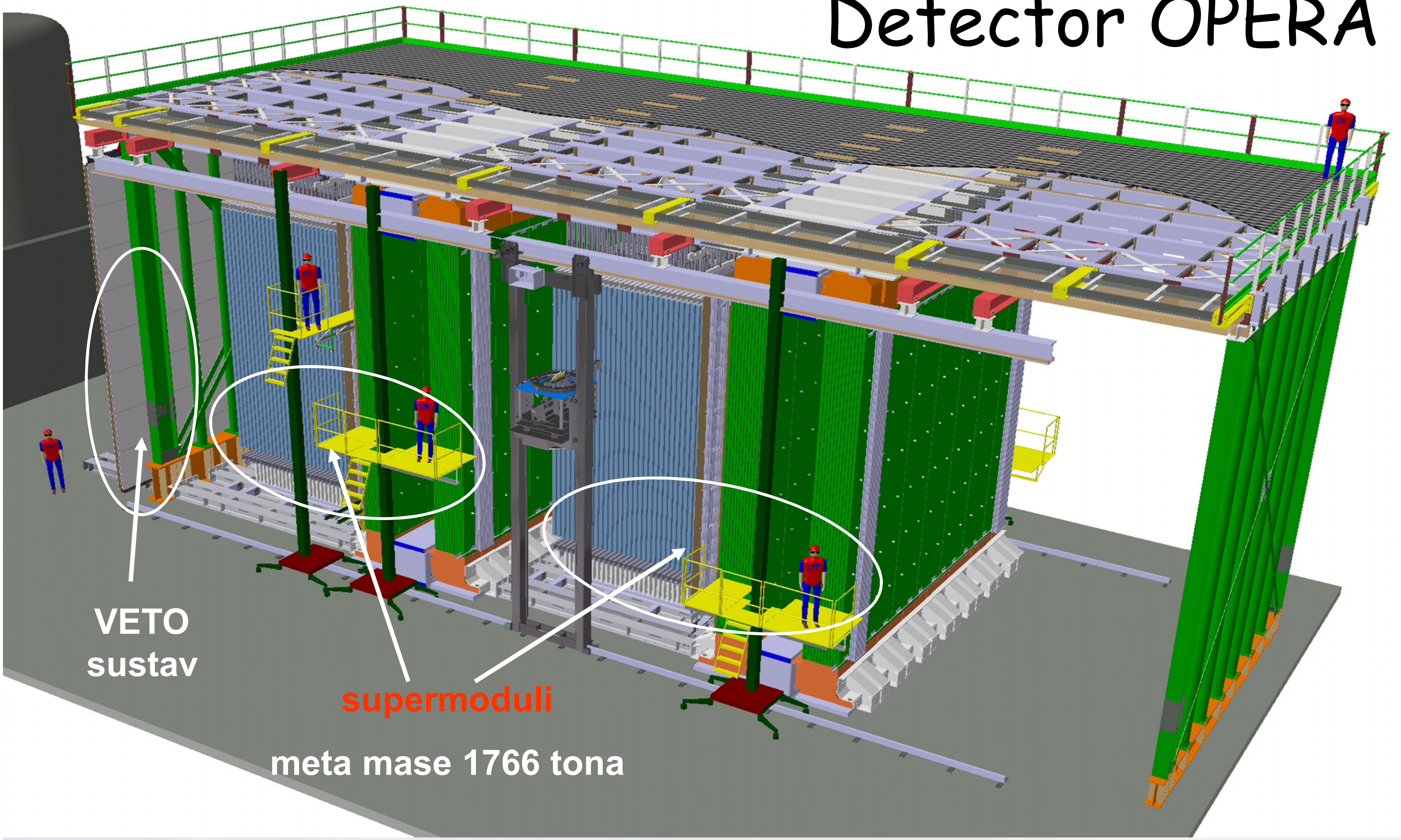




$P(\nu_\mu \to \nu_\tau) \sim 2\%$

CNGS beam is optimized for appearance of ν_τ and detection of tau lepton in Δm^2_{23} range from Super-K and maximal mixing angle

Detector OPERA



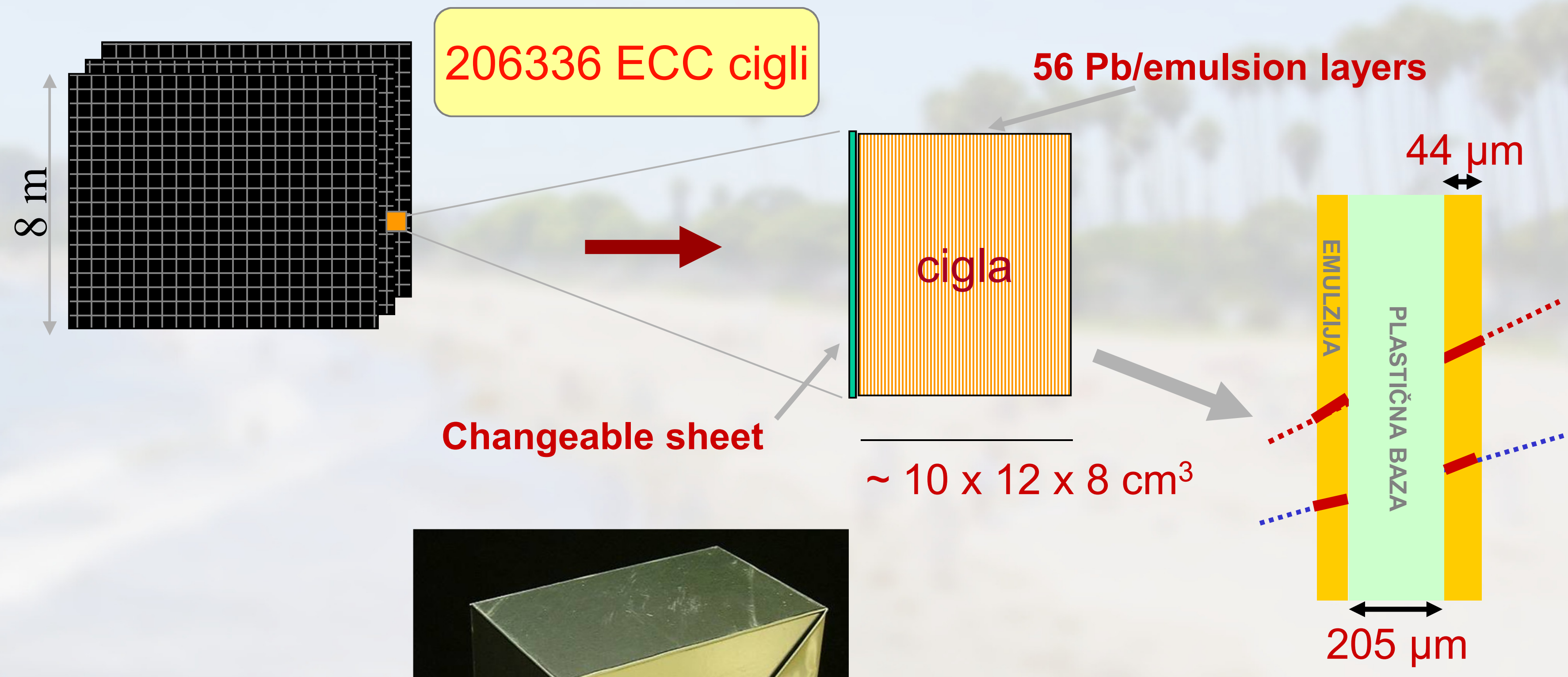
- Supermodule is made of 31 brick walls and muon spectrometer
- A wall is made of 3328 ECC bricks and 1 xy layer of scintillators (Target Tracker)
- Muon spectrometer consists of about 1000 bakelyte RPC's

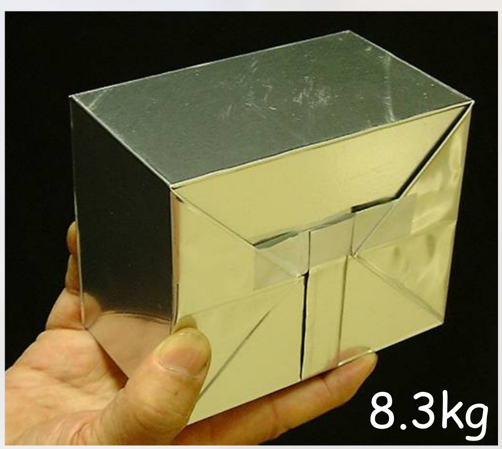
ECC (**E**mulsion **C**loud **C**hamber) brick

=

1 Changeable Sheet \+

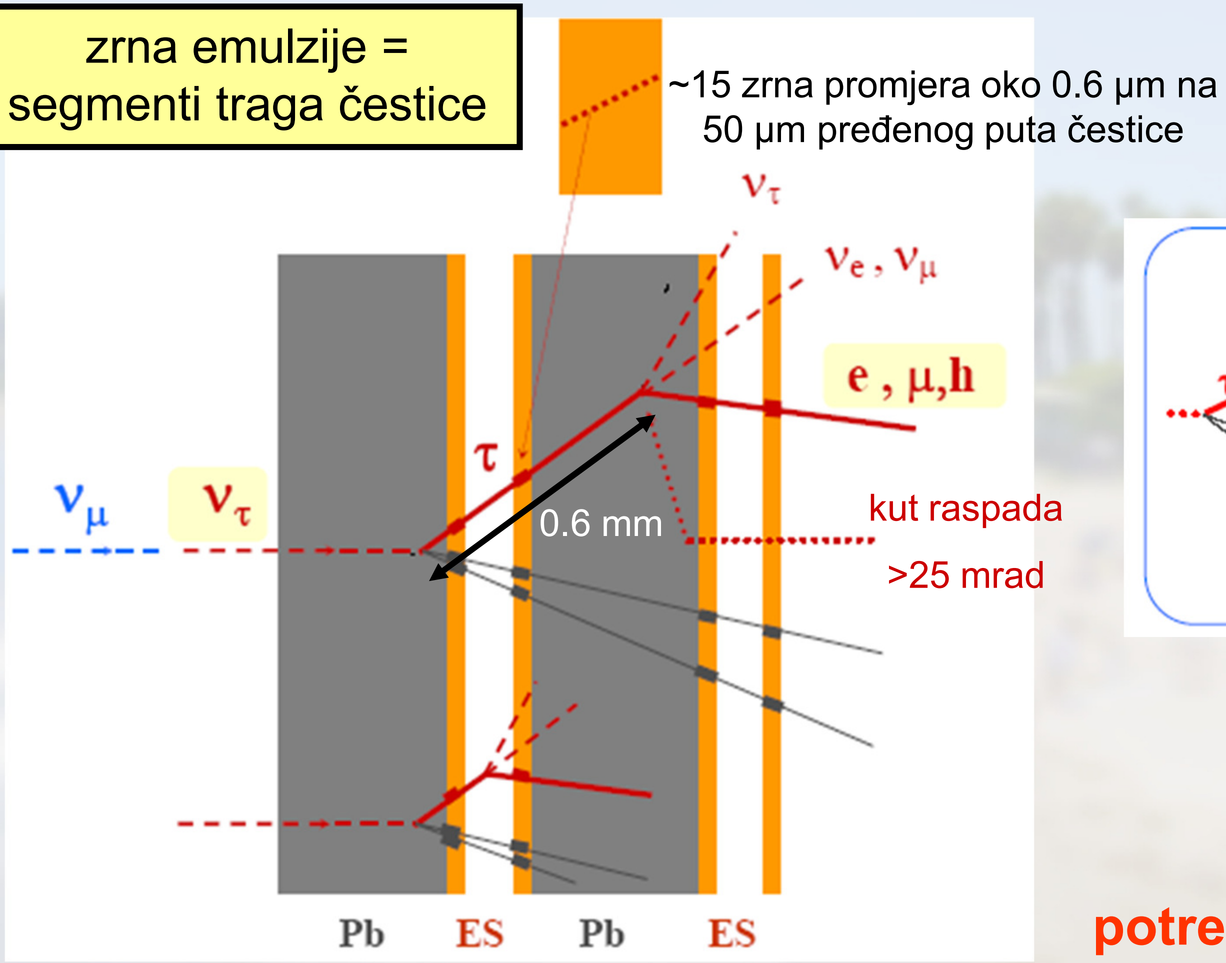
56 emulsion sheets separated by 1mm thick lead plates

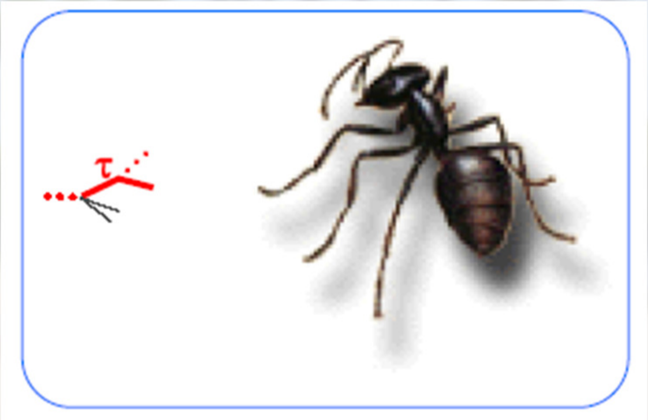




Simulirani ν_τ događaj

zrna emulzije = segmenti traga čestice



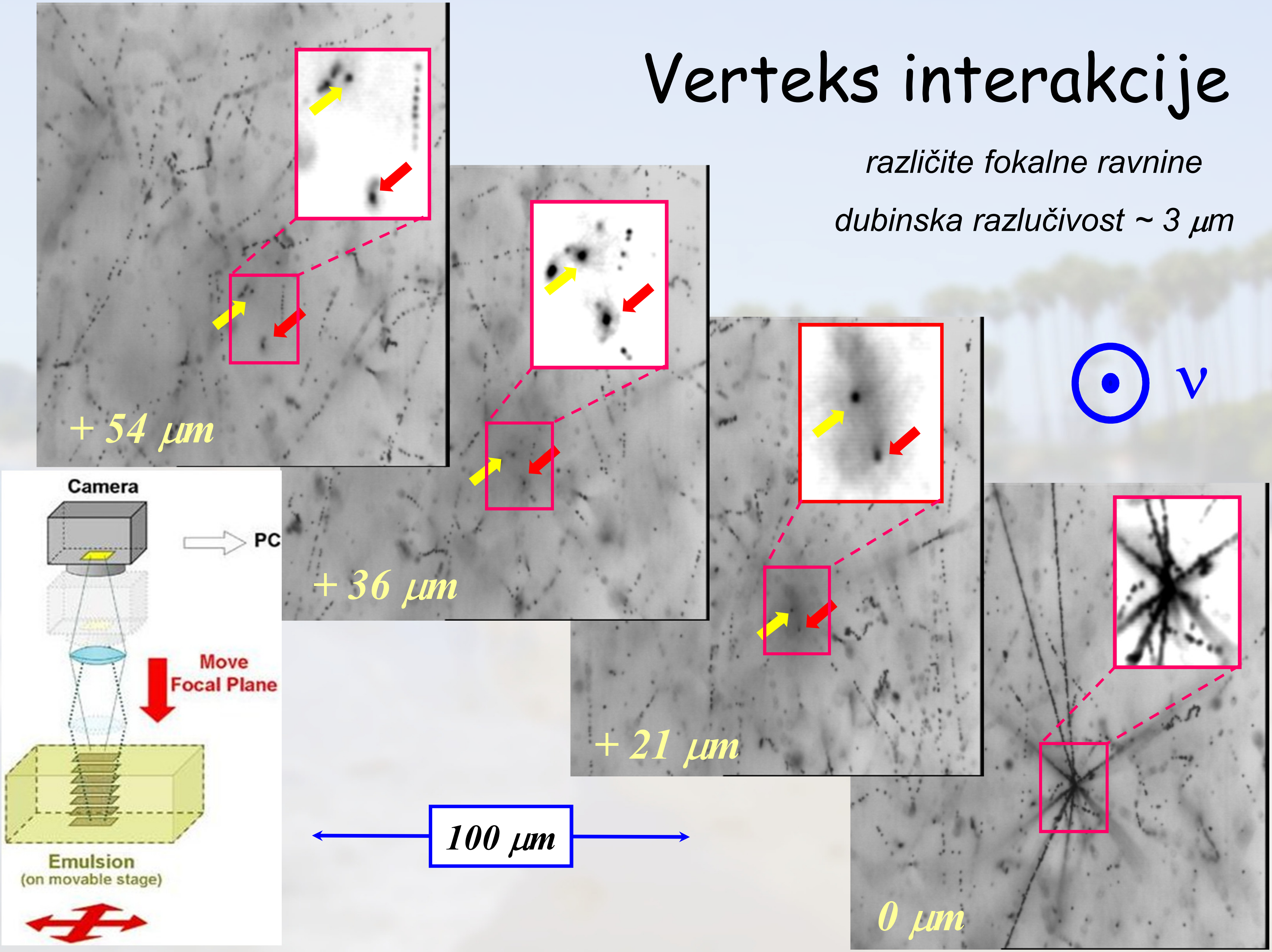


potrebna je velika prostorna razlučivost !

Verteks interakcije

različite fokalne ravnine

dubinska razlučivost ~ 3 μm



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

Dario Autiero

IPN Lyon

On behalf of the OPERA Collaboration

The OPERA Collaboration
160 physicists, 30 institutions, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

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

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

CERN: CNGS, Survey, Timing and PS groups

The geodesy group of the Università Sapienza of Rome

The Swiss Institute of Metrology (METAS)

The German Institute of Metrology (PTB)

Principle of the neutrino velocity measurement

Definition of neutrino velocity:

ratio of precisely measured baseline and time of flight

Time of flight measurement:

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

accurate determination of the baseline (geodesy)

expected small effects: long baseline required

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

Past experimental results

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

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

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

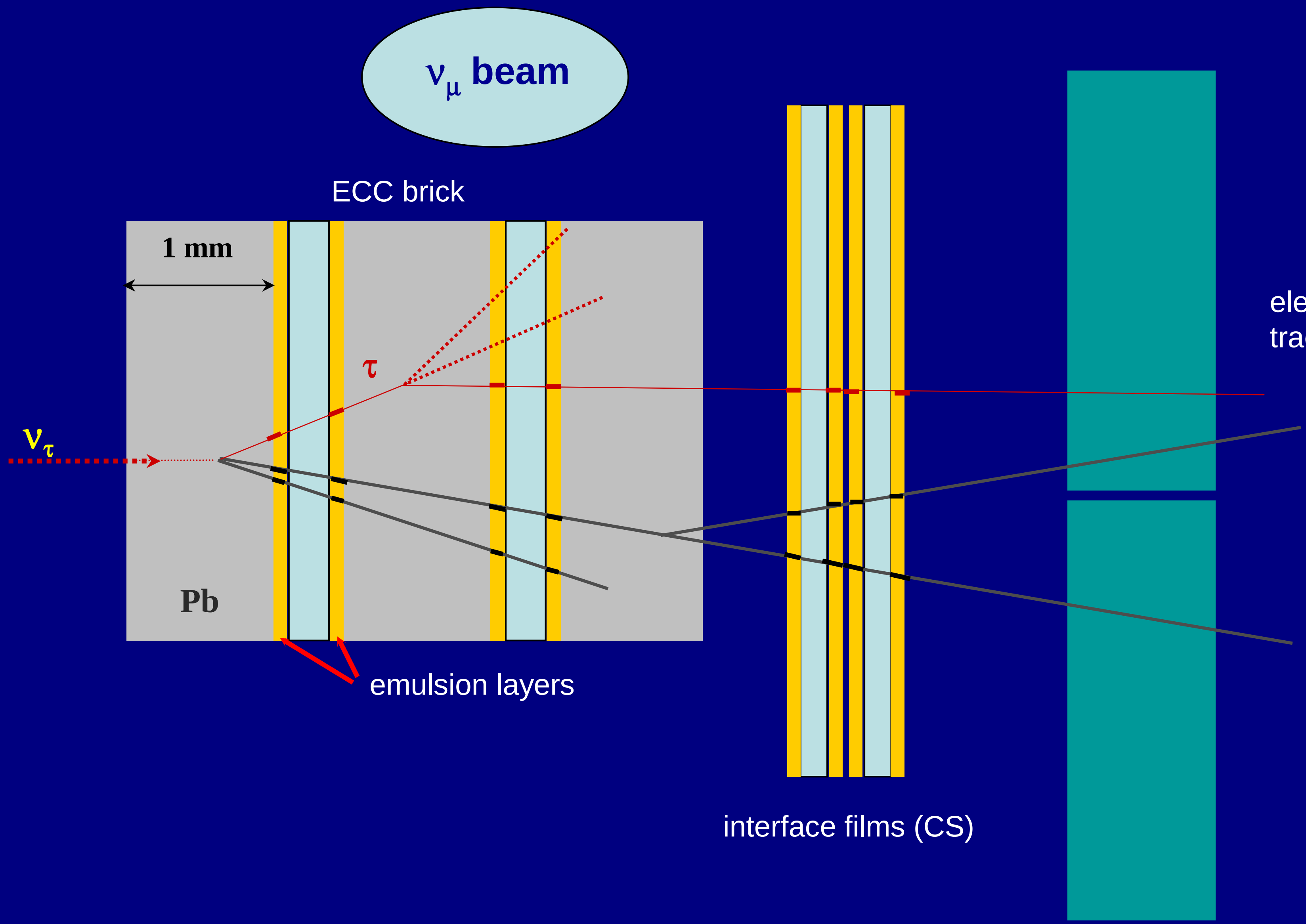
electron (anti) neutrinos, 10 MeV range, 168'000 light years baseline.
$|v-c|/c \leq 2\times10^{-9}$.
Performed with observation of neutrino and light arrival time.

MINOS (Phys. Rev. D 76 072005 2007)

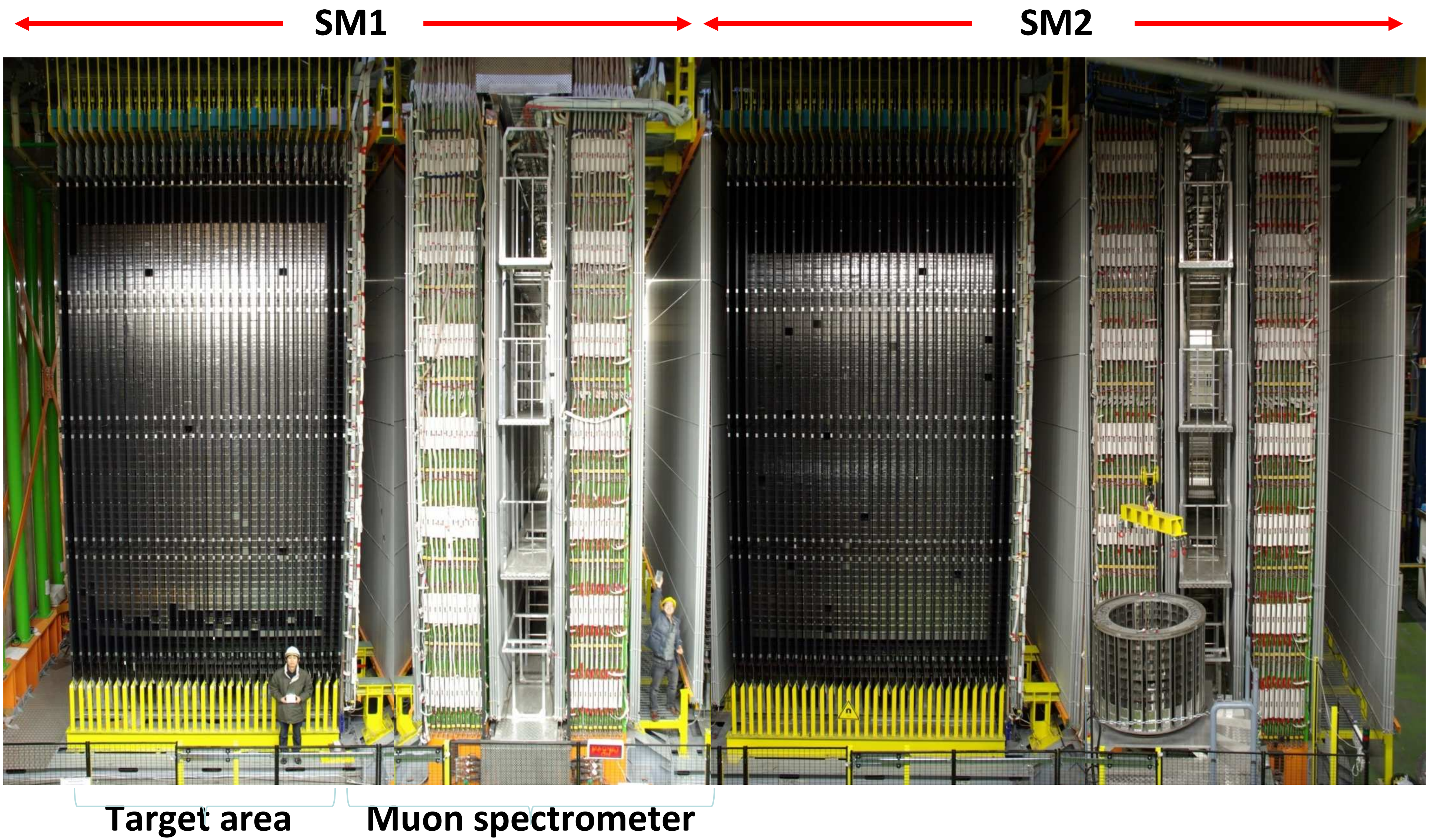
muon neutrinos, 730 km baseline, E_ν peaking at ~3 GeV with a tail extending above 100 GeV.
$(v-c)/c = 5.1 \pm 2.9\times10^{-5}$ (1.8 σ).

THE DESIGN OF THE OPERA EXPERIMENT

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



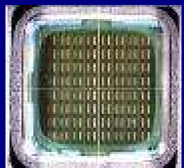
THE IMPLEMENTATION OF THE PRINCIPLE



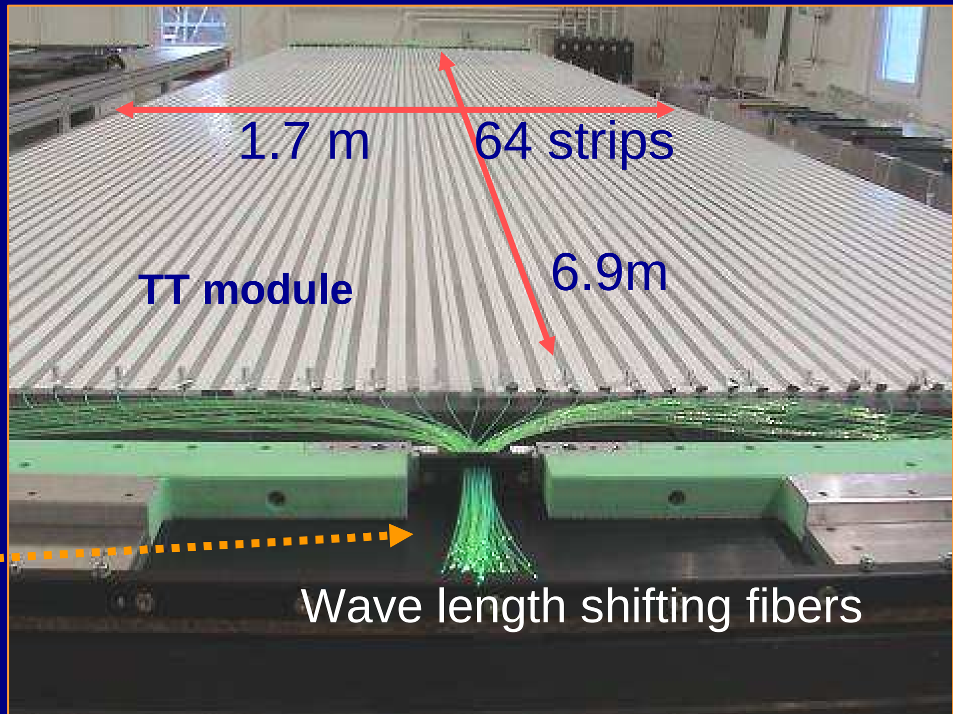
The Target Tracker (TT)

pre-location of neutrino interactions and event timing

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

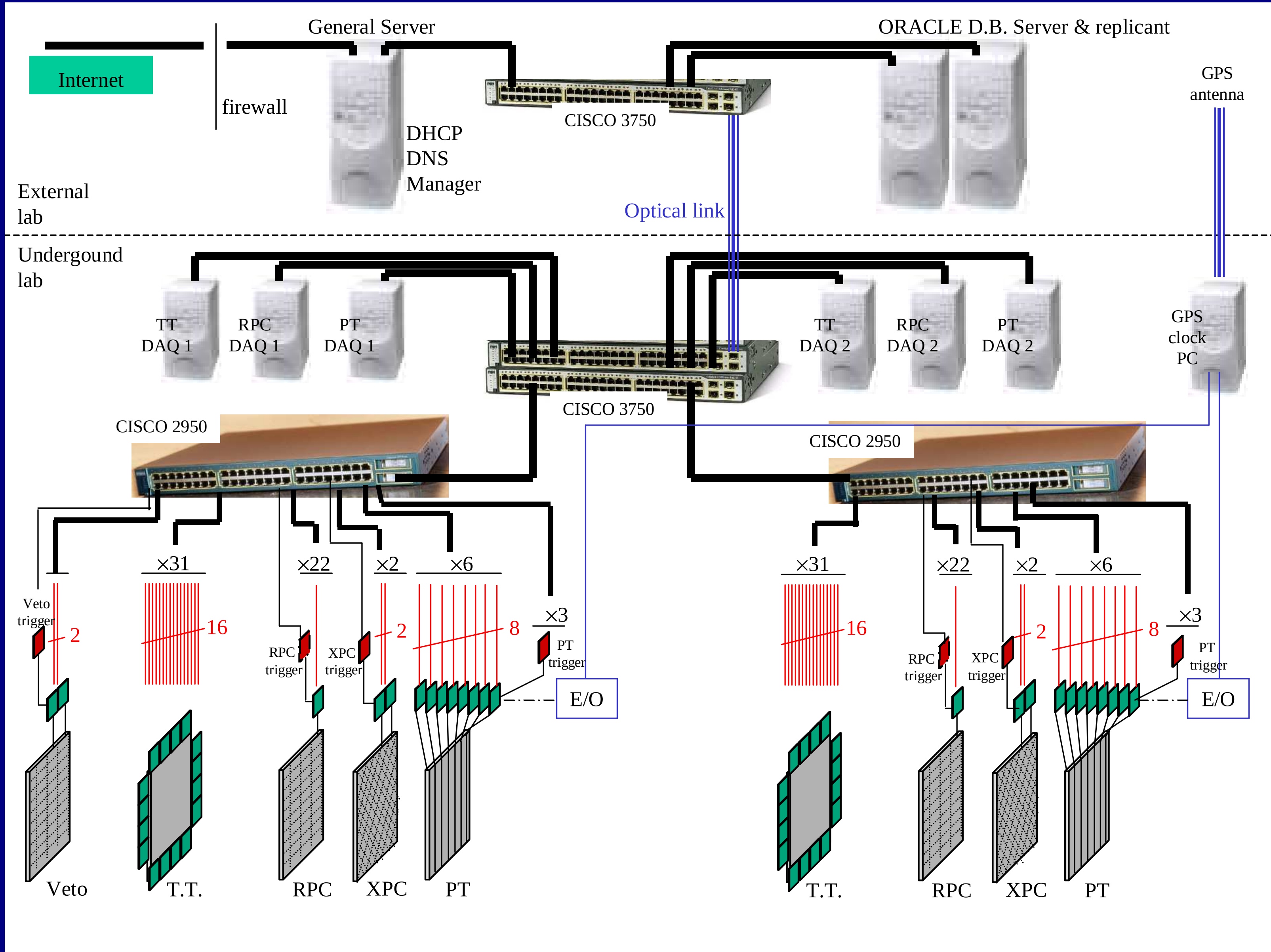


H7546



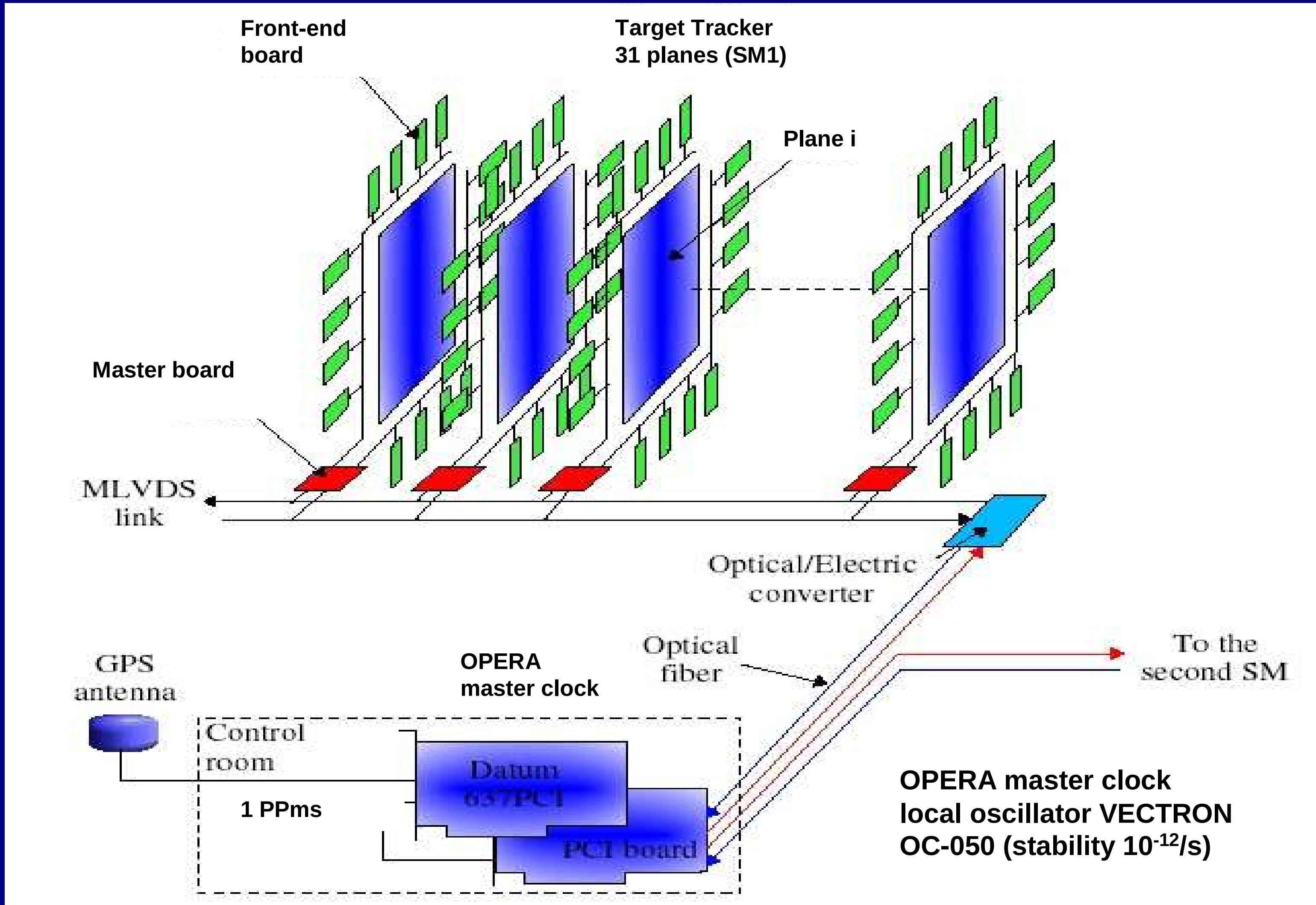
Read out by 1 Front-End DAQ board per side

OPERA readout scheme



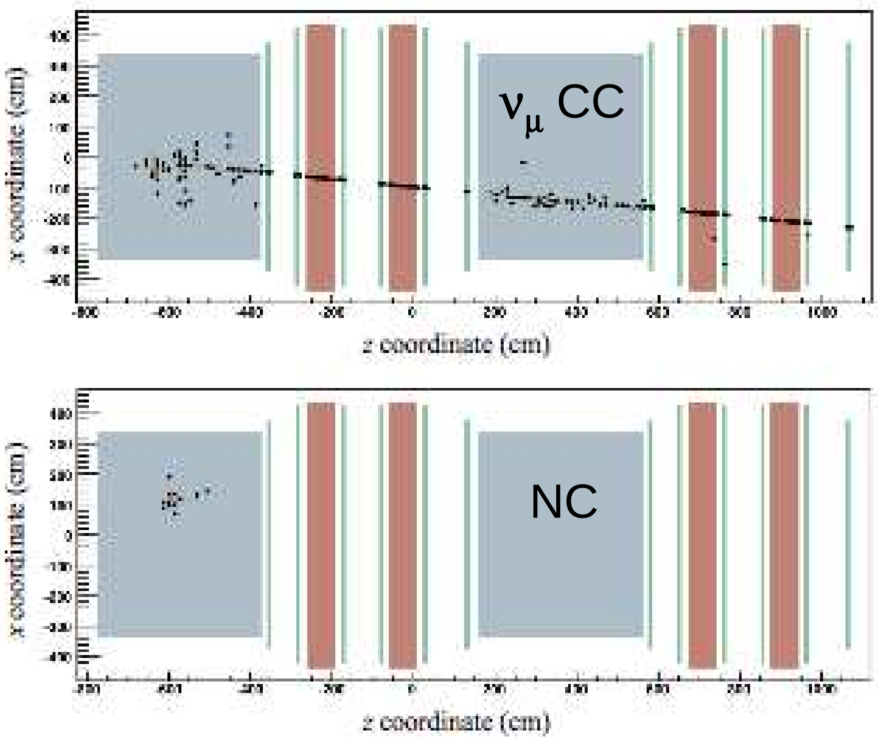
Trigger-less, asynchronous Front-End nodes (1200); Gigabit Ethernet network

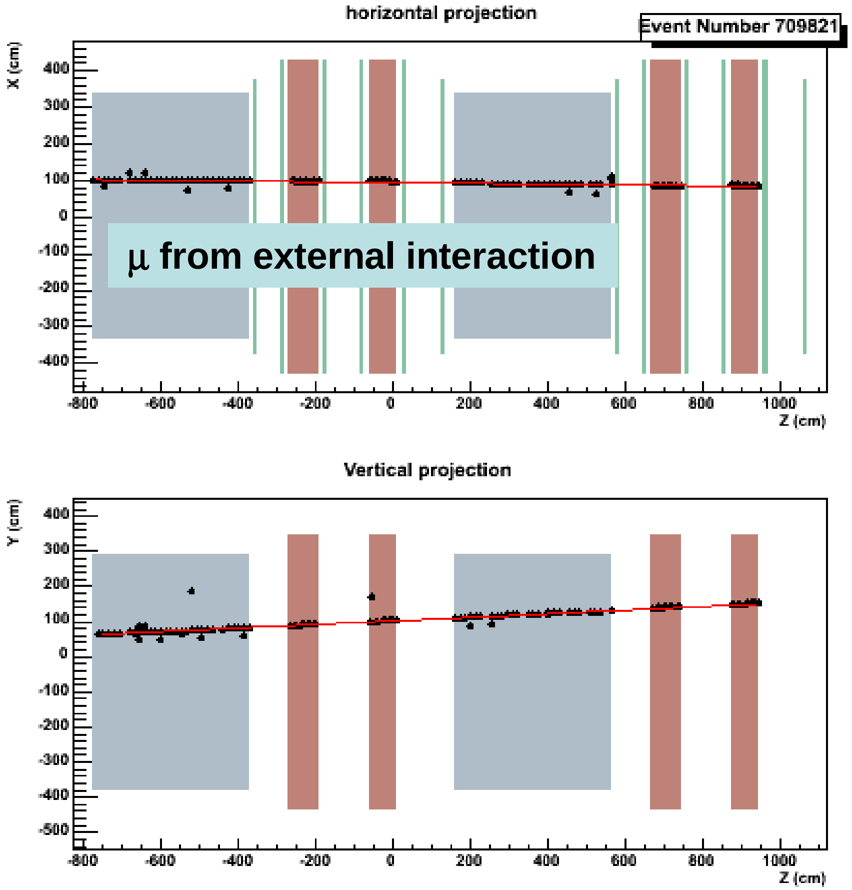
Clock distribution system (10 ns UTC event time-stamp granularity)



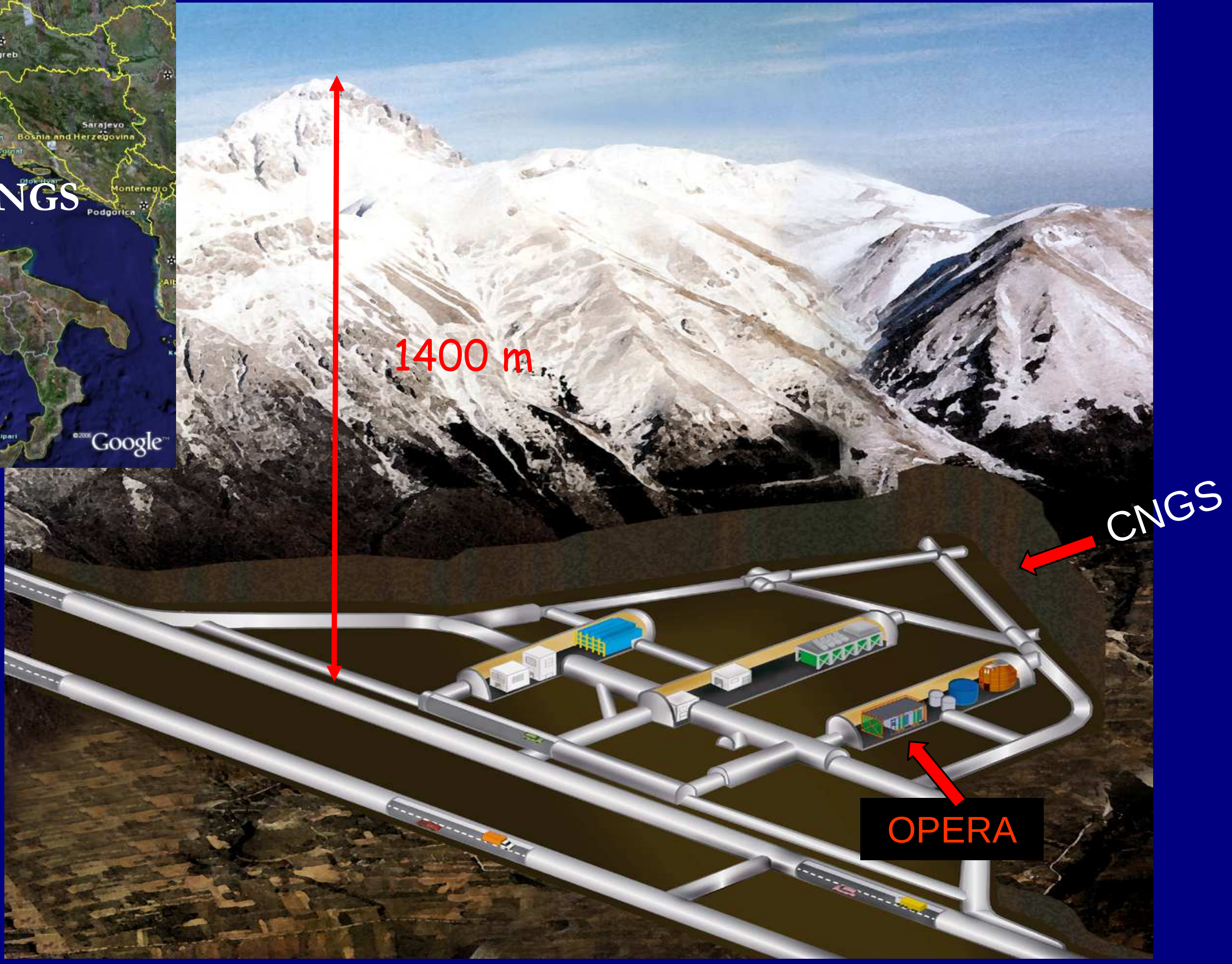
Mezzanine DAQ card common to all sub-detectors Front End nodes:
CPU (embedded LINUX), Memory, FPGA, clock receiver and ethernet

“INTERNAL” and “EXTERNAL” OPERA EVENTS

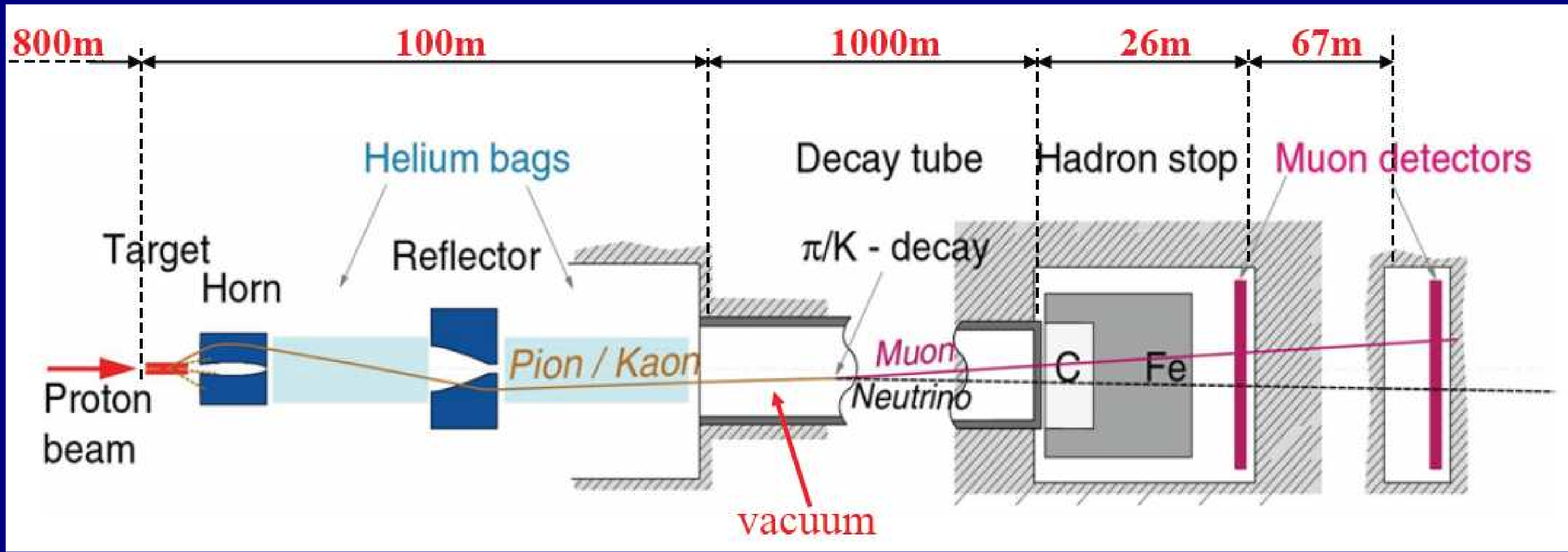




The LNGS underground physics laboratory

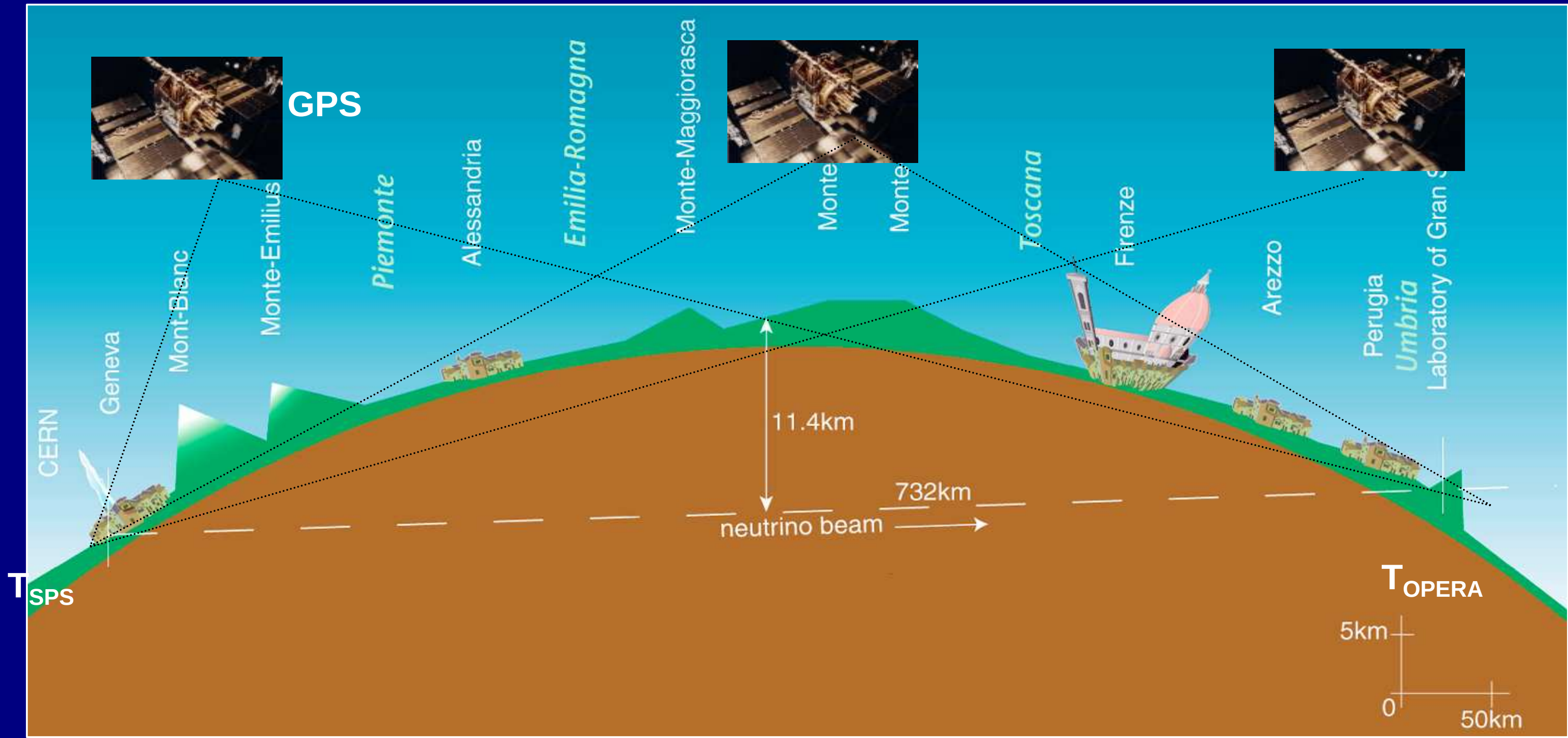


THE CNGS neutrino beam



- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5 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



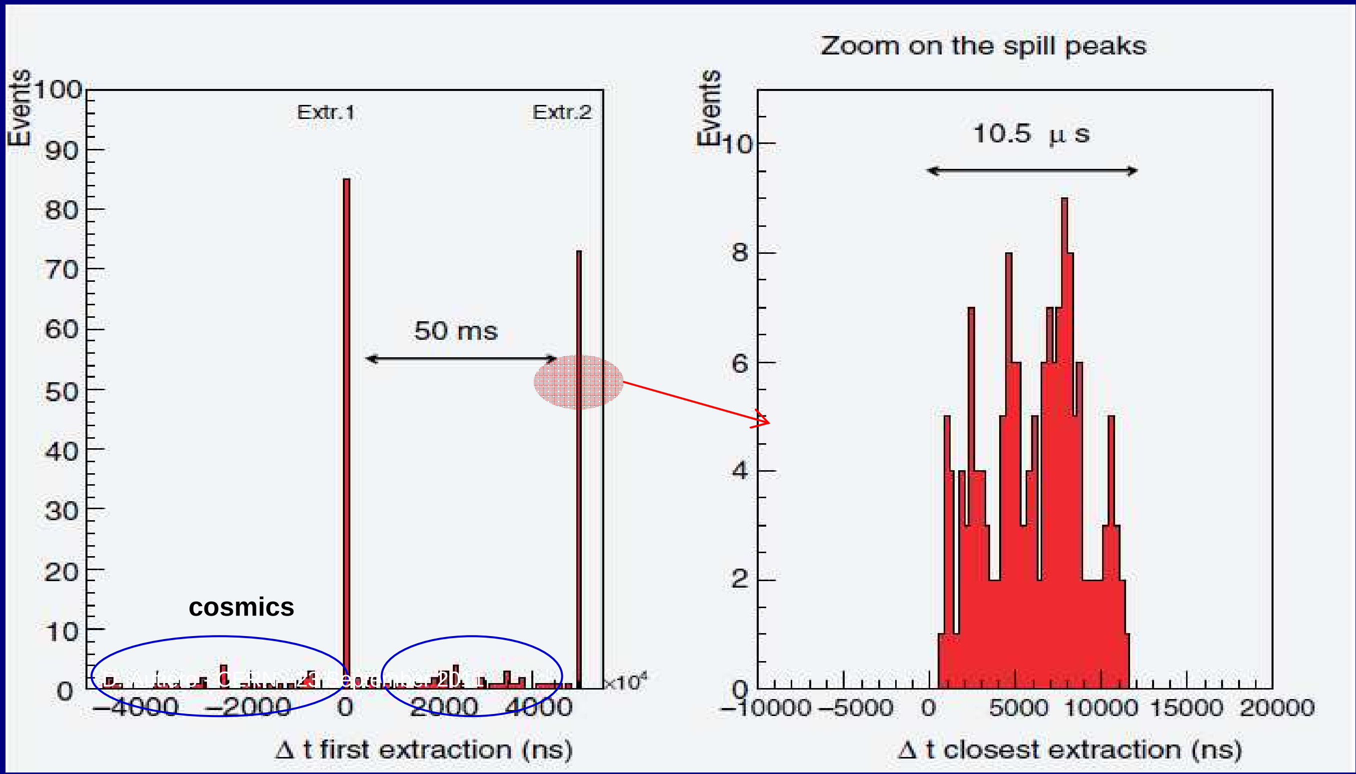
Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

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

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

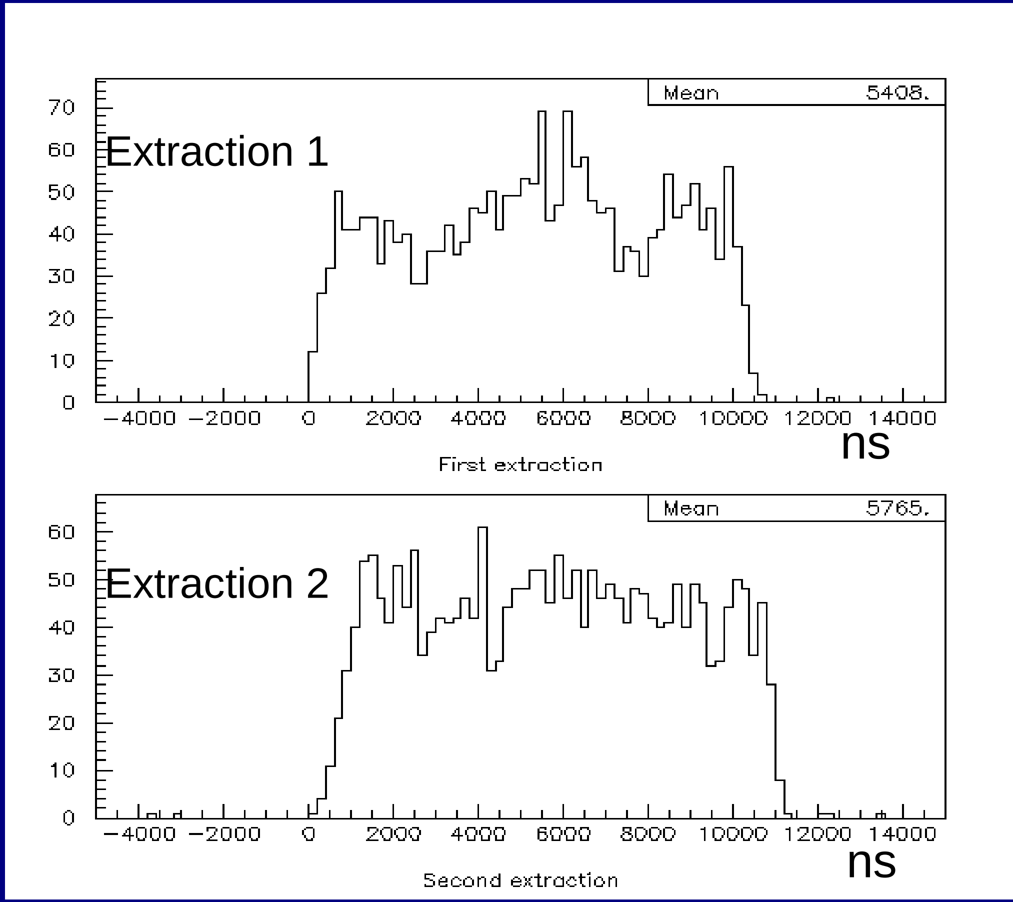


OPERA data: narrow peaks of the order of the spill width (10.5 μs)

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

Selection procedure kept unchanged since first events in 2006

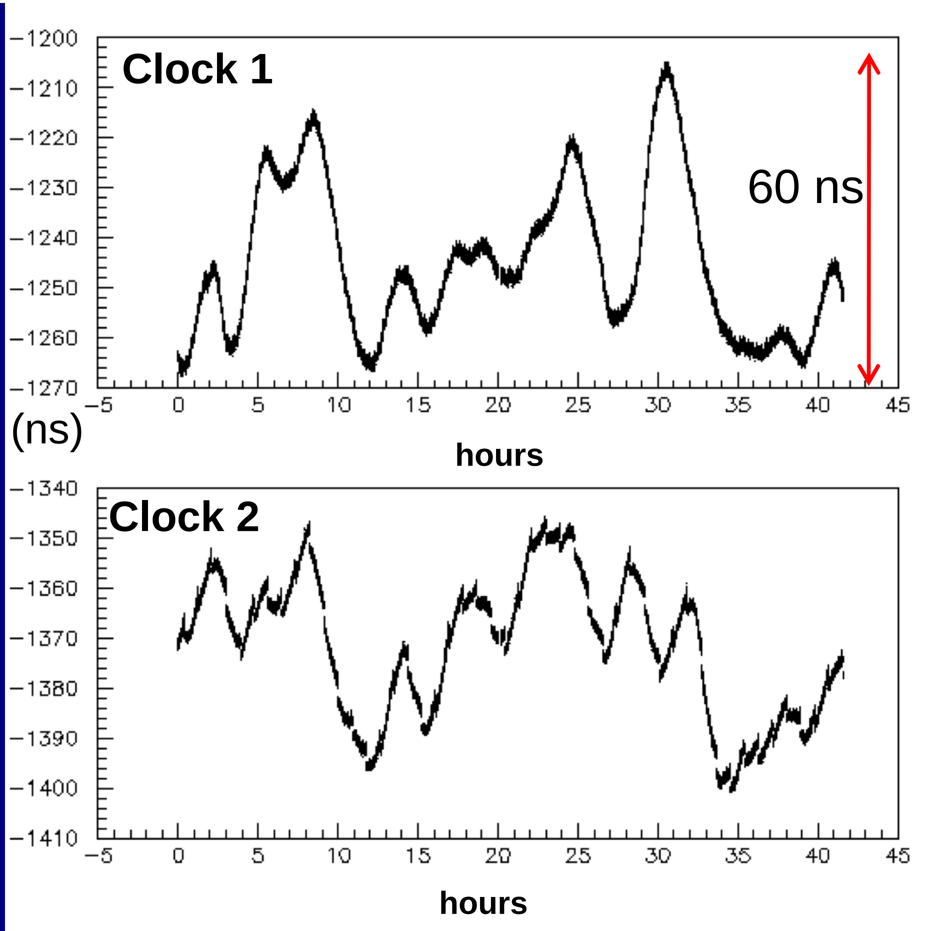
From CNGS event selection to neutrino velocity measurement



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

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

→ Need to precisely measure the protons spills



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

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

→ Need accurate time synchronisation system

Collaboration with CERN timing team since 2003

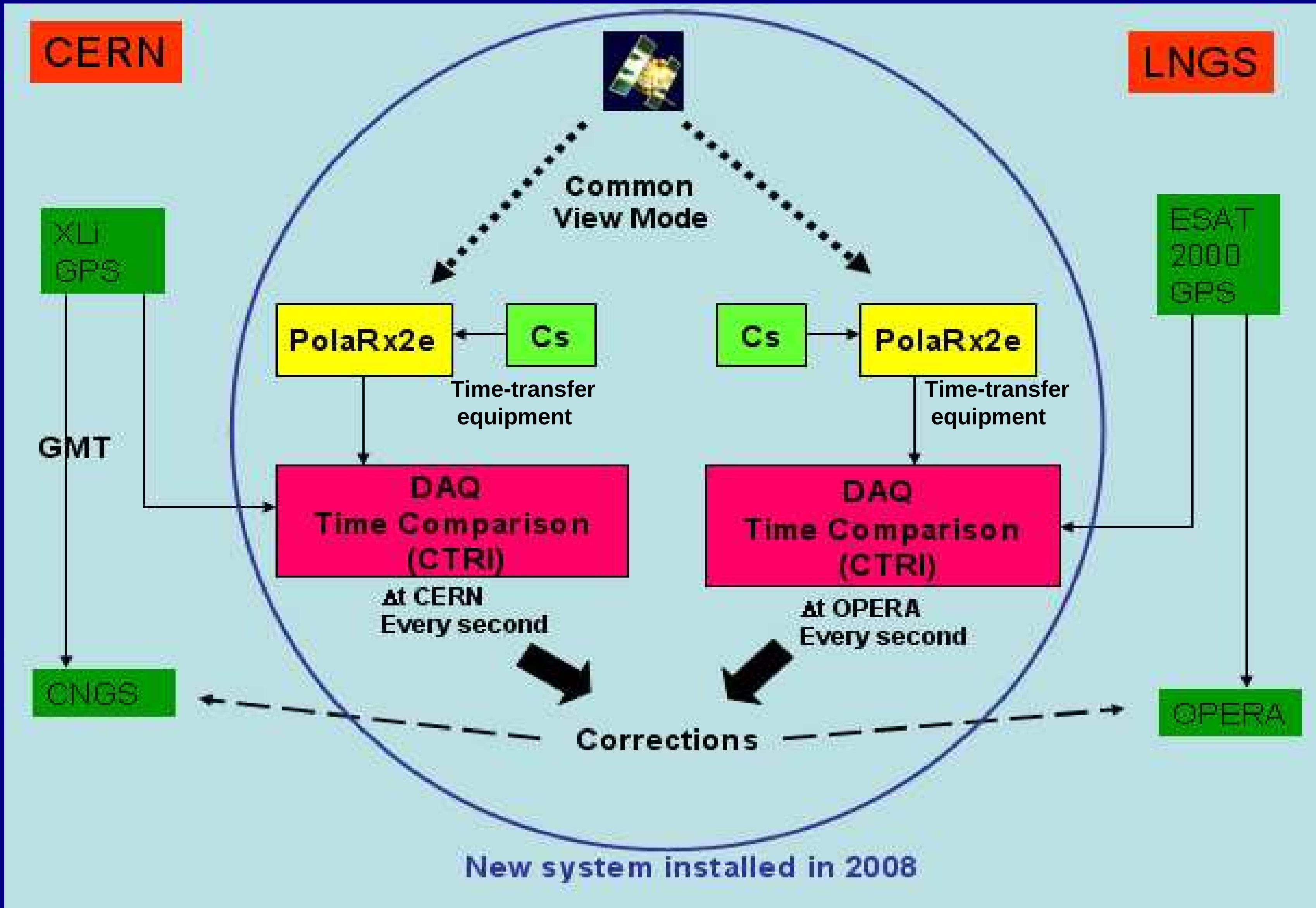
Major upgrade in 2008

OPERA sensitivity

- High neutrino energy - high statistics ~16000 events
- Sophisticated timing system: ~1 ns CNGS-OPERA synchronisation
- Accurate calibrations of CNGS and OPERA timing chains: ~ 1 ns level
- Precise measurement of neutrino time distribution at CERN through proton waveforms
- Measurement of baseline by global geodesy: 20 cm accuracy over 730 km

→ Result: ~10 ns overall accuracy on TOF with similar stat. and sys. errors

CNGS-OPERA synchronization



Standard GPS receivers ~100 ns accuracy:

CERN 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

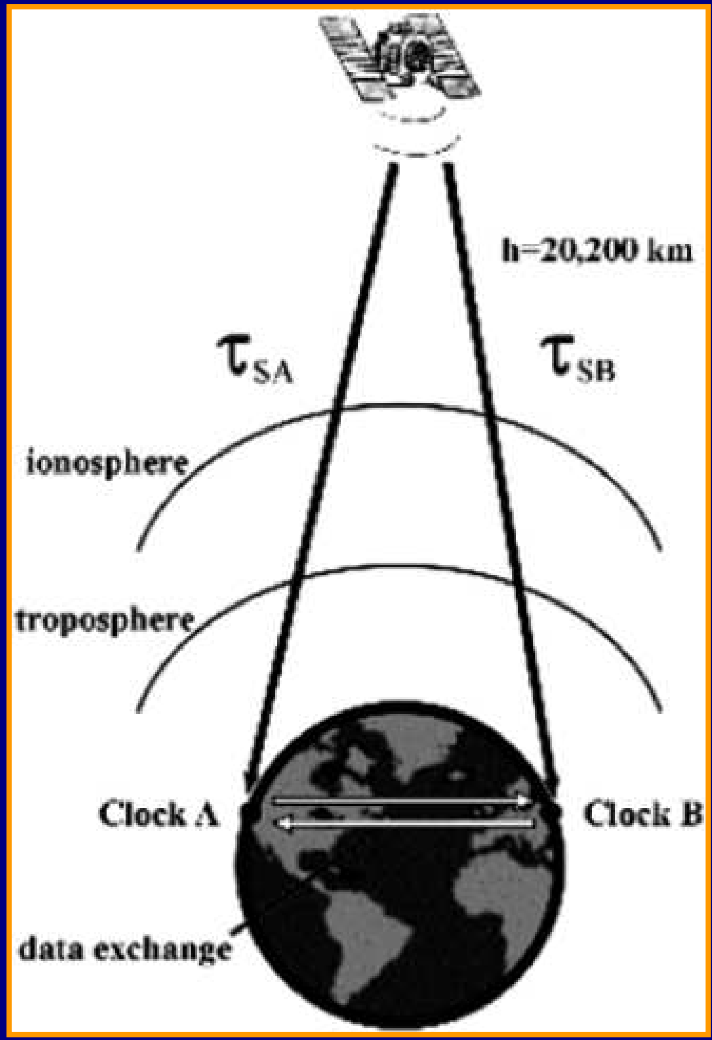
Standard GPS operation:

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

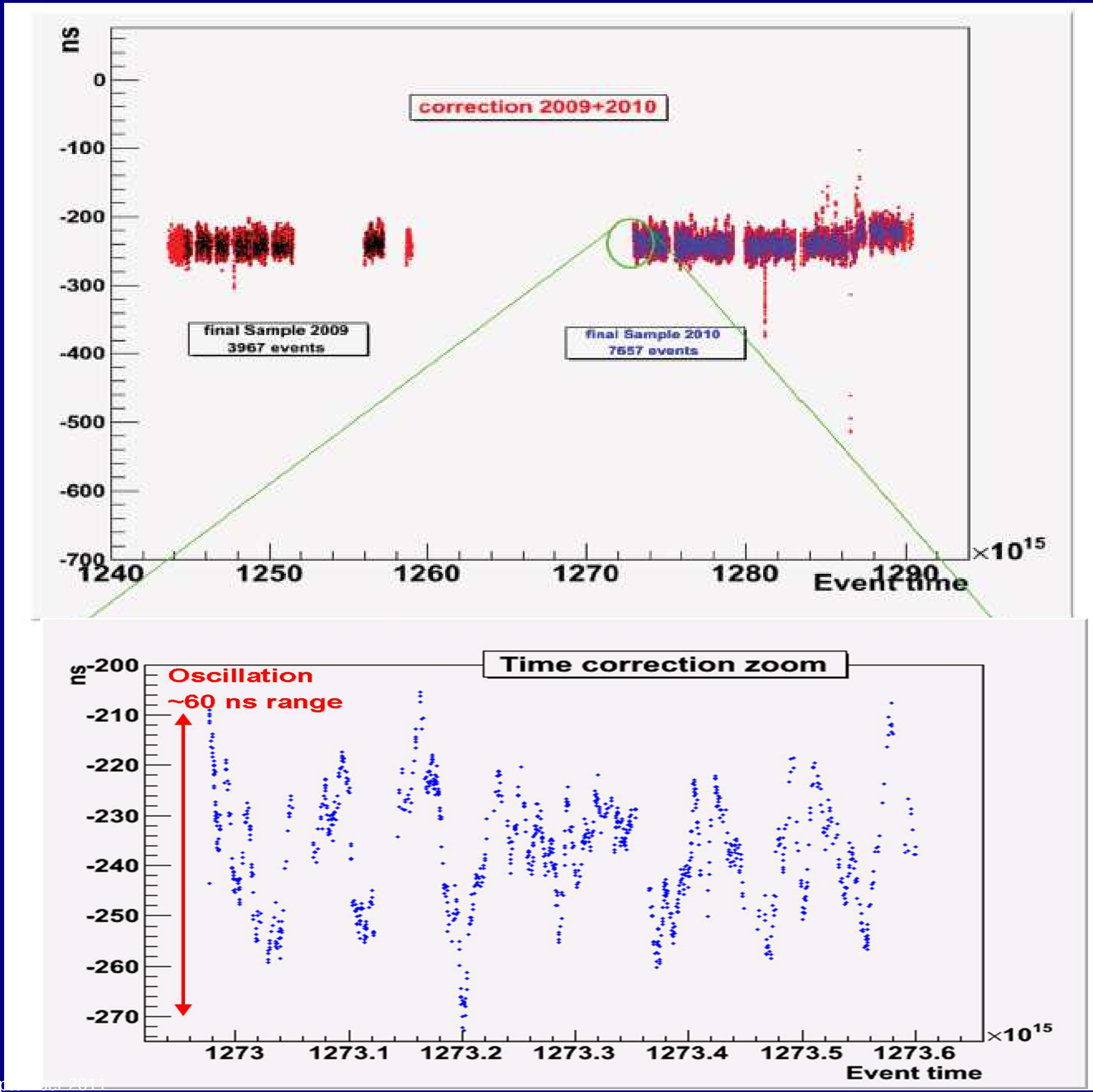
Common-view mode (the same satellite for the two sites, for each comparison):

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



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

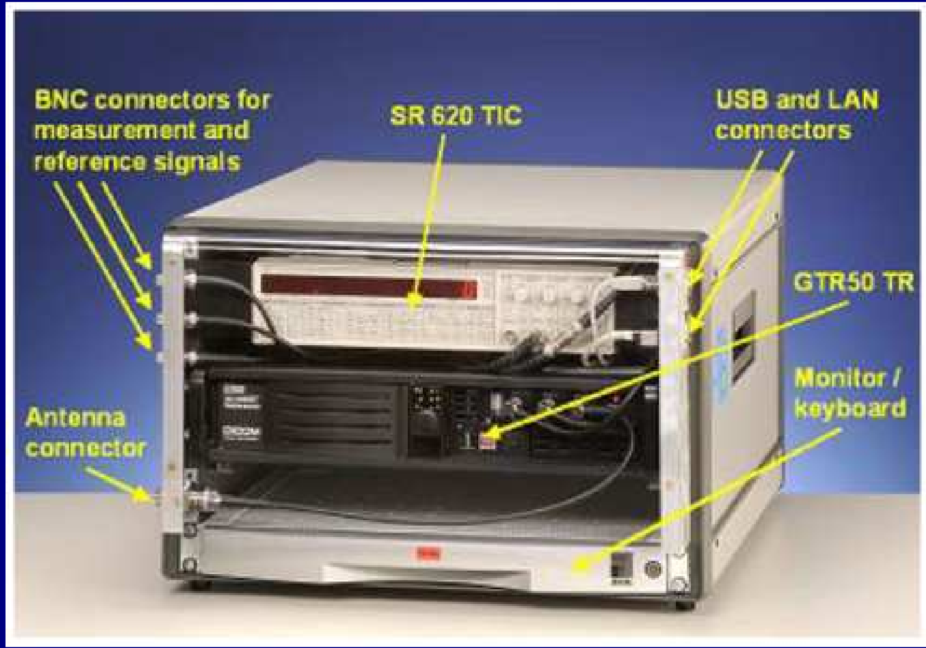


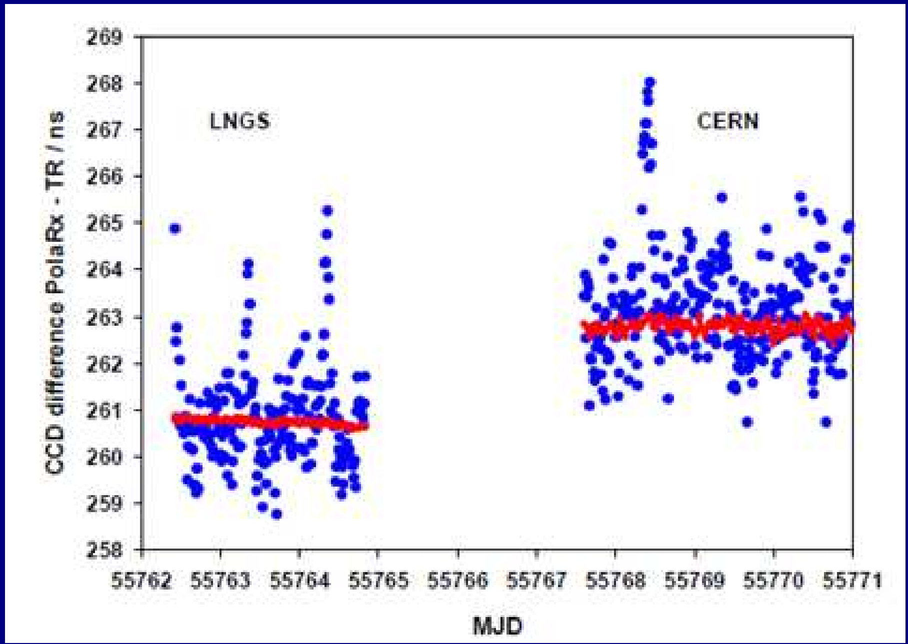
CERN-OPERA inter-calibration cross-check

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt

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

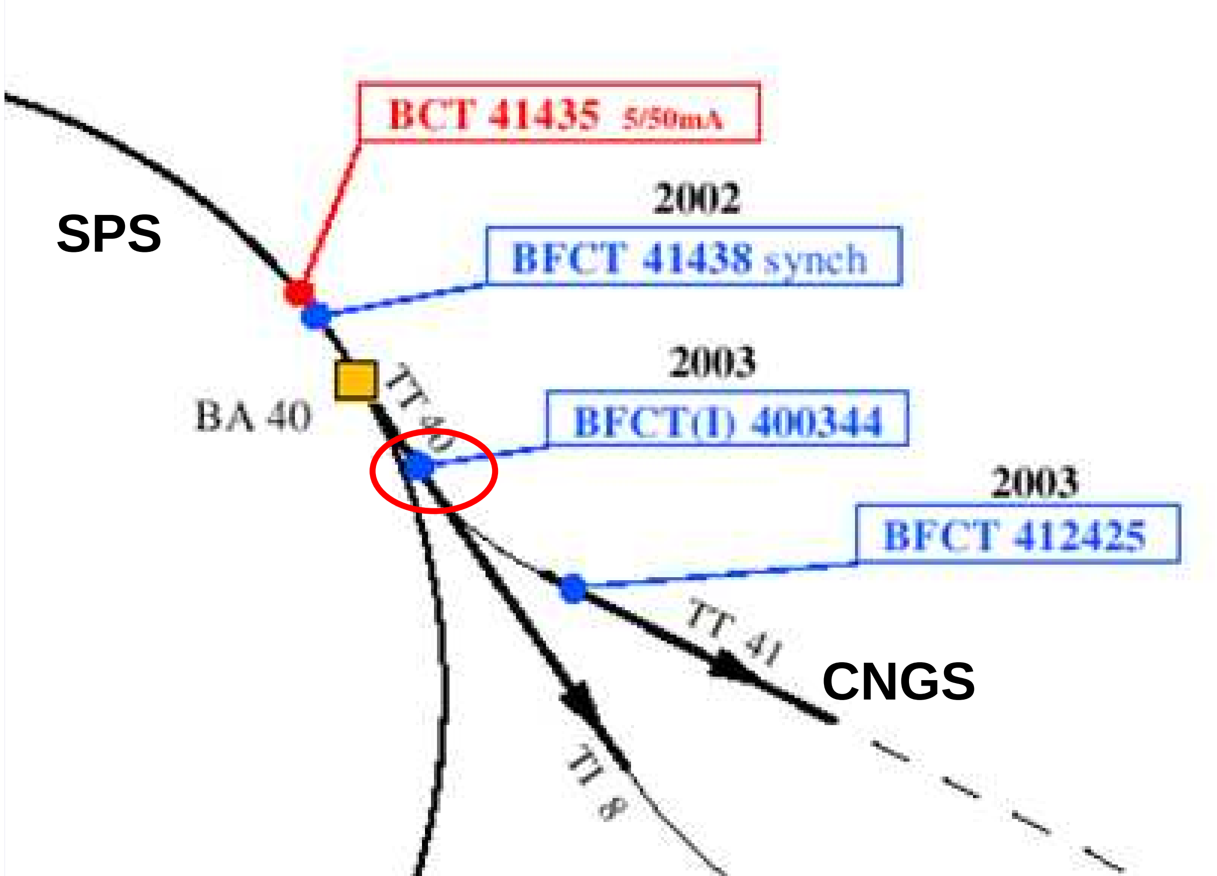
GTR50 GPS receiver, thermalised, external Cs frequency source, embedded Time Interval Counter





Correction to the time-link:

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



Proton timing by Beam Current Transformer

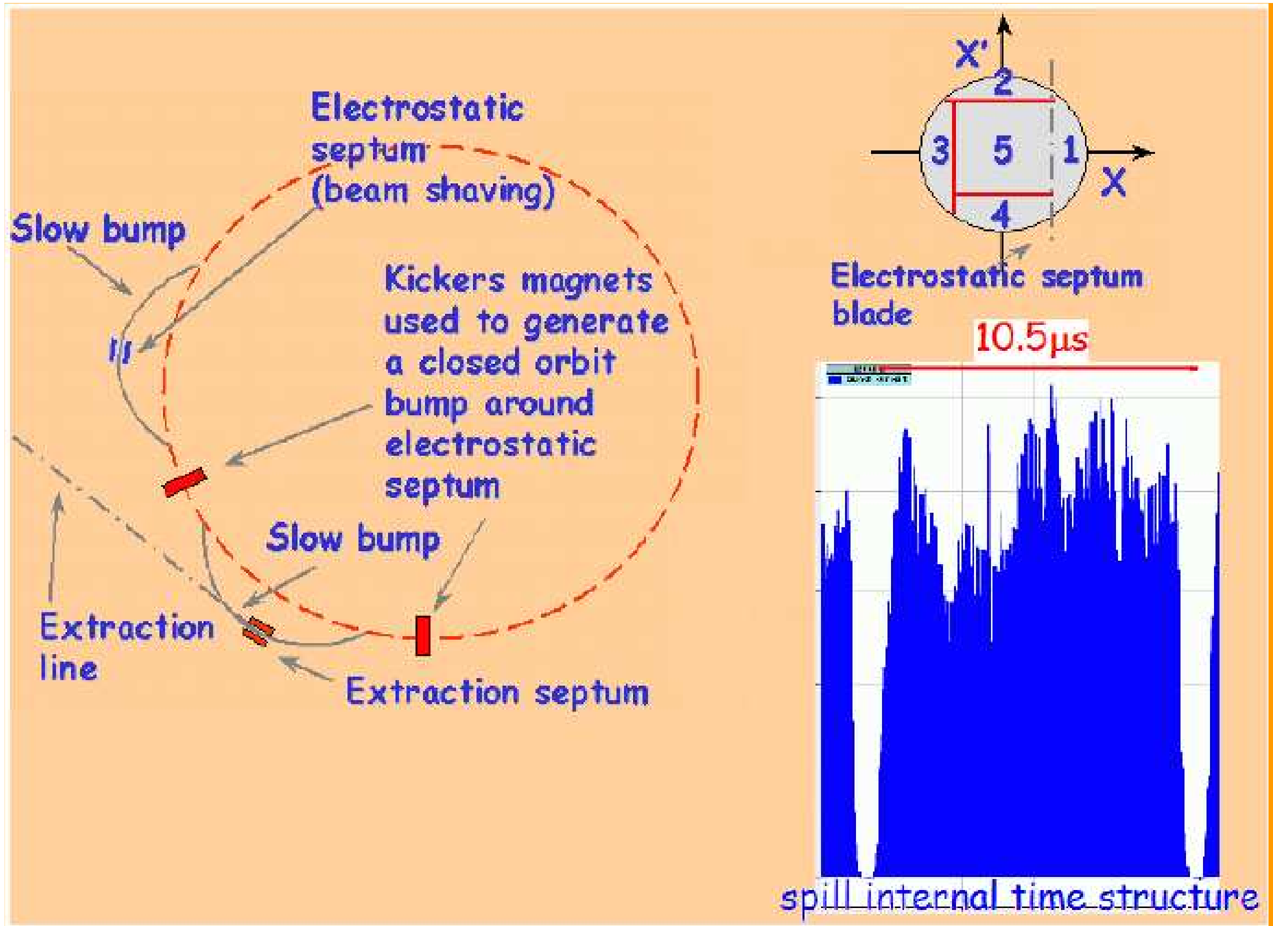
Fast BCT 400344
(~ 400 MHz)

Proton pulse digitization:

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

2010 calibration with Cs clock

Proton spill shape



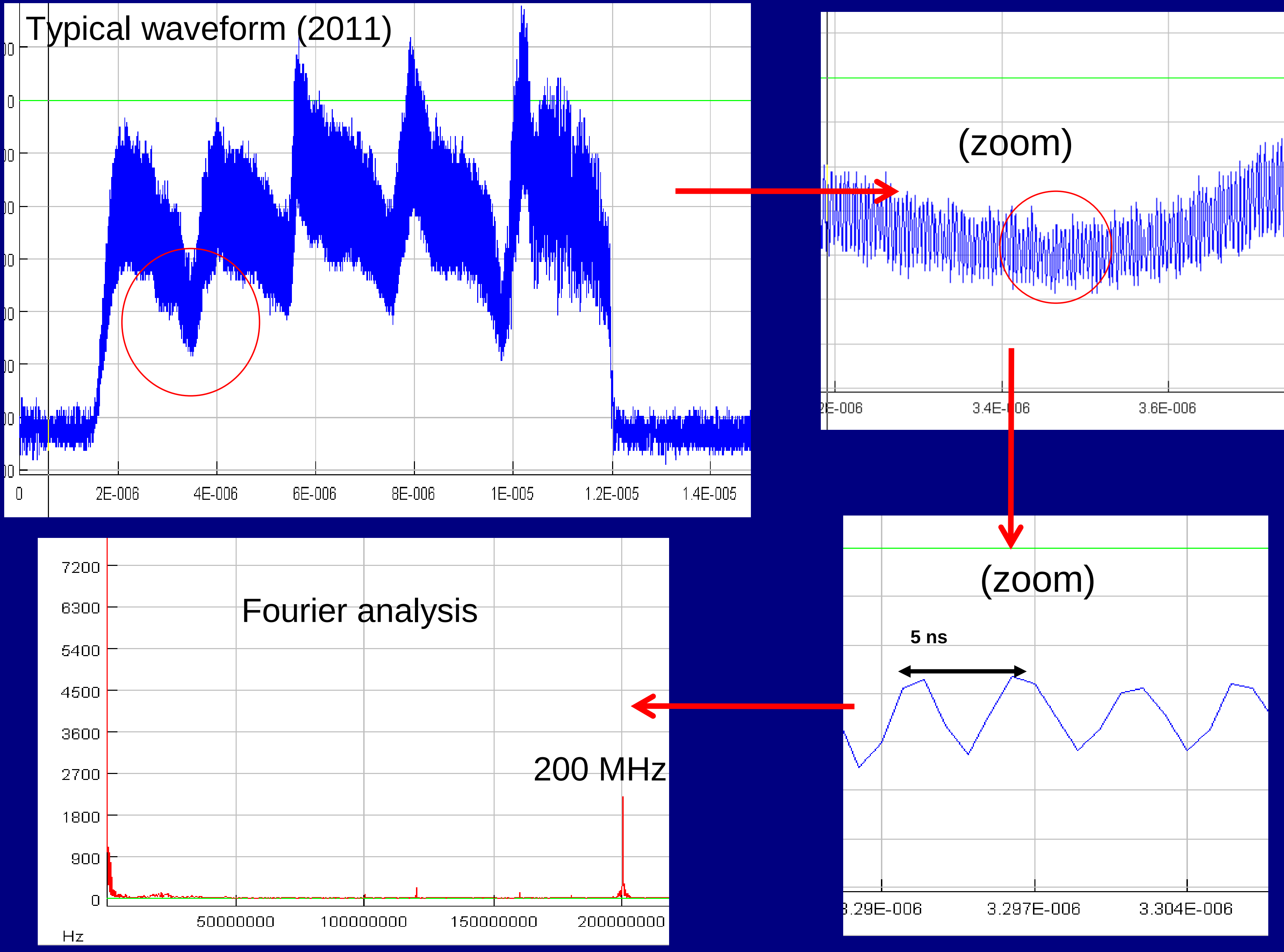
Reminiscence of the Continuous Turn extraction from PS (5 turns)

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

Shapes varying with time and both extractions

→ Precise accounting with WFD waveforms:

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



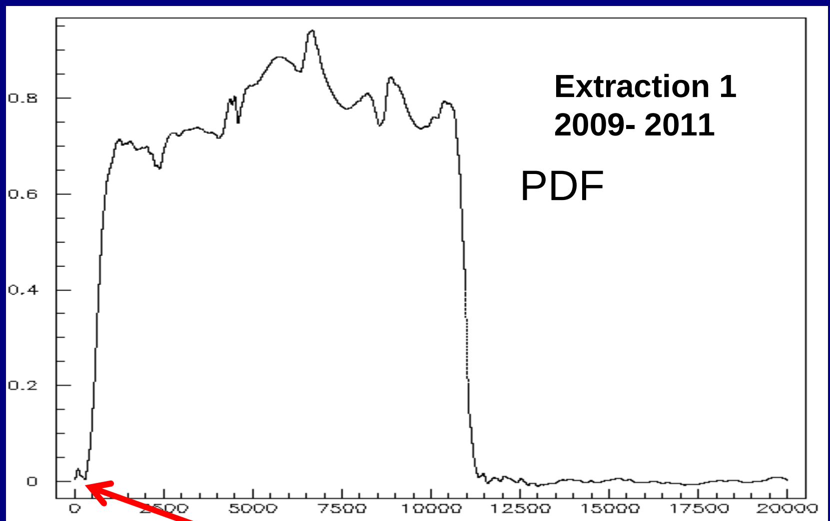
Typical waveform (2011)
0
2E-006
4E-006
6E-006
8E-006
1E-005
1.2E-005
1.4E-005
(zoom)
3.4E-006
3.6E-006
(zoom)
5 ns
3.297E-006
3.304E-006
Fourier analysis
7200
6300
5400
4500
3600
2700
1800
900
0
200 MHz
50000000
100000000
150000000
200000000
Hz

Neutrino event-time distribution PDF

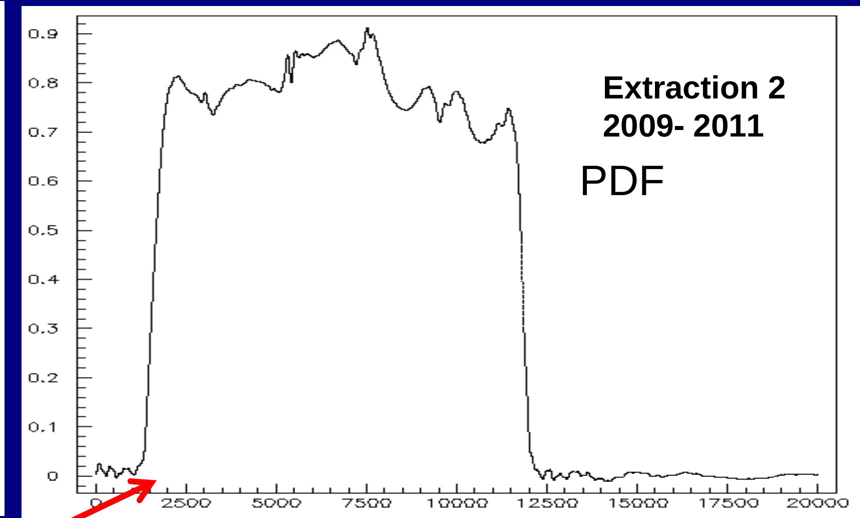
- Each event is associated to its proton spill waveform
- The “parent” proton is unknown within the 10.5 μs extraction time

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

→ compare to OPERA detected neutrino events



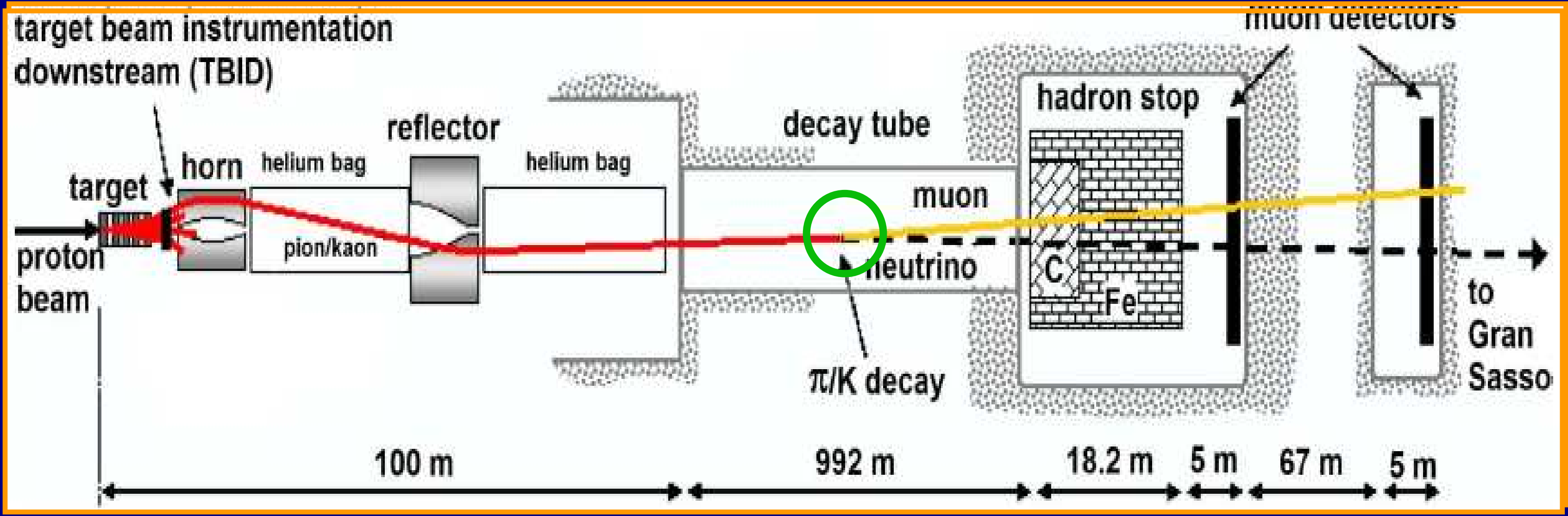
(ns)



(ns)

different timing w.r.t. kicker magnet signal

Neutrino production point



Unknown neutrino production point:

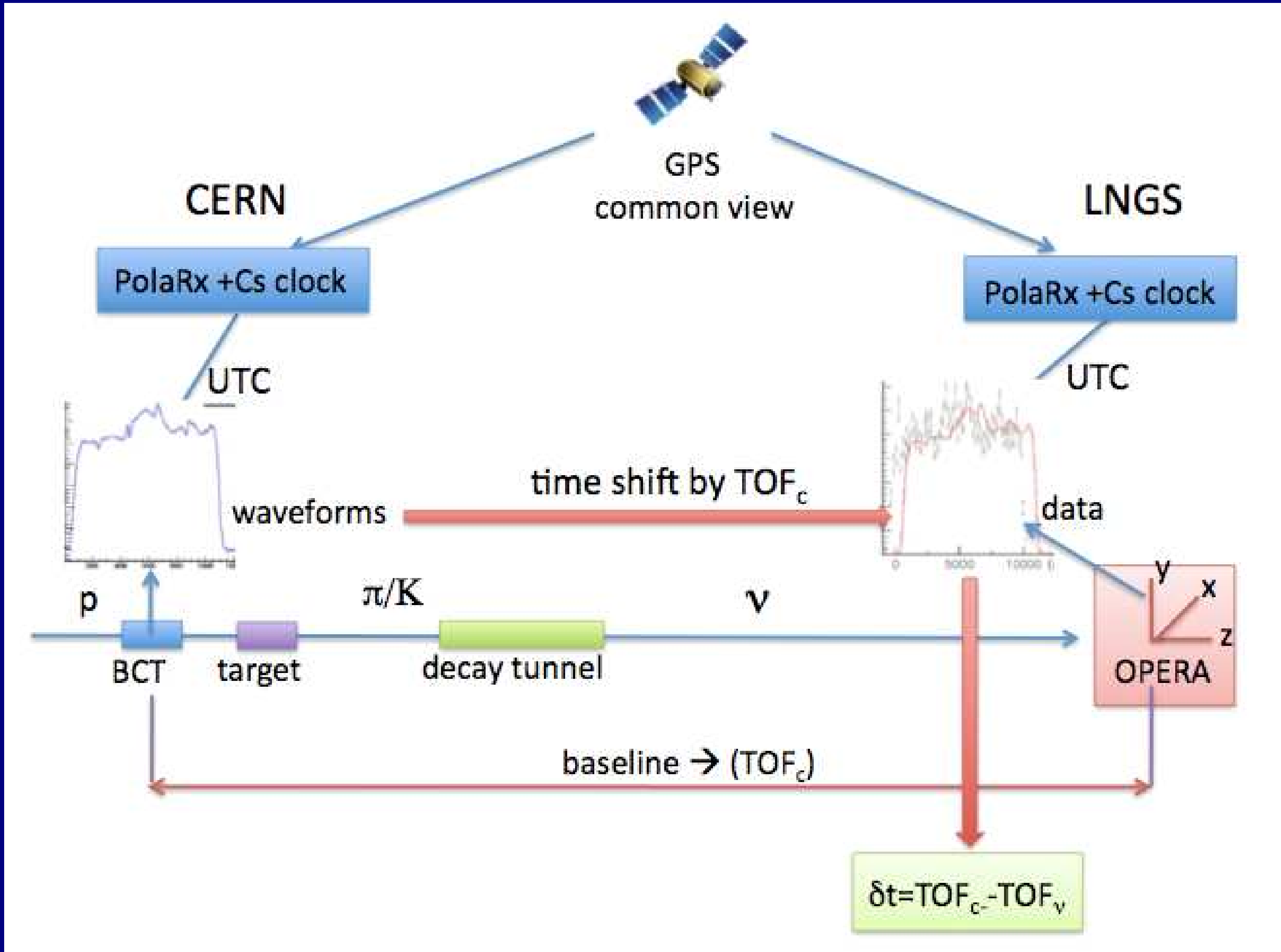
$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c}\left(\frac{1}{\beta} - 1\right) \approx \frac{z}{c}\frac{1}{2\gamma^2}$$

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

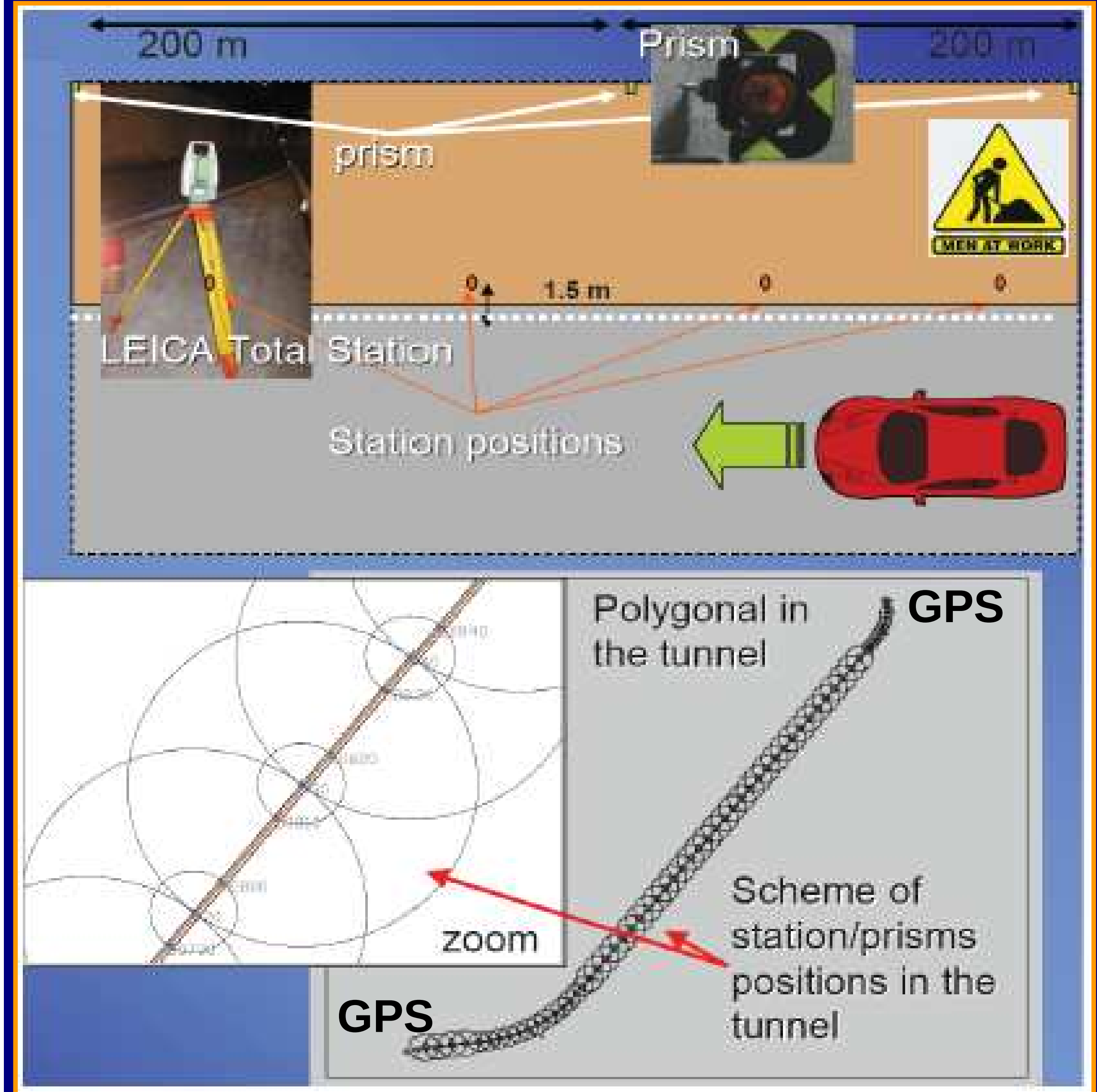
$\langle \Delta t \rangle = 1.4 \times 10^{-2}$ ns

Summary of the principle for the TOF measurement



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

Geodesy at LNGS



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

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

GPS measurements ported underground to OPERA

Combination with CERN geodesy

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

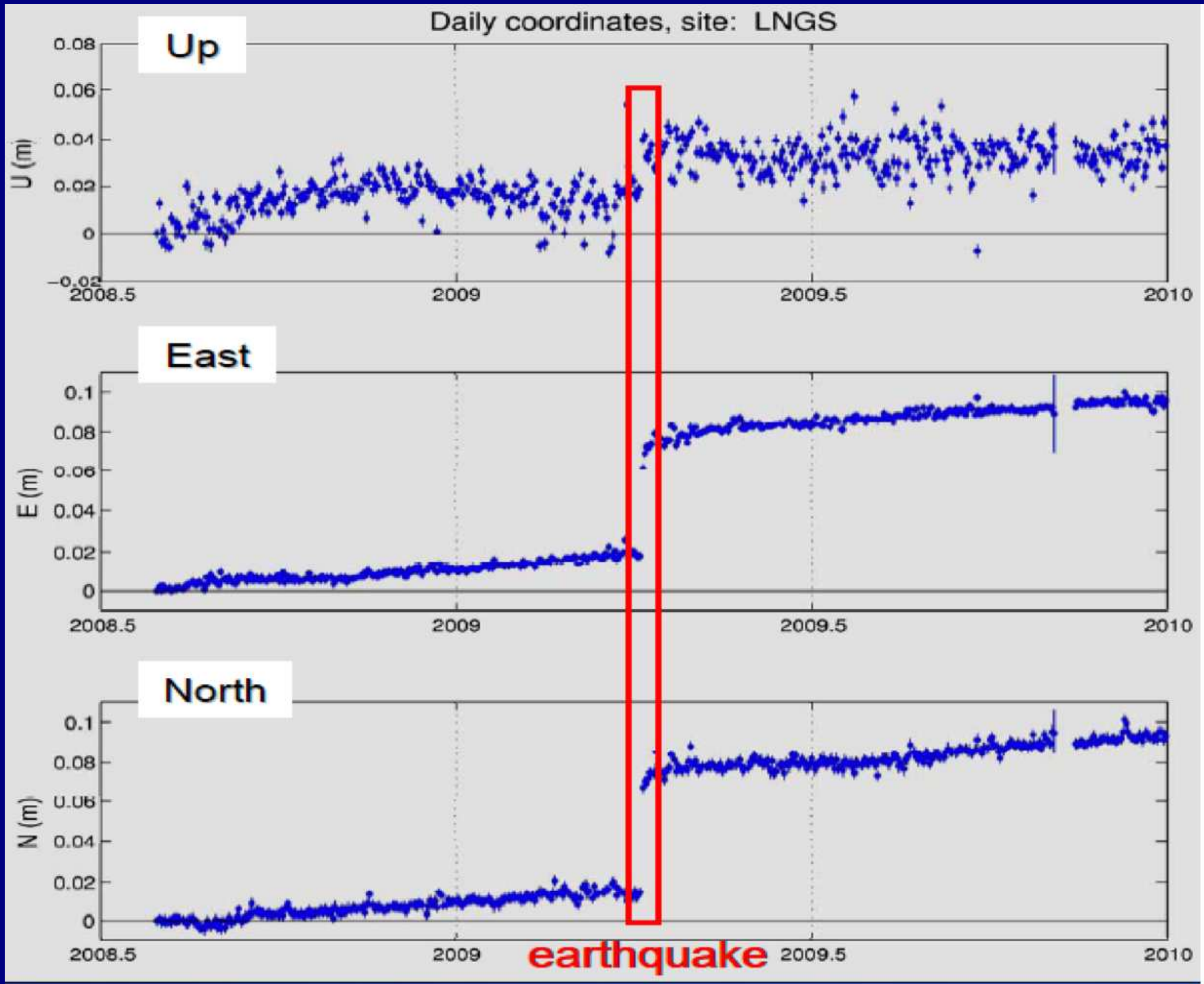
Benchmark	X (m)	Y (m)	Z (m)
GPS1	4579518.745	1108193.650	4285874.215
GPS2	4579537.618	1108238.881	4285843.959
GPS3	4585824.371	1102829.275	4280651.125
GPS4	4585839.629	1102751.612	4280651.236

LNGS benchmarks
In ETRF2000

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

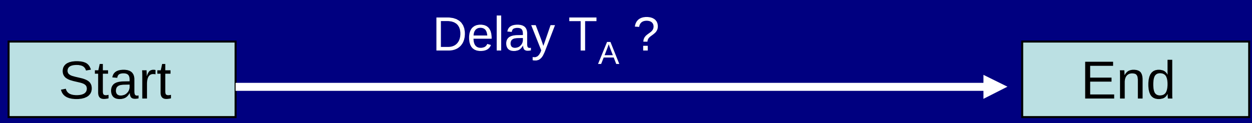
Resulting distance (BCT – OPERA reference frame)
(731278.0 ± 0.2) m

LNGS position monitoring



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

Time calibration techniques

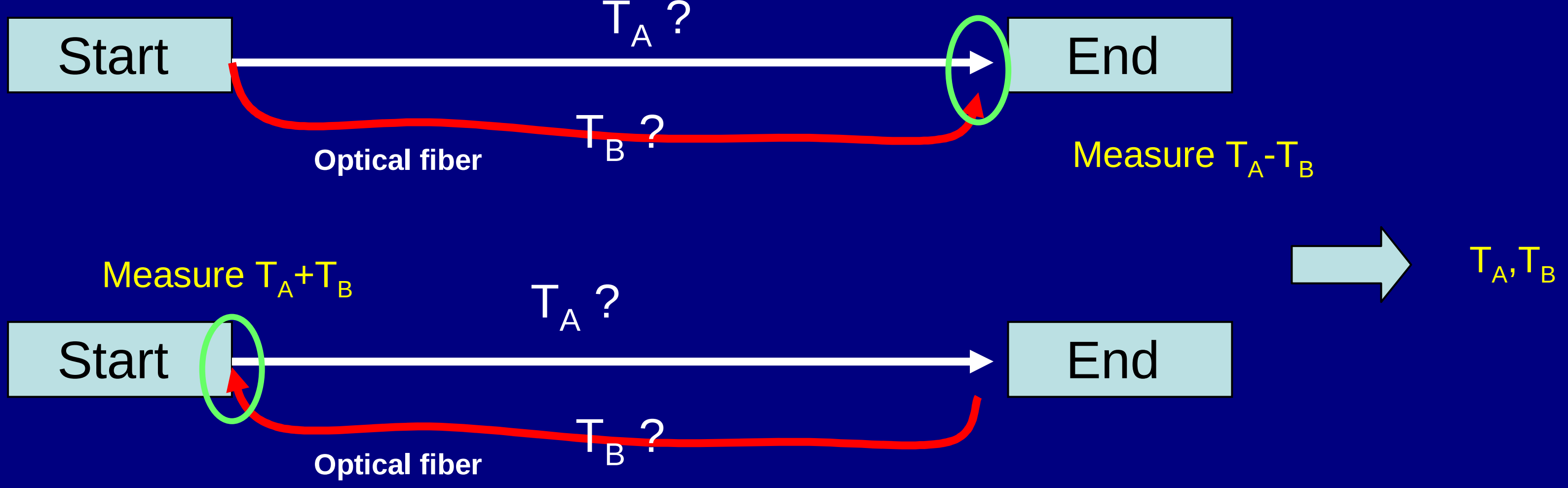


- Portable Cs-4000:

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

- Double path fibers measurement:

by swapping Tx and Rx component of the opto-chain

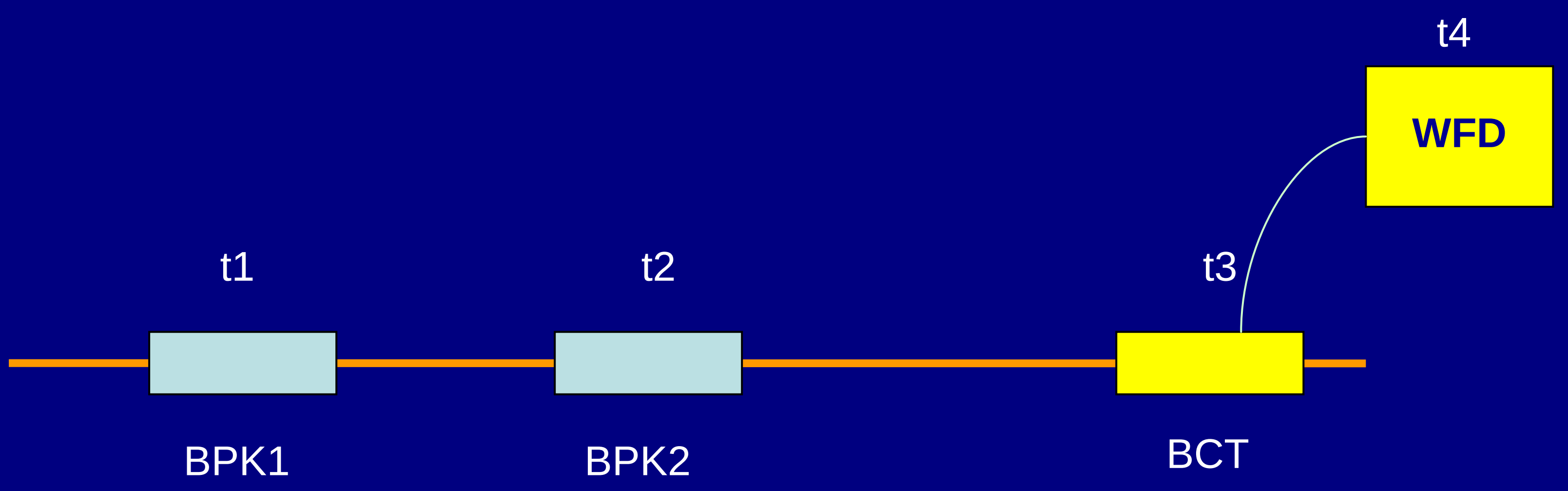


BCT calibration (1)

Dedicated beam experiment:

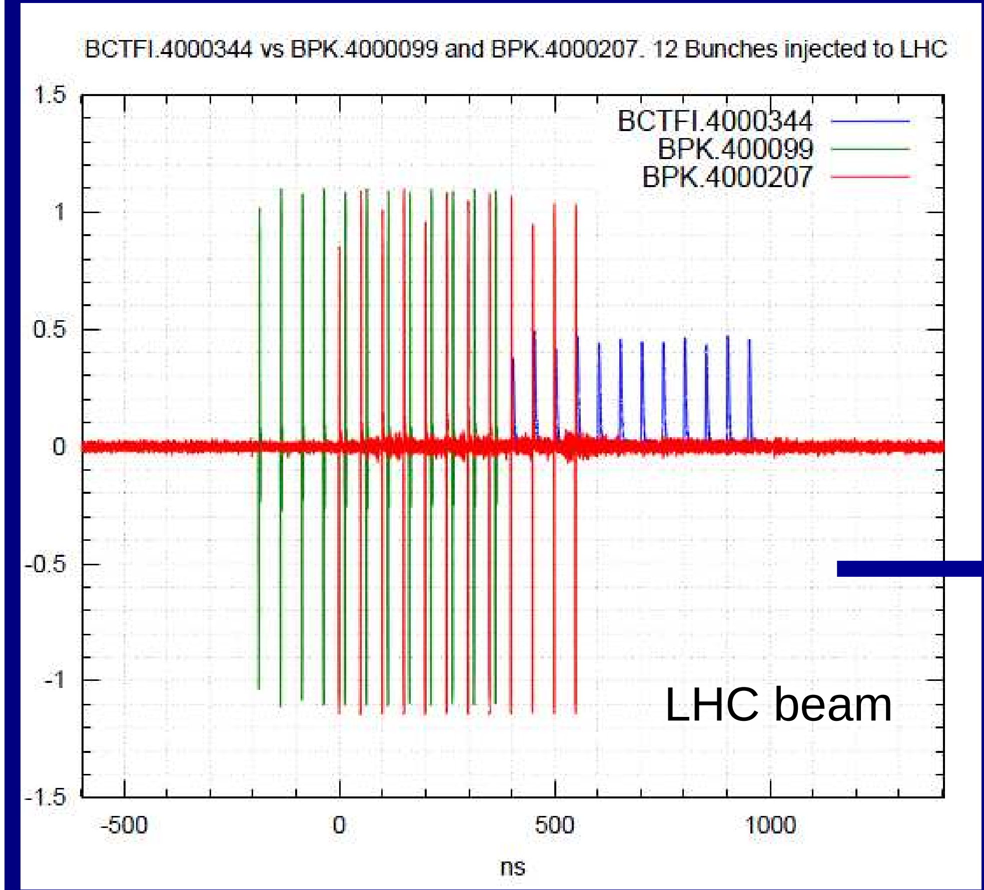
BCT plus two pick-ups (~1 ns) with LHC beam (12 bunches, 50 ns spacing)

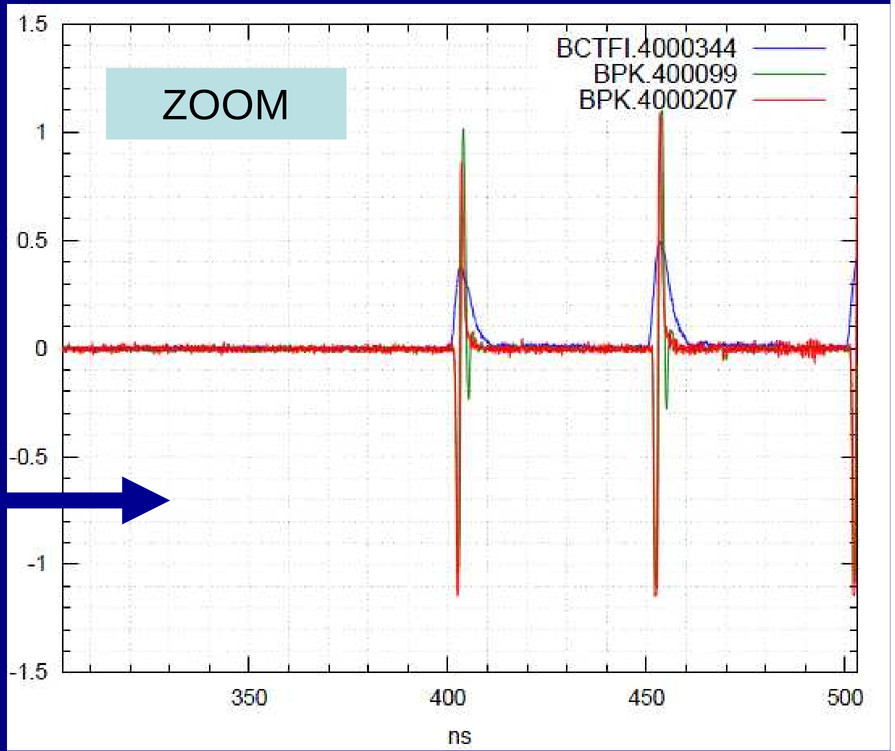
$$\Delta t_{BCT} = t4 - t3 = (580 \pm 5)\ \text{ns}$$



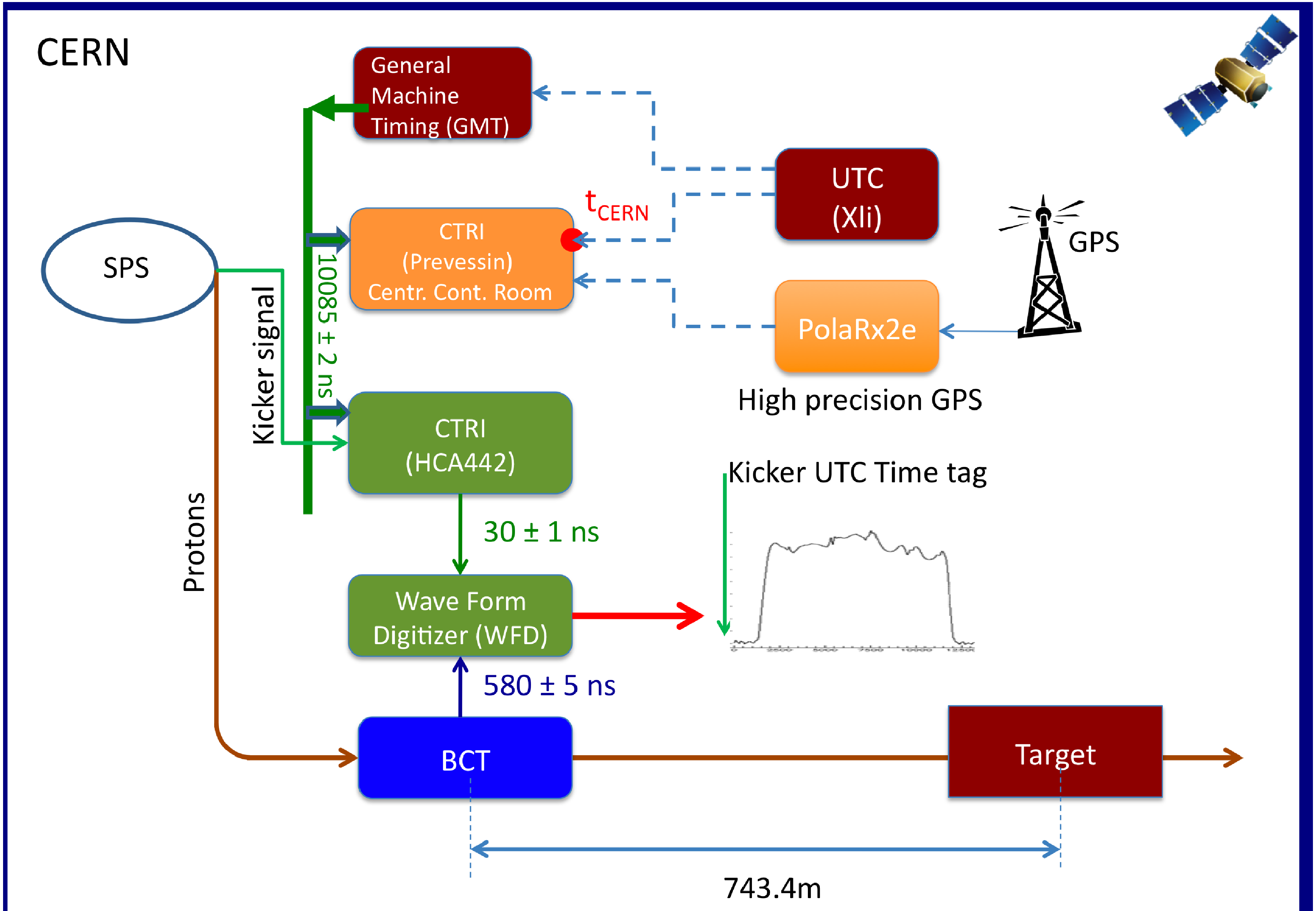
t3 : derived by t1 - t2 measurement and survey

BCT calibration (2)

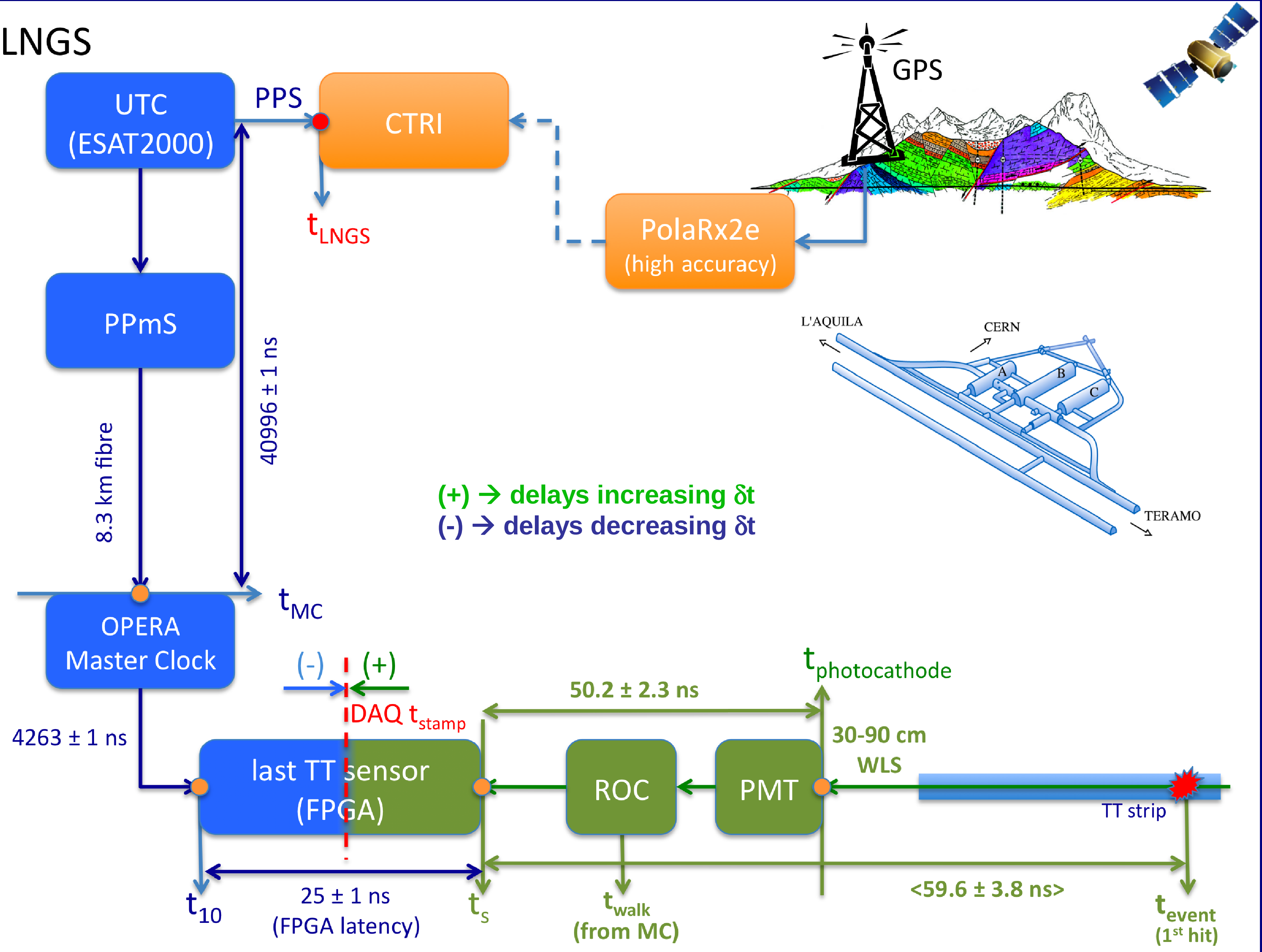




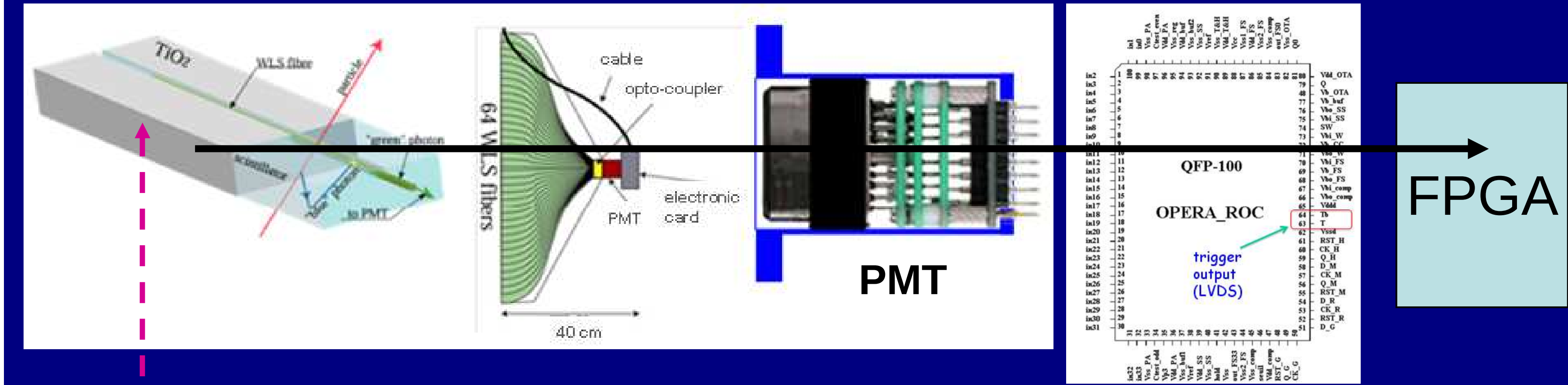
result: signals comparison after Δ_{BCT} compensation


CERN
General Machine Timing (GMT)
UTC (Xli)
t_{CERN}
CTRI (Prevessin) Centr. Cont. Room
SPS
Kicker signal
10085 ± 2 ns
PolaRx2e
GPS
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
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
t_{MC}
OPERA
Master Clock
(-)
(+)
DAQ t_{stamp}
$t_{photocathode}$
50.2 ± 2.3 ns
4263 ± 1 ns
30-90 cm
WLS
last TT sensor
(FPGA)
ROC
PMT
TT strip
t_{10}
25 ± 1 ns
(FPGA latency)
t_s
t_{walk}
(from MC)
<59.6 ± 3.8 ns>
t_{event}
(1st hit)

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

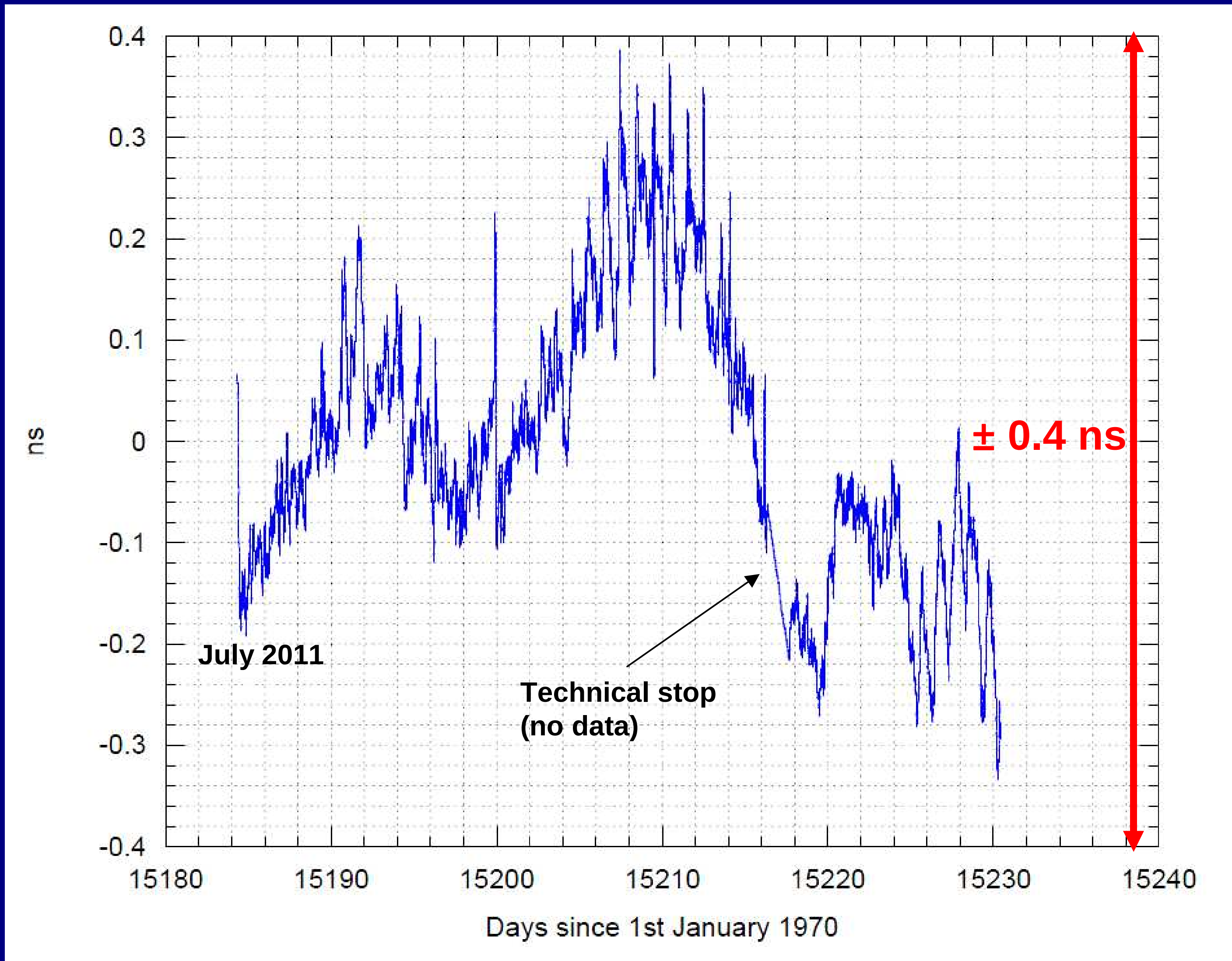
Average event time response: 59.6 ± 3.8 ns (sys)

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

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)

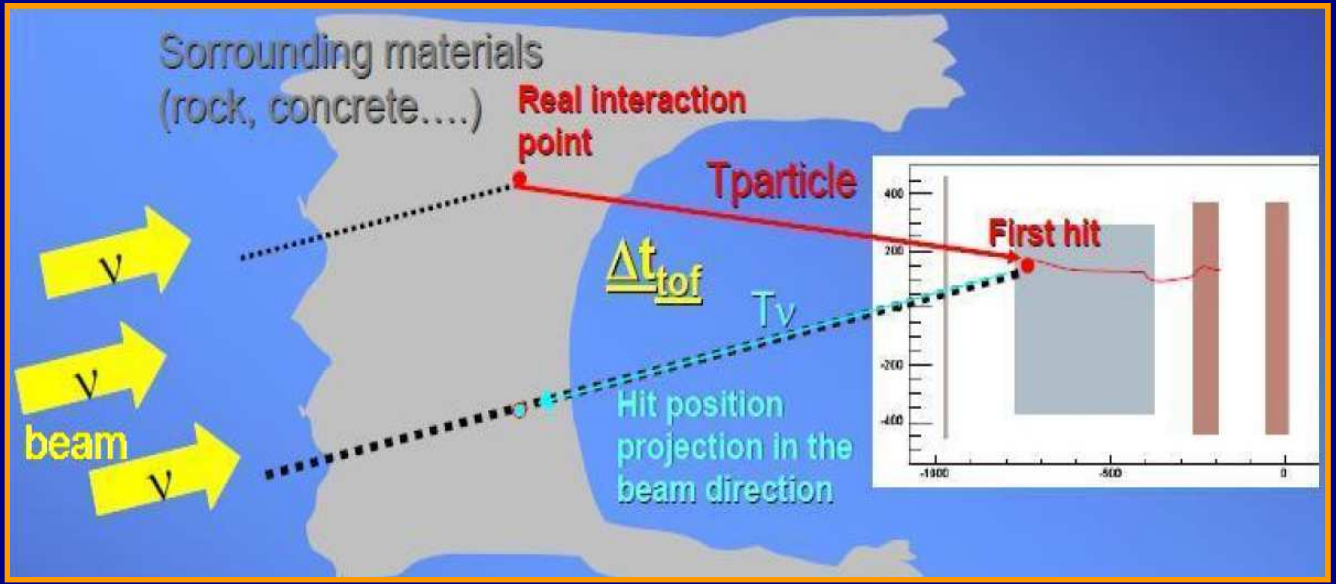


Event selection (earliest TT hit of the event as “stop”)

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

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

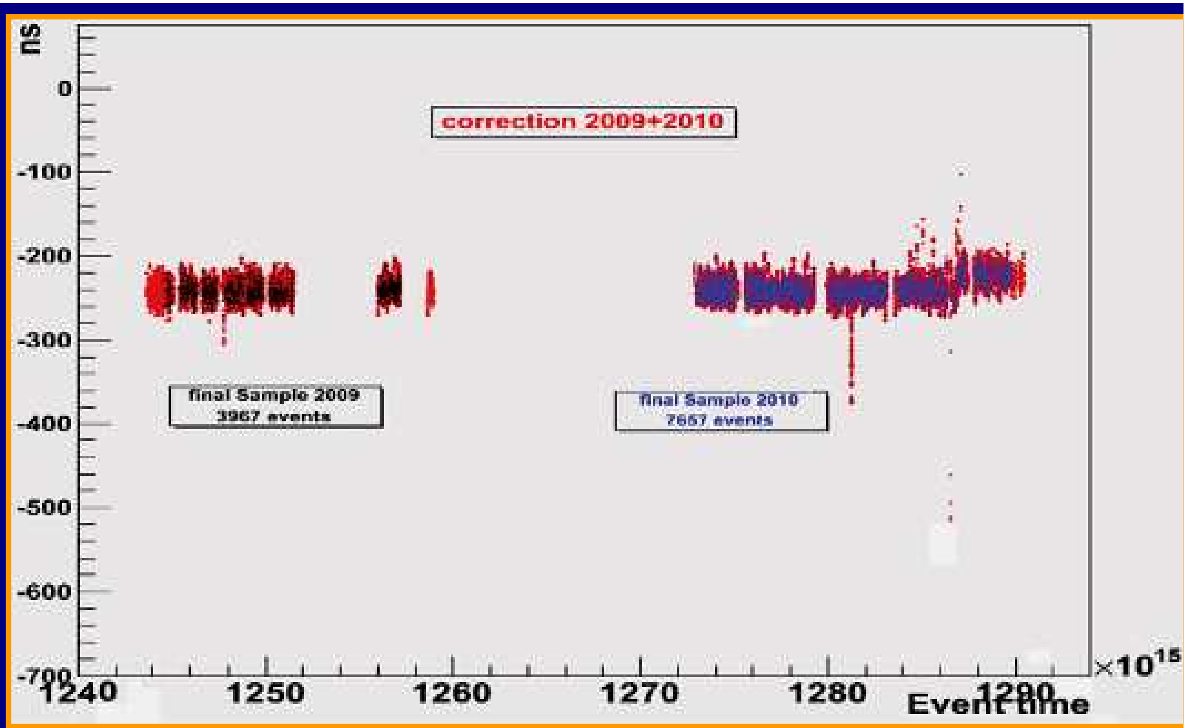
External events:
Rock interaction → require muon 3D track: 8525 events
(Timing checked with full simulation, 2 ns systematic uncertainty by adding external events)



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

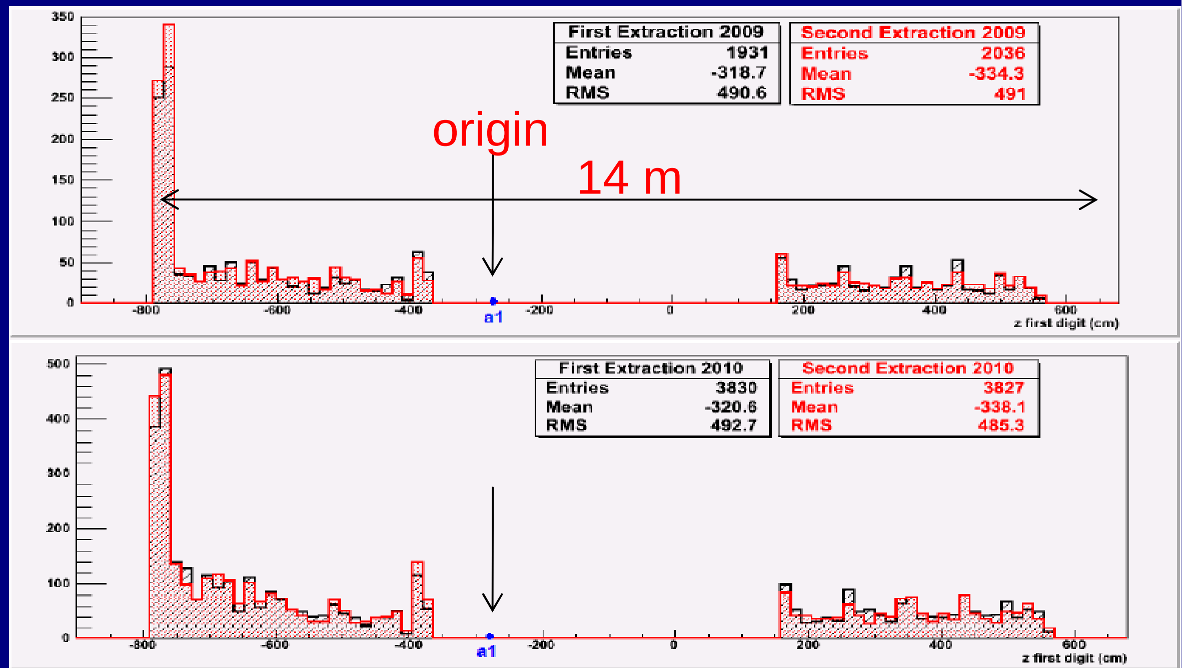
Event time corrections

Time-link correction (blue points)



Correction due to the earliest hit position

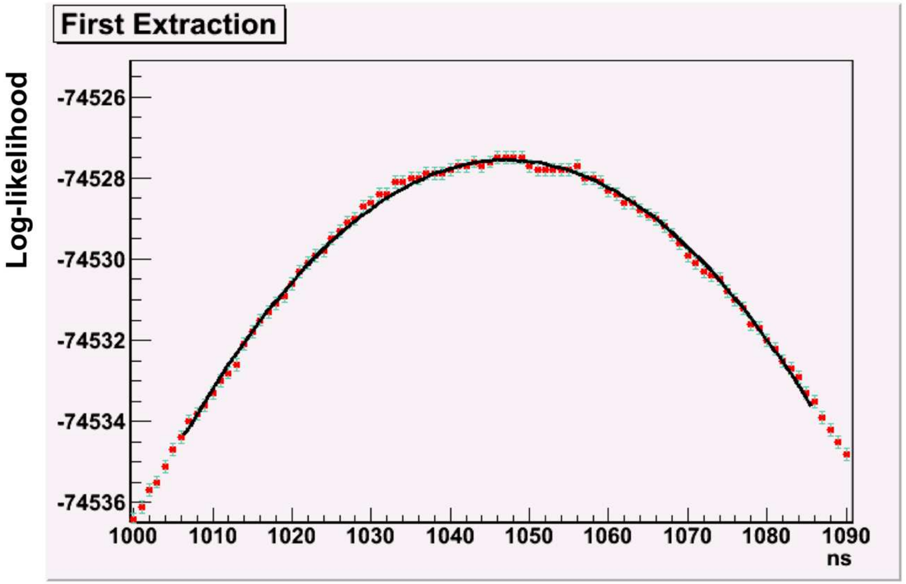
average correction: 140 cm (4.7 ns)

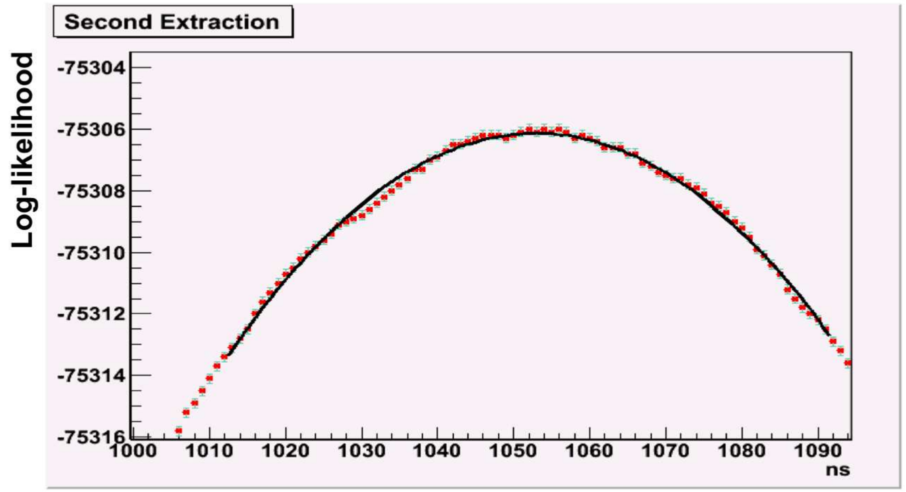


Analysis method

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

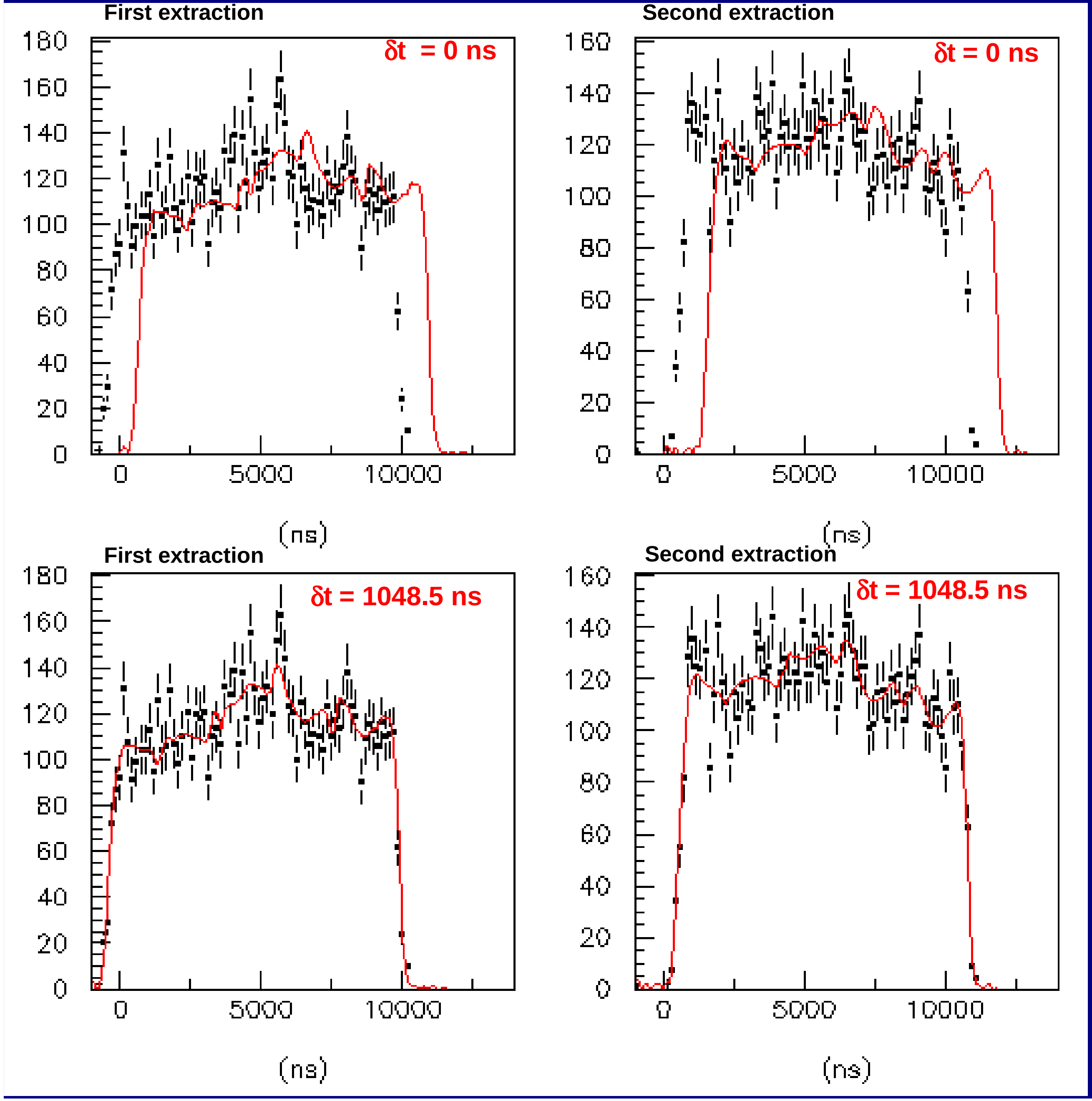
4) Ignoring the BCT and WFD delays

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



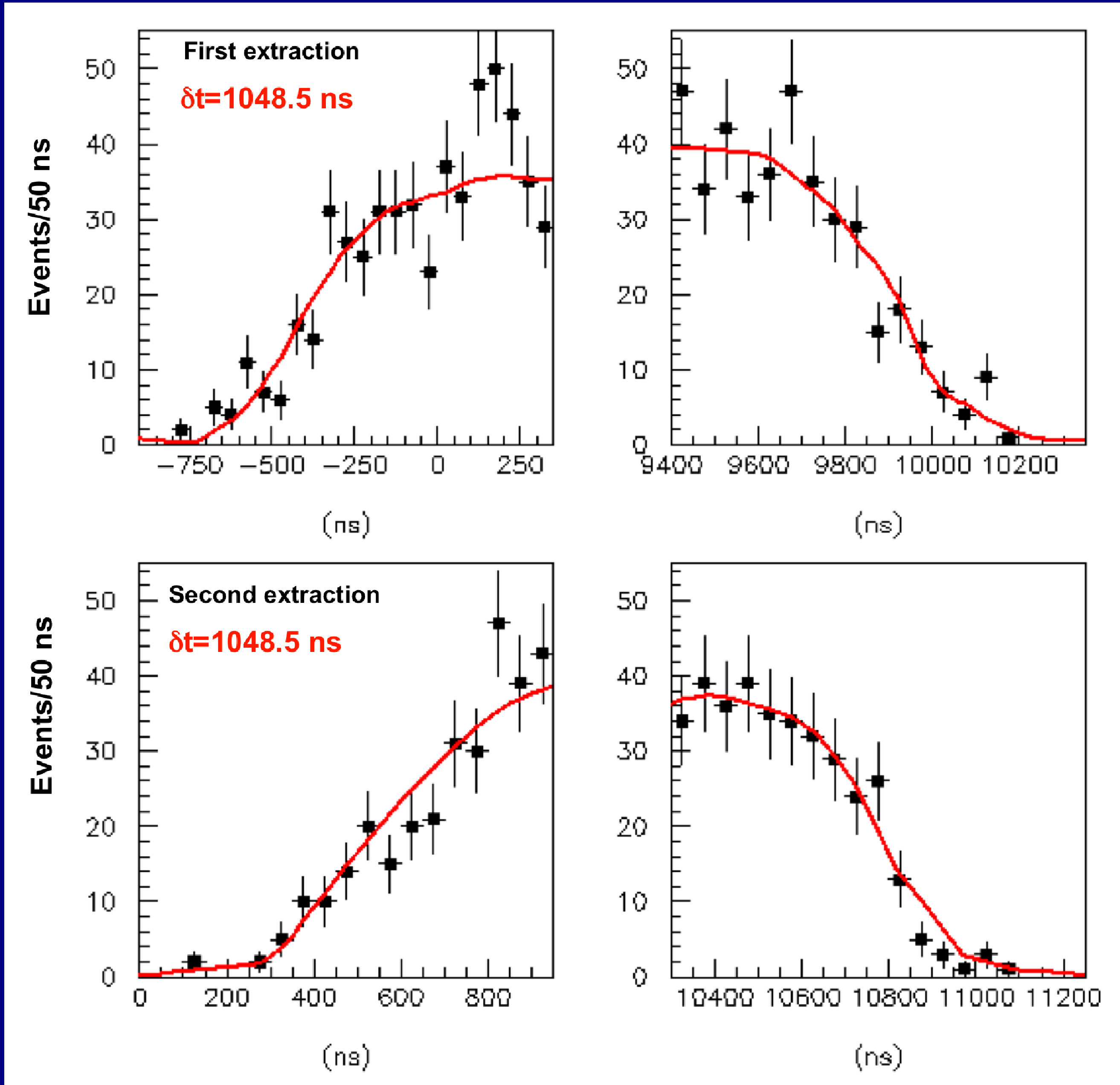
(BLIND) $\delta t = TOF_c - TOF_\nu$ =

(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



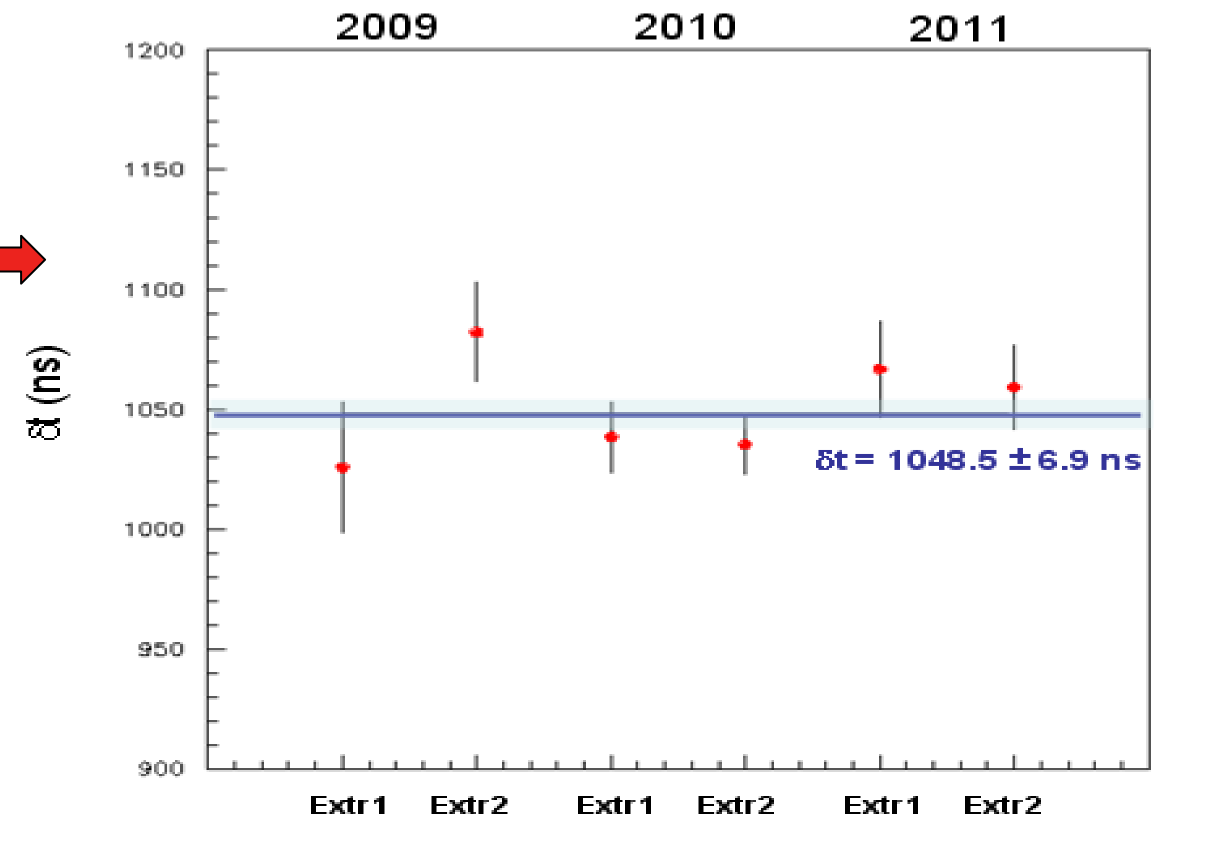
Analysis cross-checks

1) Coherence among CNGS runs/extractions

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

|d-n|: (17.1 ± 15.5) ns

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



3) Internal vs external events:

All events: δt (blind) = $TOF_c - TOF_\nu$ = (1048.5 ± 6.9 (stat.)) ns

Internal events only: (1047.4 ± 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

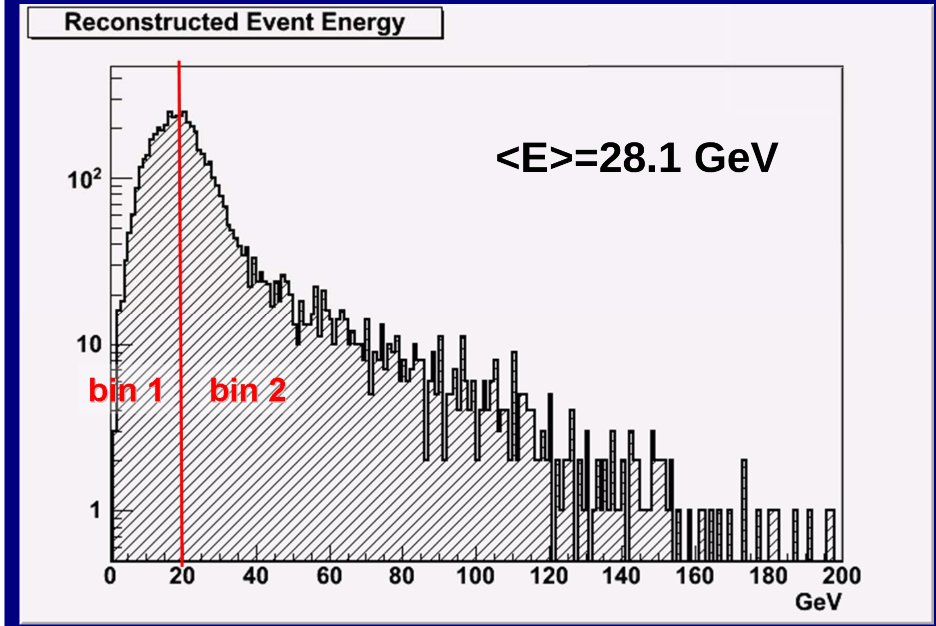
relative difference of neutrino velocity w.r.t. *c:*

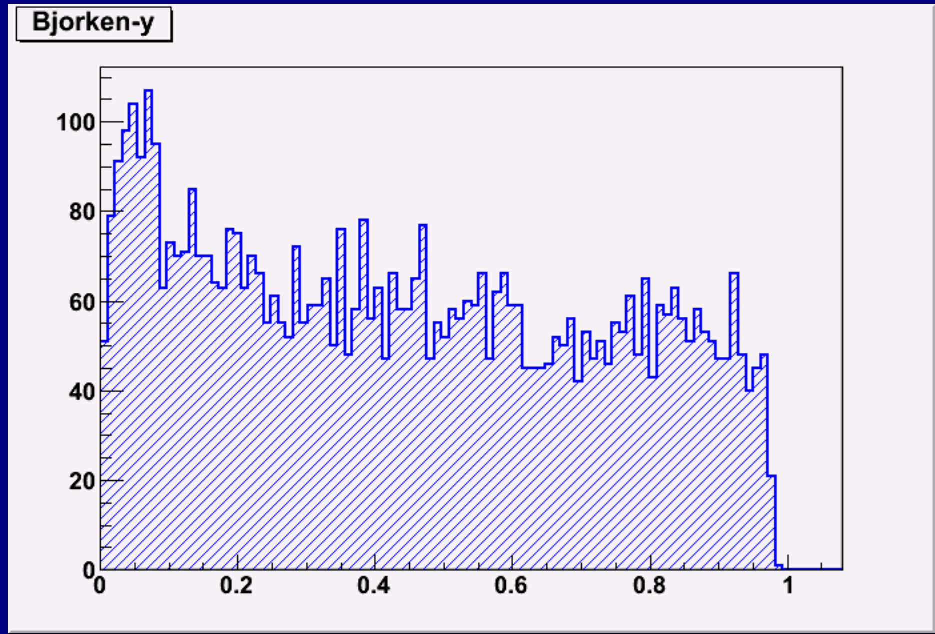
$(v-c)/c = \delta t /(TOF_c - \delta t) = (2.49 \pm 0.28\ (stat.) \pm 0.30\ (sys.)) \times 10^{-5}$

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

6.0 σ significance

Study of the energy dependence





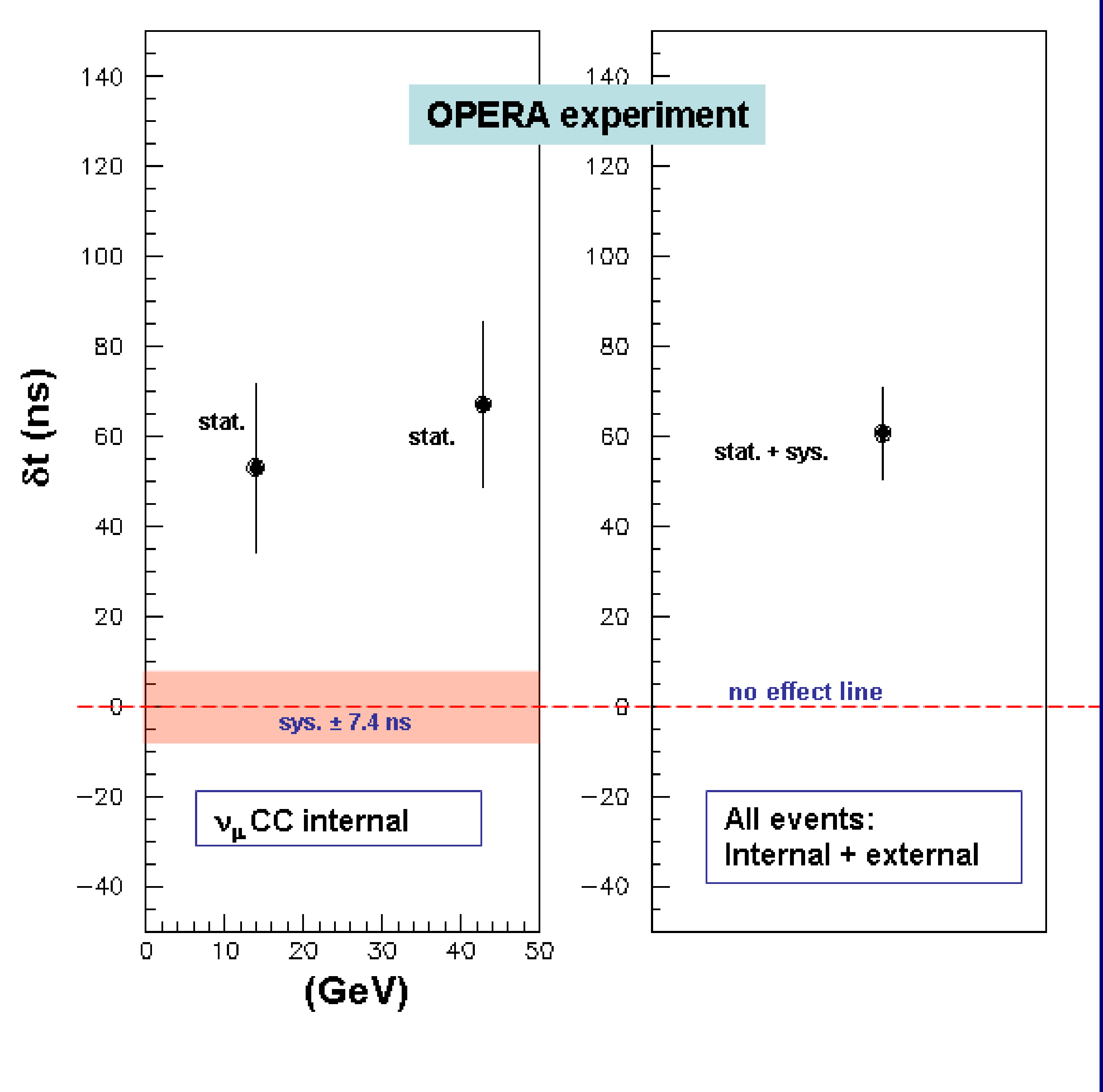
- Only internal muon-neutrino CC events used for energy measurement (5489 events)

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

- 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)

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



Conclusions (1)

• The OPERA detector at LNGS in the CERN CNGS muon neutrino beam has allowed the most sensitive terrestrial measurement of the neutrino velocity over a baseline of about 730 km.

• The measurement profited of the large statistics accumulated by OPERA (~16000 events), of a dedicated upgrade of the CNGS and OPERA timing systems, of an accurate geodesy campaign and of a series of calibration measurements conducted with different and complementary techniques.

• The analysis of data from the 2009, 2010 and 2011 CNGS runs was carried out to measure the neutrino time of flight. For CNGS muon neutrinos travelling through the Earth's crust with an average energy of 17 GeV the results of the analysis indicate an early neutrino arrival time with respect to the one computed by assuming the speed of light:

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

• 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:

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

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