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

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On behalf of the OPERA Collaboration

IIHE, Brussels, 6 October 2011

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
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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

A brief history of the neutrino

- 1914 : Lise Meitner and Otto Hahn, and James Chadwick measure continuous energy spectrum of the β-rays : incompatible with momentum-energy and angular momentum conservation in two-body decay ($^{40}K \rightarrow {}^{40}Ca + e^-$)
- 1930: Wolfgang Pauli "hits upon a desperate remedy" to preserve energy and angular momentum conservation in nuclear β decay and "invents" the neutrino $^{40}K \rightarrow {}^{40}Ca + e^- + \nu$
- 1933 : Enrico Fermi develops the β-decay (weak interaction) theory and names the "neutrino"
- 1933 : Hans Bethe and Rudolf Peierls: 1 light-year lead wall to stop half of neutrinos from β-decay $\boxed{\sigma_{\nu N} \approx 10^{-10} \sigma_{eN}}$
- 1953-56: Fred Reines et Clyde Cowan detect the first neutrino interactions at the Savannah River military nuclear power plant.
- 1955-58 : Ray Davis et al. confirm the difference neutrino/antineutrino (??? in 2011)
- 1962 : Leon Lederman, Melvin Schwartz, Jack Steinberger discover ν_μ
- 1999 : DONUT experiment at Fermi Lab discovers ν_τ

Neutrinos in the universe

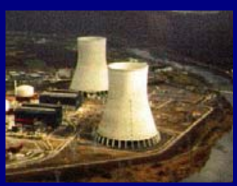
Primeval (Big bang) neutrinos density $340 / cm^3$

(yet undetected) $\frac{N_\nu}{N_{q,e}} \approx \frac{9}{11}\frac{N_\gamma}{N_{q,e}} \approx 2 \cdot 10^9$

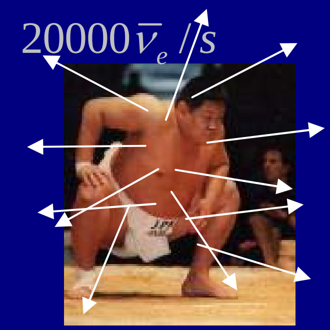
Fluxes on Earth

- Solar neutrinos $6.5 \cdot 10^{10} / cm^2 / s$

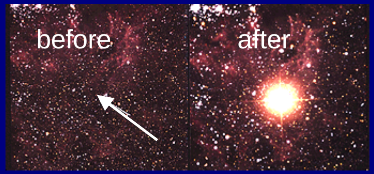
- Atmospheric neutrinos $1 \cdot 10^8 / cm^2 / s$
  (from cosmic rays interactions)
- Geo neutrinos $1 \cdot 10^7 / cm^2 / s$



- Nuclear plant neutrinos $6 \cdot 10^{20} / GW / s$



- Human (bio) neutrinos: $0.24\ mg / kg$ ^{40}K β^--radioactif
  $100 / kg / s$
- Super Novae neutrinos
  $10\,s$ flash from SN1997A in Large Magellan Cloud $4 \cdot 10^{39} / cm^2$



Neutrinos flavours and mixing

- Measurements of neutrino intrinsic properties are obtained with $\nu_\ell = \nu_e, \nu_\mu, \nu_\tau$ of definite flavour $\ell = e, \mu, \tau$ produced by CC interactions of lepton $\ell^- = e^-, \mu^-, \tau^-$

  Charged Current interaction: $\ell^- + p \to \nu_\ell + n \quad \left(\ell^- + u^{2/3} \to \nu_\ell + d^{-1/3}\right)$

- If neutrinos are massive $\Rightarrow$ a priori mixing between :

  $\nu_l \quad \ell = e, \mu, \tau$ flavour eigenstates $\equiv$ eigenstates of the CC interaction

  $\nu_k \quad k = 1, 3$ mass eigenstates

$$\boxed{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \left.\begin{aligned} \nu_\ell &= \sum_{k=1,}^{3} U_{\ell k}\, \nu_k \\ \sum_{k=1,}^{3} &\left|U_{\ell k}\right|^2 = 1 \end{aligned}\right\} \ell = e, \mu, \tau}$$

- U is a unitary matrix: 4 parameters $\begin{cases} 3 \text{ mixing angles} \\ \mathbf{1\ (3)} \text{ non trivial CP violation phase(s)} \end{cases}$

Neutrino oscillations

ν_ℓ created with momentum p at $t=0\left(L=0\right)$

$$|\nu_\ell(0)> = \sum_{k=1}^{3} U_{\ell k}\,|\nu_k>$$

ν_k propagate as $|\nu_k(t)> = e^{-iE_k t}\,|\nu_k(0)>$

ν_ℓ propagates as superposition of mass eigensates with different phases:

$$P\left(\nu_\ell(0)\to\nu_{\ell'}(L)\right) = |<\nu_{\ell'}(L)|\nu_\ell(0)>|^2 = |\sum_{k=1}^{3} U_{\ell k} e^{-im_k^2 L/2E}\; U^*_{\ell' k}|^2$$

$$\Delta m^2_{kk'} = m_k^2 - m_{k'}^2 \qquad \Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$$

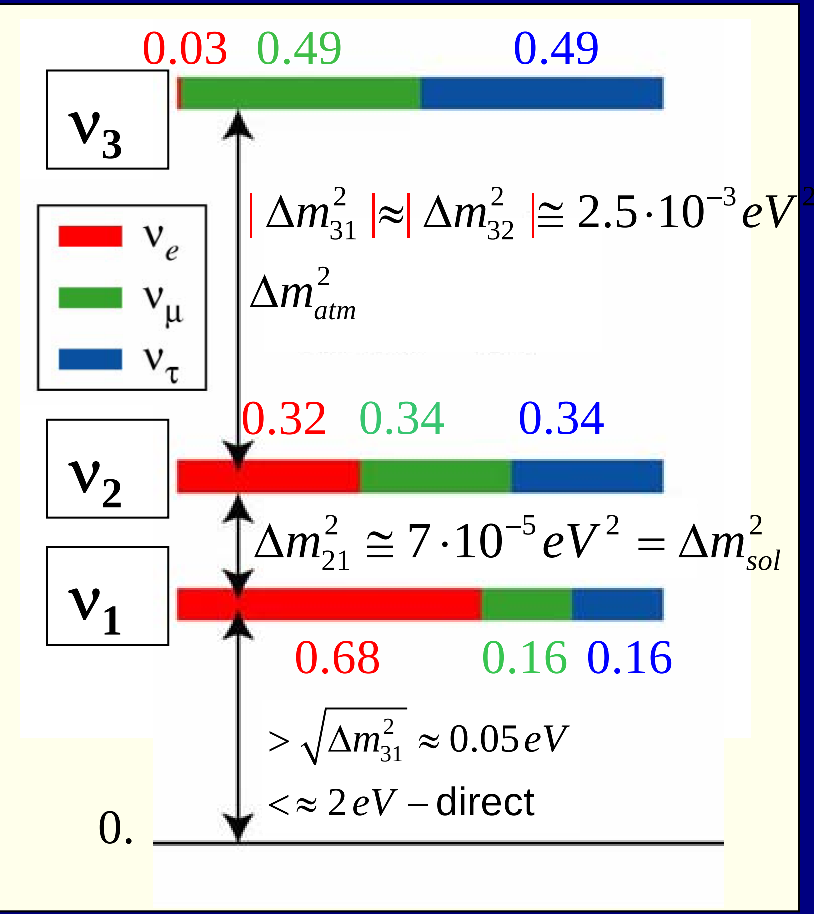
$$P(\nu_\ell(0)\to\nu_{\ell'}(L)) = \delta_{\ell\ell'} - 4\sum_{k'>k}^{1,3} \underbrace{\Re\left(U^*_{\ell'k'}U_{\ell'k}U_{\ell k'}U^*_{\ell k}\right)}_{\text{Mixings define Maximum probability}} \; \underbrace{\sin^2\frac{\Delta m^2_{kk'}\,L}{4E}}_{\text{Oscillation term}}$$

$$+2\sum_{k'>k}^{1,3} \underbrace{\Im\left(U^*_{\ell'k'}U_{\ell'k}U_{\ell k'}U^*_{\ell k}\right)}_{\text{Null if CP conserved}} \; \underbrace{\sin^2\frac{\Delta m^2_{kk'}\,L}{2E}}_{\text{Oscillation term}}$$

6 parameters : 3 mixing angles , 1 CP violation phase, 2 Δm^2_{kj}

Fortunately nature is kinder to us:

This is what we know to-day on masses and mixing



And what we do not know

- Hierarchy $m_3 \gg m_2 > m_1$?
  $m_3 \ll m_1 < m_2$?
- Absolute mass scale within limit
- $\nu \neq \bar{\nu}$ like other Fermions (Dirac neutrinos) ?
  $\nu \equiv \bar{\nu}$ (Majorana neutrinos)
  apparent $\nu \neq \bar{\nu}$ is artefact
- $U = U^*$ is U real? If phase $\Rightarrow$ CP violation

This leads to large simplifications in good first approximations

$\nu_\mu - \nu_\tau$ oscillation in appearnce mode : primary goal of the OPERA experiment

First indication in 1968: solar neutrino flux (R. Davis, J. Bahcall)

Definite experimental proof in 1998 : atmpspheric neutrino flux (Super-K)

Mostly disappearance signals: $\phi_{\nu_\ell}(L) < \phi_{\nu_\ell}(L=0)$

SNO solar neutrinos flux: $\phi_{\nu_e}(L) < \phi_{\nu_e}(L=0)$ and $\phi_\nu(L) = \phi_\nu(L=0)$

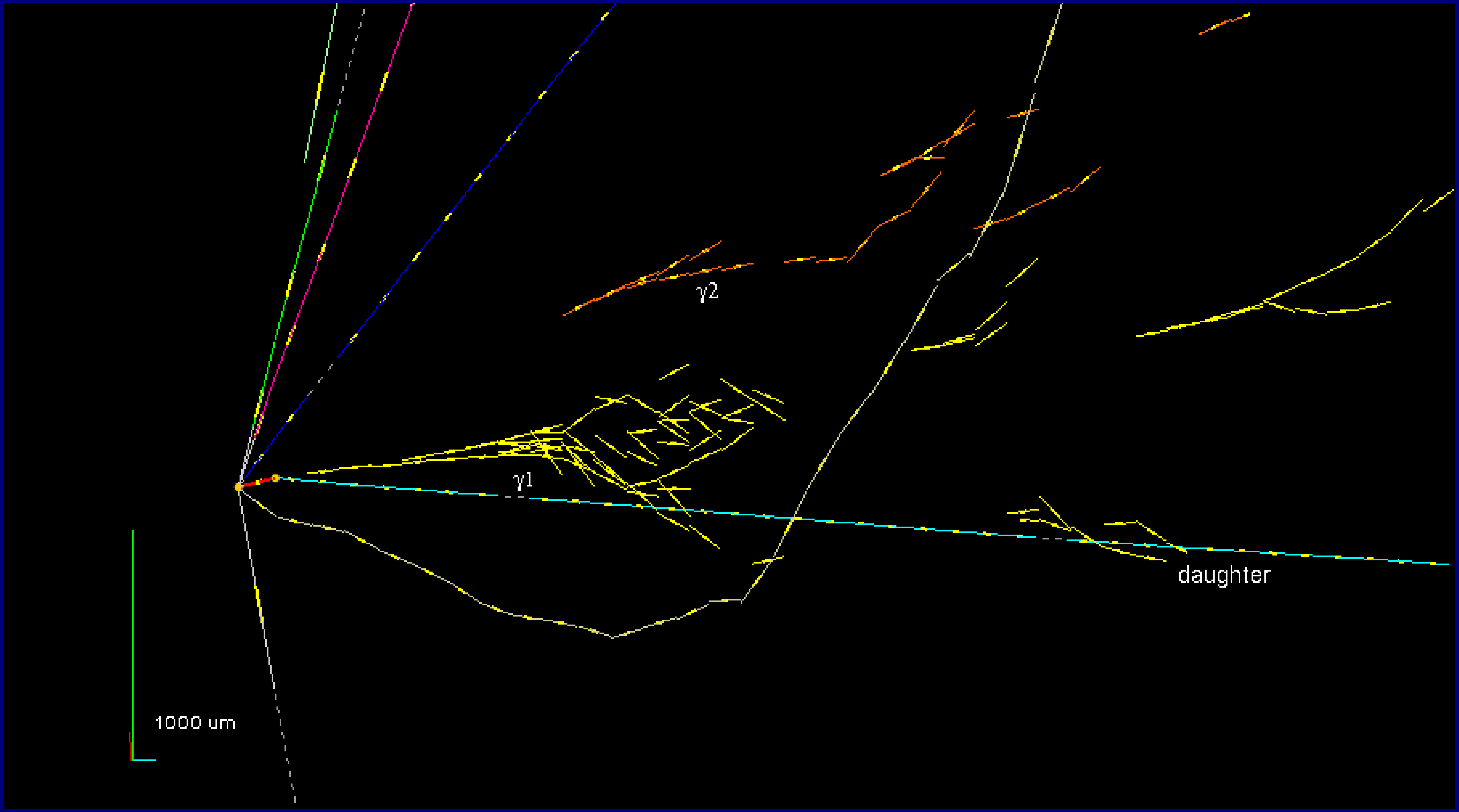
$$P(\nu_\mu \to \nu_\tau) \approx \sin^2\left(1.27\frac{\Delta m_{23}^2[eV^2]\ \ L[km]}{E[GeV]}\right) \qquad \nu_\tau + N \to \tau^- + X$$

$$m_\tau \approx 2\,m_p \quad \Rightarrow \quad E_\nu \text{ large} \qquad < E_\nu > \approx 17\,GeV$$

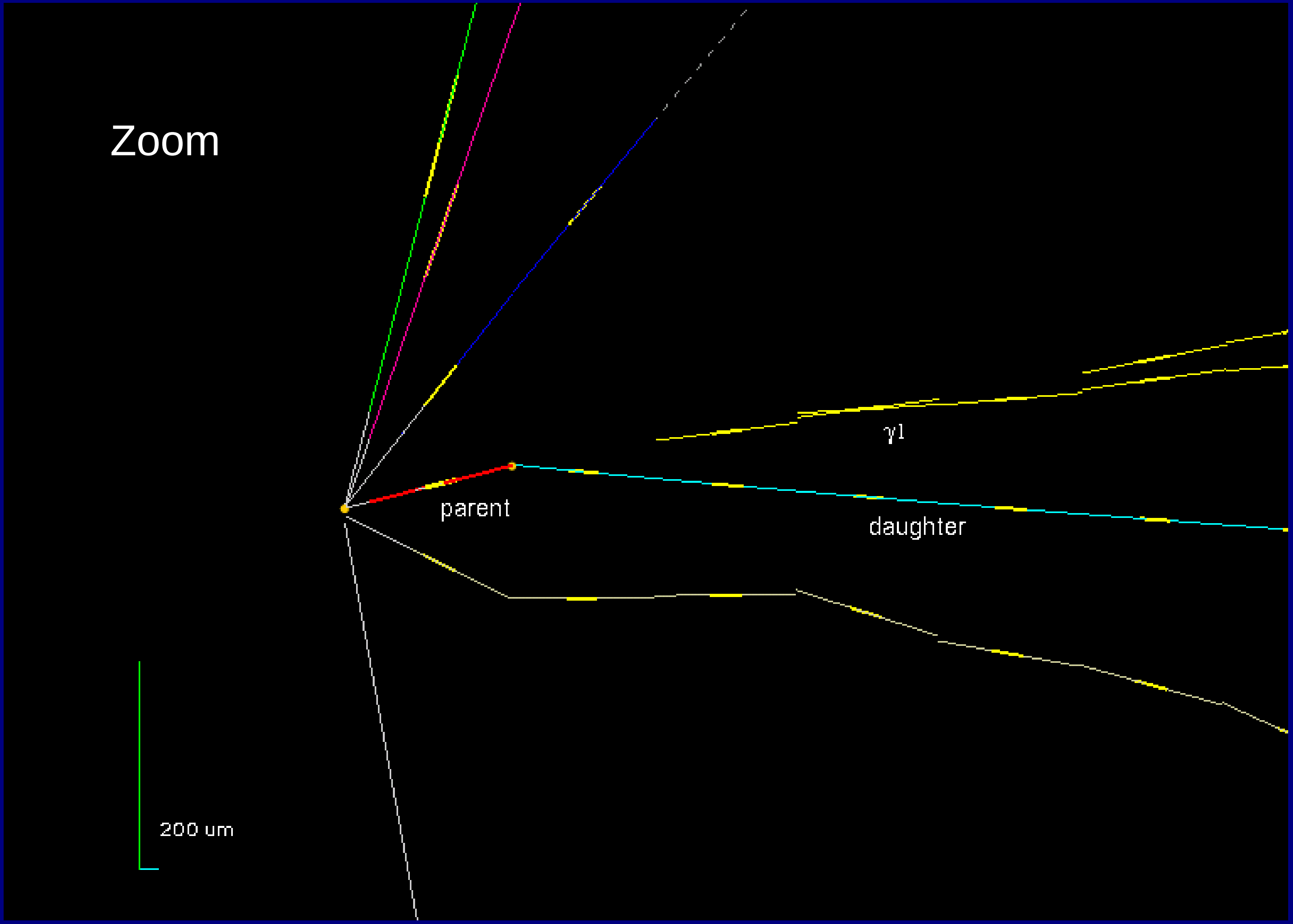
$$\Delta m_{23}^2 \approx 2.5\cdot 10^{-3}\,eV^2 \quad \Rightarrow \quad L_{osc} \approx 7\,000\,km$$

- 5 years of data taking.(2008-2012) at $L = 730\,km$
- $\approx 2\cdot 10^{20}$ $400\,GeV$ protons on neutrino target at CERN.
- $\approx 25000\,\nu_\mu$ interactions in $1250\,ton$ OPERA target.
- $\approx 110\ \nu_\tau + N \to \tau^- + X$ interactions expected.
- τ^- lifetime $\sim 3\cdot 10^{-13}\,s \ \Rightarrow\ 8-10\ \ \nu_\tau + N \to \tau^- + X$ interactions observed.
- So far 1 event observed and 1.5 expected.

Event reconstruction (1)



Event reconstruction (2)



Neutrinos velocity measurement

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

CERN: CNGS beam, Survey, Timing and PS groups

The geodesy group of the Università la Sapienza of Rome

Signees of the paper

The Swiss Federal Institute of Metrology (METAS)

The German Federal Institute of Metrology (PTB)

Principle of the neutrino velocity measurement

Definition of neutrino velocity:

ratio of precisely measured baseline and time of flight

Velocity measurement:

Tagging of neutrino production time
Tagging of neutrino interaction time by a far detector
Accurate synchronisation of the two clocks

Accurate determination of the baseline (geodesy)

Effects expected to be small : long baseline and large statistic 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)

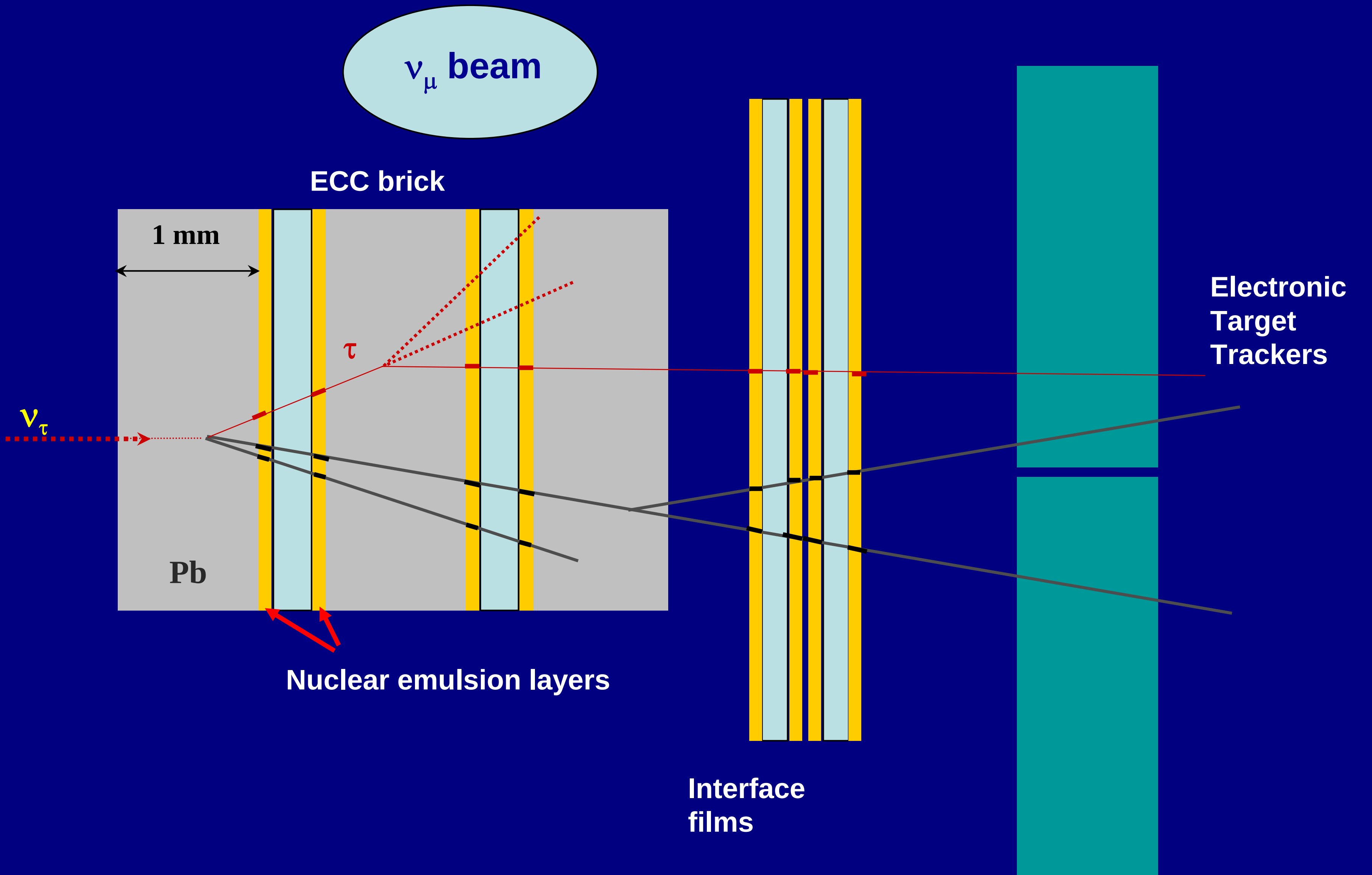
Electron (anti) neutrinos, 10 MeV range, 168'000 light years baseline.
$|v-c|/c \leq 2\times10^{-9}$.
Observation of nearly simultaneous neutrino and light arrival times (± 3 hours).
First and so far last observation of neutrinos blast from SN (Kamioka-II, IMB)

MINOS (Phys. Rev. D 76 072005 2007)

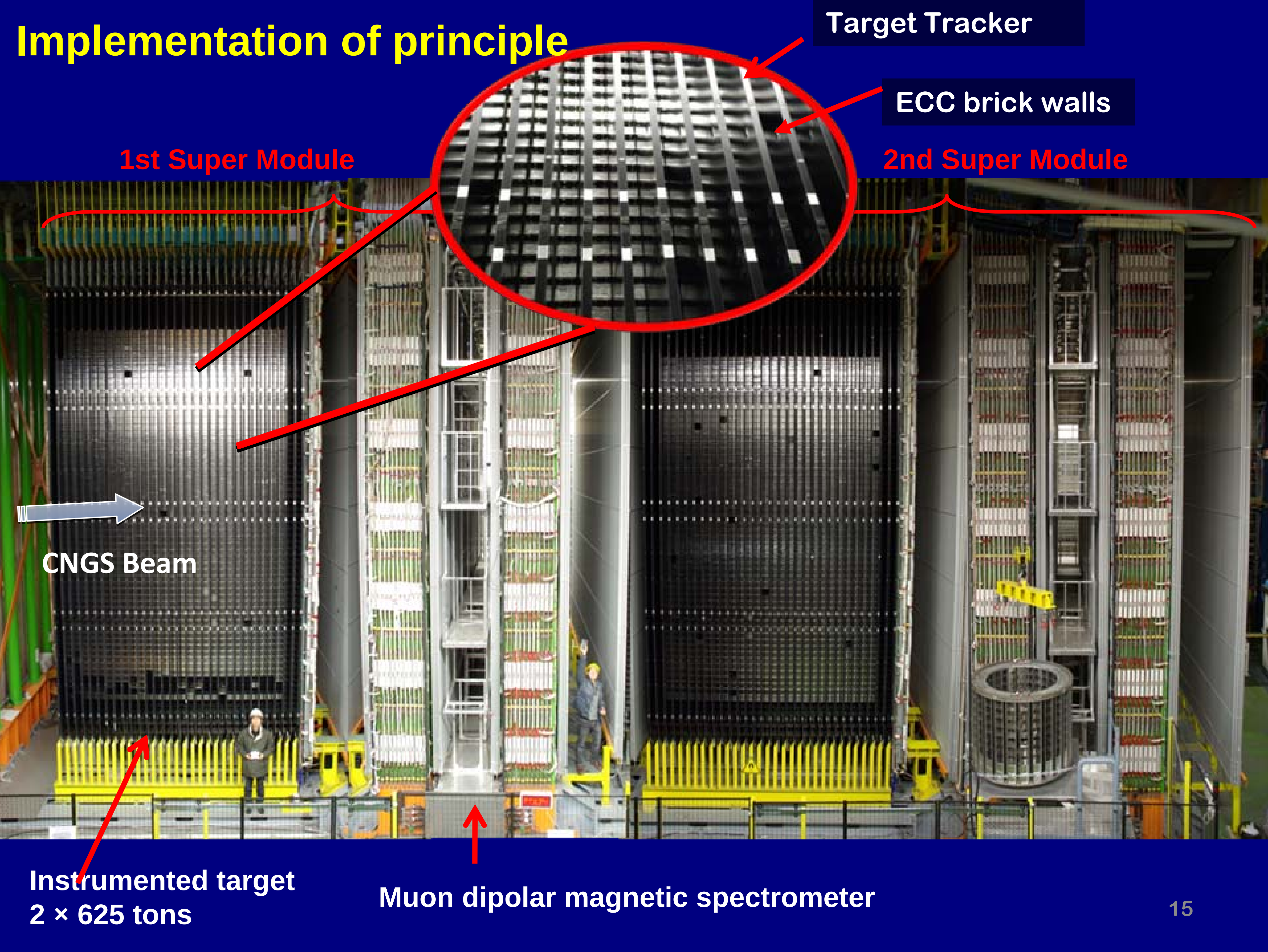
muon neutrinos, 730 km baseline, E_ν peaking at ~3 GeV with a tail extending above 100 GeV.
$(v-c)/c = (5.1 \pm 2.9)\times10^{-5}$ (1.8 σ).

The design of the OPERA experiment

ECC Bricks + Electronic Detectors for $\nu_\mu \rightarrow \nu_\tau$ Oscillation Studies



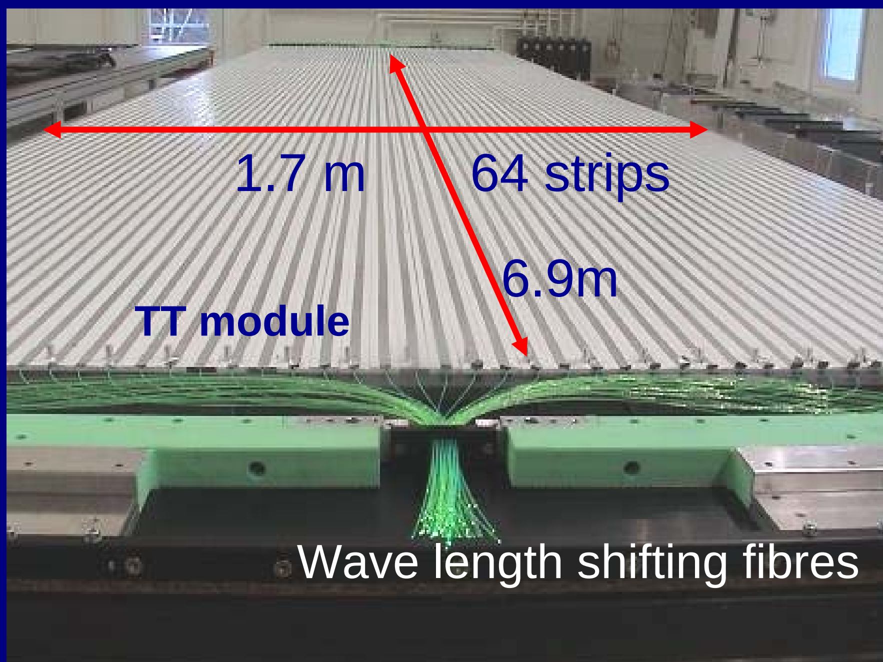
Implementation of principle

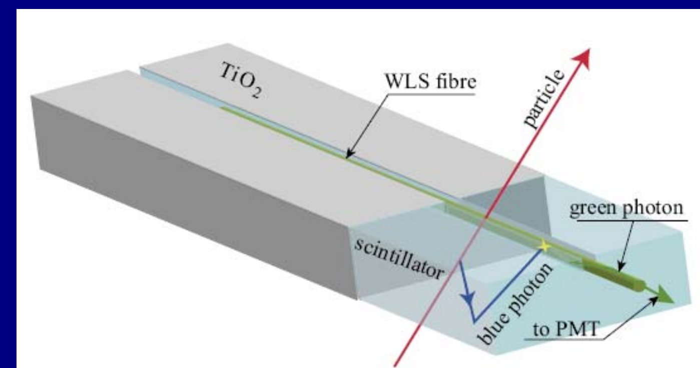


The Target Tracker (TT): main IIHE-ULB contribution to detector

Pre-location of neutrino interactions in the target and **event timing**

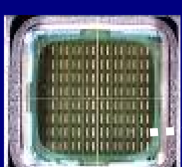
- Extruded plastic scintillator strips (2.6 cm width, 6.7 m long)
- Light collections with Wave Length Shifting fibres
- Fibres read out at either side with multi-anode 64 pixels PM Tubes (H7546)

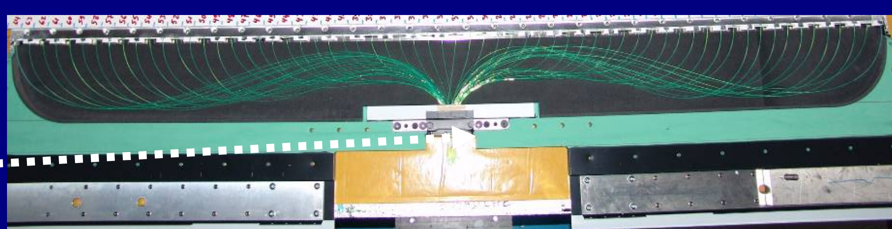




Read out by 1 Front-End DAQ board per side

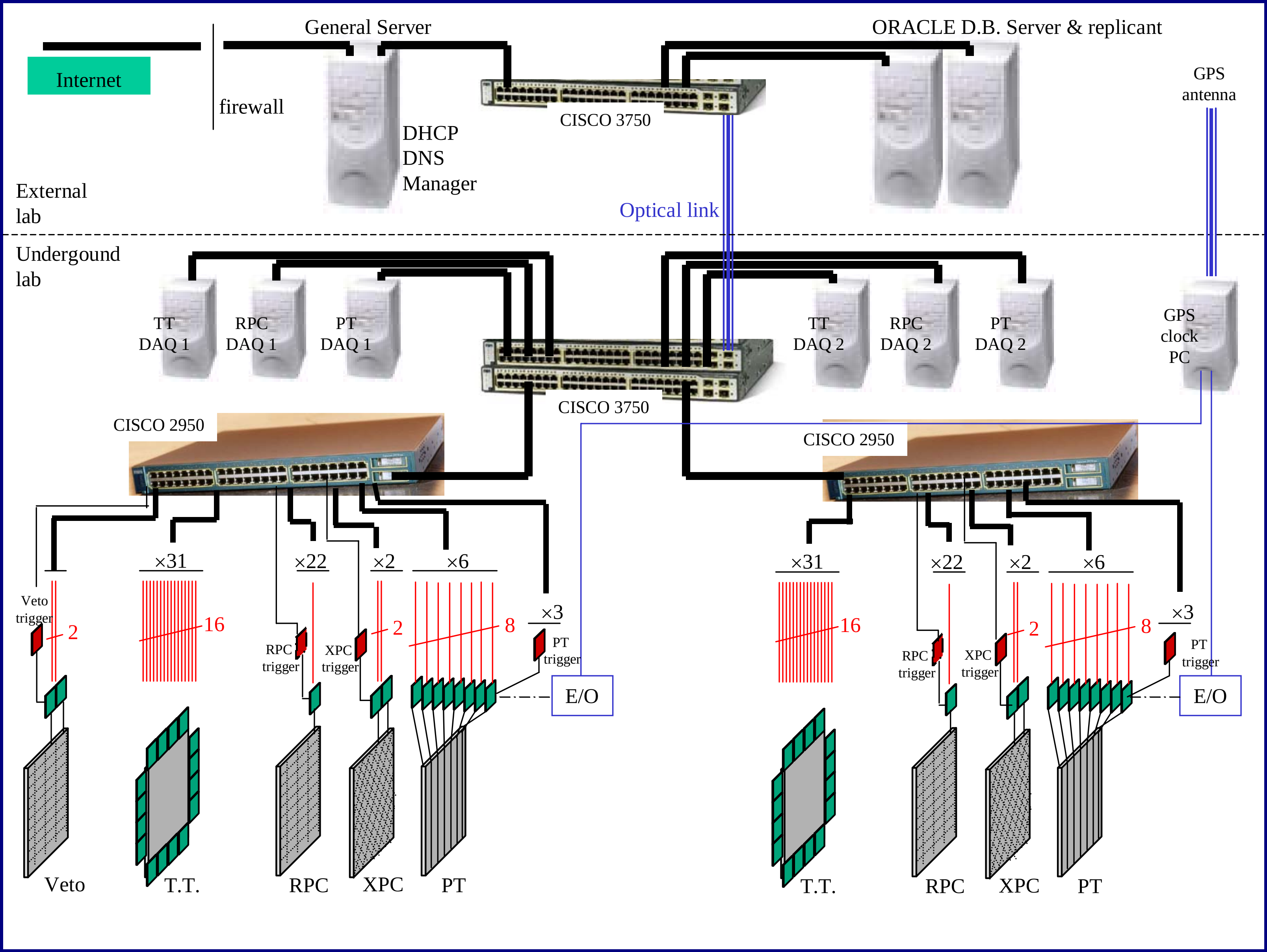
H7546





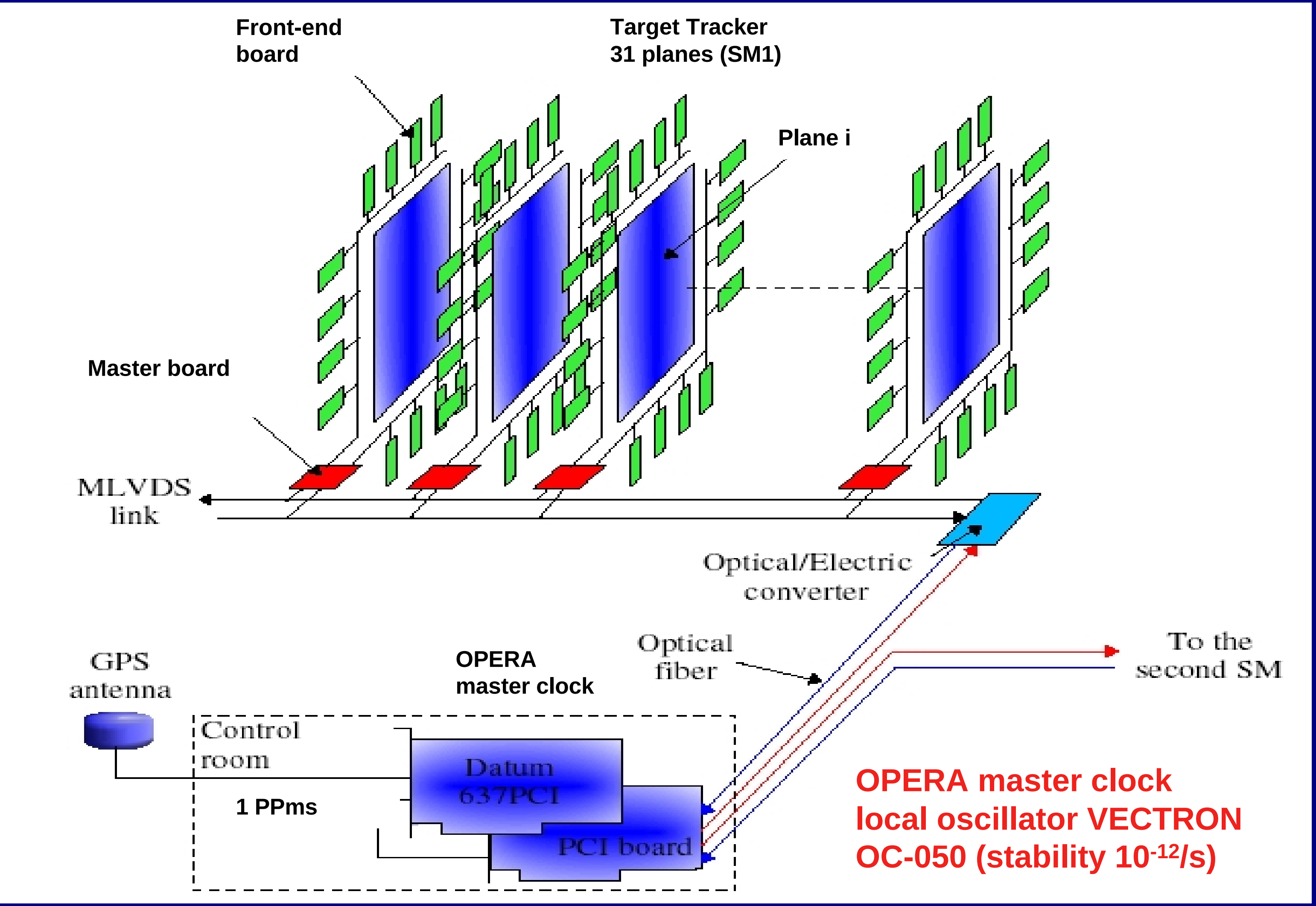
72 pairs of horizontal and vertical TT planes each made of 4 modules

OPERA readout scheme



Trigger-less, asynchronous sensors with 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

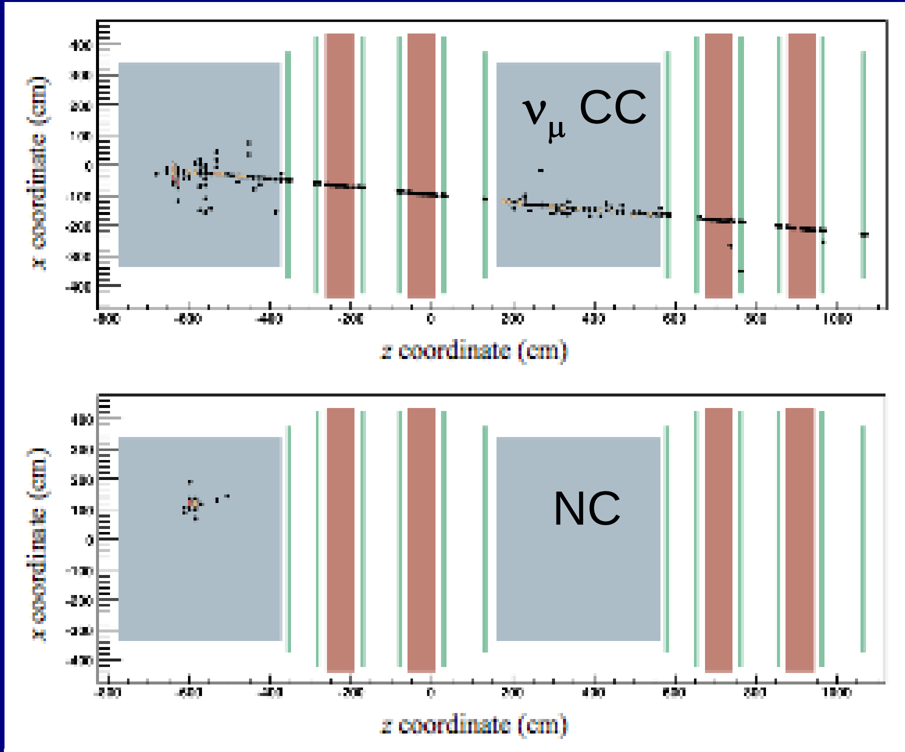
CC interaction:

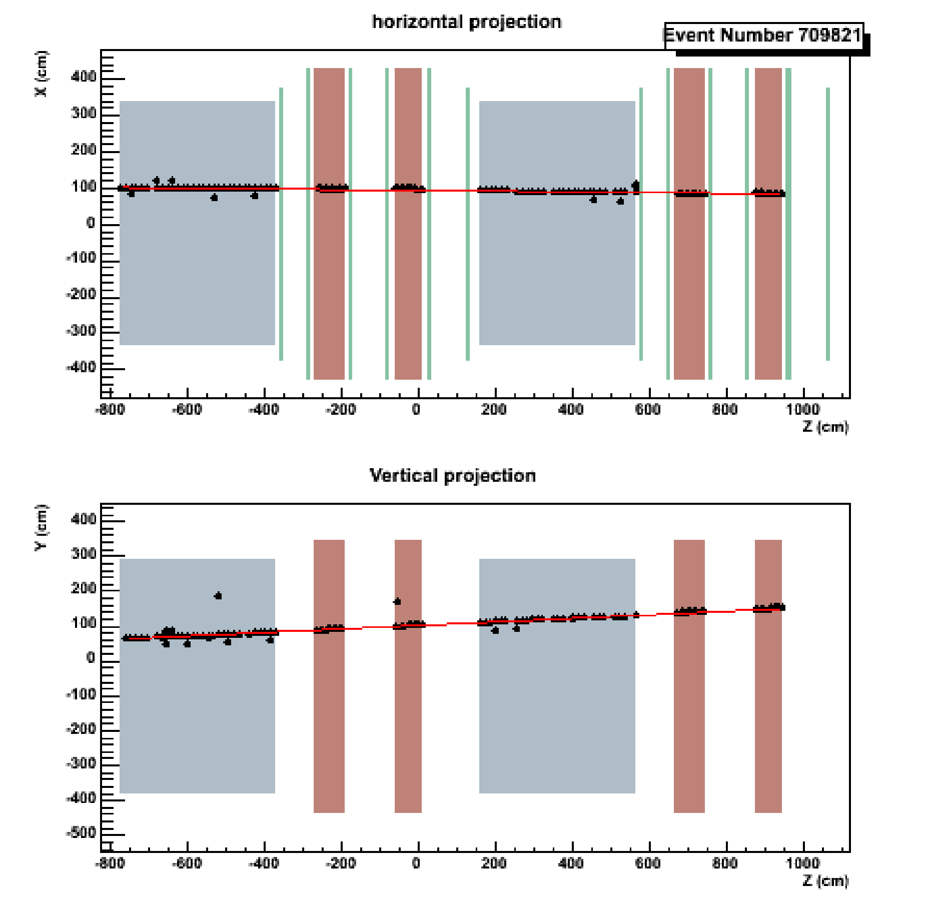
$$\nu_\ell + N \to \ell^- + X$$

$$\nu_\ell + d^{-1/3} \xrightarrow[W^-]{} \ell^- + d^{2/3}$$

ν_ℓ identified through ℓ^-

μ from external CC interaction in rock in front of OPERA





NC interaction:

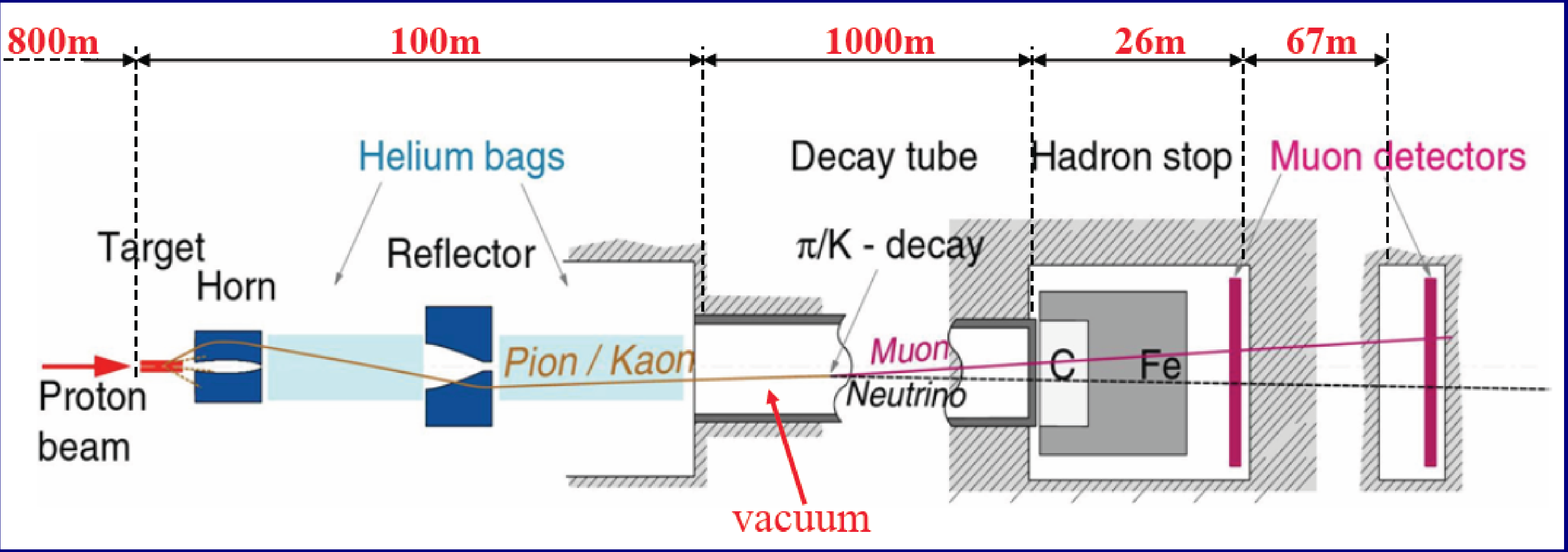
$$\nu_\ell + N \to \nu_\ell + X$$

$$\nu_\ell + q \xrightarrow[Z^0]{} \nu_\ell + q$$

ν_ℓ un-identified

The LNGS underground physics laboratory

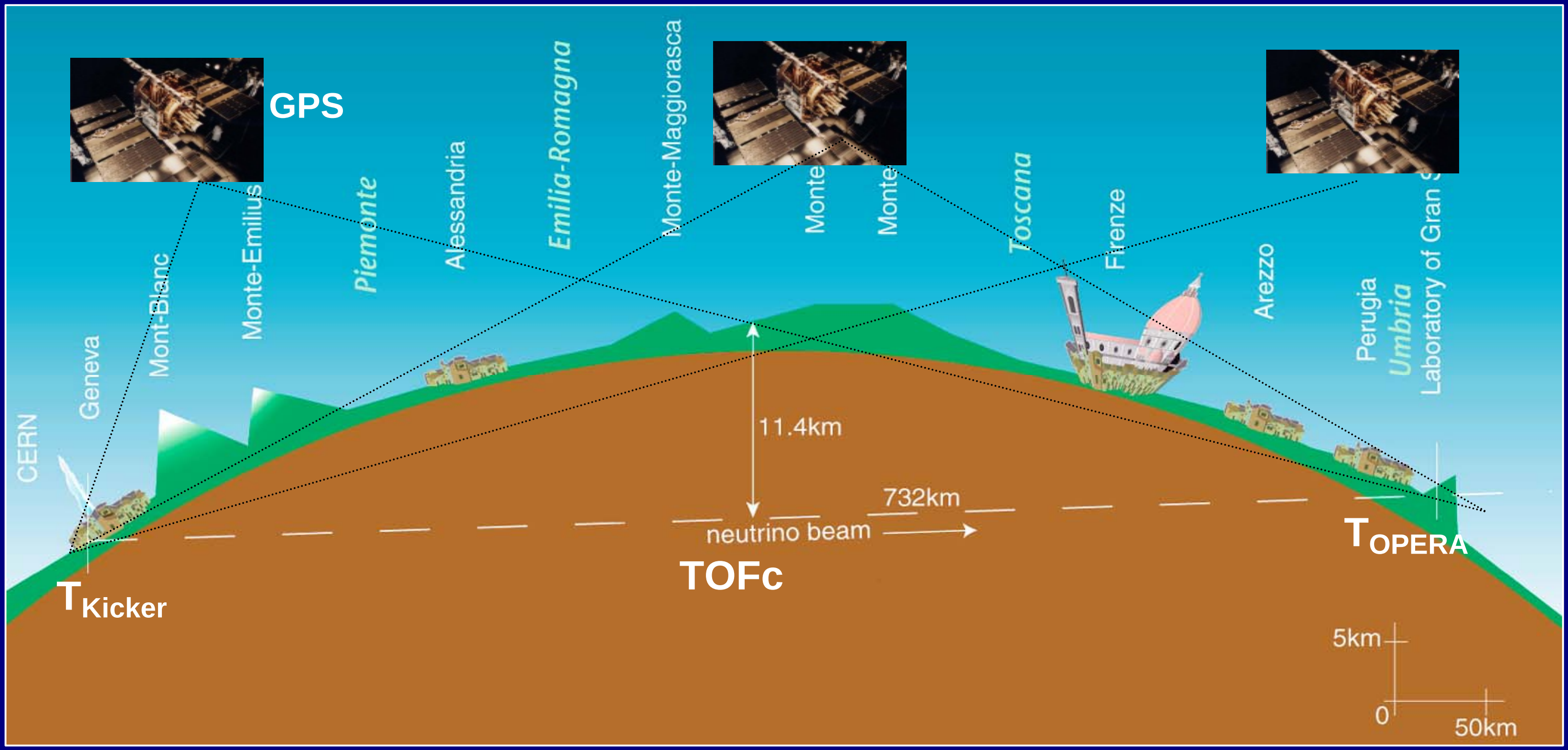
THE CERN Neutrino beam to Gran Sasso (CNGS)



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

  ~ $\mathbf{2.1\%}\ \bar{\nu}_\mu$ and $\mathbf{0.8\%}\ (\nu_e + \bar{\nu}_e)$

CNGS events selection



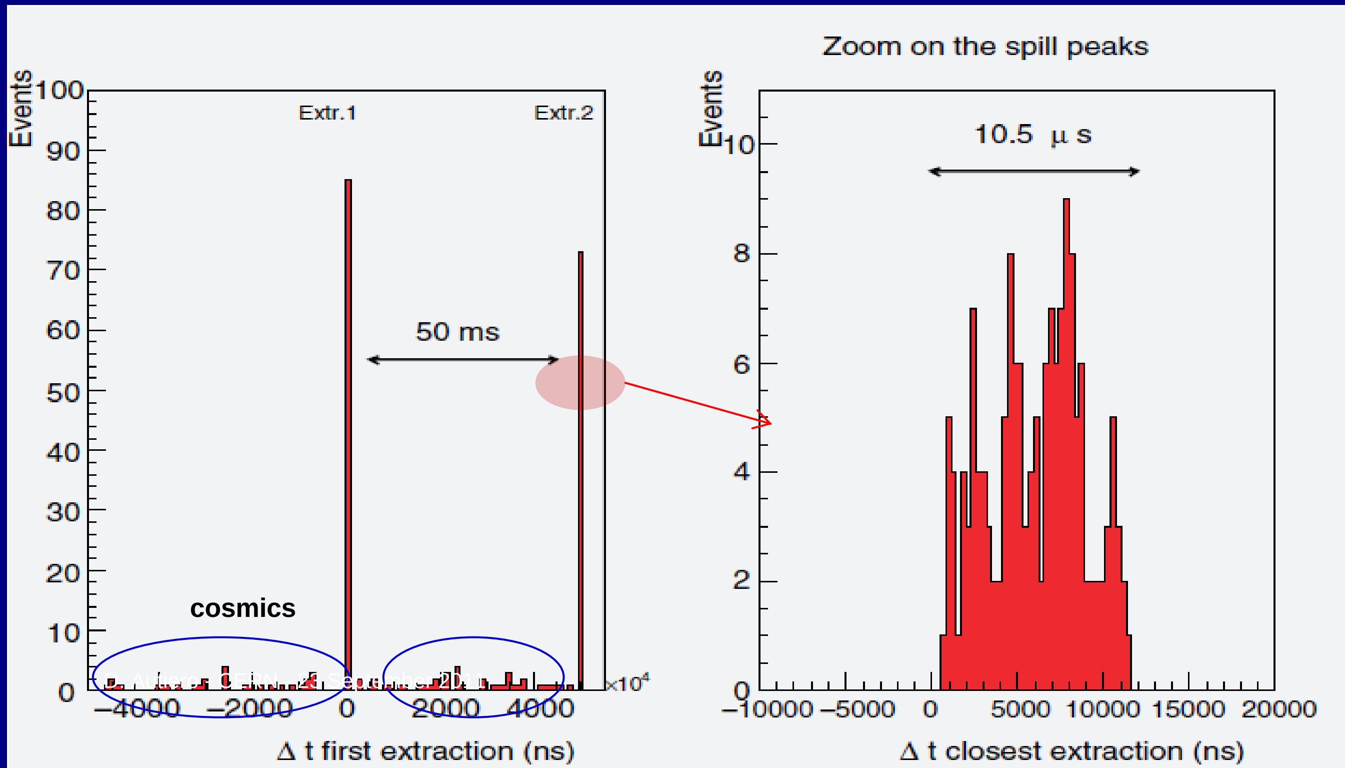
Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

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

Synchronisation with standard GPS systems ~100 ns (inadequate for velocity measurement)

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

CNGS events selection

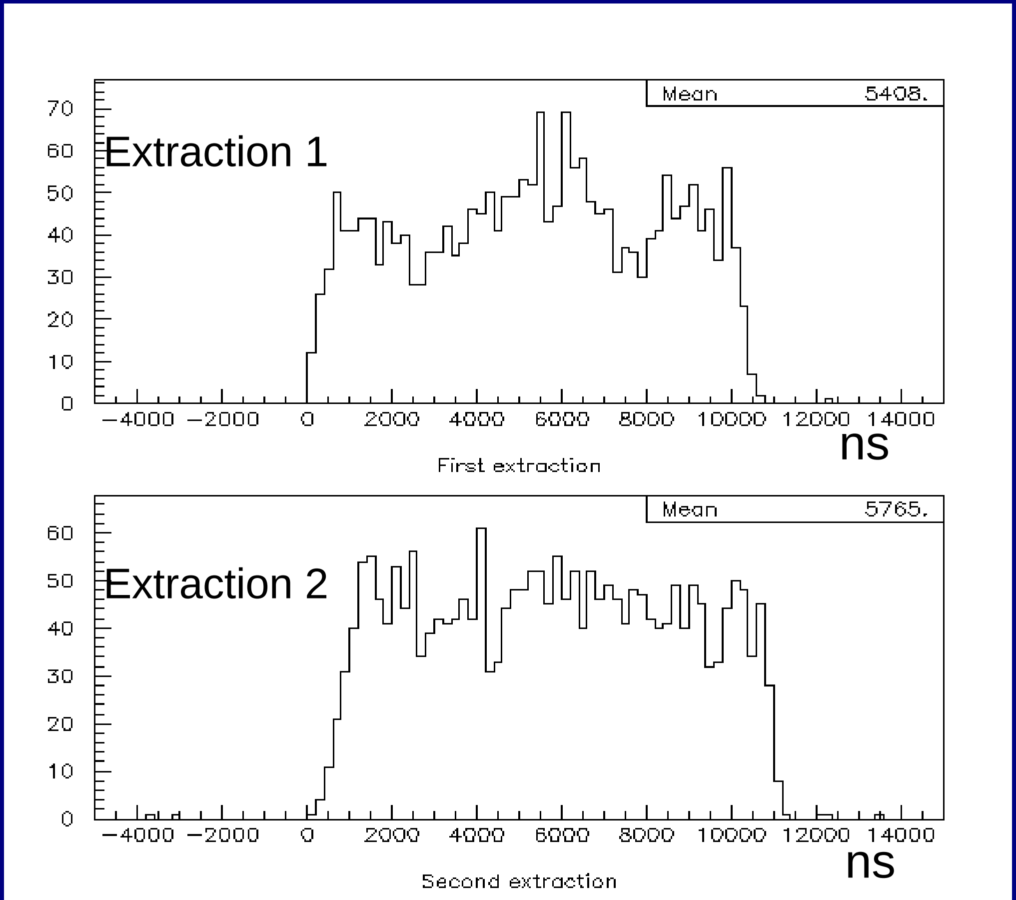


OPERA data: narrow peaks of the order of the spill width (10.5 μs)

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

Selection procedure kept unchanged since first events in 2006

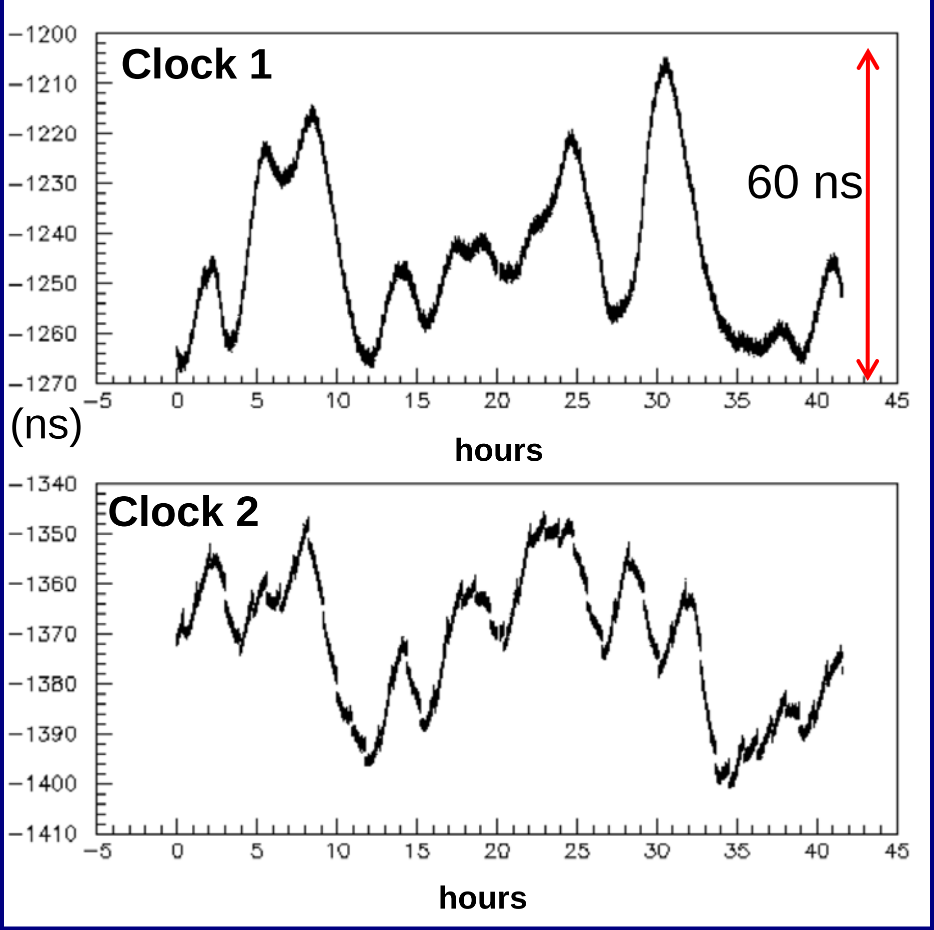
From CNGS event selection to neutrino velocity



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 precise measurement of protons time distribution during extraction



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

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

→ Need accurate time synchronisation system

Collaboration with CERN timing team since 2003

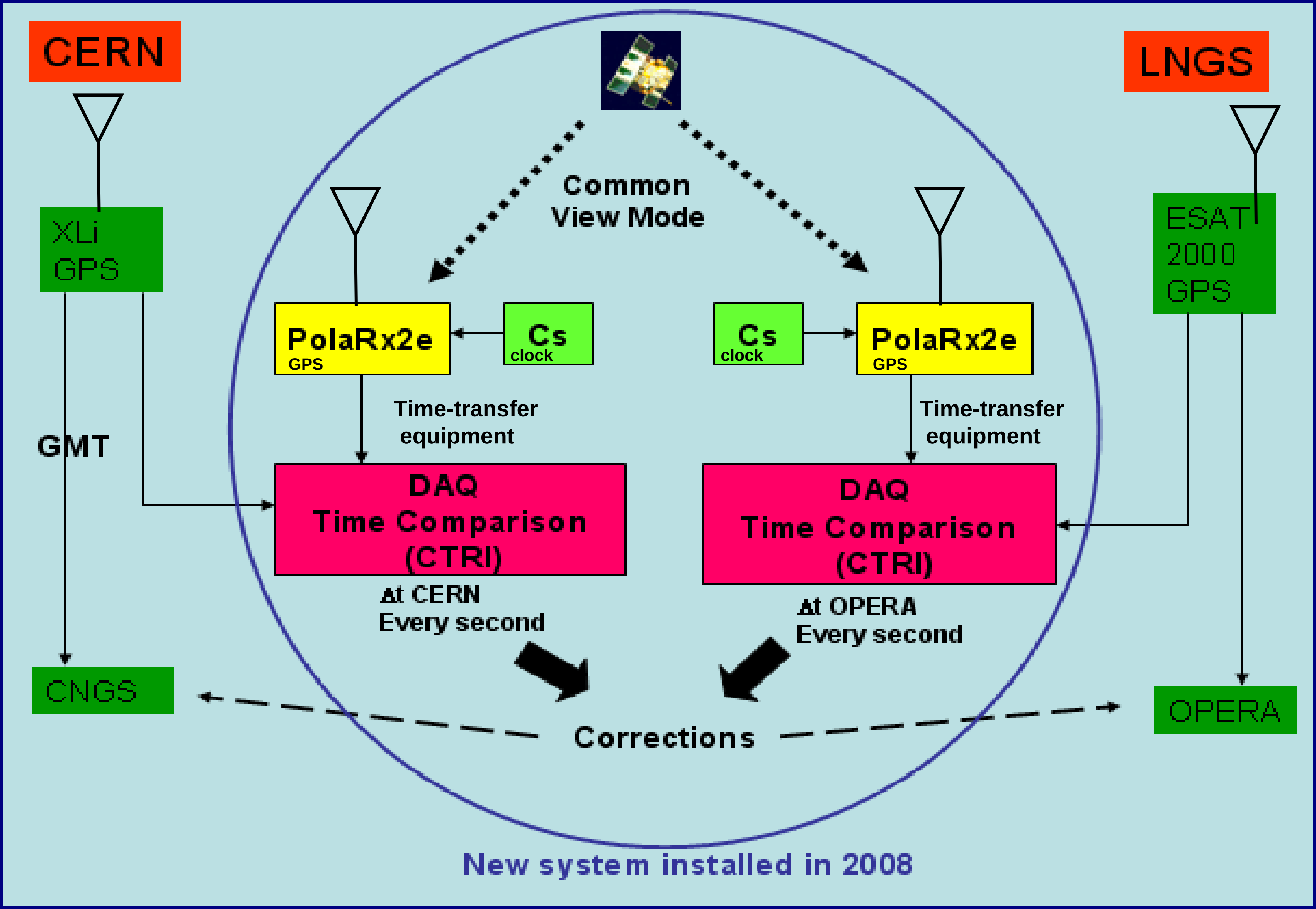
Major upgrade in 2008

OPERA sensitivity

- High neutrino energy - high statistics ~16000 events
- Sophisticated timing system: ~1 ns CERN-OPERA synchronisation
- Accurate calibrations of CNGS and OPERA timing chains: ~ 1 ns level
- Precise measurement of neutrino emission time distribution at CERN through waveforms of proton bunches
- 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 synchronisation



PolaRx2e Septentrio GPS receivers

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 GPS receivers by Septentrio:

- Developed in collaboration with Royal Observatory of Belgium (ROB)
- Frequency reference from Cs-4000 clock
- Internal time tagging of 1PPS with respect to individual satellite observations
- Offline common-view mode analysis in CGGTTS format – developed at ROB
- Use ionosphere free Precise Point Positioning (P3) code: signals at two frequencies in L-band

Standard technique for high accuracy time transfer

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

Calibration by Swiss Federal Metrology Institute (METAS)

GPS common-view mode

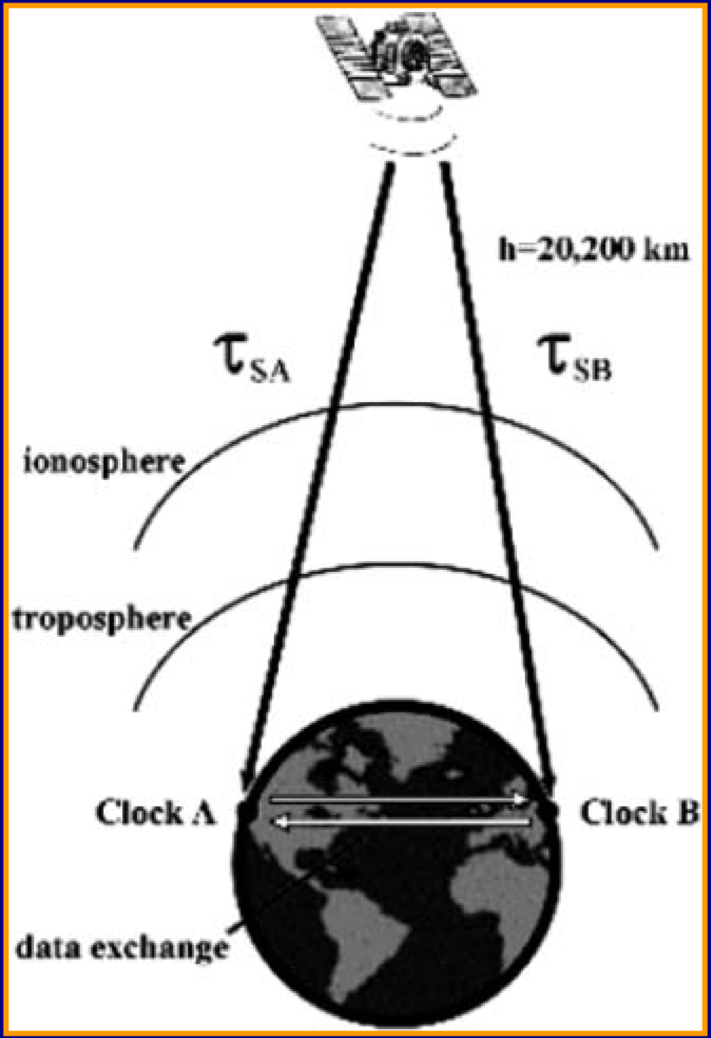
Standard GPS operation:

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

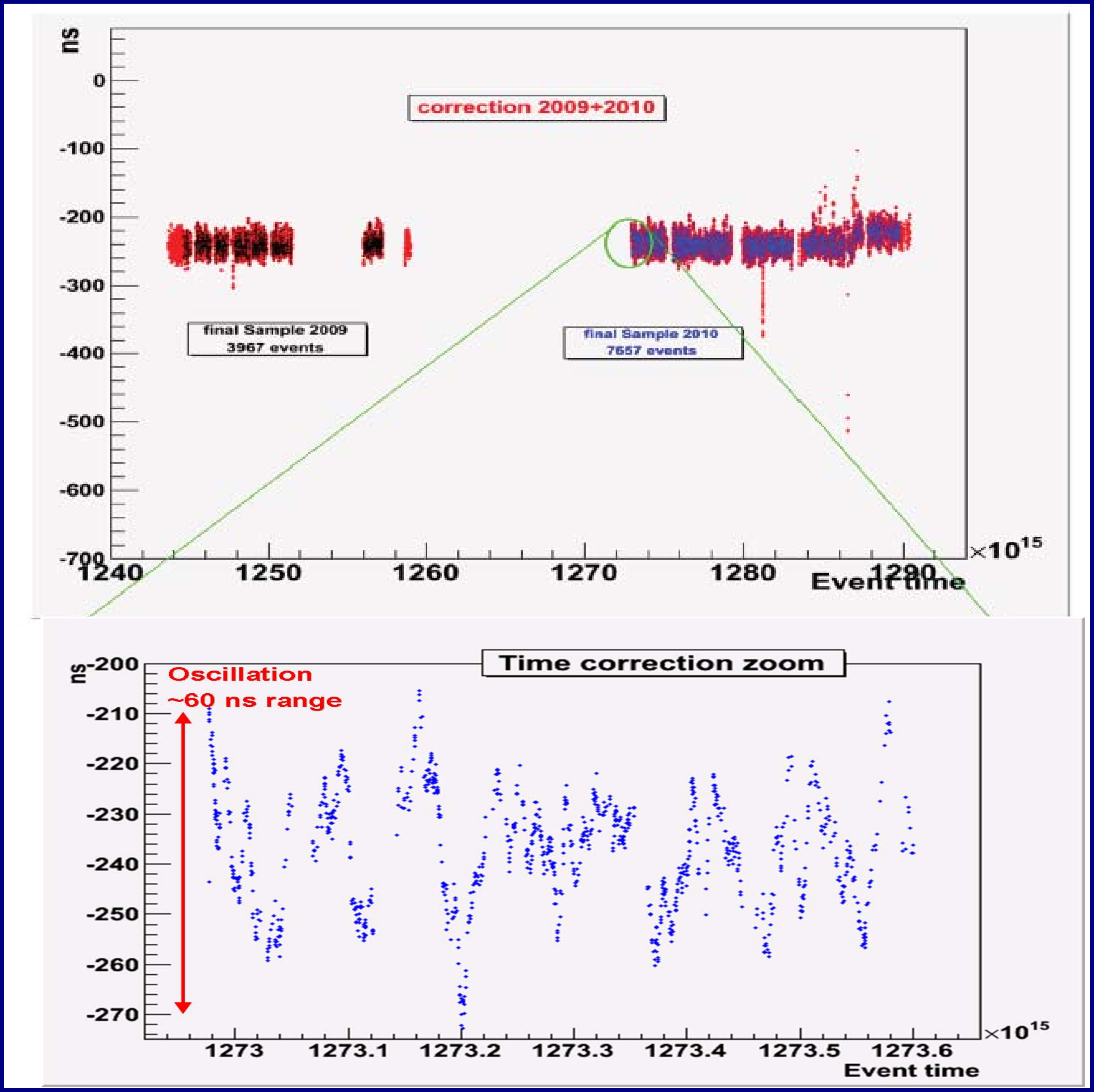
Common-view mode (the same satellite for the two sites, for each comparison):

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)

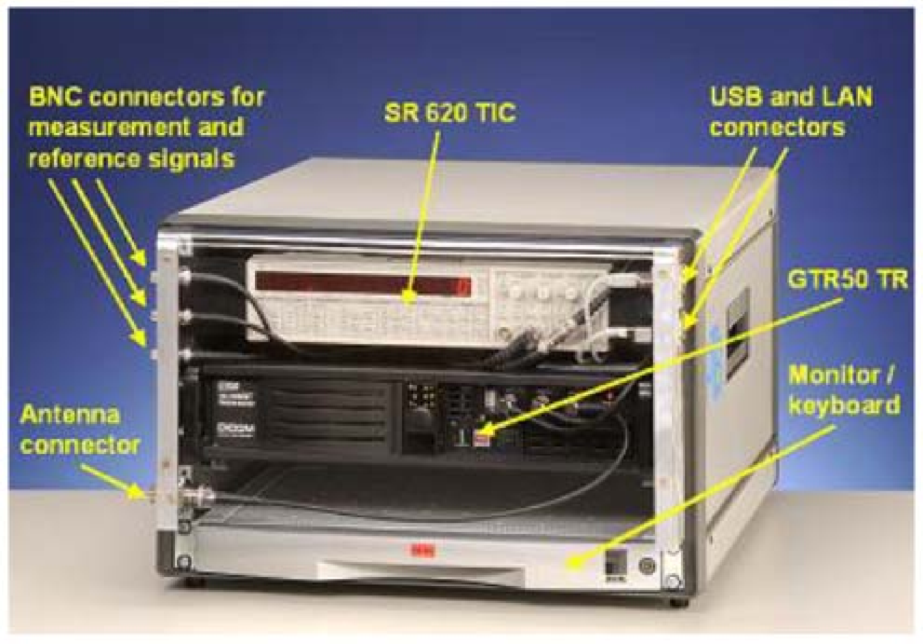


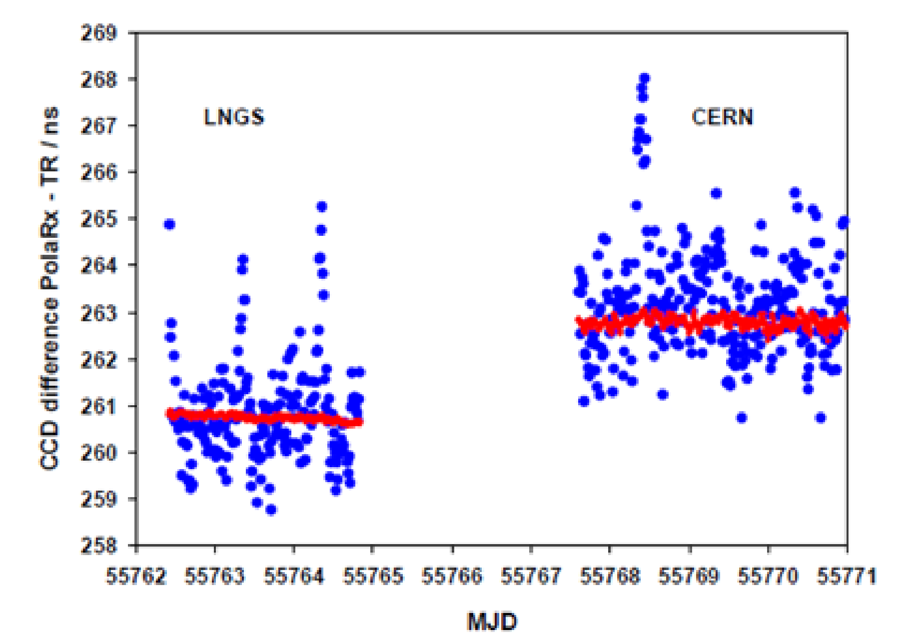
CERN-OPERA clocks inter-calibration cross-check in 2011

Independent twin-system calibration by PTB (Physikalisch-Technische Bundesanstalt)

High accuracy/stability portable Time Transfer Receiver @ CERN and LNGS

GTR50 GPS receiver, thermalised
SR620 Time Interval Counter (TIC)
Local Cs4000 External Cs frequency source
Measurements taken during several days at both sites



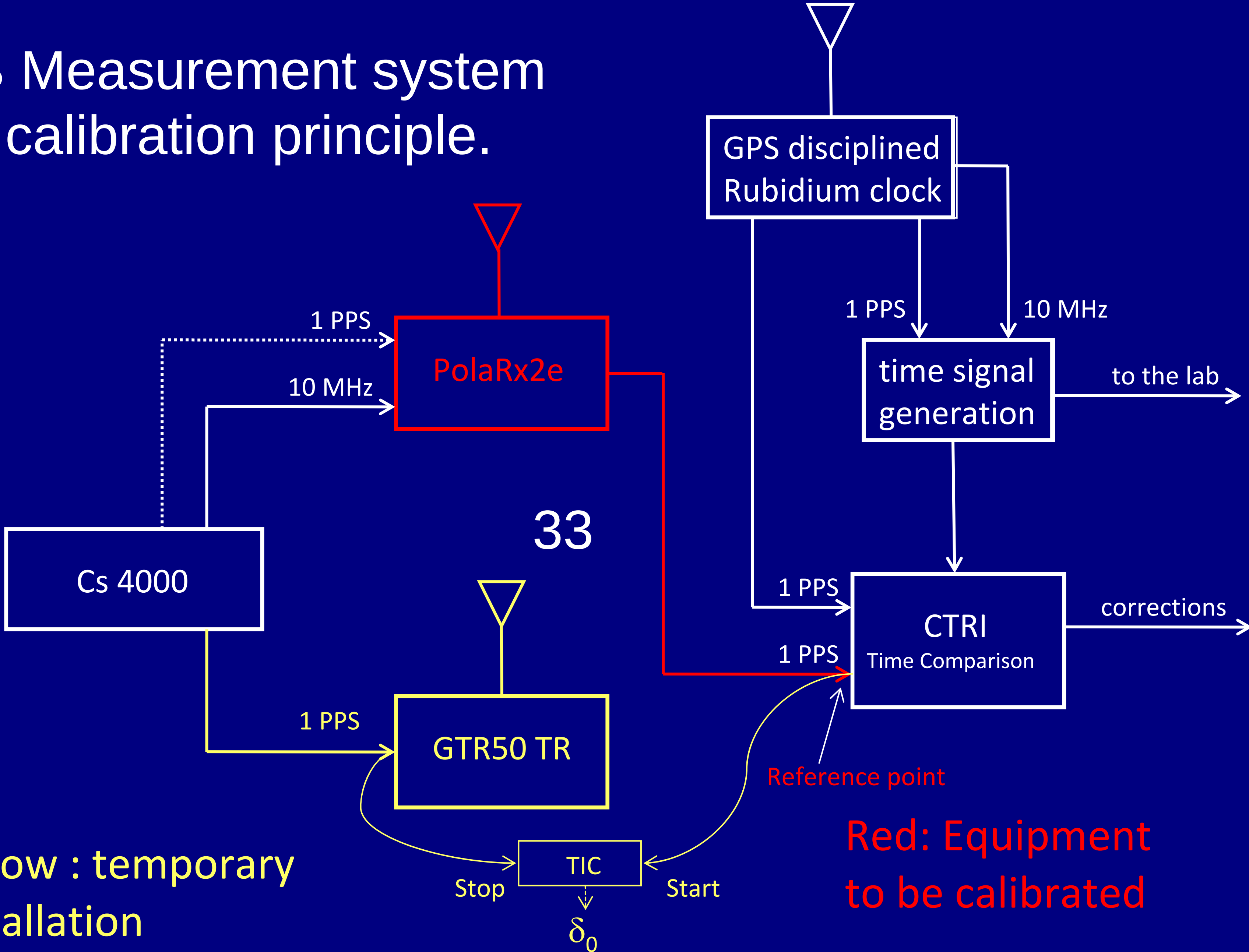


Correction by PTB to the time-link established by METAS:

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

Closure measurement:
$t_{@PTB}$(before campaign) -
$t_{@PTB}$(after campaign) = 0.04 ns

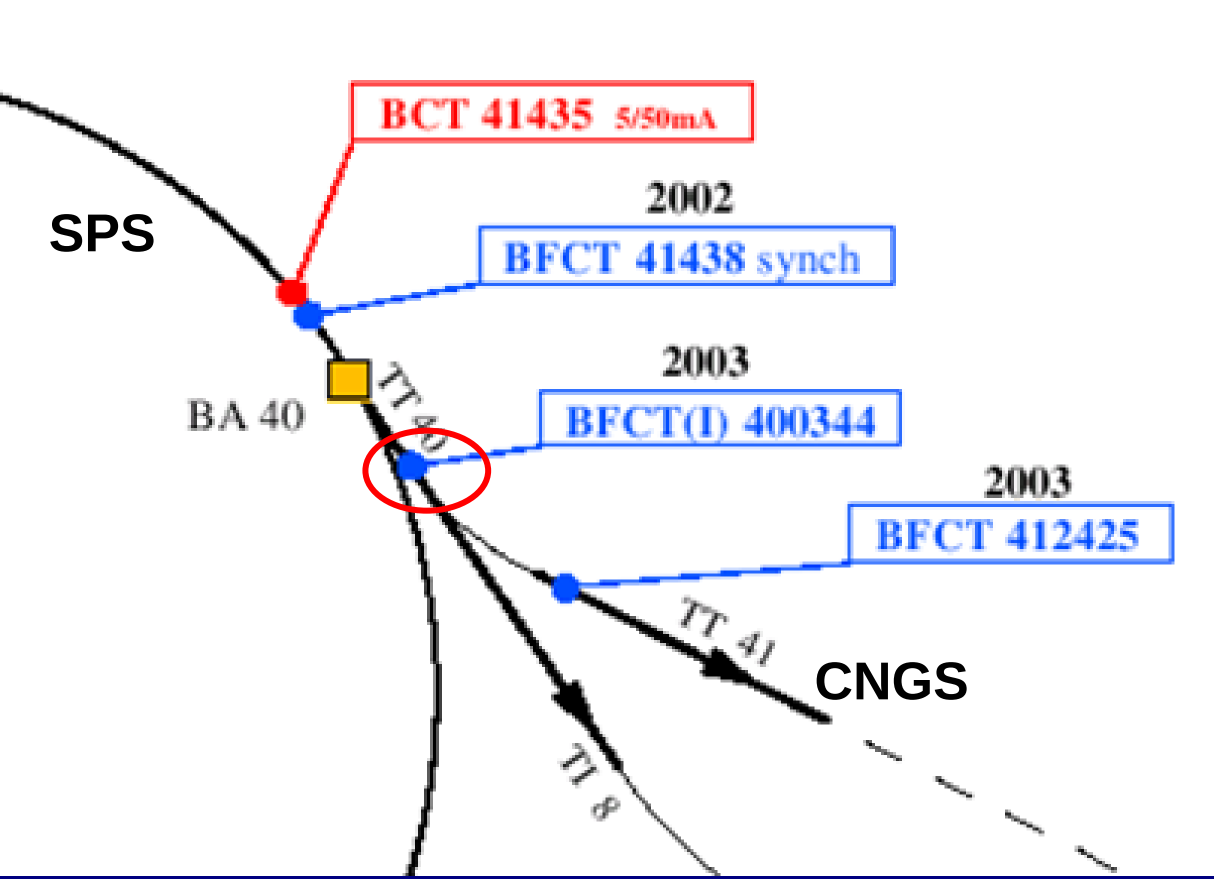
PTB Measurement system and calibration principle.



Yellow : temporary installation

Red: Equipment to be calibrated

Done at CERN and at LNGS



Proton timing by Beam Fast Current Transformer (BCT)

Fast BCT 400344
(~ 400 MHz)

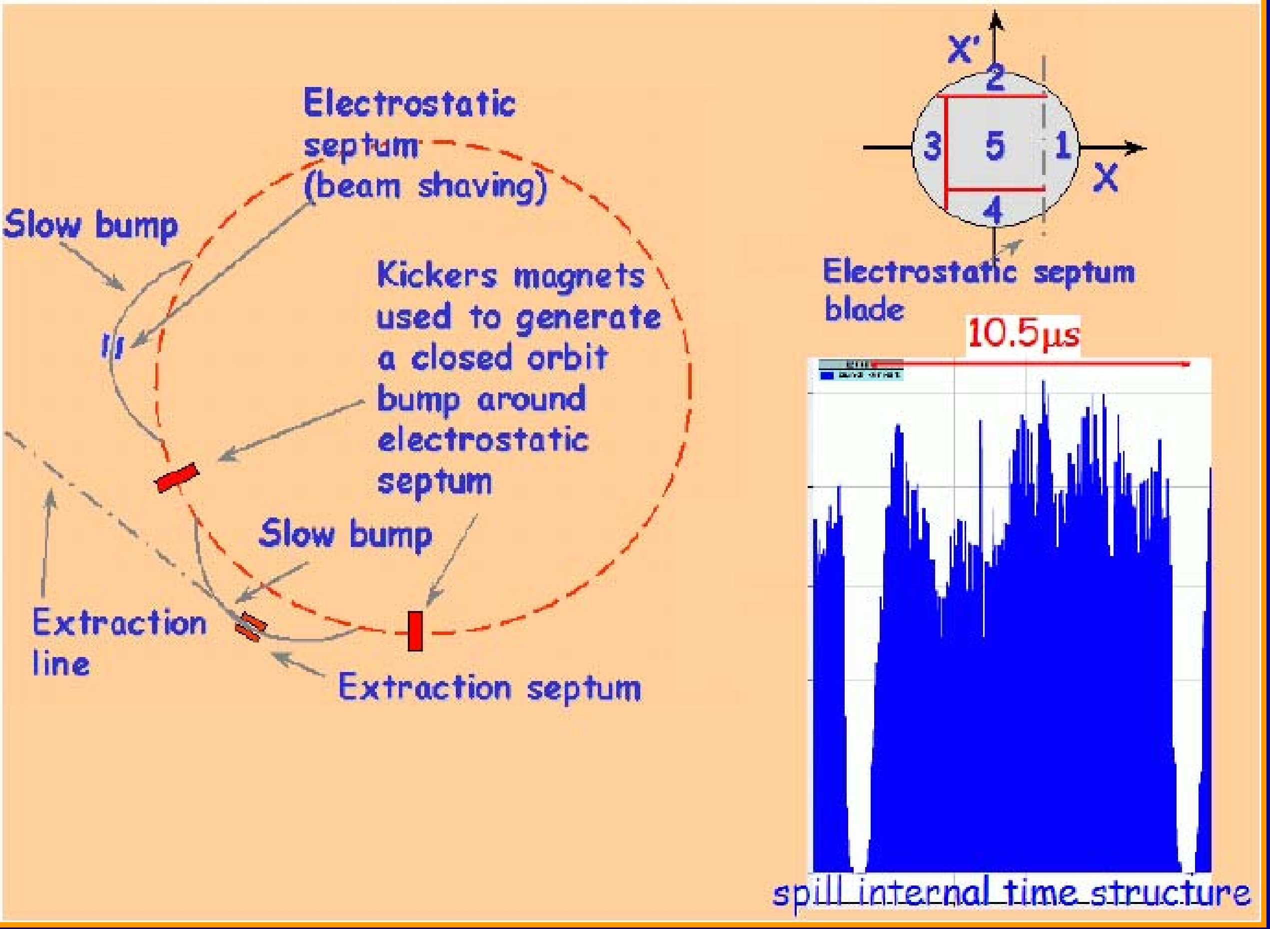
Proton pulse digitisation for each 10.5μs extraction:

• 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



Protons spill shape from PS for injection in SPS

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

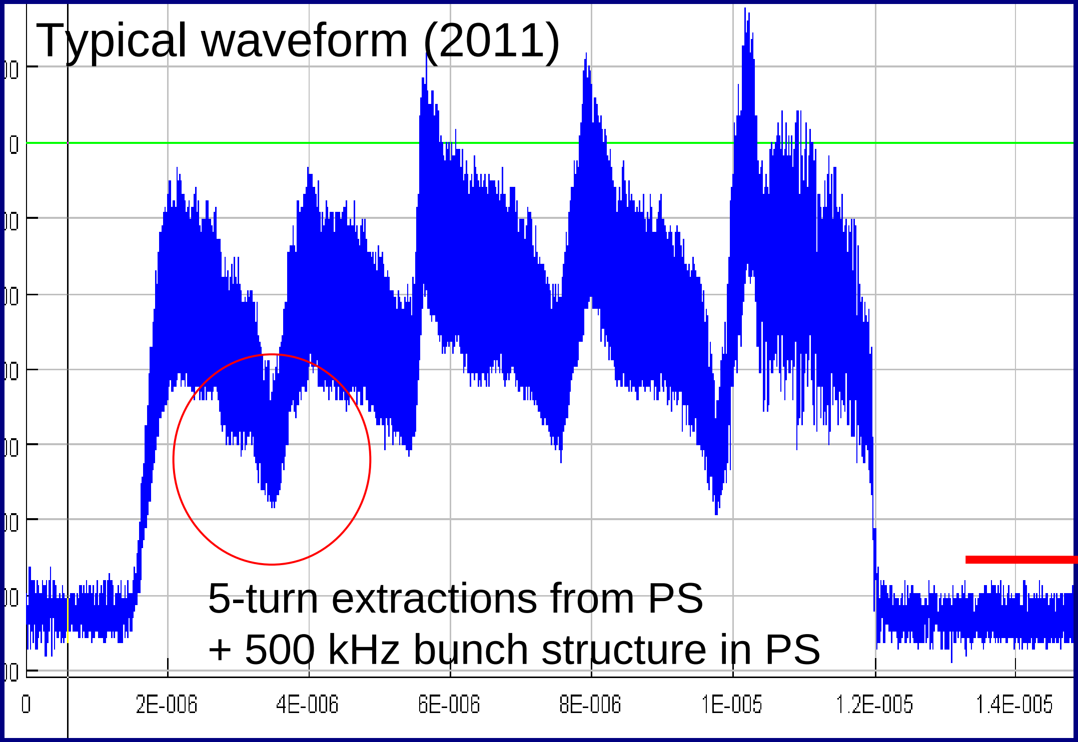
SPS circumference = 11 x PS circumference: SPS ring filled at 10/11

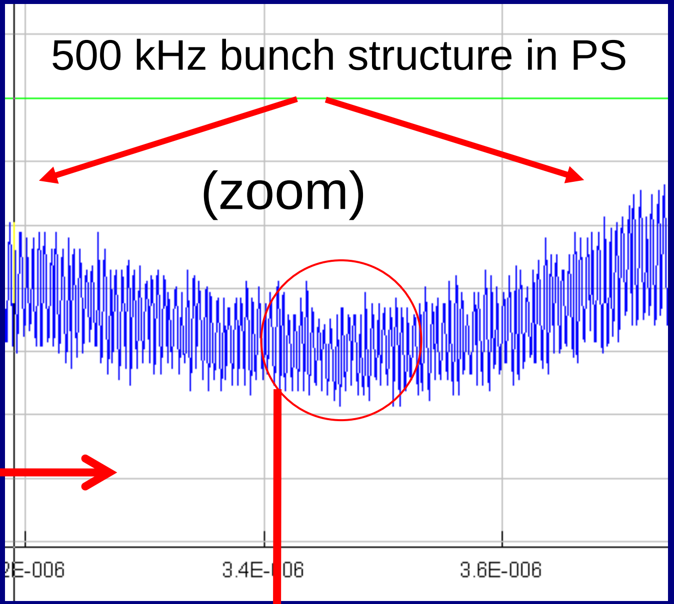
Shapes varying with time and both extractions

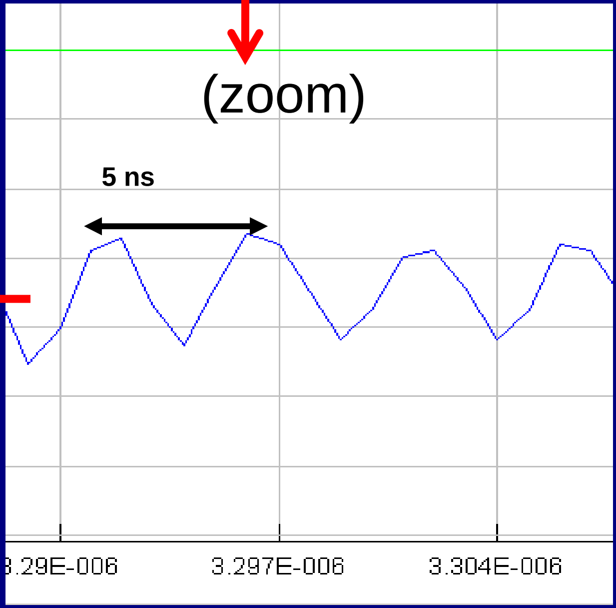
→ Precise accounting with WFD waveforms:

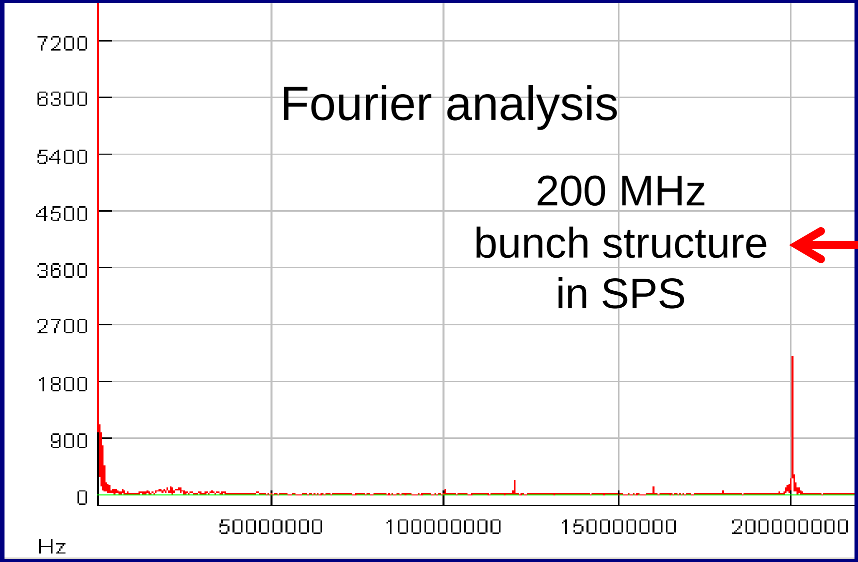
more accurate than: *e.g.* average neutrino distribution in a near detector

Beam Current Transformer (BCT) resolution









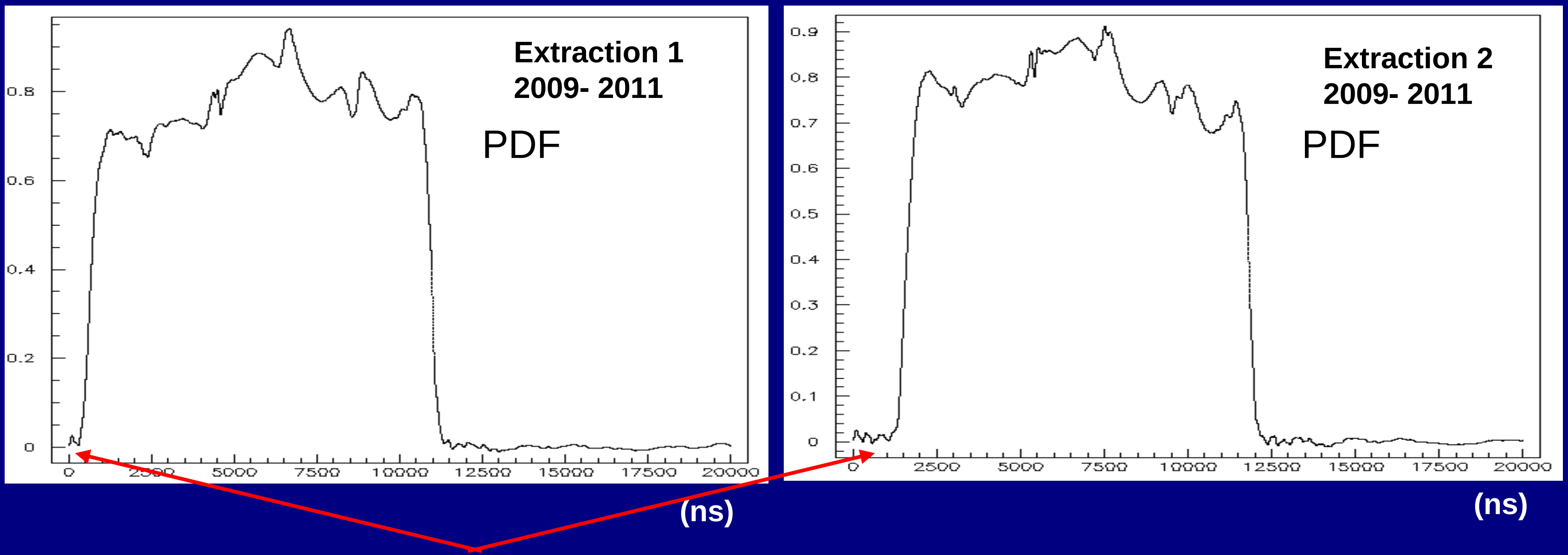
PDF of neutrino event-time distribution

- Each ν event in OPERA is associated to its proton extraction waveform at CERN
- The "parent" proton of the event is unknown within the 10.5 μs extraction time

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

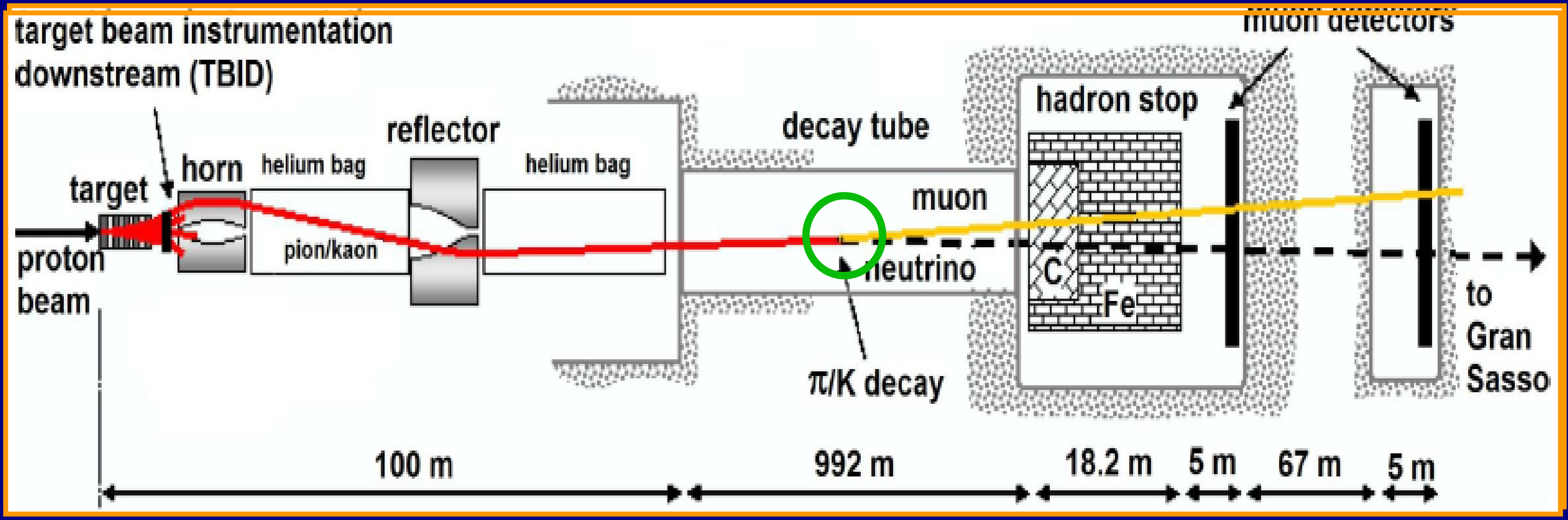
→ compare to time distribution of neutrino events detected in OPERA

Only waveforms corresponding to events detected in OPERA contribute the PDF :
~30 000 extractions and ~ 30 events (0.1%) per day



different timing w.r.t. kicker magnet signal

Unimportance of knowing the 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)

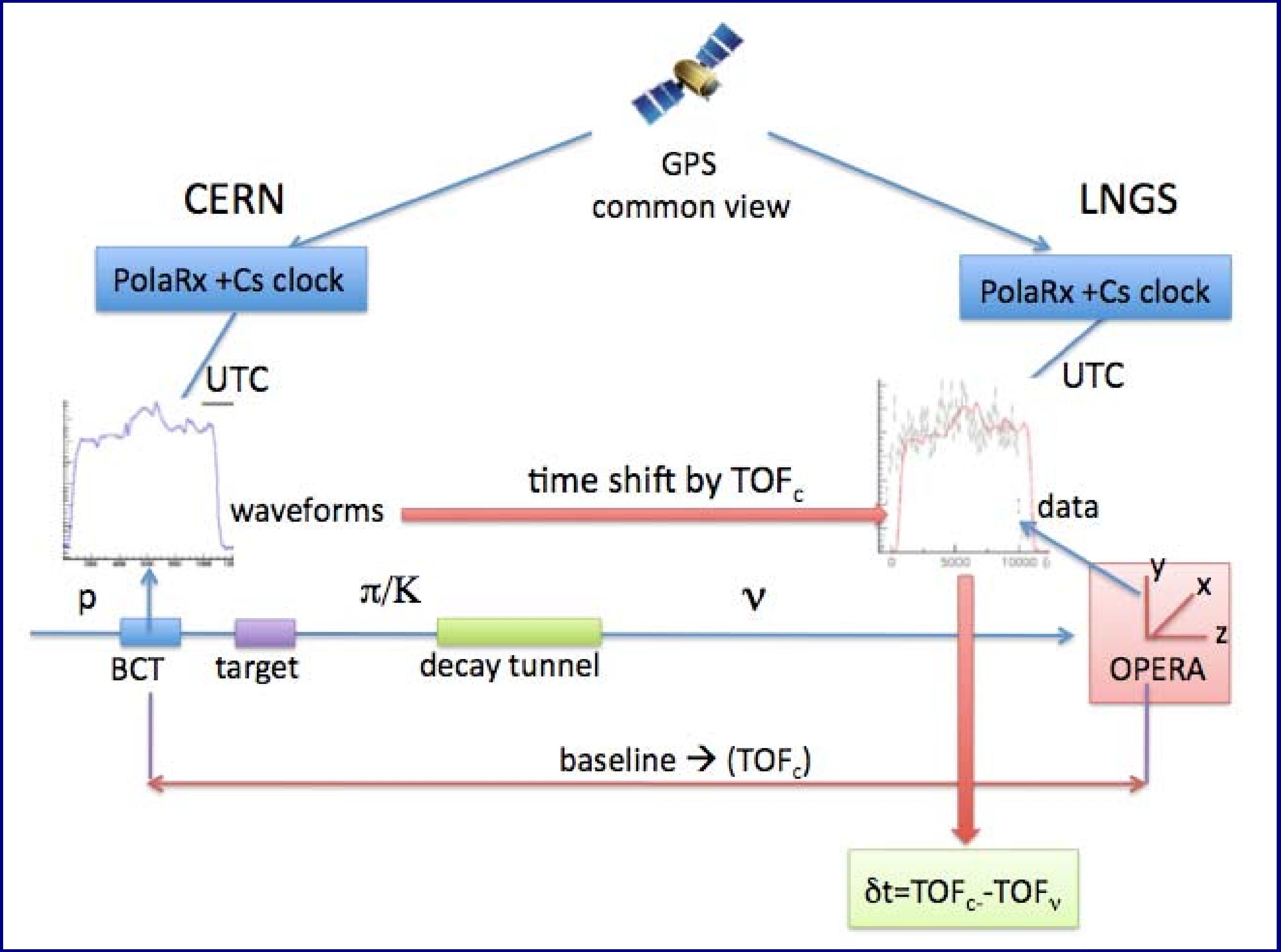
TOF_c = assuming *c* from BCT to OPERA (2439280.9 ns)

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

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

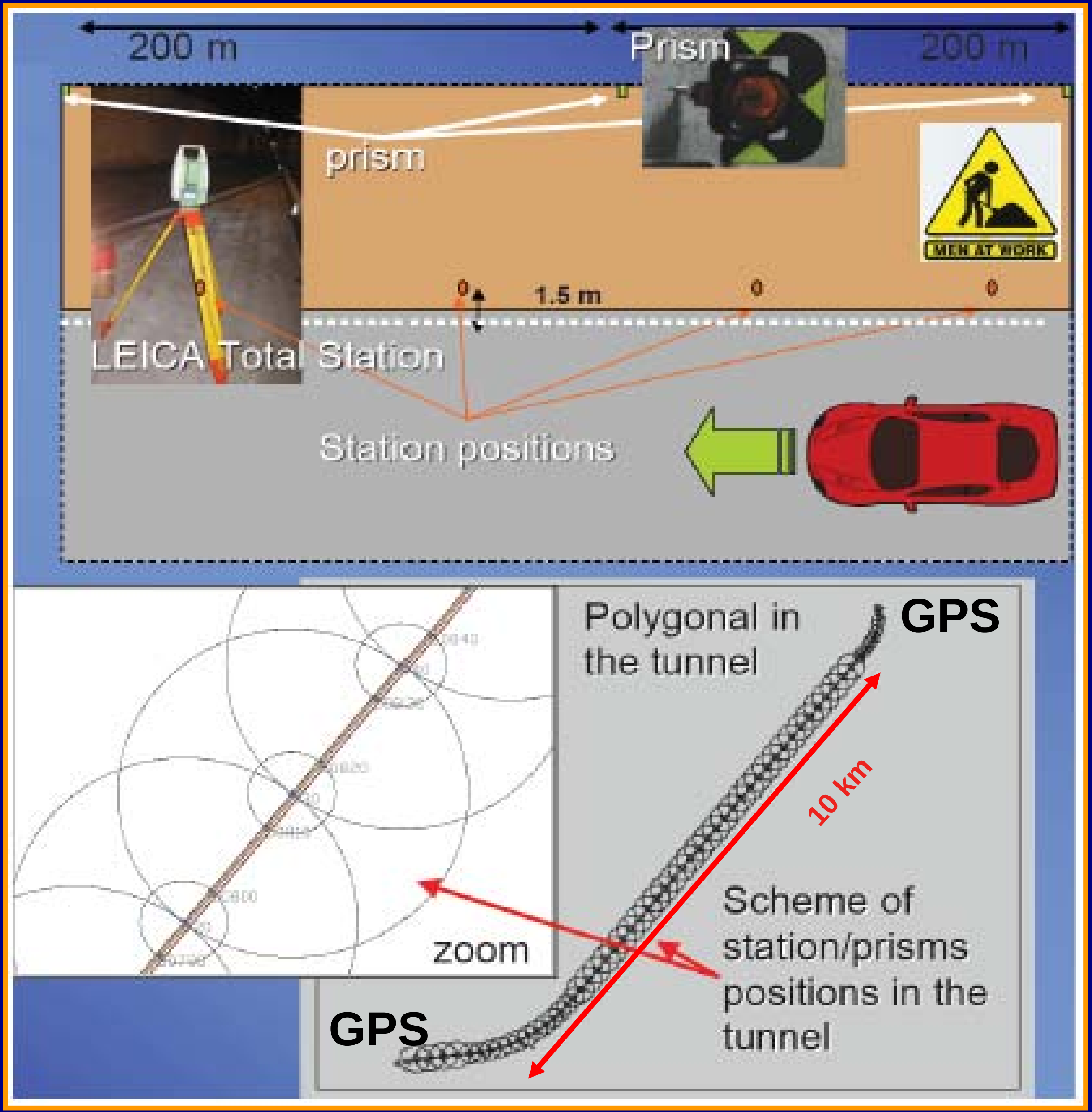
$\langle \Delta t \rangle = 1.4 \times 10^{-2}$ ns

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 la Sapienza Geodesy group)

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

GPS measurements ported underground by triangulation to OPERA reference point. Precision degraded from ~ 1 mm to 20 cm

Combination with CERN geodesy

Benchmarks measurements at CERN in ITRF1997 (International Global Reference Frame) and at LNGS in ETRF2000 (latest European Global Reference Frame) taken at different epochs and combined in the ETRF2000 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

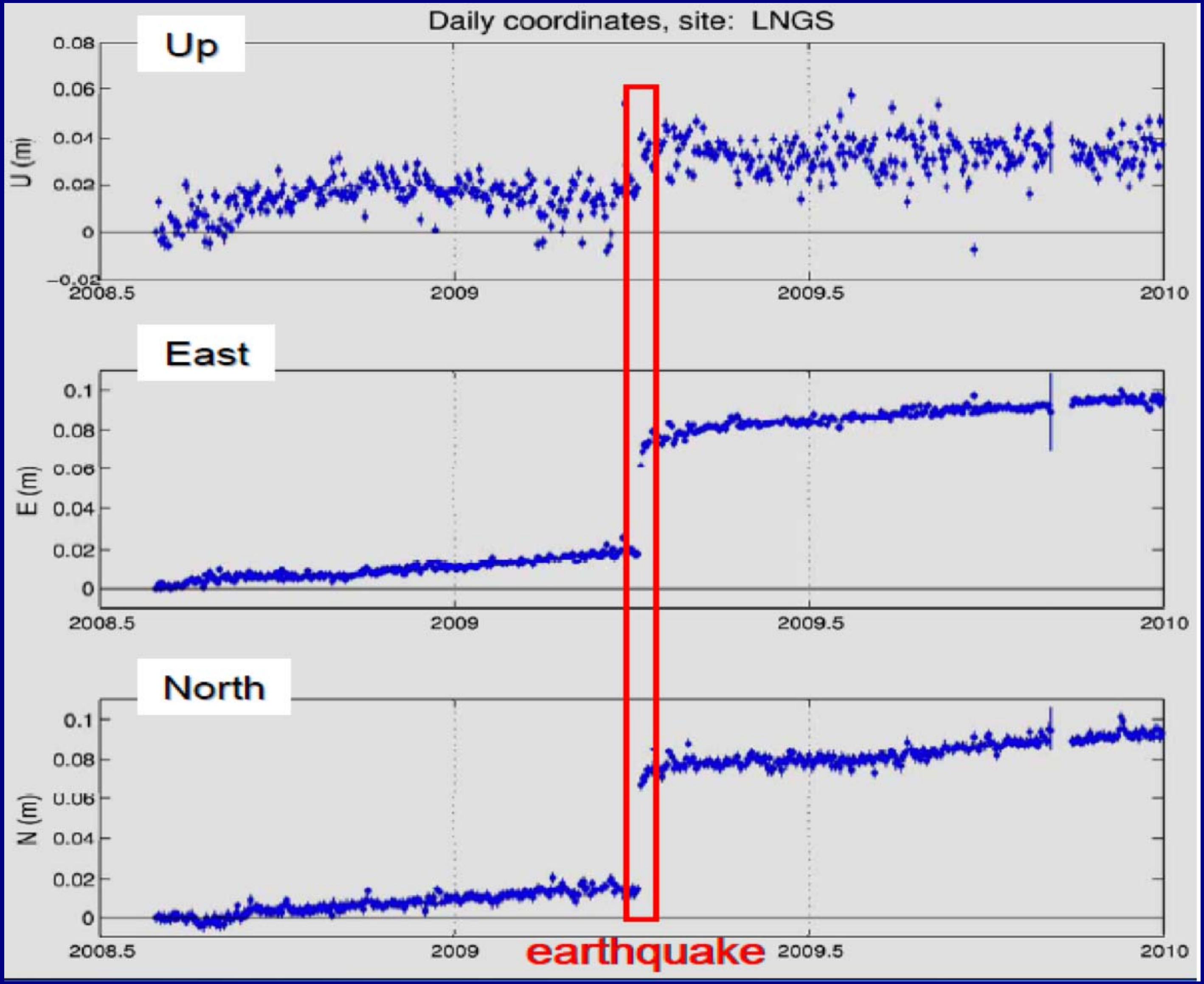
LNGS benchmarks
In ETRF2000

Cross-check: simultaneous CERN-LNGS measurement of GPS benchmarks in June 2011 – Agreement within 2 cm

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 using inclusive techniques

Start —— Delay T_A ? ——> End

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

Start ——> End

CS 1PPS CS 1PPS

• Double path fibers measurement:
by swapping Tx and Rx component of the opto-chain

Start —— T_A ? ——> End

T_B ?

Optical fiber

Measure T_A-T_B

Measure T_A+T_B

Start —— T_A ? ——> End

T_B ?

Optical fiber

$\Rightarrow$ T_A,T_B

Beam Current Transformer (BCT) calibration (1)

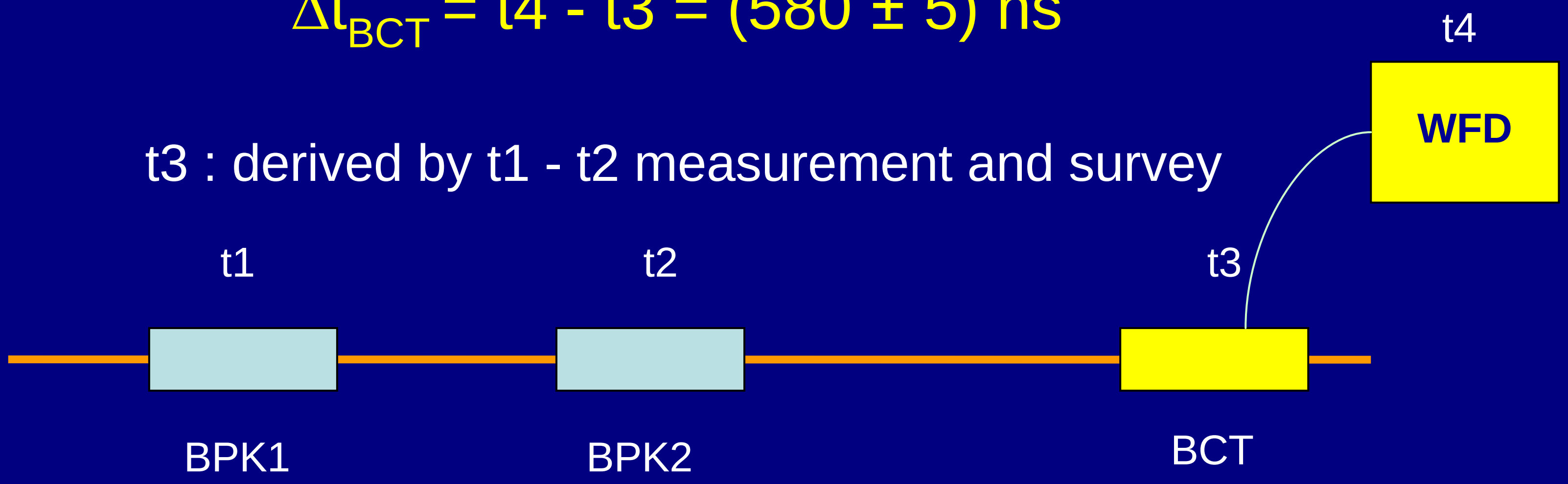
Time elapsed between beam at BCT and digitisation by Wave Form Digitiser

Measurement done by injecting PPS Cs clock signal.
Repeated with dedicated beam experiment:

BCT plus two Beam Pick-Ups (~1 ns) with LHC beam (12 bunches, 50 ns spacing)

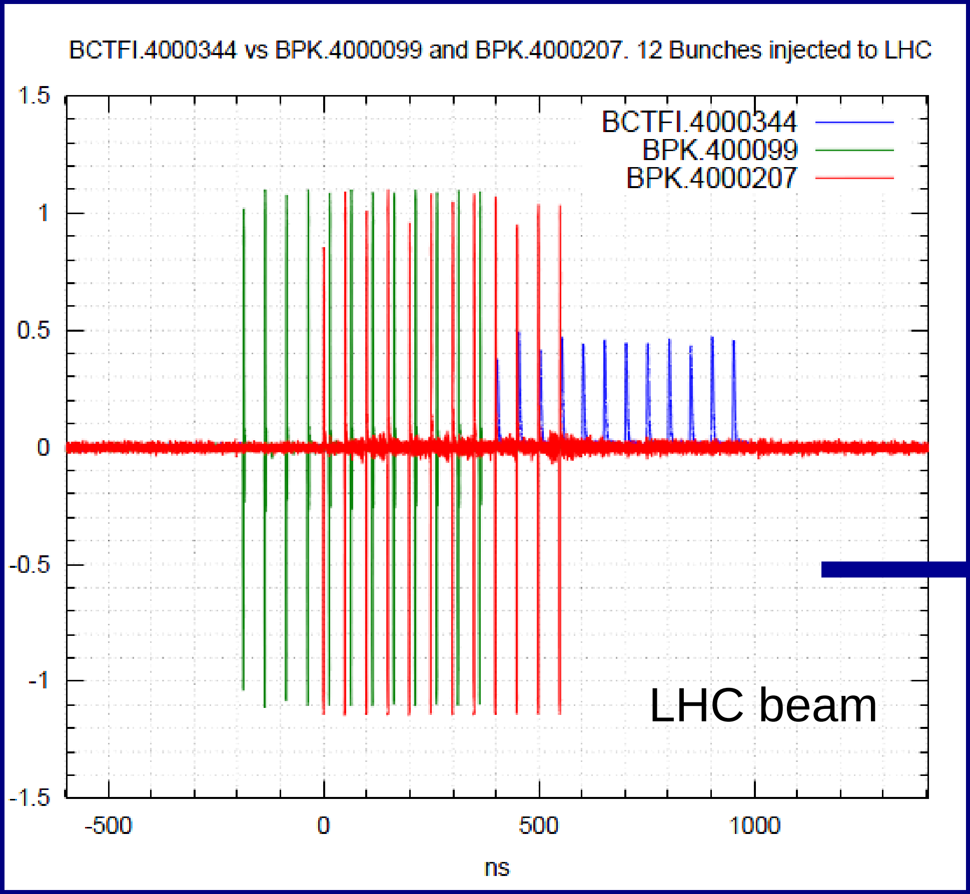
$$\Delta t_{BCT} = t4 - t3 = (580 \pm 5)\ \text{ns}$$

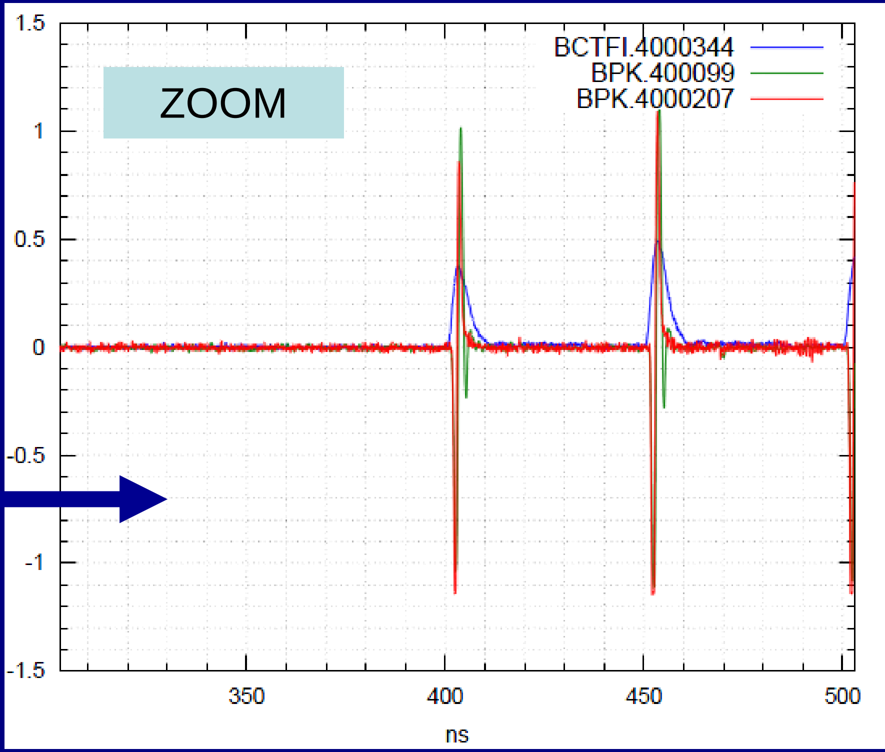
t3 : derived by t1 - t2 measurement and survey



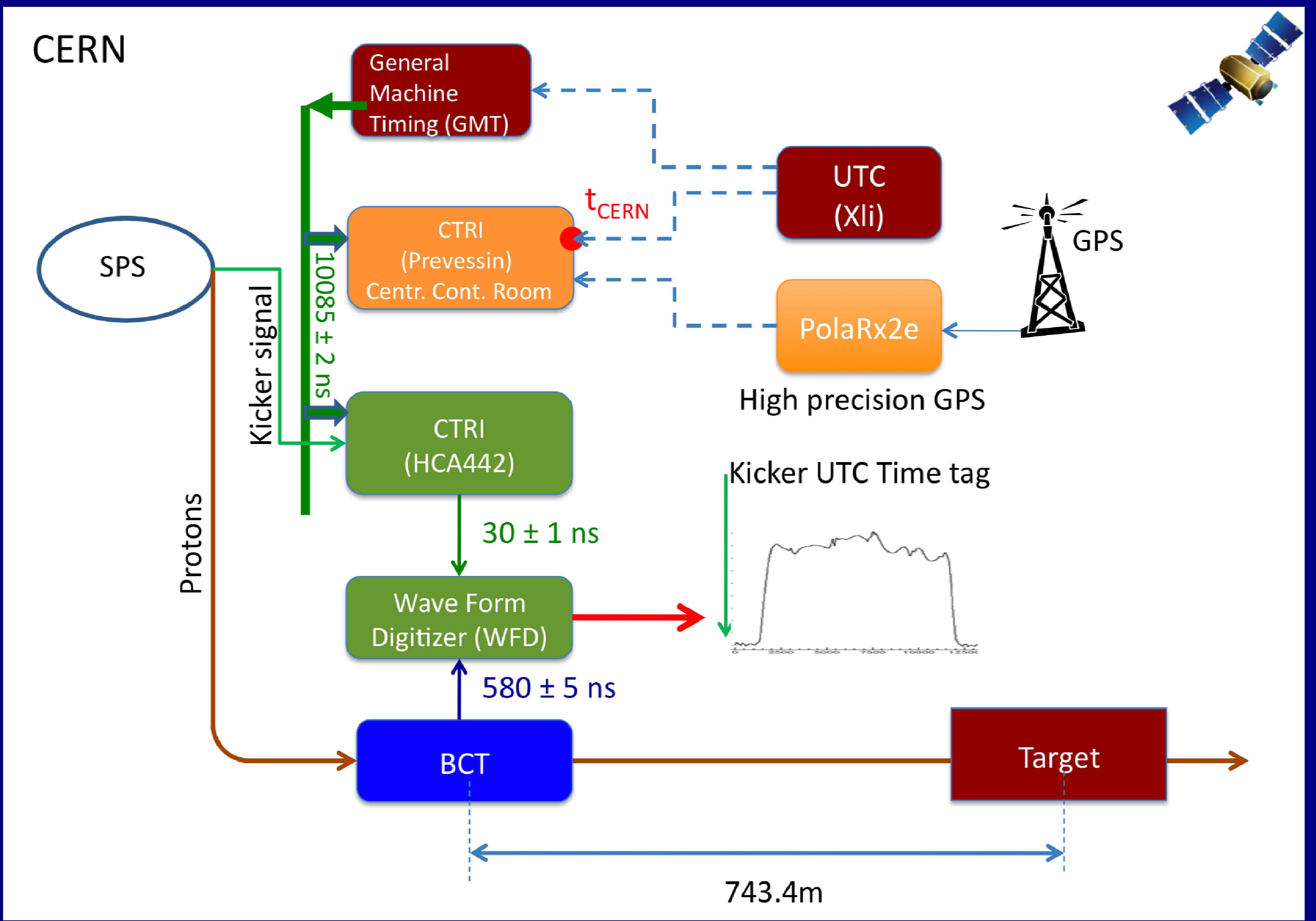
Largest contribution to systematic error : 5 ns

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

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

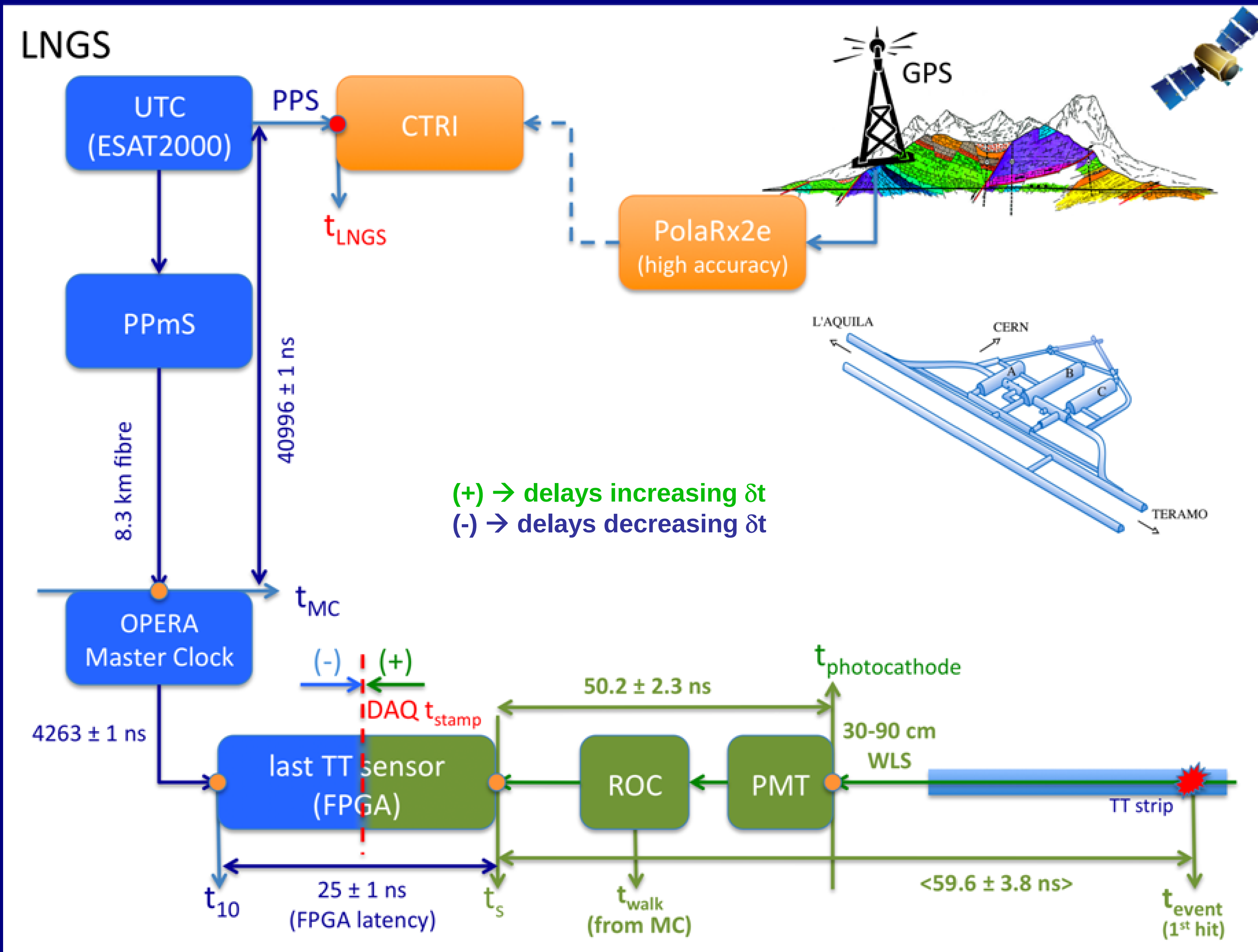
The two CTRI get the UTC distributed by GMT

→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



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}
4263 ± 1 ns
$t_{photocathode}$
50.2 ± 2.3 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)

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 fibre

→ Calibration vs. the CTRI input (40996 +-1 ns) with two ways fibre measurement (spare fibres) 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

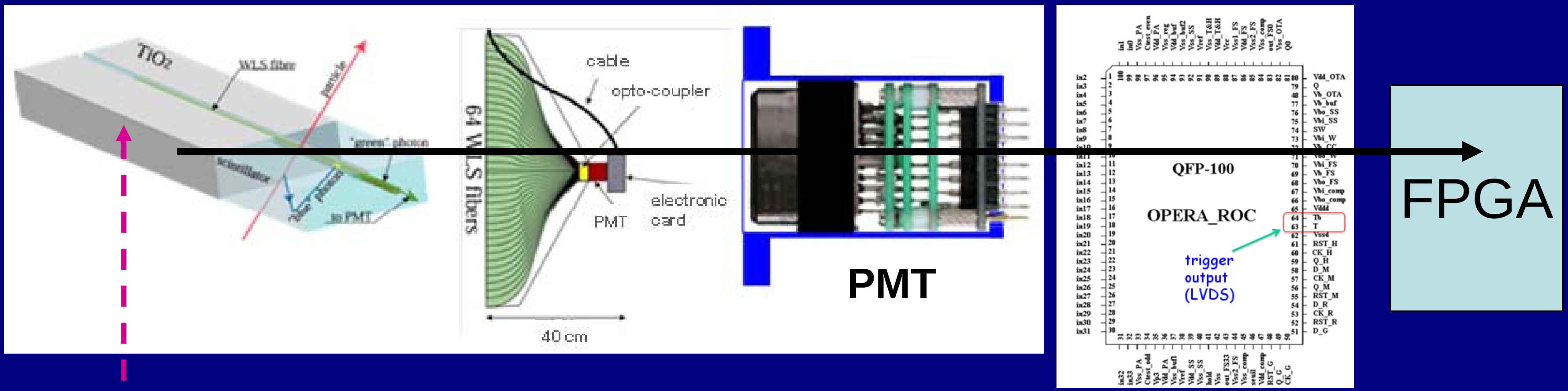
❖ FPGA latency on the F.E. in interpreting the clock signal as T0 for detector triggers (24.5 +-1 ns) measured by comparing DAQ output with oscilloscope measurements

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

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

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

TT time response measurement



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

UV laser 1 ps excitation:
→ delay from photo-cathode to FPGA input: 50.2 ± 2.3 ns

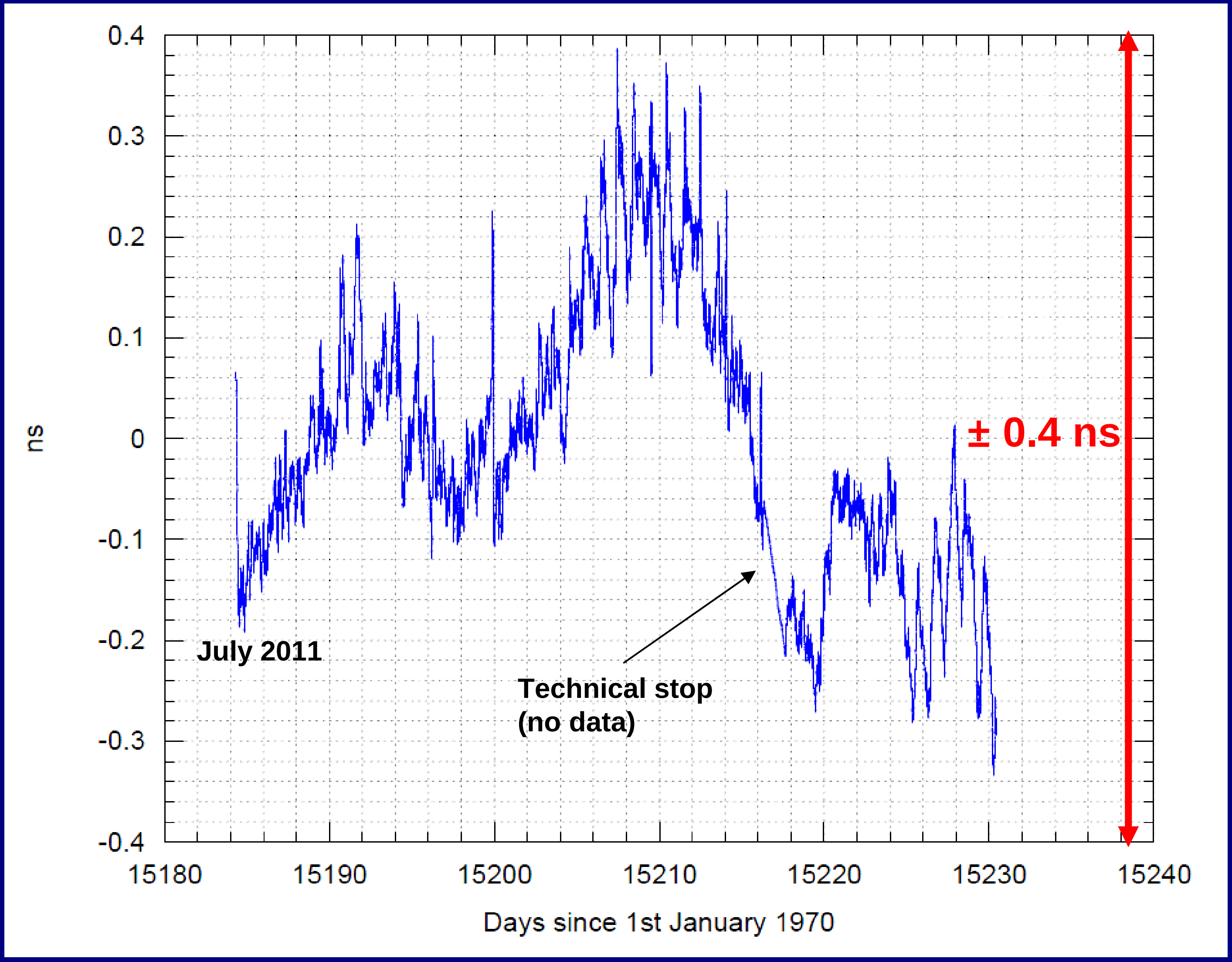
Average event time response: 59.6 ± 3.8 ns (sys)

(Including position and signal pulse height 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 inter-calibration	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)

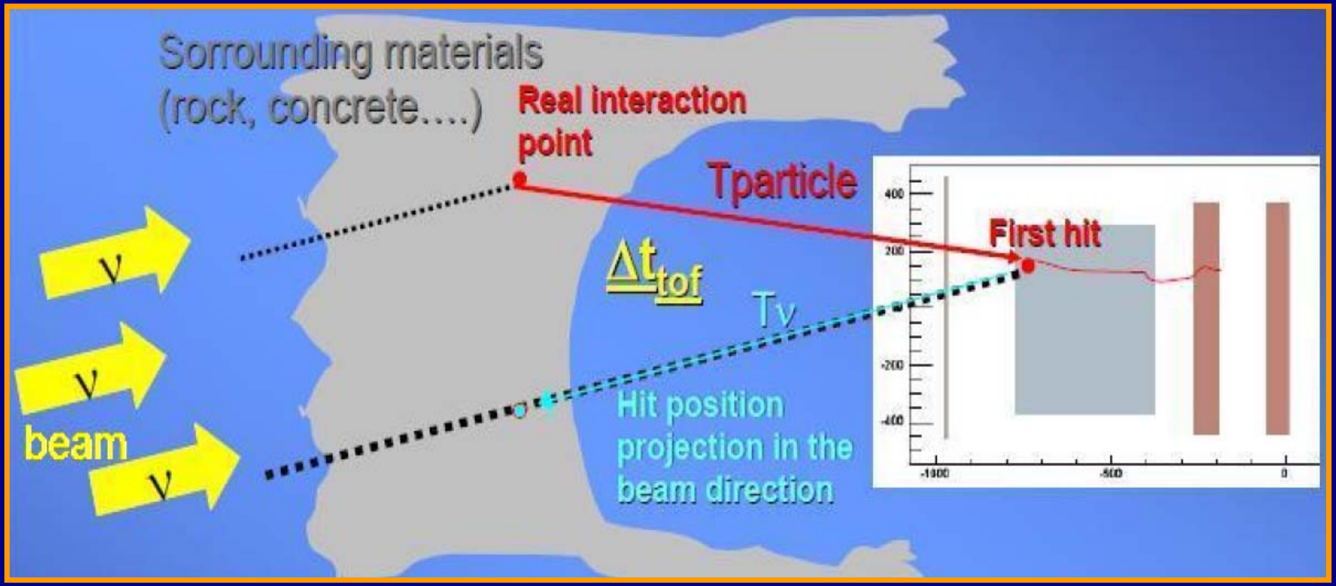


Event selection (earliest TT hit of the event as "stop")

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

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

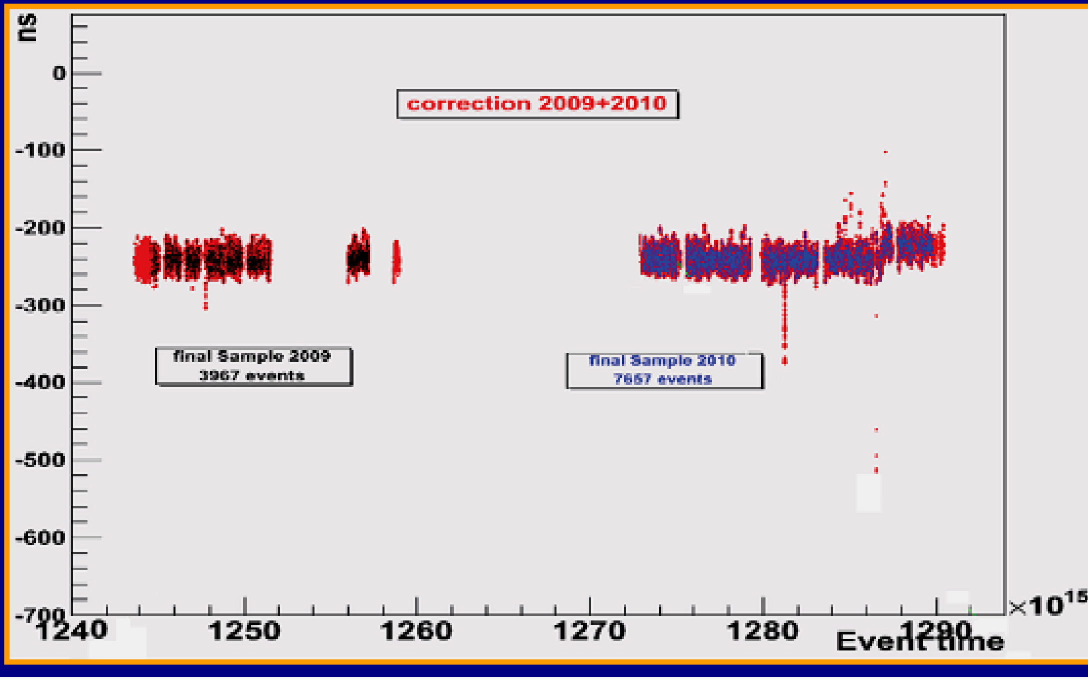
External events:
Rock interaction → require muon 3D track: 8525 events
(Timing checked with full simulation, 2 ns systematic uncertainty by adding external events)



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

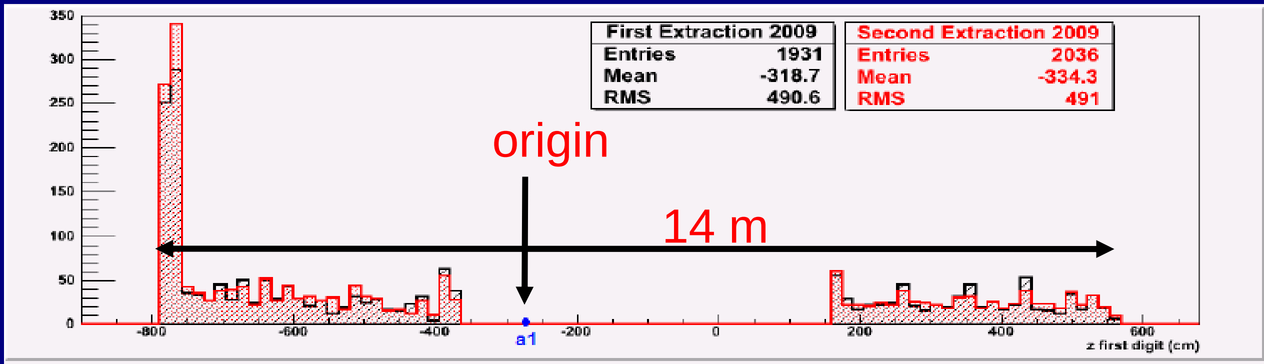
Event time corrections at OPERA

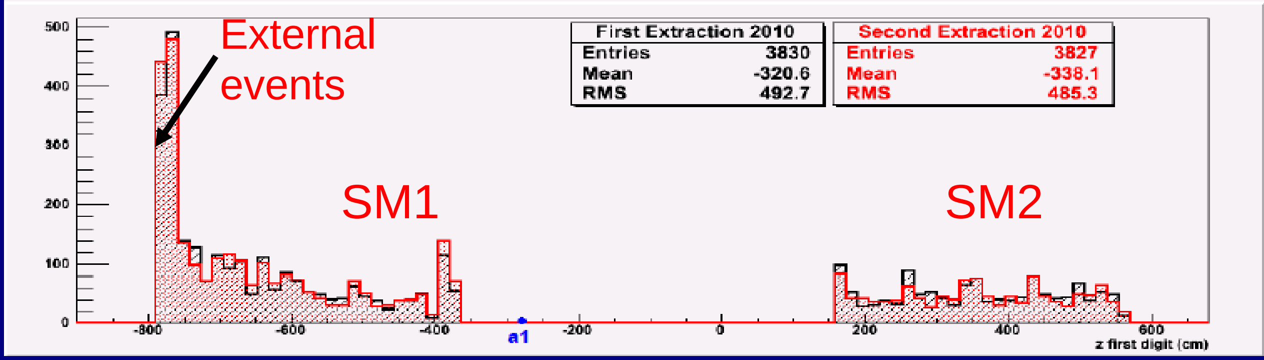
Time-link correction (blue points)



Event by event correction due to the earliest hit position

average correction: 140 cm (4.7 ns)

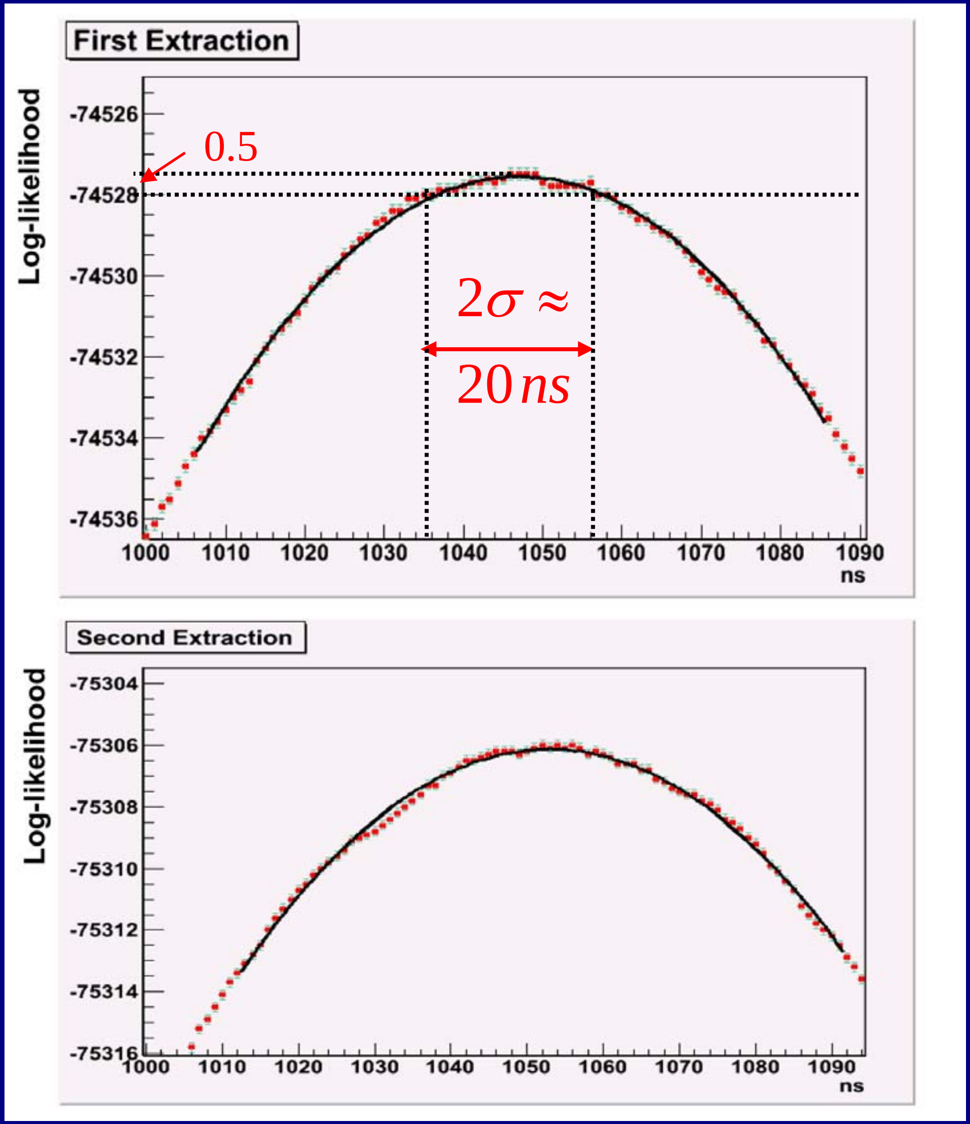




Analysis method

For each neutrino event in OPERA → proton extraction waveform

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



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

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

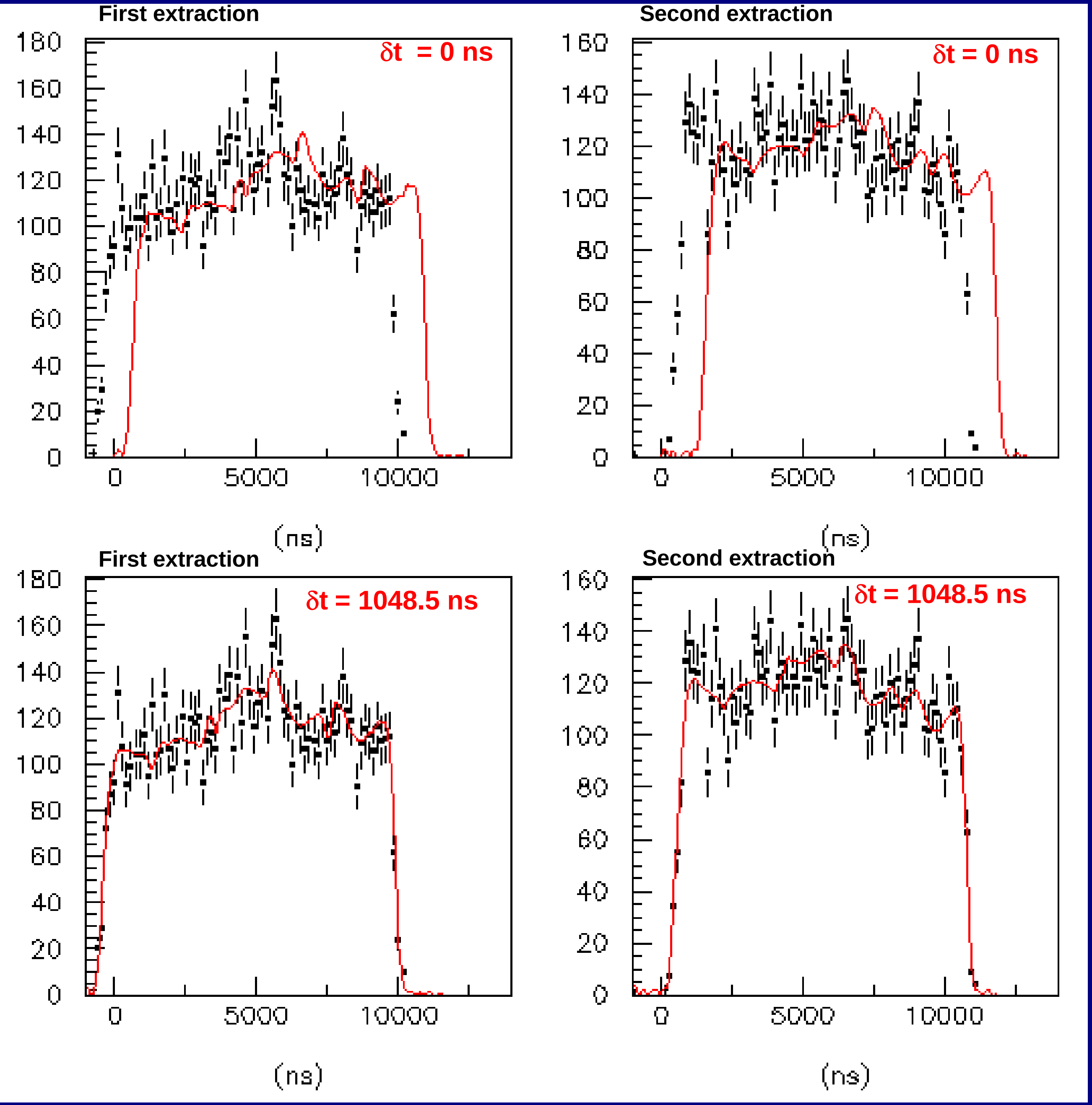
4) Ignoring the BCT and WFD delays

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 maximum likelihood adjustment



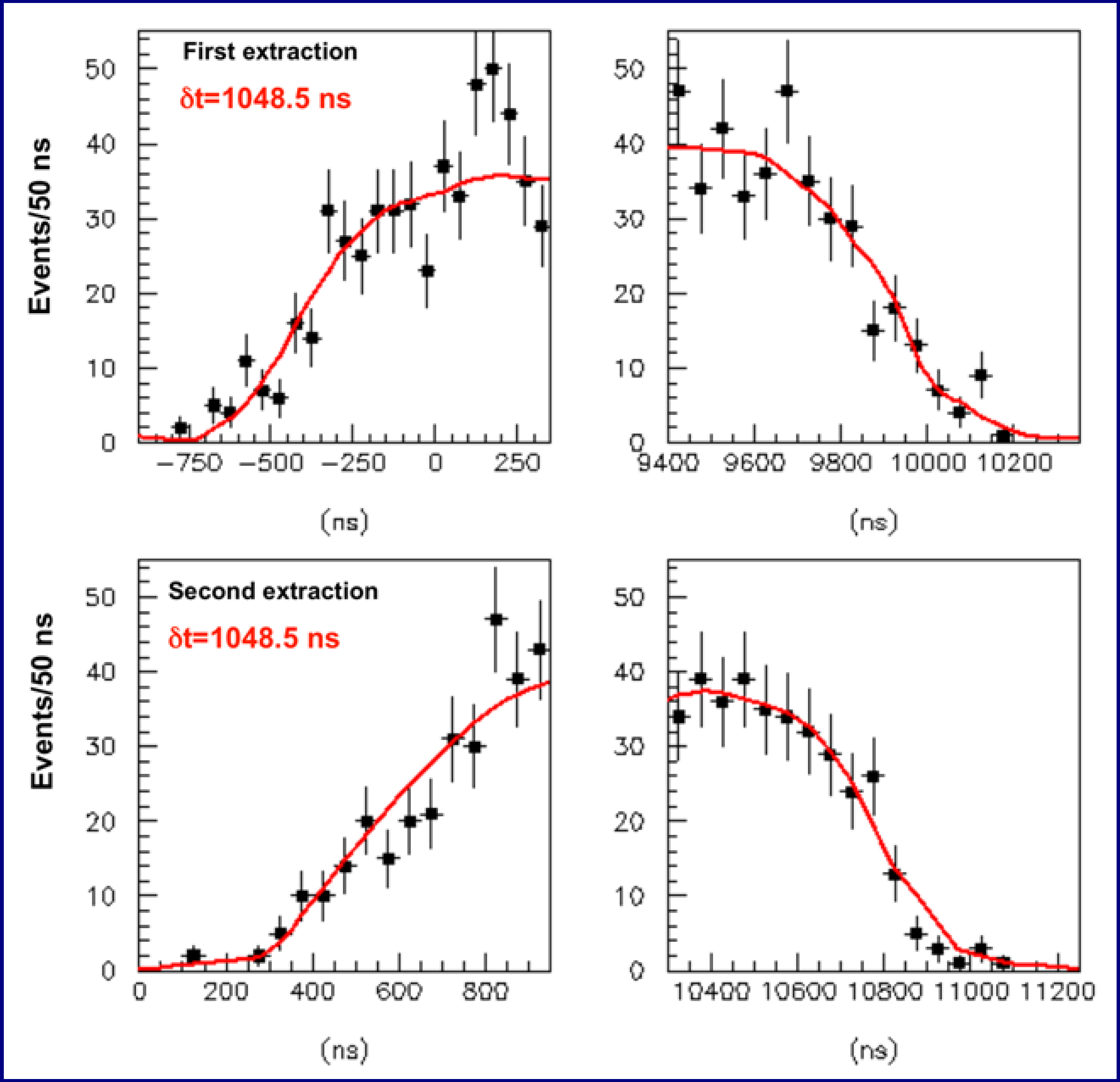
(BLIND) $\delta t = TOF_c - TOF_\nu$ =

(1048.5 ± 6.9) ns (stat)

χ^2 / NDF :

first extraction: 1.06
second extraction: 1.12

Zoom on the extractions leading and trailing edges



Preliminary:

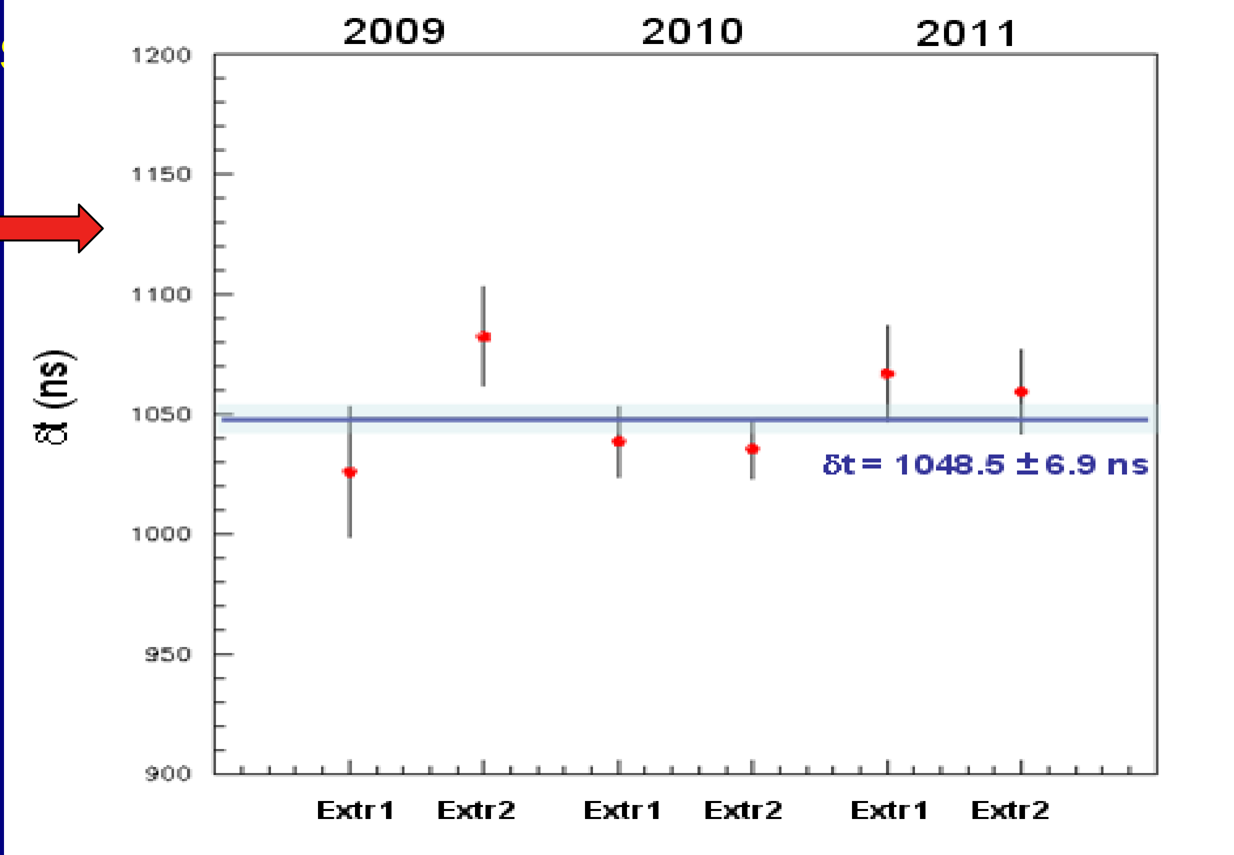
$\chi^2 / NDF = 78.4/79$

For ν arriving $50\,ns$ later

$\chi^2 / NDF = 111.1/79$

Analysis cross-checks

1) Coherence among CNGS runs/extractions



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

|day -night|: (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

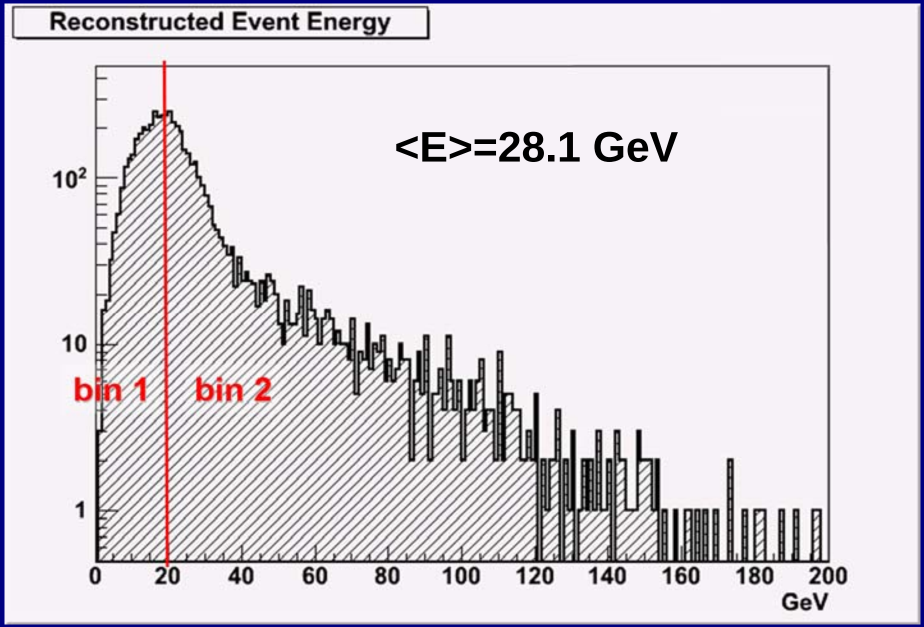
relative difference of neutrino velocity w.r.t. *c:*

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

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

6.0 σ significance

Study of the energy dependence



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

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

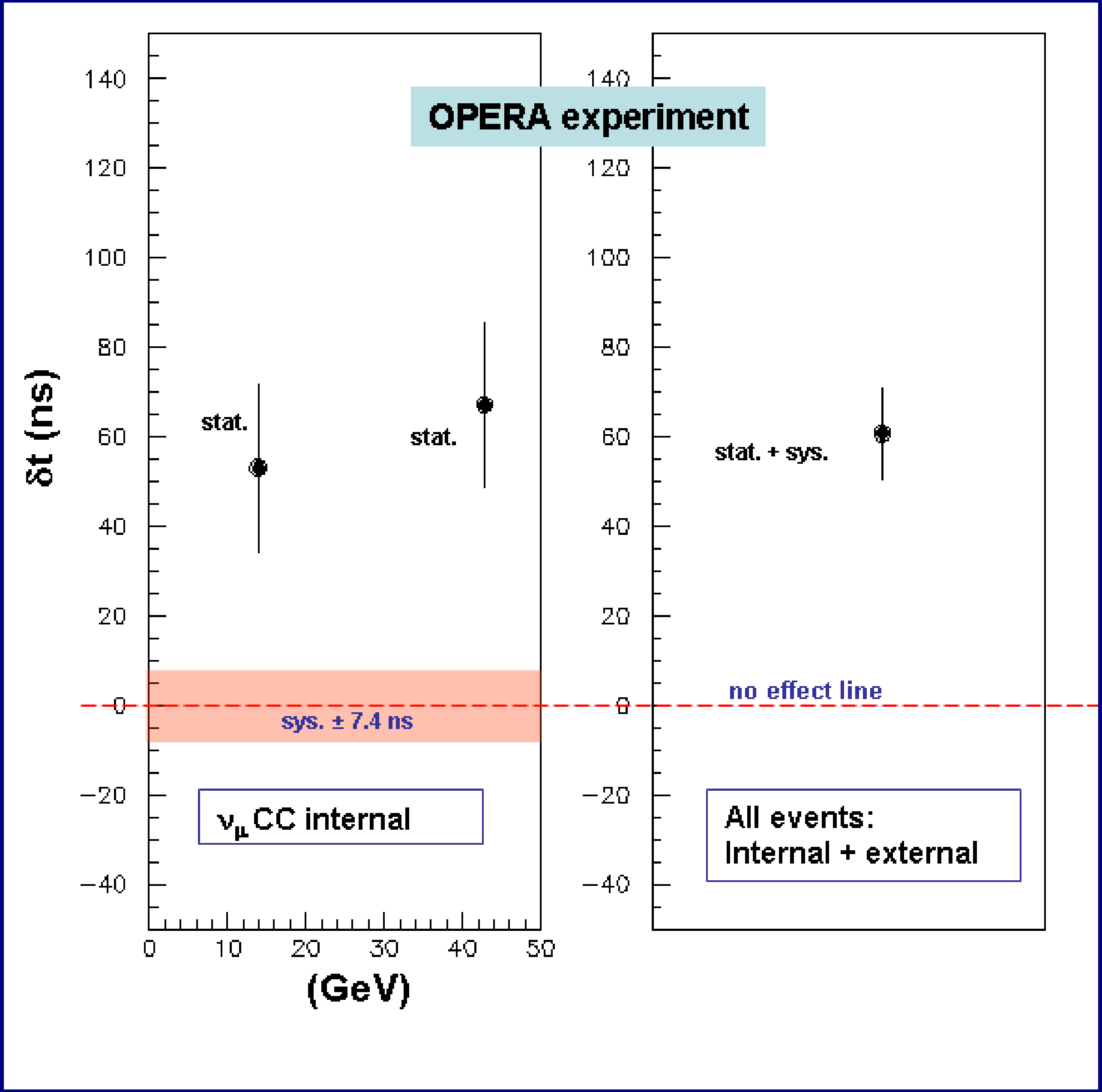
• Full MC simulation: no energy bias in detector time response (<1 ns)

→ 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:

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

• 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.

• For the same reasobn, we do not attempt any theoretical or phenomenological interpretation of the results.

As of 5/10/2011@ 11:35
55 preprints (mostly theoretical) deposited on the arXiv repository:
• Why the measurement is certainly wrong, is certainly not wrong.
• Simple explanations (physical, instrumental) of the measurement.
• Unconventional neutrino physics, models beyond special relativity and Lorentz invariance: extra-dimensions, quantum foam, …

Thank you for your attention

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

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

Effect of index of refraction in the Earth crust

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

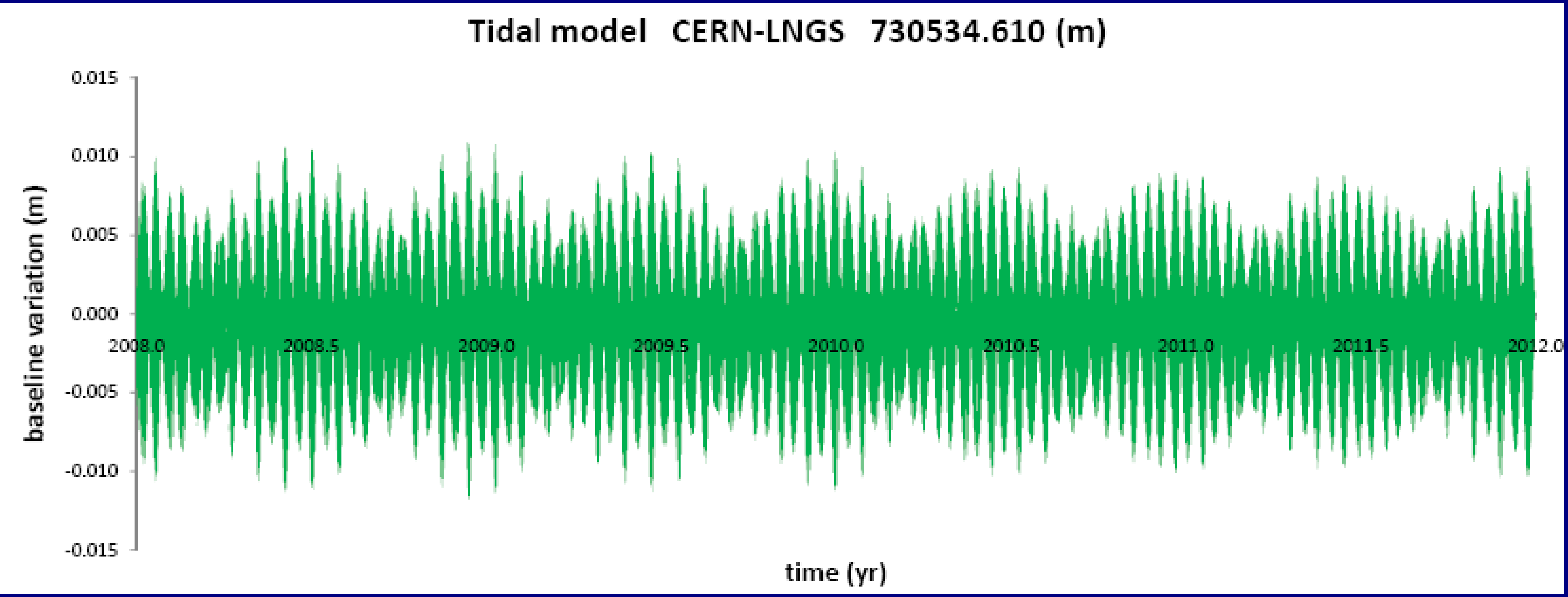
Both effects are unmeasurable by many orders of magnitute

Small effects under final estimation

Tidal effects

Effect smaller then $\mathbf{10}\ \boldsymbol{cm}$

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



Other small effects under final estimation

General relativity, composition of movements in non inertial frames

All effects evaluated by a team of general relativity experts.

Negligible effects apart for $\mathbf{4}\ \boldsymbol{ns}$ Sagnac effect on neutrino trajectory (Earth rotation):

$\Rightarrow$ slightly increases the neutrinos anticipation because Gran Sasso is East of Geneva.

Effect of rotation around the Sun is almost inertial and negligible.

Effects due to difference in altitude between Geneva and Gran Sasso negligible.

Beam related systematic

Temperature increases from $\mathbf{700}\boldsymbol{K}$ to $\mathbf{1000}\boldsymbol{K}$ from start to end of each extraction.

Effect of the thermal dilatation of the target during the spill under investigation $(\ll \mathbf{2}\boldsymbol{ns}$ to $< \mathbf{2}\boldsymbol{ns})$

$\Rightarrow$ Compute δt for low and high intensity beams.

Possible dis-uniformities on the current pulsing the horns under investigation$(\sim \mathbf{2}\ \boldsymbol{ns})$.

One example of a follow-up paper among many

On the Possibility of Superluminal Neutrino Propagation

Jean Alexandre[1], John Ellis[1,2] and Nick E. Mavromatos[1,2]

[1] Department of Physics, King's College London, Strand, London WC2R 2LS, UK
[2] Theory Division, Department of Physics, CERN, CH 1211 Geneva 23, Switzerland.

SUMMARY AND PROSPECTS

The report from OPERA of superluminal neutrino propagation is very surprising, and it may well not survive further scrutiny. Moreover, as we have shown in the earlier part of this paper, it is subject to constraints from studies of lower-energy neutrinos, specifically those emitted by SN1987a [2], and would have implications for higher-energy astrophysical neutrinos. In particular, we have argued that the SN1987a data exclude a 'conventional' Lorentz-invariant tachyonic neutrino interpretation of the OPERA data. On the other hand, as we have shown through the toy models presented in the latter part of this paper, it is possible to construct Lorentz-violating theories in which neutrinos travel faster than photons, which always travel at c. We have exhibited such models in which the superluminality either increases or decreases with energy. Superluminal neutrinos should not be discarded as a phenomenological impossibility, but rather regarded as a scenario to be probed and constrained by experiment. In particular, we have shown that the effect could depend on the orientation of the neutrino beam, and could be of opposite sign for antineutrinos. For the moment, the OPERA measurement provides a stimulus for investigating such scenarios, but Lorentz-violating superluminal fermion propagation should not necessarily be discarded out of hand, even if the OPERA result were not to be confirmed.

Nobel laureate Samuel Ting of the Massachusetts Institute of Technology in Cambridge:
"I want to congratulate you on this extremely beautiful experiment. The experiment is very carefully done, and the systematic error carefully checked;"

Many criticisms on the accuracy of the GPS measurements received from non-expert in the HEP physics community. What do experts say ?

Swiss (METAS) and German (PTB) have realised and certified the time synchronisation.

CERN survey group and Roma La Sapienza Geodesy group have realised and certified the baseline measurement.

No negative comment received from this community.

Royal Observatory of Brussels has developed the concept of “Common View Mode” for time transfer and the bi-frequency PolaRx2eTR receivers with firm Septentrio. ROB and Septentrio express that proud of the crucial role they plaid in this measurement:

http://www.astro.oma.be/EN/hotnews/index.php

http://www.astro.oma.be/GENERAL/INFO/hotnews/OPERA_fr.pdf

http://www.septentrio.com/news/press-releases/septentrio-receivers-feature-cern-experiment-measure-%E2%80%9Cfaster-light%E2%80%9D-neutrinos

Le Monde.fr

Editorial

Le doute scientifique, une attitude exemplaire

Article paru dans l'édition du 25.09.11

C'est une belle leçon de morale que viennent d'administrer les chercheurs du CNRS et du CERN, l'organisation européenne pour la recherche nucléaire, qui est aussi le plus grand laboratoire de physique du monde. Après avoir découvert, dans le cadre d'une expérience baptisée « Opera », que des particules pouvaient voyager plus vite que la lumière, l'équipe de physiciens a passé six mois à tenter de trouver une faille à cette découverte. L'enjeu est de taille : si les résultats de ces travaux sont confirmés, ils mettront à bas la théorie classique de la relativité restreinte d'Albert Einstein, loi centrale de la physique depuis 1905.

Confrontés à des résultats qui bousculent la confortable routine des certitudes, les physiciens associés à cette expérience auraient pu garder leurs travaux pour eux. Ils ont choisi la démarche inverse. Vendredi 23 septembre, ils ont publié les résultats de leurs recherches, exposant de la manière la plus ouverte les détails de leur expérience et ses données brutes.

Amenés à mettre en doute la validité d'un principe cardinal de la physique, ils offrent ainsi à la communauté scientifique tous les moyens de mettre à son tour en doute, méthodiquement, le fruit de leurs travaux. Ils s'exposent, volontairement, à la critique de leurs pairs. Au cours de ce processus, qui pourra être orageux, les arguments des uns et des autres seront entendus ; de nouvelles expériences seront sans doute menées ou imaginées, pour trancher la question. Peu à peu se dégagera un consensus, et la science en sortira plus forte, ouvrant ou non la voie à de nouvelles théories capables de mieux décrire les lois de la nature. Les « neutrinos supraluminiques » - nom de ces particules fondamentales furtives - du laboratoire souterrain de Gran Sasso, en Italie, où ont eu lieu les mesures de la vitesse de leur propagation, seront peut-être à l'origine d'une nouvelle aventure pour la science. Dans l'immédiat, ils sont surtout le symbole de la soif de savoir des communautés scientifiques, et de leur volonté de se libérer des convenances sociales, idéologiques ou économiques. Du scepticisme comme antidote à l'arrogance.

Scandales sanitaires, expertises défaillantes, corruption et conflits d'intérêts ont, depuis plusieurs années, terni l'image des scientifiques auprès du grand public. Ce qui se produit actuellement dans la communauté des physiciens est, au contraire, une remarquable manifestation de l'intégrité de la démarche scientifique.

Cette démarche a parfois été détournée par les conflits d'intérêts. Elle a pu être instrumentalisée pour créer délibérément le doute, à des fins industrielles ou commerciales - sur la nocivité du tabac, de l'amiante, du Mediator, ou sur la réalité du changement climatique. Les faits eux-mêmes finissent le plus souvent par s'imposer. Il ne reste rien, aujourd'hui, de la fusion froide ou de la mémoire de l'eau. En ces temps de double crise mondiale, économique et écologique, on ne peut que souhaiter aux économistes de s'inspirer, de l'extraordinaire liberté d'esprit des physiciens.

Portable Cs clock calibrations (1) Time tagging

Start time tagging device

UTC distribution

End time tagging device

1PPS

Time-stamp
xx ns

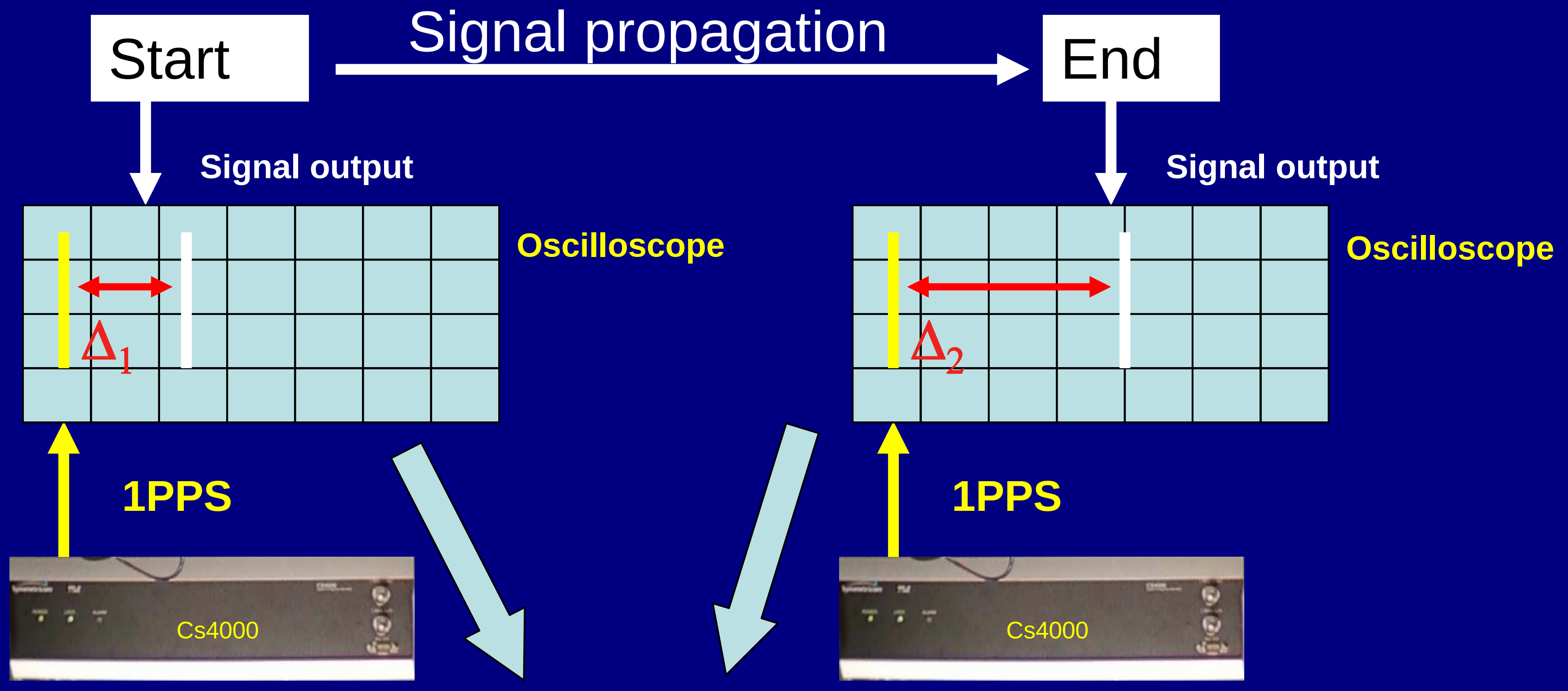
Time-stamp
yy ns

1PPS

Δ = yy -xx

UTC propagation delay

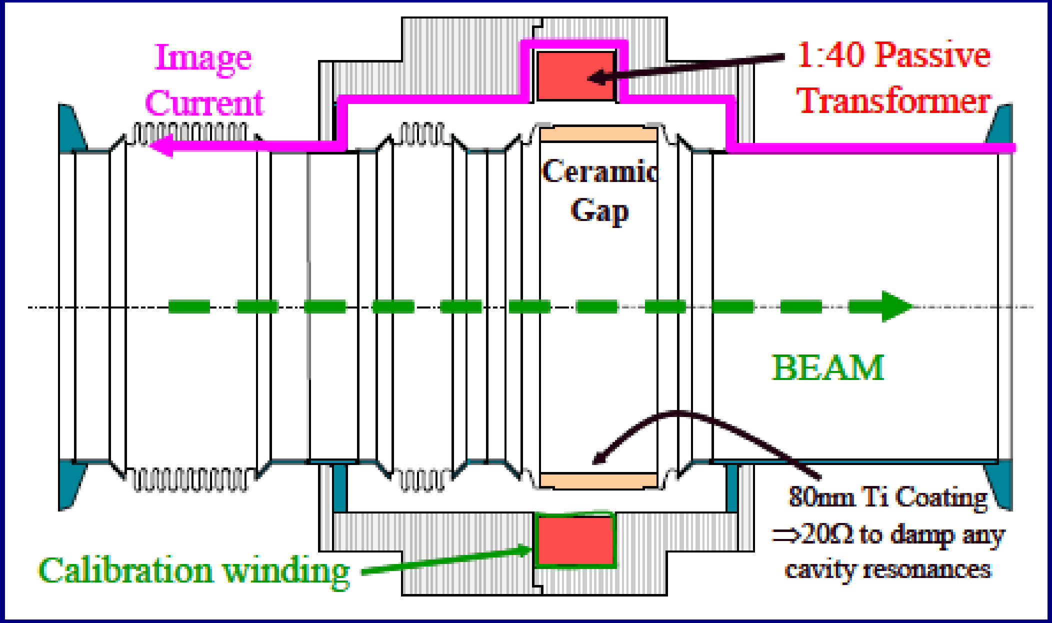
Portable Cs clock calibrations (2) Delay measurement



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

Propagation delay

Beam Fast 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)

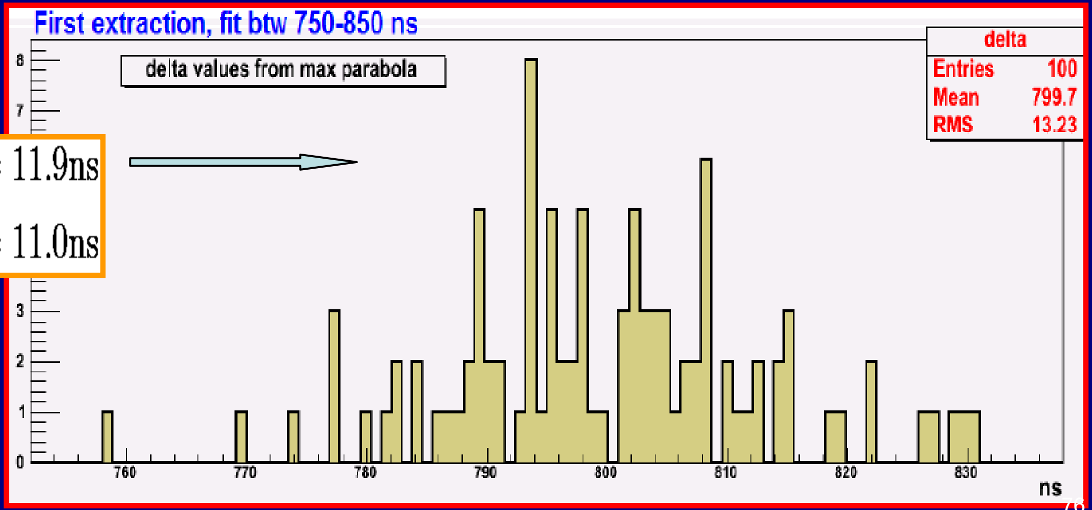
Simulated data shifted in time by a constant quantity faking a time of flight deviation.

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.

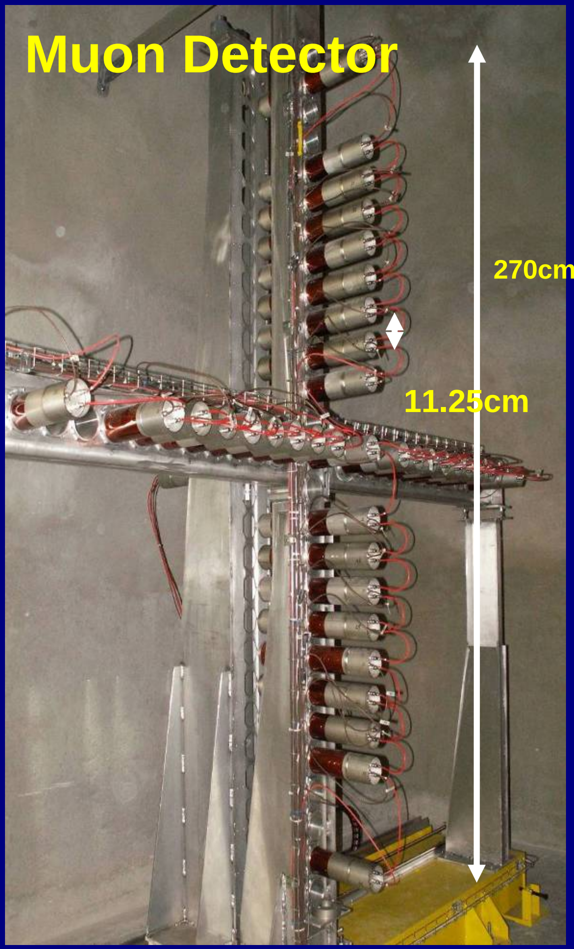
✓Average statistical error extracted from the likelihood analysis also reproducing the RMS distribution of the mean values.

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

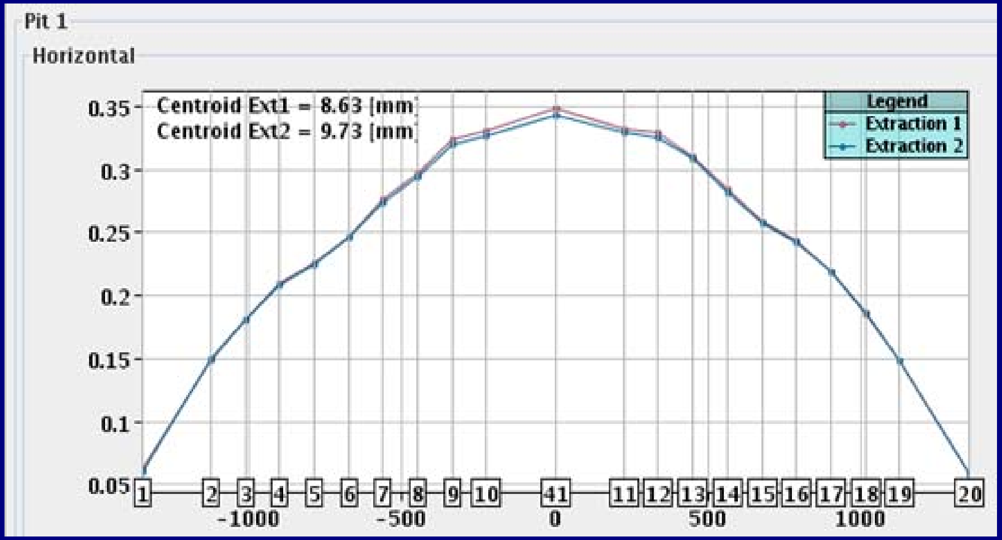


– Offset of **target vs horn** at 0.1mm level
  - Target table motorized
  - Horn and reflector tables not

→ Muon Profiles Pit 1

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

→ Muon Profiles Pit 2

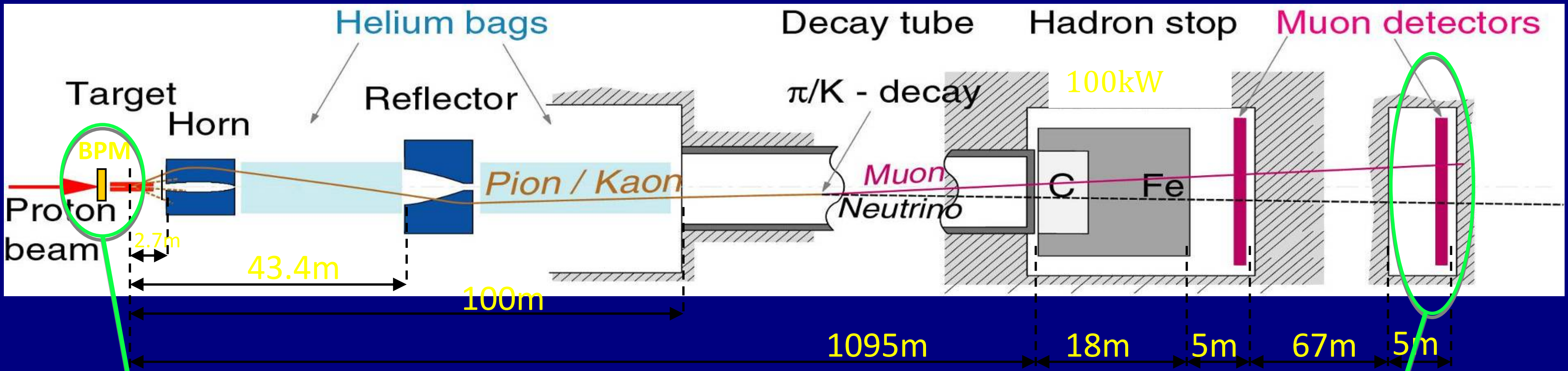


Centroid = $\sum(Q_i * d_i) / \sum(Q_i)$

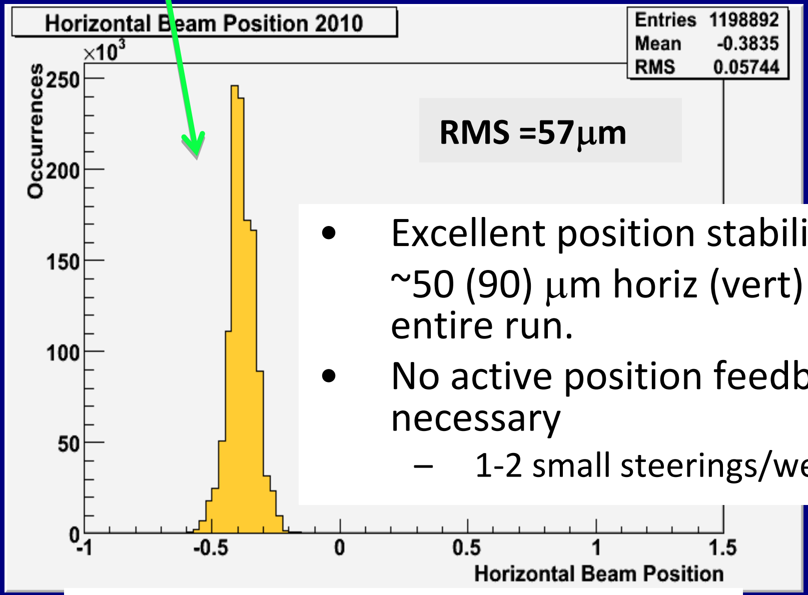
Q_i is the number of charges/pot in the i-th detector,

d_i is the position of the i-th detector.

Beam Stability



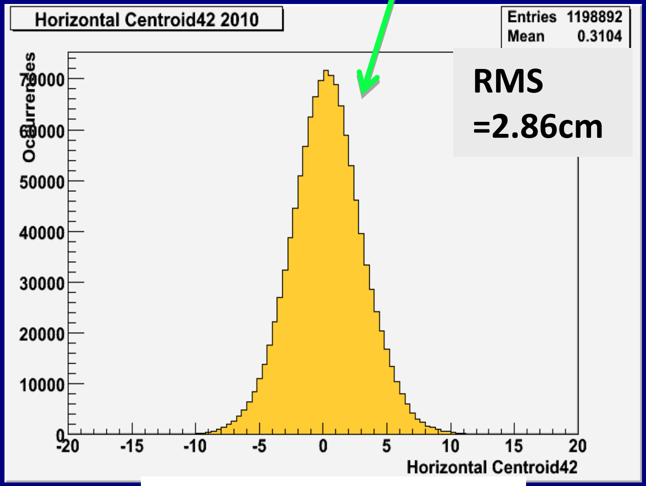
→ Beam position on target



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

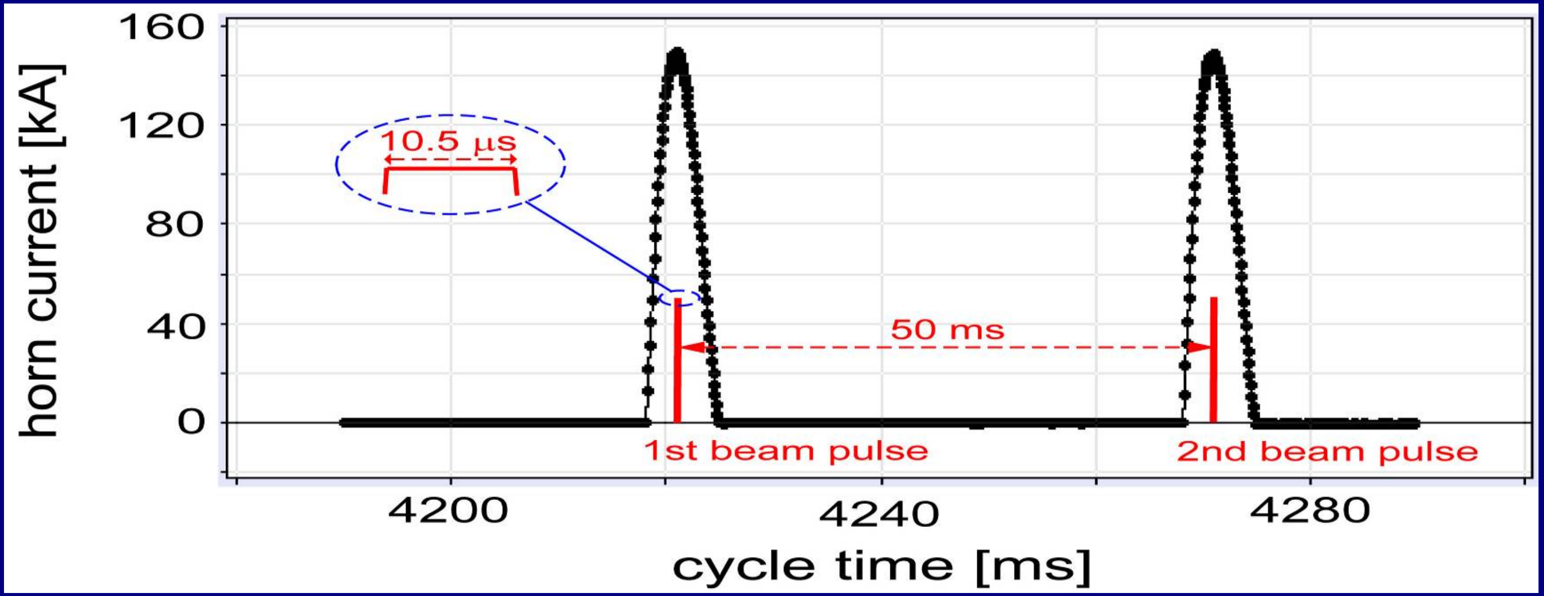
Horizontal beam position on target

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



Horizontal centroid

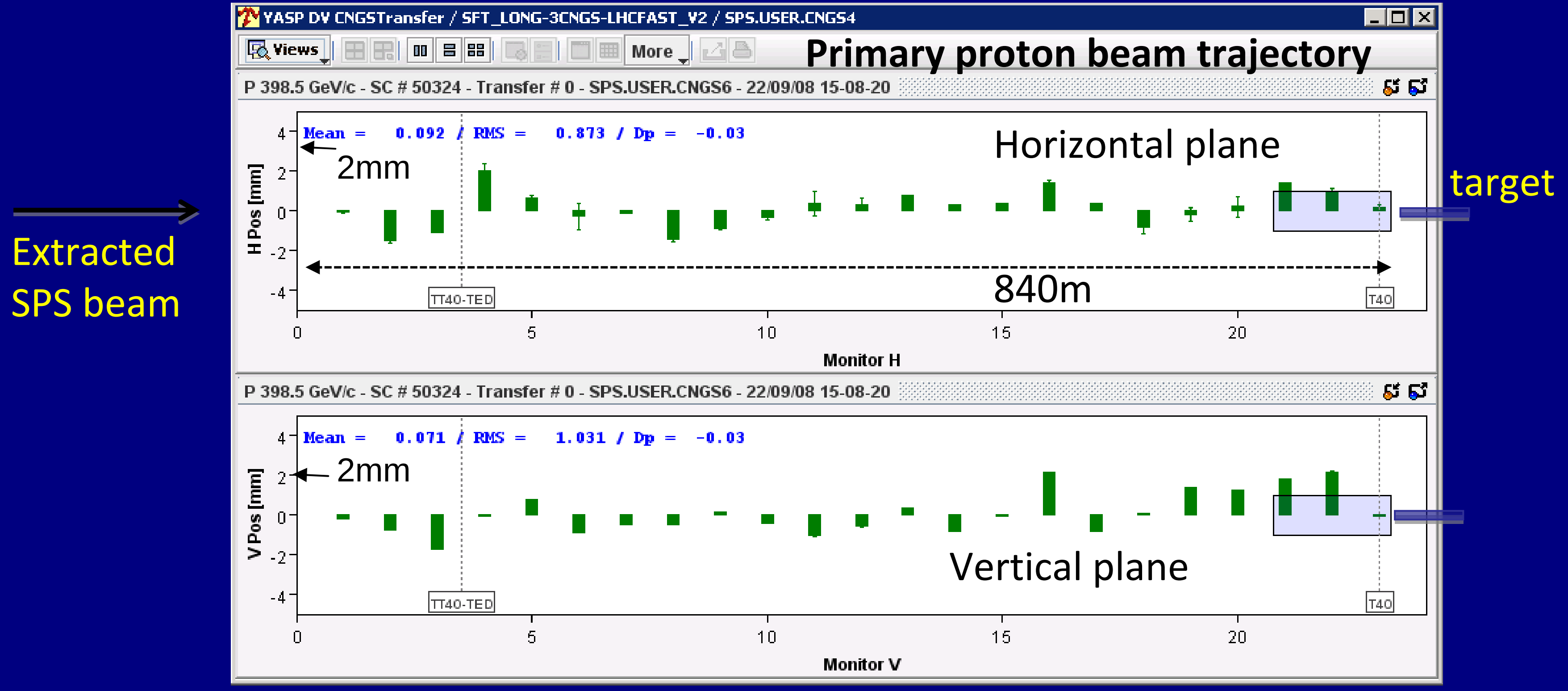
Horn/Reflector Power System



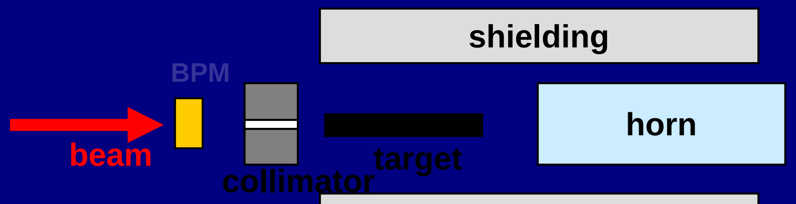
	Unit	HORN	REFLECTOR
Load Peak current	kA	150	180
Pulse duration	ms	6.5	9.8
Transformer ratio		16	32
Primary peak current	A	9375	5646
Charging voltage	V	6300	5800
Water flow for delta T=5C	l/min	75	48
Pressure	bar	1.2	1.2

CNGS Primary Beam

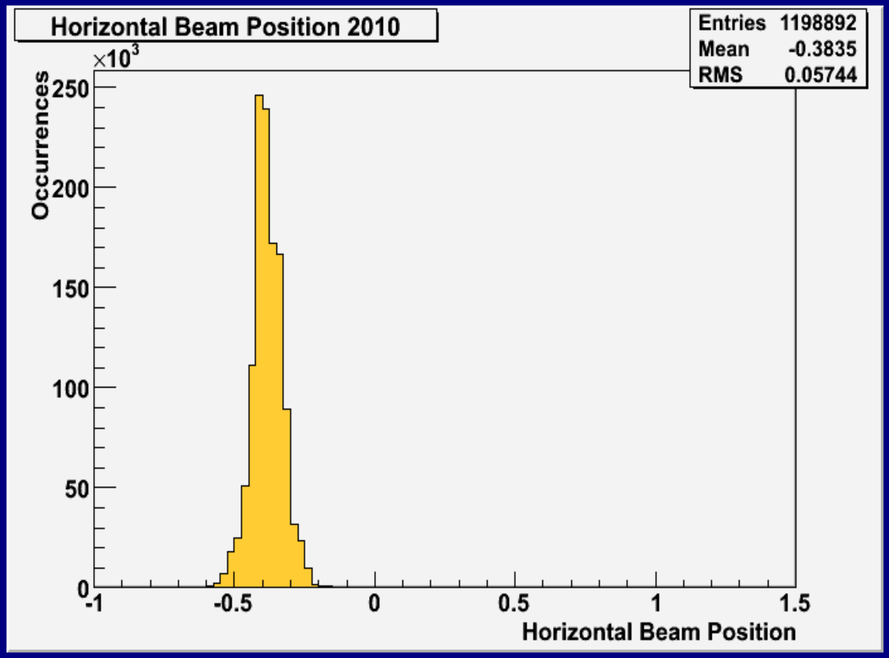
- Extraction interlock modified to accommodate the simultaneous operation of LHC and CNGS
  - Good performance, no incidents
- No extraction and transfer line losses
- Trajectory tolerance: 4mm, last monitors to +/-2mm and +/- 0.5mm (last 2 monitors)
  - Largest excursion just exceed 2mm

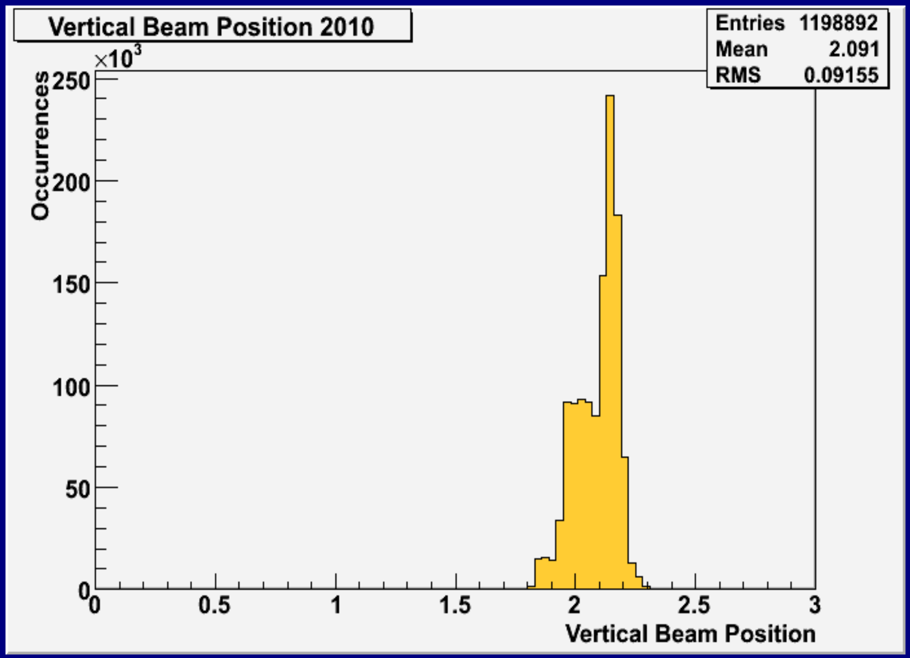


Beam Position on Target



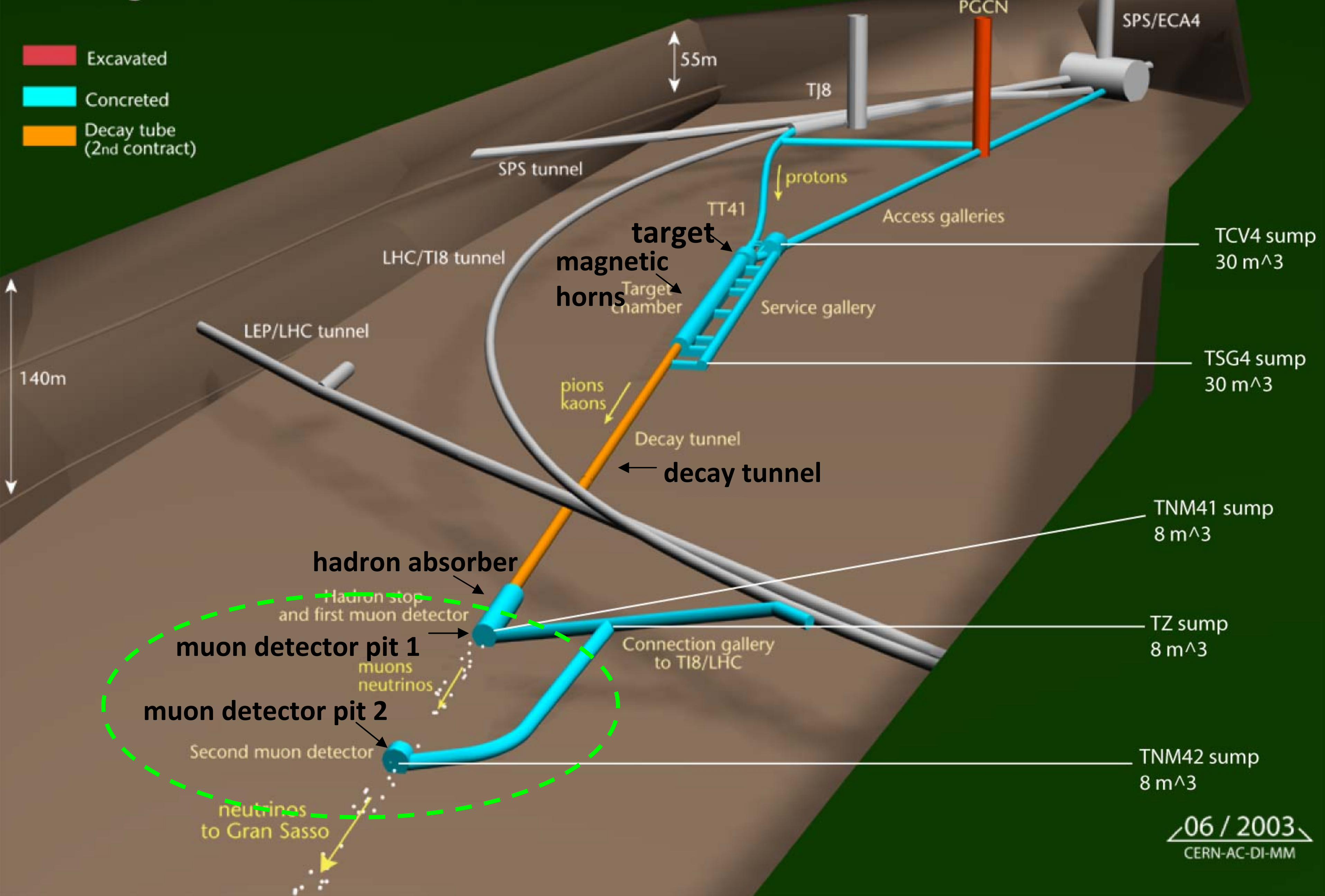
- Excellent position stability; ~50 (90) μm horiz (vert) over entire run.
- No active position feedback is necessary
  - 1-2 small steerings/week only





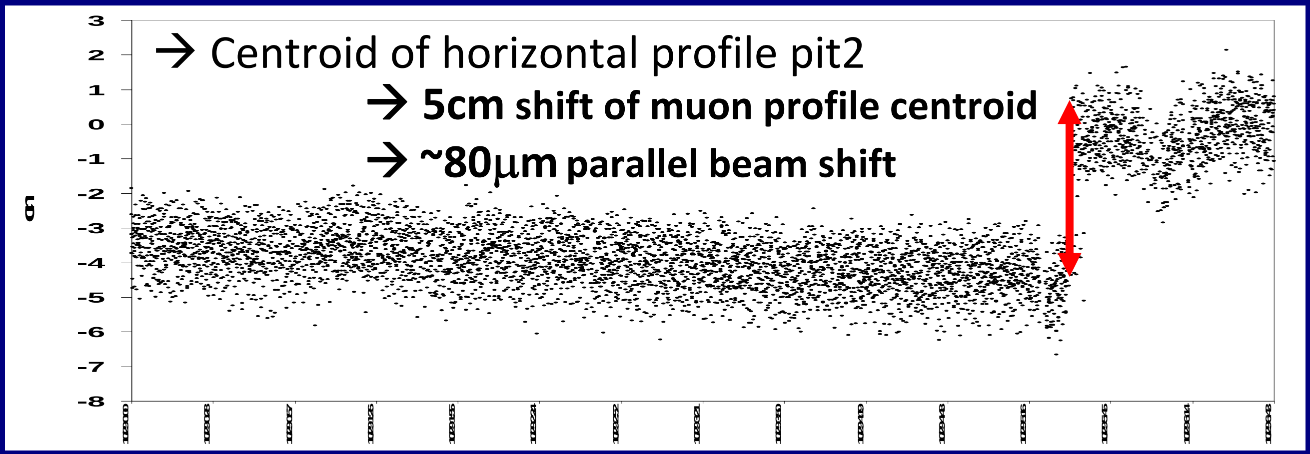
Horizontal and vertical beam position on the last Beam Position Monitor in front of the target

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

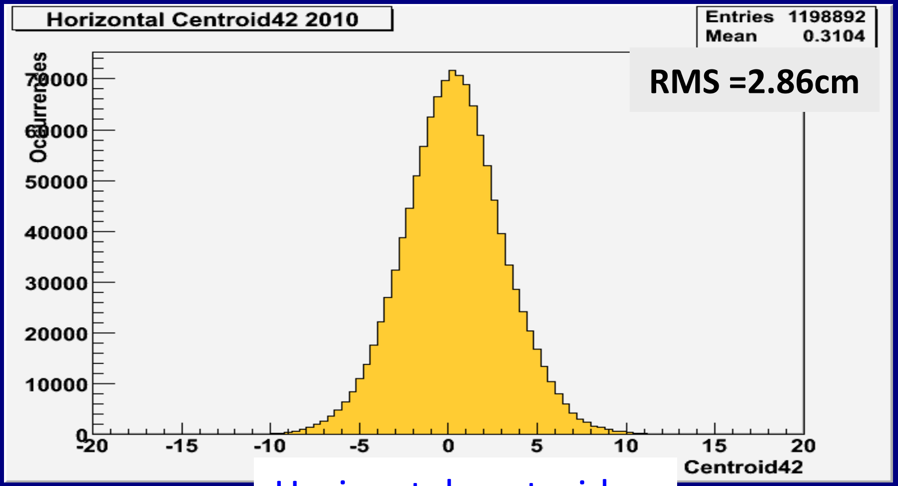


Beam Stability Seen on Muon Monitors

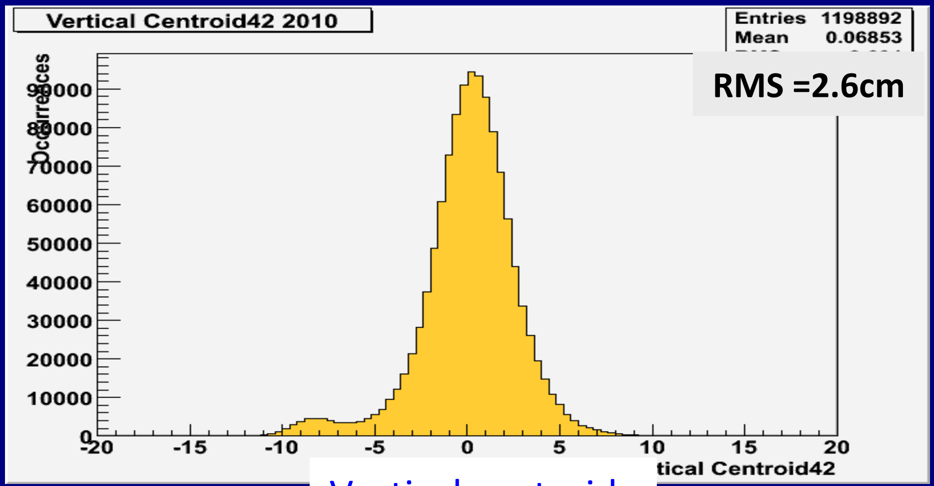
- Beam position correlated to beam position on target.
  - Parallel displacement of primary beam on T40



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

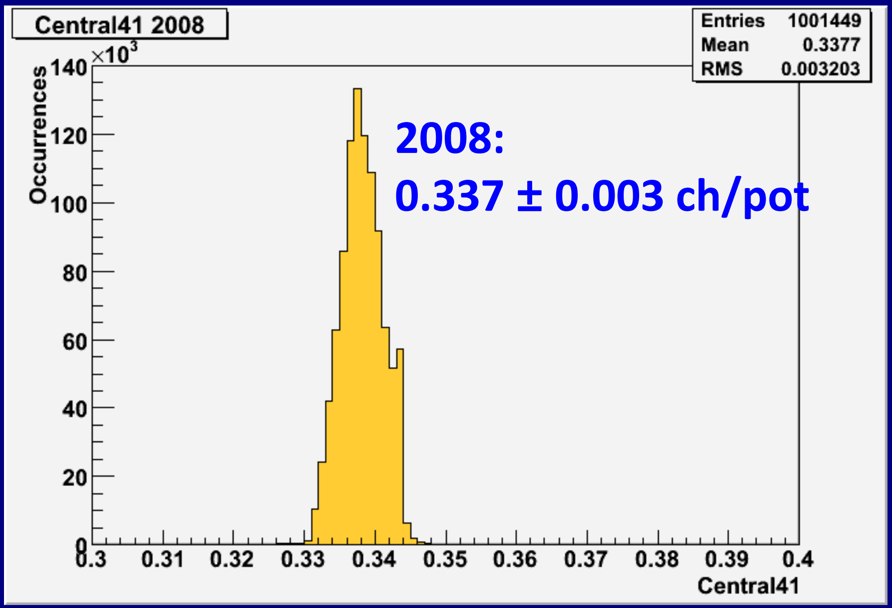


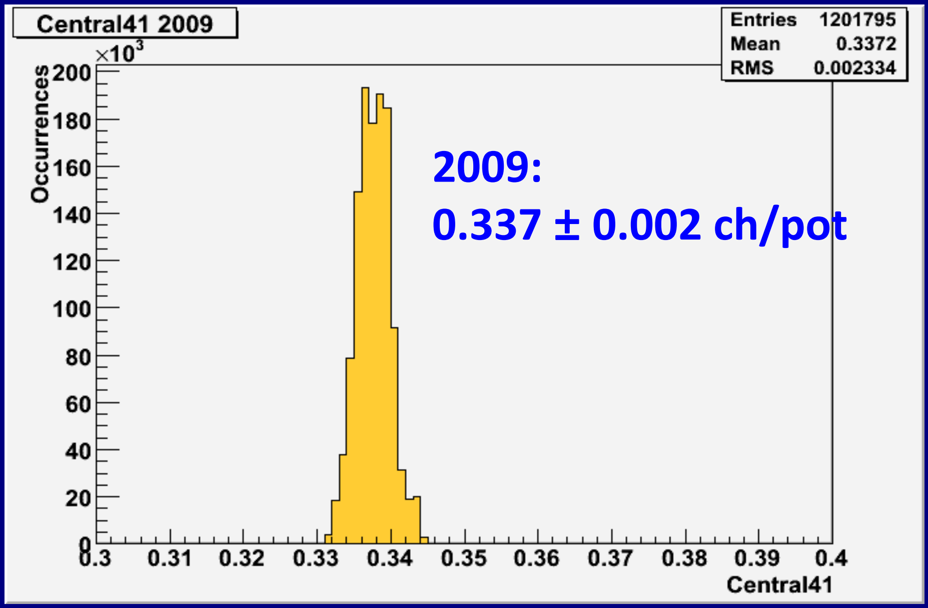
Horizontal centroid

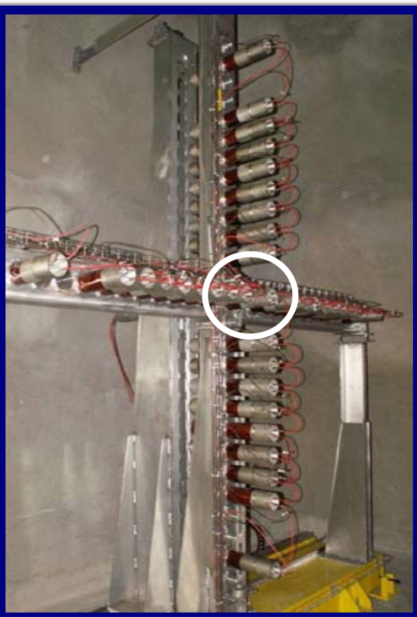


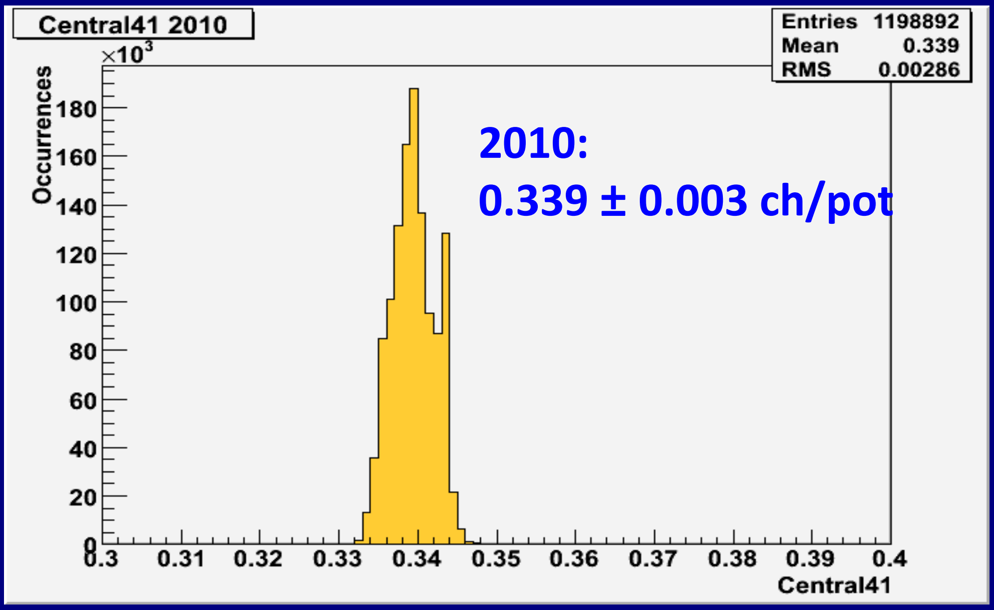
Vertical centroid

Central Muon Detector Stability, 1st Pit







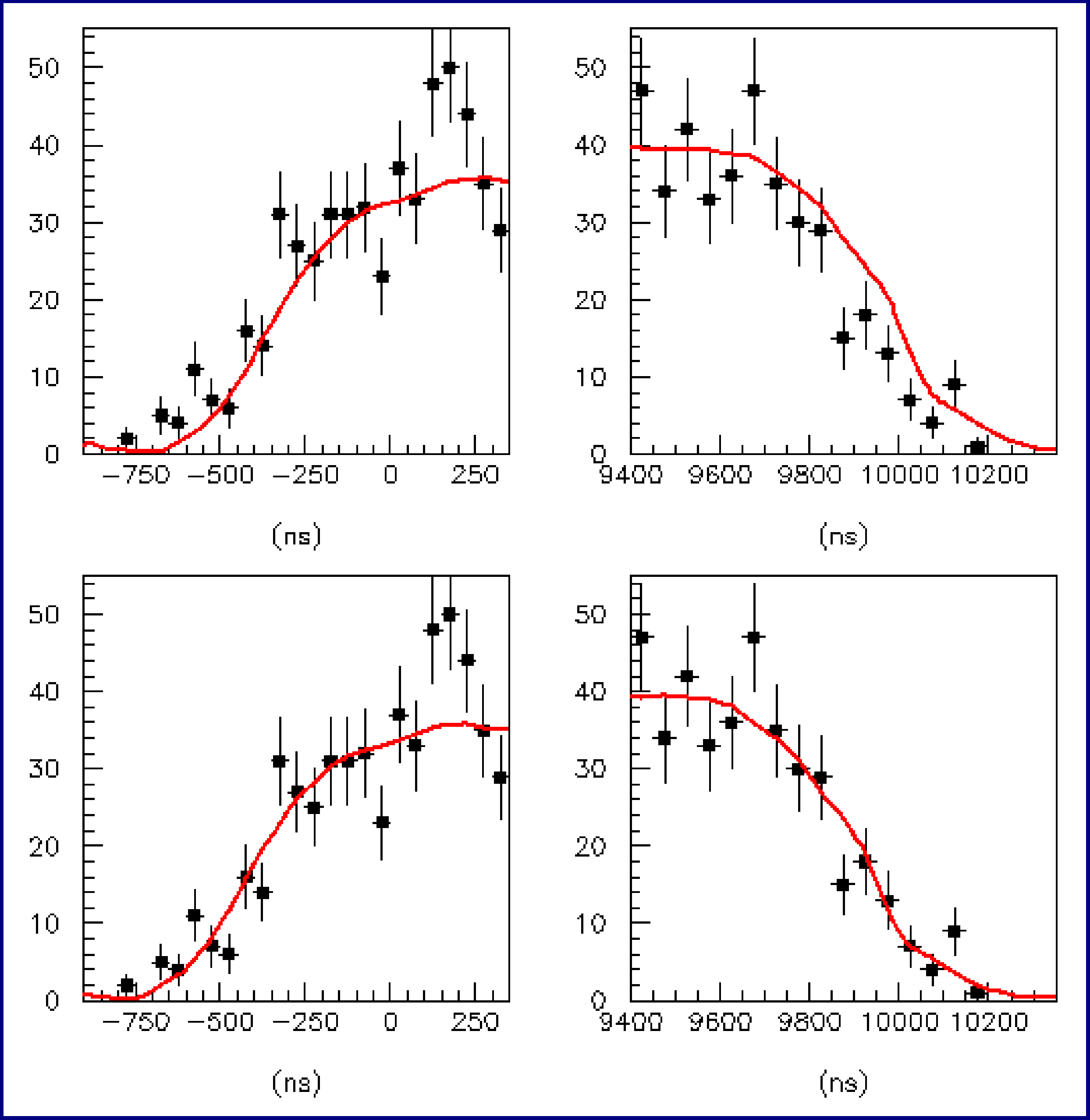


Zoom on the extractions leading and trailing edges

Extraction 1

δt = 0 ns

δt = 60.7 ns

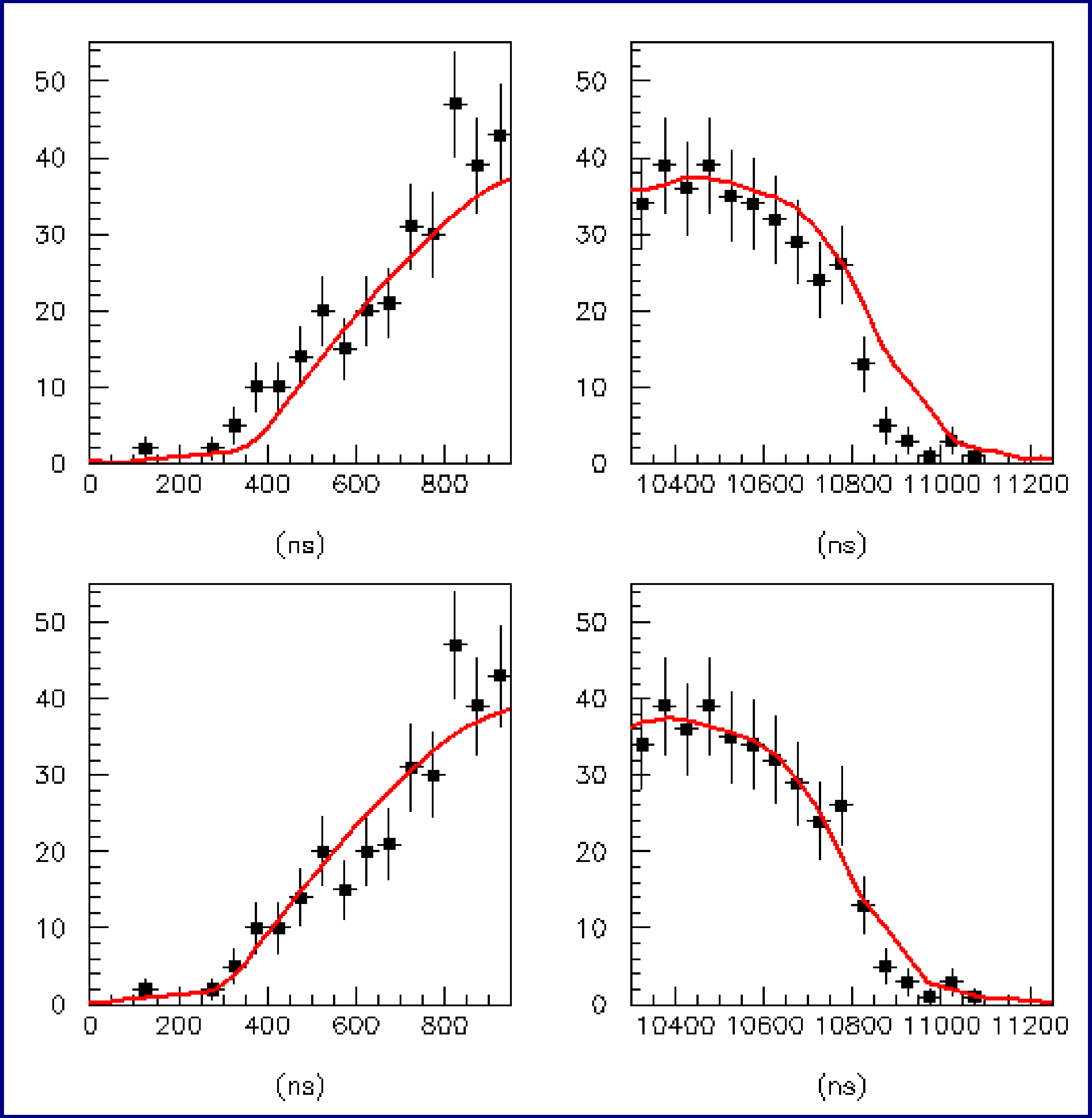


Zoom on the extractions leading and trailing edges

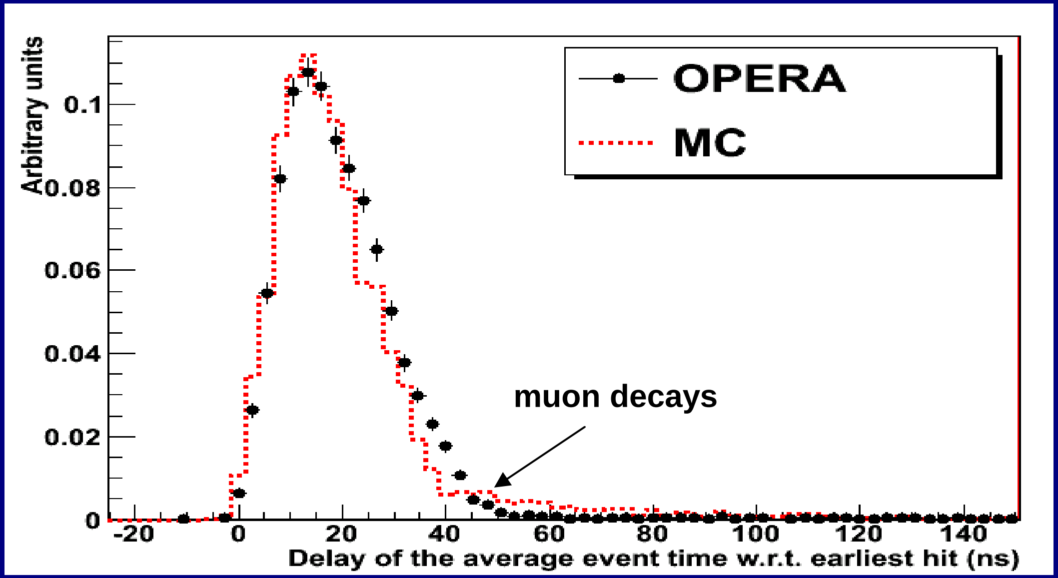
Extraction 2

δt = 0 ns

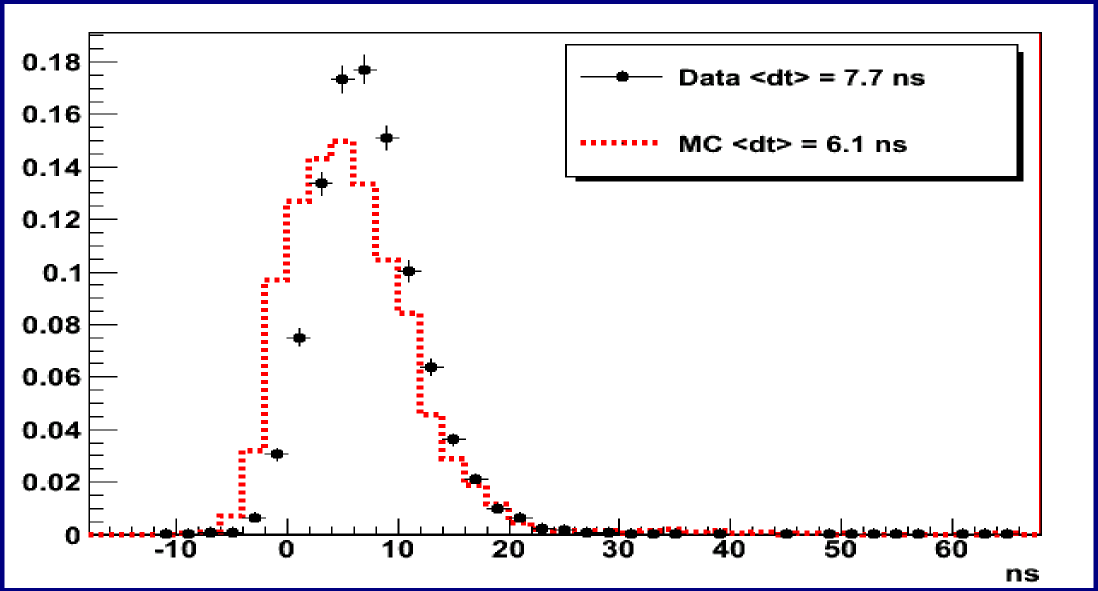
δt = 60.7 ns



Data/MC agreement for earliest hit timing



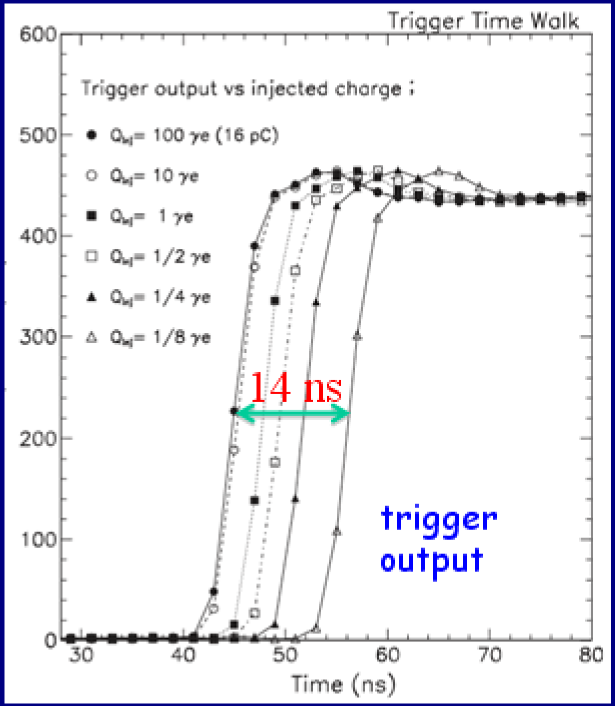
DATA vs MC
Earliest hit vs average event time (z corrected)



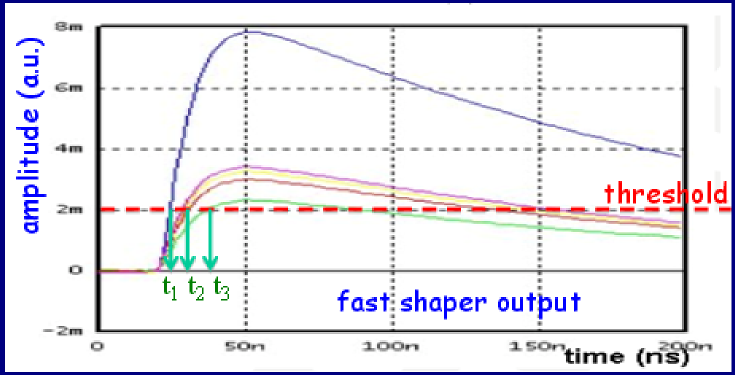
DATA vs MC
Earliest hit vs average muon track time
(z corrected)

Target Tracker simulation

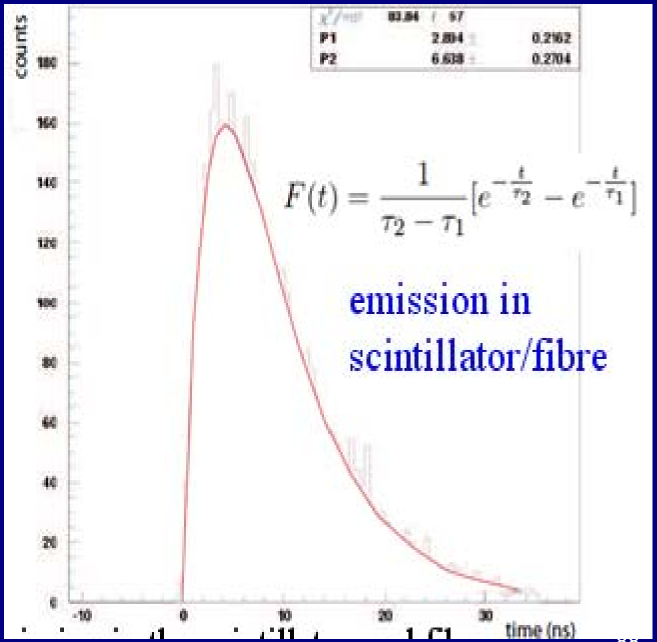
Full GEANT simulation of detector response with detailed geometry and time response parameterization from experimental measurements



Trigger threshold time walk



Arrival time distributions of photons on the photocathode



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