OPERA results on neutrino oscillations, cosmic rays and neutrino velocity

G. Rosa – Rome, Oct. 11th 2011
Dept. Of Physics – Sapienza University

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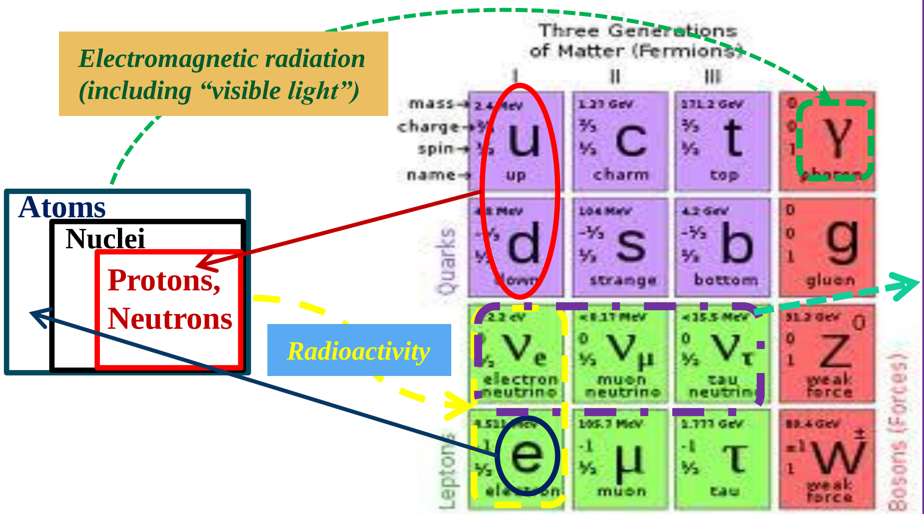
Why physicists care so much about *neutrinos* ?



Neutrino Physics

Past decades:

- **Key particles to understand “radioactivity” and build-up the elctroweak theory**
- **Basic building-blocks of matter, 3 “lepton flavours” detected**
- **Not quite “elementary”, they MIX and thus they have (tiny) mass (*Neutrino Oscillations*)**

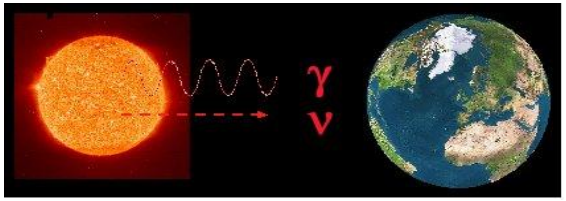
Present issues:

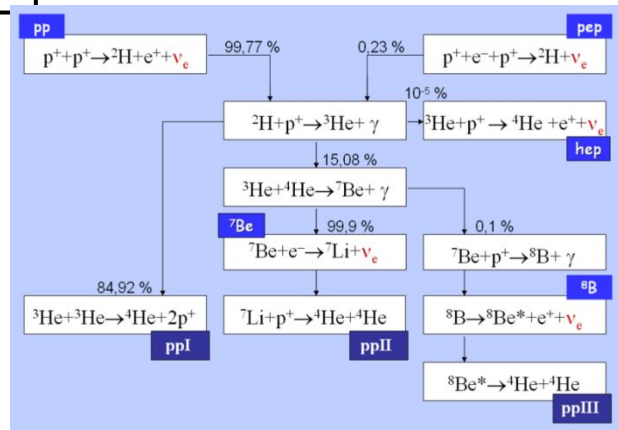
➔ **Unique probes of fundamental processes** ***(“beyond the Standard Model”)***

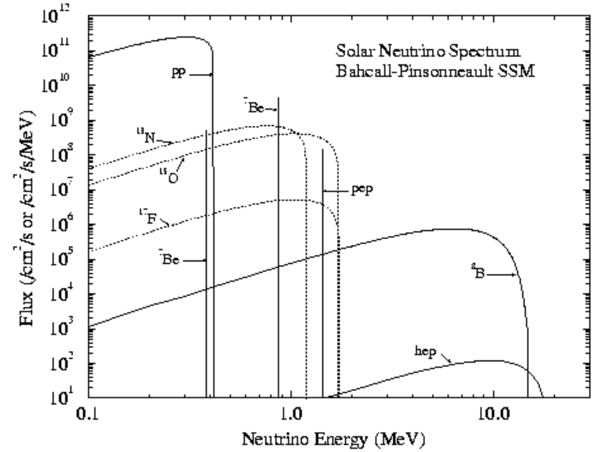
➔ **Messangers of the deep-inside stars (and planets) and early-stage collapsing objects (e.g. supernovae); relics of the primordial universe (*Solar model, Astrophysics, Geoneutrinos, Cosmology , dark matter?*)**

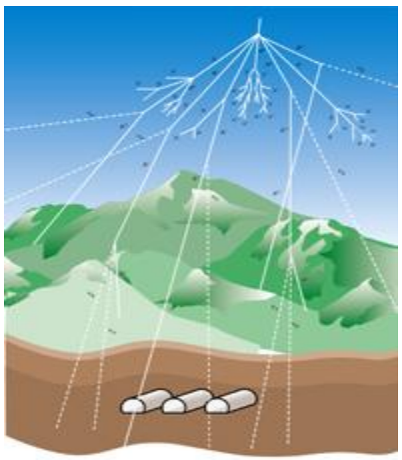
➔ **Properties still unknown: all mixing parameters, mass, mass hyerarchy, Dirac/Majorana nature, CP-violation, any “sterile” partner…**

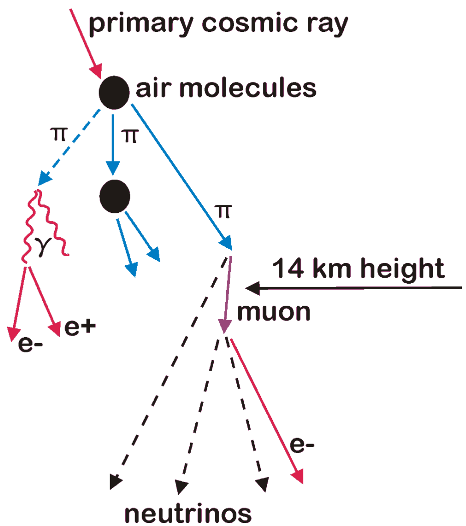
Natural neutrino sources…

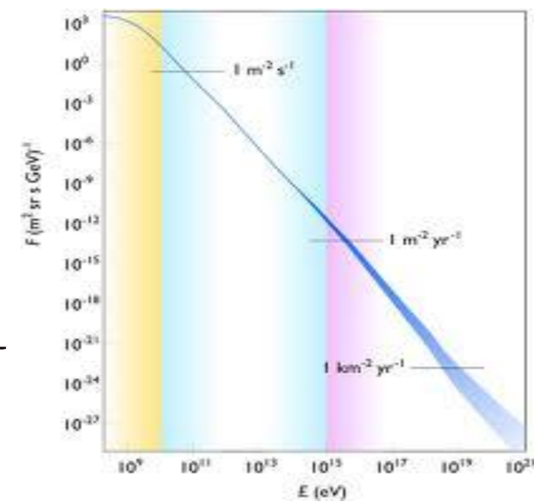












…"Also":

Supernova Neutrinos (~10 MeV)

Relic "Big-Bang" Neutrinos (250 meV)

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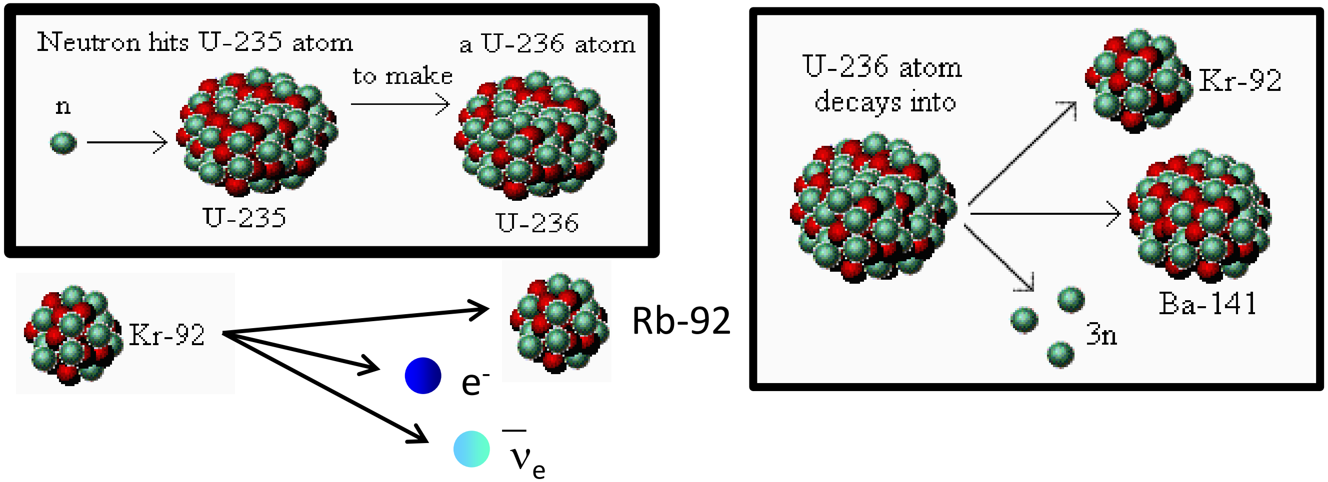
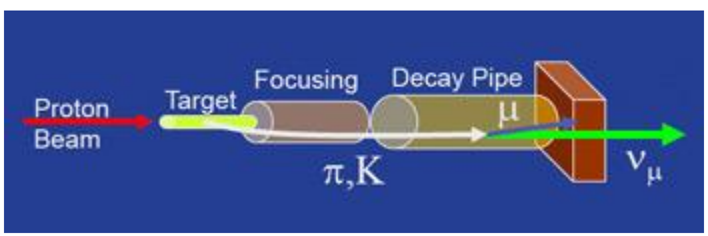
…and artificial neutrino sources

Nuclear reactors



- Reactors = only source of a pure anti-neutrino beam, pure electron-flavor beam!
- Anti-neutrinos are emitted by the radioactive fissile products when they disintegrate via beta decay (~few MeV Energy)

Accelerators



Main process: $\pi, K \rightarrow \mu + \nu_\mu$
ν_e contamination from muon decay & K

…A price to pay to "enjoy" neutrinos: HUGE detectors needed!...

3x3 Unitary Mixing Matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

…e.g. ν mixing & "oscillations"

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric terms | Unknown terms | Solar terms

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

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OPERA: first direct detection of neutrino oscillations in ν_τ appearance mode

following the Super- Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams.

The PMNS 3-flavor oscillation formalism predicts:

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2(\Delta m^2_{23} L/4E)$$

Requirements:

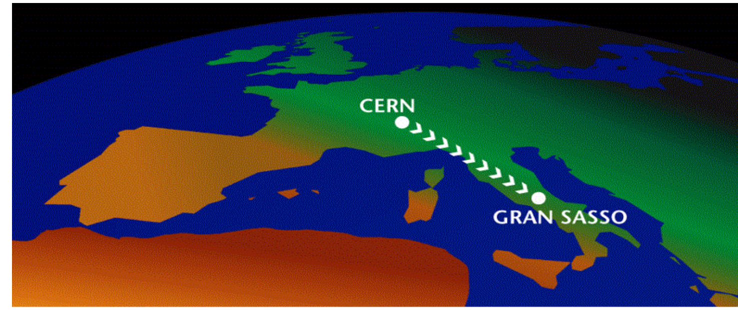
1) ~"pure" ν_μ beam, 2) long baseline, 3) high neutrino energy, 4) high beam intensity, 5) detect short lived τ's

Oscillation Project with Emulsion tRacking Apparatus

Provide a direct evidence of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

look for ν_τ appearance in a pure ν_μ beam

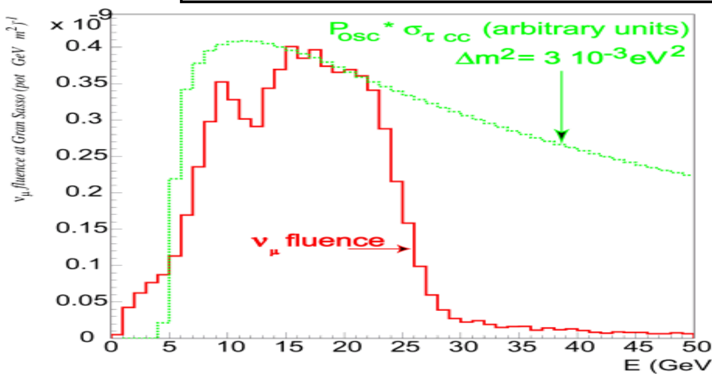
beam: **CNGS**



$<E\nu_\mu>$	17 GeV
$(\nu_e+\bar{\nu}_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu$ / ν_μ	2.1%
ν_τ prompt	negligible

At the given distance (732 Km), ν_μ flux optimized to maximize the ν_τ charged current interactions
<L/E> = 43 Km/GeV

"hybrid" detector with **ECC target**



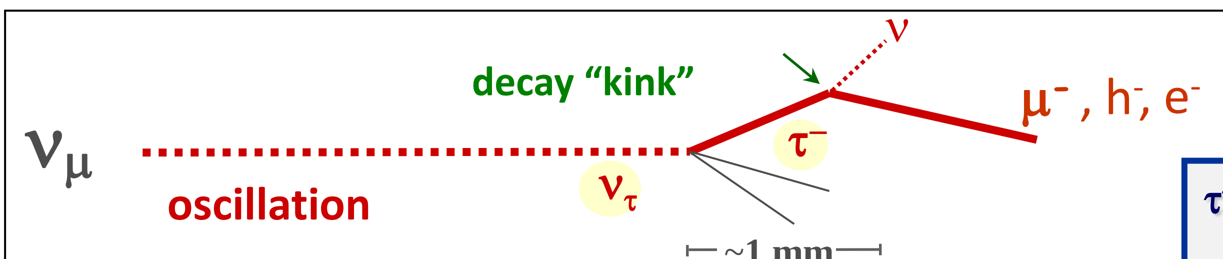
- Long-baseline, flavour oscillation: small fraction of ν_τ ; Far-away source, low flux, weak interaction:

  → *large* target *mass* required (as usual for ν's ...)

- CC interactions of ν_τ tagged by the τ *decay* *($c\tau$= 87 µm)* :

  → need *high spatial resolution* & *lepton Id*
  (background rejection, including charm production and decay)

***Hybrid* technique:** tracking apparatus with "many" **Emulsion Cloud Chamber** target units



τ^- ↳ :	$\mu^-\ \nu_\tau\ \nu_\mu$	(17.4%)	Kink
	$e^-\ \nu_\tau\ \nu_e$	(17.8%)	Kink
	$h^-\ \nu_\tau\ n\ \pi^o$	(49.5%)	Kink
	$\pi^+\ \pi^-\ \pi^-\ \nu_\tau\ n\pi^o$	(14.5%)	*Multiprong*

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

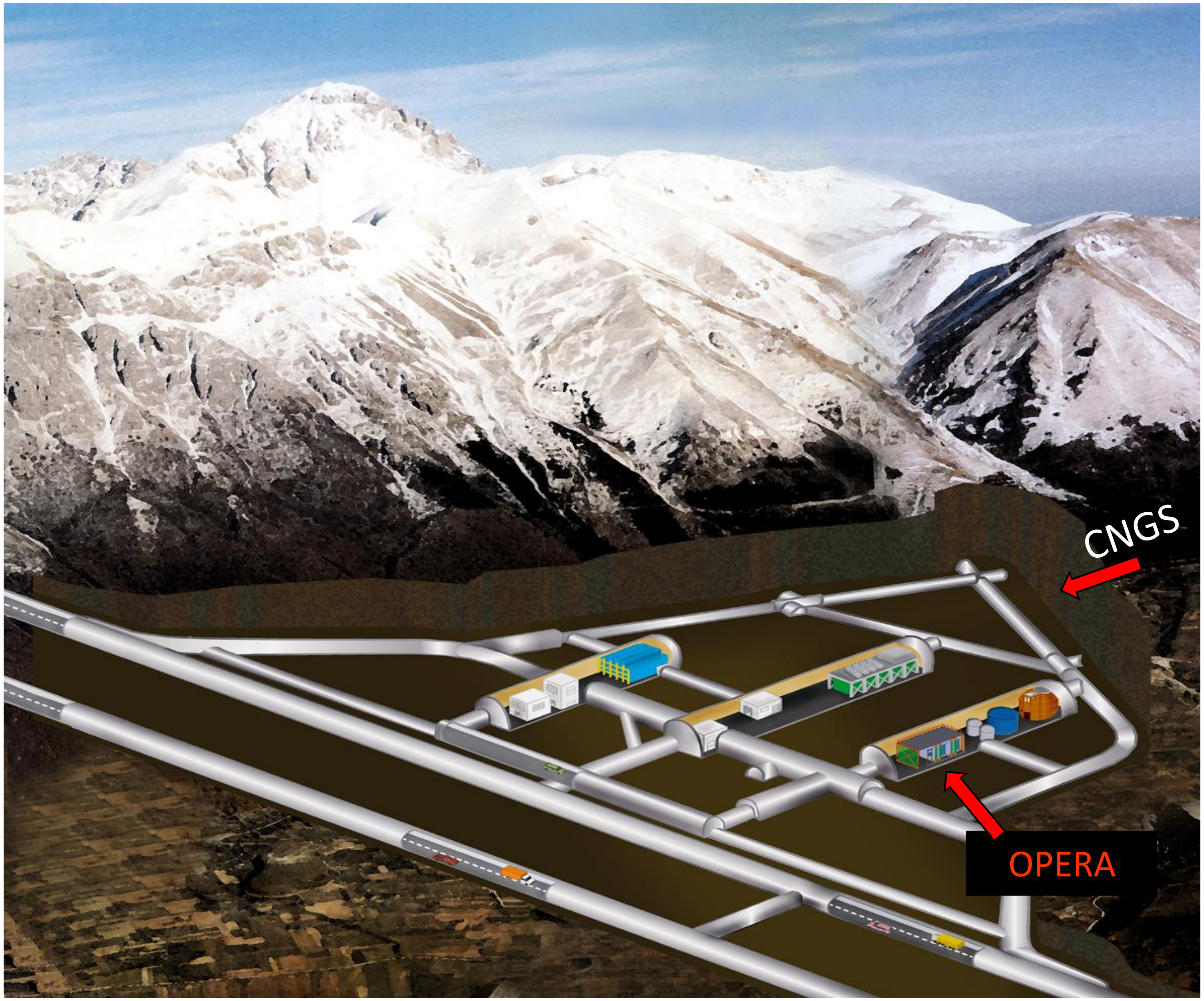
Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

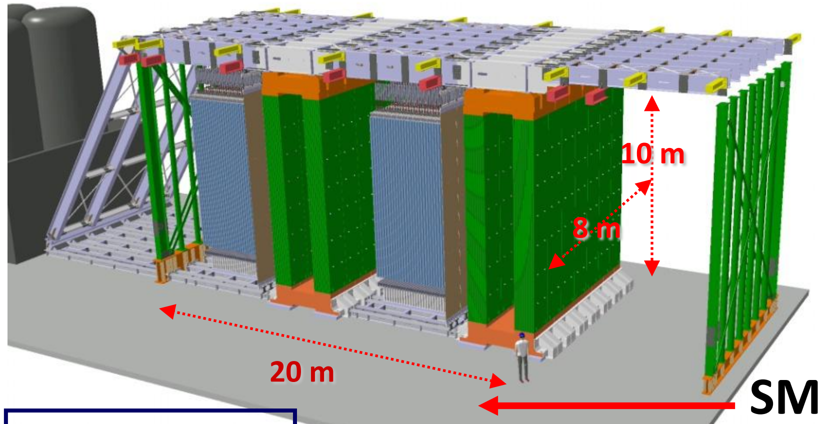
http://operaweb.lngs.infn.it/scientists/?lang=en



Rome, L'Aquila

Teramo

Detector overview



Modular, Hybrid Detector:

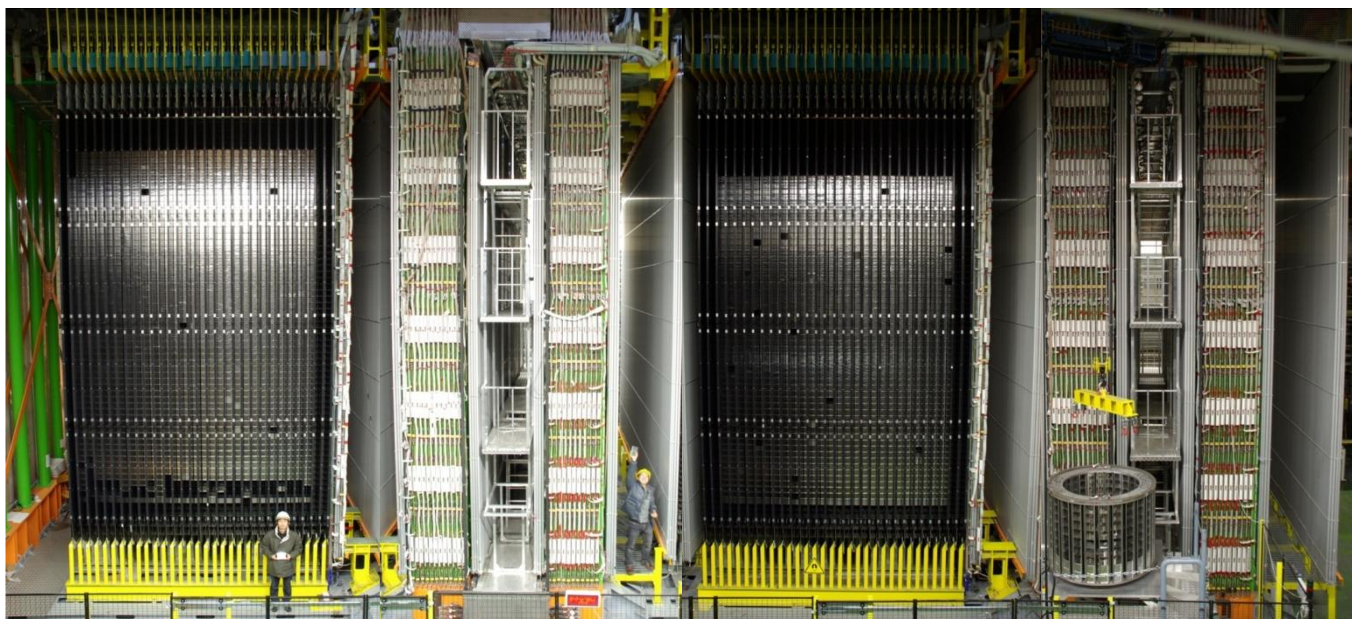
Two *supermodules*, each consisting of

- a Target Section (total target mass: 1.25 kton)
  - 31 Target Tracker modules (scintillator strips) & Walls of target units (*ECC bricks*)
- a Magnetic Spectrometer (XPC, RPC, Drift tubes)
- Upstream: VETO (glass RPC)
- Both sides: Brick Manipulation System (BMS)
- Data Taking: (1) LNGS DAQ : ethernet nodes + time stamp
  (2) Emulsion scanning [Europe and Japan]
  … & several facilities for brick & emulsion film handling

Hall C
Gran Sasso Lab

SM1 SM2

CNGS beam



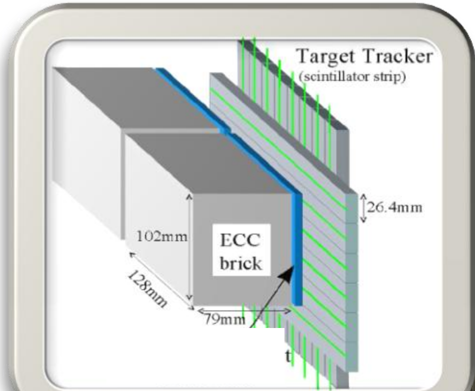
Veto

Target tracker

Spectrometer:

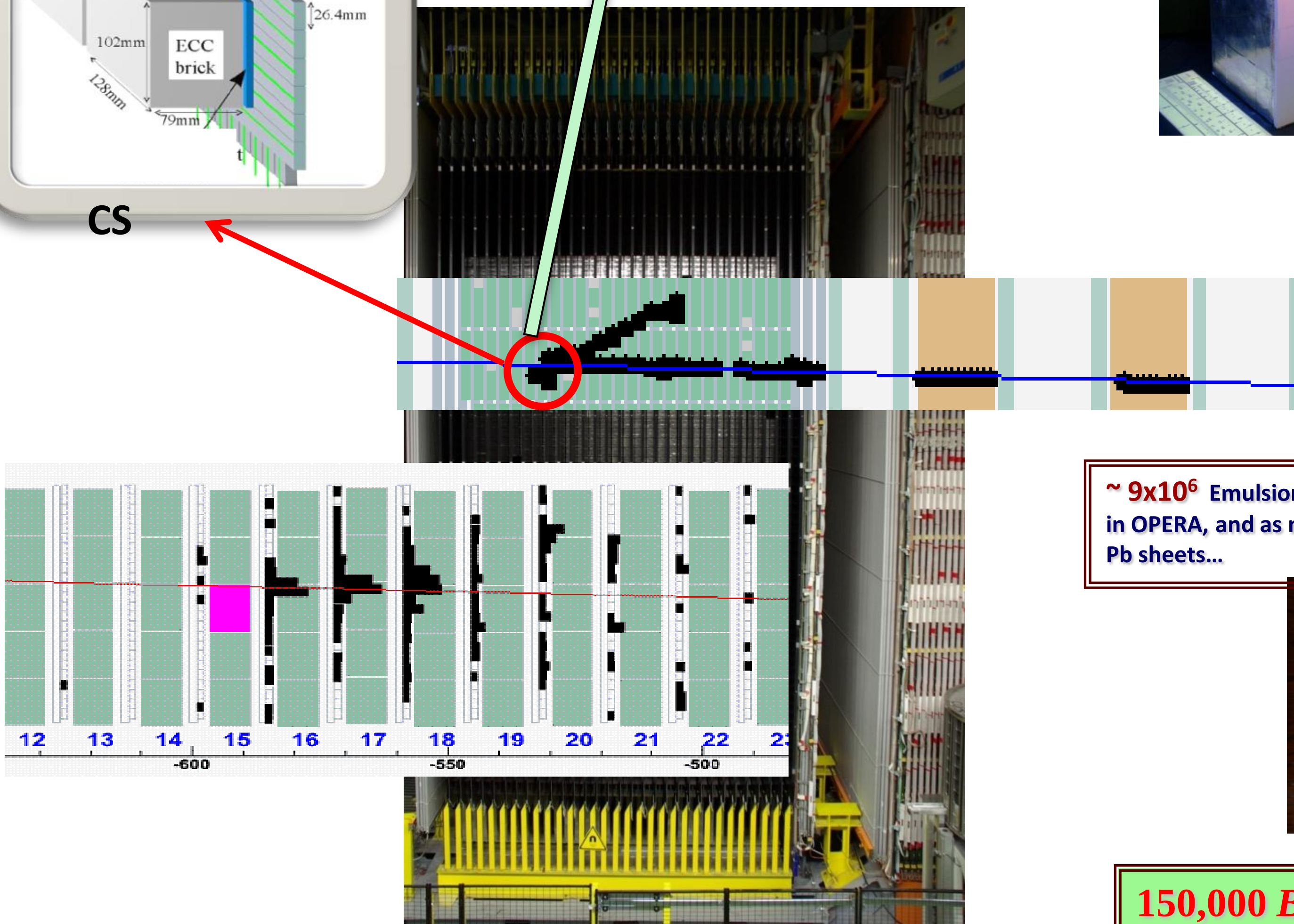
BMS

A "hybrid", complex experiment…

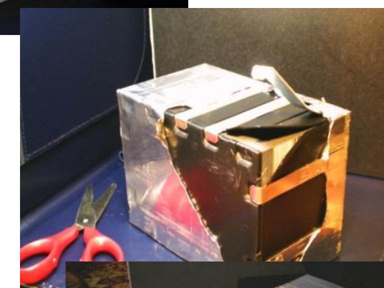


CS

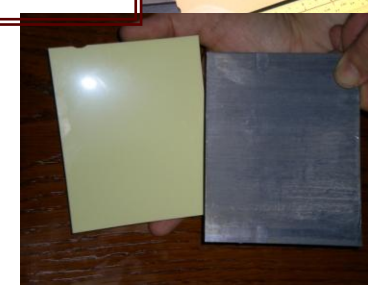
Extract brick and CS, scan CS.
Confirm the event in the brick.
Develop brick: ship to scanning labs.



12.5x10.2 cm²
8 cm thick
8.4 kg, 10 X_0
(94% Pb)



~ 9×10^6 Emulsion films in OPERA, and as many Pb sheets…



150,000 *Bricks* in OPERA
("brick"= ECC target unit)

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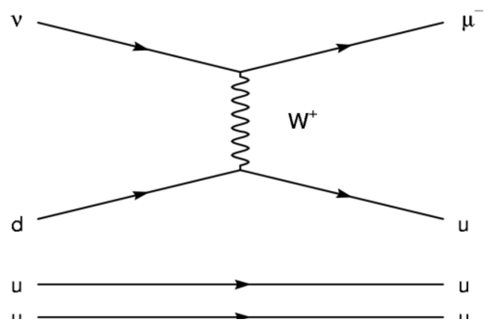
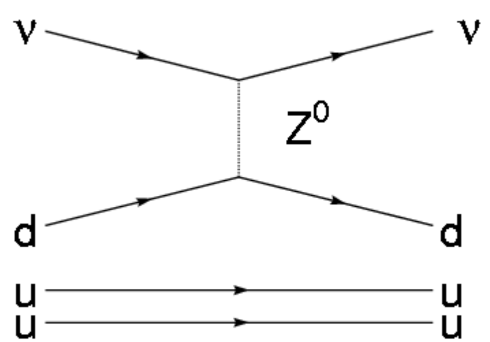
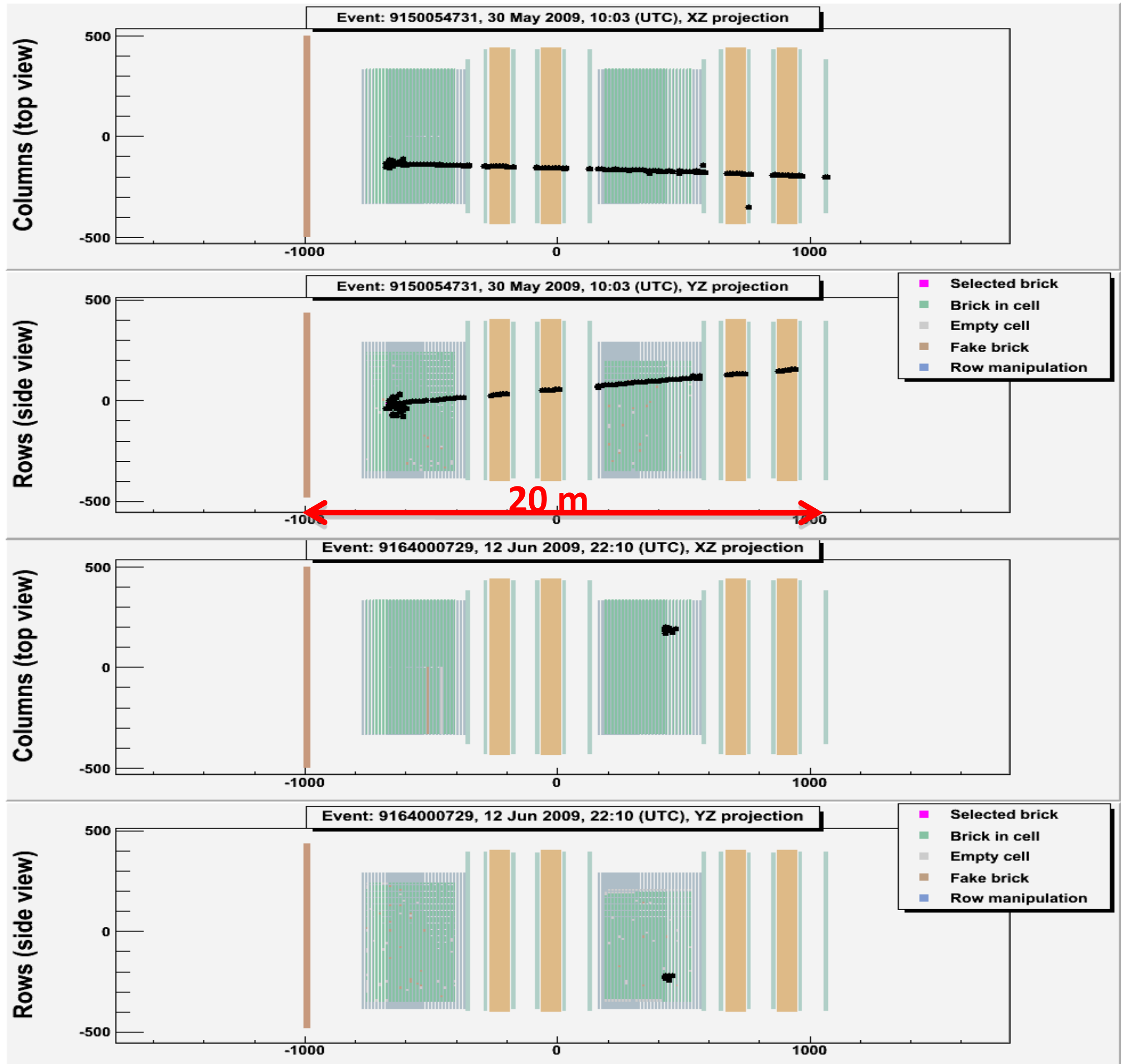
CNGS-induced "internal" events in the *electronic detectors*

Most of them are ν_μ induced "charged current" (CC) or "neutral current (NC) events





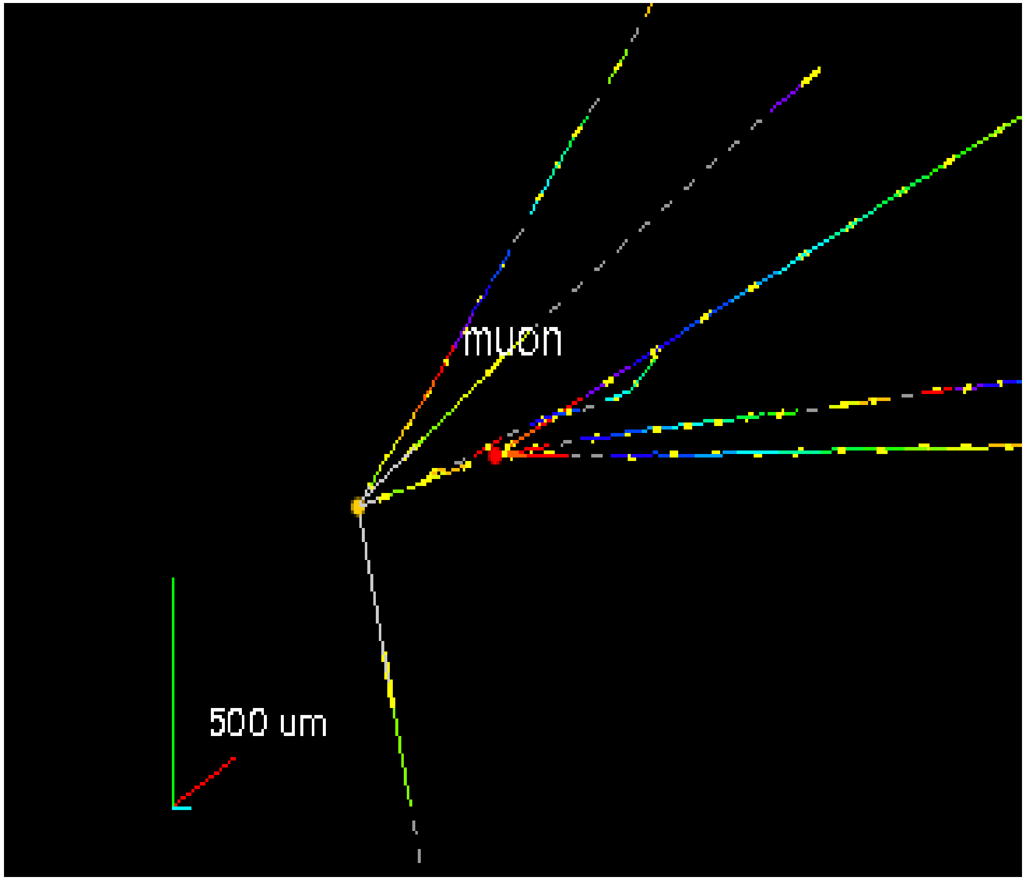
…but a few ν_e and some rare ν_τ may be hidden inside each event: catch them!



Event classification: "with muon/ muonless"

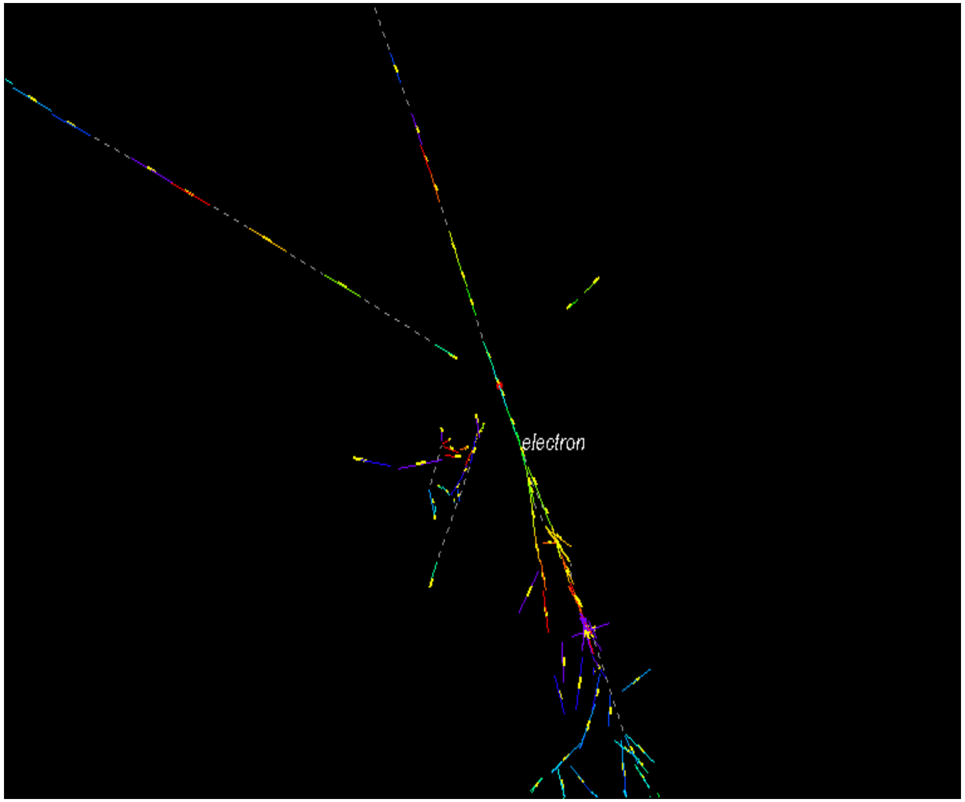
Lepton flavour unvealed (CC only!) after ***emulsion plate scanning and measurements …***

Example 1: a muon-neutrino, with a short-lived "charmed" particle produced



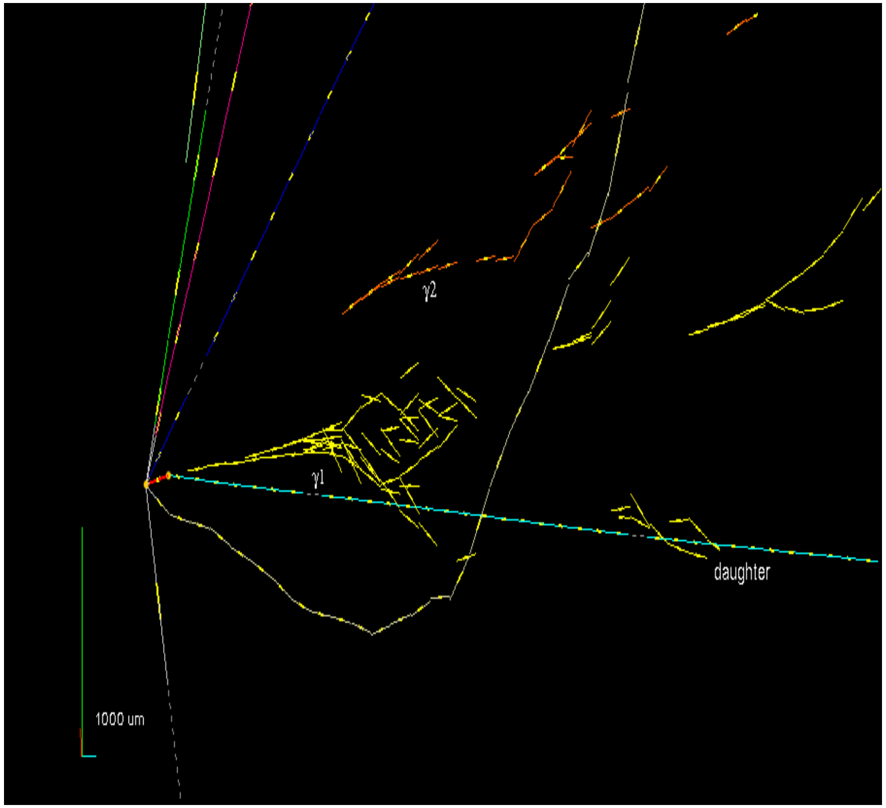
Lepton flavour unvealed (CC only!) after *emulsion plate scanning and measurements …*

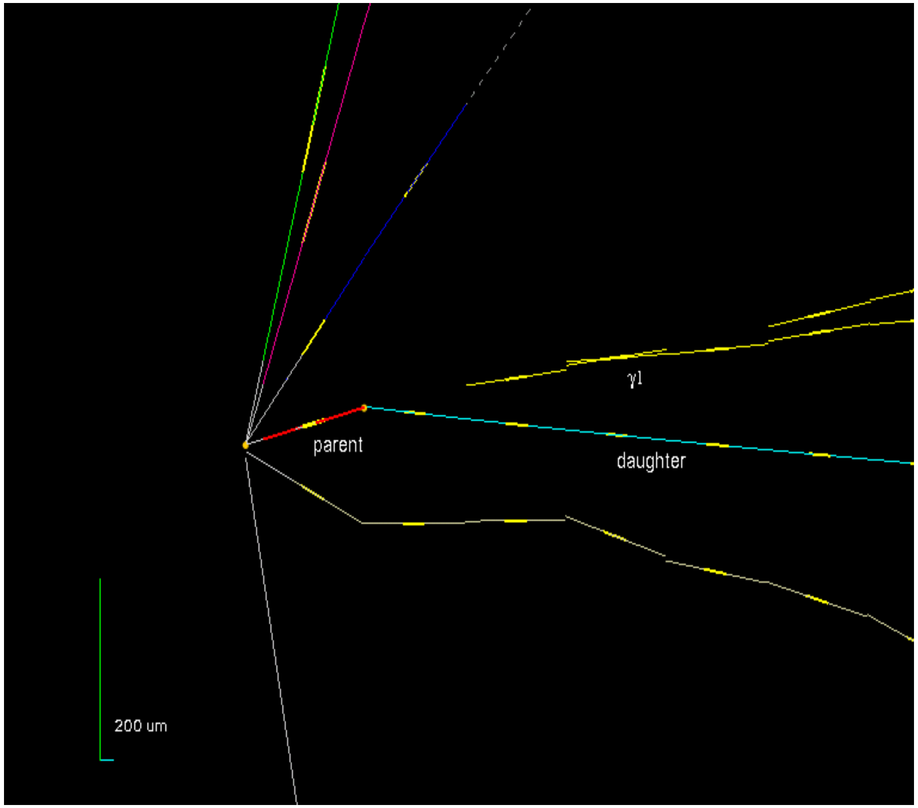
Example 2: an electron-neutrino identified by its "e.m. showering"



Lepton flavour unvealed (CC only!) after *emulsion plate scanning and measurements …*

Example 3: "the" tau-neutrino event catched by its decay topology and… the many checks done



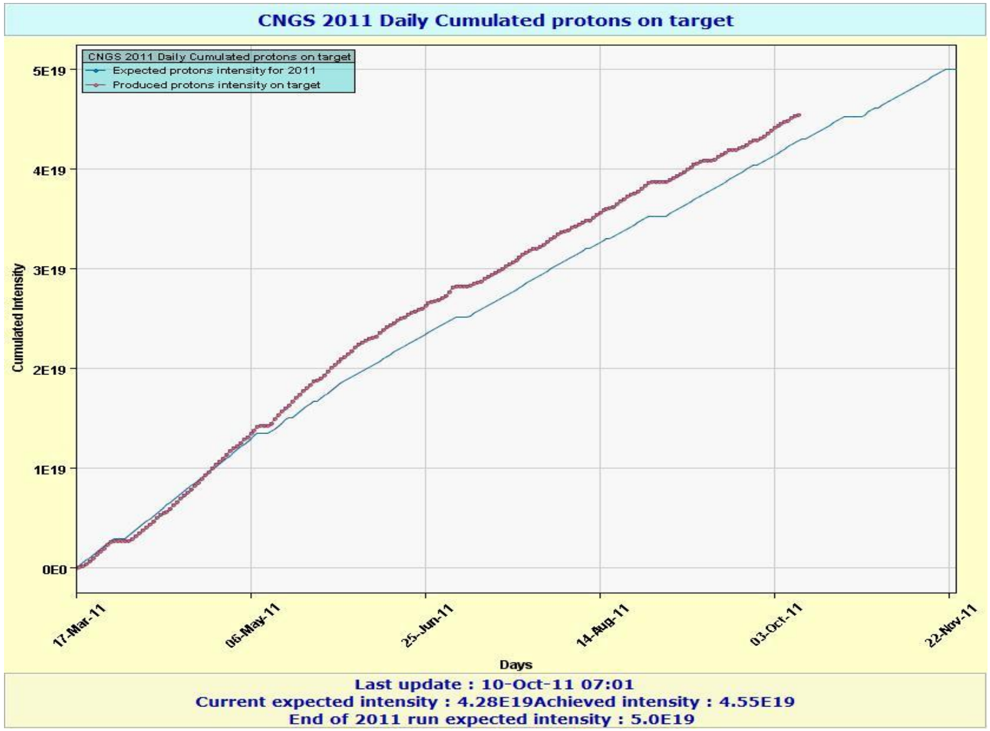


All details in Phys. Lett. B 691 (2010) 138-145
"Observation of a first nu-tau candidate in the OPERA experiment in the CNGS beam "

Status of CNGS data taking: "protons on target" (p.o.t.)

	beam days	# p.o.t.*	SPS eff.	events in the bricks	run
2007		0.082×10^{19}		38	commissioning
2008	123	$1.78\text{x}10^{19}$	61%	1698	Physics runs
2009	155	$3.52\text{x}10^{19}$	70%	3693	Physics runs
2010	187	$4.04\text{x}10^{19}$	81%	4248	Physics runs

+ 2011 run in good progress
($4.55 \cdot 10^{19}$ p.o.t. as of October 10th)



…hope same perfomance in 2012
(➔~$2 \cdot 10^{20}$ p.o.t. overall,
20,000 events in the bricks)

Status of the oscillation analysis

Analysis of 2008-2009 runs ~ completed
arXiv-1107.2594v1 – submitted

	0mu	1mu	All
Events predicted by the electronic detector	1503	3752	5255
Interactions located in ECC	519	2280	2799
Located in dead material	54	245	299
Decay search performed	494	2244	2738

Charm events as a control sample (data versus MC)

Topology	Observed events	Expected events		
		Charm	Background	Total
Charged 1-prong	13	15.9	1.9	17.8
Neutral 2-prong	18	15.7	0.8	16.5
Charged 3-prong	5	5.5	0.3	5.8
Neutral 4-prong	3	2.0	<0.1	2.1
Total	39	39.1±7.5	3.0±0.9	42.2±8.3

Status of the oscillation analysis

Decay channel	Number of signal events expected for	
	22.5×10^{19} p.o.t.	Analysed sample
$\tau\rightarrow\mu$	1.79	0.39
$\tau\rightarrow e$	2.89	0.63
$\tau\rightarrow h$	2.25	0.49
$\tau\rightarrow 3h$	0.71	0.15
Total	7.63	1.65

One ν_τ candidate observed in the $\tau\rightarrow$ h channel $\leftrightarrow$ Expected signal events

Background re-evaluated

Decay channel	Number of background events for:							
	22.5×10^{19} p.o.t.				Analysed sample			
	Charm	Hadron	Muon	Total	Charm	Hadron	Muon	Total
$\tau\rightarrow\mu$	0.025	0.00	0.07	0.09 ± 0.04	0.00	0.00	0.02	0.02 ± 0.01
$\tau\rightarrow e$	0.22	0	0	0.22 ± 0.05	0.05	0	0	0.05 ± 0.01
$\tau\rightarrow h$	0.14	0.11	0	0.24 ± 0.06	0.03	0.02	0	0.05 ± 0.01
$\tau\rightarrow 3h$	0.18	0	0	0.18 ± 0.04	0.04	0	0	0.04 ± 0.01
Total	0.55	0.11	0.07	0.73 ± 0.15	0.12	0.02	0.02	0.16 ± 0.03

Sept. 2011 update (+1000 ev, 2010 run): 52 charm candidates, 20 ν_e candidates, 1 ν_τ candidate
Speed-up of tau search with "wise cuts" & electron-neutrino study in progress

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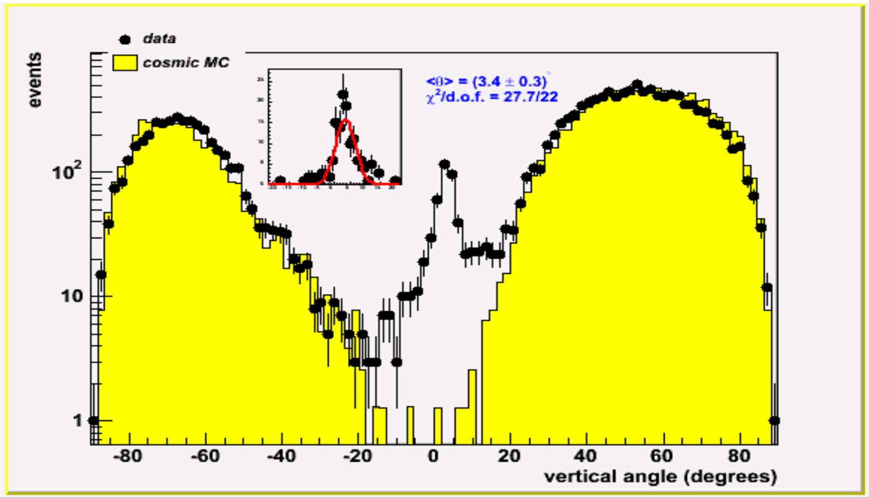
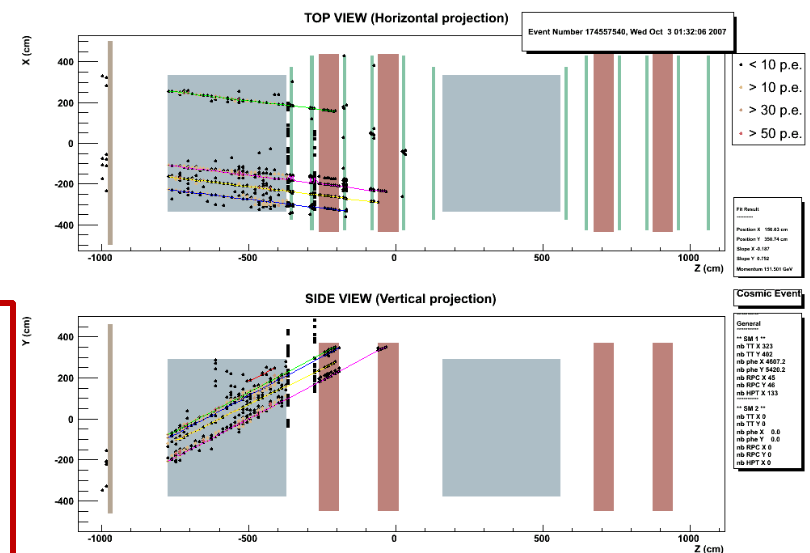
Cosmic-ray Data in OPERA (muons reaching the underground detector)



Easy separation from CNGS events by:
- **timing (see next topic…)**
- **direction of single muon/muon bundle**



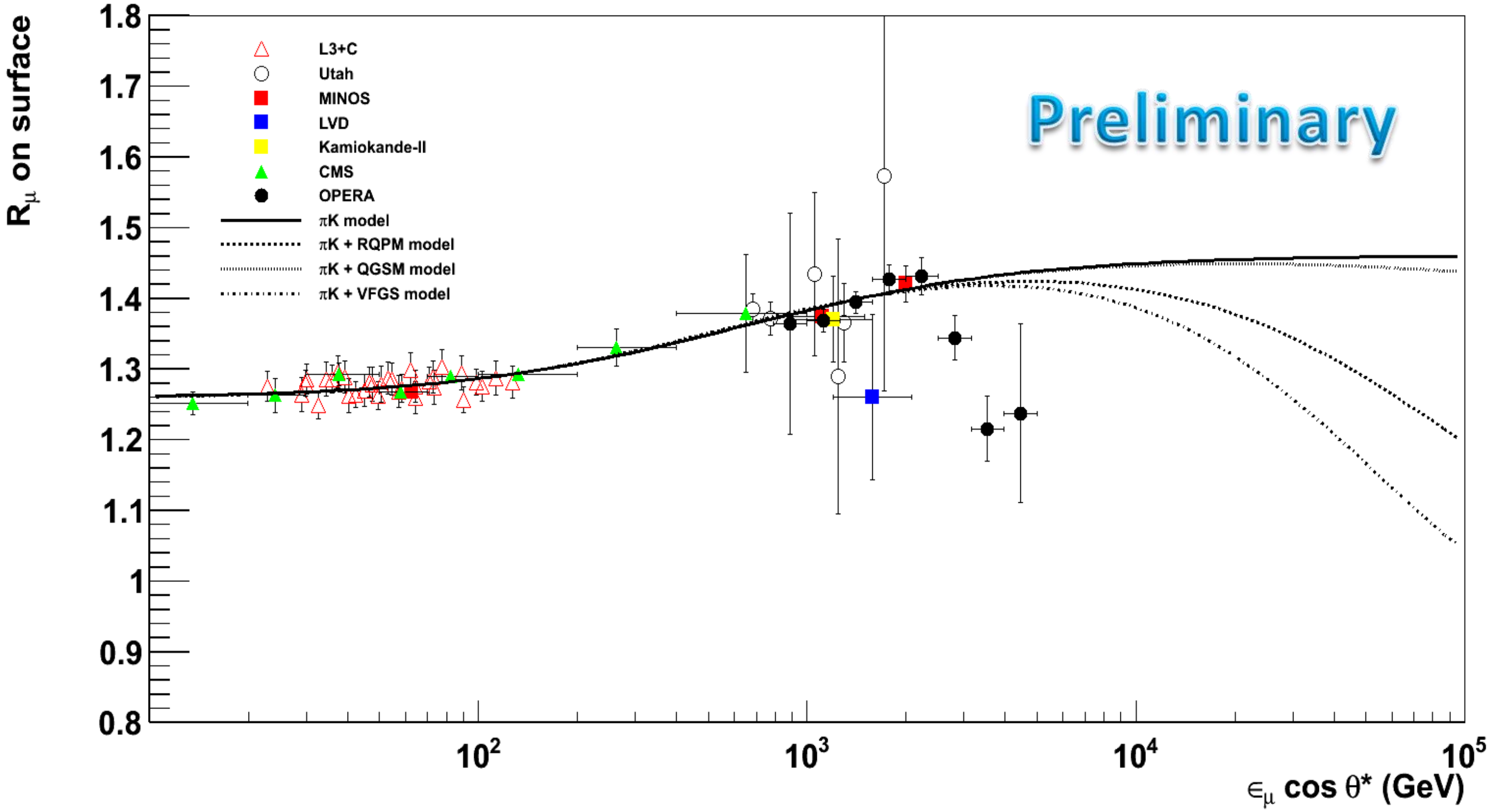
First results published in Eur. Phys. J. C 67 (2010) 25

Preliminary analysis of new data recently released
1454057 μ collected during
2008-2009-2010 CNGS runs
corresponding to 407.1 days of livetime

Presented by M. Sioli at the TAUP 2011 Conference

Cosmic-ray Data in OPERA

R_μ measurements with $E_\mu \cos\theta^* > 1$ TeV



Drop observed after π/K rise. Speculation on the possible physical nature:

- Sudden change in the n/p ratio in the all-nucleon spectrum?
- Strong scaling violation in the forward fragmentation region for π/K mesons?
- Upraise of a new muon component?

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

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)

T. Adam et al. [OPERA Collaboration]
"Measurement of the neutrino velocity with the OPERA detector in the CNGS beam
ArXiv:1109.4897 [hep-ex]

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Past experimental results

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

high energy ($E_\nu > 30$ 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).

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

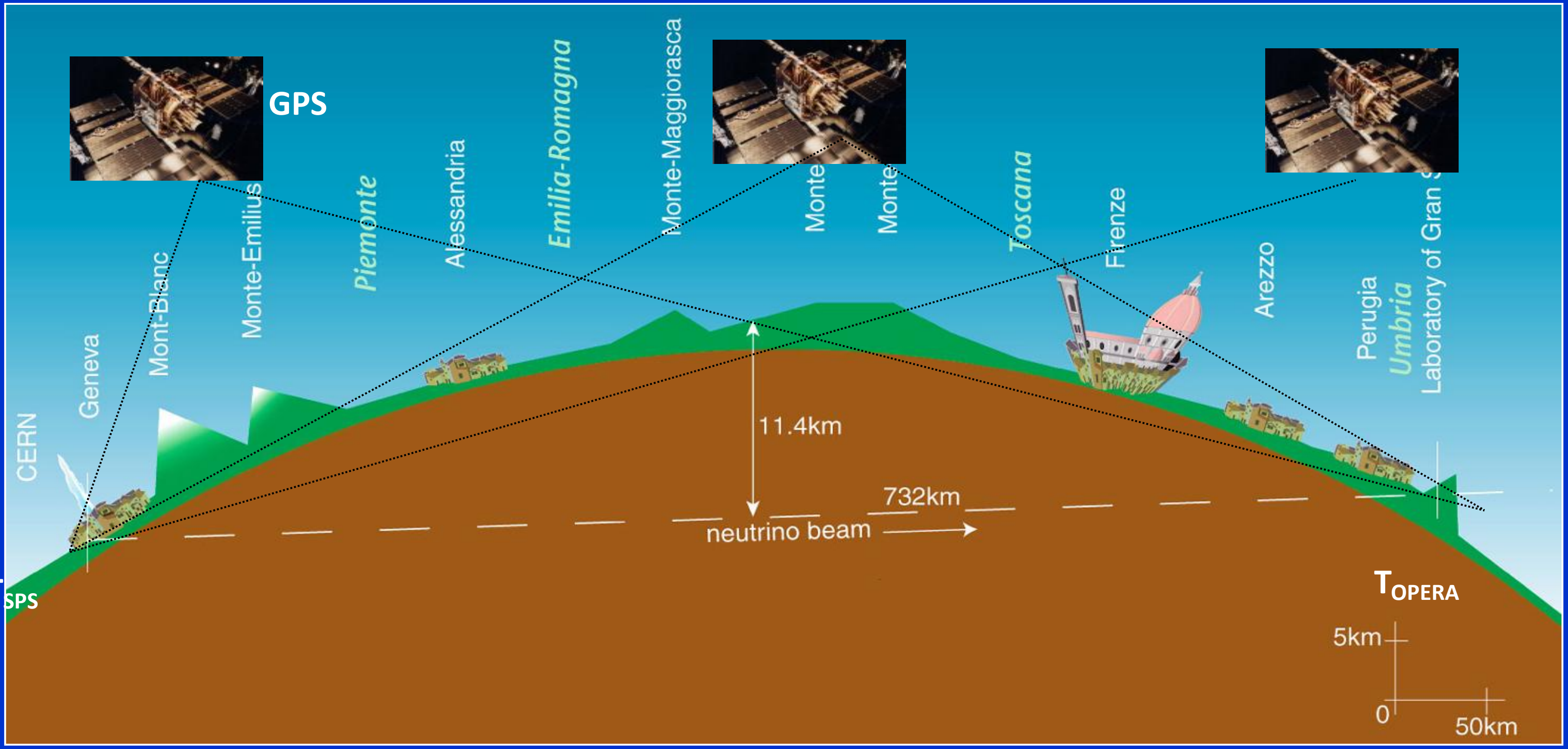
tagging of neutrino interaction time by a far detector

accurate determination of the baseline (geodesy)

expected small effects: long baseline required

adequate level of systematic errors reached

CNGS events selection



T_{SPS} T_{OPERA}

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

Geodesy at LNGS ***(→ M. Crespi, A. Mazzoni)***

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

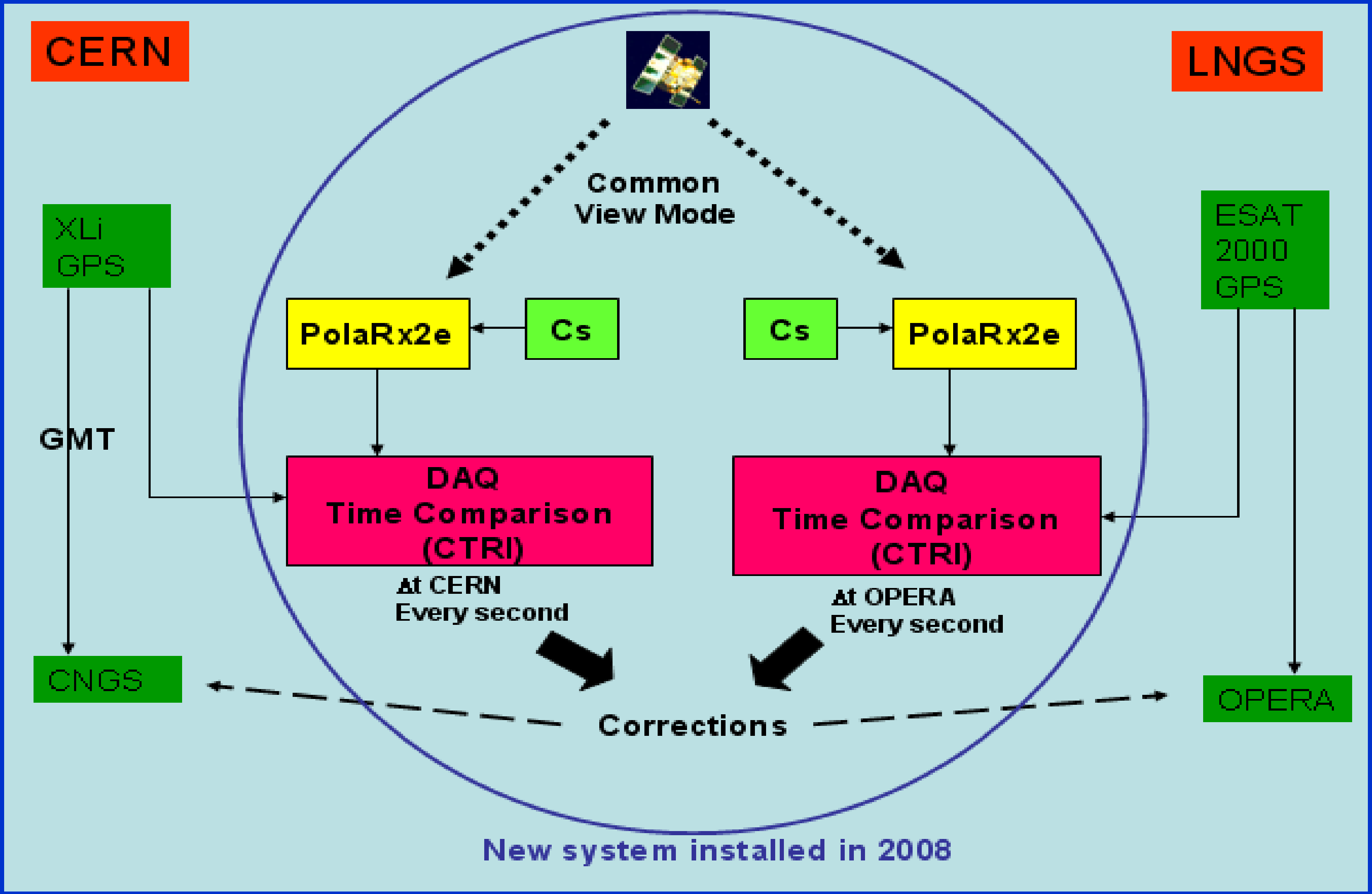
LNGS benchmarks
In ETRF2000

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

Resulting distance (BCT – OPERA reference frame)

(731278.0 ± 0.2) m

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

GPS common-view mode

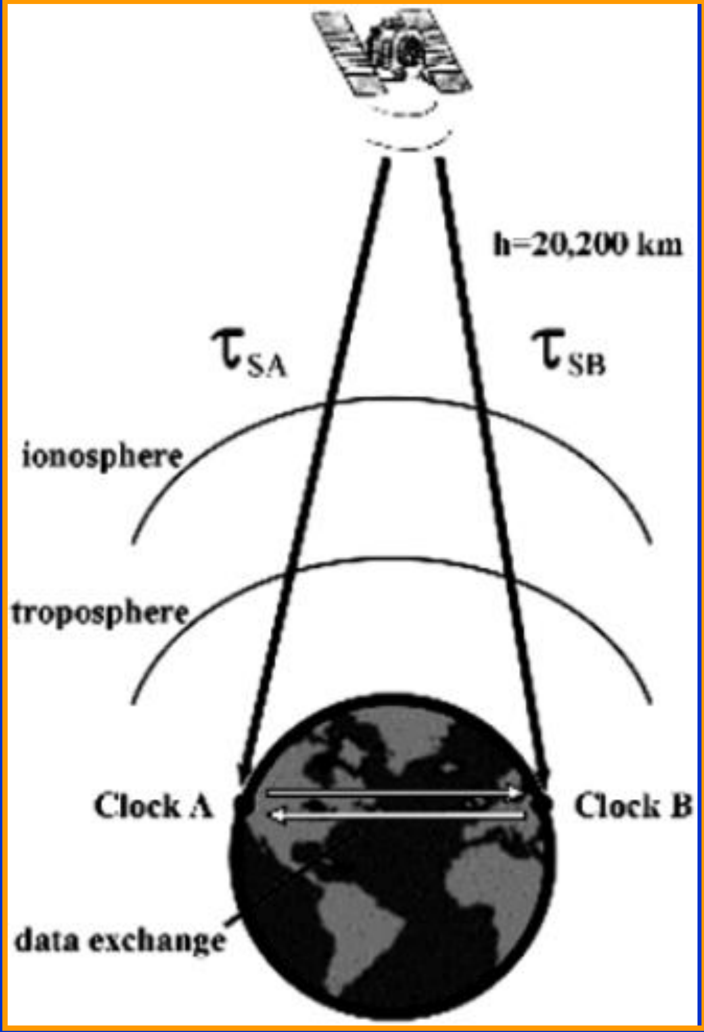
Standard GPS operation:

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

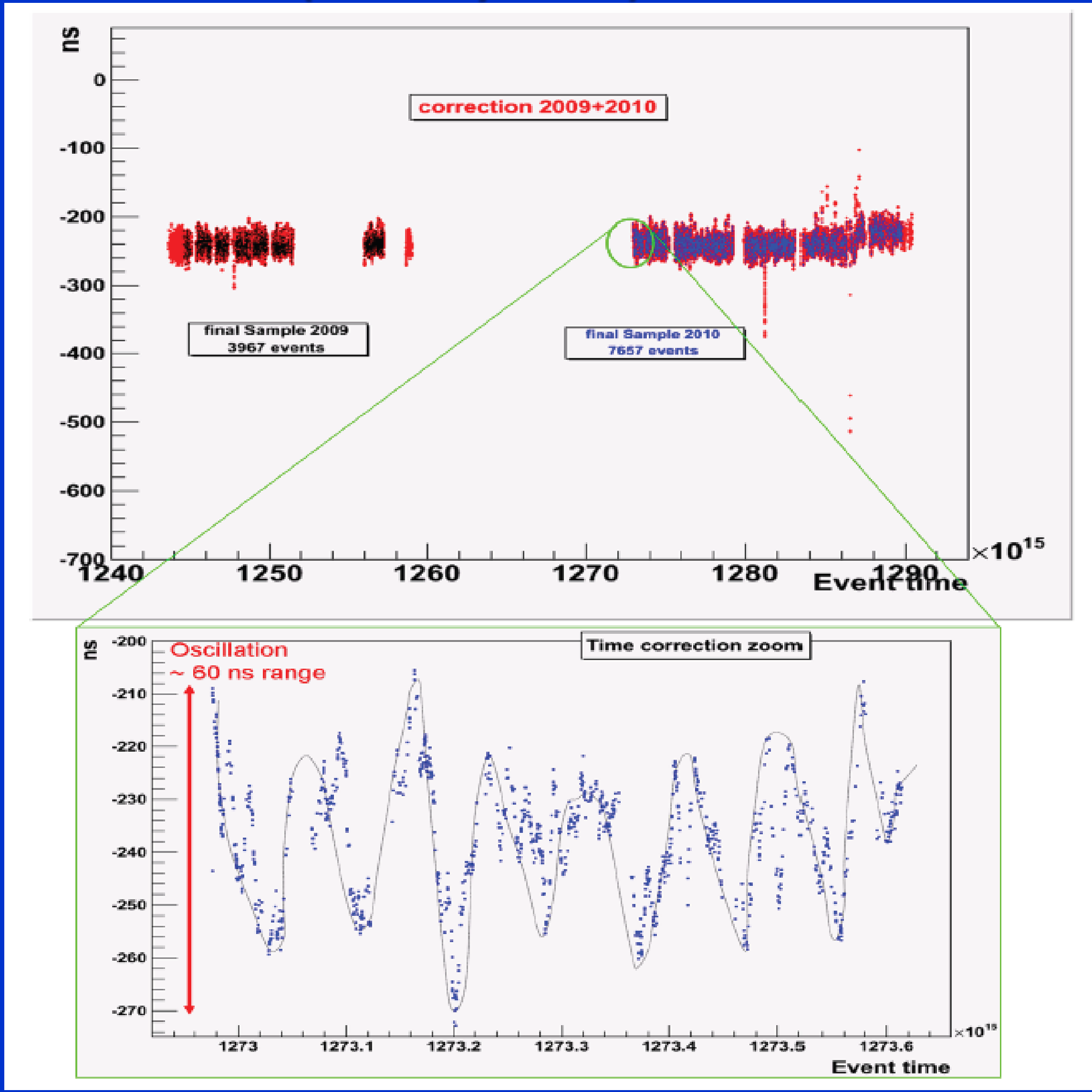
Common-view mode (the same satellite for the two sites, for each comparison):

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

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



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

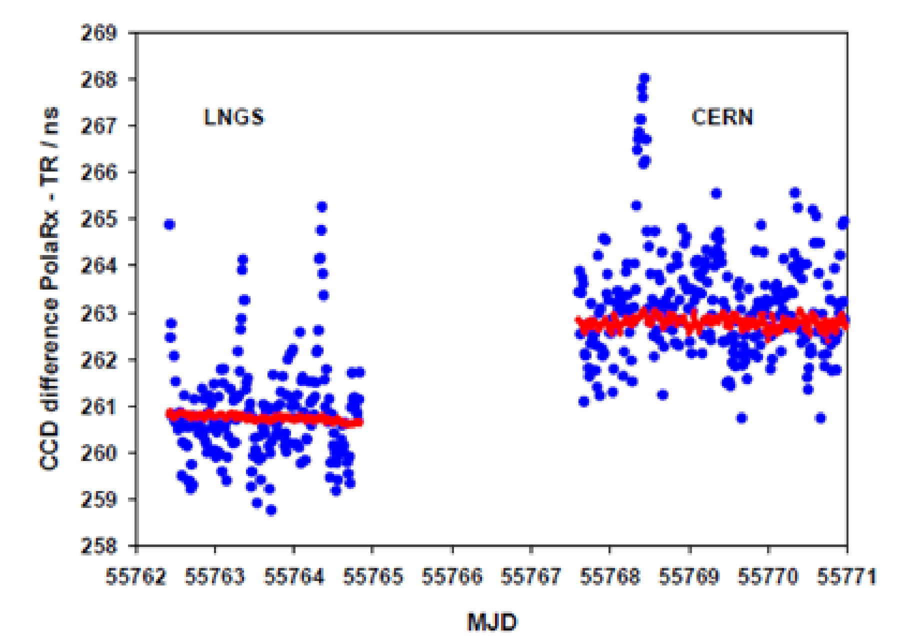


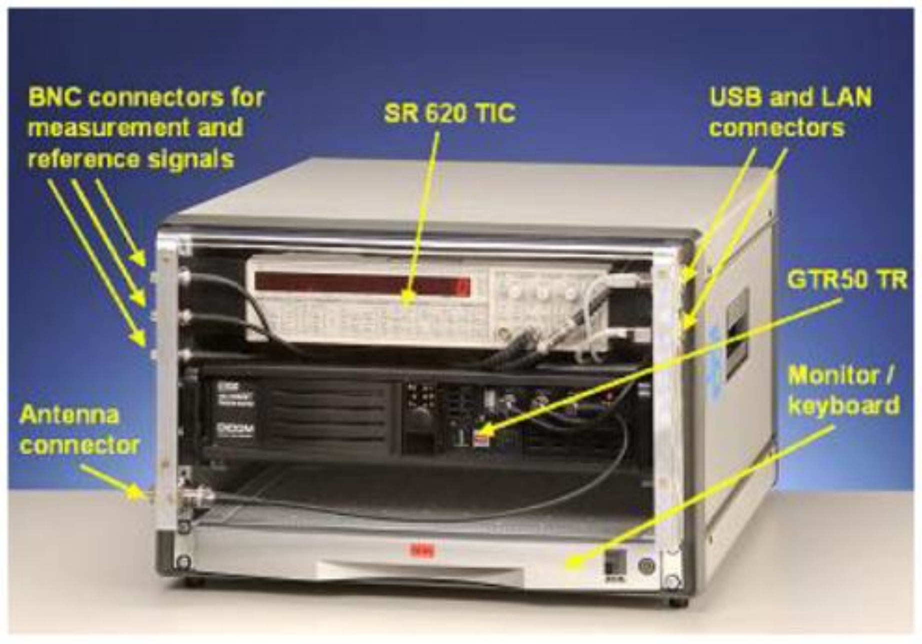
CERN-OPERA inter-calibration cross-check

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt

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

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

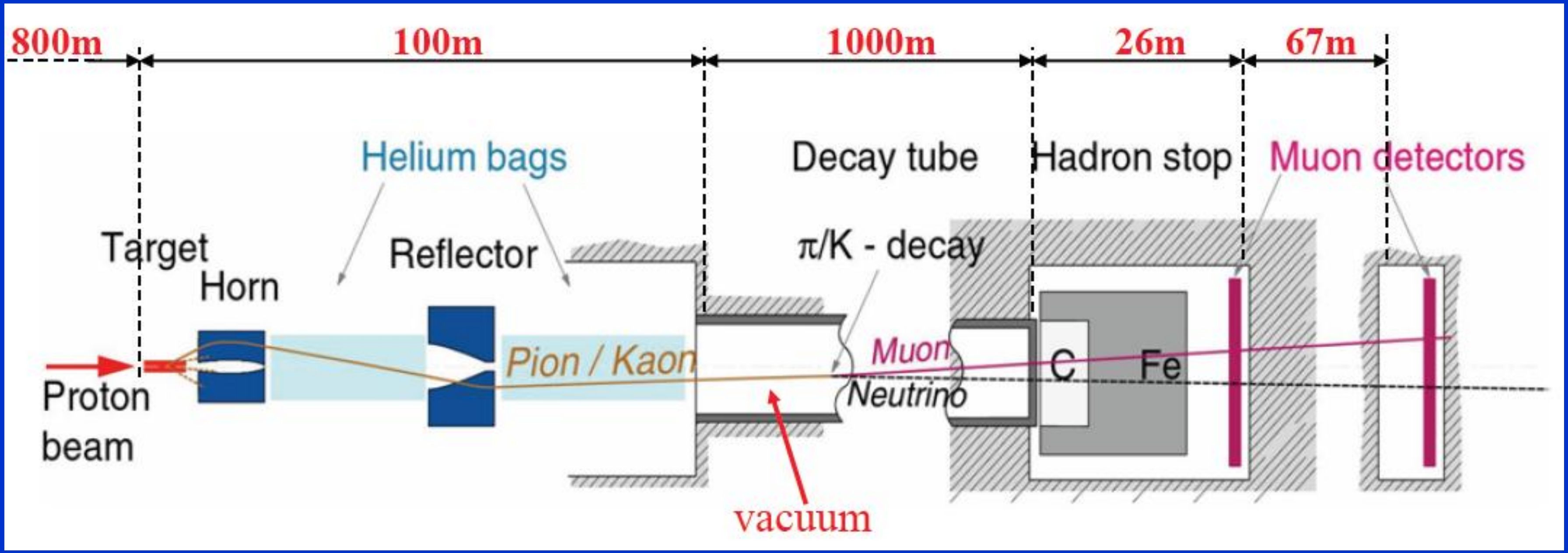




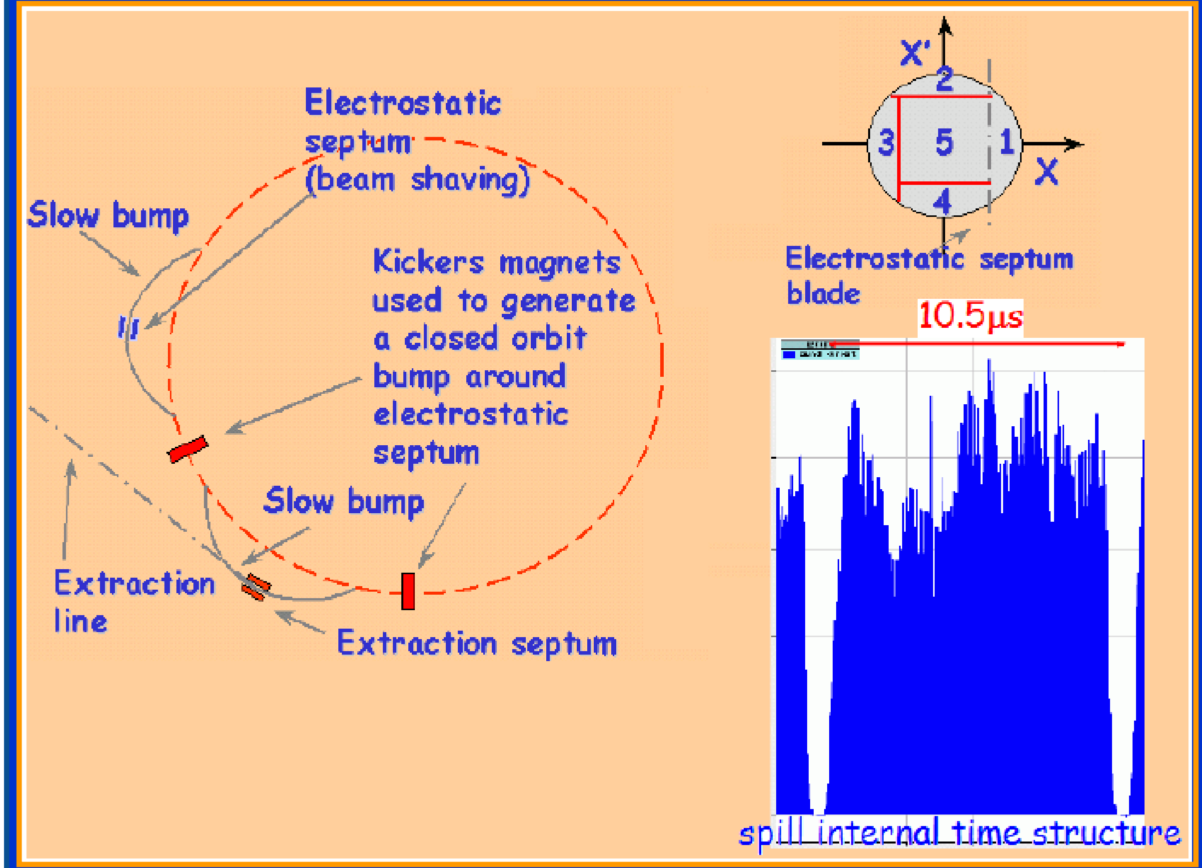
Correction to the time-link:

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

THE STARTER: the CNGS neutrino beam



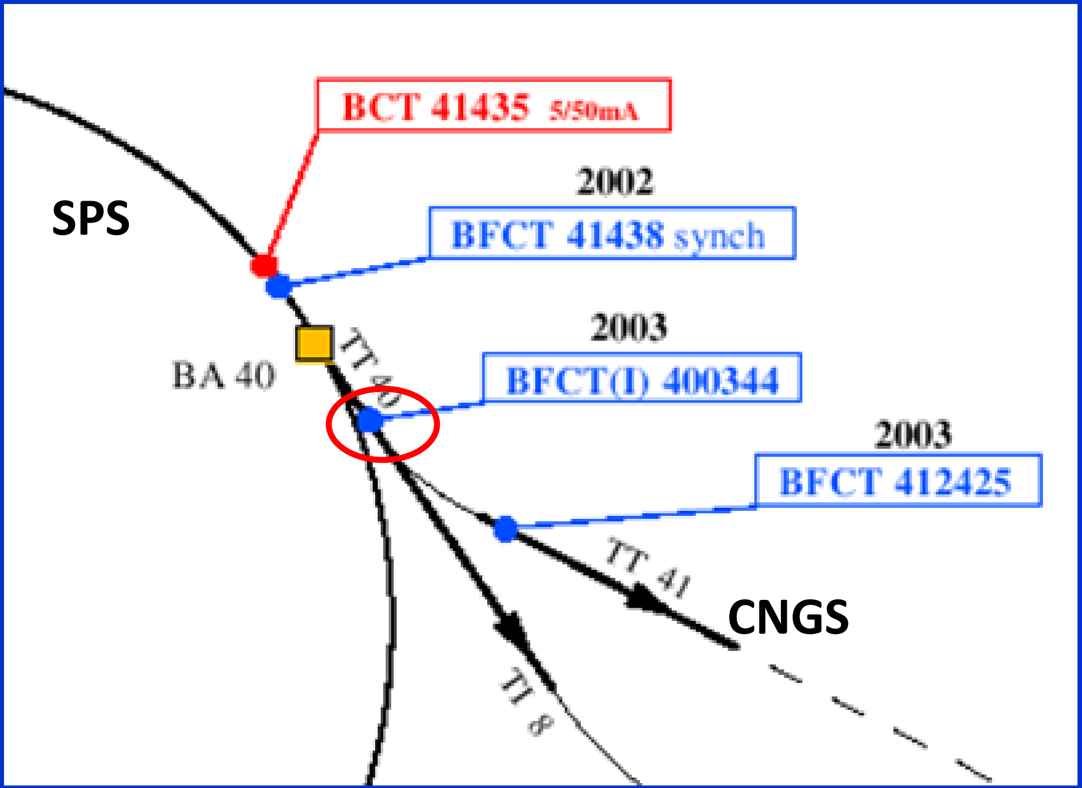
- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5 μs extractions (by kicker magnet) separated by 50 ms
- Beam intensity: 2.4 10^{13} proton/extraction
- ~ pure muon neutrino beam (<E> = 17 GeV) travelling through the Earth's crust



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

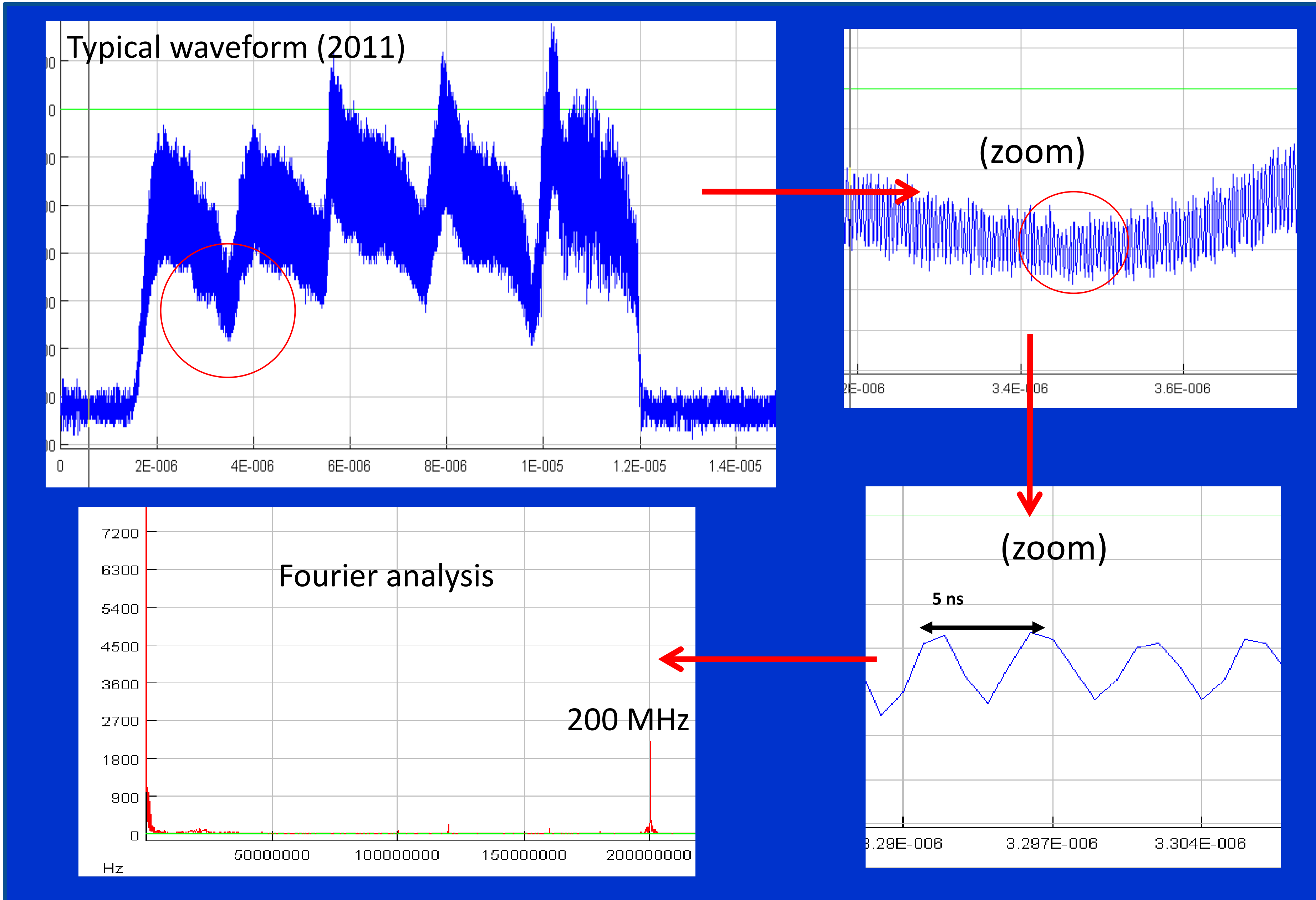


Proton timing by Beam Current Transformer

Fast BCT 400344(~ 400 MHz)

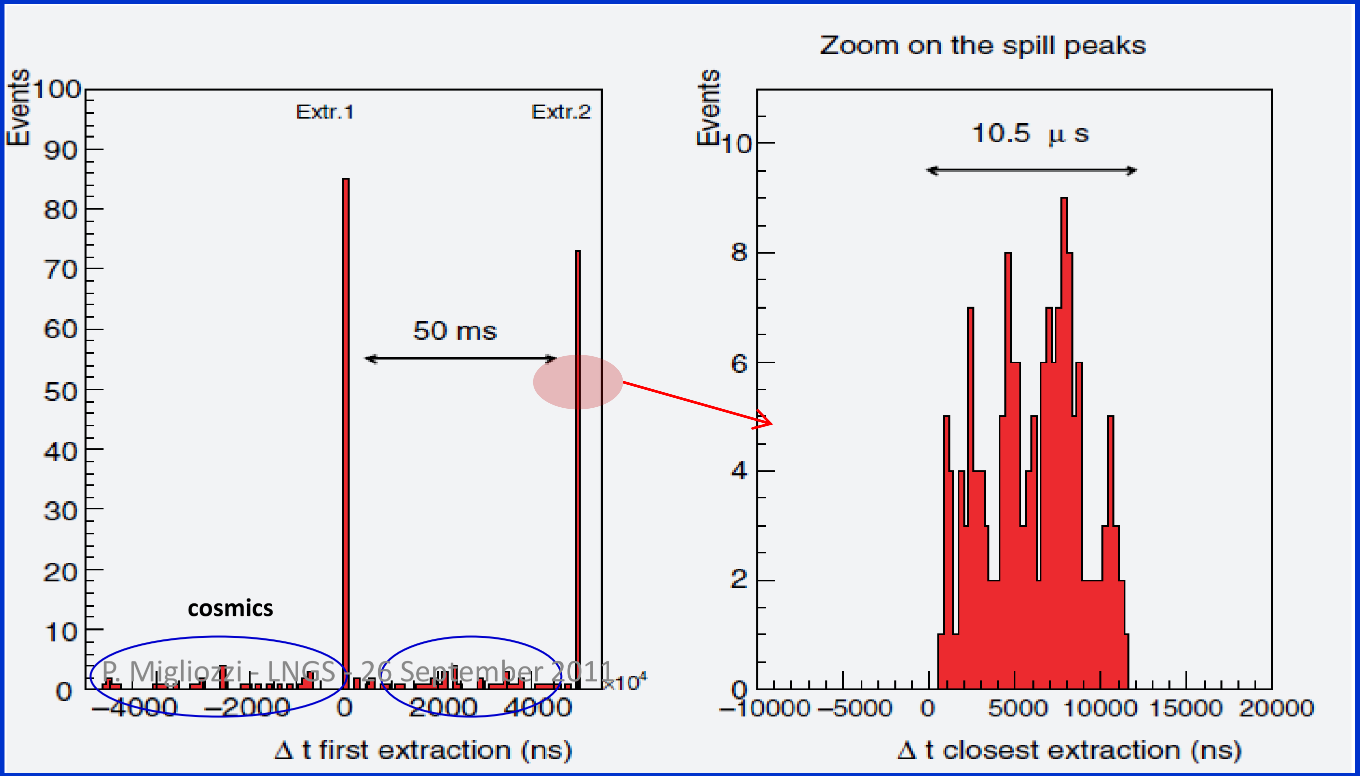
Proton pulse digitization:
- Acqiris DP110 1GS/s waveform digitizer (WFD)
- WFD triggered by a replica of the kicker signal
- Waveforms UTC-stamped and stored in CNGS database for offline analysis

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

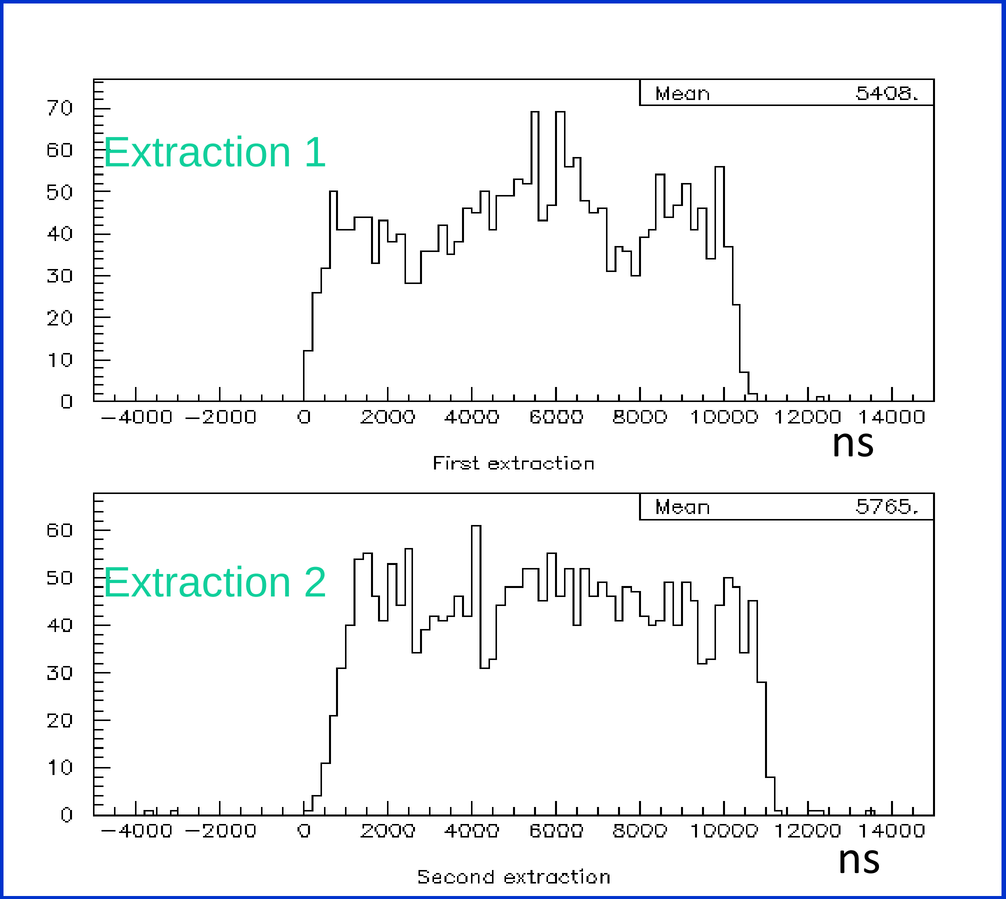
CNGS events selection



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

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

Measurement of the neutrino event time distribution



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

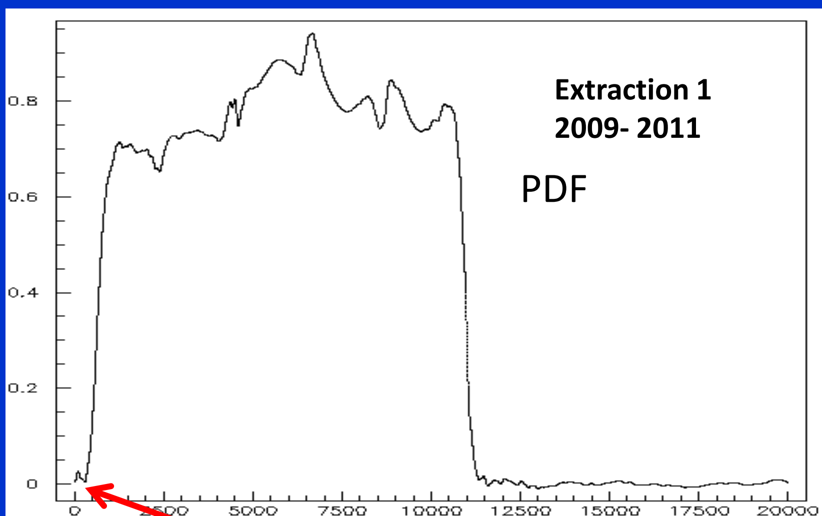
→ Need to precisely measure the protons spills

Neutrino event-time distribution PDF

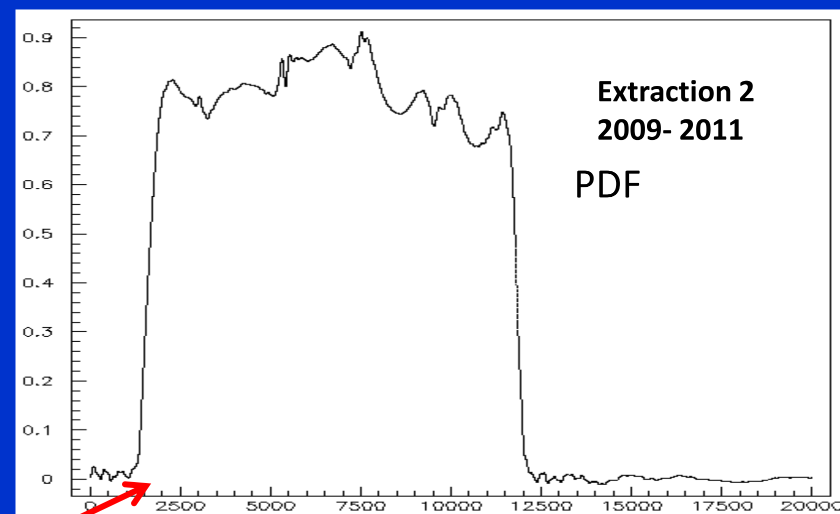
- Each event is associated to its proton spill waveform
- The "parent" proton is unknown within the 10.5 μs extraction time

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

→ compare to OPERA detected neutrino events

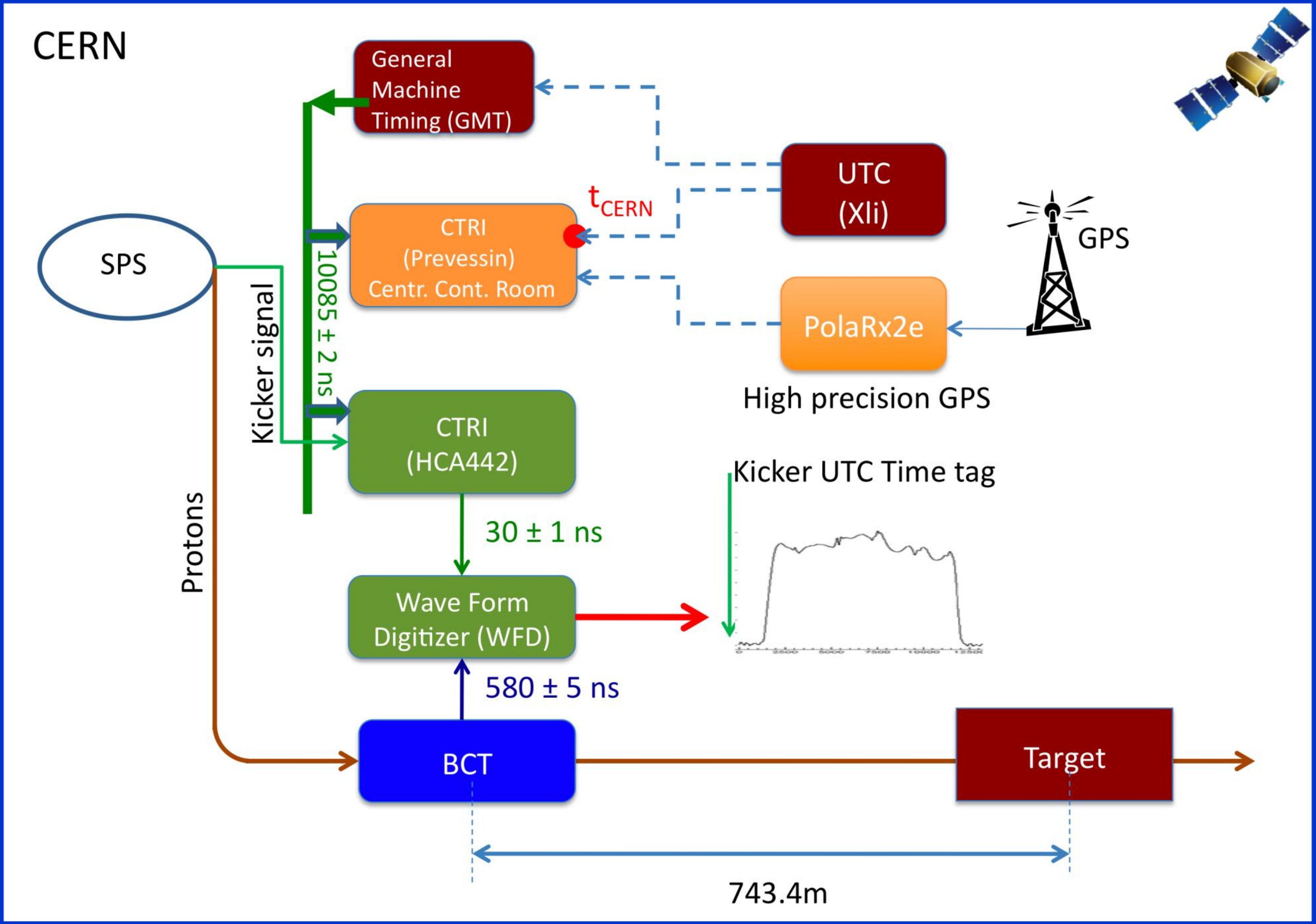


(ns)

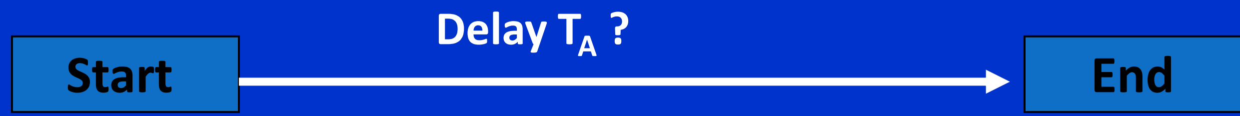


(ns)

different timing w.r.t. kicker magnet signal

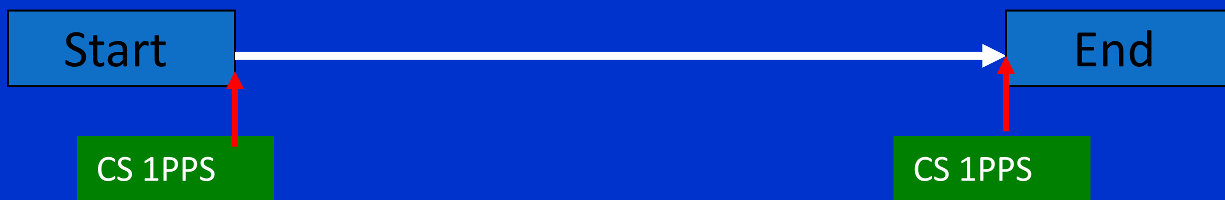

CERN
General Machine Timing (GMT)
UTC (Xli)
t_{CERN}
CTRI (Prevessin) Centr. Cont. Room
GPS
SPS
PolaRx2e
High precision GPS
Kicker signal
10085 ± 2 ns
CTRI (HCA442)
Kicker UTC Time tag
Protons
30 ± 1 ns
Wave Form Digitizer (WFD)
580 ± 5 ns
BCT
Target
743.4m

Time calibration techniques



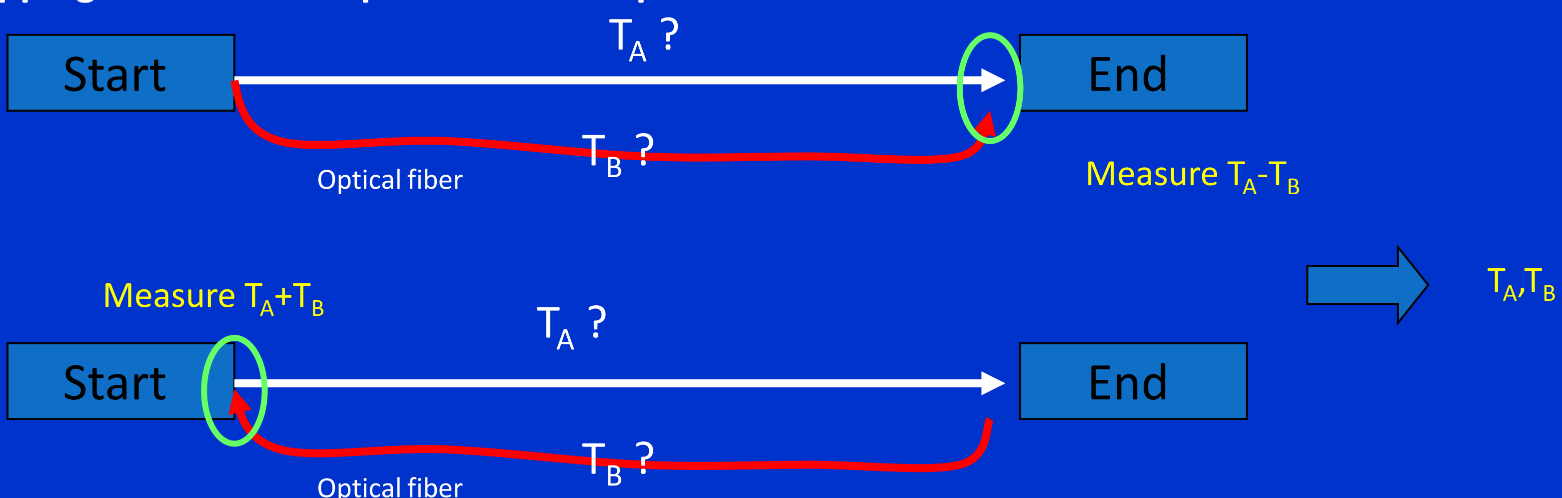
- **Portable Cs-4000:**

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

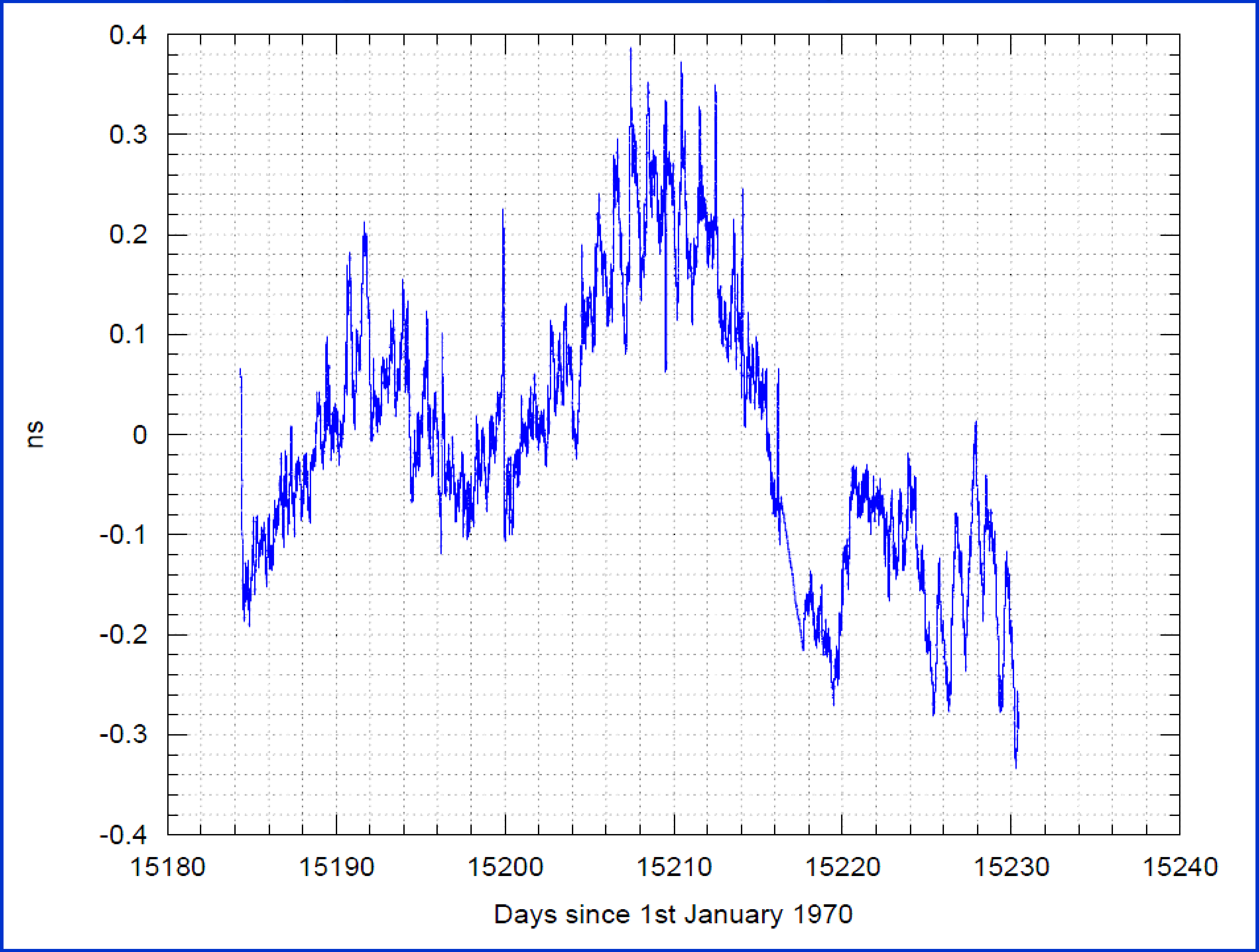


- **Double path fibers measurement:**

by swapping Tx and Rx component of the opto-chain



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

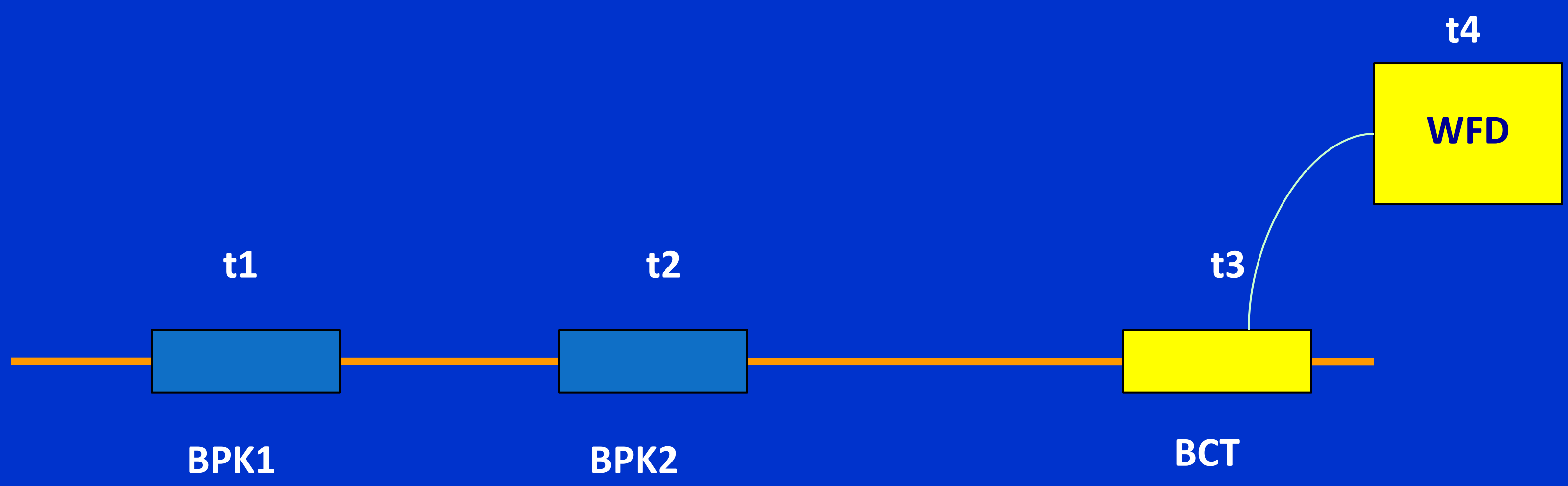


BCT calibration (1)

Dedicated beam experiment:

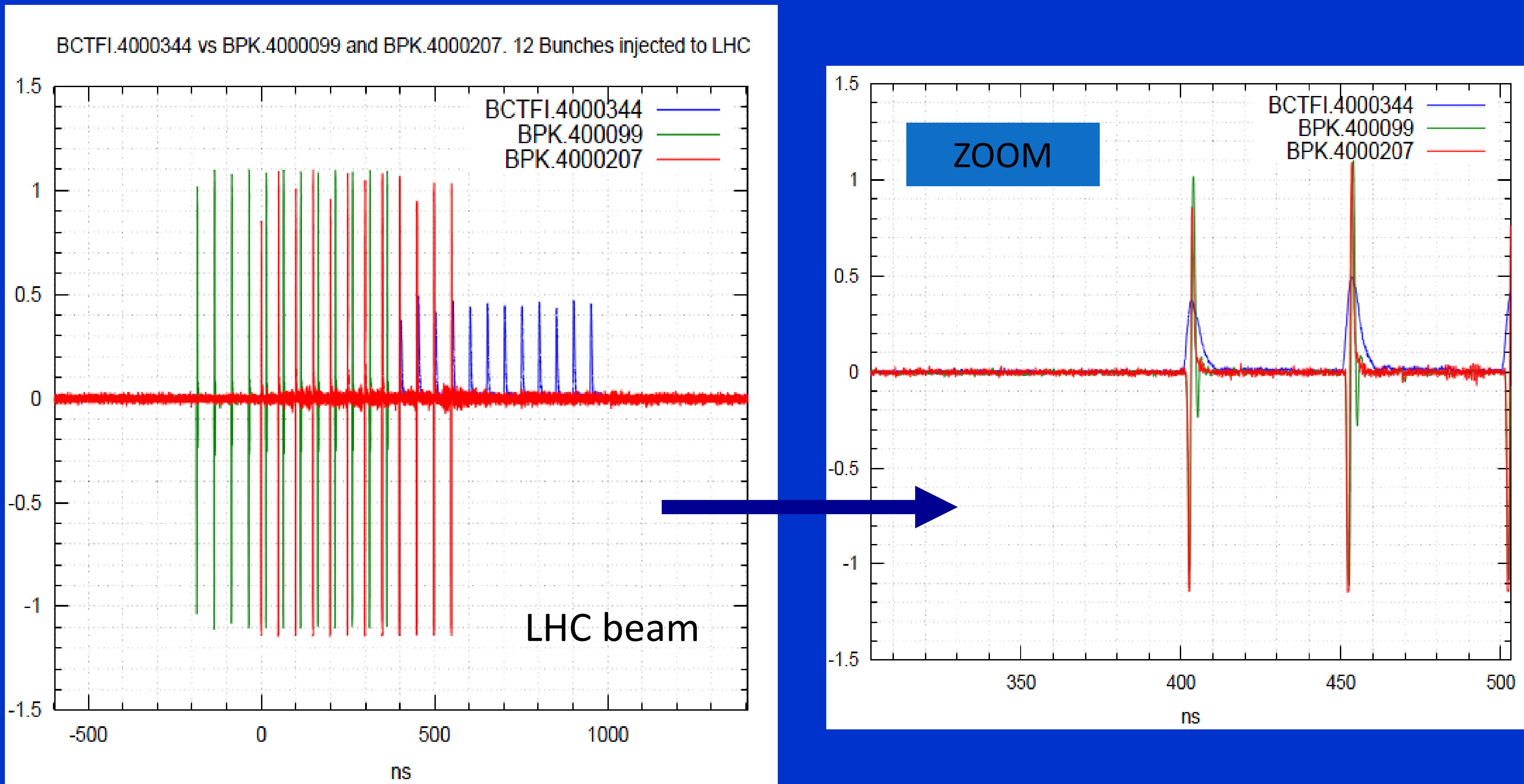
BCT plus two pick-ups (~1 ns) with LHC beam (12 bunches, 50 ns spacing)

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



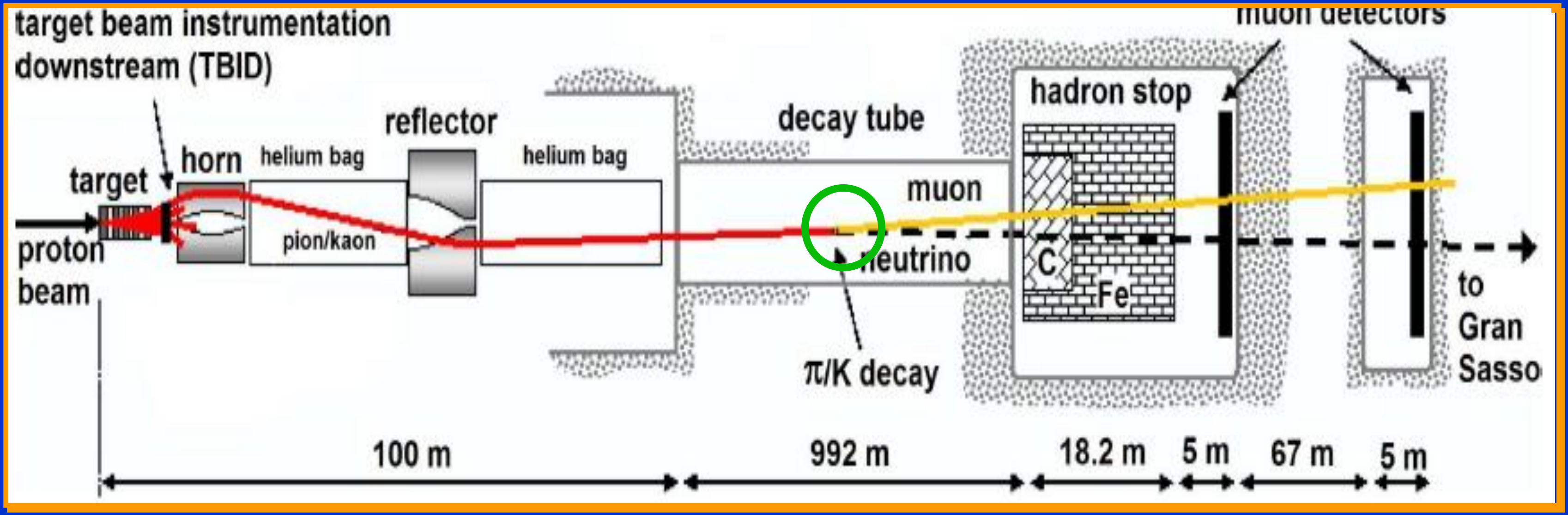
t3 : derived by t1 - t2 measurement and survey

BCT calibration (2)



result: signals comparison after Δ_{BCT} compensation

Neutrino production point



Unknown neutrino production point:

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

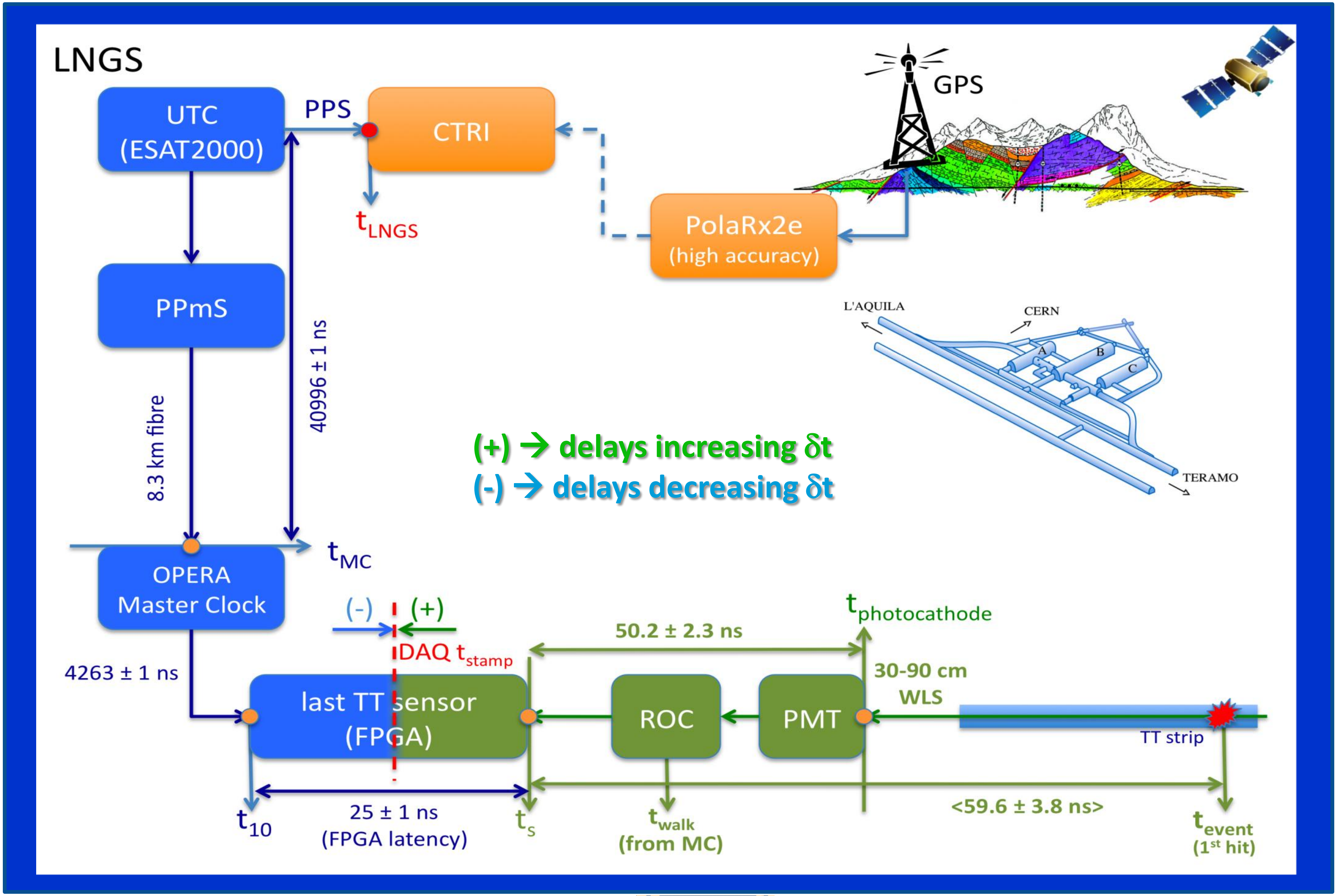
1)accurate UTC time-stamp of protons
2)relativistic parent mesons (full FLUKA simulation)

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

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

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

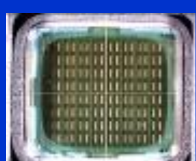
$\langle \Delta t \rangle = 1.4 \times 10^{-2}$ ns


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}
4263 ± 1 ns
last TT sensor (FPGA)
50.2 ± 2.3 ns
$t_{photocathode}$
30-90 cm WLS
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)

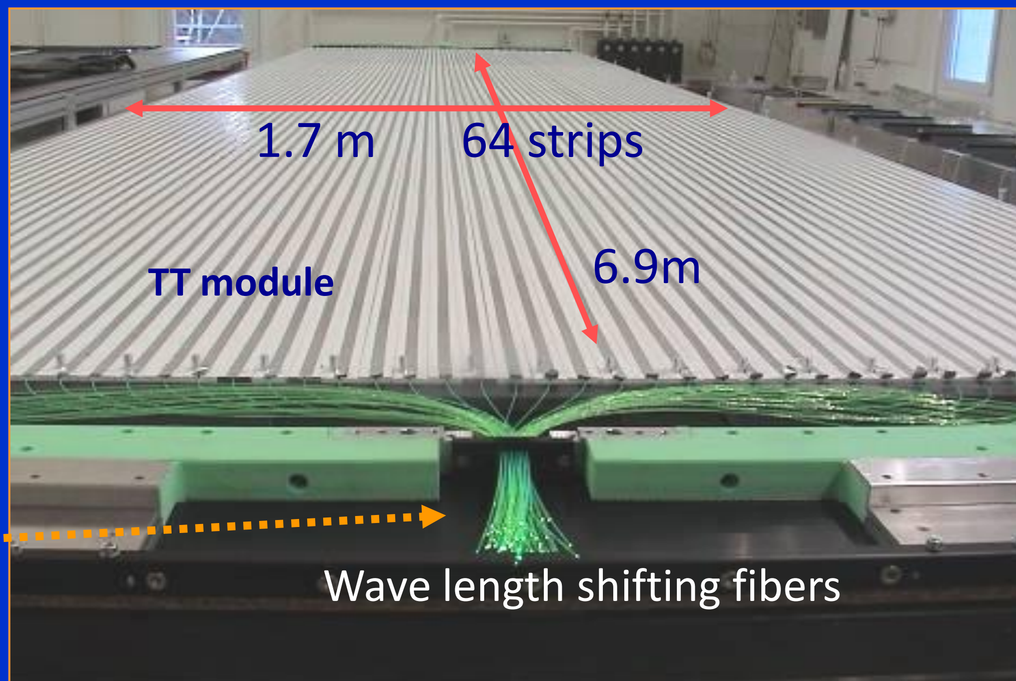
The Target Tracker (TT)

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)

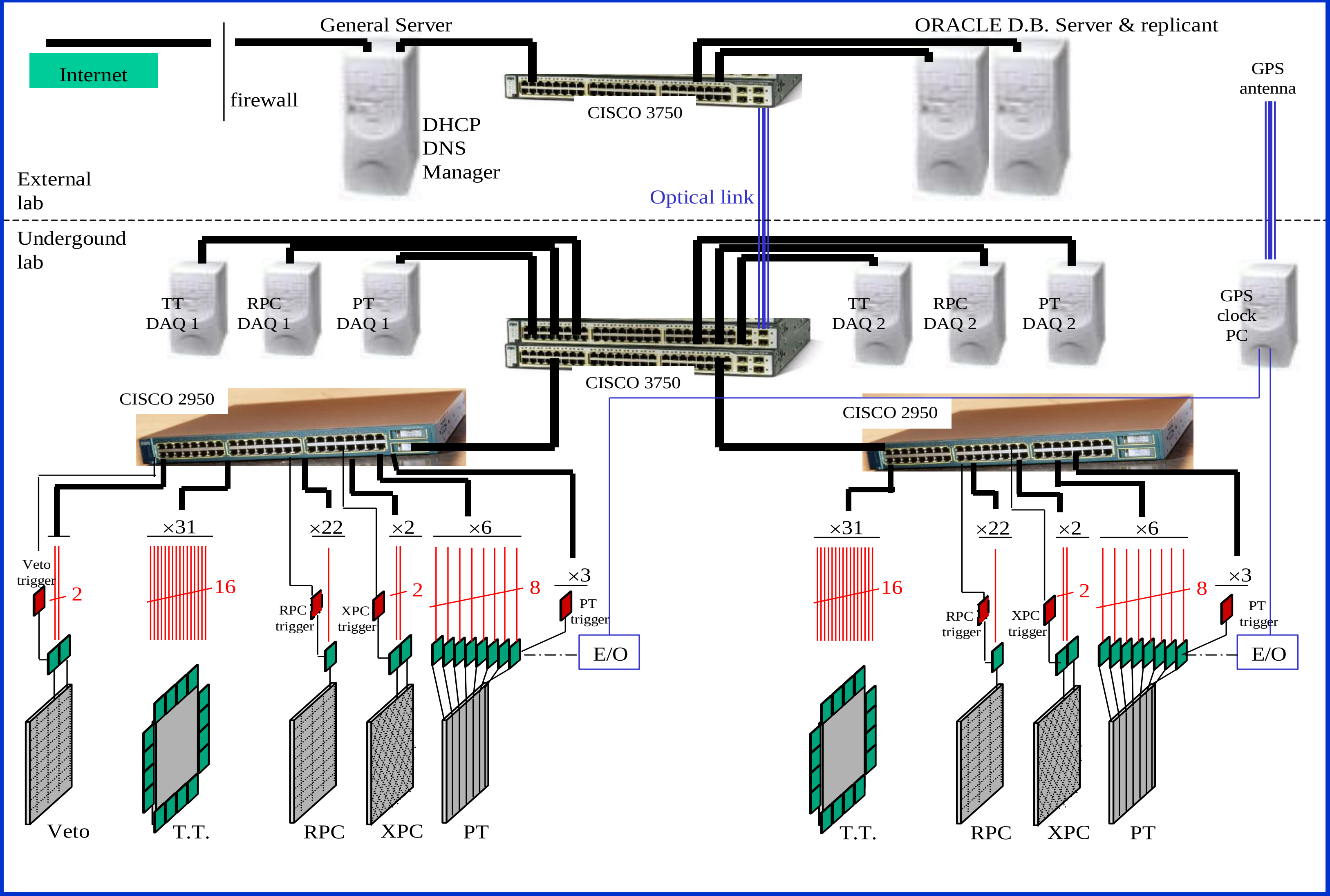


H7546



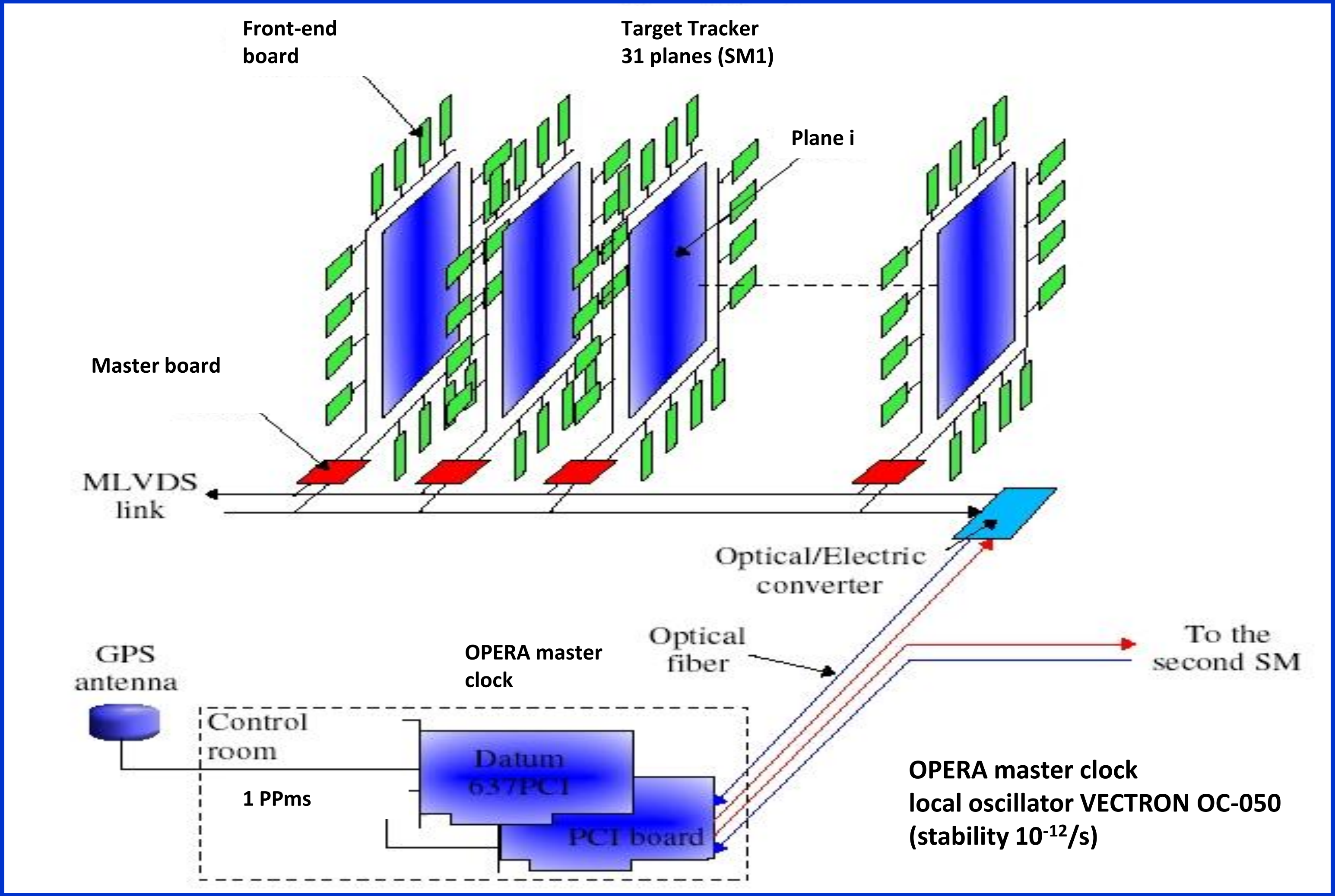
Read out by 1 Front-End DAQ board per side

OPERA readout scheme



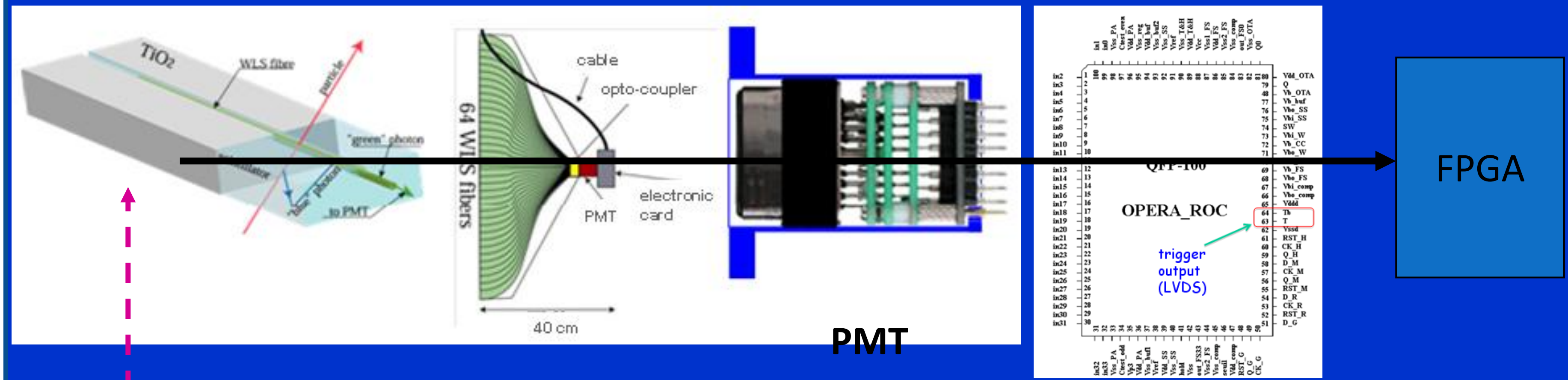
Trigger-less, asynchronous Front-End nodes (1200); Gigabit Ethernet network

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

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

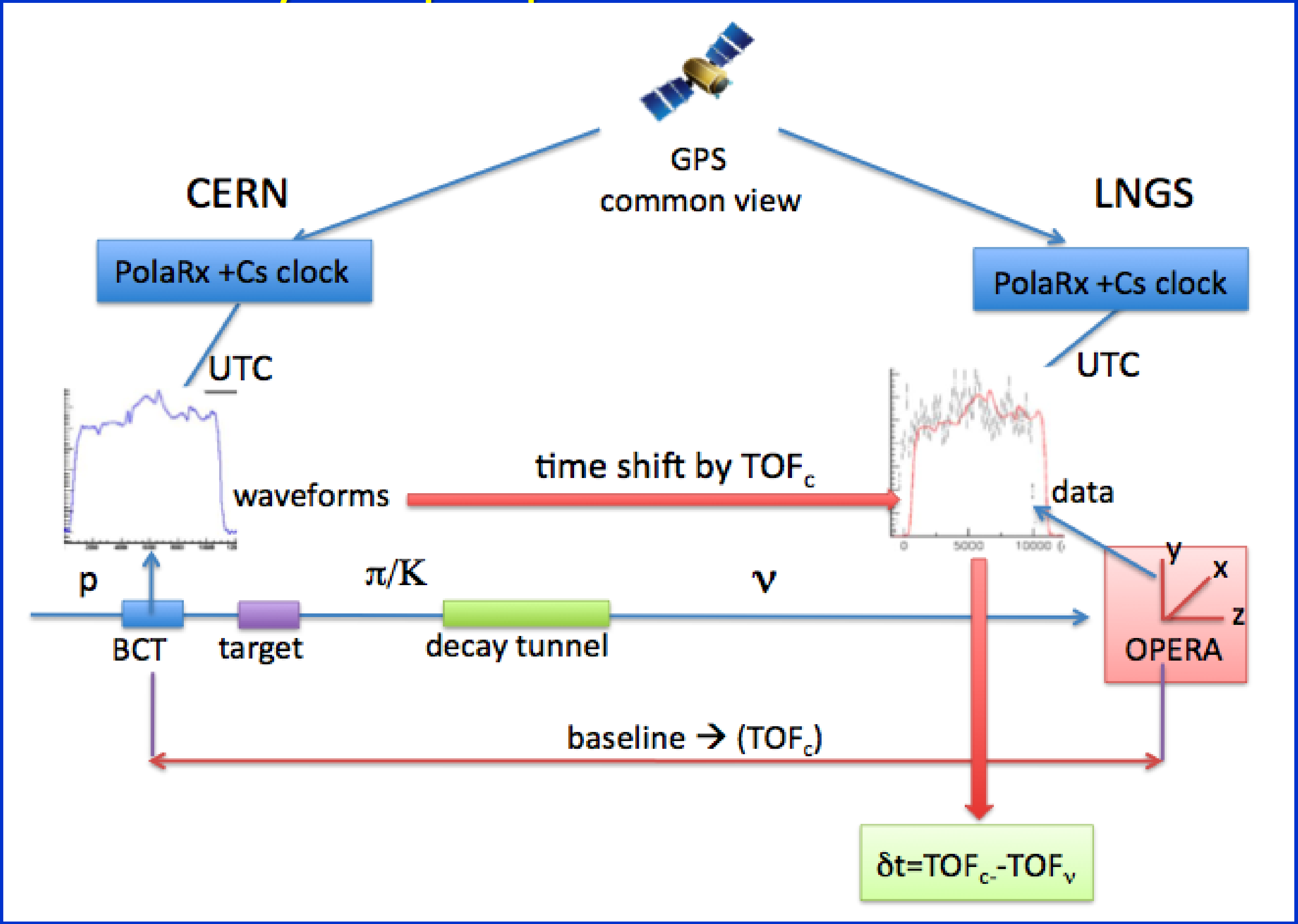
Average event time response: 59.6 ± 3.8 ns (sys)

(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

Summary of the principle for the TOF measurement



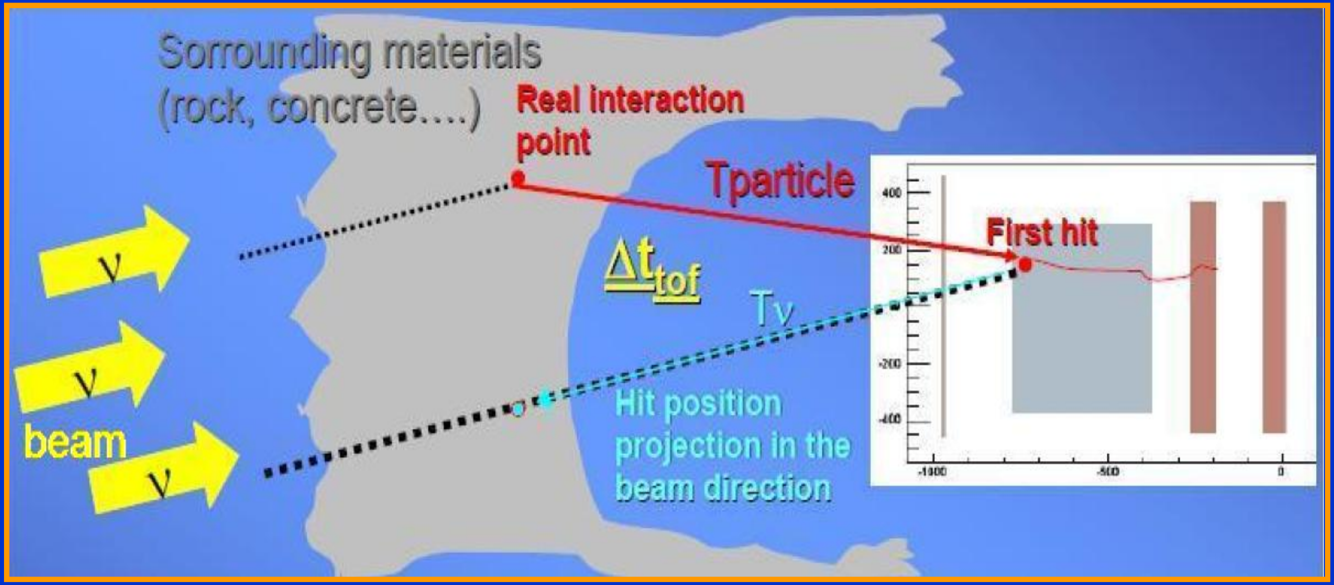
Measure $\delta t = TOF_c - TOF_\nu$

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

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

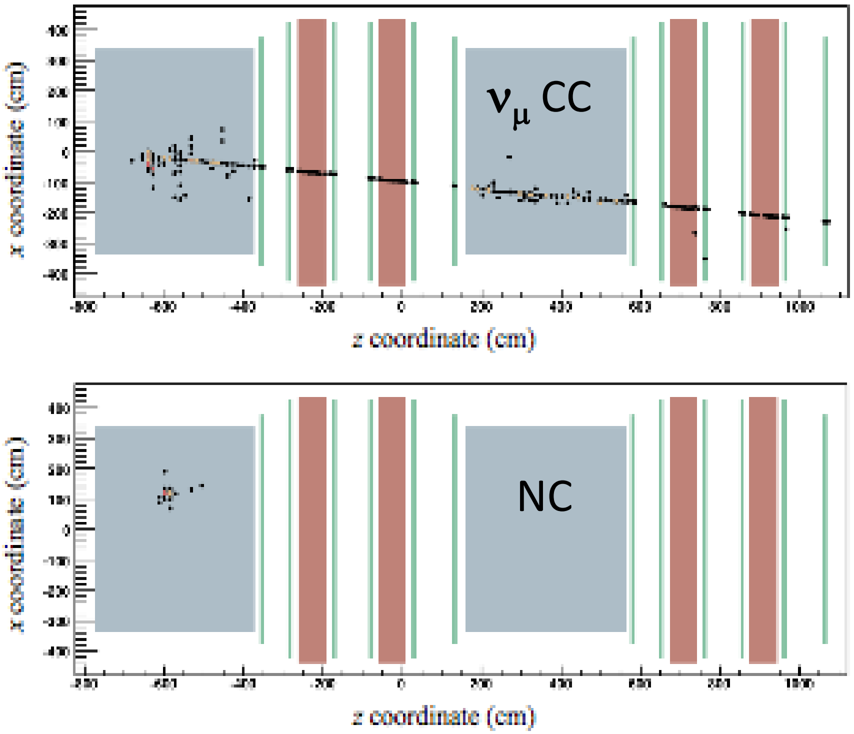
Internal events:
Same selection procedure as for oscillation searches: **7586 events**

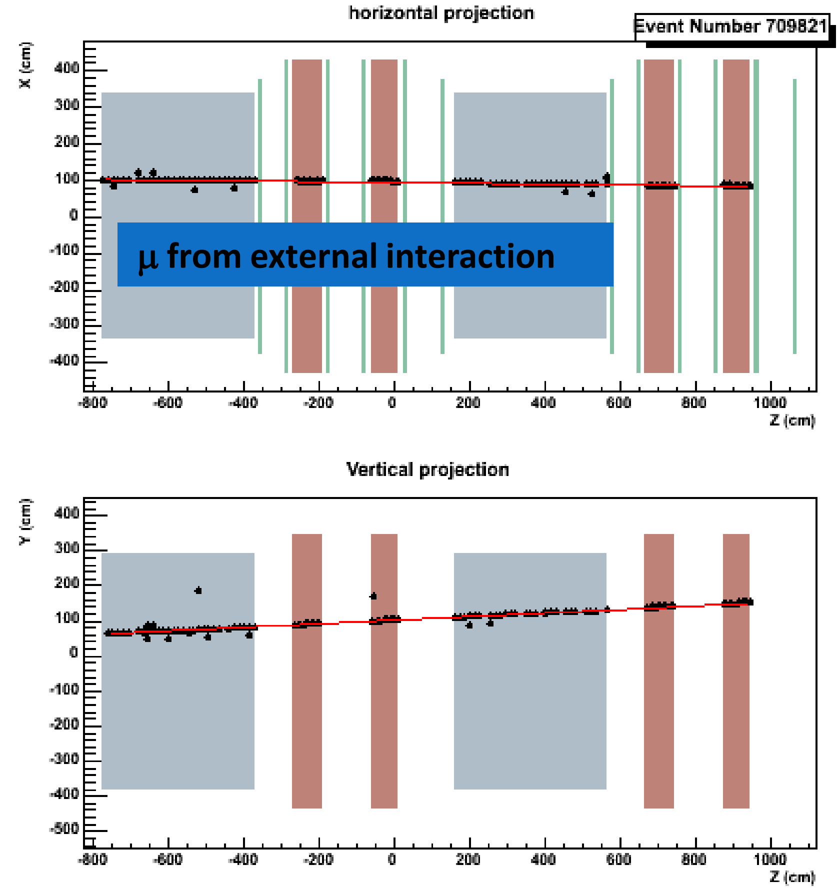
External events:
Rock interaction → require muon 3D track: **8525 events**
(Timing checked with full simulation, 2 ns systematic uncertainty by adding external events)



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

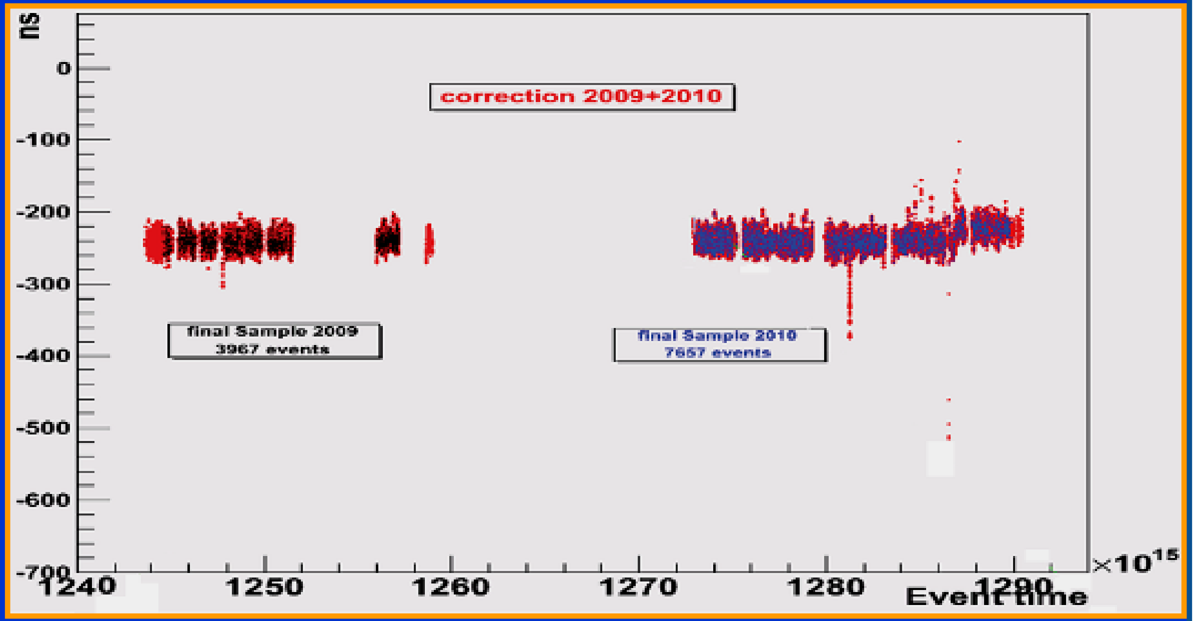
“INTERNAL” and “EXTERNAL” OPERA EVENTS

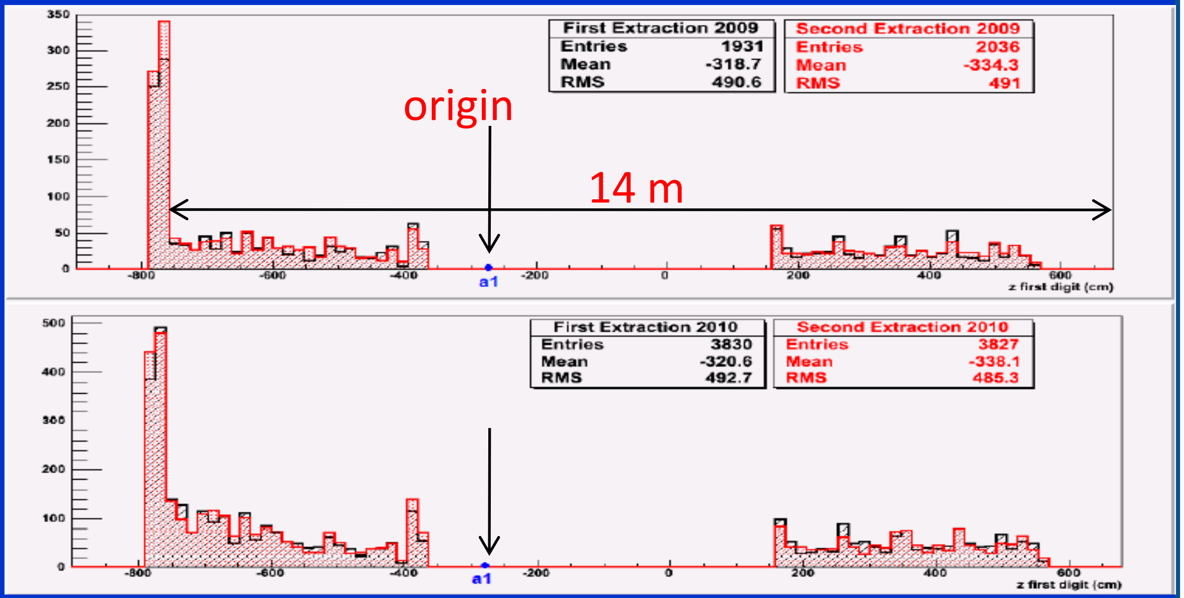




Event time corrections

Time-link correction (blue points)





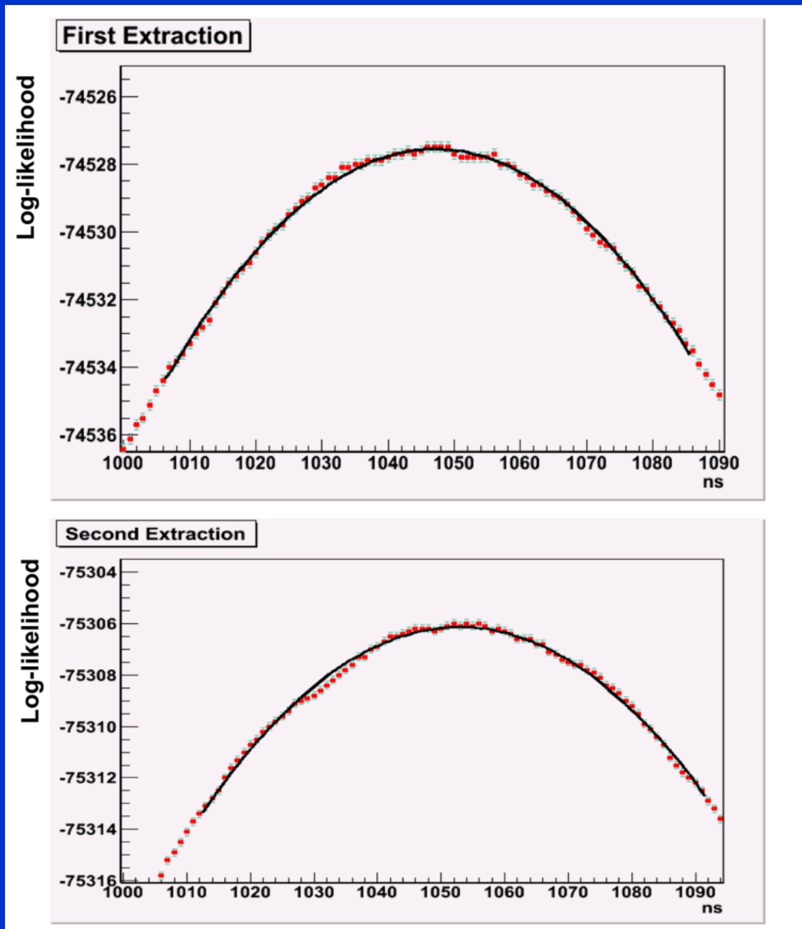
Correction due to the earliest hit position

average correction: 140 cm (4.7 ns)

Analysis method

For each neutrino event in OPERA → proton extraction waveform

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



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

Maximised versus δt:

$\delta t = TOF_c - TOF_\nu$

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

statistical error evaluated from log likelihood curves

“Blind “ analysis

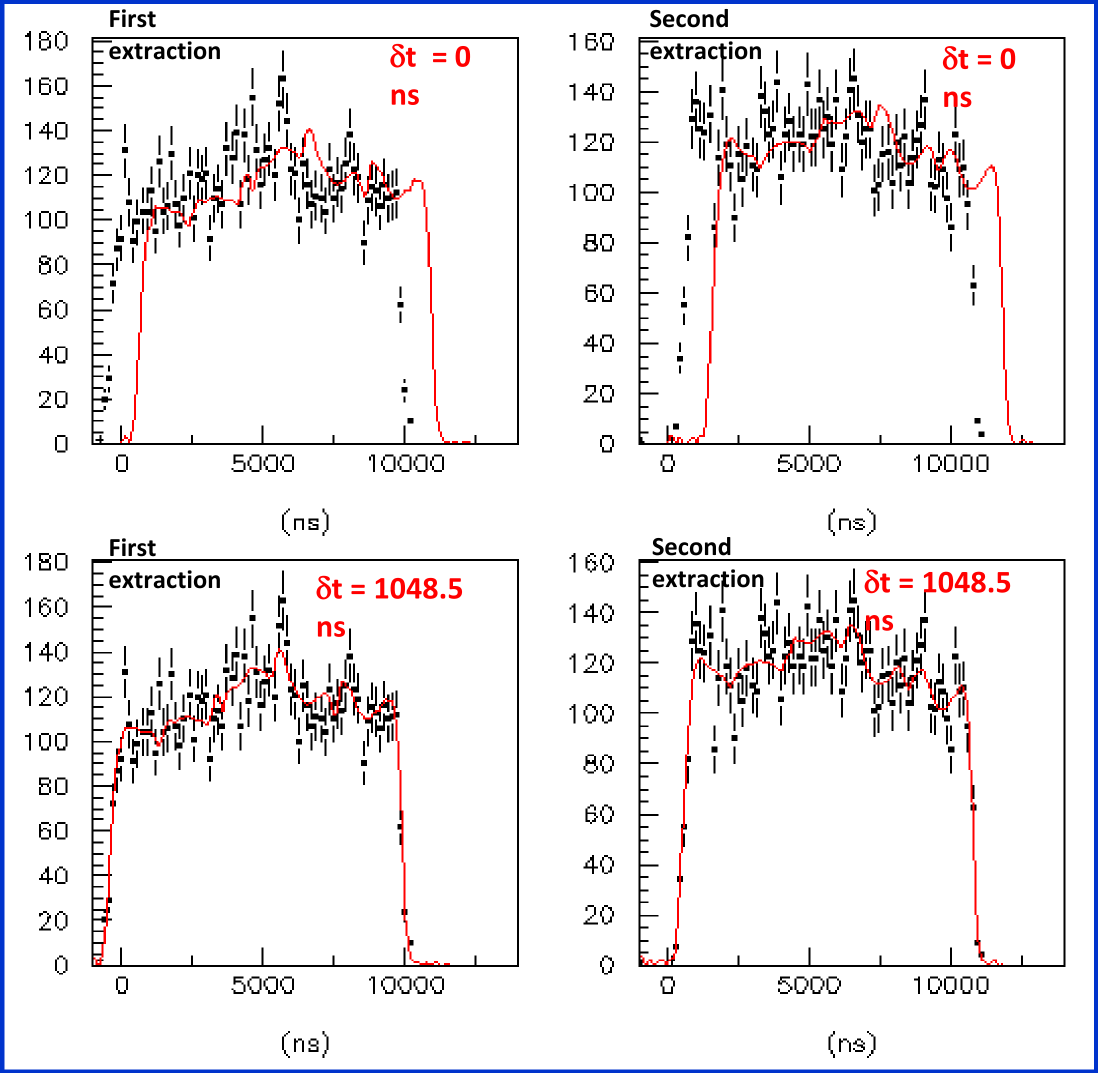
Analysis deliberately conducted by referring to the obsolete timing of 2006:

1) Wrong baseline, referred to an upstream BCT in the SPS, ignoring accurate geodesy
2) Ignoring TT and DAQ time response in OPERA
3) Using old GPS inter-calibration prior to the time-link
4) Ignoring the BCT and WFD delays
5) Ignoring UTC calibrations at CERN

→ Resulting δt by construction much larger than individual calibration contributions ~ 1000 ns

→ “Box” opened once all correction contributions reached satisfactory accuracy

Data vs PDF: before and after likelihood result



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

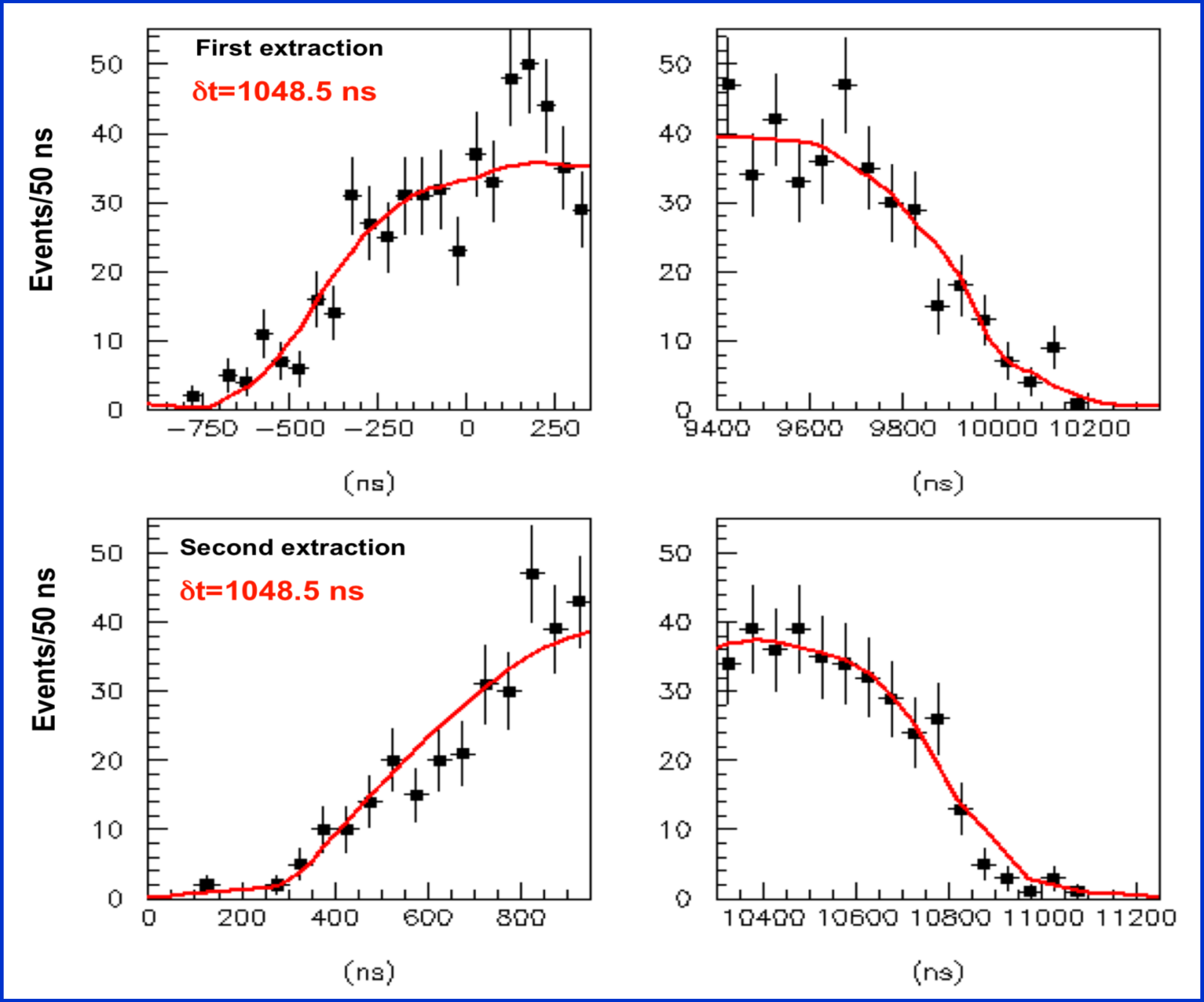
(1048.5 ± 6.9) ns (stat)

χ^2 / ndof :

first extraction: 1.06

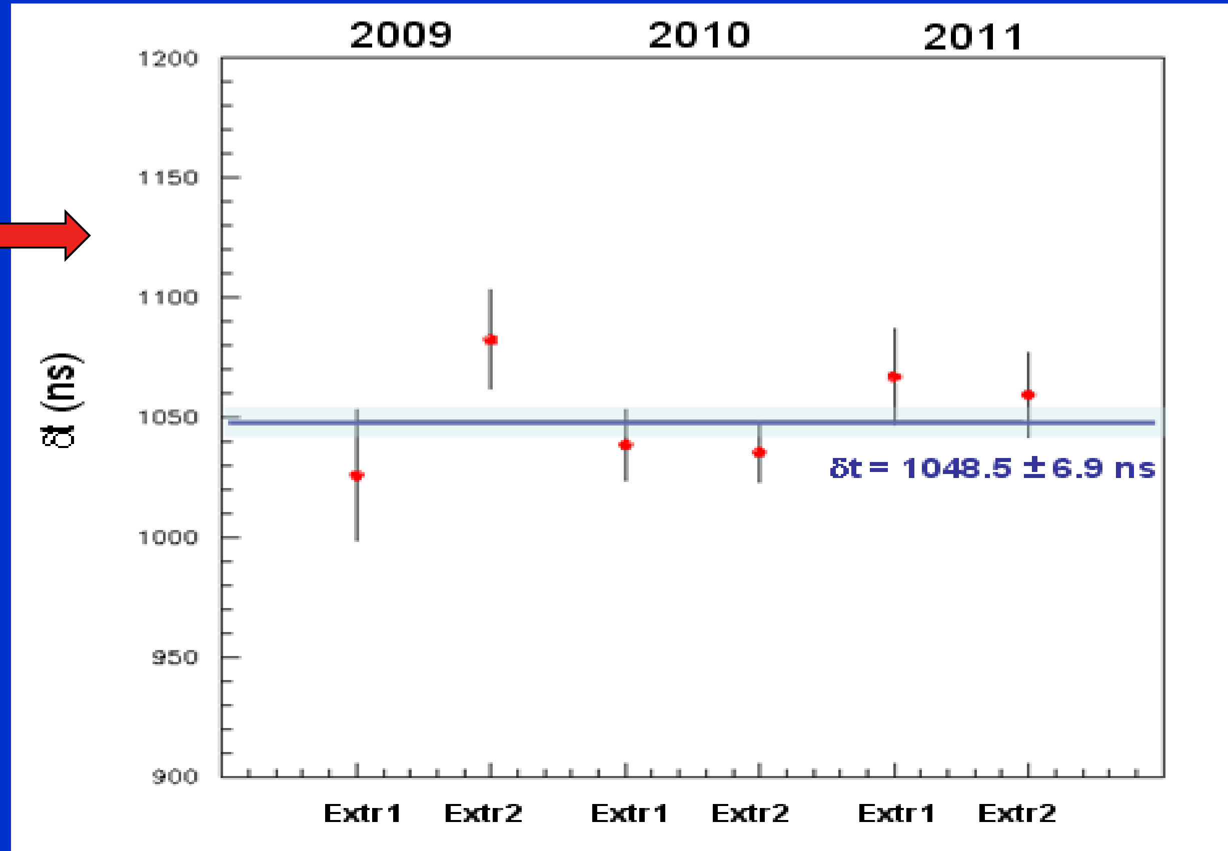
second extraction: 1.12

Zoom on the extractions leading and trailing edges



Analysis cross-checks

1) Coherence among CNGS runs/extractions



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

|d-n|: (17.1 ± 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

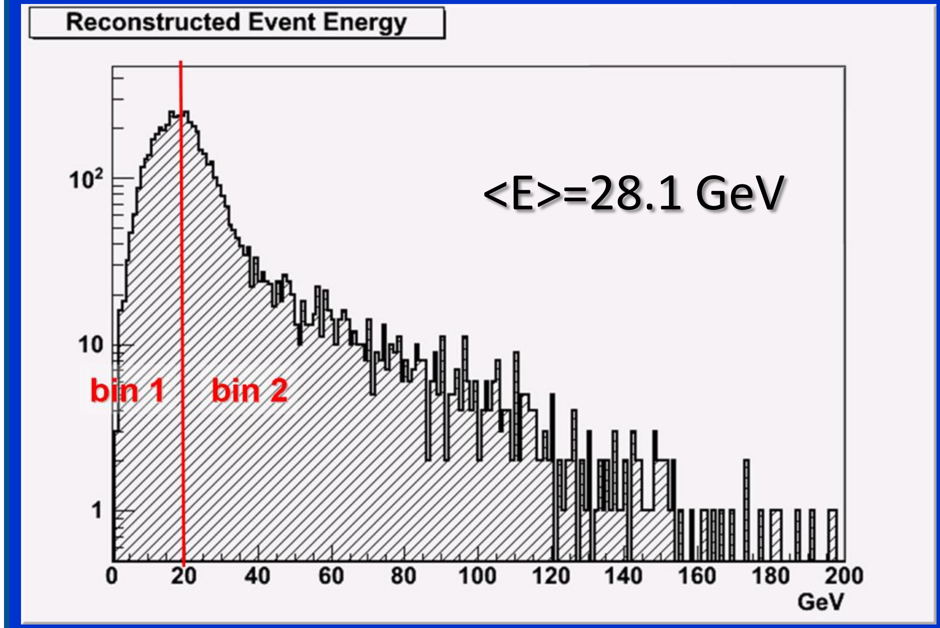
relative difference of neutrino velocity w.r.t. *c:*

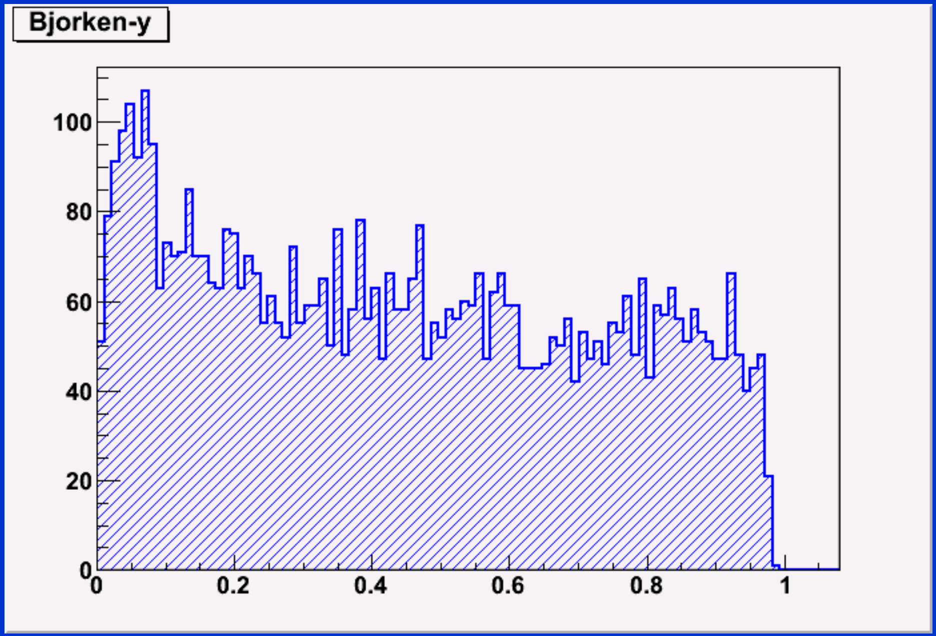
$(v-c)/c = \delta t / (TOF_c - \delta t) = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$

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

6.0 σ significance

Study of the energy dependence





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

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

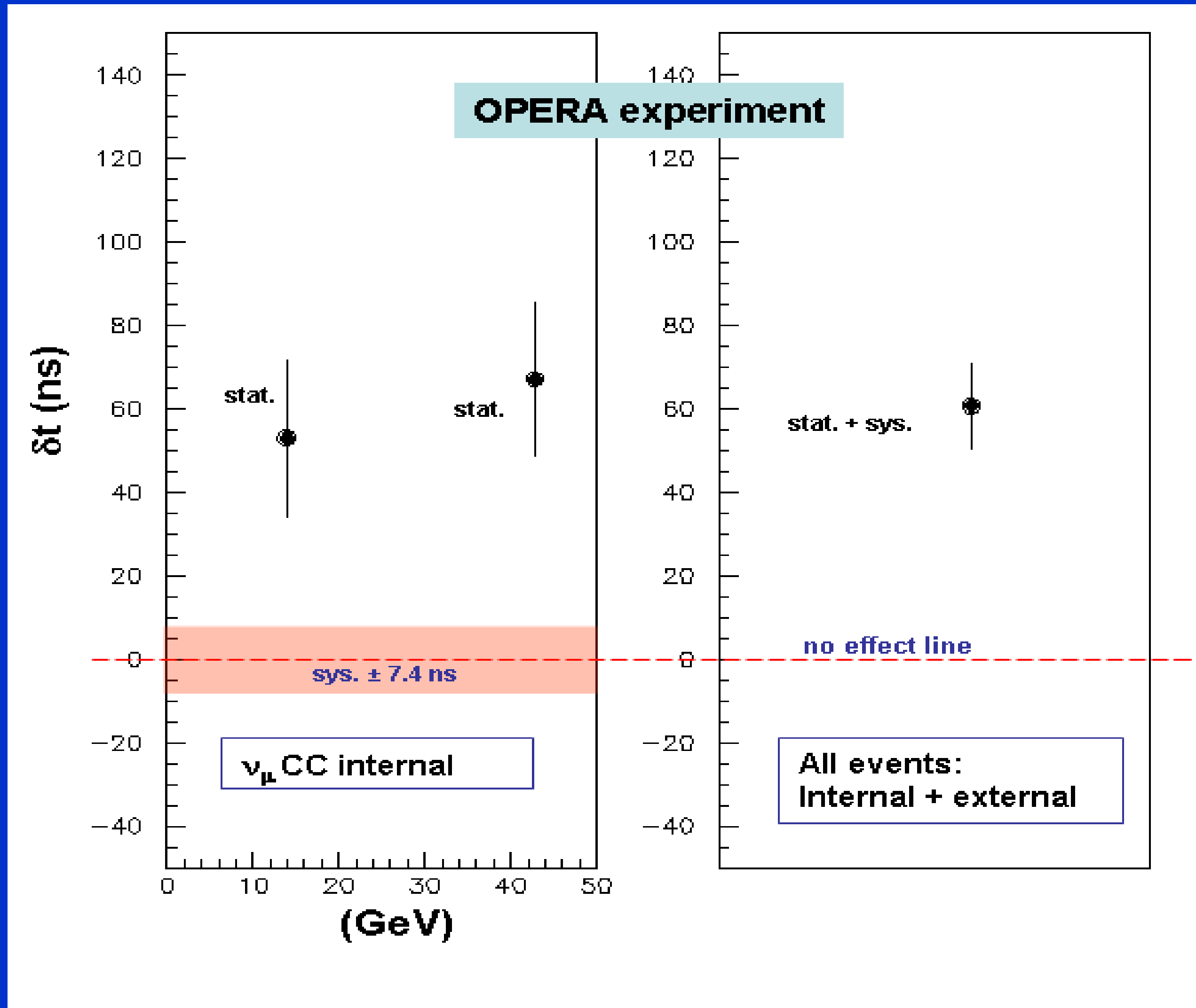
- Full MC simulation: no energy bias in detector time response (<1 ns)

→ systematic errors cancel out

$\delta t = TOF_c\text{-}TOF_\nu = (60.3 \pm 13.1\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ 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



OPERA

G. Rosa – Rome, Oct. 11th 2011
Dept. Of Physics – Sapienza University

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.

(My) conclusions (3)
[The Day After…]

Results scrutinized worldwide by the scientific community

Apart from "skepticism" and "irony", many valuable hints to improve/clarify the issue

Questions about geodesy, time synchronization, calibration methods ~answered

Main concern (and criucial point): rely on BCT timing and the corresponding reference PDF. Further analysis in progress

The "anomaly" till now survived, but unknown systematics could still be there

Interesting experimental follow-up envisaged by MINOS, T2K, and CNGS itself (e.g. Pulsed beam operation, muon pit monitoring, OPERA checks with RPC etc.)

I do not feel allowed to "hope it is true" or "do not believe by prejudice": mostly I'm CURIOUS to see the outcome, and I'll stick to the experimental protocol [do (accurate) measurements, estimate systematics and statistical errors, and make results PUBLIC]

More news to follow ….

Thank you for coming!