

Neutrini superluminali: OPERA/ICARUS

Alessandro Menegolli

Contenuti

- Il risultato di OPERA sui neutrini superluminali
- Previsioni sullo spettro dei ν_μ CC @ LNGS
- Risultati di ICARUS T600 sullo spettro dei ν_μ CC
- La misura diretta del tempo di volo dei ν_μ in ICARUS

Caveat

- OPERA non misura direttamente la velocità del neutrino intesa come $\Delta x / \Delta t$, ma un anticipo del tempo di arrivo del neutrino rispetto al tempo di arrivo che il neutrino avrebbe se viaggiasse alla velocità della luce nel vuoto.
- In questa presentazione non si intende dare un'interpretazione teorica o fenomenologica dei risultati.

Neutrini superluminali in OPERA

(OPERA Collaboration, ArXiv 1109.4897v2)

http://www.nu.to.infn.it/SuperLuminal_Neutrino/

http://www.hep.ph.ic.ac.uk/~shitov/nu_tachyon_arxiv_paper_short_digest.htm

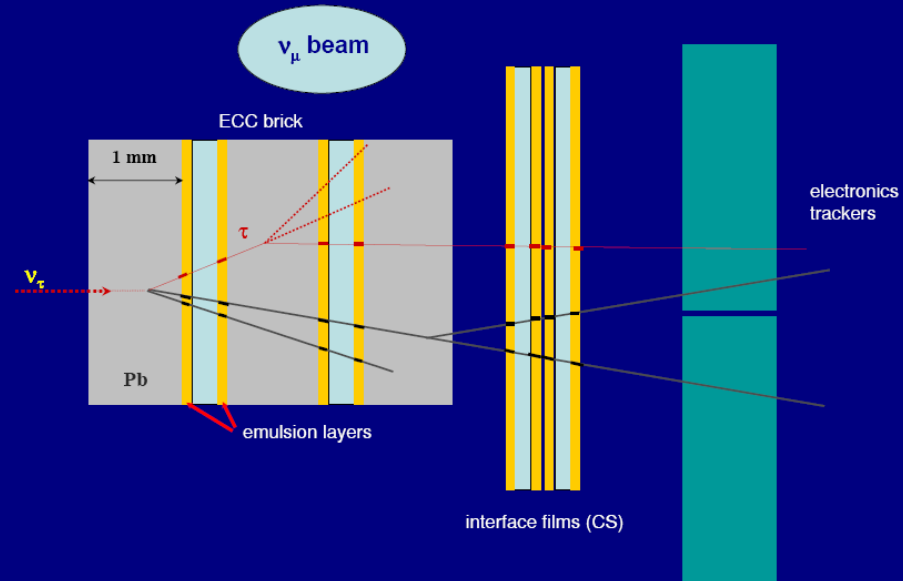
<http://web.mit.edu/redingtn/www/netadv/XftlNu.html>

144 ArXiv preprints sull'argomento a partire dal 22 Settembre 2011 al 6 Dicembre 2011:

~ 2 preprints/giorno!!!

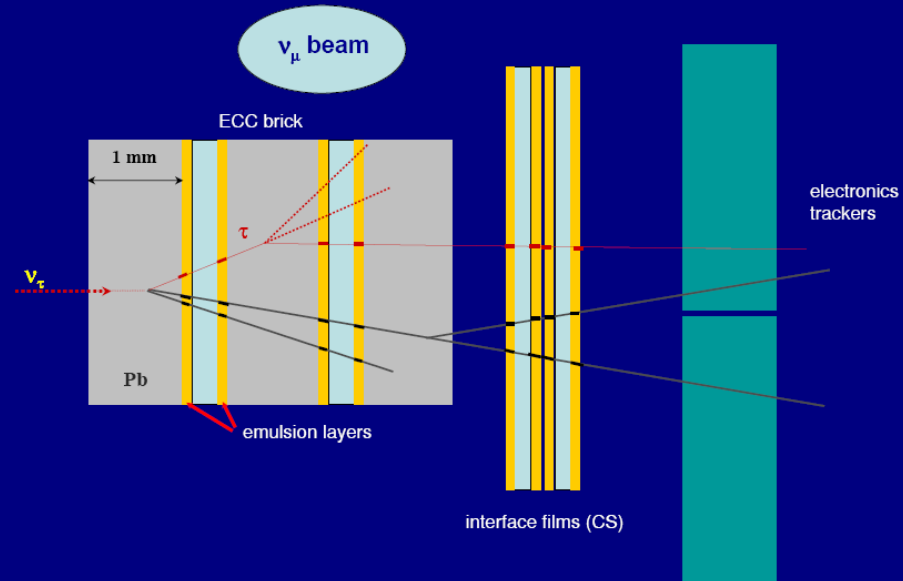
OPERA

THE DESIGN OF THE OPERA EXPERIMENT ECC BRICKS + ELECTRONIC DETECTORS FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATION STUDIES

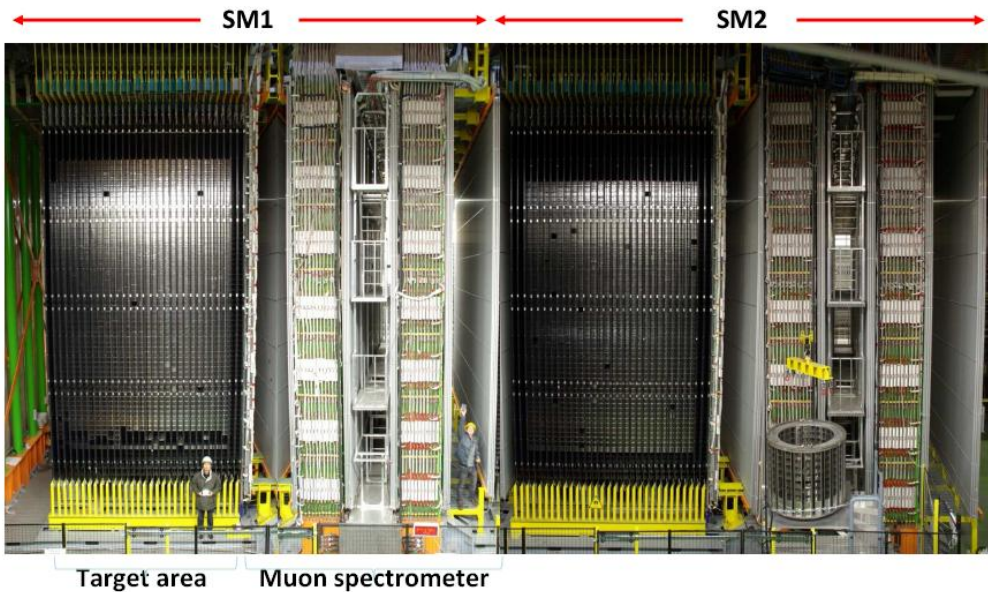


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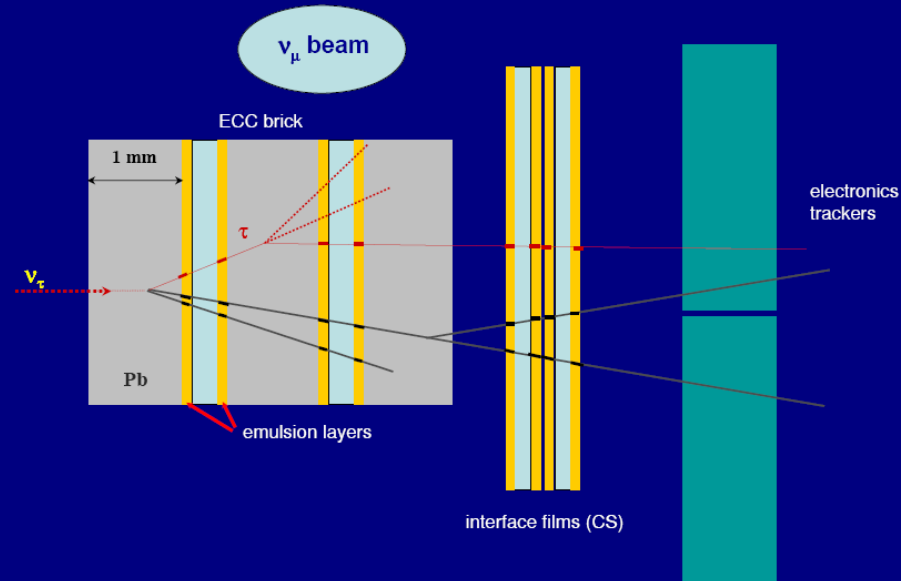


THE IMPLEMENTATION OF THE PRINCIPLE

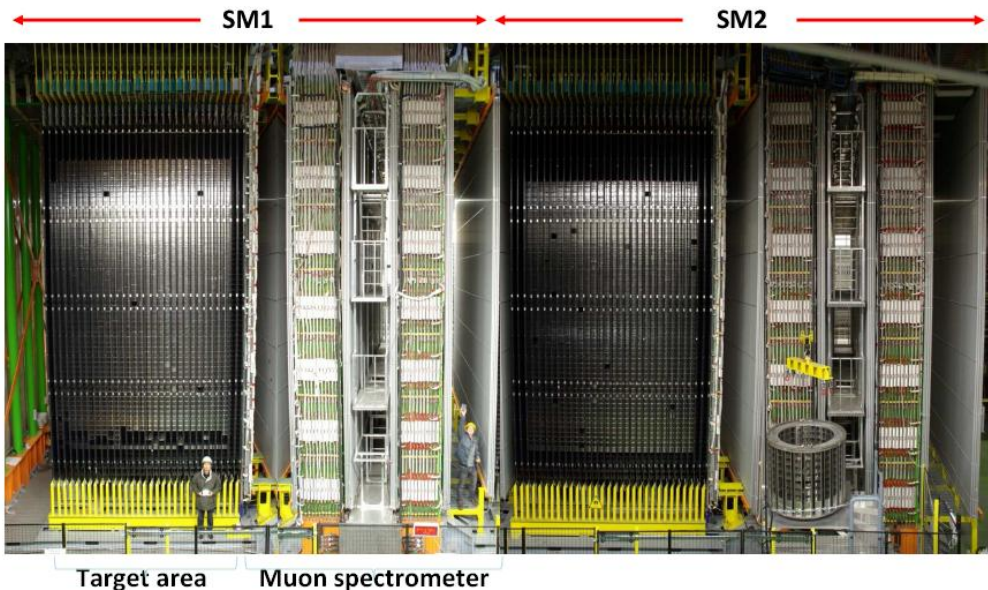


OPERA

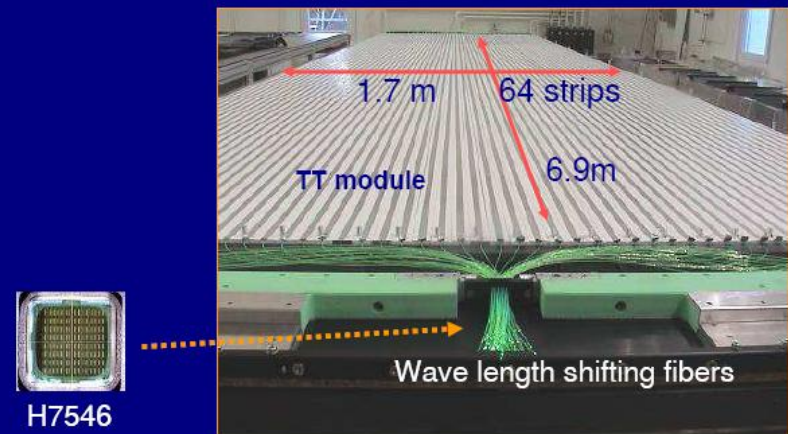
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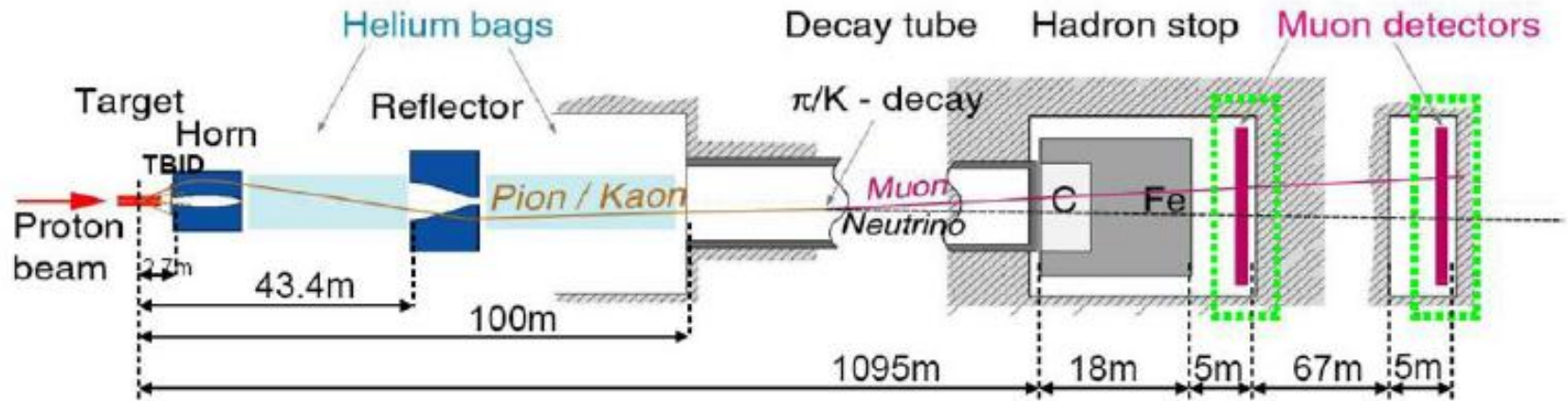
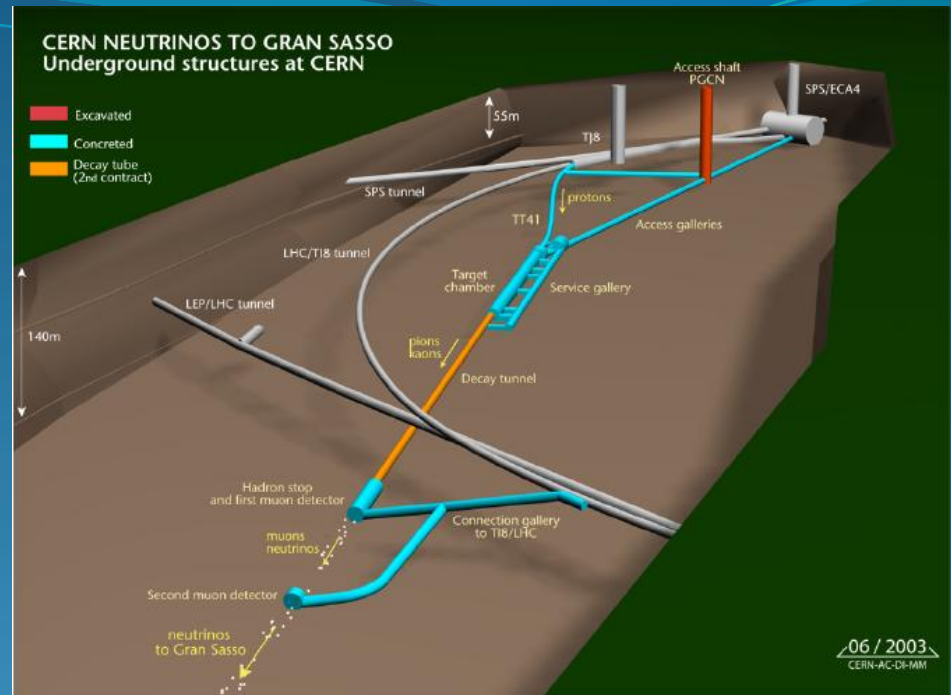
THE IMPLEMENTATION OF THE PRINCIPLE



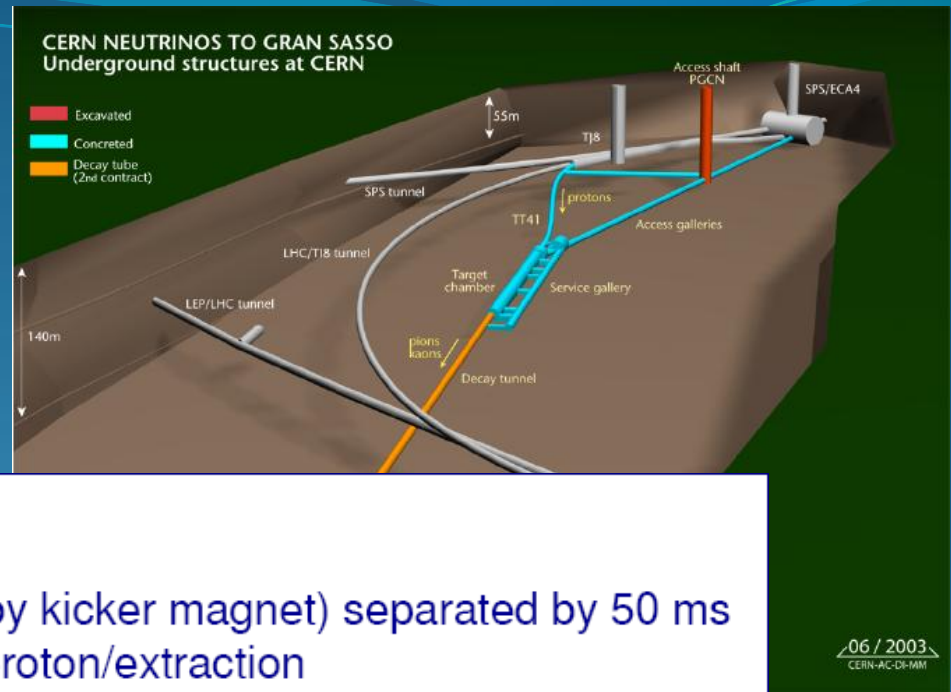
Horizontal and vertical scintillator strips for timing and neutrino interaction localization



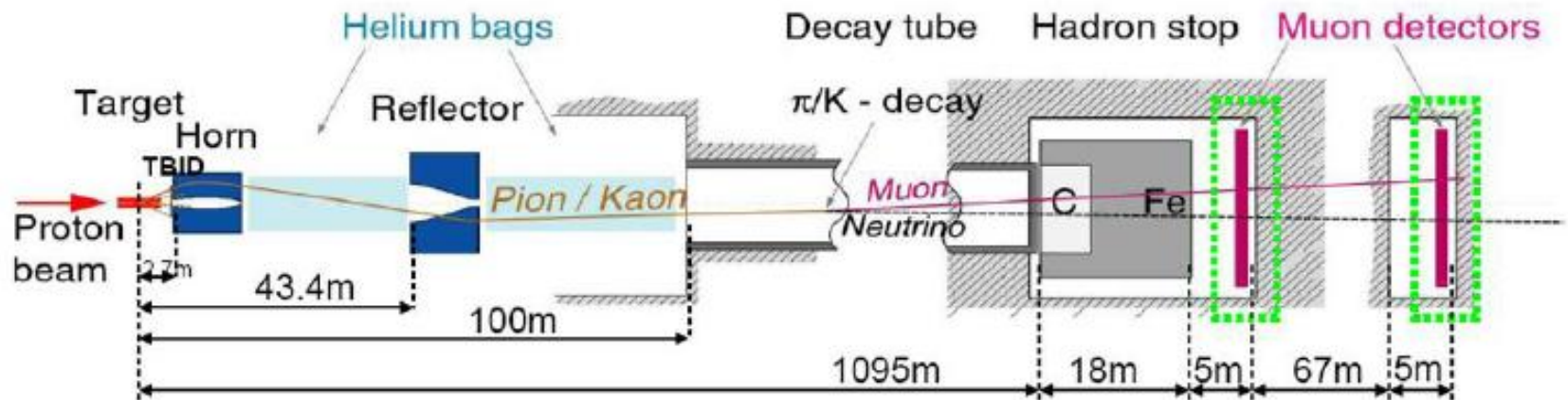
Il fascio CNGS



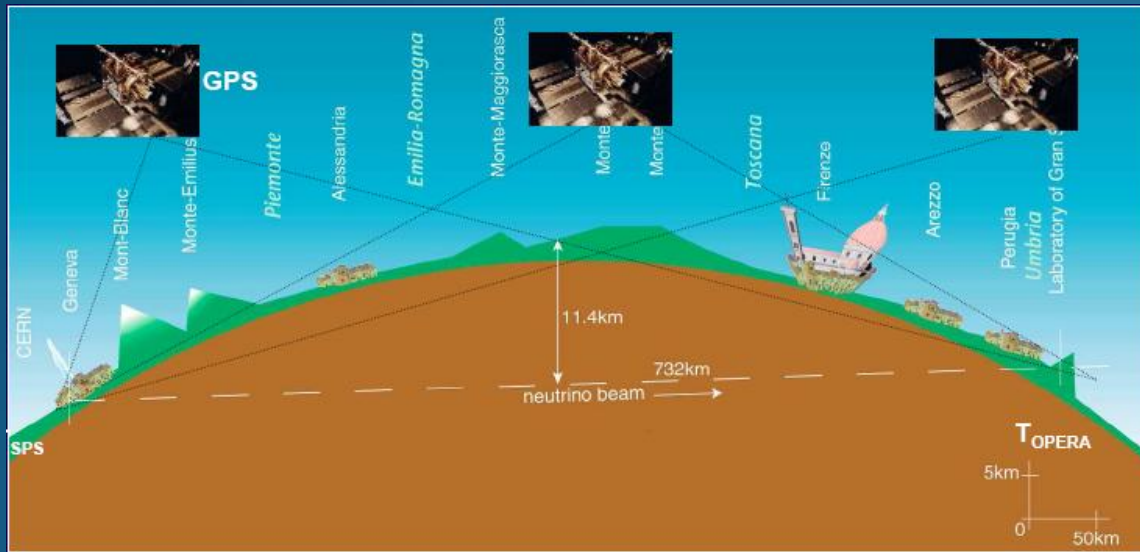
Il fascio CNGS



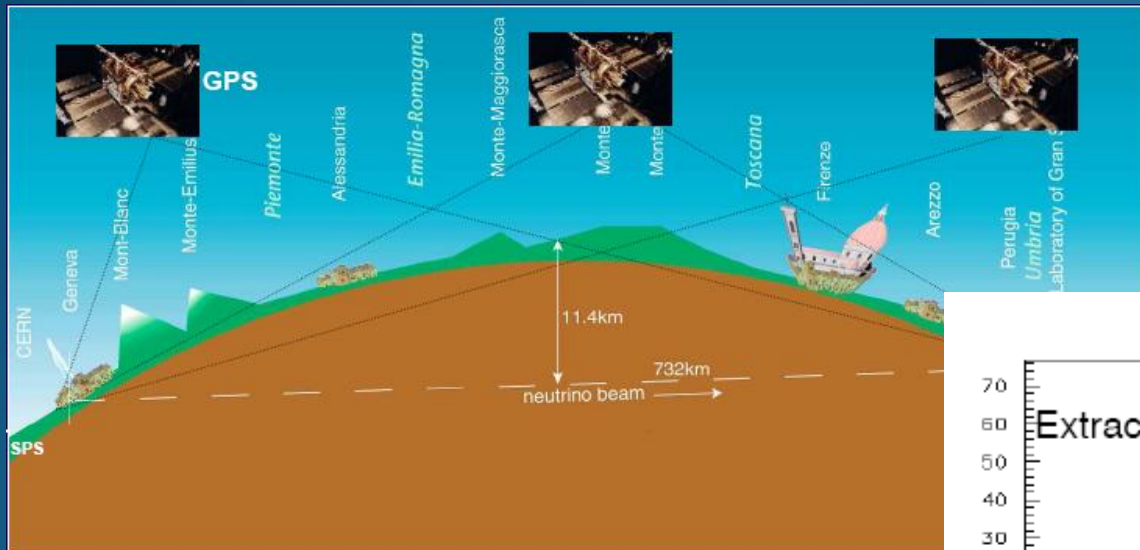
- SPS protons: 400 GeV/c
- Cycle length: 6 s
- Two 10.5 μ s extractions (by kicker magnet) separated by 50 ms
- Beam intensity: $2.4 \cdot 10^{13}$ proton/extraction
- ~ pure muon neutrino beam ($\langle E \rangle = 17$ GeV) travelling through the Earth's crust



Selezione degli eventi

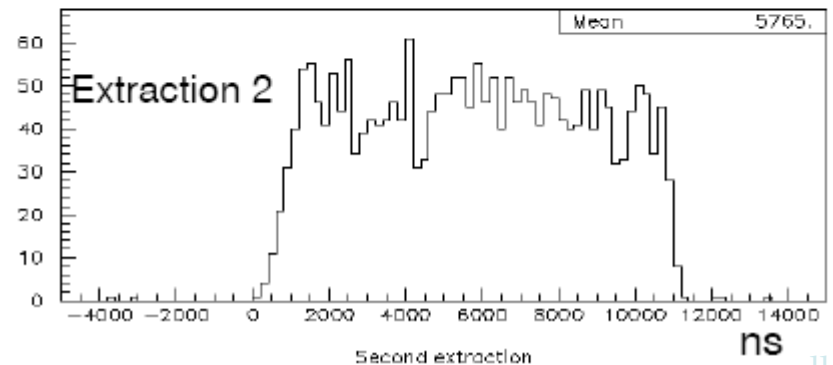
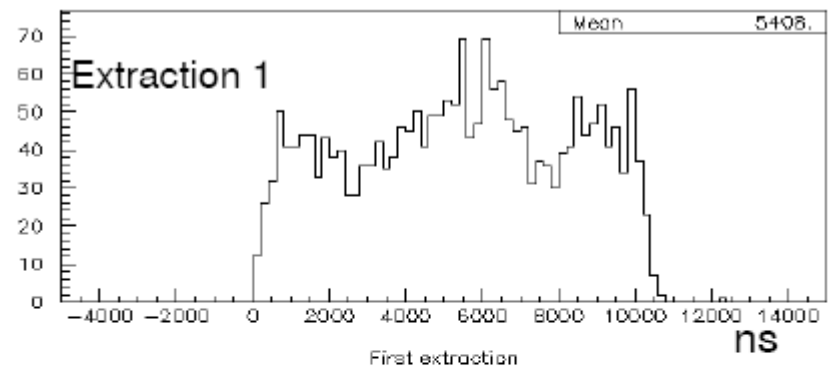


Selezione degli eventi

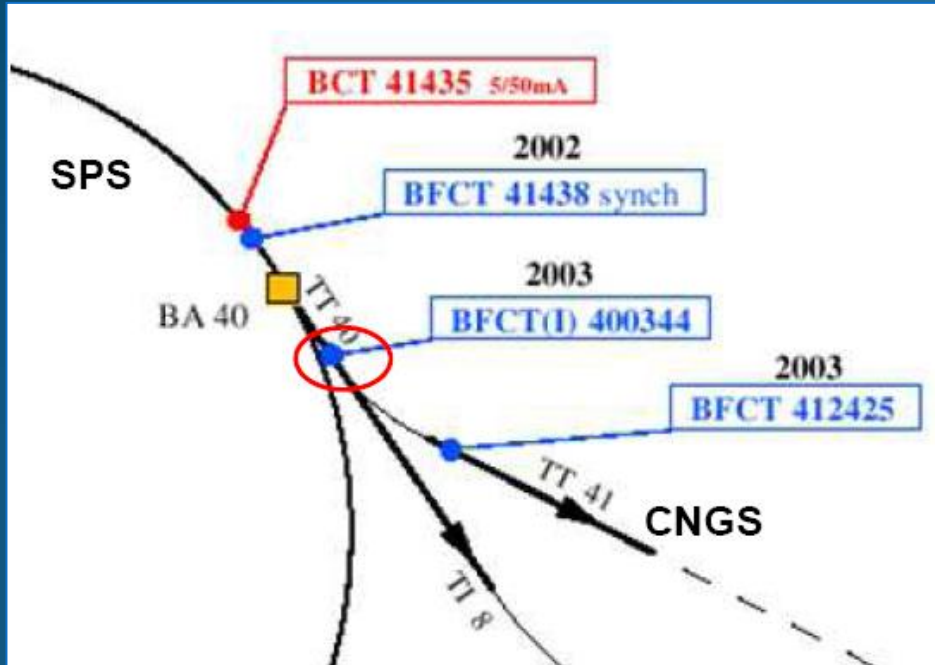


Distribuzione dei tempi di arrivo dei neutrini in OPERA

Il tempo di arrivo dei neutrini (UTC time-stamp) è misurato rispetto al tempo di kicker del magnete che estrae i protoni dal fascio SPS

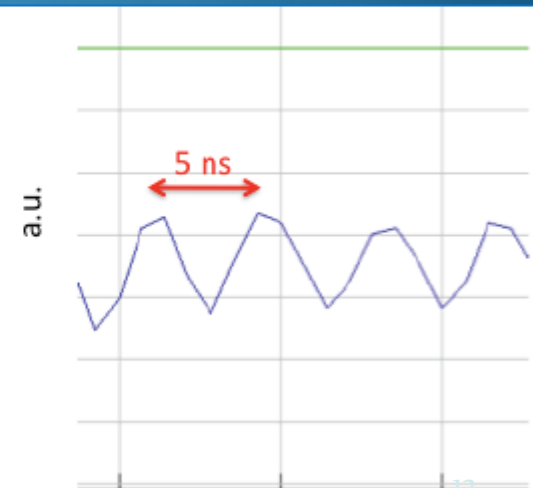
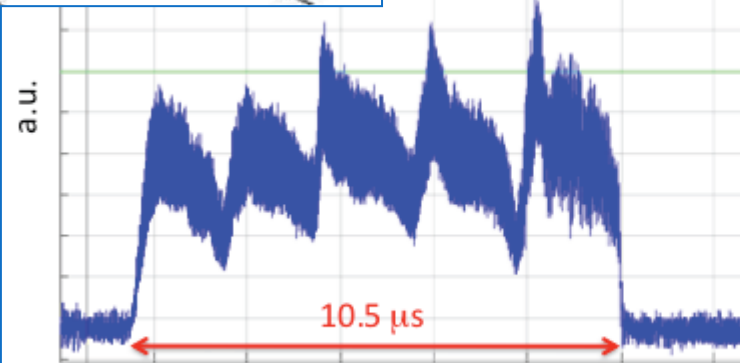


Proton timing: Beam Current Transformer (BCT)

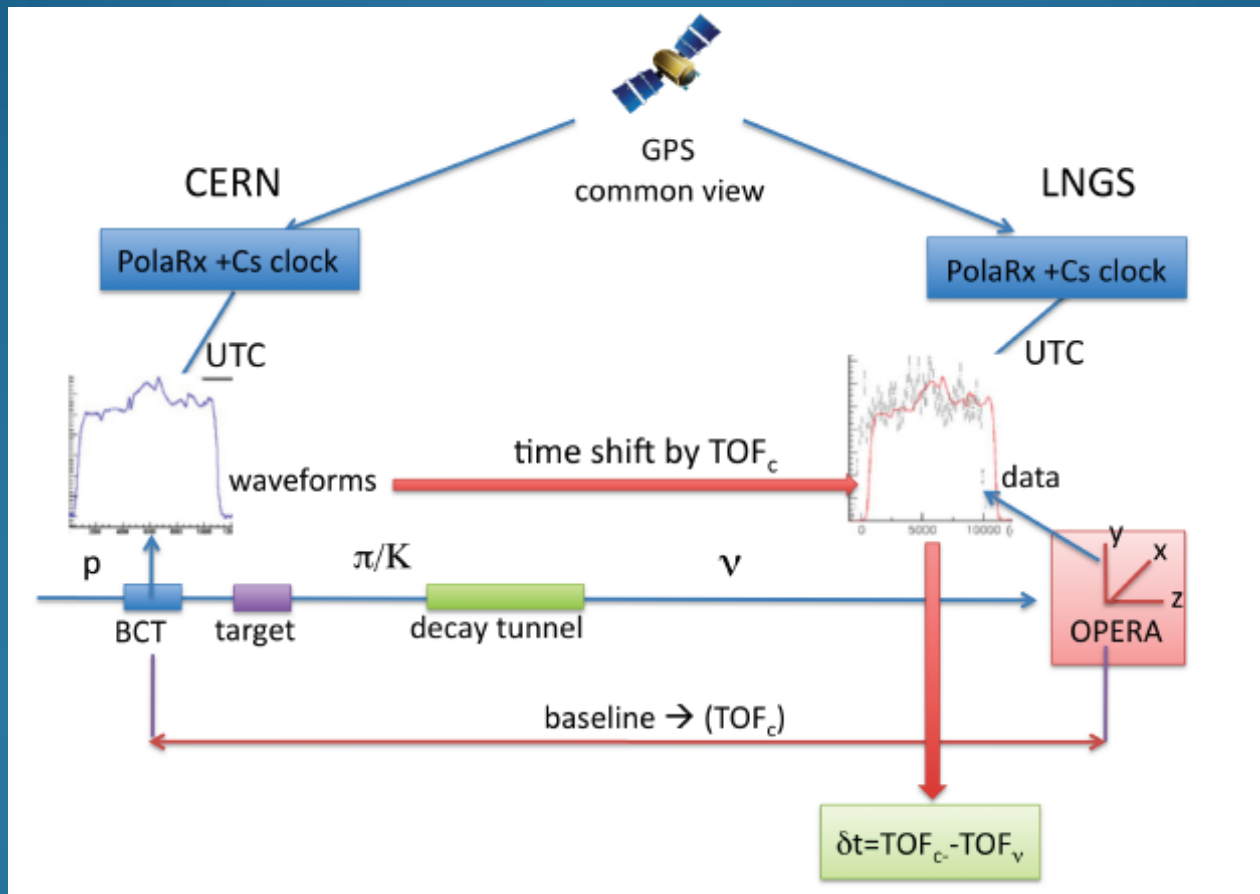


Proton pulse digitization:

- 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

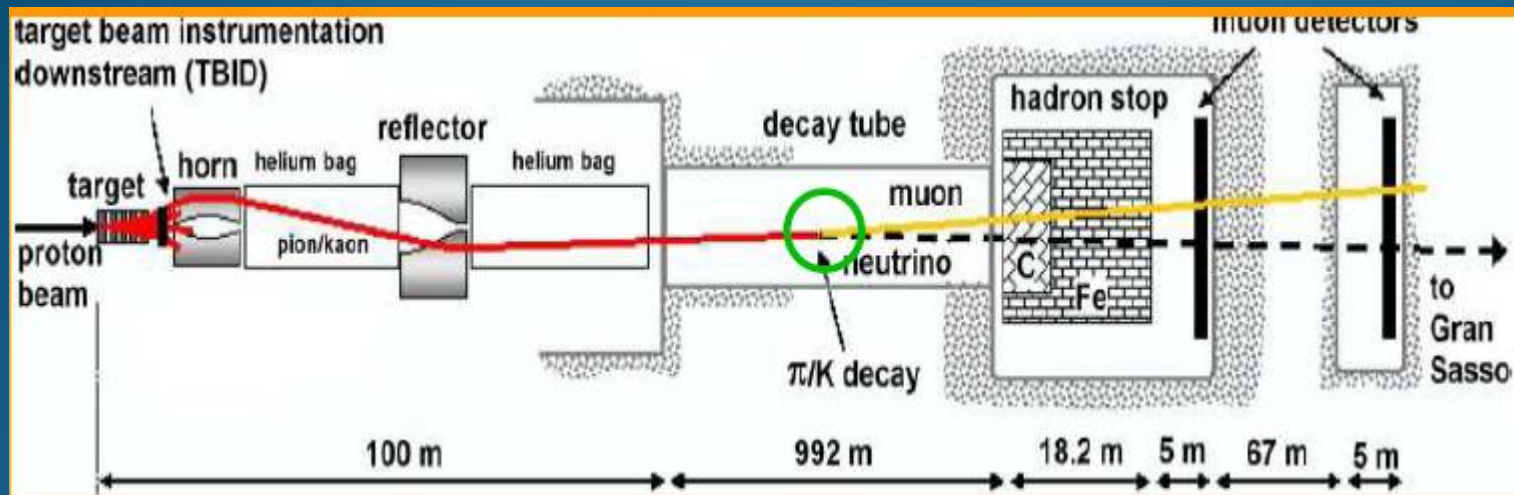


La misura del ν_μ TOF



Si misura $\delta t = \text{TOF}_c - \text{TOF}_\nu$

Punto di produzione del ν ???



Unknown neutrino production point:

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

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

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

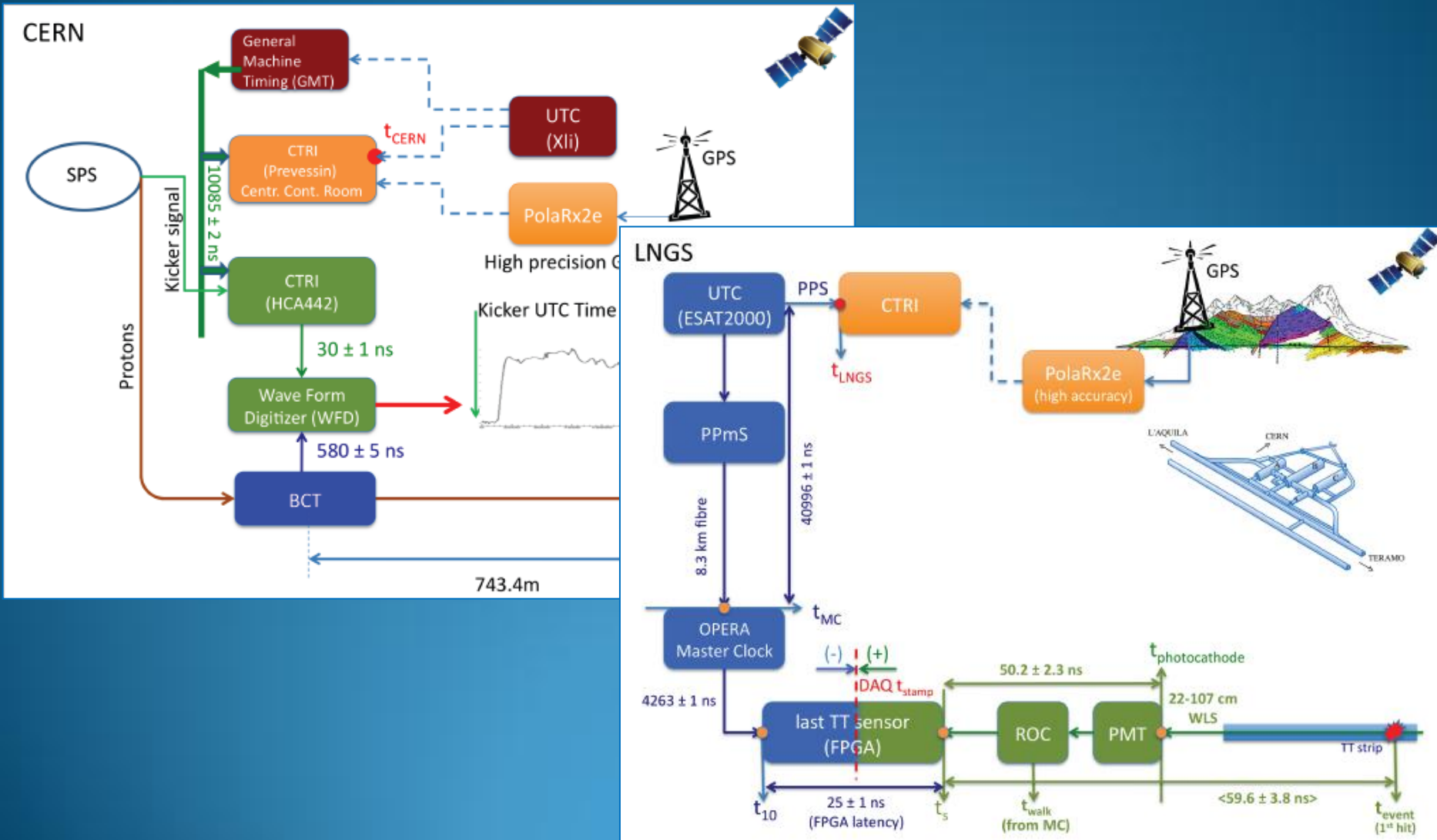
TOF_{true} = accounting for speed of mesons down to decay point

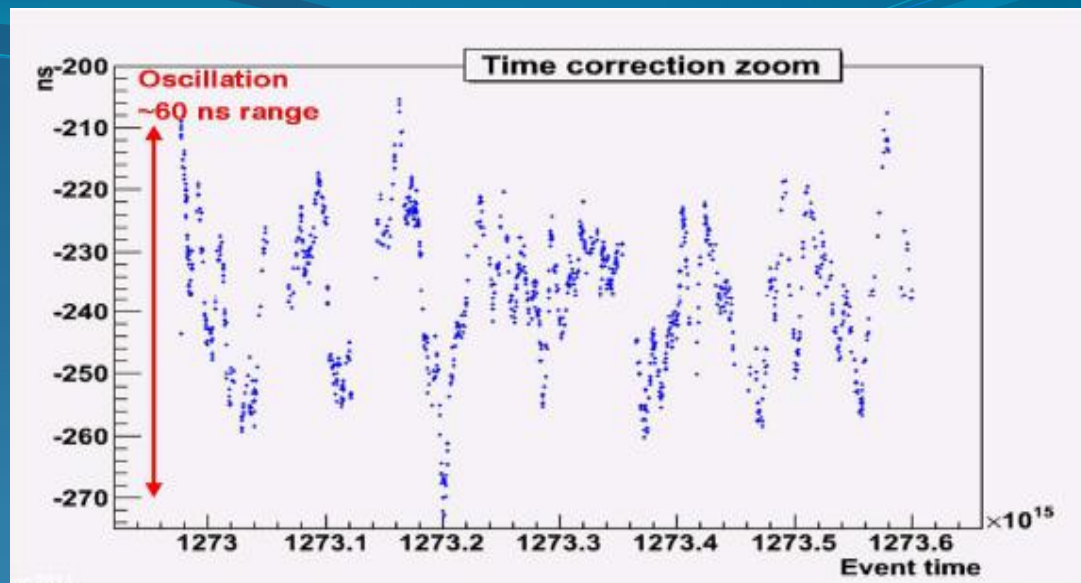
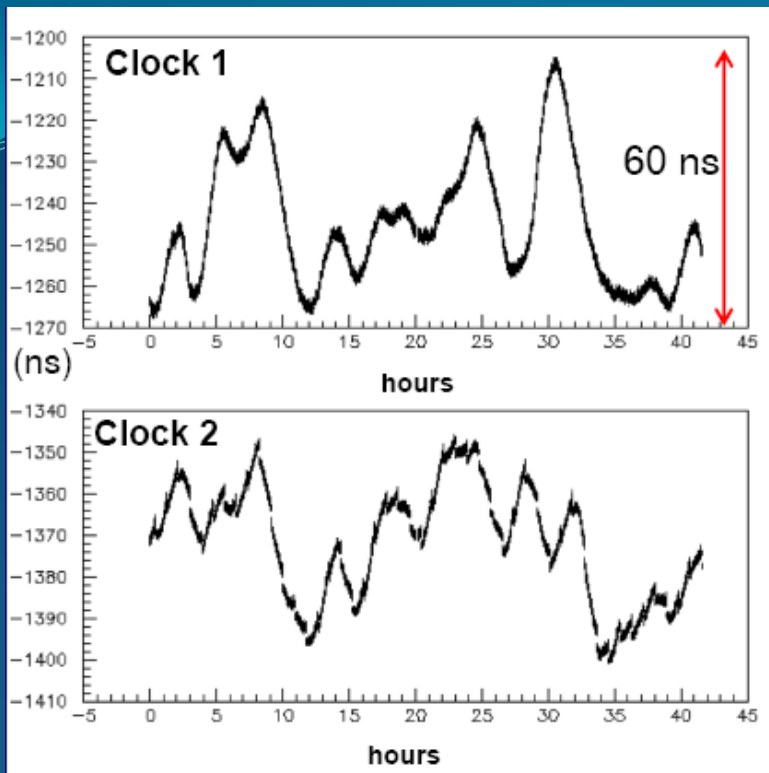
$$\Delta t = \text{TOF}_{\text{true}} - \text{TOF}_c$$

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

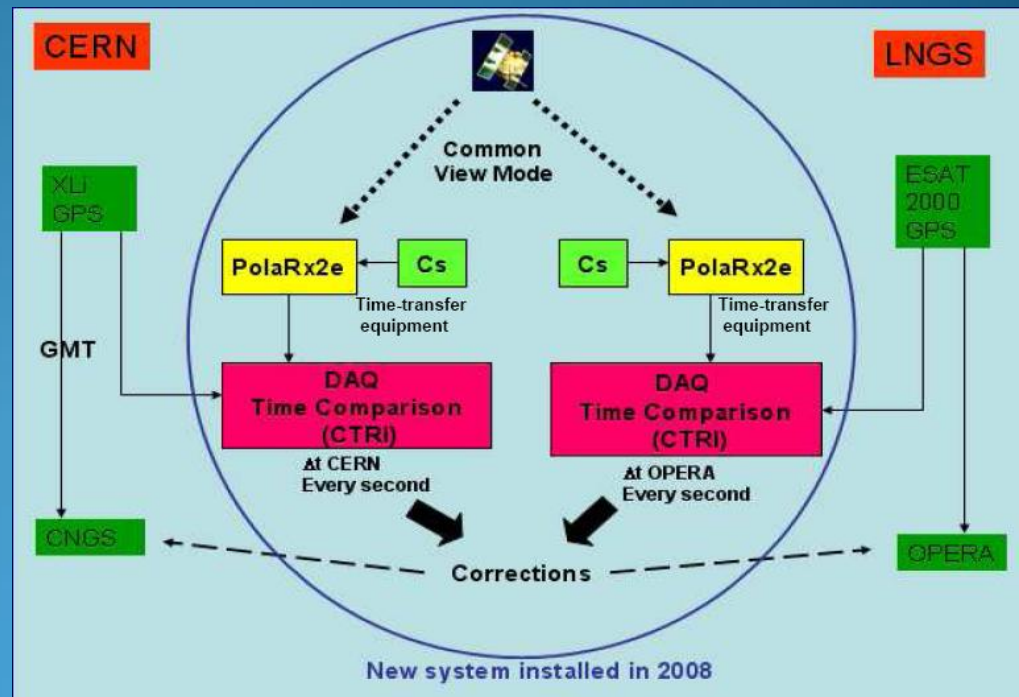
[illegible]

Sistema di timing: CERN + LNGS





Sistemi gemelli di GPS receiver + Cs atomic clock Installati al CERN e ai LNGS nel 2008

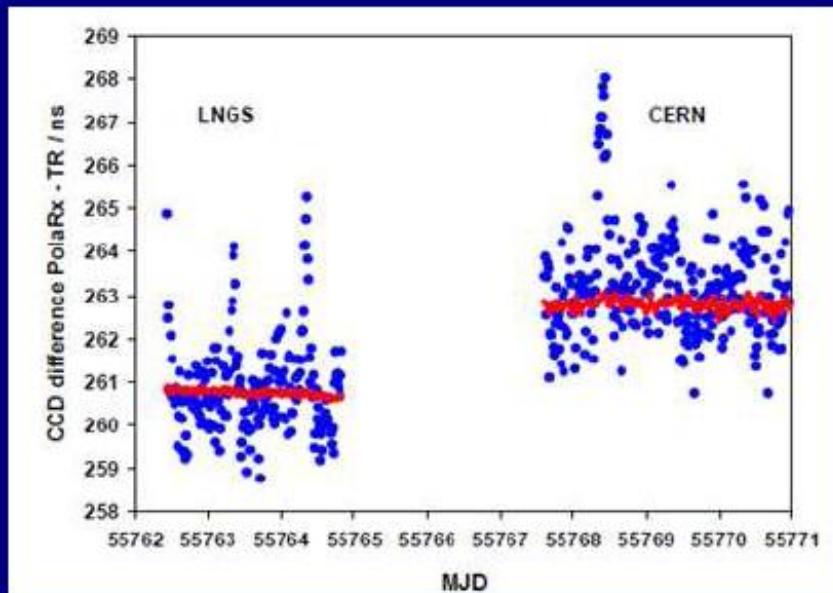
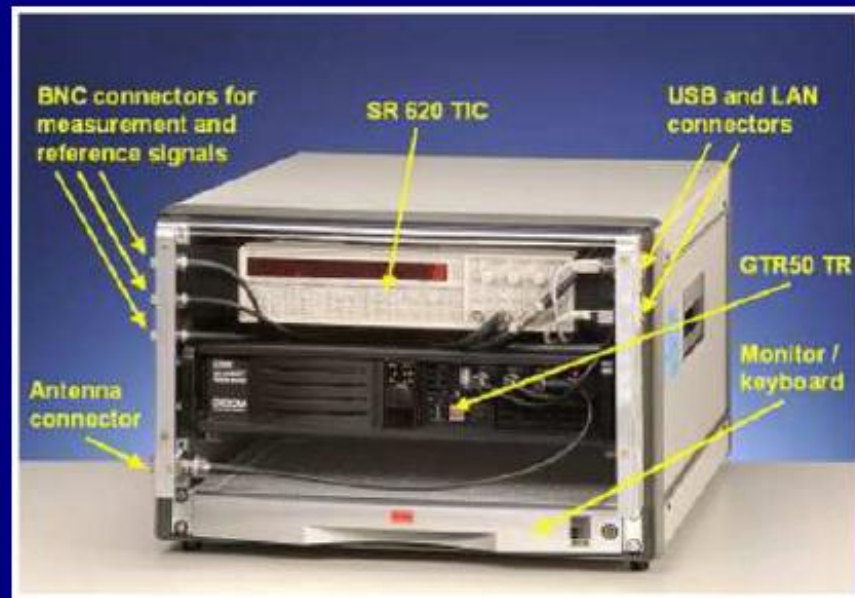


Calibrazione degli orologi CERN/LNGS

Independent twin-system calibration by the **Physikalisch-Technische Bundesanstalt**
(Federal German Metrology Institute)

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

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

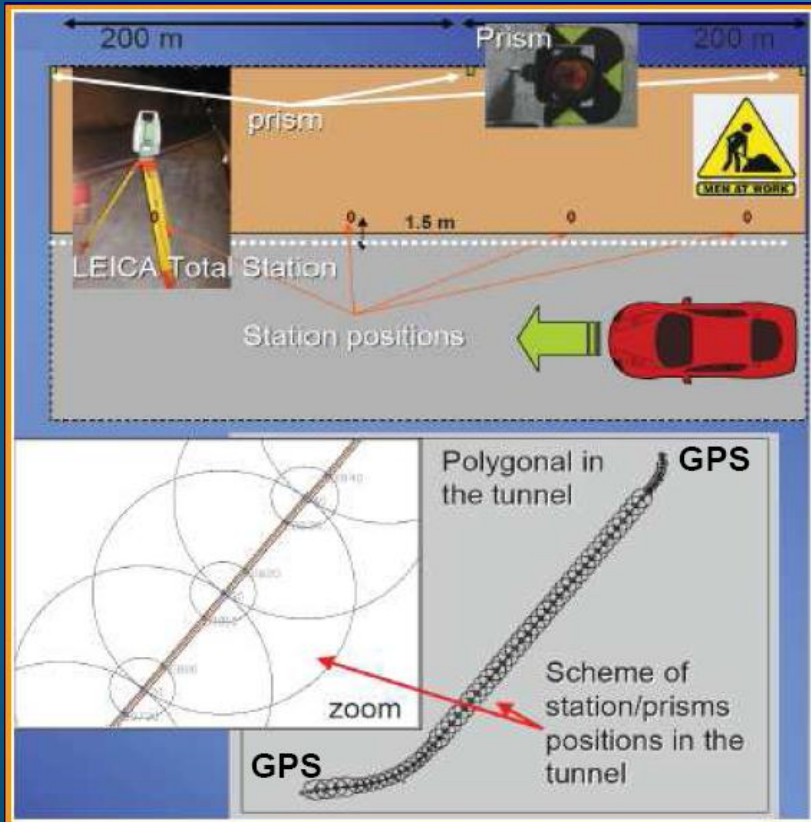


Correction to the time-link:

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

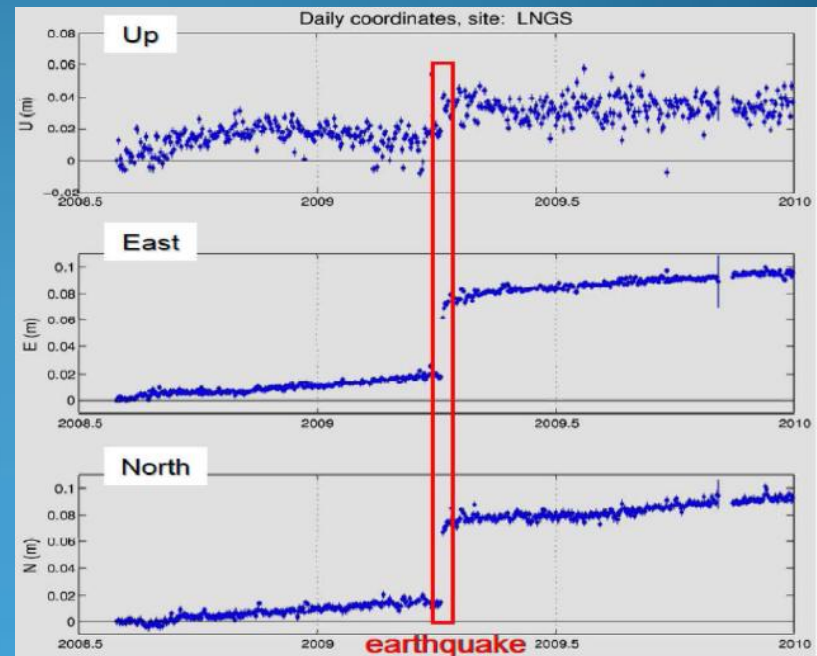
Misura della posizione

Misure GPS portate underground dai
due lati del tunnel (10 Km)
(Roma La Sapienza Geodesy 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

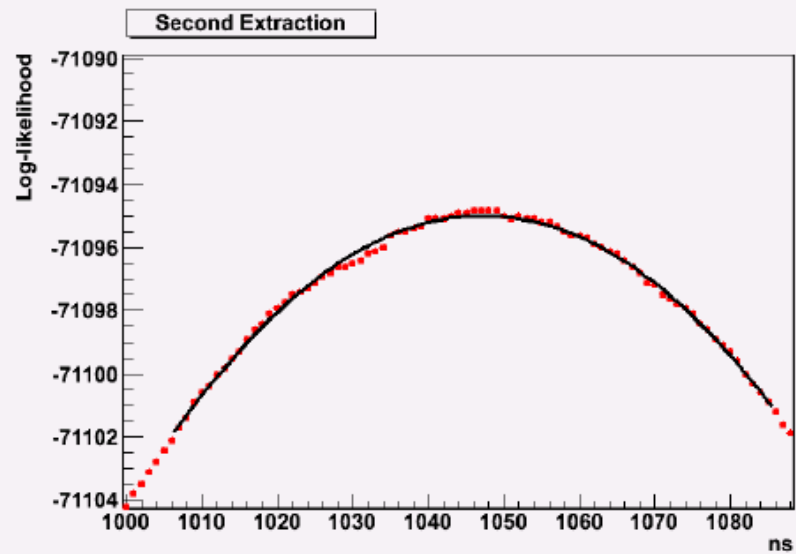
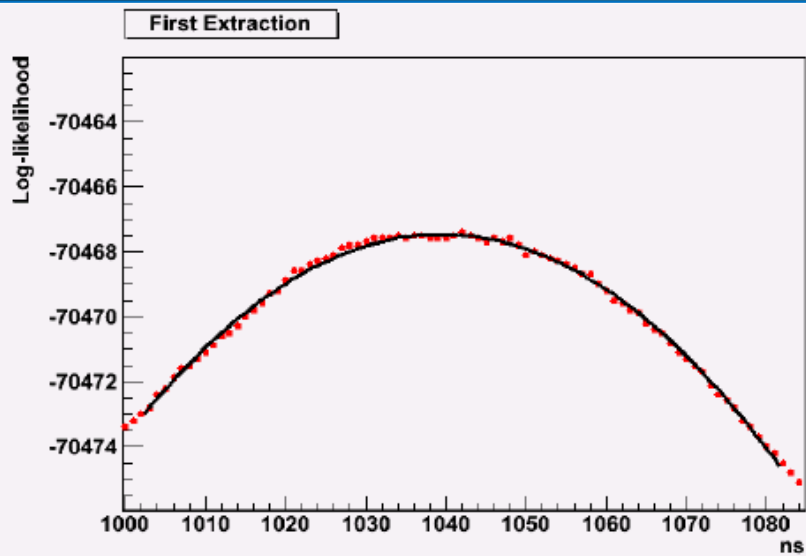
Resulting distance (BCT – OPERA reference frame)
(731278.0 ± 0.2) m

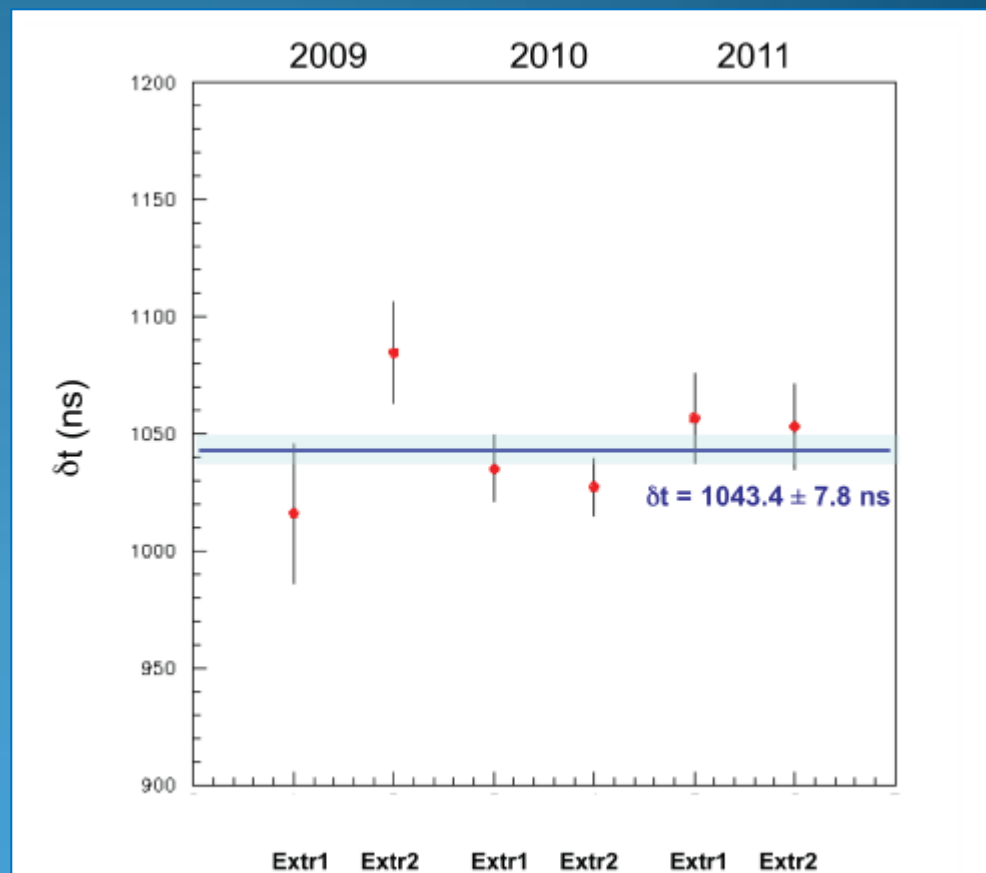
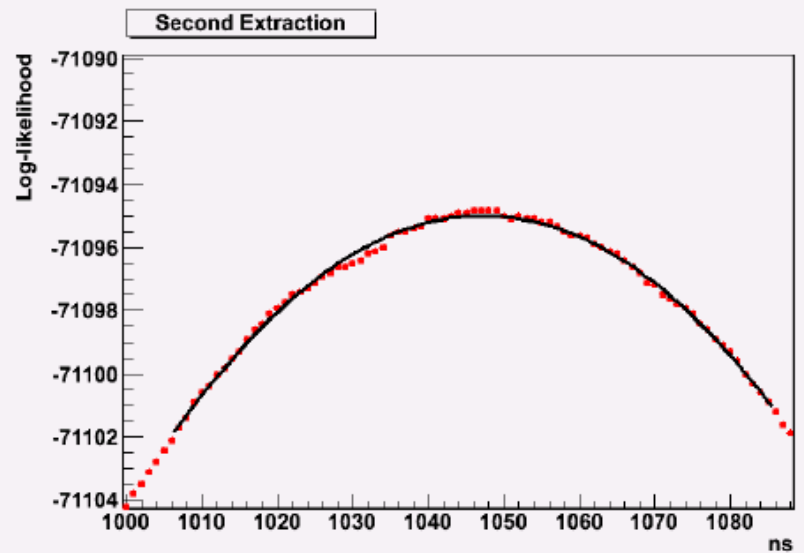
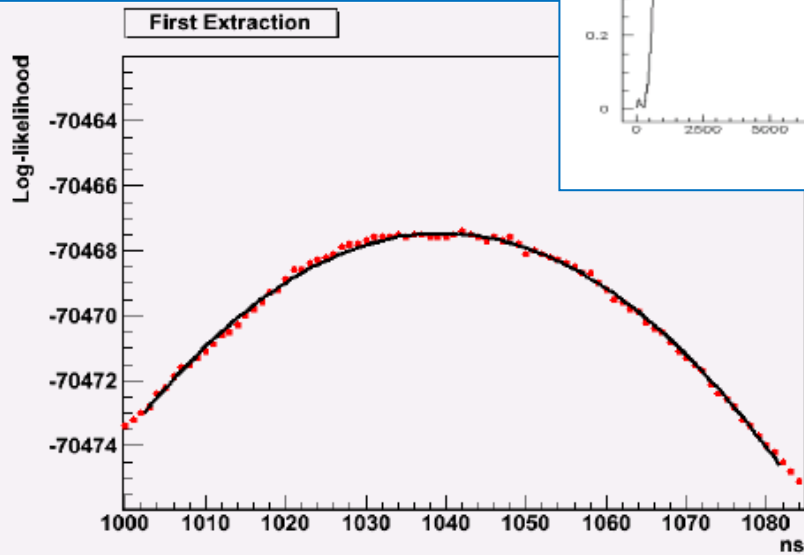
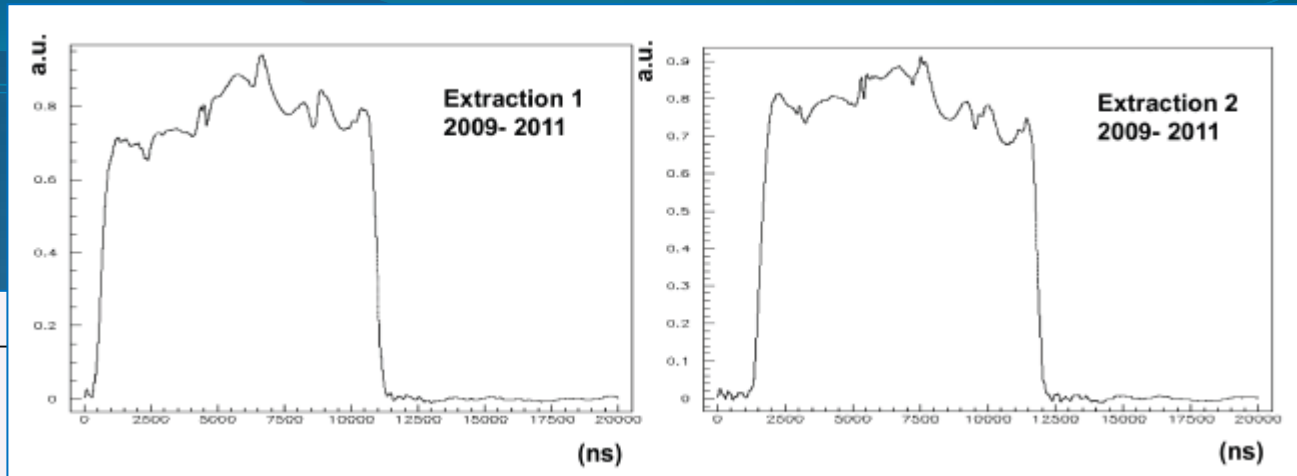


Analisi: maximum log-likelihood

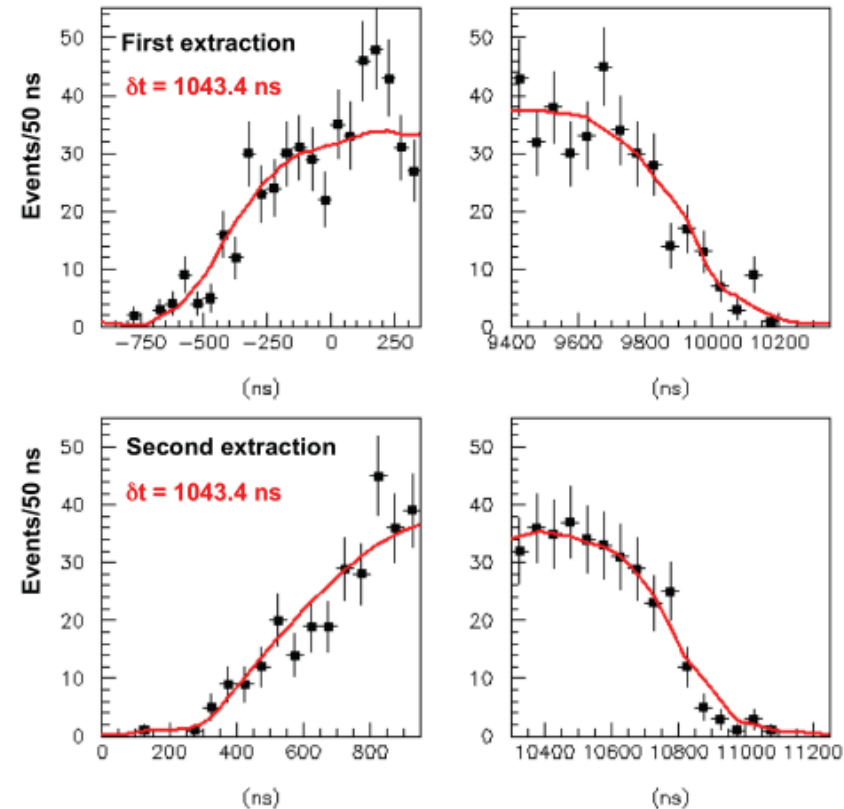
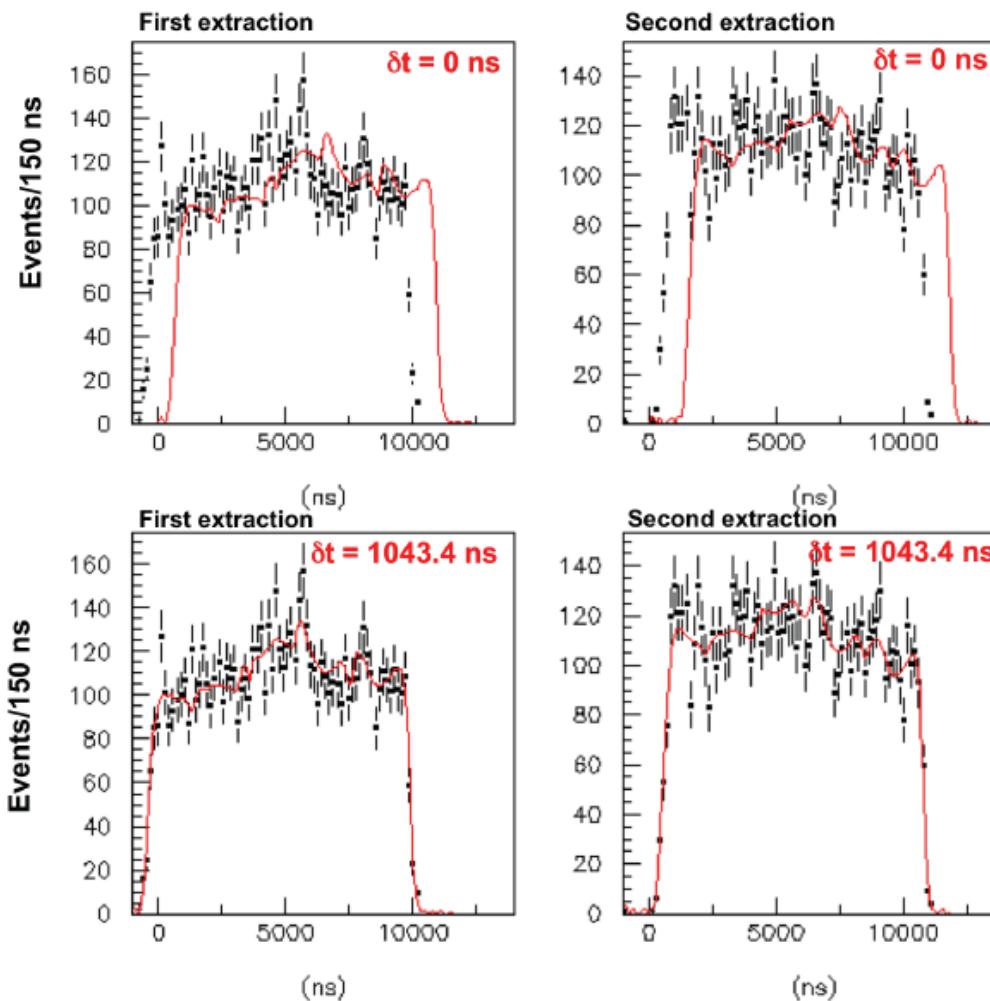
$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \quad k = 1, 2 \text{ extractions}$$

- Per ogni interazione di neutrino si prende la corrispondente Proton Waveform. Tutte le waveform sono normalizzate a uno e sommate: si costruisce così la PDF $w(t)$.
- La funzione di likelihood da massimizzare è funzione della singola variabile δt che va aggiunta al time tag t_j degli eventi di OPERA.
- Il riferimento temporale degli eventi è quello del Proton Waveform Digitizer, assumendo che i neutrini abbiano $v = c$.
- Si costruisce la log-likelihood, e si esegue un fit parabolico per trovarne il massimo.





$$\delta t (\text{blind}) = \text{TOF}_c - \text{TOF}_v = (1043.4 \pm 7.8 (\text{stat.})) \text{ ns.}$$



Sistematiche

	Blind analysis (ns)	Final analysis (ns)	Correction (ns)
	2006	2011	
Baseline	2440079.6	2439280.9	
Earth rotation		2.2	
Correction baseline			-796.5
CNGS delays:			
UTC calibration	10092.2	10085.0	
Correction UTC			-7.2
WFD	0	30	
Correction WFD			30
BCT	0	-580	
Correction BCT			-580
OPERA Delays:			
TT response	0	59.6	
FPGA	0	-24.5	
DAQ clock	-4245.2	-4262.9	
Correction OPERA			17.4
GPS Corrections:			
Synchronisation	-353	0	
Time-link	0	-2.3	
Correction GPS			350.7
Total correction			-985.6

$$\delta t = \text{TOF}_c - \text{TOF}_e = 1043.4 \text{ ns} - 985.6 \text{ ns} = (57.8 \pm 7.8 \text{ (stat.)}) \text{ ns.}$$

Sistematiche

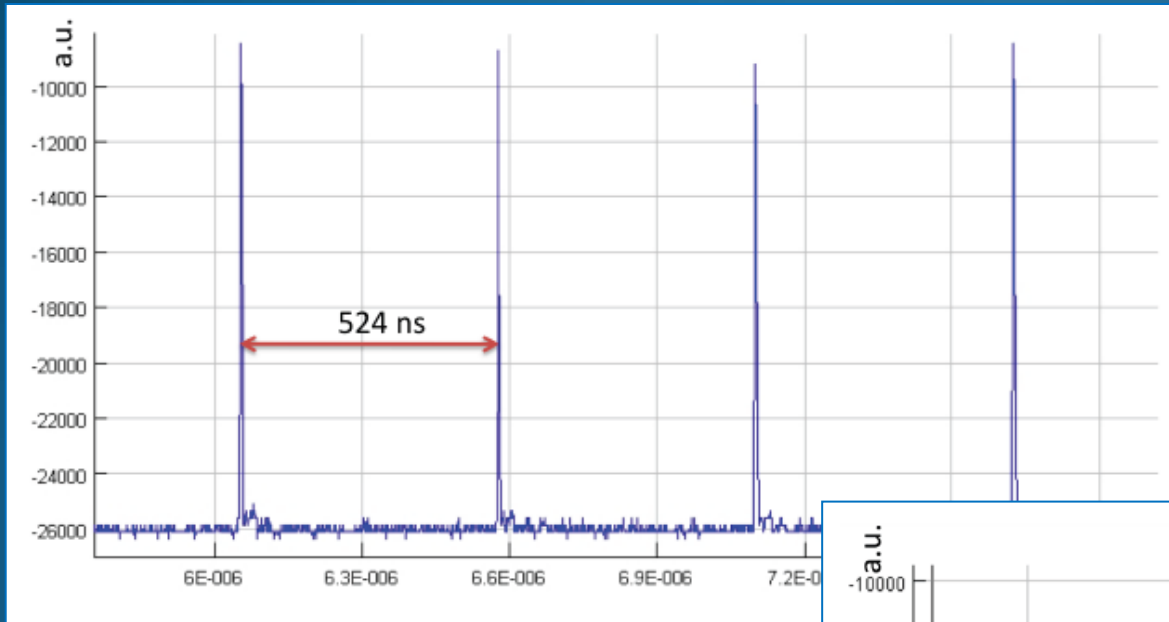
	Blind analysis (ns) 2006	Final analysis (ns) 2011	Correction (ns)
Baseline	2440079.6	2439280.9	
Earth rotation		2.2	
Correction baseline			-796.5
CNGS delays:			
UTC calibration	10092.2	10085.0	
Correction UTC			-7.2
WFD	0	30	
Correction WFD			30
BCT	0	-580	
Correction BCT			-580
OPERA Delays:			
TT response	0	59.6	
FPGA	0	-24.5	
DAQ clock	-4245.2	-4262.9	
Correction OPERA			17.4
GPS Corrections:			
Synchronisation	-353	0	
Time-link	0	-2.3	
Correction GPS			350.7
Total correction			-985.6

Systematic uncertainties	ns	Error distribution
Baseline (20 cm)	0.67	Gaussian
Decay point	0.2	Exponential (1 side)
Interaction point	2.0	Flat (1 side)
UTC delay	2.0	Gaussian
LNGS fibres	1.0	Gaussian
DAQ clock transmission	1.0	Gaussian
FPGA calibration	1.0	Gaussian
FWD trigger delay	1.0	Gaussian
CNGS-OPERA GPS synchronisation	1.7	Gaussian
MC simulation for TT timing	3.0	Gaussian
TT time response	2.3	Gaussian
BCT calibration	5.0	Gaussian
Total systematic uncertainty	-5.9, +8.3	

$$\delta t = \text{TOF}_c - \text{TOF}_v = (57.8 \pm 7.8 \text{ (stat.) } {}^{+8.3}_{-5.9} \text{ (sys.)}) \text{ ns.}$$

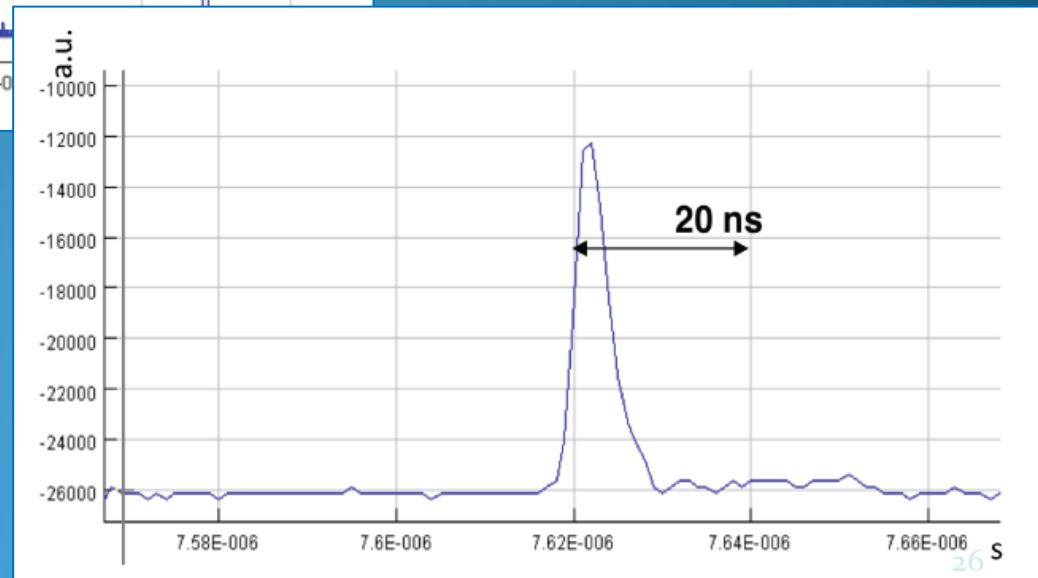
$$\text{Se } \delta = v^2 - 1 \text{ (c = 1): } \delta = 5 \cdot 10^{-5}$$

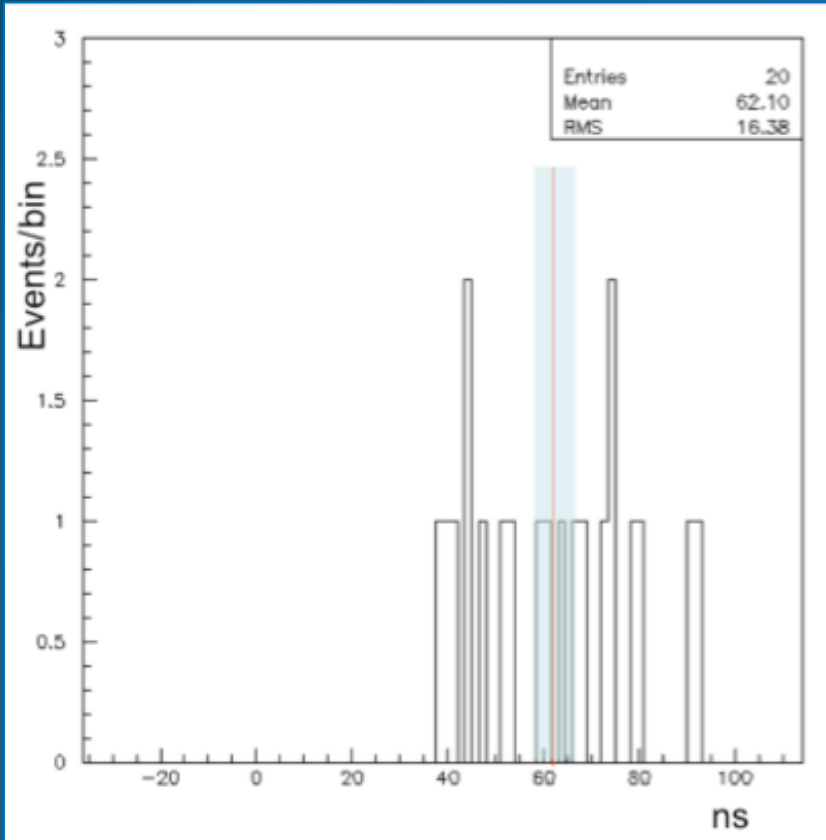
Il test con il fascio a bunch (22 Ottobre-6 Novembre)



Ogni evento di neutrino è ora associato senza ambiguità al proprio bunch originario!

- una singola estrazione
- quattro bunches con FWHM = 2.5 ns
- distanza tra i bunch: 524 ns
- $1.1 \cdot 10^{12}$ protoni per ciclo





Distribuzione dei δt ottenuti dagli eventi di neutrino estratti dal fascio a bunch

20 eventi selezionati: $\delta t = 62.1 \pm 3.7$ ns
(RMS = 16.4 ns)



Esclusi possibili bias che influenzino l'analisi statistica basata sulle PDF costruite con le Proton Waveform

Un effetto “Cherenkov” dei neutrini superluminali

(Cohen e Glashow, PRL **107**, 181803 (2011); Villante e Vissani, ArXiv 11104591v1 [hep-ph])

Consideriamo il parametro $\delta = v^2 - 1$ ($c = 1$): il claim di OPERA è $\delta = 5 \cdot 10^{-5}$

Se i ν_μ con energia dell'ordine delle decine di GeV viaggiano a velocità superiori a quella della luce, si prevede che alcuni processi altrimenti proibiti siano cinematicamente permessi. Ad esempio:

$$\nu_\mu \longrightarrow \begin{cases} \nu_\mu + \gamma \\ \nu_\mu + \nu_e + \bar{\nu}_e \\ \nu_\mu + e^+ + e^- \end{cases}$$

In particolare il terzo processo (Bremsstrahlung di coppie) procede attraverso un'interazione in corrente debole neutra, la cui soglia in energia risulta pari a:

$$E_0 = 2m_e / \sqrt{v_\nu^2 - v_e^2} \approx 2m_e / \sqrt{\delta}.$$

Con il valore δ di OPERA, $E_0 = 140$ MeV

In particolare si possono stimare la rate di emissione di coppie e la rate di perdita di energia lungo in percorso:

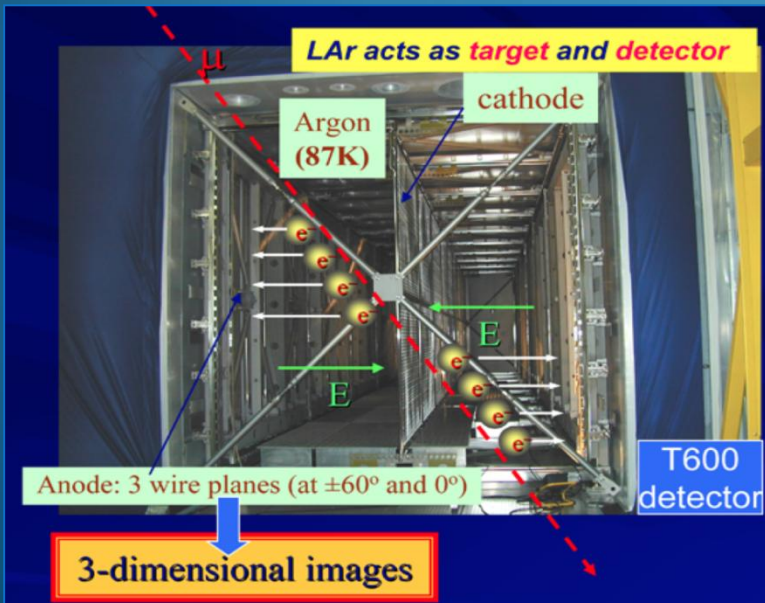
$$\Gamma = k' \frac{G_F^2}{192\pi^3} E^5 \delta^3 \quad \frac{dE}{dX} = -k \frac{G_F^2}{192\pi^3} E^6 \delta^3$$

Si può quindi calcolare l'energia finale del neutrino dopo una distanza L in funzione dell'energia iniziale:

$$\frac{1}{E_{\nu f}^5} - \frac{1}{E_{\nu i}^5} = 5k \frac{G_F^2}{192\pi^3} \delta^3 L$$

Con il δ di OPERA si trova che la probabilità che un neutrino superluminale del fascio CNGS di energia maggiore di 12.5 GeV arrivi al Gran Sasso è trascurabile.

ICARUS T600 @ LNGS



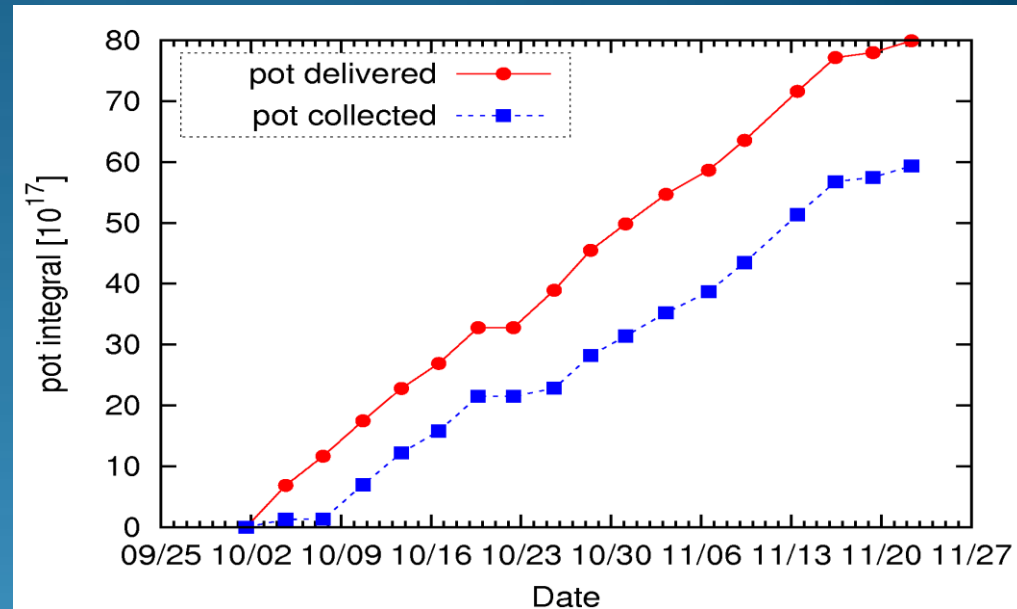
- Two identical T300 modules
(two chambers per module)
 - Liquid Ar active mass: ≈ 476 t
 - $(17.9 \times 3.1 \times 1.5$ for each TPC) m^3
 - drift length = 1.5 m
 - $E_{\text{drift}} = 500 \text{ V/cm}$; $v_{\text{drift}} = 1.589 \text{ mm}/\mu\text{s}$
- Three readout wire planes per chamber, at $0, \pm 60^\circ$, 3 mm plane spacing
 - ≈ 53.000 wires, 3 mm pitch
 - Two induction planes, one collection
- PMTs for scintillation light (128 nm)
 - 20+54 PMTs , 8" $\varnothing$
 - wave shifter (TPB)

Key feature: LAr purity form electro-negative molecules (O_2 , H_2O , CO_2).

Target: 0.1 ppb O_2 equivalent = 3 ms lifetime
(4.5 m drift @ $E_{\text{drift}} = 500 \text{ V/cm}$).

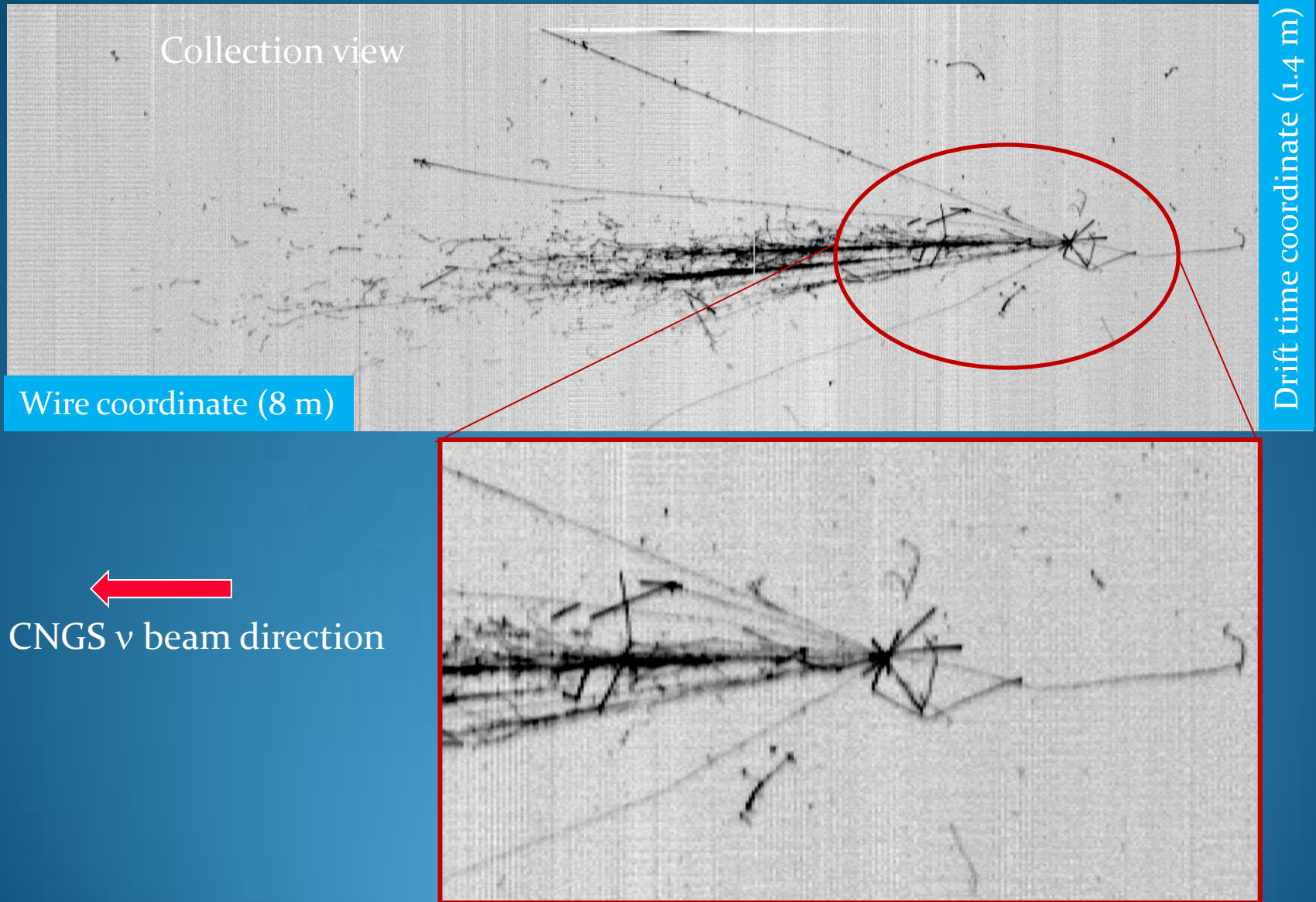
CNGS run 2010

- ICARUS fully operational since Oct. 1st 2010.
- $5.8 \cdot 10^{18}$ pot collected in Oct. 1st - Nov. 22th 2010.

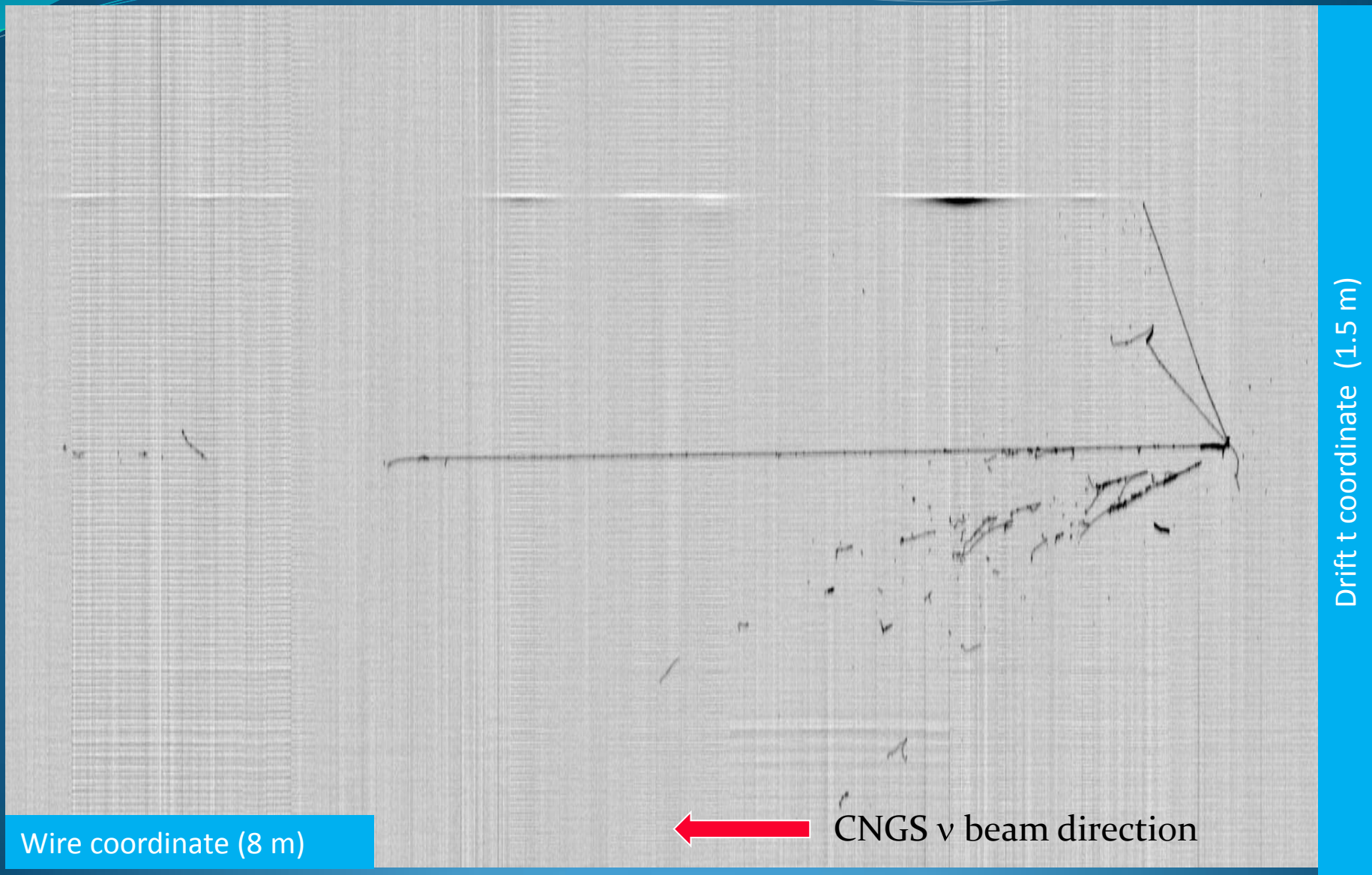


Event type	Collected	Expected
ν_{μ} CC	115	129
ν NC	46	42
ν XC *	7	-
Total	168	171

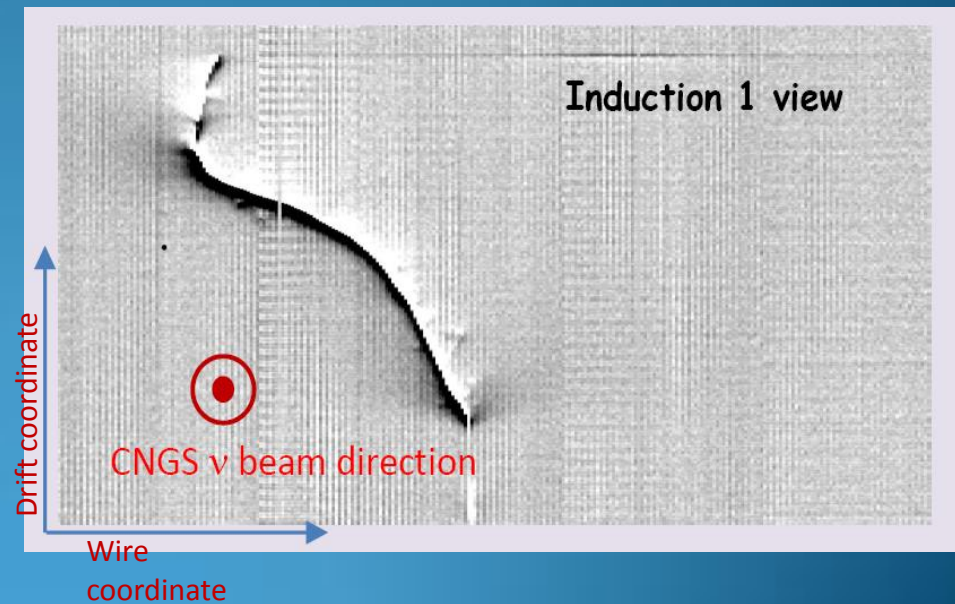
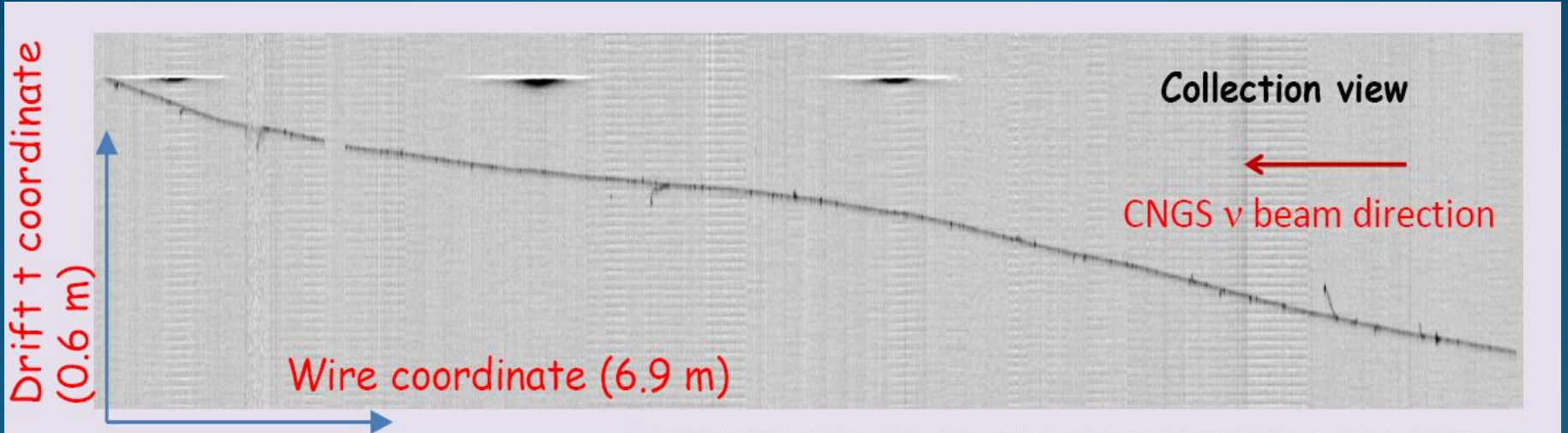
First CNGS ν interaction in ICARUS T600



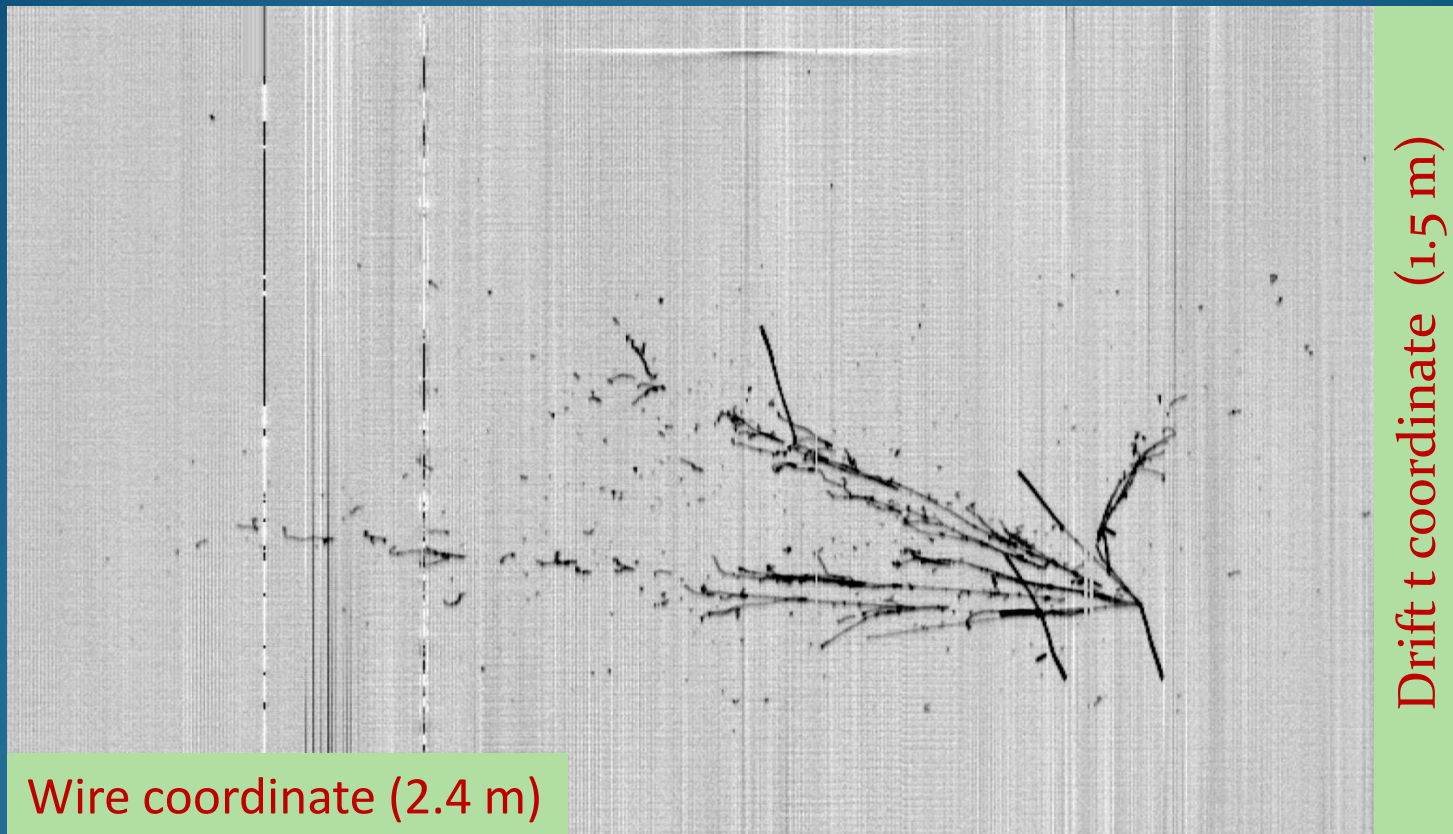
Another CNGS CC ν interaction



CNGS CC ν interaction in the rock

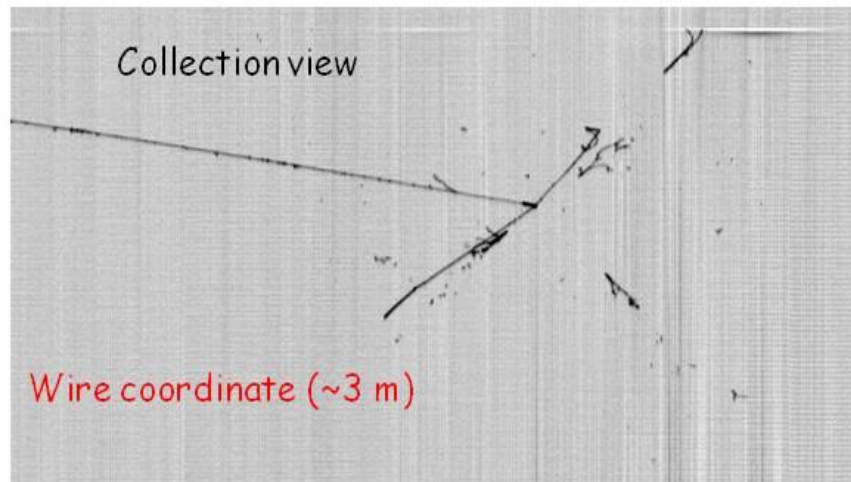


CNGS NC ν interaction

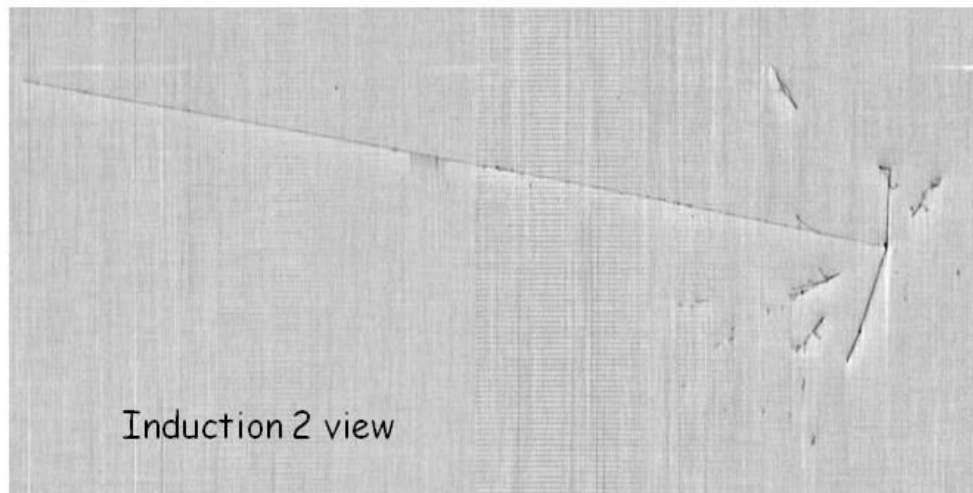
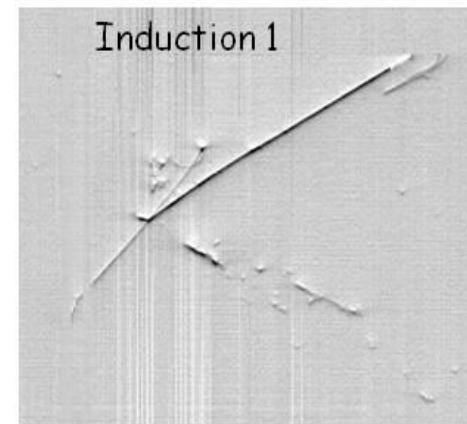


← CNGS ν beam direction

CNGS CC ν interaction with π^0 production



←
CNGS ν beam direction

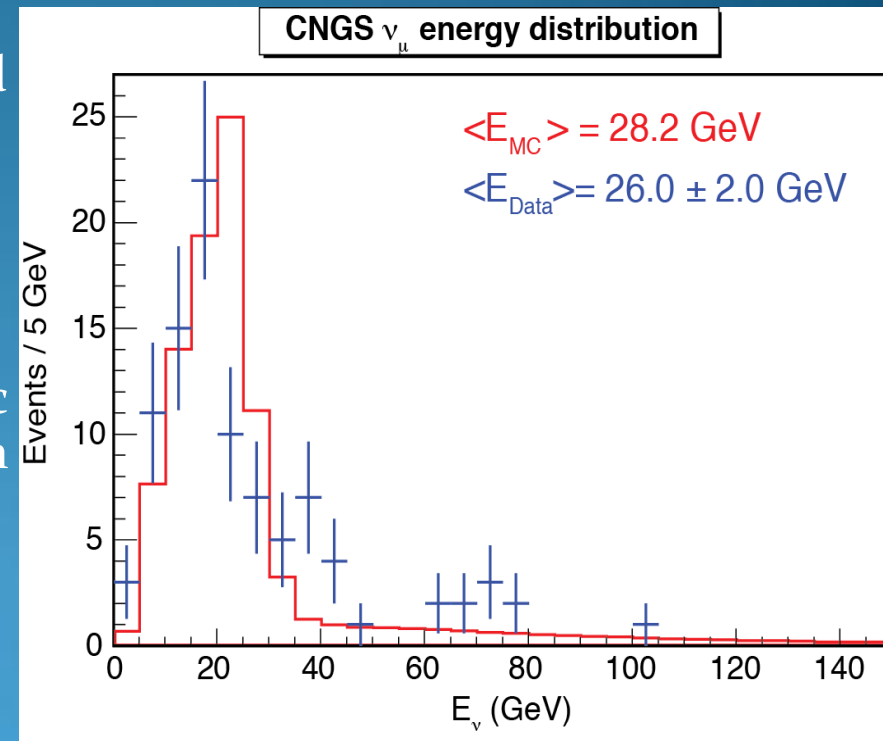


ICARUS: spettro CC 2010

(ICARUS Collaboration, ArXiv 1110.3763v2 [hep-ex])

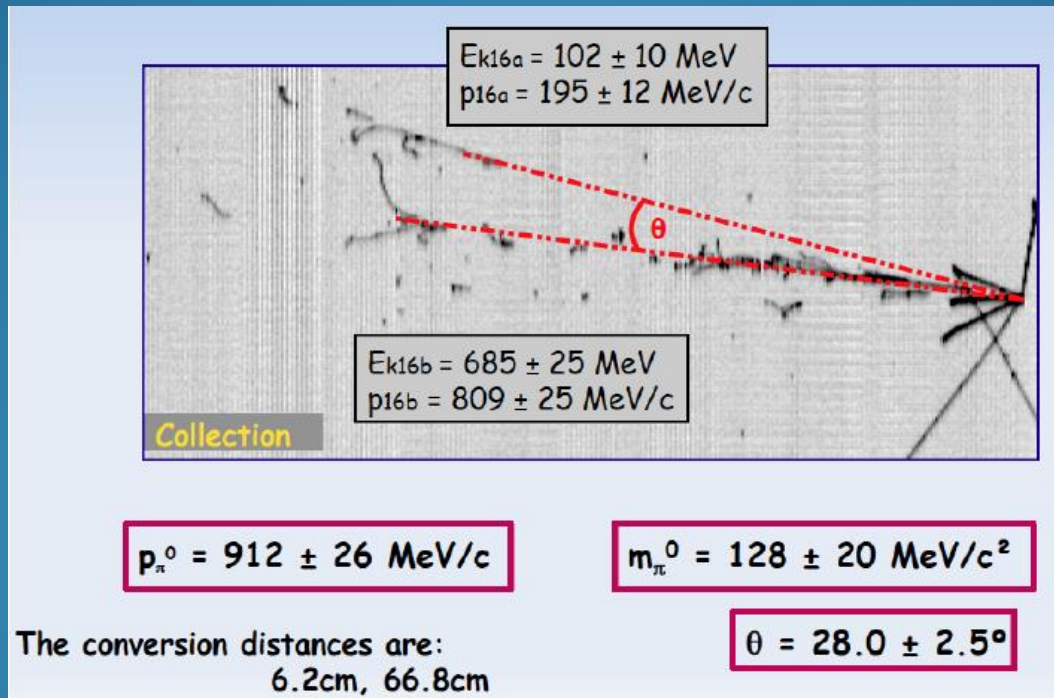
Total measured energy of 2010 ν_μ CC:

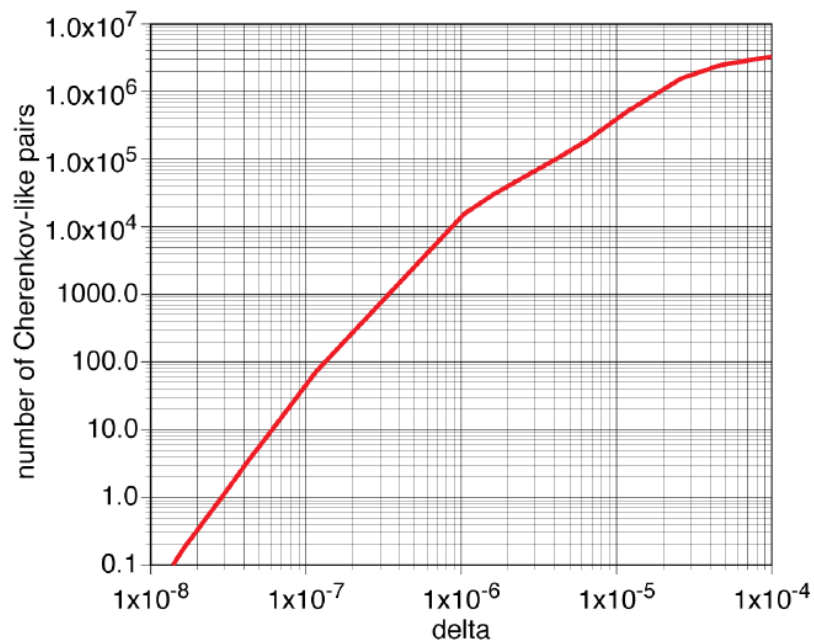
- Lepton and hadronic jet reconstructed separately
- μ momentum via multiple scattering
- hadron energy from calorimetric measurement + MC corrections for non containment/non compensation.



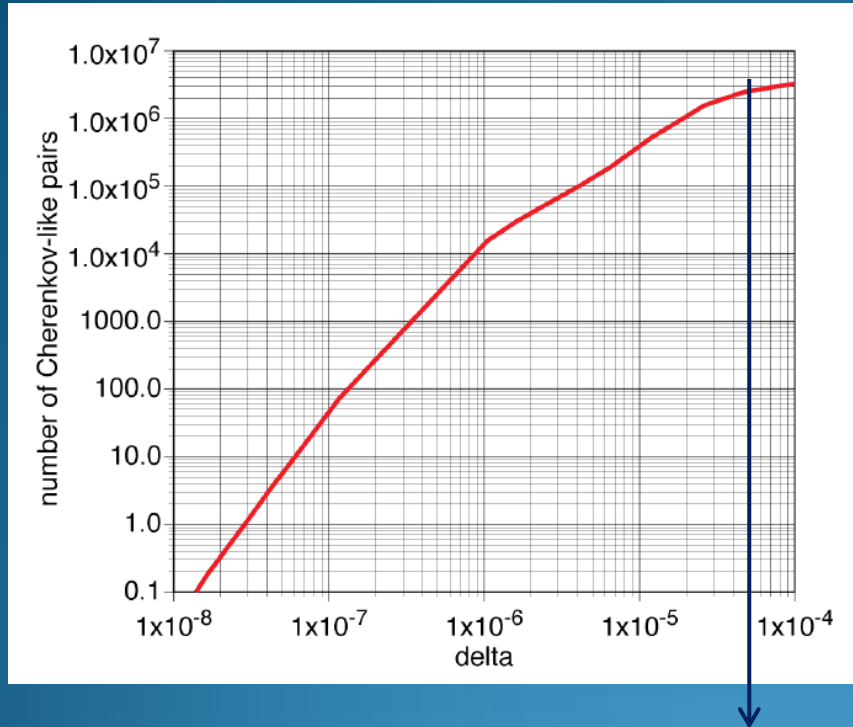
Nell'ipotesi di Cohen e Glashow, non ci aspettiamo interazioni di ν_μ CC sopra i 12.5 GeV. Il risultato di ICARUS non indica alcuna deviazione visibile dalle rate attese per i neutrini ν_μ CC dal fascio CNGS al Gran Sasso.

Inoltre, dalla misura della rate di eventi del tipo $\nu_\mu \rightarrow \nu_\mu e^+ e^-$ generati all'interno del rivelatore dal passaggio di neutrini superluminali ICARUS T600 mette un limite superiore a δ .





Numero eventi di tipo coppie $e^+ e^-$ in ICARUS T600 nel 2010 in funzione di δ



Numero eventi di tipo coppie $e^+ e^-$ in ICARUS T600 nel 2010 in funzione di δ

$$\delta = 5 \cdot 10^{-5} \longrightarrow 2 \cdot 10^6 \text{ coppie!}$$

Limite date le energie dei neutrini in ICARUS T600 (ci sono 10 eventi con $E > 60$ GeV!):

$$\delta < 4 \cdot 10^{-8}$$

I dati di ICARUS T600 quindi pongono un limite superiore al parametro $\delta < 4 \cdot 10^{-8}$

Le stesse argomentazioni si possono applicare ad altri due esperimenti:

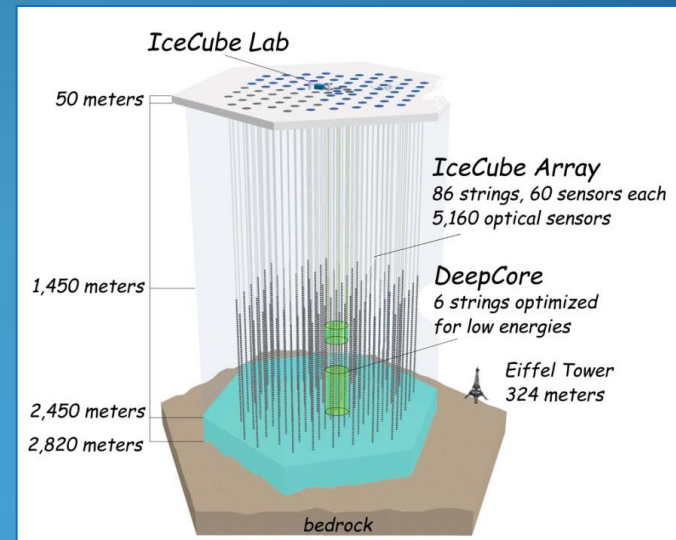
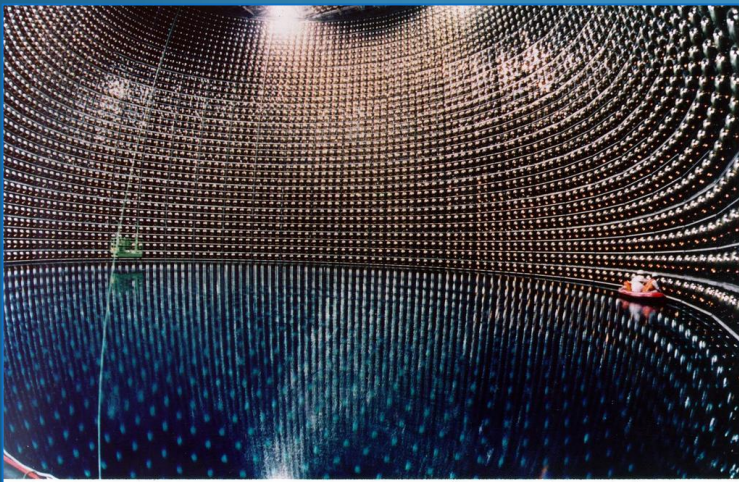
1) SuperKamiokande: osserva ν atmosferici che attraversano la Terra “dal basso”:

$$1 \text{ GeV} < E < 1 \text{ TeV}; L = 10.000 \text{ Km} \rightarrow \delta < 1.4 \cdot 10^{-8}$$

2) IceCube: osserva sciame generati da che ν attraversano la Terra:

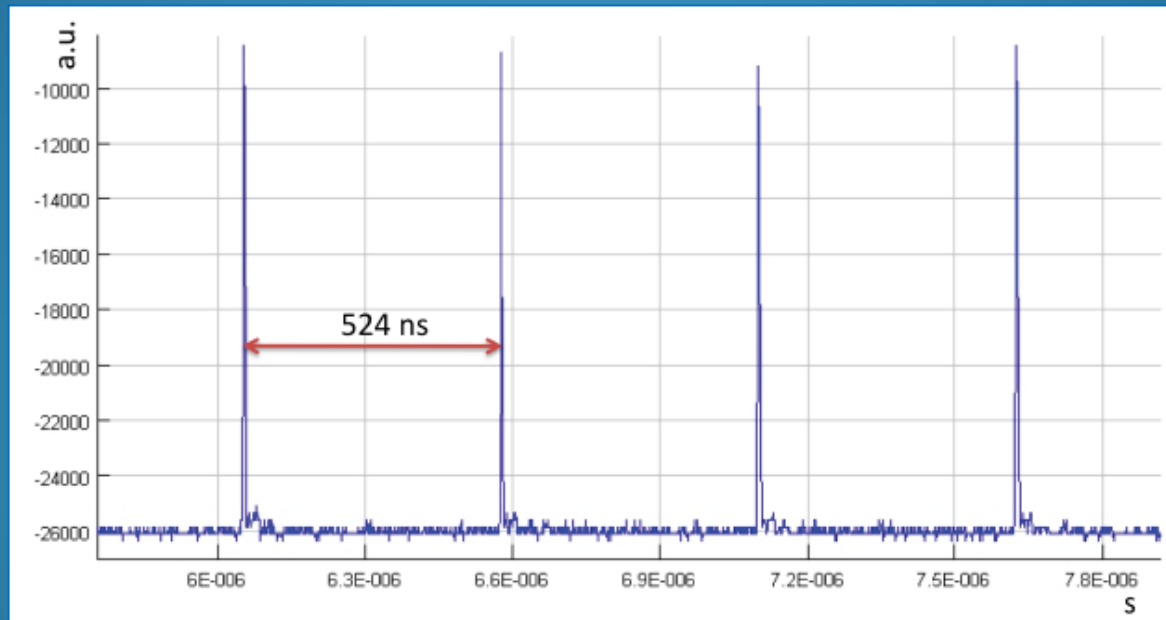
$$E < 100 \text{ TeV}; L > 500 \text{ Km} \rightarrow \delta < 1.7 \cdot 10^{-11}$$

Inoltre l'osservazione dei ν ($\sim 10 \text{ MeV}$) della SN1987A danno come limite $\delta < 4 \cdot 10^{-9}$



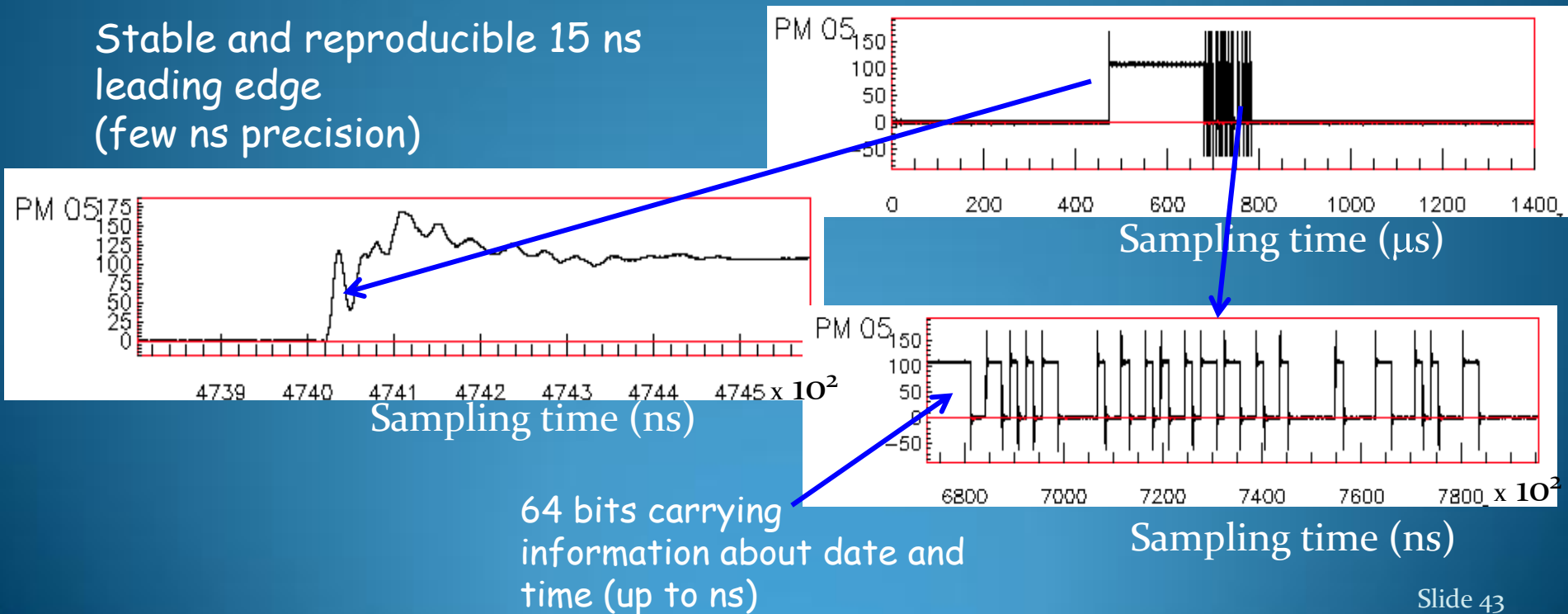
ν TOF test measurement with ICARUS T600 @ the CNGS bunched beam

- A new campaign of measurement on the neutrino time of flight was performed in the period from October 22nd to November 6th 2011 based on the CNGS beam ran in low intensity mode ($\sim 10^{12}$ pot/spill) with a spill structure made of four LHC like extractions, each with a width of 2.5 ns, separated by 524 ns (1/4 of a PS revolution time).

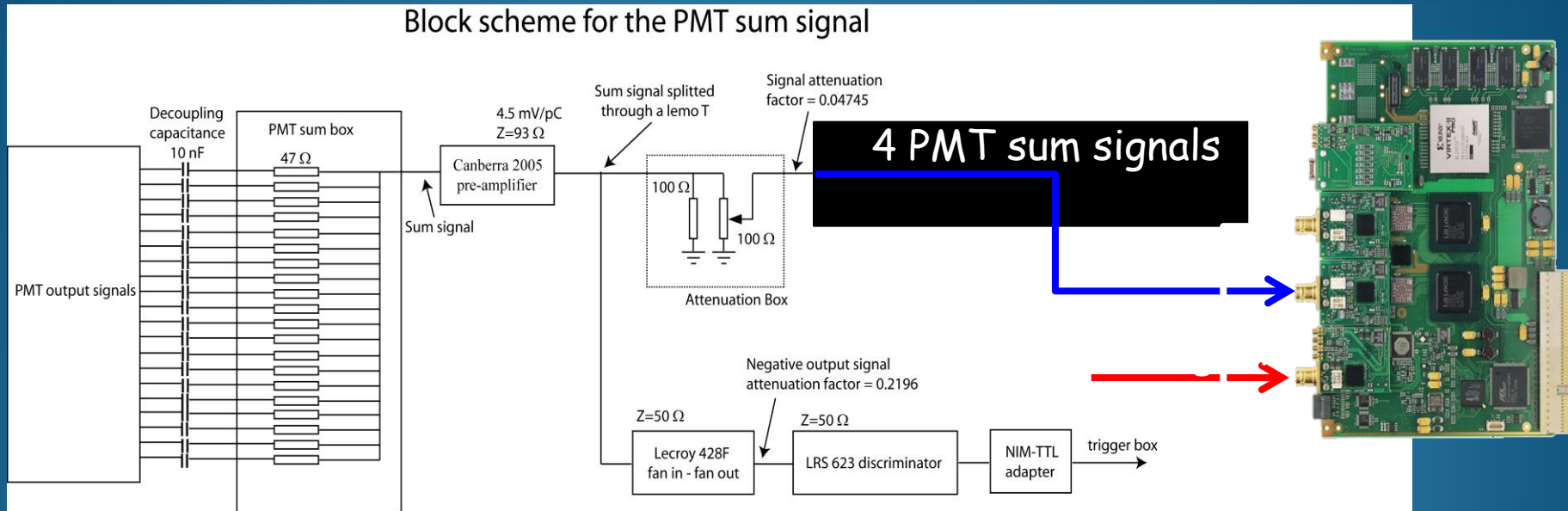


- The timing signal, distributed by the LNGS laboratory, consists of a TTL positive edge sent out every ms and followed, after $200\ \mu\text{s}$, by a pulsed structure whose logical states contain the information on the absolute time related to the first edge. This signal is generated in the external laboratory and sent to the underground halls via $\sim 8\ \text{km}$ of dedicated optical fiber. *This introduces a delay of $\sim 40\ \mu\text{s}$ that needs to be accurately calibrated.*

Stable and reproducible 15 ns leading edge
(few ns precision)

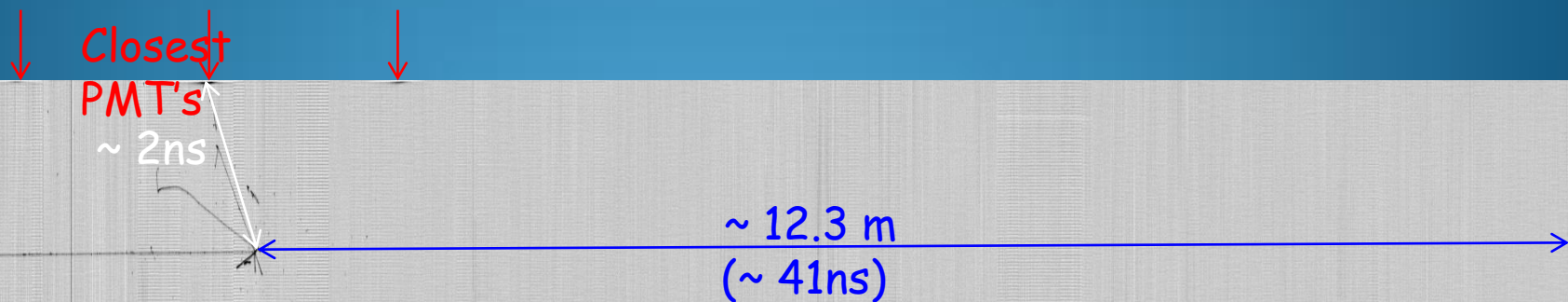


- The PMT signals, integrated with a fast preamplifier, are recorded together with the absolute time signal distributed by the LNGS laboratory.



- The AC240 boards are triggered by the ICARUS-CNGS trigger: PMT signals (~ 85 phe threshold) in coincidence with a $200 \mu\text{s}$ gate opened around the CNGS neutrino arrival time as predicted by the CERN-SPS proton extraction “Early Warning Signal”

- The time interval between PMT and LNGS timing signals, measurable with few ns precision, allows the determination of the absolute time of the scintillation light pulse in the T600 detector.
- In order to measure the neutrino arrival time, some additional corrections have to be included namely:
 - the distance of the event from the closest PMT
 - the position of the interaction vertex along the 18 m of the detector length, allowing the use of the T600 upstream wall position as reference point for neutrino timing.
- Both corrections can be deduced from the event topology in the T600 through visual scanning. Events in the standard ICARUS DAQ and the new AC240 based DAQ are associated through their common absolute time.



- To complete the analysis, additional accurate calibration (at ns level) are required:
- PMT signal propagation (~ 180 ns) and phe transit time in PMT (~ 75 ns) (laser diodes, electric field calculations).
- Position of the T600 upstream wall measured w.r.t. the LNGS reference frame to calculate neutrino flight path.
- LNGS timing signal delay (~ 40 μ s): in collaboration with LNGS, exploiting the equipment provided by OPERA after calibration of their optical fiber.
- Time corrections/delays at the CERN site are available (i.e. timing distribution delay ~ 10 μ s, BCT delay ~ 580 ns).
- Finally, the CERN-LNGS synchronization have to be acquired (OK from OPERA Collaboration).

Prospects for 2012

- The CERN managements is proposing to perform an additional measurement campaign with the CNGS bunched beam (up to 12 bunches of 2.5 ns separated by 150 ns) for a period of $\sim$ few weeks at the restarting of the accelerator complex in 2012.
- The Borexino experiment is setting up an independent clock synchronization system at LNGS, located in the external Labs.
- ICARUS will profit also of this system (in parallel of the existing one), sending a signal generated at trigger level, which will also be recorded in a channel of the AC240 DAQ system.

Conclusioni ...?

La misura di OPERA sul tempo di volo del neutrino dal CERN al Gran Sasso indica un arrivo anticipato del ν rispetto a quello calcolato assumendo come velocità quella della luce nel vuoto:

$$\delta t = \text{TOF}_e - \text{TOF}_\nu = (57.8 \pm 7.8 \text{ (stat.) } {}^{+8.3}_{-5.9} \text{ (sys.)}) \text{ ns.}$$

$$\delta = v^2 - 1 \text{ (} c = 1 \text{)} = 5 \cdot 10^{-5}$$

Alcuni studi prevedono che neutrini superluminali possano perdere parte della loro energia lungo il percorso emettendo coppie e^+e^- . Questo effetto non viene visto ad esempio da ICARUS T600, che misura lo spettro in energia dei neutrini dal fascio CNGS (lo stesso di OPERA).

Nel 2012 una campagna di misure dedicate condotta anche da altri esperimenti (ICARUS, Borexino, MINOS, T2K) permetterà forse di chiarire la questione.



Grazie per l'attenzione!

