Rencontres du Vietnam

Qui Nhon, 15 – 21 July 2012

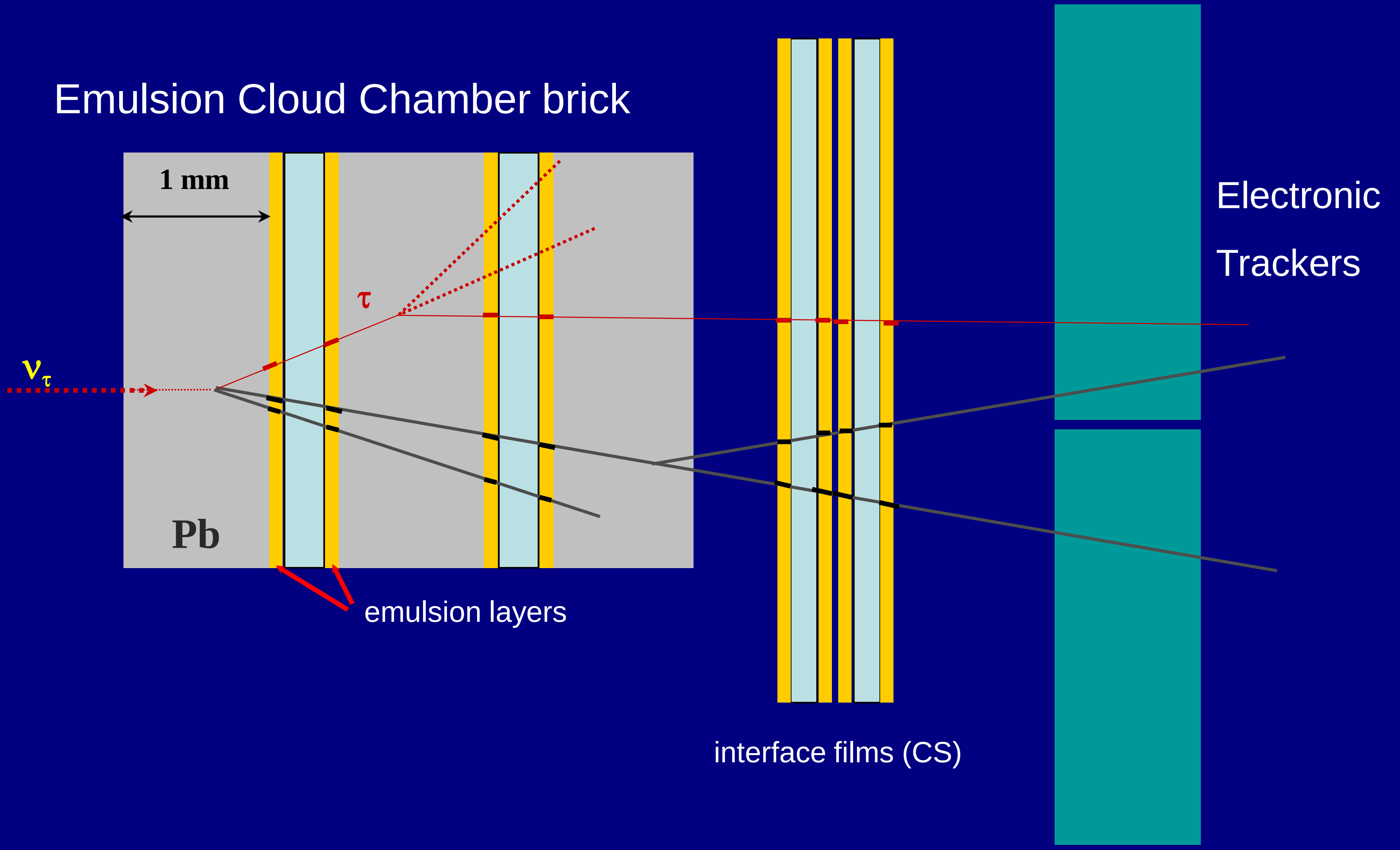
Results from OPERA

Dario Autiero, **IPNL Lyon**

OPERA

THE DESIGN OF THE OPERA EXPERIMENT

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

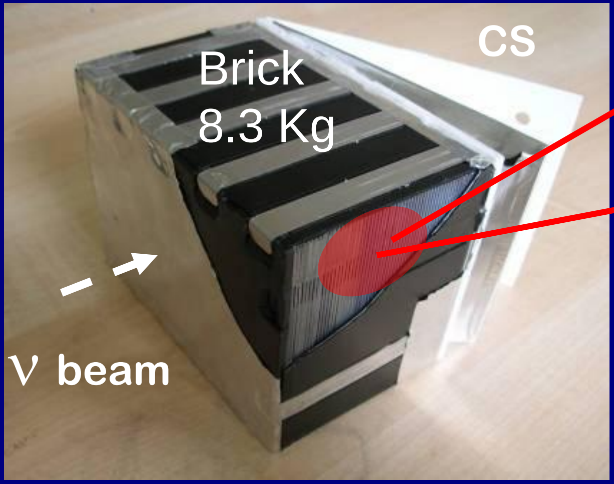


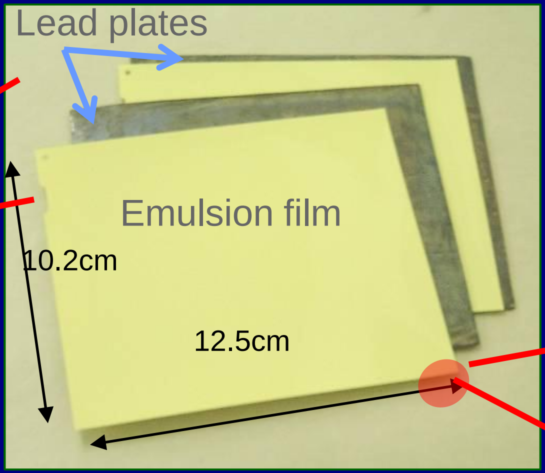
OPERA basic unit: the « Brick »

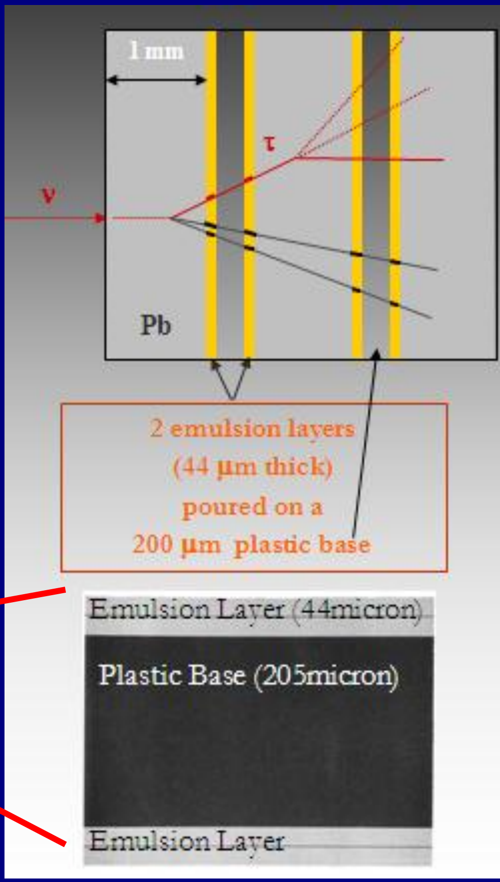
Based on the concept of the **E**mulsion **C**loud **C**hamber :

- 57 emulsion films + 56 Pb plates
- interface to electronic detectors: removable box with 2 films (Changeable Sheets)

→ High space resolution in a large mass detectors with a completely modular scheme





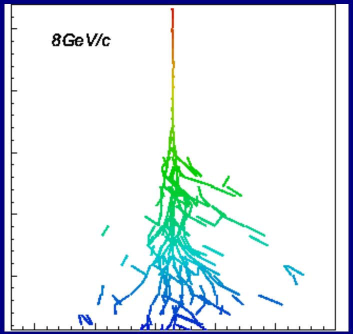


Tracks reconstruction accuracy in emulsions:

$\Delta x \approx 0.3\ \mu m$ $\Delta\theta \approx 2$ **mrad**

Bricks are complete stand-alone detectors:

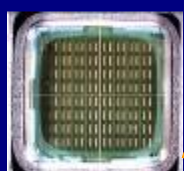
- ✓ Neutrino interaction vertex and kink topology reconstruction
- ✓ Measurement of hadrons momenta by multiple Coulomb scattering
- ✓ dE/dx: pion/muon separation at low energy (at end of range)
- ✓ Electron identification and measurement of the energy of electrons and gammas (electromagnetic calorimetry)



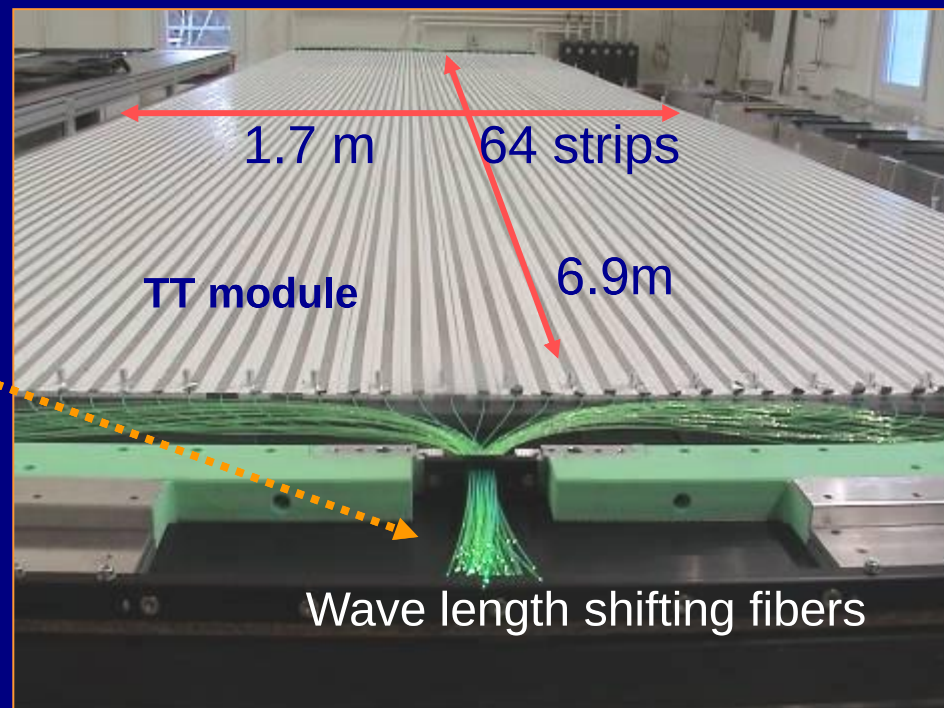
The Target Tracker (TT)

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)



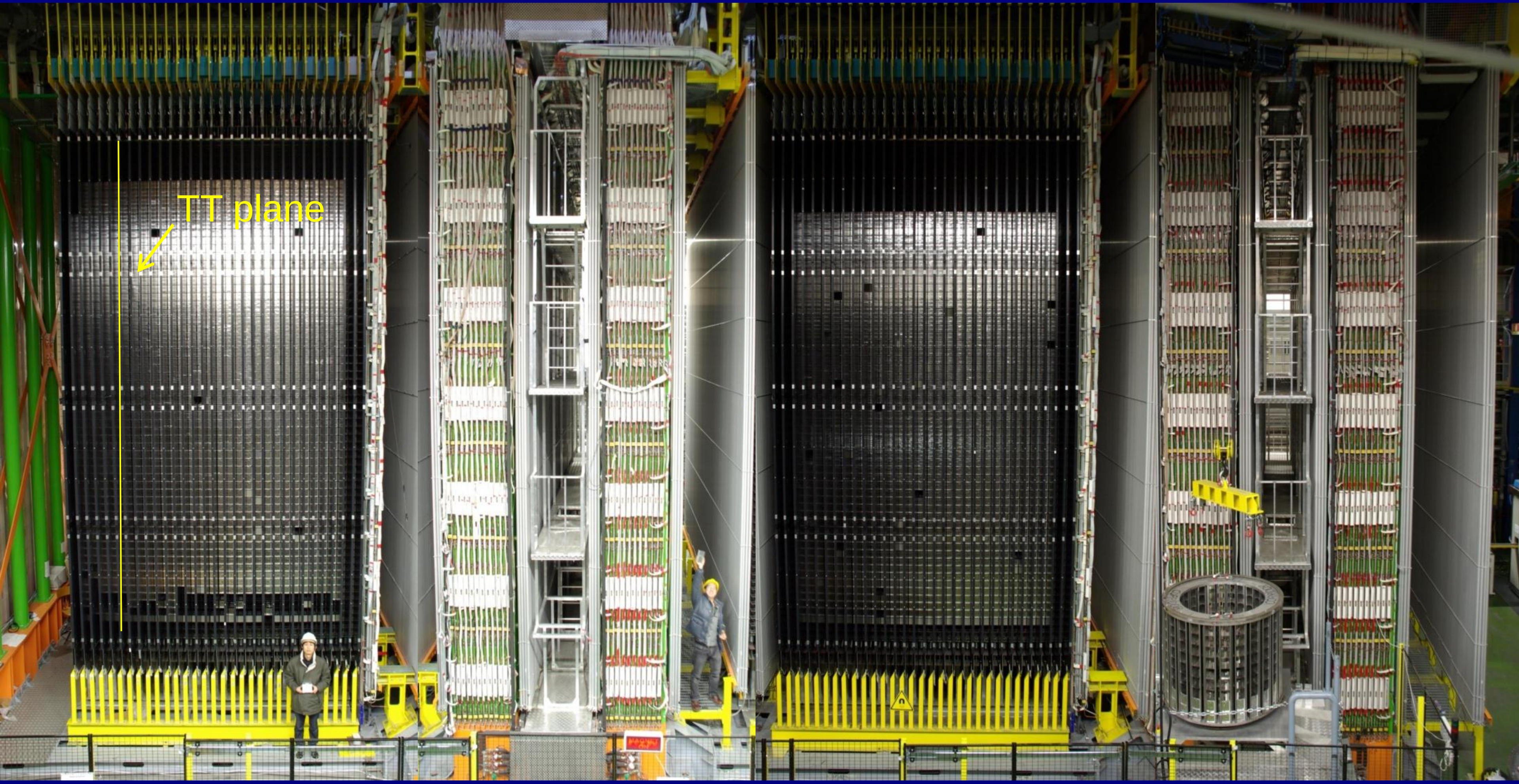
H7546



Read out by 1 Front-End DAQ board per side

THE IMPLEMENTATION OF THE PRINCIPLE

SM1 **SM2**



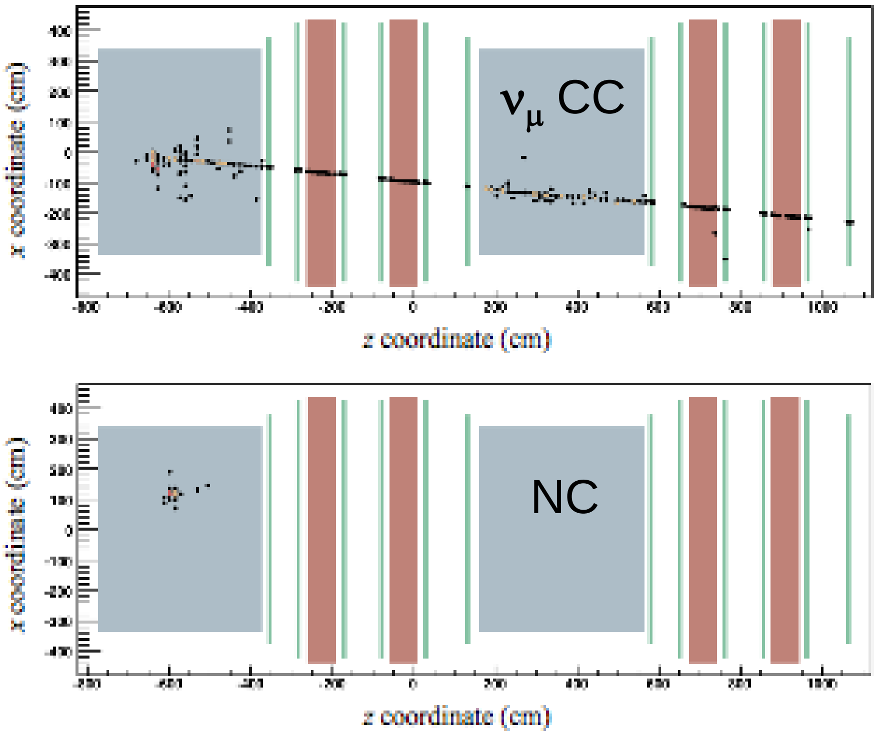
Target area

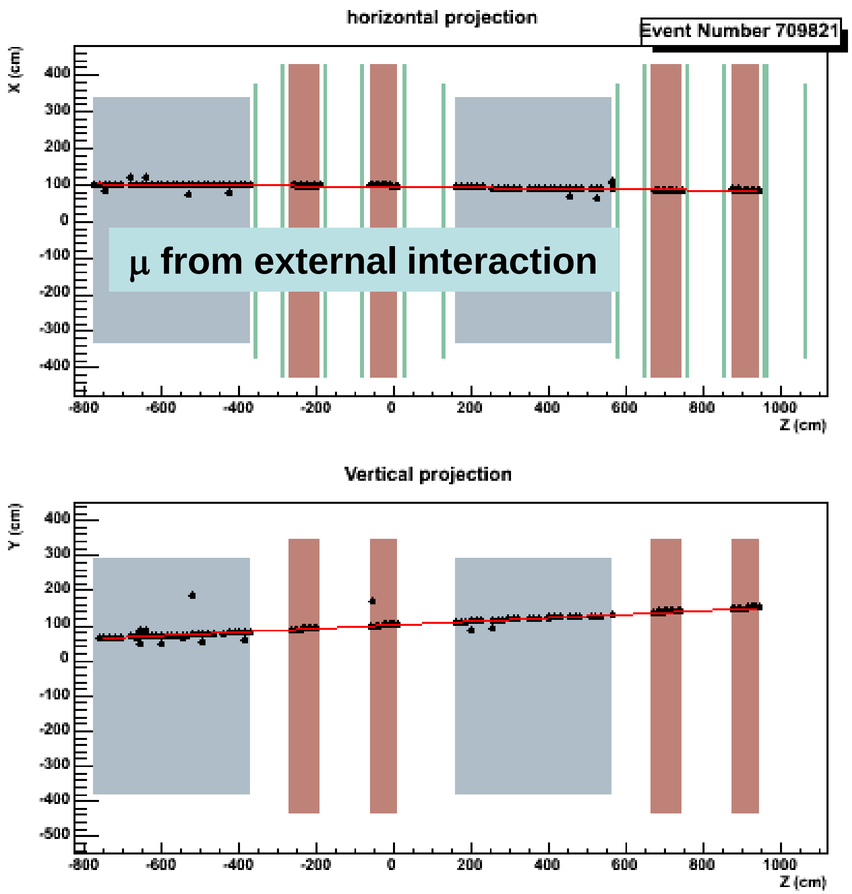
Muon spectrometer

31 TT planes

1400 m of rock overburden
→ c.r. flux 1 μ /m^2/hour

Neutrinos seen by the OPERA detector

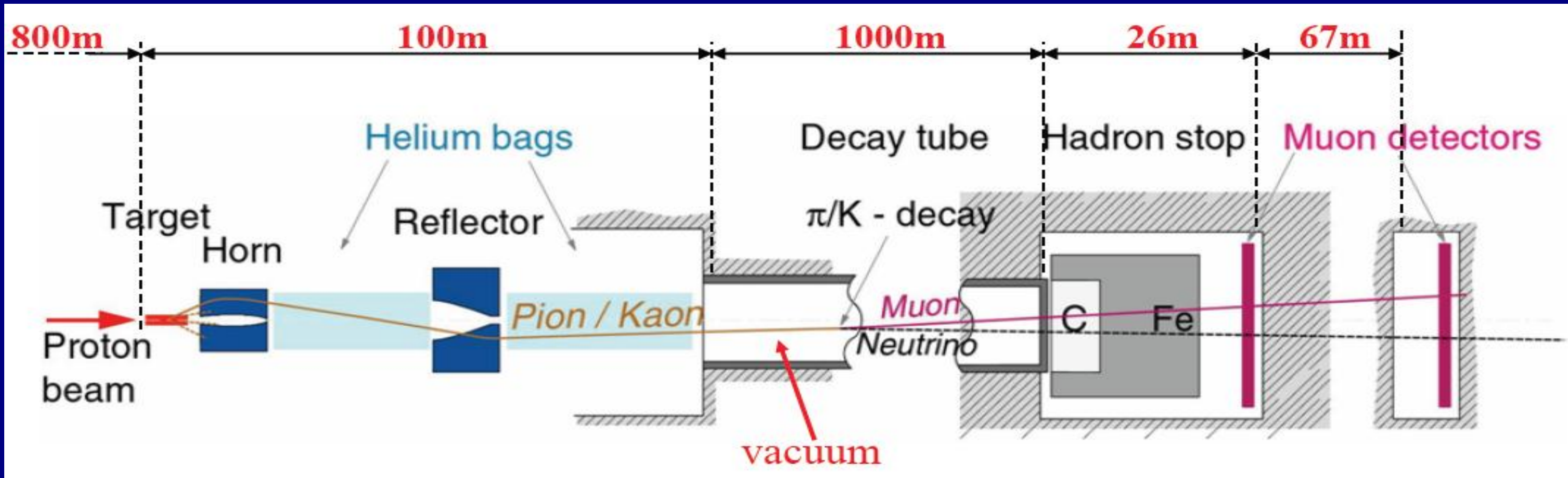




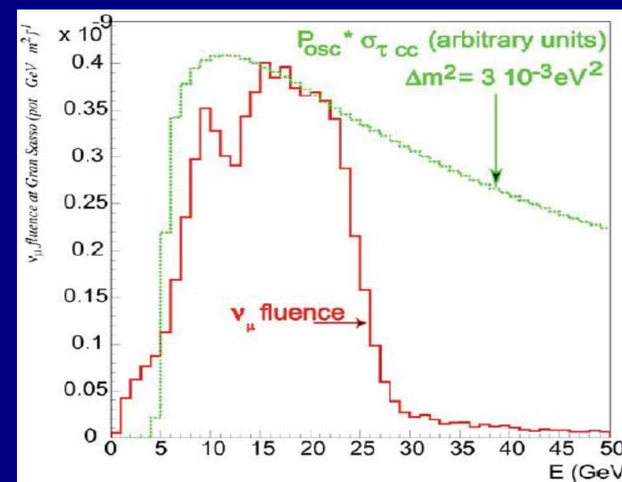
"INTERNAL"
EVENTS

"EXTERNAL"
EVENTS
(neutrino interactions in the rock)

The CNGS neutrino beam



- SPS protons: 400 GeV/c
- **Every: 6 s → two pulses of 10.5 μ separated by 50 ms**
- Proton pulses extracted by kicker magnet
- Beam intensity: 2.0 10^{13} proton/extraction
- ~ pure muon neutrino beam (<E> = 17 GeV)



<E (ν_μ)>	17 GeV
L	730 km
L/E	43 Km/GeV
$(\nu_e + \nu_e)/\nu_\mu$ CC	0.87%
ν_μ / ν_μ CC	2.1%
ν_τ prompt	negligible

→ Expected interactions for 22.5 10^{19} pot

~ 23600 ν_μ CC+NC

~ 170 ν_e + ν_e CC

~ 115 ν_τ **CC (Δm^2 =2.5 x 10^{-3} eV^2)**

After efficiencies: ~ 8 tau decays with <1 bck events

OPERA sensitivity

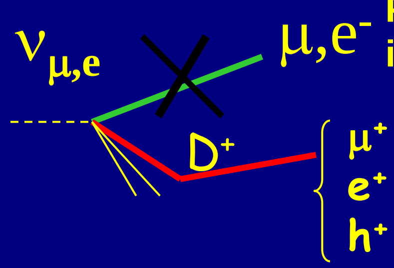
τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Background
$\tau \to \mu$	**17.7**	**1.79**	**0.09**
$\tau \to e$	**17.8**	**2.89**	**0.22**
$\tau \to h$	**49.5**	**2.25**	**0.24**
$\tau \to 3h$	**15.0**	**0.71**	**0.18**
All	**BR*eff ~8%**	**7.63**	**0.73**

5 years of nominal beam (4.5 E19 pot/year)

All channels: BR*global efficiency ~8%

Possible additional kinematical handles ($\tau \to h$)
→ need solid understanding of hadronic system by comparing to real data (ν_μ CC)

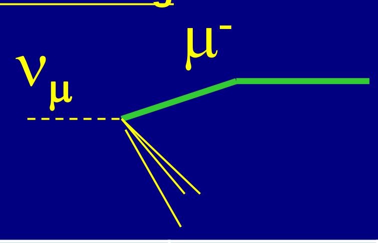
(All channels) Charm production in CC



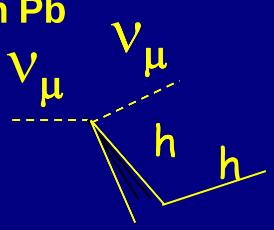
Primary lepton not identified

Good (~95%) muon identification is fundamental !

($\tau \to \mu$)
Coulombian large angle scattering of muons in Lead



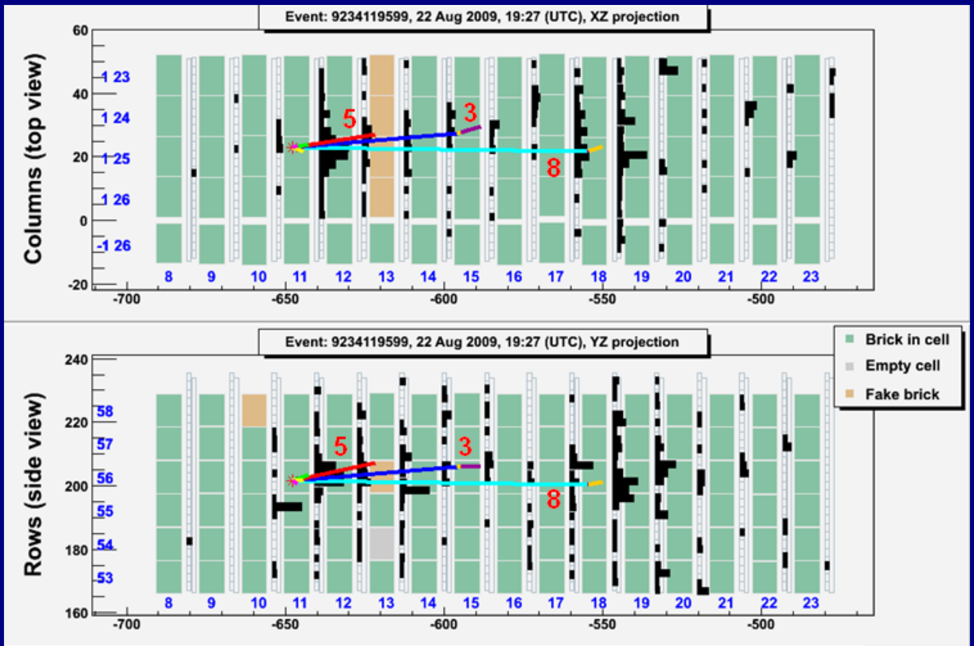
($\tau \to h$)
Hadronic interactions in Pb



	$\tau \to e$	**$\tau \to \mu$**	**$\tau \to h$**	**$\tau \to 3\pi$**	**Total**
Charm	0.22	0.02	0.14	0.18	0.55
Muon scattering	0	0.07	0	0	0.07
Hadronic interactions	0	0	0.11	0	0.11
Total	0.22	0.09	0.24	0.18	0.73

Charm production cross section, fragmentation and B.R. from 2010 CHORUS results
→ BCK 1.6/2.4 (hadronic/muonic channel) times larger than in OPERA proposal

→ Extra handles for BCK suppression (NJP 2012 14 033017)

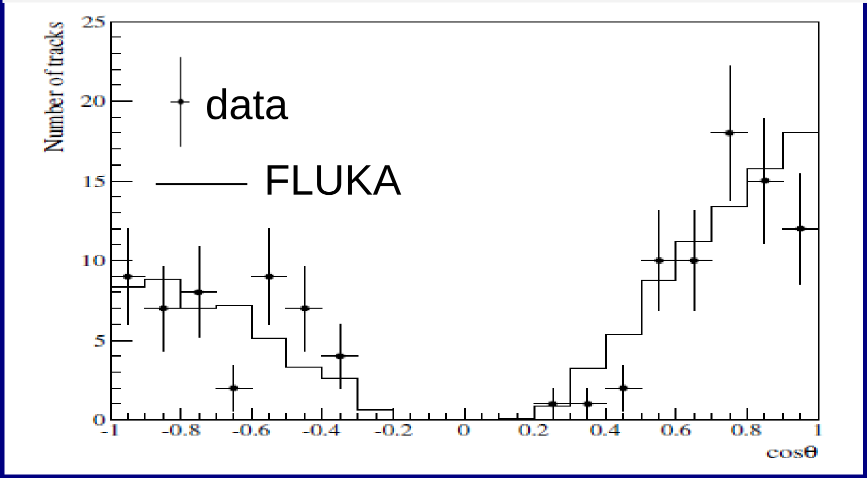


1) Tracks follow down:

primary tracks followed (through several bricks) to assess the muonless nature of the event.
Applied since first tau candidate in 2010
Fully implemented in simulations

- ✓ Hadronic interactions
- ✓ dE/dx at end of range
- ✓ Range vs momentum correlation

Reduce by a factor ~2 residual probability of 5% undetected large angle muons



2) Search for highly ionizing particles emitted in hadronic interactions

→ Decreases hadronic background by 20%

Good agreement between experimental data and simulations (example 8 GeV pion test exposure)

Neutrino velocity measurement

Time
Neutrinos production time (CERN)
Neutrinos interaction time (OPERA detector)

Space
Accurate determination of the distance (Geodesy)

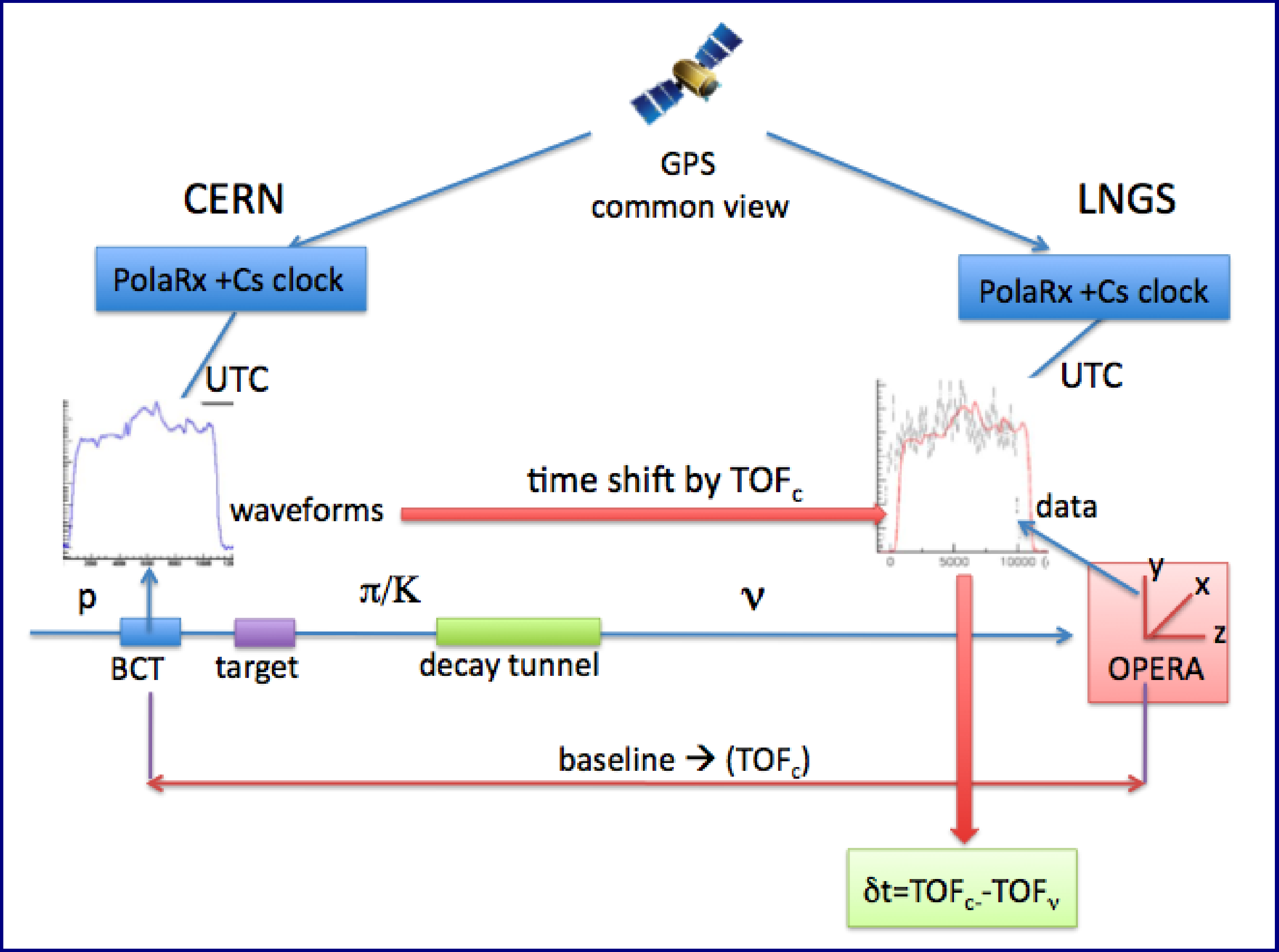
→ Largest application of metrology techniques in HEP

2009-2011 measurement with standard CNGS beam → Blind analysis: "box" opened after assessment of delays (previously fixed to arbitrary values):

- High neutrino energy - high statistics ~15000 events
- Precise measurement of neutrino time distribution at CERN through proton waveforms
- Sophisticated timing system: ~1 ns CNGS-OPERA synchronization
- Calibrations techniques of CNGS and OPERA timing chains: ~ 1 ns level
- Measurement of baseline by global geodesy: 20 cm accuracy over 730 km (longest neutrino baseline actually available)

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

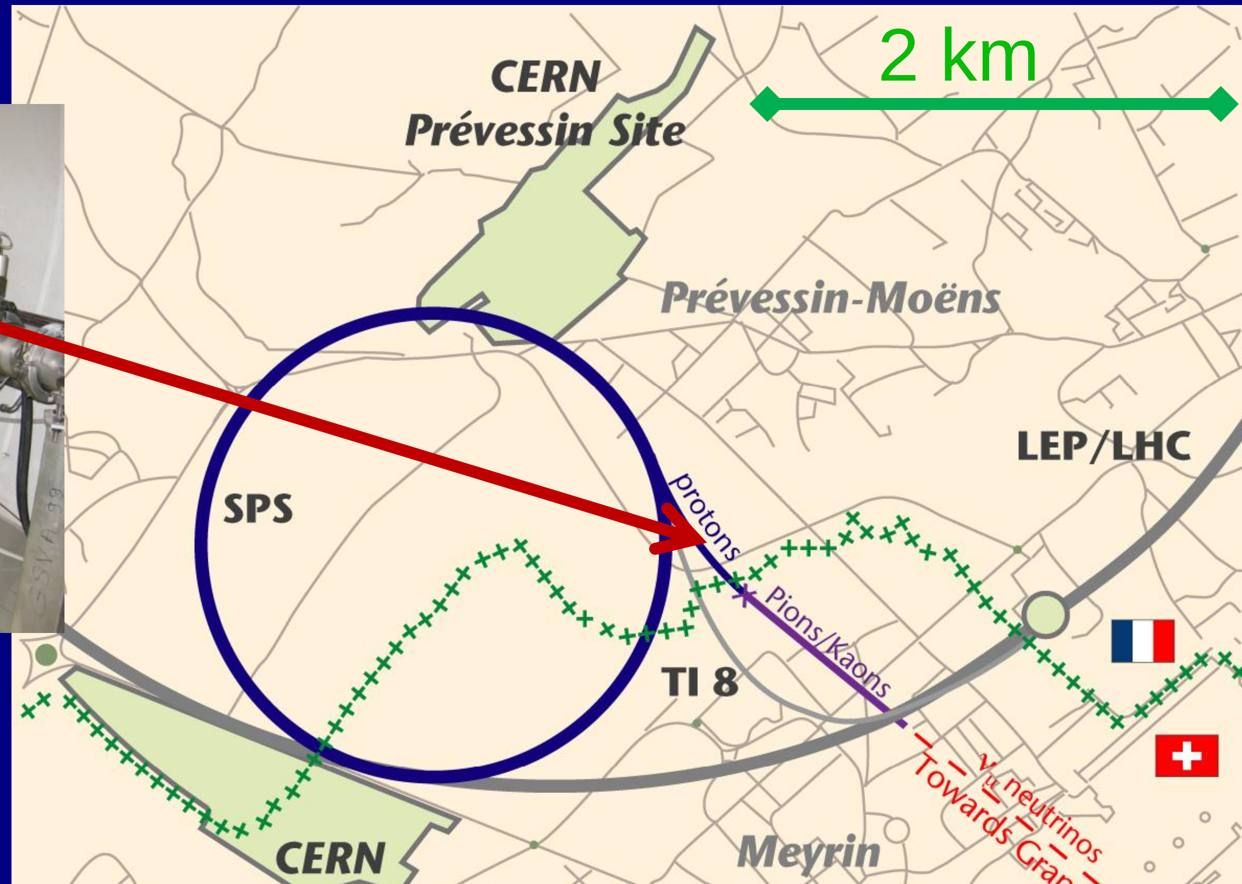
Summary of the principle for the TOF measurement



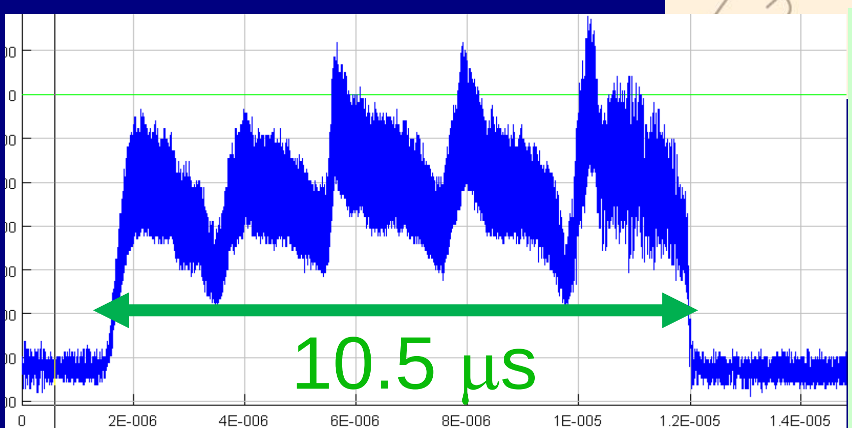
Measure $\delta t = TOF_c - TOF_\nu$

Protons timing

Beam Current Transformer



Recorded waveform of a protons pulse



Proton pulse digitization:

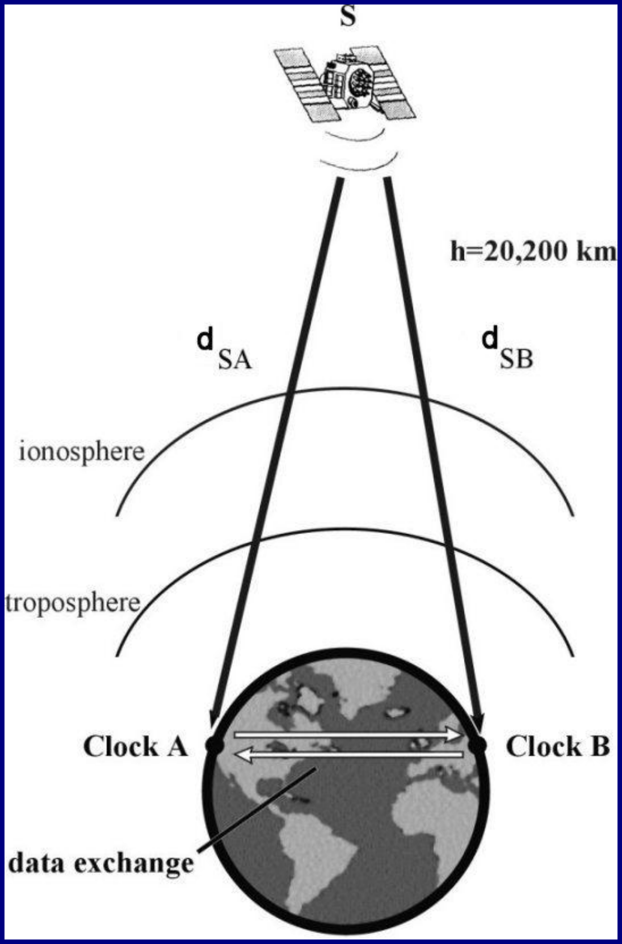
- Acqiris DP110 1GS/s waveform digitizer (WFD)
- WFD triggered by a replica of the kicker signal
- Waveforms UTC-stamped and stored in CNGS database for offline analysis

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

Twin geodetic GPS receiver PolaRx2e + Cs clock → Time-transfer (~1 ns accuracy)

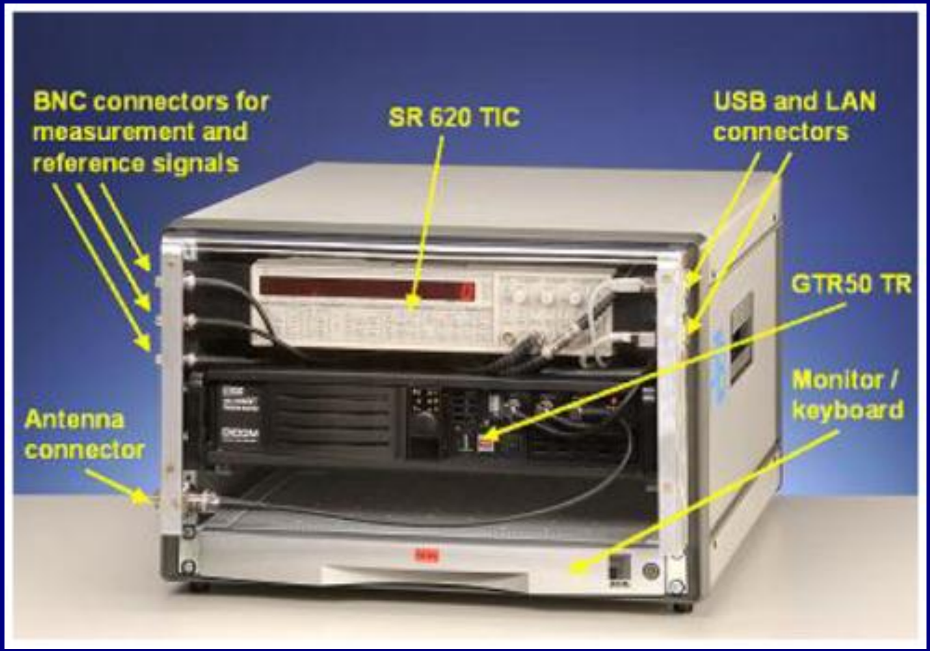
Standard technique used in TAI (International Atomic Time) by BIPM

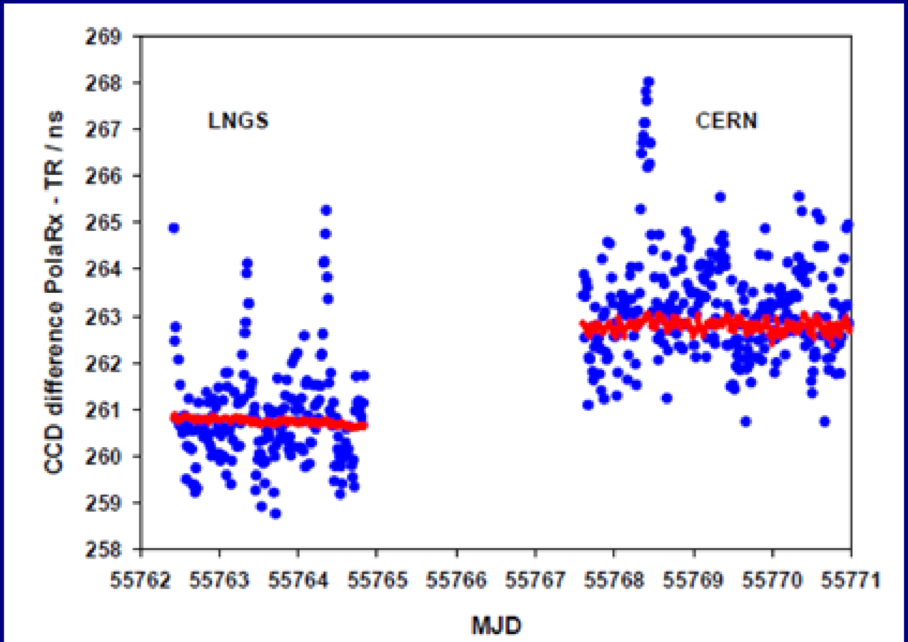
CERN-OPERA inter-calibration cross-check

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

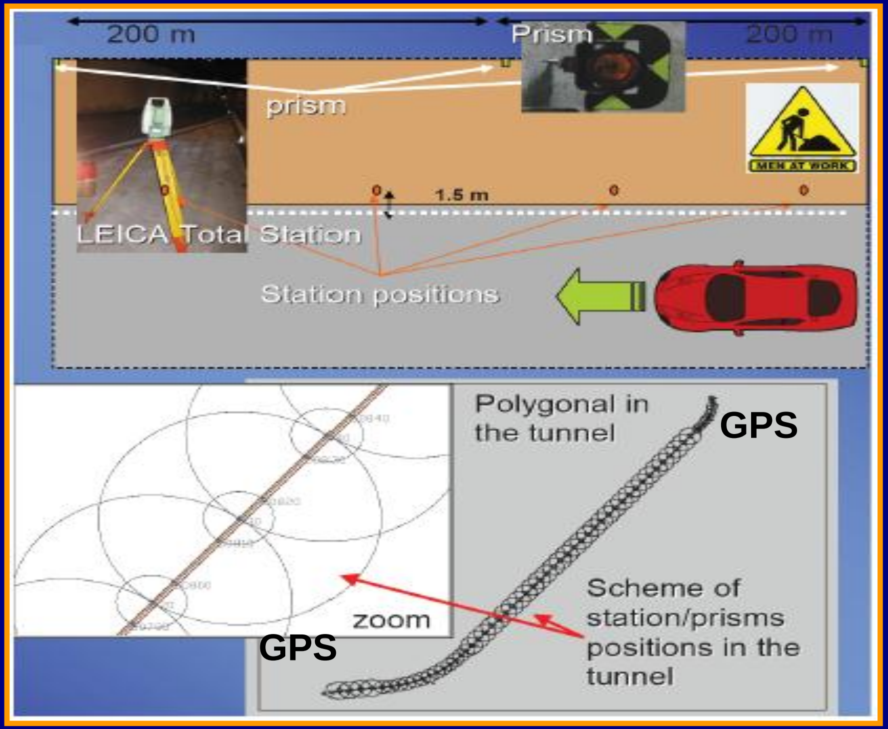




Correction to the time-link:

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

Geodesy at LNGS

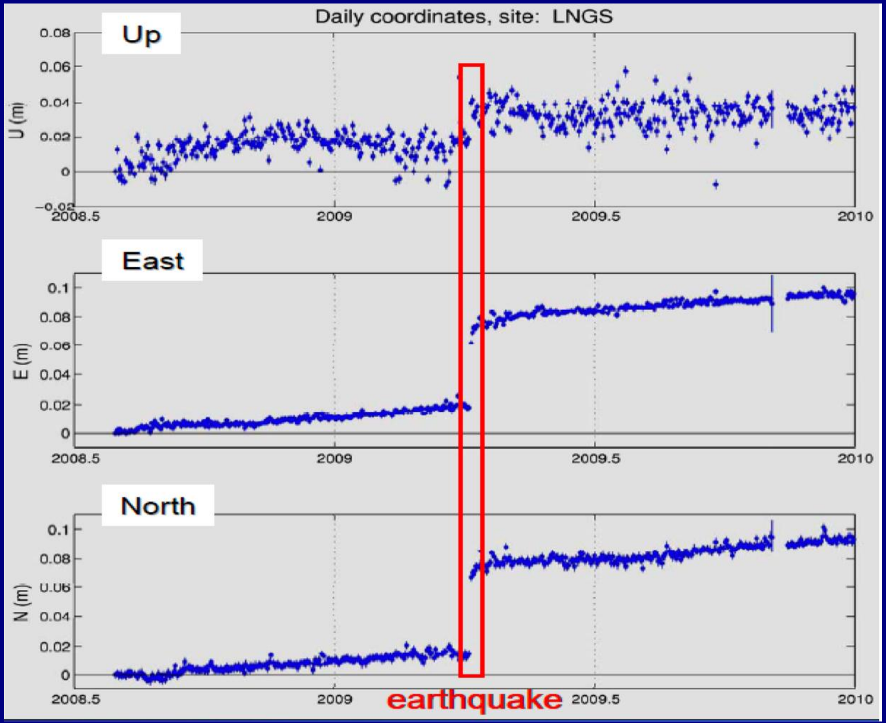


Dedicated measurements at LNGS: July-Sept. 2010

2 new GPS benchmarks on each side of the 10 km highway tunnel → ported underground to OPERA

CERN and LNGS measurements combined in ETRF2000

Distance
CERN BCT-OPERA
(731278.0 ± 0.2) m



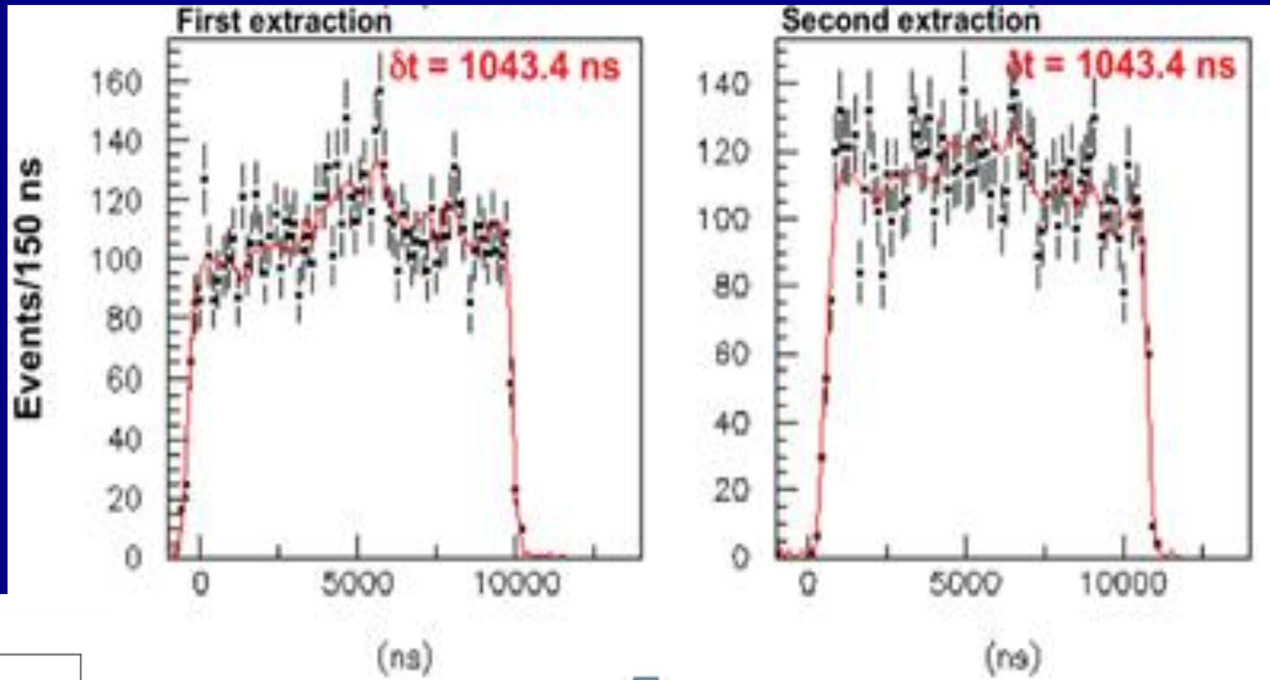
Monitor continental drift and important geological events (e.g. 2009 earthquake)

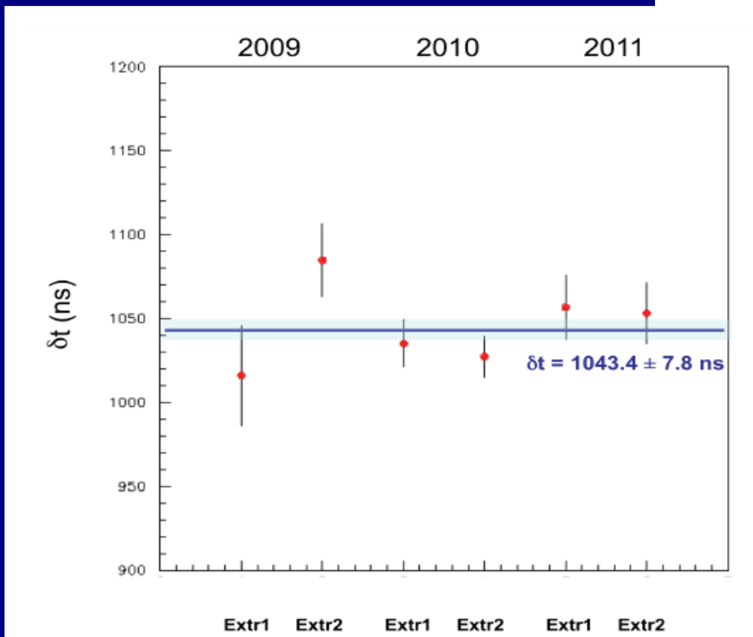
Neutrino data vs protons: after delay determination (2009-2011) ~15000 neutrinos (September 2011)

Dots: neutrino events
Red line: protons PDF

Likelihood maximization
As a function of δt

Blind result:
$\delta t = TOF_c - TOF_\nu =$
(1043.4 ± 7.8) ns





Blind cross-checks:

- ✓ Accuracy of analysis method
- ✓ Stability in the 3 years
- ✓ Day/night
- ✓ Warm/cold
- ✓ External/internal interactions
- ✓ Running conditions, beam intensity

Opening the box

timing and baseline corrections

	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**

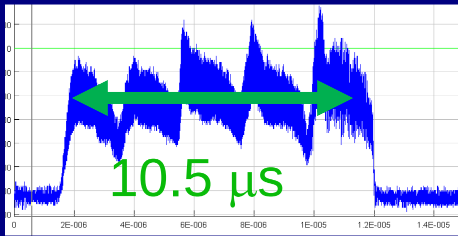
systematic uncertainties

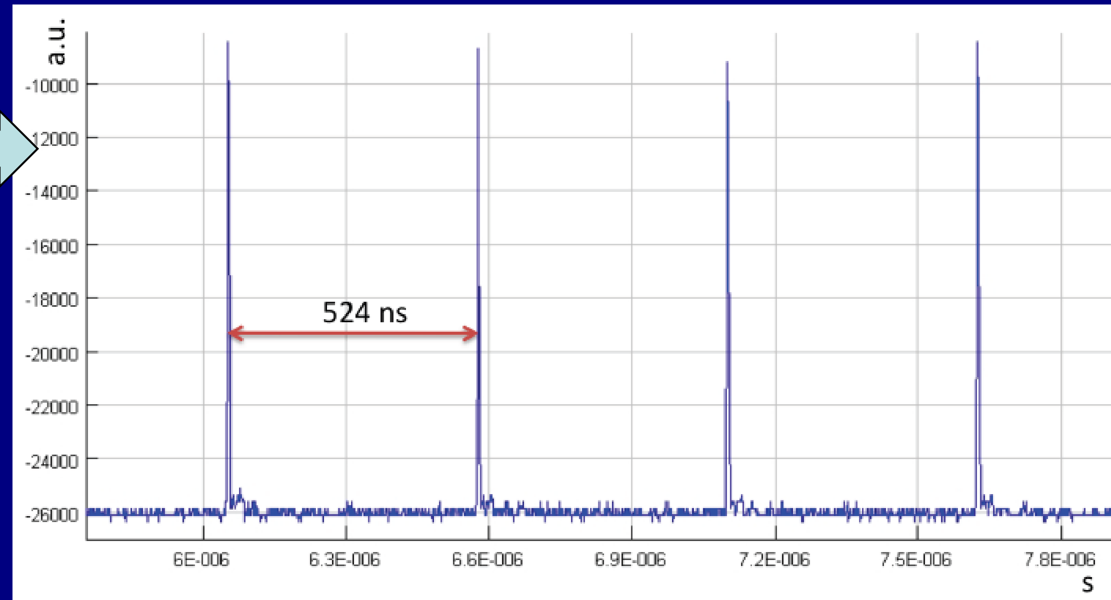
Systematic uncertainties	ns	Error distribution
Baseline (20 cm)	0.67	Gaussian
Decay point	0.2	Exponential (1 side)
Interaction point	2.0	Flat (1 side)
UTC delay	2.0	Gaussian
LNGS fibres	1.0	Gaussian
DAQ clock transmission	1.0	Gaussian
FPGA calibration	1.0	Gaussian
FWD trigger delay	1.0	Gaussian
CNGS-OPERA 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**	

Result as presented in September 2011

UNBLIND: $\delta t = (57.8 \pm 7.8\ (\text{stat.})\ \ -5.9\ +8.3\ (\text{sys.}))$ ns

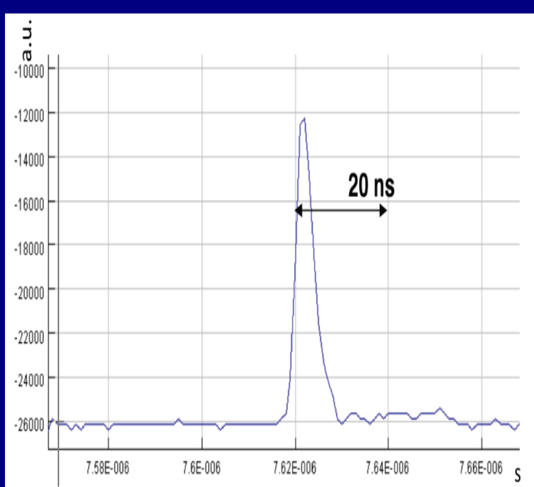
Test with a short-bunch wide-spacing beam (22/10 - 6/11 2011)





- 1 extraction/CNGS cycle
- 4 bunches/extraction ~3 ns
- 524 ns gaps

- **1.1×10^{12} pot/cycle → ~60 less intensity than standard CNGS**



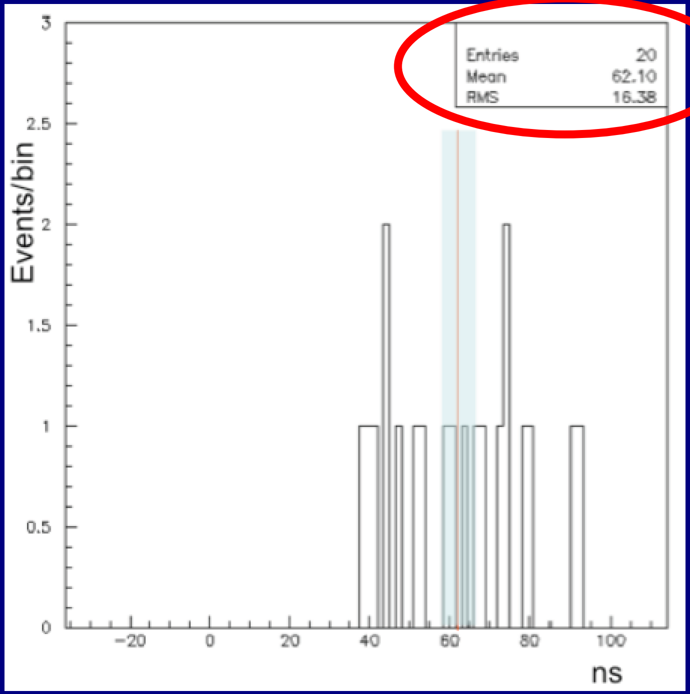
Unambiguous attribution of events to single peaks

✓ Event by event analysis
(no cumulative PDF), no treatment of waveforms

✓ Exclude possible sys. related to long pulses
Target behavior, horns, aiming accuracy

✓ Less critical measurement of waveforms/ BCT response

Results with a short-bunch wide-spacing beam



Time of flight individually measured for 20 neutrinos

RMS dominated by instrumental resolution in relating the Master Clock 20 MHz to GPS sync signal → ±25 ns jitter

→ $\delta t = TOF_c - TOF_\nu =$ (62.1 ± 3.7 (stat.)) ns

(2009-2011) PDF analysis (57.8 ± 7.8 (stat.)) ns

→ Result excluding biases related to PDF based analysis

September seminar + bunched beam results (paper submitted to JHEP on Nov. 17th 2011, arXiv:1109.4897)

Conclusions slide/sentences in the paper:

- 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

Further investigations since November 2011

- Discussion of a new bunched beam campaign (indicative date May 2012) with improved beam performance (100 ns bunch spacing, a factor 3 more intensity). More accurate study for possible energy dependence and measurement with anti-neutrinos. Other LNGS experiments (ICARUS, BOREXINO, LVD) involved.

- Development of a new time-transfer system at CERN and LNGS based on the White-Rabbit protocol (self-calibrating continuous delay measurement)

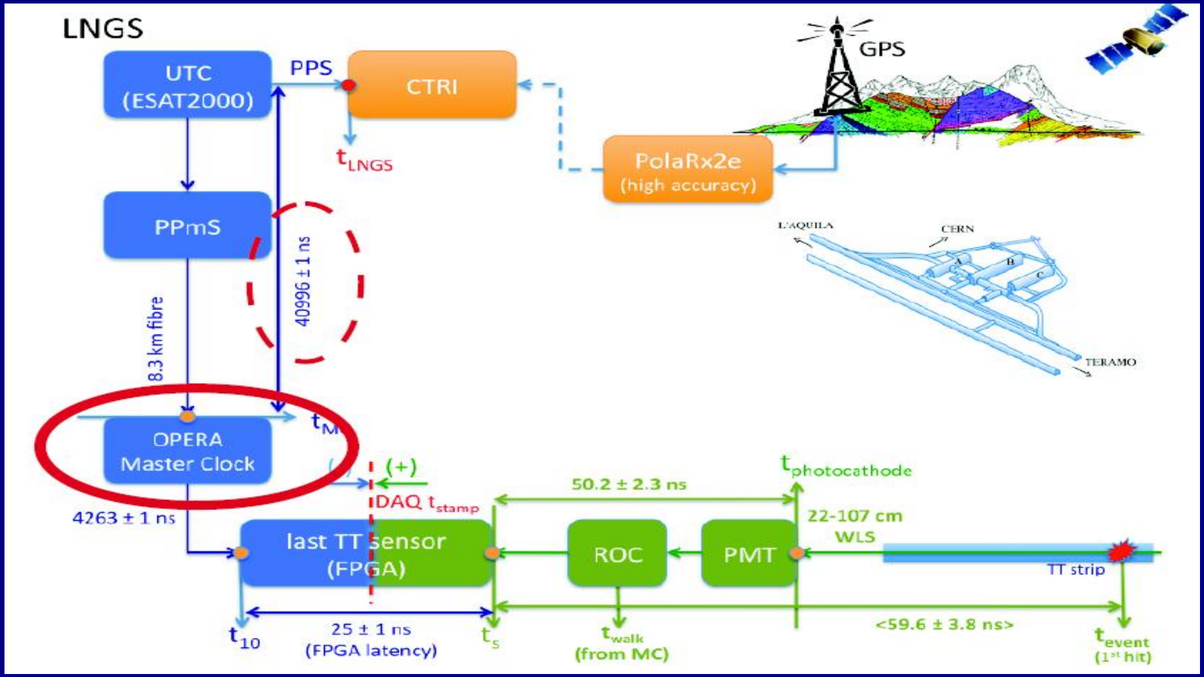
- Developments for DAQ upgrade → for May 2012 run by including TDCs at the level of the Master clock (±25 ns jitter) and FE sensors (± 5 ns jitter)

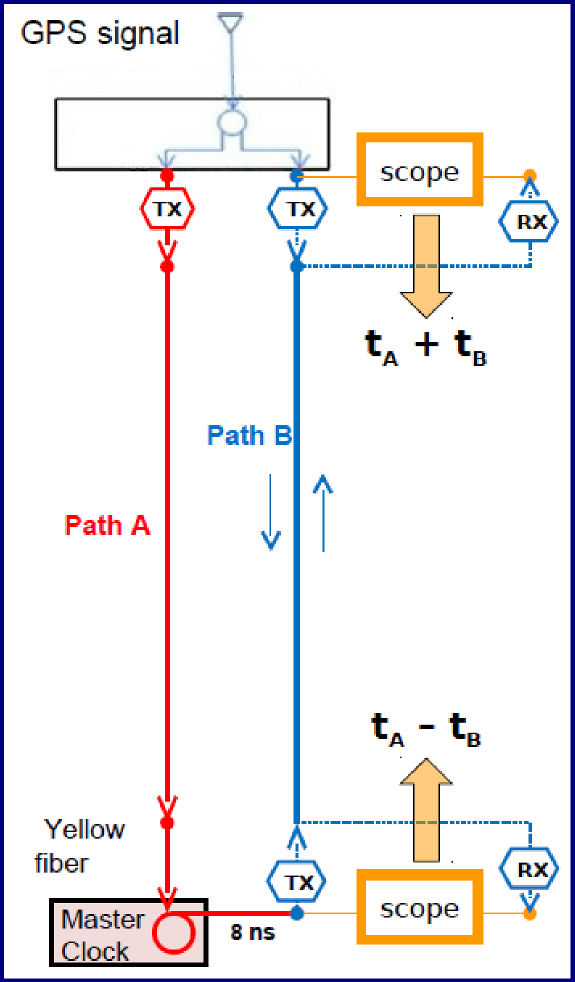
- Additional checks on the Geodesy at CERN on the underground transport of external GPS measurements

- Additional checks on GPS timing with a two-way satellite transfer measurement and possible time-transfer via optical fibers

- Additional measurements at LNGS (winter 2011 shutdown):
  → identified two unknown sources of bias on TOF, going in opposite directions (22 Feb. 2012)

Connection of the 8.3 km fiber bringing to the OPERA Master Clock the signal of the LNGS GPS system





Re-measurement campaign Dec. 2011 – Feb. 2012

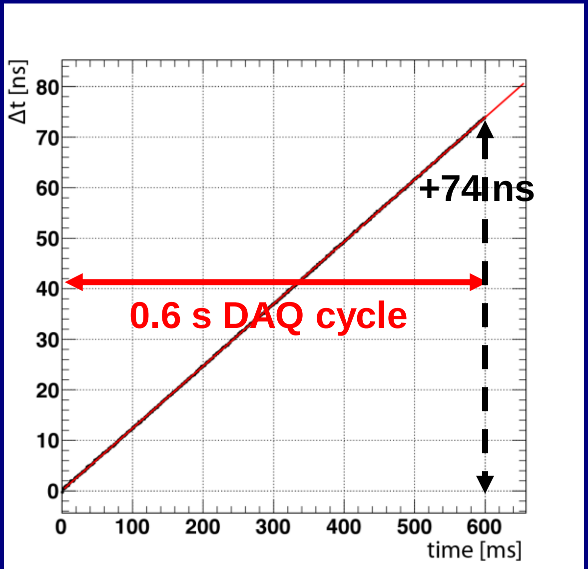
First measurements in Dec. 2011 showing a delay increased by 73.2 ns (underestimation of neutrino TOF)

Further measurements agreeing at ~ns level with ones performed in 2006/2007

Suspected an anomalous condition in the fiber connection → characterized detection delay as a function of the amount of light

Not known: when the problem occurred, the connection condition and its time stability

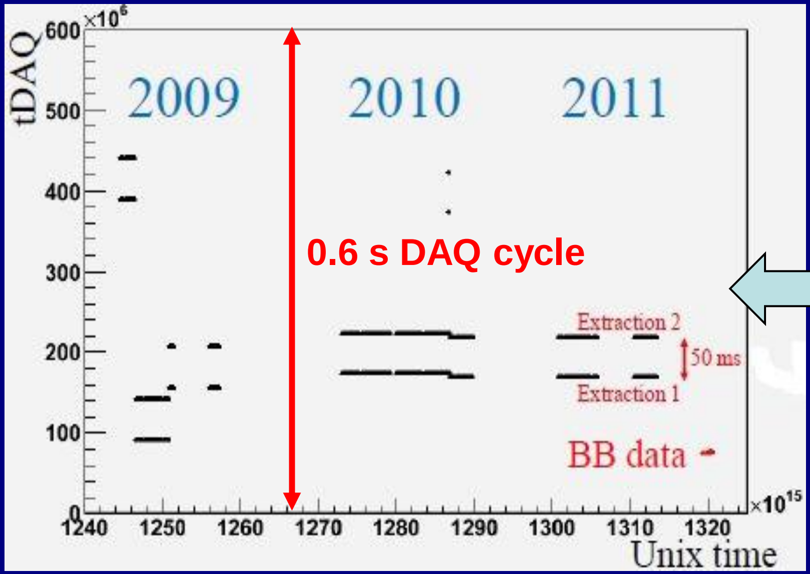
OPERA Master Clock local OCXO oscillator



10 MHz clock free running over 0.6 s (DAQ cycle) to increment the 10 ns fine counter for time-stamp (after x2 x5 multiplications)

Recalibrations w.r.t. the 10 MHz by Cs clock show a frequency offset of +0.124 ppm

The OCXO oscillator runs faster than nominal, the events time-stamps are artificially delayed
→ Overestimation of the neutrino TOF



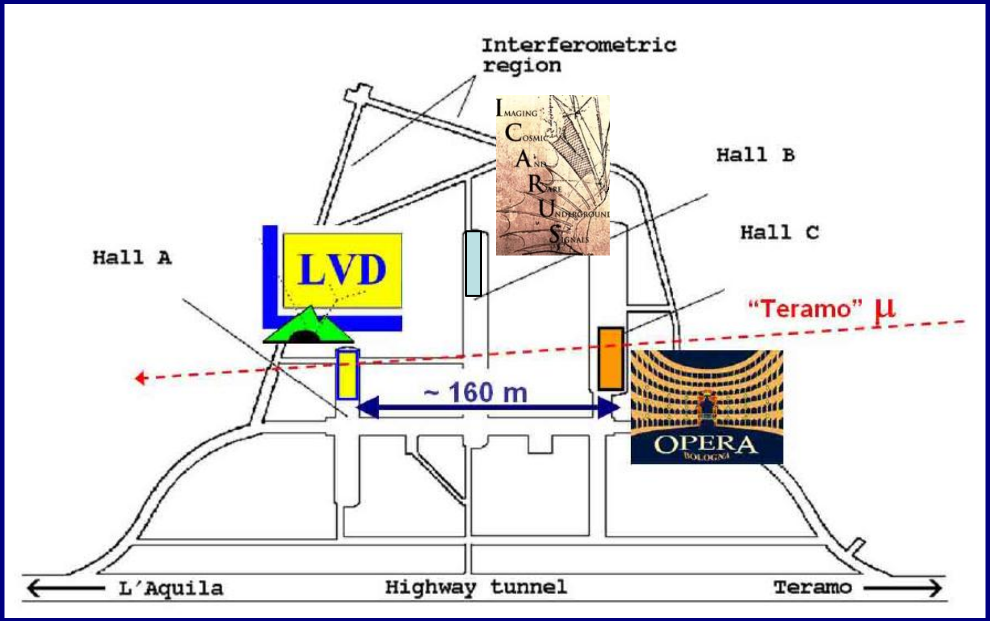
Bias may reach up to 74 ns for events occurring exactly at the end of the 0.6 s DAQ cycle

CNGS events are not uniformly distributed within DAQ cycles

Times bound to fixed values (CNGS and OPERA DAQ based on 0.6 s cycles locked on the GPS)

Corrections calculable but origin and time stability of frequency offset are not known

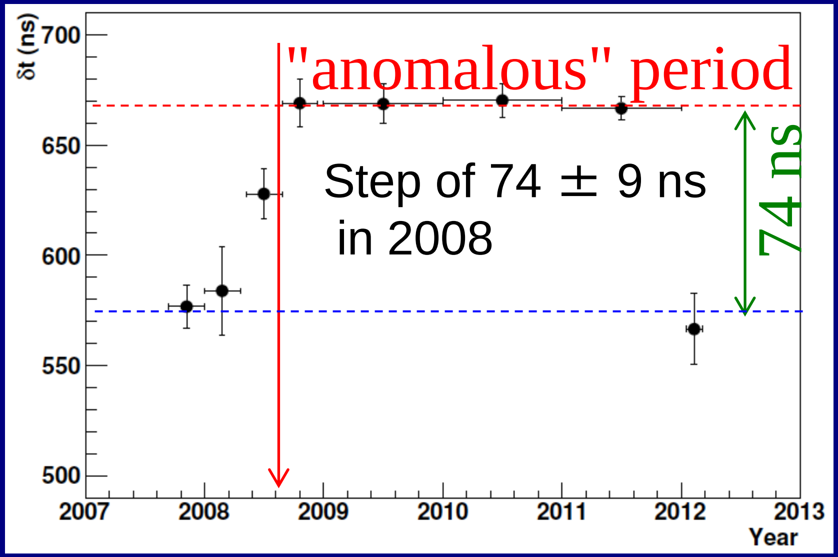
OPERA-LVD horizontal cosmic ray muons coincidences



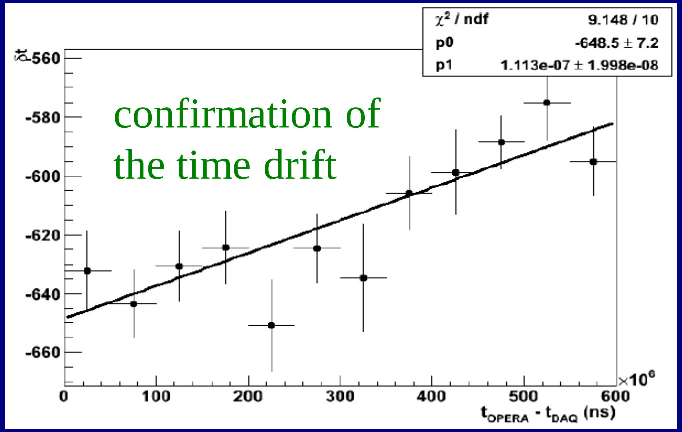
Coincidences search motivated by high Pt CR studies

Both detectors with common time origin (old LNGS GPS ESAT 2000)

Monitor horizontal muons TOF as a function of time (~2 events/week)



OCXO frequency offset visible also with CR muons (uniformly distributed in 0.6s). Looks similar for all years



DAQ cycle

Reinterpretation of 2011 results accounting for winter shutdown measurements and LVD correlations

2009-2011 results with long pulses:

$$\delta t = TOF_c - TOF_\nu = (6.5 \pm 7.4\ (stat.)\ ^{+8.3}_{-8.0}\ (sys.))\ ns$$

$$(v-c)/c = \delta t/(TOF'_c - \delta t) = (2.7 \pm 3.1\ (stat.)\ ^{+3.4}_{-3.3}\ (sys.)) \times 10^{-6}$$

November 2011 short pulses: $\delta t = 1.9 \pm 3.7$ ns (same syst. errors)

New direct measurement campaign of 10-24 May 2012:

1) **Improvements in OPERA timing**

New OPERA master clock installed

a) Better timing → time resolution twice better

b) Better local oscillator, small frequency offset 5ns/s (124 ns/s old oscillator)

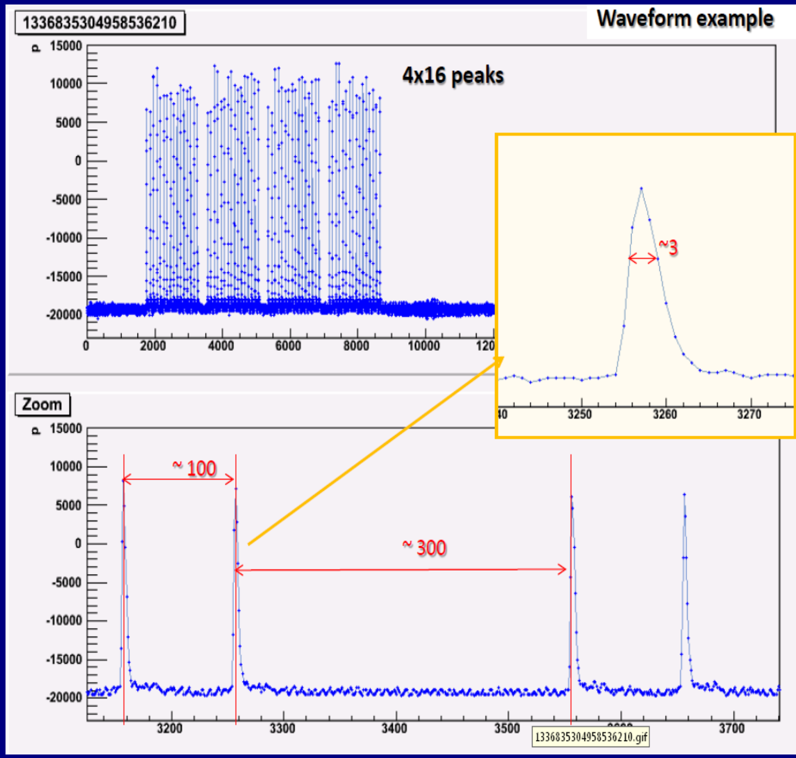
c) Continuous monitoring of the local oscillator frequency and fiber transmission delay using the "White Rabbit" system

d) Better stability of Master Clock delay response with respect to light input from the fiber

2) Improvements in the CNGS beam timing structure

November 2011: 4 short bunches separated by 524 ns

May 2012: 64 short bunches separated by 100 ns



3) Improvements in timing equipment systematics

a) Double GPS system
b) White Rabbit monitoring of all time transfer delays at CERN and LNGS
c) Beam Current Transformer (BCT) calibration redone. Before: BCT systematic error of 5 ns (the largest sys. error affecting the measurement). Now → reduced to 1 ns
d) Two independent subdetectors in OPERA (TT and RPC)

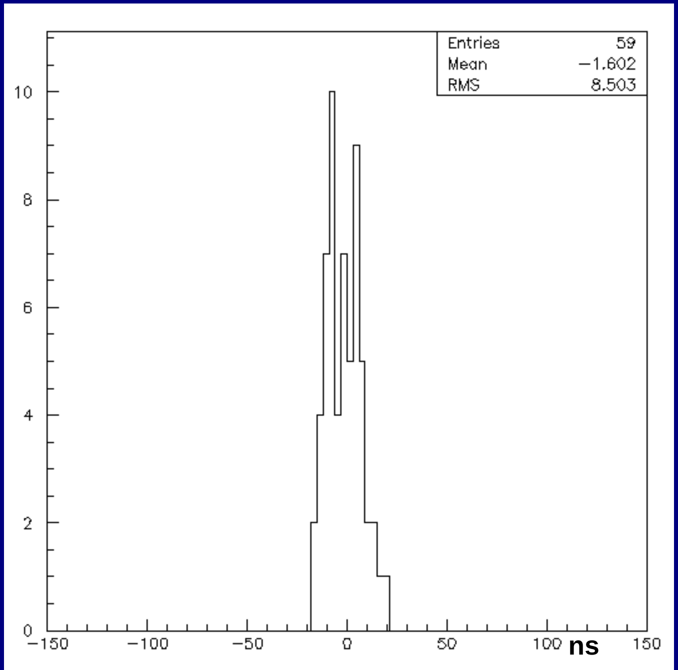
106 events collected

59 events selected by the analysis cuts (factor 3 better statistics, factor 2 better resolution, redundancy)

Preliminary result:

$$\delta t = \left(-1.6 \pm 1.1\ (stat.)^{+6.1}_{-3.7}\ (sys)\right)\ \text{ns}$$

$$\frac{v-c}{c} = \frac{\delta t}{TOF_c - \delta t} = (-0.7 \pm 0.5\ (\text{stat.})^{+2.5}_{-1.5}\ (\text{sys.})) \times 10^{-6}$$



Consistency of 4 LNGS experiments May 2012 data (S. Bertolucci, Kyoto conference)

- **Borexino:** δt = 2.7 ± 1.2 (stat) ± 3(sys) ns
- **ICARUS:** δt = 5.1 ± 1.1(stat) ± 5.5(sys) ns
- **LVD:** δt = 2.9 ± 0.6(stat) ± 3(sys) ns
- **OPERA:** δt = 1.6 ± 1.1(stat) [+ 6.1, -3.7](sys) ns

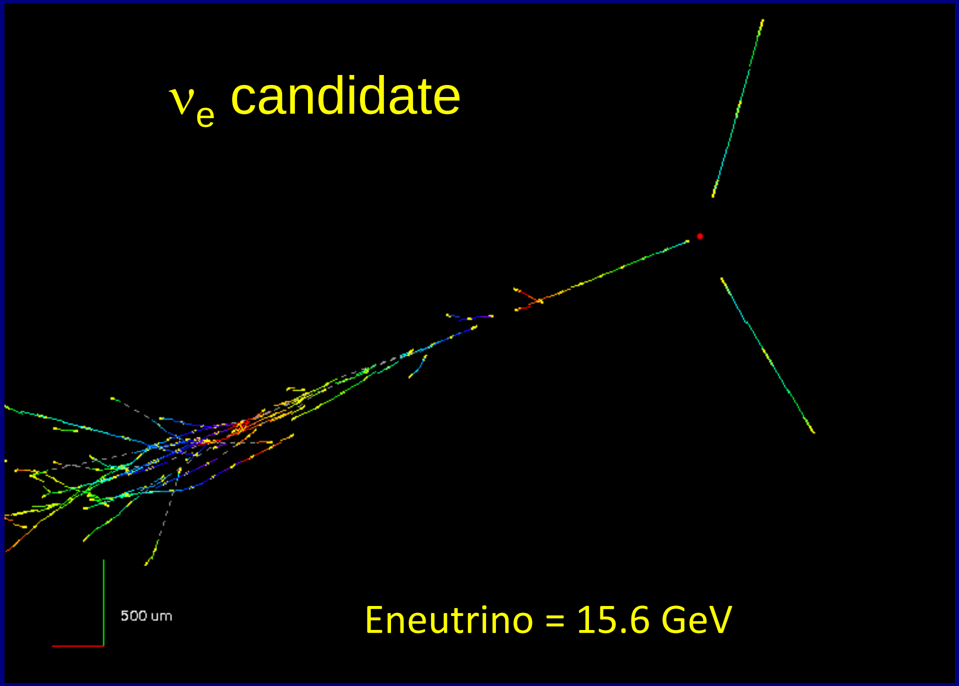
OPERA timeline:

- 2000 proposal approval
- 2006 first CNGS neutrinos observed with electronic detectors only (no bricks present)
- 2008 end of target filling, first physics run

Year	Proton On Target POT	Number of Neutrino Interactions	Integrated POT / Proposal Value
2008	1.78×10^{19}	1698	7.9%
2009	3.52×10^{19}	3557	23.6%
2010	4.04×10^{19}	3912	41.5%
2011	4.84×10^{19}	4210	63.0%
2012	($\sim 4.7 \times 10^{19}$)	(~4050)	(~84%)

- 14.2 x 10^{19} POT up to 2011
- Expected POT at the end of 2012 RUN: 18.9 x 10^{19} (proposal goal: 22.5×10^{19})

- Events found in the scanned subsample:
  - 19 ν_e CC candidates (consistent with beam ν_e BG:19.2 events)
  - 2 ν_τ CC candidates 2.1 ν_τ CC expected, BG: 0.2 events

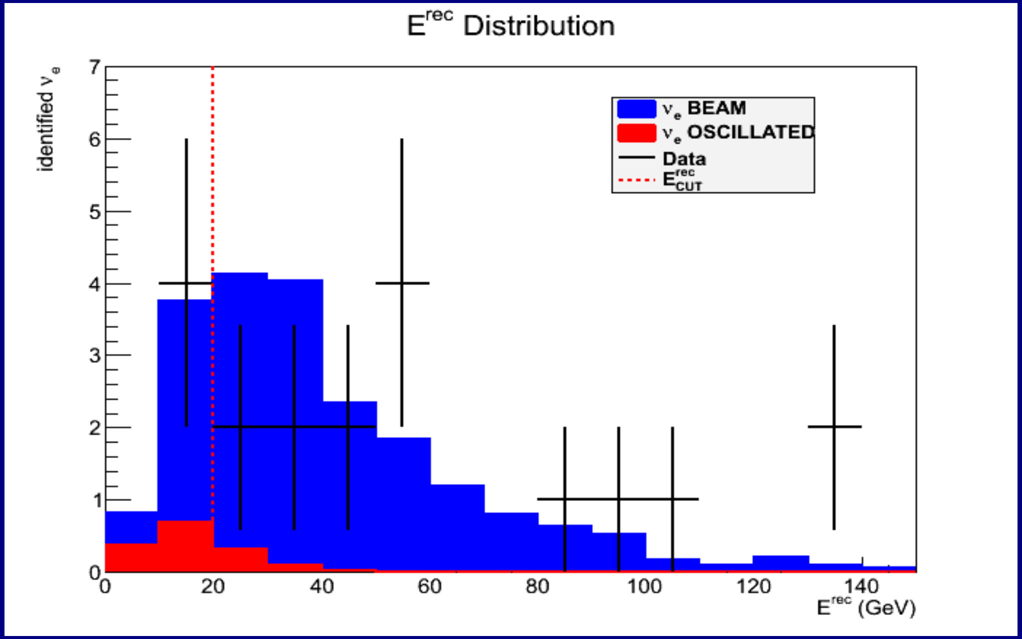


Expected events:

- oscillated ν_e 1.5
- beam ν_e BG 19.2

→Observed ν_e : 19 events

ν_e CC candidates energy distribution



After low-energy selection (Eν<20GeV):

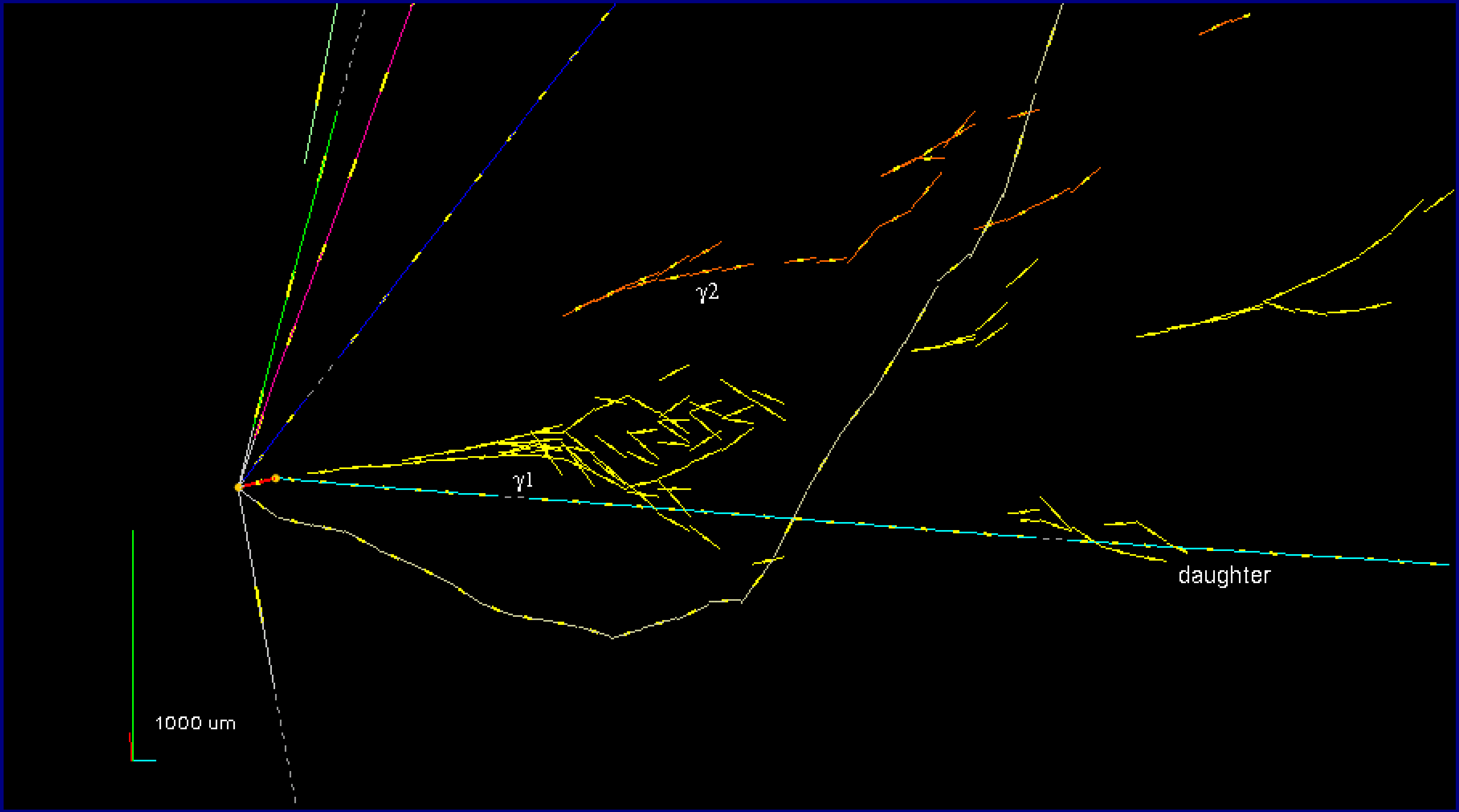
Expected events:

- **oscillated 1.1,**
- **beam ν_e BG 3.7**

Observed ν_e : 4 events.

First OPERA ν_τ candidate (single hadronic prong τ decay)

http://arxiv.org/abs/1006.1623
Physics Letters B (PLB-D-10-00744)



ν_τ **+ N → τ^- + X**

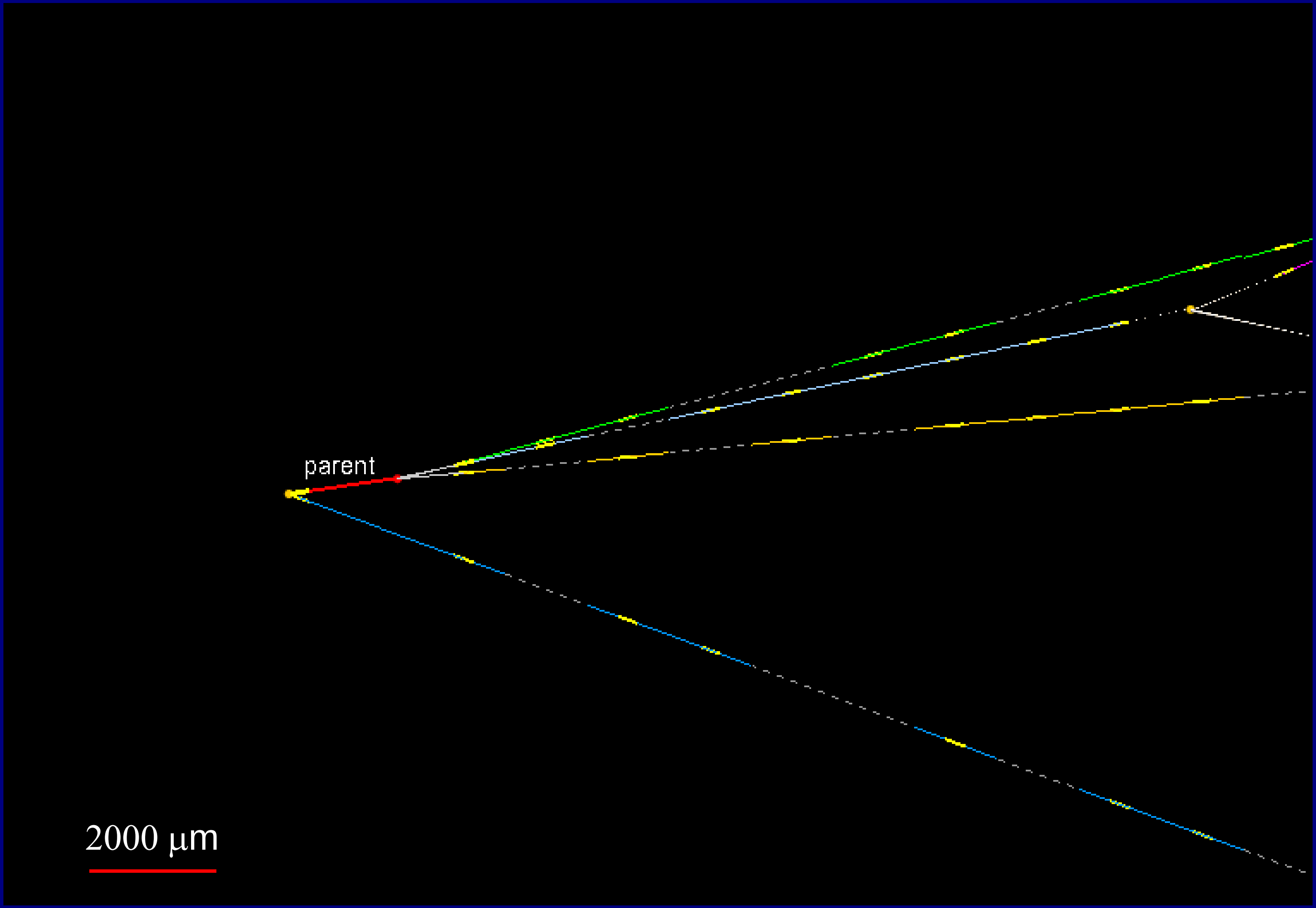
$\tau^- \rightarrow \rho^- + \nu_\tau$

$\rho^- \rightarrow \pi^- + \pi^0$

$\pi^0 \rightarrow \gamma + \gamma$

Visible tau decay topology with kink and two gammas

3 prongs tau candidate (Neutrino 2012)



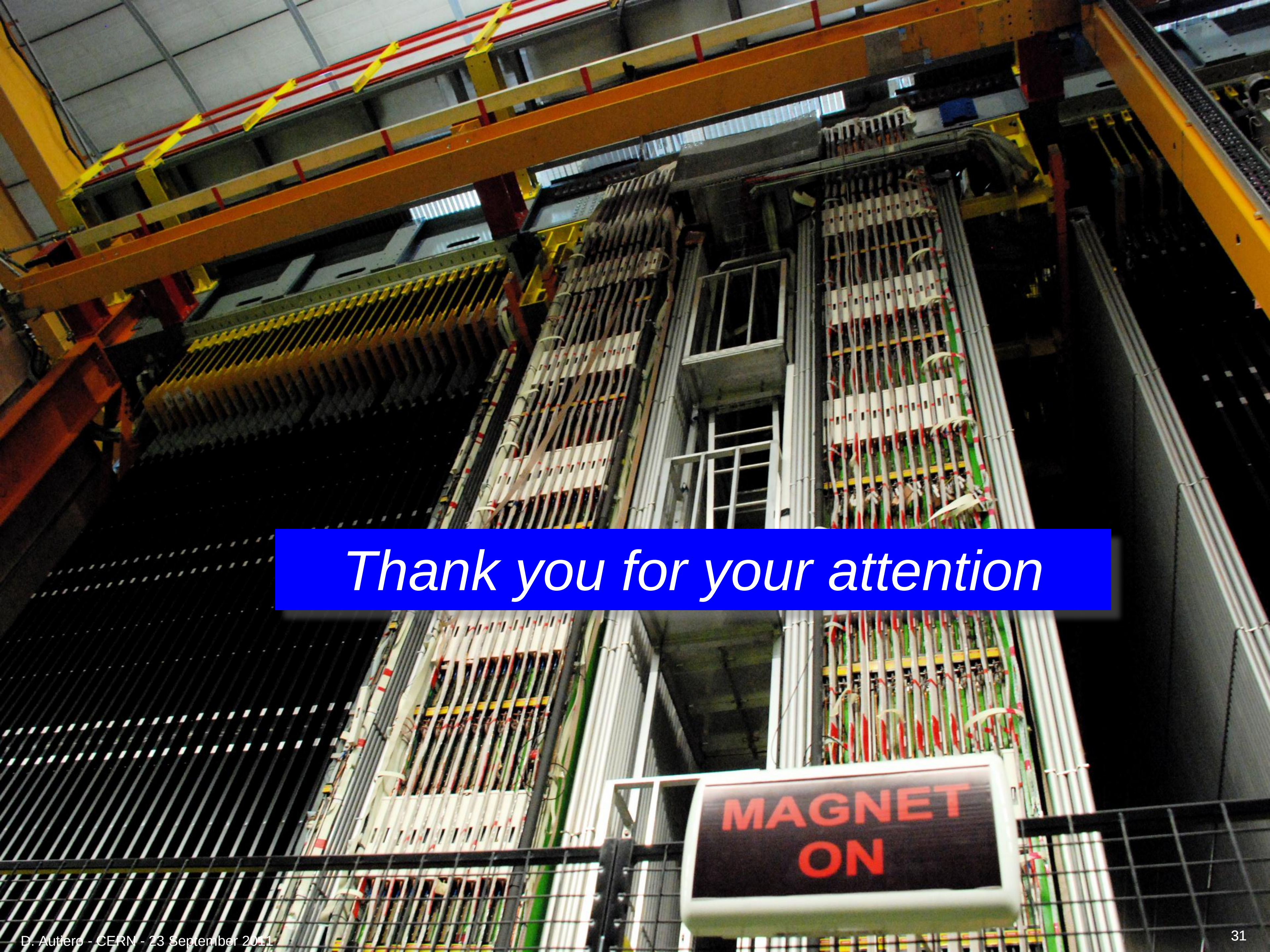
Conclusions:

- The study of $\nu\mu \rightarrow \nu\tau$ oscillations in appearance mode represented a big technological and scientific challenge. The OPERA experiment approved in the year 2000 after the completion of its target filling took its first physics run in 2008. By the end of the 2012 run ~1.9 10^{E}20 protons on target (84% of nominal statistics) are expected.

- Two tau candidates have been published so far (2.1 taus expected with a background of 0.2 events for the corresponding sample analyzed so far: 2008+2009 fully analyzed , 2010+2011 partially analyzed)

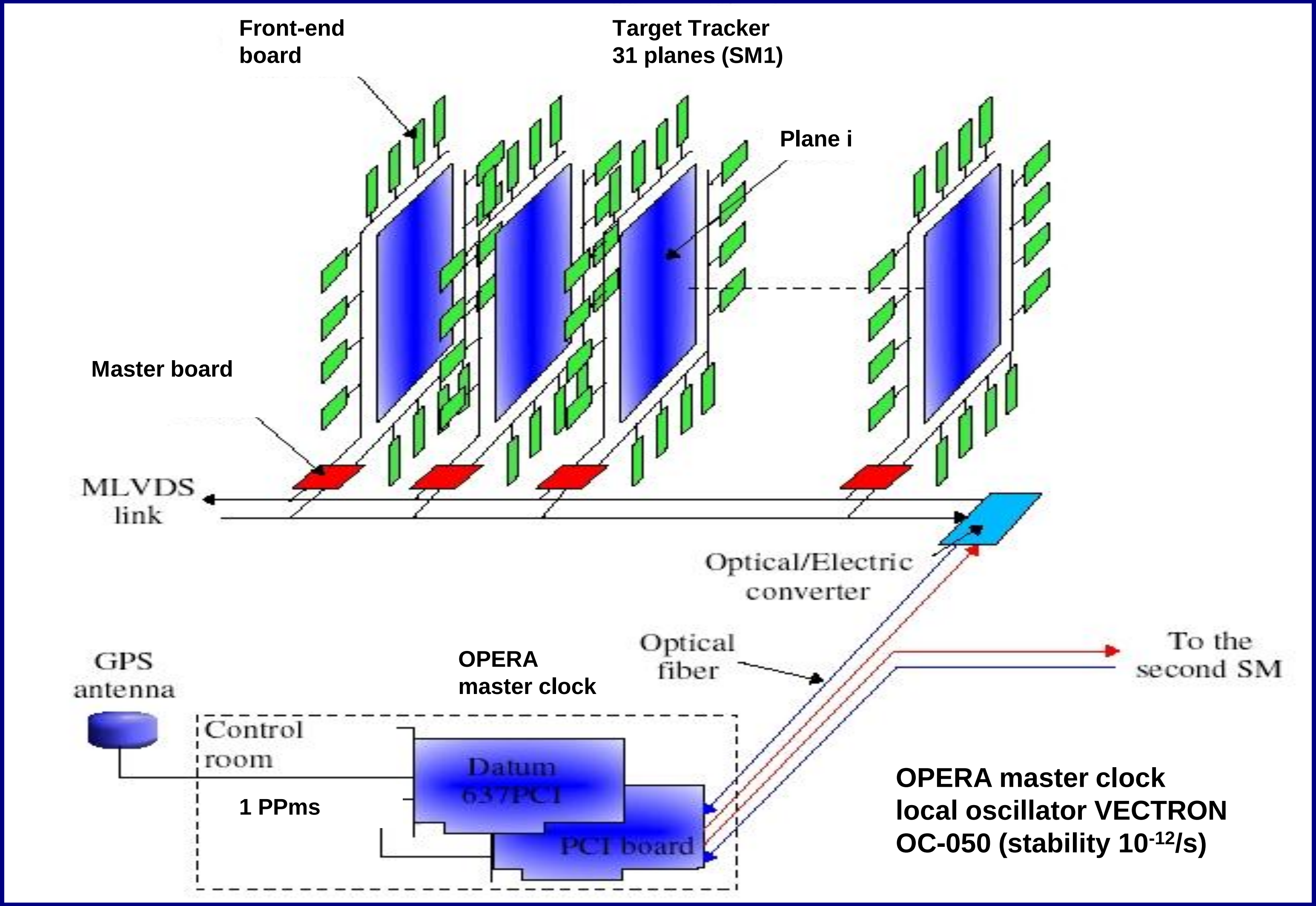
- OPERA opened the way for high precision measurements of neutrino velocity and its methodology and pioneering geodesy and timing measurements, now in common with other experiments

- While continuing the search for unaccounted systematic errors, the OPERA Collaboration discovered two effects affecting the TOF anomaly. These were further investigated with C.R. studies. A new direct measurement in May 2012 gave a result compatible with the speed of light



Thank you for your attention

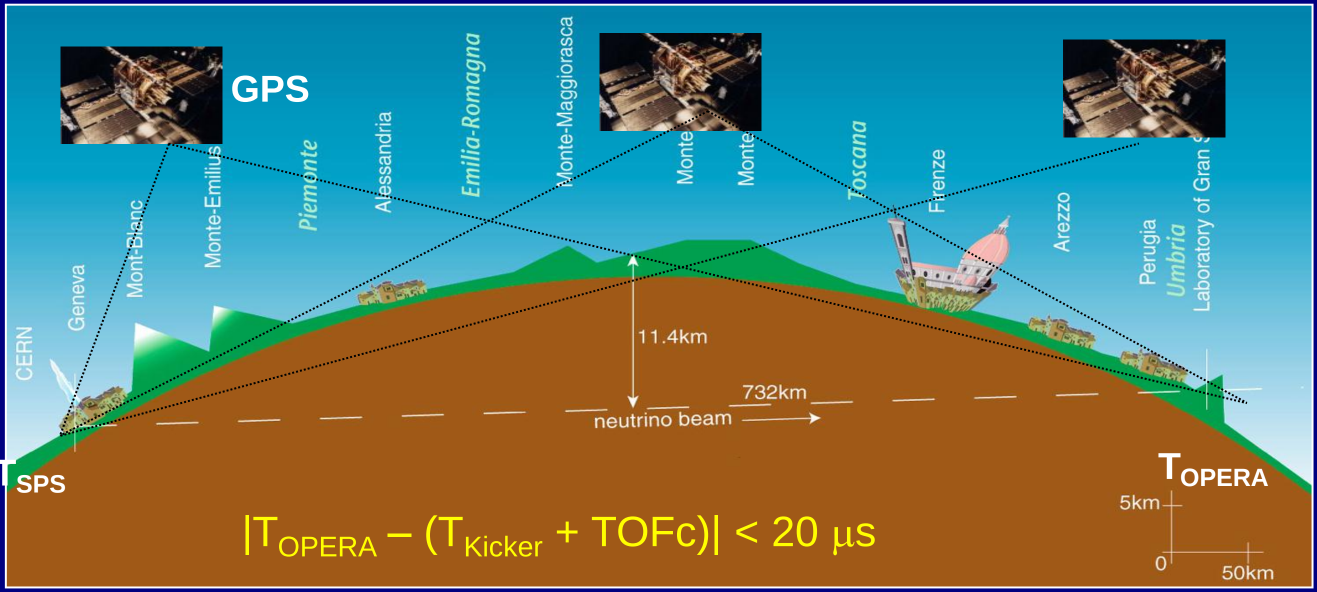
Clock distribution system (10 ns UTC event time-stamp granularity)



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

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

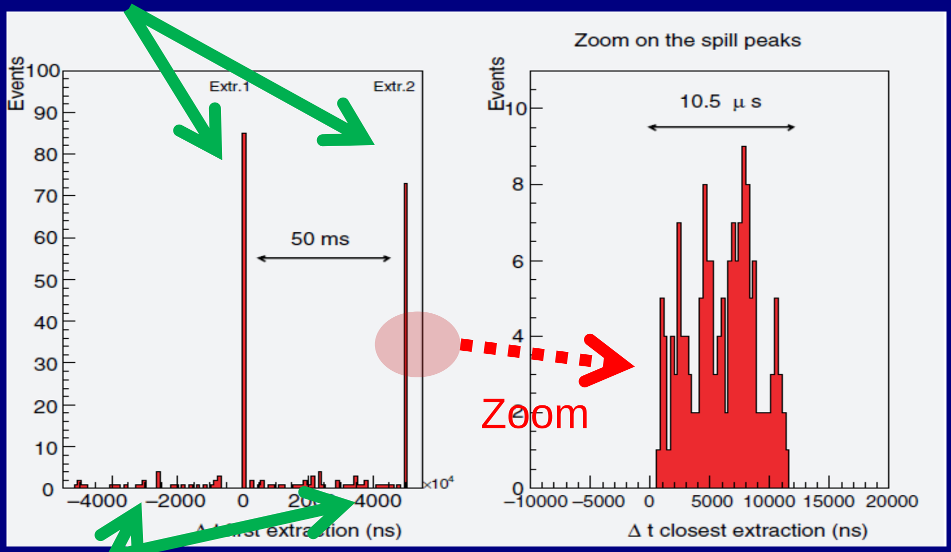
CNGS events selection



Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events (since 2006)

~100 ns accuracy conventional GPS systems

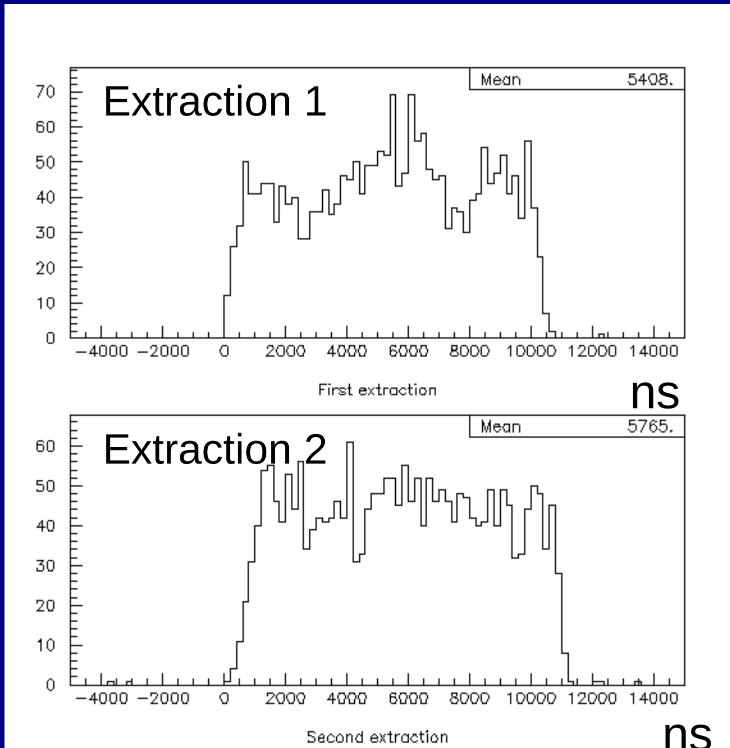
Neutrinos

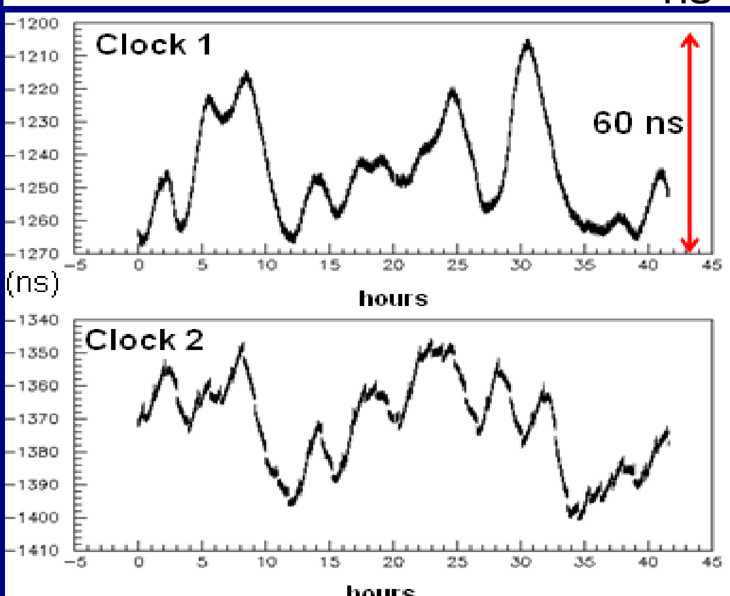


Time distribution of neutrino interactions in OPERA

Negligible cosmic rays background → $O(10^{-4})$ in the 10.5 μs spill

From CNGS events selection to neutrino velocity measurement





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

1) Not flat
2) Different timing for the two protons extractions

→ Need to precisely measure the protons spills

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

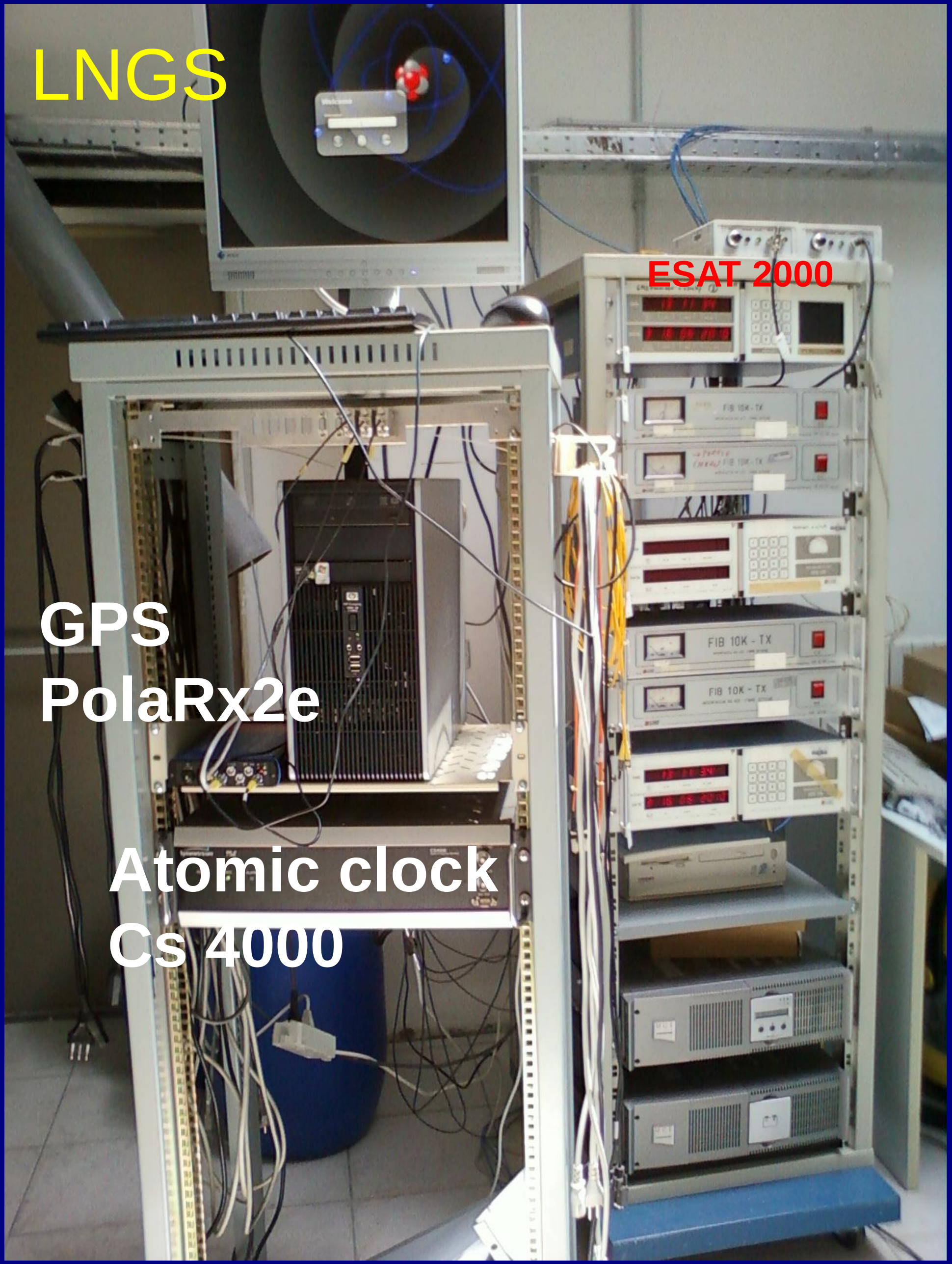
1) Large oscillations of GPS clocks 1PPs
2) Uncertainties on CERN-OPERA synchronization

→ Need accurate time synchronization system

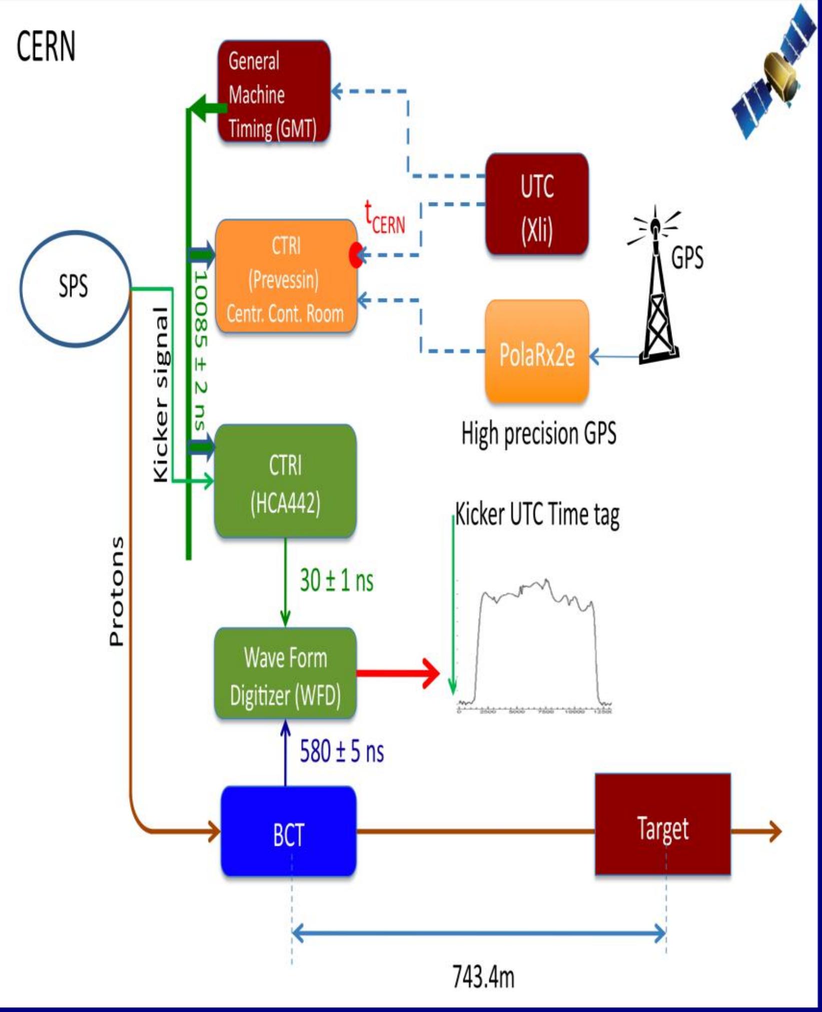
Collaboration with CERN timing team since 2003

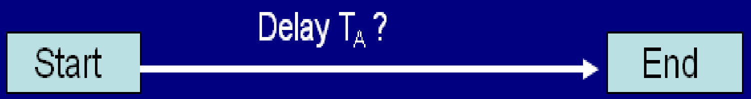
→ **Major upgrade in 2008**

Twin system PolaRx2e GPS - Cs clock



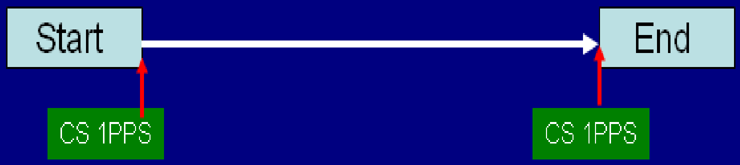
Time calibration techniques





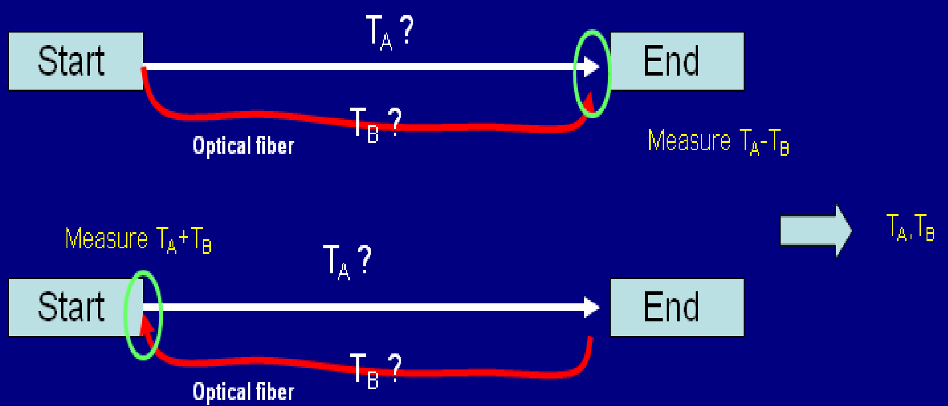
- **Portable Cs-4000**:

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



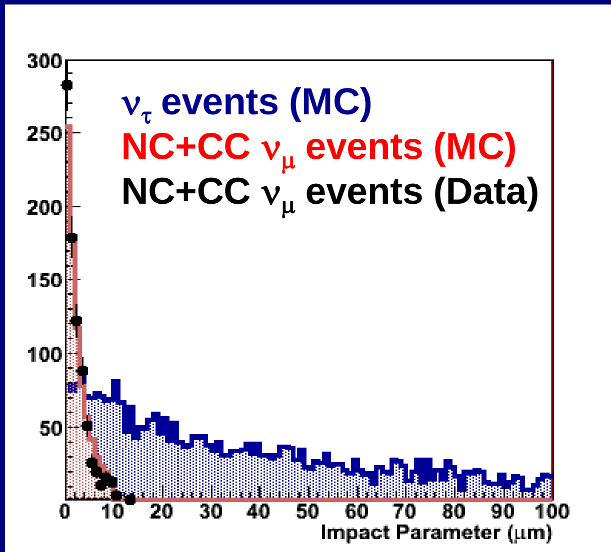
- **Double path fibers measurement:**

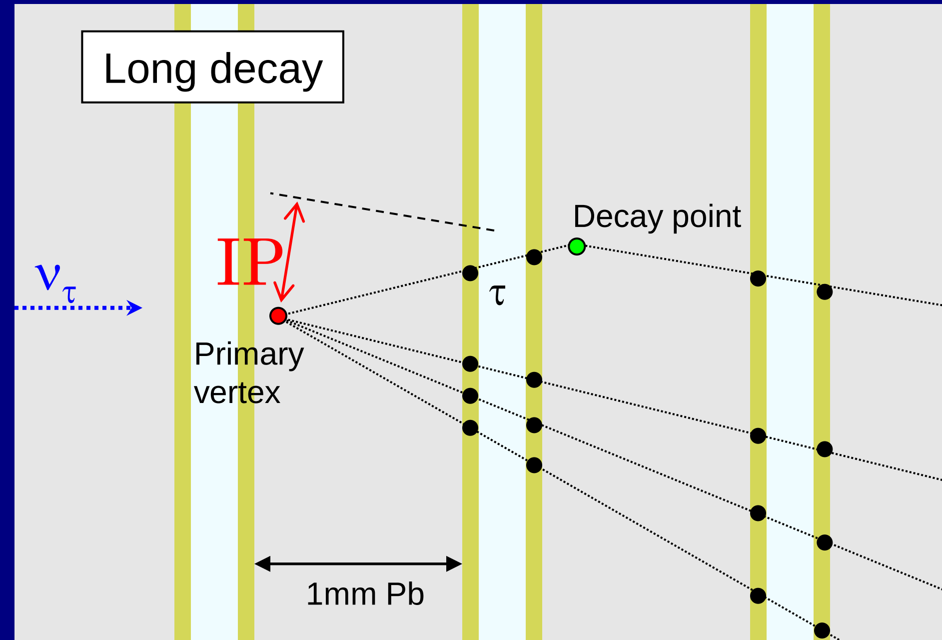
by swapping Tx and Rx component of the opto-chain



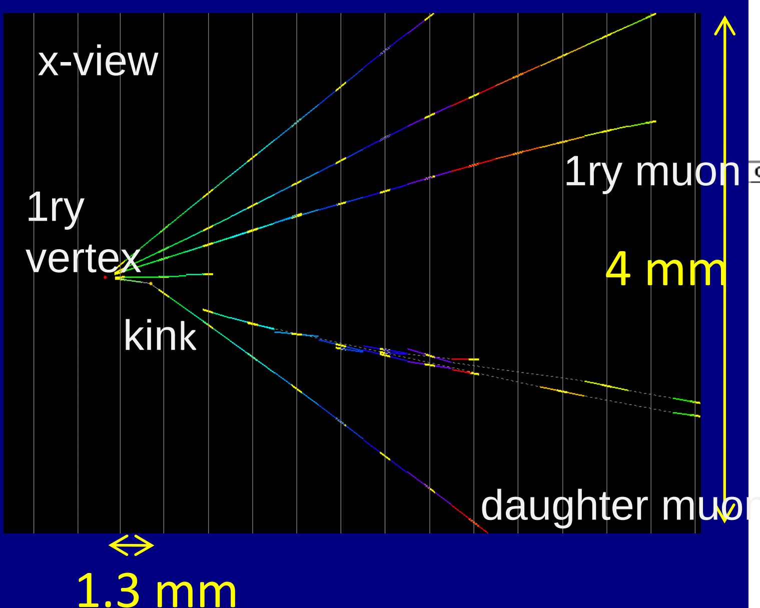
→ Local time transfer calibrations at CERN and LNGS
- Chains of several elements
- Two independent techniques used (double path, portable Cs)

Impact parameter distribution



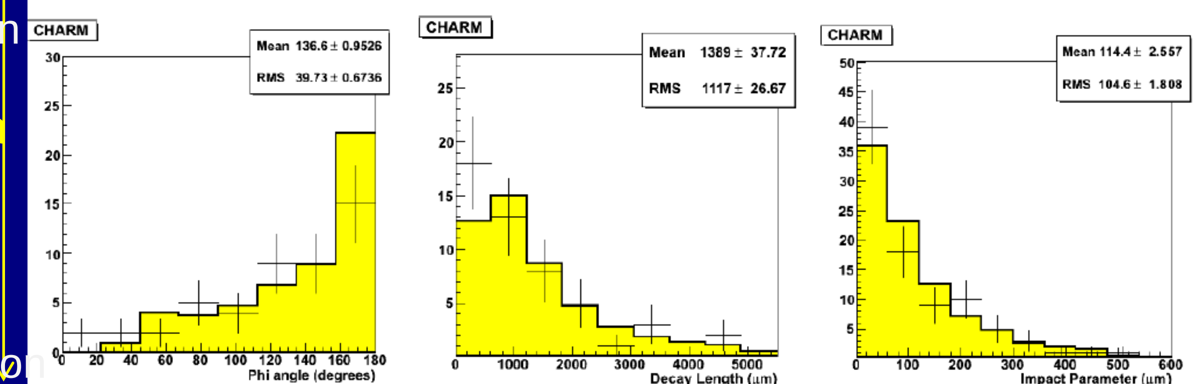


Charm dimuon candidate



Charm Data/MC Comparison

Detected : 49 events ⇔ Expected 51±7.5 events



Phi angle Decay length Impact Parameter

OPERA nominal analysis flow applied to the τ->1 h kink candidates:

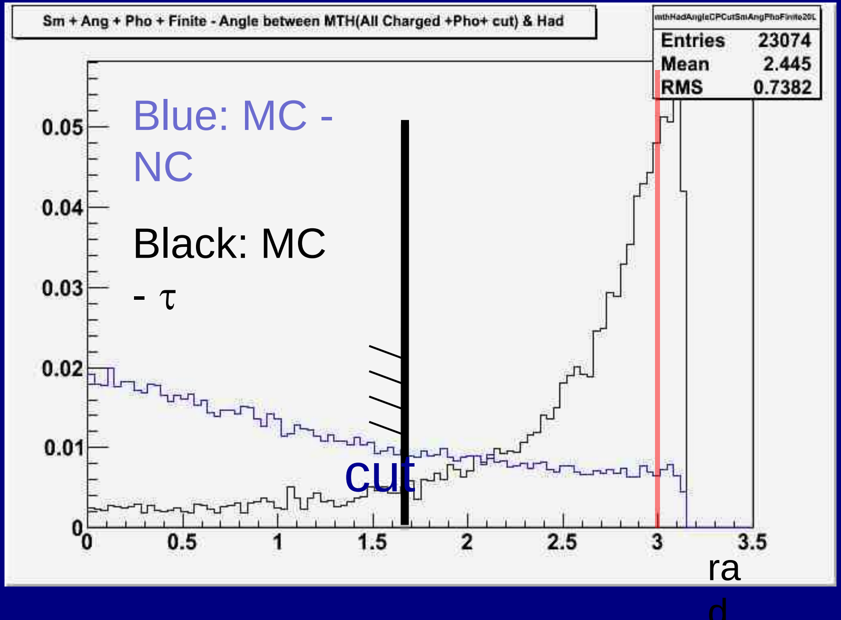
- kink occurring within 2 lead plates downstream of primary vertex
- kink angle larger than 20 mrad
- daughter momentum higher than 2 GeV/c
- decay Pt higher than 600 MeV/c,
  300 MeV/c if ≥ 1 gamma pointing to the decay vertex

Decay

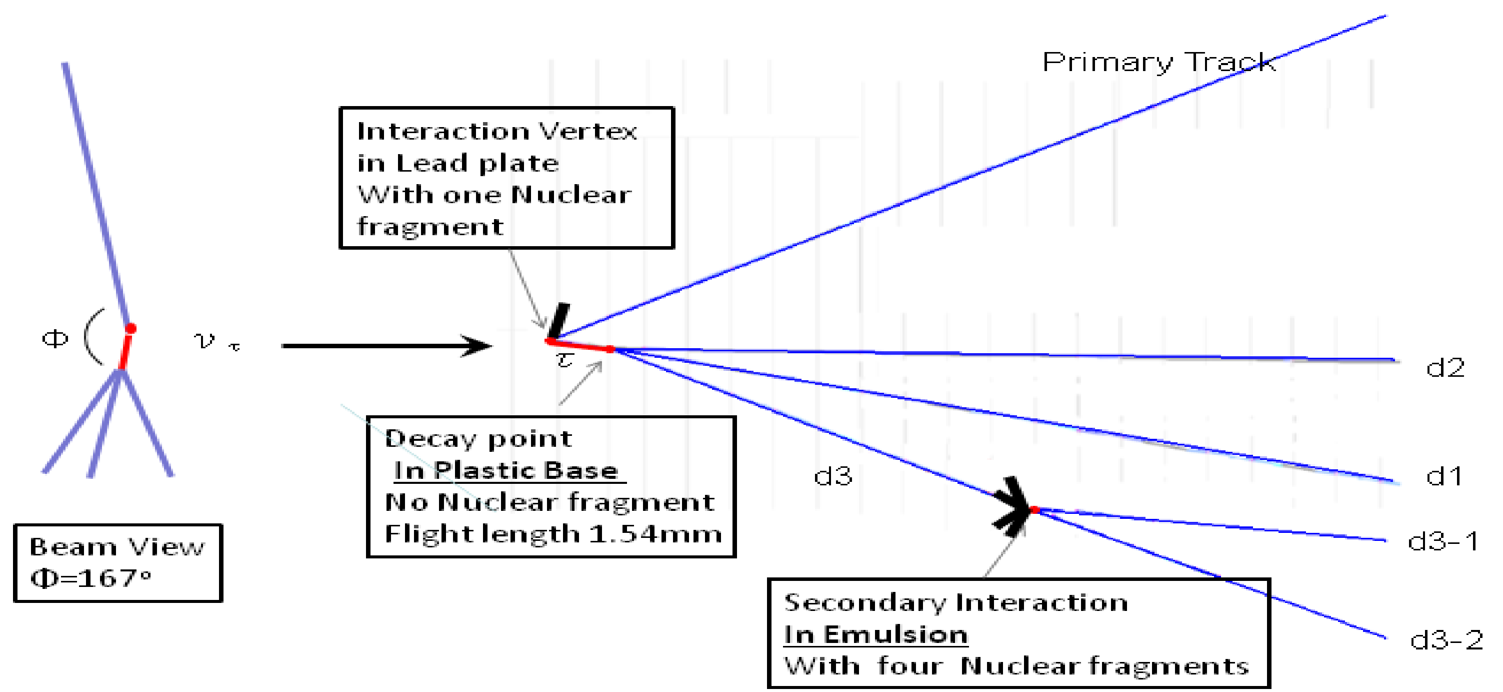
- missing Pt at primary vertex lower than 1 GeV/c
- azimuthal angle between the resulting hadron momentum direction and the parent track direction larger than $\pi/2$ rad

Event kinematics

Variable	Value
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter(GeV/c)	**12^{+6}_{-3}**
Pt decay (MeV/c)	**470^{+230}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**



Schematics of the event



	Cut	Value	Error
Phi (Tau - Hadron) [degree]	>90	167.8	± 1.1
average kink angle [mrad]	< 500	87.4	± 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4	± 1.7
Min Invariant mass [GeV/c^2]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c^2]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11