# Updated results of the OPERA neutrino-velocity analysis

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*on behalf of the OPERA Collaboration*

LNGS Workshop, March 28th 2012

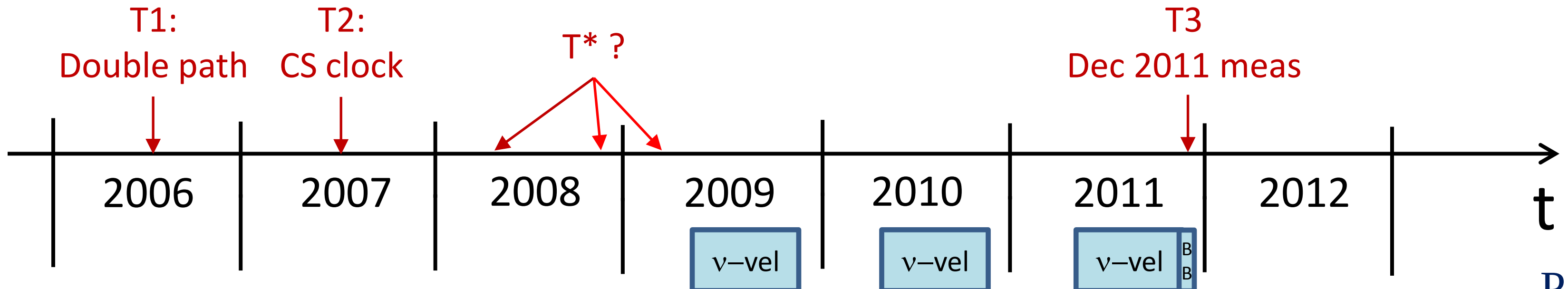
# A brief storyline

- September 23rd 2011: public release of the result
  - seminar and first neutrino-velocity paper from OPERA (1109.4897v1): $\delta t = (60.7 \pm 6.9 \pm 7.4)$ ns
- Intense activity within the Collaboration to assess the result under different and complementary perspectives
  - Analysis checks: events selection, event time definition, etc
  - Statistical checks (Maximum Likelihood fit)
  - General and Special Relativity issues
  - Delayed double cosmic muon events
- Oct-Nov 2011: Bunched Beam (two weeks)
  - Excluded major systematic effects related to the statistical procedure
  - New version of the paper (1109.4897v2): $\delta t = (62.1 \pm 3.7)$ ns
- Dec-Feb 2011: measurement campaign of the timing chain
  - 8.3 km fiber delay from the LNGS-GPS to the OPERA Master Clock
  - Frequency of the OPERA Master Clock oscillator
- Interpretation and understanding of the overall picture
  - OPERA-LVD cosmic ray coincidence study

# December 2011 measurements

- December 2011 measurement campaign: the "trigger"
  - Measurement of the 8 km fiber delay: a crucial point (the last measurements dated back to 2006 and 2007)
  - New repeated high-accuracy measurements did not confirm the value found in the past:
    - 2006 measurements: $t_{fiber} = (41001.4 \pm 0.3)$ ns
    - 2011 measurements: $t_{fiber} = (41074.6 \pm 0.5)$ ns

    $\Delta t_{fiber} = (73.2 \pm 0.6_{\ stat})$ ns
  - After re-plugging the fiber connector the old 2006 result was restored back
  - First indication of a "drift" in the OPERA timestamps within the 0.6 s DAQ cycle
- Two fundamental questions to answer
  - 1) What's the source of the $\Delta t_{fiber}$ delay difference and of the drift effect?
  - 2) How long these two anomalies were there?



# Q1: what did it happen?

Answers to these questions came in Feb 2011 (G. Sirri's talk)

## 1) Source of the $\Delta t_{fiber}$ delay difference

- A not-proper fiber connection to the OPERA PCI board may induce an artificial delay which propagates up to the last TT sensor
- This is due to the response of the analog circuit to an attenuated light intensity
- It is possible to obtain *stable configurations* which produce delays up to ~100 ns
- This effect goes in the direction to *decrease* the neutrino ToF (if not corrected)

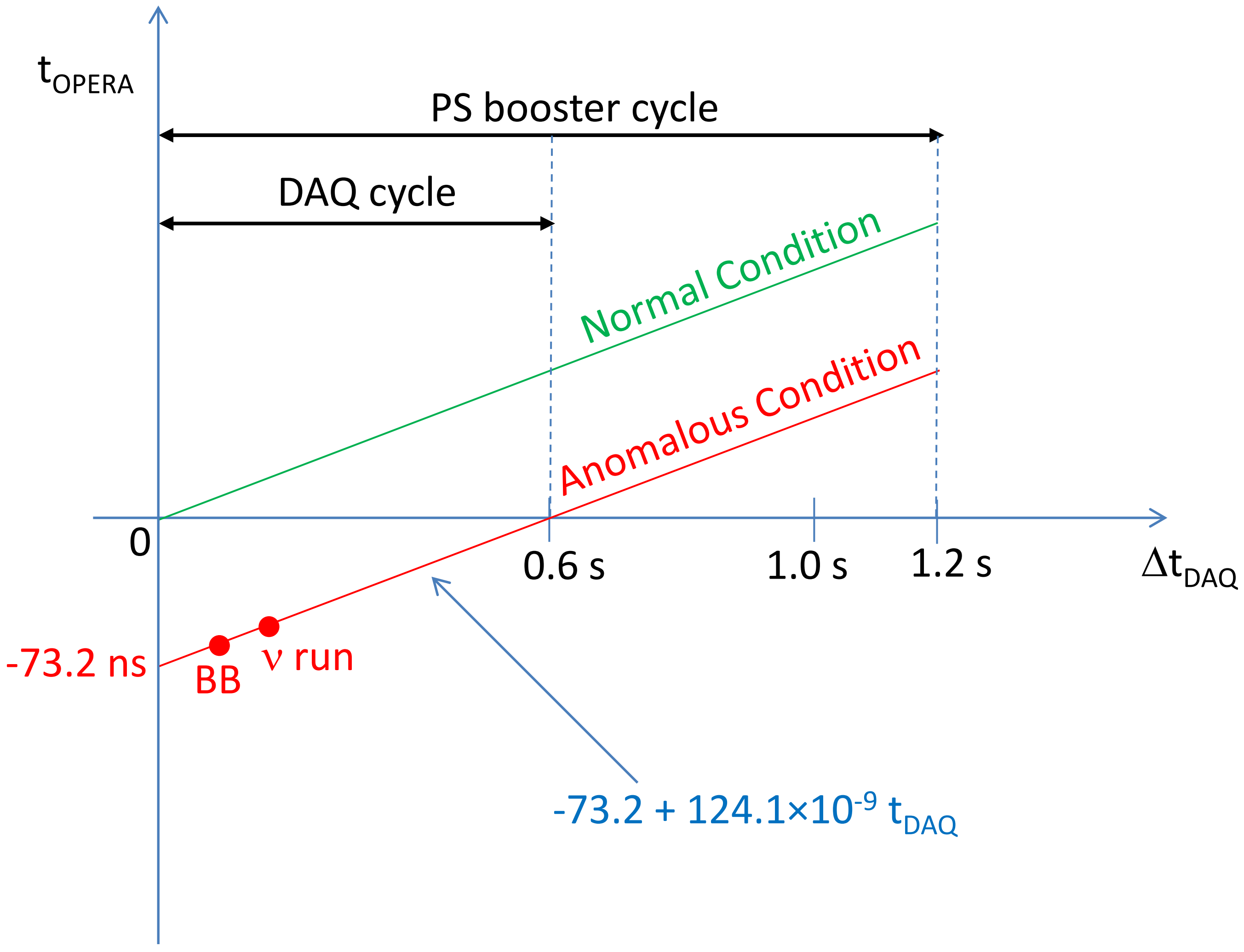
## 2) Source of time-stamp drift

- Accurate measurements have shown that the 20 MHz OPERA internal oscillator has a frequency slightly larger than the nominal one
- That induces a linear shift of event timestamps within the DAQ cycle with a slope

$$\alpha = (124.08 \pm 0.08)\ \text{ns/s}$$

- This effect goes in the direction to *increase* the neutrino ToF (if not corrected)

# A working model



# Q2: when did it happen?

- Since we know that 2009+2010+2011+BB data are perfectly compatible in terms of NuVel analysis (they are “aligned in time”), we are forced to invoke one of the twos:

    1) The AC arose between the end of the BB and T3 by an intervention on the fiber connector

    2) The AC arose at time T* after T2 and before the 2009 neutrino run by an intervention on the fiber connector

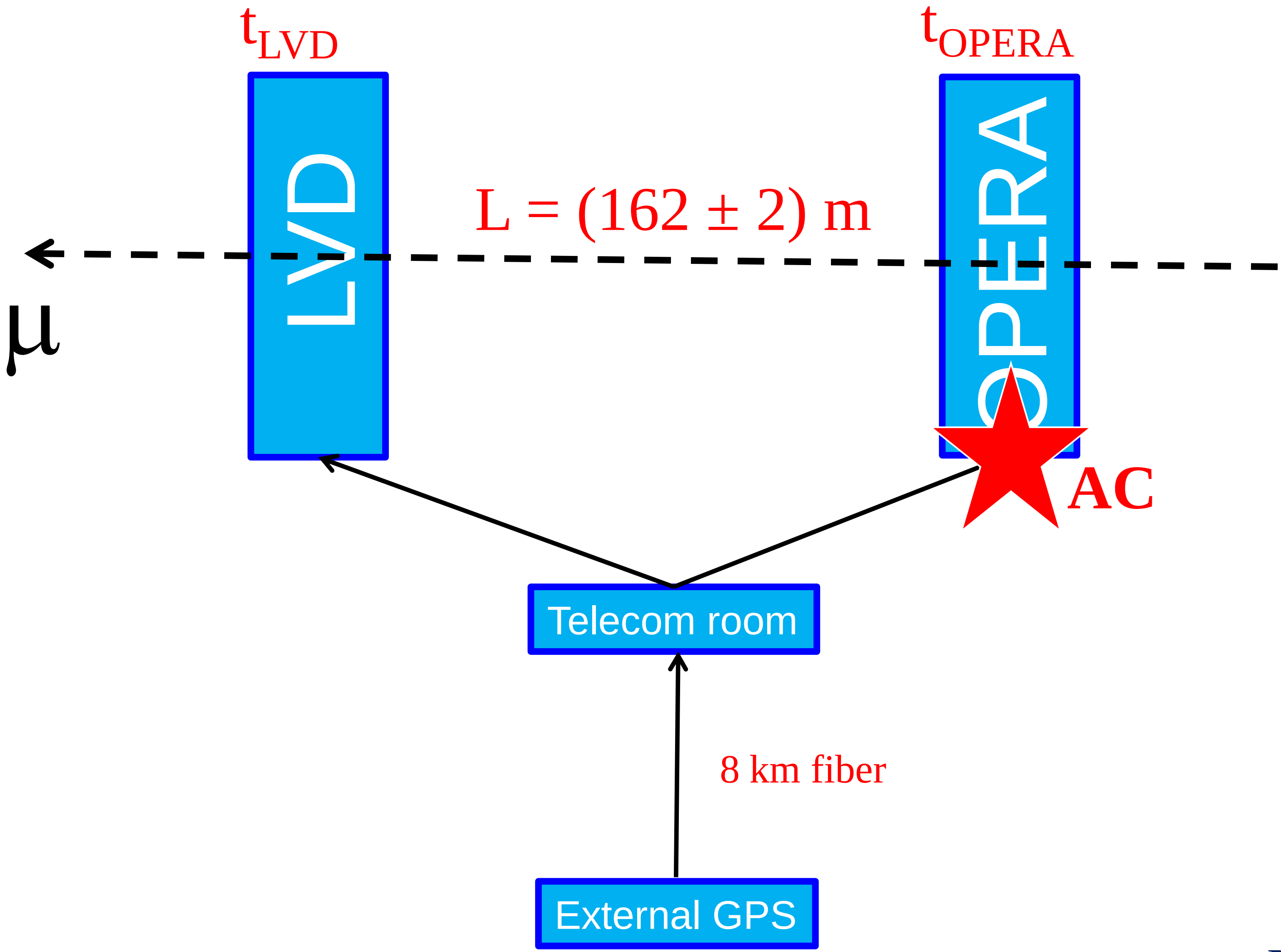
- If the second case we can distinguish three periods:
  - $t < T2 < T^*$: system in Normal Condition
  - $T^* < t < T3$: system in AC with superluminal neutrinos
  - $t > T3$: system back again in Normal Condition
- The AC arose at the level of the OPERA Master Clock. The AC is therefore related only to OPERA and not to the other experiments at LNGS.
- We have then a beautiful handle to perform our checks using the well calibrated OPERA-LVD coincidence analysis for cosmic ray studies.

# LVD-OPERA coincidences
(Prof. Zichichi's talk)

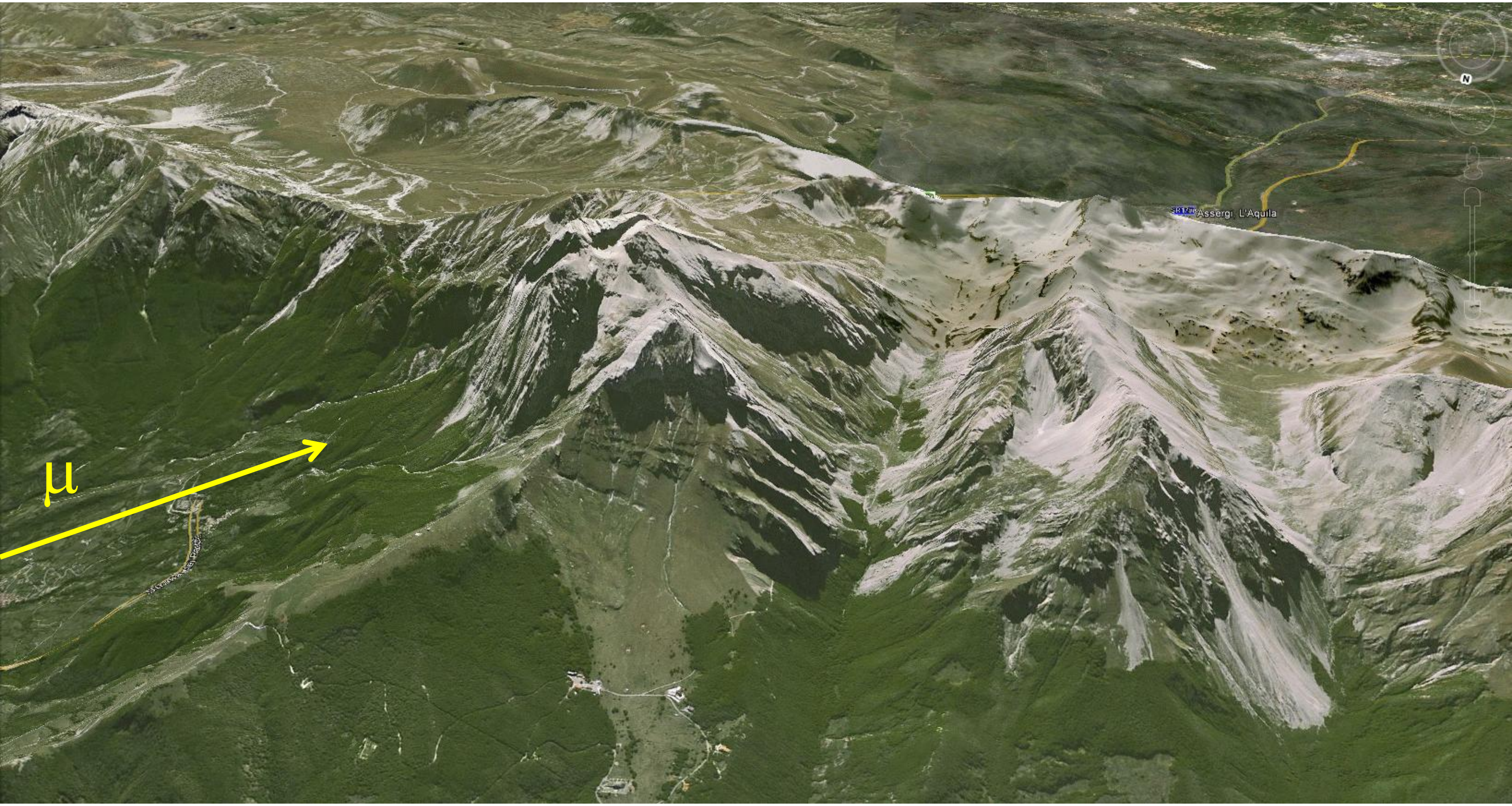
- The analysis started in 2009 following an LVD-OPERA agreement to exchange data to perform searches for high $p_T$ phenomena interesting for pQCD studies
- Analysis still in progress, so far not event found
- Instead several cosmic muon detected impinging OPERA first and LVD after: muons from the Teramo Valley where the rock thickness is relatively small ($\langle h \rangle \approx 2200$ m, $\langle \theta \rangle \approx 85^o$)

→ we have an high energy muon beam ($\langle E_\mu \rangle \approx 270$ GeV) to cross-calibrate the two detector timing systems

# OPERA-LVD coincidences

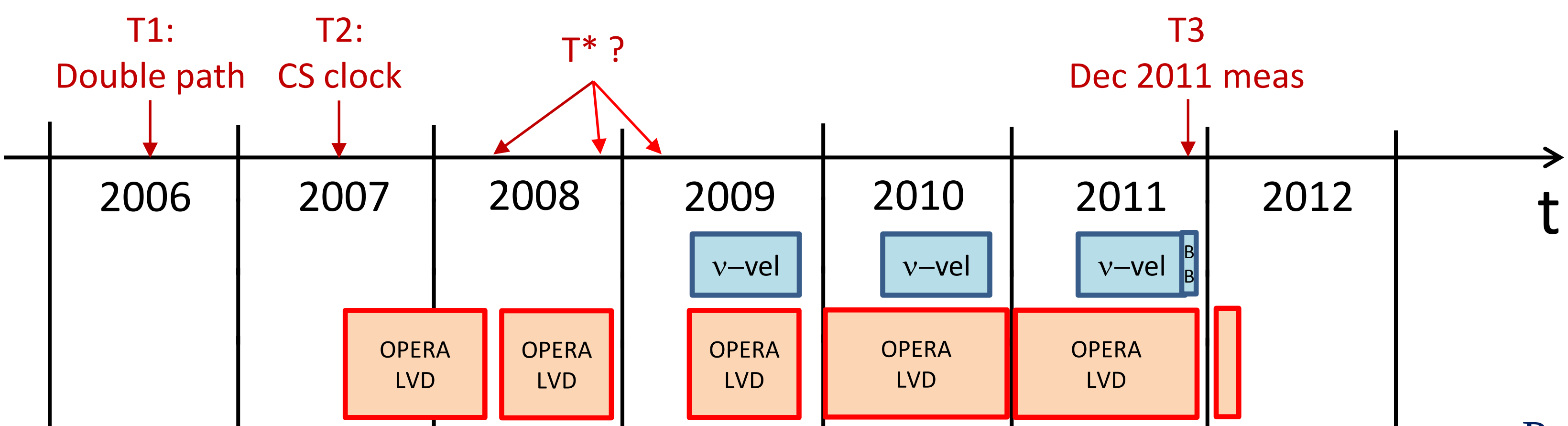


# Teramo muons



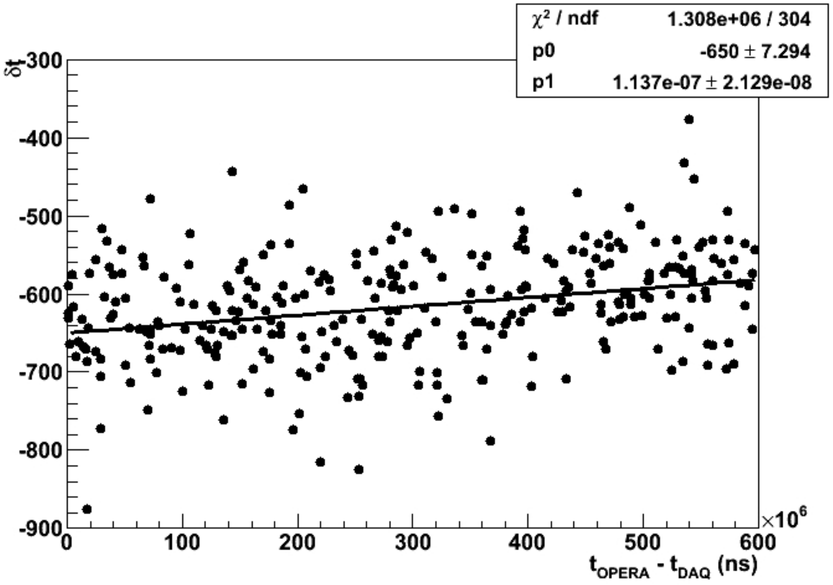
# OPERA-LVD coincidences

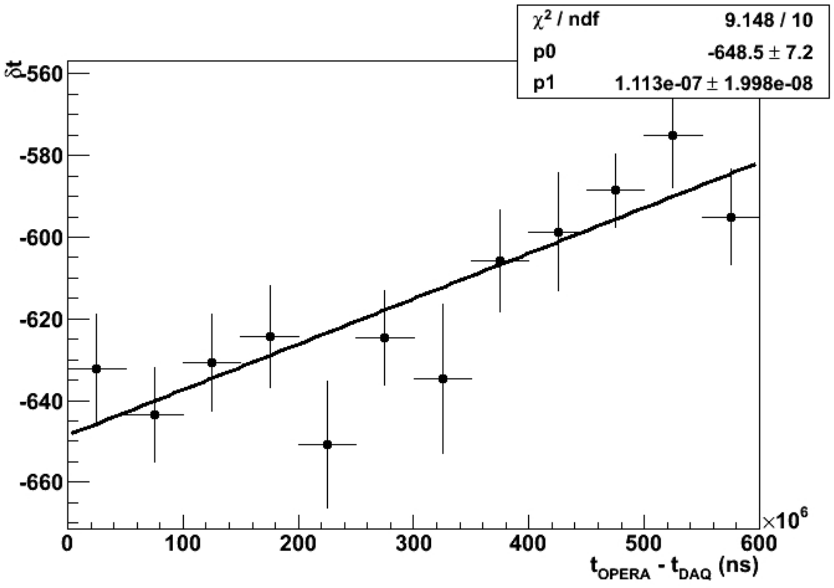
| | | | | | | Random coincidences | | | | Signal | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Period** | **OPERA** | | **LVD** | | **Days in common** | **Rate OPERA (Hz)** | **Rate LVD (Hz)** | **Expected in ±1 ms** | **Observed in ±1 ms** | **Expected Teramo m** | **Observed Teramo m** |
| 2007 | 28/08/2007 | 31/12/2007 | 27/08/2007 | 31/12/2007 | 58.2 | 0.184 | 0.095 | 177.1 | 162 | 15.7 | 21 |
| 2008 | 01/01/2008 | 05/12/2008 | 01/01/2008 | 07/12/2008 | 263.7 | 0.073 | 0.095 | 314.2 | 323 | 71.2 | 64 |
| 2009 | 01/06/2009 | 23/11/2009 | 31/05/2009 | 01/12/2009 | 171.1 | 0.124 | 0.098 | 359.0 | 351 | 46.2 | 49 |
| 2010 | 31/12/2009 | 31/12/2010 | 01/01/2010 | 01/01/2011 | 326.5 | 0.063 | 0.097 | 346.3 | 369 | 88.2 | 63 |
| 2011 | 31/12/2010 | 07/12/2011 | 01/01/2011 | 01/01/2012 | 336.9 | 0.063 | 0.098 | 360.6 | 395 | 91.0 | 109 |
| 2012 | 09/01/2012 | 02/03/2012 | 01/01/2012 | 03/03/2012 | 50.8 | 0.051 | 0.094 | 41.9 | 37 | 11.1 | 9 |
| | | | | | **1207.2** | | | **1599.1** | **1637** | **323.3** | **315** |



# Times within the OPERA DAQ cycle

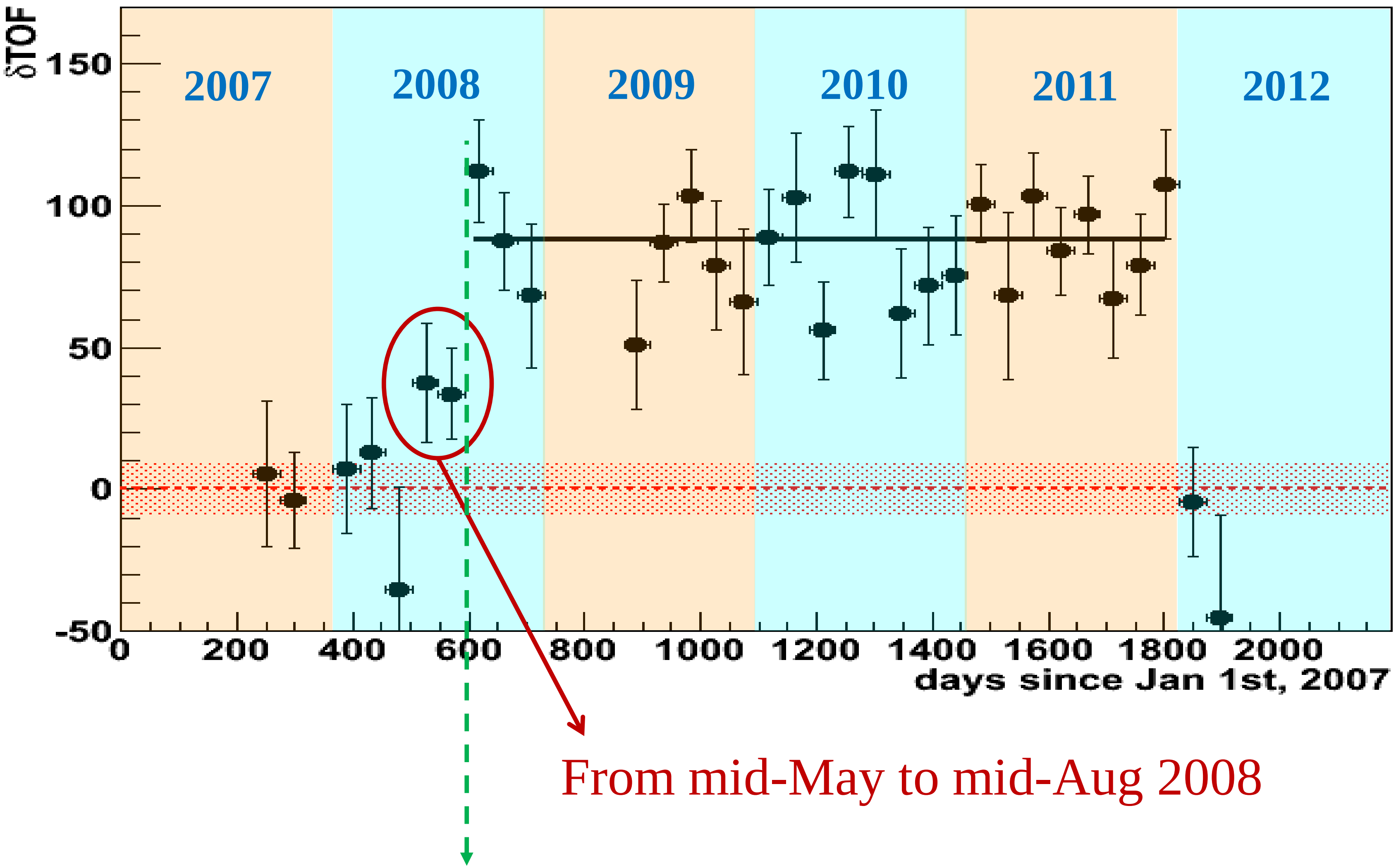
- Teramo μ's TOFs show a clear dependence within the 0.6 s OPERA DAQ cycle
- The fitted slope (114±20) ns/s is compatible with:
  - drift slope directly measured on the DAQ in Dec 2011
  - Vectron frequency in Feb 2012: 124.08 ± 0.08 ns/s




Function used to correct TOF data: $t^{*}_{OPERA} = t_{OPERA} - 124\times10^{-9}\ t_{DAQ}$

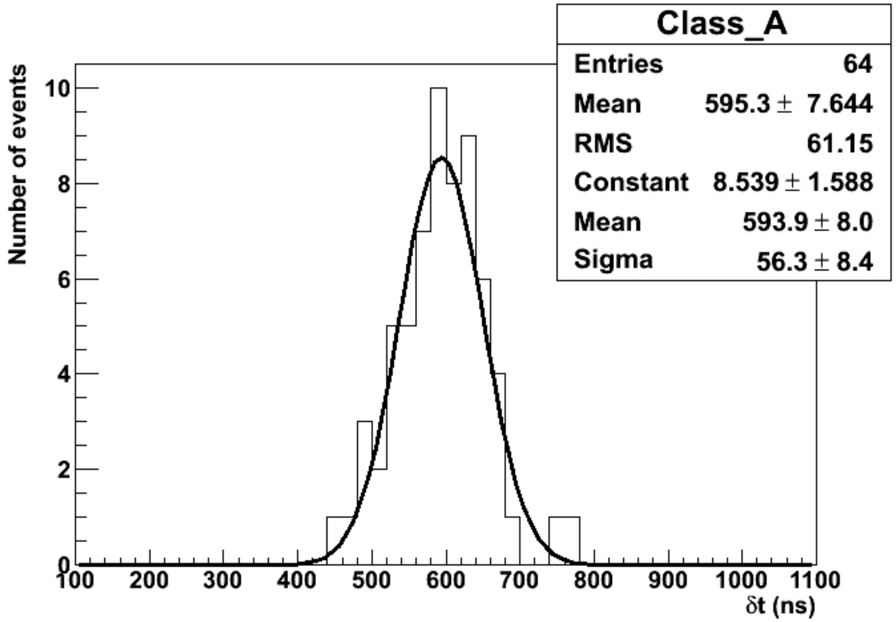
# Stability, a thinner binning

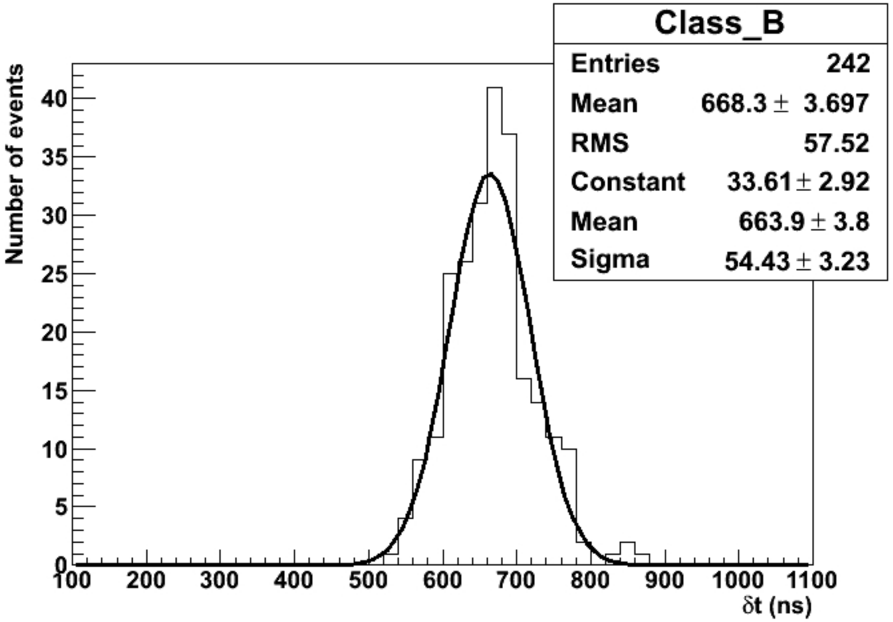


# Teramo muons

**NC** = t < T* OR t > T3

**AC** = t > T* AND t < T3



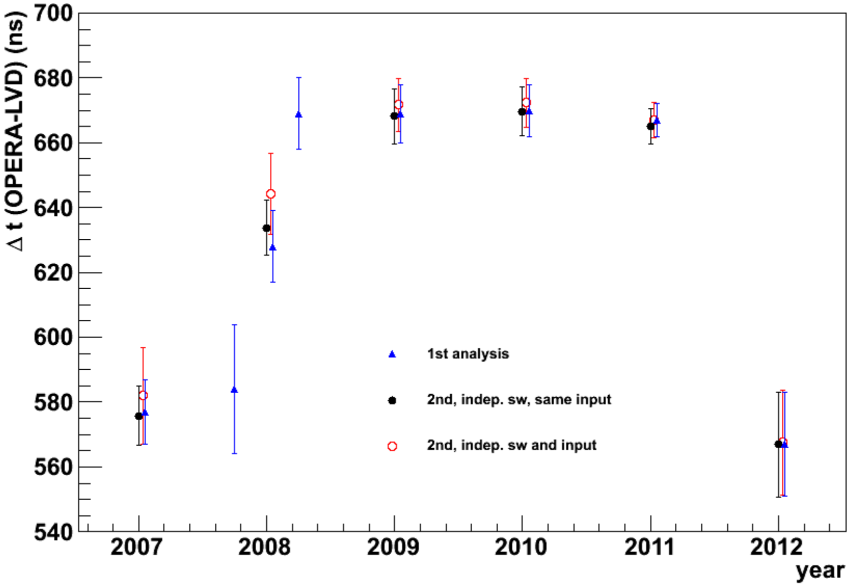




$$\langle AC \rangle - \langle NC \rangle = (73 \pm 9)\ \text{ns}$$

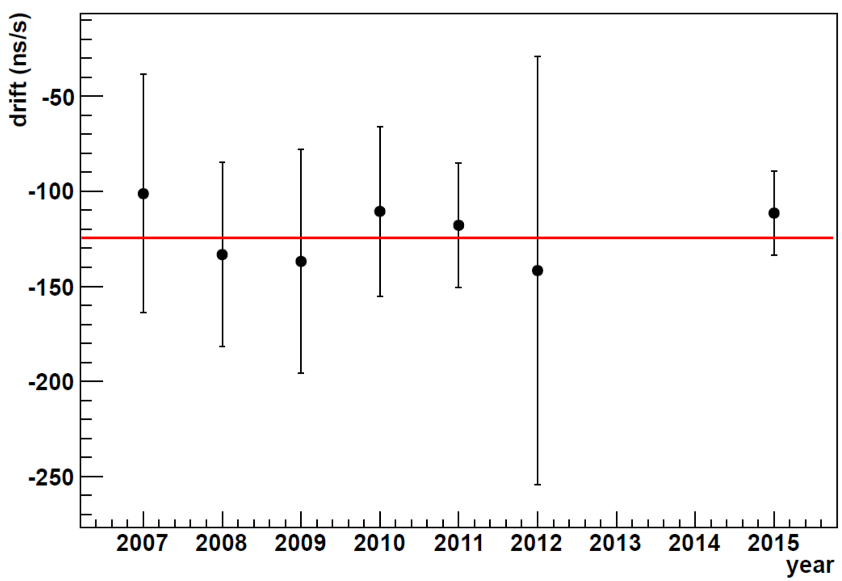
- Different at 8 σ level
- To be compared with (73.2 ± 0.6) ns difference in the fiber delay measured in December 2011
- σ = 55 ns, coherent with what found by the LVD Collaboration with CNGS passing muons: single-tank resolution ~50 ns
- ⟨NC⟩ − L/c = (55 ± 10) ns compatible with LVD counter-clock delay

# Independent OPERA analysis

- An independent analysis was carried out:
  - Using the same input files and independent software
  - Using independent input files and independent software
- Complete agreement with the main analysis




$\delta t = t_{LVD} - t_{OPERA}$ by year

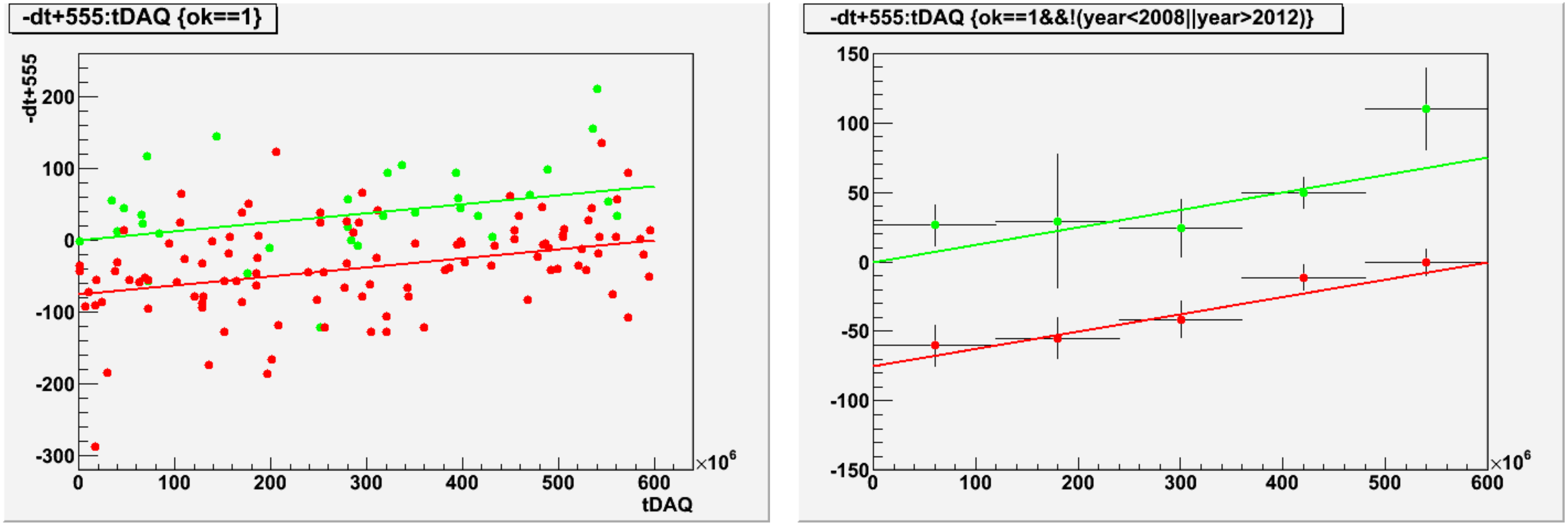



OPERA oscillator drift by year

# Testing the model

1) Cosmic rays (Teramo muons)

→ cosmic rays are uniformly distributed within the DAQ cycle

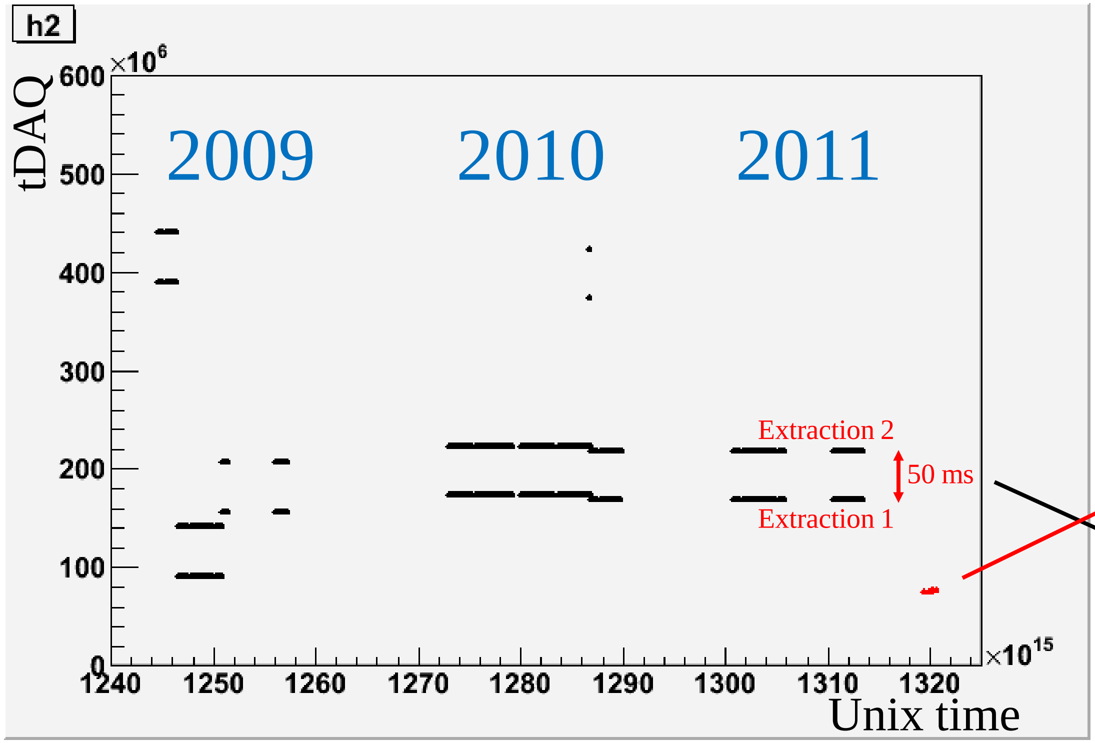



Green = NC (t < T* OR t > T3)

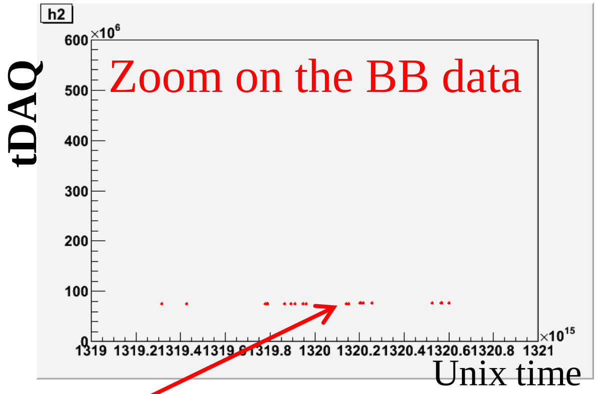
Red = AC (t > T* AND t < T3)

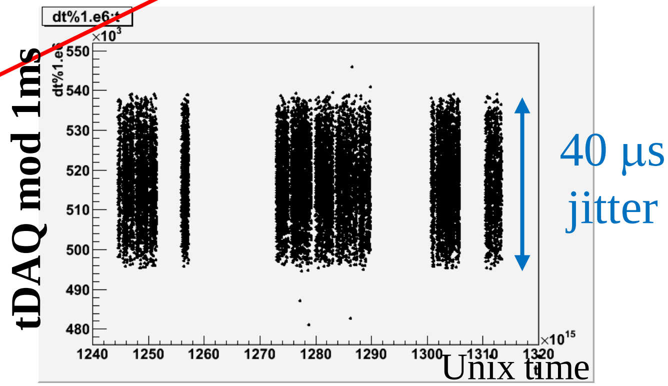
# Testing the model

2) CNGS neutrino events are not uniformly distributed within the DAQ cycle: DAQ cycle is one half of the PS booster cycle (1.2 s) → <u>we can predict the ν anticipation</u>




Each segment corresponds to a system stop/restart



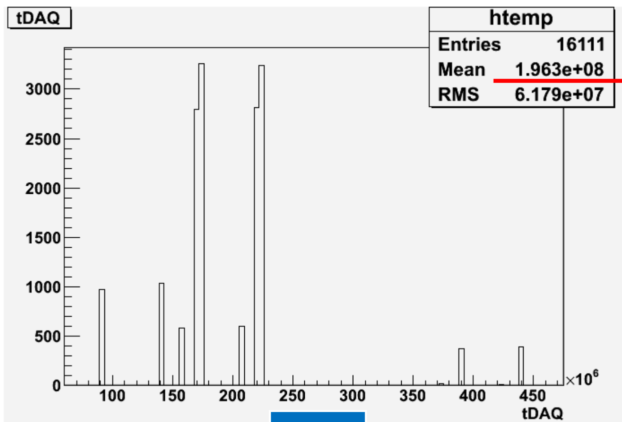




tDAQ modulo 1 ms in all runs

# Testing the model

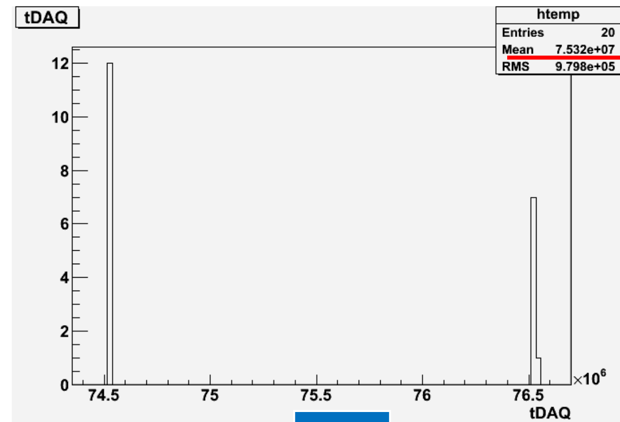
## 2) CNGS neutrino events → we can explain the ν anticipation

**Standard CNGS runs**




~200 ms

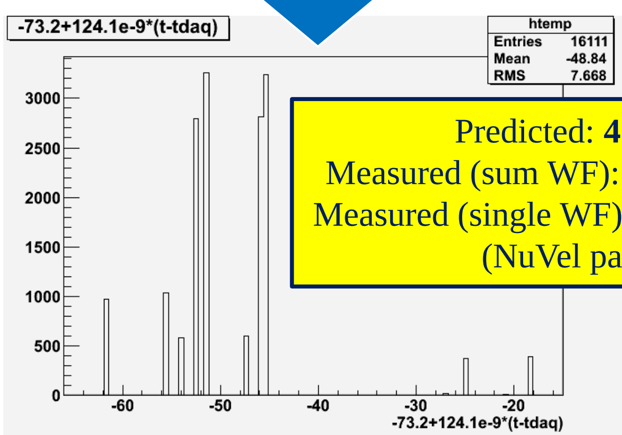
**Bunched Beam run**



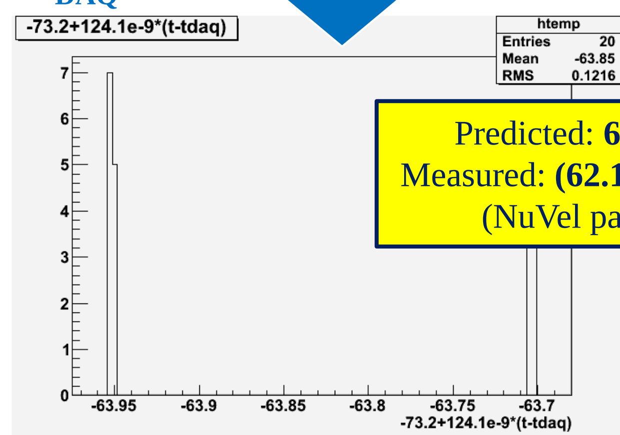

~75 ms

event-by-event correction

$$t = -73.2 + 124.1\times10^{-9}\, t_{DAQ}$$



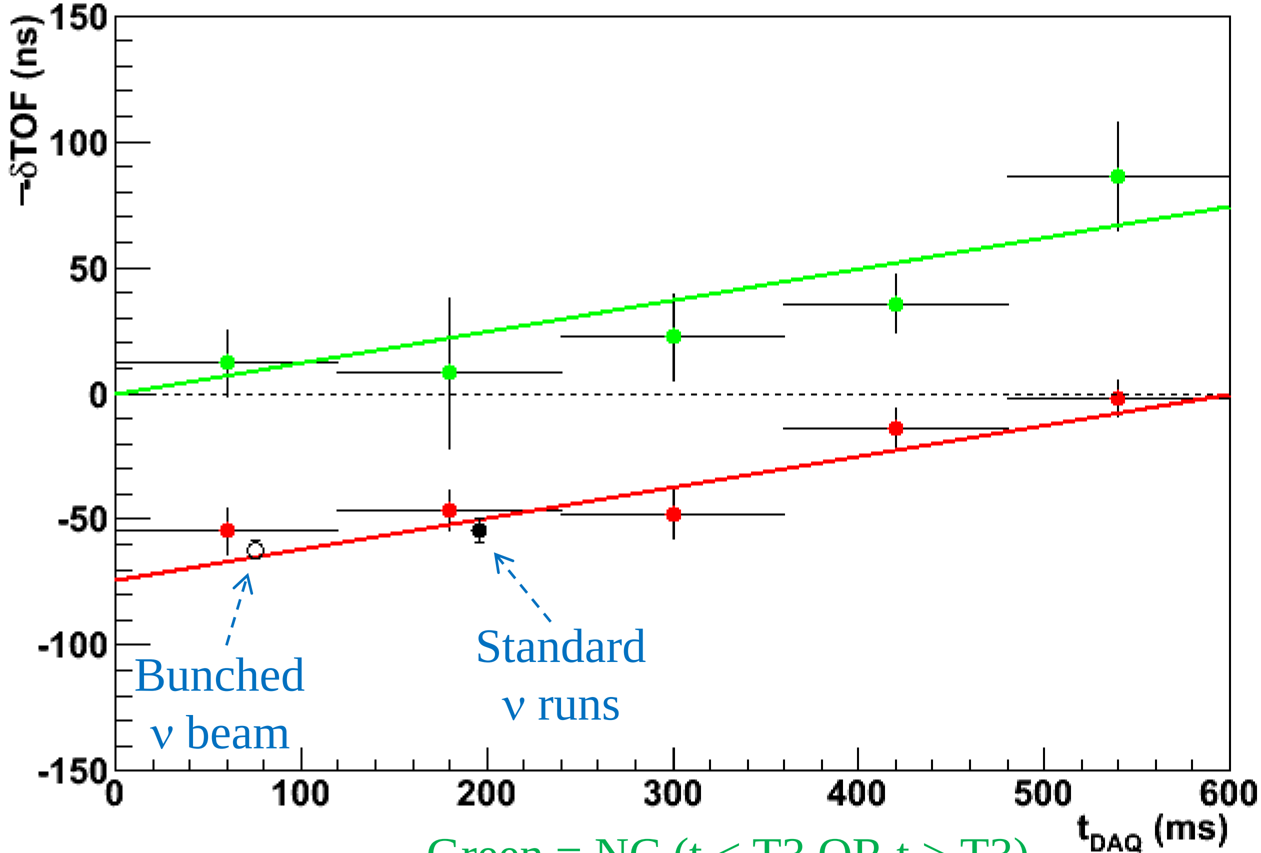

Predicted: **48.8 ns**
Measured (sum WF): **(57.8 ± 7.8) ns**
Measured (single WF): **(54.5 ± 5.0) ns**
(NuVel paper)




Predicted: **63.8 ns**
Measured: **(62.1 ± 3.7) ns**
(NuVel paper)

# The global picture

Cosmic and neutrino events alltogether show a coherent and self-consistent picture of all the observations

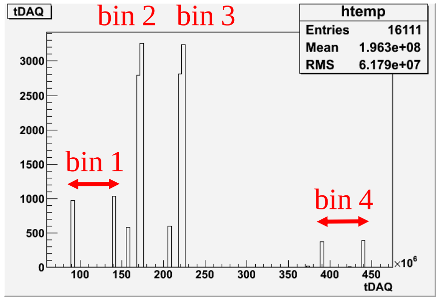


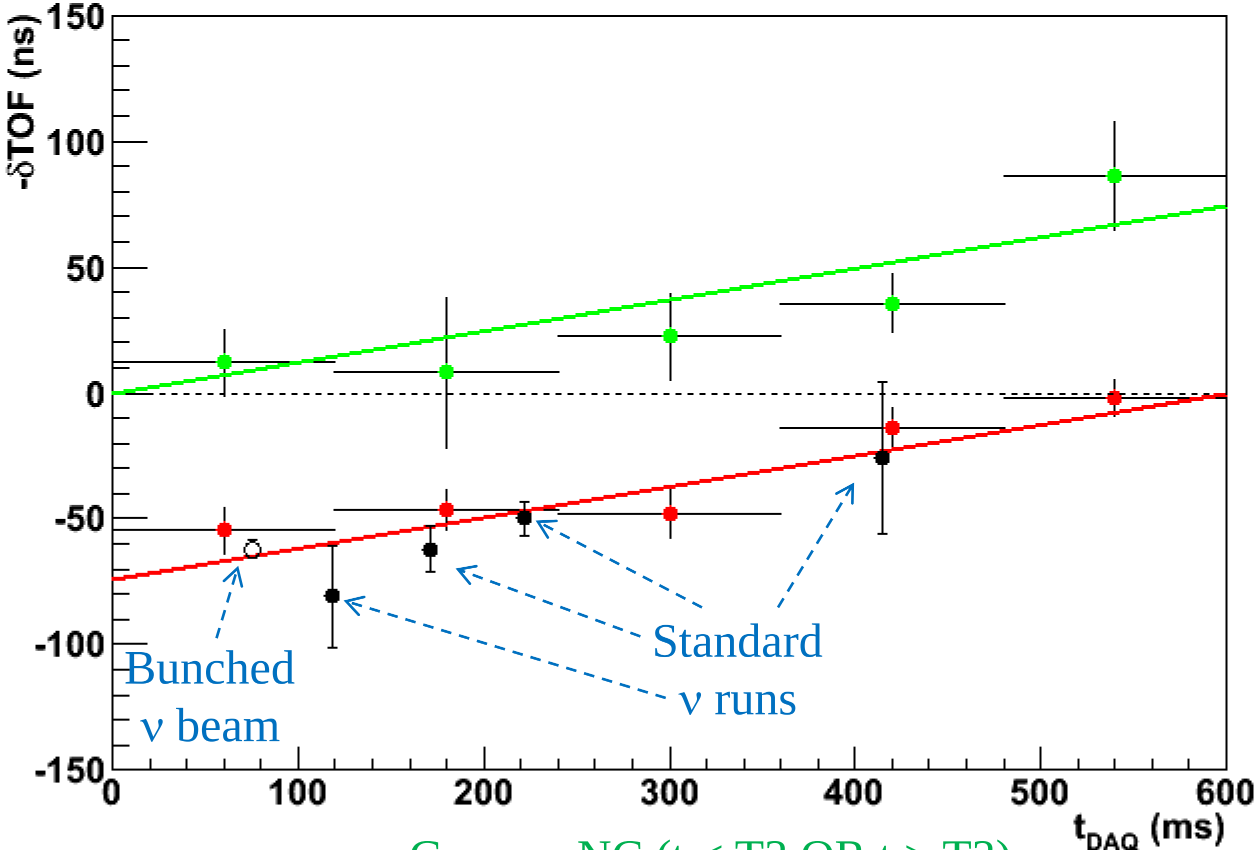

Green = NC (t < T3 OR t > T3)

Red = AC (t > T3 AND t < T3)

# A more global picture…

Some neutrino events were located in different DAQ ranges and we could fit with the Maximum LL the corresponding values




Green = NC (t < T3 OR t > T3)

Red = AC (t > T3 AND t < T3)

# Correction of the BB data

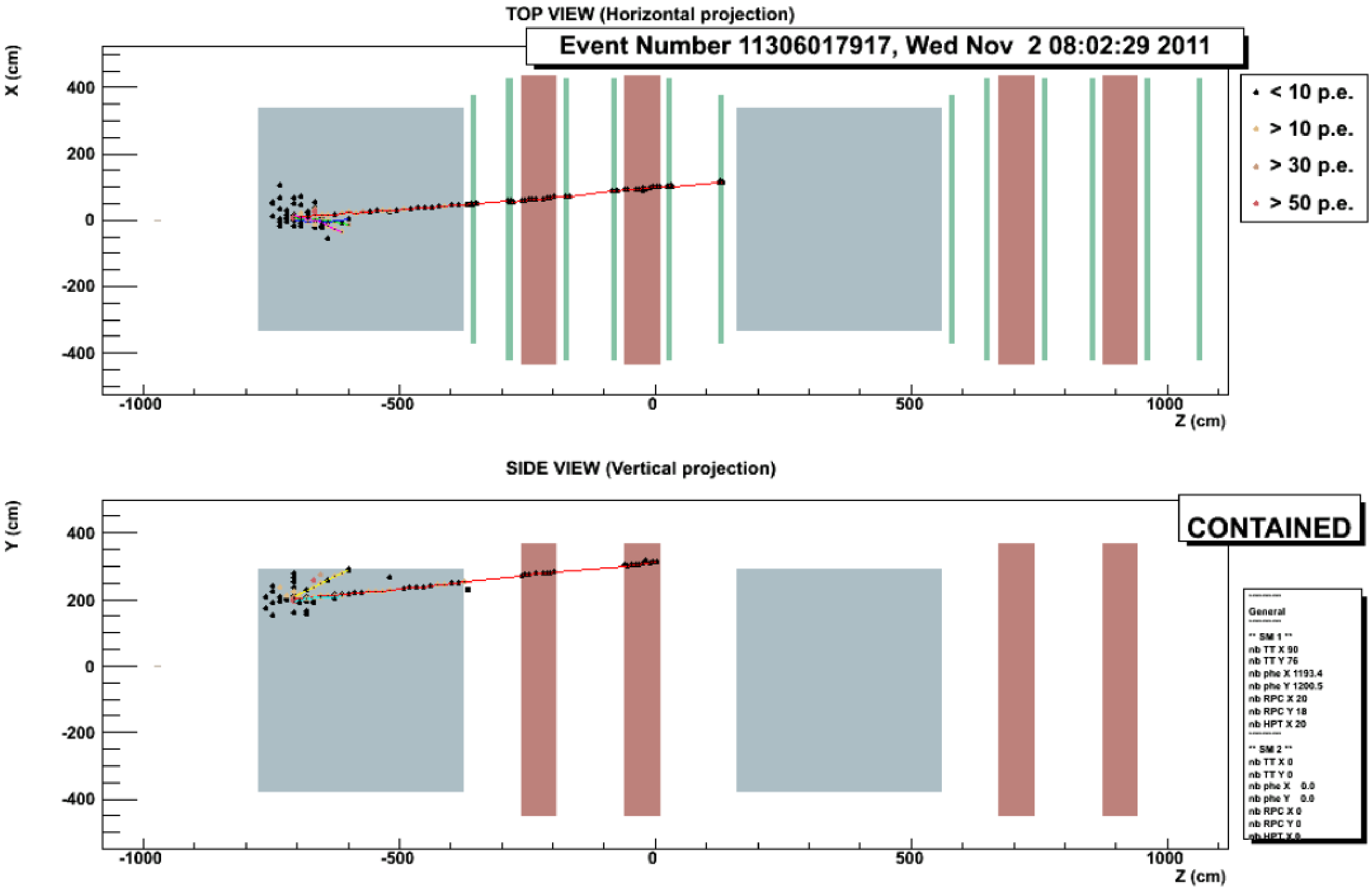
- Bunched Beam data were taken from Oct 22nd 2011 up to Nov 11th 2011 (~2 weeks)
- Single extraction of 4 bunches ~3 ns long separated by 524 ns
- 1/60 of the standard-CNGS intensity
- $4\times10^{16}$ pot in total → 35 beam events
- 20/35 events used for the analysis (discarded events were mostly "spectrometer events")
  - 6 events "internal"
  - 14 events "external"
- Expected statistical uncertainty:

$$\sigma_{BB} = \Delta T_{DAQ}/\sqrt{12} \oplus \Delta T_{jitter}/\sqrt{12} \oplus \sigma_{TT\text{-}prop} \approx 10/\sqrt{12} \oplus 50/\sqrt{12} \oplus 7.3 \approx 16\ \text{ns}$$

$$\delta_{TOF} = \sigma_{BB}/\sqrt{N} = 16/\sqrt{20} \approx 3.6\ \text{ns}$$

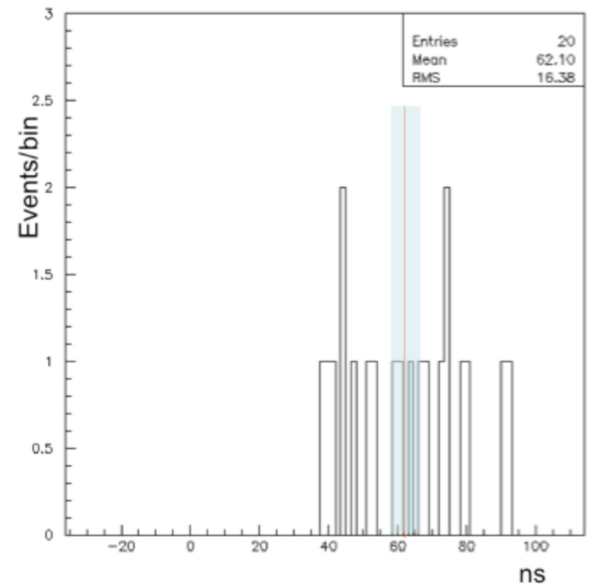
- Expected systematical uncertainty:
  - Similar to the "standard neutrino run" (at the basic level only the uncertainty on the statistical procedure cancels out)

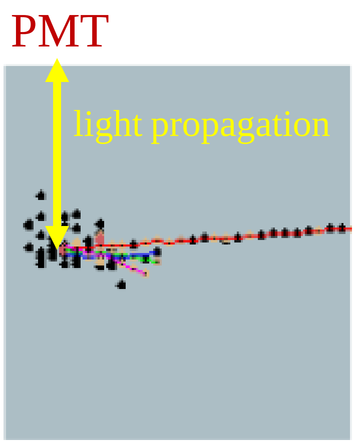
# One BB event in OPERA



# Considerations on the BB analysis

- Dominant contribution to the BB time spread:
  - 50 ns jitter of the PPmS signal latch by the Master Clock → cured for the 2012 BB run (expected accuracy ~1 ns)
- 10 ns DAQ granularity
  - Improvable for the 2012 BB run (expected accuracy ~1 ns)
- 7.3 ns spread due to the TT light propagation:
  - Average contribution of 9.4 ns computed by Monte Carlo as due to random event impact point in the transverse coordinate of the TT bar (7.3 RMS spread)
  - Improvable for the 2012 BB considering event-by-event correction according to the precise impact point along the scintillator strip



# Unfolding the result

Under the following assumptions:

1. The 73.2 ns offset was there in a stable way since mid-2008 or – at least – during the two weeks of BB run (motivated by the *LVD-OPERA coincidences* and by the *connector stability studies*)
2. The 124.1 ns/s drift was there in a stable way since mid-2008 or – at least – during the two weeks of BB run (motivated by the *LVD-OPERA coincidences*)

we can correct the BB result for the two effects:

$$\delta t = 62.1 + 124.1\times10^{-9}\times75.3\times10^{6} - 73.2 = -1.7 \text{ ns}$$

The statistical error is not affected by the offset nor by the drift

$$\delta t = ( -1.7 \pm 3.7 ) \text{ ns} \qquad \text{[only stat]}$$

The result is ***preliminary*** and an interpretation in terms of *(v-c)/c* is deliberately not attempted

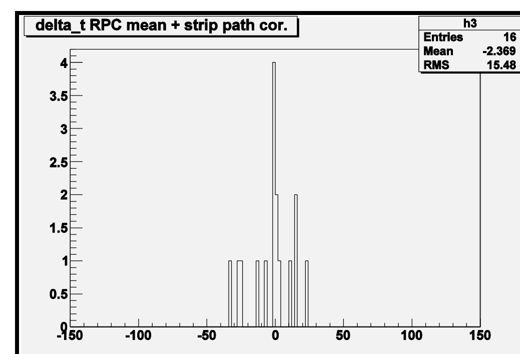
# About the systematic error

The present known sources of sytematic errors were reported in the arXiv paper:

| 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** | |

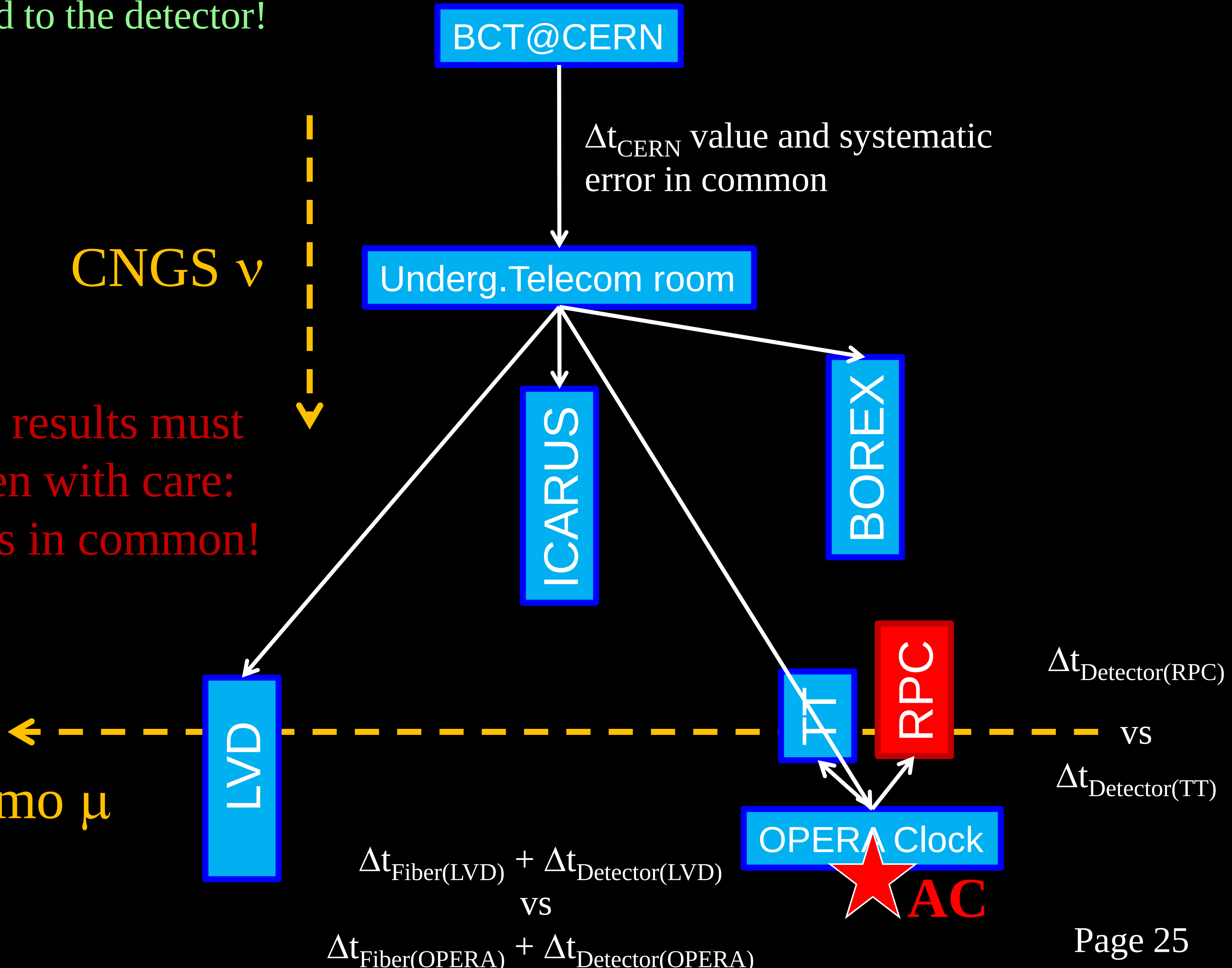
An analysis performed with the RPC timing algorithm described in A. Bertolin's talk on 16 of the 20 events lead to a result within **0.7 ns** from what quoted above with a similar statistical uncertainty

→ High confidence on the TT and RPC detector cross-time-calibrations!



LNGS experiments all together: a way to reduce the systematic error related to the detector!

$$\Delta t_i = \Delta t_{CERN} + \Delta t_{Fiber(i)} + \Delta t_{Detector(i)}$$




All our results must be taken with care: $\Delta t_{CERN}$ is in common!

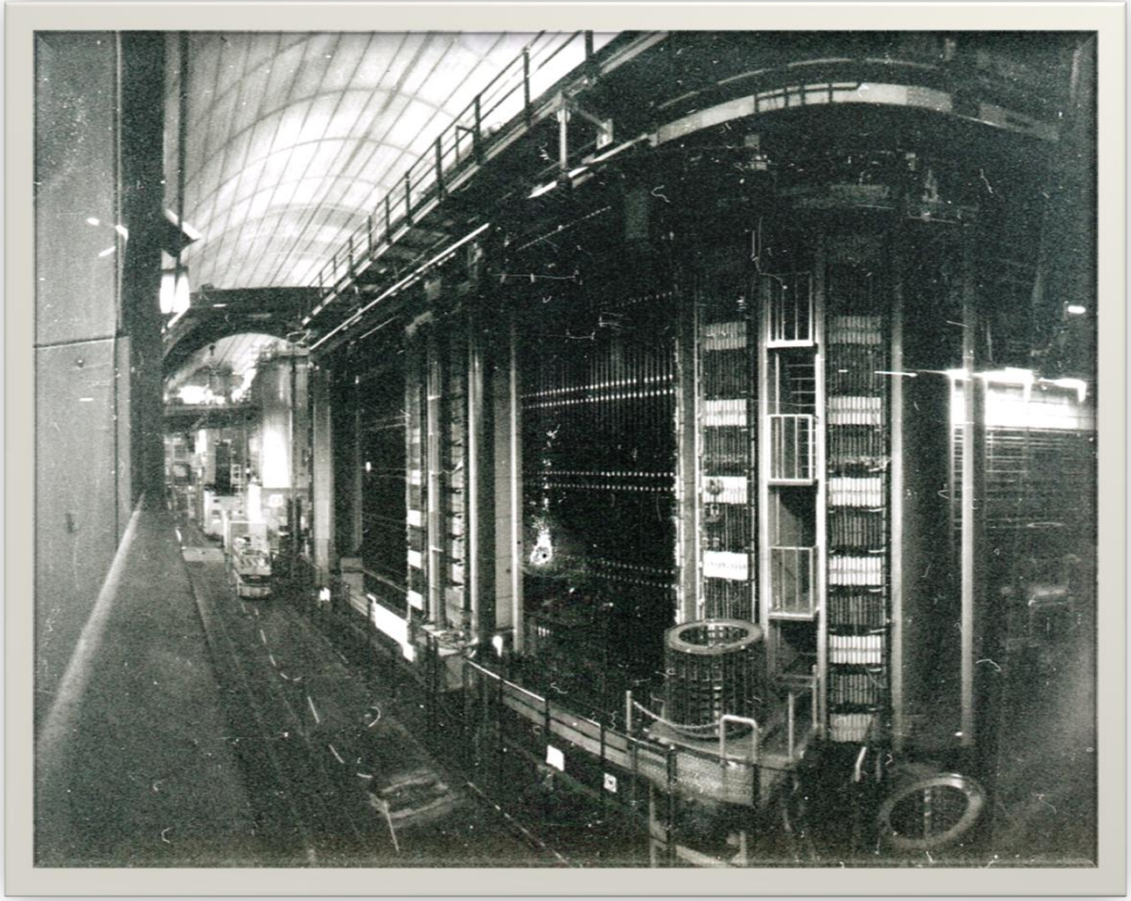
# Conclusions (1)

- OPERA opened the way for high precision measurements of neutrino velocity using an absolute ToF technique
  - All the pioneering geodesy and timing measurements performed by the OPERA Collaboration may now be used by all the LNGS experiments to perform their analyses
- During an throrough data scrutiny to find out unaccounted systematic errors the OPERA Collaboration discovered two effects which may explain the anomaly
  - A time shift caused by a not-proper fiber connection (ToF up)
  - An anomalous internal oscillator frequency (ToF down)
- The LVD-OPERA coincidence study is a key tool since (at present) it's the only way to shed light on what happend in the past four years
  - The analysis indicates when the AC set in and when the NC was restored
  - The analysis also indicates that the drift was there since a long time
  - It allowed to build a coherent working model for the NuVel analysis

# Conclusions (2)

- Even if the two effects newly found – together with the LVD-OPERA coincidence study – provide a robust interpretation of the results only the forthcoming BB will allow us to provide a firm conclusion
  - Because many hints are not a proof (in science) and the matter is of exceptional importance
  - New BB data will be taken under perfectly controlled conditions (White Rabbit system) and with an improved timing resolution
  - With a new BB we could reach sub-$10^{-6}$ sensitivities on $\delta v/c$
  - A new BB would allow the study of the energy dependence and other second-order effects on an event-by-event basis, free from the overall systematic error on the absolute ToF value

# OPERA scrutinized by itself



*(Handmade pinhole camera, 26 hours exposure)*

The OPERA detector impressed in an <u>OPERA emulsion</u>!

*Credits: Donato Di Ferdinando – INFN Bologna*