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

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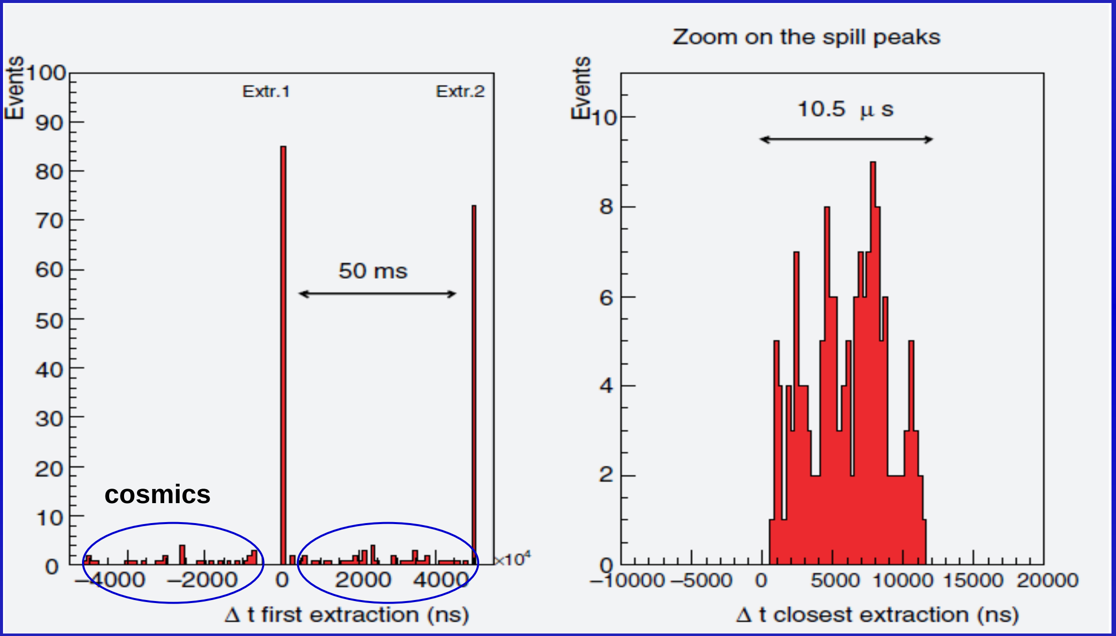
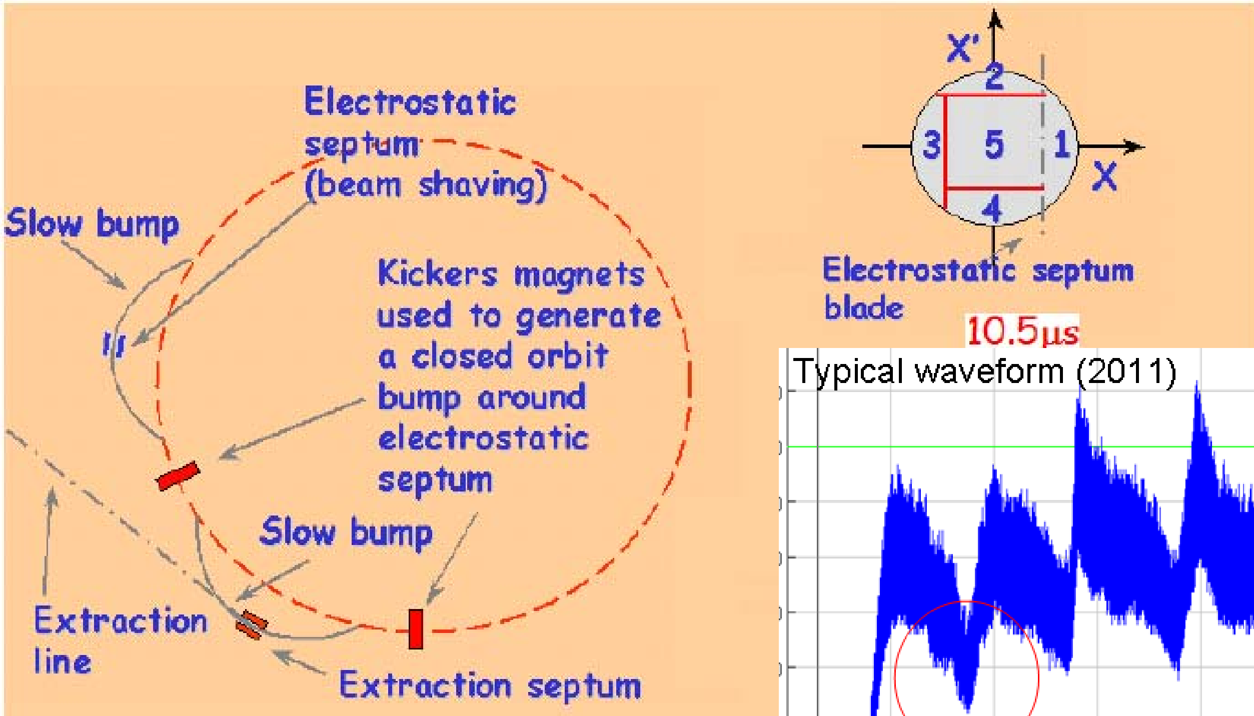
OPERA result on the neutrino velocity measurement presented at CERN on 23 September 2011 based on the analysis of the “standard” CNGS neutrino beam

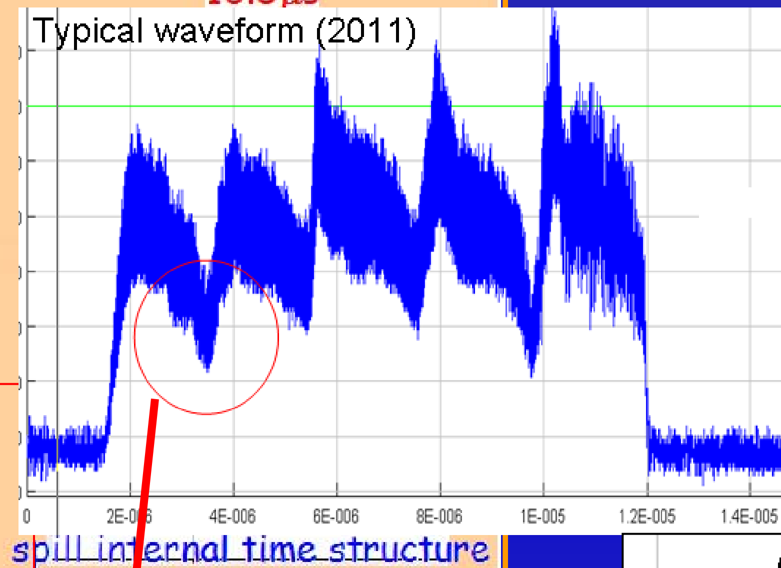


OPERA data: narrow peaks of the order of the **spill width=10.5 μs**

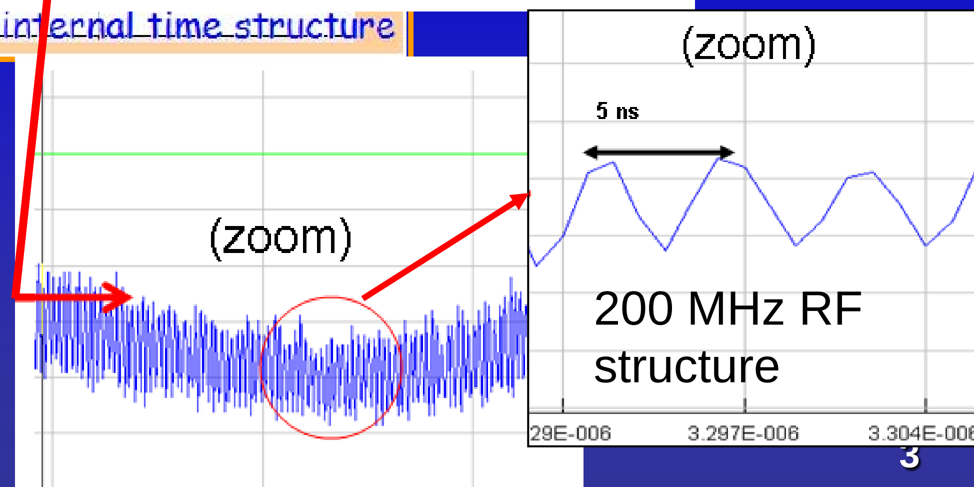
Negligible cosmic-ray background: *O*(10-4)

Proton spill shape





Spill shape as seen by the BCT on the proton beam line



Reminiscence of the Continuous Turn extraction from PS (5 turns)
SPS circumference = 11 x PS circumference: SPS ring filled at 10/11

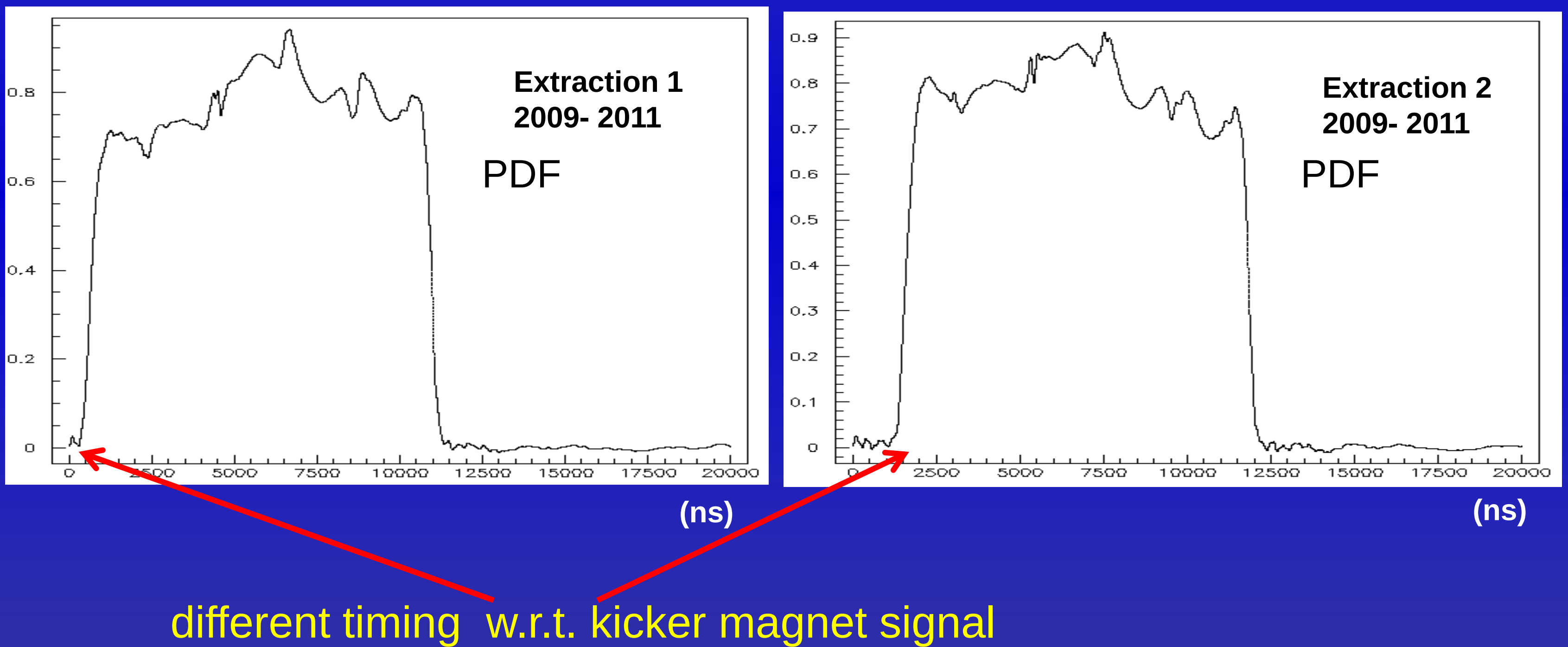
Shapes varying with time
Precise accounting with WFD waveforms

Neutrino event-time distribution PDF(1)

- **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



Neutrino event-time distribution PDF(2)

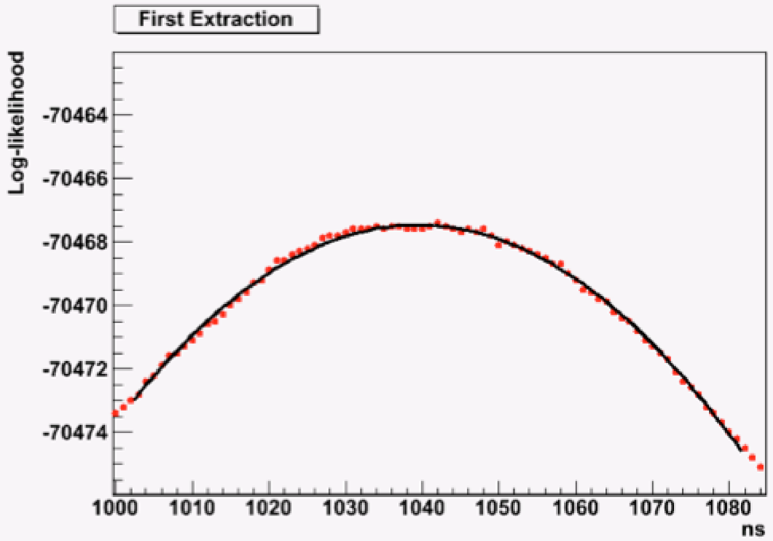
- **White noise present at the level of the single waveforms averaged out**
- **200 MHz RF structure still present in the final PDF**
- **Coherent noise affecting the central part of the distribution due to an electromagntic disturbance of the electronics occuring with a constant delay w.r.t. the kicker magnet pulse, NOT related to the proton beam**

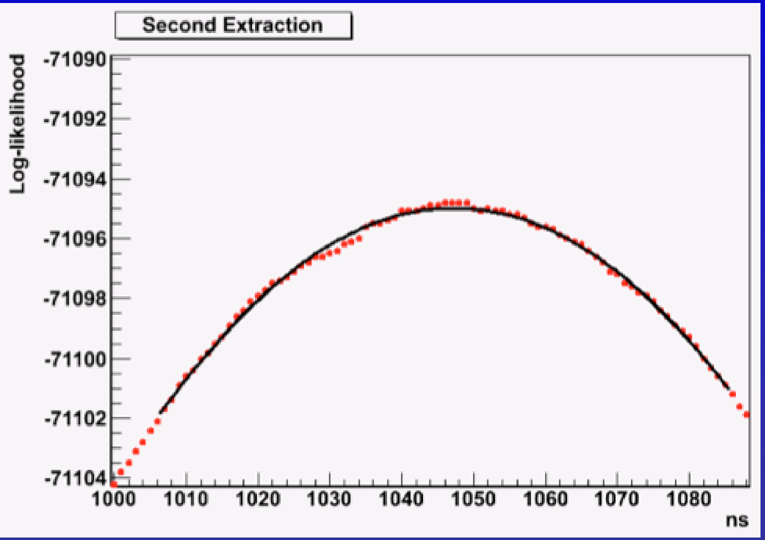
→ Final PDF needed to be filtered

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

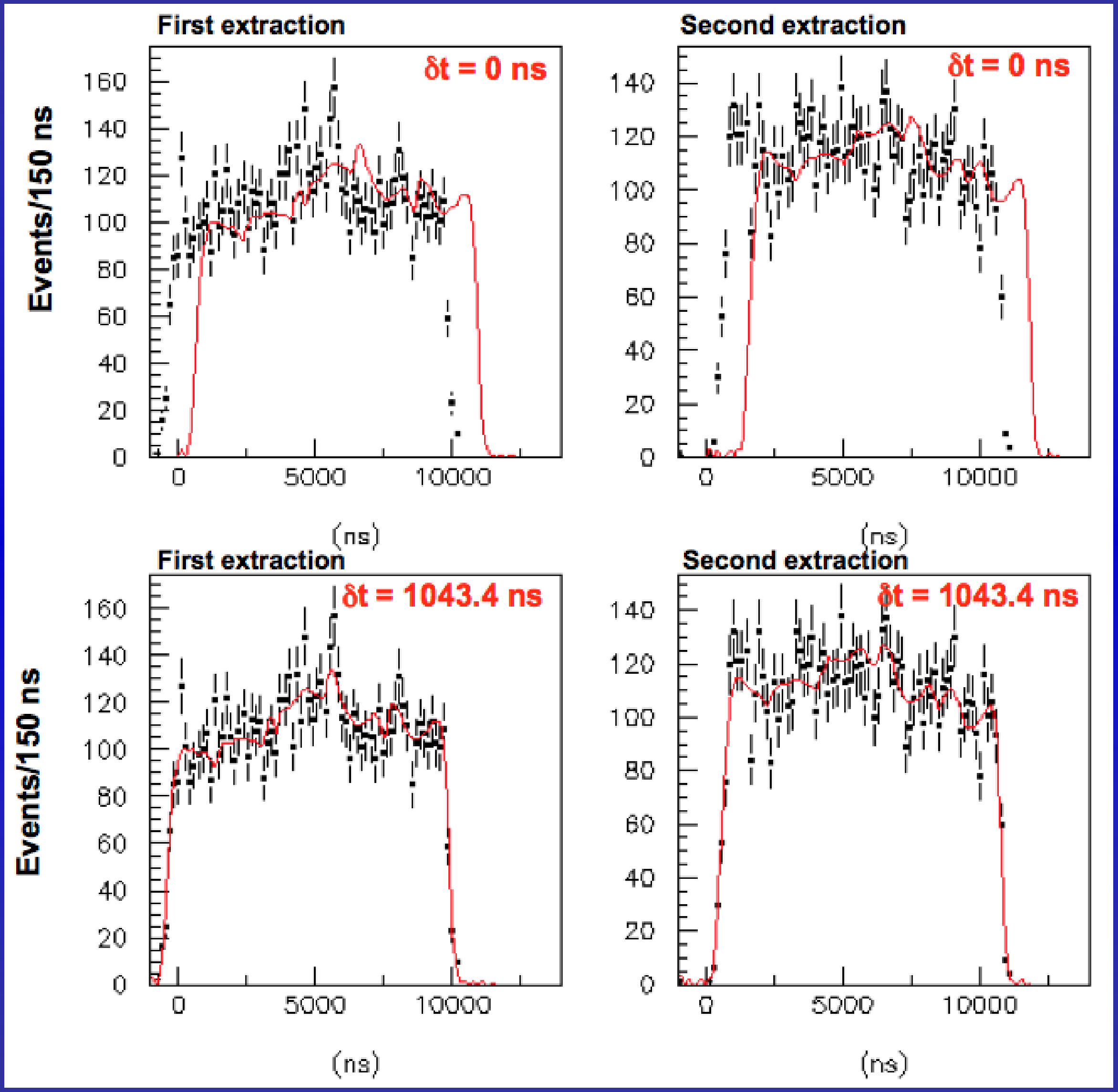
Separate likelihood for each extraction

Maximised versus δt: $\delta t = TOF_c - TOF_\nu$





Data vs PDF: before and after likelihood result



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

(1043.4 ± 7.8) ns (stat)

χ^2 / ndof :

first extraction: 1.1
second extraction: 1.0

Results(1)

Opening the box:

timing and baseline corrections

	Blind 2006	Final analysis	Correction (ns)
Baseline (ns)	2440079.6	2439280.9	
Earth rotation (ns)		2.2	
Correction baseline			-796.5
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			**-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**	

Results(2)

For CNGS ν_μ "standard" beam, <E> = 17 GeV:

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

(1043.4 ± 7.8 (stat.)) ns – 985.6 ns = (57.8 ± 7.8 (stat.) $^{+8.3}_{-5.9}$(sys.)) ns

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

$(v-c)/c = \delta t / (TOF_c - \delta t) = (2.37 \pm 0.32\ (\text{stat.})\ ^{+0.34}_{-0.24}(\text{sys.})) \times 10^{-5}$

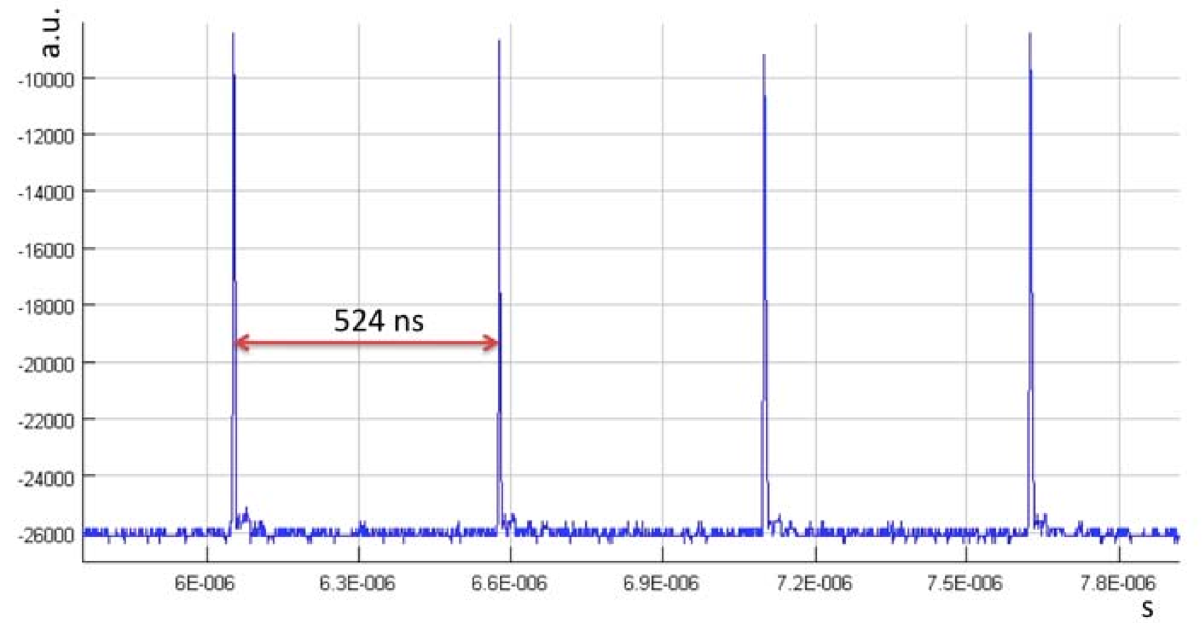
(730085 m used as neutrino baseline from parent mesons average decay point)

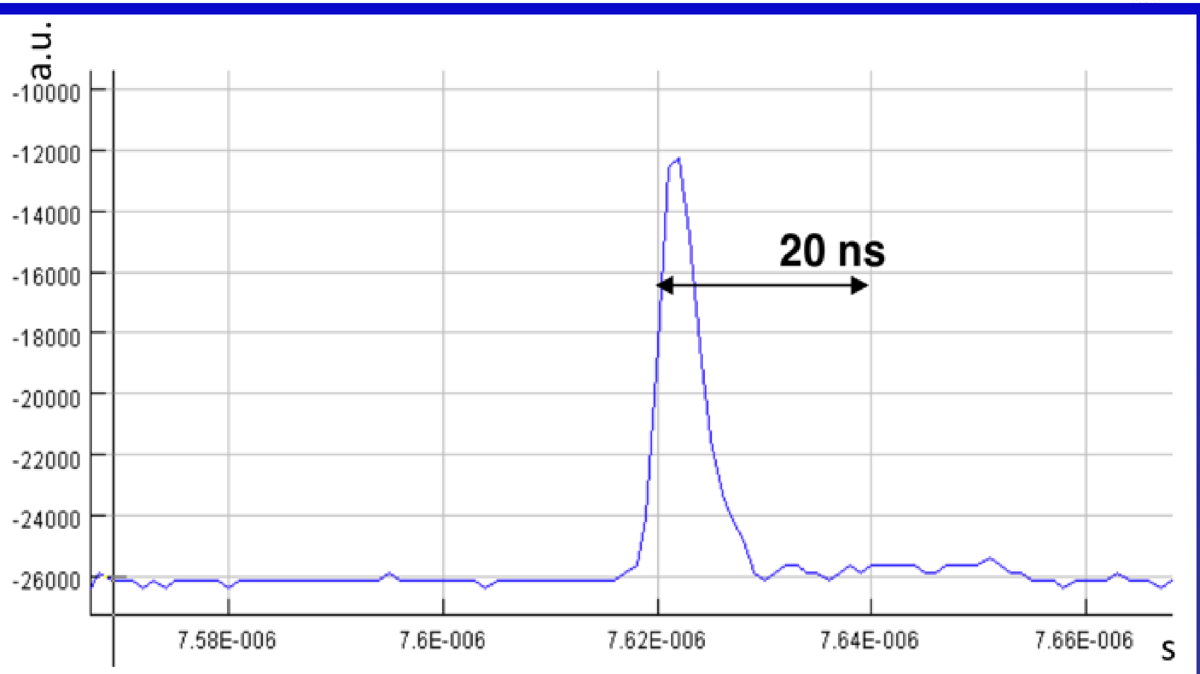
6.2 σ significance

Single wave-form analysis Likelihood built by associating each neutrino interaction to its waveform instead of using the global PDF

Compatible Result with a systematic error of 4.4 ns is attributed to this result by comparing different filtering conditions and treatment of the waveform baselines

Test with a short-bunch wide-spacing beam





4×10^{16} pot accumulated

Proton bunch-length 3ns

35 beam-related events

20 events selected

•Run: October 22- November 6

•This beam allowed us to perform the TOF measurement at single-event level

•Price to pay: reduction of intensity (about 60 times less) → 35 neutrino events collected by the OPERA detector

•Same data selection as for the previous analysis: 20 events retained after quality cuts: 6 internal interaction, 14 external

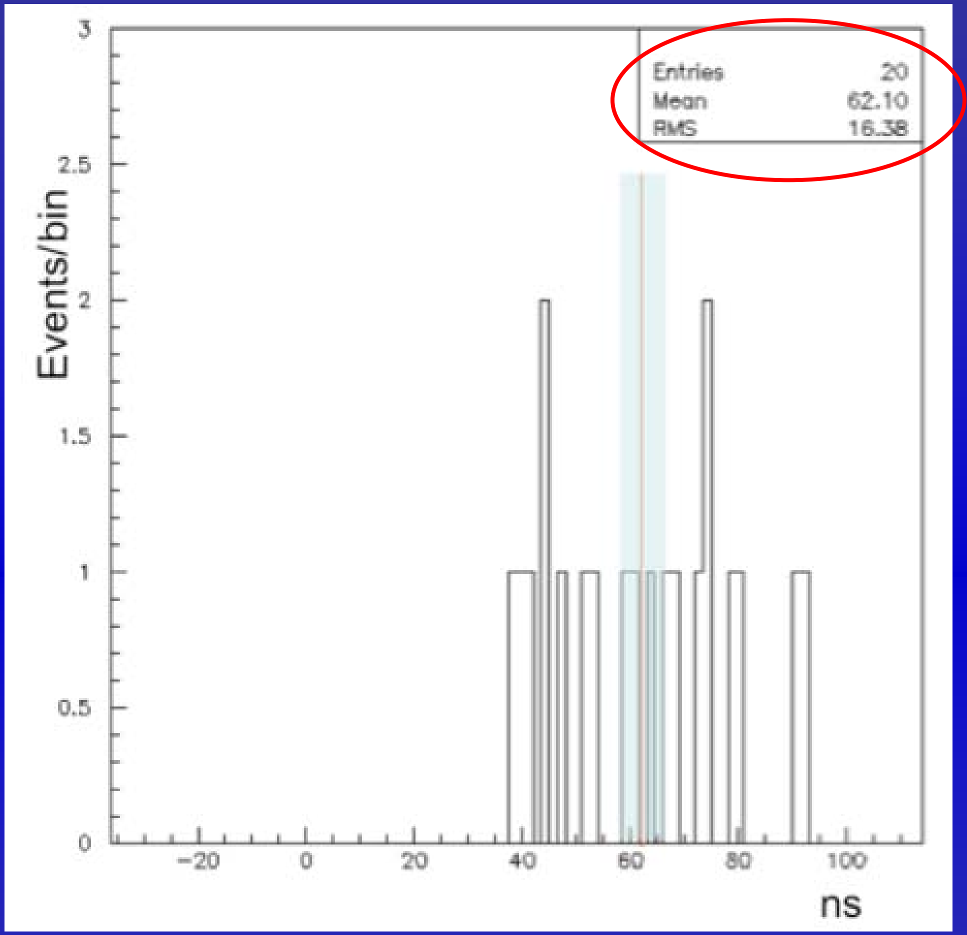
•Events distribuited in all the 4 bunches

GOOD POINTS:

•Excluding possible systematic effects related to the use of the PDFs and to their statistcal treatment

•Each neutrino event unambigously associated to its proton bunch

Result



$\delta t = (62.1 \pm 3.7 \text{ (stat.)})$

The systematic uncertainties are equal or smaller than those affecting the result with the nominal CNGS beam

The result is in agreement with the (57.8 ± 7.8) ns of the main analysis and the statistical accuracy achieved is as small as 3.7 ns with only 20 events.

This test allow us to exclude:

• Possible biases affecting the statistical analysis based on the PDFs

• A possible bias related to the response of the beam line to long proton pulses such as:

  - Target aiming accuracy
  - horns timing
  - Target temperature increase

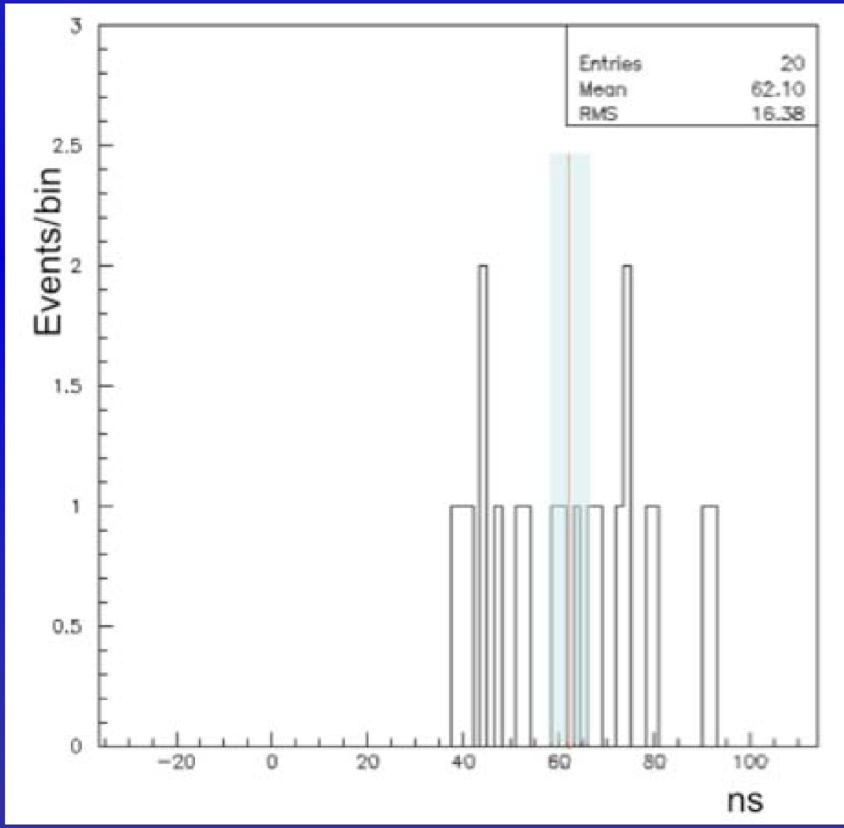
• Pulse duration effects in the BCT response

Moreover waveforms filtering does not apply and we avoid the procedure adopted for removing the noise

Perspectives

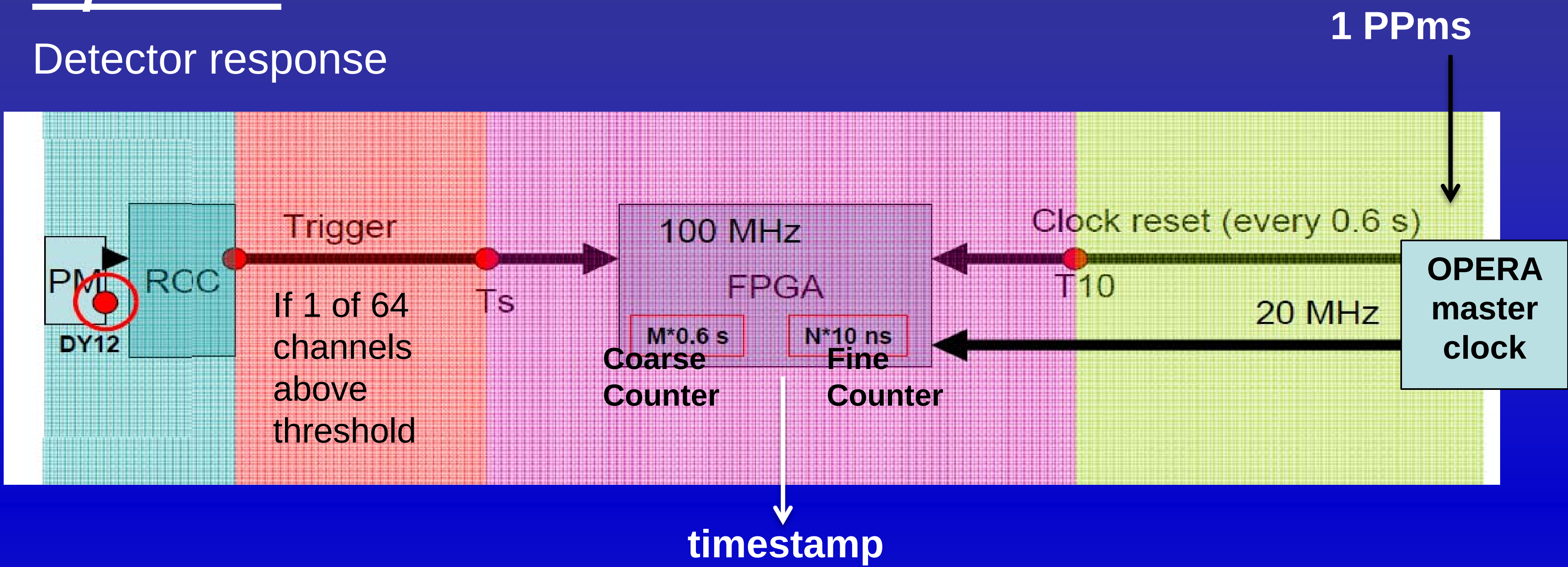
- **Collect more data with a bunched beam run for some weeks in 2012**

- **Upgrade of the OPERA master clock to reach 100 MHz performance in order to have a better resolution**



Spares

Detector response



Delay from photo-cathode to FPGA input (UV laser excitation): 50.2 ± 2.3 ns

Average time response: 59.6 ±3.8 ns (sys) (including position and p.h. dependence, ROC time-walk, DAQ quantization effects accounted by simulations)

±25 ns jitter:

20 MHz frequency is multiplied in order to make a 10 ns sub-sampling of the external PPms GPS signal (to match its to the DAQ granularity of 10 ns).

This operation is performed but a mechanism which was setup in order technically to work in absence of external GPS signal interfers with it.

→the 10 ns sample which is connected to the 1PPms randomly cycles among the 5 possible ones withing the 50 ns bin and independently of the real timing of the PPms GPS signal

→instead of having 10ns resolution at the level of connecting the 0.6 s reset signal to the UTC we go back to the 50 ns resolution intrinsic to the oscillator of the master clock.

The result of that is that we have a jitter of +-25 ns affecting the reset signal and so the time tagging of our events.

This jitter is completely uncorrelated with respect to the trigger timing, since it is there independently on the presence of events.