The OPERA Neutrino Velocity Measurement

Presented by Björn Wonsak

The 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

Additional Collaborators

- 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)

Overview

- Introduction
- The OPERA Experiment
- Time Synchronisation
- Measurement Principle
- Determination of the Flight Distance
- Time Calibration
- Data Analysis
- Conclusions

Past Experimental Results

- FNAL experiment (Phys. Rev. Lett. 43 (1979) 1361)
  - Muon neutrinos, high energy (E_ν > 30 GeV), short baseline (550 m)
  - Comparison of muon-neutrino and muon velocities (1 ns bunches)
  - Tested deviations down to $|v-c|/c \leq 4\times10^{-5}$

- SN1987A (see e.g. Phys. Lett. B 201 (1988) 353)
  - Electron (anti) neutrinos, 10 MeV range, 168'000 light years baseline
  - Performed with observation of neutrino and light arrival time
  - Tested deviations down to $|v-c|/c \leq 2\times10^{-9}$

- MINOS (Phys. Rev. D 76 072005 2007)
  - Muon neutrinos, E_ν peaking at ~3 GeV with a tail extending above 100 GeV, 730 km baseline
  - Comparison of time distribution (~10 μs) in near and far detector
  - Result: $(v-c)/c = 5.1 \pm 2.9\times10^{-5}$ (1.8 σ)

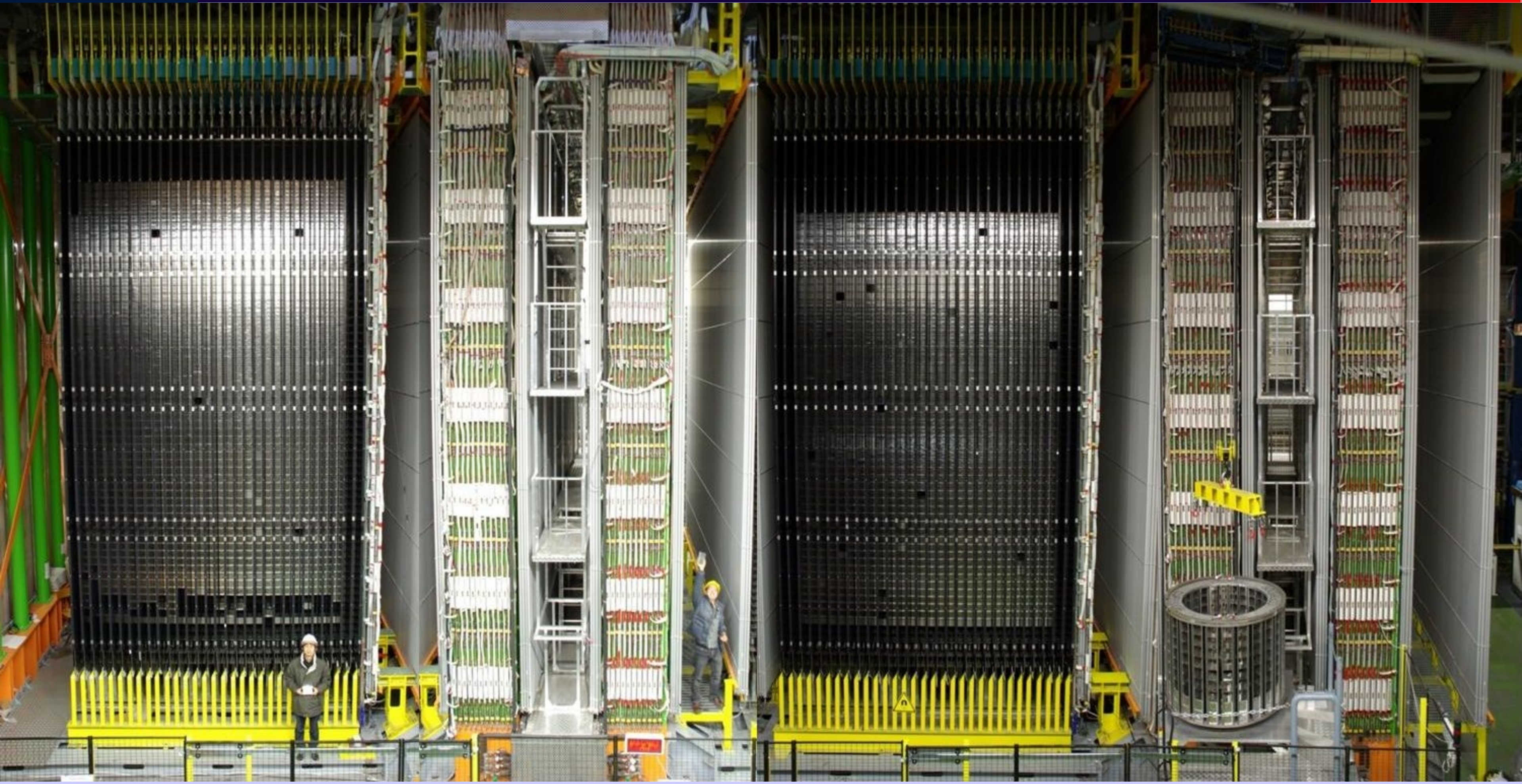
The OPERA Experiment

Long baseline neutrino oscillation experiment

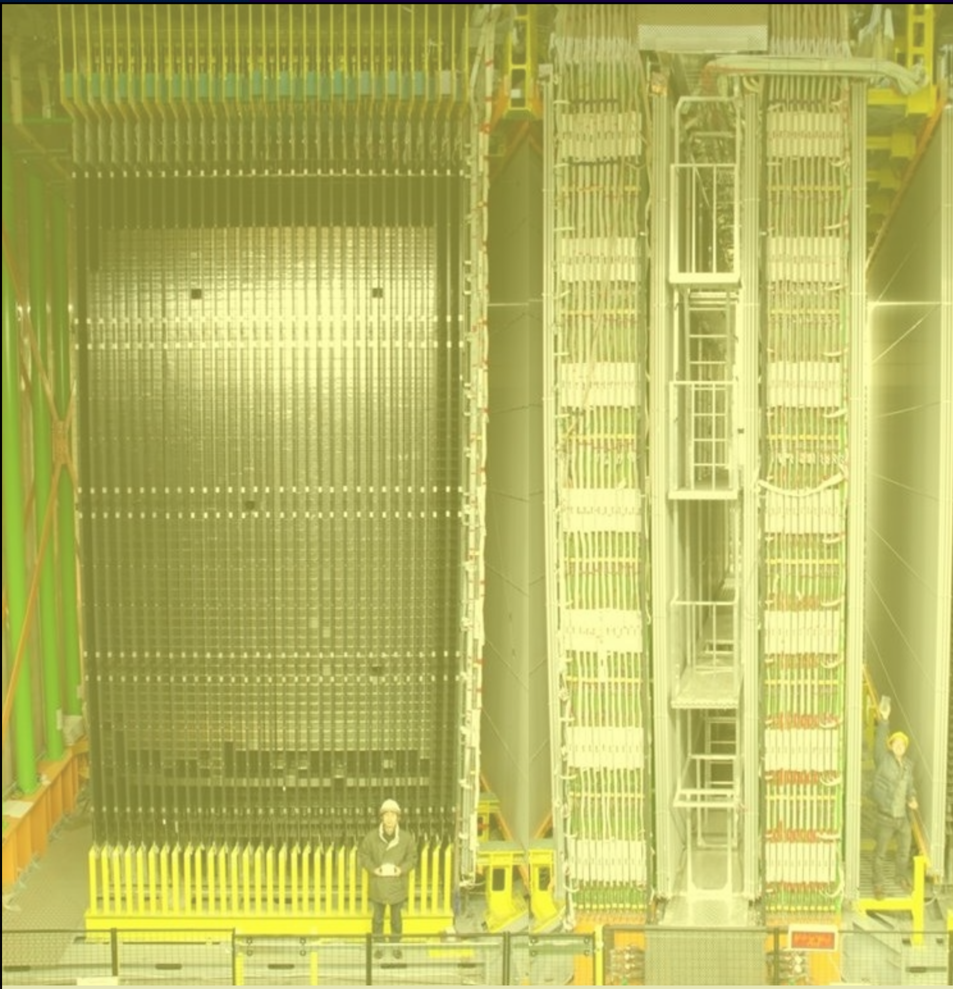
Very pure ν_μ beam from CERN to LNGS

Goal:
Observation of ν_τ appearance

The OPERA Detector

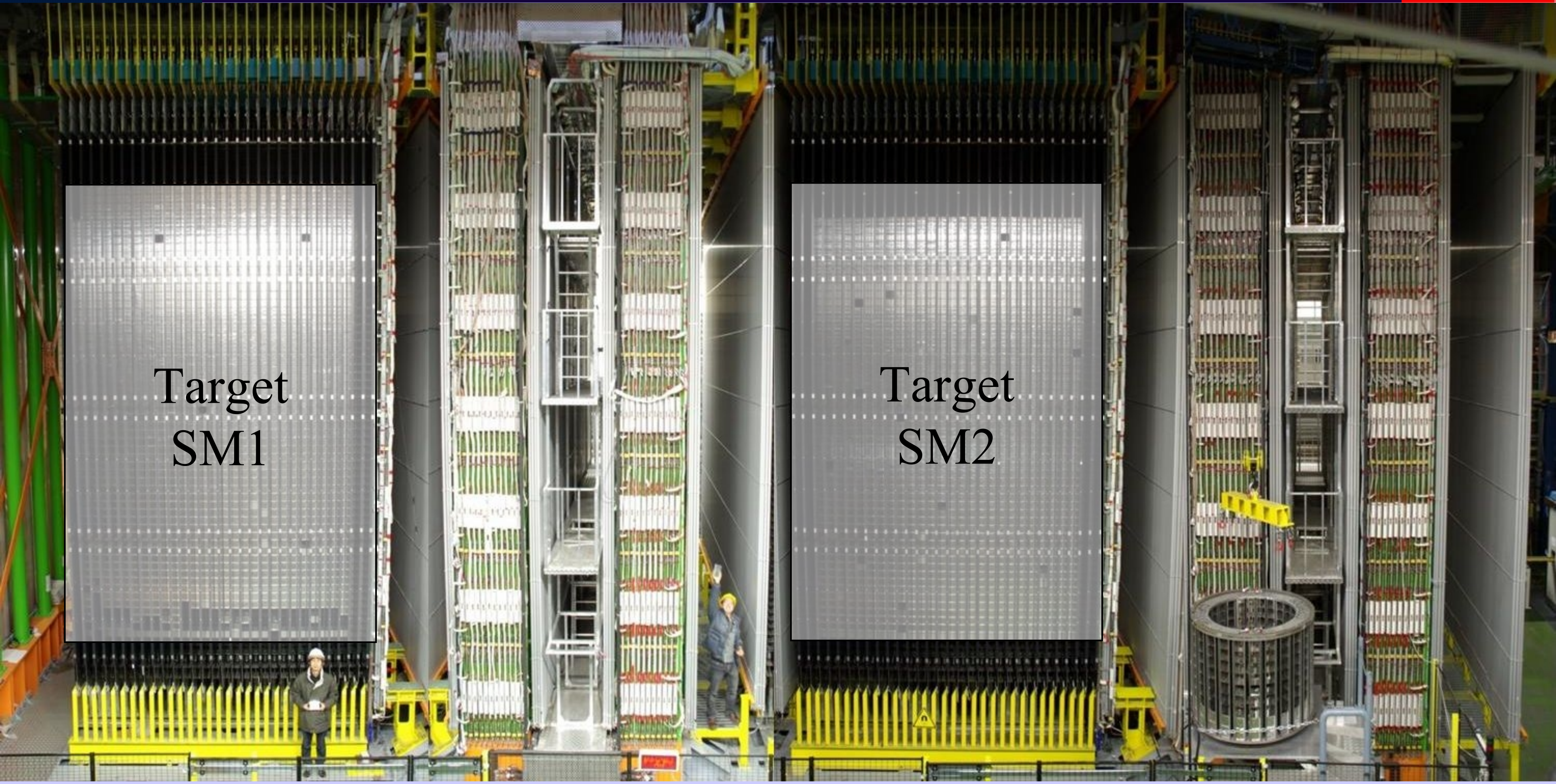


The OPERA Detector


Super Module 1 (SM1)


Super Module 2 (SM2)

The OPERA Detector

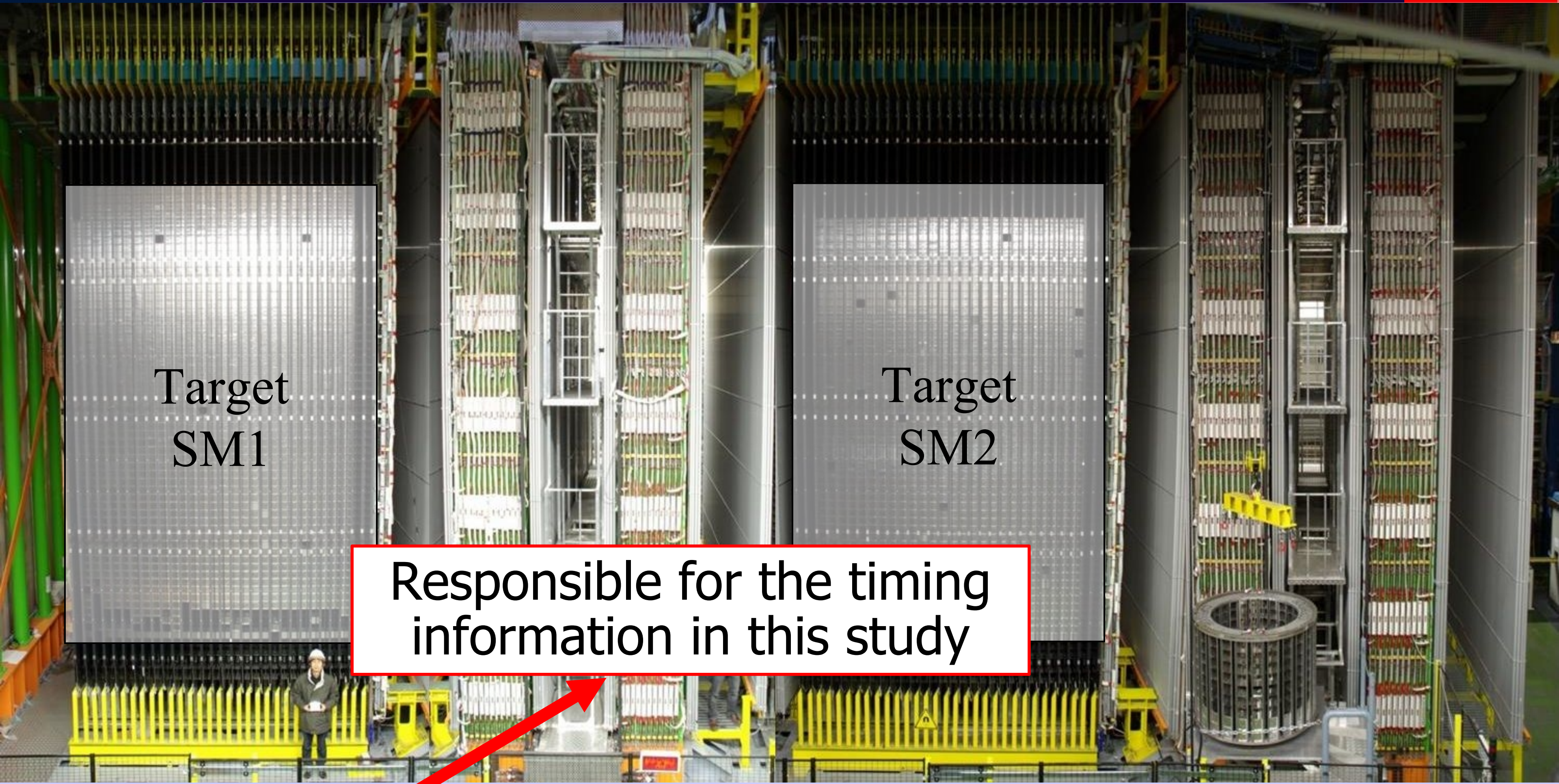


Target Region:

- Target Tracker (Scintillator)
- Lead/Emulsion Bricks (75.000 per SM)

Target mass: ~1.25 kton

The OPERA Detector



Target Region:
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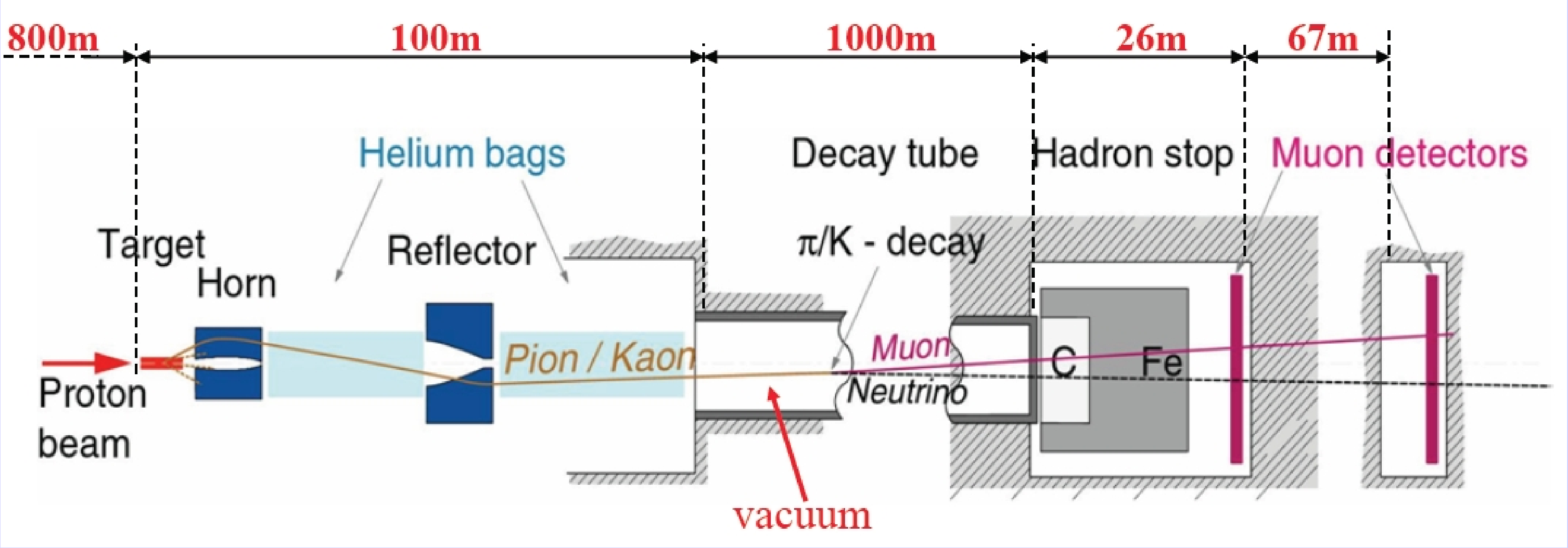
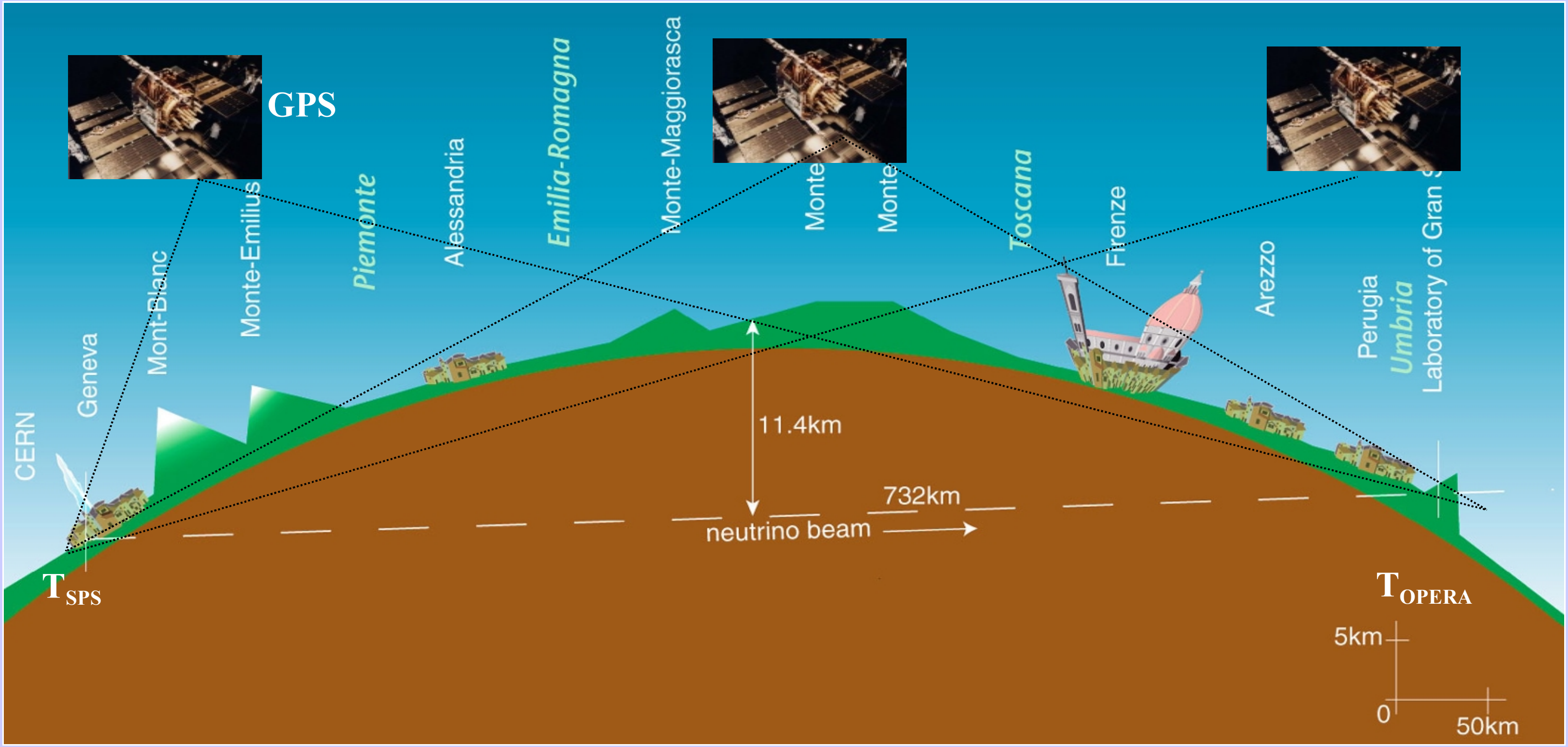
The CNGS Neutrino Beam



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

CNGS Event Selection

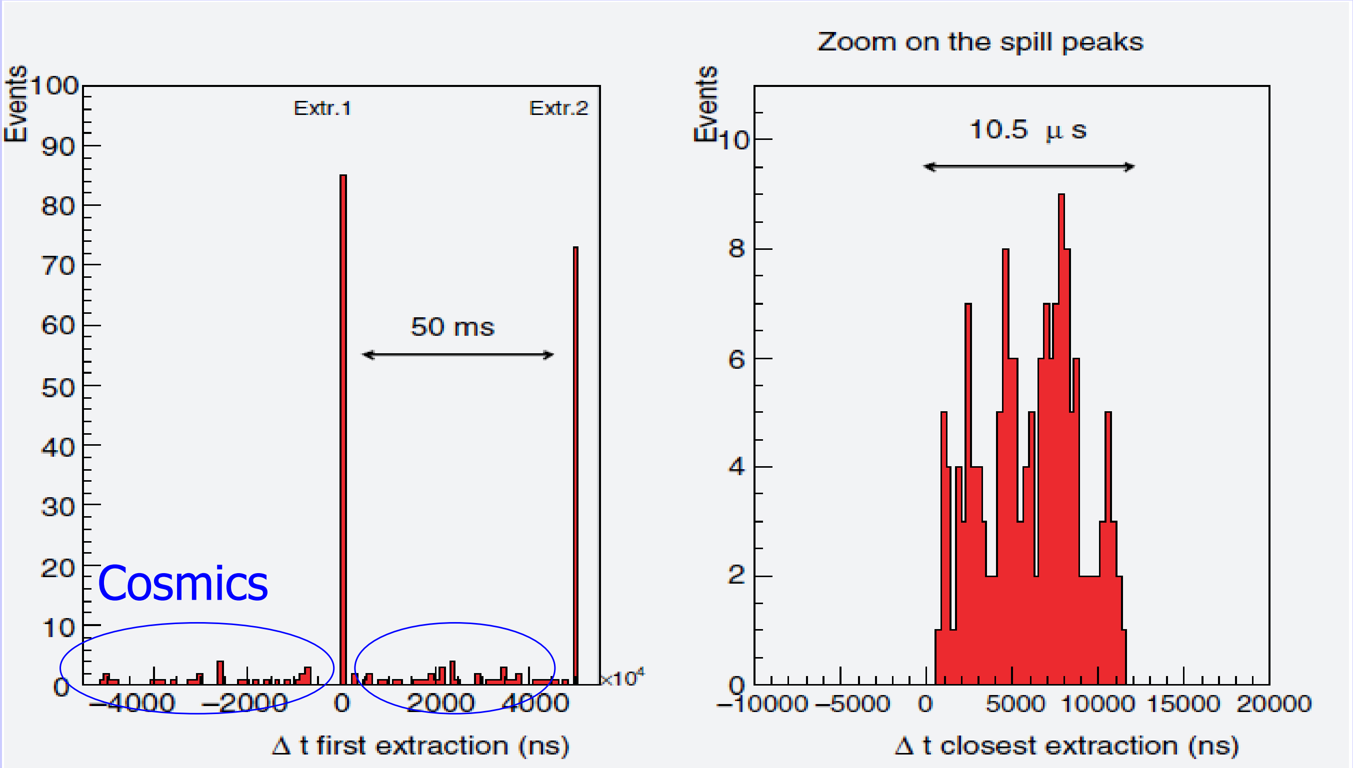


- Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

$$|T_{OPERA} - (T_{Kicker} + TOF_c)| < 20\ \mu s$$

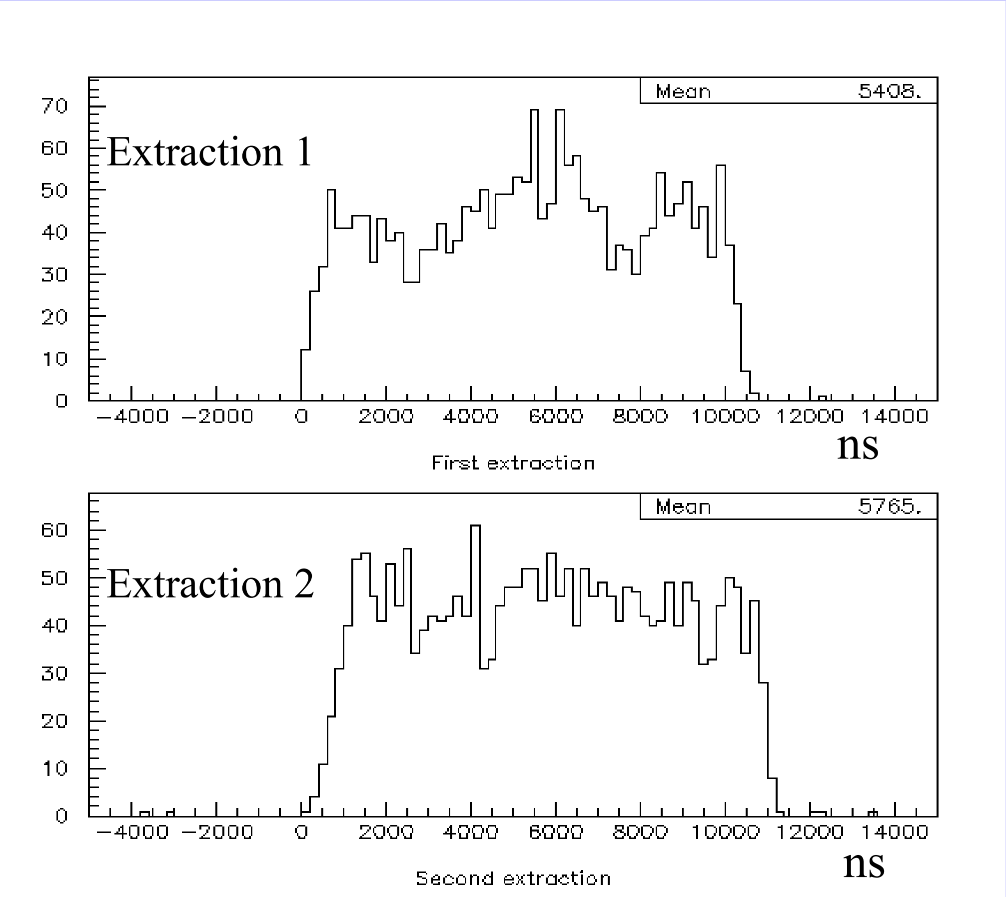
- Synchronisation with standard GPS systems ~100 ns (inadequate for our purposes)

CNGS Event Selection



- OPERA data: narrow peaks of the order of the spill width (10.5 μs)
- Negligible cosmic-ray background: $\mathcal{O}(10^{-4})$
- Selection procedure kept unchanged since first events in 2006

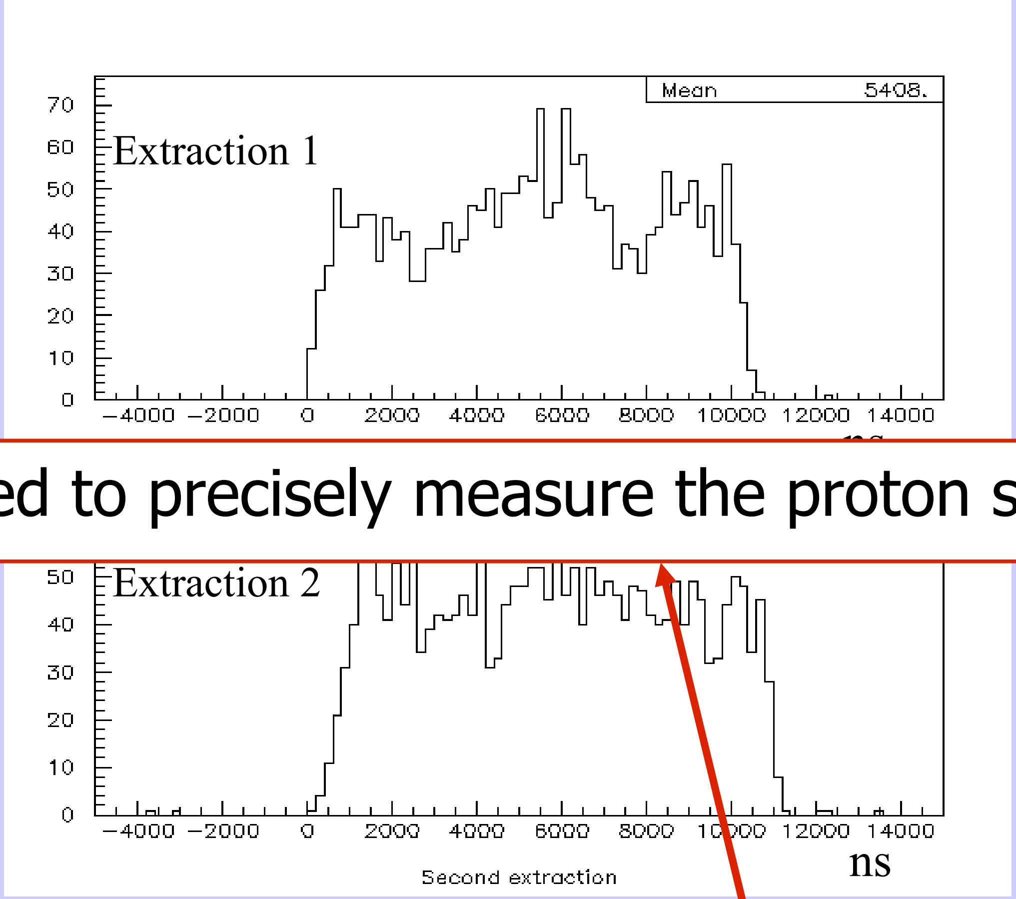
From CNGS Event Selection to Neutrino Velocity Measurement



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

- Not flat
- Different timing for first and second extraction

From CNGS Event Selection to Neutrino Velocity Measurement

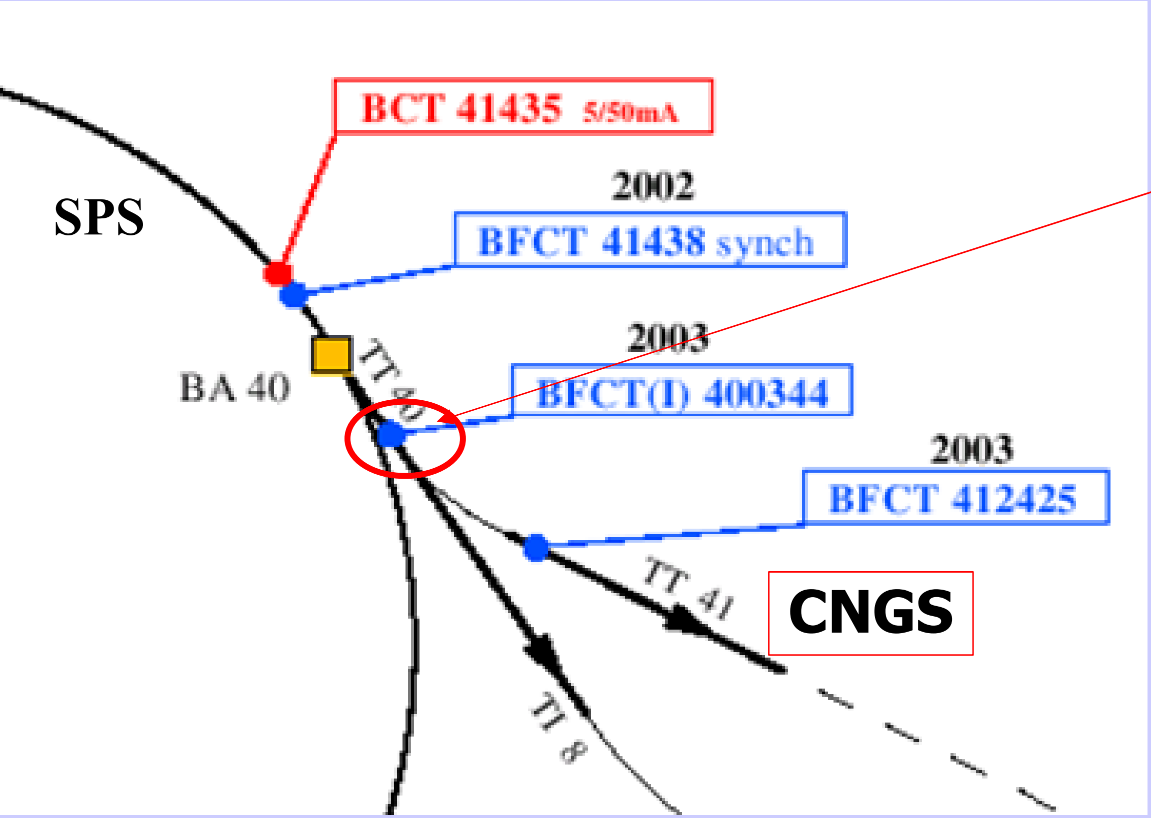


→ Need to precisely measure the proton spills

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

- Not flat
- Different timing for first and second extraction

Proton Timing by Beam Current Transformer (BCT)



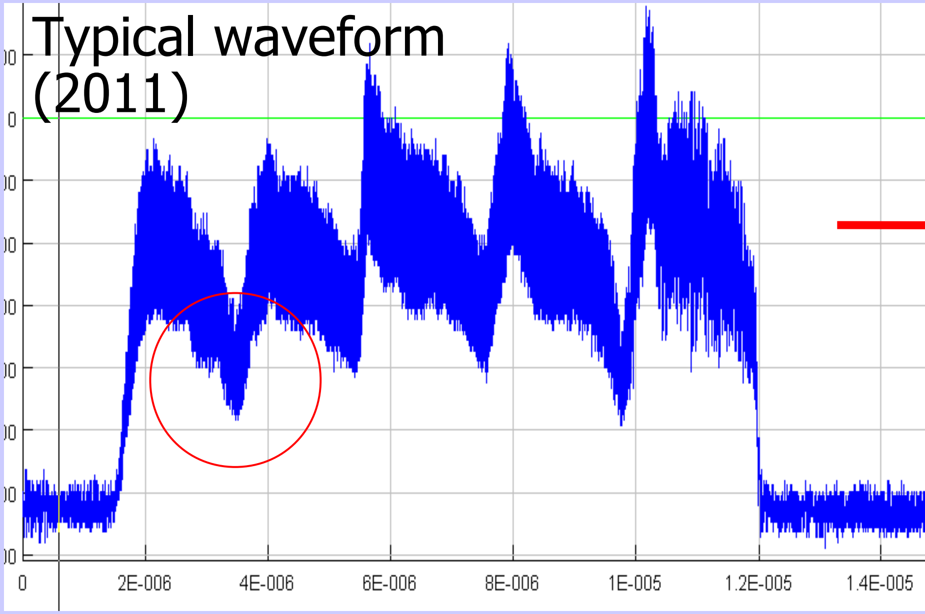
Fast BCT 400344
(~ 400 MHz)

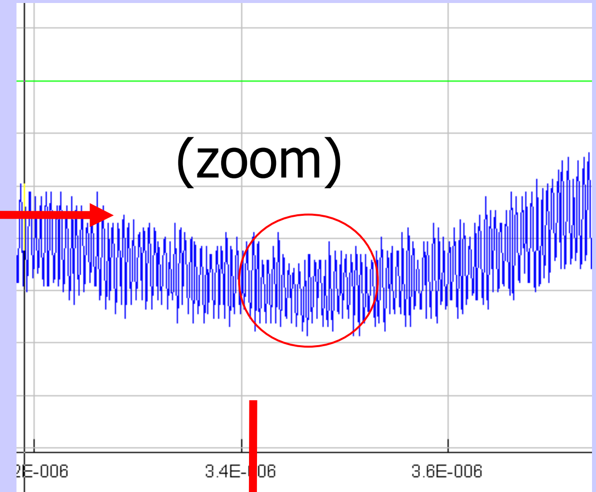
Proton pulse digitization:

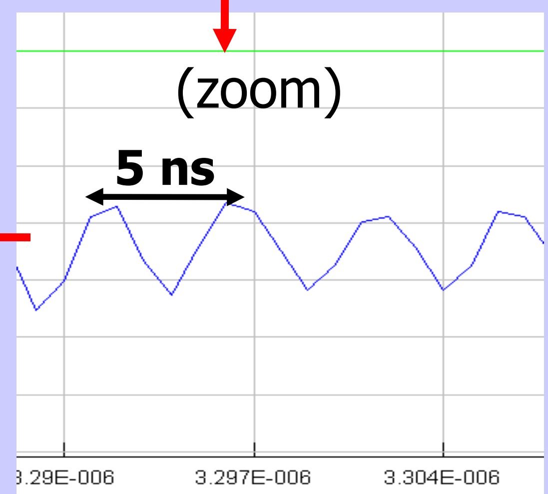
- Acqiris DP110 1GS/s waveform digitizer (WFD)
- WFD triggered by a replica of the kicker signal
- Waveforms UTC-stamped and stored in CNGS database for offline analysis

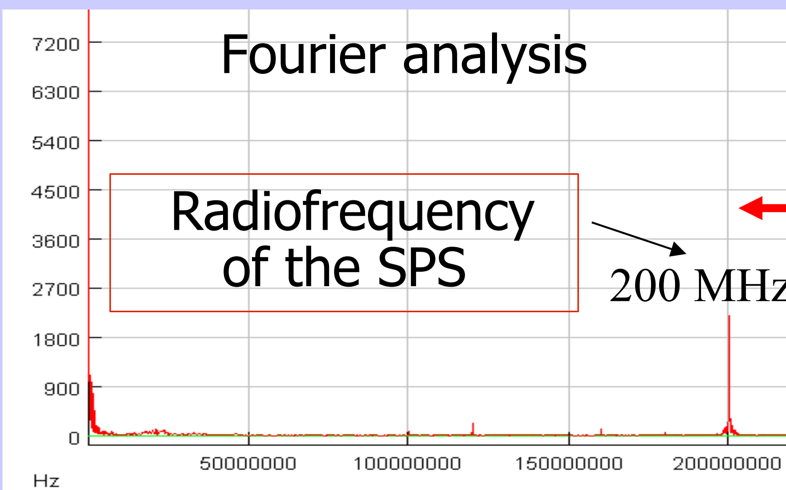
2010 calibration with Cs clock

Proton Spill Shape







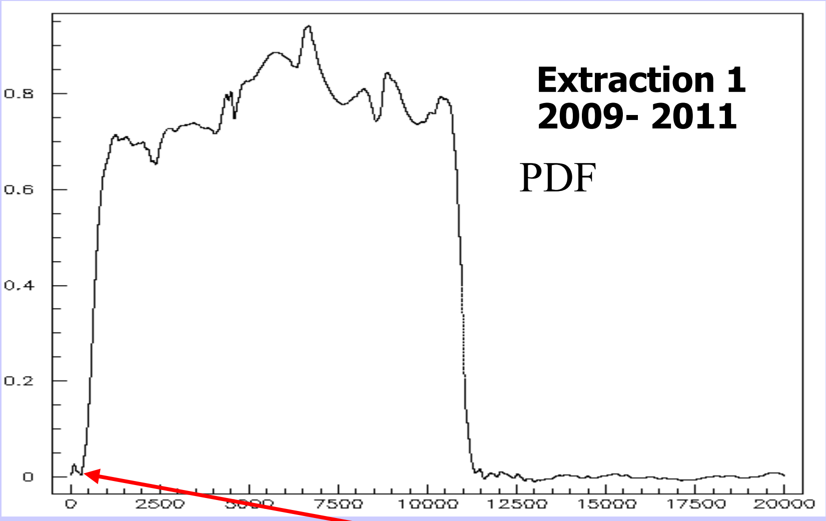


Neutrino Event-time Distribution PDF

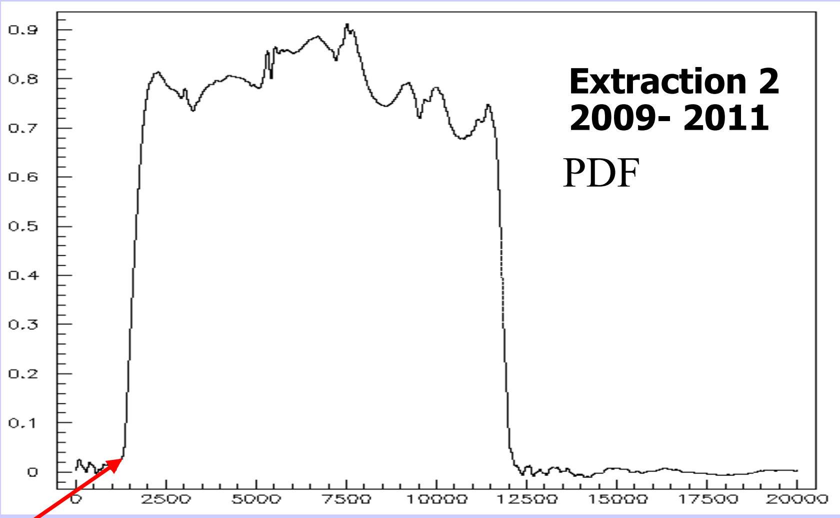
- Each event is associated to its proton spill waveform
- The “parent” proton is unknown within the 10.5 μs extraction time

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

→ Compare to OPERA detected neutrino events



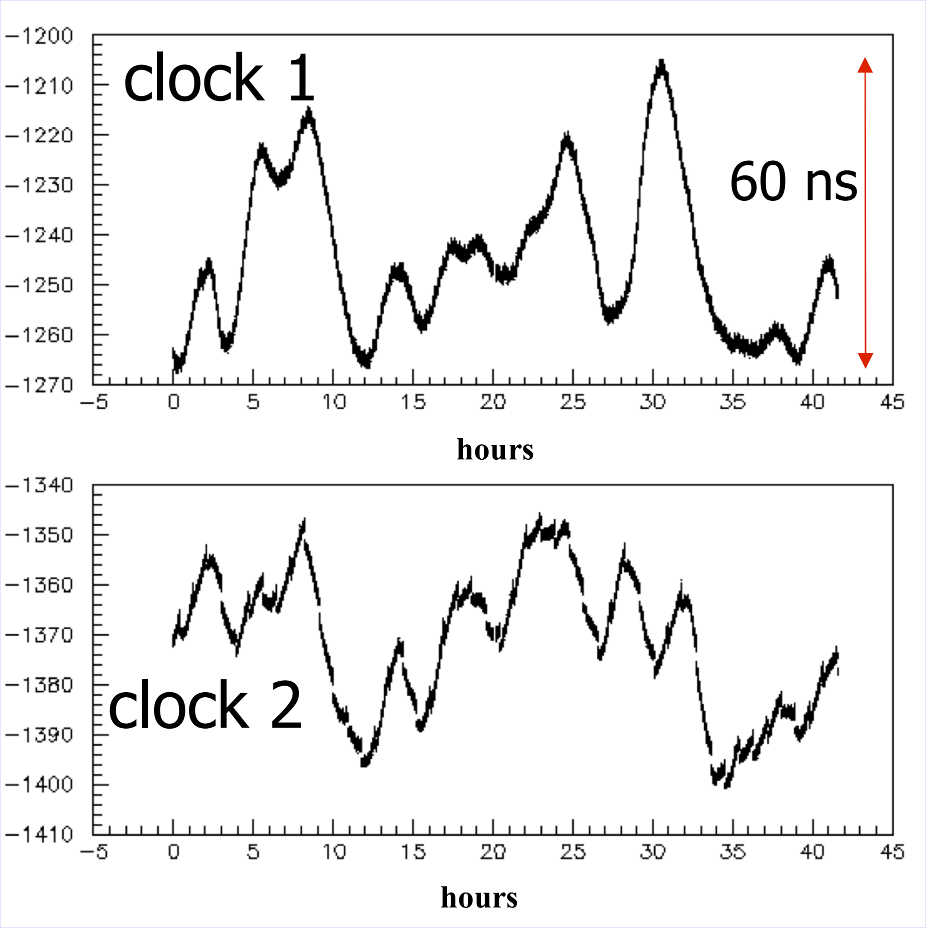
(ns)



(ns)

Different timing w.r.t. kicker magnet signal

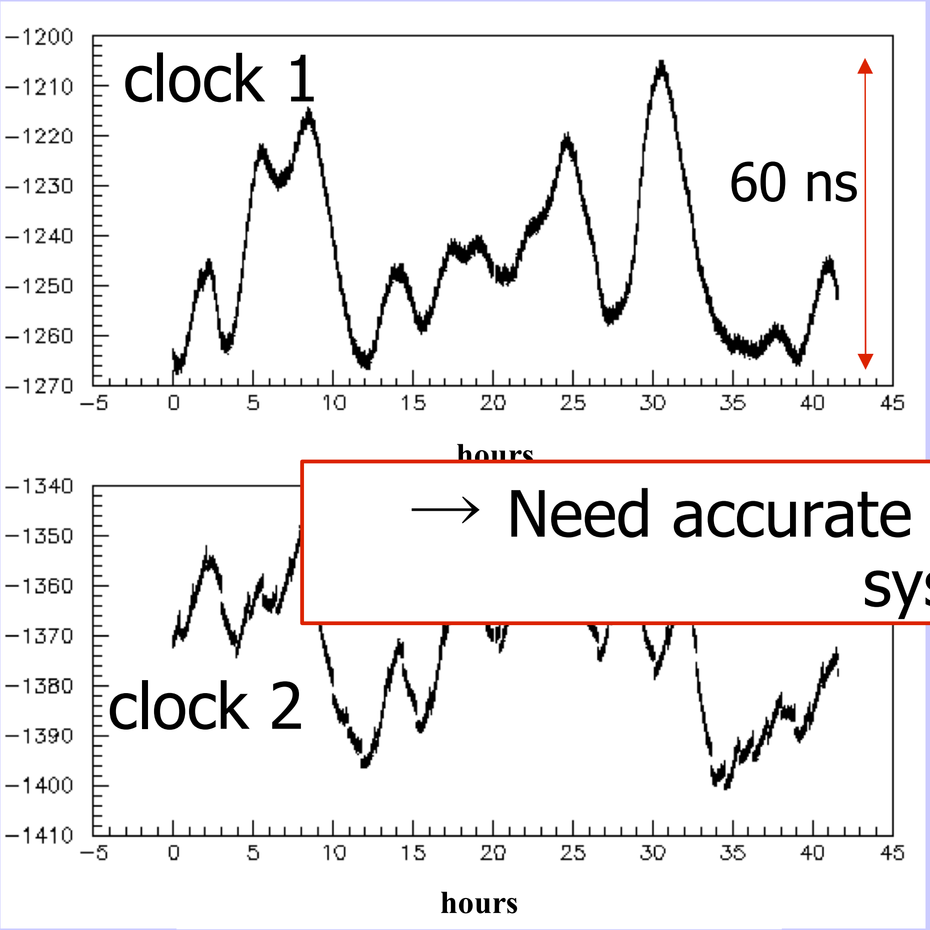
GPS Clocks at LNGS



Comparison to Cs clock:

- Large oscillations
- Uncertainties on CERN-OPERA synchronisation

GPS Clocks at LNGS



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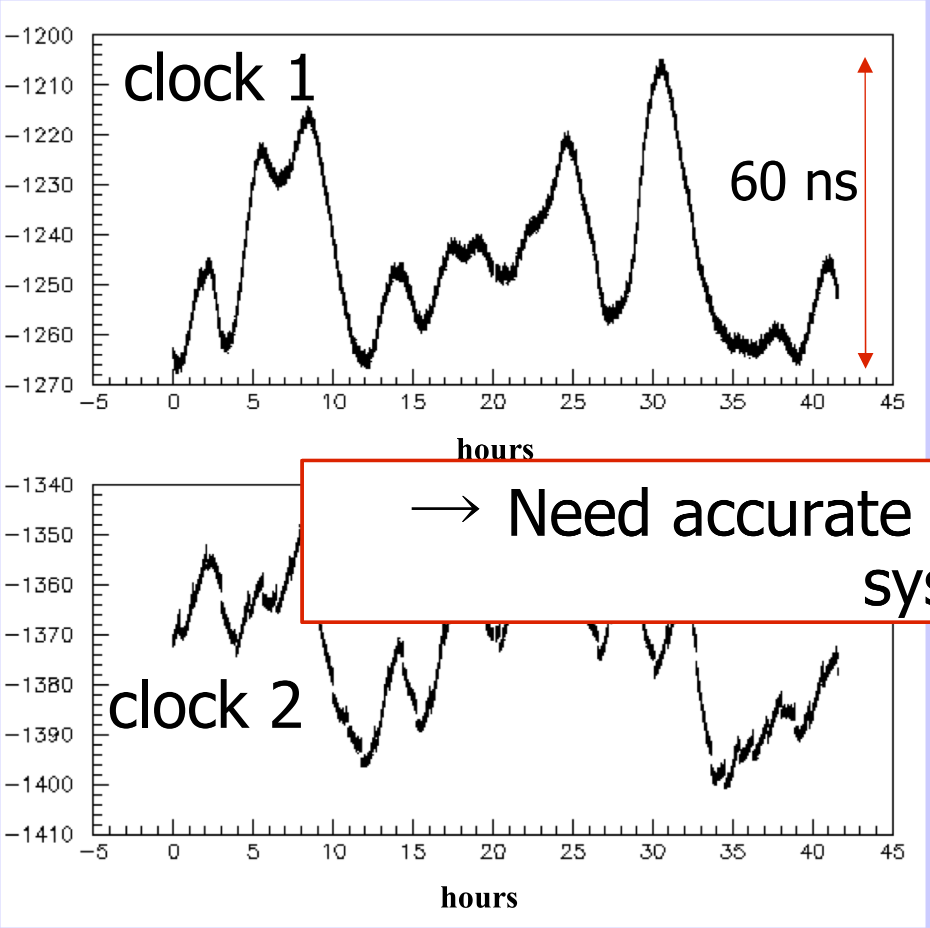
→ Need accurate time synchronisation system

GPS Clocks at LNGS



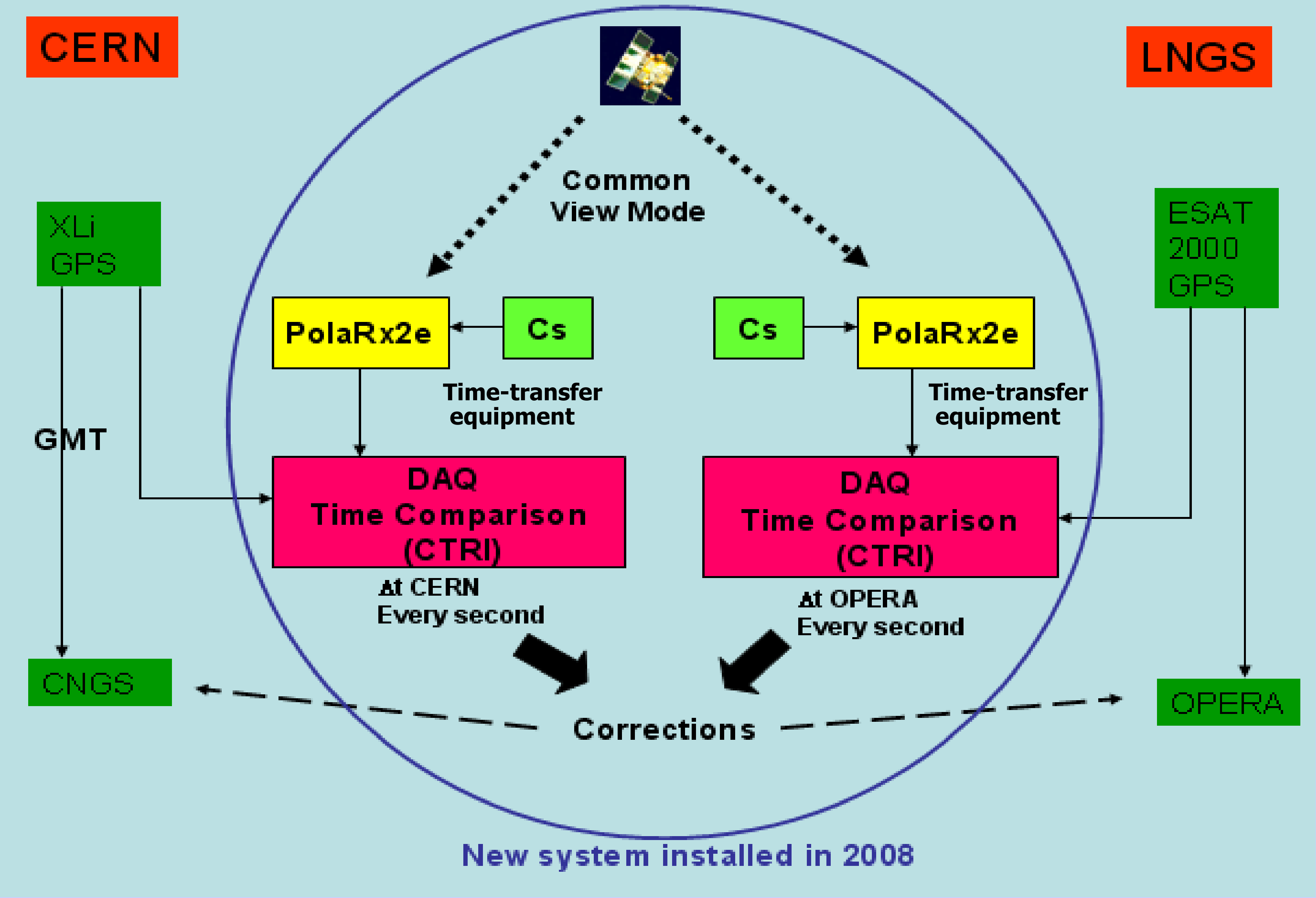
Comparison to Cs clock:

- Large oscillations
- Uncertainties on CERN-OPERA synchronisation

→ Need accurate time synchronisation system

- Collaboration with CERN timing team since 2003
- Major upgrade in 2008

CERN-OPERA Synchronisation



New Synchronisation Gear

2008: installation of a twin high accuracy system calibrated by METAS (Swiss metrology institute)

→ Septentrio GPS PolaRx2e + Symmetricom Cs-4000

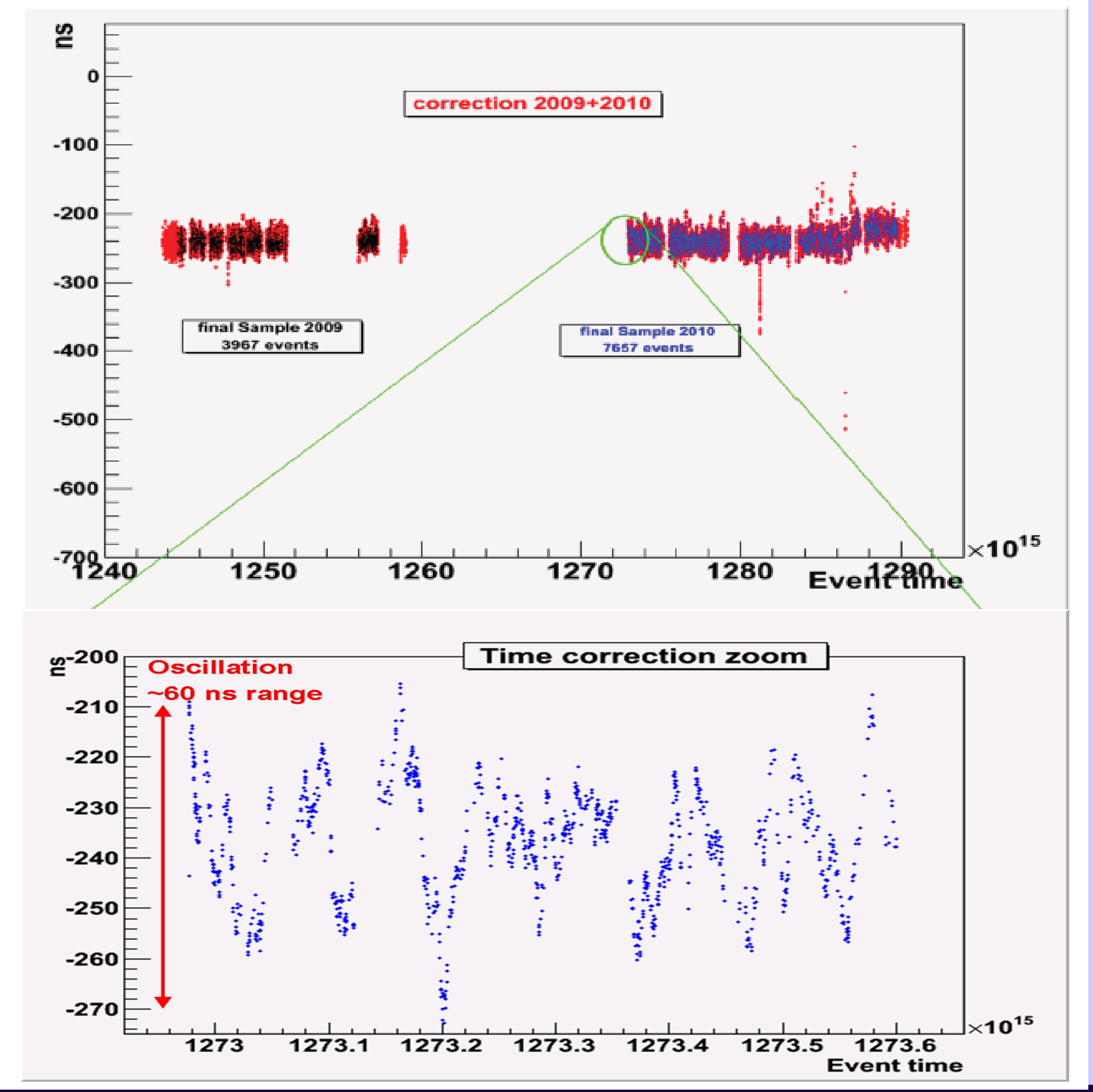
PolaRx2e (GPS-Receiver):

- 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

Result: TOF Time-link Correction (Event by Event)

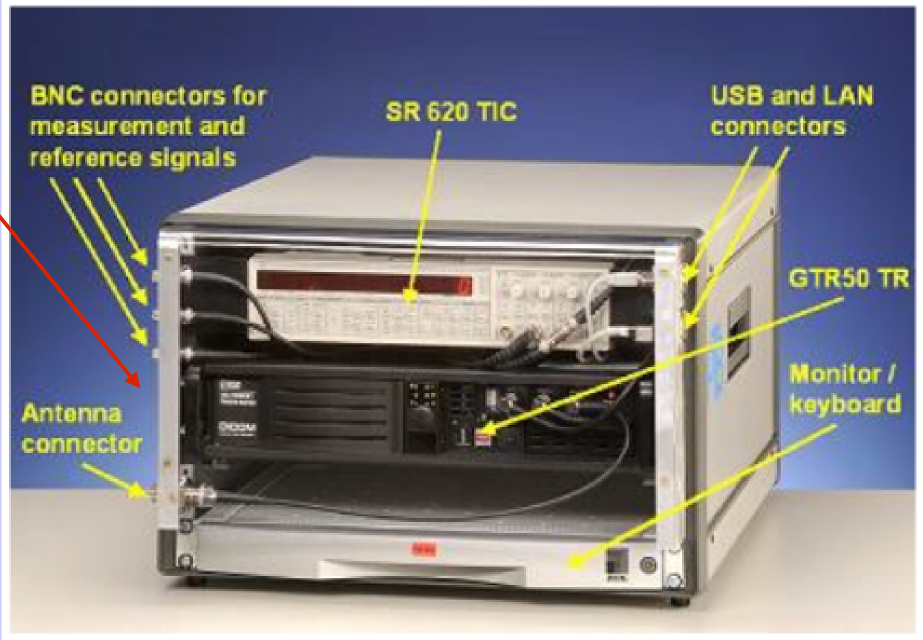


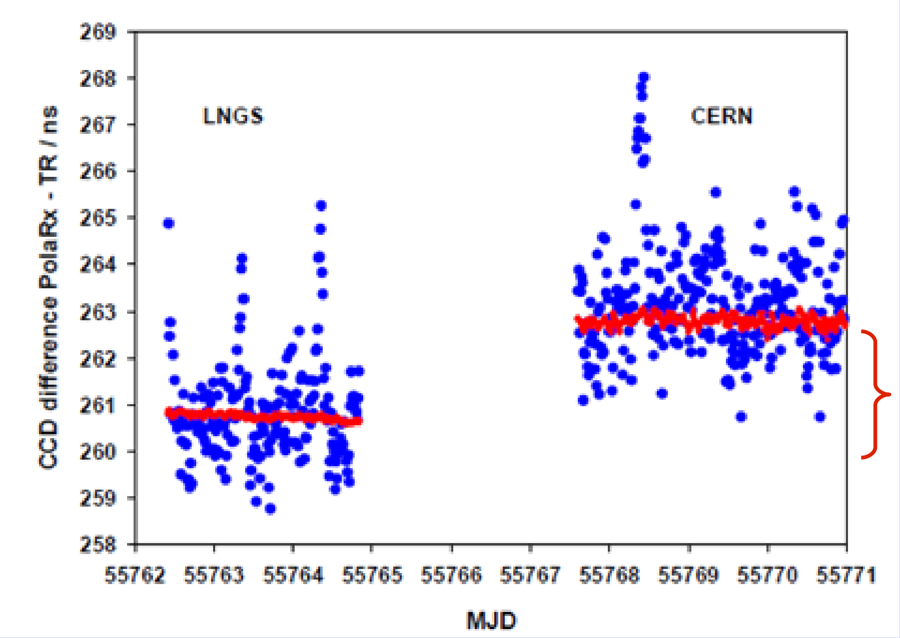
CERN-OPERA Inter-calibration Cross-check

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt (PTB)

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

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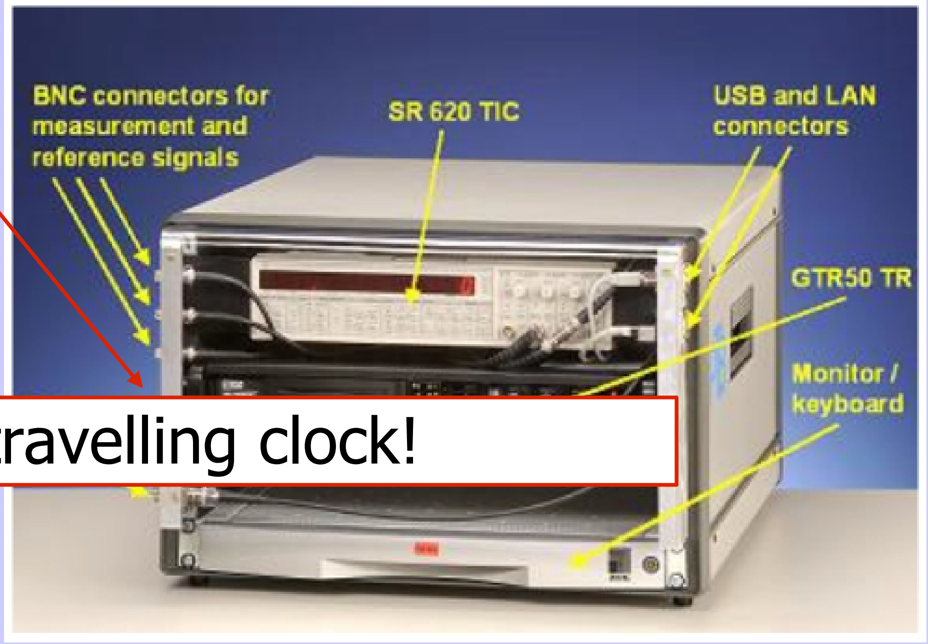
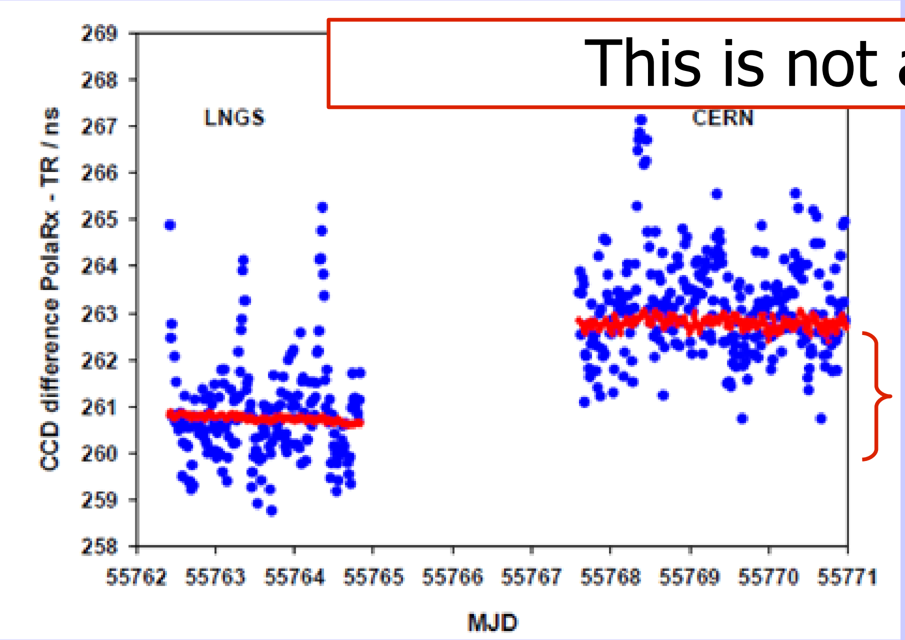


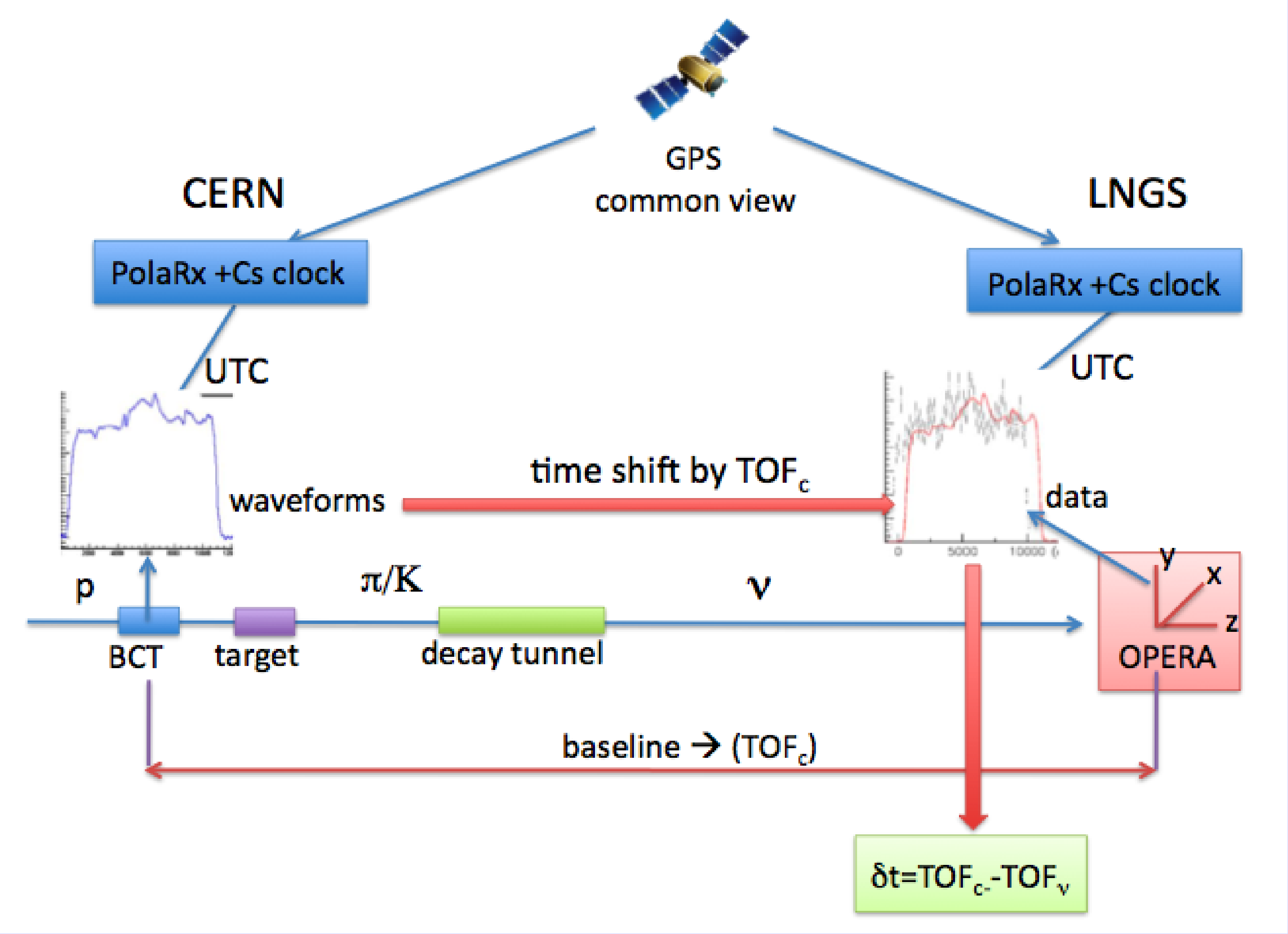
This is not a travelling clock!



Correction to the time-link:

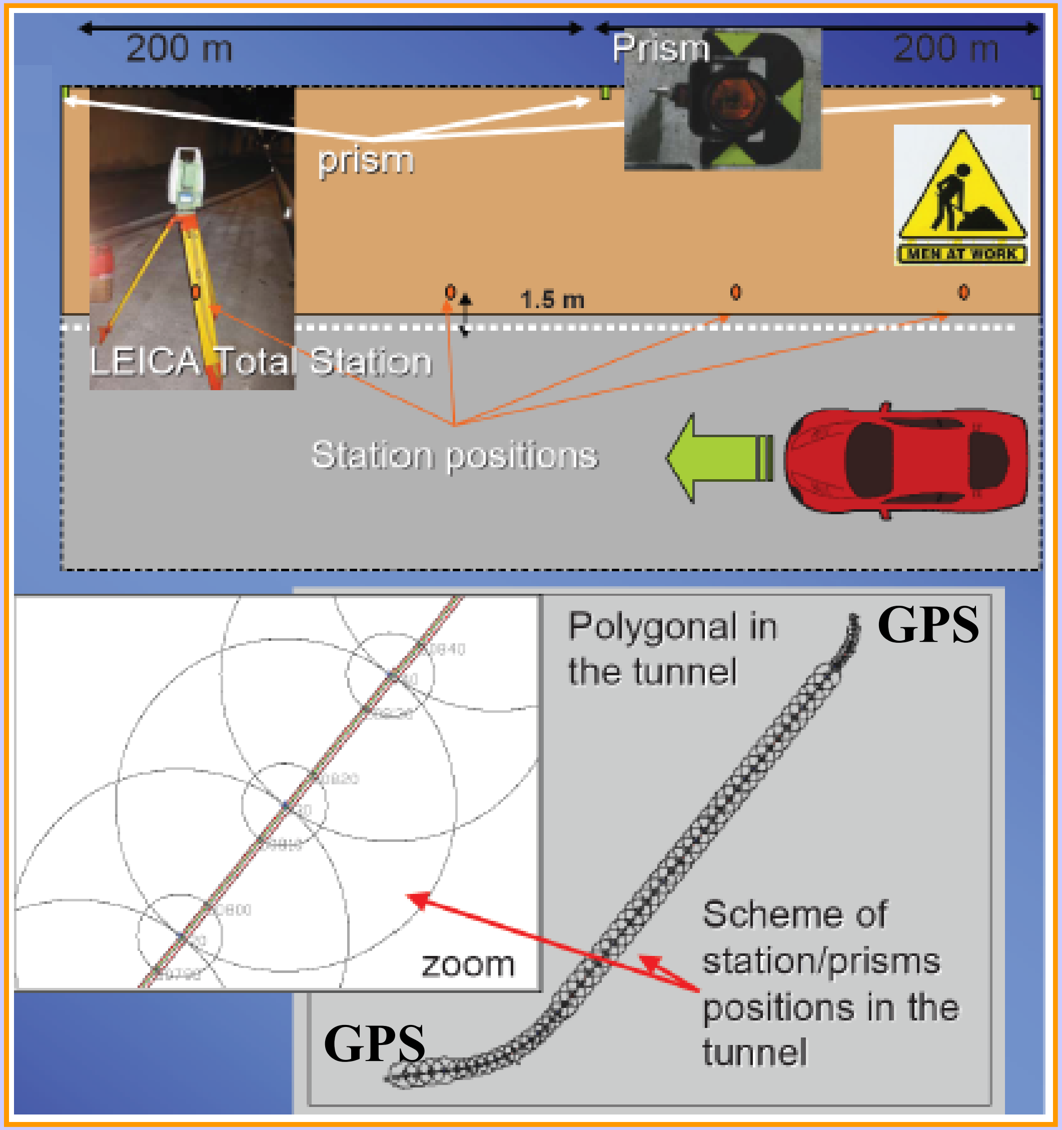
$t_{CERN} - t_{OPERA} = (2.3 \pm 0.9)$ ns

Summary of the Principle for the TOF Measurement



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

Geodesy at LNGS



- Dedicated measurements at LNGS: July-Sept. 2010

(Rome Sapienza Geodesy group)

- 2 new GPS benchmarks on each side of the 10 km highway tunnel

- GPS measurements ported underground to OPERA

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)

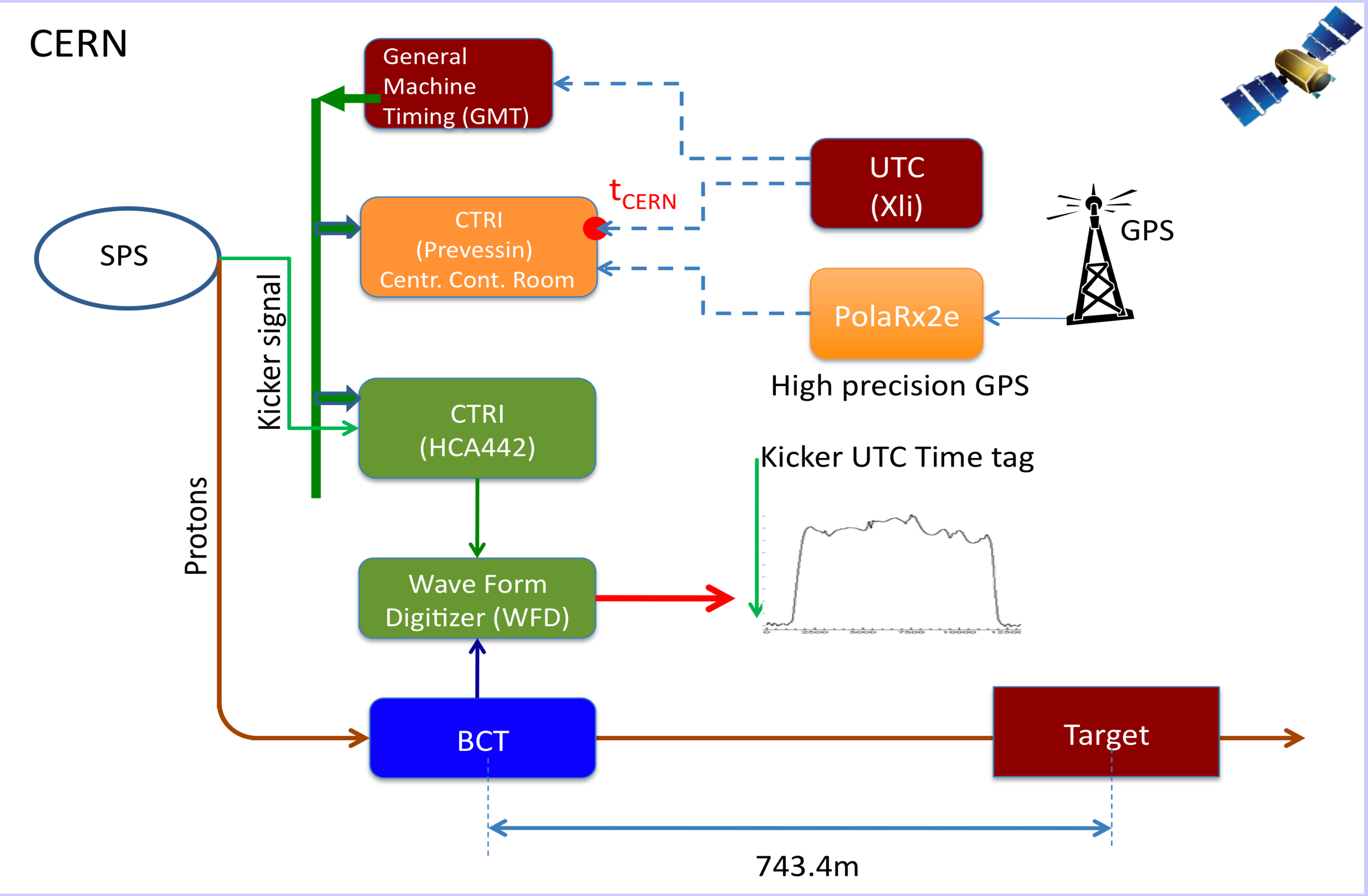
Benchmark	X (m)	Y (m)	Z (m)
GPS1	4579518.745	1108193.650	4285874.215
GPS2	4579537.618	1108238.881	4285843.959
GPS3	4585824.371	1102829.275	4280651.125
GPS4	4585839.629	1102751.612	4280651.236

LNGS benchmarks
In ETRF2000

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

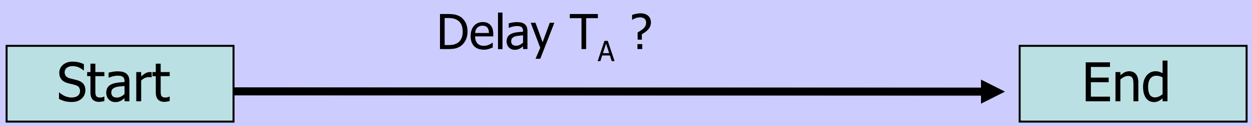
Resulting distance (BCT – OPERA reference frame)
(731278.0 ± 0.2) m

Overview CERN Timing

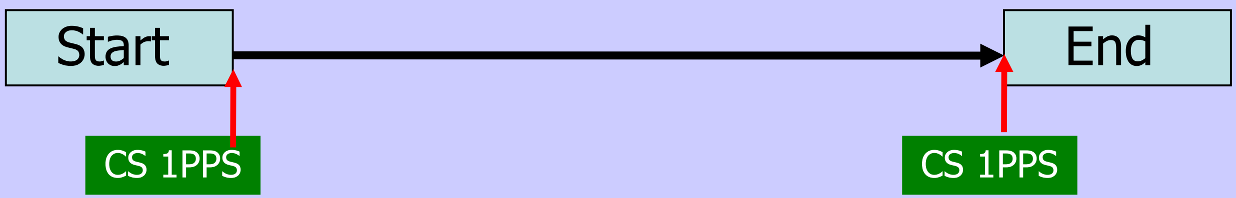


Time Calibration Techniques

- Portable Cs-4000:

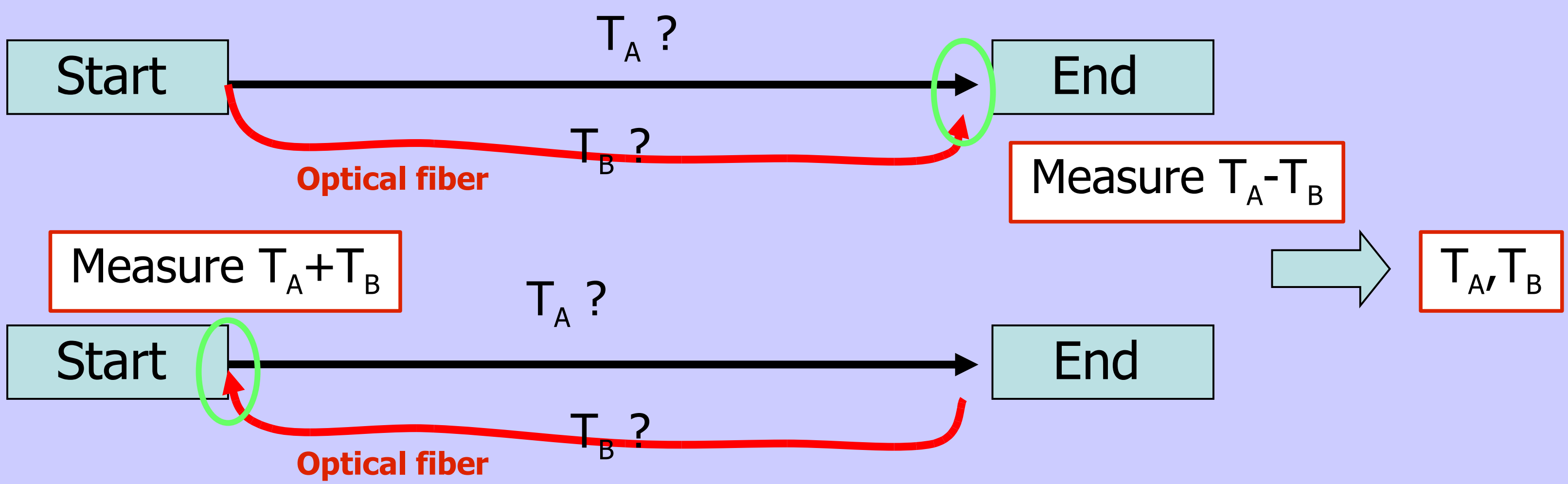


Comparison: time-tags vs 1PPS signal (Cs clock) at the start- and end-point of a timing chain



- Double path fibers measurement:

by swapping Tx and Rx component of the opto-chain



BCT Calibration

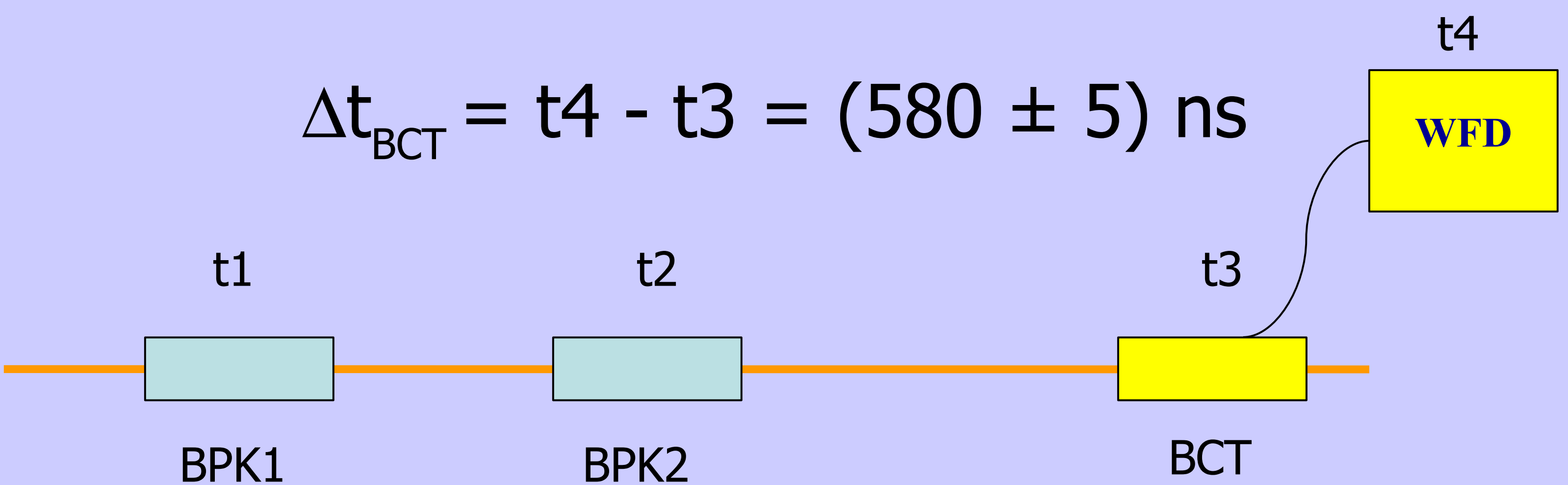
Delay between BCT and WFD:

- Standard Calibration Techniques (Oscilloscope+Cs-clock):

$$\Delta t_{BCT} = t4 - t3 = (581 \pm 10) \text{ ns}$$

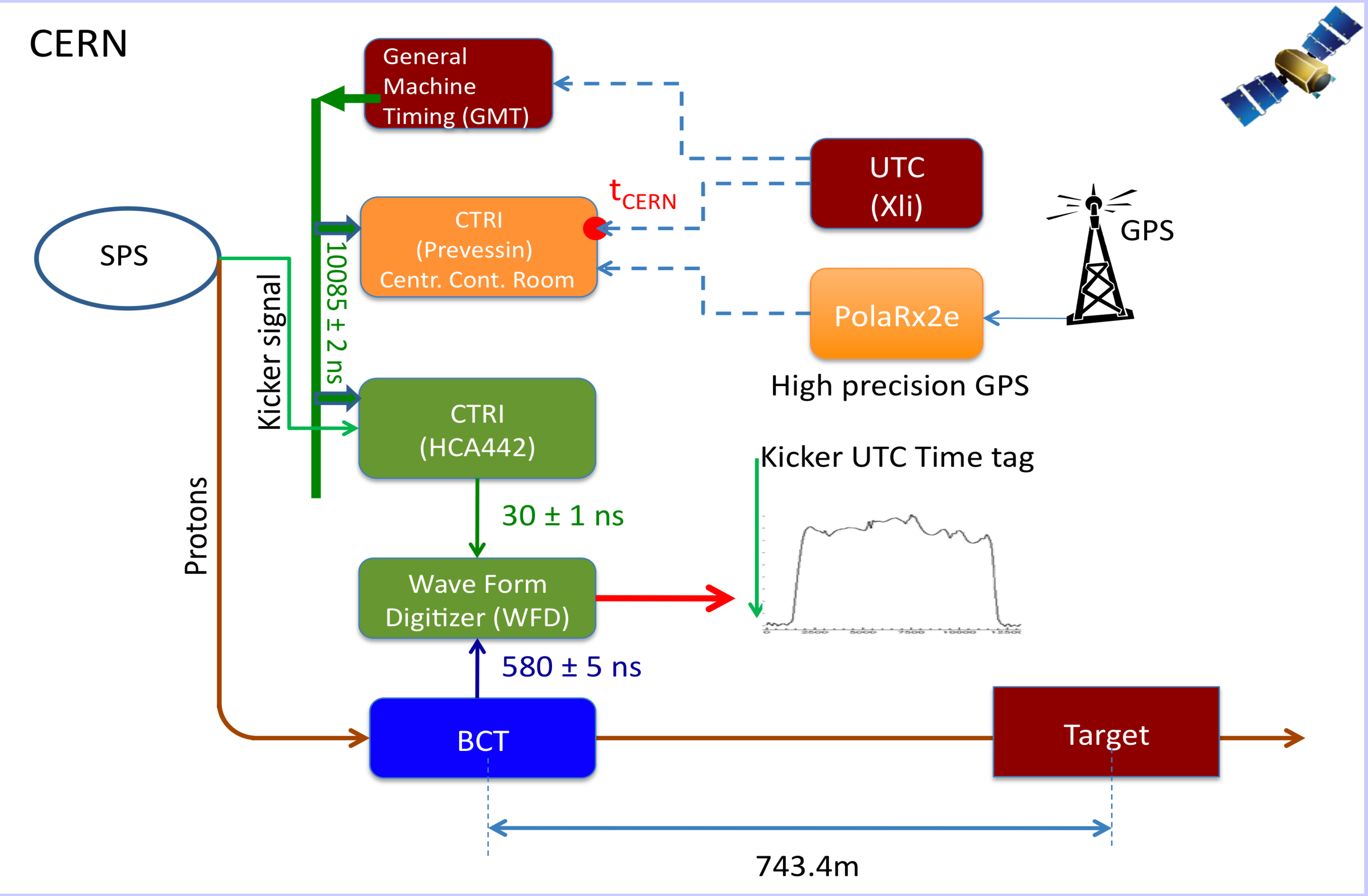
- Dedicated beam experiment:
  - BCT plus two beam pick-ups (BPK) with ~1 ns time response with LHC beam (12 bunches, 50 ns spacing)

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

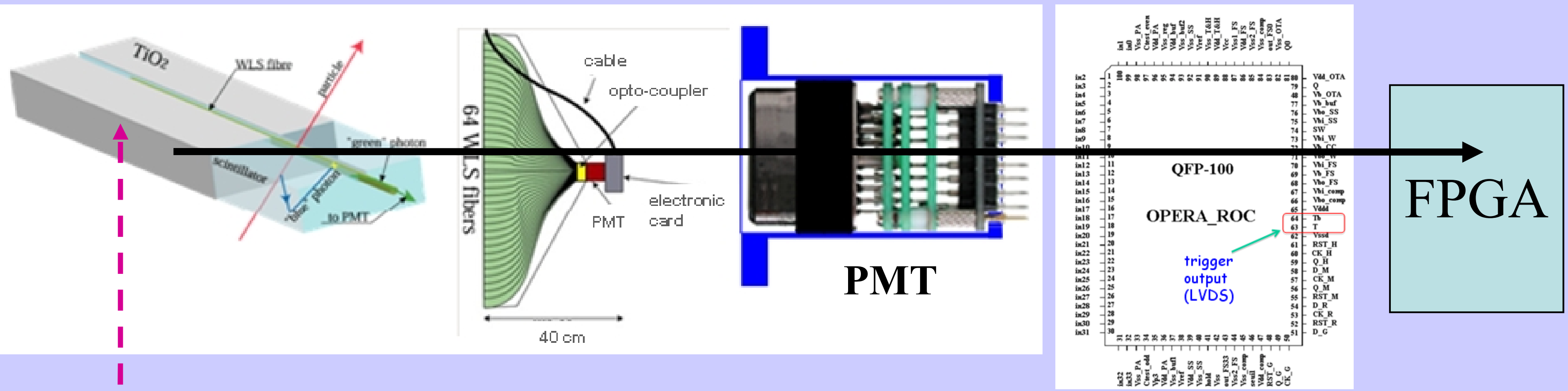


t3 : derived by (t1 - t2) measurement and extrapolation to BCT position

Overview CERN Timing



TT Time Response Measurement



Scintillator, WLS fibers, PMT, analog FE chip (ROC) up to FPGA trigger input

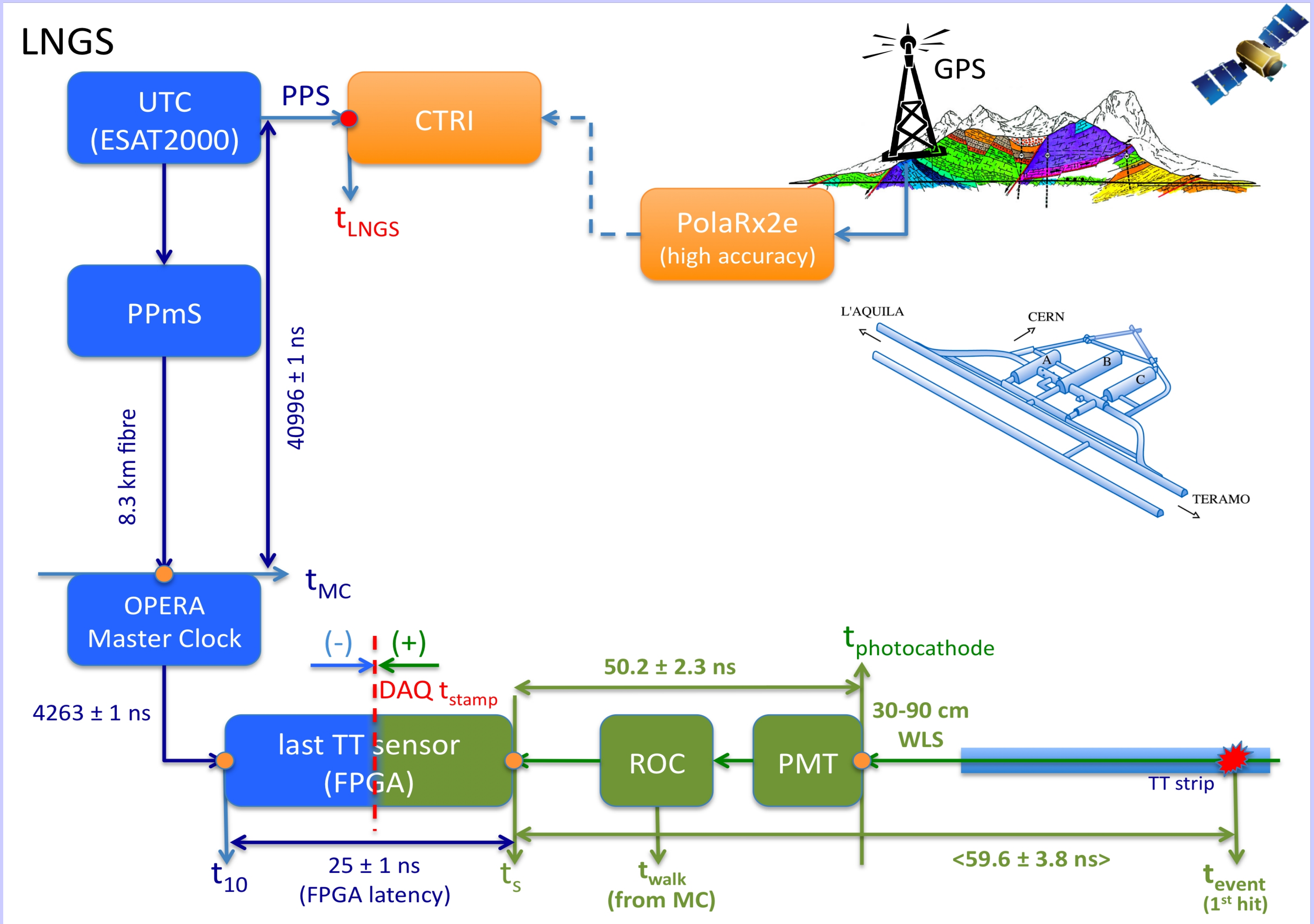
UV laser excitation:

→ 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)

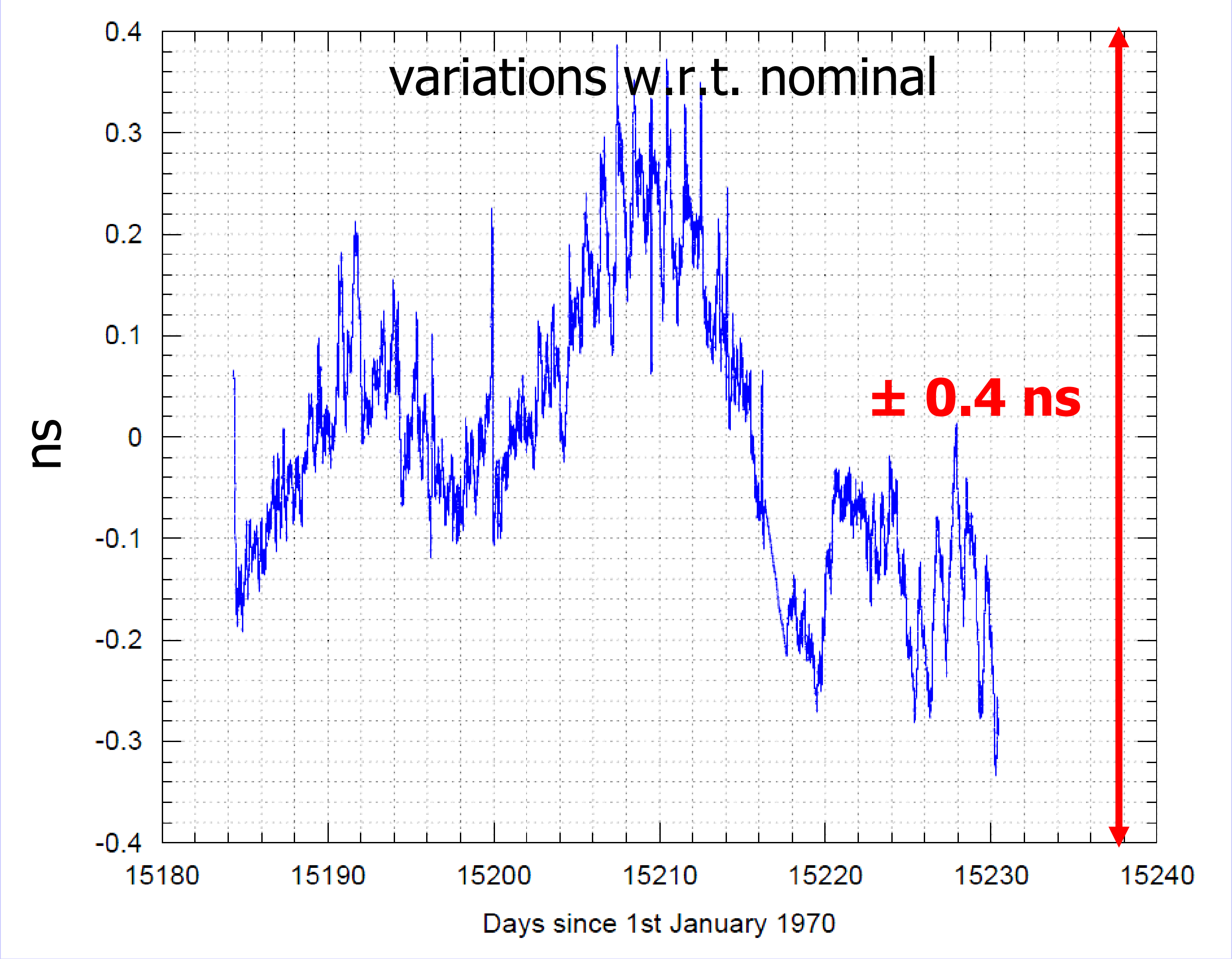
Overview LNGS Timing



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

Continuous Two-way Measurement of UTC Delay at CERN



Event Selection

Earliest TT hit of the event as "stop"

Individual Corrections:

- Time-link correction (synchronisation between CERN and LNGS)
- Position w.r.t common reference point (average correction: 140 cm ≈ 4.7 ns)

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

Internal Events:

Same selection procedure as for oscillation searches: 7586 events

External Events:

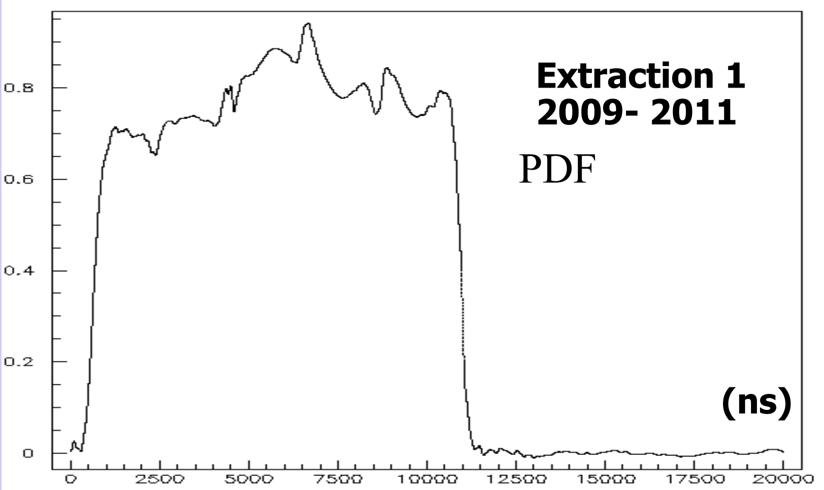
Rock interaction → require muon 3D track: 8525 events

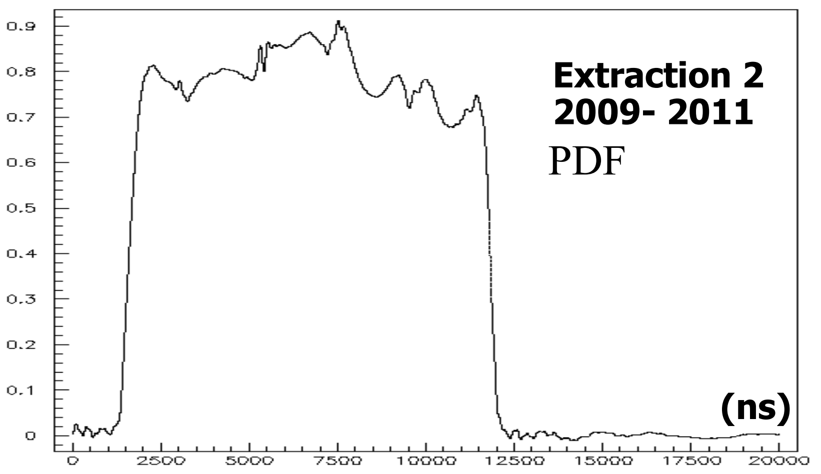
(Timing checked with full simulation, 2 ns systematic uncertainty by adding external events, otherwise agreement between data and MC)

Analysis Method

For each neutrino event in OPERA → proton extraction waveform (normalised)

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





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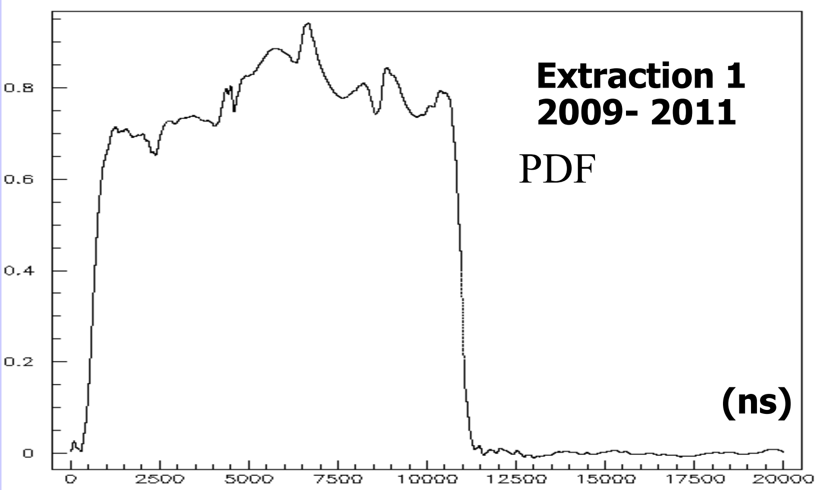

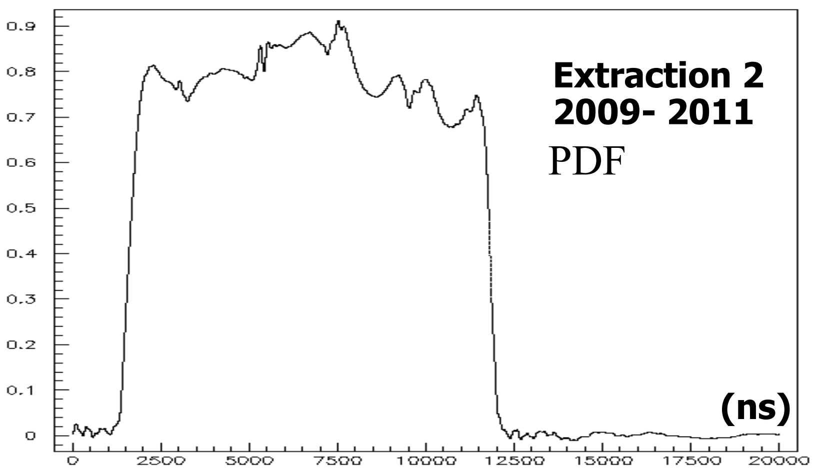

$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \qquad k=1,2 \text{ extractions}$$

(unbinned, 1 ns scan of δt)

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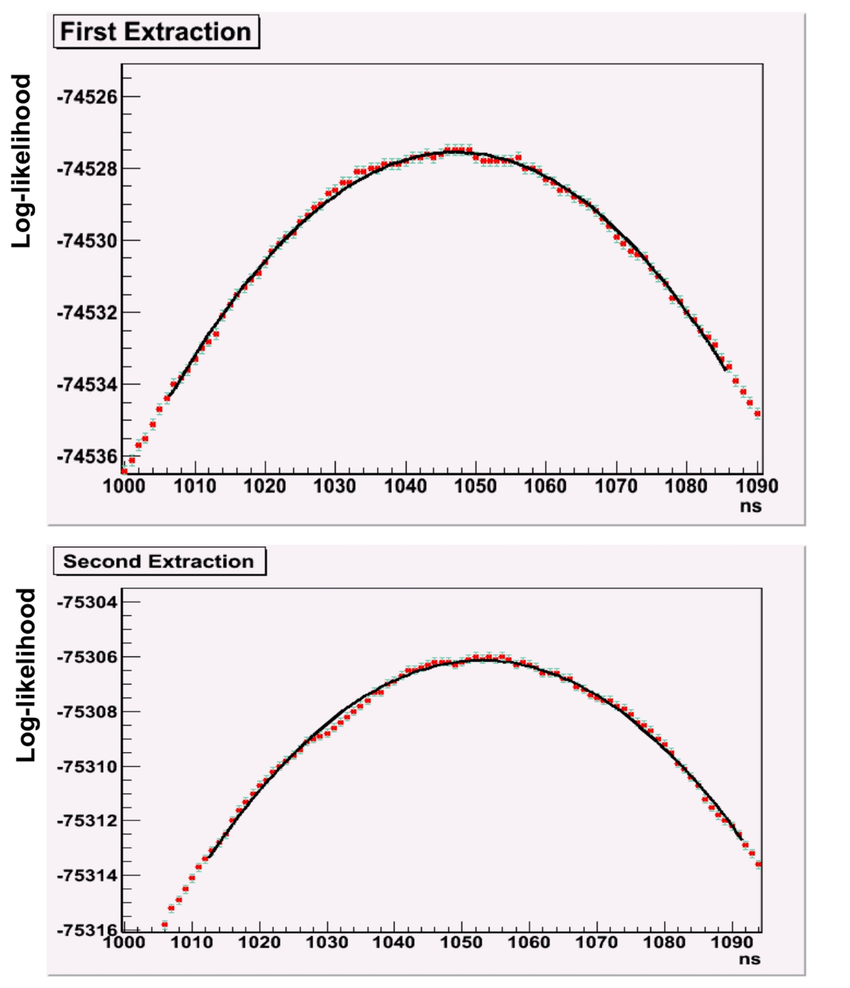


$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \qquad k=1,2 \text{ extractions}$$

(unbinned, 1 ns scan of δt)

<u>Maximised versus δt:</u>

$\delta t = TOF_c - TOF_\nu$

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

statistical error evaluated from log likelihood curves

Blind Analysis

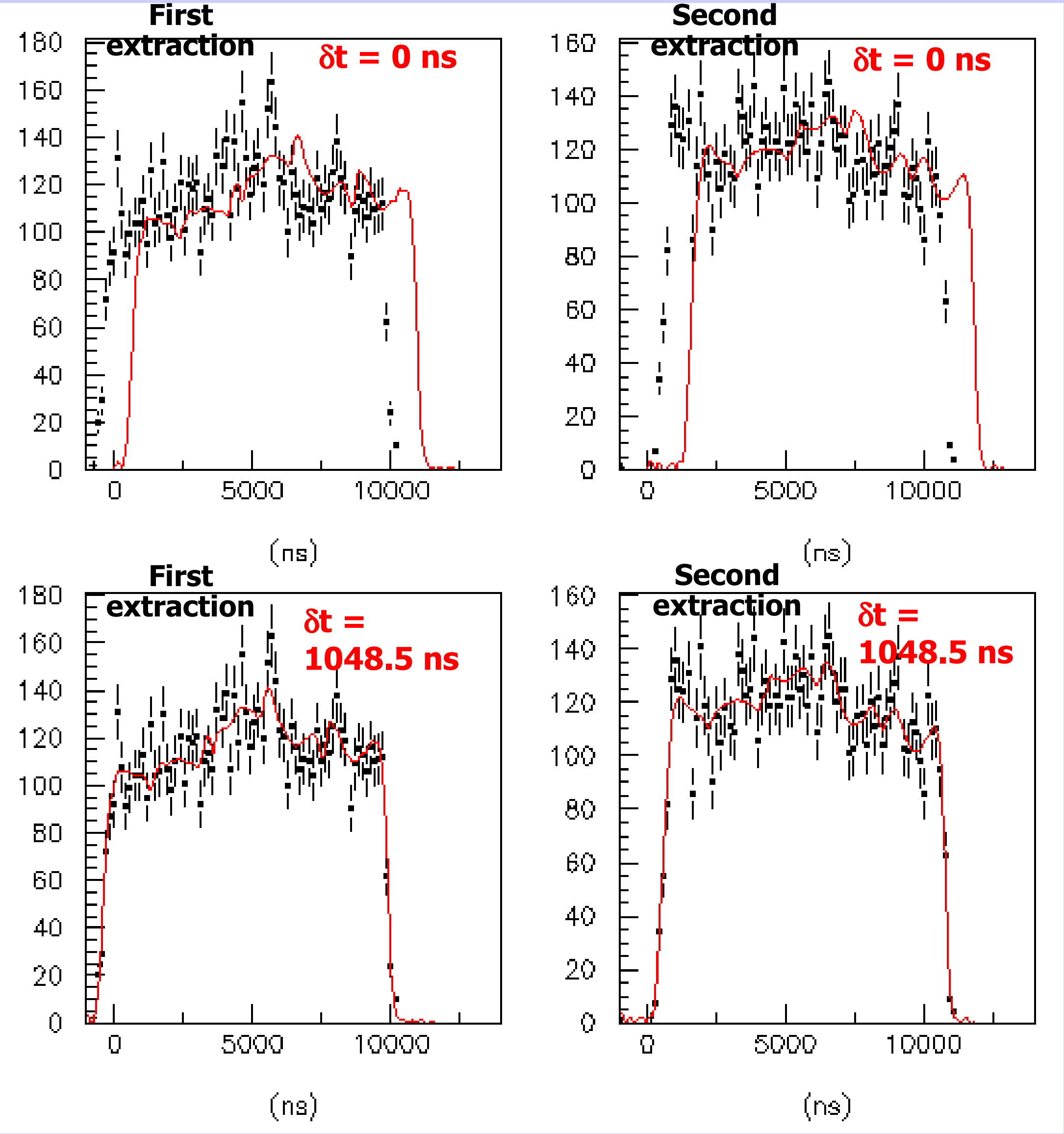
Analysis deliberately conducted by referring to the obsolete timing of 2006:

- Wrong baseline, referred to an upstream BCT in the SPS, ignoring accurate geodesy
- Ignoring TT and DAQ time response in OPERA
- Using old GPS inter-calibration prior to the time-link
- Ignoring the BCT and WFD delays
- 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) $\delta t = TOF_c - TOF_\nu =$

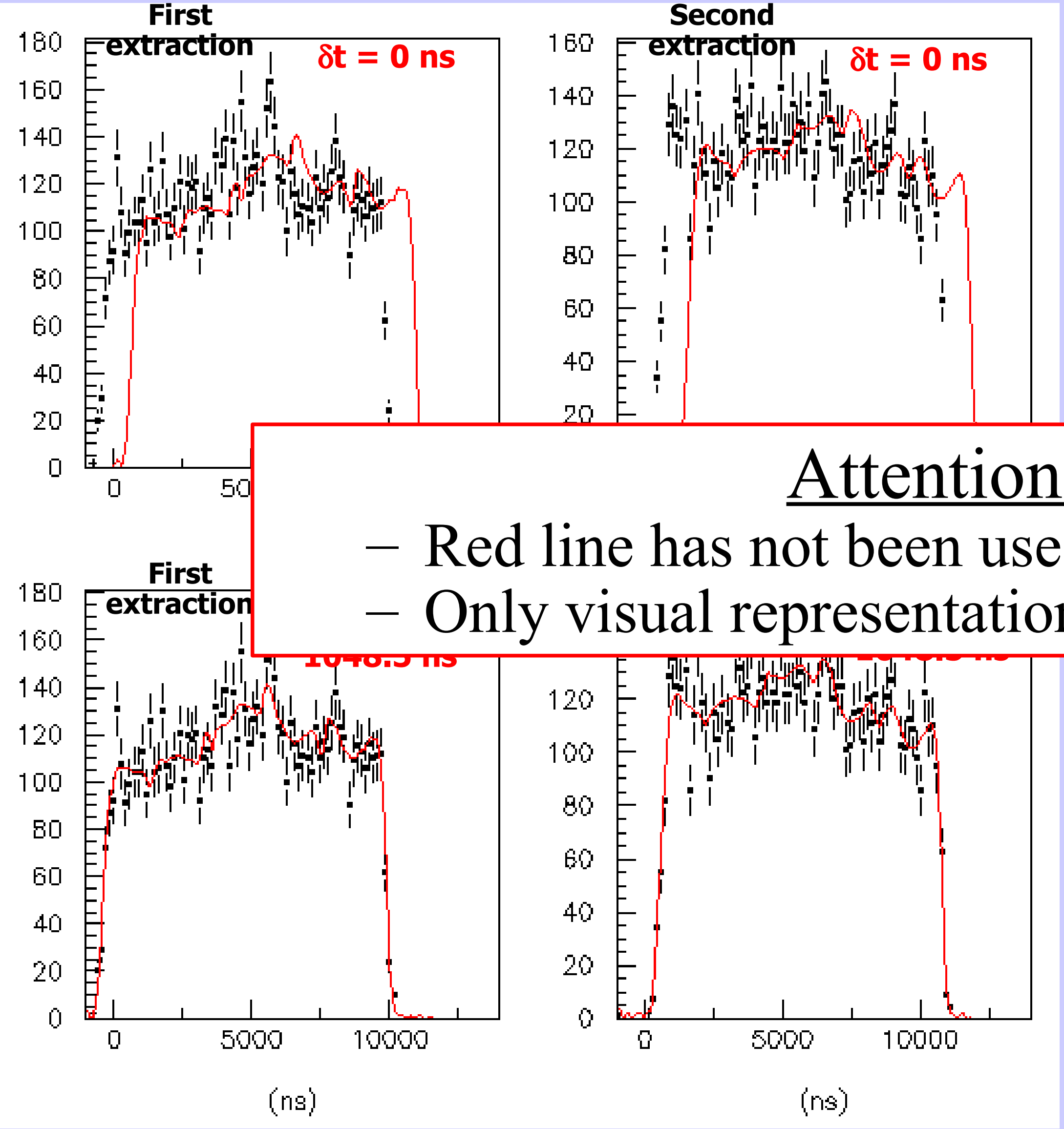
(1048.5 ± 6.9) ns (stat)

χ^2 / ndof :

first extraction: 1.06

second extraction: 1.12

Data vs PDF: Before and After Likelihood Result



Attention:

- Red line has not been used to extract δt
- Only visual representation of the agreement

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

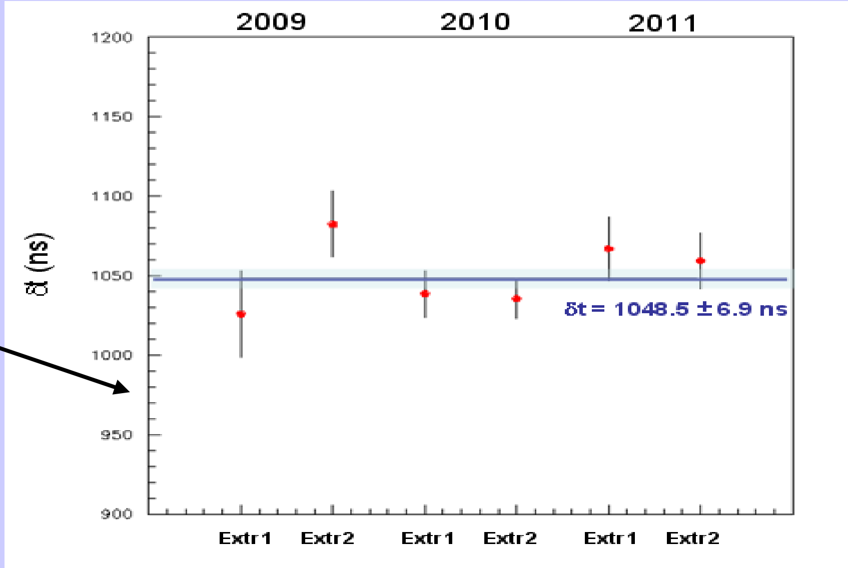
(1048.5 ± 6.9) ns (stat)

first extraction: 1.06

second extraction: 1.12

Analysis Cross-checks

- Coherence among CNGS runs/extractions



- 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

- Internal vs external events:
  - All events: δt (blind) = TOF_c - TOF_ν = (1048.5 ± 6.9 (stat.)) ns
  - Internal events only: δt (blind) = (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:

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

$(1048.5 \pm 6.9\ (\text{stat.}))\ \text{ns} - 987.8\ \text{ns} = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))\ \text{ns}$

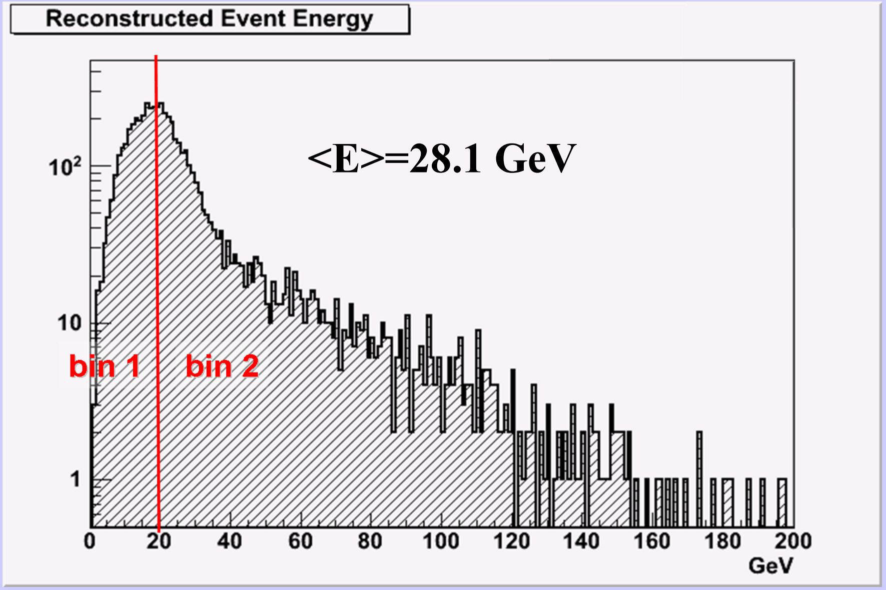
Relative difference of neutrino velocity w.r.t. c:

$(v-c)/c = \delta t / (TOF_c - \delta t) = (2.49 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.})) \times 10^{-5}$

(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)

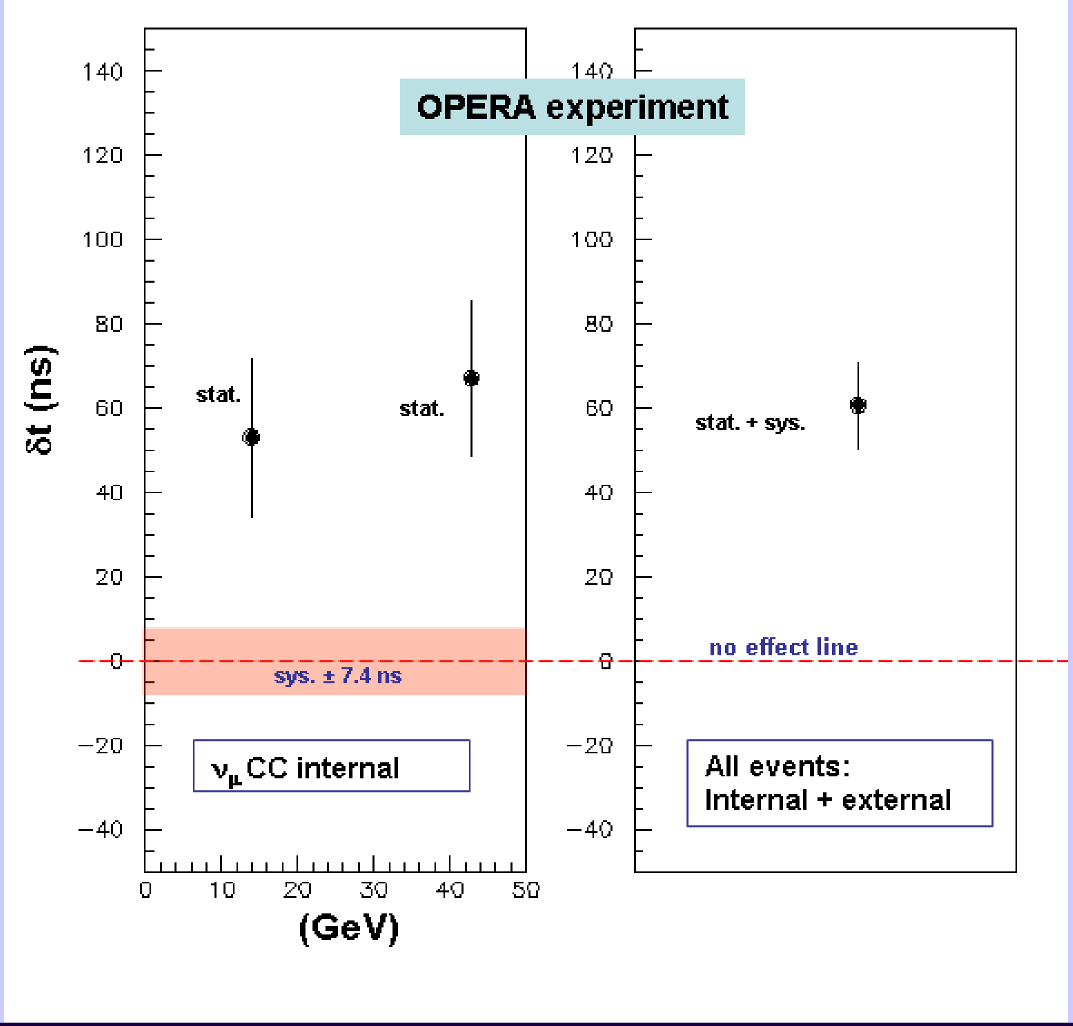
  $\rightarrow$ Systematic errors cancel out

$\delta t = TOF_c - TOF_\nu = (60.3 \pm 13.1\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ ns for $\langle E_\nu \rangle = 28.1$ GeV

(Result limited to events with measured energy)

Study of the Energy Dependence

No clues for energy dependence within the present sensitivity in the energy domain explored by the measurement



Additional Considerations:

Effects of Relativity

- Rotation of the Earth

→ Sagnac Effect: a few ns, to be confirmed

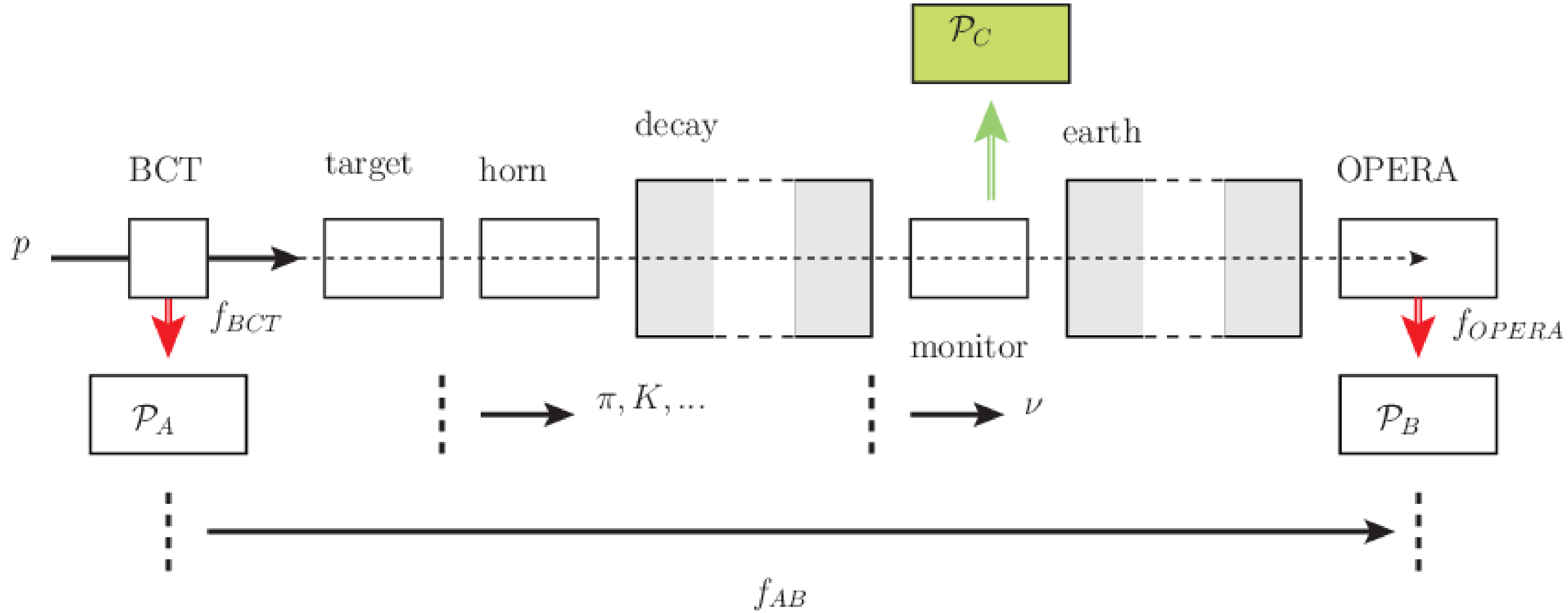
- Gravitational field of Earth

→ relative effect on Schwartzschild geodesics: 10^{-8}

- Different gravitational potential at CERN and LNGS

→ red-shift, relative effect on synchronisation: 10^{-13}

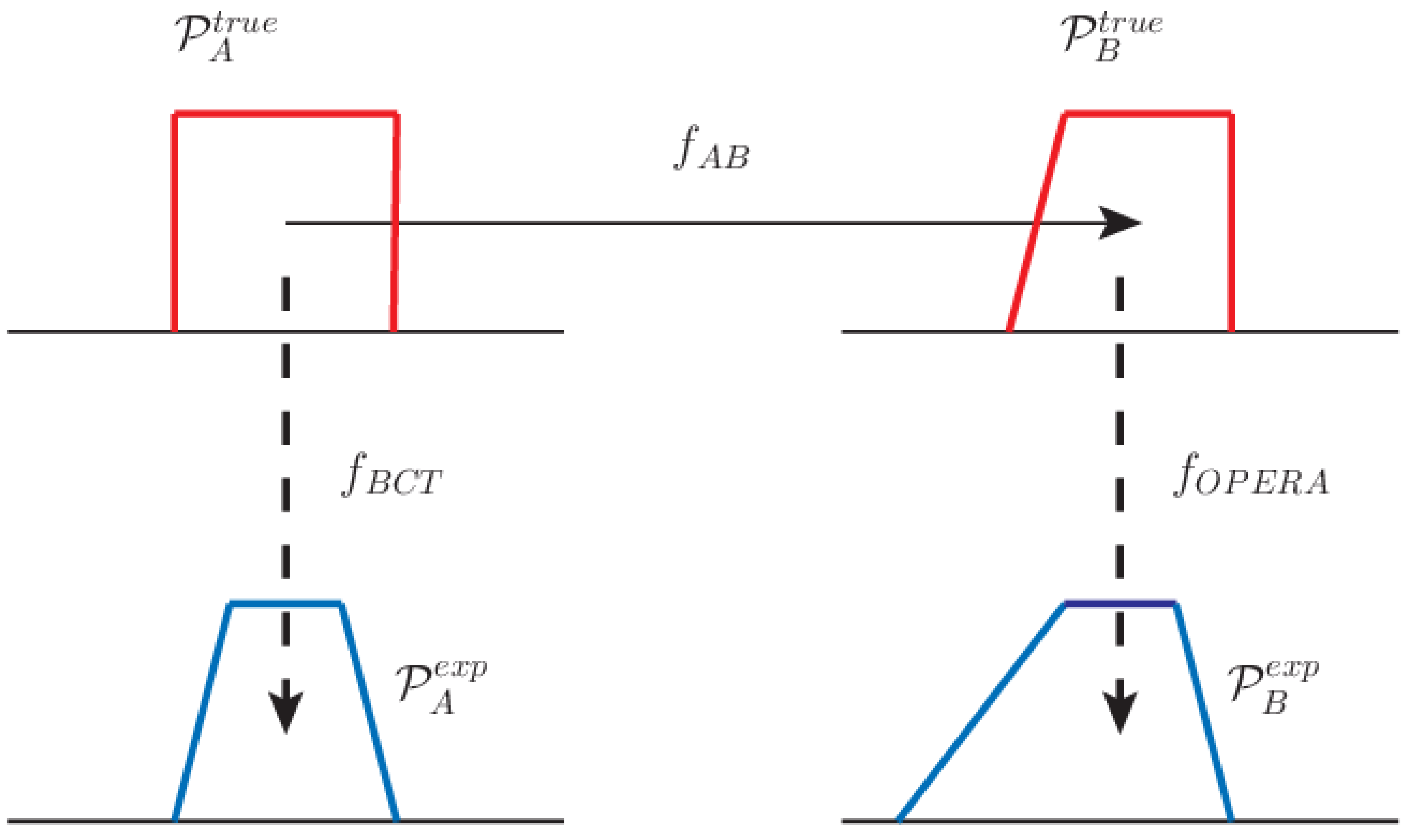
From Proton Spill to Neutrino Time Distribution



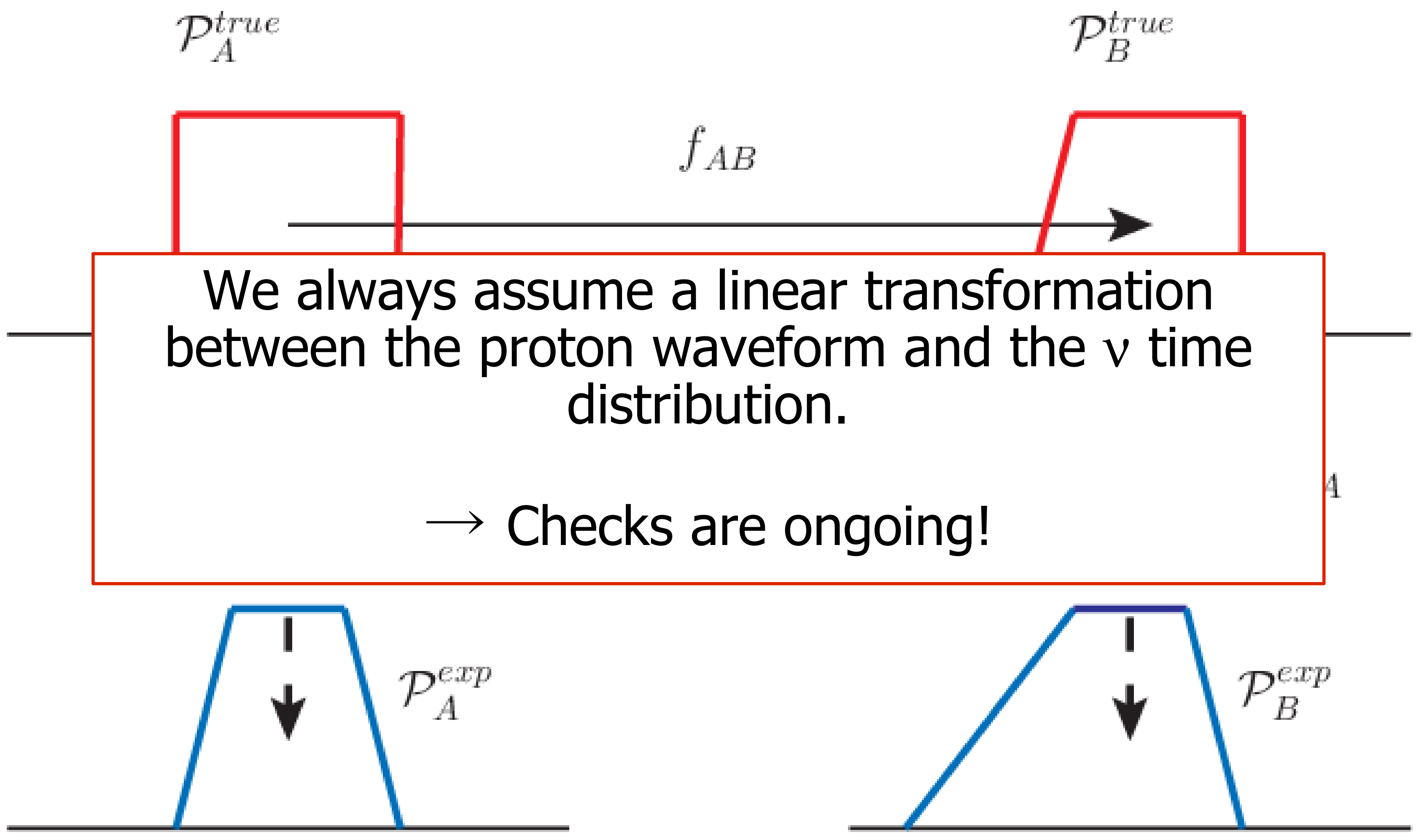
Are their any unknown systematics here?

If yes: Take care of them or introduce systematical error on fit!

From Proton Spill to Neutrino Time Distribution



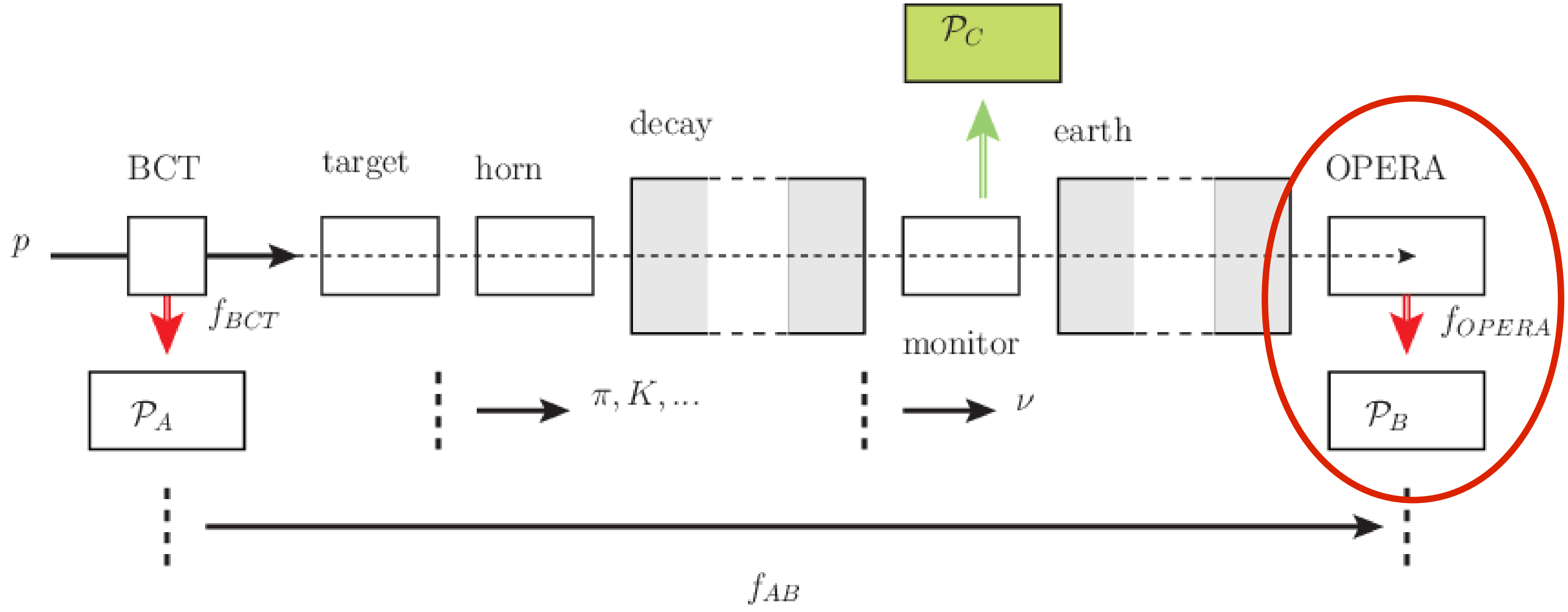
From Proton Spill to Neutrino Time Distribution



We always assume a linear transformation between the proton waveform and the ν time distribution.

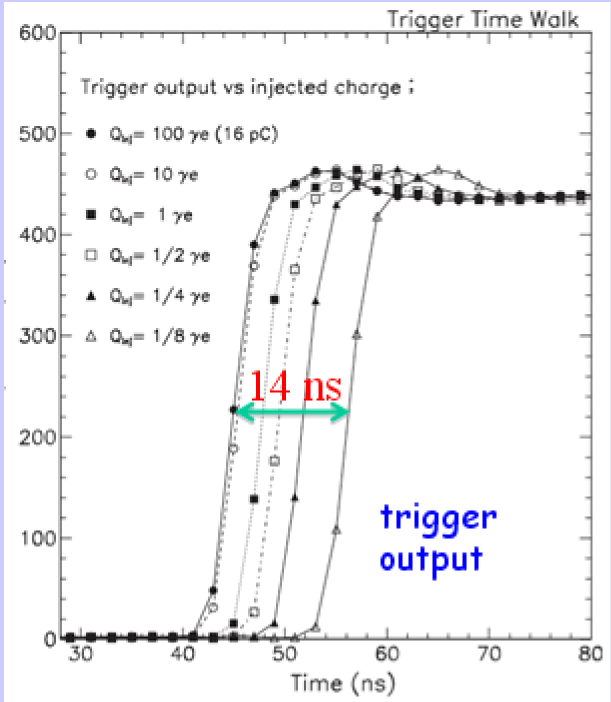
→ Checks are ongoing!

OPERA Detector Timing

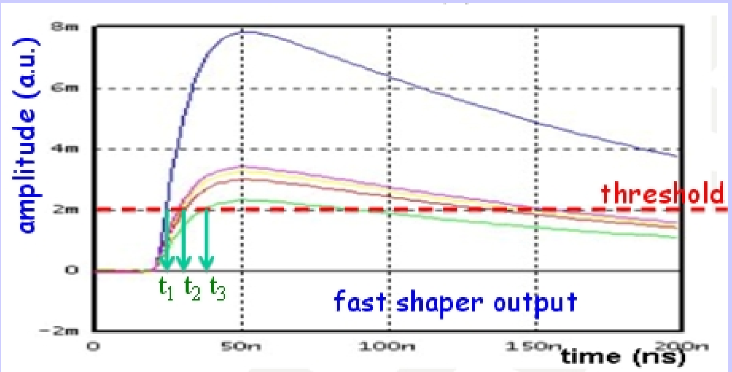


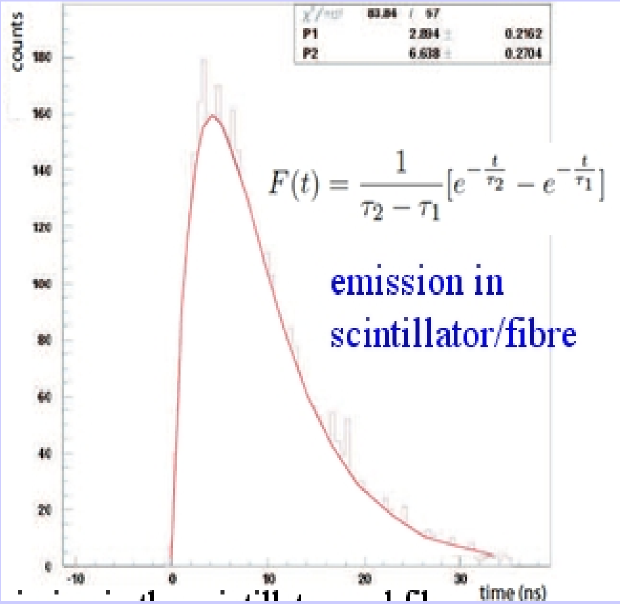
Target Tracker Simulation

Full GEANT simulation of detector response with detailed geometry and time response parametrization from experimental measurements



Trigger threshold time walk

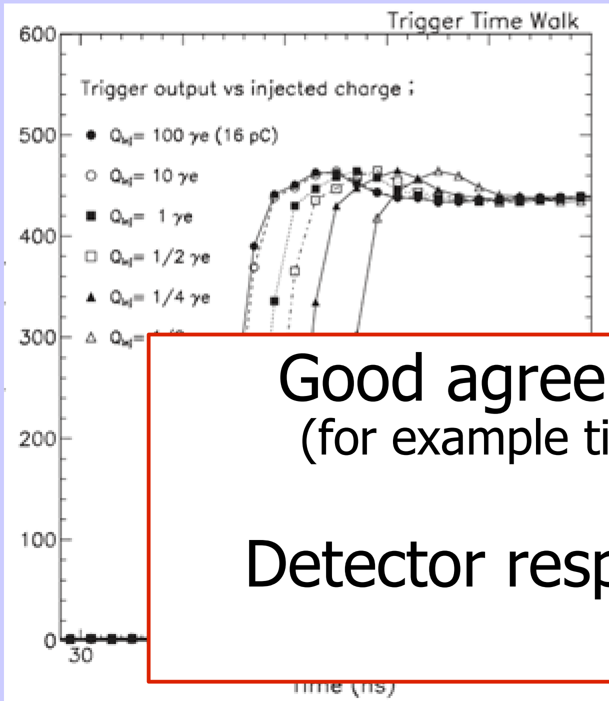




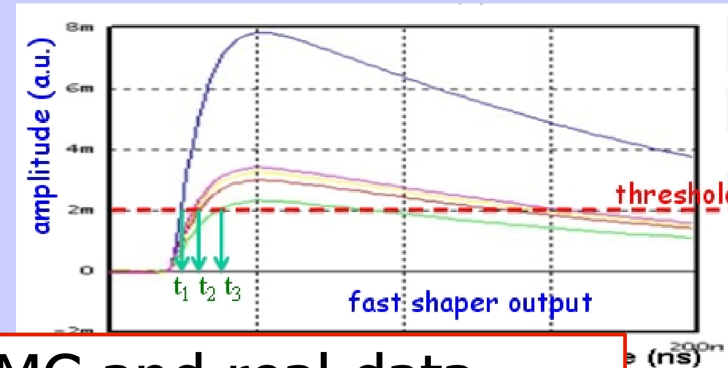
Arrival time distributions of photons on the phototcatode

Target Tracker Simulation

Full GEANT simulation of detector response with detailed geometry and time response parametrization from experimental measurements

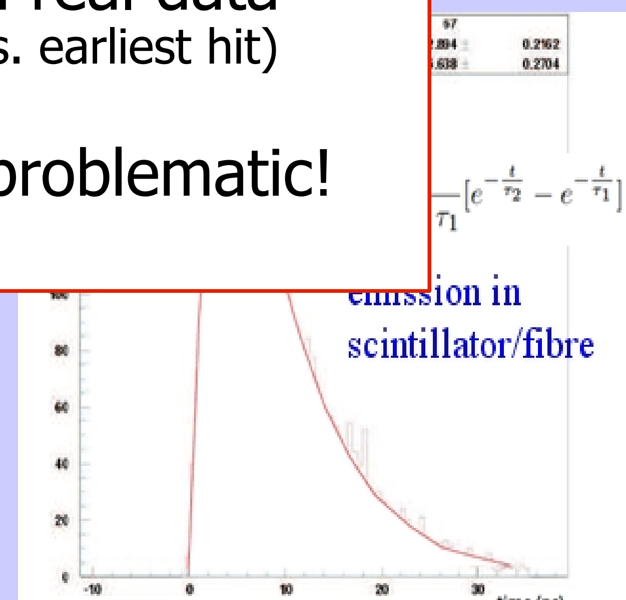


Trigger
threshold
time walk



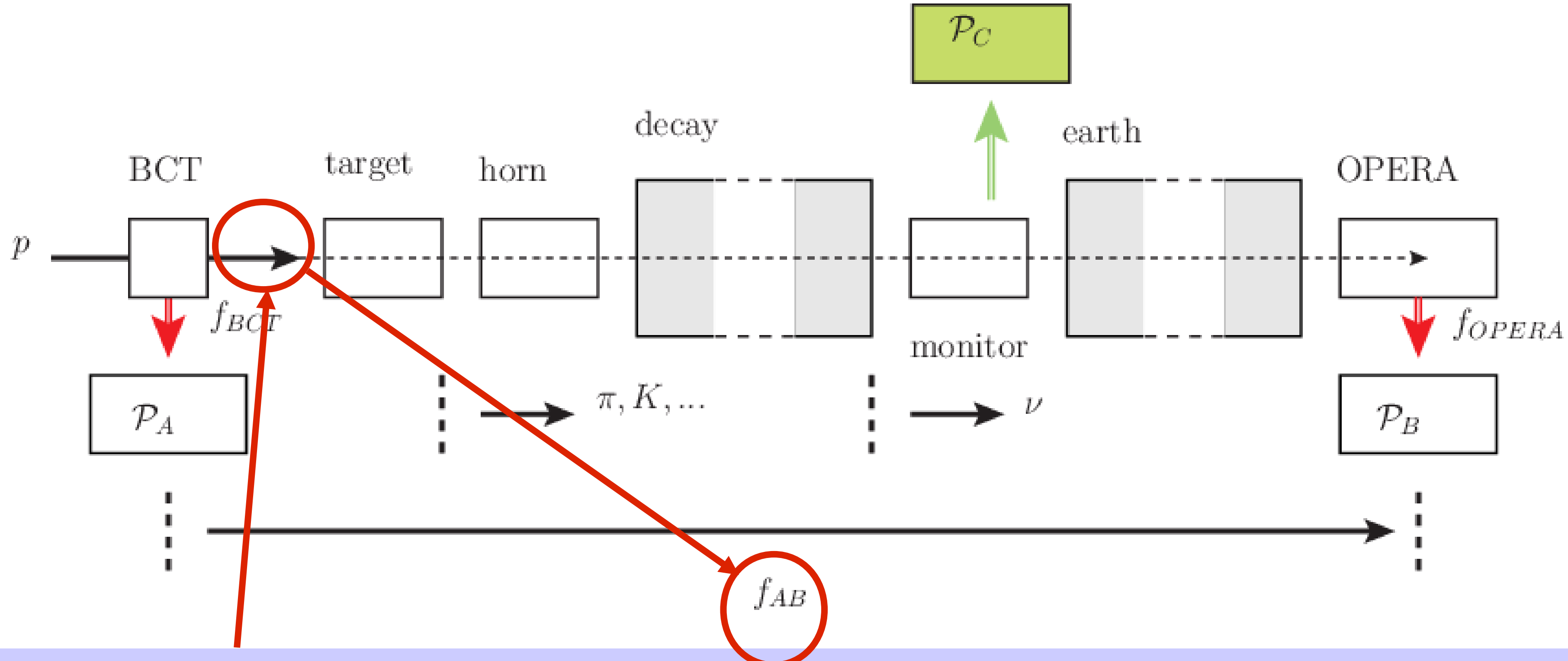
Good agreement between MC and real data
(for example time of reconstructed vertex vs. earliest hit)

Detector responds seems to be unproblematic!



Arrival time distributions of
photons on the phototcatode

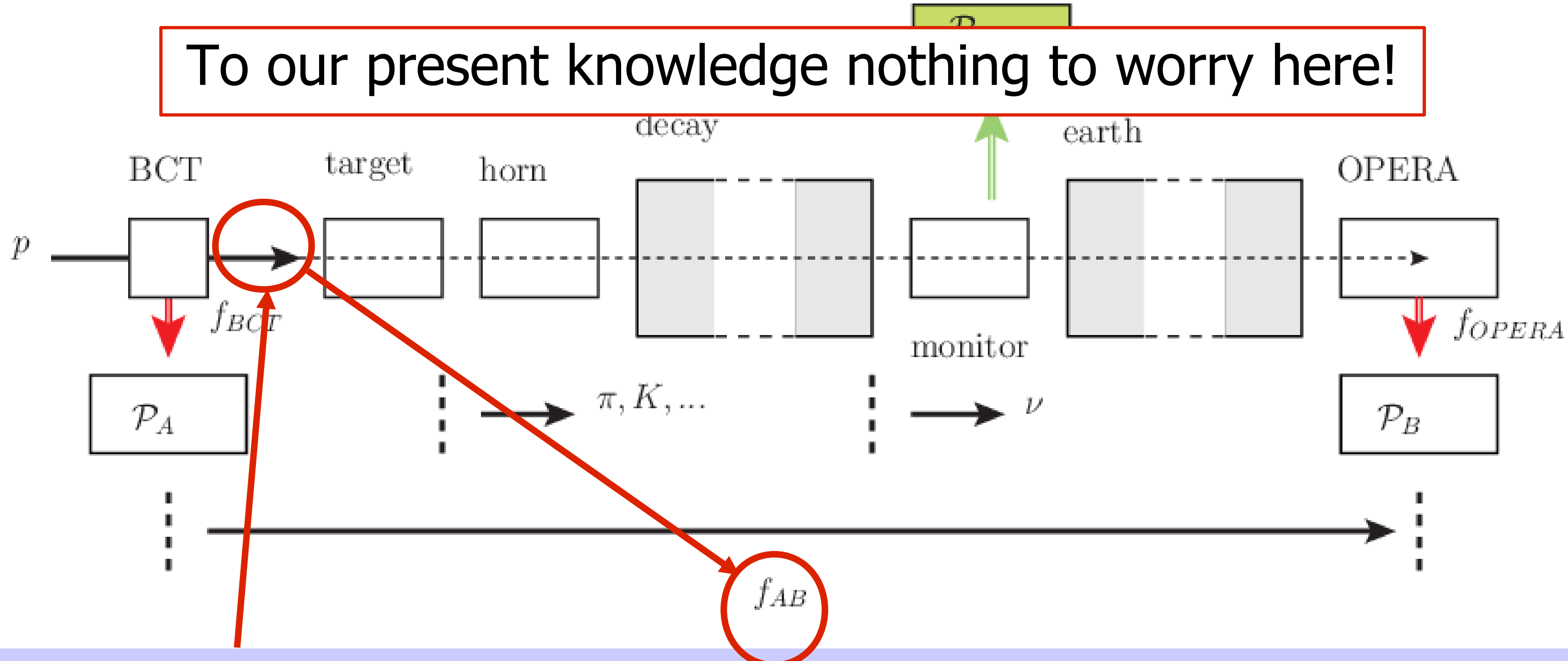
Effects from the Beam



- No acceleration between BCT and target
- Only magnetic beam transfer
- Transfer practically lossless

Effects from the Beam

To our present knowledge nothing to worry here!



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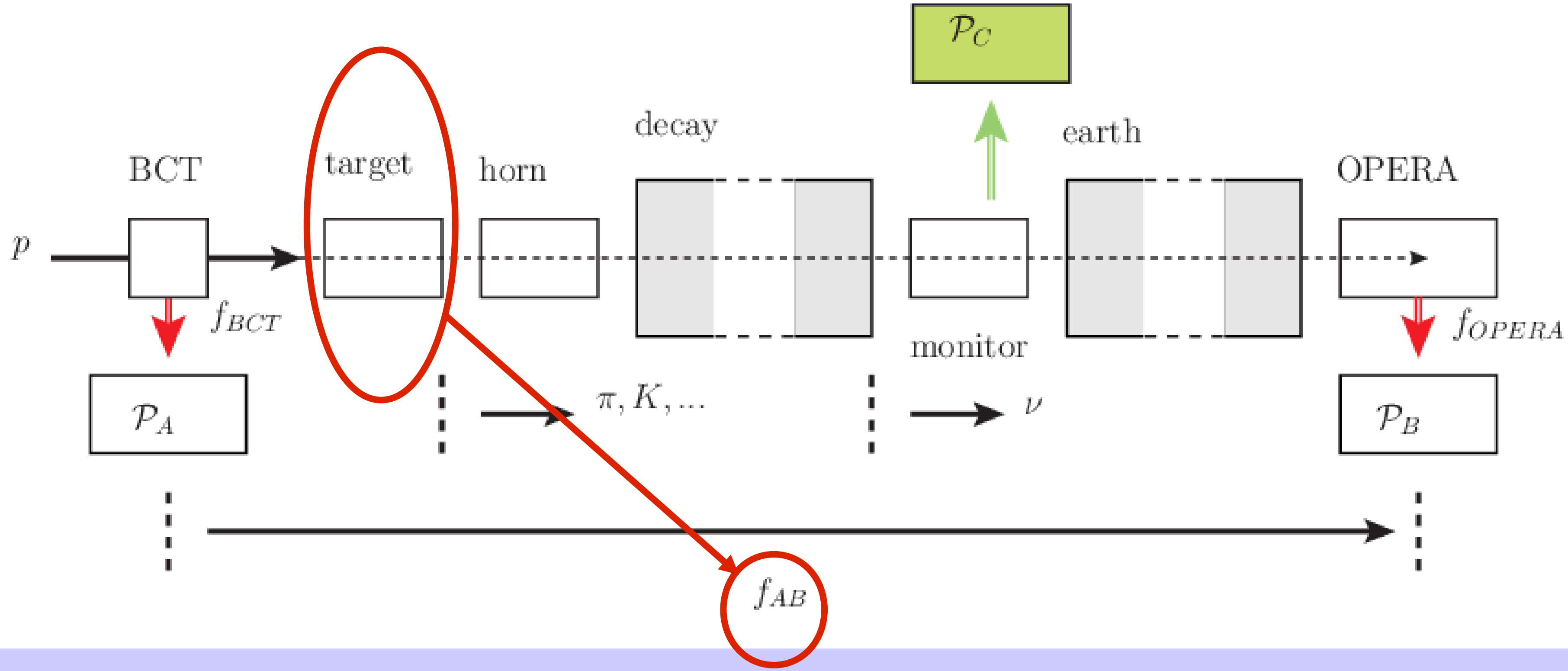
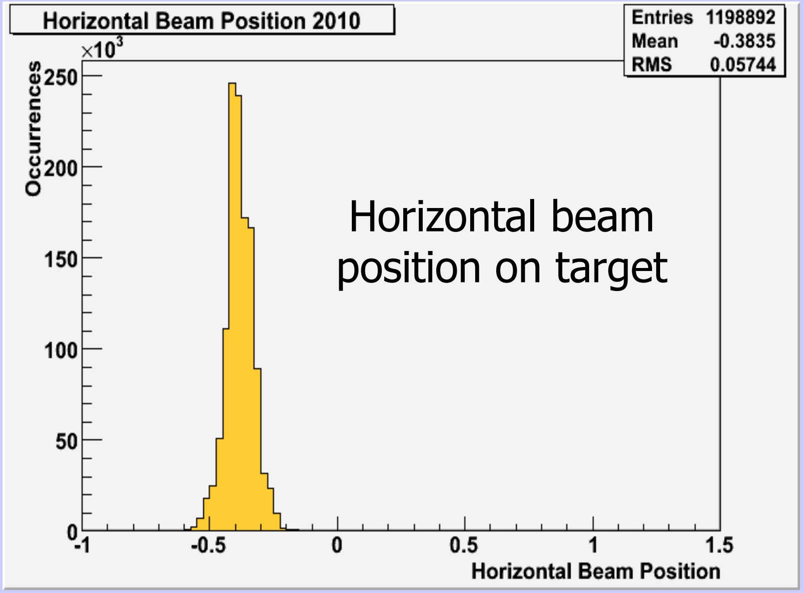
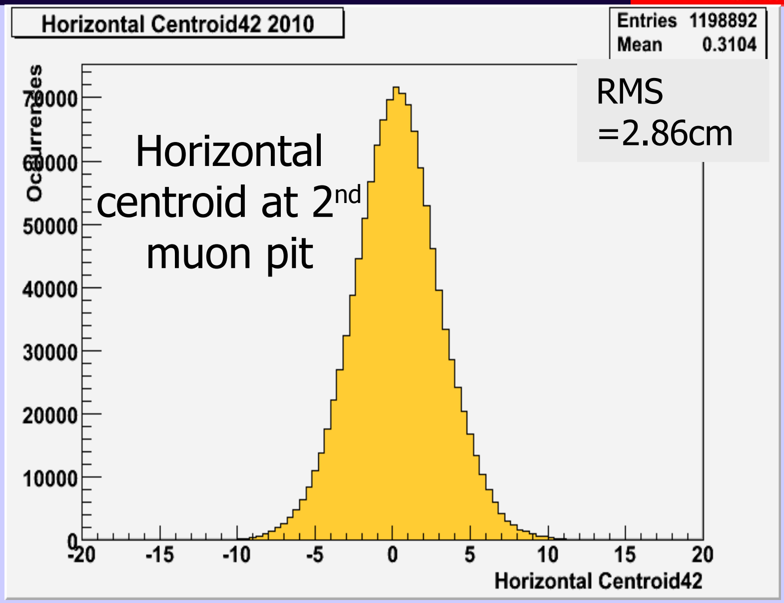
Effects from the Beam



Beam Stability

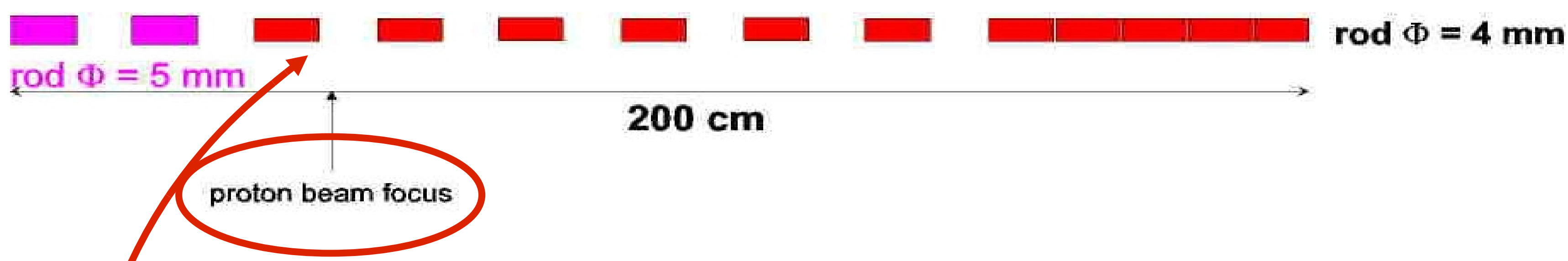




- Beam accurately aimed at center
- Excellent position stability : 50 (90) μm RMS on horizontal (vertical) position

→ Position stability of muon beam in 2nd pit is ~2-3cm rms

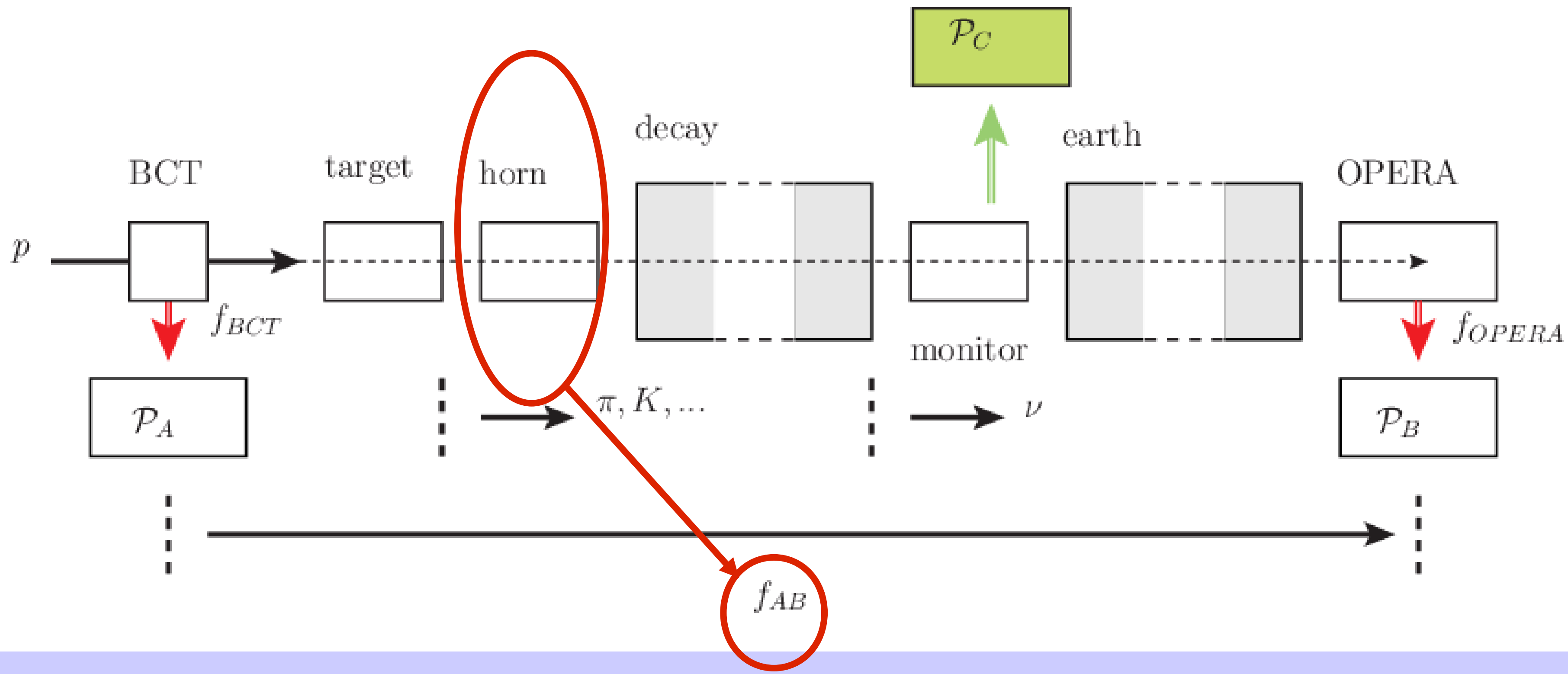
Temperature Effects in Target



13 graphite rods: 10 cm long with 9cm spacing

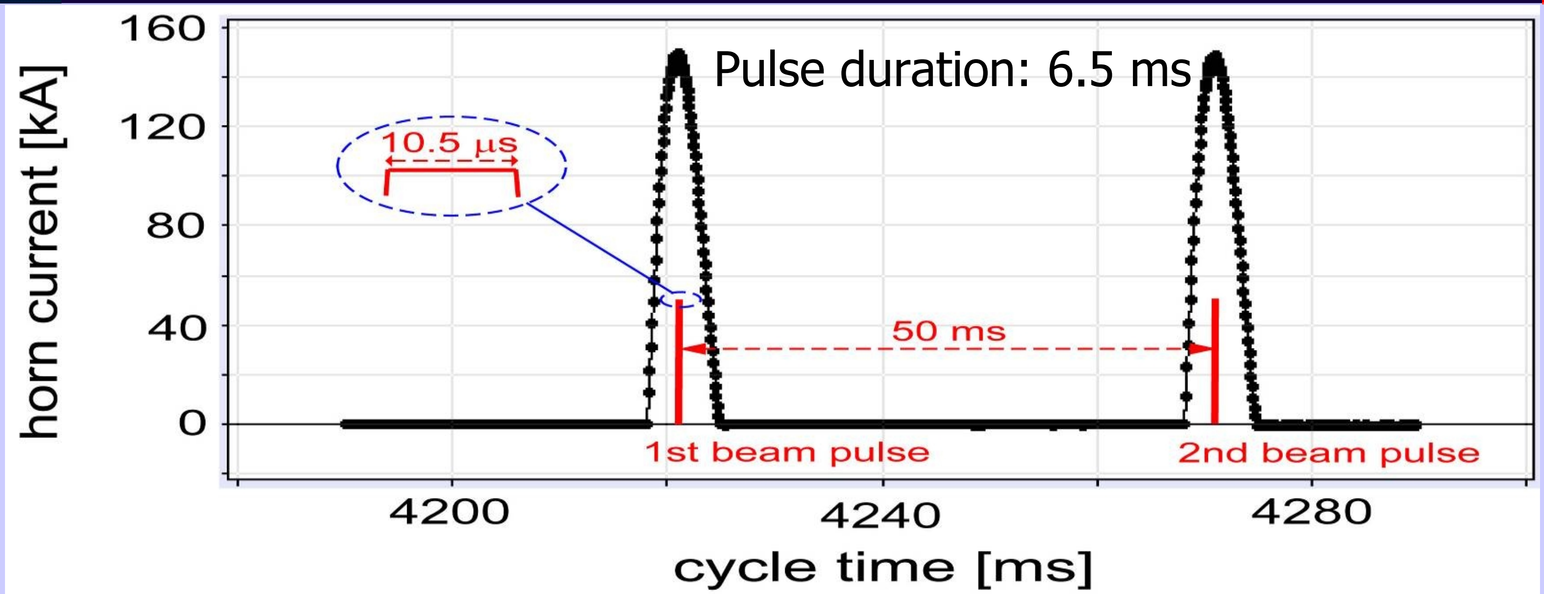
- FLUKA+BIG2 (2d hydrodynamic code) simulation done
- Density variation due to heating during extraction negligible

(max 0.3% → small displacement of interaction point, but the target has 3.3 λ)



Horn & Reflector

Current of Horn/Reflector Power System

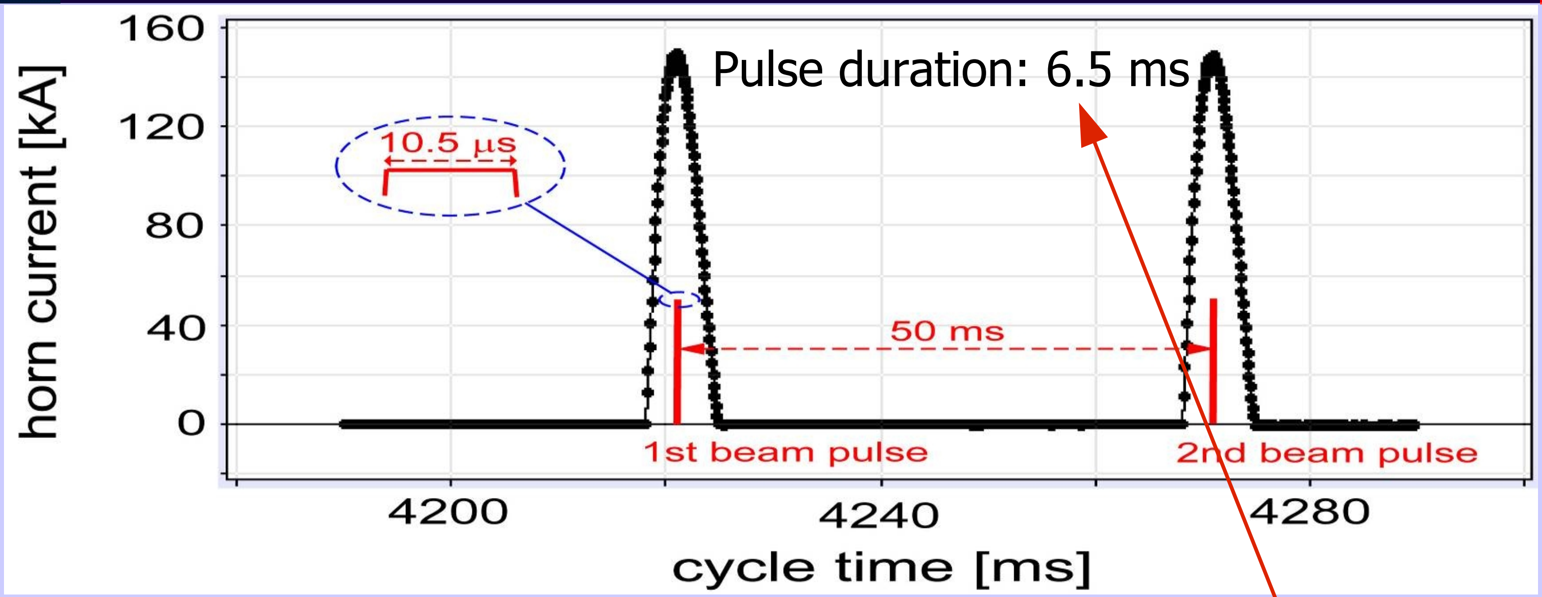


- Continuously monitored
- Test: Shift pulse by 100 μs

$\rightarrow$ Decrease of muon flux < 1%

$\rightarrow$ Pulse timing does not affect ν timing

Current of Horn/Reflector Power System



10 ms for reflector

- Continuously monitored
- Test: Shift pulse by 100 μs

$\rightarrow$ Decrease of muon flux < 1%

$\rightarrow$ Pulse timing does not affect ν timing

Statistical Considerations

Several additional statistical tests performed

- χ^2-test for different ranges of distribution (front, back, central, total)
  - ~90% of information in flanks
  - All results in good agreement
  - No systematic effect visible within statistical accuracy
  - No deviation of χ^2 residuals over the range of the time distribution visible
- Goodness of fit for maximum likelyhood method also well within expectations
- Kolmogorov-Smirnov test
  - High probabilities for both with and without 60 ns
  - Higher for 60 ns

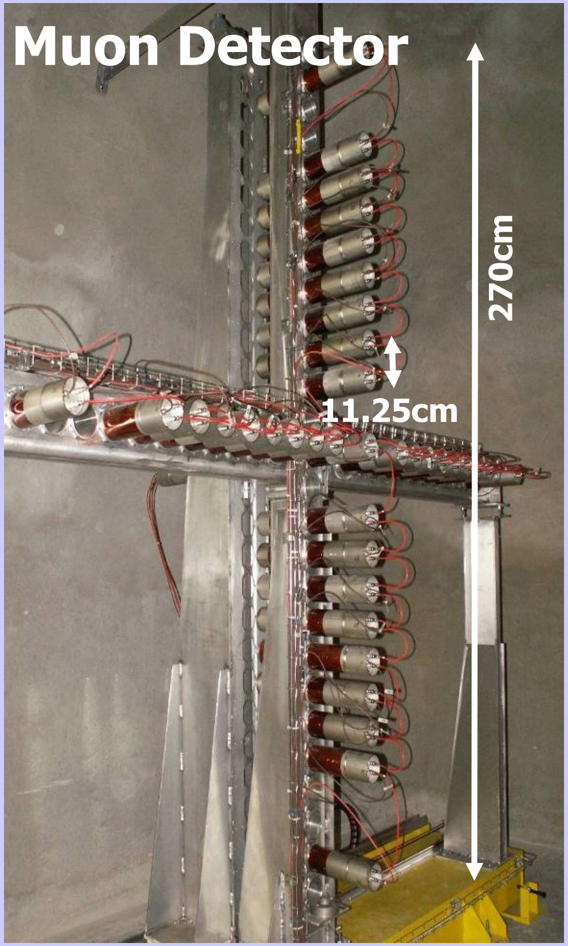
Statistical Considerations

Several additional statistical tests performed

- χ^2-test for different ranges of distribution (front, back, central, total)
  - ~90% of information in flanks
  - All results in good agreement
  - No systema
  - No deviatio stribution visible
- Goodness of fit for maximum likelyhood method also well within expectations
- Kolmogorov-Smirnov test
  - High probabilities for both with and without 60 ns
  - Higher for 60 ns

More tests ongoing!

Time Distribution in Muon Pit



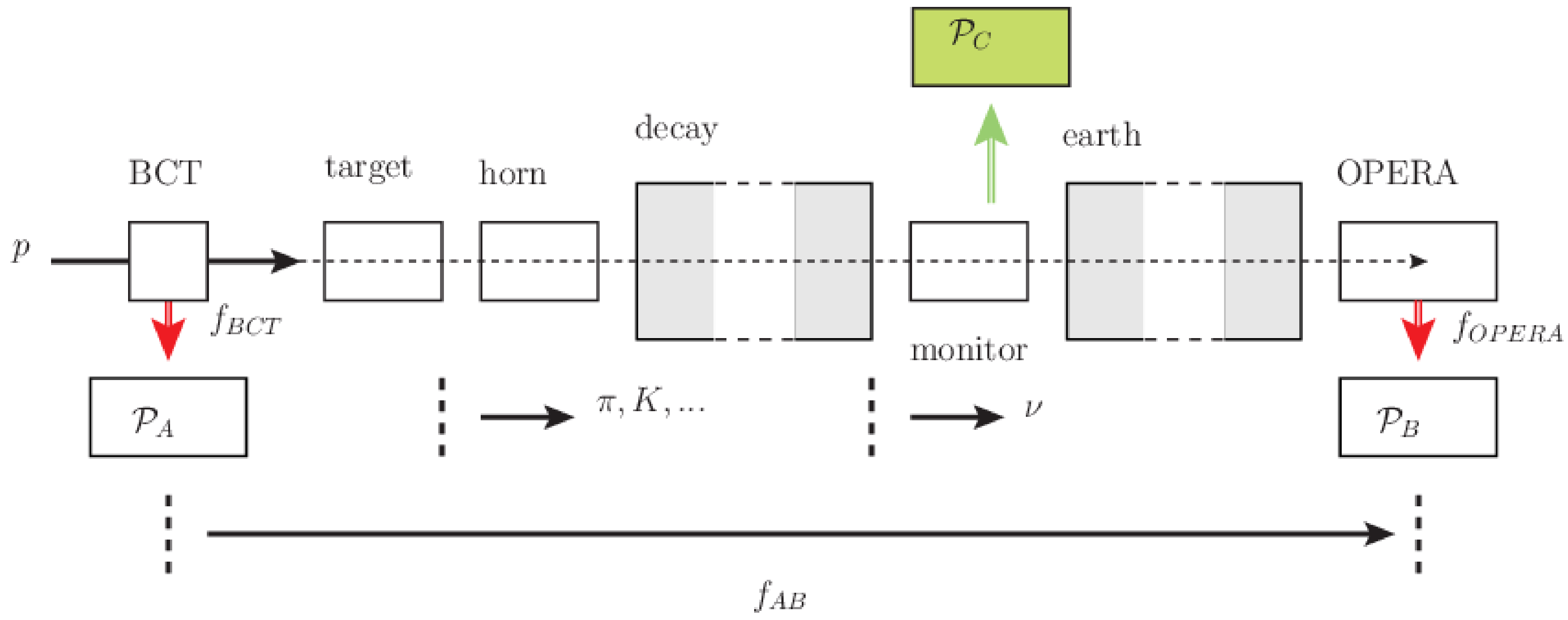
<u>Existing muon monitors:</u>

- Two pits separated by 67 m rock
- Ionization chambers
- Very sensitive to any beam changes!

→ Online feedback on quality of neutrino beam

- No information on time distribution

- Upgrade planned



So far no critical influence on measurement found here!

Ultimate test could be a beam with finer structure.

Conclusions (1)

- OPERA uses a new method to measure the neutrino velocity
- Dedicated measurement campaign to understand systematics, including:
  - Synchronisation
  - Time calibration
  - Geodesy
- Compare ν time distribution at OPERA and proton waveform at CERN

  $\rightarrow$ $\delta t = TOF_c - TOF_\nu = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ ns

- Indicates a neutrino velocity higher than the speed of light:

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

with an overall significance of 6.0 σ.

Conclusions (2)

This has to be compared to former results:

Experiment	Energy	ν-typ	(v-c)/c
FNAL	> 30 GeV	ν_μ	$\leq 4\times10^{-5}$
SN1987A	~10 MeV	$\bar{\nu}_e$	$\leq 2\times10^{-9}$
MINOS	~3 GeV+tail	ν_μ	$5.1 \pm 2.9\times10^{-5}$

- Within statistical errors no energy dependence found in OPERA
  - But it also can not be excluded

- Every input/criticism welcome

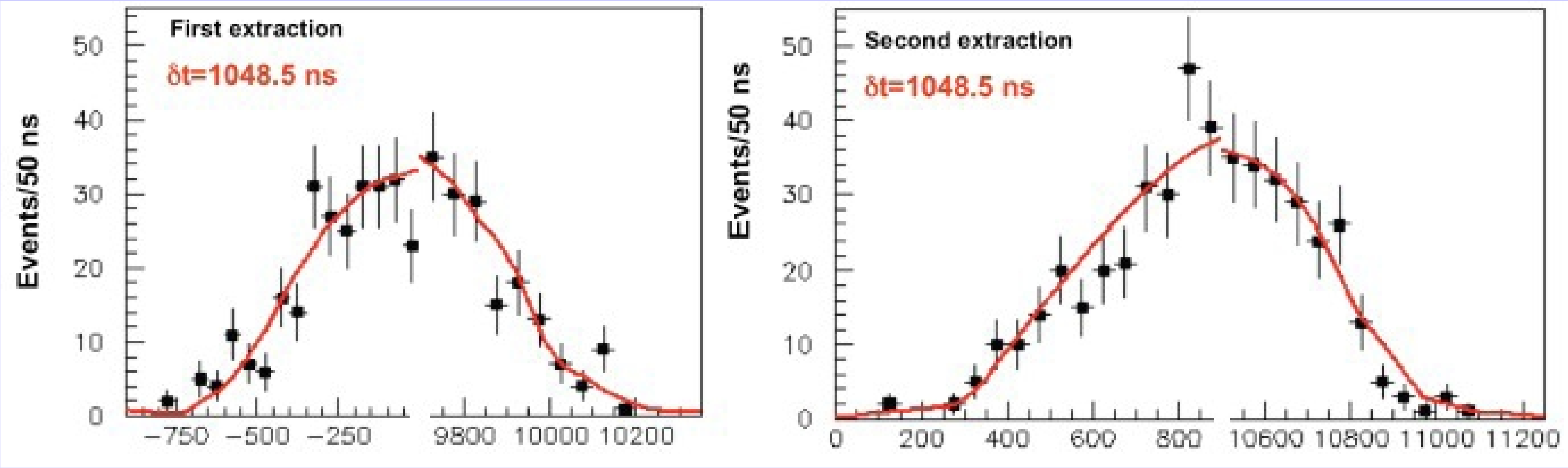
Thank you for your attention

Backup Slides

A Naive Way to Estimate the Statistical Error

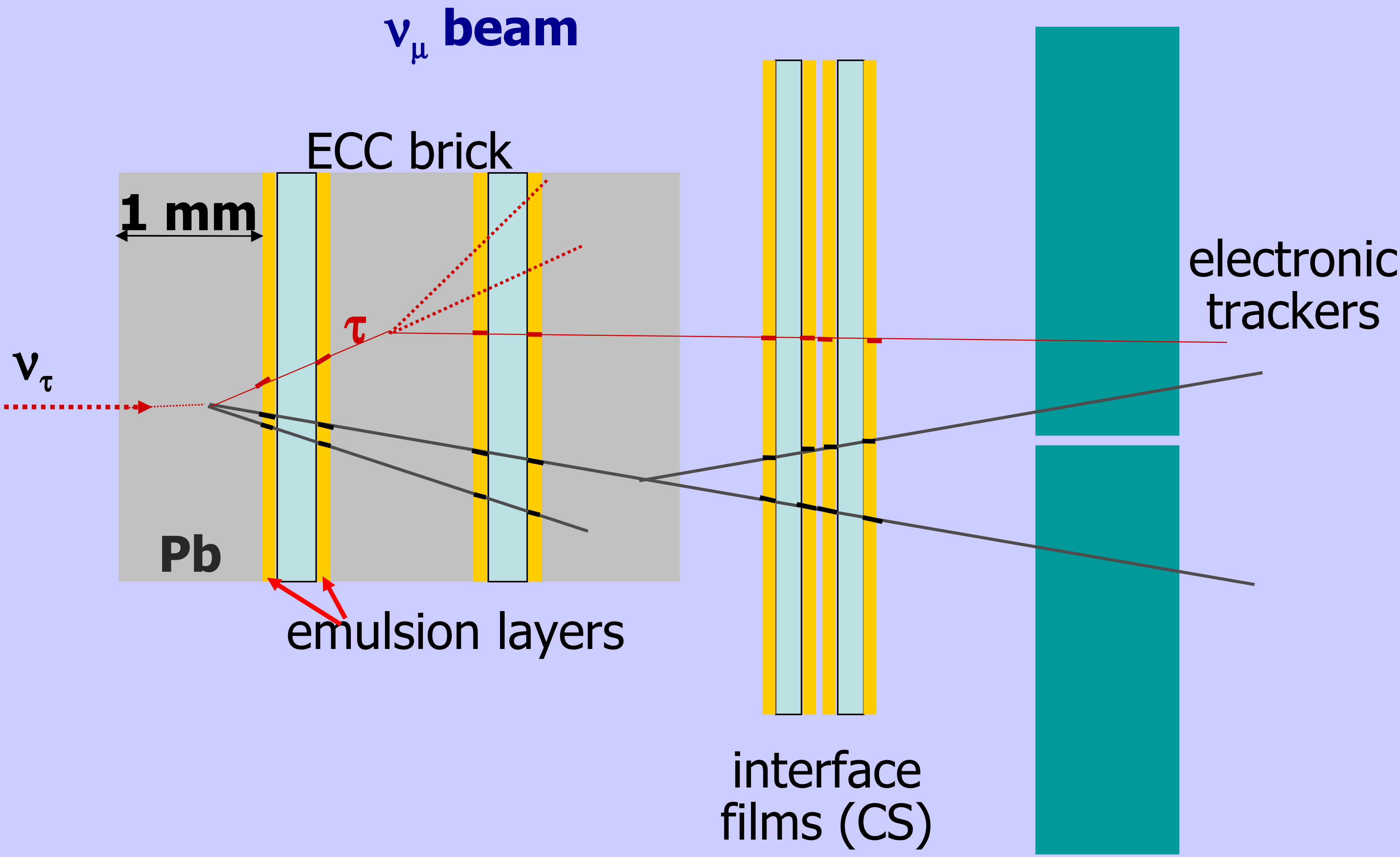
- Idea: Fit each flank with a Gaussian
  - Slope → Fit range
  - Average σ of Fits: 260 ns
  - Number of Events in all 4 flanks: 919

→ $\sigma_{\text{Guess}} = 260\text{ns}/\sqrt{919} \approx 8.7\text{ns}$

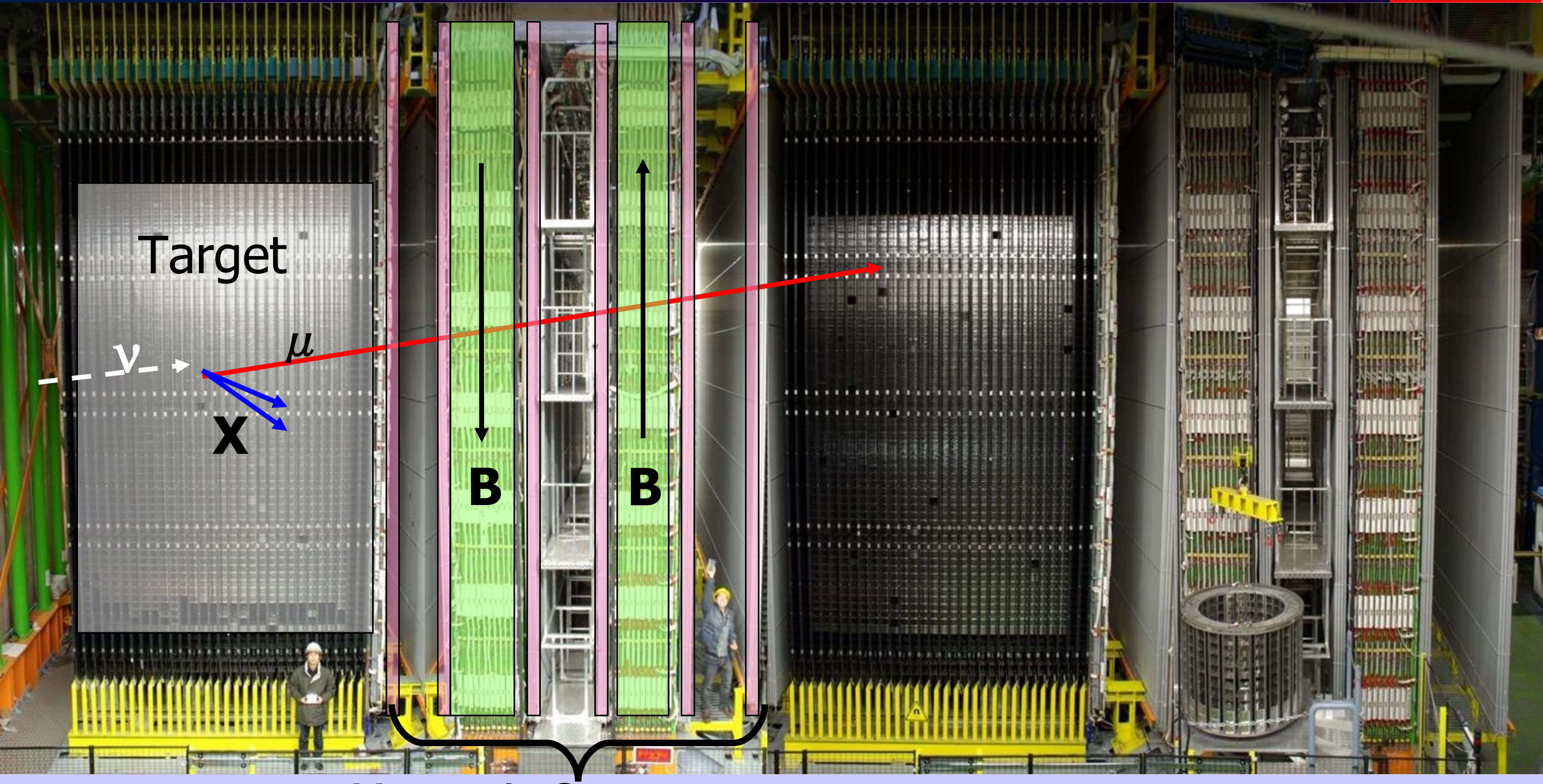


See: http://johncostella.webs.com/neutrino-blunder.pdf

The OPERA Detector



The OPERA Detector

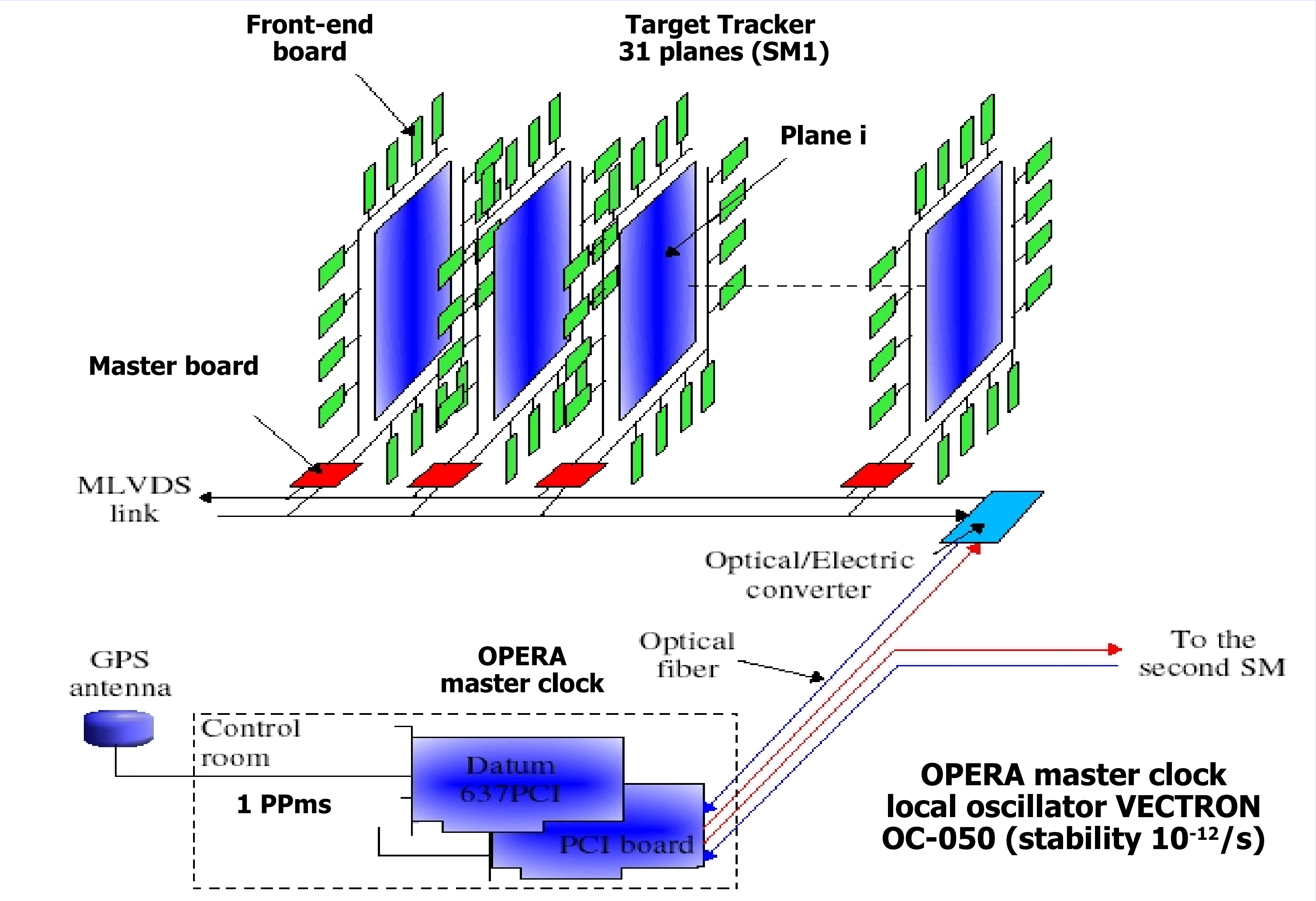


Magnetic Spectrometer:

Magnet Region:
Iron & RPCs

Precision Tracker:
6 planes of drift tubes

Clock Distribution System



- UTC event time stamp with 10 ns granularity

Measurement Principles

<u>Definition of neutrino velocity:</u>

ratio of precisely measured baseline and time of flight

Main Components:

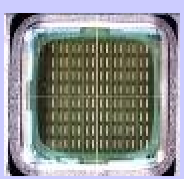
- tagging of neutrino production time
- tagging of neutrino interaction time by a far detector
- accurate synchronisation of time tagging systems at both sides
- accurate determination of the baseline (geodesy)

- blind analysis: “box” opened after adequate level of systematic errors was reached

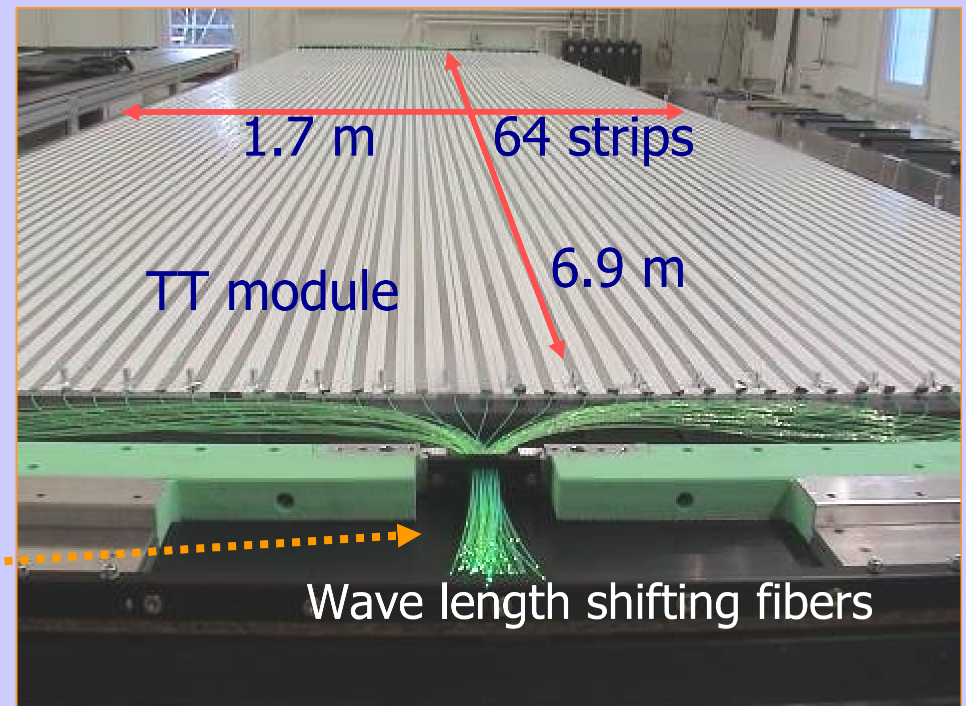
The Target Tracker (TT)

Task: Pre-location of neutrino interactions and event timing

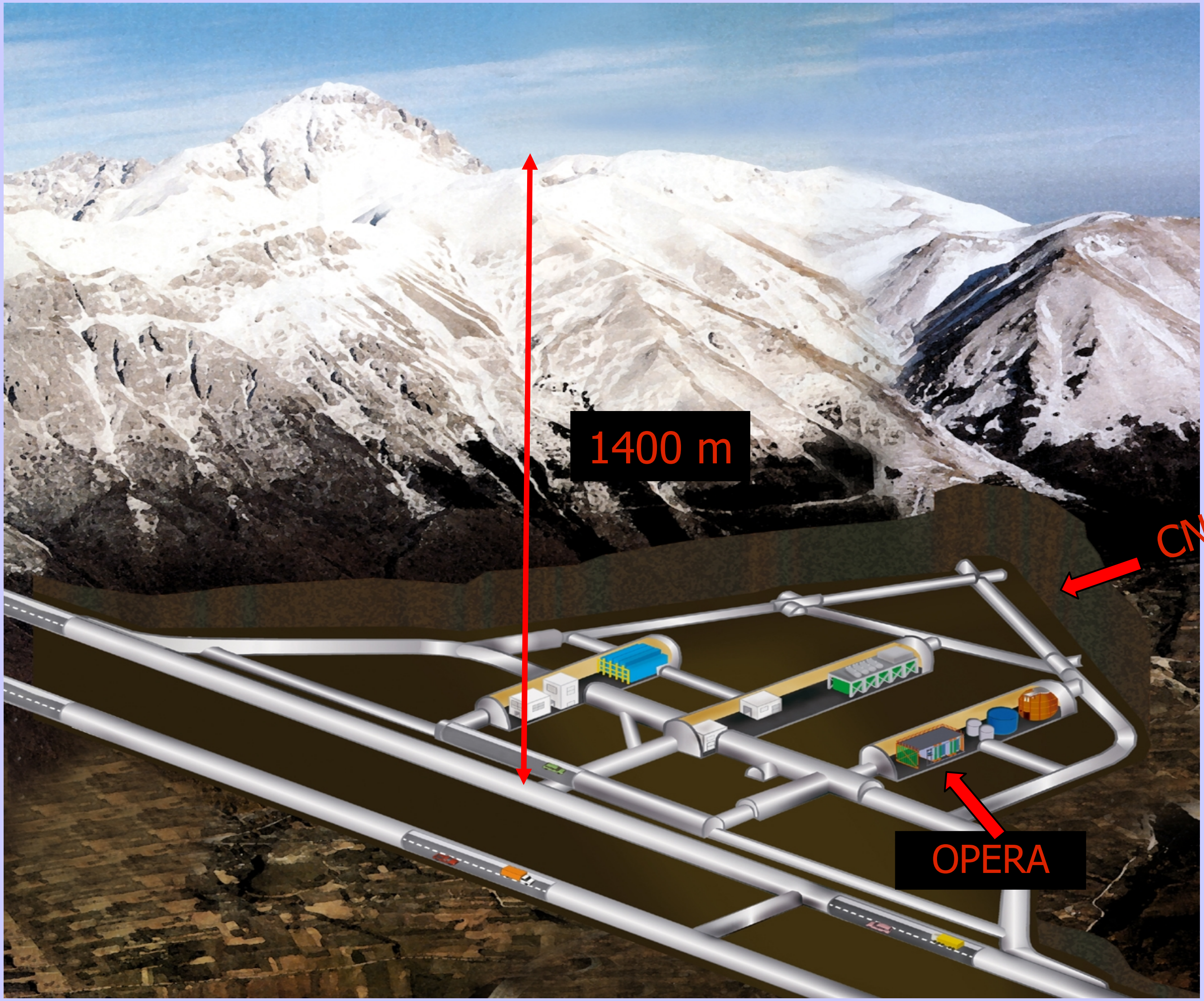
- Extruded plastic scintillator strips (2.6 cm width)
- Light collections with WLS fibres
- Fibres read out at either side with multi-anode 64 pixels PMTs (H7546)
- Read out by 1 Front-End DAQ board per side



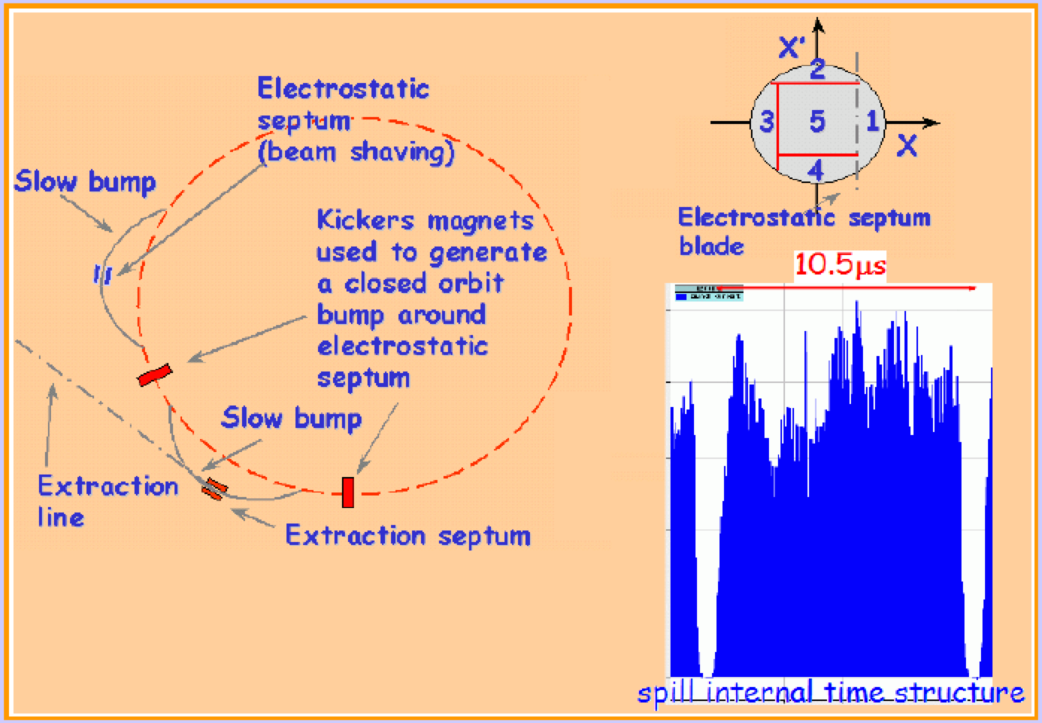
H7546



The LNGS Underground Lab



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

- <u>Precise accounting with WFD waveforms:</u>

more accurate than: *e.g.* average neutrino distribution in a near detector

OPERA Sensitivity

- High neutrino energy - high statistics ~16000 events
- Sophisticated timing system: ~1 ns CNGS-OPERA synchronisation
- Accurate calibrations of CNGS and OPERA timing chains: ~ 1 ns level
- Precise measurement of neutrino time distribution at CERN through proton waveforms
- Measurement of 730 km baseline by global geodesy: 20 cm accuracy

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

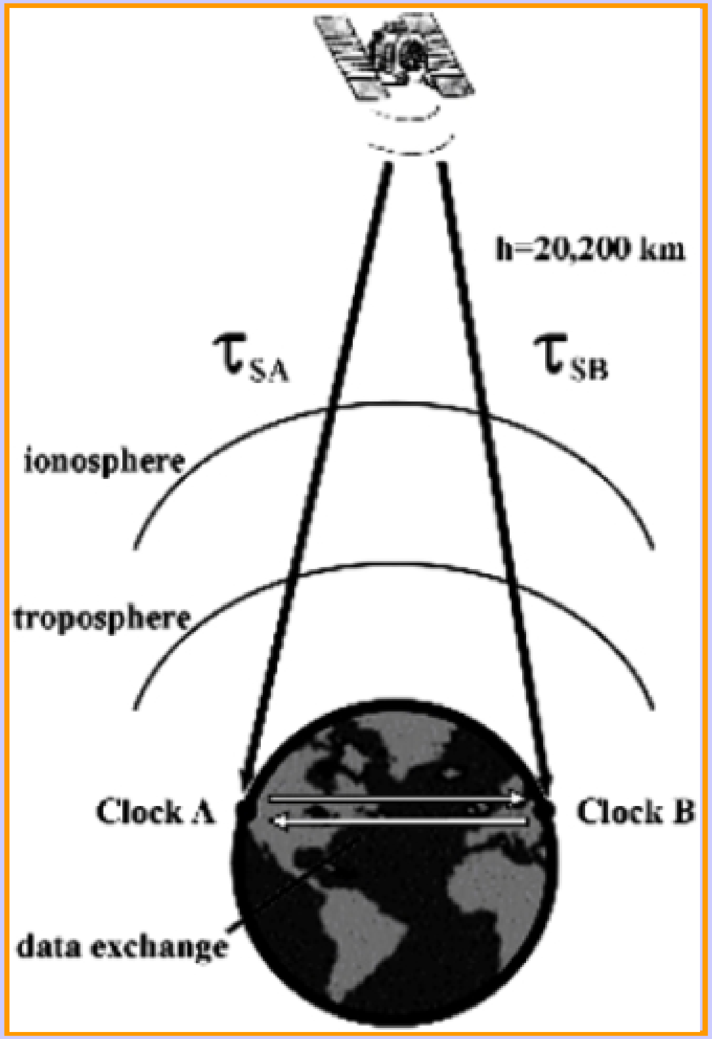
GPS Common-view Mode

Standard GPS operation:

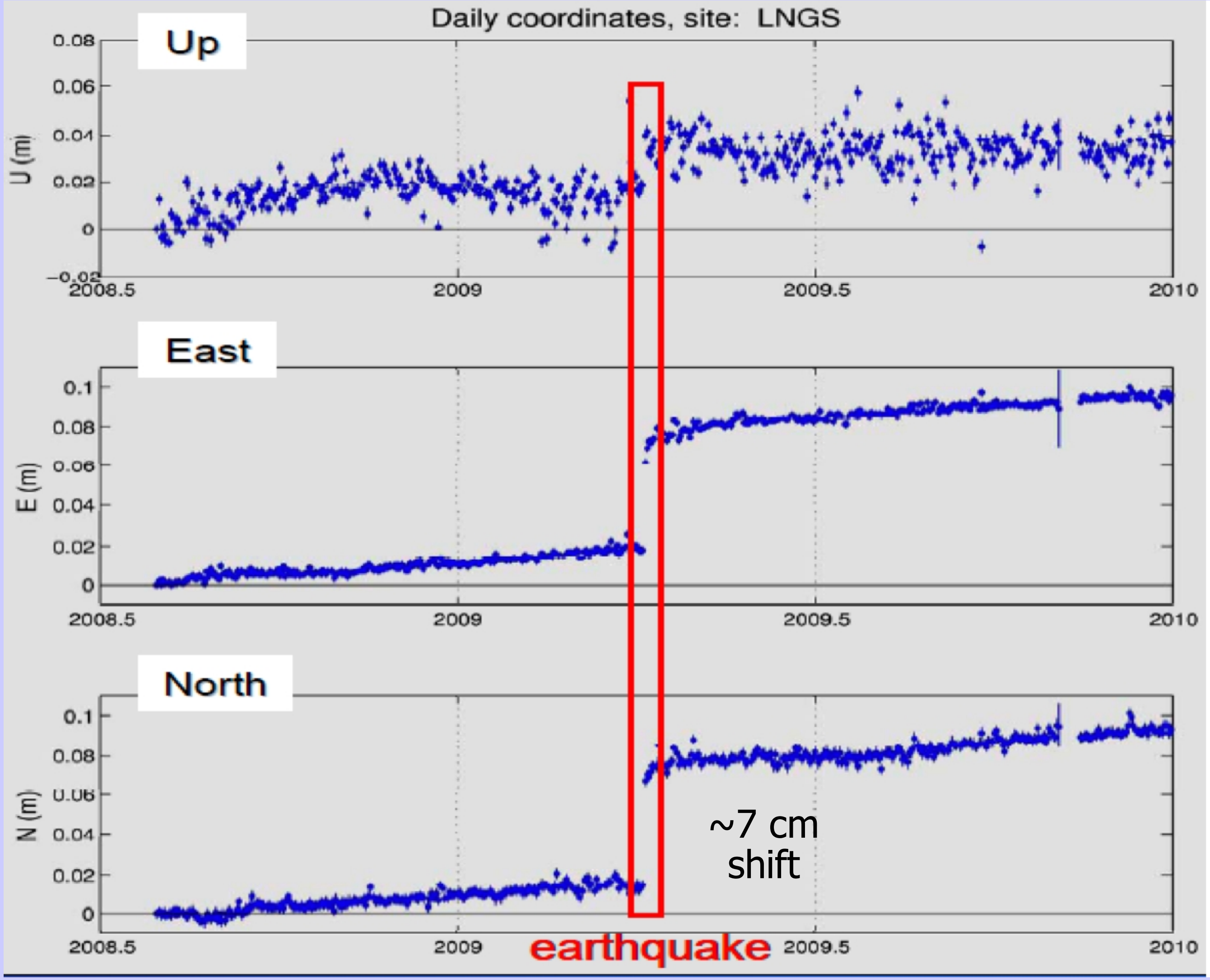
- resolves x, y, z, t with ≥ 4 satellite observations

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

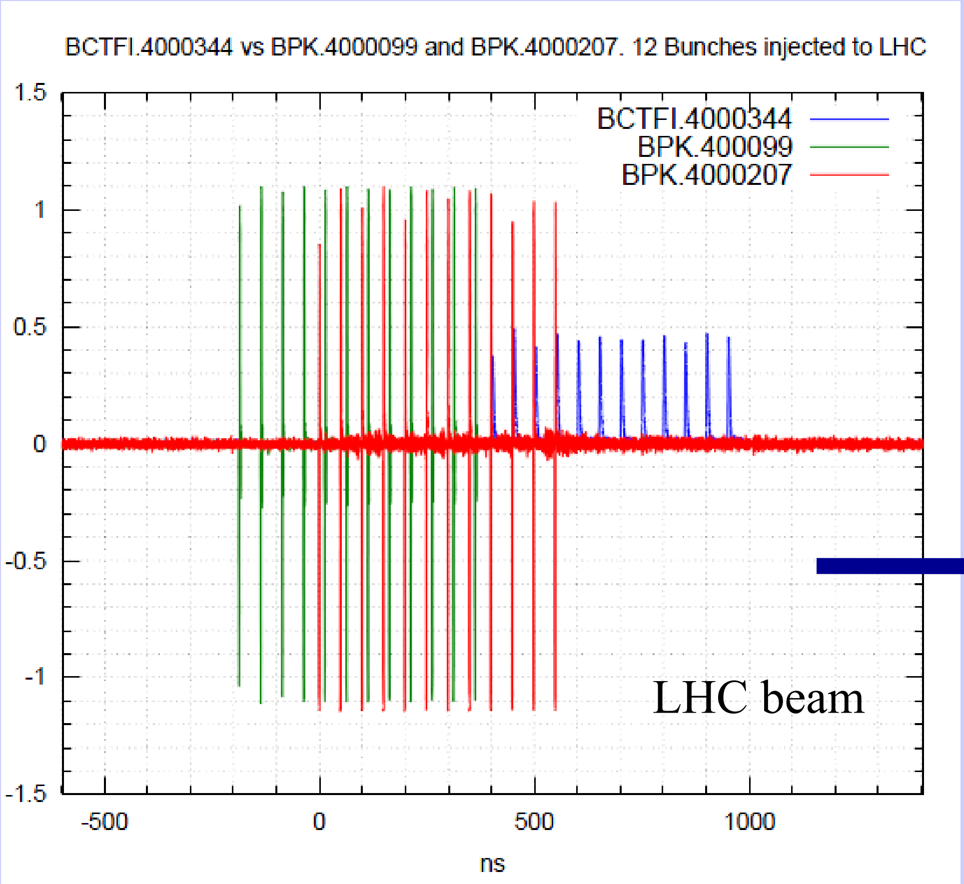


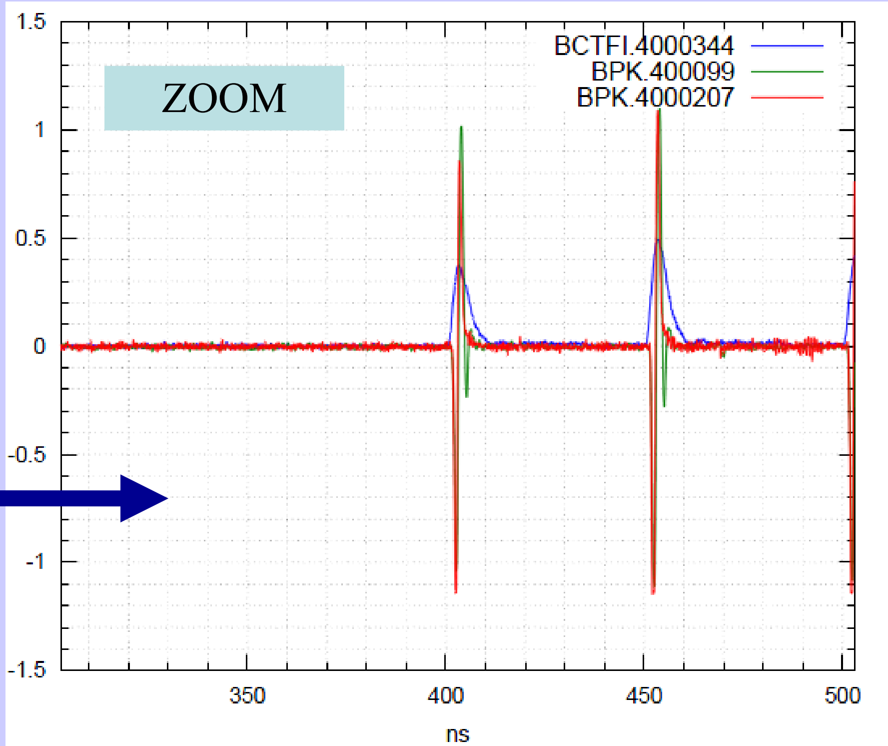
LNGS Position Monitoring



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

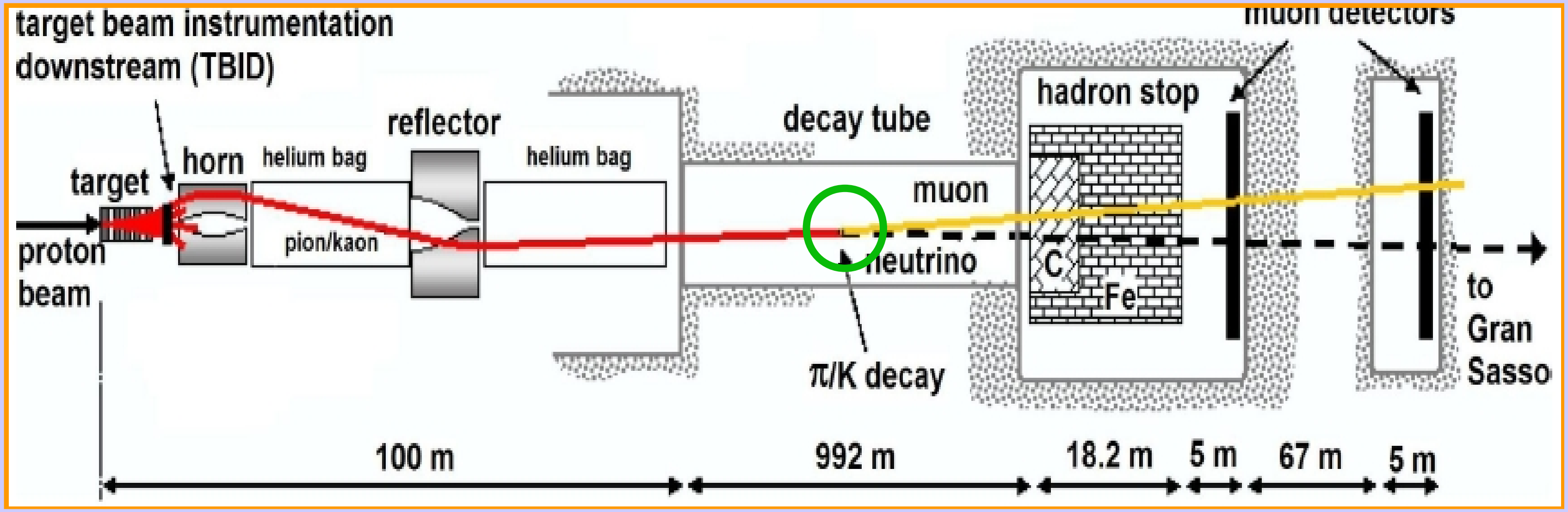
BCT Calibration (2)





Result: Signals comparison after Δ_{BCT} compensation

Neutrino Production Point



<u>Unknown neutrino production point:</u>

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

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

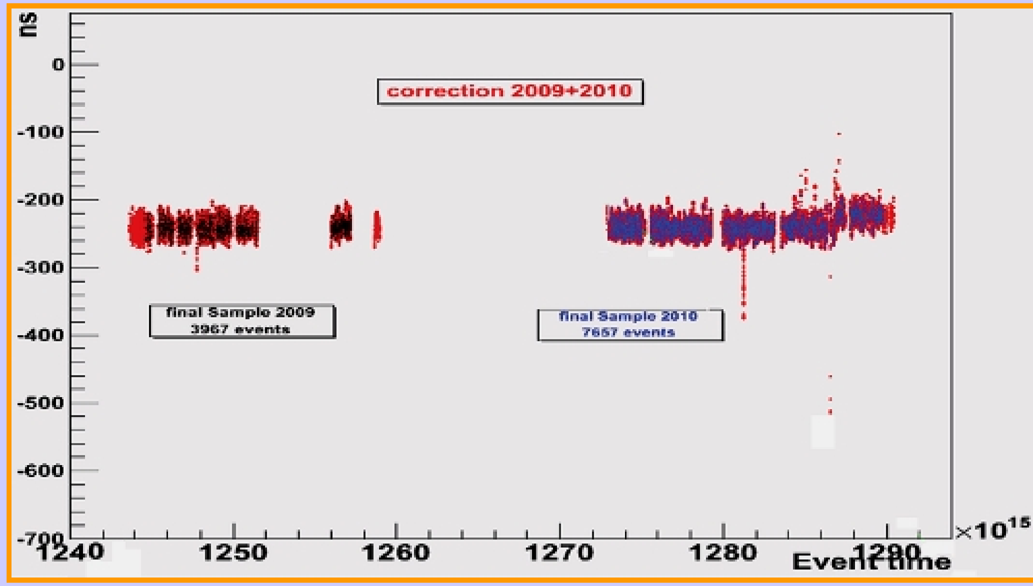
TOF_c = assuming *c* from BCT to OPERA (2439280.9 ns)

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

$\Delta t = TOF_{true} - TOF_c$ → $\boxed{\langle \Delta t \rangle = 1.4 \times 10^{-2}\ \text{ns}}$

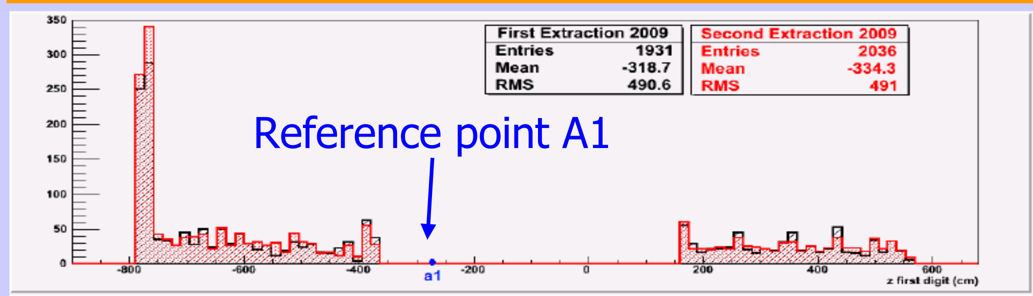
Event Time Corrections

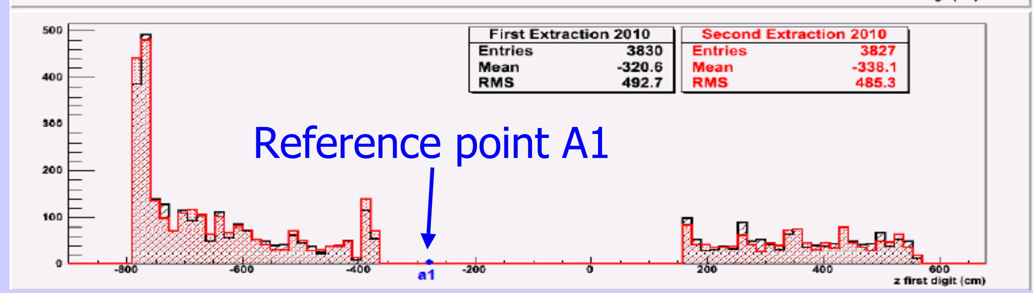
Time-link correction (blue points)



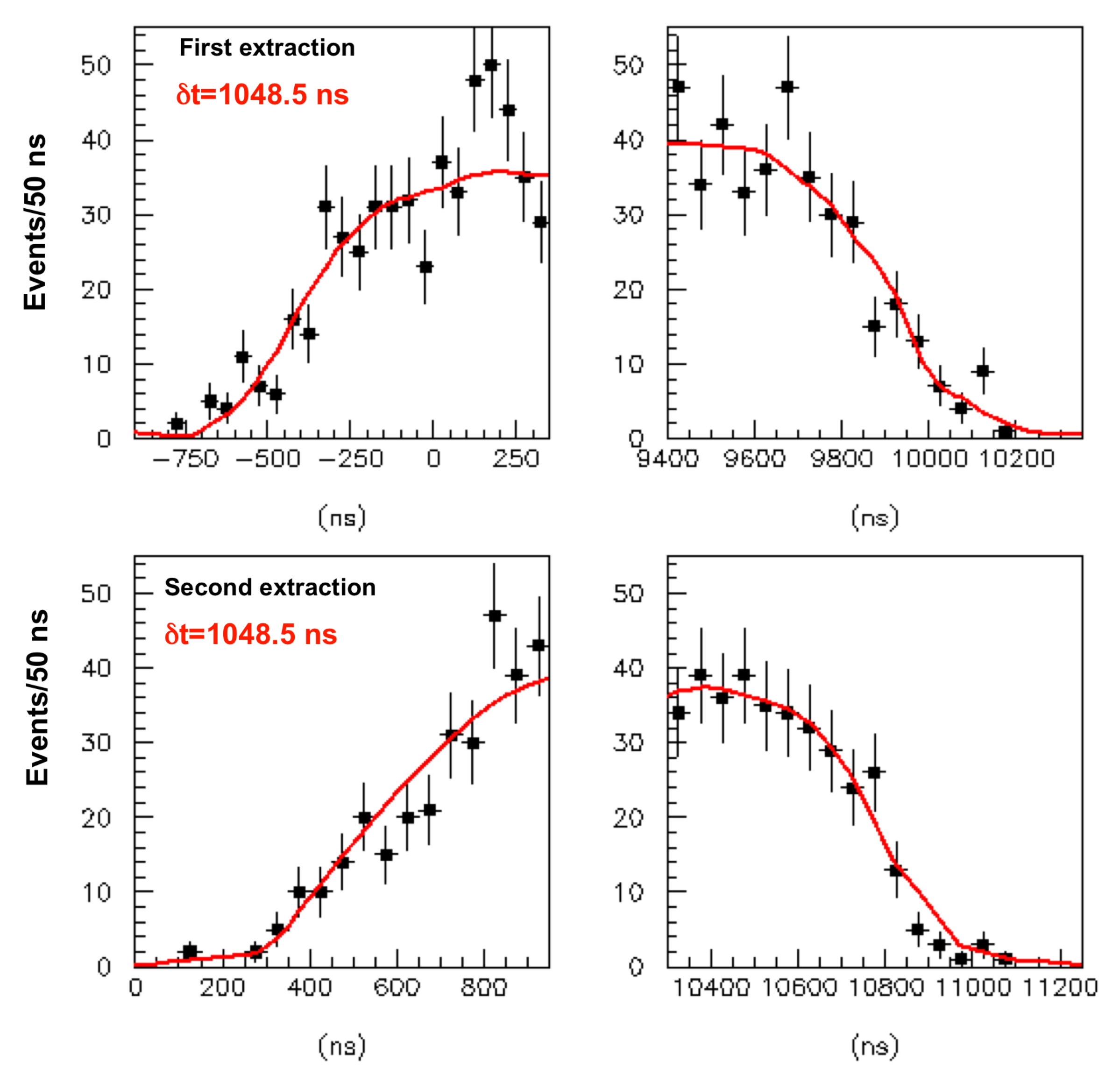
Correction due to the earliest hit position

average correction: 140 cm (4.7 ns)





Zoom on the Extractions Leading and Trailing Edges

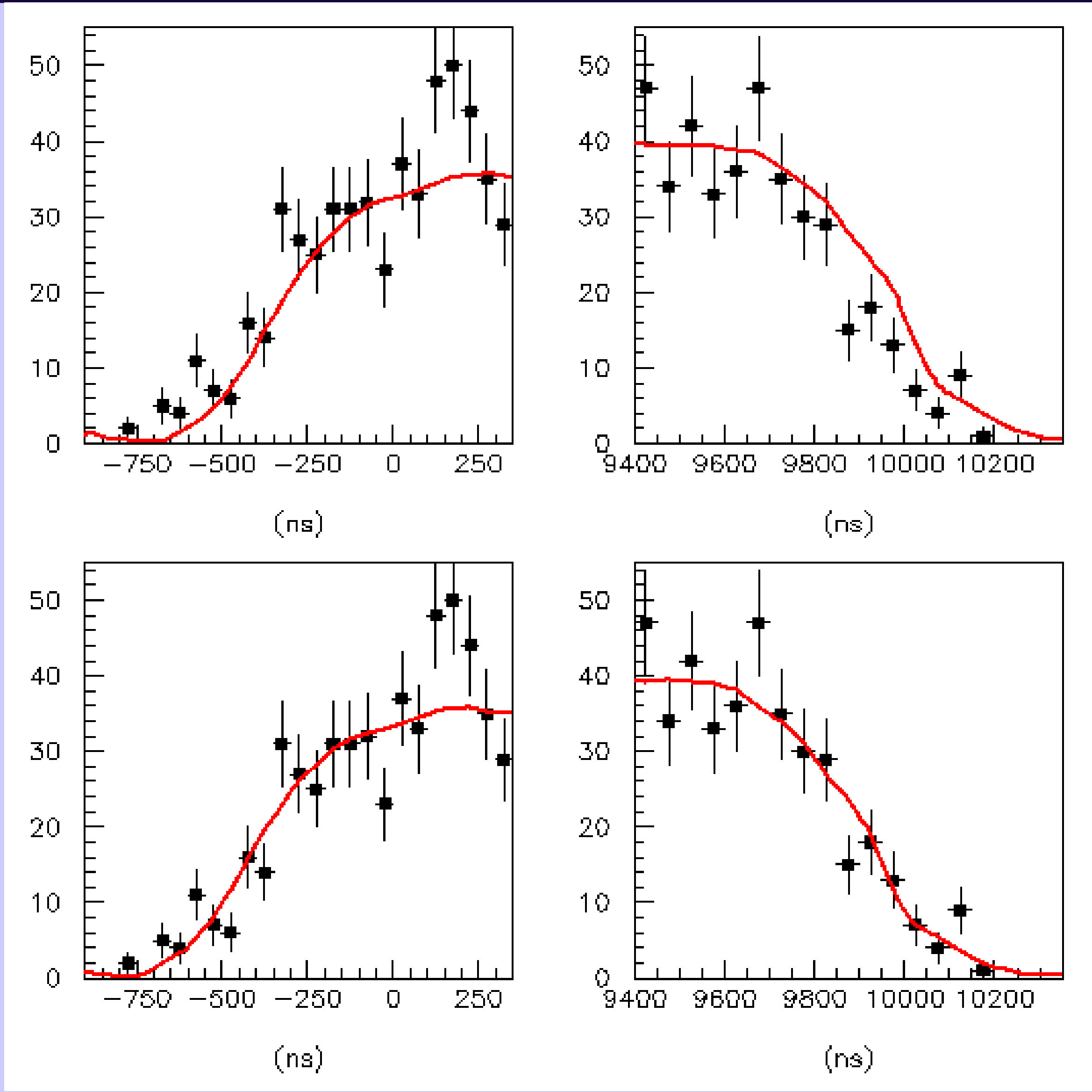


Zoom on the Extractions Leading and Trailing Edges

Extraction 1

$\delta t = 0$ ns

$\delta t = 60.7$ ns

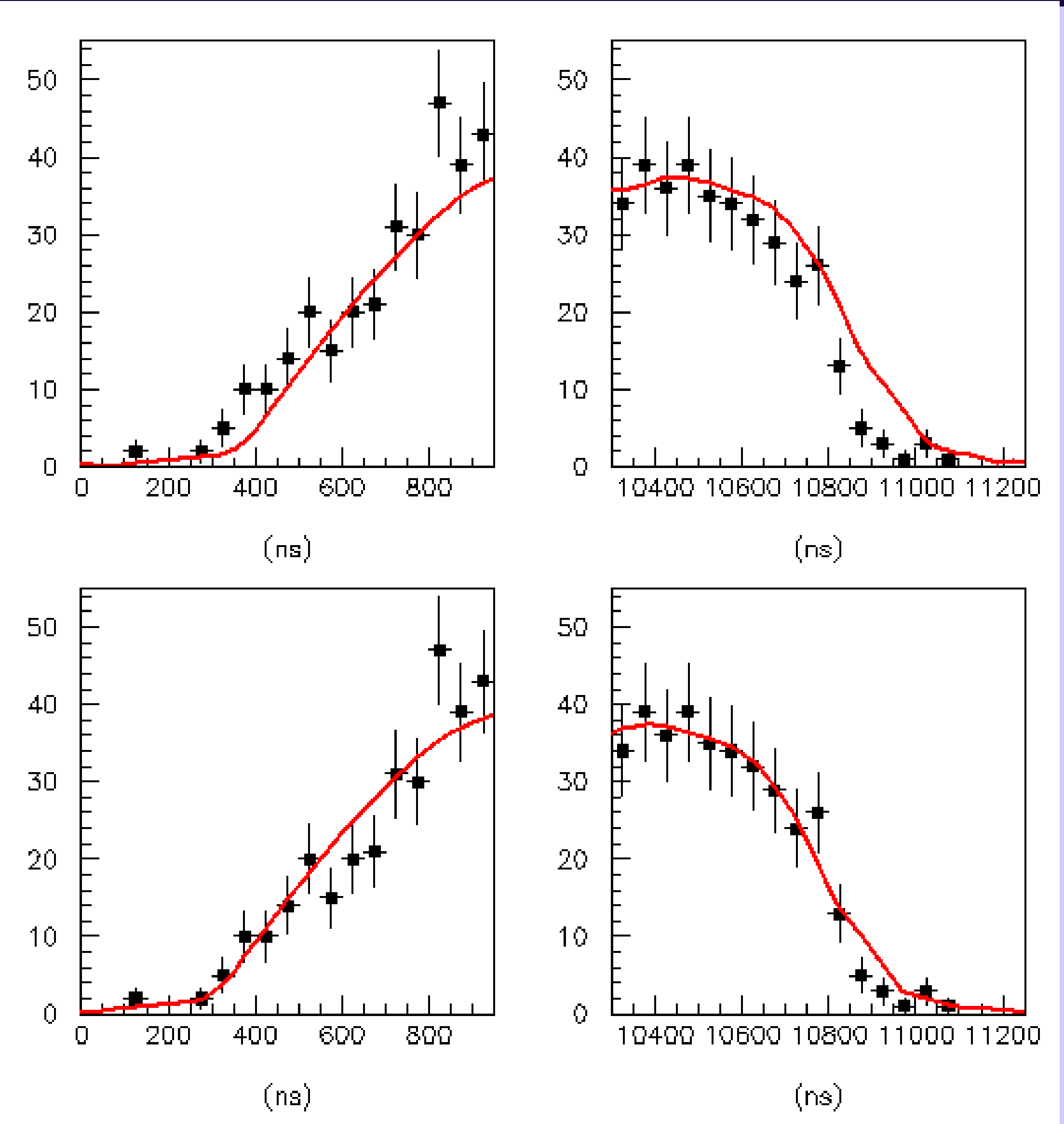


Zoom on the Extractions Leading and Trailing Edges

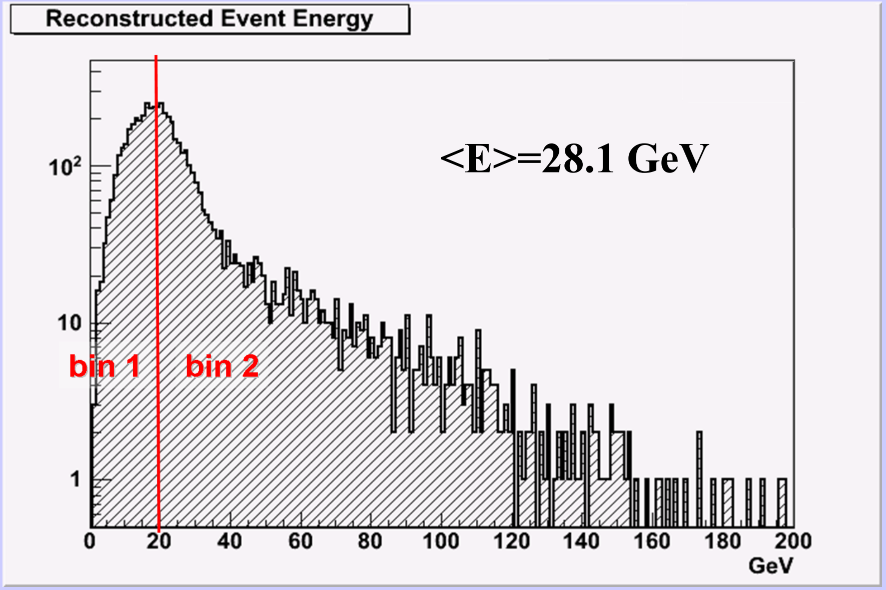
Extraction 2

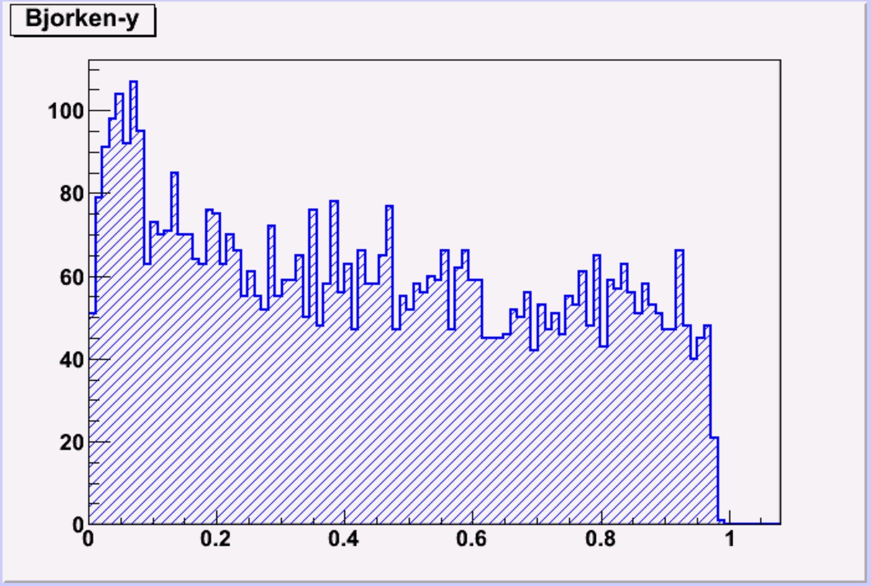
$\delta t = 0$ ns

$\delta t = 60.7$ ns



Study of the Energy Dependence





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

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

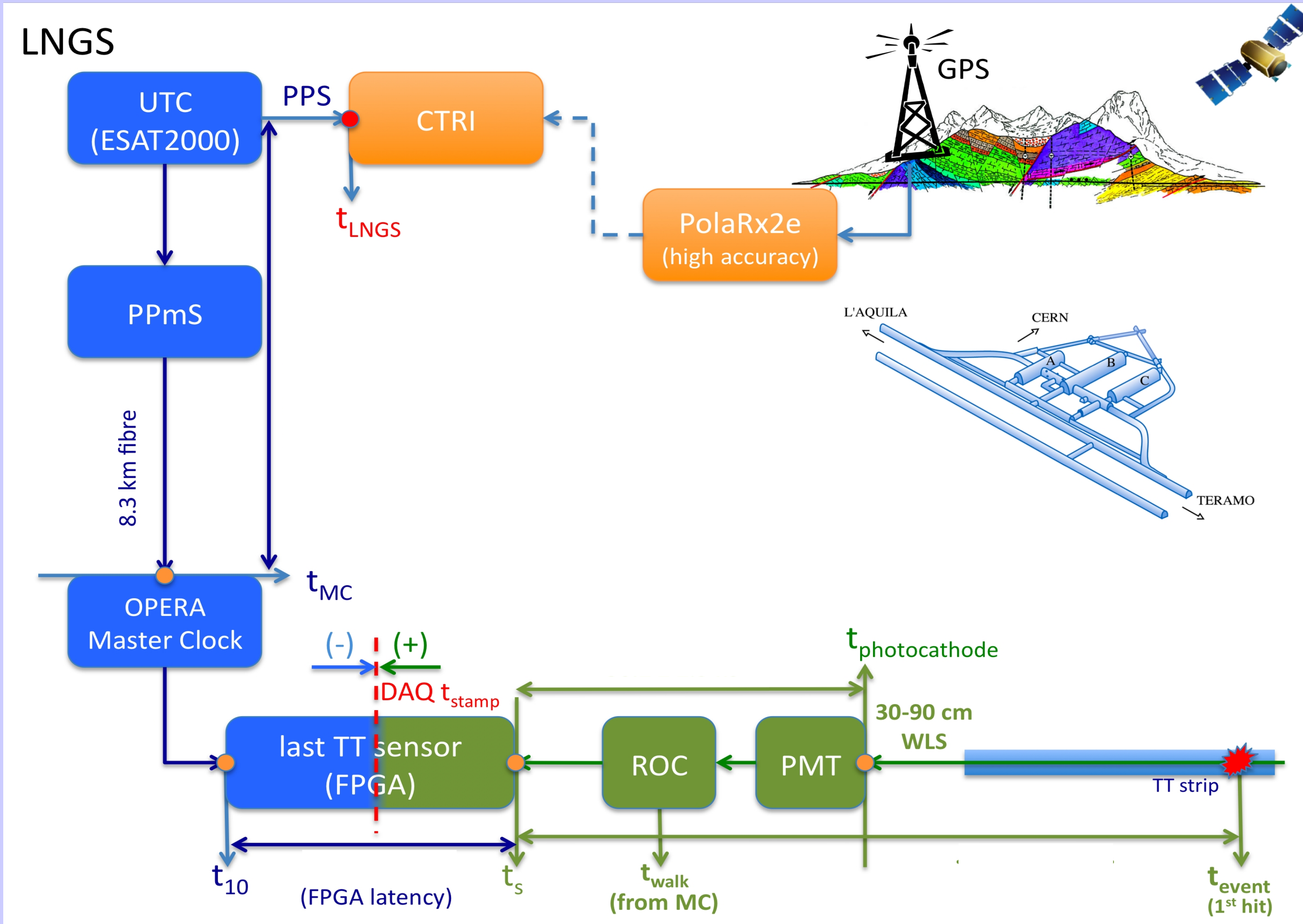
- Full MC simulation: No energy bias in detector time response (<1 ns)

  $\rightarrow$ Systematic errors cancel out

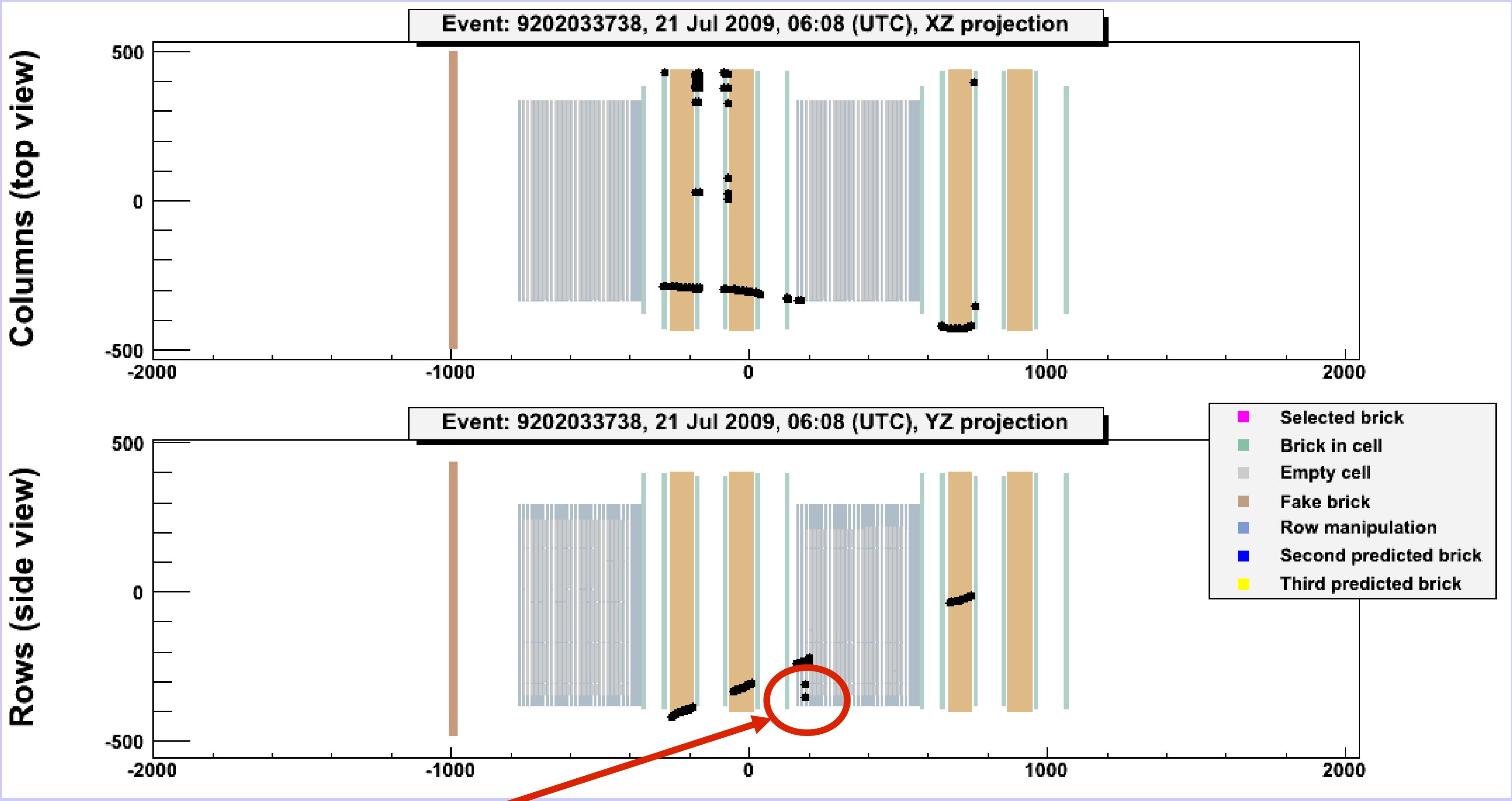
$\delta t = TOF_c - TOF_\nu = (60.3 \pm 13.1\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ ns for $\langle E_\nu \rangle = 28.1$ GeV

(Result limited to events with measured energy)

Overview LNGS Timing



Data Cleaning



- Earliest TT-signal due to noise

→ Event cast away