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

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on behalf of the **OPERA** collaboration

bmb+f - Förderschwerpunkt
OPERA
Großgeräte der physikalischen Grundlagenforschung

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the OPERA collaboration

~160 scientists, 30 institutes, 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

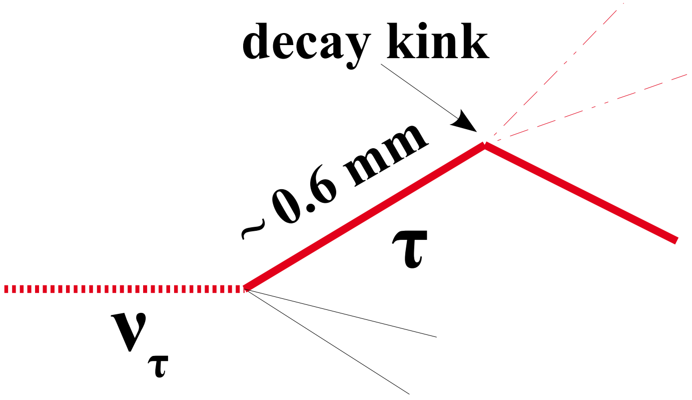
additional contribution for neutrino velocity measurement:
CERN: CNGS, survey, timing and PS groups
PTB (National metrology institute, Germany)
METAS (National metrology institute, Switzerland)
Università Sapienza (Rome University, Italy): Geodesy group

overview

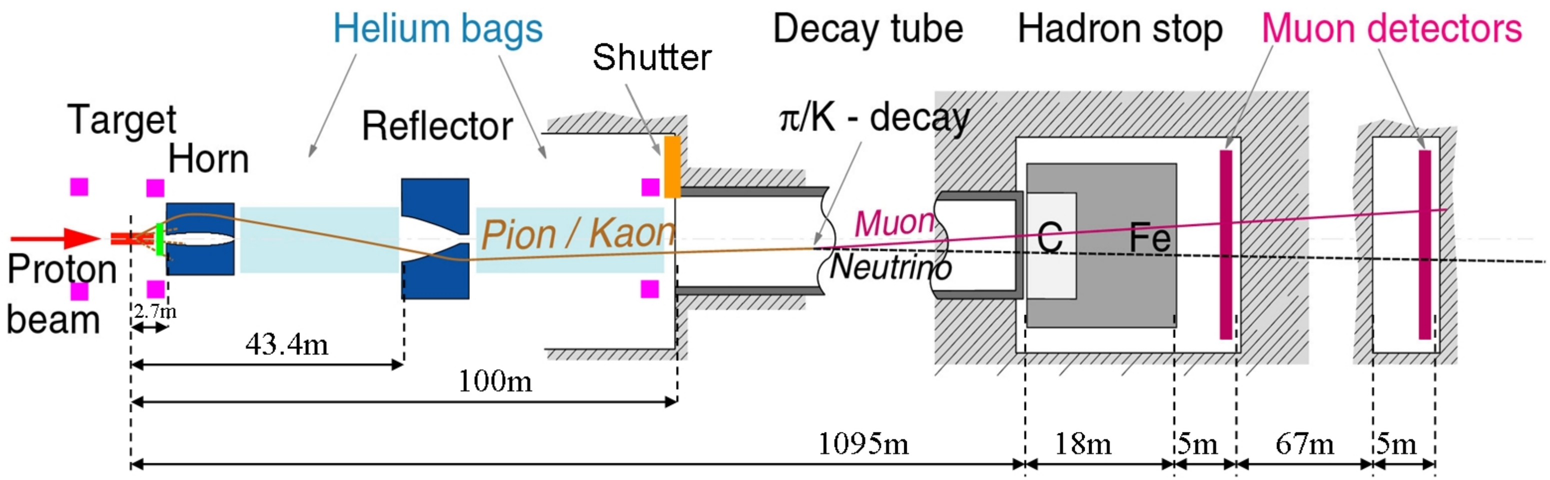
- the OPERA experiment
  - the CNGS neutrino beam
  - the OPERA detector
- neutrino time-of-flight measurement
  - experimental concept
  - 2011 results
  - recent developments
  - outlook

the OPERA experiment

- main physics goal:
  - first direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations
- concept:
  - long baseline ν_μ beam, $E_\nu \gg E_{thresh}(CC\ \nu_\tau)=3.5GeV$
  - event-by-event detection of τ leptons
- requirements:
  - high target mass (~1000t)
  - high spatial resolution (~1µm)
  - very low background rate



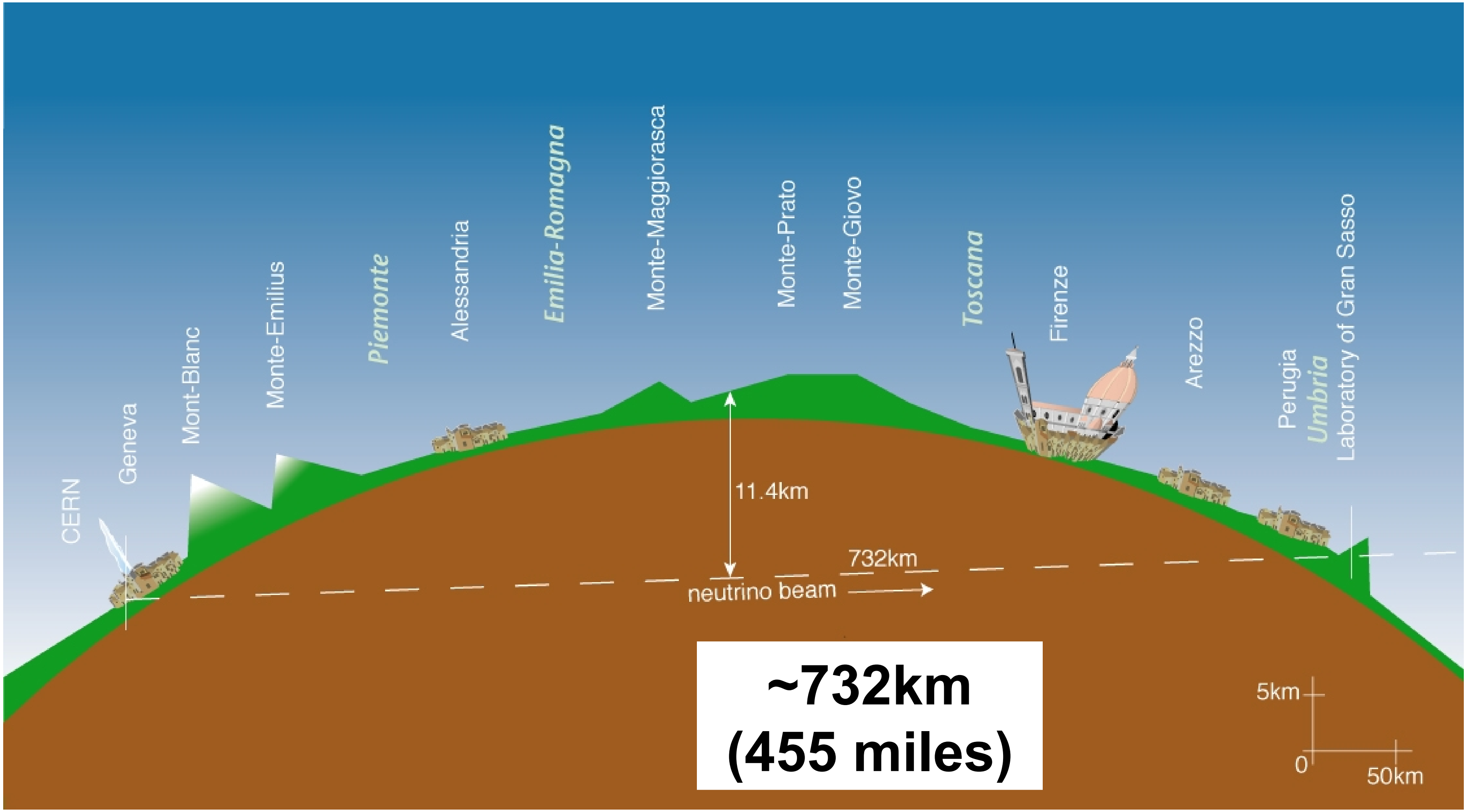
the CNGS neutrino beam



$\langle E_{\nu_\mu} \rangle$	17 GeV	
$\bar{\nu}_\mu/\nu_\mu$	2.1%	(CC interactions)
ν_e/ν_μ	0.89%	(CC interactions)
$\bar{\nu}_e/\nu_\mu$	0.06%	(CC interactions)
ν_τ/ν_μ	$< 10^{-4}$%	(CC interactions)

about 2.1×10^{13} POT per extraction, 2 extractions per SPS filling

neutrino propagation



~732km (455 miles)

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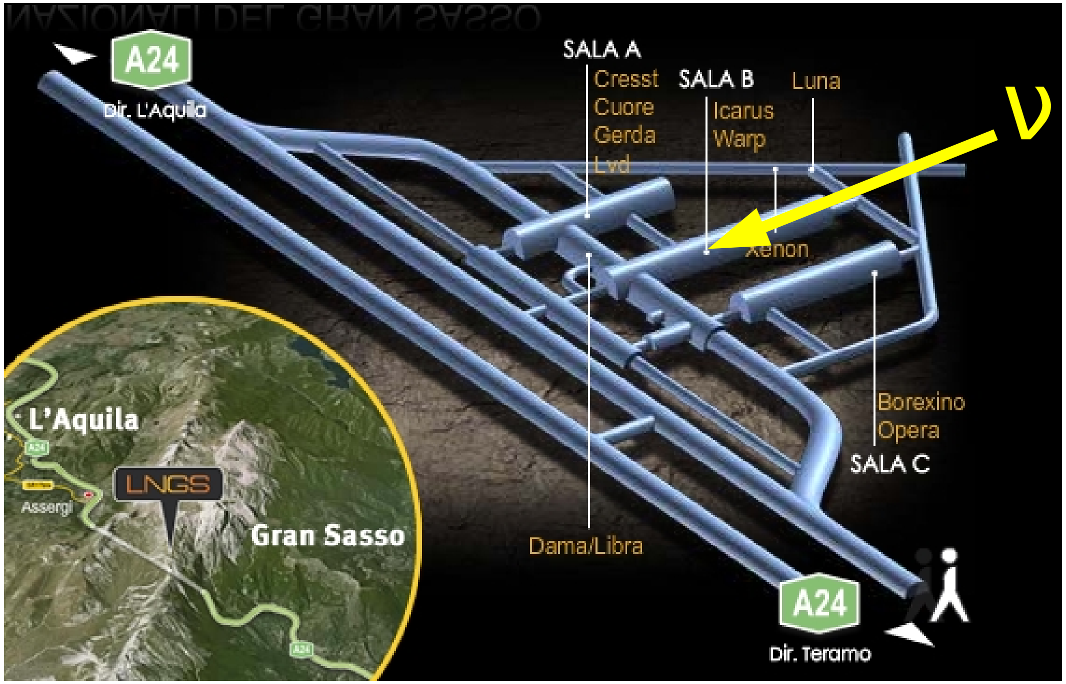
neutrino propagation

- LNGS underground lab
  - under 1400m rock (3800mwe)
  - highway access



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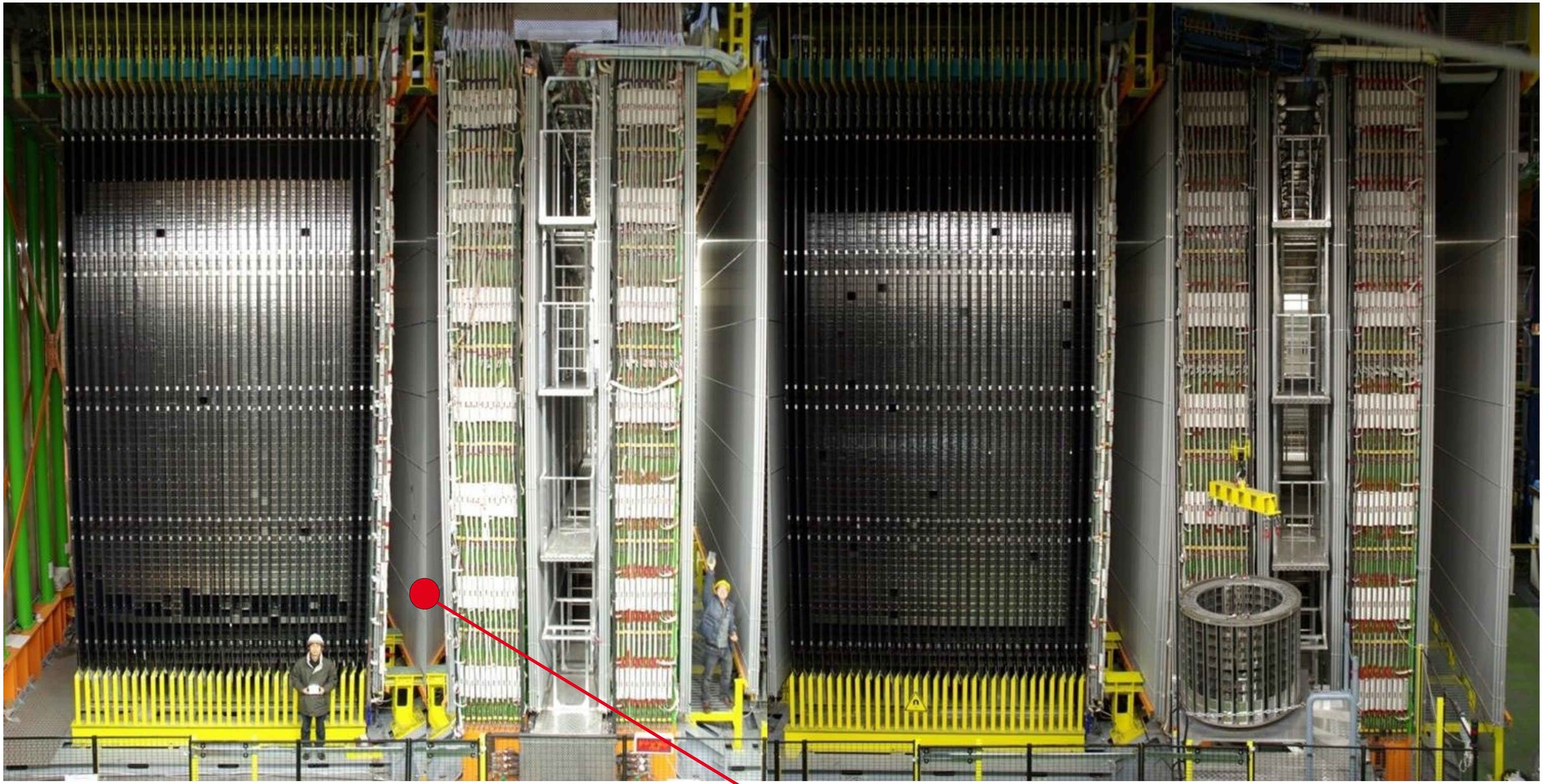
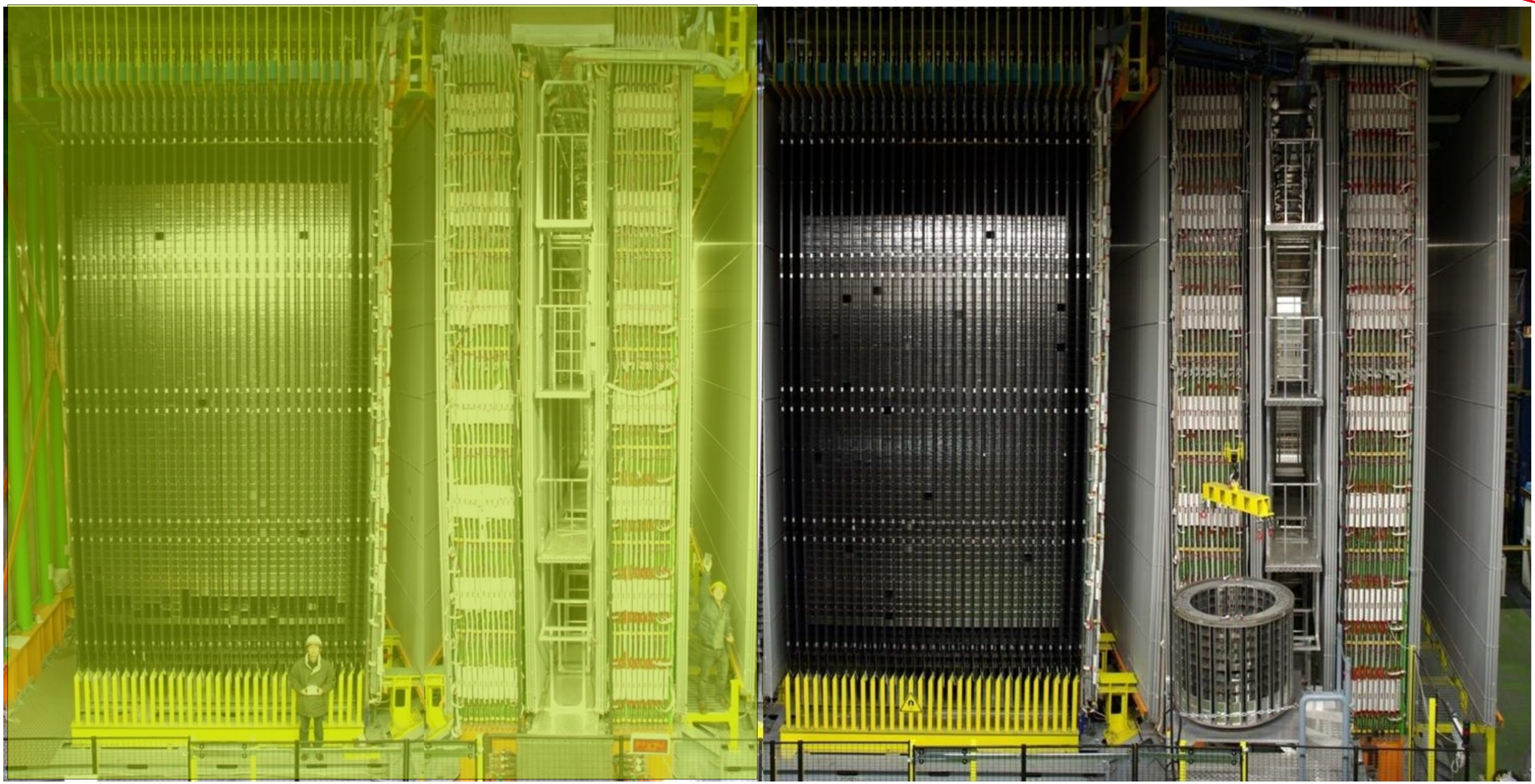
the OPERA detector



neutrinos

reference point for TOF measurement: “A1”

the OPERA detector



super module 1 super module 2

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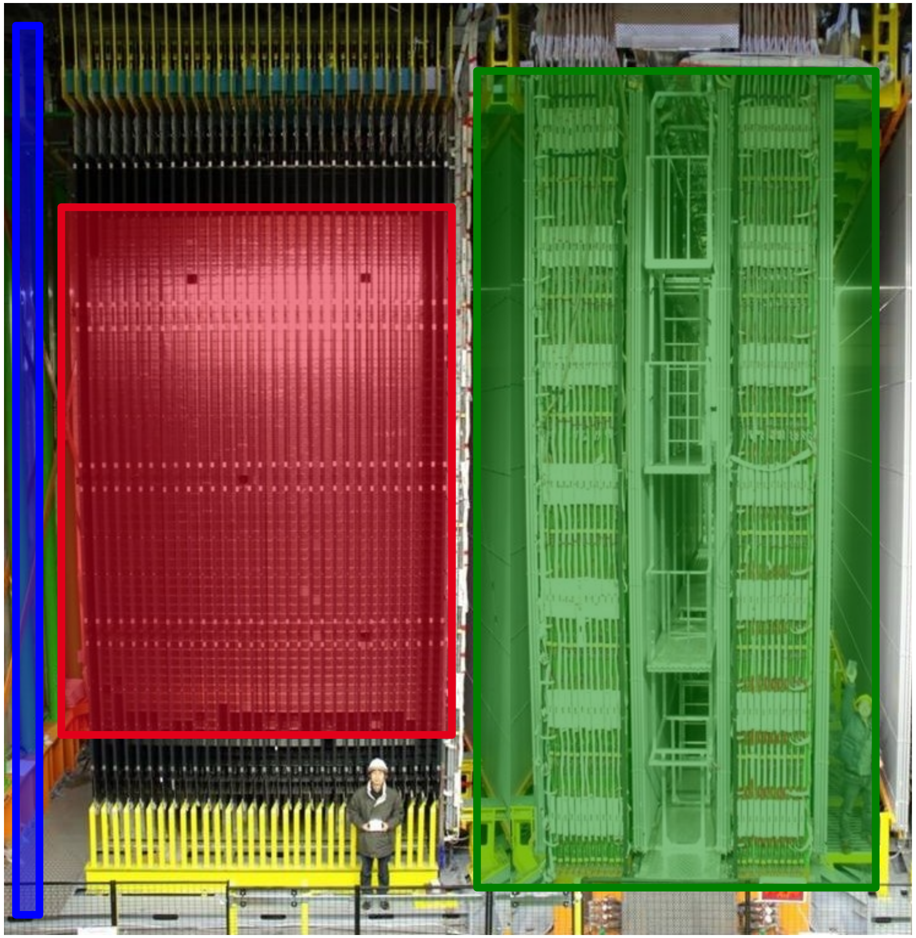
the OPERA detector



super module 1

veto (only SM1)
RPC

target section
75,000 ECC bricks per SM
31 pairs of planes of
horiz. and vert. plastic
scintillator strips

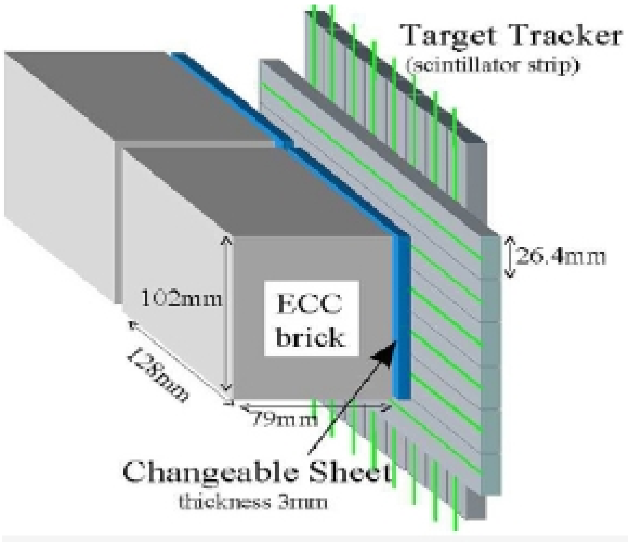
spectrometer
1.5T dipole magnet
RPC inner trackers
drift tubes

target section

- 31 walls per SM
  - lead/emulsion ECC
  - Changeable Sheets
  - horizontal scintillator strips
  - vertical scintillator strips

passive, excellent spatial/angular resolution

active, excellent time resolution (~1ns), spatial resolution ~1cm



time-of-flight measurement

introduction

- definition of time-of-flight (TOF)

$$TOF_\nu = t_B - t_A - \text{delays}$$

- “typical” TOF measurement principle
  - measure the neutrino production time t_A
  - measure the distance between production and detection
  - measure the neutrino detection time t_B
- definition of neutrino velocity:

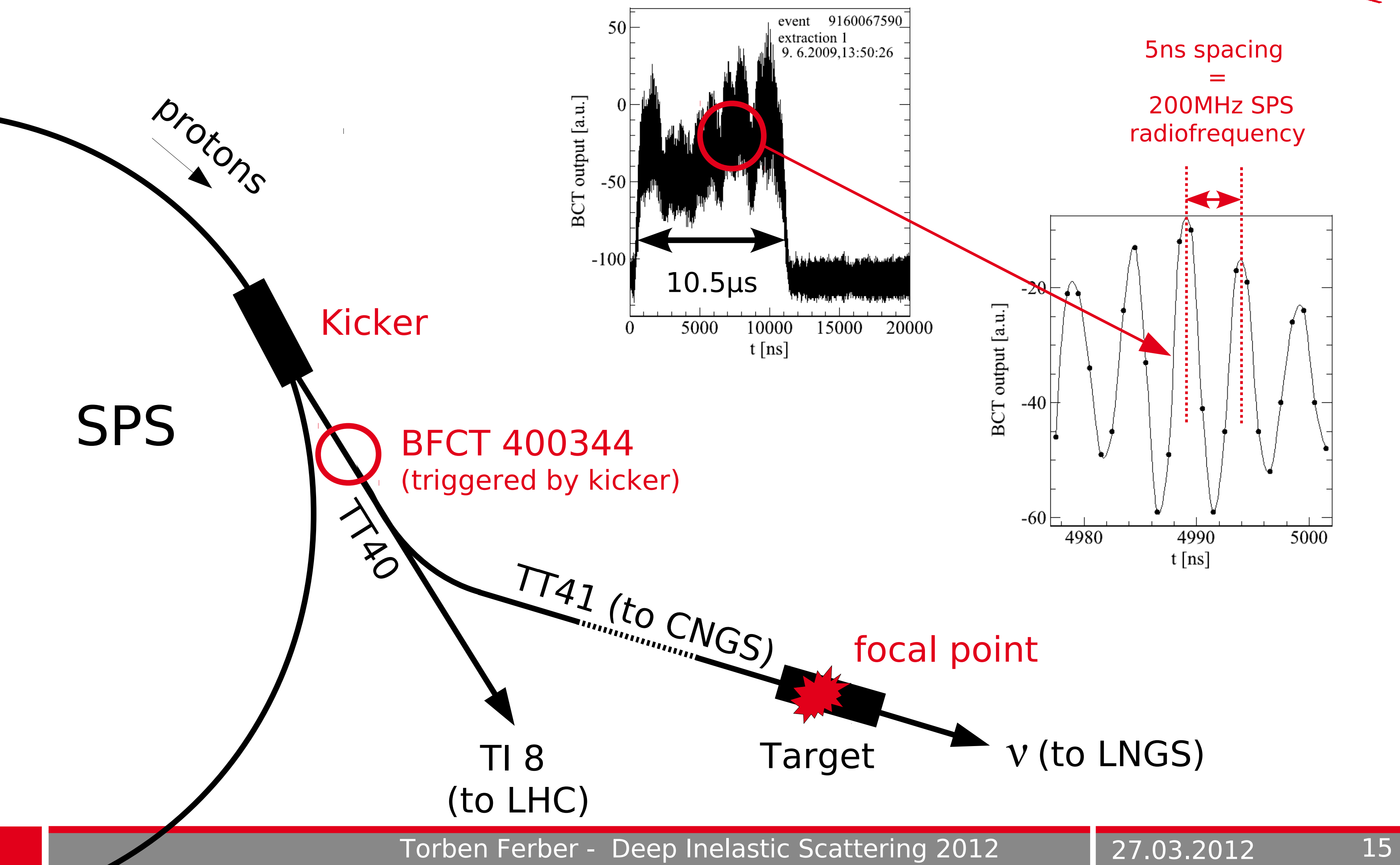
$$v_\nu = \text{distance}/TOF_\nu$$

- blind analysis (delays)

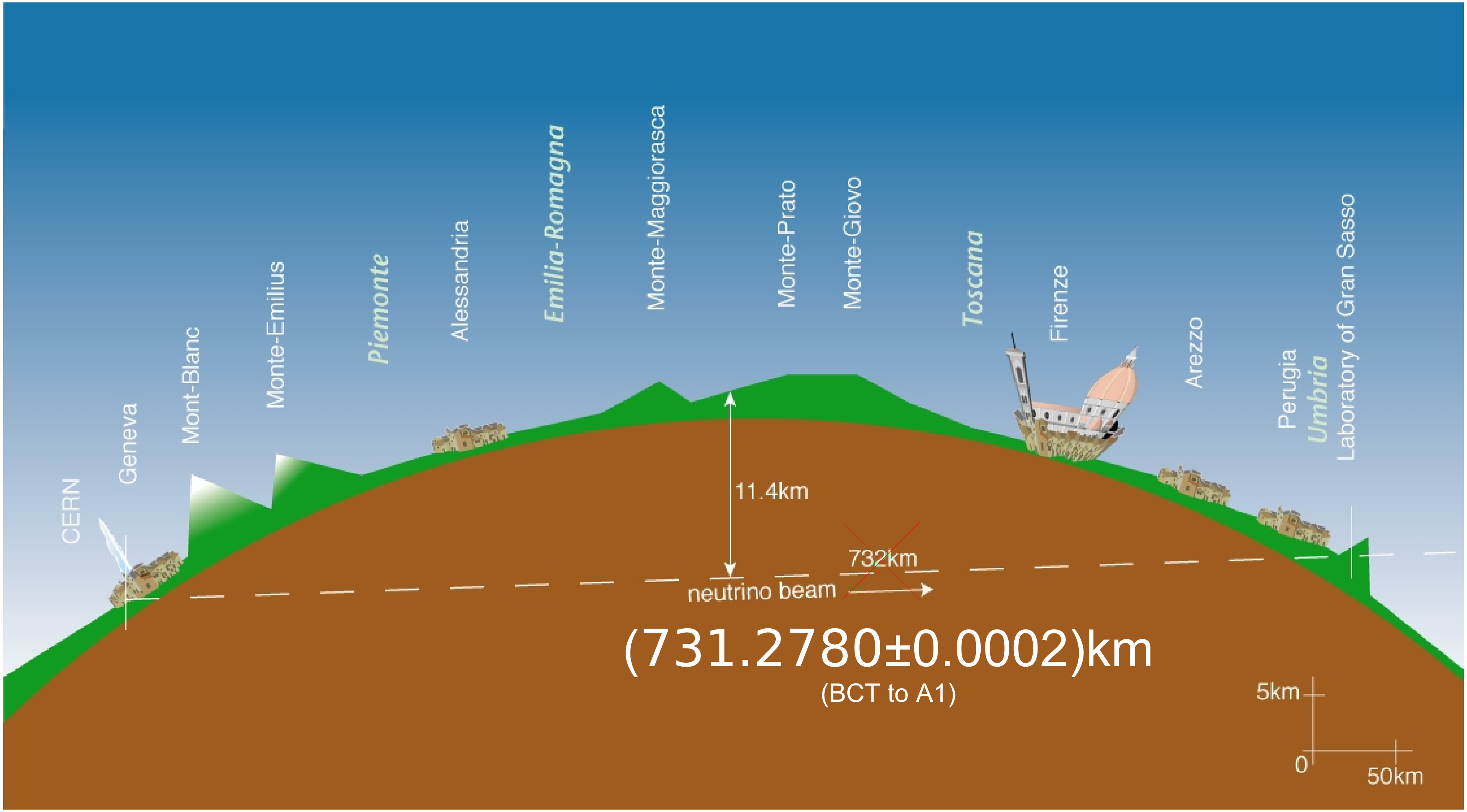
brief history

- 1979: FNAL *(Phys. Rev. Lett. 43 (1979) 1361)*
  - short distance, 30 GeV ν_μ, comparison of ν_μ and μ TOF
  - $|v-c|/c \leq 4\times10^{-5}$
- 1988: SN1987A *(Phys. Lett. B 201 (1988) 353)*
  - very long distance (168.000 light years), 10 MeV anti-ν_e, comparison of ν and photon arrival time (not SN mod.-dep.)
  - $|v-c|/c \leq 2\times10^{-9}$
- 2007: MINOS *(Phys. Rev. D 76 (2007) 072005)*
  - 730km distance, ~3 GeV ν_μ, near detector comparison
  - $(v-c)/c = (5.1 \pm 2.9)\times10^{-5}$
- 2011: OPERA
  - 730km distance, ~17 GeV ν_μ, proton BCT comparison

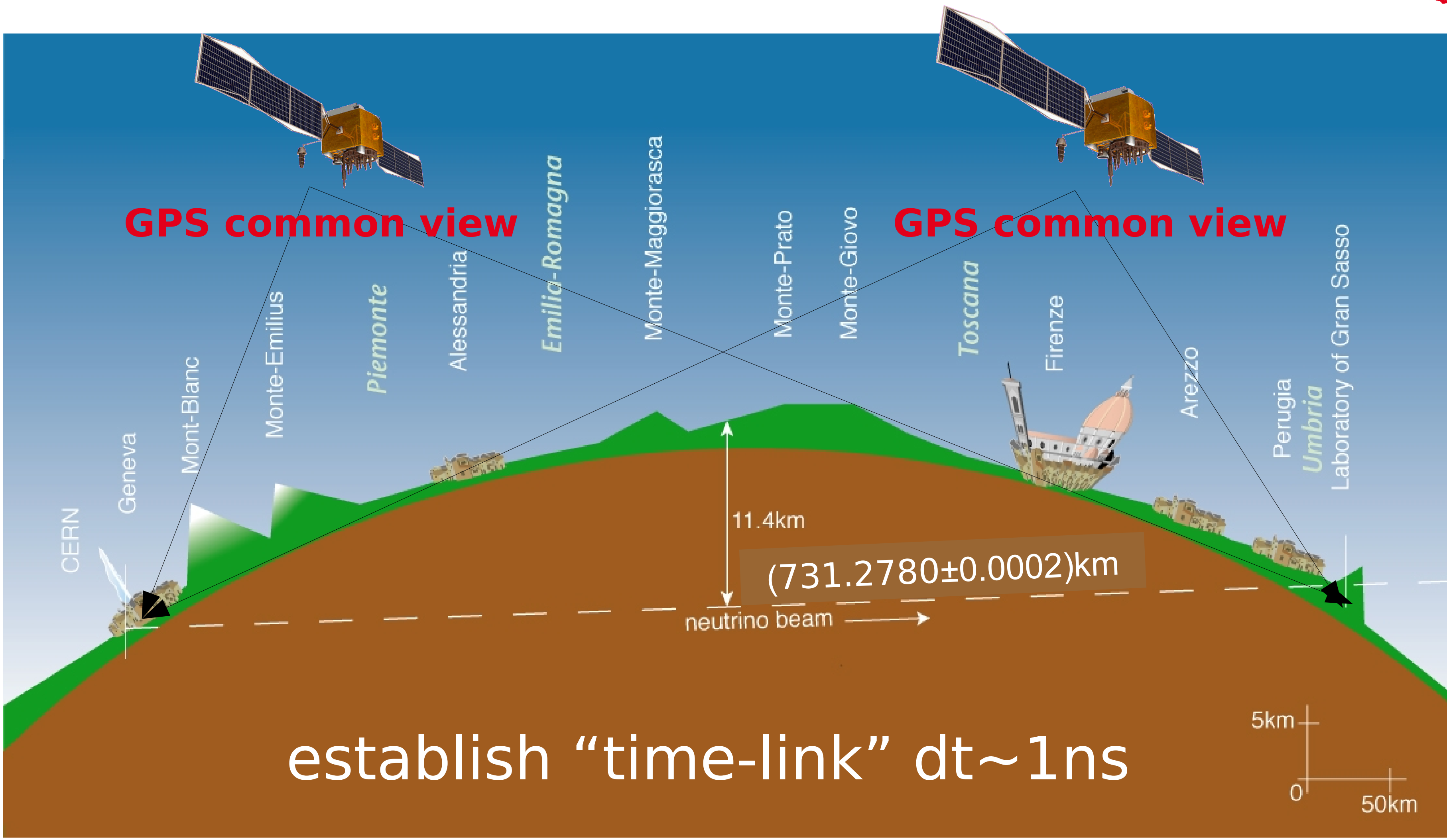
production time t_A



distance measurement

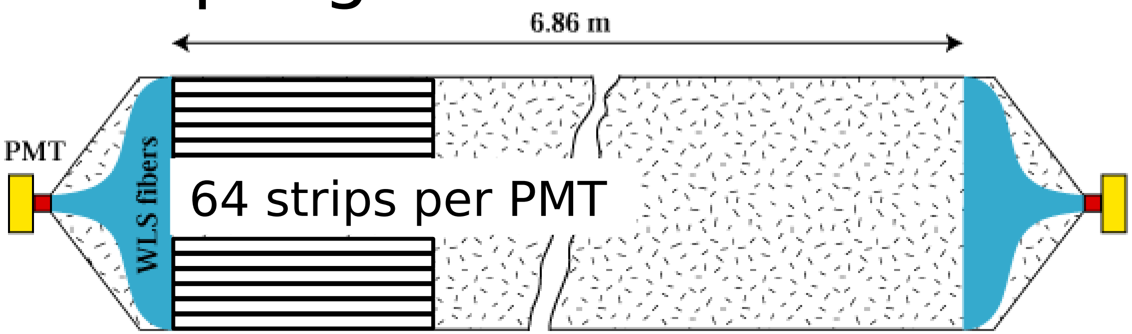


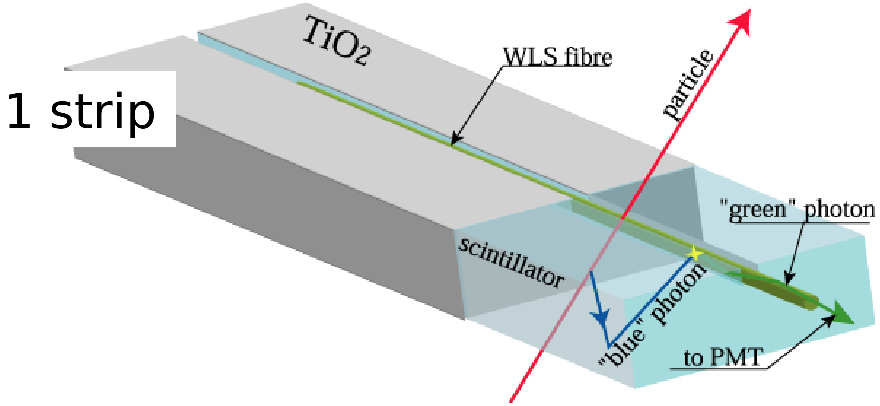
clock synchronization

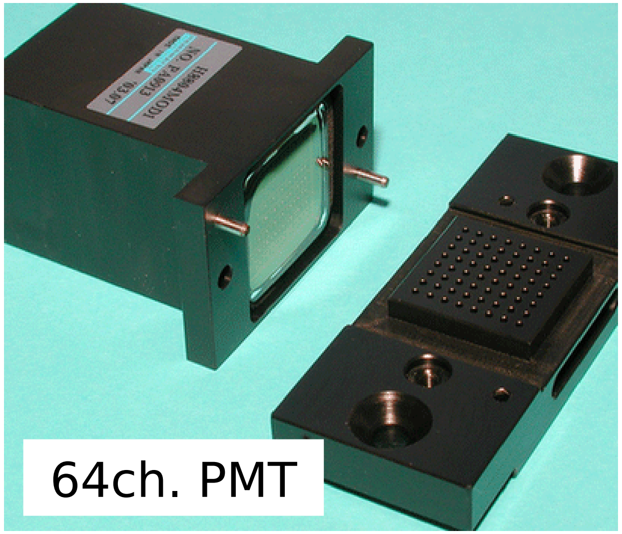


neutrino detection time t_B

- use plastic scintillators only
- first hit in target trackers is the stop signal







September 2011

event selection

- selection of neutrino events
  - internal events (within fiducial volume, same as for the oscillation search): 7586
  - external events (interactions in rock) with reconstructed 3D muon track: 8525 (±2ns additional uncertainty)
  - at least 4 satellites in common view
  - first hit not isolated in time or space

→ 7235 internal and 7988 external events

- if neutrino event passes selection:
  select the corresponding BCT waveform

analysis

- original method:
build likelihood from summed waveforms

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

- alternative method:
build likelihood from single waveforms, (smaller stat. uncertainty, additional syst. uncertainty):

$$\mathrm{L}(\delta t) = \prod_j w_j(t_j + \delta t)$$

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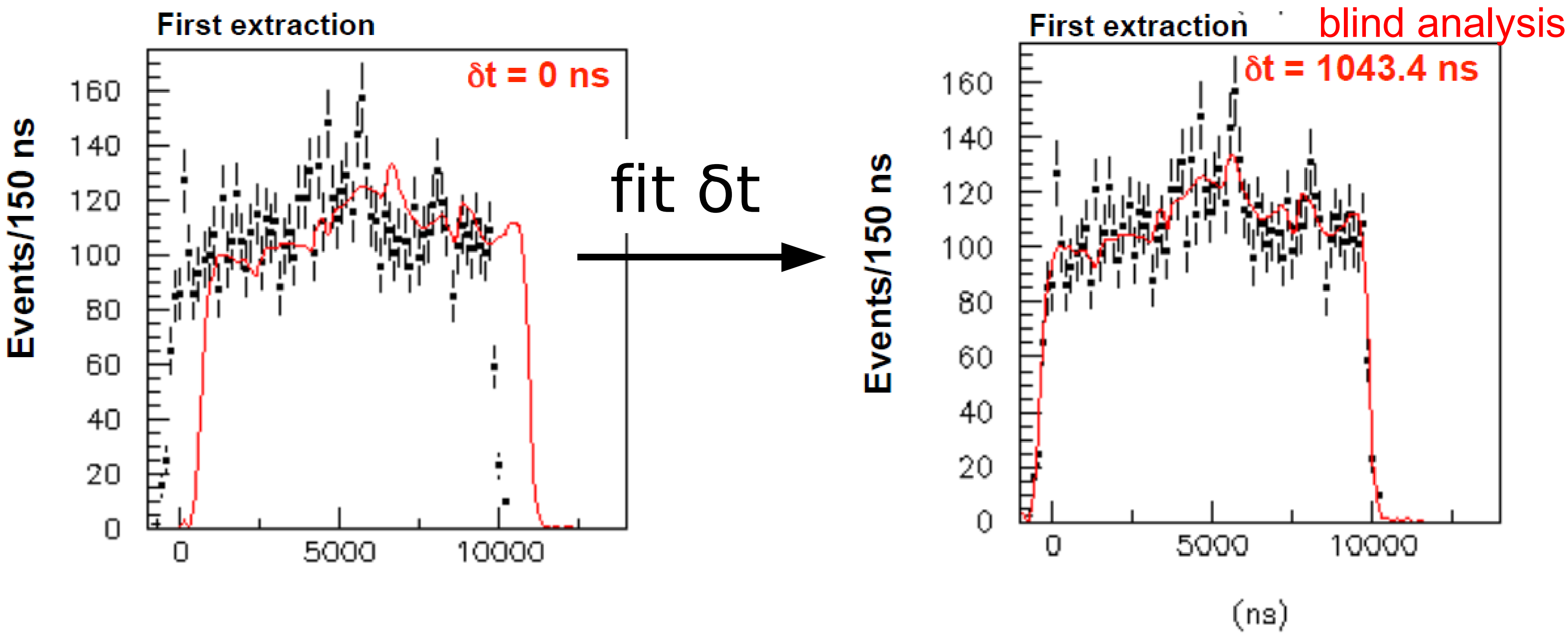
analysis

the red curve is for visualization only!



under investigation

original method: $(57.8 \pm 7.8\ \text{(stat.)}\ ^{+8.3}_{-5.9}\text{(sys.)})$ ns

alternative method: $(54.5 \pm 5.0\ \text{(stat.)}\ ^{+9.6}_{-7.2}\text{(sys.)})$ ns

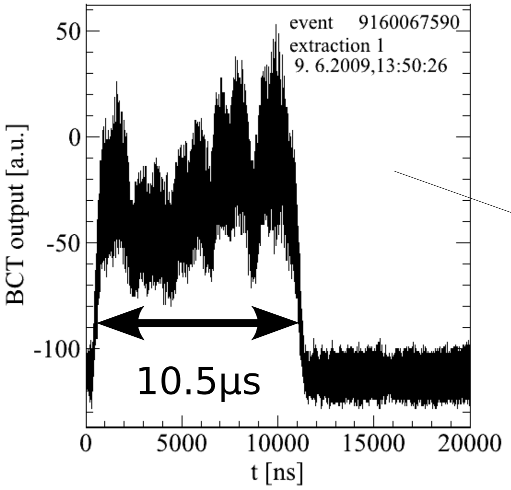
November 2011

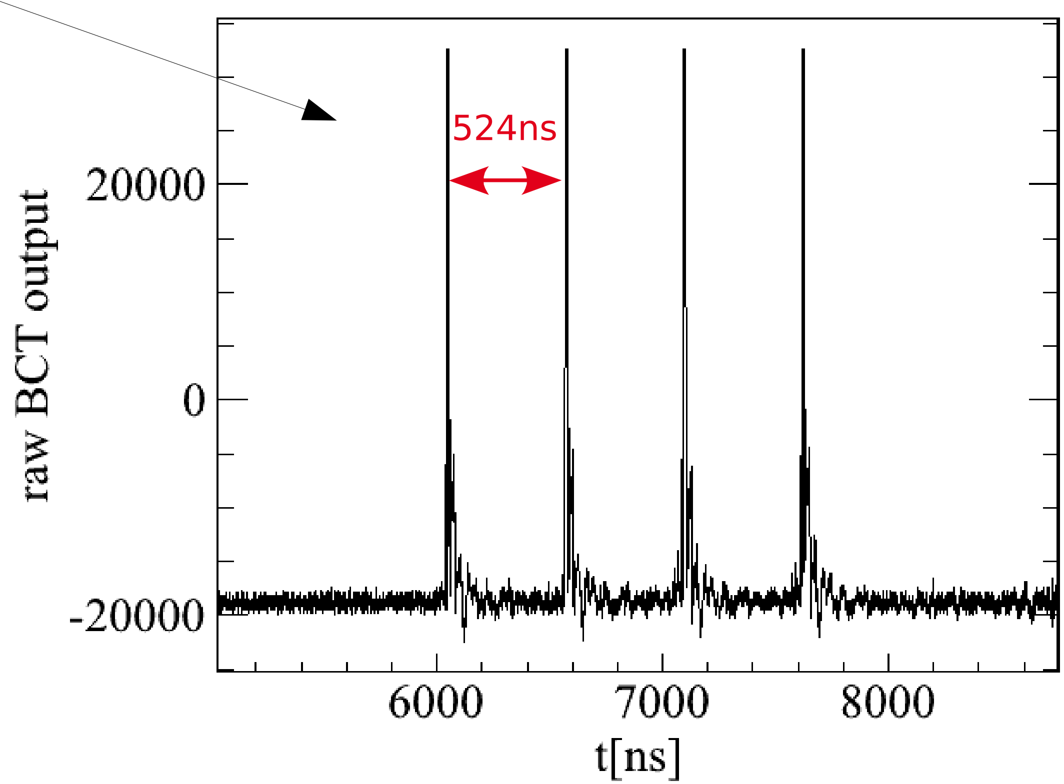
bunched beam (1)

- bunched beam: instead of 10.5µs extractions:
  4 single, 3ns-wide bunches, separated by 524ns
  → single-event TOF measurement!
- October 22 to November 6, 2011
- beam intensity lower than nominal (~1/60)
- collected 35 events, same selection criteria, same delay corrections

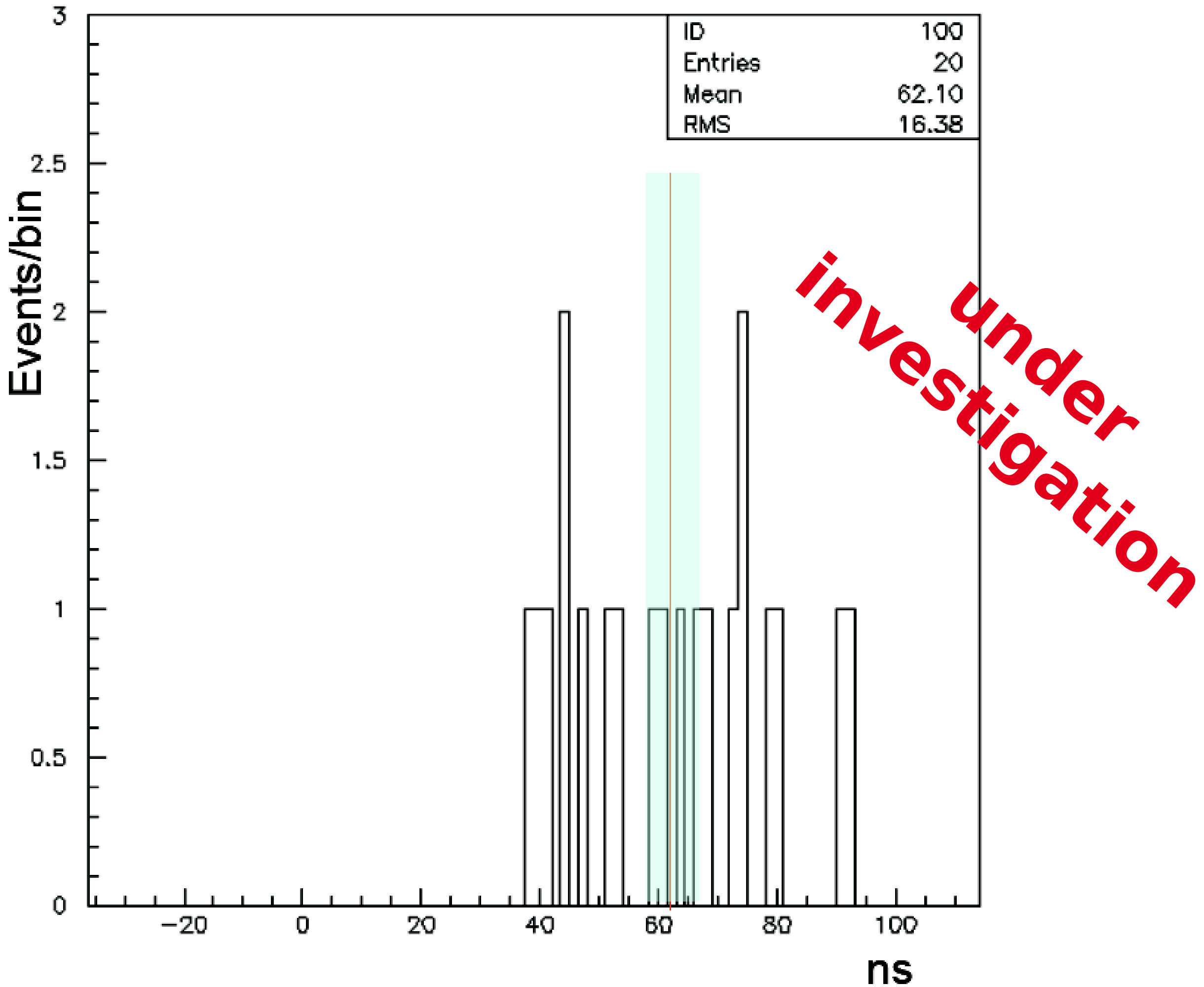
→ 14 external and 6 internal events

bunched beam (2)





bunched beam (3)



bunched beam method: (62.1±3.7 (stat.) $^{+8.3}_{-5.9}$(sys.)) ns

December 2011 - February 2012

OPERA statement

“**The OPERA Collaboration** [...] **has identified two issues that could significantly affect the reported result**.

[...] the **oscillator used to produce the events time-stamps** [...]

[...] the **connection of the optical fiber** [...]” (Feb. 23rd 2012)

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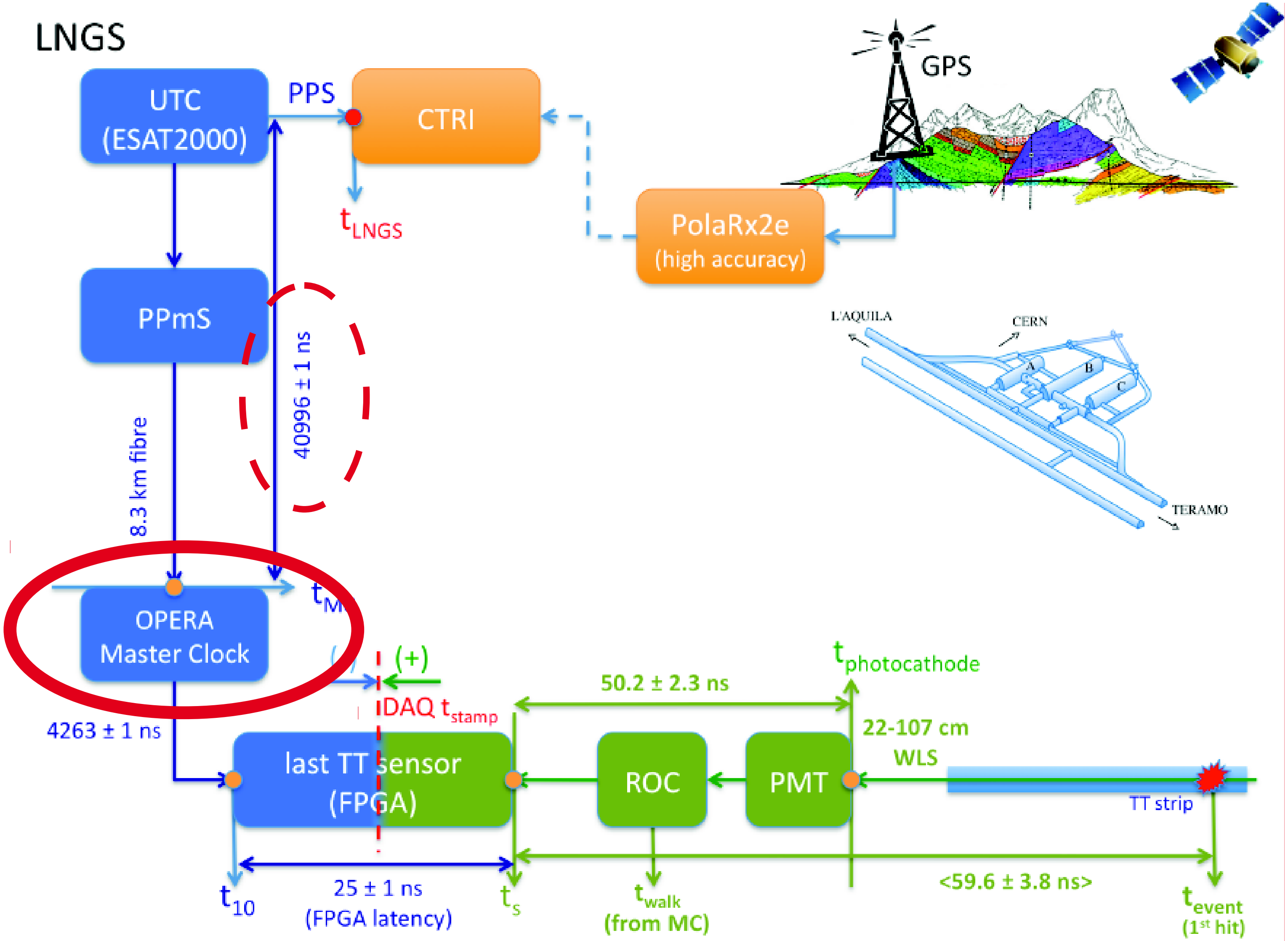
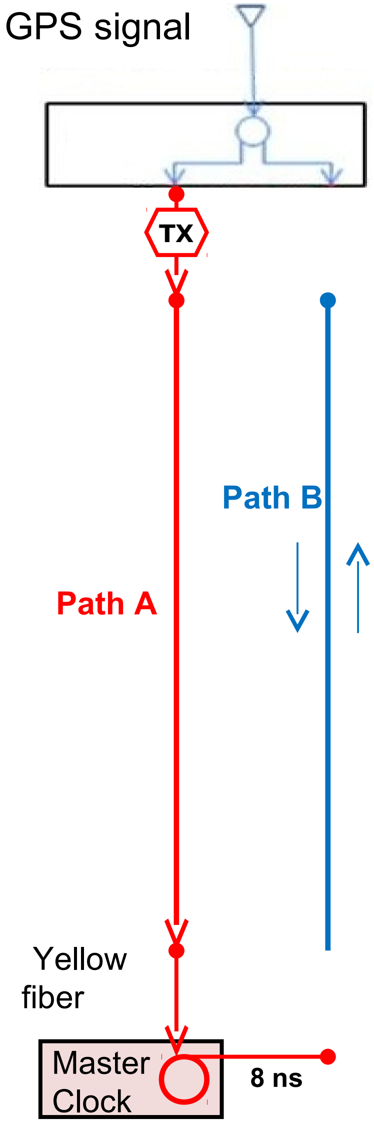
LNGS timing

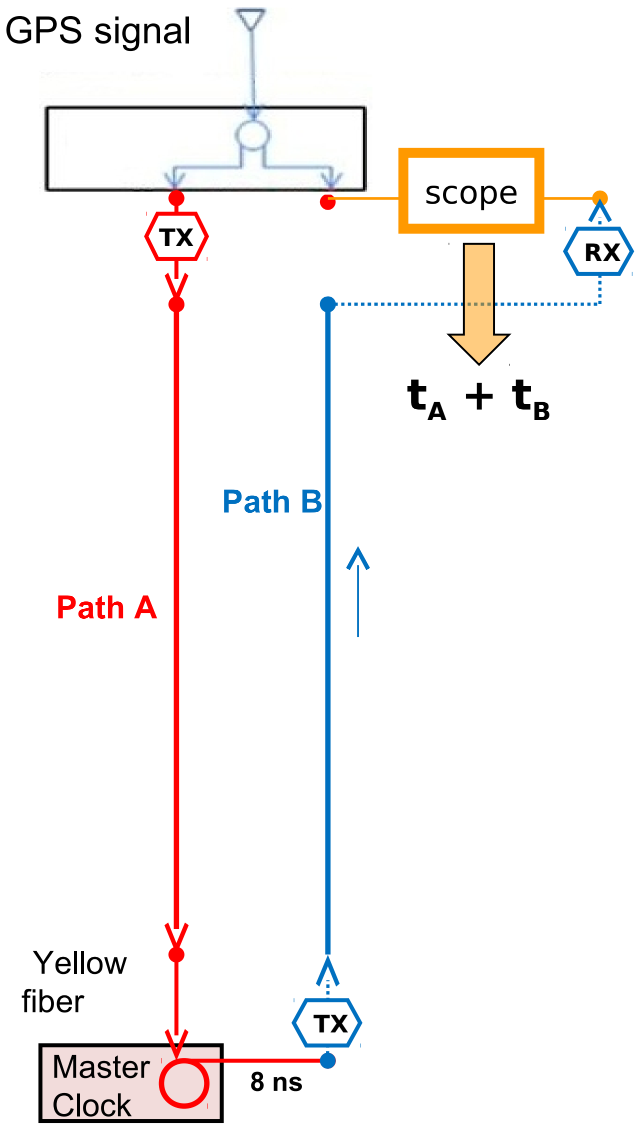


connection of the optical fiber



- ~8.3km long optical fiber
- dedicated campaign Dec11-Feb12
- “two ways measurements” using the same auxiliary fiber

connection of the optical fiber



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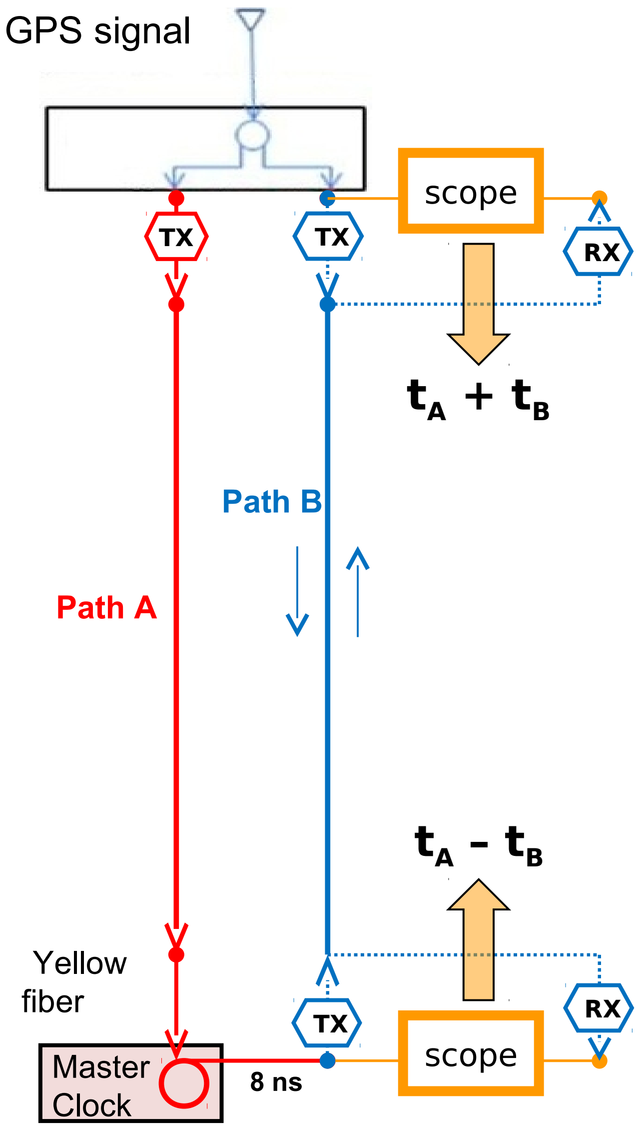
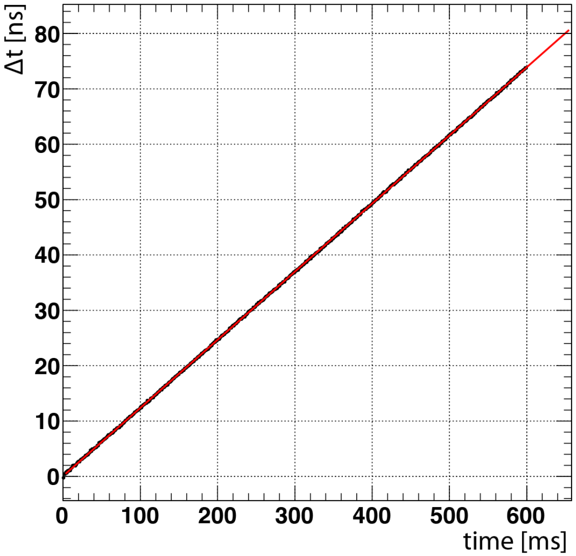
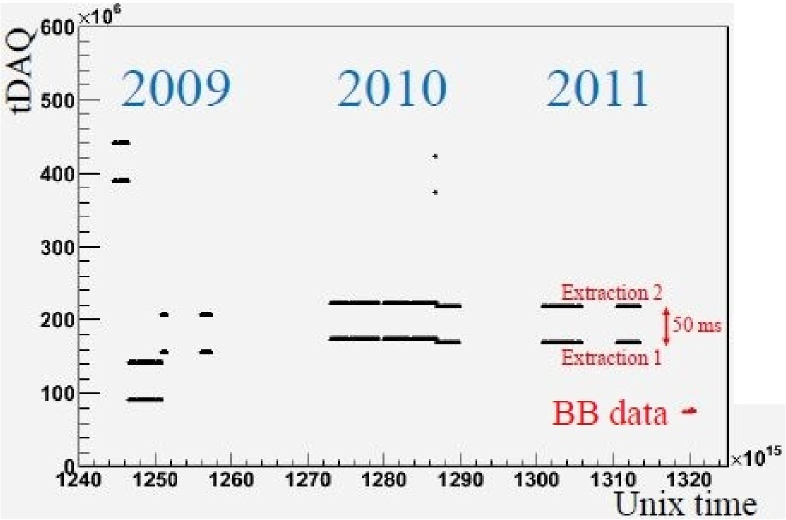


- ~8.3km long optical fiber
- dedicated campaign Dec. 11-Feb. 12
- “two ways measurements” using the same auxiliary fiber
- identified issue: “yellow fiber” connection to Master Clock (MC), dependence of MC analogue circuit response to input light amplitude

→ measured TOF is 74ns too short if fiber delay measured in early Dec. 2011 is taken, it is unchanged if delay measured before 2008 and after 13 Dec 2011 is taken: time when anomalous condition occurred and stability of it is unknown

oscillator (master clock)





- OPERA DAQ is reset every 0.6s
- Within 0.6s long cycle, DAQ timing is performed by an internal 20MHz counter of the Master Clock (MC)

→ internal MC frequency found too high by $\Delta f/f = 1.23 \times 10^{-7}$, OPERA DAQ timestamps are delayed, measured TOF is up to 74ns too long (depending on position in DAQ cycle)

→ CNGS events are NOT equally distributed within each DAQ cycle (event-by-event correction)

TOF summary (1)

- OPERA TOF result under investigation

- time unkown when anomalous conditions occurred during data taking:

  To add information, study of OPERA-LVD coincidences using cosmic muons is being finalized, release is foreseen tomorrow (seminar at LNGS)

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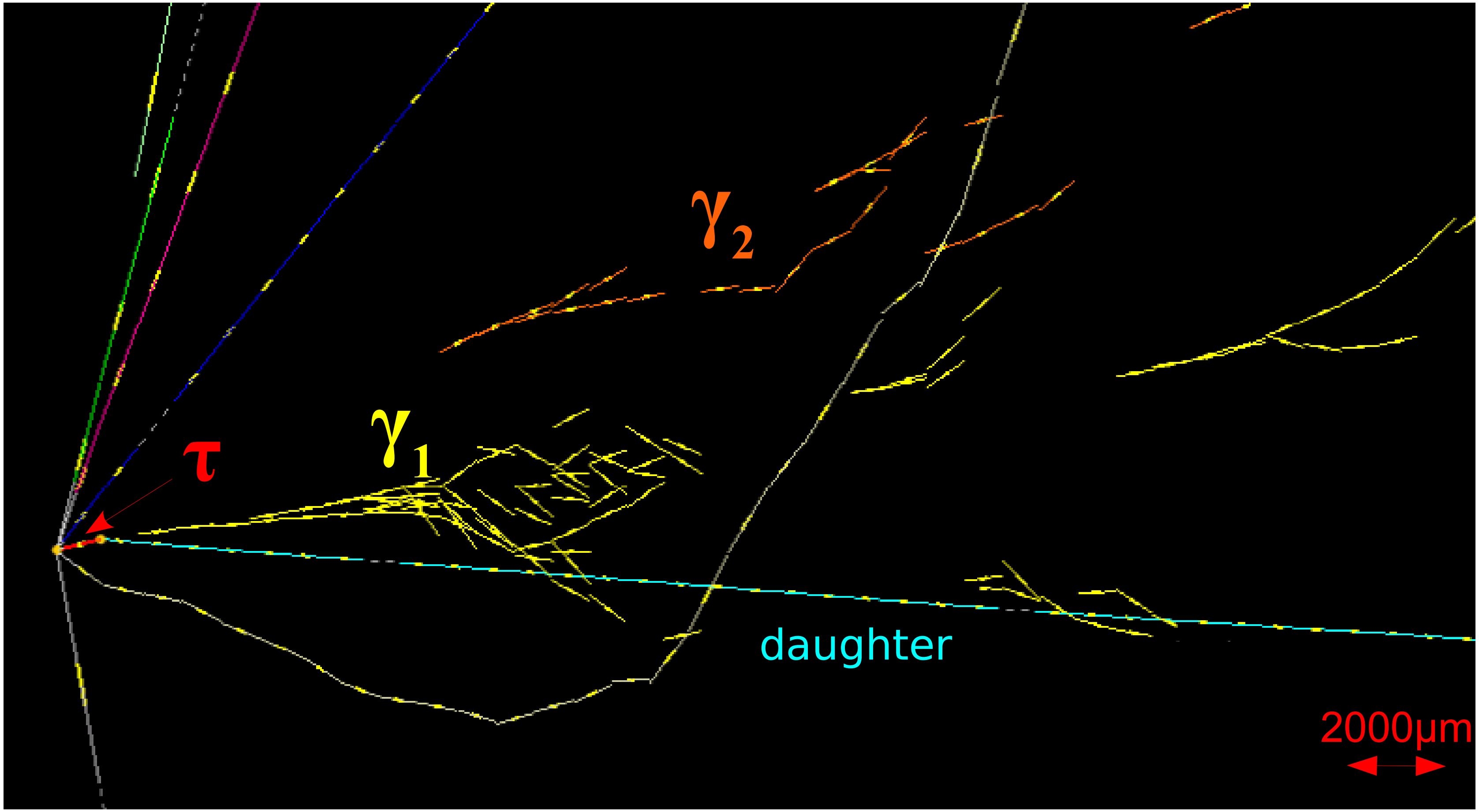
TOF summary (2)

- While additional investigations are being performed to unambiguously quantify the size of the combined effects on the observed neutrino velocity result, the Collaboration is looking forward to perform a new measurement as soon as a new bunched beam will be available in 2012.

- Note: all LNGS experiments share the (BCT based) CERN timing, the GPS common view hardware and the CERN-LNGS distance measurement.

overall summary

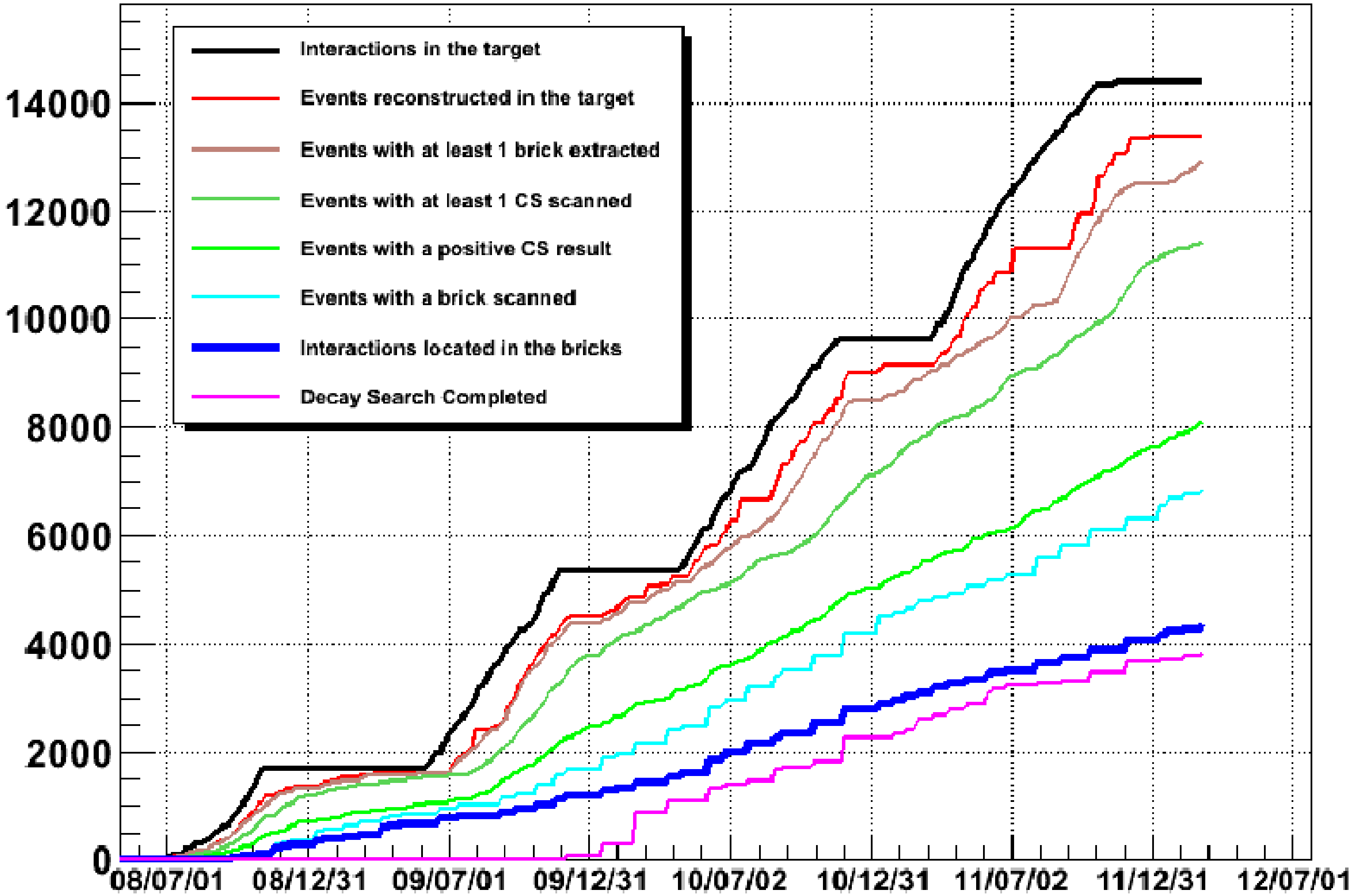
- OPERA is a neutrino oscillation experiment
- found 1 ν_τ candidate, while 0.05±0.01 bkgd. events were expected. The analyzed sample corresponds to about 25% of the overall data collected until end of 2012
- electron neutrino appearance results in 2012
- no data taking in 2013 (CERN shutdown)



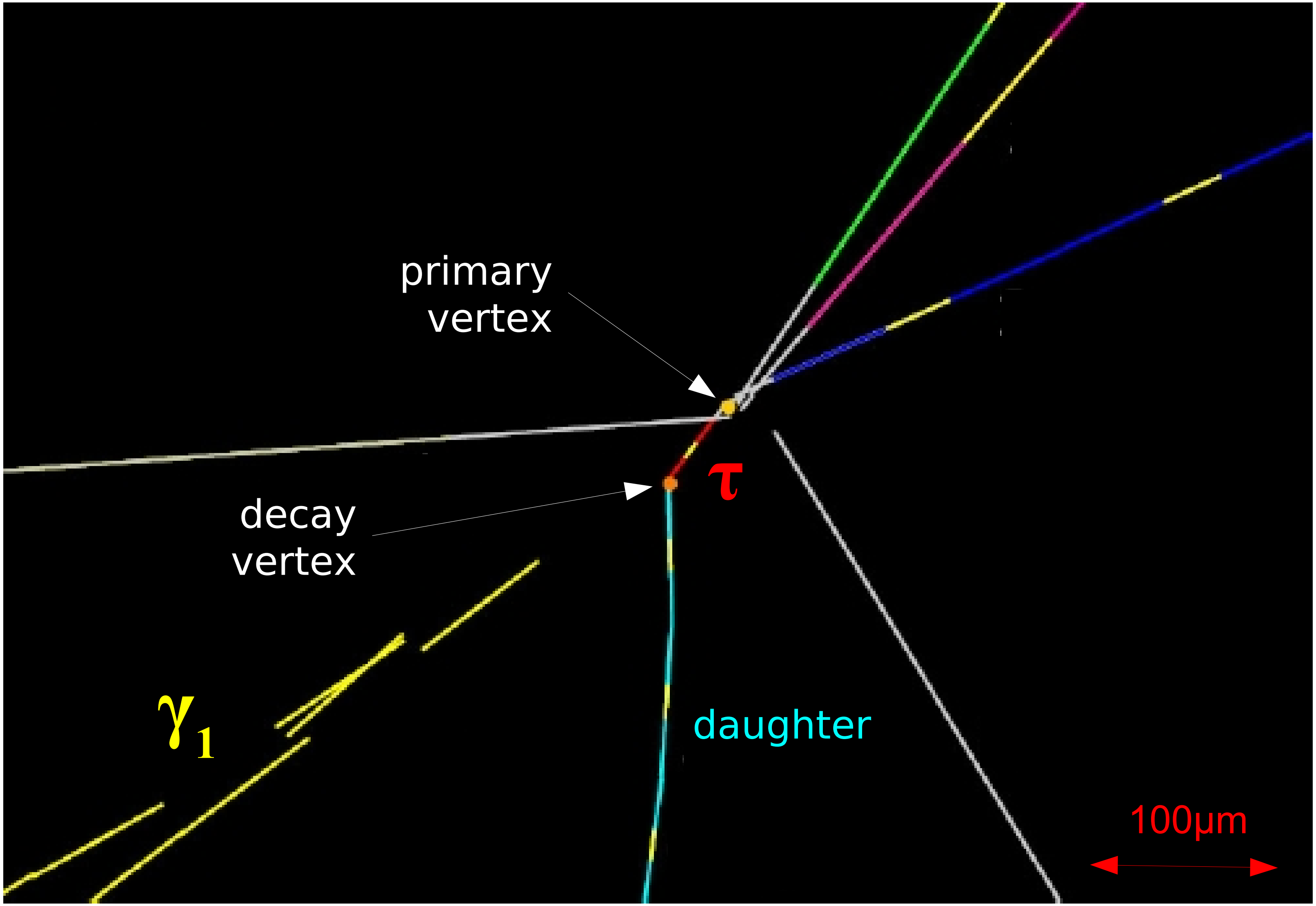
Thank you!

backup

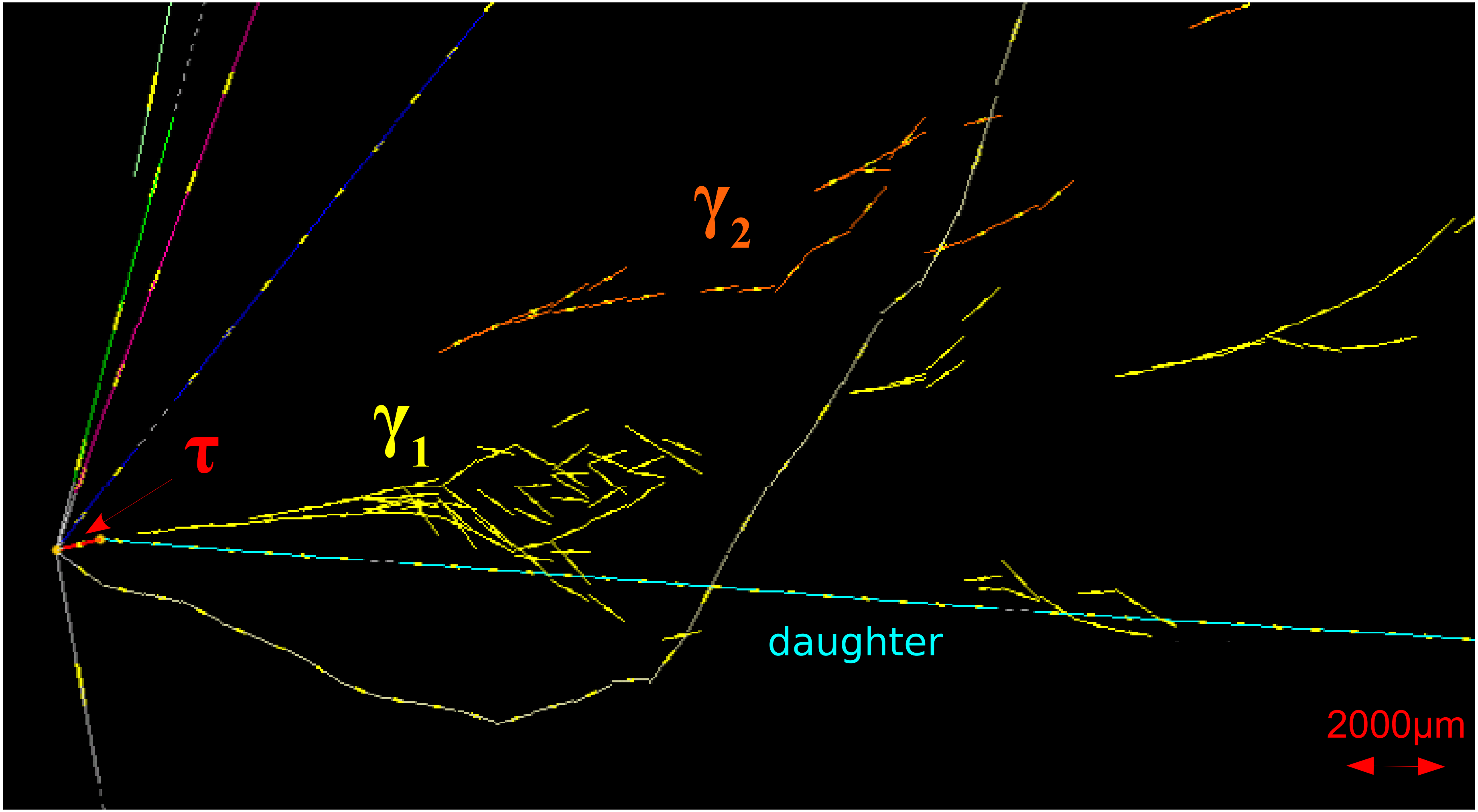
search procedure status



tau candidate event (1)



tau candidate event (2)



selection cuts, tau candidate

Variable	Cut-off	Value
Missing P_T at primary vertex (GeV/c)	<1.0	$0.57^{+0.32}_{-0.17}$
Angle between parent track and primary hadronic shower in the transverse plane (rad)	$> \pi/2$	3.01 ± 0.03
Kink angle (mrad)	>20	41 ± 2
Daughter momentum (GeV/c)	>2	12^{+6}_{-3}
Daughter P_T when γ-ray at the decay vertex (GeV/c)	>0.3	$0.47^{+0.24}_{-0.12}$
Decay length (μm)	<2 lead plates	1335 ± 35

kinematical analysis, tau cand.

- kinematical analysis:
  - two EM showers (γ_1 and γ_2) pointing towards decay vertex, invariant mass: (120 ± 20(stat.) ± 35(syst.))MeV/c²

    hypothesis: $\pi^0 \to \gamma\gamma$ ($m_{\pi 0}$=135MeV/c²)

  - daughter is a charged hadron, most likely a charged pion, invariant mass (π+2γ): $(640^{+125}_{-80}\ \text{(stat.)}^{+100}_{-90}\ \text{(syst.)})\,\text{MeV/c}^2$

    hypothesis: $\rho^- \to \pi^0 \pi^-$ ($m_{\rho-}$=770MeV/c²)

  - single-prong hadronic tau decay

    hypothesis: $\tau^- \to \rho^- + \nu_\tau$ (B.R. ~25%)

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

    $\pi^0 \to \gamma\gamma$

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tau background and efficiency

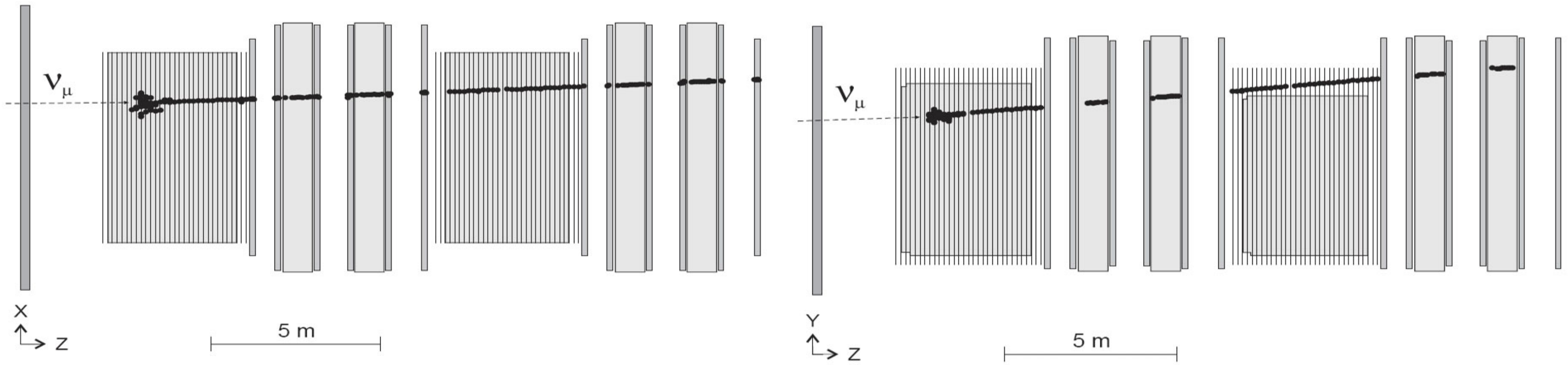
Decay channel	Number of background events expected for 22.5×10^{19} p.o.t.				4.88×10^{19} p.o.t.			
	Charm	Hadron	Muon	Total	Charm	Hadron	Muon	Total
$\tau \to \mu$	0.025	0.00	0.07	0.09 ± 0.04	0.00	0.00	0.02	0.02 ± 0.01
$\tau \to e$	0.22	0.00	0.00	0.22 ± 0.05	0.05	0.00	0.00	0.05 ± 0.01
$\tau \to h$	0.14	0.11	0.00	0.24 ± 0.06	0.03	0.02	0.00	0.05 ± 0.01
$\tau \to 3h$	0.18	0.00	0.00	0.18 ± 0.04	0.04	0.00	0.00	0.04 ± 0.01
Total	0.55	0.11	0.07	0.73 ± 0.15	0.12	0.02	0.02	0.16 ± 0.03

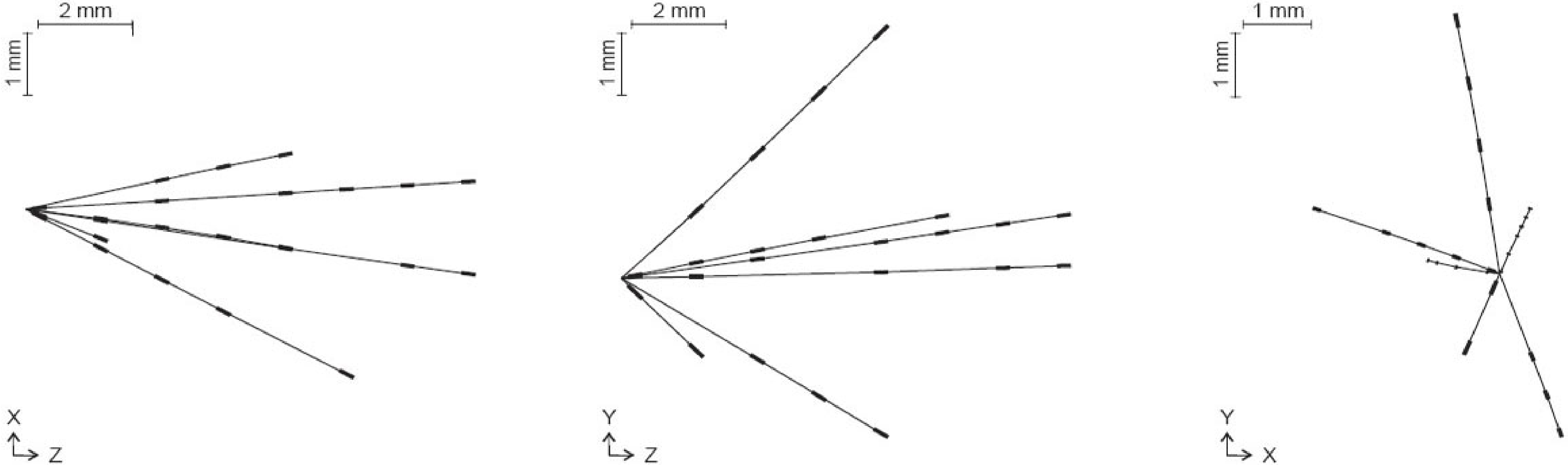
Decay channel	Number of signal events expected for 22.5×10^{19} p.o.t.	4.88×10^{19} p.o.t.	Interaction vertex location efficiency	Global τ detection efficiency
$\tau \to \mu$	1.79	0.39	0.54	0.09
$\tau \to e$	2.89	0.63	0.59	0.14
$\tau \to h$	2.25	0.49	0.59	0.04
$\tau \to 3h$	0.71	0.15	0.64	0.04
Total	7.63	1.65	0.59	0.07

charm candidates

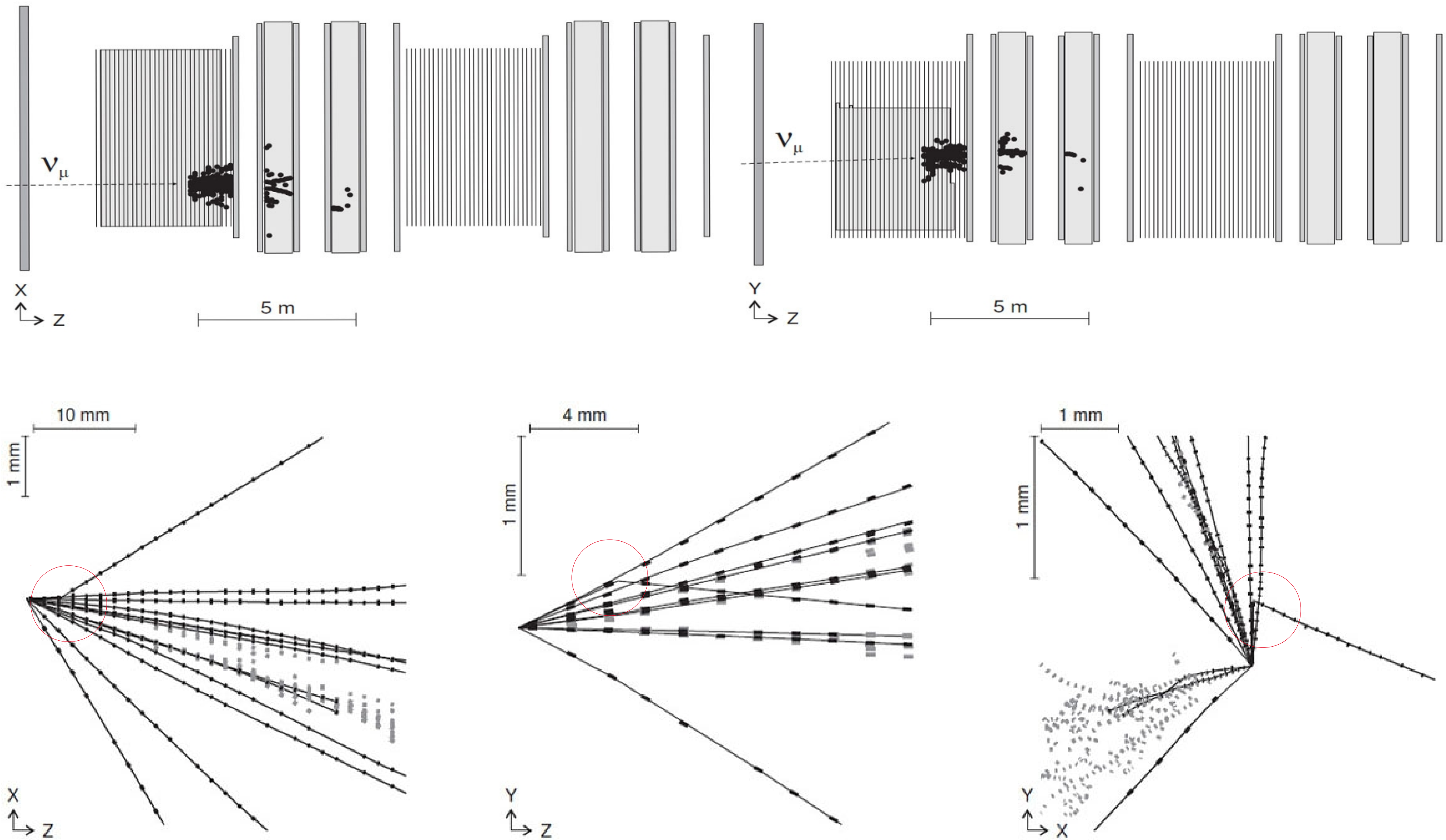
Topology	Observed charm candidate events	Expected events		
		Charm	Background	Total
Charged 1-prong	13	15.9	1.9	17.8
Neutral 2-prong	18	15.7	0.8	16.5
Charged 3-prong	5	5.5	0.3	5.8
Neutral 4-prong	3	2.0	<0.1	2.1
Total	39	39.1 ± 7.5	3.0 ± 0.9	42.2 ± 8.3

ν_μ CC event

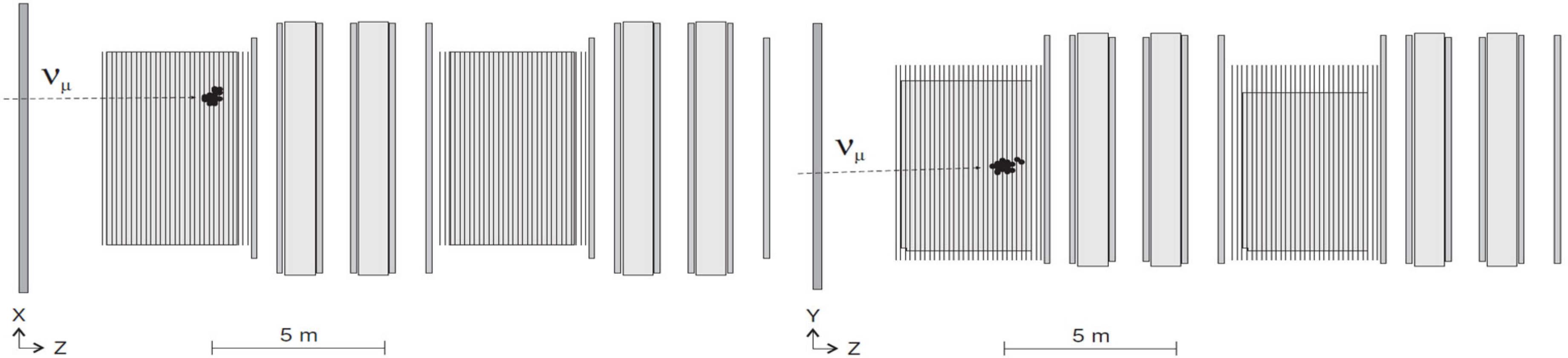


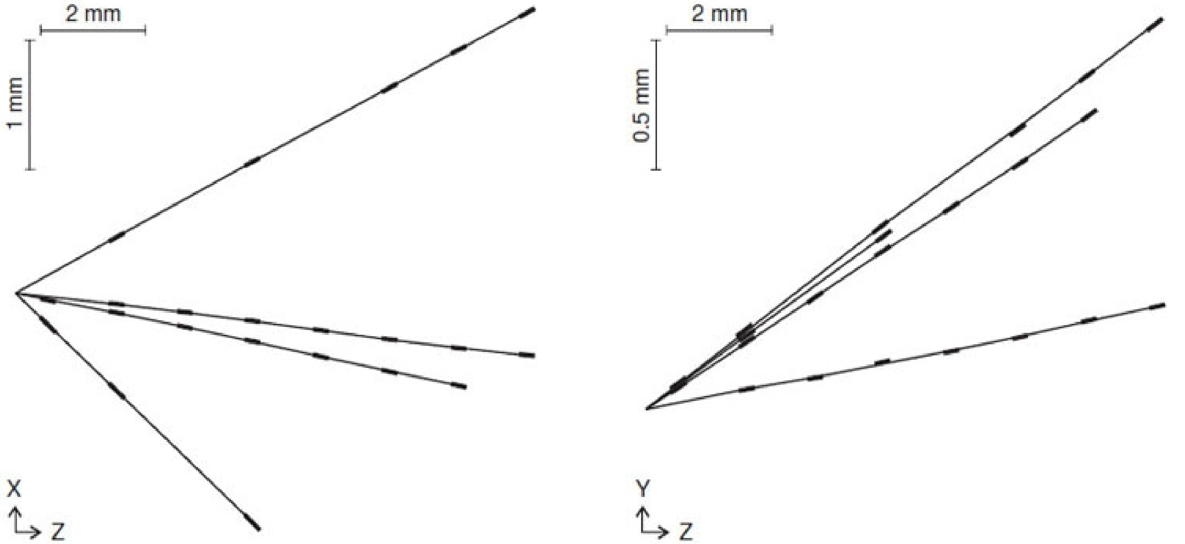


ν_μ charm event

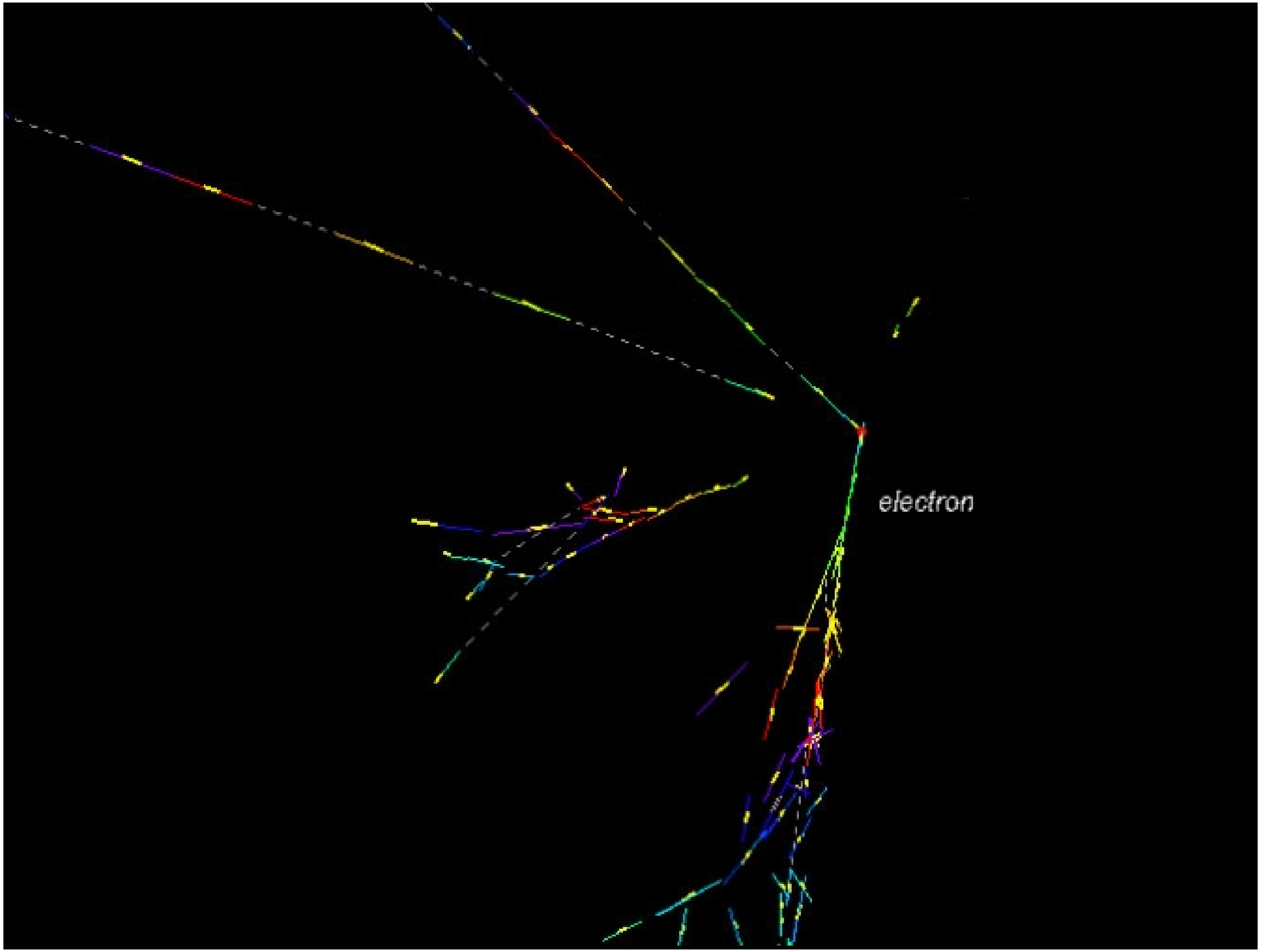


ν NC event





ν_e candidate



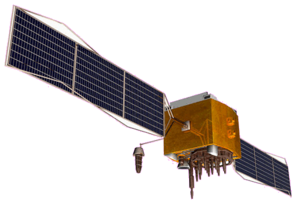
clock synchronization

- identical system of GPS receivers and Cs clocks at CERN and LNGS
- use GPS "common view": the same satellites seen by receivers at CERN and LNGS
- dual-frequency GPS, "ionosphere-free" P3 code
- locations at CERN and LNGS known with high accuracy
- calibrated by METAS, cross-checked by PTB
- establish "time-link" dt~1ns

distance measurement

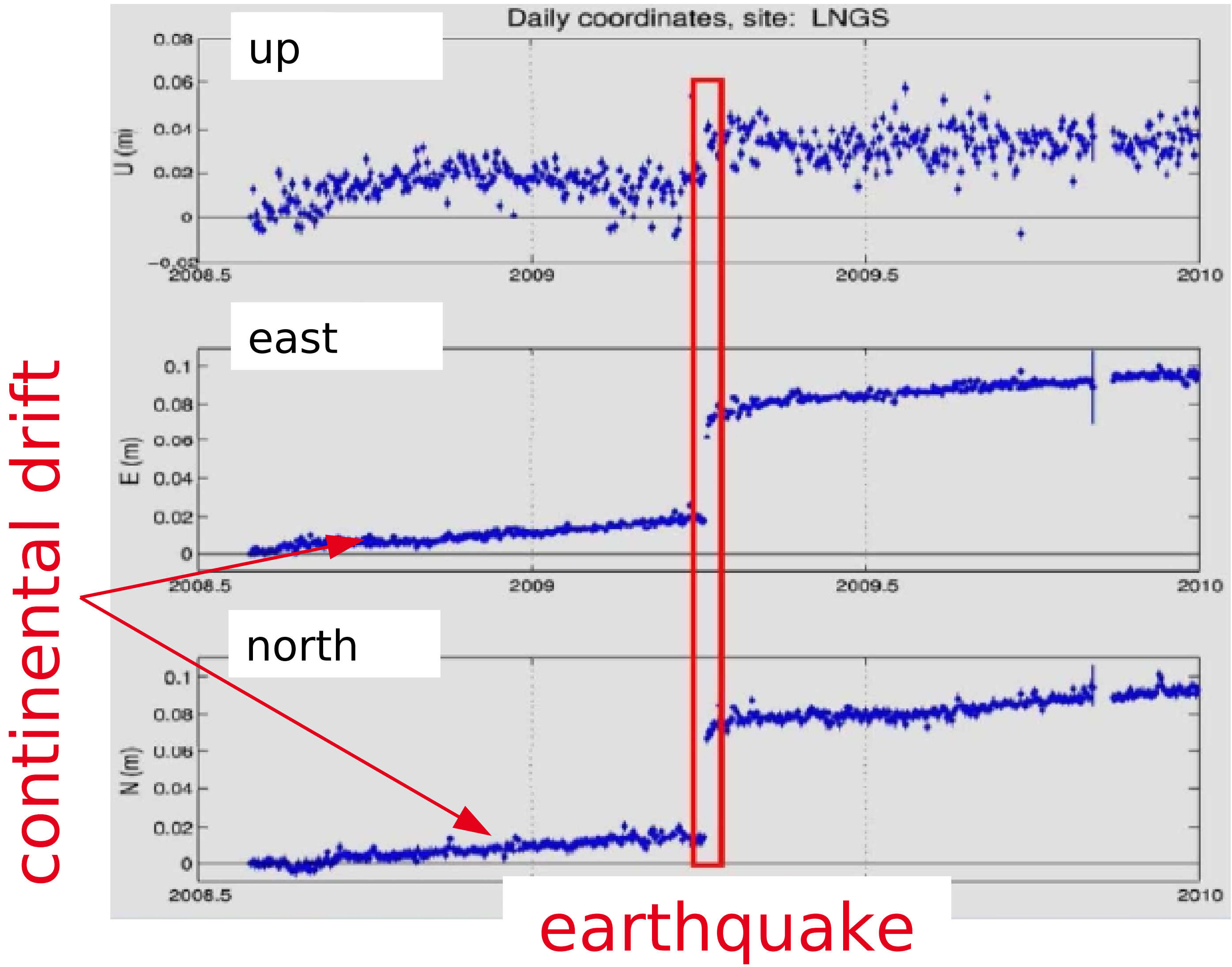
- CERN ↔ LNGS above-ground: GPS
  - establish new GPS benchmarks on both sides of the 10km highway tunnel
  - measure reference GPS points at CERN and LNGS (2010)
  - cross-checked CERN and LNGS reference points (June 2011)
- LNGS ↔ OPERA underground: optical
  - block traffic (partially*) on highway, use theodolites

    (* reason for “bad” accuracy of only 0.2m)



$$d(\mathrm{OPERA}_{A1}-\mathrm{CERN}_{BCT}) = (731278.0 \pm 0.2)\ \mathrm{m}$$

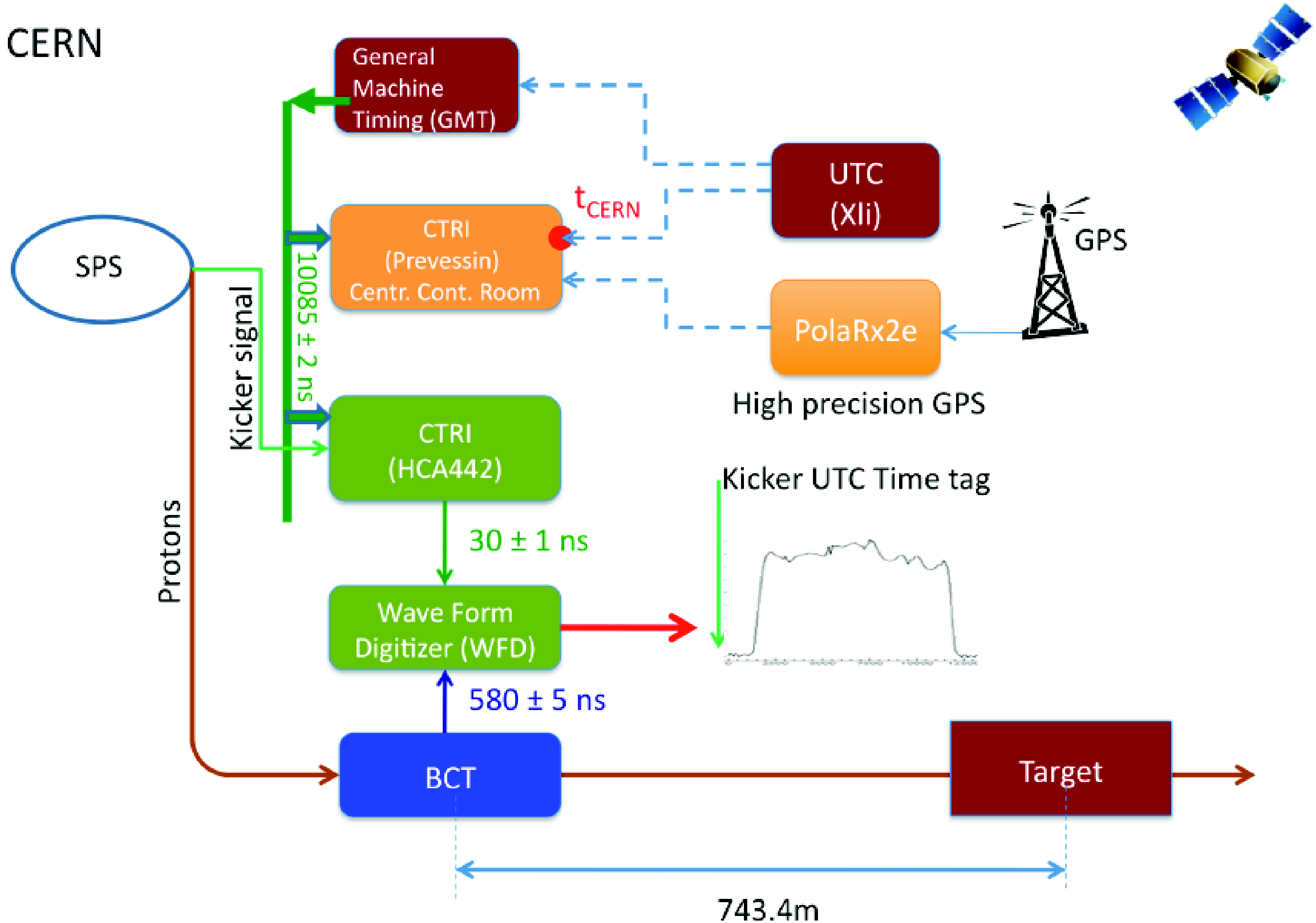
LNGS position monitoring



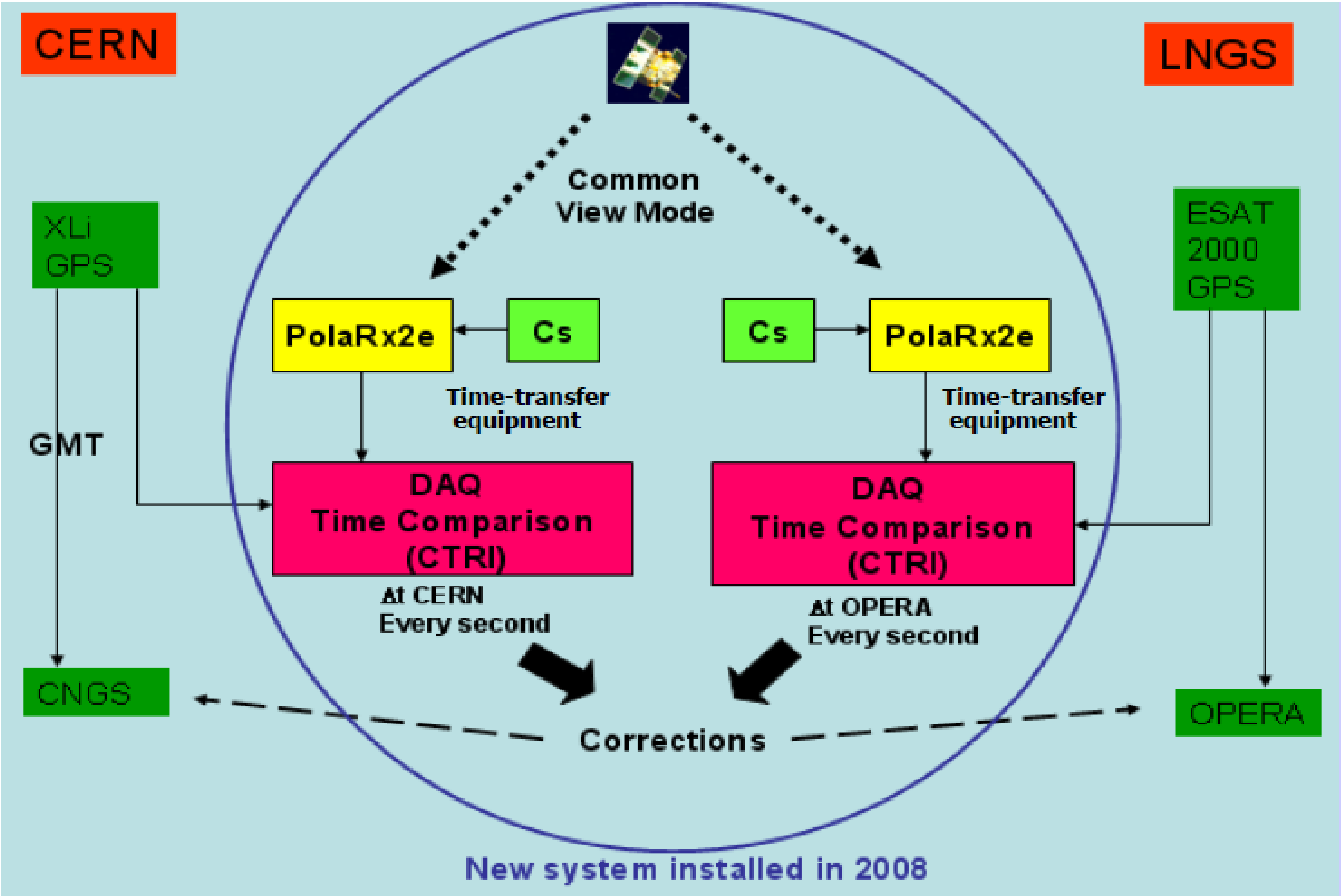
systematic uncertainties

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**	

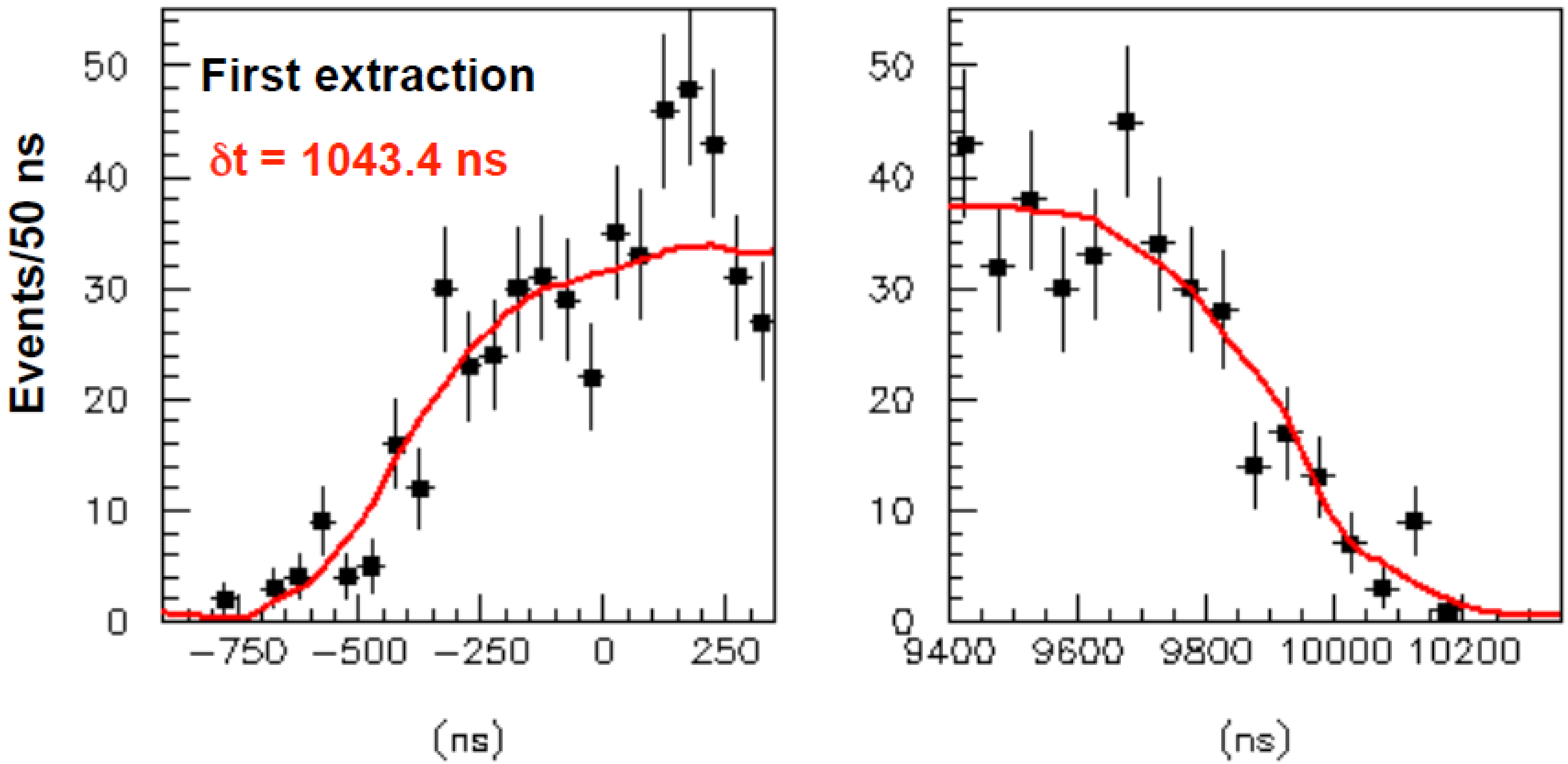
CERN timing


CERN
General Machine Timing (GMT)
UTC (XIi)
t_{CERN}
GPS
SPS
CTRI (Prevessin) Centr. Cont. Room
PolaRx2e
High precision GPS
Kicker signal
10085 ± 2 ns
CTRI (HCA442)
Kicker UTC Time tag
Protons
30 ± 1 ns
Wave Form Digitizer (WFD)
580 ± 5 ns
BCT
Target
743.4m

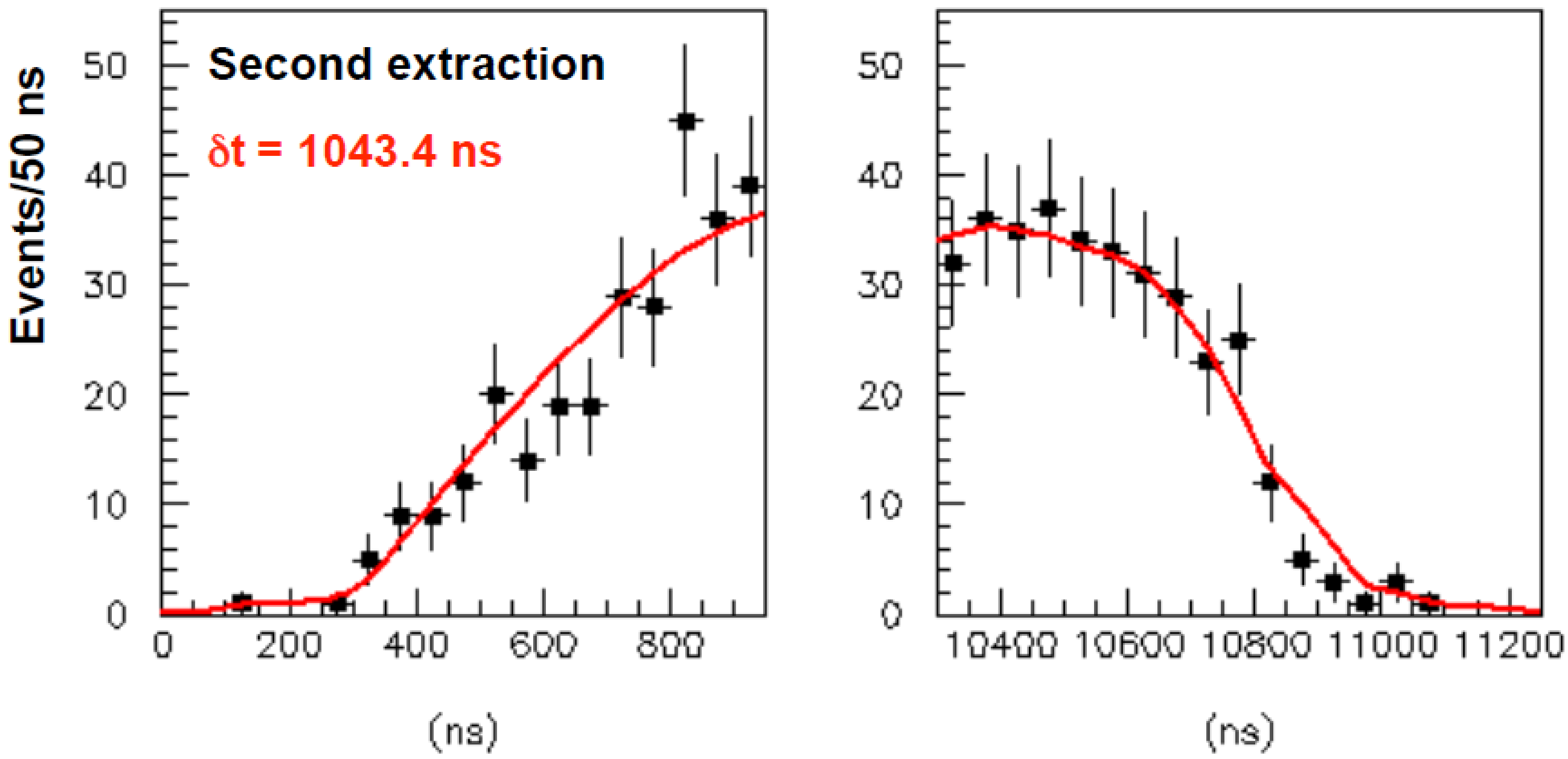
clock synchronization



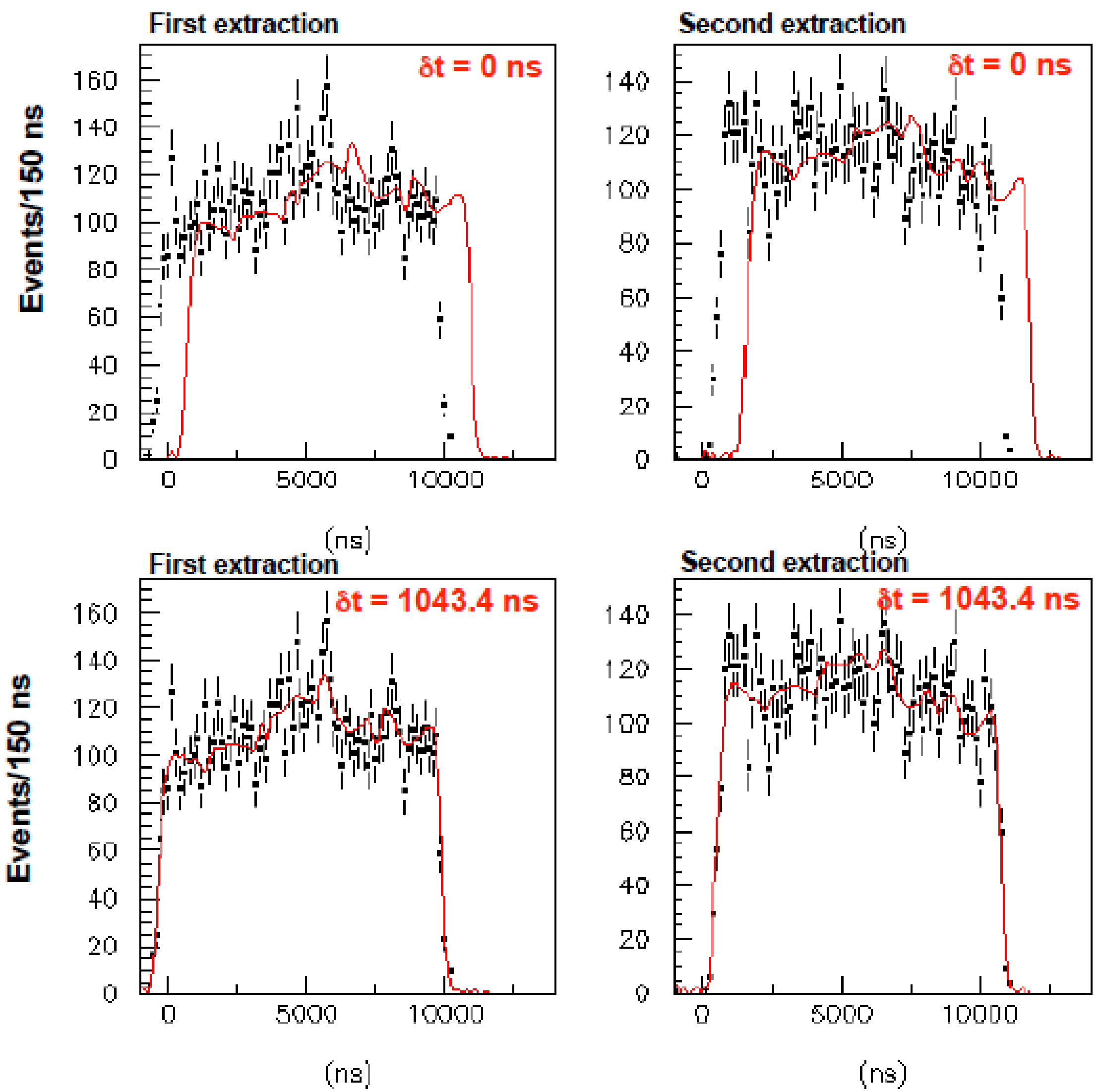
edges extraction 1



edges extraction 2



fit


First extraction
δt = 0 ns
Second extraction
δt = 0 ns
First extraction
δt = 1043.4 ns
Second extraction
δt = 1043.4 ns
Events/150 ns
Events/150 ns
(ns)
(ns)
(ns)
(ns)
0
5000
10000

first hit distribution

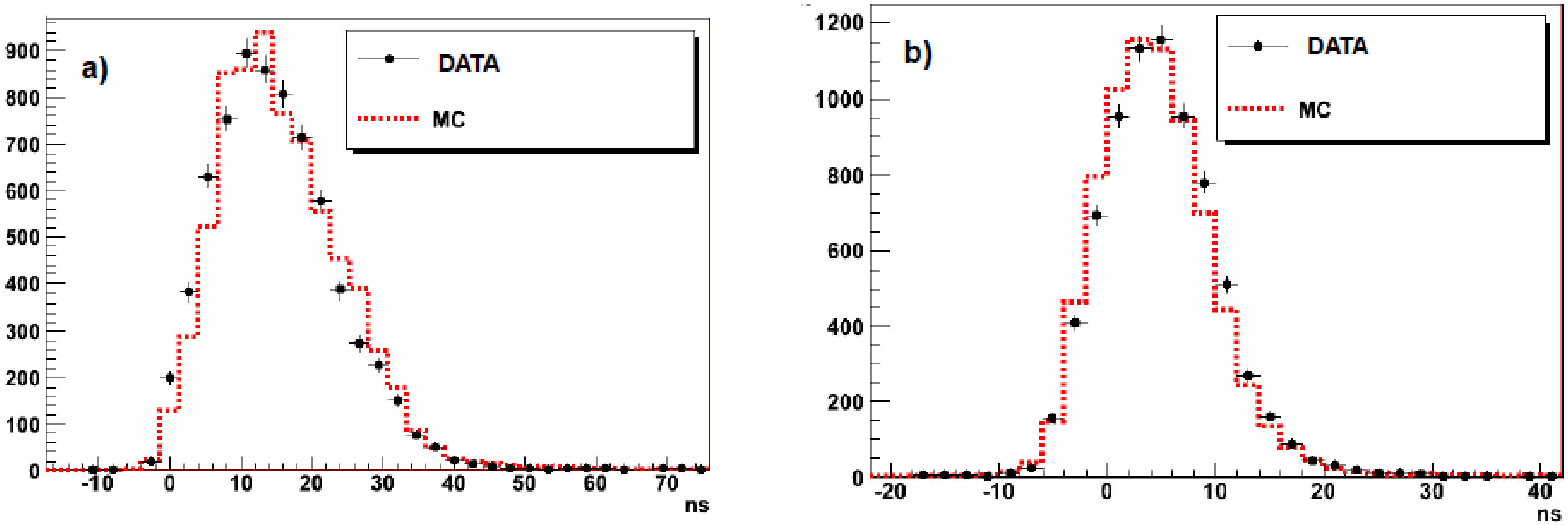


Fig. 9: Distribution of the time difference between the earliest TT hit and: a) the average time of the event, b) the average time of the muon track. Dots with error bars indicate data and the dotted line simulated events. Plot a) includes only internal events while plot b) only external events. The distributions are corrected for the longitudinal position of the hits.