Neutrino velocity measurement with ICARUS

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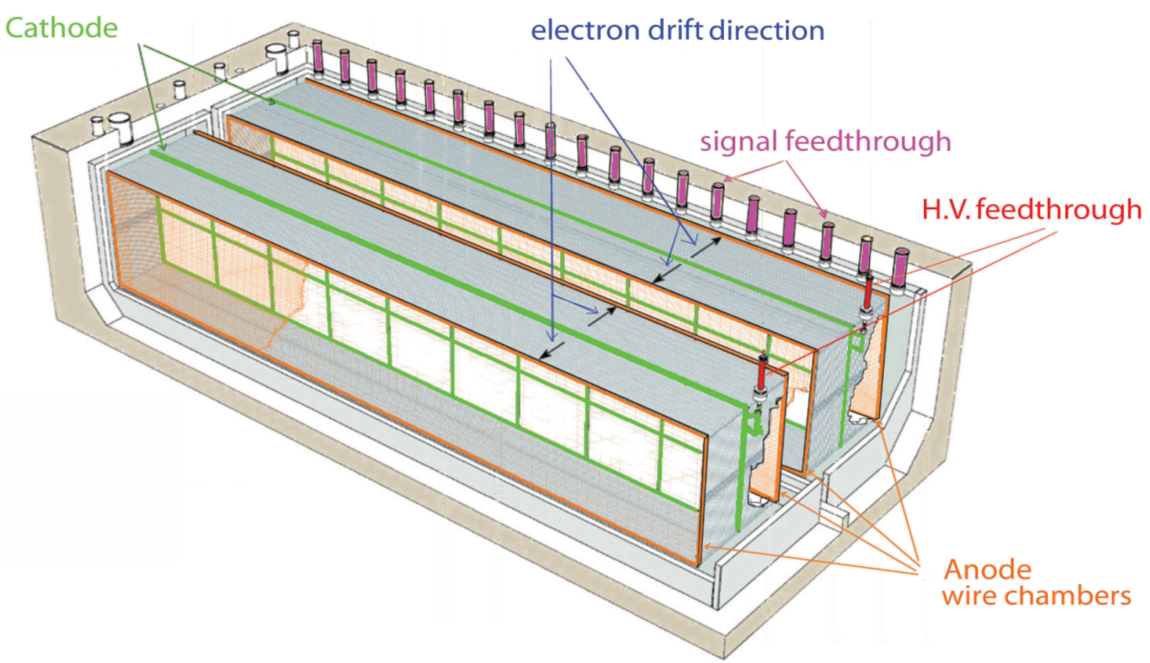
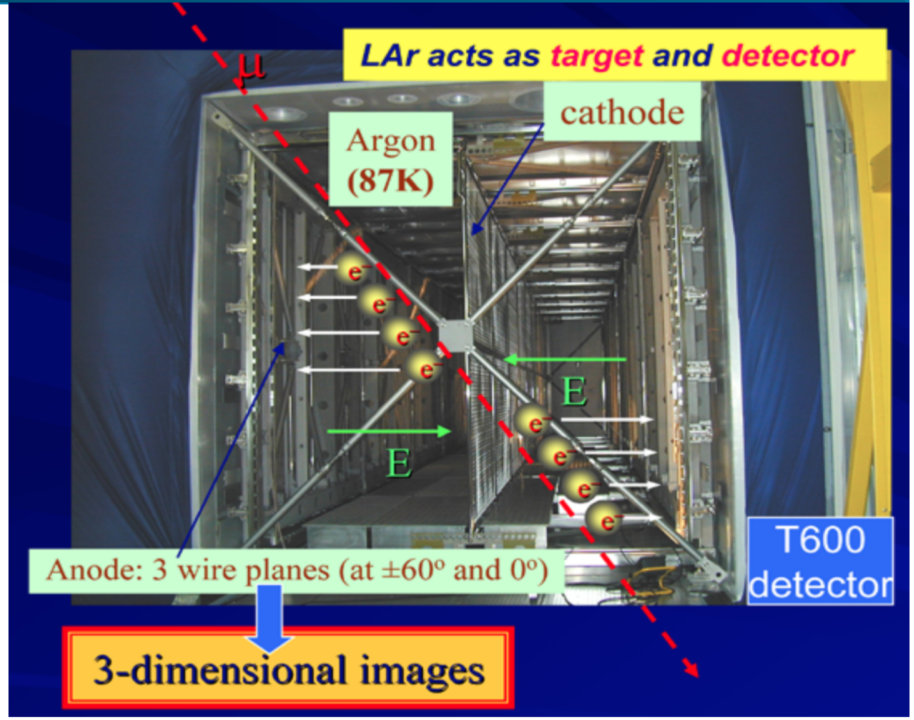
LNGS, 28-3-2013 – Mini workshop on neutrino velocity

ICARUS contribution to the superluminal neutrino problem

- A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS. (ICARUS Coll. and A. Cohen (Boston Univ.), arXiv:1109.6562)
- Measurement of the neutrino time-of-flight with the ICARUS detector at the CNGS beam. (ICARUS Coll. and P. Alvarez Sanchez, J. Serrano (CERN), arXiv:1203.3433)
- Participation in the new measurement campaign in 2012.

The ICARUS T600 detector





- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

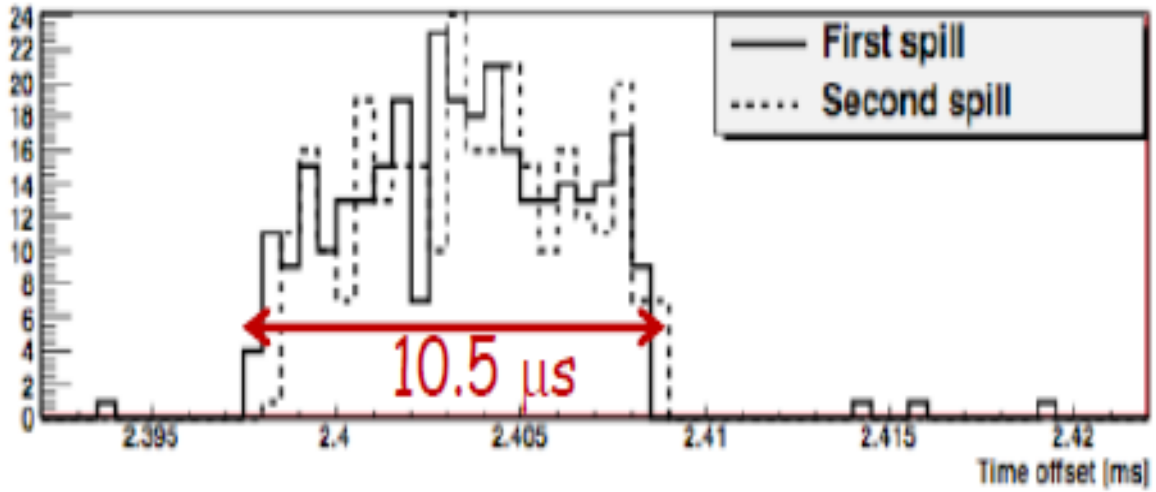
Key feature: LAr purity from electro-negative molecules (O_2, H_2O, CO_2).
Now: 0.05 ppb (O_2 equivalent) -> 6 ms lifetime.

The ICARUS T600 light detection system

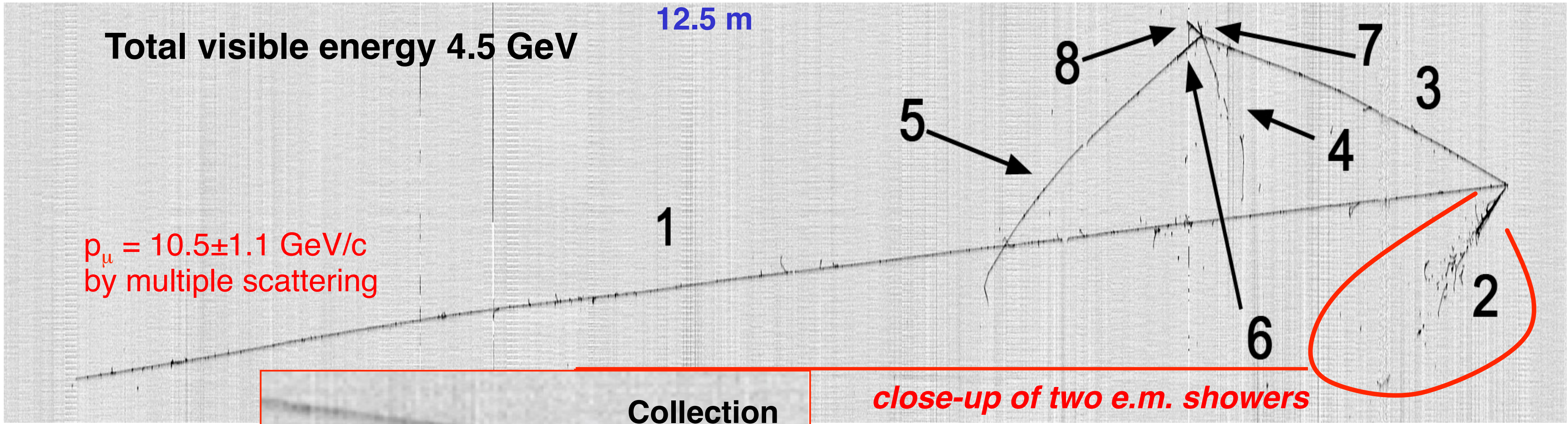
- Scintillation light produced by ionizing events (~$2.5 \cdot 10^7\ \gamma$/GeV) in the LAr-TPC is recorded with 74 (20+54) 8" PMT's.
- The PMT's in ICARUS T600 are organized in arrays behind the 4 wire chambers (1L, 1R, 2L, 2R). The 4 sums of the signals from the PMT arrays are used for triggering and to locate each event within the drift direction (T=0).
- The trigger threshold at about 100 phe allows detecting events with energy deposition as low as few hundred MeV with full efficiency.
- The scintillation in LAr has two distinct components with 6 ns (1/4 of the total) and 1.5 (3/4) μs decay time. About 4% of the γ (10^6/GeV) are emitted within 1 ns from the ionization process: 50-100 phe/GeV/D^2[m] are recorded on the PMT's (D = distance in m from ionizing track to PMT).

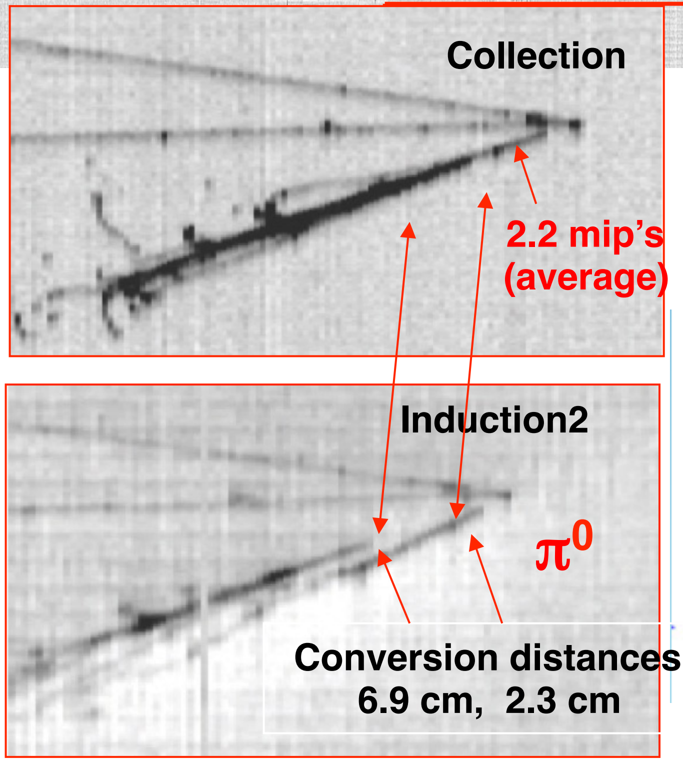
ICARUS CNGS trigger

- CNGS "Early Warning" signal sent 80 ms before SPS proton extraction, containing the predicted extraction time of the 2 consecutive CNGS spills (10.5 μs).
- Trigger: photomultiplier sum signal for each chamber within 60 μs wide beam gate, open in coincidence with SPS proton extraction.
- 80 triggers per day recorded at a rate of about 1 mHz, with a time distribution in agreement with spill duration.
- 2.40 ms offset value in agreement with ~2.44 ms ν-tof (~40 μs fiber transit time from external lab to Hall B).



LAr-TPC: powerful technique. Run 9927 Event 572





$M^*_{\gamma\gamma}$ = 125±15 MeV/c^2

Primary vertex:

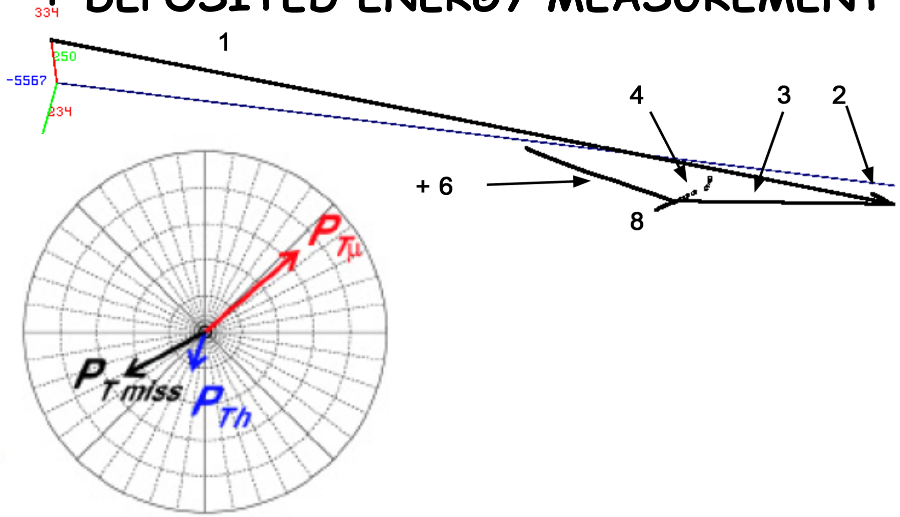
- very long μ (1),
- e.m. cascade (2),
- π (3).

Secondary vertex:

Longest track (5) is μ coming from stopping K (6),

μ decay is observed.

ALL PARTICLES RECONSTRUCTED IN 3D
+ DEPOSITED ENERGY MEASUREMENT



Total transverse momentum ~ 250 MeV
(consistent with Fermi momentum)

Search for the analogue of Cherenkov radiation by CNGS neutrinos at superluminal speeds in ICARUS

Search for superluminal ν's radiative processes in ICARUS

- Cohen and Glashow [Phys. Rev. Lett., 107 (2011) 181803] argued that superluminal ν should loose energy mainly via e^+e^- brehmstrahlung:

$$\frac{dE}{dx} = \frac{5}{112}\frac{G_F^2}{192\pi^3}E_\nu^6\delta^3 \qquad \Gamma = \frac{2}{35}\frac{G_F^2}{192\pi^3}E_\nu^5\delta^3$$ (Γ: Emission rate)

resulting in $0.78 \cdot E_\nu$ energy lost /emission on average where $\delta = (v_\nu^2 - c^2)/c^2$

- The process kinematics, folded in the CNGS beam, has been studied with a full FLUKA simulation, for several values of δ parameter.
  - for $\delta = 5\ 10^{-5}$ (OPERA) full ν event suppression for $E_\nu > 30$ GeV and
  - $\sim 10^7$ e^+e^- pairs /10^{19} pot•kt expected in ICARUS, appearing as isolated e.m. shower with $E_{dep} > 200$ MeV, pointing to CNGS beam axis within 150 mrad and without hadronic activity.

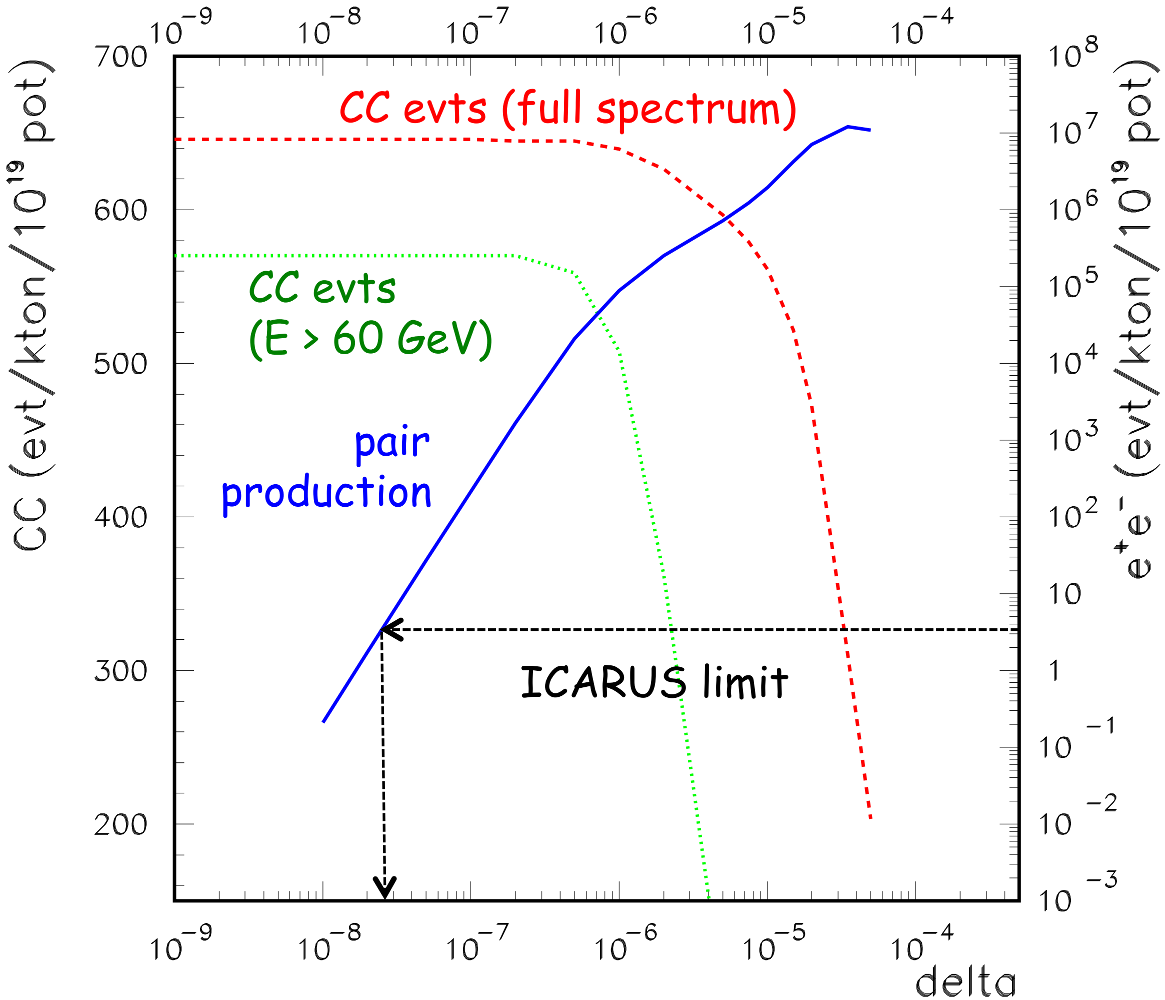
- Effects searched in $6.7\ 10^{18}$ pot·kt CNGS ICARUS exposure (2010/11).
  - No spectrum suppression found in both NC and CC data (~ 400 events).
  - No e^+e^- pair event candidate found.

ICARUS result on superluminal δ parameter

- The lack of pair bremsstrahlung events in CNGS ICARUS 2010/2011 data, allows to set the limit:

$\delta = (v_\nu^2 - c^2)/c^2 < 2.5\ 10^{-8}$ 90% CL

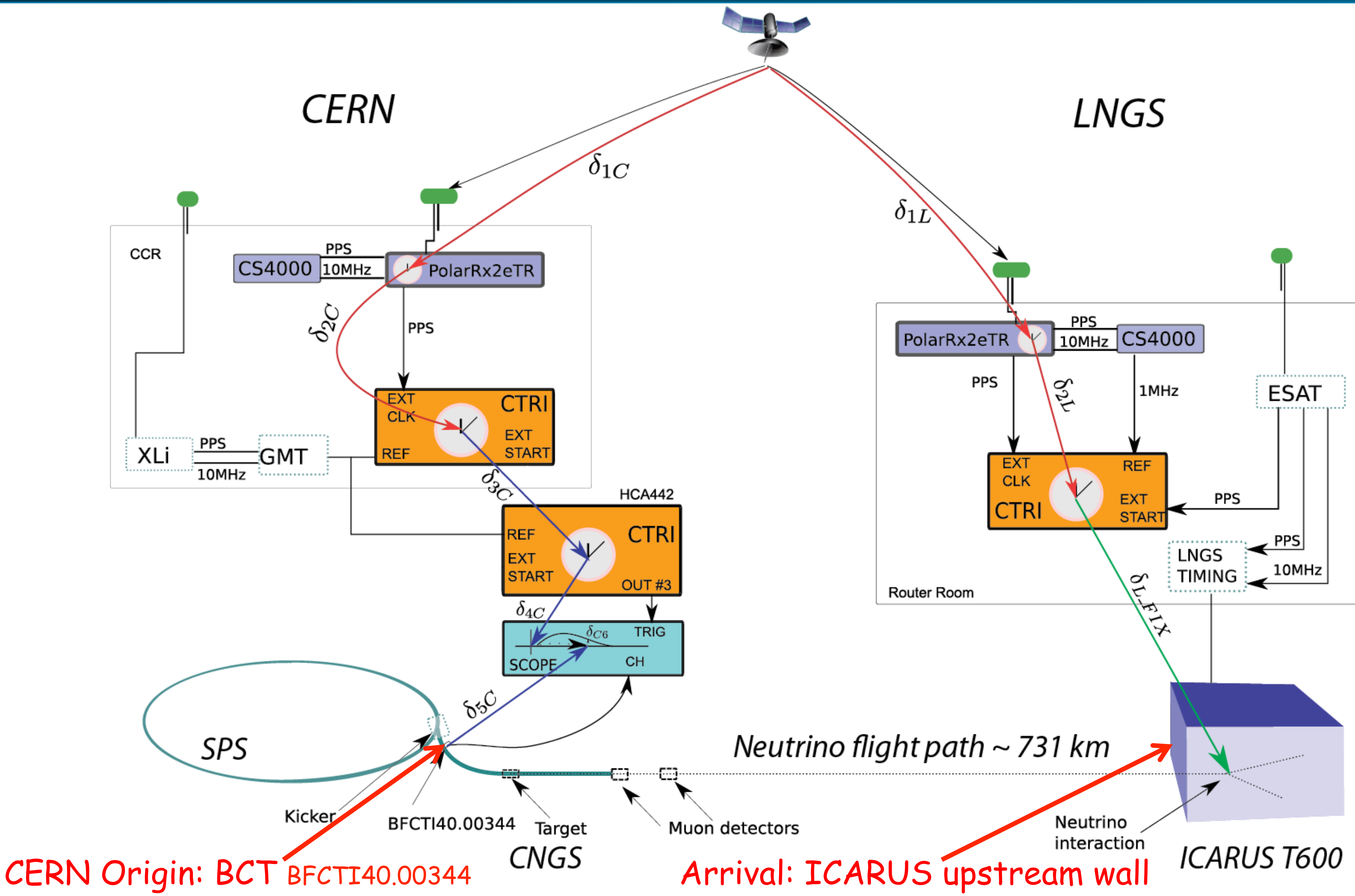
  - comparable to the SuperK limit $\delta < 1.4\ 10^{-8}$ from the lack of depletion of atmospheric ν's,
  - somewhat larger than the lower energy velocity constraint $\delta < 4\ 10^{-9}$ from SN1987A.



- The remaining ICARUS 2011 events (3 x more statistics) and 2012 data will be available but, due to δ^3 dependence of pair bremsstrahlung cross section, no major improvement on δ sensitivity is expected.

Measurement of neutrino time-of-flight with the ICARUS detector in the CNGS beam

CERN-LNGS time-link for neutrino tof measurement

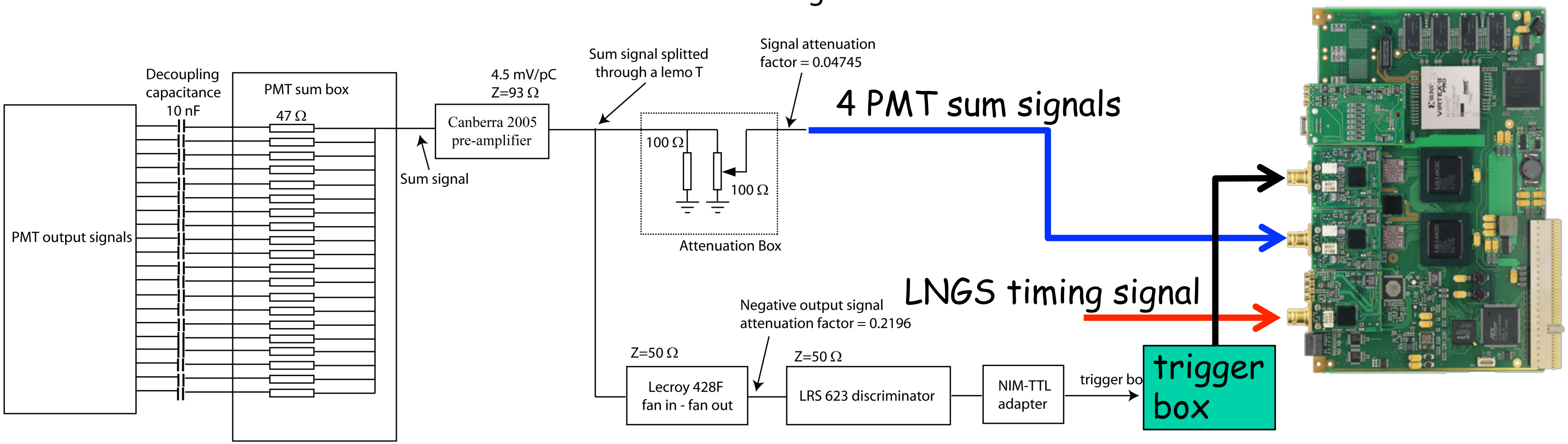


Proton extr. time and BCT waveforms, recorded with ACQIRIS 1 GS/s DP110, logged into CNGS DB at CERN, replicated at LNGS thanks to “Servizio di Calcolo”

ν t.o.f measurement with ICARUS in CNGS bunched beam

- For the 2011 CNGS bunched beam run, the ICARUS PMT readout was equipped with an independent DAQ system derived from that of the WArP experiment, based on three "2-channel, 8-bit, 1-GHz ACQIRIS AC240" digitizer boards.
- The 4 PMT-Sum signals, integrated with a fast CANBERRA 2005 preamplifier, are recorded together with the absolute time signal distributed by the LNGS laboratory (PPmS).

Block scheme for the PMT sum signal



- The PMT-DAQ is triggered by the ICARUS-CNGS trigger.

PMT-DAQ scheme

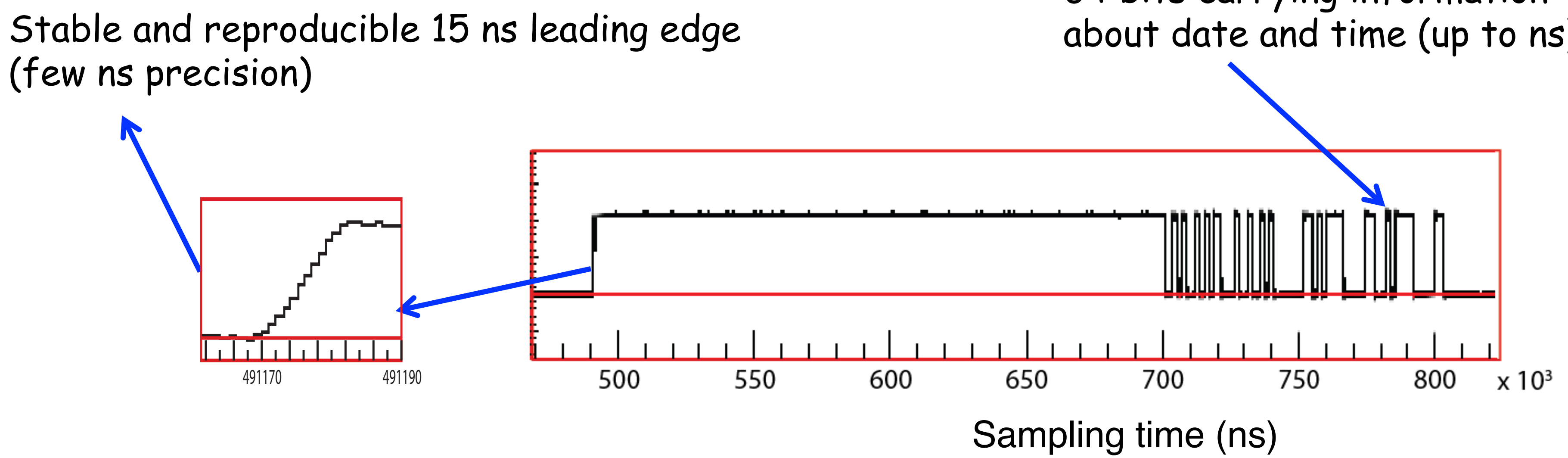
- The dynamic range of AC240 boards can be adjusted to signal pulse height, and ranges from a minimum of 50 mV up to a maximum of 1 V, easily matching the ICARUS PMTs signal range (~ 3 phe/ADC #).
- Channel-to-channel synchronization: < 10 ps; Board-to-bards synchronization: 16 ns (with special jumpers ~ 0.1 ns). Stability: < 1 ppm.

PMT-DAQ layout

- Similarly to ICARUS, in the new PMT-DAQ signals are continuously read out/stored in a circular memory (24 KB/ch depth corresponding to 24 μs time interval, sampling at 1 GHz).
- When a CNGS trigger occurs, additional data are readout and stored in an additional memory buffer until the required time interval is fully readout (1400 μs, ~1.4 MB/channel). The content of both buffers is then sent to the ICARUS data storage.

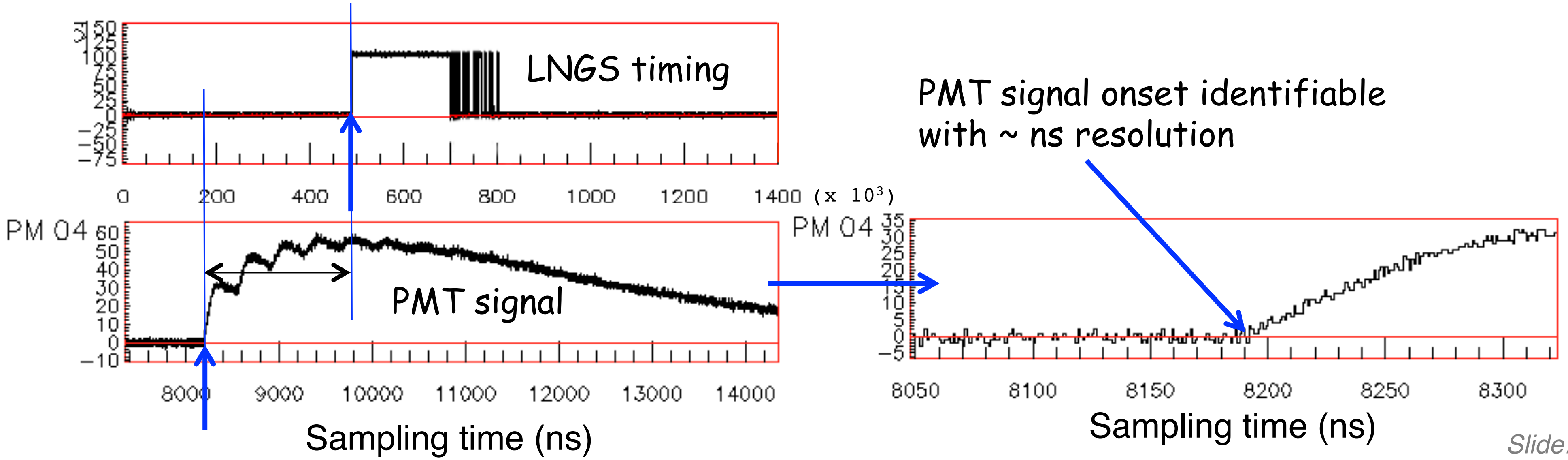
LNGS timing signal

- LNGS timing signal (PPmS) consists of a TTL 15 ns positive edge sent out every ms and followed, after 200 μs, by a pulsed structure whose logical states contain the information on the absolute time of the first edge. This signal generated in the external lab is sent to underground Halls via ~ 8 km of dedicated optical fiber.
- *This introduces a 42036.6±1.3 ns delay accurately calibrated in Dec. 2011 in collaboration with the LNGS "Technical and Research divisions (Computing and Electronics Services)".*



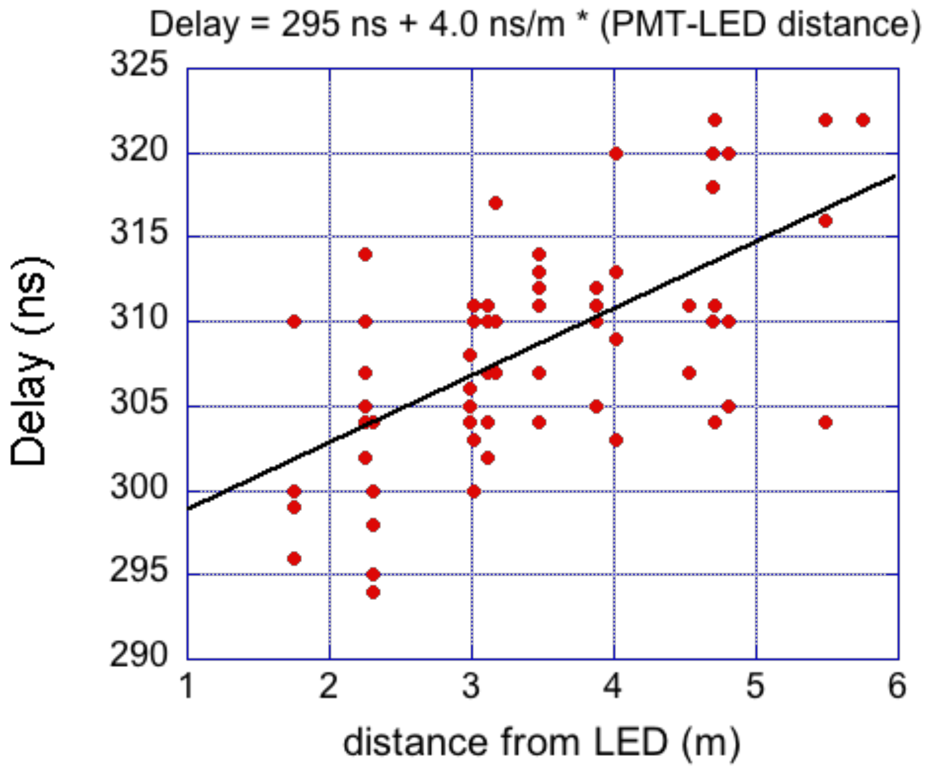
ICARUS PMT signal timing

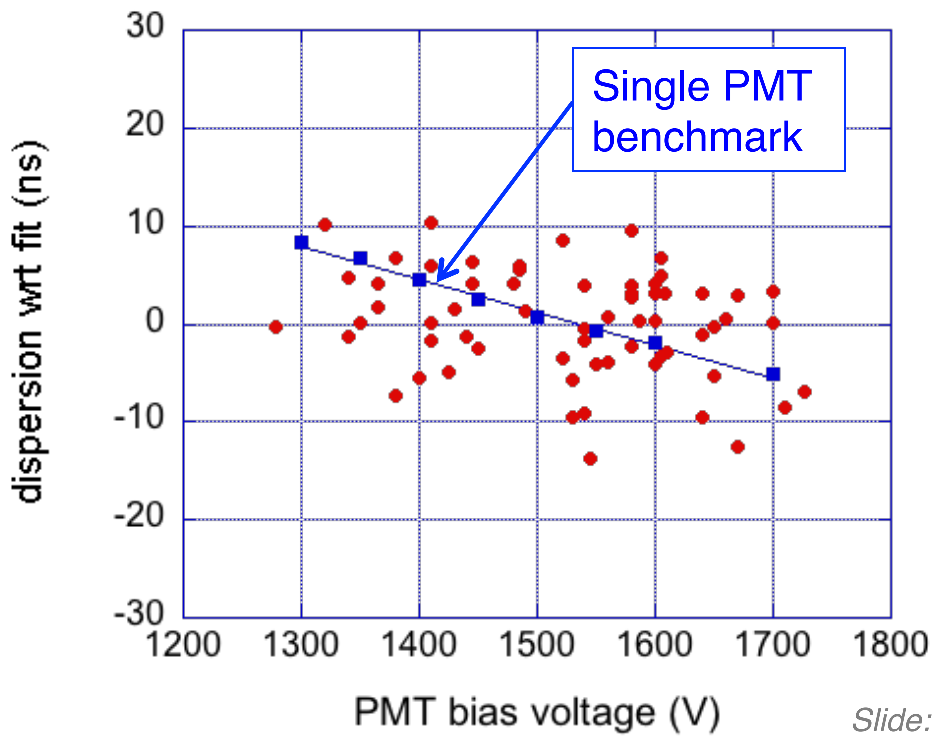
- PMT and timing signals are recorded on the same AC240 boards. The time interval between these 2 signals, measurable with few ns precision, allows the determination of the absolute time of the scintillation light pulse in the T600 detector.
- Propagation of signals from PMT's to the AC240 boards including transit time in PMT (nominal value: ~75 ± 2 ns) and CANBERRA (~5ns) *has also been accurately calibrated (with LED's in LAr and signal reflections): 299 (1L), 293 (1R) 295 (2L) 295 (2R) ± 5.5 ns (mainly due to PMT transit time spread vs bias voltage).*



Calibration of PMT's signal propagation

- Blue LED's immersed in LAr on top of Cathode
- Measurement of individual PMT's signals delay in agreement with measurement PMT-Sum with full cabling chain and measurement of each cable section with test pulse.
- Residual delay fluctuation (±5.5 ns) compatible with variation of PMT transit time w.r.t biasing voltage.

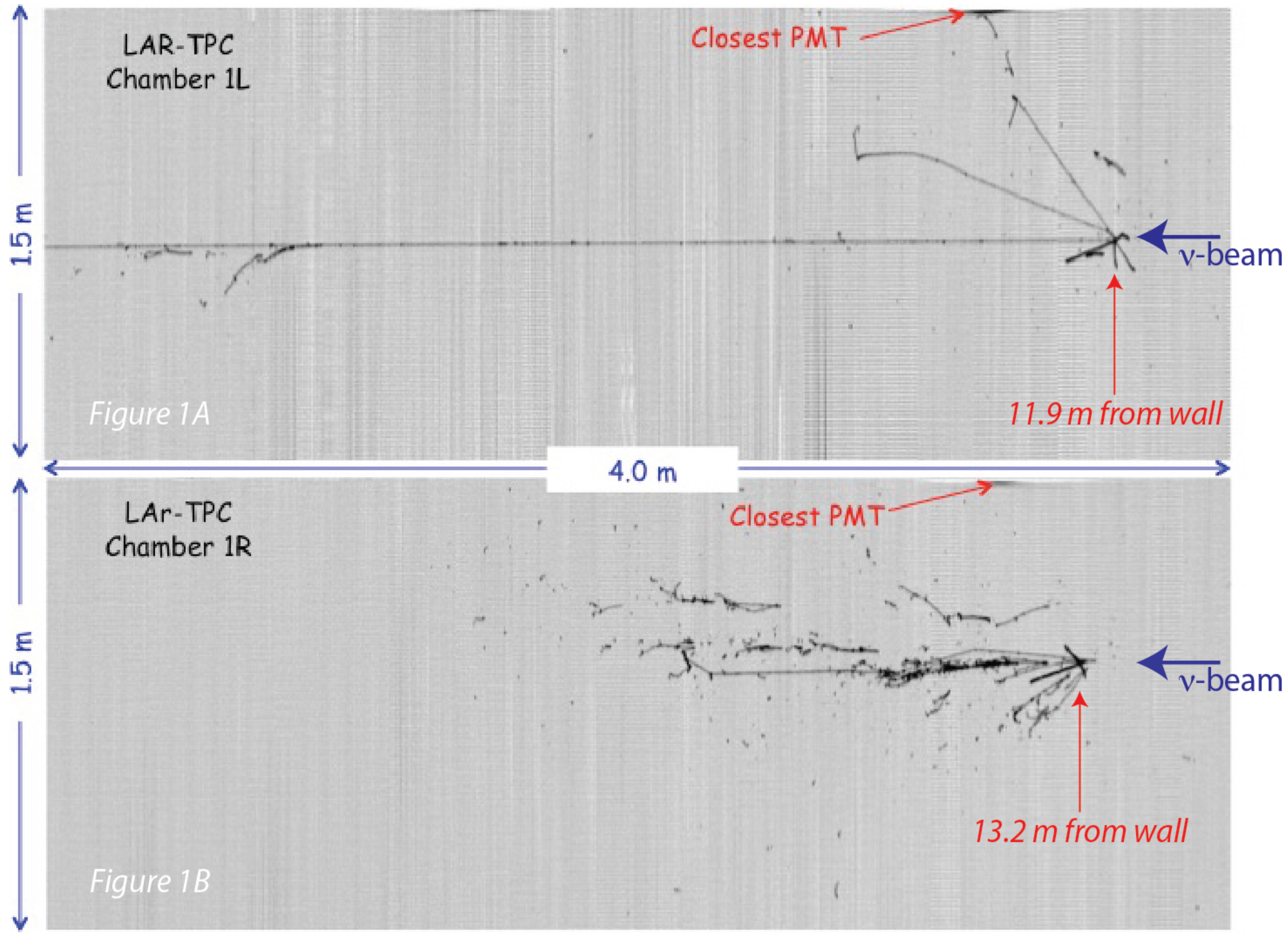




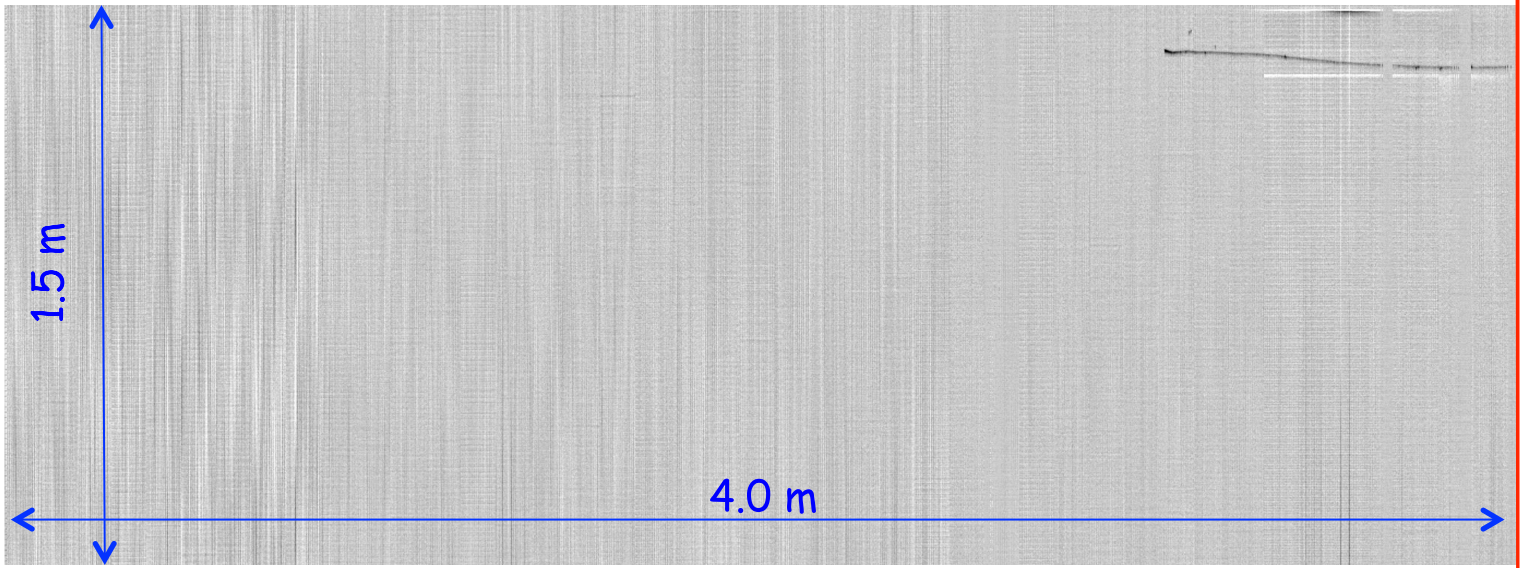
Data taking with bunched CNGS

- ICARUS started data taking with the low intensity bunched beam (4 bunches/spill, 3 ns FWHM, 524 ns separation) on October 27th.
- Unfortunately, due to an undetected time shift of 2 ms of the Early Warning Signal w.r.t. the actual CERN-SPS proton extraction time, ICARUS DAQ trigger gate was opened after the ν arrival at LNGS, resulting in empty events.
- The problem was spotted out and settled on October 31st. Until November 5th, ICARUS collected ~2.2 10^{16} pot.
- In this period ICARUS observed 7 beam-associated events, consistent with the expected overall event rate:
  - 2 CC ν_μ events
  - 1 NC ν event
  - 1 stopping + 3 crossing μ's from ν interaction in upstream rock

CC and NC neutrino events

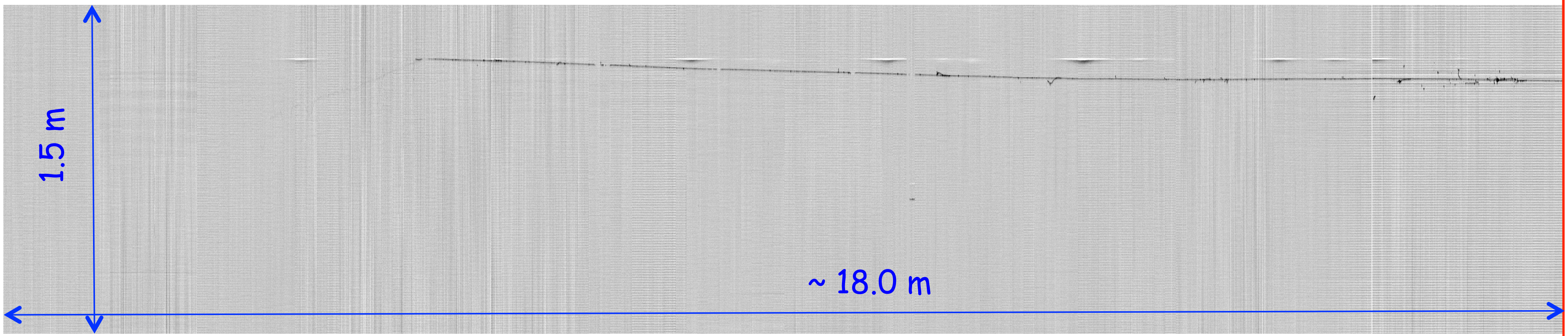


Stopping and through-going muons



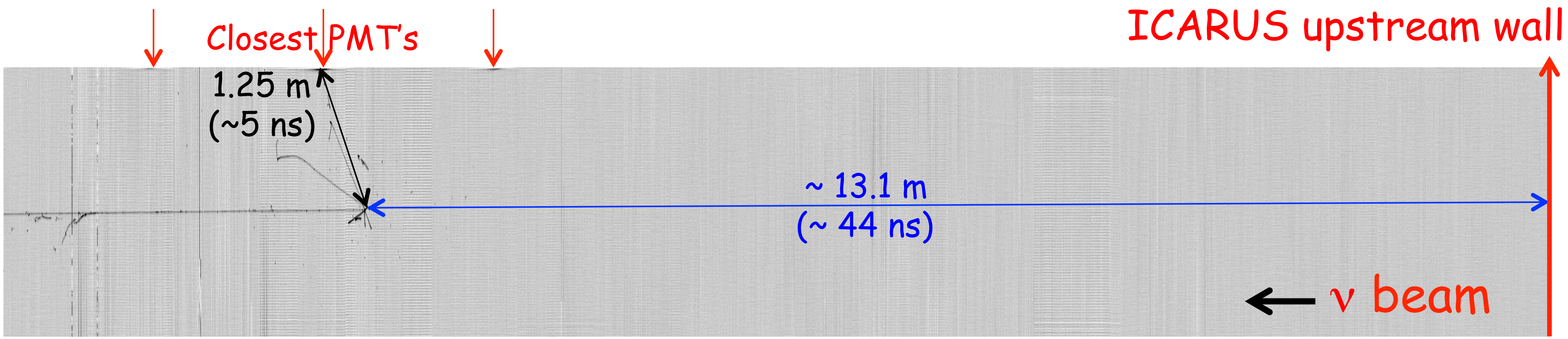
NOTE THE DIFFERENT ASPECT RATIOS

← ν beam



Neutrino arrival time

- To use the upstream wall position of ICARUS active volume as reference point for neutrino timing, some additional corrections have to be included namely:
  - the position of the interaction vertex along the 18 m of the detector length
  - the distance of the event vertex from the closest PMT.
- Both corrections can be precisely deduced from the event topology in the LAr-TPC through visual scanning. Events in the standard ICARUS DAQ and the new AC240 based DAQ are associated through their common acquisition time.



Neutrino event timing ($tof_\nu = T_{stop} - T_{start}$)

Starting Time @ CERN BCT:
$T_{START} = T_{CERN} + \Delta_{FIX\_C} + \Delta_{VAR\_C}$

Arrival Time @ ICARUS entry wall:
$T_{STOP} = T_{LNGS} + \delta_{L\_FIX} + \Delta_{VAR\_L}$

- T_{CERN}: CERN SPS p-extraction time.
- *Fixed delay:* $\Delta_{FIX\_C} = D_1 + \delta_{3C} + \delta_{4C} + \delta_{5C}$
  D1 = -99216 ns (overall offset CERN -GPS time bases);
  δ_{3C} = 10078±2 ns;
  δ_{4C} = 27±1 ns;
  δ_{5C} = -580±5 ns.
- *Variable corr.:* $\Delta_{VAR\_C} = \delta_{1C} + \delta_{2C} + \delta_{6C}$
  δ_{1C}, δ_{2C} (GPS related);
  δ_{6C} p-pulse delay w.r.t. SPS extract. (±1.3ns due to p-bunch width).

- T_{LNGS}: LNGS PPmS time on AC240.
- *Fixed delay:* δ_{L_FIX} = 42037±1.3 ns (PPmS signal propagation).
- *Variable corr.:* $\Delta_{VAR\_L} = \delta_{1L} + \delta_{2L} - (\delta_{3L} - \delta_{4L}) - \delta_{5L} - \delta_{6L} - \delta_{7L}$
  δ_{1L}, δ_{2L} (GPS related);
  $\delta_{3L} - \delta_{4L}$ (±2ns) PPmS-PMT delay;
  δ_{5L} (±5.5ns) PMT cabling delay;
  δ_{6L} (<±0.1ns) vertex position in LAr;
  δ_{7L} (<±1ns) vertex-PMT distance.

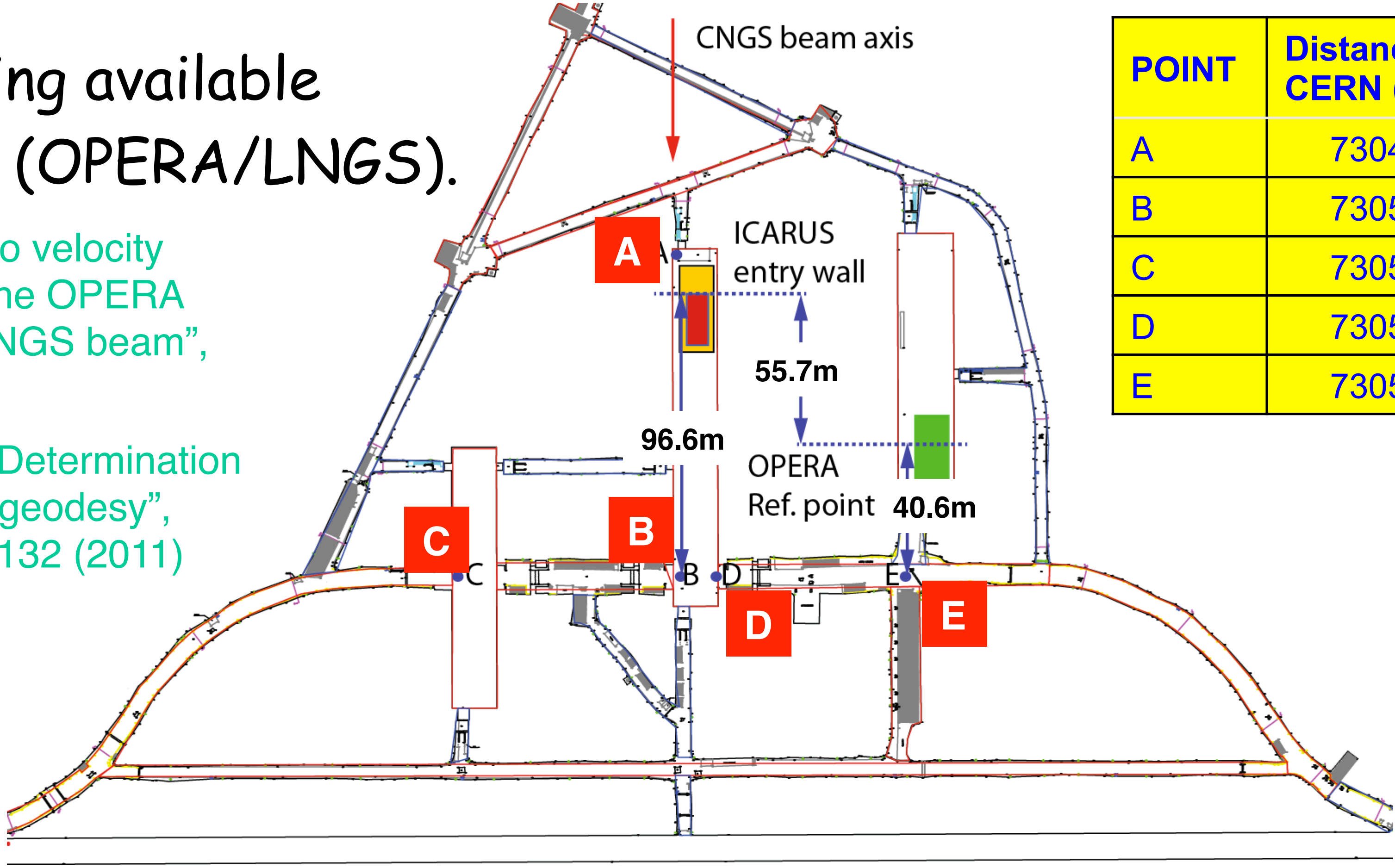
δ_{1C}, δ_{2C}, δ_{1L}, δ_{2L}: variable corrections calculable from GPS data.
Recipe, developed by OPERA/CERN, publicly available since end February 2012.
Estimated residual fluctuations on ($\delta_{1C} + \delta_{2C} - \delta_{1L} - \delta_{2L}$): ±2ns

CERN-ICARUS baseline estimation

Rely on existing available geodesy data (OPERA/LNGS).

G. Brunetti, "Neutrino velocity measurement with the OPERA experiment in the CNGS beam", PhD Thesis (2011)

G. Colosimo et al., "Determination of the CNGS global geodesy", OPERA public note 132 (2011)



POINT	Distance to CERN (m)
A	730465.4
B	730575.2
C	730575.6
D	730575.2
E	730574.9

- The distance from CERN origin (BCT) to ICARUS upstream wall is: 731222.3 ± 0.5 m. The expected time of flight for v = c from the BCT position at CERN and the T600 upstream wall is 2439098 ± 1.7 ns (including 2.2 ns contribution due to earth rotation).

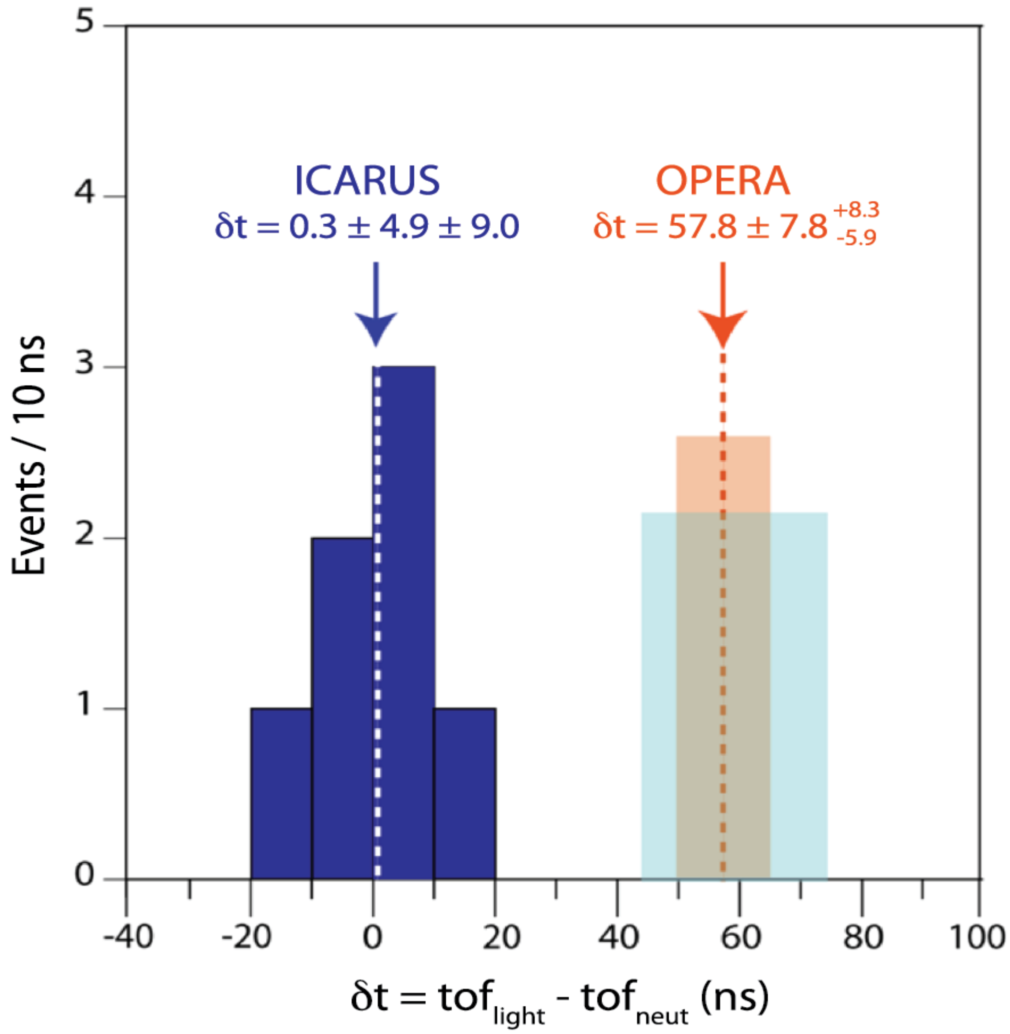
Summary of neutrino events and related corrections

Event #	1	2	3	4	5	6	7
General properties of the event							
Date	31-Oct	1-Nov	1-Nov	2-Nov	2-Nov	2-Nov	4-Nov
Time (UTC+1)	08:41:22.554	03:57:00.954	09:11:56.154	02:49:16.556	11:18:51.356	16:53:41.756	23:31:27.356
Run number	10949	10949	10949	10950	10951	10951	10956
Event Number	338	1247	1885	1053	91	802	773
Type of event	Mu-rock	Nu-NC	Nu-CC	Mu-rock	Nu-CC	Mu-rock	Mu-rock
TCP chamber (PMT array)	1R(1L)	1R(1L)	1L(1L)	2L(2R)	1L(1L)	2L(2R)	2L(2R)
CERN related data							
CERN extr. time, T_{CERN} (CERN t-base, ns)	133004	113399	114172	131046	116852	117040	118340
1st CERN time link correction, δ_{1C} (ns)	2443	2457	2464	2487	2500	2507	2558
2nd CERN time link correction, δ_{2C} (ns)	86603	86590	86585	86564	86556	86537	86500
BCT delay (first bunch), δ_{6C} (ns)	6047	6044	6049	6055	6050	6041	6046
P-transit time @ BCT, T_{START} (GPS t-base ns)	138406	118799	119579	136461	122267	122434	123753
LNGS related data							
LNGS PPmS time, T_{LNGS} (LNGS t-base, ns)	3000000	3000000	3000000	3000000	3000000	3000000	3000000
1st LNGS time link correction, δ_{1L} (ns)	-7316	-7317	-7321	-7318	-7313	-7312	-7323
2nd LNGS time link correction, δ_{2L} (ns)	7035	7030	7062	7029	7064	7060	7041
LNGS time on AC240, δ_{3L} (ns)	471602	491167	489889	474031	487231	486570	486296
PMT time on AC240, δ_{4L} (ns)	(*) 8196	8193	8194	8190	8185	8204	8212
PMT cable delay, δ_{5L} (ns)	299	299	299	295	299	295	295
Vertex position correction, δ_{6L} (ns)	0	40	44	16	28	5	1
PMT position correction, δ_{7L} (ns)	12	11	5	13	4	13	13
Event time in ICARUS, T_{STOP} (GPS t-base, ns)	2578030	2558421	2559730	2575578	2562406	2563101	2563357
Neutrino time-of-flight calculation							
$T_{STOP} - T_{START}$ (ns)	2439632	2439622	2440151	2439117	2440139	2440667	2439604
Nearest proton bunch	2	2	3	1	3	4	2
Bunch related additional time (ns)	524	524	1048	0	1048	1572	524
Neutrino time of flight (tof_{nu}, ns)	2439104	2439098	2439103	2439117	2439091	2439095	2439080
$\delta t = tof_c - tof_{nu}$ (ns, tof_c = 2439098ns)	-6	0	-5	-19	+7	+3	+18

For clarity, all times are referred to the CERN (UTC+1) time as T=0.

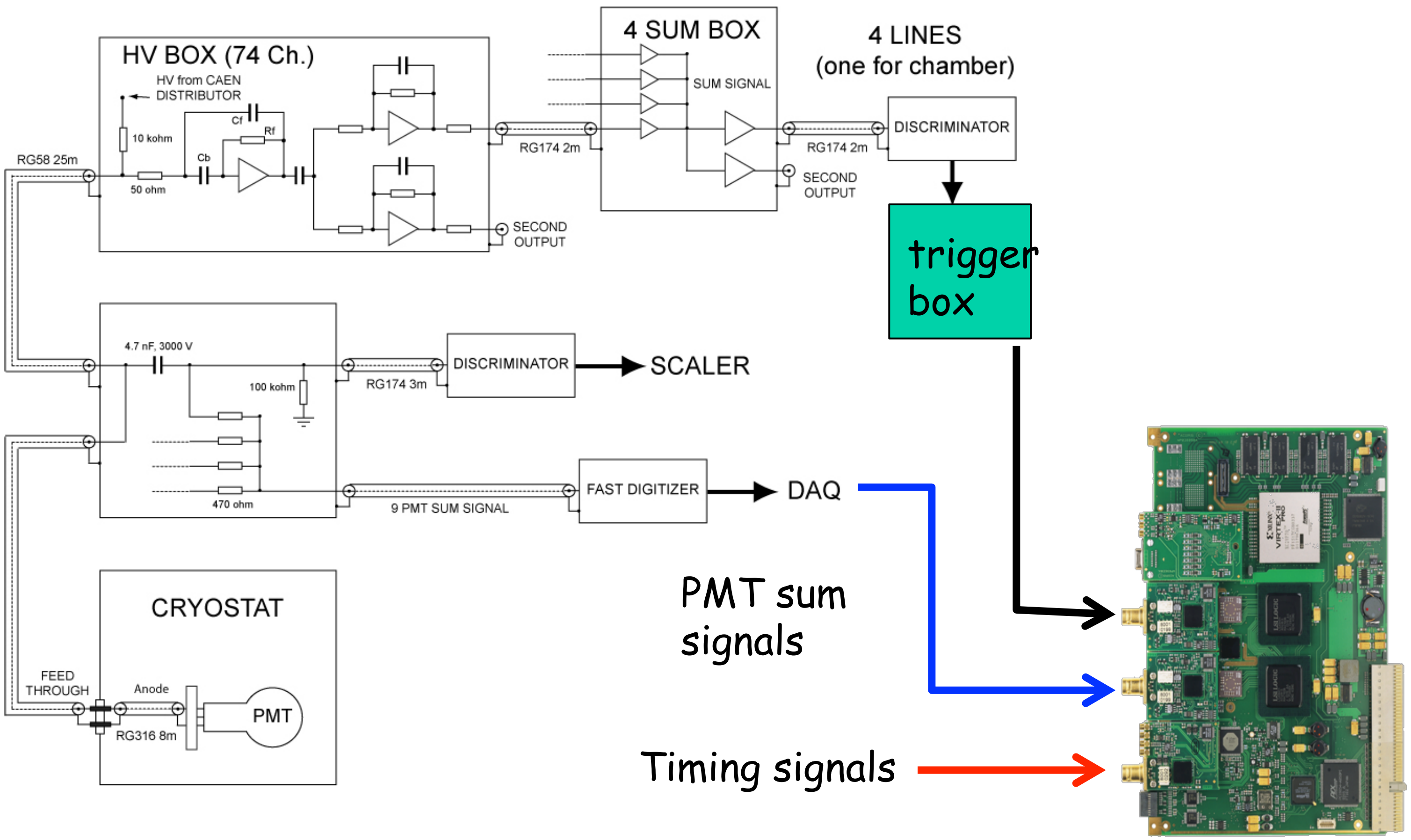
Neutrino time of flight result

- The average $\delta t = tof_c - tof_\nu$ of the 7 events is +0.3 ns with an r.m.s. of 10.5 ns and ~9 ns systematic error, obtained from combining in quadrature all quoted uncertainties.
- The statistical error on the average (4.9 ns) is estimated from a Student distribution with 6 d.o.f.
- ν velocity compatible with speed of light



Perspectives for 2012 run

- The new dedicated PMT-DAQ system proved to work as expected. Some improvements have been already implemented:
  - Direct PMT-sum signal recording with higher granularity (x 3)
  - All DAQ AC240 board synchronization at 0.1 ns



Timing and position measurement upgrades

- Three time distribution systems will be available :
  - In parallel with the recording of the existing LNGS PPmS signal, ICARUS will send a trigger signal, for time stamping, to the new independent clock synchronization system at LNGS, presently under installation in the external Labs by Borexino Collaboration.
  - Moreover ICARUS will profit of the additional timing distribution system over the "White Rabbit" protocol which be soon operation at LNGS under responsibility of CERN.
    - the provided PPmS signal will be recorded on PMT-DAQ
    - the available time stamping feature will be exploited.
- ICARUS will contribute to the new geodetic measurement campaign with Borexino/LVD foreseen for next months.

Thank you

BACKUP SLIDES

Search for superluminal ν's radiative processes in ICARUS

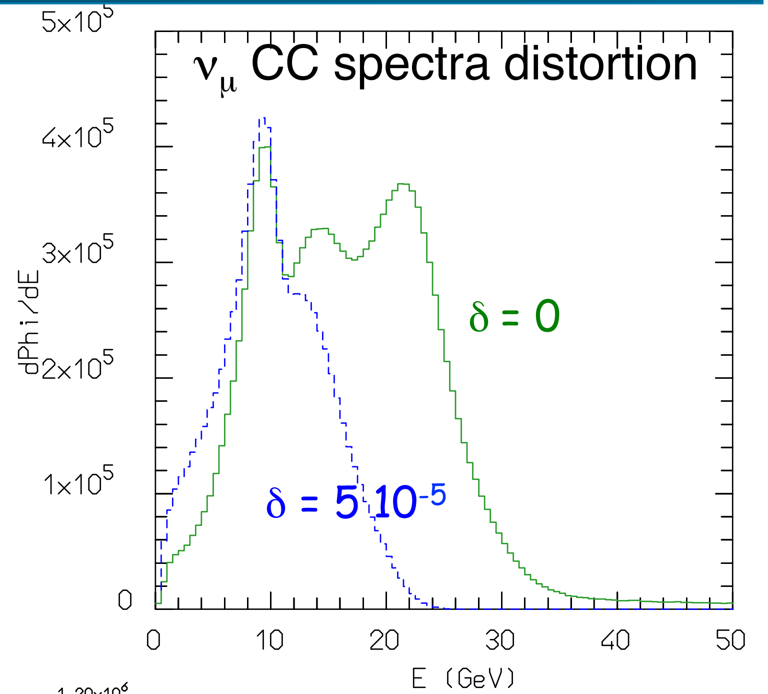
- Cohen and Glashow [Phys. Rev. Lett., 107 (2011) 181803] argued that superluminal ν's should loose energy by producing γ and e^+e^- pairs, through Z_0 mediated processes, as for Cherenkov light emission:
  - The neutrino energy loss and pair emission rates are :

$$\frac{dE}{dx} = \frac{5}{112}\frac{G_F^2}{192\pi^3}E_\nu^6\delta^3 \qquad \Gamma = \frac{2}{35}\frac{G_F^2}{192\pi^3}E_\nu^5\delta^3$$

  - with $\delta = (v_\nu^2 - c^2)/c^2$, resulting in (Γ/E) (dE/dx) ~ 0.78 E_ν energy lost per emission on average.
  - To properly account for the actual process kinematics, a full FLUKA MC simulation of the effect, embedded in the CNGS beam, has been performed for several values of δ parameter:
    - for $\delta = 5\ 10^{-5}$ the resulting mean free path is 490 Km at E_ν ~ 19 GeV with a deflection angle ~√δ comparable with CNGS beam width; full event suppression for E_ν > 30 GeV expected.
    - e^+e^- emission angle w.r.t incoming ν direction is also O(√δ).

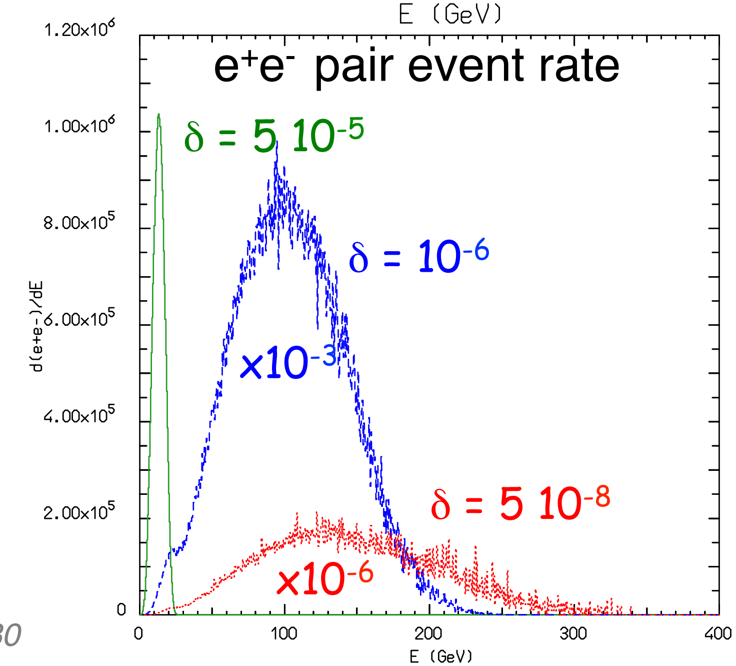
Expectations:

- Both e^+e^- production and ν spectrum distortion have been studied to probe superluminal effects and test OPERA claim ($\delta \sim 5\ 10^{-5}$). The e^+e^- signature allows to test much smaller values of δ, close to the SN1987A limit ($\delta < 4\ 10^{-9}$).



Expected ν event rate and e^+e^- pair production spectra for 10^{19} pot*kt of ICARUS exposure and different δ values

δ	CC (all flavours)	NC (all flavours)	CC>60 GeV ($\nu_\mu + \bar{\nu}_\mu$)	e^+e^-
0	644	203	57	0
$5 \cdot 10^{-8}$	644	203	57	27
$5 \cdot 10^{-7}$	643	203	56	$2.1 \cdot 10^4$
$5 \cdot 10^{-6}$	594	188	8.5	$7.2 \cdot 10^5$
$5 \cdot 10^{-5}$	203	85	$< 10^{-6}$	$1.1 \cdot 10^7$

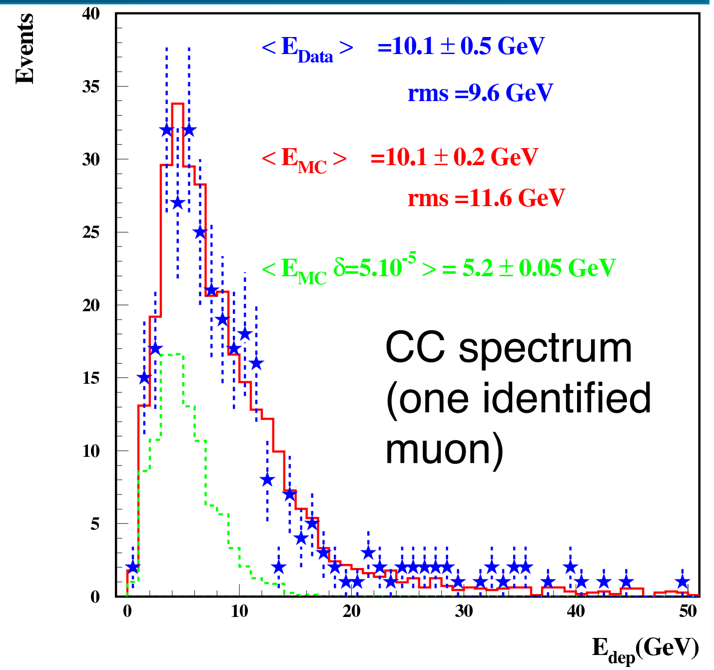


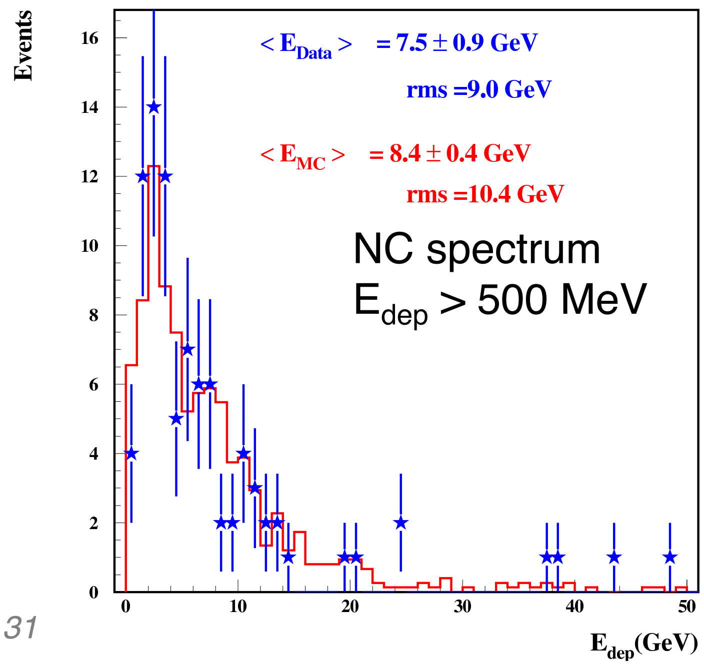
CNGS ν spectrum distortion in ICARUS

- Data from 2010 and part of 2011 CNGS runs ($5.05\ 10^{18}$ pot·kt fiducial exposure).
- Bias-free analysis:
  - calorimetric measurements of raw event energy deposition in ICARUS (only correction for signal quenching in LAr applied).
  - 2.5 m downstream fiducial volume cut on interaction vertex to identify muon tracks (for CC /NC separatation).

Rates	Observed	Expected δ=0	Expected δ=5 10^{-5}
CC	308	315 ± 5	98.1 ± 2
NC	89	93.1 ± 3	33.0 ± 1
ν_μ CC, E_{dep}>25GeV	25	18 ± 1.3	< 10^{-6}

- Experimental E_{dep} distributions for CC and NC events in agreement with MC expectations for undistorted (δ = 0) CNGS ν beam.
- E_ν > 30 GeV full event suppression, predicted for δ = $5{\cdot}10^{-5}$, not observed.





Search for e^+e^- pairs in CNGS beam with ICARUS

- Both $\nu_x \rightarrow \nu_x + \gamma$ and $\nu_x \rightarrow \nu_x + e^+e^-$ events would appear as isolated narrow e^+e^- pairs:
  - no hadronic activity;
  - single e.m. shower E_{dep} > 200 MeV with vertex within fiducial volume and pointing towards the CNGS beam axis within 150 mrad.
- Hypothetical background sources investigated through MC simulations for both NC/CC interactions also in surrounding material/rock. Residual after the selection cuts:
  - Coherent π^0 production: 0.14 ± 0.03; Quasi-elastic CC ν_e: 0.04 ± 0.01

  Control sample (loose cuts):
  - 1 event with a single isolated π^0 detected (1.4±0.05 expected).
  - 1 isolated γ event observed at 60° w.r.t. beam direction (2±0.4 predicted without angular cuts).
- No real events survives the selection: ~7.4 10^6 e^+e^- pairs expected for $\delta \approx 5\ 10^{-5}$ and integrated exposure of 6.7 10^{18} pot·kt