Recent results from the ICARUS experiment

Measurements concerning neutrino velocity

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On behalf of the ICARUS Collaboration

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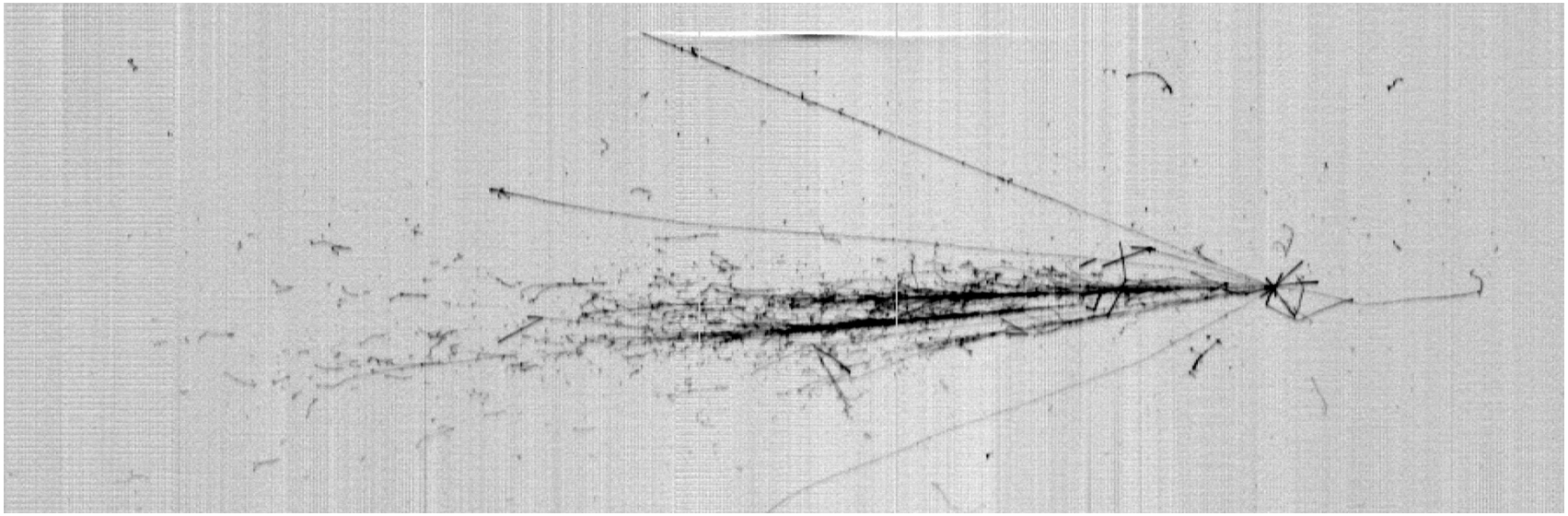

Outline

- The ICARUS experiment
- Reconstruction software and analysis
- Measurements related to neutrino velocity
- Summary

The ICARUS Collaboration

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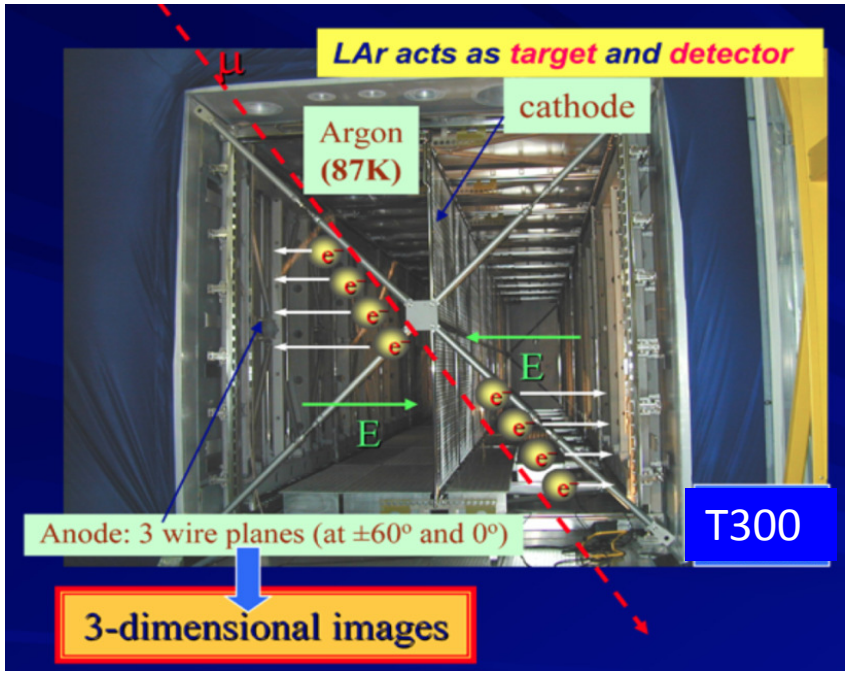
The ICARUS detector (T600)

The **Liquid Argon Time Projection Chamber** (*electronic bubble chamber*)
[C. Rubbia: CERN-EP/77-08 (1977)] capable of providing a 3D imaging of any charged particle with:

- high granularity (spatial resolution of the detector ~ 1 mm^3);
- excellent calorimetric properties.

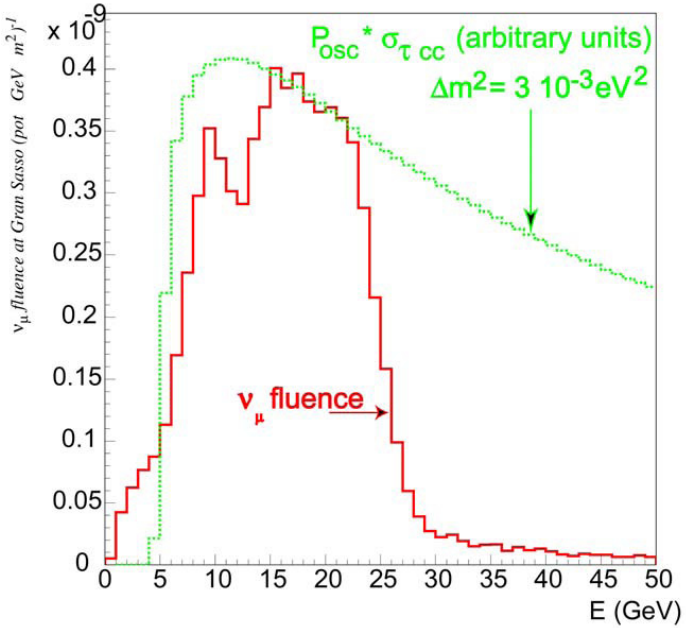


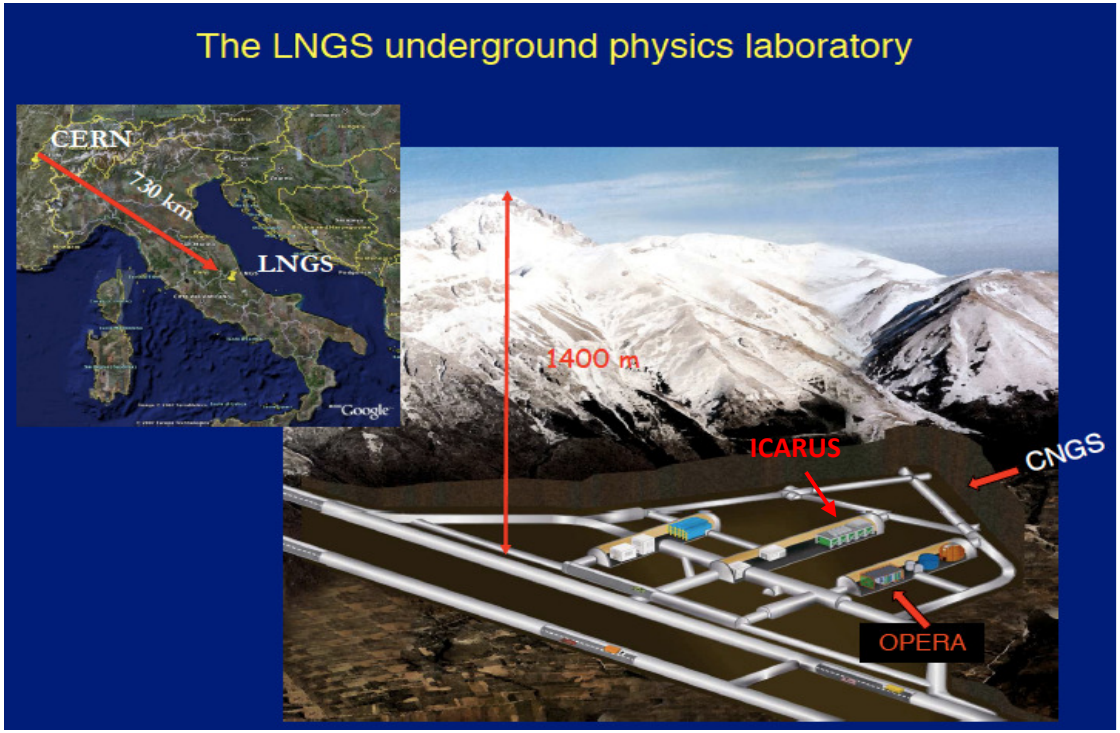
- ionization and scintillation signals are exploited,
- PMTs signal is used for triggering,
- continuous probing of wire signals as a function of time allows 3D reconstruction.

- Total LAr mass 600 t, active mass 476 t
- Two identical T300 modules
  (2 TPC chambers for each module).
- TPC characteristics:
  - (17.9 x 3.1 x 1.5 for each TPC) m3;
  - drift length = 1.5 m;
  - E_{drift} = 0.5 kV/cm; v_{drift} = 1.6 mm/μs.
- 3 readout wire planes/chamber at 0°, +-60°,
  3 mm plane and wire spacing:
  - ~ 53000 wires;
  - two induction planes and one collection
- PMTs for scintillation light (128 nm):
  - (20+54) PMTs.

CNGS – CERN Neutrinos to Gran Sasso

Conventional beam based on protons from the SPS accelerator at CERN





Energy distribution of ν_μ fluence and $P_{OSC} \times \sigma_{\nu_\tau\ CC}$

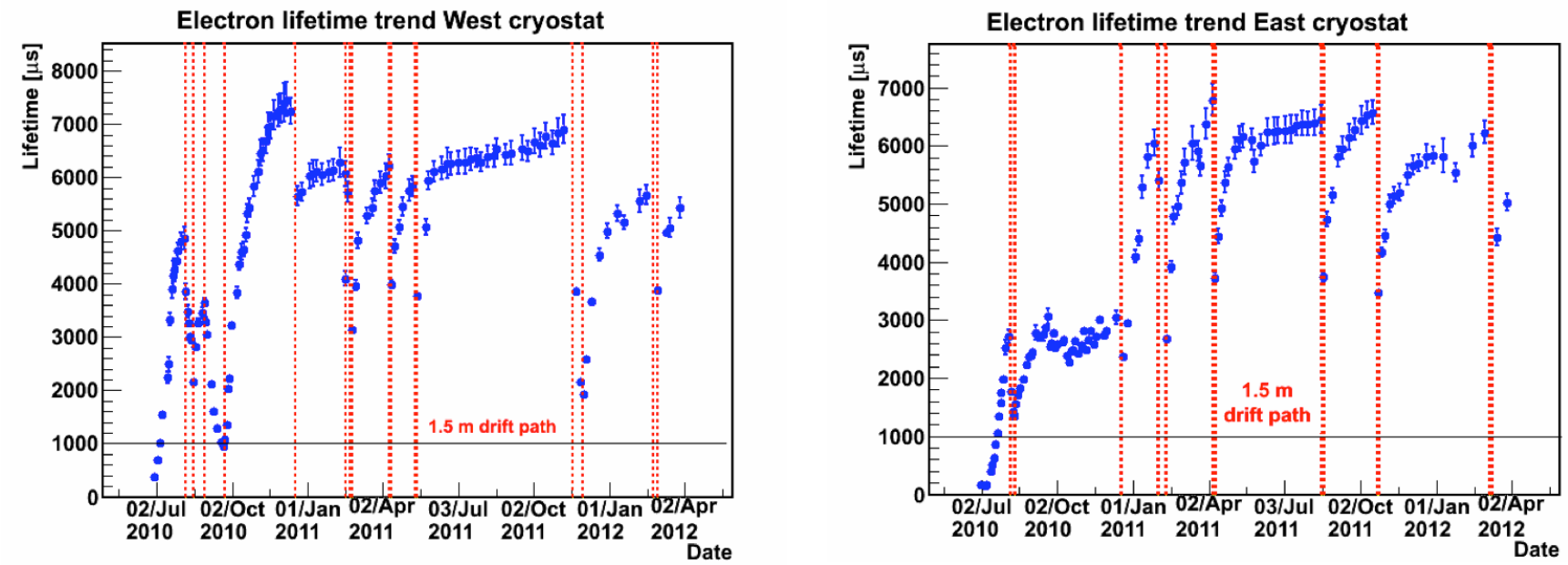
<E> ~ 17GeV

$\nu_e/\nu_\mu \sim 0.8\%$, $\bar{\nu}_\mu/\nu_\mu \sim 2.1\%$, $\bar{\nu}_e/\nu_\mu \sim 0.07\%$

LAr purification

Key feature: LAr purity from electro-negative molecules (O_2, H_2O,$C0_2$).

LAr continuously filtered, electron ionization life-time is measured



τ_{ele} > 5 ms

corresponding to a maximum charge attenuation of 17% at 1.5m

Would allow operation at larger drift distances

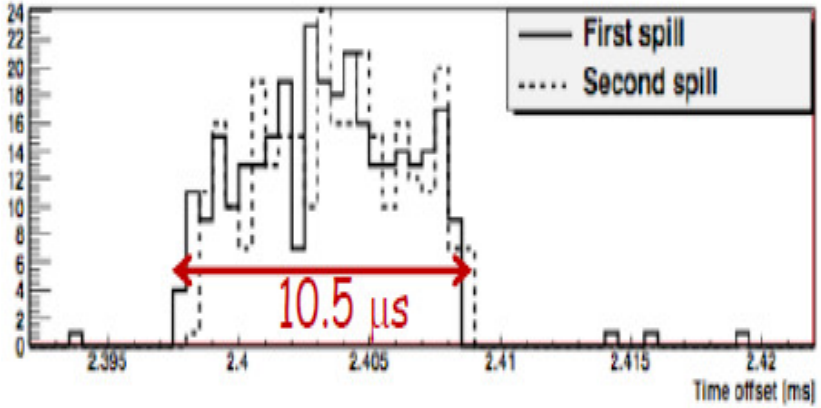
Trigger

CNGS trigger:

•CNGS "Early Warning" signal sent 80 ms before the p extraction. It contains the predicted extraction time of the 2 spills (10.5 μs each, 50ms apart)

•Photomultiplier sum signal for each chamber in coincidence with beam gate (wide - 60 μs)

•80 events per day are recorded with a trigger rate of about 1 mHz.



Cosmic ray trigger :

•Photomultiplier sum signal, requiring coincidence of two adjacent chambers (50% cathode transparency)

• Globally 35 mHz trigger rate achieved: ~130 cosmic events/h:

SuperDedalus :

A new trigger system based on wire signals is under installation and testing

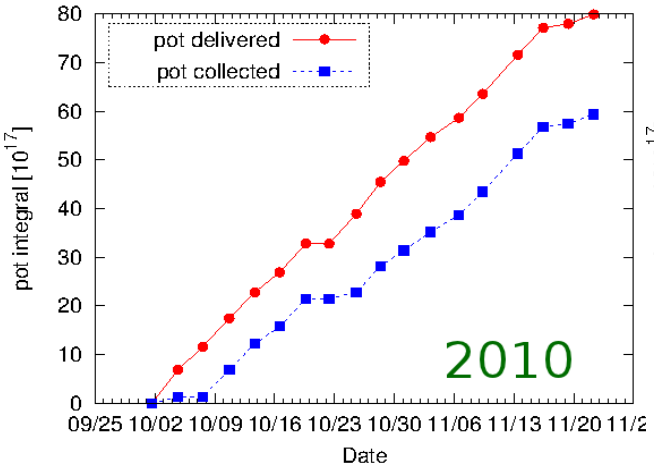
ICARUS T600 physics potential

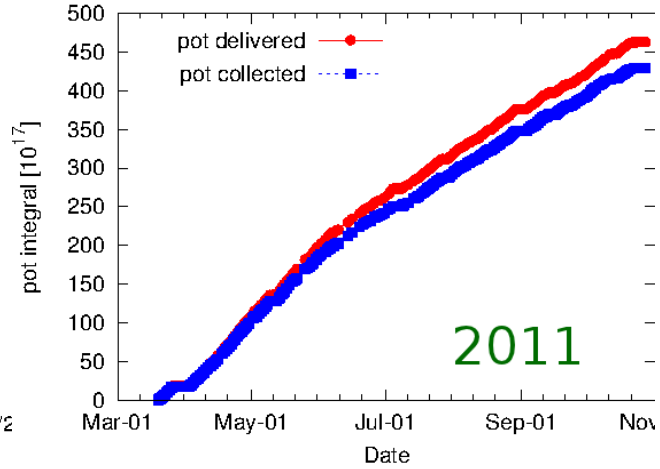
- The detector is collecting “bubble chamber like” CNGS events:
  - CC event rate ≈ 1300 ev/year
  - NC event rate ≈ 400 ev/year
  - Muons from GS rock ≈ 5500 ev/year (3700 on TPC front face)
  - Intrinsic beam ν_e CC ≈ 12 ev/year
  - ν_μ => ν_τ detecting τ decay with kinematical criteria (1.3 τ ->e /year)
  - ν_μ => ν_e (θ_{13}) from e-like CC events excess at E < 20GeV (2.2 CC/year)
  - Search for sterile neutrinos in LSND parameter space, with e-like CC events excess at E>10GeV .

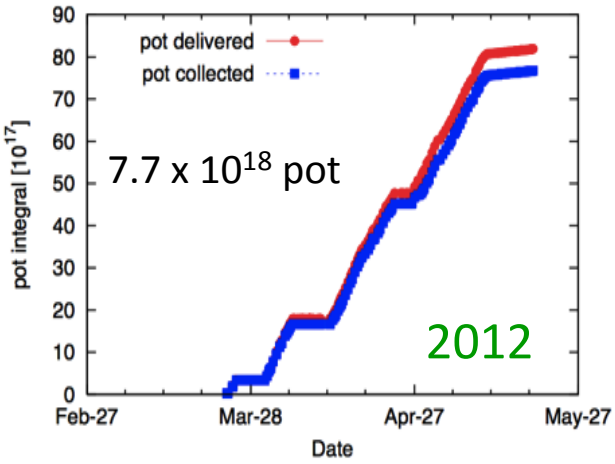
- The T600 is also collecting simultaneously “self triggered” events:
  - ≈ 100 ev/year of atmospheric ν CC interactions.
  - Supernova neutrino detection (≈ 200 ev from 10kpc)
  - Proton decay with 3 x10^{32} nucleons , zero bckg. in some of the channels

CNGS neutrino runs

	2010	2011
time of operation	October - November	March - November
pot deliv (coll)	$8 \times 10^{18}(5.8 \times 10^{18})$	$47.8 \times 10^{18}(44.4 \times 10^{18})$
detector lifetime	up to 90%	93%







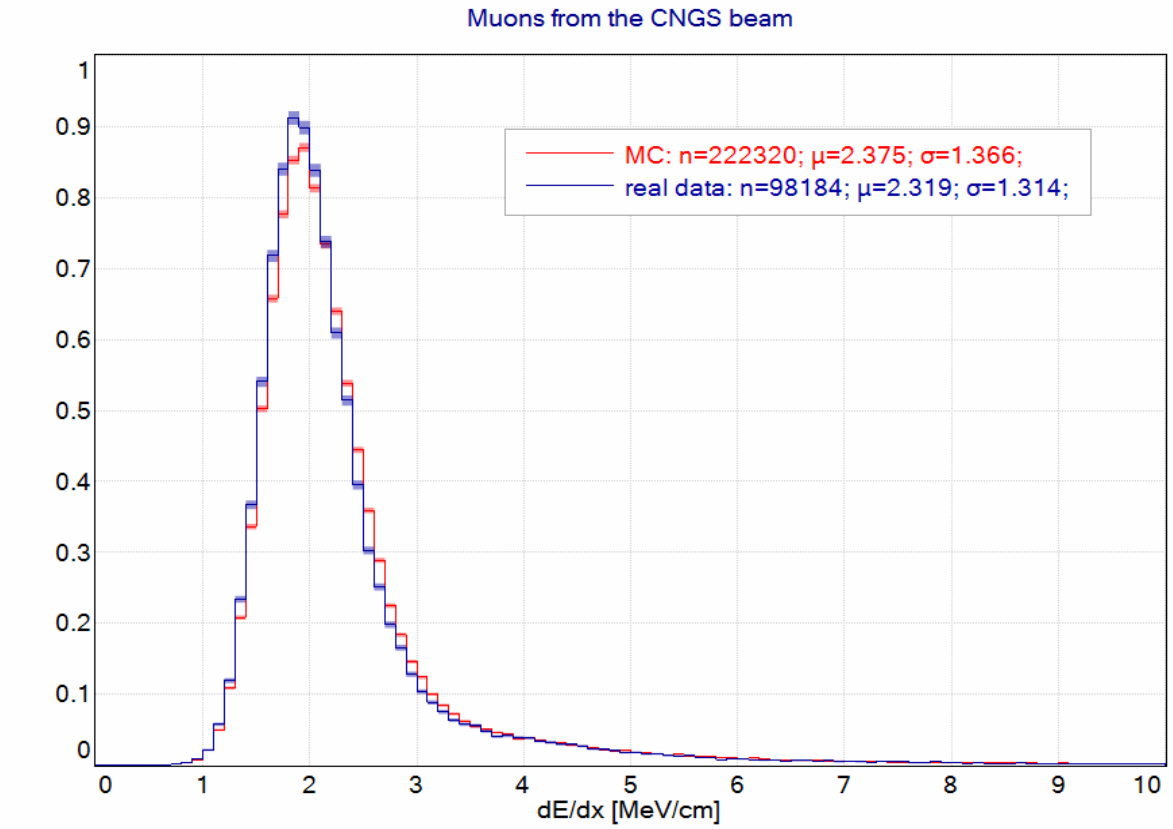
2010 data kept as a training/control sample,
2011 data used for physics analysis,
2012 - March 23rd detector started to collect new CNGS events.
November 2011 & May 2012: timing measurement with bunched beam

Event reconstruction

- Progresses in 3D reconstruction, leading to better performances especially for horizontal tracks
- Progresses in the Particle Identification Algorithm
- Progresses in automatic reconstruction: vertex finding, clustering, track finding
- Development of tools for calorimetric reconstruction

Some examples follow

CNGS muons



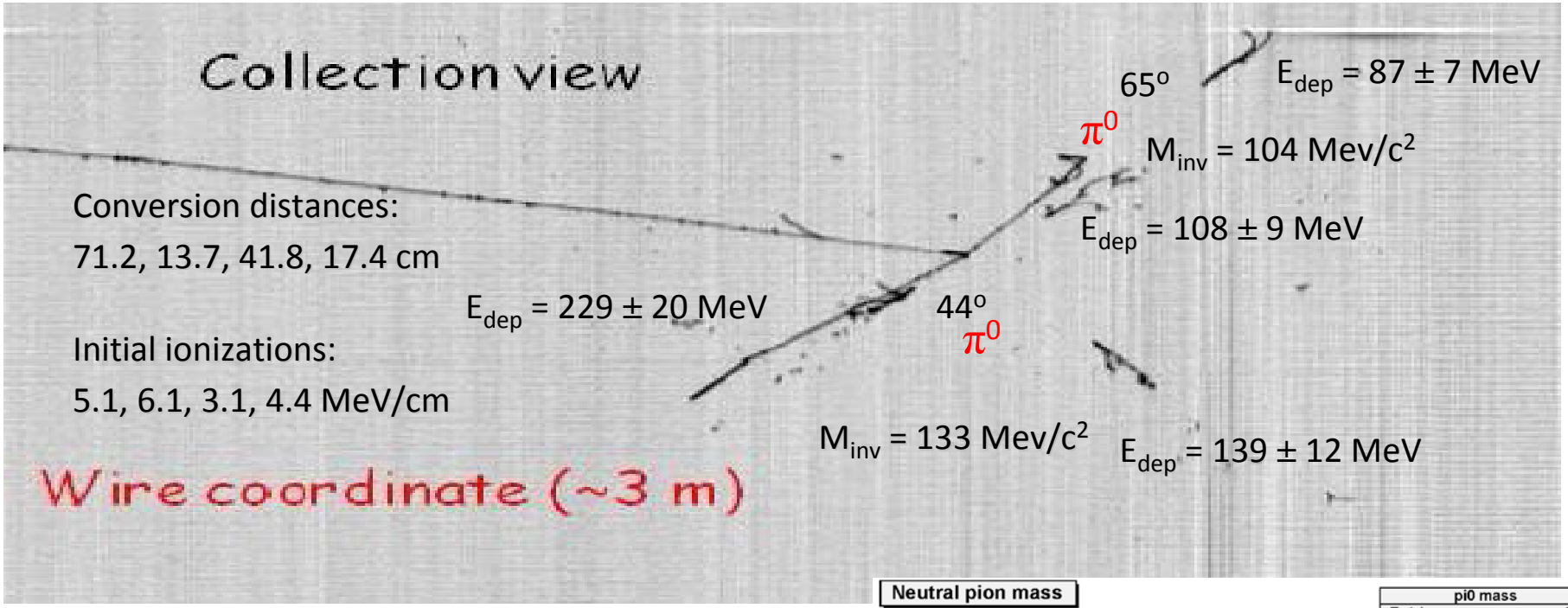
dE/dx distribution for real and MC muon tracks from CNGS events

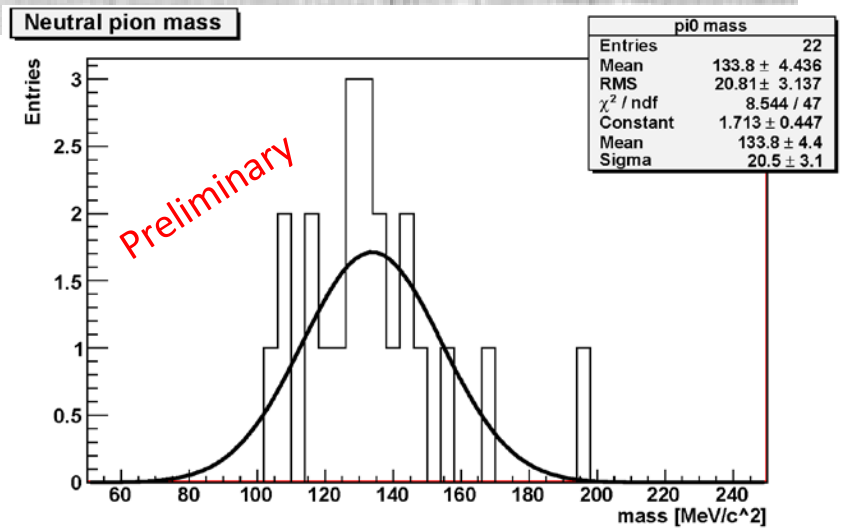
Tracks reconstructed in 3D. Delta rays and showers excluded.

Same reconstruction on MC muons with CNGS spectrum.

Very nice agreement (~ 2-3%) – still possible small differences between conditions of data and MC (noise patterns and their effects on δ ray selection)

π^0 reconstruction in CNGS event



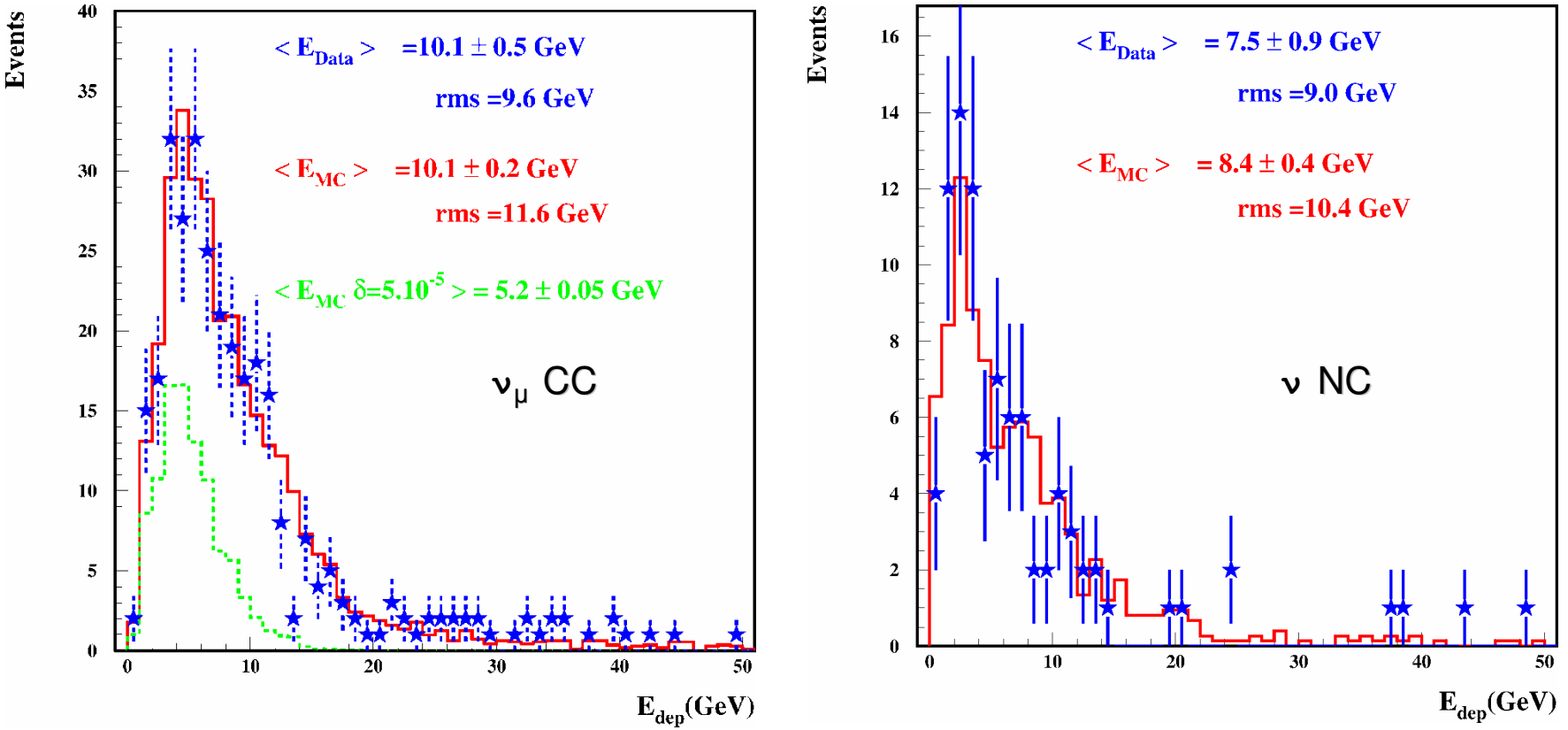


π^0-showers identified by

- Photon conversion separated from primary vertex
- Reconstruction of invariant mass
- Ionization in the first segment of showers

(1 mip or 2 mips)

Total energy deposition in CNGS ν events



Comparison of the predicted (full MC) and detected deposited energy spectrum from NC and CC events on 2010 statistics and a subset of the 2011 statistics

Search for superluminal ν's radiative processes in ICARUS

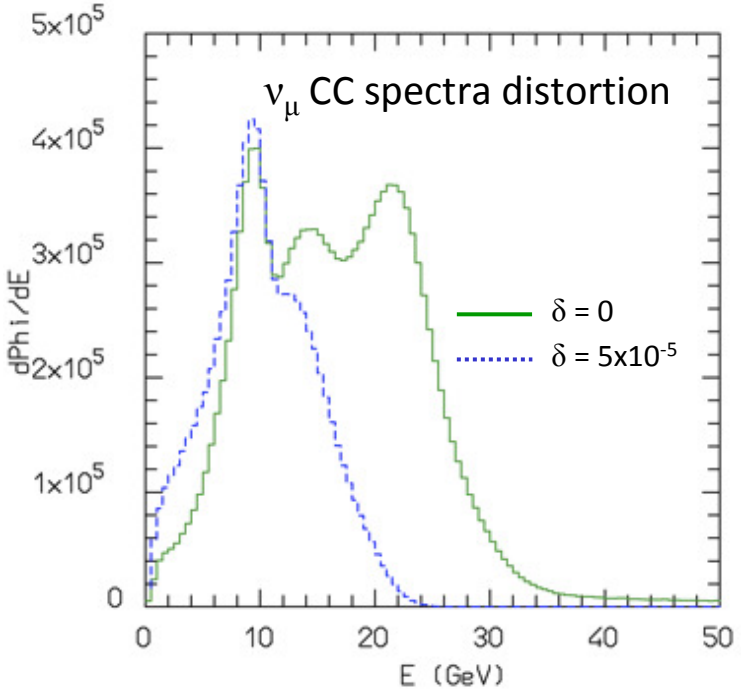
- Cohen and Glashow [Phys. Rev. Lett., 107 (2011) 181803] argued that superluminal ν's should loose energy mainly via e+e- bremsstrahlung, on average 0.78•E_ν energy loss/emission

- Full FLUKA simulation of the process kinematics, folded in the CNGS beam, studied as a function of $\delta = (v_\nu^2 - c^2)/c^2$

  Predictions for $\delta = 5 \times 10^{-5}$ (OPERA first claim):

  – full suppression of ν events with E > 30 GeV

  – ~10^7 e+e- pairs /10^{19} pot/kt in the ICARUS detector



Search for superluminal ν's radiative processes – results

[Phys. Lett. B 711 (2012), 270-275, e-Print: arXiv:1110.3763v3]

- Effects searched in 6.7x 10^{18} pot·kt ICARUS exposure (2010/11) to CNGS
  - No spectrum suppression found in both NC , CC data (~ 400 events)

Rates	Observed	Expected δ=0	Expected δ=5 x 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	< 10^{-6}

- No full suppression of events with $E_\nu > 30$ GeV
- No e+e- pair bremsstrahlung event candidate found

•The lack of pairs in CNGS ICARUS 2010/2011 data, sets the limit:

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

comparable to the SuperK limit $\delta < 1.4 \times 10^{-8}$, somewhat larger than the lower energy velocity constraint $\delta < 4 \times 10^{-9}$ from SN1987A.

CERN-LNGS time-link for neutrino tof measurement

[arXiv:1203.3433v3, accepted for publication in Phys. Lett. B]

$tof_\nu = T_{stop} - T_{start} + \delta_{GPS}$

$\delta_{GPS} = \delta_{1C} + \delta_{2C} - \delta_{1L} - \delta_{2L}$ $\pm$ 2ns

variable corrections calculated from GPS data

$T_{START} = T_{CERN} + \delta_{SPS} + \Delta_{FIX\_C}$

$T_{STOP} = T_{LNGS} + \delta_{L\_FIX} + \Delta_{VAR\_C}$

$\Delta_{VAR\_L} = -(\delta_{3L} - \delta_{4L}) - \delta_{5L} - \delta_{6L} - \delta_{7L}$

δ_{3C} = 10078±2 ns;
δ_{4C} = 27±1 ns;
δ_{5C} = -580±5 ns.

$\delta_{3L} - \delta_{4L}$ (±2ns) PPmS-PMT delay
δ_{5L} (±5.5ns) PMT cabling delay;
δ_{6L} (<±0.1ns) vertex position in LAr
δ_{7L} (<±1 ns) vertex-PMT distance

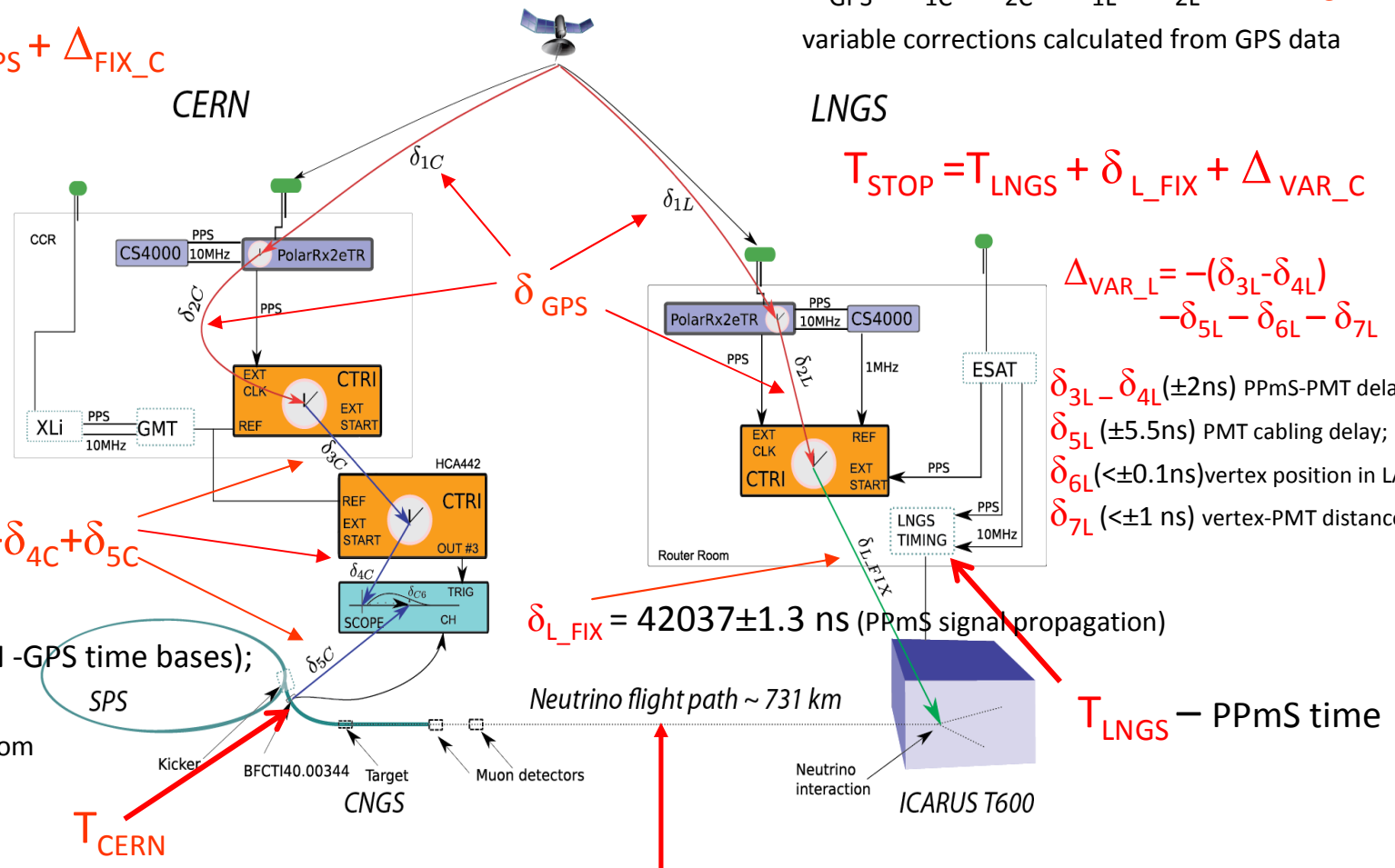
$\Delta_{FIX\_C} = D_1 + \delta_{3C} + \delta_{4C} + \delta_{5C}$

D_1 = -99216 ns
(overall offset CERN -GPS time bases);

δ_{SPS} - p-pulse delay from SPS extract : ±1.3ns due to p-bunch width

δ_{L_FIX} = 42037±1.3 ns (PPmS signal propagation)

T_{LNGS} – PPmS time

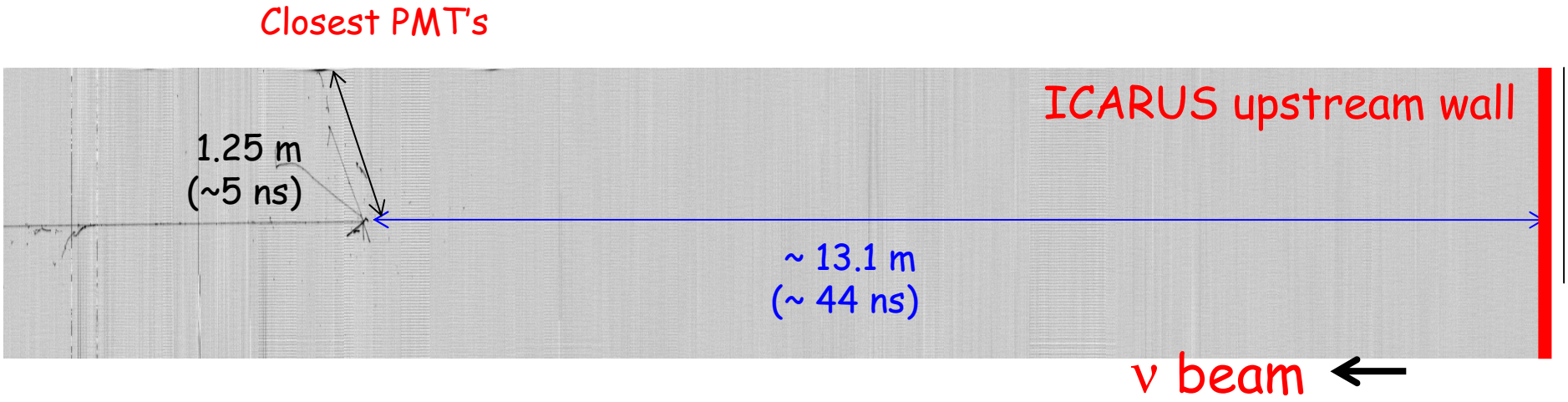


T_{CERN}
CERN SPS p-extraction time

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

Neutrino time of flight with bunched beam

- Bunched beam: 4 bunches/spill, 3 ns FWHM, 524 ns separation
- From October 31st to Nov. 5th ICARUS observed 7 bunched-beam events
- Timing from ICARUS PMT readout equipped with an independent DAQ
- Reference point : upstream wall of active volume -> corrections needed:
  - the position of interaction vertex along 18 m of detector length
  - the distance of event vertex from closest PMT
- Both corrections precisely (~1ns) deduced from event topology in LAr-TPC through visual scanning.

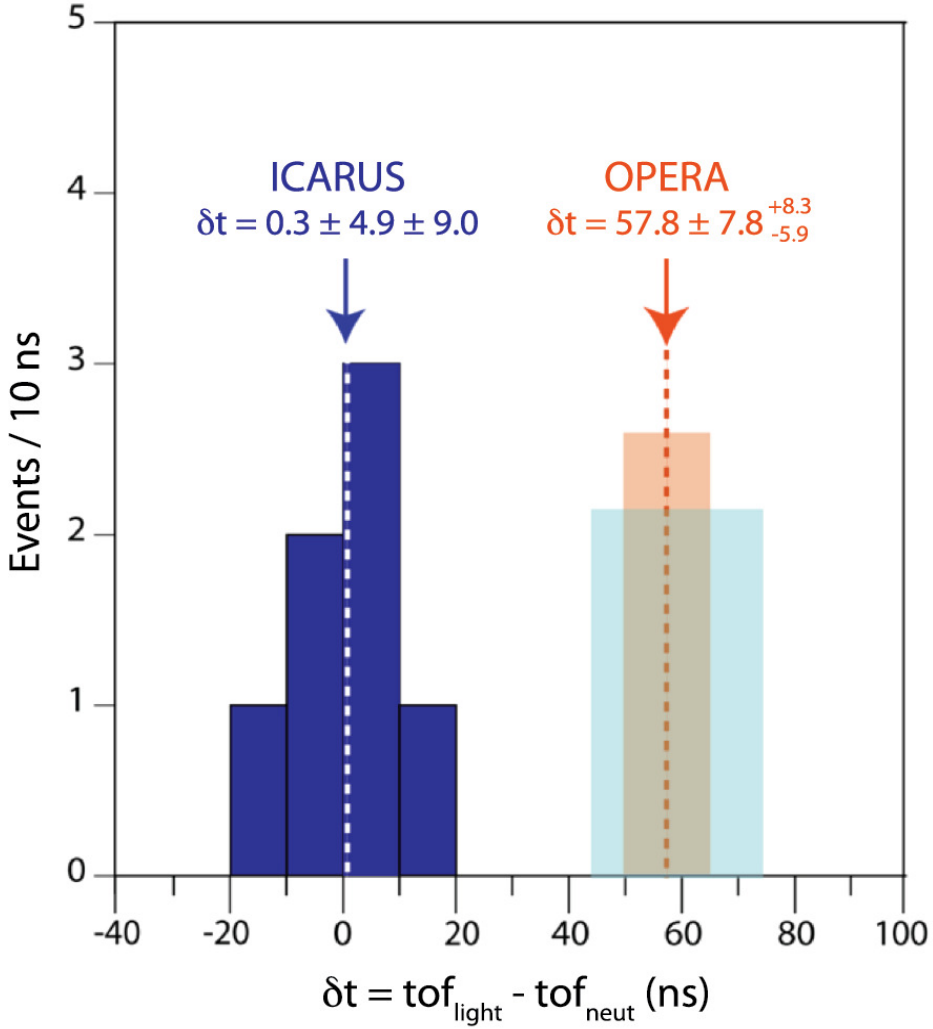


Neutrino time of flight result

- The average $\delta t = tof_c - tof_\nu$ for the 7 events is +0.3 ns
- The statistical error of 4.9 ns is estimated from a Student distribution with 6 d.o.f ;

  the systematic error of ~9 ns is due to uncertainties of time delay measurements.
- ν velocity, compatible with speed of light, is in disagreement with the OPERA first claim
- Presently analyzing data with the new bunched beam run (separate analyses - Opera, Borexino, LVD)
- News – in May ICARUS observed

  25 events



The main measurement error for OPERA experiment concerns the optical fibre connector that brings the external GPS signal to the OPERA master clock, which was not functioning correctly when the measurements were taken.

Summary

- ICARUS @ LNGS is taking data with the CNGS beam in stable conditions since October 2010. Data analysis is on-going and the software is developed.
- ICARUS will be recording cosmic and CNGS neutrino events in 2012 and only cosmic events in 2013.
- The successful assembly and operation of ICARUS is the experimental proof that this technique is suitable for large scale experiments.
- Neutrino velocity is compatible with speed of light (measurements in ICARUS),
- We are currently analyzing data for the May bunched beam which was dedicated to the measurement of neutrino velocity. Results will be available soon.

BACK-UP

CERN Press Release – 16 March 2012

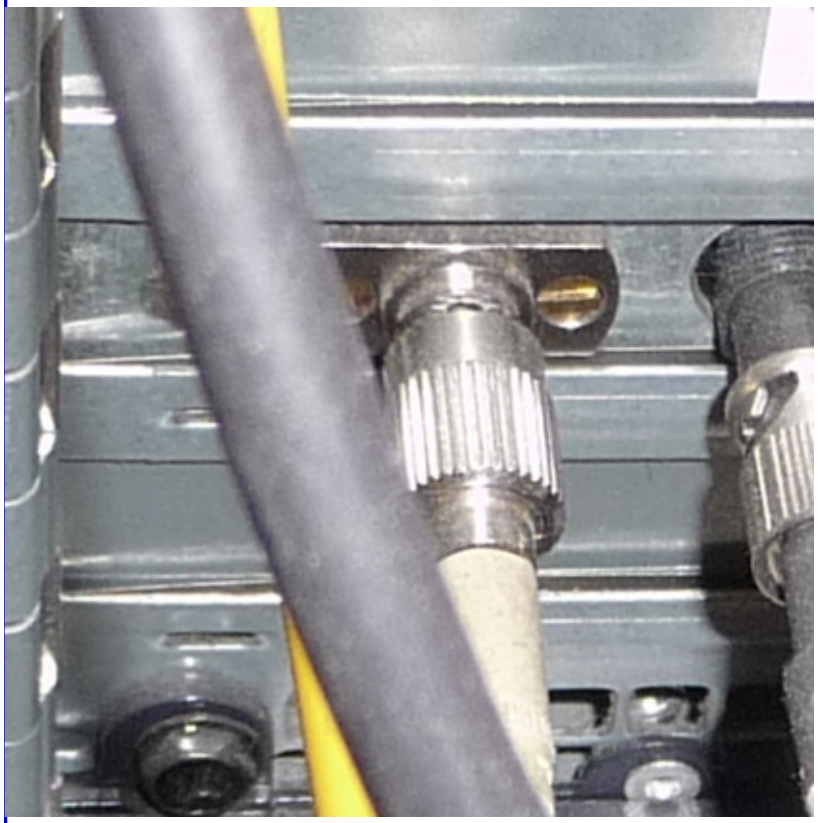
The ICARUS experiment at the Italian Gran Sasso laboratory has today reported a new measurement of the time of flight of neutrinos from CERN to Gran Sasso. The ICARUS measurement, using last year's short pulsed beam from CERN, indicates that the neutrinos do not exceed the speed of light on their journey between the two laboratories. This is at odds with the initial measurement reported by OPERA last September.

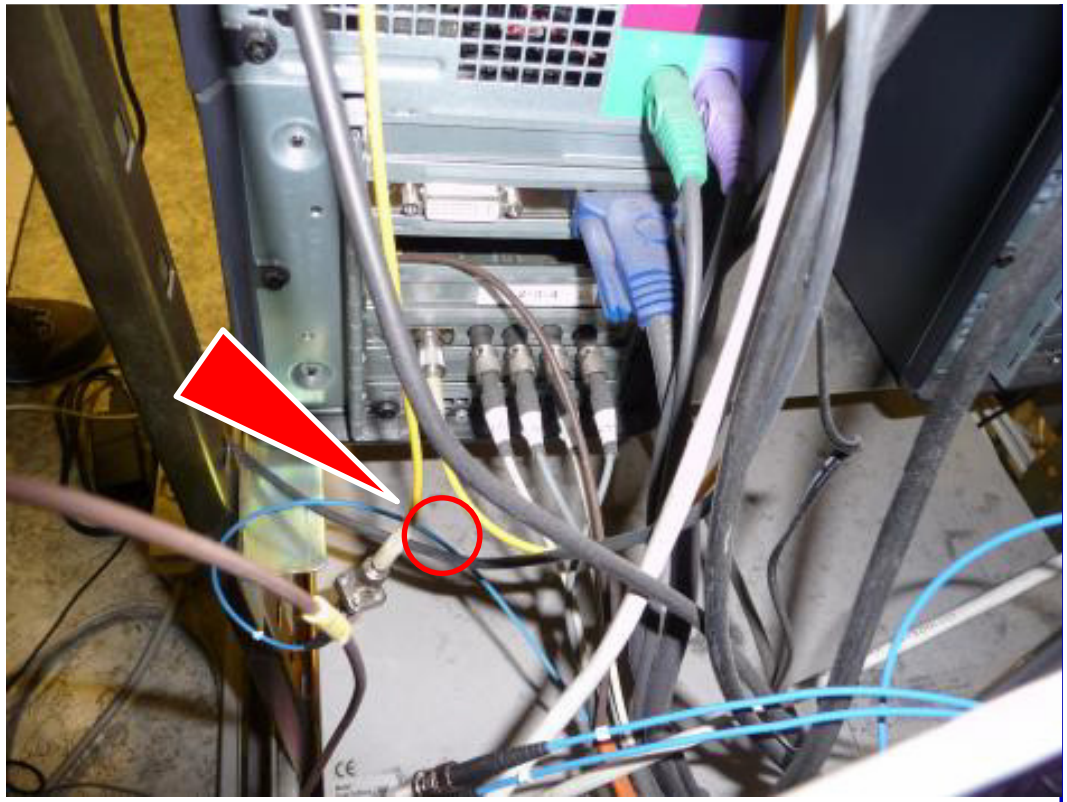
"The evidence is beginning to point towards the OPERA result being an artefact of the measurement," said CERN Research Director Sergio Bertolucci*, "but it's important to be rigorous, and the Gran Sasso experiments, BOREXINO, ICARUS, LVD and OPERA will be making new measurements with pulsed beams from CERN in May to give us the final verdict. In addition, cross-checks are underway at Gran Sasso to compare the timings of cosmic ray particles between the two experiments, OPERA and LVD. Whatever the result, the OPERA experiment has behaved with perfect scientific integrity in opening their measurement to broad scrutiny, and inviting independent measurements. This is how science works."*

The ICARUS experiment has independent timing from OPERA and measured seven neutrinos in the beam from CERN last year. These all arrived in a time consistent with the speed of light.

Pictures of the Rack hosting the OPERA Master Clock

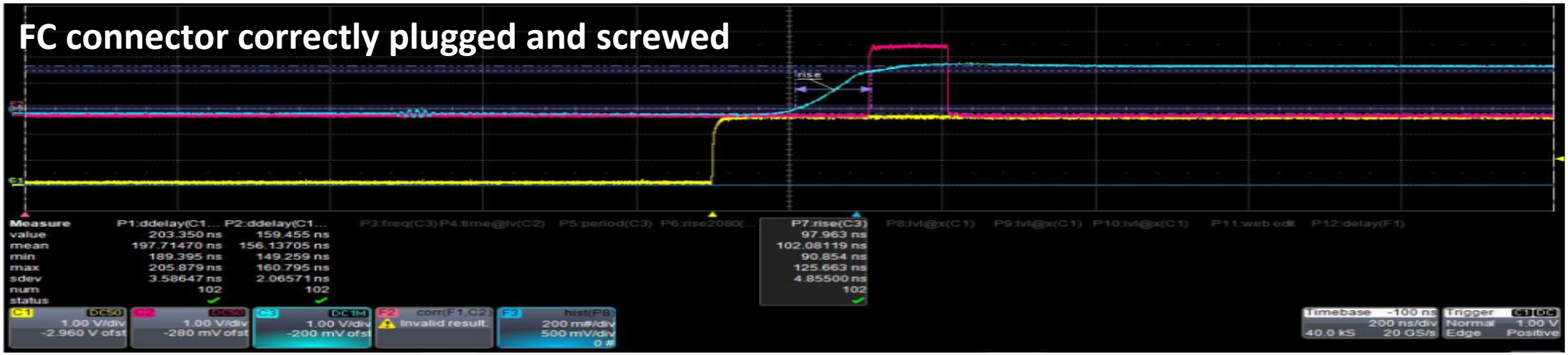
FC fiber connector incorrectly plugged already by October 2011.

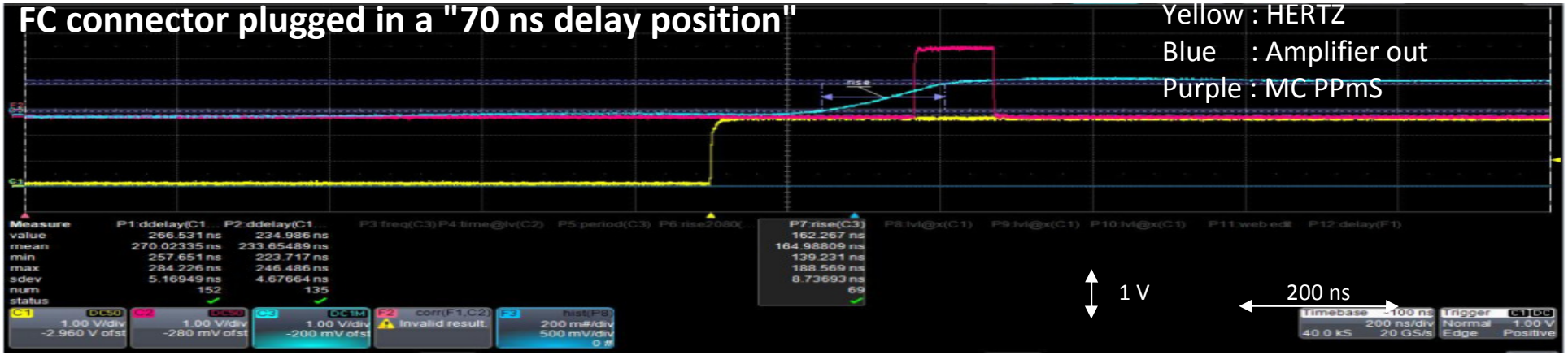




The OPERA collaboration has informed its funding agencies and host laboratories that it has identified two possible effects that could have an influence on its neutrino timing measurement. These both require further tests with a short pulsed beam. If confirmed, one would increase the size of the measured effect, the other would diminish it. The first possible effect concerns an oscillator used to provide the time stamps for GPS synchronizations. It could have led to an overestimate of the neutrino's time of flight. The second concerns the optical fibre connector that brings the external GPS signal to the OPERA master clock, which may not have been functioning correctly when the measurements were taken. If this is the case, it could have led to an underestimate of the time of flight of the neutrinos. The potential extent of these two effects is being studied by the OPERA collaboration. New measurements with short pulsed beams are scheduled for May.

Delay measured at an early stage of the amplifier circuit





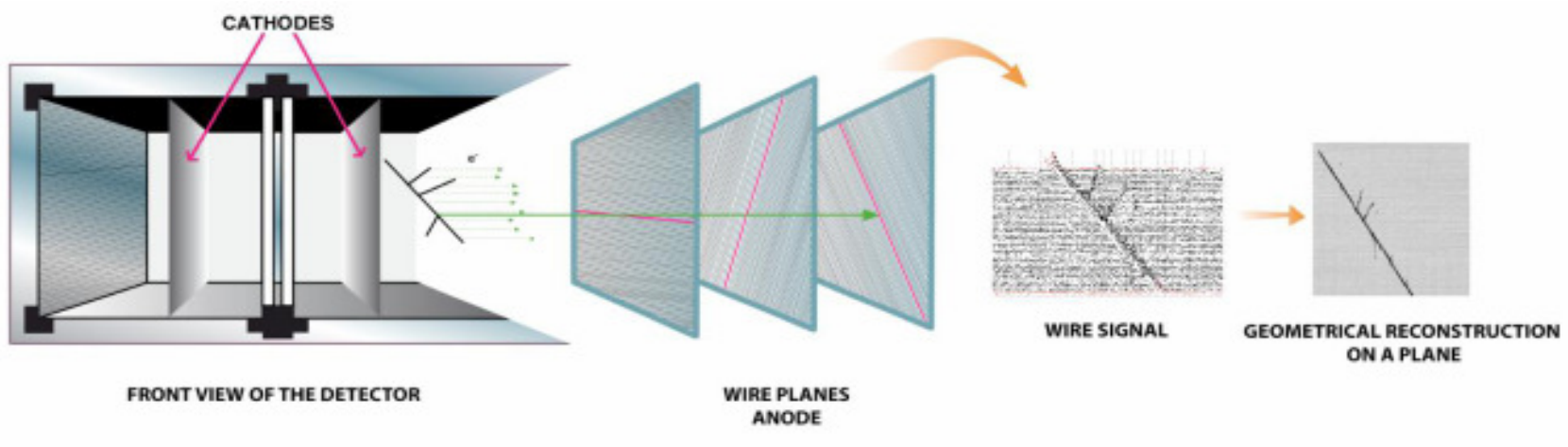
<u>The effect is related to the charging up of the photodiode capacity.</u>

The Reset signal sent to the sensors is delayed by the same amount as the MC PPmS.

 Underestimate of the neutrinos ToF

The detection technique

- The **Liquid Argon Time Projection Chamber** [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging of any ionizing event (*electronic bubble chamber*) in addition with:
  - continuously sensitive, self triggering;
  - high granularity (spatial resolution of the detector ~ 1 mm);
  - excellent calorimetric properties.

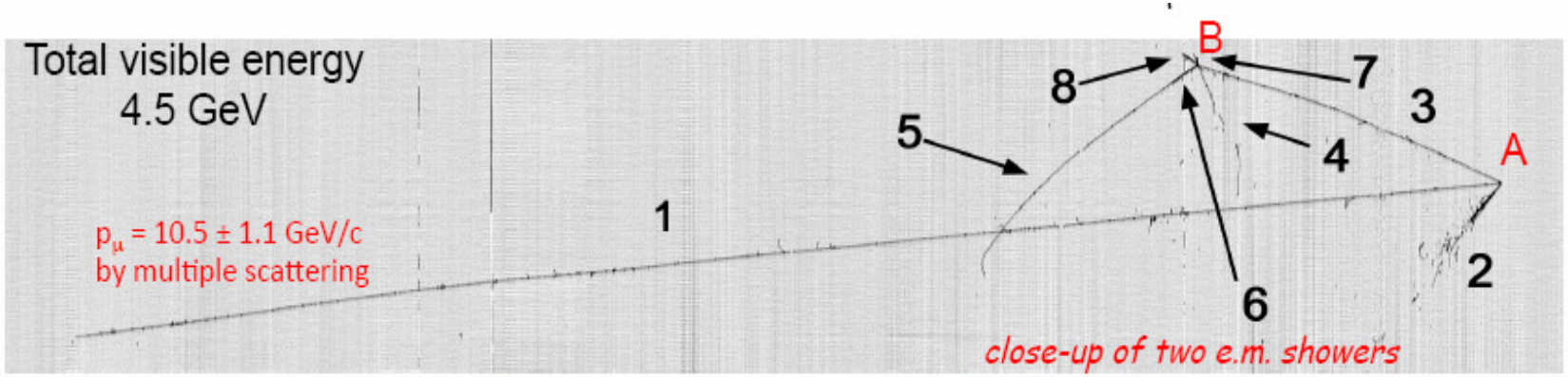


- Electrons from ionizing track are drifted in LAr by uniform electric field. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by collection plane.

Key feature: LAr purity. Impurities form electro-negative molecules (O2, H2O, CO2).

Target: 0.1 ppb O2 equivalent = 3ms lifetime (4.5 m drift @ Edrift = 500 V/cm).

Full reconstruction of a typical CNGS CC ν_μ event



Primary vertex (A):

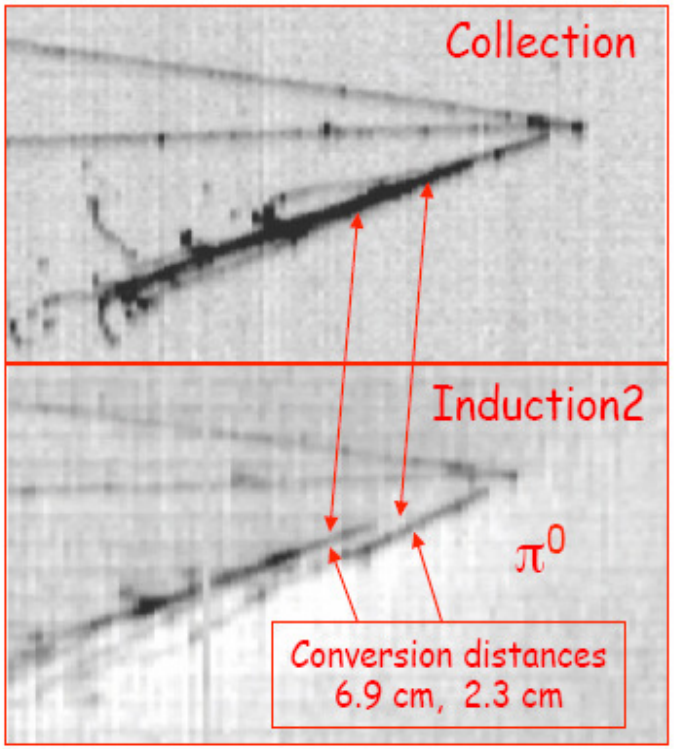
(1) long muon (uncontained)

(2) e.m. Cascades

(3) pion

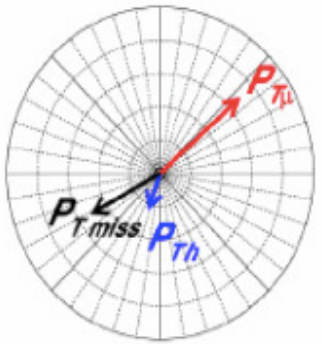
Secondary vertex (B):

the longest track (5) is a μ coming from stopping kaon (6). The μ decay is also observed



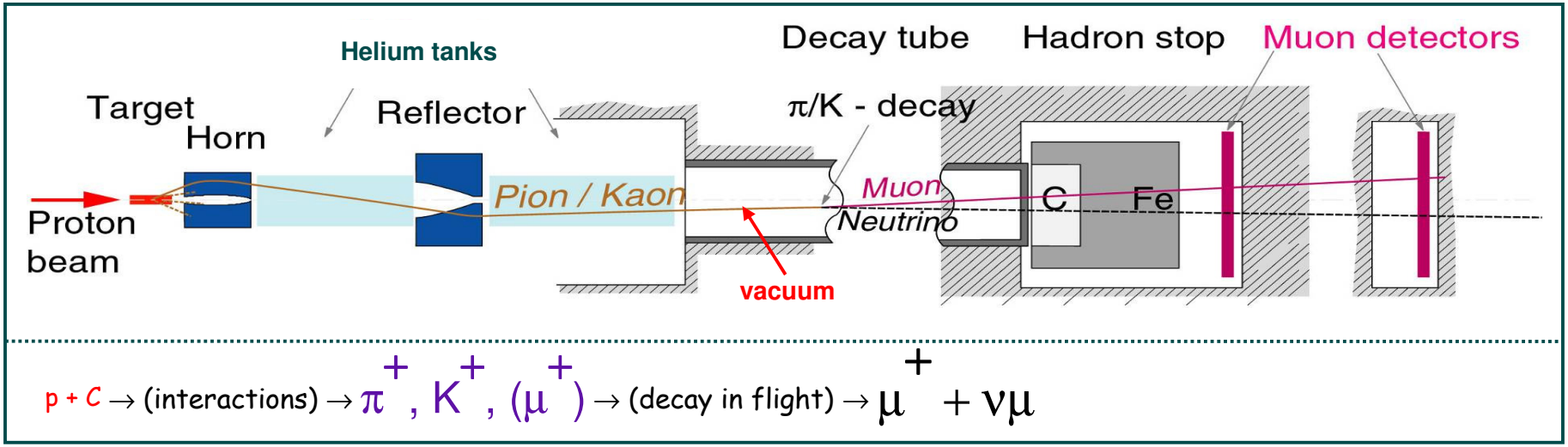
$M^*\gamma\gamma = 125 \pm 15$ MeV/c^2

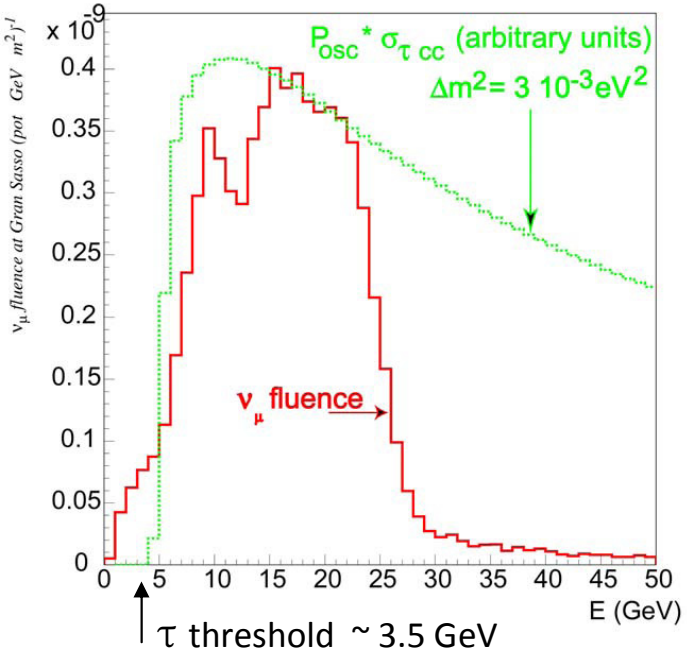
Total transverse momentum is consistent with Fermi distr.



P_T unbalance ~ 250 MeV

CNGS – CERN Neutrinos to Gran Sasso





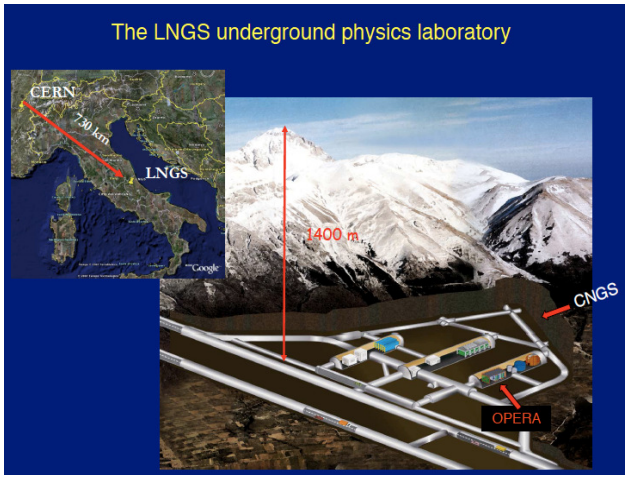
Energy distribution of ν_μ fluence

<E> ~ 17GeV

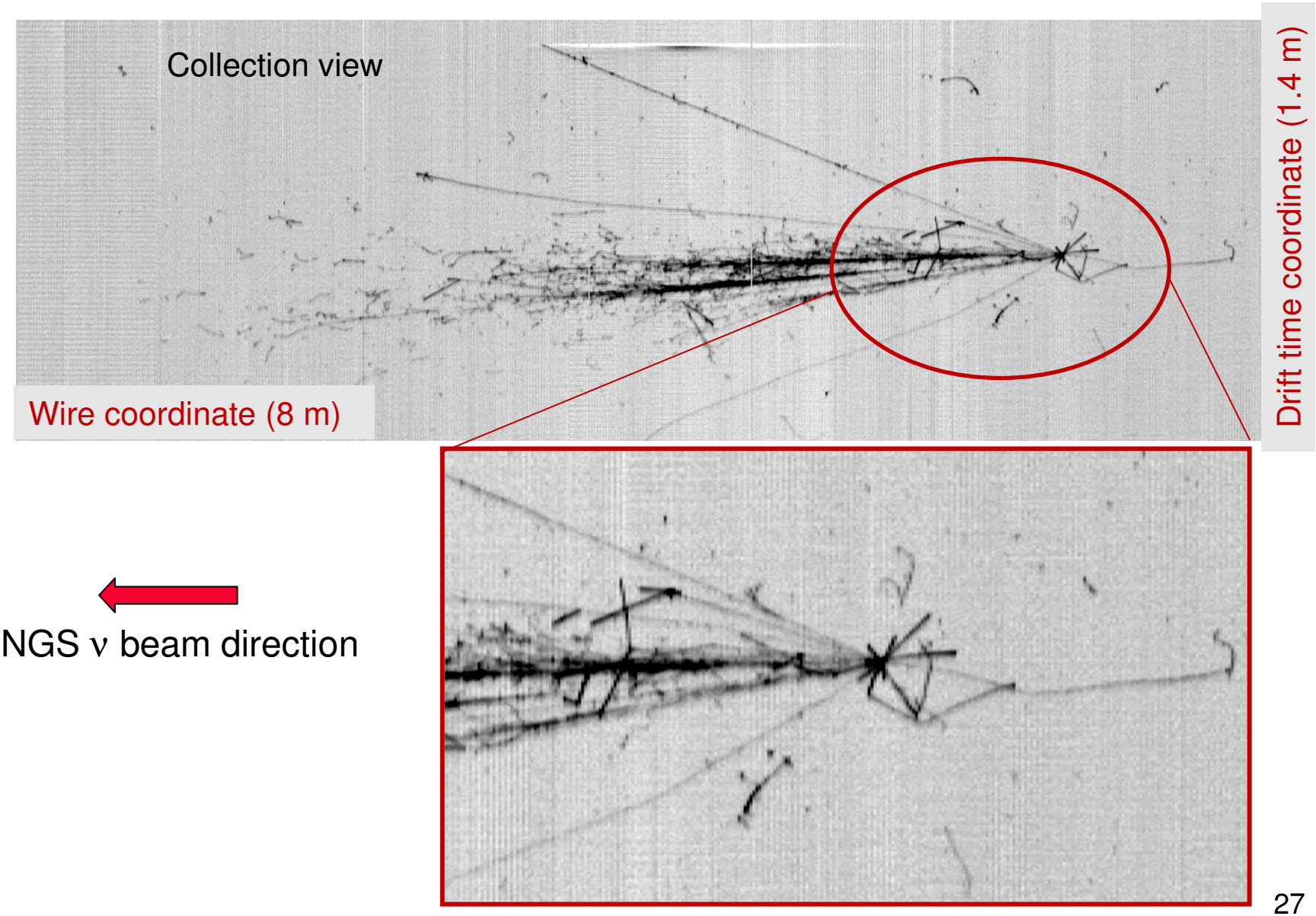
ν_e/ν_μ ~ 0.8%

$\bar{\nu}_\mu/\nu_\mu$ ~ 2.1%

$\bar{\nu}_e/\nu_\mu$ ~ 0.07%



First CNGS ν_μ interaction in ICARUS T600 – 28.05.10



ICARUS T600 reconstruction performances

TRACKS:

- Momentum of high energy particles is measured via multiple scattering: $\Delta p/p \approx$ 10-15% depending on track length and p.
- Stopping particles energy is measured by charge integration.
- Stopping particle identification by means of dE/dx vs E.

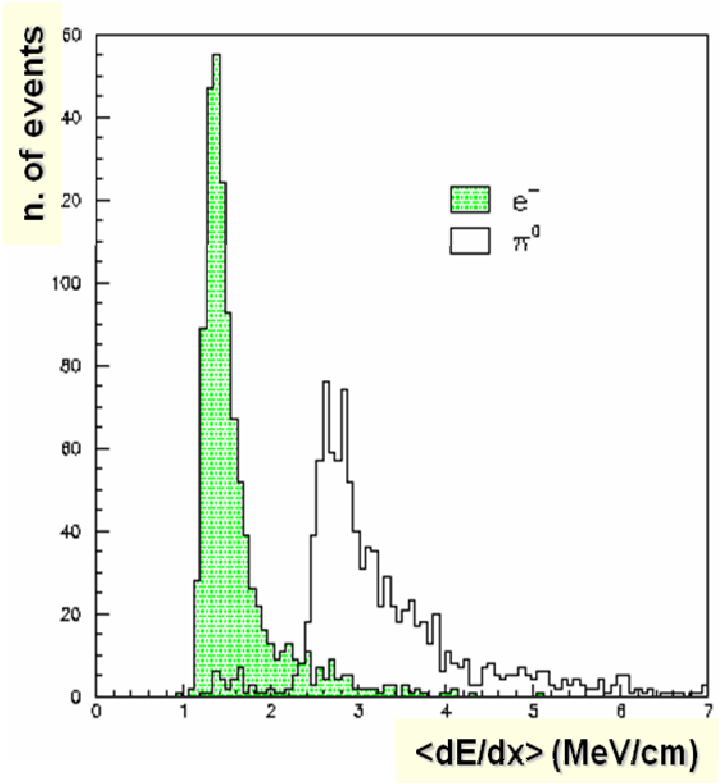
} Requires good spatial reconstruction

CASCADES:

- The total energy of cascades is measured by charge integration corrected for recombination.

Very good e/π^0 separation by means of dE/dx in the first part of the cascade.

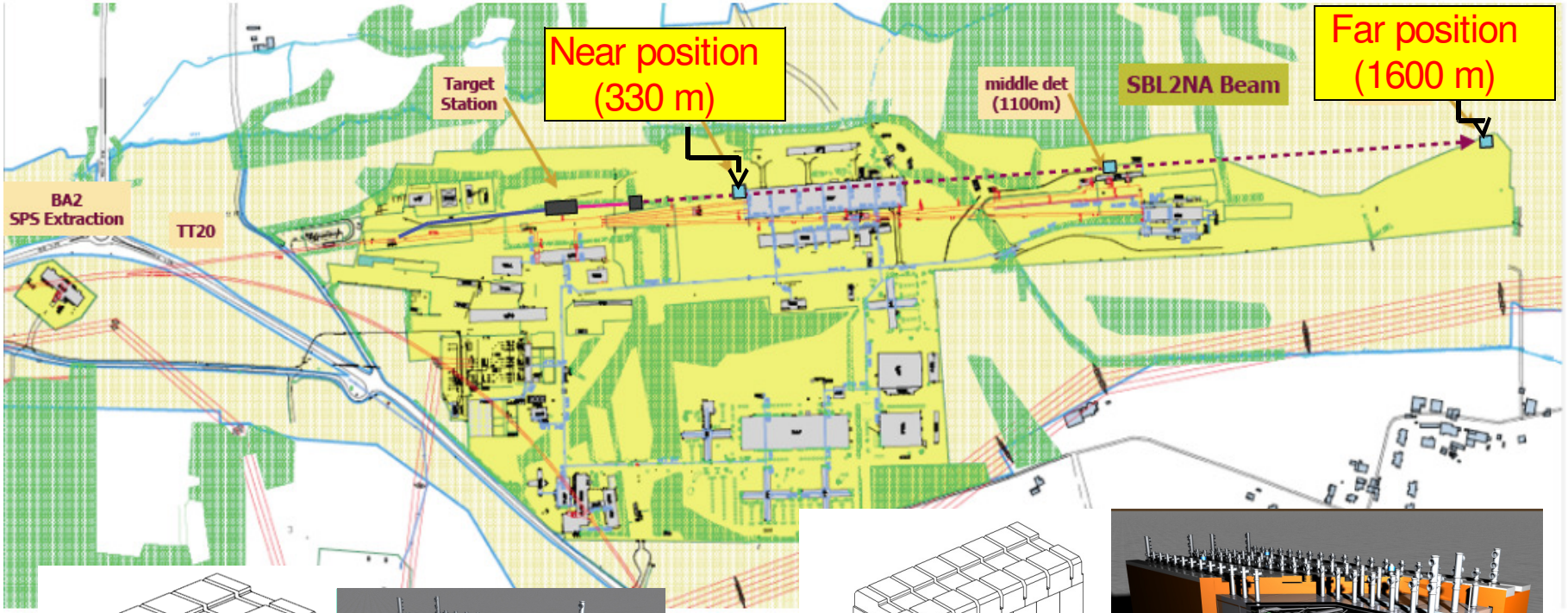
NC π^0 background rejected at 0.1% level while keeping 90% of ν_e CC

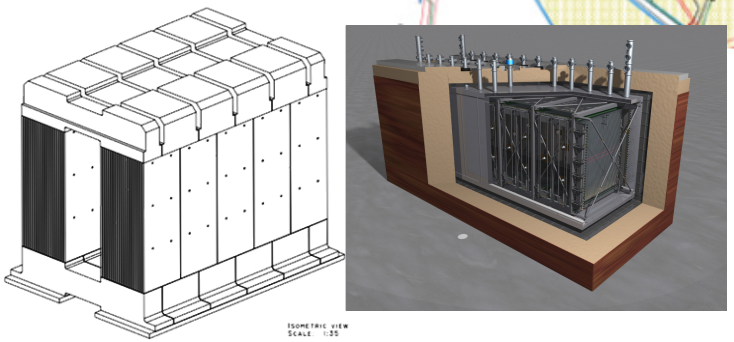


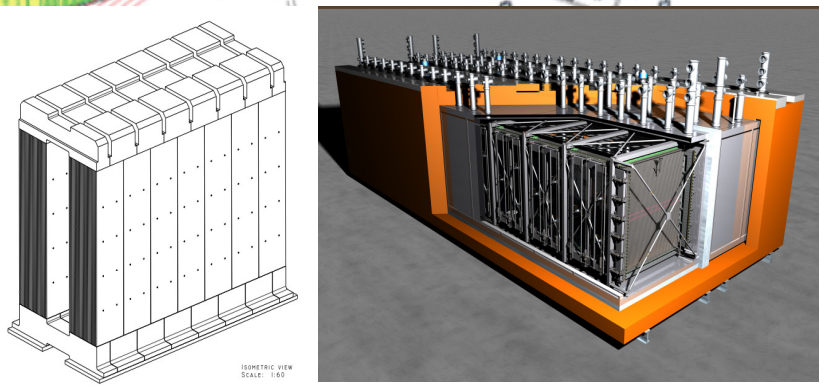
ENERGY RESOLUTIONS:

Low energy eletrons	$\sigma(E)/E = 11\%/\sqrt{E(MeV)} + 2\%$
Electromagnetic showers	$\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
Hadron shower (pure Lar)	$\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

New Neutrino Facility in the CERN North Area







NEAR

New detector T150 identical to ICARUS but of smaller size

FAR

T600 moved from LNGS to CERN with new insulation