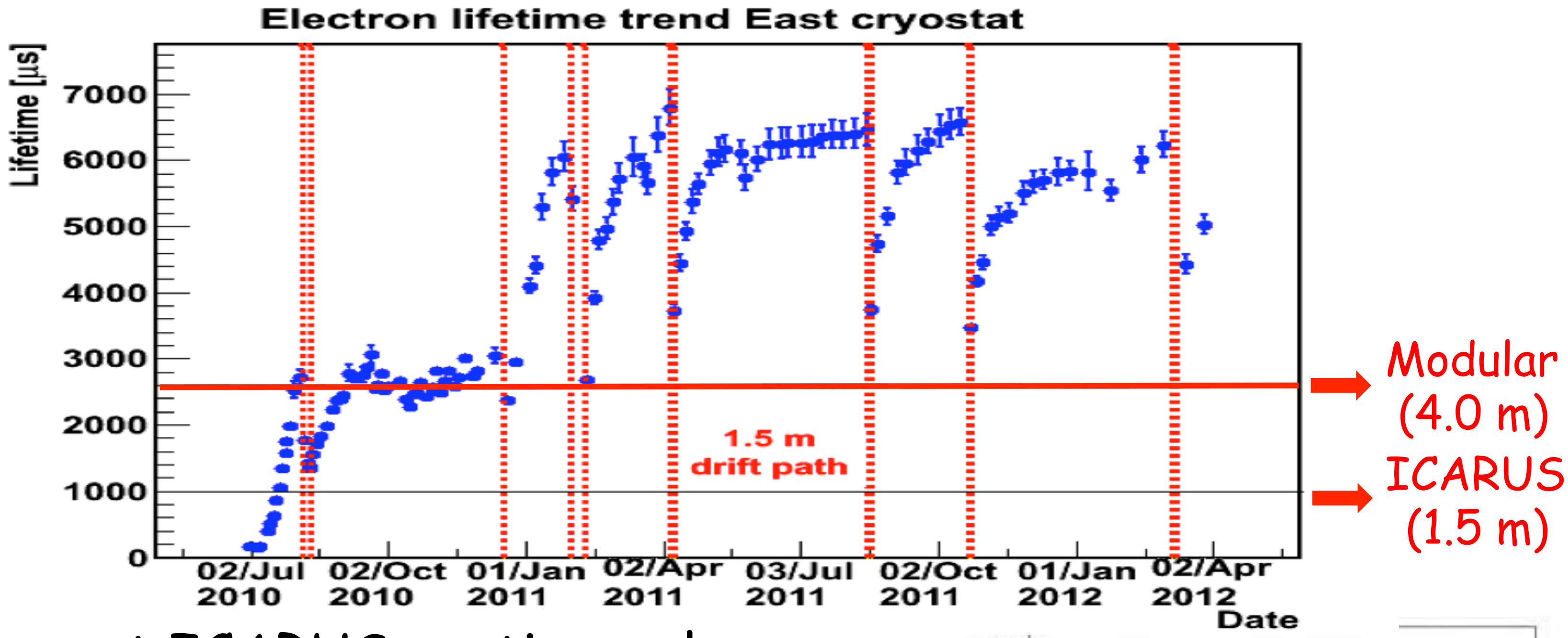
A realistic programme to explore CP violation in the leptonic sector

Carlo Rubbia
LNGS-Assergi, Italy
CERN, Geneva, Switzerland

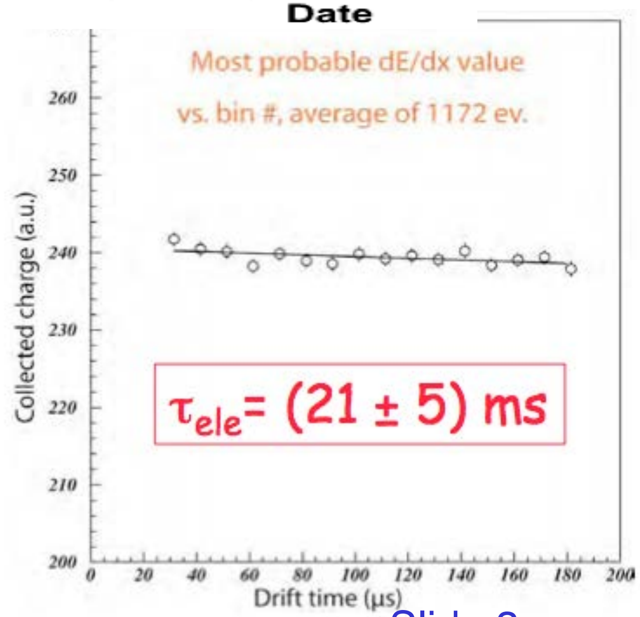
From θ_{13} to CP violation

- Contrary to the theorists' expectations of a θ_{13} as small as 10^{-4} or less, Nature has decided otherwise: $\sin^2(2\theta_{13}) \approx 0.1$.
- The recent beautiful results from Daya Bay and Reno have demonstrated that the value of θ_{13} is ≈ 9°, opening the way to a meaningful search of CP violation in the leptonic sector.
- At the oscillatory maximum, the $\nu\mu$ -> νe is now about 0.06, compared with a beam associated νe background of 0.002.
- Therefore both beta-beams and other super-beams are not necessary and "ordinary" Van Der Meer horns are adequate
- Although the interesting energy domain of the neutrinos is in the few GeV range, depending on the distance, a very high power of the proton beam remains the premium value.
- In our view, the very large LAr-TPC "bubble chamber", following the ICARUS technology, is the best and feasable technology for a CP violation search of θ_{13} related νe events.

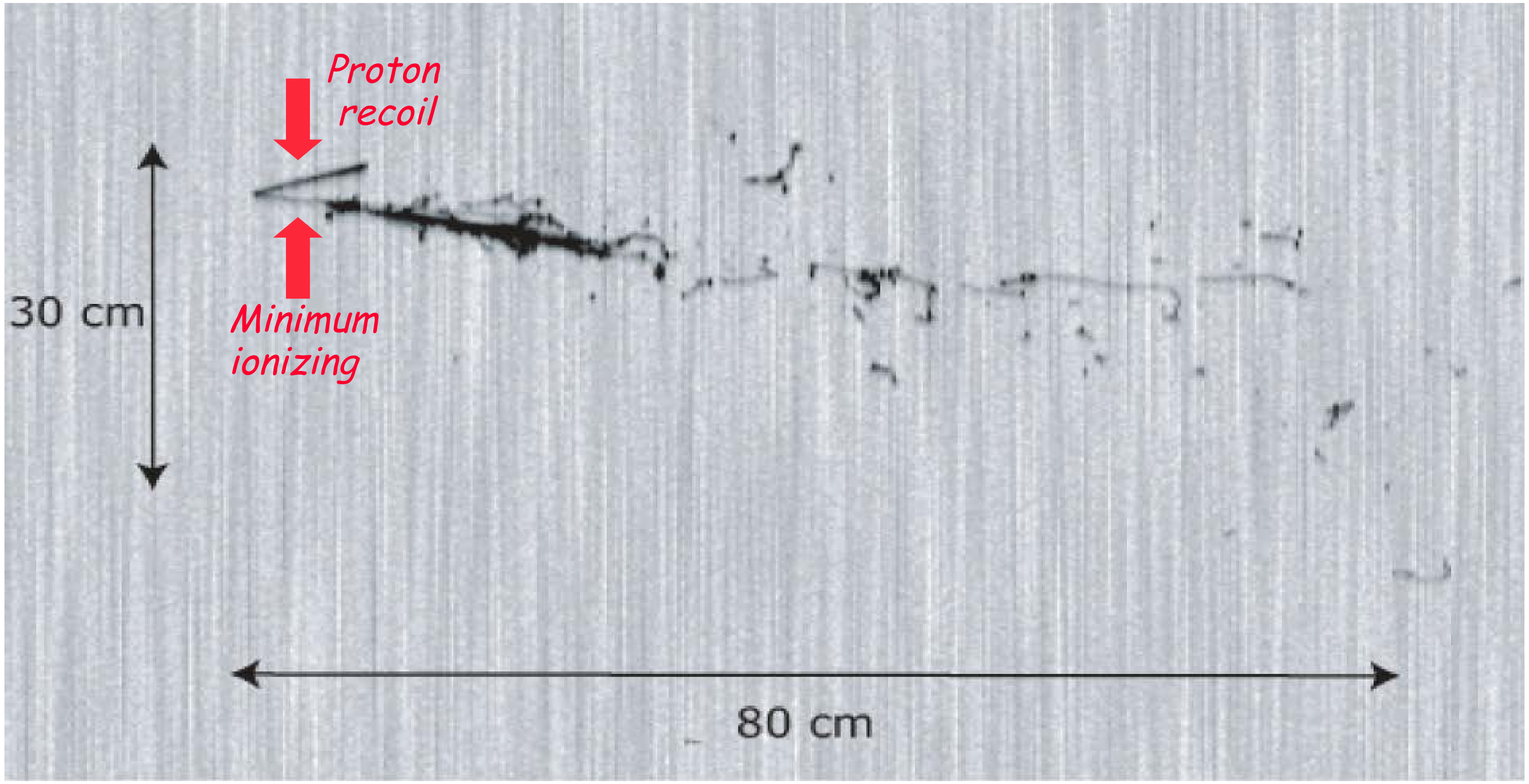
The key to LAr –TPC: the free electron lifetime



- The present ICARUS continuously operated during 1.5 years with 720 ton of LAr has been demonstrated a ≥ 4.5 m free electron drift length.
- Recently, extremely large τ_{ele} have been measured in a 50 litres LAr-TPC.
- The best result has been $\tau_{ele} \approx$ 21 ms, namely≈ 15 ppt Oxygen equivalent.



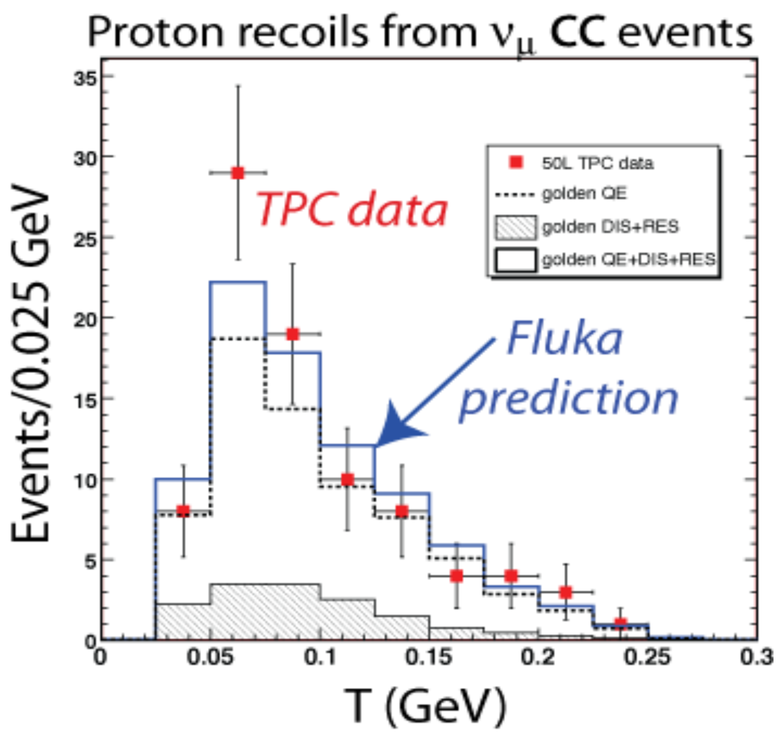
A ν_e QE interaction at ~ 1.5 GeV in LAr

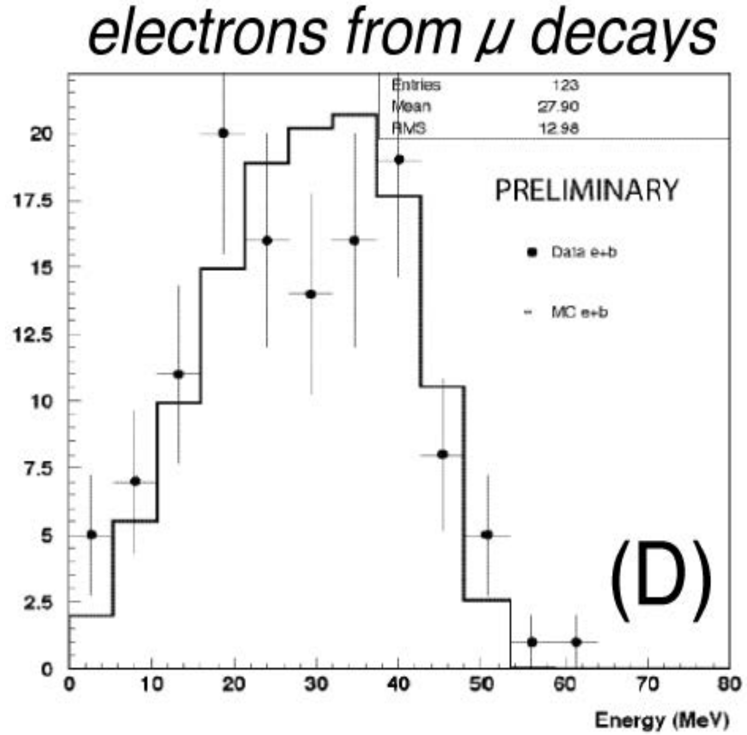


- π^0 from NC are rejected by photon vertex identification, invariant mass reconstruction and dE/dx measurement: the expected π^0 mis-interpretation probability is 0.1 %, with νe detection efficiency of 90 % within the fid. volume.
- The typical energy resolution of νe events is ≈ 15 %.

Excellent energy determinations of QE events

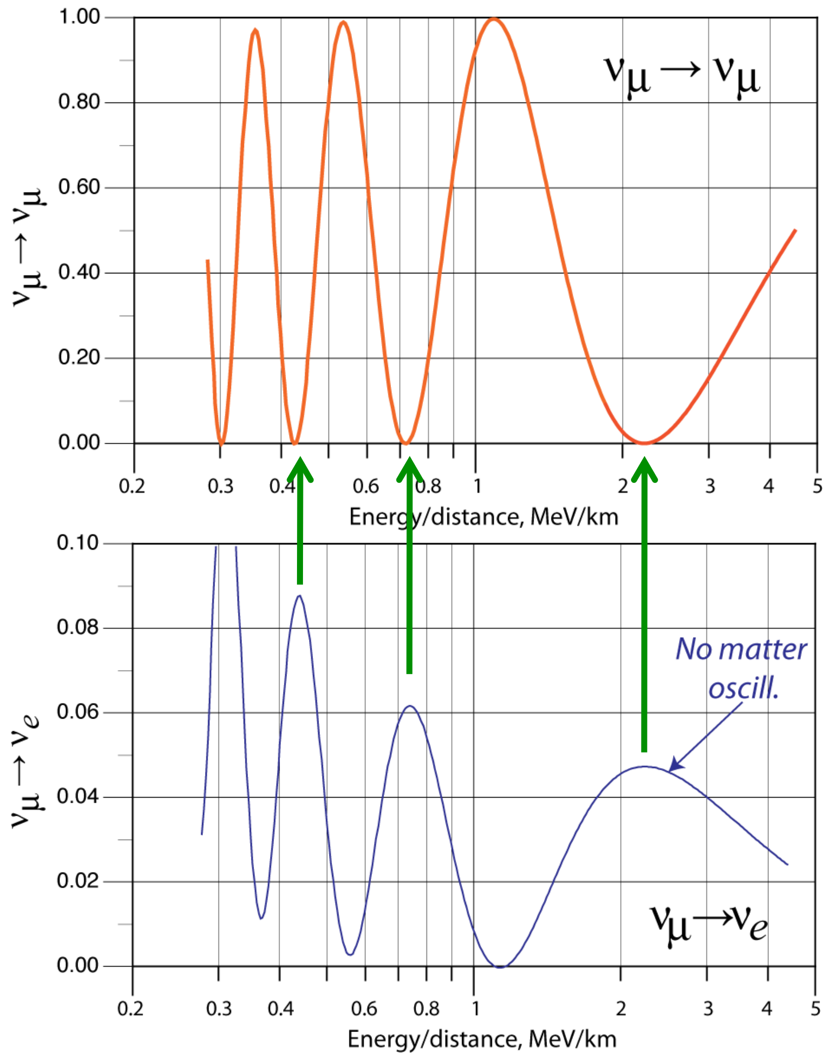
- [ν_e CC -> electron + proton] LAr-TPC events from the θ_{13}-dependent process are compared with experiments:
  - visible *proton energies* from QE ν_μ events at the CERN-SPS and comparison with Fluka predictions.
  - Observed excellent *electron energy* resolution of Michel decay electron from muon decays at rest.





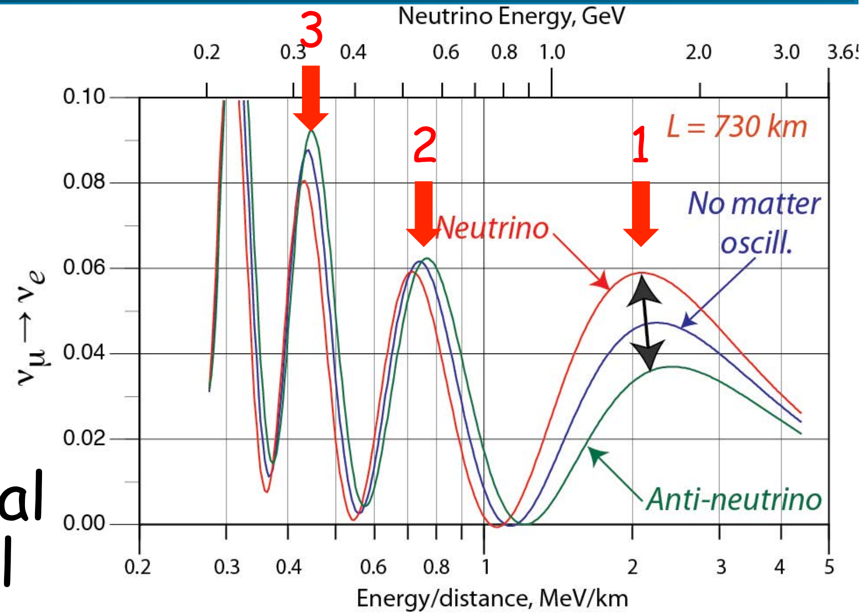
Main evolution of θ_{13} related effect with distance

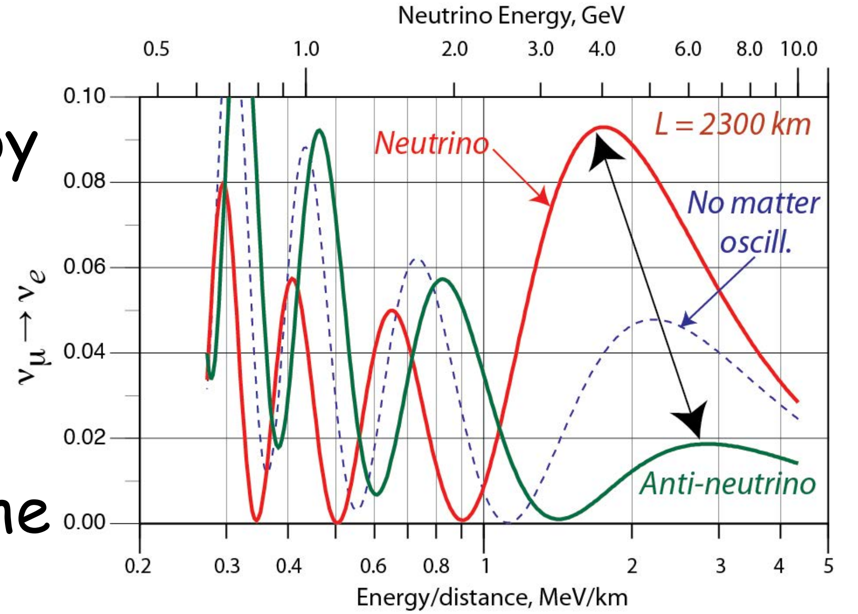
- Let us assume an initial ν_μ beam. After a E/L distance we have
  - A main surviving ν_μ-> ν_μ CC rate oscillating between 0 and ≈100%
  - A ν_μ-> ν_e CC rate, strongly dependent on θ_{13}.
  - A ν_μ-> ν_τ CC rate which is sterile since below threshold
  - Total NC rates unaffected.
- Assuming *CP conservation* and *no matter oscillations* we have an identical behavior for ν and ν-bar CC rates, with maxima of ν_μ-> ν_e where ν_μ-> ν_μ has minima, but moving closer to each other.



Matter oscillations and no CP violation

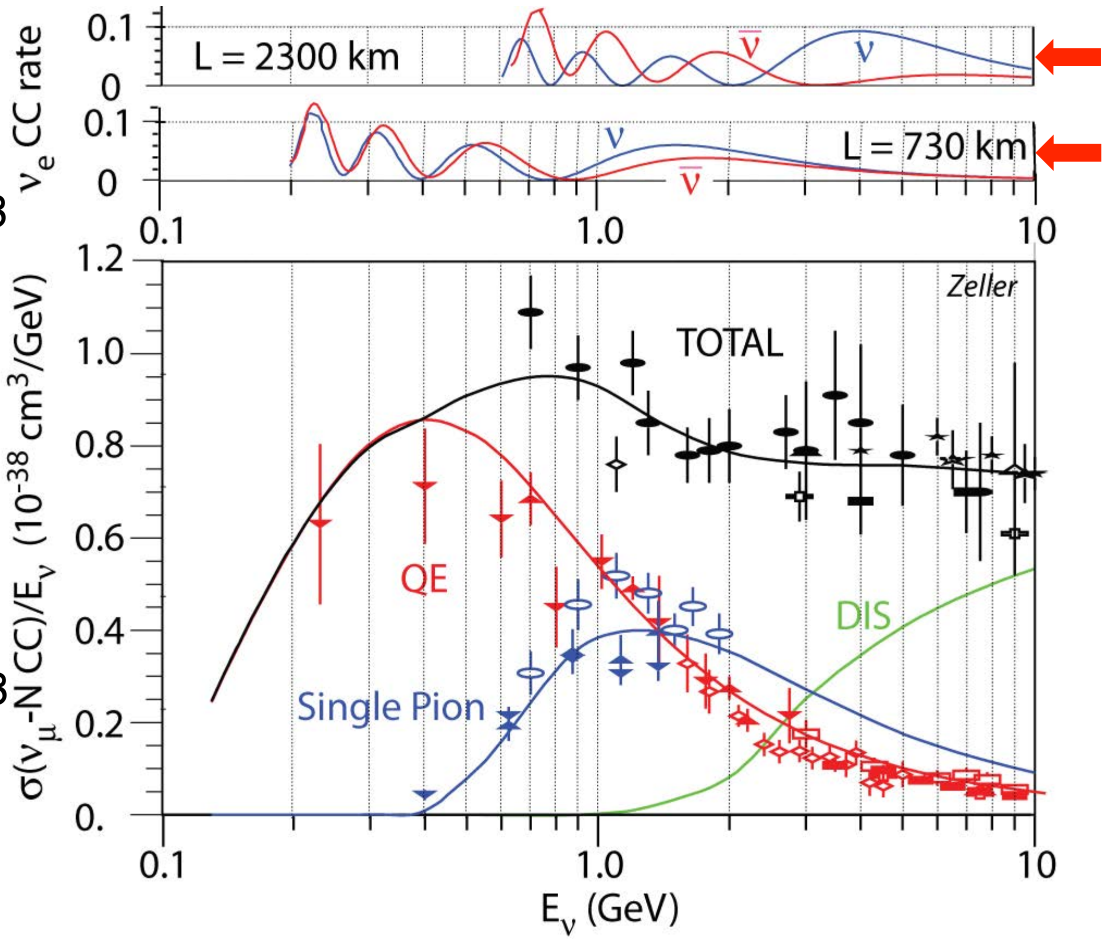
- Matter oscillations have:
  - a mild effect at 730 km, for the first peak and a very tiny effect for the critical second and third peaks.
  - a huge difference of ν vs. anti-ν at 2300 km, proportional to the relatively unknown local density and nature of rocks. The position and shape of all peaks are strongly affected by the matter oscillations.
- This strongly supports ≈ 730 km when compared to 2300 km.
- There are other no counter-indications and in all locations the LAr-TPC is the optimal solution.



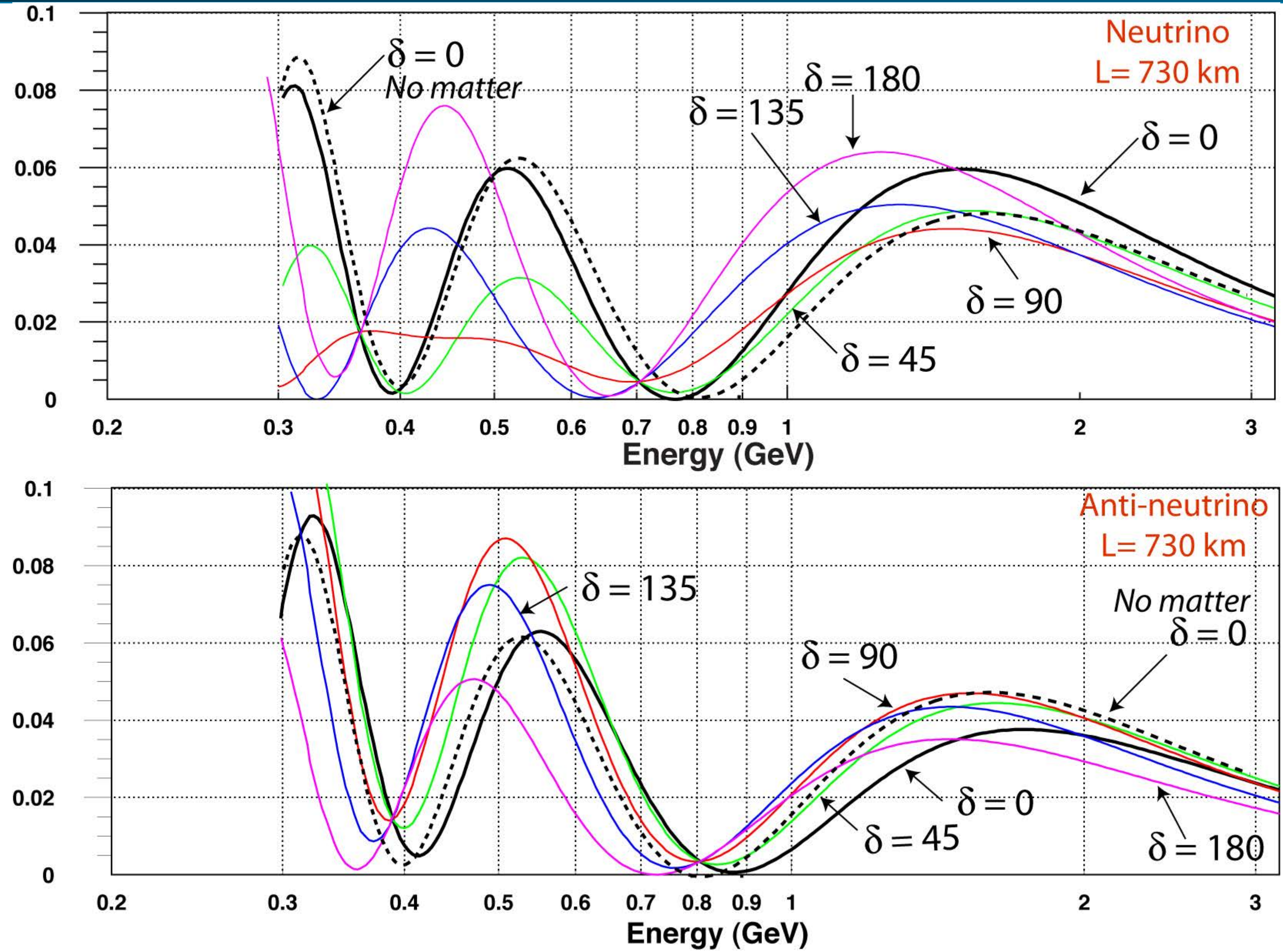


Neutrino CC cross sections in an iso-scalar target (Ar)

- The CC cross sections are characterized by a dominance:
  - At L=730 km of quasi-elastic and single pion
  - At L=2300 km of deep inelastic events
- The $\nu_\mu \rightarrow \nu_e$ conversion rate generated by the presence of the large θ_{13} is shown both for ν and ν-bar and both L values.
- How can one separate at L =2300 km the discovery of a CP violating phase of the θ_{13} oscillation from the signals from matter related effects ?



Variation with the CP violation phase δ° at L =730 km

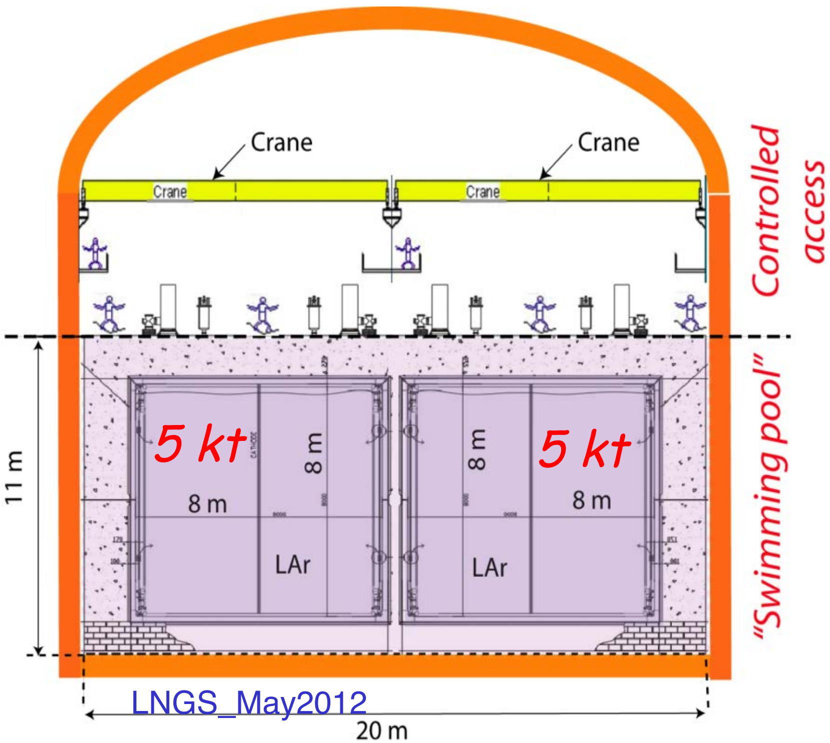


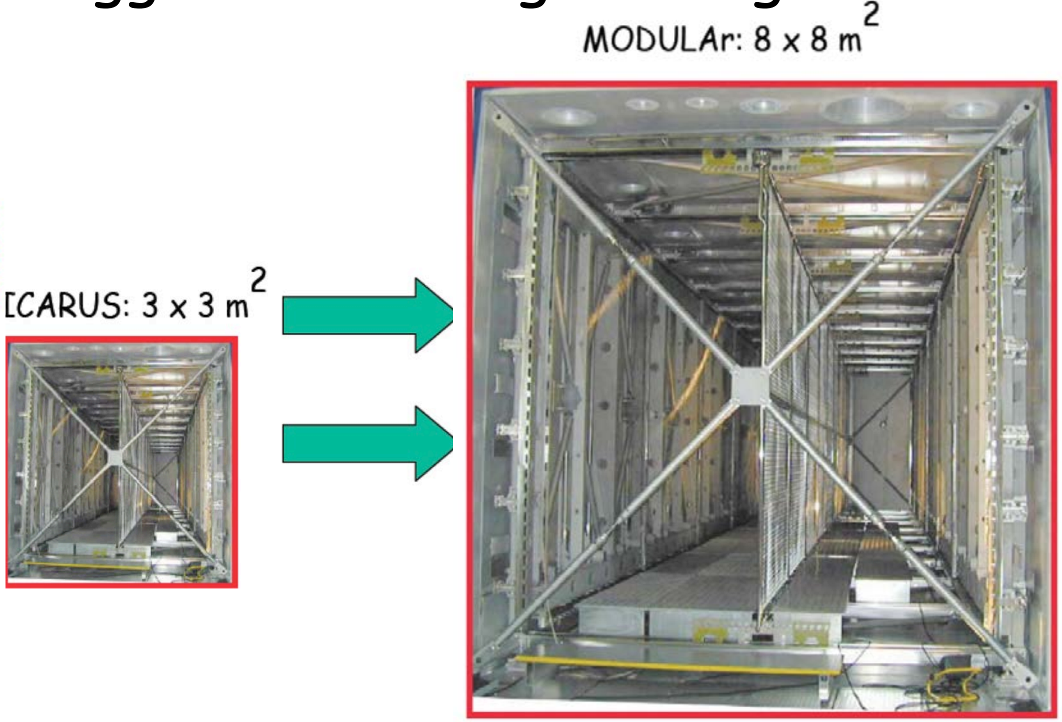
The "Modular" approach

- The most naïve design would assume a single (may be ≈100 kton) LAr container of a huge size. But the dimensions of most events under study (beam-ν, cosmic ray-ν, proton decays) are of much smaller dimensions.
- For instance, the whole volume of ultra-pure LAr will be totally contaminated even by a tiny accidental leak (ppb). A spare container vessel for ≈100 kton are unrealistic.
- Fortunately increasing the size of a single container does not introduce significant physics arguments in its favour.
- A modular structure with several separate vessels, each of a few thousand tons, is to us a more realistic solution.
- A reasonable single volume unit could be of 8 x 8 m^2 cross section, a drift gap of 4 m and a length of about 60 m, corresponding to 3840 m^3 of liquid or 5370 t of LAr.
- Two units should be located side to side with 10 kt mass.

The MODULAr detector

- Each gap is a scaled-up version of ICARUS (x 2.66^3):
  - 8 X 8 m^2 LAr cross section and about 60 m length
  - Two gaps within a same cryogenic volume: 10'740 ton
  - 4 m drift (2.66 ms), E_{drift} = 0.5 kV/cm, H.V.: -200 kV
  - 3-D imaging like ICARUS, 6 mm pitch (~50000 chs)
  - PM's will extract the trigger and timing LAr signal.





From ICARUS to Modular

- The continuous operation of ICARUS detector over 2 years opens the way to the development of a new line of modular elements which may be repeated progressively to reach the largest conceivable LAr-TPC sensitive masses.
- The new detector will maintain the majority of components that have been developed with industry for ICARUS.
- Negative ions inside the detector drift extremely slowly (≈ 1 mm/s at 500 V/cm) and may produce space charge distortions proportional to ≈ $(gap)^2$ and may require field stabilization beyond a critical gap volume.
- A very efficient mixing of the LAr is crucial to ensure a very uniform free electron yield, purity and drift speed.
- Technically, its extension of a gap to the 5 kt scale is entirely straightforward and smoothly realized without major changes, depending on the physics goals.

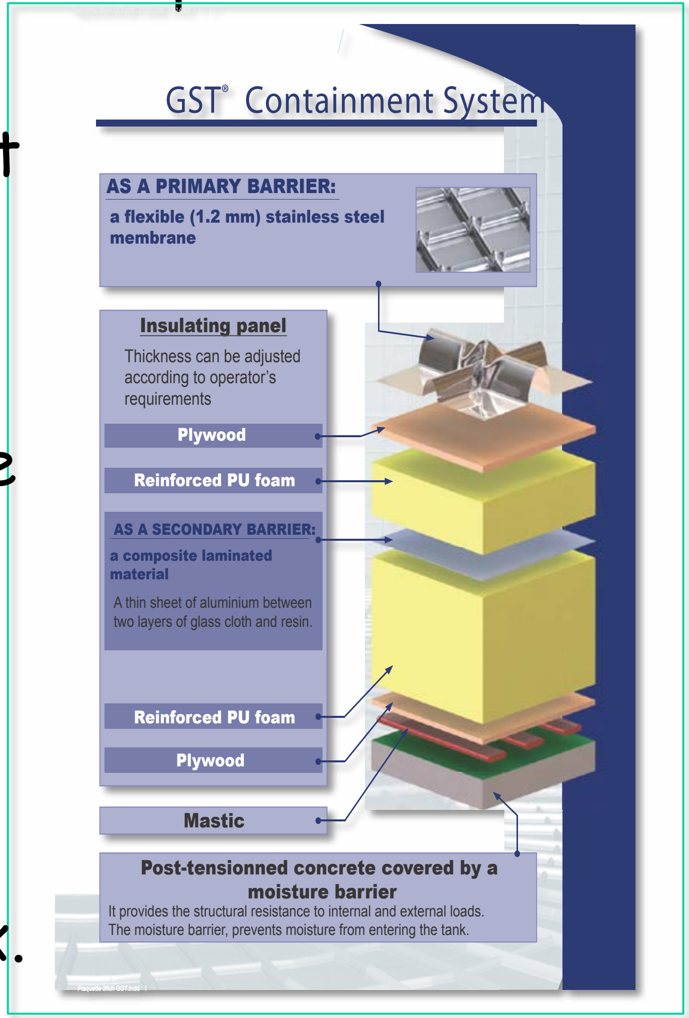
Modular: a much simpler solution

- The detector has been considerably streamlined with respect to ICARUS in order to reduce the number of components, its cost and to increase its reliability
- The modular structure permits to repeat the engineering design in a series of several subsequent units, reducing progressively both cost and construction times.
- ICARUS has already demonstrated that filling and maintaining over many years of a large amount of ultra-pure LAr could be done in stable conditions inside a dedicated underground cave and strict safety conditions.
- At the cost of 600 Euro/ton, the value of ultra-pure LAr for the initial filling of 21.5 kt module is about 15 MEuro.
- At the available rate of 500 t/d, namely 1/8 of the present LAr European production, each 21.5 kt module can be filled in about two months.

Few separate elements…

- The structure of the Lar-TPC is made with a remarkably small number of industrially produced simple elements:

1. Purely passive outer insulation (no vacuum). Membrane tanks represent the reference technique developed over 50 years, widely used for large industrial storage vessels and ships for liquefied natural gas (GST) The over all cryogenic loss is of 50 kWatt for each 21.5 kt module.
2. Aluminium vessels of welded extruded profiles, like ICARUS, designed to be super clean, high vacuum-tight and to stand 1 bar max. operating internal overpressure.



3. *A self-supporting structure* holding the frame with the wire planes at each lateral wall .The structure is identical to the one developed for the ICARUS, each made of three closely spaced wire planes 60° apart.

4. The *HV supply* at 220 kV at the centre of each gap.

5. *The PM's for the scintillation trigger* mounted behind the wire planes.The HV plane is transparent to PM's light.

6. *A system for recirculation and purification* both in the liquid and gas phases, to ensure that the whole liquid is flowing orderly with high purity inside the vessel volume

7. *A cabling port system* to ensure the electric connections of the wire signals and of the PM's readout.

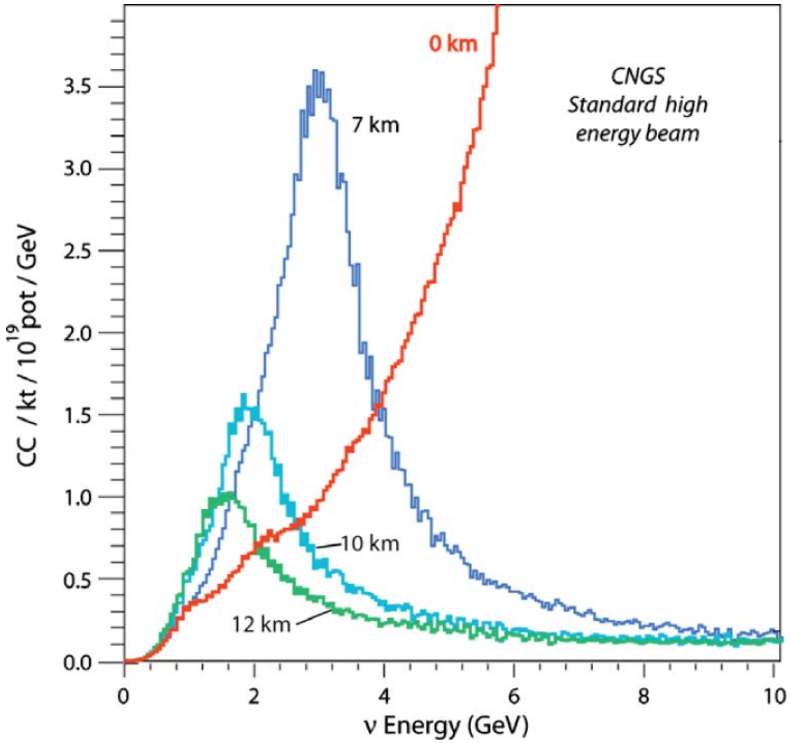
- The inner structures of the huge container are therefore extremely simple, being primarily thin linear structures along the edges of the container, the rest remaining essentially free of structures.

The next LNGS neutrino detector

- The ICARUS-T600 has collected a large number of neutrino events that have perfected the technology and provided a rich amount of experimental physics.
- The T600 is a necessary step toward the realisation *of any much larger LAr-TPC detector anywhere in the world.*
- The T600 has provided absolutely essential experience, required in order to develop sensibly a "next step".
- This novel proposal is focused on three main activities:
  - *The existing ν beam* from the 400 GeV SPS with modest changes to produce optimal beam configuration.
  - *A new experimental area* about 10 km off-axis from the LNGS, away from the protected area of the Gran Sasso National Park, at about 1.2 km of equiv. w. depth.
  - *A new LAr-TPC "Modular" detector* made of several independent volumes, each one of about 5 kt fiducial mass.

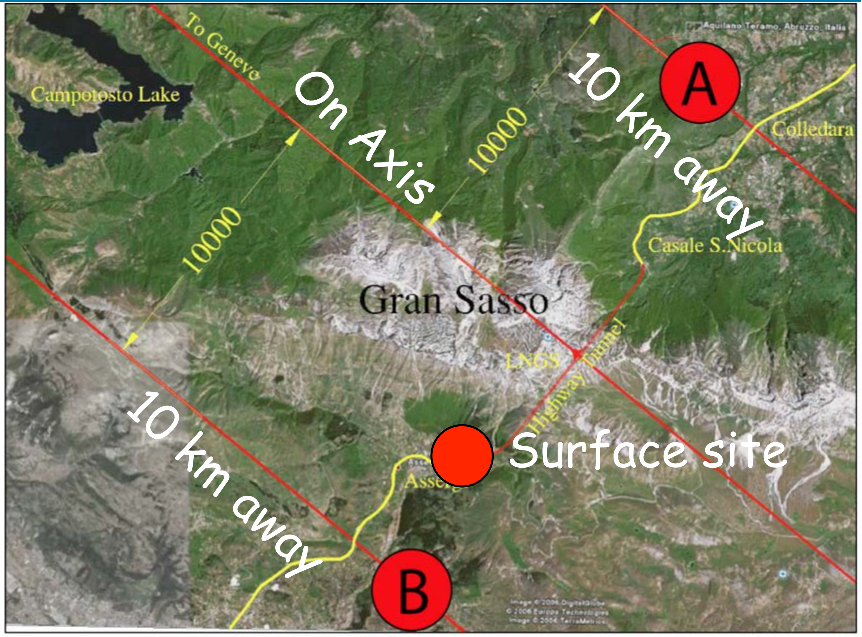
Tentative design for off-axis CNGS beam

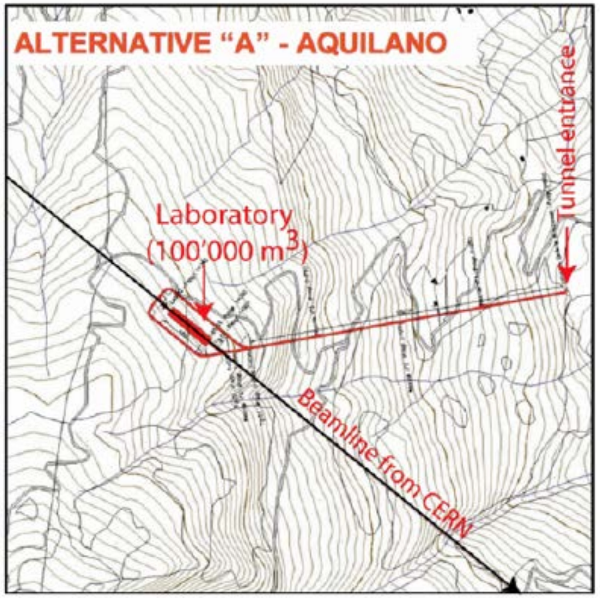
- We can assume that in several years from now, a dedicated 6 s cycle SPS and an efficiency factor of 70% may become possible. In addition the beam power should be increased to 550 kW from the present value of 275 kW.
- These factors should bring the integrated proton beam intensity to 2.4×10^{20} POT/yr
- Substantial improvements are possible with a focussing layout at a lower energy : for instance and 10 km off-axis and a different beam focussing we have found a gain of 2.5x for $E_\nu \leq 2.5$ GeV.
- The length of the decay tunnel may be substantially shortened within the existing installation.



The new LNGS Halls

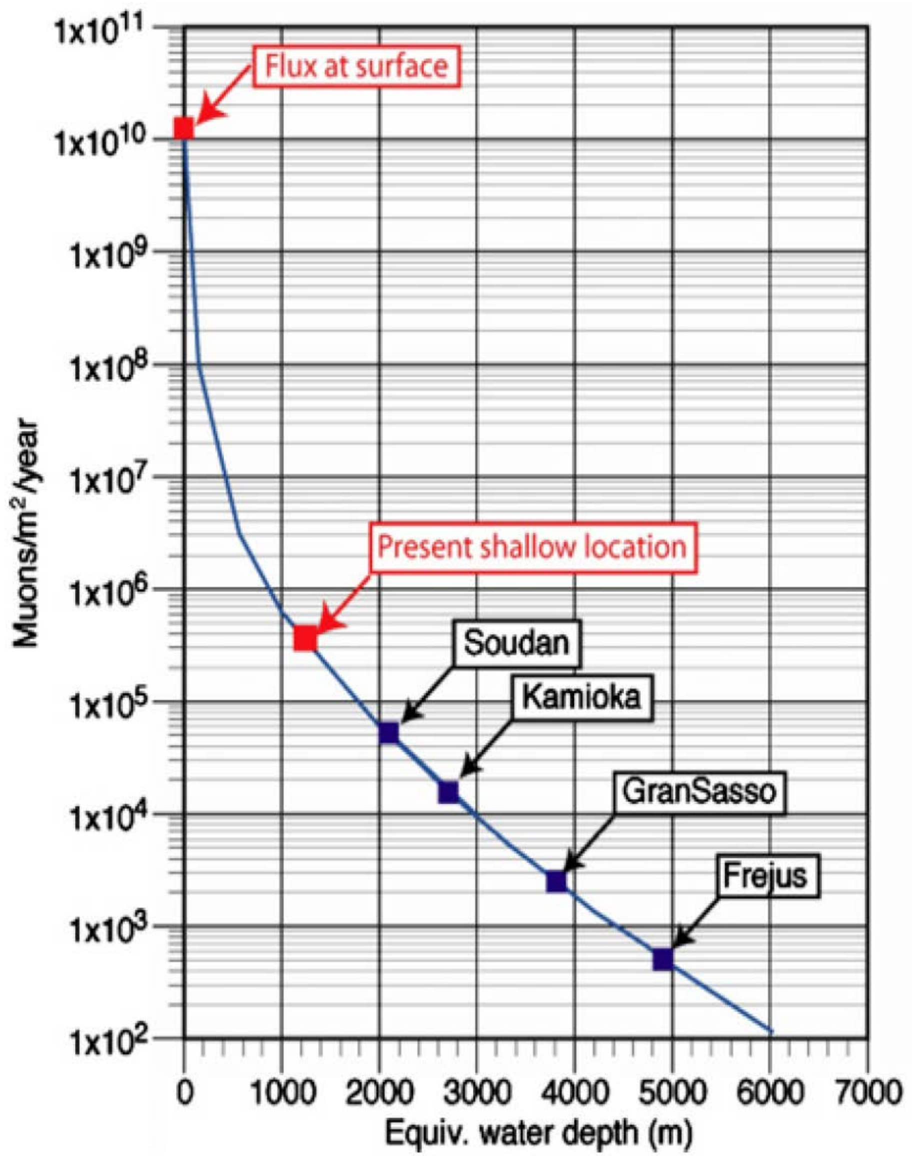
- New experimental hall at shallow-depth
  - ➢ ≈ 100 x 10^3 m^3 (present LNGS halls: 180 x 10^3 m^3)
  - ➢ 10 km Off-Axis w.r.t. present CNGS beam axis
  - ➢ two sites proposed out of Parco Naturale del Gran Sasso and far from high-way
  - ➢ A in Aquilano (Teramo side) and B in Camarda (L'Aquila side)
- Both below 1.2 km eq. water depth
- Good rock, no water, no special safety or environmental limitations
- Site A slightly preferred because of the shortest distance of the tunnel access
- LNGS on surface also available (7 km off axis)





How shallow should it be ?

- The underground laboratory may be at a depth, which is much shallower than the one of the main Laboratory. The high event rejection power of the LAr-TPC detector will ensure the absence of backgrounds not only from the neutrinos from the CNGS but also for proton decay and cosmic neutrinos.
- A depth of about 400 m of rock, corresponding to about 1.2 km of equivalent water depth has been chosen.



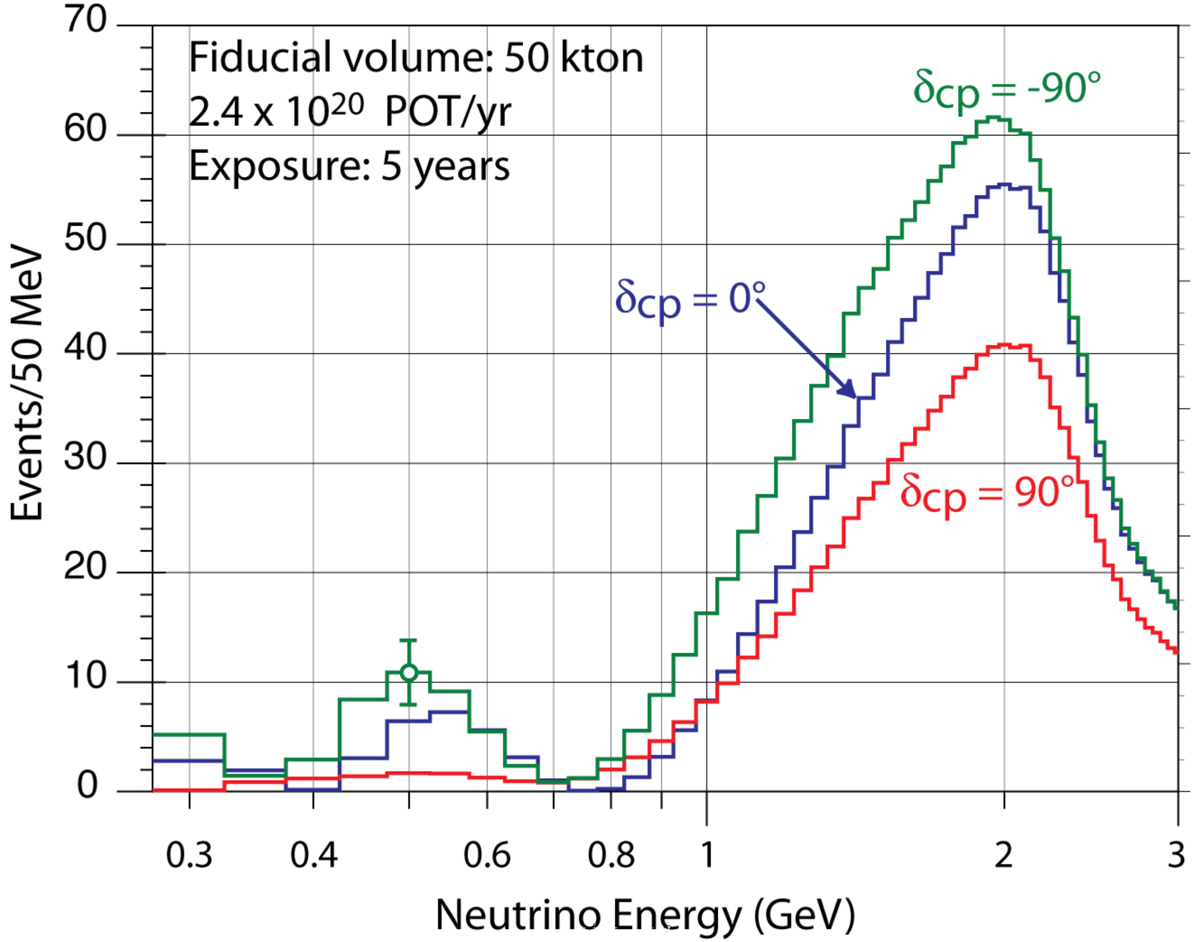
A new way of calibrating the neutrino beam

- The usual long baseline neutrino oscillations experiments, are based on "far" and a "near" detector closer to target, which however present very substantial differences.
- We propose as an alternative to add to the main off-axis detector a much smaller on-axis module (f.i. inside HALLB), which both see the same proton target/beam as a point like source. A ICARUS-NESSIE like mass is adequate for on-axis events, presumably with an iron $\mu^{\pm}$ spectrometer.
- Once the comparison with calculations is perfected with high statistics on-axis, one can derive precisely also the expectation for the beam off –axis, both for $\nu\mu$ and νe.
- Indeed the on-axis to off-axis neutrino flux translation represent a very important correlation, since the neutrino beam spectra are both derived from the same "Jacobian peak" and the two-body π and K decay kinematics.

A first cost estimate, based on ICARUS know-how

- Based on the long experience with ICARUS and a firm cooperation with industries in the realization of the detectors, a relatively firm estimate of the costs may be given.
- The cost, including contingencies, based on the above list of items 1-7 is as follows:
  - Engineering design and prefabrication costs: 10 M€
  - Construction and installation of first 10 kt: 40 M€
  - Scale reduction and other 4 modules (40 kt): 120 M€
  - LAr procurement for 50 kt fiducial mass 40 M€
- Total construction cost for a 50 kt fiducial mass 210 M€
- Total with additional extension of + 20 kt 285 M€
- Excavated volume for 50 kt fiducial mass 1.25×10^5 m^3

CP violating phase determination at the CNGS



Energy range	CP-conservation	$\delta_{CP} = 90°$	$\delta_{CP} = -90°$
E < 3 GeV	1459.7	1088.1	1715.3
E < 1.5 GeV	343.2	261.1	495.6
E < 0.8 GeV	32.5	14.4	52.9
E < 0.45 GeV	8.7	4.7	19.9

Concluding remarks

- The value of $\sin^2(2\theta_{13}) \approx 0.1$ opens the way to an experimental program on CP violation in the ν-sector.
- An optimal distance of the neutrino beam is about L ≈700 km, i.e. the existing CNGS beam, a compromise between distance, optimal events energies and acceptable contributions due to matter related effects.
- The existing CERN-SPS to LNGS is an adequate choice, with standard horn and reasonable improvements of the neutrino flux. Both off-axis in a dedicated shallow depth hall at ≈ 10 km away and an on-axis calibration are needed.
- Following the experience from ICARUS, an optimal technology is the one based on a MODULAR set of LAr-TPC detectors with appropriate total mass (≈ 50 kton).
- ICARUS related experience shows that the extrapolation to MODULAR is feasible without an extensive R&D and at a reasonable cost (cheaper than GLACIER).

Thank you !