35 years after Gargamelle: the Renaissance of the "Bubble chamber" neutrino physics

Carlo Rubbia

CERN, Geneva, Switzerland

INFN-Assergi, Italy

A Gargamelle neutrino event

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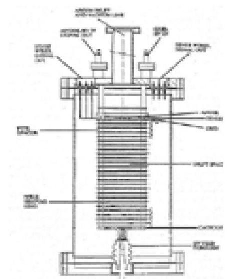
Charm production in a neutrino interaction
The total visible energy is 3.58 GeV.

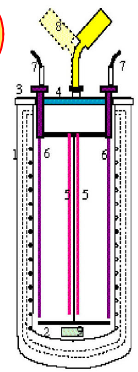
The path to massive liquid Argon detectors



24 cm drift wires chamber

CERN 1

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.



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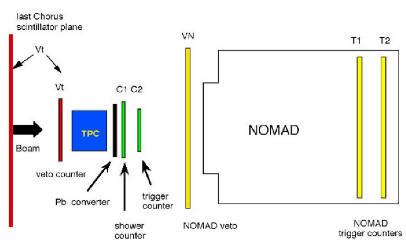
3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

Laboratory work



50 litres prototype
1.4 m drift chamber

CERN 3

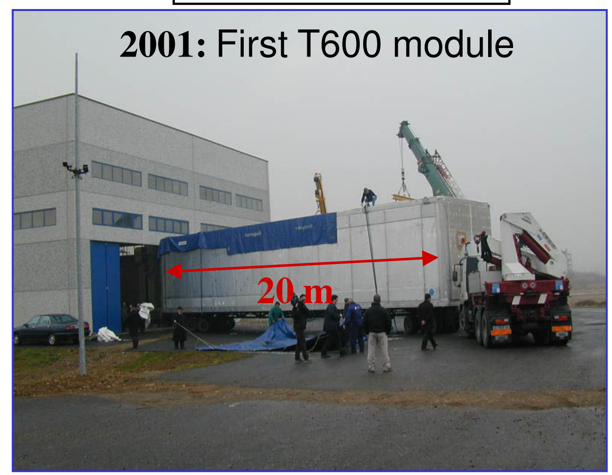
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m³ industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

T600 detector



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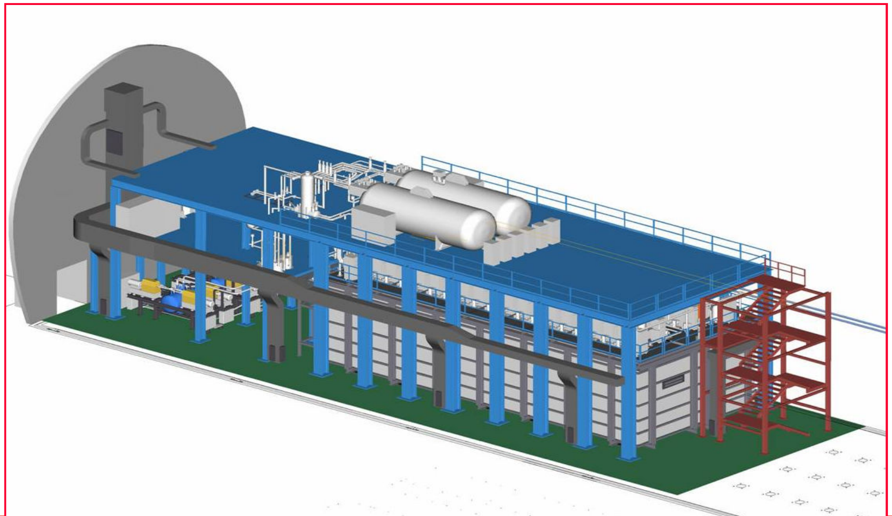
Cooperation with industry

T600 in hall B (CNGS2-2009)



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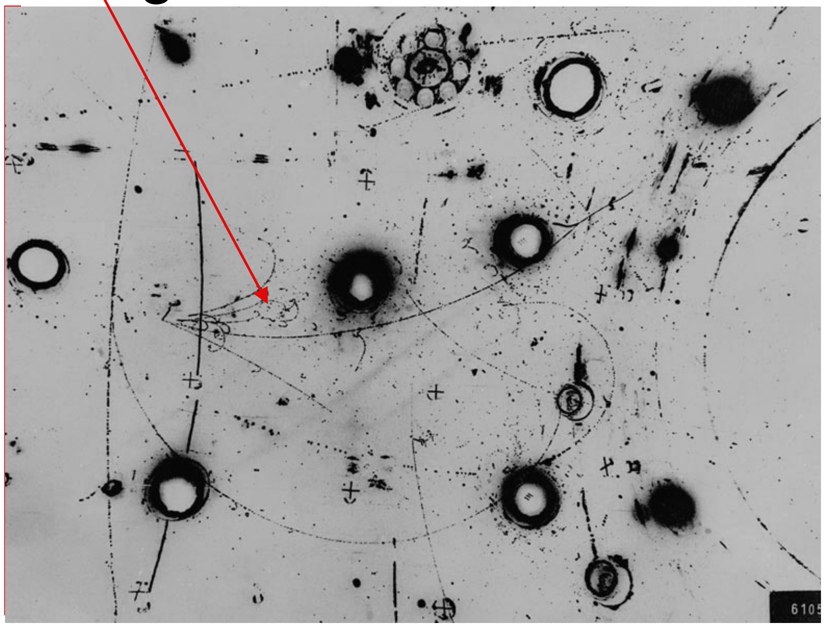
Thirty years of progress........

Bubble diameter ≈ 3 mm (diffraction limited)

LAr is a cheap liquid (≈1CHF/litre), vastly produced by industry

Gargamelle bubble chamber   ICARUS electronic chamber



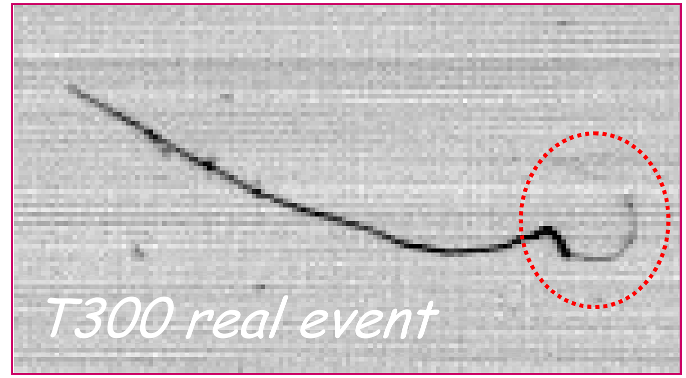
"Bubble" size $3 \times 3 \times 0.3$ mm^3

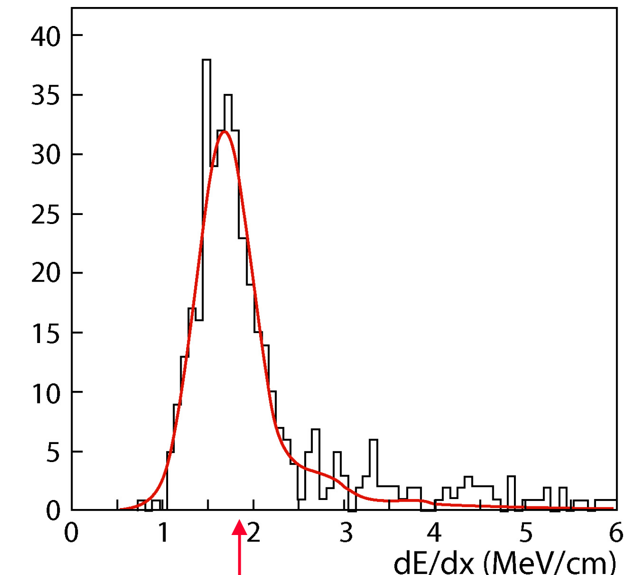
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

Summary of LAr TPC performances

- Tracking device
  - Precise event topology
  - Momentum via multiple scattering
- Measurement of local energy deposition dE/dx
  - e / γ separation (2%X_0 sampling)
  - Particle ID by means of dE/dx vs range
- Total energy reconstruction of the events from charge integration
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events





dE/dx distribution along a single muon track

RESOLUTIONS

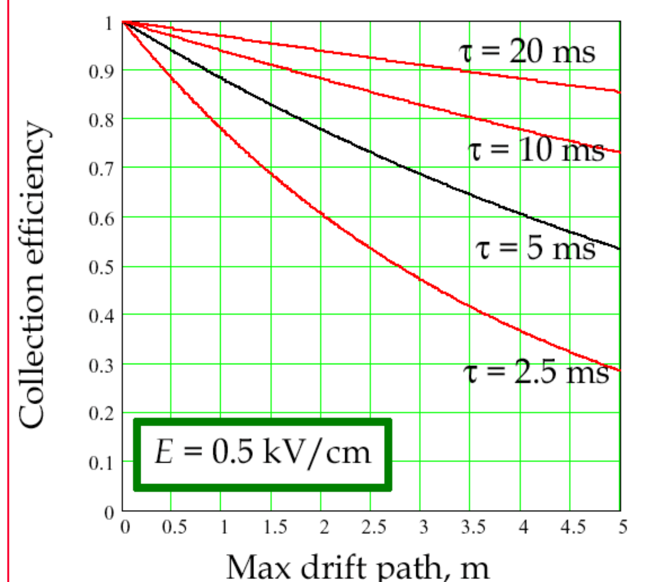
Low energy electrons: σ(E)/E = 11% / √ E(MeV)+2%

Electromagn. showers: σ(E)/E = 3% / √ E(GeV)

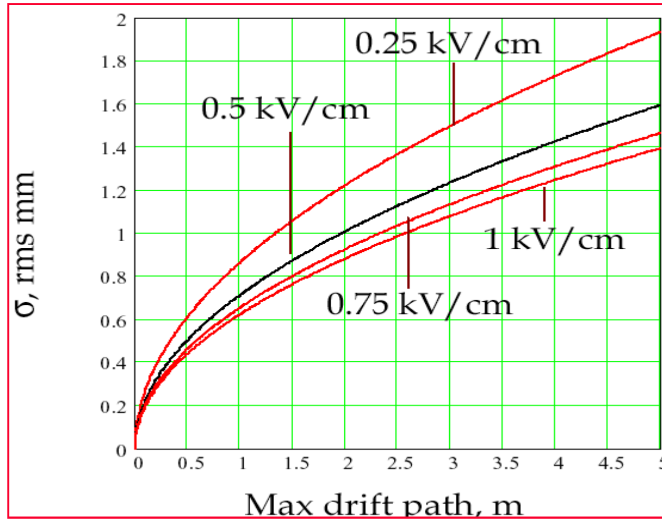
Hadron shower (pure LAr): σ(E)/E ≈ 30% / √ E(GeV)

The key features of LAr imaging

- The main technological challenge of the development of the cryogenic liquid Ar chamber is the capability of ensuring a sufficiently long free electron lifetime.
- Indeed the free electron path in a liquid is ≈ 600 times shorter than in a gas. For instance 10 ms lifetime corresponds to a 30 ppt (t=trillion !) of Oxygen equivalent.
- At 500v/cm, a 5m drift length corresponds to a drift time of 3.1 ms (1.6 m/ms).
- The intrinsic bubble size (rms diffusion) is given by $\sigma_D[mm] = 0.9\sqrt{T_D[ms]}$
- The values for 5m drift are $\langle\sigma_D\rangle \approx$ 1.1 mm and $\sigma_{max} \approx$ 1.6 mm , tiny with respect to the wire pitch (≥ 2mm).

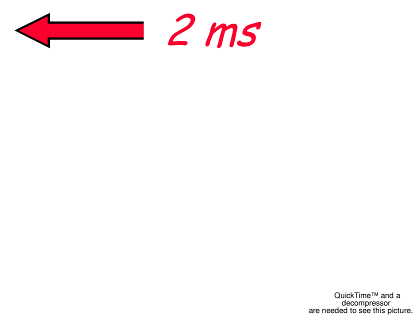


Drifting charge attenuation versus drift path at different electron lifetimes



“Purity”: state of the art in 2001

- During 2001 a first real size test of the 1/2 of the T600 detector was performed on surface in Pavia.
- In the detector the drift length was set to 1.5 m, corresponding to a drift time of about 1 ms.
- The purity performance at that time is shown here, measured both with purity monitors and muon tracks.



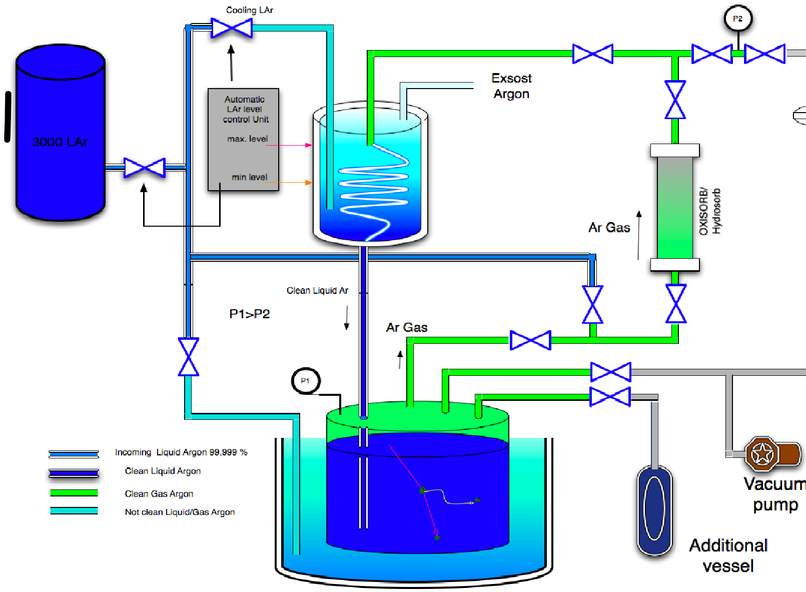
- A considerable progress over the last few years has permitted to reach industrial purification techniques which are capable of a much better performance.

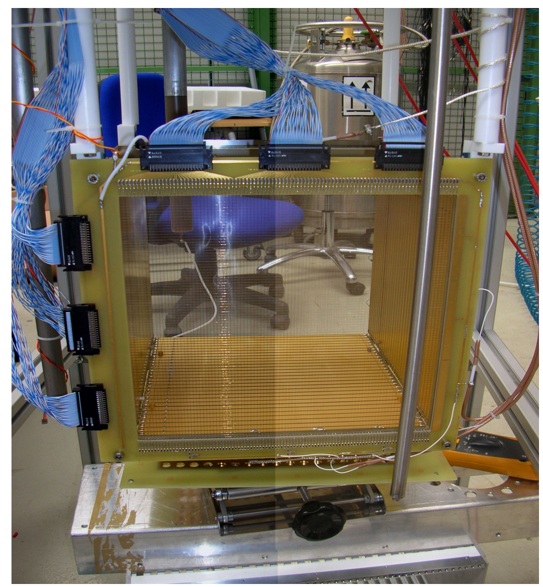
Purification in the liquid and in the surrounding gas

- According to the kinetic theory, the densities (p/cm^3) of the (gaseous) contaminating impurities are the same in the liquid and in the gas regions.
- But since the density of the (cold) Argon gas is some 200 times smaller than the one of the liquid, the *fractional density* of impurities is correspondingly larger in the gas. However the drift speed of diffusion of impurities is very slow, << 1 m/s and the establishing of the equilibrium may take a fraction of an hour.
- For instance in the case of ICARUS and at the design rate of 100 Nm^3/h — although the flow represents only the equivalent of about 120 litres/hour of LAr in a 400 m^3 volume — the purification rate will be of the order of 0.12/(400/200) = 1/16 hour^{-1}, much faster than the one with the standard liquid purification.
- During steady conditions, the speed of purification in the liquid and in the gas will have to be optimized on the actual purity requirements — for instance as measured by the muon tracks throughout the detector — and the cryogenic consumptions will have to be adjusted correspondingly.
- Incidentally, the liquid/gas/liquid process would require zero energy in the reversible iso-temperature limit with no losses

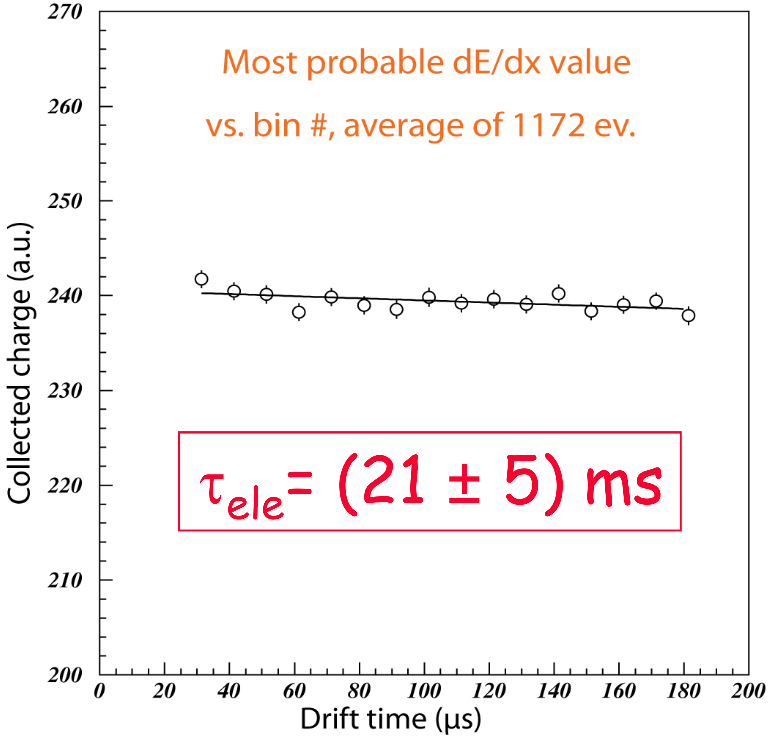
Recent progress in experimental purity achievements

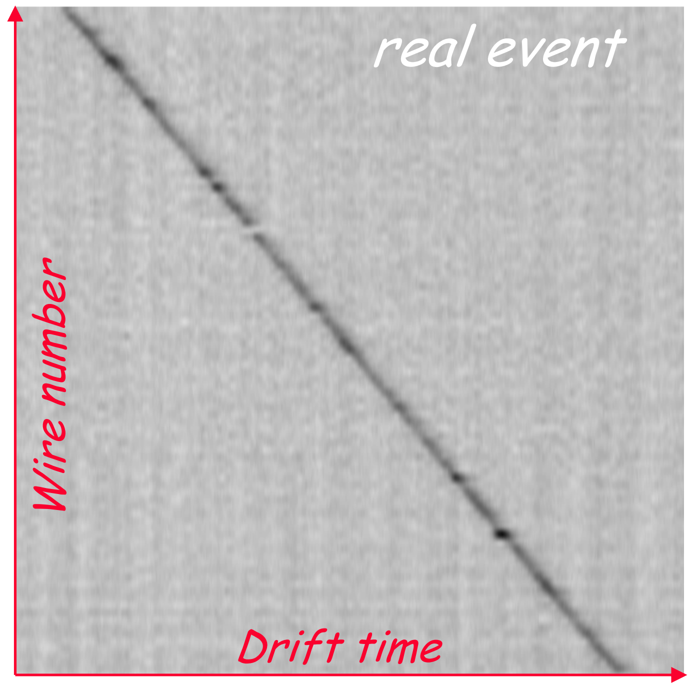
- New industrial purification methods have been developed at an exceptional level, especially remnants of O2 and N2, which have to be initially and continuously purified.
- Extremely high τ_{ele} have been determined with cosmic μ's.
- The short path length used (30 cm) is compensated by the high accuracy in the observation of the specific ionization
- The result here reported is τ_{ele} ≈21 ms corresponding to ≈15 ppt, namely a ≈10^{-11} molecular impurities in Ar





- The measured value to the experimental τ_{ele} corresponds to an attenuation of about 10 % for a longest drift of 5 meters, opening the way to exceptionally long drift distances.





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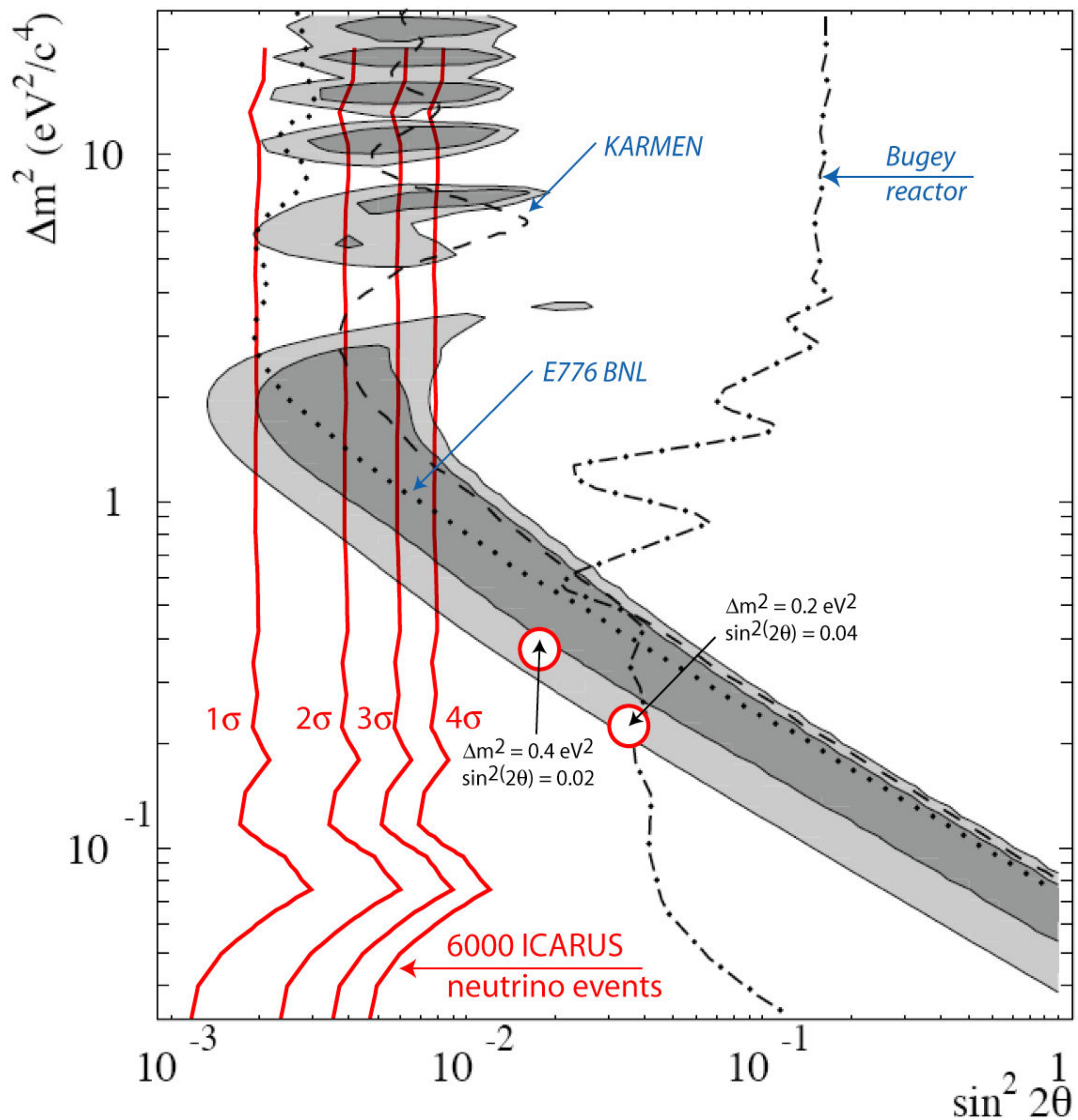
ICARUS (CNGS2): the first large scale LAr experiment

- ICARUS represents a major milestone in the practical realization of a large scale LAr detector. Successfully operated on surface in Pavia in 2002, will soon be operational in the underground HallB of LNGS.
- The T600 at LNGS will collect simultaneously "bubble chamber like" neutrino events events of different nature
- Cosmic ray events
  - ≈ 100 ev/year of unbiased atmospheric CC neutrinos.
  - Solar neutrino electron rates >5 MeV.
  - Supernovae neutrinos.
  - A zero background proton decay with 3 x 10^{32} nucleons for "exotic" channels.
- CERN beam associated events: 1200 ν_μ CC ev/y and 7-8 ν_e CC ev/year
  - Observation of neu-tau events in the electron channel (with sensitivity comparable to OPERA
  - A search fo sterile neutrinos
- In the remainder of the presentation, the "next step" i.e. a proposed search of sterile neutrinos with the CERN PS beam will be described.

Sterile neutrino search with CNGS2 (ICARUS)

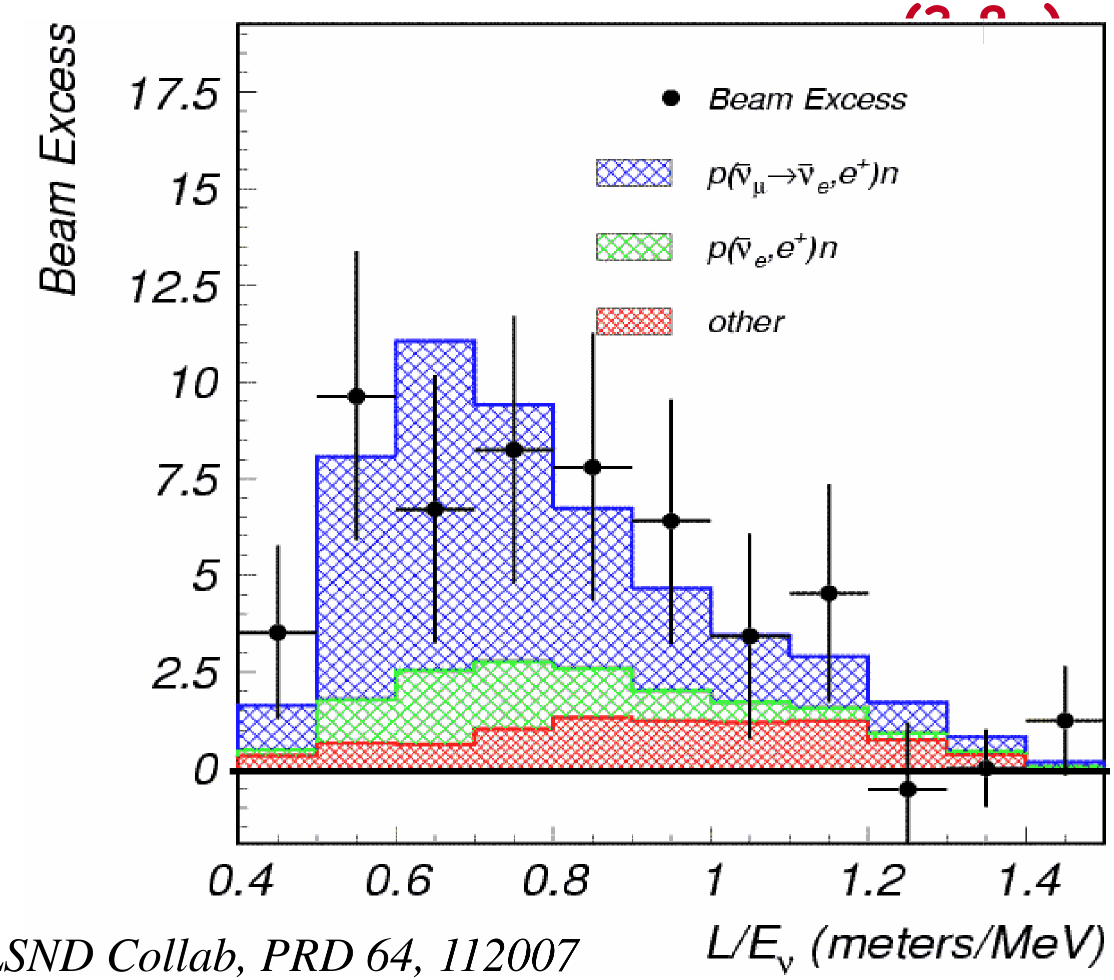
- The $\sin^2(2\theta)$-Δm^2 explored region covers most of LNSD allowed areas and extends to lower values of Δm^2
- Two indicated points are reference values of MiniBooNE proposal and of previous slides
- Data taking will be enough to exclude $\sin^2(2\theta)$ values $> 5\ 10^{-3}$ at 3 σ with ν (!)
- Smaller $\sin^2(2\theta)$ are not explored. *An additional LAr experiment at PS is proposed for ν and ν-bar.*



Presentation CERN workshop, May 2009

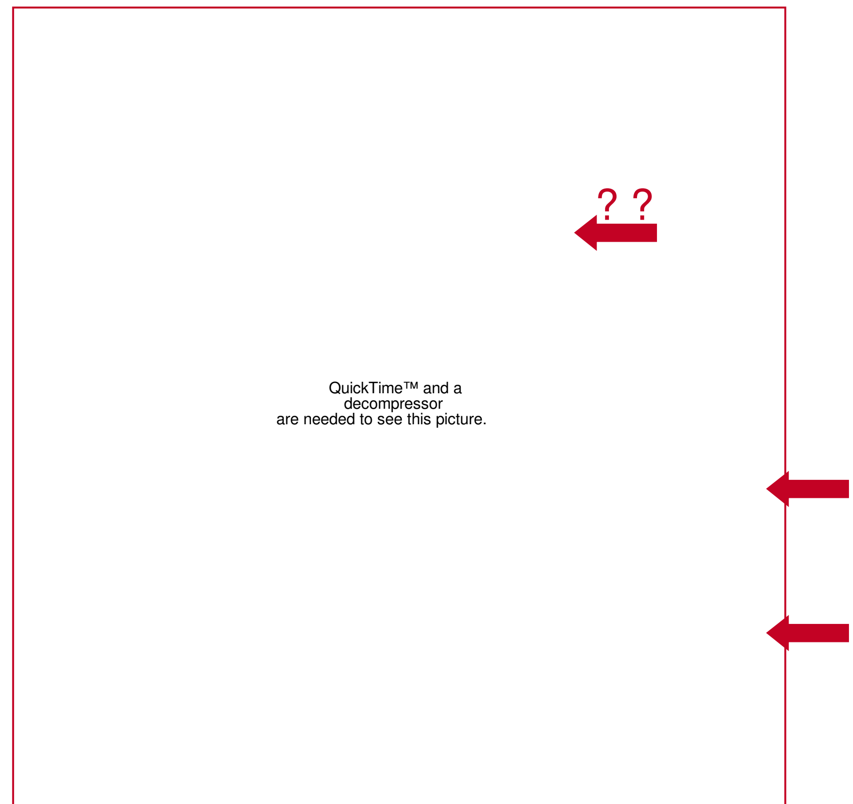
The LSND anomaly: antineutrino oscillations ?

LSND has observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam, 87.9 ± 22.4 ± 6.0



LSND Collab, PRD 64, 112007

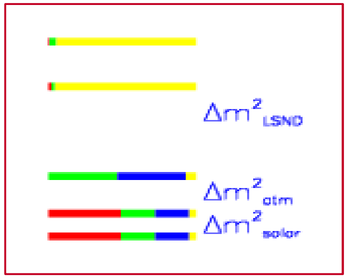
Points -- LSND data
Signal (blue)
Backgrounds (red, green)



- 3 oscillation signals, if confirmed, require new physics beyond the SM

Many theoretical hypothesis…..

3+2 Sterile Neutrinos	Sorel, Conrad, & Shaevitz (PRD70(2004)073004)



← Additional, sterile neutrinos ?

← Standard neutrinos

MaVaNs & 3+1	Hung (hep-ph/0010126)
Sterile Neutrino	Kaplan, Nelson, & Weiner (PRL93(2004)091801
CPT Violation & 3+1 Sterile Neutrino	Barger, Marfatia, & Whisnant (PLB576(2003)303)
Quantum Decoherence	Barenboim & Mavromatos (PRD70(2004)093015)
Lorentz Violation	Kostelecky & Mewes (PRD70(2004)076002) Katori, Kostelecky, Tayloe (hep-ph/0606154)
Extra Dimensions	Pas, Pakvasa, & Weiler (PRD72(2005)095017)
Sterile Neutrino Decay	Palomares-Ruiz, Pascoli, & Schwetz (JHEP509(2005)48)

And so on….

The MiniBooNE experiment at FNAL (1998-today)

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MiniBooNE experiment: antineutrino data

- MiniBooNE result for anti-neutrino events, the direct analog of LSND, is based on 3.39 x 10^{20} POT.
- The result is inconclusive with respect to the LNSD result.
- LSND is still alive and well.

MiniBooNE limit at 90 %

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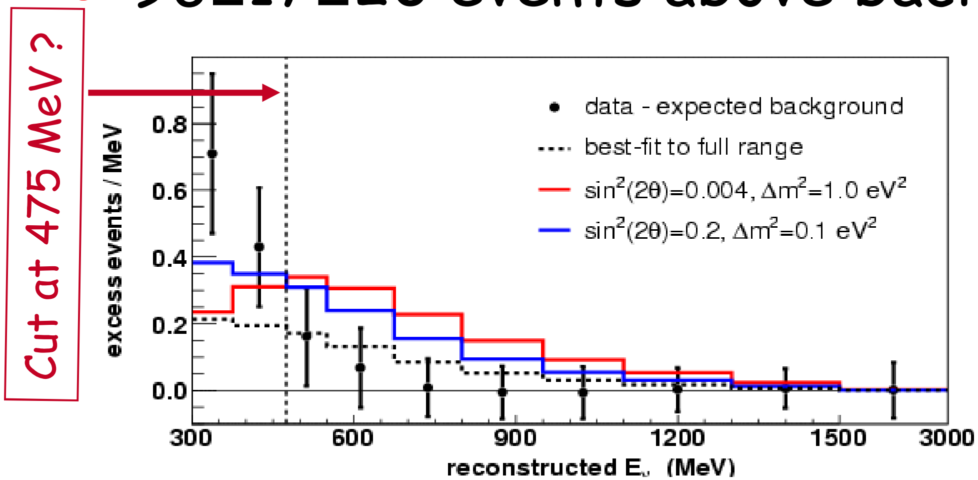
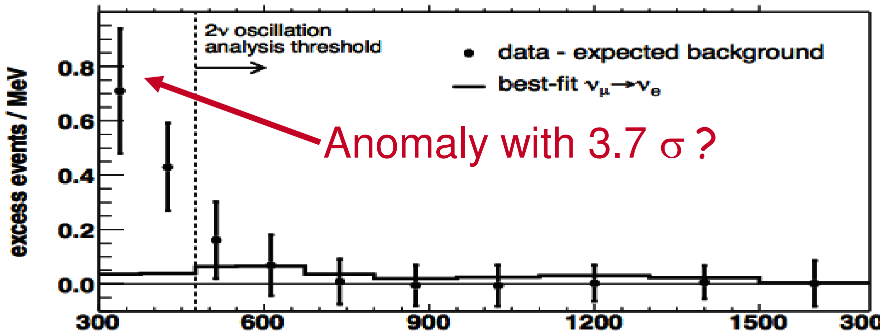
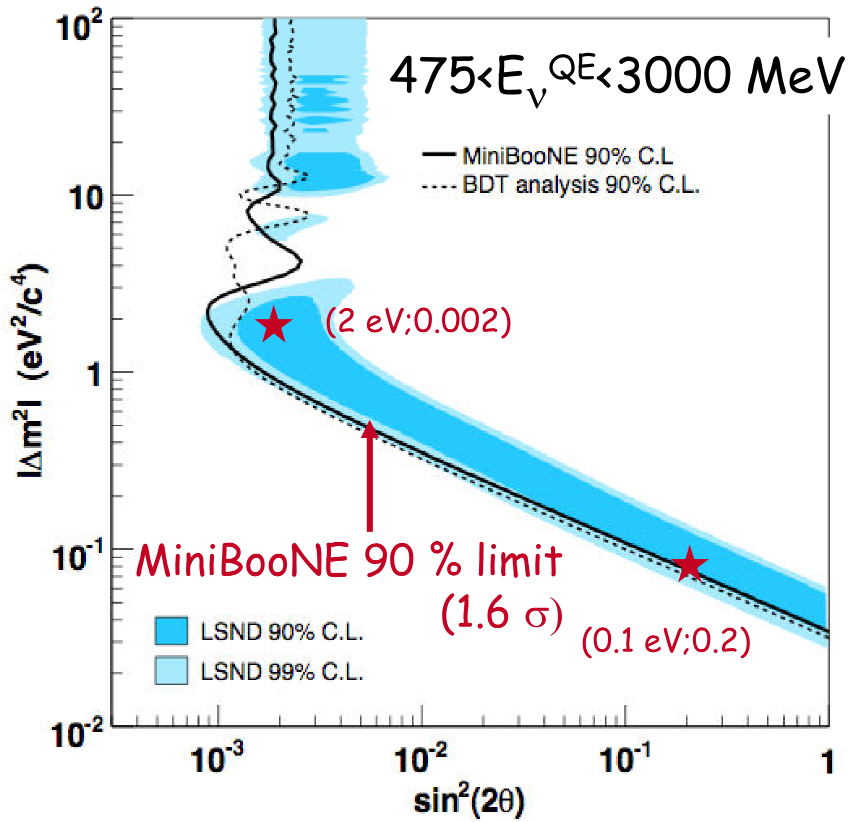
MiniBooNE experiment: neutrino data

- MiniBooNE result for neutrino events is based on 6.46 x 10^{20} POT, corresponding to 1.5x10^5 $\nu\mu$ CC-QE events
- We expect 375ve CC-QE intrinsic background events. with a possible LSND signal of ~200 ve CC-QE events
- 96±17±20 events above background, for 300 < E_ν^{QE} < 475MeV:







Theoretical considerations: a signal with 5 neutrinos ?

- In models with more than one sterile neutrino (see for instance Maltoni and Schwetz, Phys. Rev. D 76, 093005 (2007)) MiniBooNE results are in perfect agreement with the LSND appearance evidence.
- However, if all other disappearance data are taken into account (3+2) oscillations are no longer in full agreement.

Fit to LSND, KARMEN, NOMAD, MB

Global fit to all experimental data

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The CPS neutrino beam

- The PS proton beam at 19.2 GeV/c is extracted from the PS via TT2, TT1 and TT7. The magnetic horn is designed to focus particles of momentum around 2 GeV/c.
- The decay tunnel is about 50 m long, followed by an iron beam stopper. There are two positions for the detection of the neutrinos.
- The far (main) location is at 850 m from the target; a secondary location is foreseen at a distance of 127 m from the target. MiniBooNE was at 550 m from the target.

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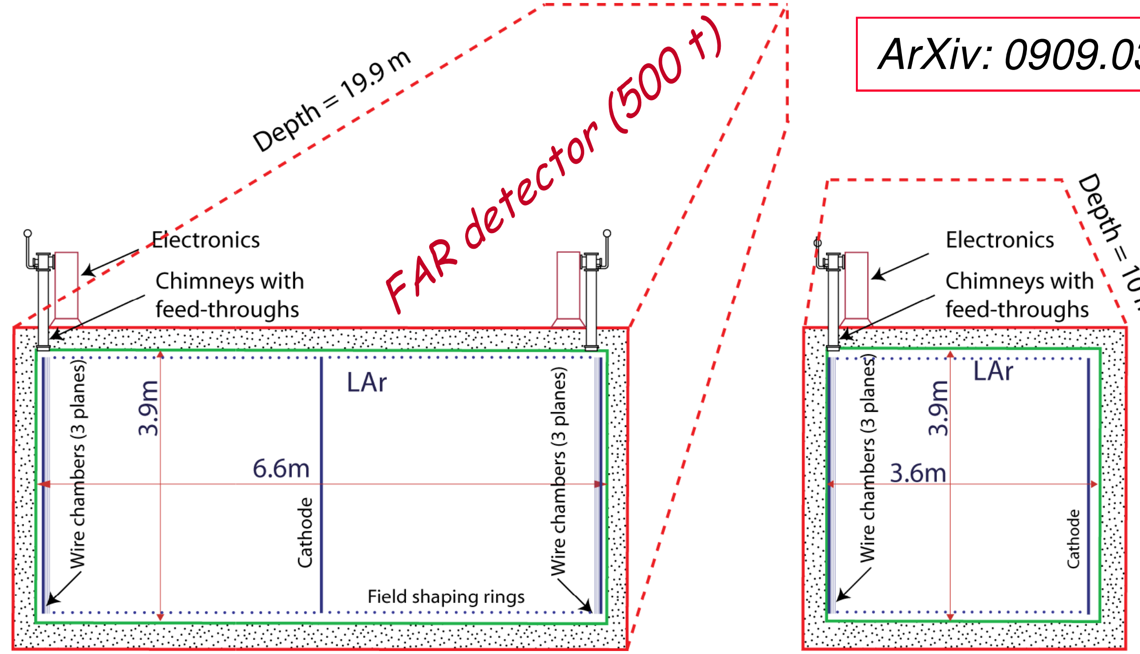
A new detector with roughly the T600 total mass

- Two separate containers
- inner volume FAR: **6.6 x 3.9 x 18 m³**
- inner volume NEAR: **3.6 x 3.9 x 8 m³**
- 4 wire chambers with 3 readout planes at 0°, ±60°
- Total number wires ≈10'000
- Maximum drift = 3.6 m
- HV = -180 kV @ 0.5 kV/cm

ArXiv: 0909.0355



NEAR detector (150 t)

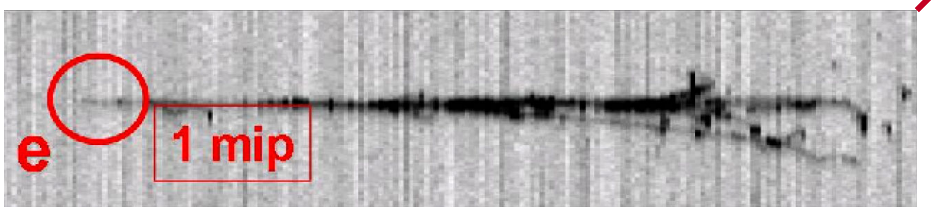
	FAR	NEAR
Fiducial mass	500 t	150 t
Distance from target	850 m	127 m
ν_μ interactions	1.2 x 10^6	18 x 10^6
QE ν_μ interactions	4.5 x 10^5	66 x 10^5
Events/burst	0.17	2.5
Intrinsic ν_e from beam	9000	120000
Intrinsic ν_e from beam (E_ν < 3 GeV)	3900	54000
ν_e oscillations: $\Delta m^2 = 2.\ eV^2;\ sin^2 2\theta = 0.002$	1194	1050
ν_e oscillations: $\Delta m^2 = 0.4\ eV^2;\ sin^2 2\theta = 0.02$	2083	2340

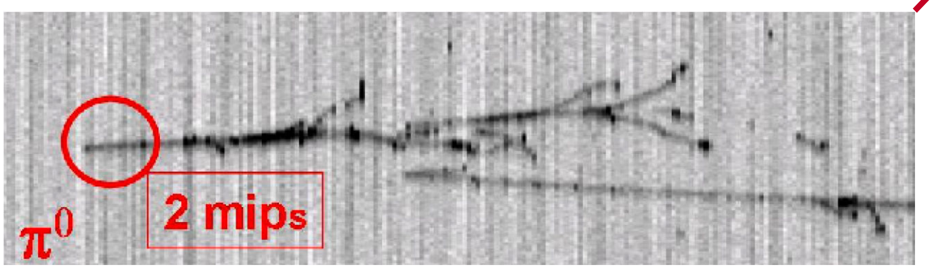
- Set-up heavily simplified with respect to ICARUS
- Cheaper, cryogenic vessel with ≈ 1 m thick perlite walls
- Wire chamber mechanics, purification system and readout electronics "cloned" from the ICARUS set-up
- Very quick construction schedule.

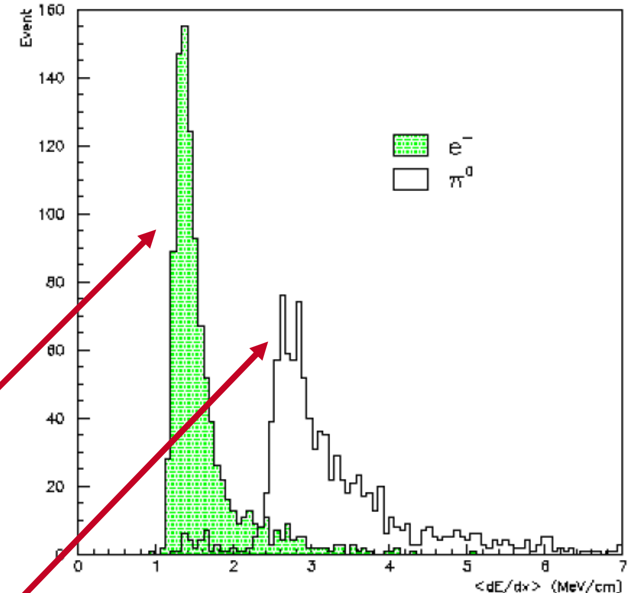
C. Rubbia, CERN, 0ct09

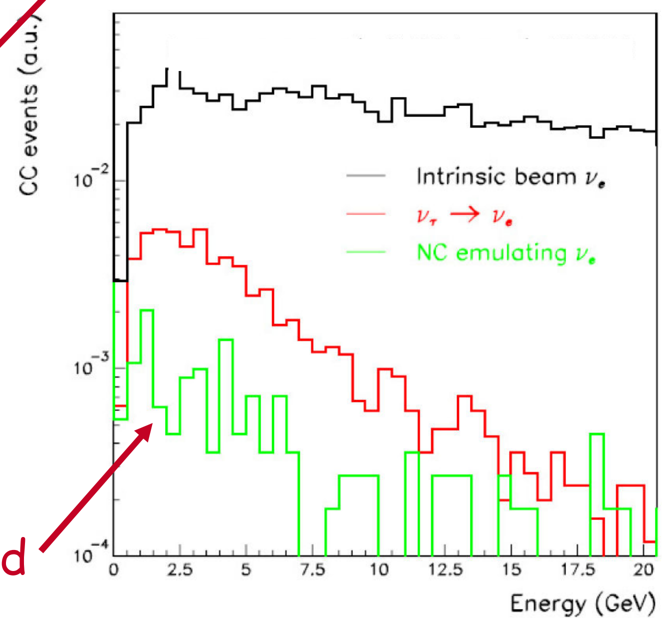
π^0 backgrounds

- NC in LAr suppressed by:
  - ↑ topology (γ conversion from vertex)
  - ↑ reconstruction of π^0 mass
  - ↑ electron/photon separation (dE/dx)
- Electron identification eff. = 90 %
- Residual misidentification < 0.1%









NC-e background

- The present proposal is a search for spectral differences of electron like specific signatures in *two identical detectors* but at two different neutrino decay distances.
- *In absence of oscillations*, apart some beam related small spatial corrections, the two spectra are a precise copy of each other, independently of the specific experimental event signatures and without any Monte Carlo comparisons.

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decompressor
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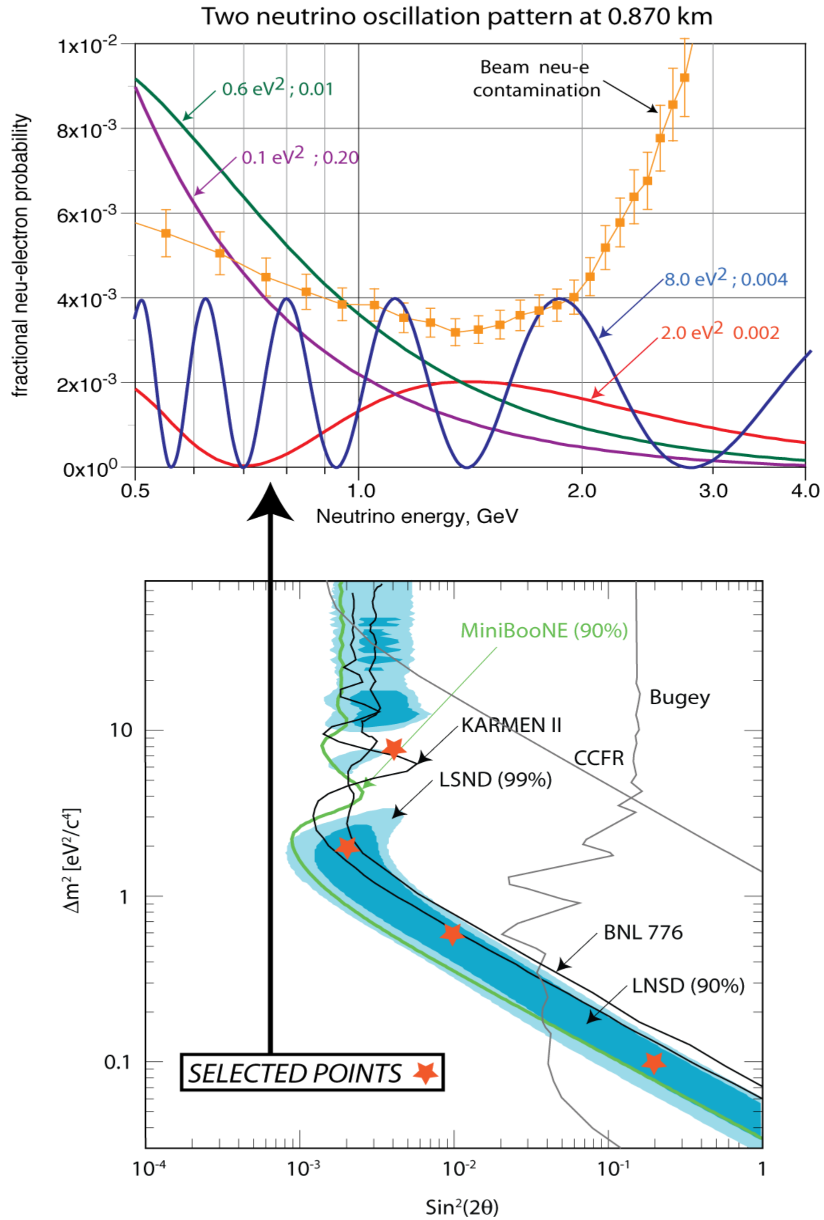
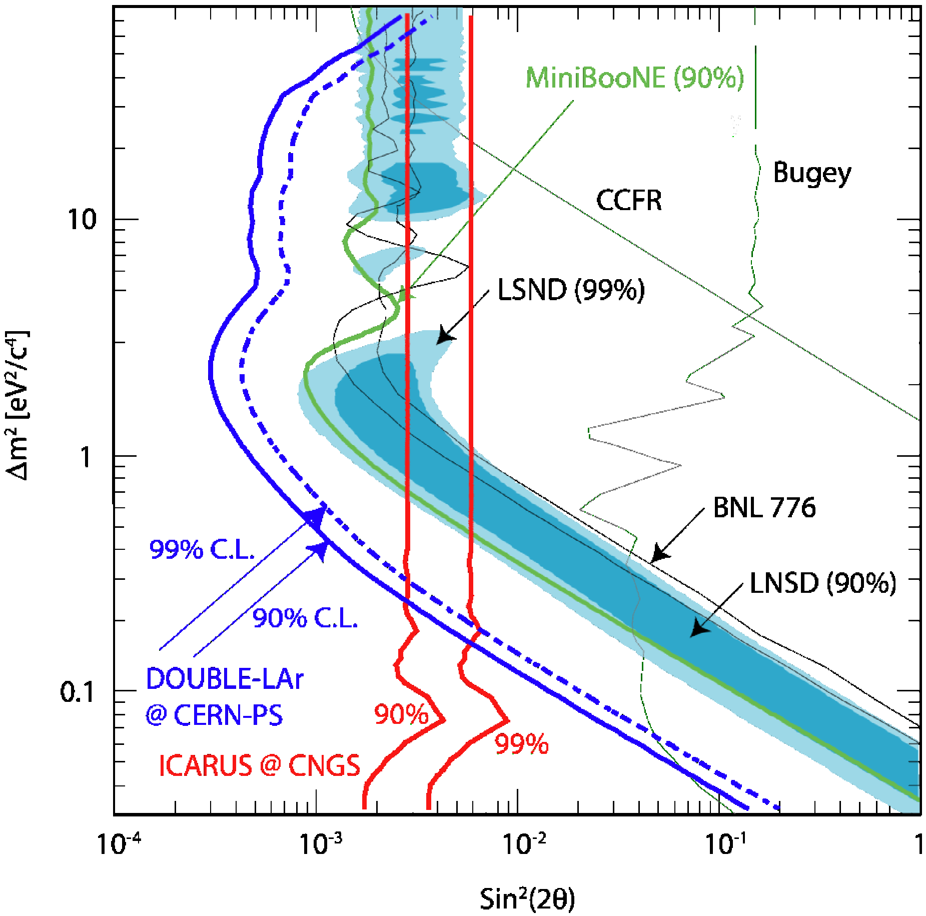
- Therefore an exact, observed proportionality between the two ν_e spectra implies directly the absence of neutrino oscillations over the measured interval of L/E.

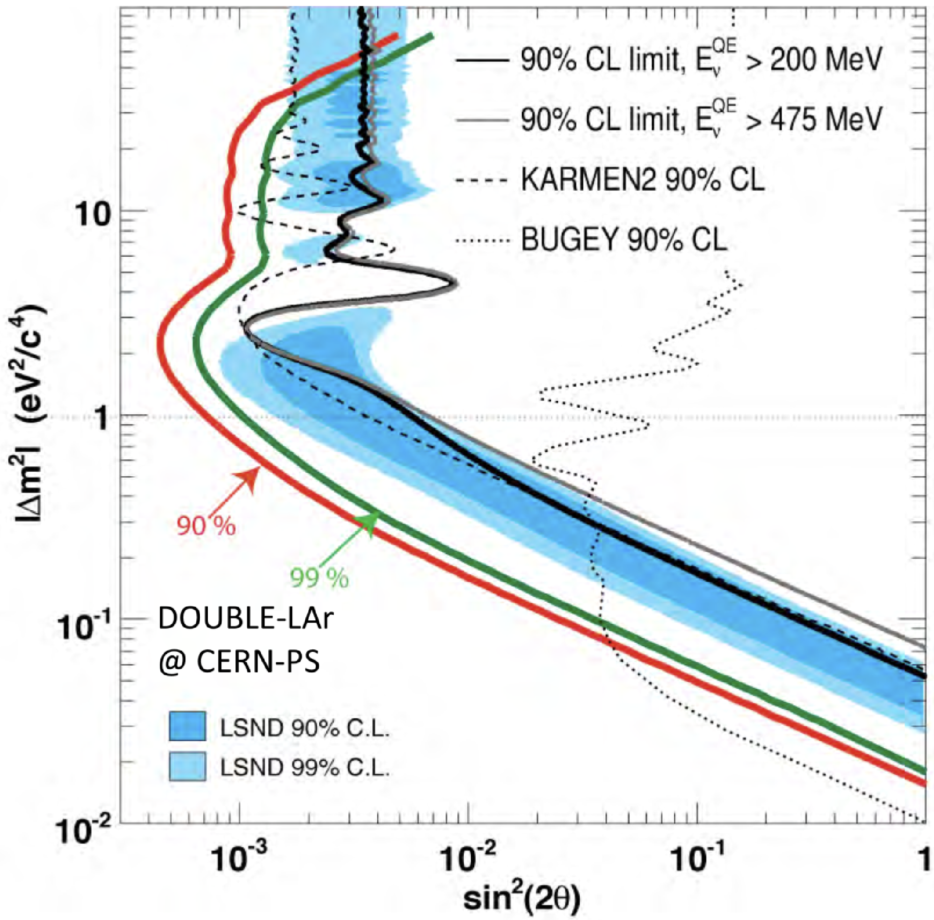
New features of the CERN proposal

- It appears that the present proposal, unlike LNSD and MiniBooNE, can determine both the mass difference and the value of the mixing angle.
- Very different and clearly distinguishable patterns are possible depending on the values in the (Δm^2 – $\sin^2 2\theta$) plane.
- The intrinsicν-e background due to the beam contamination is also shown.
- The magnitude of the LNSD expected oscillatory behaviour, for the moment completely unknown, is in all circumstances well above the backgrounds, also considering the very high statistical impact and the high resolution of the experimental measurement.



Comparing sensitivities





Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) and anti-neutrino (right) for 2.5 10^{20} pot. The LSND allowed region is fully explored both for neutrinos. In the neutrino case, the expectations from CNGS2/ICARUS T600 at LNGS are also shown.

The future of the LAr

- A number of possible future experiments with masses much larger than T600 have been discussed by a number of authors and are a subject of discussion for the long range future of neutrino physics and perhaps proton decay.
- These authors have presented masses of 5'000 and up to 100'000 tons, namely between 10x and 200x the today'sT600.
- But containing the LAr is not enough: for instance purity levels of 10^{-11} O_2 equivalent must be created and maintained.
- In our view, before translating more or less generic R&D into a detector of such an enormous magnitude, intermediate steps must be performed, consolidating realistically the physics already possible with detectors of the present size.
- Gargamelle has already shown that remarkable results may be obtained with a very sensitive detector even if much smaller than the one of larger and coarser calorimeters of that time.
- There may be a similar opportunity in the future, paving on the same time the way to the much larger ultimate facilities.

Conclusions

- Neutrinos have been the origin of an impressive number of "Surprises". It has been demonstrated that the sum of the strengths of the coupling of different ν is very close to 3. *But it is only assuming that neutrinos, in similarity to charged leptons, have unitary strengths that the resulting number of neutrinos is 3.*
- Recent results have shown that a precise identity between neutrino and charged lepton families is not automatically granted. The recent observation of the extraordinarily large neutrino mixings when compared to naive Cabibbo-like expectations from quarks, the absence of right-handed partners, the possibility of Majorana-like couplings, the small masses and so on, leave a large number of potential features untested. The experimentally measured weak coupling strengths are only rather poorly known, leaving room for many other alternatives.
- It is only because the masses of known neutrino species are so small, that their contribution to the Dark Matter of the Universe can be neglected. The situation may be altered by the additional presence of sterile neutrinos, if sufficiently massive. The presence of massive sterile neutrinos may contribute to the Dark Matter problem.

Thank you !