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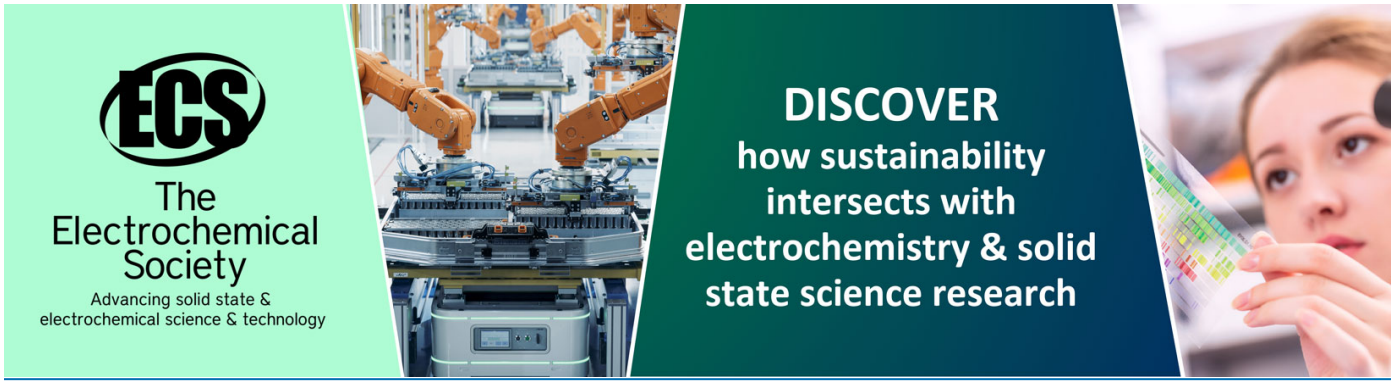

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The ICARUS Liquid Argon TPC: A neutrino "bubble chamber" after Gargamelle

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Abstract. The success of the bubble chamber in high energy physics was due to two fundamental characteristics: (1) it provided a massive target (2) with complete imaging and reconstruction of the events. In this context, the Liquid Argon Time Projection Chamber can be considered as a modern fully electronic "bubble chamber". In this talk, we review the developments that led to the ICARUS T600 detector.

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The need of visual detectors of high target density

- The success of the bubble chamber as a main tool in high energy fixed target physics is due to two characteristics:
  - It provides a massive target, of substantial density
  - It provides complete imaging and reconstruction of the events in itself
- This technology has permitted in the past very substantial advances based on :
  - Single events with complete reconstruction (e.g. discovery of Ω-)
  - Surprise events, i.e. topologies not a priori expected (e.g. Gargamelle neutral currents)
- Technology is costly and complicated
  - It requires high pressures and mechanical expansion
  - Its sensitivity is limited to about a few milliseconds
  - Optics limits viewing of large volumes

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A Gargamelle neutrino event

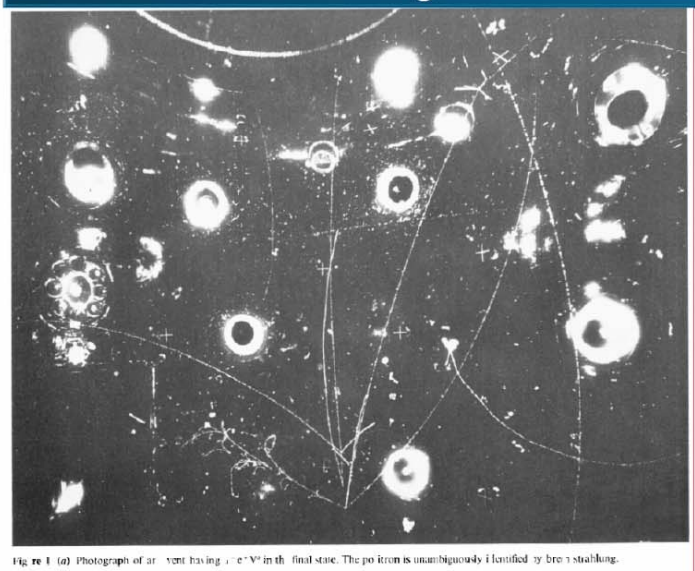
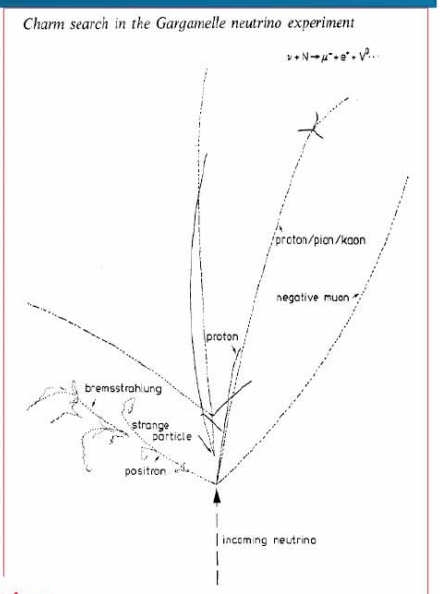


Fig re 1 (a) Photograph of ar vent having e⁻ V⁰ in th final state. The po itron is unambiguously i lentified by bre n strahlung.



. (b) Sketch of the event shown in figure 1(a).

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

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The ICARUS initial idea

- A multi-kton detector based on a new powerful detection technique:
  - the Liquid Argon Time Projection Chamber
    - [C. Rubbia: CERN-EP/77-08 (1977)]
  - first proposed to INFN in 1985
    - [ICARUS: Imaging Cosmics And Rare Underground Signals: INFN/AE-85/7]
  - capable of providing a 3D imaging of any ionizing event ("electronic bubble chamber") with in addition:
    - continuously sensitive
    - Operating without pressure, eventually underground
    - high granularity (~mm)
    - self triggering
    - excellent calorimetric properties
    - particle identification (through dE/dx vs range)

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Noble liquid as tracking medium

- Ideal material for detection of ionizing radiation:
  - Dense (≈ g/cm^3), homogeneous, target and detector
  - Does not attach electrons (long drift paths in liquid phase)
  - High electron mobility (≈quasi-free drift electrons)
  - Commercially easy to obtain (in particular, liquid Argon)
  - Can be made very pure, with many impurities freezing out
  - Inert, not flammable

Argon constitutes 0.9 % of air content

Type	Density (ρ/ cm^3)	Energy loss dE/dx (MeV/cm)	Radiation length X_0 (cm)	Collision length λ (cm)	Boiling point @ 1 bar (K)	Thermal electron mobility (cm^2/Vs)	
Neon	1.2	1.4	24	80	27.1	high&low	
Argon	1.4	2.1	14	80	87.3	500	€
Krypton	2.4	3.0	4.9	29	120	1200	€€
Xenon	3.0	3.8	2.8	34	165	2200	€€€

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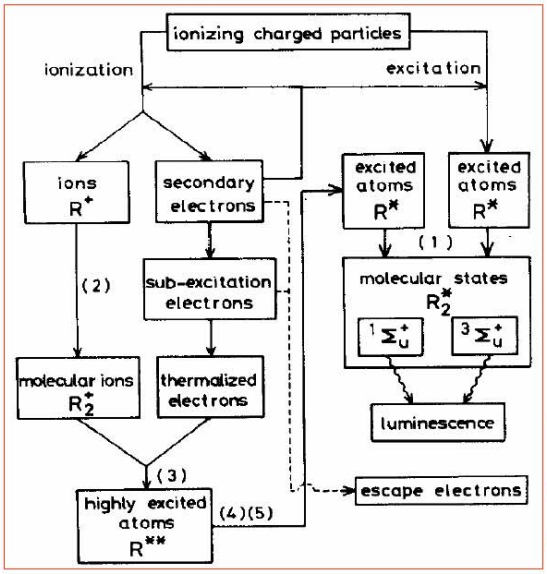
Processes induced by charged particles in liquid Argon



M. Suzuki et al., NIM 192 (1982) 565

When a charged particle traverses medium:

- Ionization process
- Scintillation (luminescence)
  - UV spectrum (λ=128 mn)
  - Not energetic enough to further ionize, hence, argon is transparent
  - Rayleigh-scattering
- Cerenkov light (if fast particle)

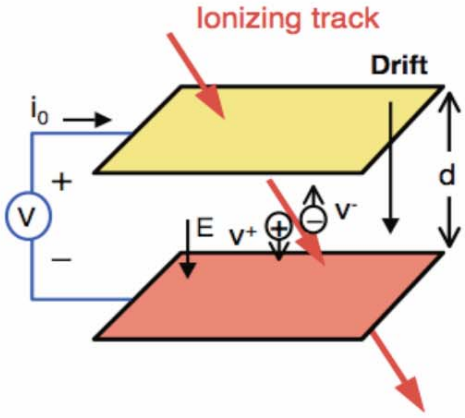
→ *UV light*

→ *Charge*

→ *Cerenkov light (if β>1/n)*

The pioneering work of T.DOKE must be acknowledged

Signals from dielectric liquids



The "work" performed by the power supply which puts electrons and ions in movement is given by:

$$dW = eE(v^+ + v^-)dt = Vi_0 dt$$

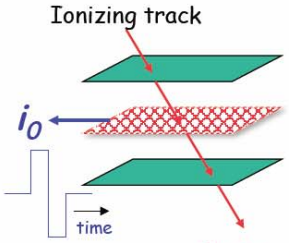
from which the current and charge are:

$$i_0 = e\,(v^+ + v^-)/d$$

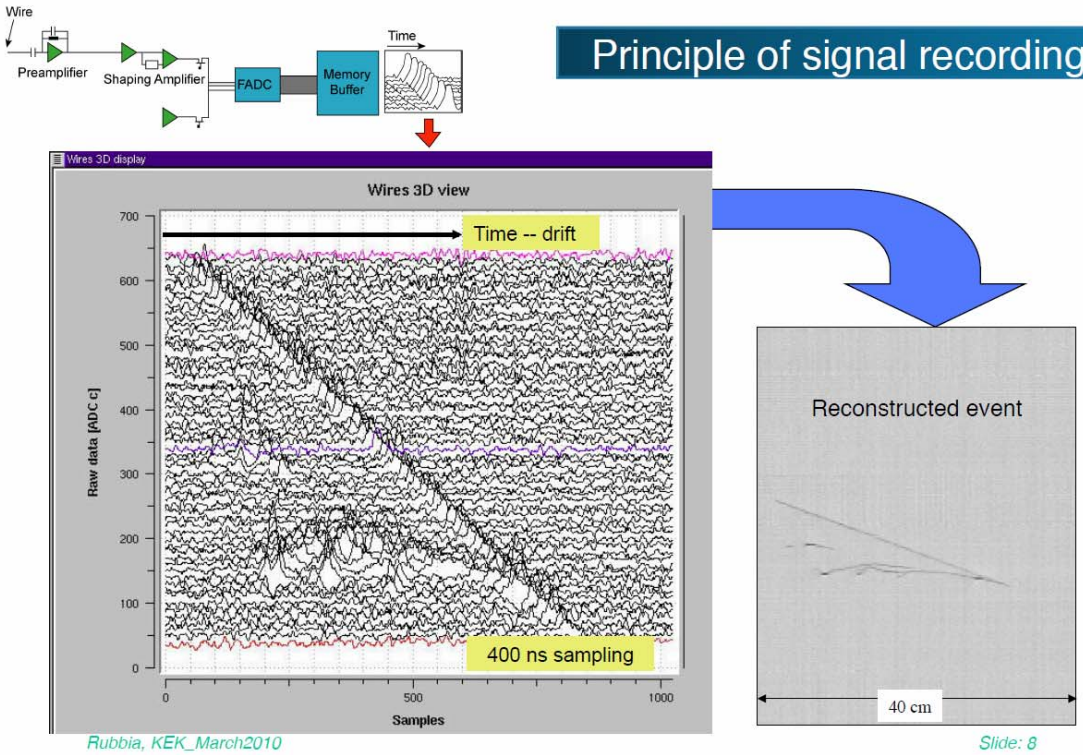
$$Q^{\pm} = e(d - x^{\pm})/d$$

since $v^- / v^+ \approx 10^5$, electron current is dominant.

If a grid is inserted on the path of the electron, the work changes sign under traversal and so does the current, with a total charge collected equal to zero



Principle of signal recording



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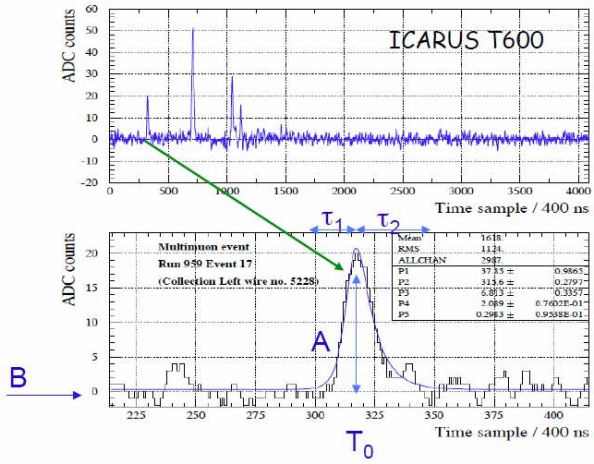
Signal extraction procedure

Collection plane wire analysis: charge = signal area



$$f(t) = B + A \frac{e^{-\frac{t - T_0}{\tau_2}}}{1 + e^{-\frac{t - T_0}{\tau_1}}}$$

B = baseline
A = amplitude
τ_1 , τ_2 = rise and fall time
T_0 = peak position

The same empirical function used to fit Ionization hits and test pulse hits (calibration)

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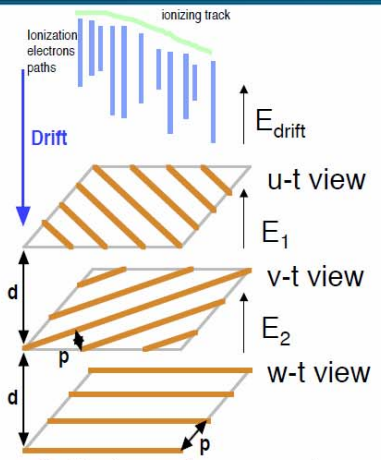
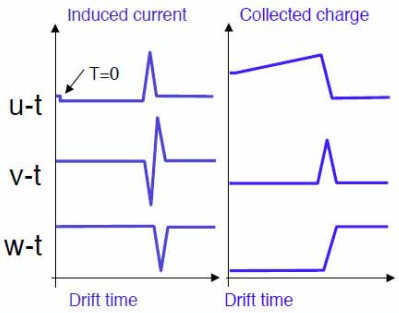
Non distructive readout: the induction signals (3D)





With at least 3 views, a three-dimensional localization of position for each value of t

The drifting electron is traversing several transparent wires arrays oriented in the direction of the required view. The ionizing track records in each of them a *triangular induction signal.*
Finally the electron charge is *collected* by the collection plane.
The generated topological view of the event is the one seen by a camera at infinity with the optical axis in the direction of the wires.

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Grid shielding and transparency

- Best signal localization and charge collection is realized if each grid perfectly shields the adjacent electrodes.
  - Shielding inefficiency σ is a pure geometrical effect:

$$\sigma = \frac{p}{2\pi d}\ln\left(\frac{p}{2\pi r}\right) \qquad p = 3mm; d = 3mm; r = 75\,\mu m \Rightarrow \sigma = 18\%$$

    - Depends on pitch p, wire radius r and distance from other grids d.
  - Full transparency is required not to loose signals along the path before reaching the collecting grid

$$\frac{E_1}{E_2} > \frac{1+\rho}{1-\rho} \qquad \rho = \frac{2\pi r}{p} \qquad \frac{E_1}{E_2} > 1.4 \Rightarrow \text{Full transparency}$$

    - Depends on E-field ratio across the grid
    - For equal fields loss is twice the geometrical cross-sect

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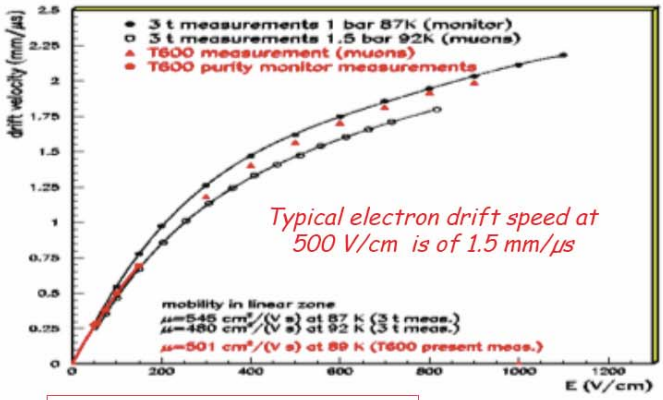
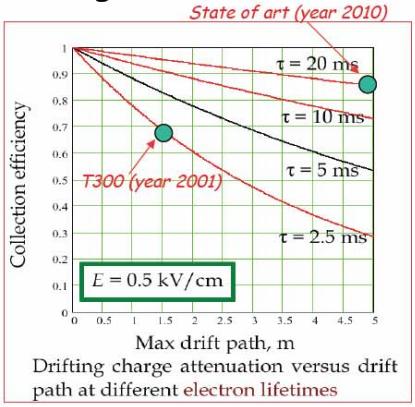
Free electron drift velocity in LAr

- How fast can free electron drift in Liquid Argon ?





Fit Function: $v_D = \frac{\mu \cdot E}{1 + \beta \cdot E}$ ← Electron mobility, μ = 542 cm²/V/s

μ ≈ T^-3/2

$v_{DRIFT} \approx \frac{Ee}{m_e} \cdot \frac{\lambda}{v_T}$ → Mean free path; → Maxwellian velocity

Velocity saturation factor β^-1 ≈ 450 V/cm
Accounts for loss of linearity when electron is no longer thermalized

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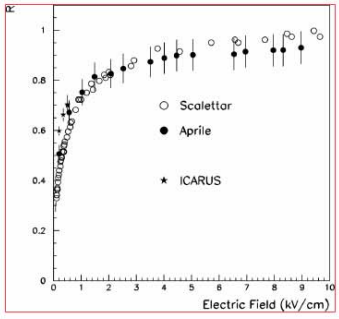
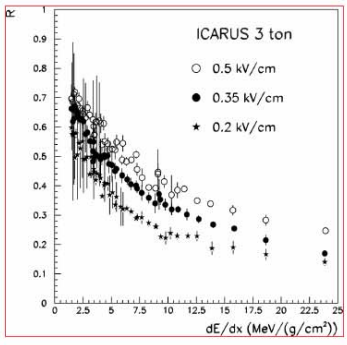
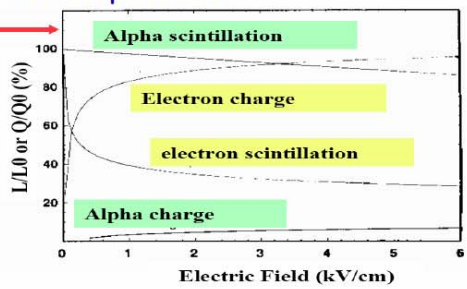
Free electron yield in LAr

- Strong e⁻-ion recombination due to comparable thermalization distance (~140 nm) and e⁻-ion separation.
- Both geminate (Onsager) and columnar (Jaffe) active depending on dE/dx and E.F.
- Observed dE/dx linearity (particle i.d.) and energy resolution
- Additional scintillation light is generated in the recombination process





Relative scintillation and electron charge for electrons (m.i.) and alpha particles



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Free electron lifetime in LAr

- The density of the Liquid Argon is about 1000 times larger than the one of Argon gas at pnt. Therefore the mean free path for free electron drift is correspondingly shorter.
- The presence of electron trapping polar impurities can be expressed in equivalent Oxygen molar densities

$$\tau \approx 300\mu s \times \frac{1\,ppb}{N(O_2)}$$

- Because of temperature (87 K) most of the contaminants freeze out spontaneously.
- Main residual contaminants are O_2, H_2O, CO_2 and N_2.
- The goal: 10 ms lifetime for a 30 ppt (t=trillion !) of Oxygen equivalent !

A. Bettini et al., NIM A305 (1991) 177

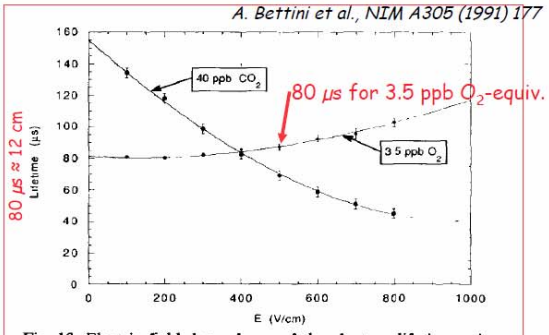

Fig. 12. Electric field dependence of the electron lifetime τ in purified LAr doped with 40 ppb CO_2 and 3.5 ppb O_2. Lines are drawn to guide the eye.

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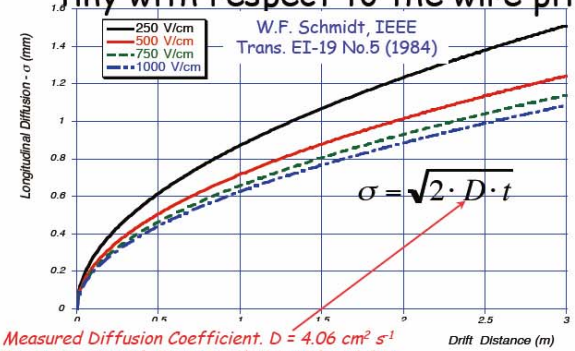
Free electron diffusion in LAr

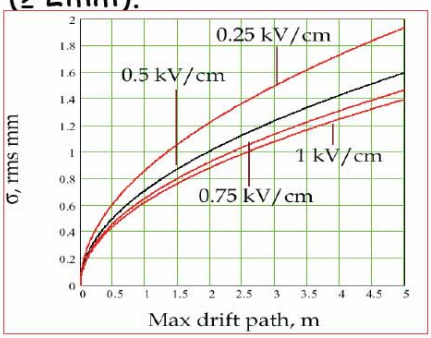
- At 500v/cm, a 5m drift length corresponds to a drift time of 3.1 ms (1.6 m/ms).
- The intrinsic bubble size (rms diffusion) is given by

$$\sigma_D[mm] = 0.9\sqrt{T_D[ms]}$$

- 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).



Measured Diffusion Coefficient. D = 4.06 cm² s⁻¹ In agreement with Einstein relation with mobility for quasi thermal electrons.



Lateral diff. ~ longitudinal diff.

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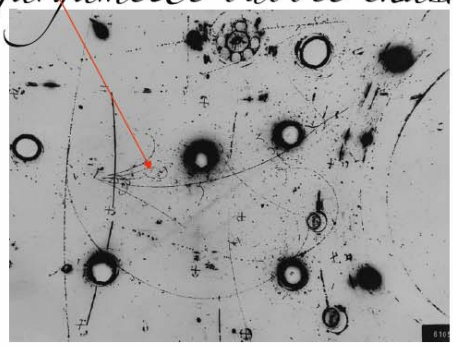
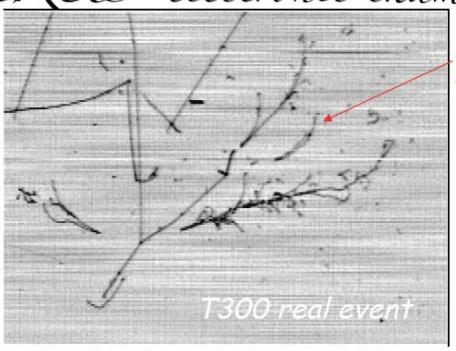
Thirty years of progress.....

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

Bubble diameter ≈ 3 mm (diffraction limited)

Gargamelle bubble chamber ICARUS electronic chamber





Medium	Heavy freon		Medium	Liquid Argon	
Sensitive mass	3.0	ton	Sensitive mass	Many ktons	
Density	1.5	g/cm3	Density	1.4	g/cm3
Radiation length	11.0	cm	Radiation length	14.0	cm
Collision length	49.5	cm	Collision length	54.8	cm
dE/dx	2.3	MeV/cm	dE/dx	2.1	MeV/cm

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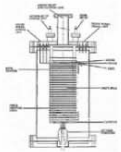
The path to massive liquid Argon detectors

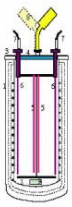


24 cm drift wires chamber CERN 1

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

2

3 ton prototype

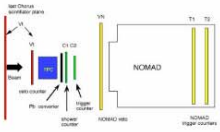


1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

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.

T600 detector

4

10 m³ industrial prototype

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

5

Cooperation with industry

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First T300 cryostat during construction (2001)

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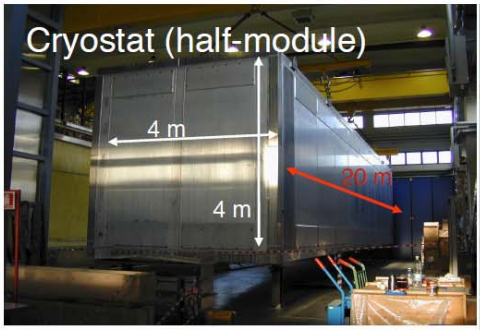
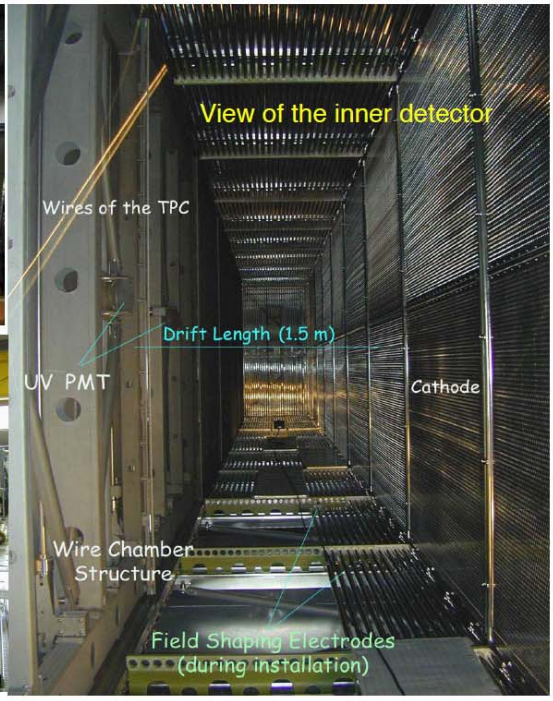
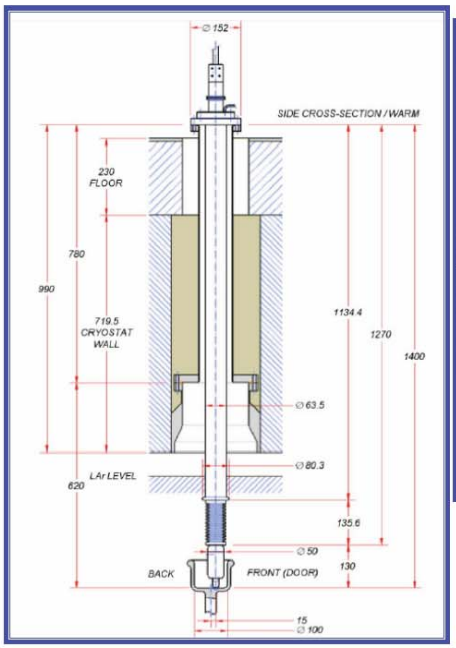
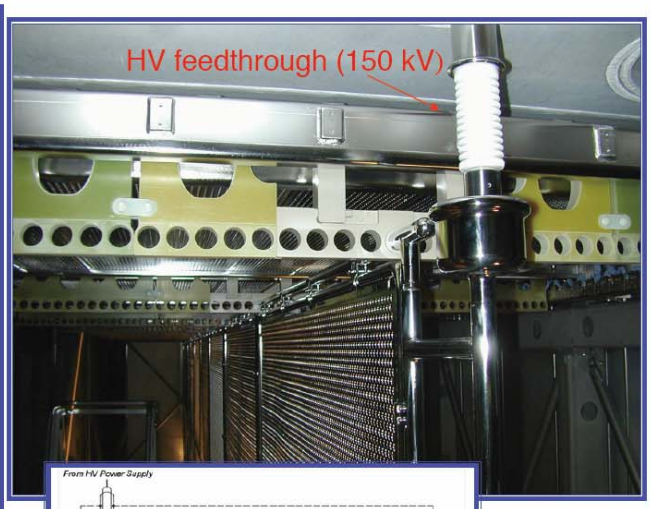
ICARUS T300 prototype

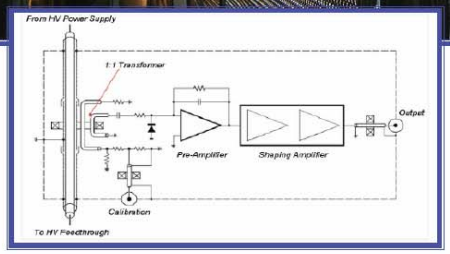




High voltage system







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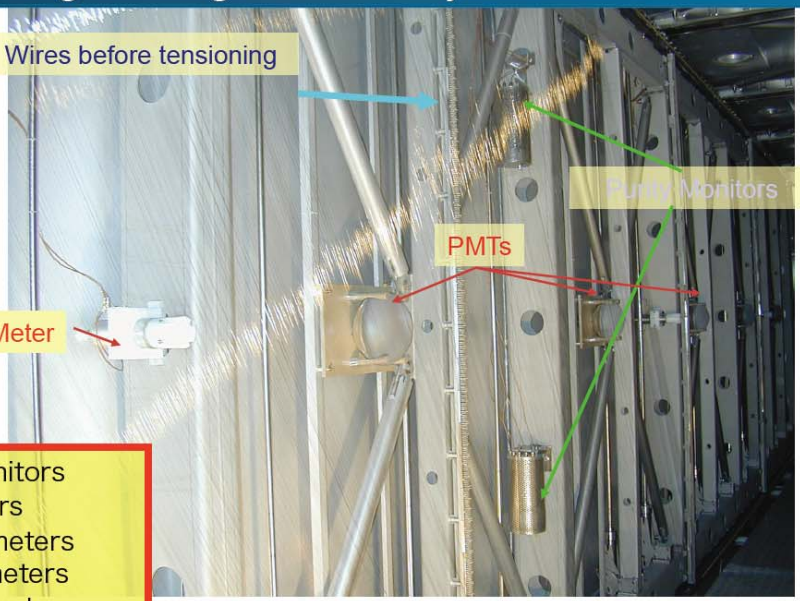
Charge and light readout system

Three wire planes and a PMT



6	LAr purity monitors
16	LAr level meters
7	wire position meters
8	wall position meters
30	temperature probes
20	PMTs (54 in the second)

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Electronic racks (54000 ch.)

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Technical run in Pavia

Walking on the detector…

August 2001

…and observing cosmic ray events

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Filling procedures

- Filling procedure towards the ultra pure (ttb) LAr:
  - Use ultra high vacuum standards for detector components design, construction, cleaning and assembly;
  - Removal of air and outgassing of surfaces by evacuating the argon container volume to the molecular vacuum level (≈ 10^{-5} mbar);
  - Fast cooling (to minimize out-gassing) and filling with ultra-purified LAr;
  - Recirculation/purification of the gas phase to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks on the openings (typically located on the top of the device) in the bulk liquid;
  - Recirculation/purification of the bulk liquid volume to further reduce the impurities concentration.

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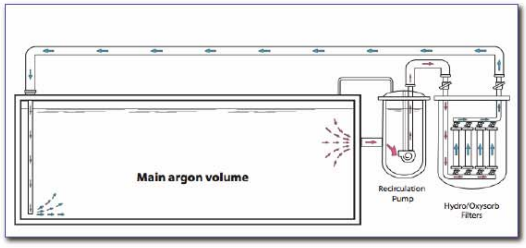
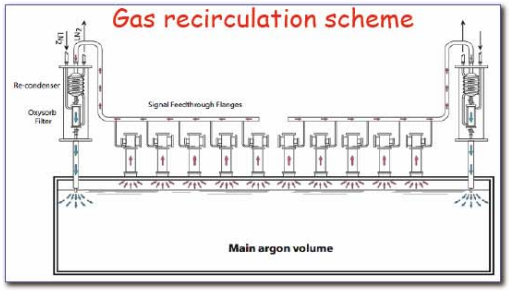
Purification in the liquid and in the surrounding gas

- According to the kinetic theory, the densities of the gaseous contaminating impurities are approximately the same in the liquid and in the gas regions.
- Since the density of the cold Argon gas is much smaller than in the liquid, the *fractional density* of impurities is correspondingly larger in the gas.
- For ICARUS and at the design rate of 100 Nm^3/h— the gas driven purification speed will be of the order of 1/16 $hour^{-1}$, much faster than the one with the standard liquid purification.
- Incidentally, the liquid/gas/liquid process would require zero energy in the reversible iso-temperature limit with no losses

Liquid recirculation scheme



Gas recirculation scheme



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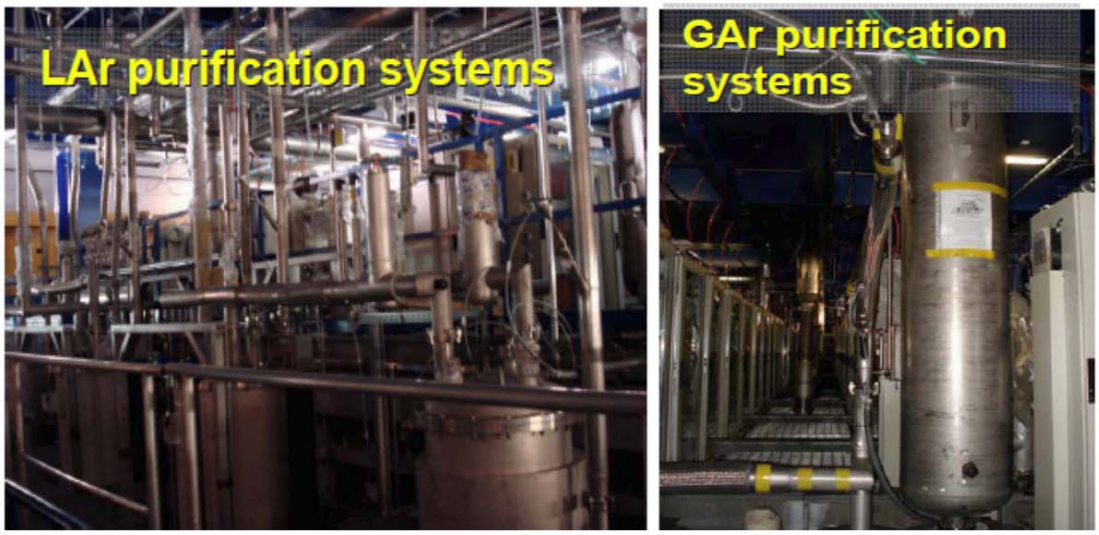
Purification systems for the T600.

Liquid recirculation

Gas recirculation



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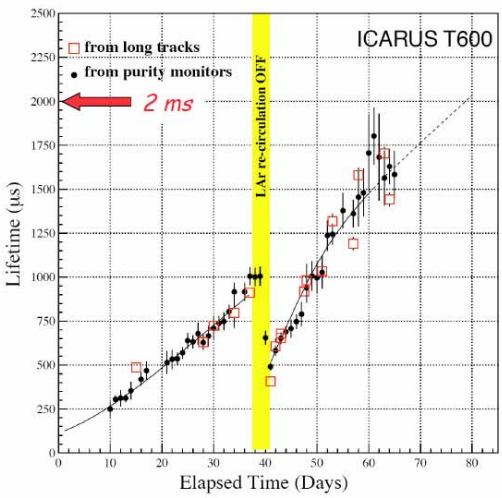
"Purity": state of the art in 2001

- 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.

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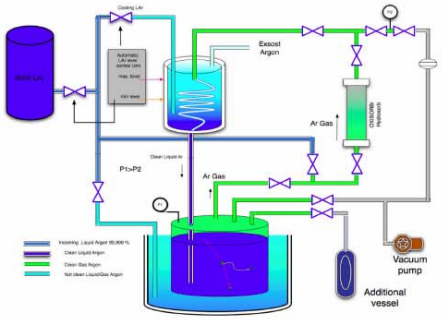
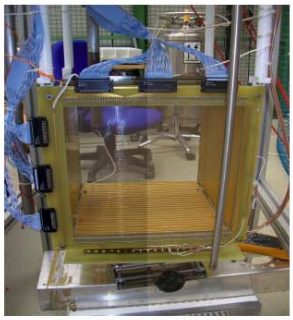
Recent progress in experimental purity achievements

- 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 ν'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





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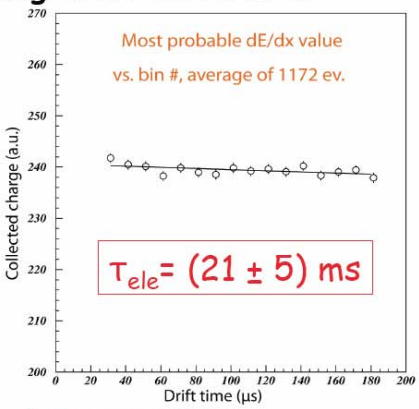
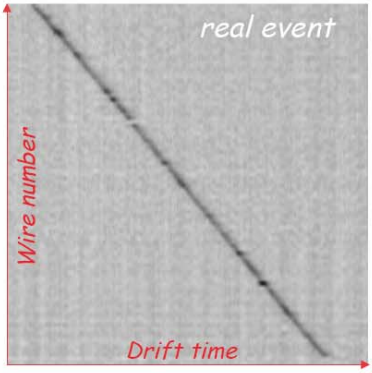
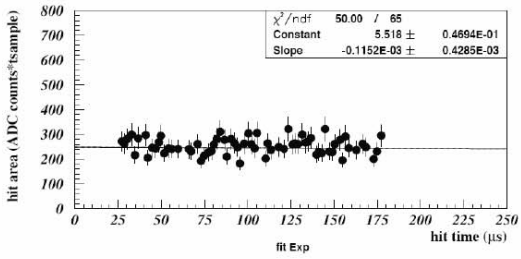
Purity achievement

- The measured value to the experimental τ_{ele} corresponds to an attenuation of about 15 % for a longest drift of 5 meters, opening the way to exceptionally long drift distances.







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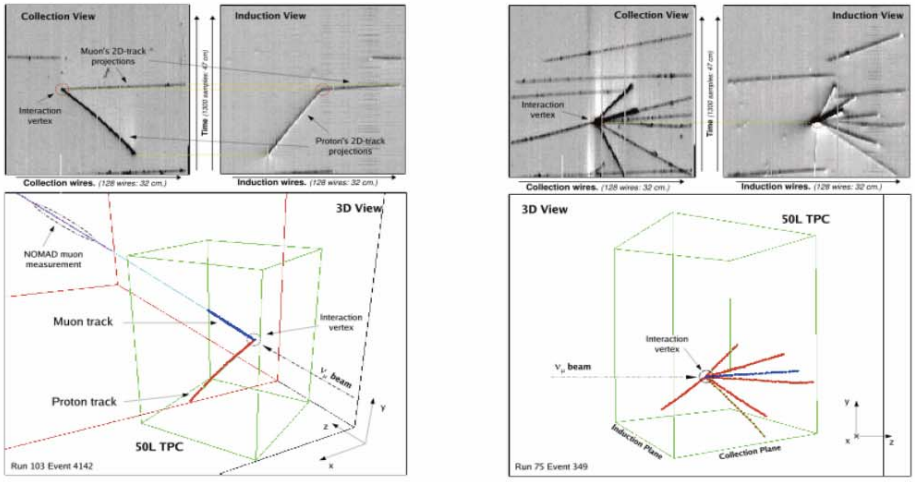
Quasi-elastic neutrino interactions at CERN

- 50 liter LAr-TPC exposed to CERN WANF (NOMAD as muon spectrometer)
  - Full 3D event kinematics reconstruction, particle id, momentum balance, π^0 rejection



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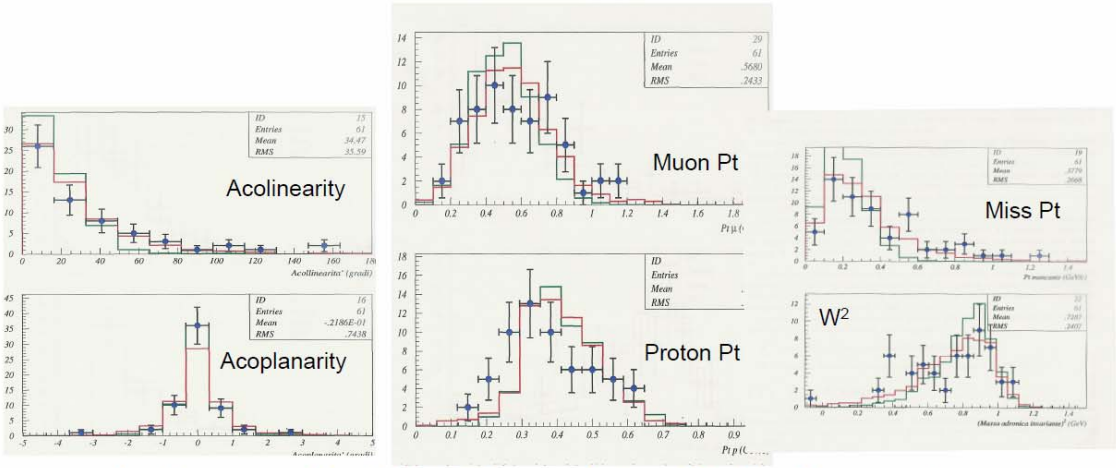
Quasi-elastic event reconstruction at CERN

Selection of ~ 200 pure lepton-proton final state with exactly one proton T_p>50 MeV (range > 2 cm) and any number protons T_p<50 MeV



Good agreement with FLUKA expectations (Red line), accounting for Nuclear Fermi motion and re-interactions in nuclei.

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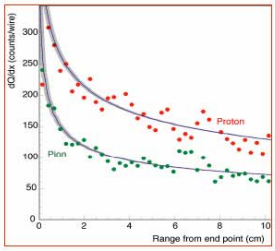
Summary of LAr TPC performances

- 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



RESOLUTIONS

Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

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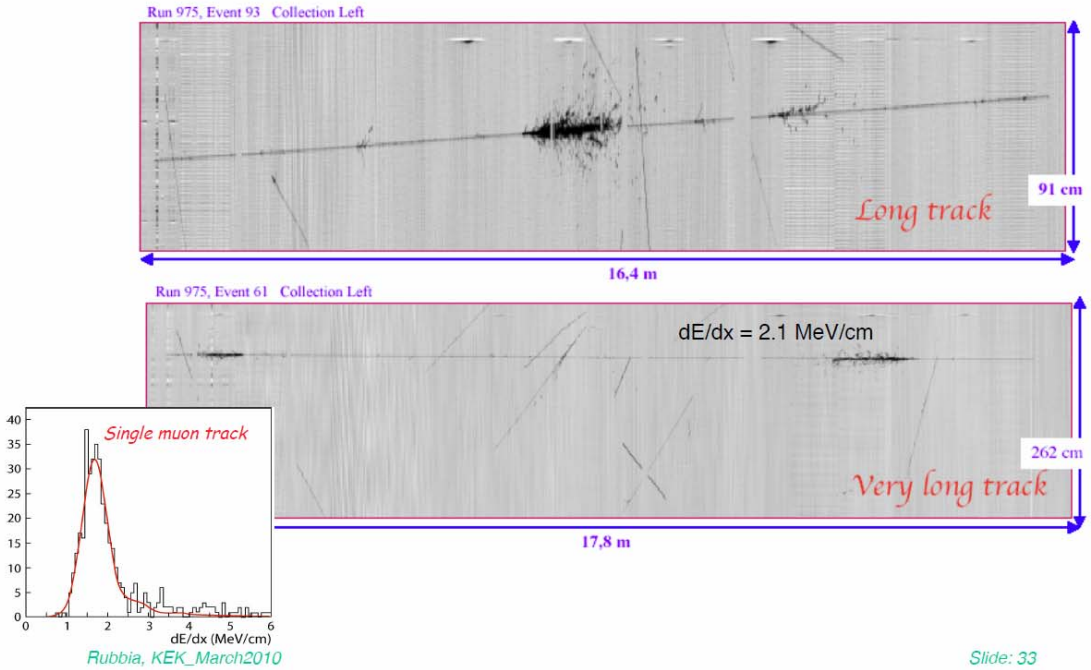
Long muon tracks



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Muon momentum measurement with multiple scattering

In case of non-contained events

Multiple Scattering is the key tool to measure momentum, essential for atmospheric and CNGS ν

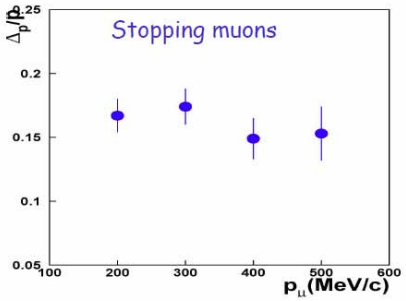
- Kalman filter method applied to segmented tracks (L_{seg} = segment length)
- Momentum p extracted from measurement of deflection angle θ and from χ^2 of the fit

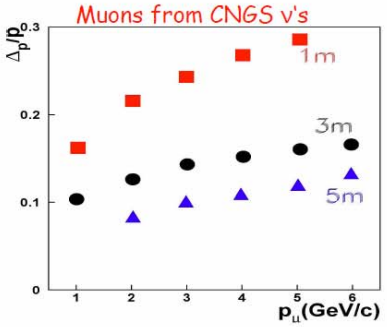
Deflection angle contributions:

$$\theta_{MS} \propto \sqrt{L_{seg}}/p \quad \leftarrow \text{MS angle}$$

$$\theta_{det} \propto L_{seg}^{-3/2} \quad \leftarrow \text{detector resolution}$$

- procedure validated on cosmic ray data (stopping μ's) – extended to higher energy with MC calculations
- Resolution $\Delta p/p$ depends mainly on track length : on μ's from CNGS ν's $\Delta p/p$ ~16%





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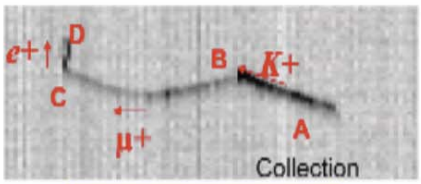
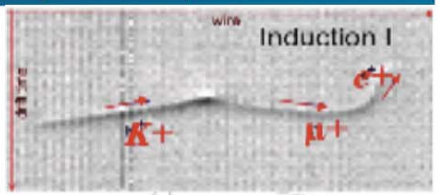
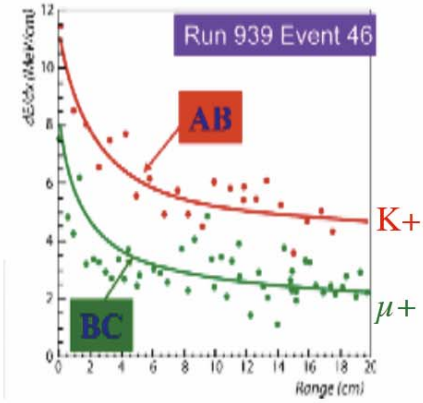
Particle Identification ($k^+ \rightarrow \mu^+ \rightarrow e^+$)



$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$

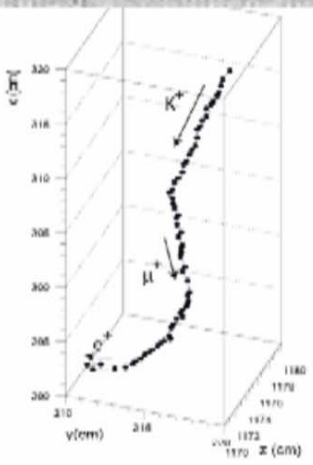
T300 real event





Efficient particle identification due to precise 3D reconstruction, dE/dx, range measurement:

- stopping power;
- recognition of secondary particle production after decay/interaction.



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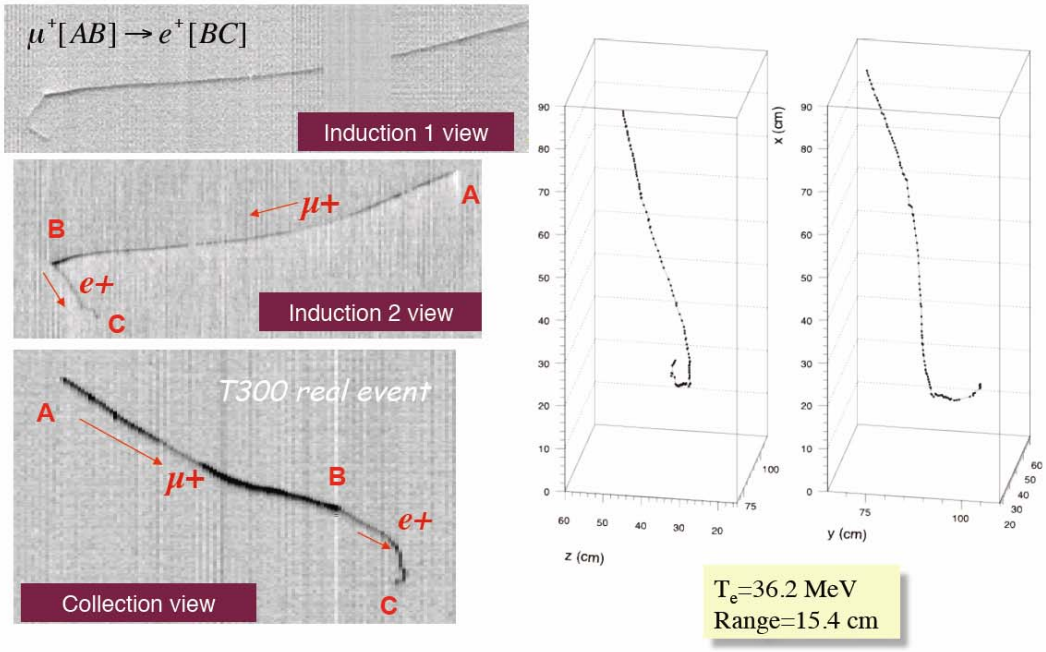
3D reconstruction (stopping μ)



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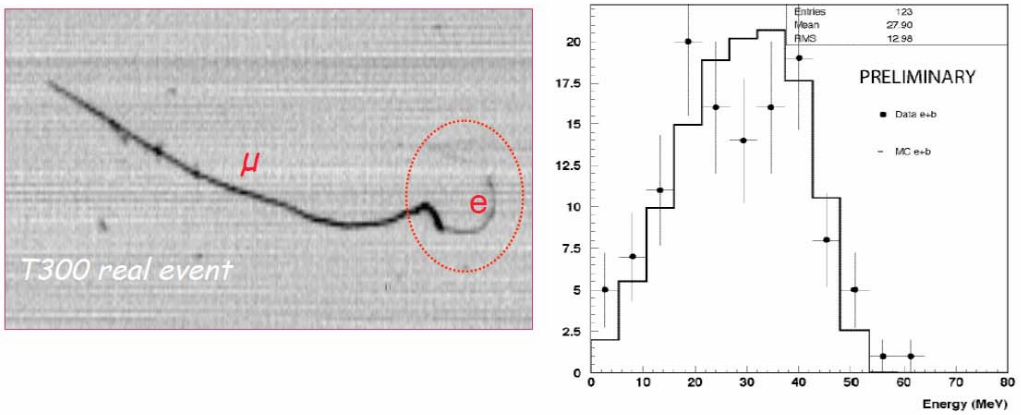
Energy resolution from μ-decays

Michel electrons (μ - e decays)



Energy resolution: $\frac{\sigma}{E} = \frac{(13 \pm 2)\%}{\sqrt{E(MeV)}} \oplus (1.8 \pm 0.3)\%$

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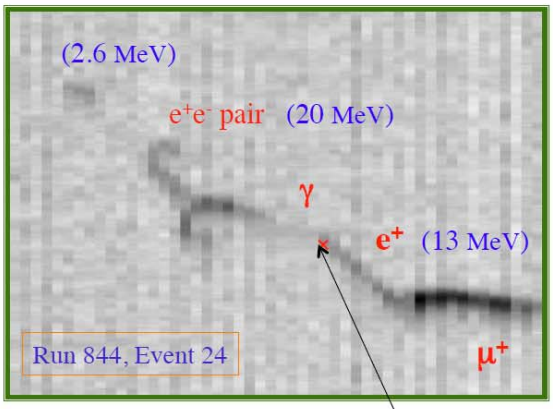
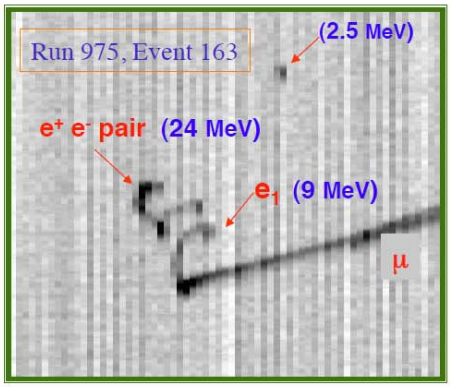
Bremsstrahlung+ Pair-production





≈20% of positron from μ decays expected to annihilate before stopping

Annihilation point

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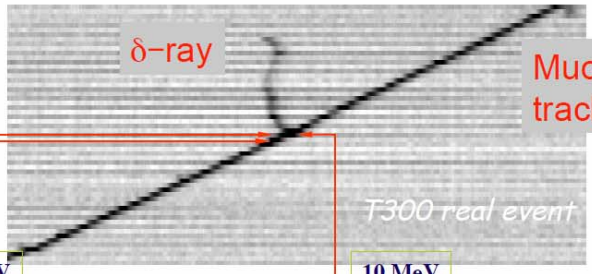
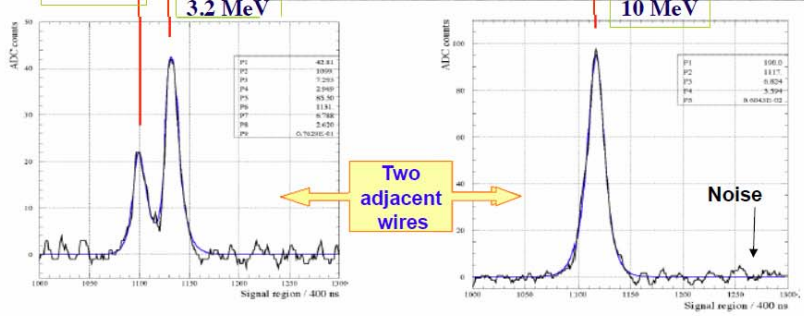
Low energy detail

Single wire performance





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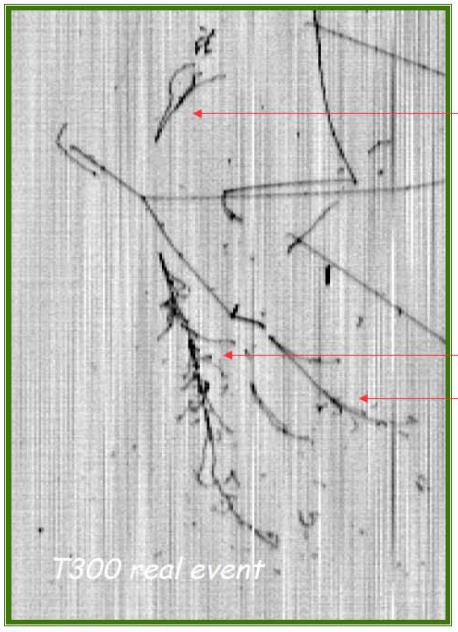
Pi-zero identification



- Reconstruction of π^0-showers

$$M_{inv} = \sqrt{2E_1E_2\cos(\theta_{12})}$$

158 MeV

752 MeV

140 MeV

θ = 141°

M_{inv} = 650 MeV

θ = 25°

M_{inv} =140 MeV

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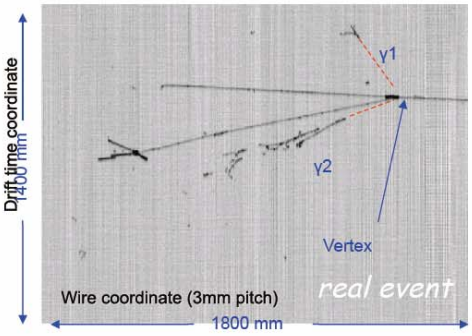
π^0 reconstruction

230 hadronic interactions with π^0 -> $\gamma\ \gamma$ candidates have been selected from ICARUS T300 Pavia run



The average (γ,γ) invariant mass is in agreement with the π^0 mass hypothesis ($m_{\pi 0}$ = 135 MeV/c^2);

$$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys)\text{MeV/c}^2$$

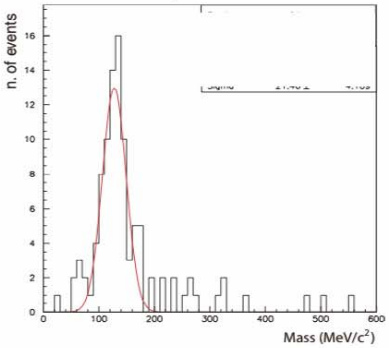
The systematic error is mostly due to calibration

The measured photon radiation length is

$$X_{\gamma,meas} = (17.4 \pm 0.8)\text{cm}$$

in agreement with expectations:

$$X_{\gamma,\text{exp}} = \frac{9}{7}\cdot 14\text{cm} = 18\text{cm}$$



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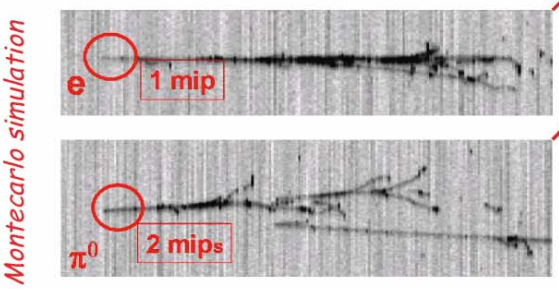
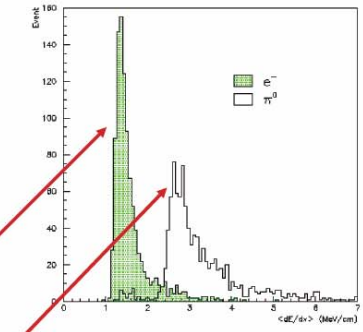
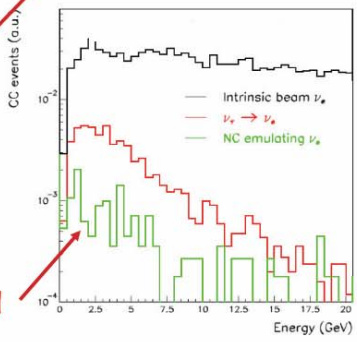
Electron – π^0 separation

- 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%



Montecarlo simulation





NC-e background

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The ICARUS Collaboration in CNGS2

A. Ankowski[1], M. Antonello[2], P. Aprili[3], F. Arneodo[3], B. Baibussinov[4], M. Baldo Ceolin[4], G. Battistoni[5], L. Barzè[6], P. Benetti[6], A. Borio[6], E. Calligarich[6], M. Cambiaghi[6], F. Carbonara[7], F. Cavanna[2], S. Centro[4], A. Cesana[5], K. Cieslik[8], D. B. Cline[17], A. G. Cocco[7], A. Dabrowska[8], R.Dolfini[6], C. Farnese[4], A. Fava[4], A. Ferrari[5], G. Fiorillo[7], S. Galli[2], D. Gibin[4], A. Gigli Berzolari[6],A.Giuliano[9],K.Graczyk[1],S. Gninenko[10], A. Guglielmi[4],C. Juszczak[1], J. Holeczek[11], D. Kielczewska[12], M. Kirsanov[10], J. Kisiel[11], T. Kozlowski[13], N. Krasnikov[10],M. Lantz[5], G. Mannocchi[9], M. Markiewicz[8], Ch. Matthey[17], V. Matveev[10], A. Menegolli[6], G. Meng[4],C. Montanari[6], S. Muraro[5], J. Nowak[1], S. Otwinowski[17], O. Palamara[3], L. Periale[9], G. PianoMortari[2], A. Piazzoli[6], P. Picchi[9], F. Pietropaolo[4], W. Polchlopek[14], M. Posiadala[12], P. Przewlocki[13], A. Rappoldi[6],.G. L. Raselli[6], E. Rondio[13], M. Rossella[6], C. Rubbia[3], P. Sala[5], L. Satta[9], D. Scannicchio[6], Y. Seo[17], E. Segreto[3],F. Sergiampietri[15], J. Sobczyk[1], D. Stefan[8], J, Stepaniak[13], R. Sulej[16], M. Szarska[8], M. Terrani[5], G. Trinchero[9], F. Varanini[4], S. Ventura[4], C. Vignoli[6], T. Wachala[8], A. Zalewska[8], K. Zaremba[16] B. Lisowski[17], H. Wang[17], X. Yang[17]

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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. ~1-2 ev/day
  - 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
- Other unexpected phenomena

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The ICARUS detector in underground Hall B of LNGS

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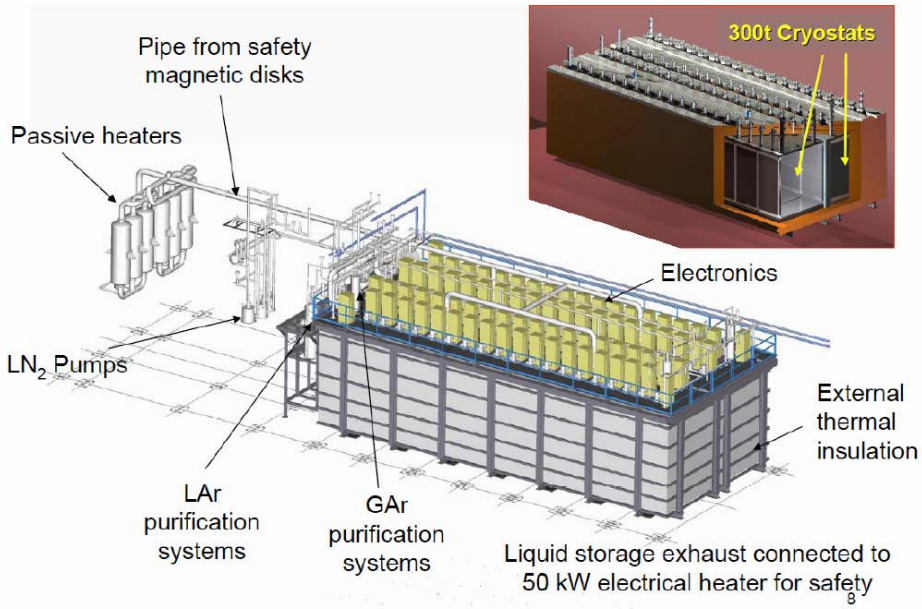
The ICARUS-T600 layout



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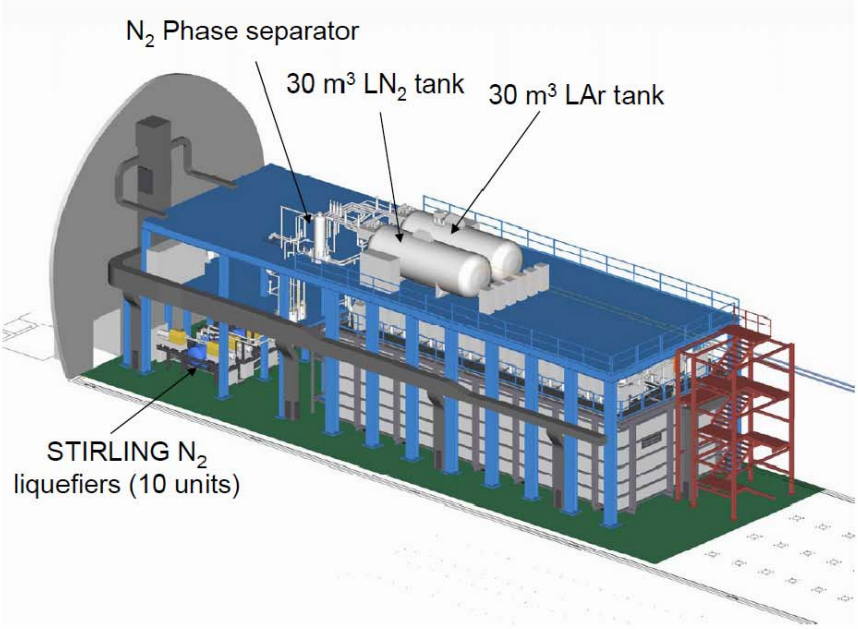
The over-all physical plant



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T600 in hall B (CNGS2-2010)

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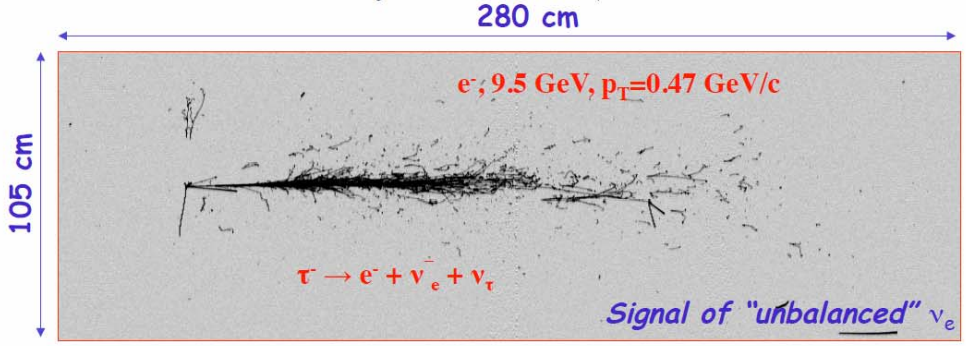
ICARUS: CNGS2 searching for the ν_τ signature.

- CERN beam associated events: 1200 ν_μ CC ev/yr and 8 ν_e CC ev/yr for 4.5 x 10^{19} pot/yr beam intensity
- The electron decay channel is a quite significant goal also for the present T600 mass, uniquely characterized by a large transverse momentum unbalance due to the emission of the two neutrinos.
- Several background free ν_τ events are expected in 3 yrs data taking.

CNGS ν_τ interaction, E_ν=18.7 GeV



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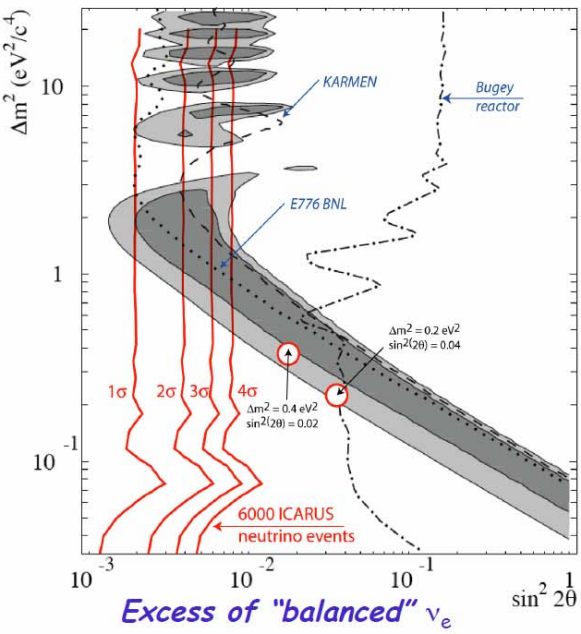
Sterile neutrino search with CNGS2 (ICARUS)

- 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.*



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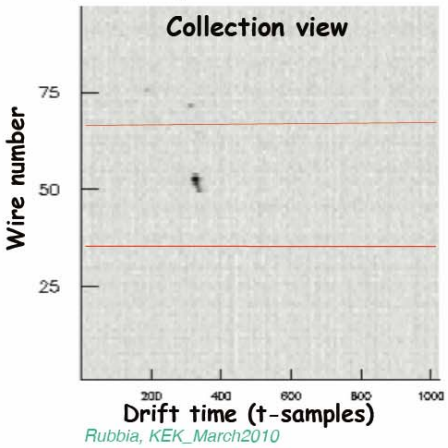
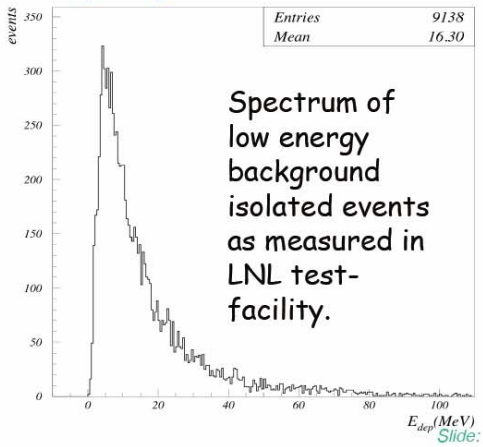
Triggering "low energy events"

- ICARUS-T600 is a self-triggering detector exploiting both scintillation light and TPC wire signals.
- Wire signals are used for local trigger purposes to select isolated low energy event (solar ν, SN ν), atmospheric ν's and p-decays. Well suited also for very large LAr-TPC's.





Spectrum of low energy background isolated events as measured in LNL test-facility.

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Neutrinos !?

- 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.* The situation may be altered by the additional presence of sterile neutrinos.
- The experimentally measured weak coupling strengths are only rather poorly known, leaving room for many other alternatives.
- *Are neutrino a simple carbon copy repetition of quarks?*
- Important discoveries may be ahead:
  - CP violation in the lepton sector
  - Sterile neutrino and other "surprises"
  - Majorana or Dirac ν's;ν-less β-decay,ν-masses

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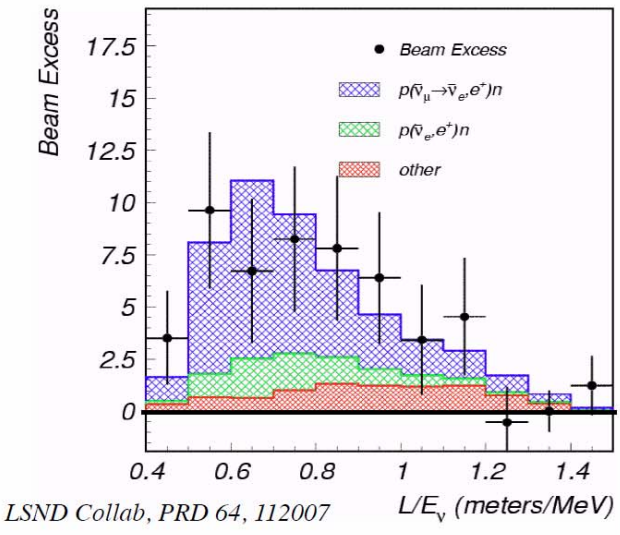
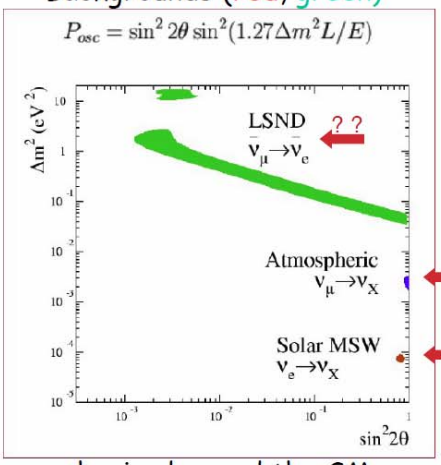
The LSND Experiment: antineutrino oscillations ?

LSND has observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam, 87.9 ± 22.4 ± 6.0 **(3.8σ)**



LSND Collab, PRD 64, 112007

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



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

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Many theoretical hypothesis…..

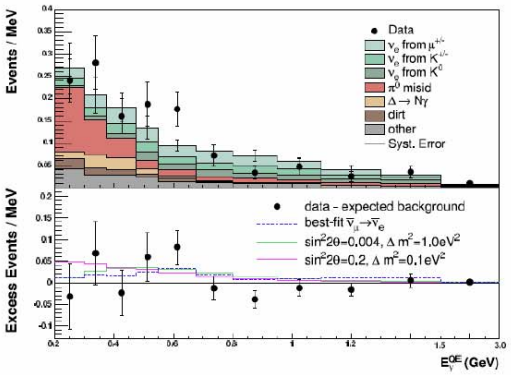
3+2 Sterile Neutrinos	Sorel, Conrad, & Shaevitz (PRD70(2004)073004)
	← Additional, sterile neutrinos ?
	← Standard neutrinos
MaVaNs & 3+1	Hung (hep-ph/0010126)
Sterile Neutrino	Kaplan, Nelson, & Weiner (PRL93(2004)091801
CPT Violation & 3+1 Sterile Neutrino	Barger, Marfatia, & Whisnant (PLB576(2003)303)
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)

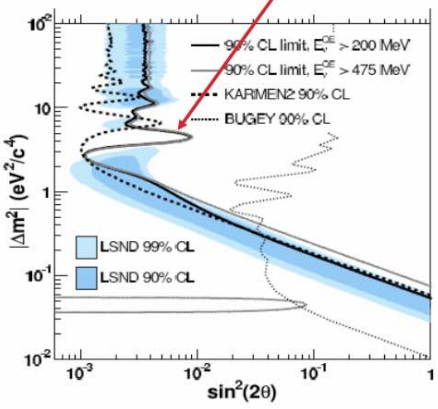
Rubbia, KEK_March2010 *And so on….* Slide: 54

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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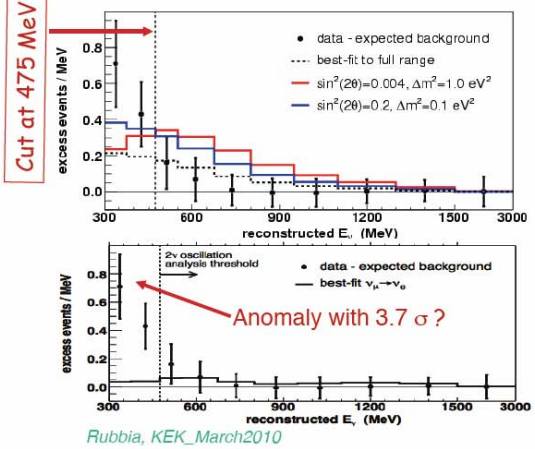
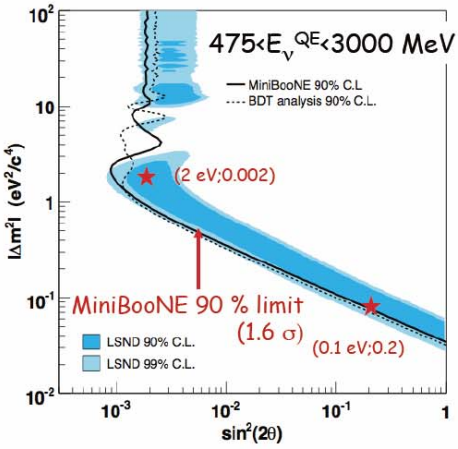
MiniBooNE experiment: neutrino data

- 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 375 ν e CC-QE intrinsic background events. with a possible LSND signal of ~200 ν e CC-QE events
- 96±17±20 events above background, for 300 < E_ν^{QE} < 475MeV:





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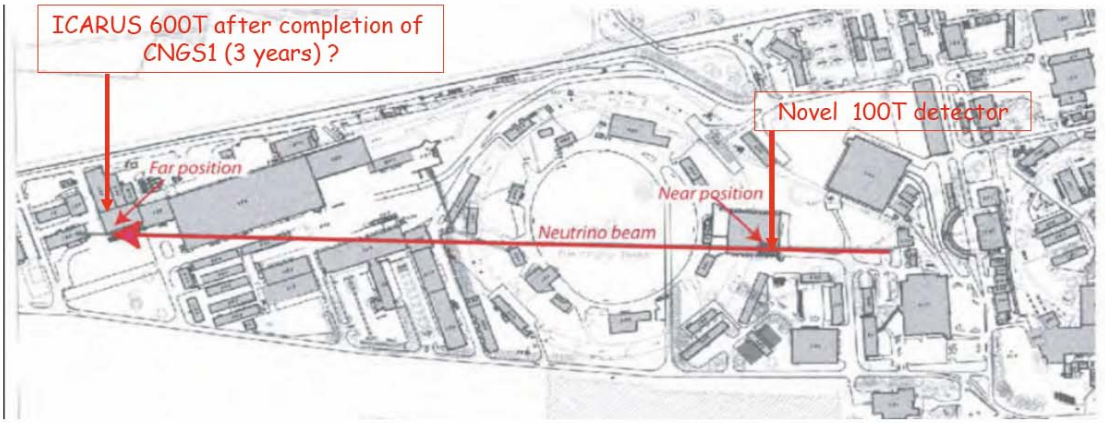
ICARUS after CNGS2: The CERN- PS neutrino beam



- The PS proton beam at 19.2 GeV/c is extracted via TT2, TT1 and TT7.
- The magnetic horn is designed to focus particles of momentum≈2GeV/c.
- The decay tunnel is about 50 m long, followed by an iron beam stopper

Two positions are foreseen for the detection of the neutrinos
The far (main) location at 850 m from the target (600T);
The near location at a distance of 127 m from the target (100T).

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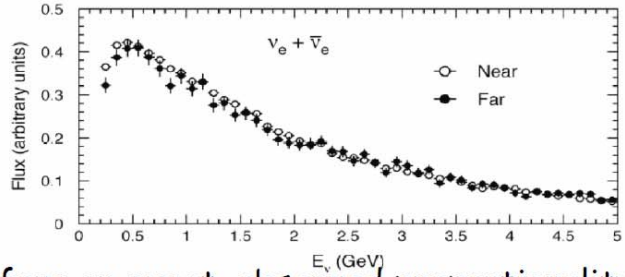
Unique features of the CERN SPS beam

- 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* the two ν_e observed spectra are a precise copy of each other, independently of the specific experimental event signatures and without any Monte Carlo comparisons.



The two ν_e spectra in the far (850 m) and near (127 m locations are nearly identical

- 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.

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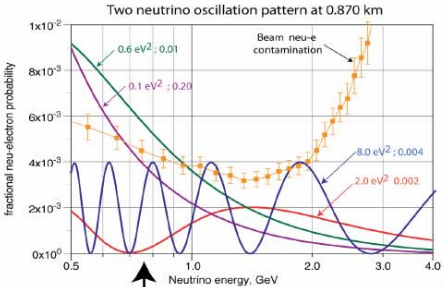
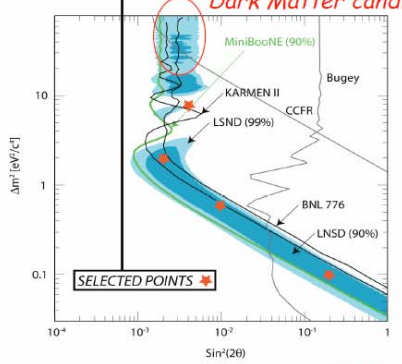
New features of the CERN proposal

- 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 actual values in the (Δm^2 - $\sin^2 2\theta$) plane.
- The intrinsic ν_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 background, also considering the very high statistical impact and the high resolution of the experimental measurement.



Dark Matter candidate !



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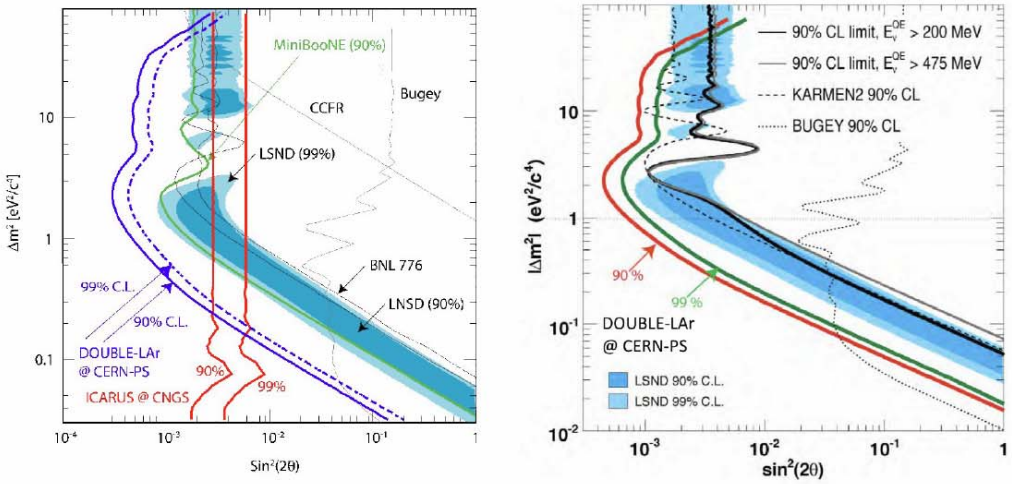
Comparing sensitivities



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.

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From T600 to multi-kton LAr-TPC: a MODULAr approach

- The MODULAr proposal is focused on the following three main items:
  - a new neutrino beam derived from the existing horn focussing and the proton beam line from the 400 GeV SPS, eventually with an increased intensity. Relatively modest changes in the neutrino beam focussing of CERN will produce a nearly optimal beam configuration.
  - A new experimental area, eventually enlarged in future phases, to be realised about 10 km off-axis from the main laboratory, away from the protected area of the Gran Sasso National Park. The high event rejection power of the LAr-TPC detector will ensure the absence of backgrounds not only for the neutrinos from the CNGS but also for proton decay and cosmic neutrinos if a shallow depth location (1.2 km of equilavent water depth) is provided.
  - A new LAr-TPC Imaging underground detector made of several identical units, each of about 10 kt fiducial mass. As a first step, a total of about 20 kt will be realised along the lines of the vast R&D work carried out over the last decades. This programme may eventually be further improved with additional modules, depending of the developments of the programmes with and without accelerators.

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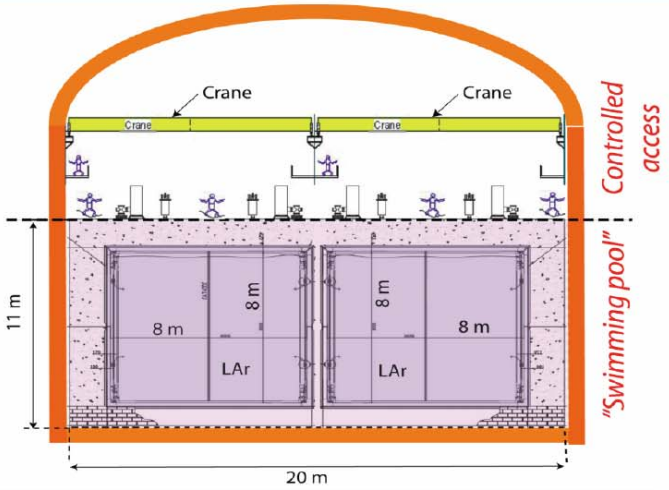
The MODULAr concept

- Indicative cross section of the T600 "clone" in the dedicated "swimming pool like" underground hall.
- It is made of two twin separate LAr containers made of Aluminum extruded structures, thermally stabilized with forced N2 circulation.
- Outside the dual structure, an about 1.5 m thick perlite wall provides spontaneous, passive heat insulation.
- The region on top of the "swimming pool" is accessible to auxiliary equipments.
- *Total L Ar mass for a detector 60 m long (3 x ICARUS) is about 10'000 tons. Same gaps as for ICARUS, but 4 m drift.*



The volume of each of the two gaps should be about 8 x 8 m² and 60 m long, corresponding to 3840 m3 of liquid or 5370 t of LAr. The drift length is 4 m. A reasonable three-plane wire pitch should be of the order of 6 mm, twice the value of the T600. The full detector is made of two such dewars.

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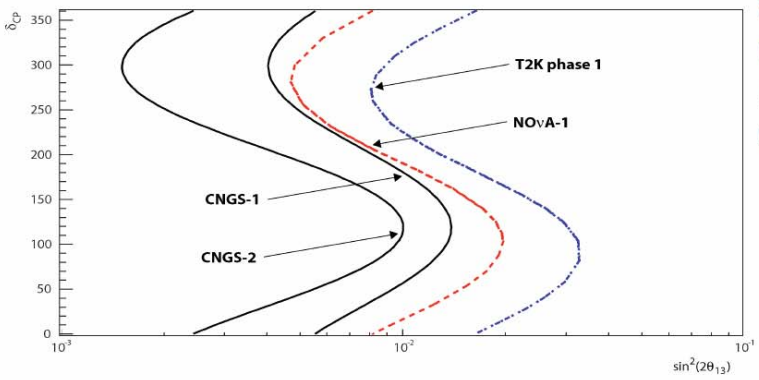
3σ MODULAr sensitivity to θ_{13} and δ_{CP}



CNGS-1: 1.2x10²⁰ pot/y
CNGS-2: 4.3x10²⁰ pot/y
Δm_{23}^2 = 2.5 x10⁻³eV²
normal mass hierarchy

GLoBES calculation:
5 % beam systematics
ΔE/E = 15 %

Rates for 20 kt mass, 5 y and 1.2x10²⁰ pot/y → $\sin^2(2\theta_{13})$ = 0.1

	ν_μ CC	bg	signal	$S/\sqrt{bg}$
MODULAr	13000	70	390	47
NOνA (20kt)		19.5	142	32
T2K		23	103	23

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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's T600.
- 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.

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Thank you !

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