A 100 ton liquid argon TPC as T2K near detector ?

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Abstract

- The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration.
- The ICARUS experiment, which acts as an observatory for the study of neutrinos and the instability of matter, is starting to come together. In the summer of 2001, the first module of the ICARUS T600 detector passed brilliantly a series of tests. The year 2004 should see the detector's installation at the Underground Gran Sasso Laboratory.
- In this talk, we discuss possible future and independent applications of the technique. More details can be found in the following references:

- Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment, A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003, Italy, hep-ph/0402110
- Ideas for future liquid Argon detectors, A. Ereditato and A.Rubbia, Proc. Third International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, NUINT04, March 2004, Gran Sasso, Italy,
- Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches, A. Ereditato and A.Rubbia, Proc. Workshop on Physics with a Multi-MW proton source, May 2004, CERN, Switzerland
- Very massive underground detectors for proton decay searches, A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, Italy, March 2004, hep-ph/0407297
- Liquid Argon TPC: mid & long term strategy and on-going R&D, A.Rubbia, Proc. Int. Conf. on NF and Superbeam, NUFACT04, Osaka, Japan, July 2004

The liquid Argon TPC technology

Liquid Argon medium properties

- A Historical View On the R&D for liquid Rare Gas detectors, T. Doke, NIM A 327 (1993) 113 and references therein.

	Water	Liquid Argon
Density (g/cm^3)	1	1.4
Radiation length (cm)	36.1	14.0
Interaction length (cm)	83.6	83.6
dE/dx (MeV/cm)	1.9	2.1
Refractive index (visible)	1.33	1.24
Cerenkov angle	42°	36°
Cerenkov $d^2N/dEdx$ (β=1)	≈ 160 eV^{-1} cm^{-1}	≈ 130 eV^{-1} cm^{-1}
Muon Cerenkov threshold (p in MeV/c)	120	140
Scintillation (E=0 V/cm)	No	Yes (≈ 50000 γ/MeV @ λ=128nm)
Long electron drift	Not possible	Possible (μ = 500 cm^2/Vs)
Boiling point @ 1 bar	373 K	87 K

When a charged particle traverses LAr:

1) Ionization process

$W_e = 23.6 \pm 0.3$ eV

2) Scintillation (luminescence)

$W_\gamma = 19.5$ eV

UV “line” (λ=128 nm ⇔ 9.7 eV)

No more ionization: Argon is transparent

Only Rayleigh-scattering

3) Cerenkov light (if relativistic particle)

☞ **Charge**

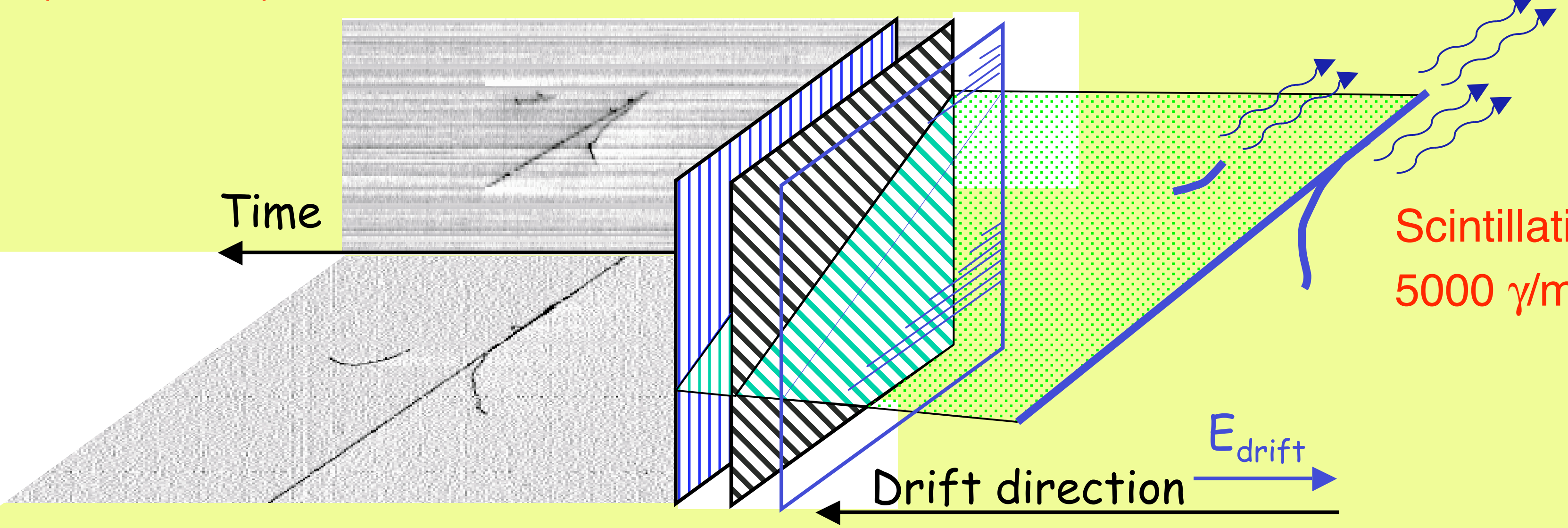
☞ **Scintillation light (VUV)**

☞ **Cerenkov light (if β>1/n)**

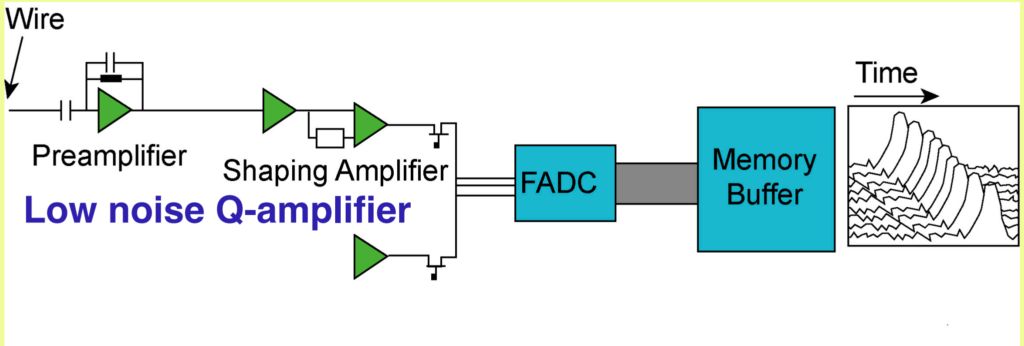
Scintillation & Cerenkov light can be detected independently !

The Liquid Argon TPC principle

Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)



Scintillation light yield ~ 5000 γ/mm @ 128 nm



Continuous waveform recording → image

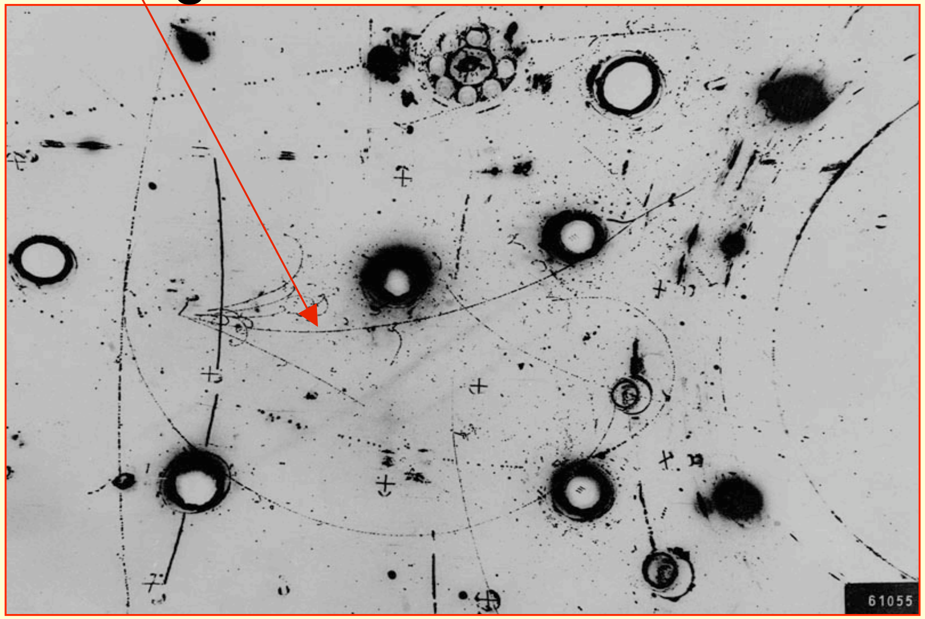
- The Liquid Argon Time Projection Chamber: a new concept for Neutrino Detector, C. Rubbia, CERN-EP/77-08 (1977).
- A study of ionization electrons drifting large distances in liquid and solid Argon, E. Aprile, K.L. Giboni and C. Rubbia, NIM A251 (1985) 62.
- A 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A332 (1993) 395.
- Performance of a 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A345 (1994) 230.
- The ICARUS 50 l LAr TPC in the CERN neutrino beam, ICARUS Collab, hep-ex/9812006 (1998).

Liquid Argon TPC: an electronic bubble chamber

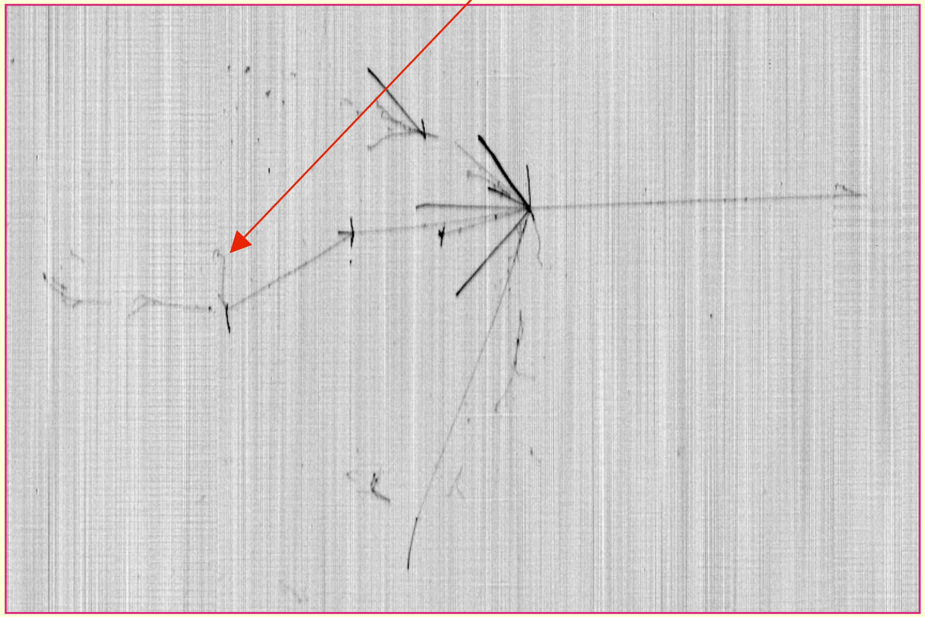
Bubble diameter ≈ 3 mm (diffraction limited)

Bubble size ≈ 3x3x0.4 mm^3

Gargamelle bubble chamber

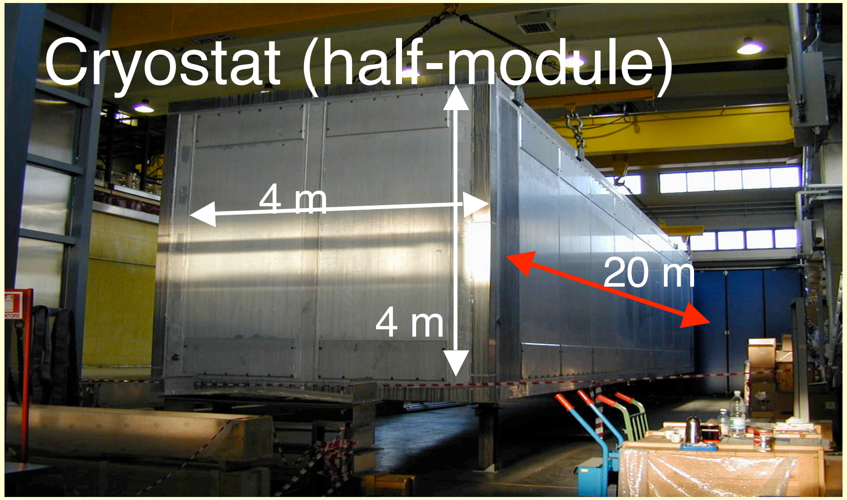


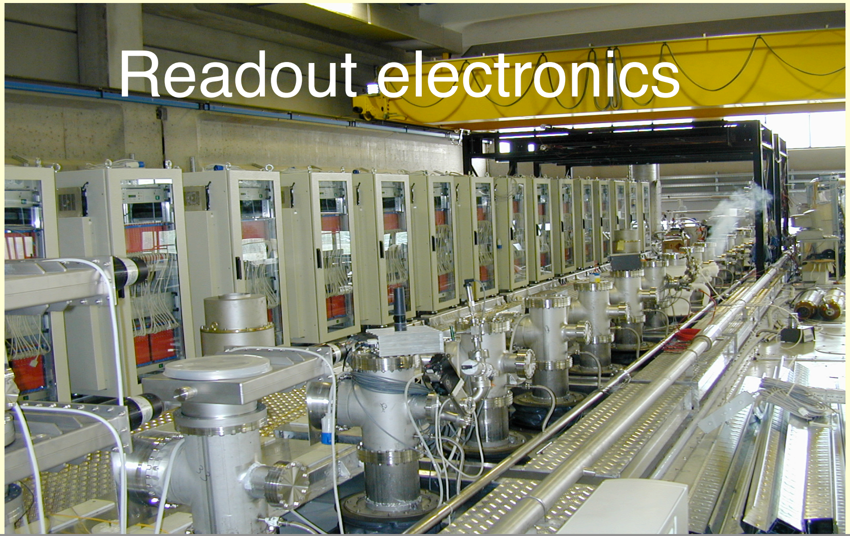
ICARUS electronic chamber



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





ICARUS T600 detector

- Design, construction and tests of the ICARUS T600 detector, ICARUS Collab, NIM A527 329 (2004).
- Study of electron recombination in liquid Argon with the ICARUS TPC, ICARUS Collab, NIMA523 275-286 (2004).
- Detection of Cerenkov light emission in liquid Argon, ICARUS Collab, NIM A516 348-363 (2004).
- Analysis of the liquid Argon purity in the ICARUS T600 TPC, ICARUS Collab, NIM A516 68-79 (2004).
- Observation of long ionizing tracks with the ICARUS T600 first half module, ICARUS Collab, NIM A508 287 (2003).
- Measurement of the muon decay spectrum with the ICARUS liquid Argon TPC, ICARUS Collab, EPJ C33 233-241 (2004).

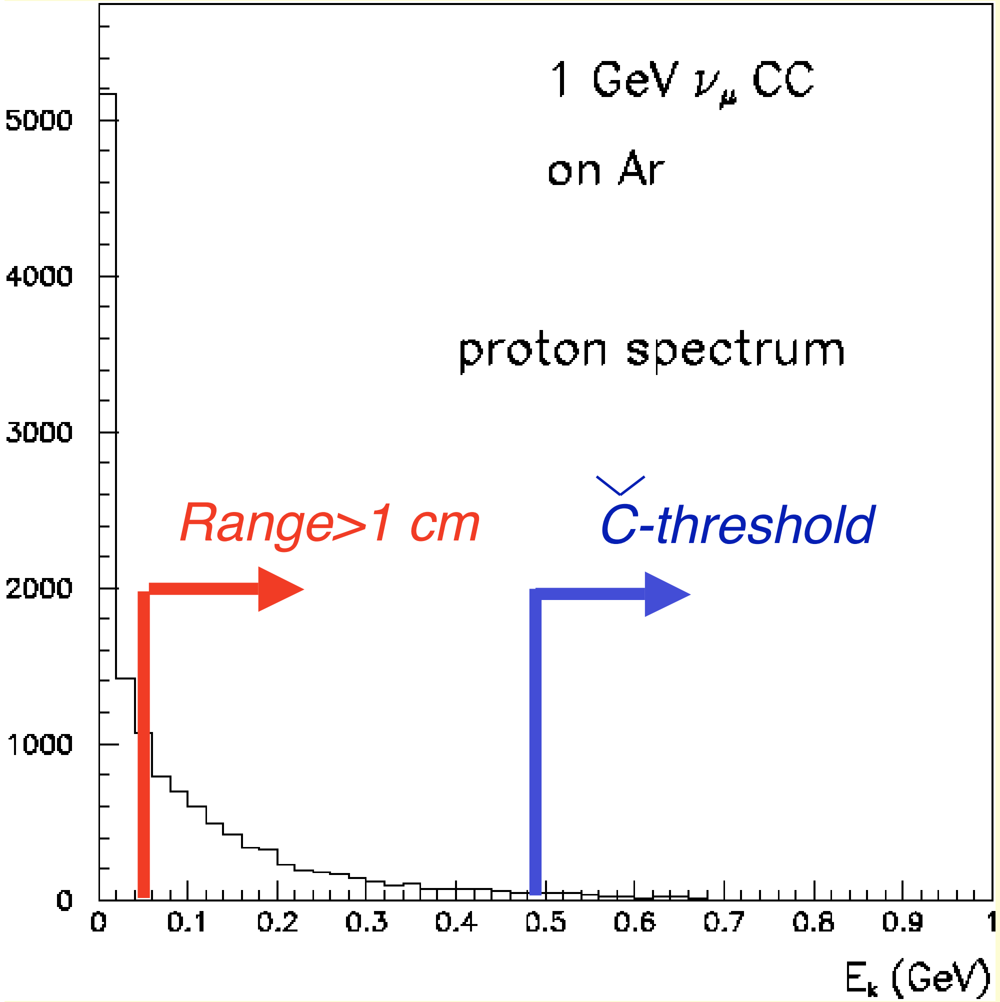
What the Liquid Argon TPC provides

- Bubble-chamber-like event reconstruction capability
- Tracking with unbiased imaging & reconstruction AND full-sampling calorimetry
- Fully active, homogeneous and isotropic
- Very good resolution (energy (calorimetry), angular (tracking))
- Broad energy range (from MeV … multi-GeV) with high event reconstruction efficiency
- Low particle identification thresholds
- Muon, pion, kaon, proton particle ID and separation (dE/dx vs range)
- e/π^0 separation
- $\mu/\pi^\pm$ separation
- Shallow depth conceivable
- Possible to embed in magnetic field for charge discrimination

Implementation conceivable at different mass scale (e.g. 100 ton …100 kton)

Example: proton detection thresholds

E_ν = 1 GeV (MC)



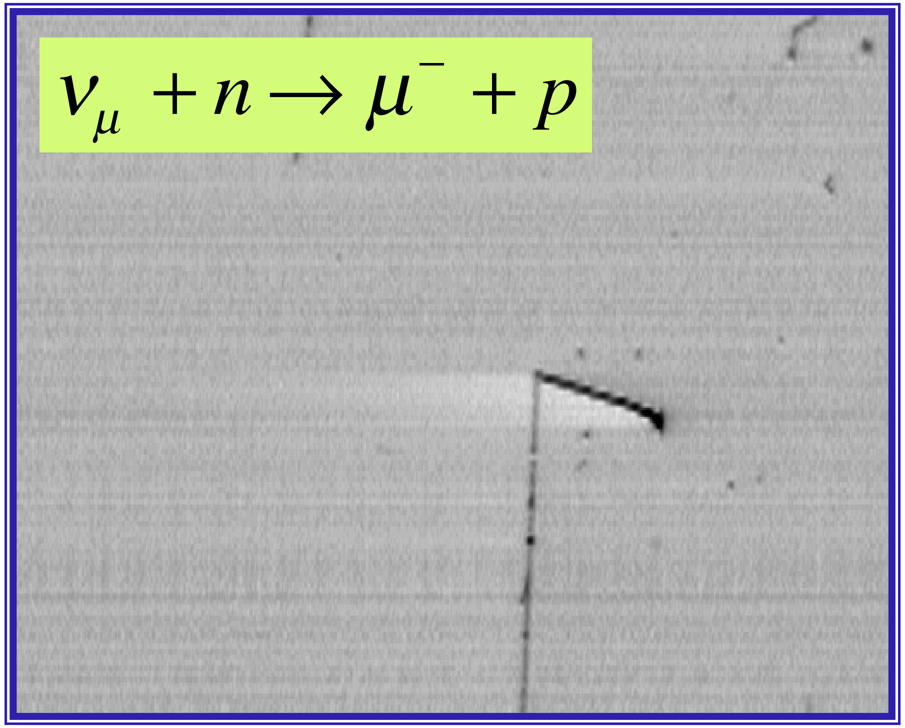
Protons

Kinetic energy T (MeV)	Momentum p (MeV/c)	Range in LAr (cm)
10	43	0.14
40	280	0.93
70	370	4.19
100	446	7.87
300	813	51.9
500	1094	116

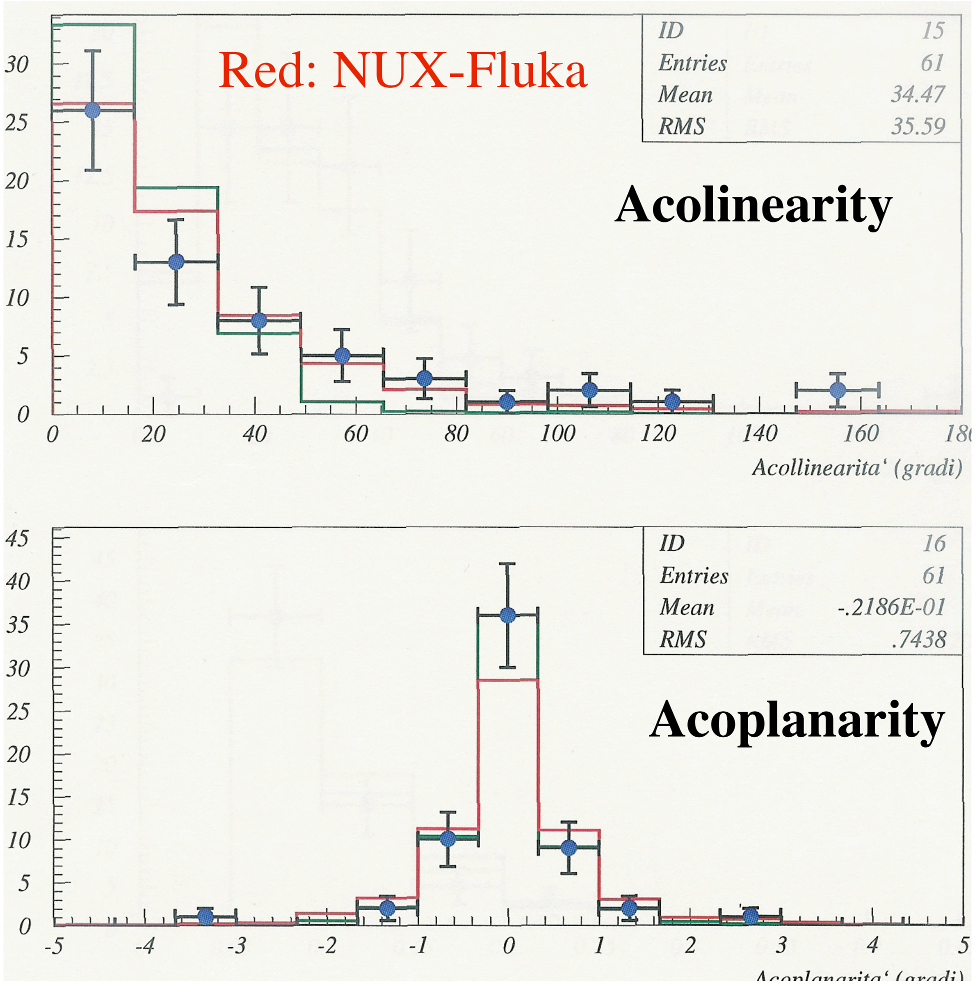
Particle	Cerenkov thr. in H_2O MeV/c	range in LAr cm
e	0.6	0.07
μ	120	12
π	159	16
K	568	59
p	1070	110

Quasi-elastic interactions in 50 liter exposed to CERN WANF

- Selection of pure lepton-proton final state with exactly one proton T_P>50 MeV and any number protons T_P<50 MeV

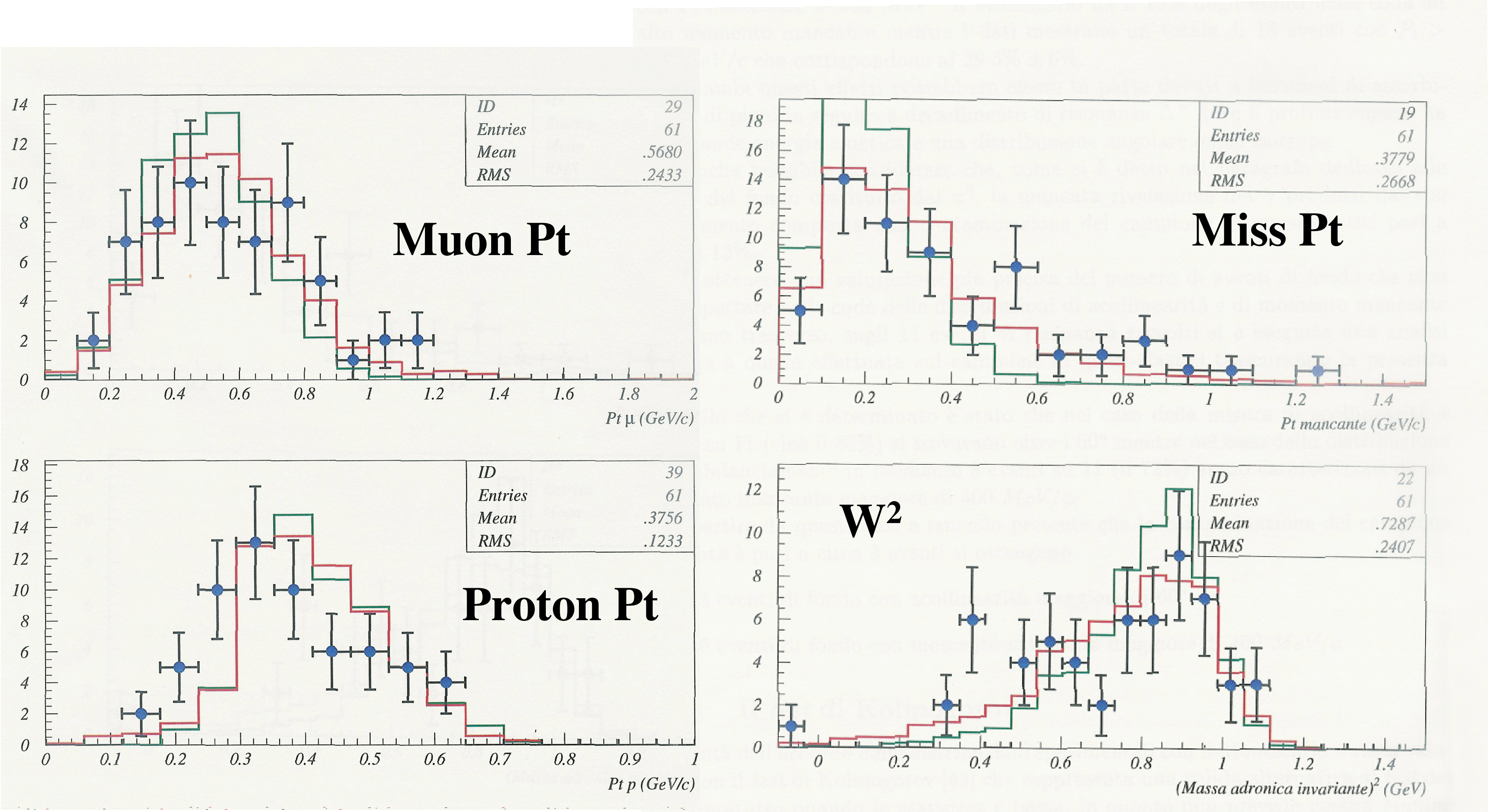


Real neutrino event



B. Boschetti's thesis (Milano, 1998)

Quasielastic events (50 liter exposed to CERN WANF)

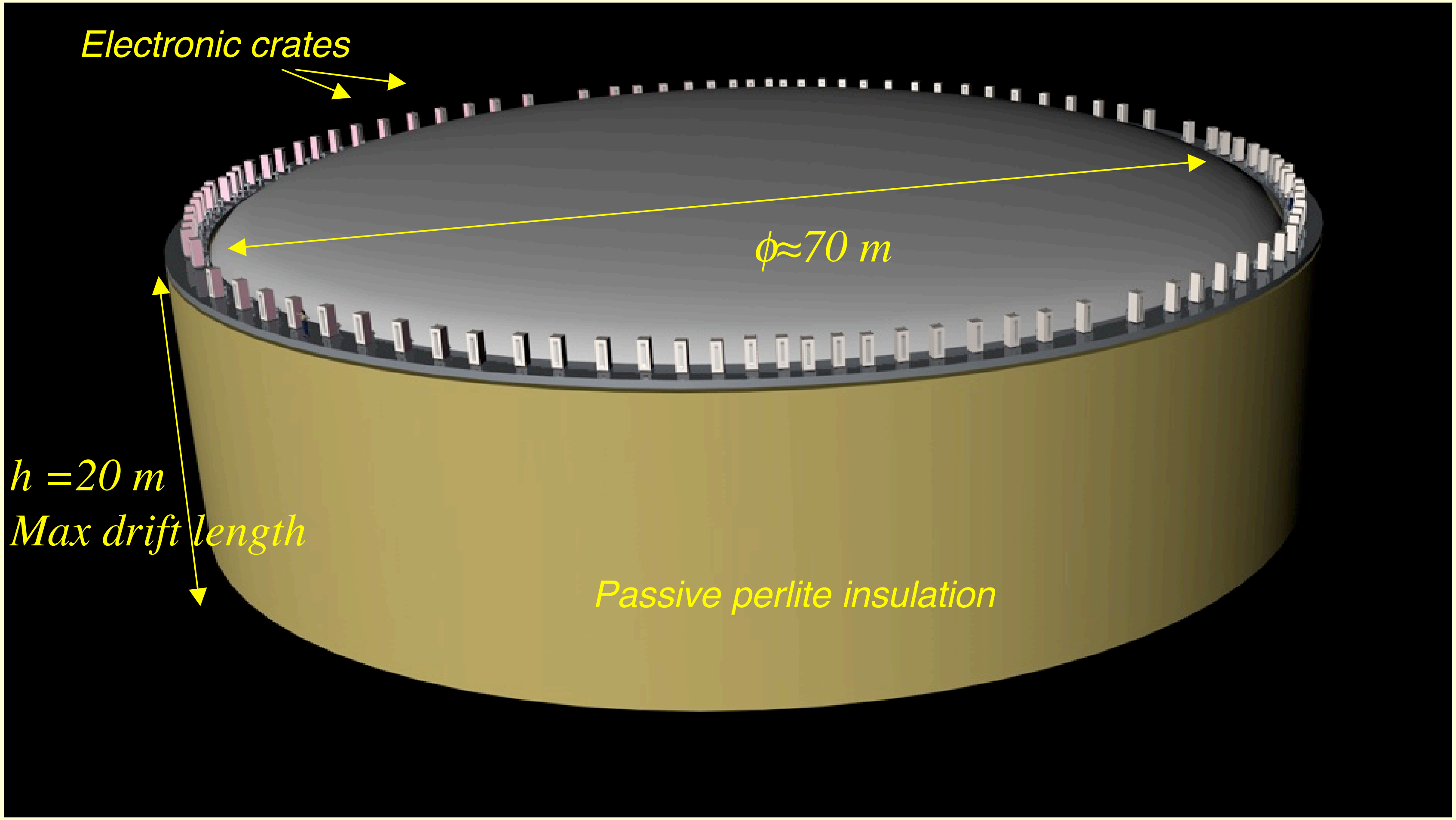


- **Good agreement with NUX-FLUKA expectations**

Red: NUX-Fluka

B. Boschetti's thesis (Milano, 1998)

A 100 kton liquid Argon TPC detector



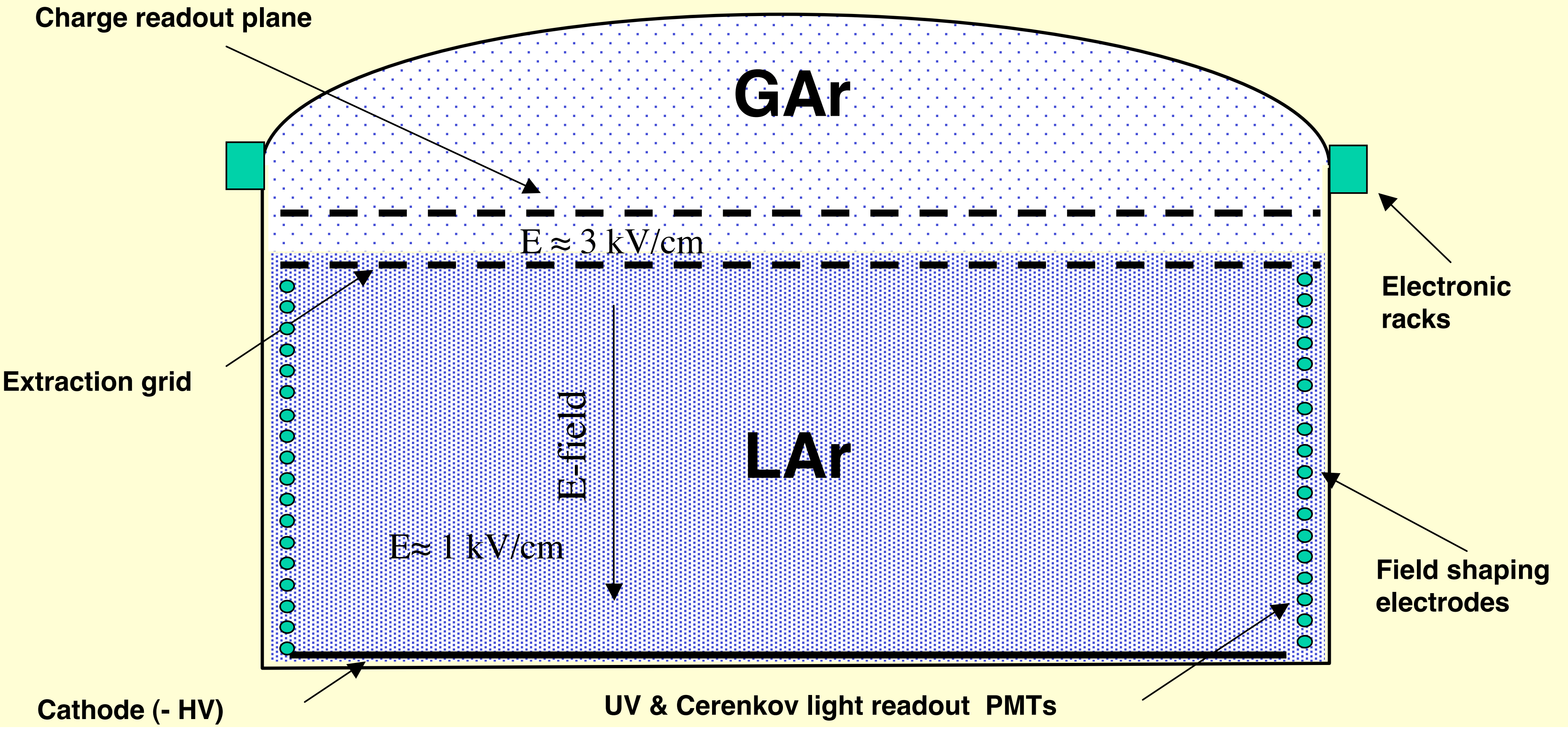
A detector for ν astrophysics, ν beams, and nucleon decay

Single module cryo-tanker based on industrial LNG technology

A tentative detector layout

Single detector: charge imaging, scintillation, Cerenkov light

Dewar	$\phi \approx 70$ m, height ≈ 20 m, perlite insulated, heat input ≈ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	73000 m^3, ratio area/volume $\approx$ 15%
Argon total mass	102000 tons
Hydrostatic pressure at bottom	3 atmospheres
Inner detector dimensions	Disc $\phi \approx 70$ m located in gas phase above liquid phase
Charge readout electronics	100000 channels, 100 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 1000 immersed 8“ PMTs with WLS
Visible light readout	Yes (Cerenkov light), 27000 immersed 8“ PMTs of 20% coverage, single γ counting capability



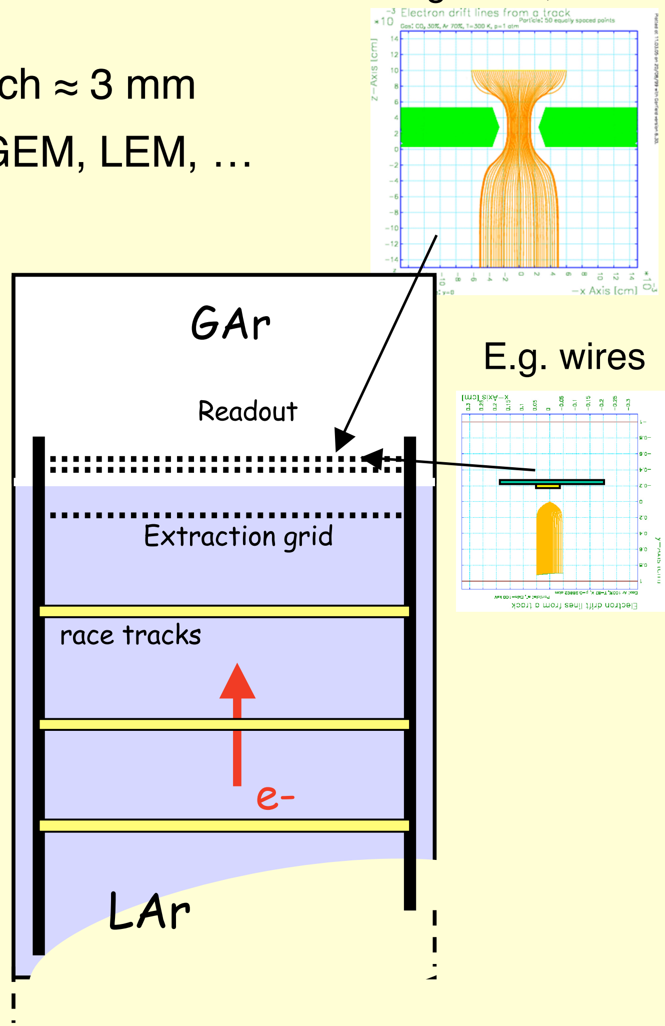
Charge extraction, amplification, readout

Detector is running in **BI-PHASE MODE** to allow for a very long drift path

- Long drift (≈ 20 m) ⇒ charge attenuation to be compensated by charge amplification near anodes located in gas phase (18000 e^- / 3 mm for a MIP in LAr)
- Amplification operates in proportional mode
- After maximum drift of 20 m @ 1 kV/cm ⇒ diffusion ≈ readout pitch ≈ 3 mm
- Amplification can be implemented in different ways: wires+pad, GEM, LEM, …

Electron drift in liquid	**20 m maximum drift, HV = 2 MV for E = 1 kV/cm, $v_d \approx$ 2 mm/μs, max drift time ≈ 10 ms**
Charge readout view	**2 perpendicular views, 3 mm pitch, 100000 readout channels**
Maximum charge diffusion	**$\sigma \approx$ 2.8 mm ($\sqrt{2Dt_{max}}$ for D = 4 cm²/s)**
Maximum charge attenuation	**$e^{-(t_{max}/\tau)} \approx$ 1/150 for τ = 2 ms electron lifetime**
Needed charge amplification	**From 100 to 1000**
Methods for amplification	**Extraction to and amplification in gas phase**
Possible solutions	**Thin wires ($\phi \approx$ 30 μm) + pad readout, GEM, LEM, …**

E.g. LEM, GEM



Ongoing studies and R&D strategy

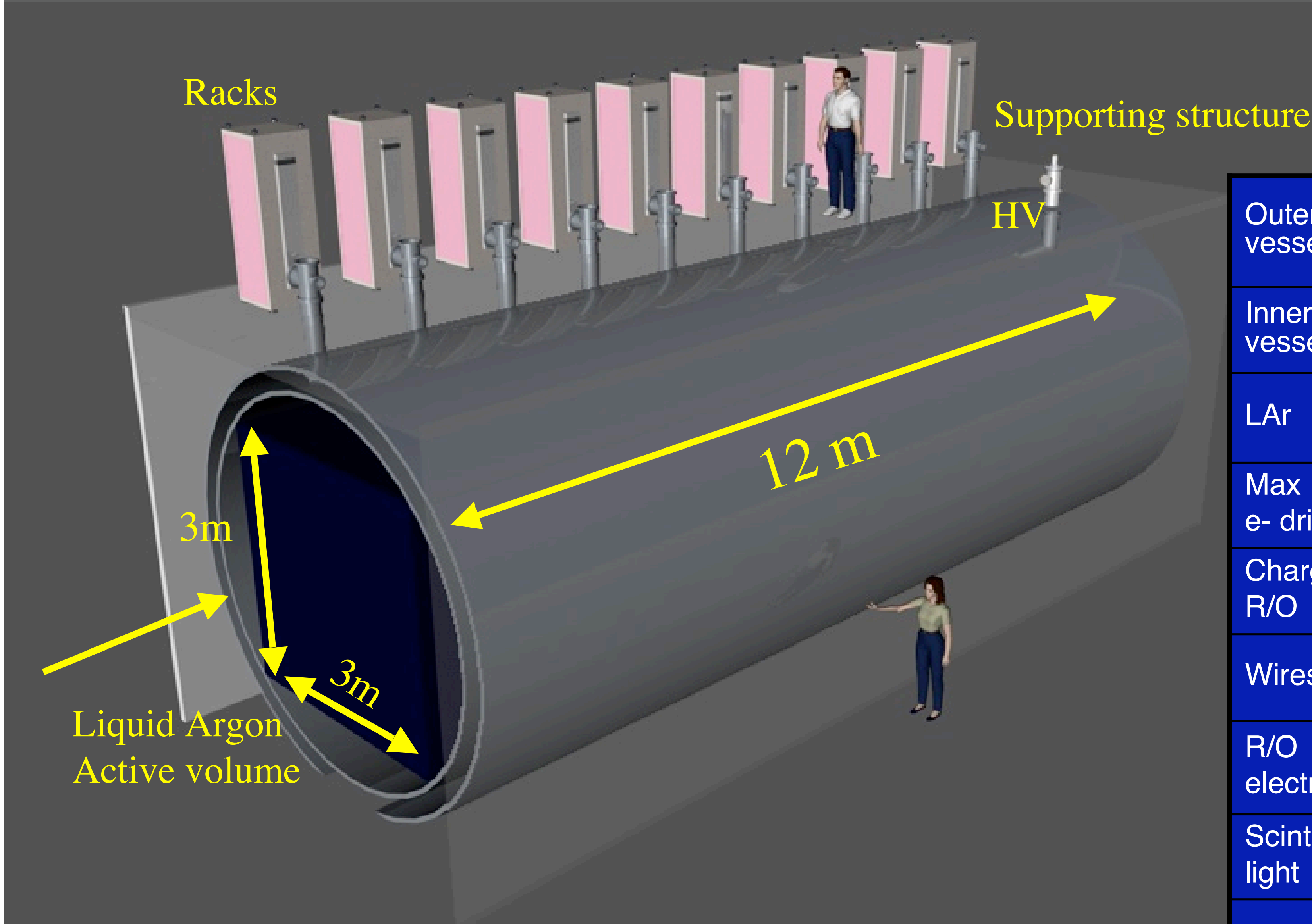
Engineering studies, dedicated test measurements, detector prototyping, simulations, physics performance studies in progress:

- **Study of suitable charge extraction, amplification and imaging devices**
- **Understanding of charge collection under high pressure**
- **Realization and test of a 5 m long detector column-like prototype**
- **Study of LAr TPC prototypes immersed in a magnetic field**
- **Study of large liquid underground storage tank, costing**
- **Study of logistics, infrastructure and safety issues for underground sites**
- **Physics studies and phenomenology**

- A 10% full-scale prototype ?
- Shallow depth acceptable
- Physics program on its own (e.g. sensitivity for $p \rightarrow \nu K$: $\tau > 10^{34}$ yrs for 10 years running)

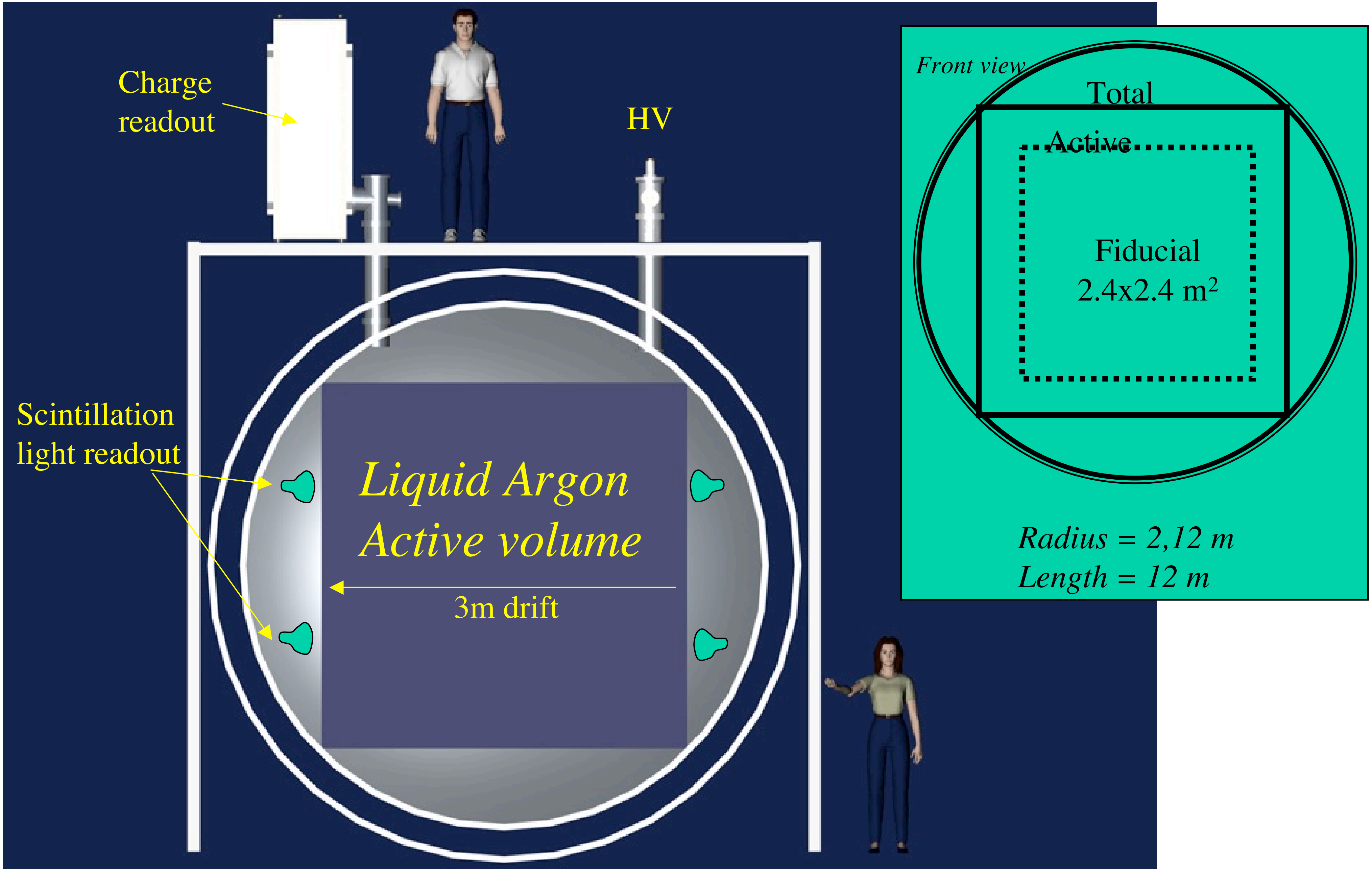
A 100 ton liquid argon TPC at T2K

Conceptual design of the ~100 ton LAr TPC:



Outer vessel	$\phi \approx$ 5m, L≈13m, 15mm thick, weight ≈ 22 t
Inner vessel	$\phi \approx$ 4,2 m, L ≈ 12 m, 8 mm thick, ≈ 10 t
LAr	Total ≈ 240 t Fiducial ≈ 100 t
Max e- drift	3 m @ HV=150 kV E = 500 V/cm
Charge R/O	2 views, ± 45° 2 (3) mm pitch
Wires	≈10000 (7000) ϕ = 150 μm
R/O electr.	on top of the dewar
Scintill. light	Also for triggering
B-field	possible

Conceptual design study of a ≈100 ton active LAr detector:

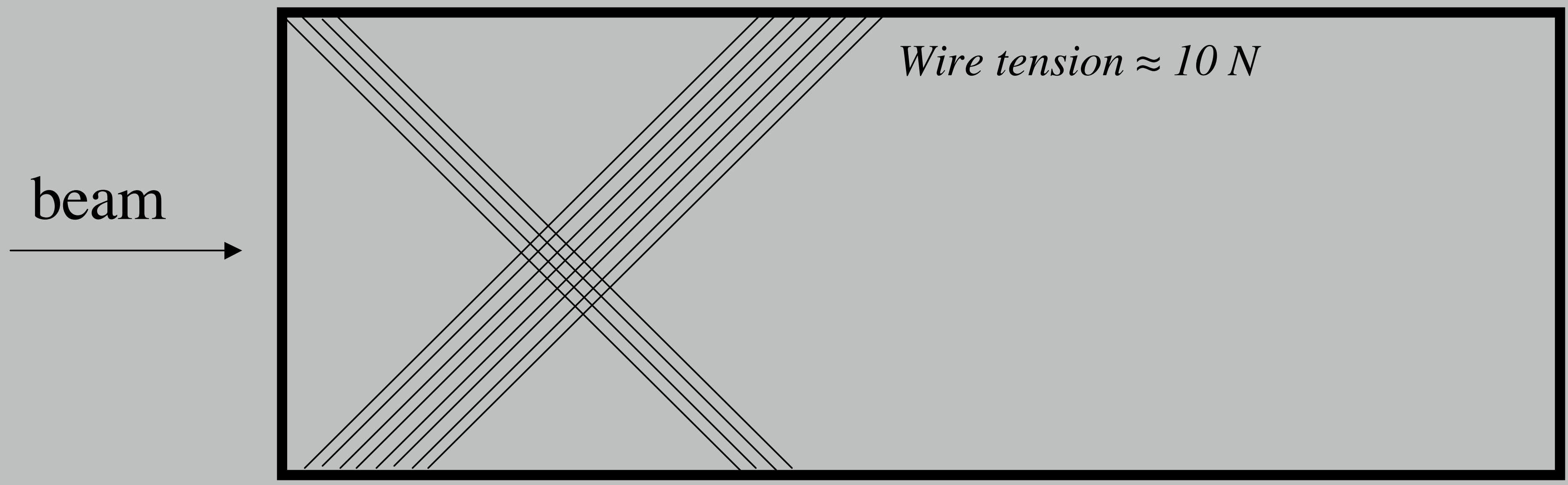


Readout chamber

<u>*Baseline assumptions:*</u>

Two wire planes, ±45°, ***<u>3 mm pitch</u>****, ϕ 150 μm*

Wire tension ≈ 10 N



3535 wires

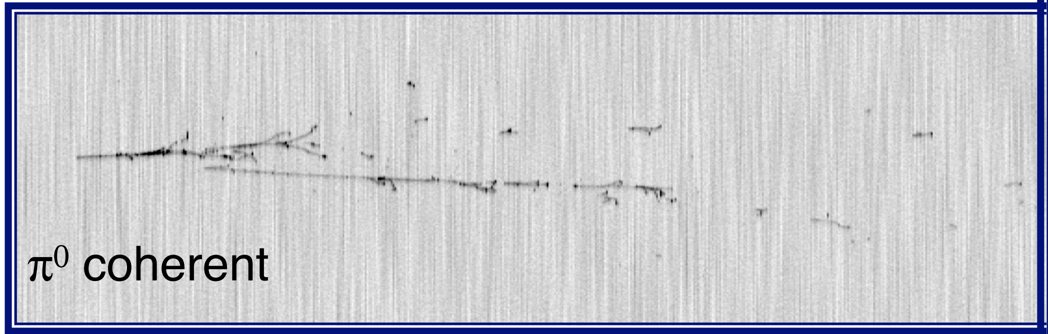
7071 wires in total

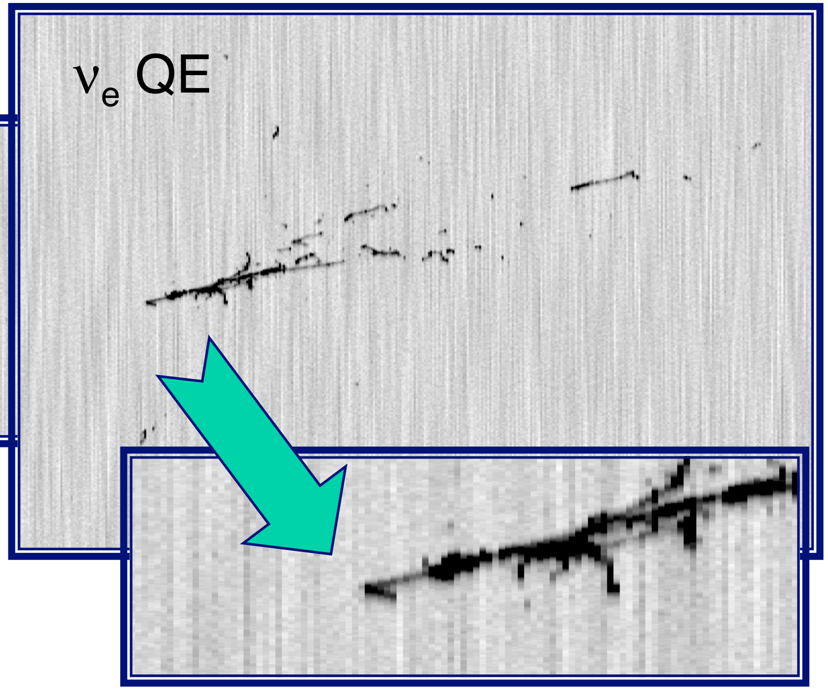
2121 long
1414 short

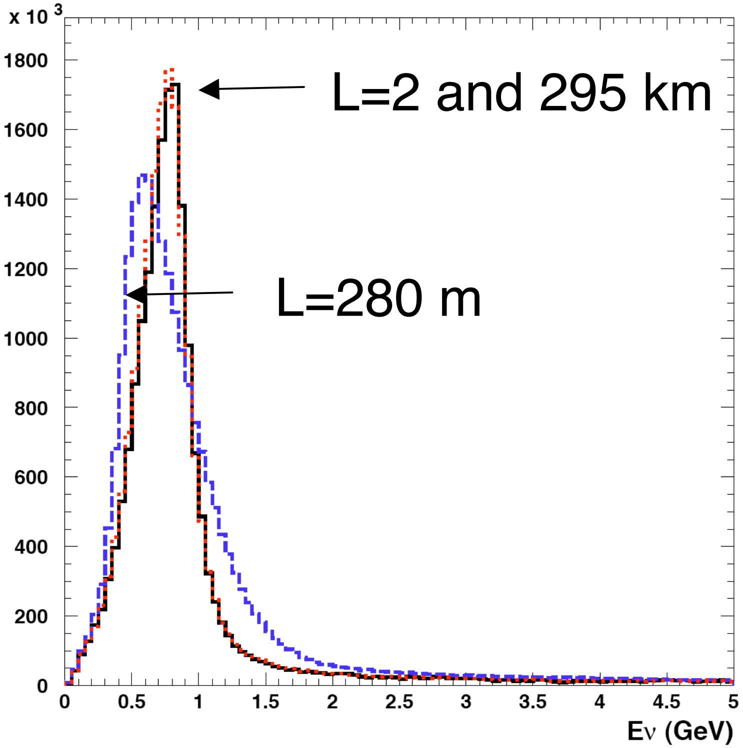
221 units of 32 wires

Example of simulated neutrino interactions:

full simulation, digitization, and noise inclusion







100 ton @ L=2000 m

Beam	E_{peak}(GeV)	ν_μ	ν_e
OA2	0.7	300000/yr 0.1/spill	5800/yr 45/day

A 100 ton liquid argon TPC at T2K: why and how?

- There is strong interest in the physics program of T2K by European collaborators who are willing to provide a sensible contribution to the project

- A 100 ton liquid Argon TPC provides an ideal “fine-grain” detector at the 2km position with a O(100K events/yr) statistics

- The LAr TPC combines tracking (event topology, proton, …) AND calorimetry (electrons, π^0, …) in a homogeneous, isotropic and fully active medium. Reconstruction biases are small, many times negligible.

- The mass scaling properties of the LAr TPC make it conceivable to maintain the high granularity ($\approx 0.02X_0$ sampling) and reach a fiducial mass of 100 tons

- Further optimization of geometry, granularity ($< 0.02X_0$?), etc. should driven by physics requirements and space limitations in underground hall

- Possibility to consider LAr in connection with Water Cerenkov target should be physics driven: LAr “standalone” or “embedded” ?

- This detector would be very relevant for an HK phase

Example of physics items (I)

- **Measurement of ν_μ CC events**
  - ➥ Provide independent measurement of “off-axis near” flux
  - ➥ Excellent muon identification makes selected sample clean
  - ➥ Unbiased reconstruction
  - ➥ Low detection threshold in LAr compared to WC allows for an independent classification and measurement of event samples in the GeV region
    - ☛ Independent systematic on nQE/QE ratio
    - ☛ Independent systematic on energy scale
  - ➥ Systematic in extrapolation of 1 kton WC to SuperK
    - ☛ Independent study of reconstruction effects in WC with recorded events in LAr
  - ➥ Energy independent detection and measurement efficiency for SubGeV and MultiGeV events
    - ☛ High efficiency measurement of high energy muon neutrinos from kaon decays to provide extra handle on ν_e component of the beam

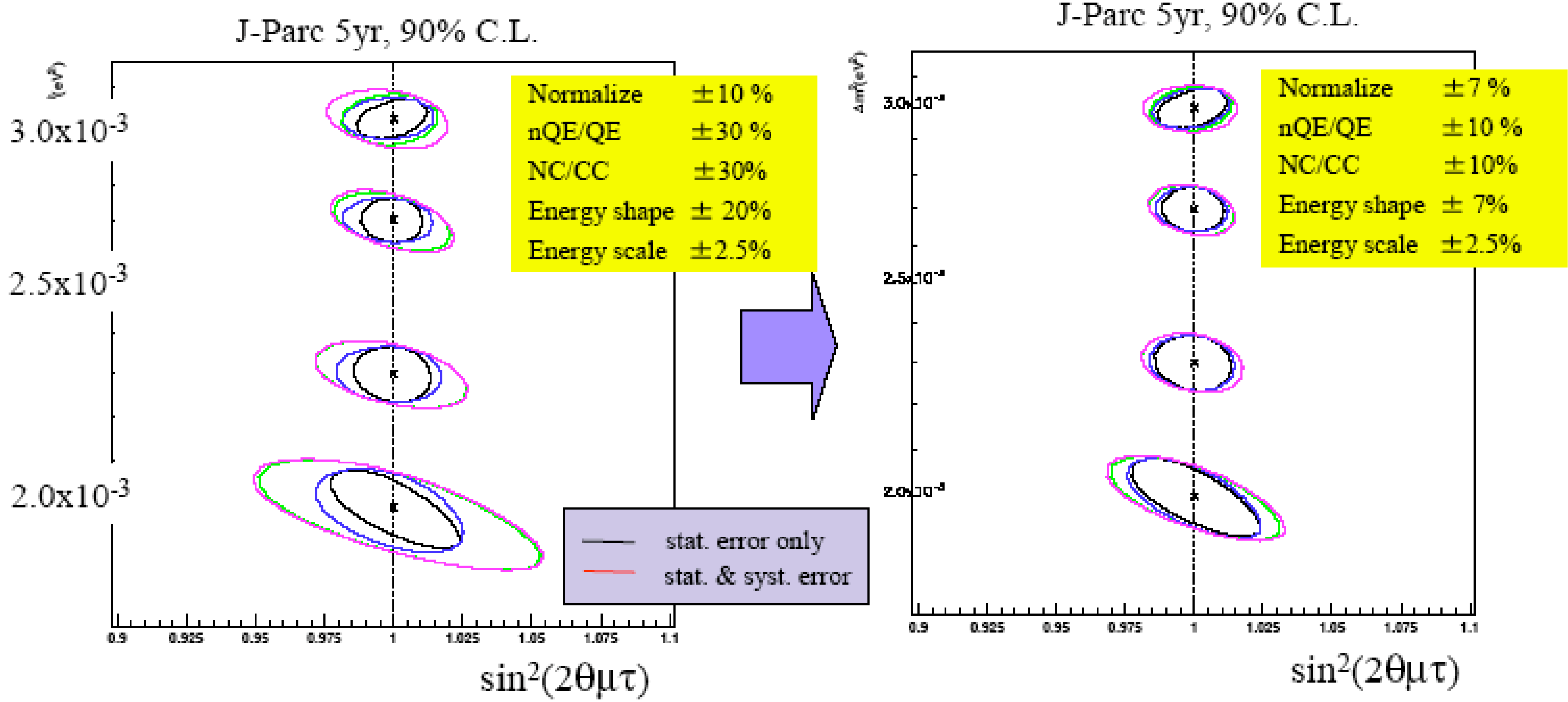
Example of physics items (II)

- **Measurement of ν NC events**
  - Clean measurement of π^0 production thanks to event and particle identification
    - Independent systematic on NC/CC ratio
    - Independent measurement of coherent π^0 production (look for absence of tracks at vertex)

- **Measurement of intrinsic ν_e CC events**
  - Excellent event and particle identification giving clean e/μ and e/π^0 separation
  - Unbiased reconstruction
    - Independent measurement of ν_e contamination, well separated from π^0 background
    - Combined with NC background gives independent and separated components ν_e and π^0 background at far detector

- **"Standard model" neutrino interactions in the GeV region**
  - Bubble-chamber like imaging
    - DIS+resonances modeling, QE modeling
    - Binding, Fermi-motion, Pauli-exclusion, NN-correlations PDF modifications
    - Other nuclear effects (rescattering)
    - Form factors

Effect of systematic errors

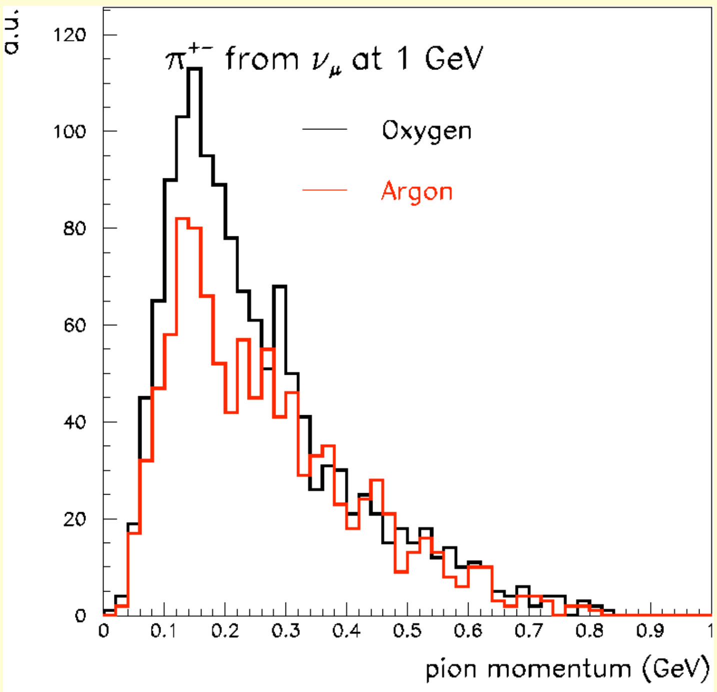


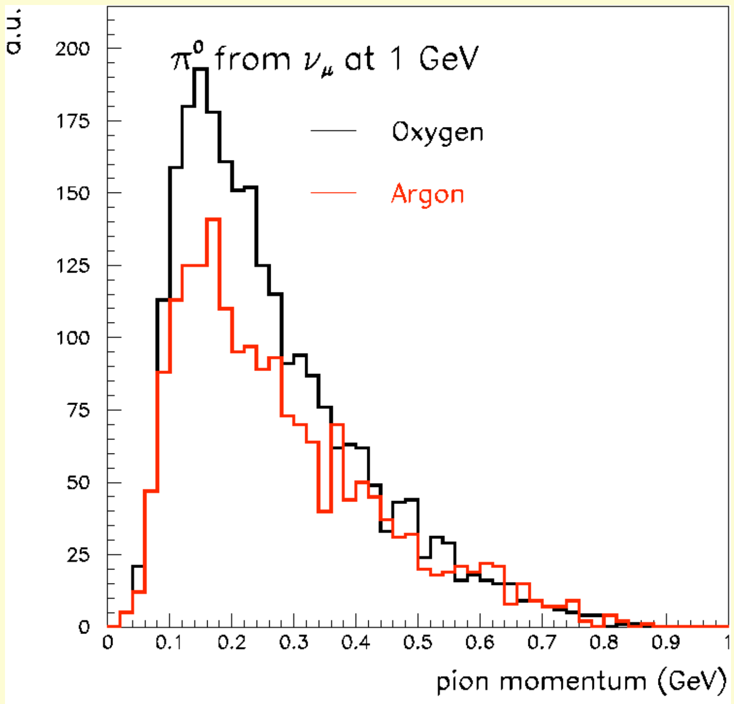
- Larger systematic error affects precise measurement of oscillation parameters
- Reducing systematic errors is important (especially for low Δm^2)

K. Okumura (KEK, Jan 2004)

Possible systematics from nuclear effects ?

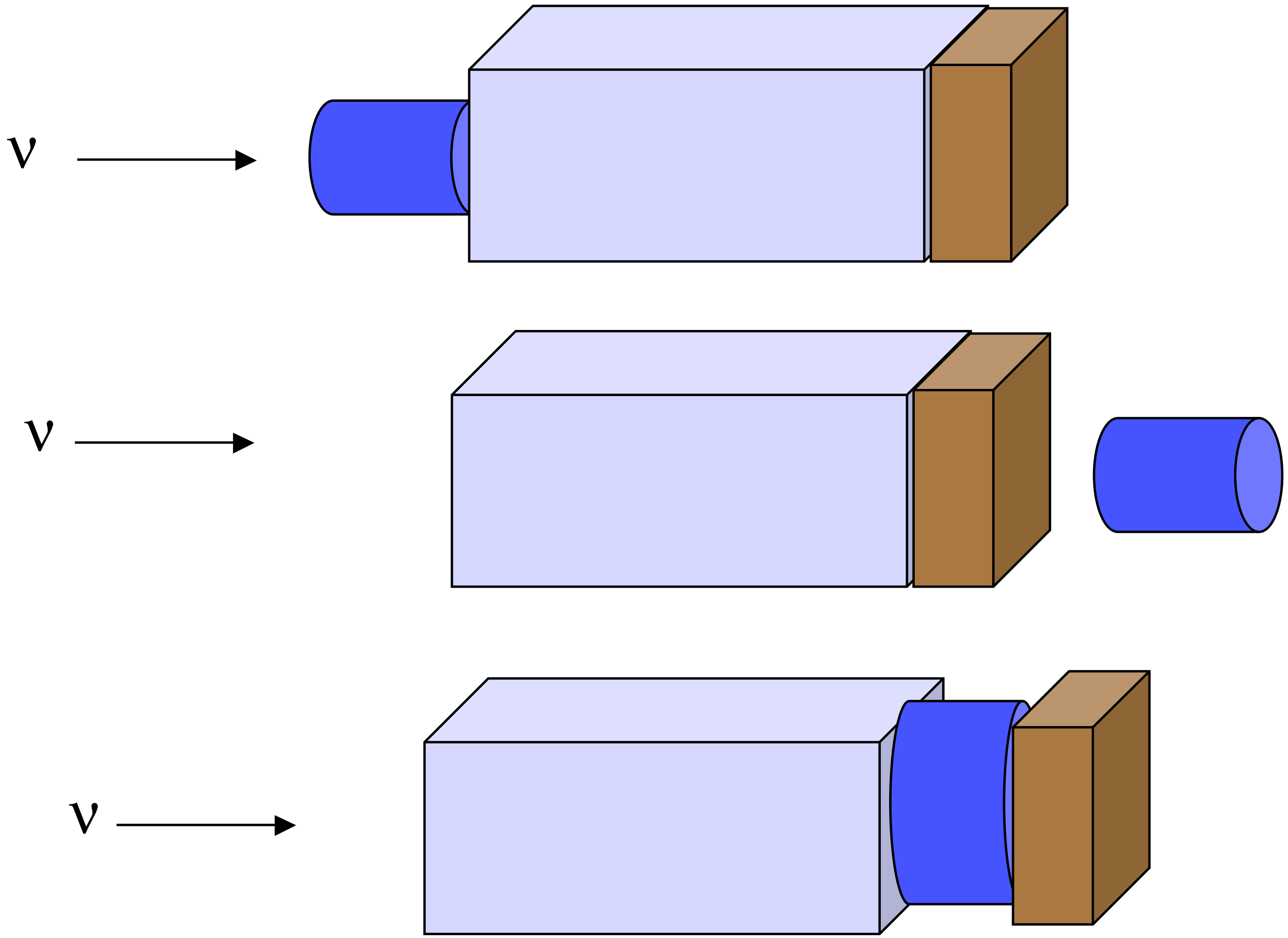
- Extrapolation from Water to Argon targets
  - ➥ How big is this effect and how to control it?
  - ➥ For pion absorption, effect is expected to scale like $A^{1/3}$
    - ☛A 30% correction on absorption rate
- Consider possibility to insert water target (ice) within liquid Argon volume
- Might require some preliminary measurements where water and argon target can coexist





Geometry optimization: stand-alone or embedded?

- Various options can be considered



A: “stand-alone”

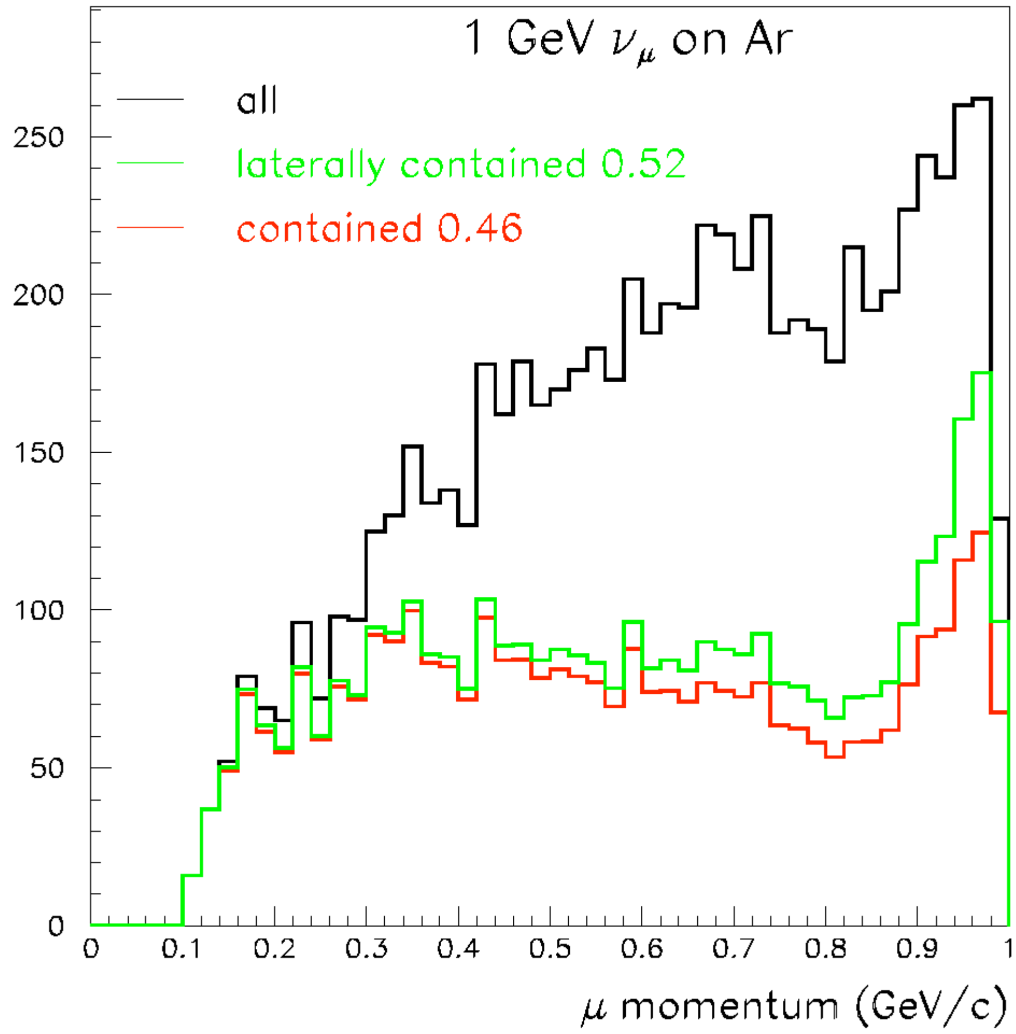
B: “stand-alone”

C: “embedded”

Study by C. Walter

Geometry optimization: muon measurement

- Fiducial 2.4x2.4 m^2
- Monoenergetic neutrinos E=1 GeV
- 46% of muons are fully contained (stop inside LAr)
  - ➥ Kinetic energy error < 3%
- Escaping muons can still be identified and measured
  - ➥ Multiple scattering
  - ➥ dE/dx method
  - ➥ Momentum error ≈30%

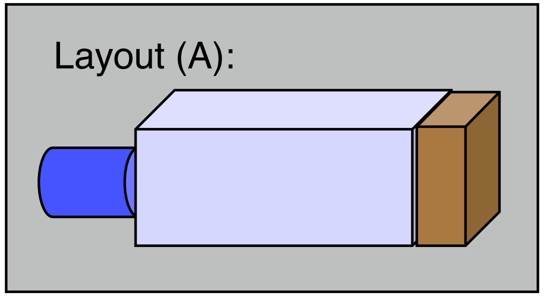


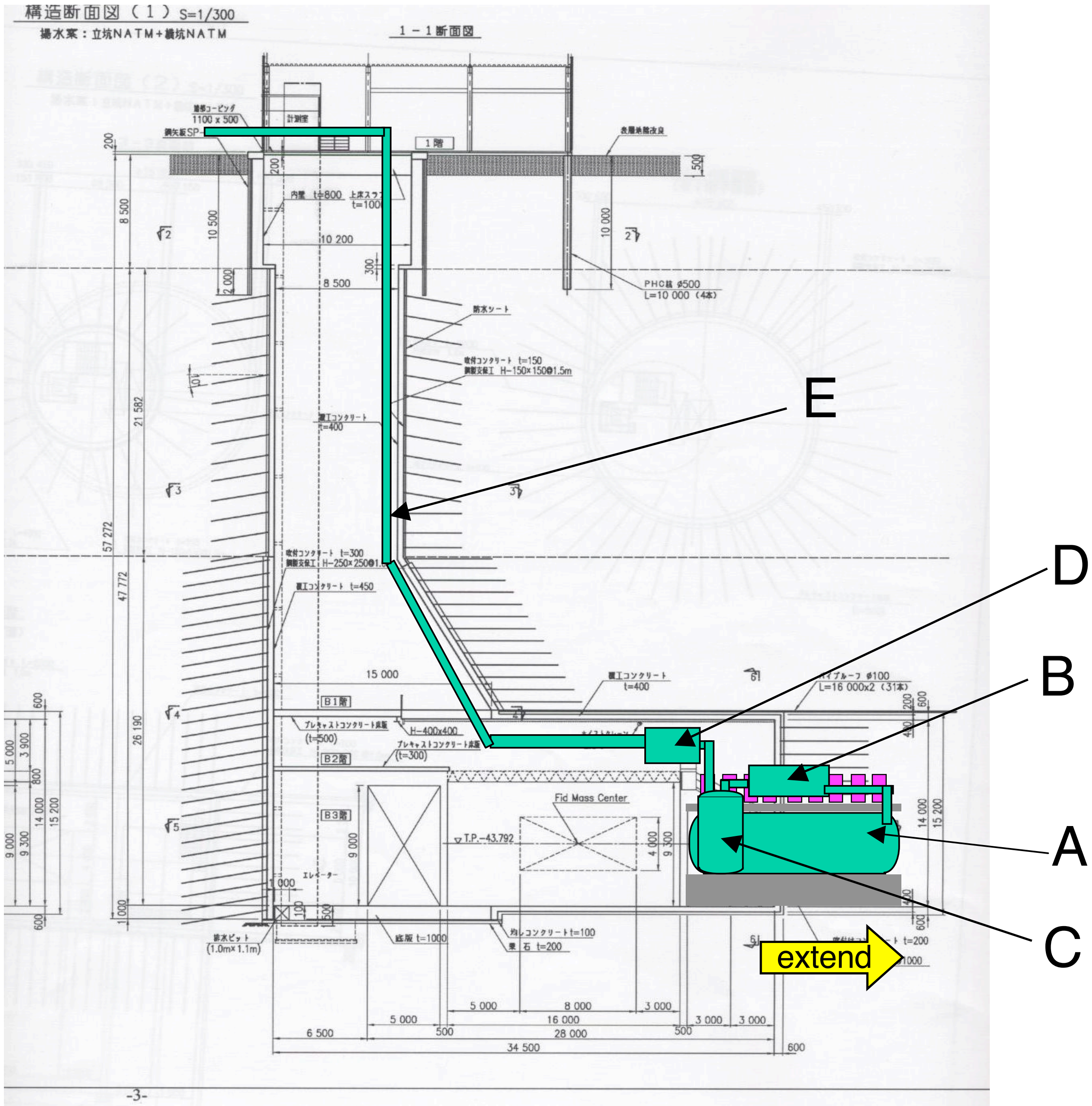
Preliminary considerations for installation at 2 km site

Warning: Boundary conditions set by cavern geometry not yet taken into account !

A tentative schematic on space requirement (I)

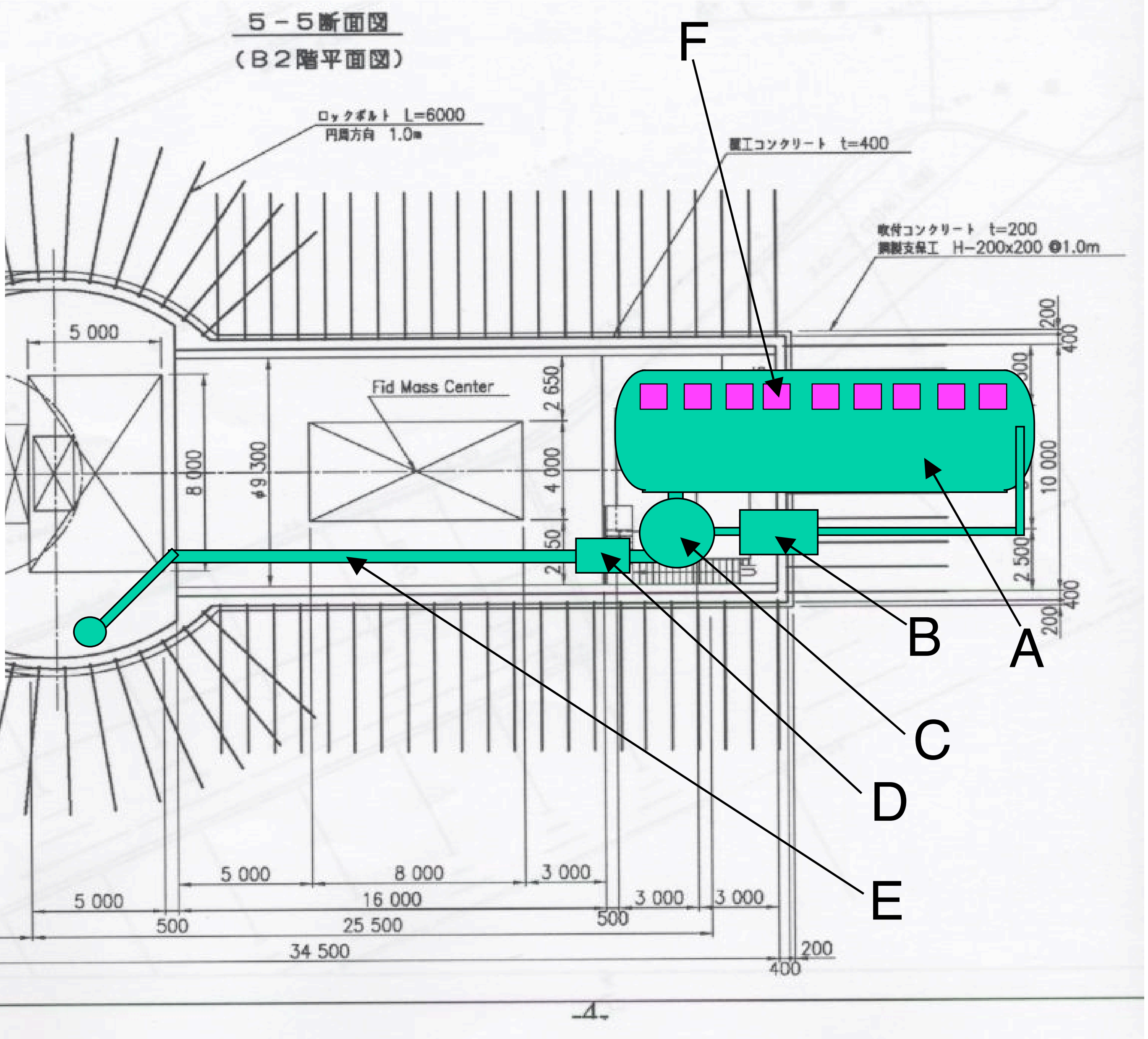
A: Detector dewar
B: LAr Purification
C: Buffer
D: Heat exchanger and expansion valve
E: Argon pipes



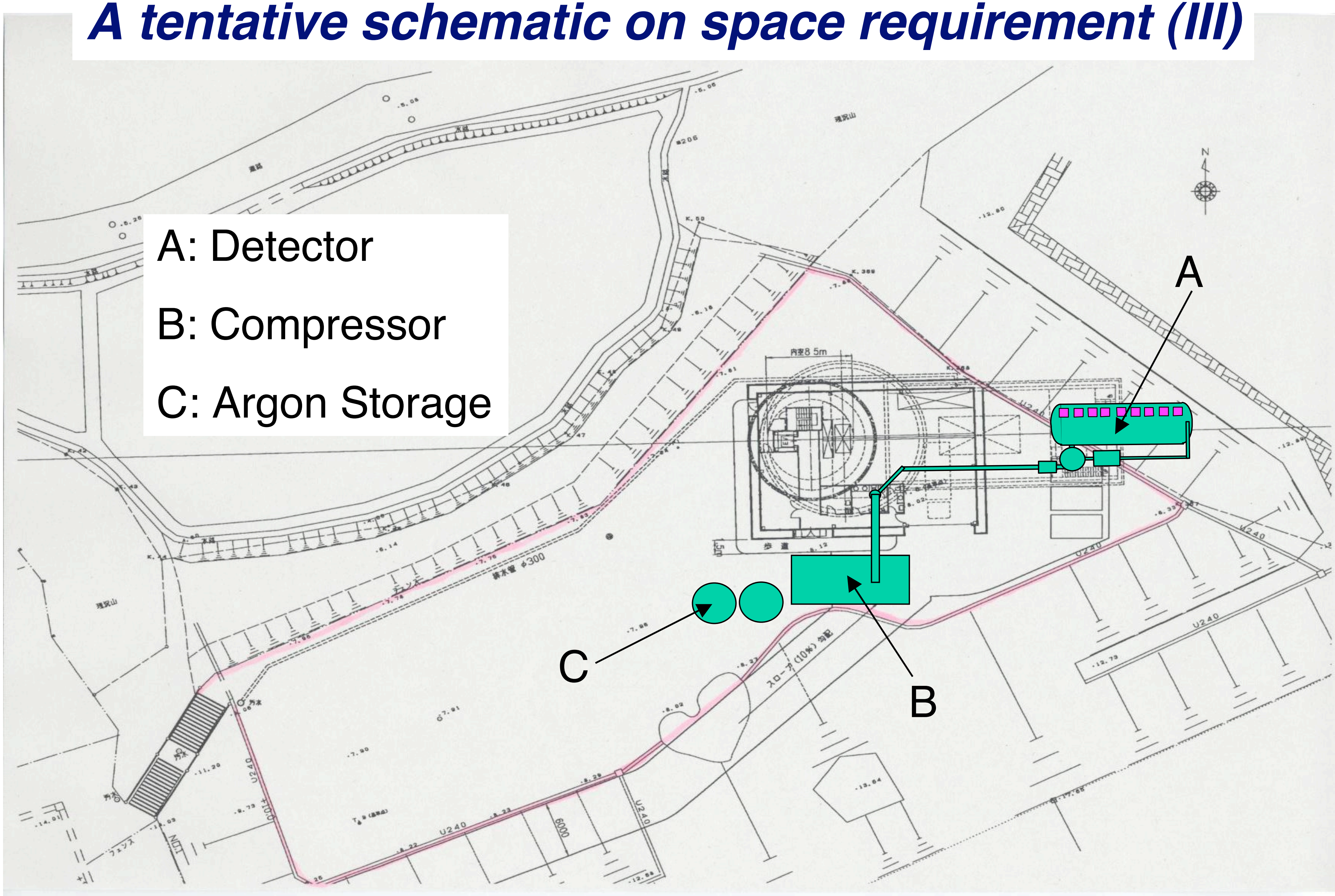


A tentative schematic on space requirement (II)

- A: Detector
- B: LAr Purification
- C: Buffer
- D: Heat exchanger and expansion valve
- E: Argon pipes
- F: Electronics Racks

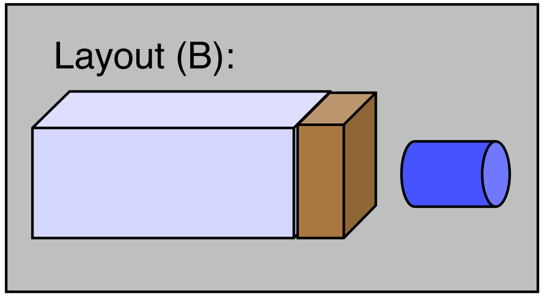


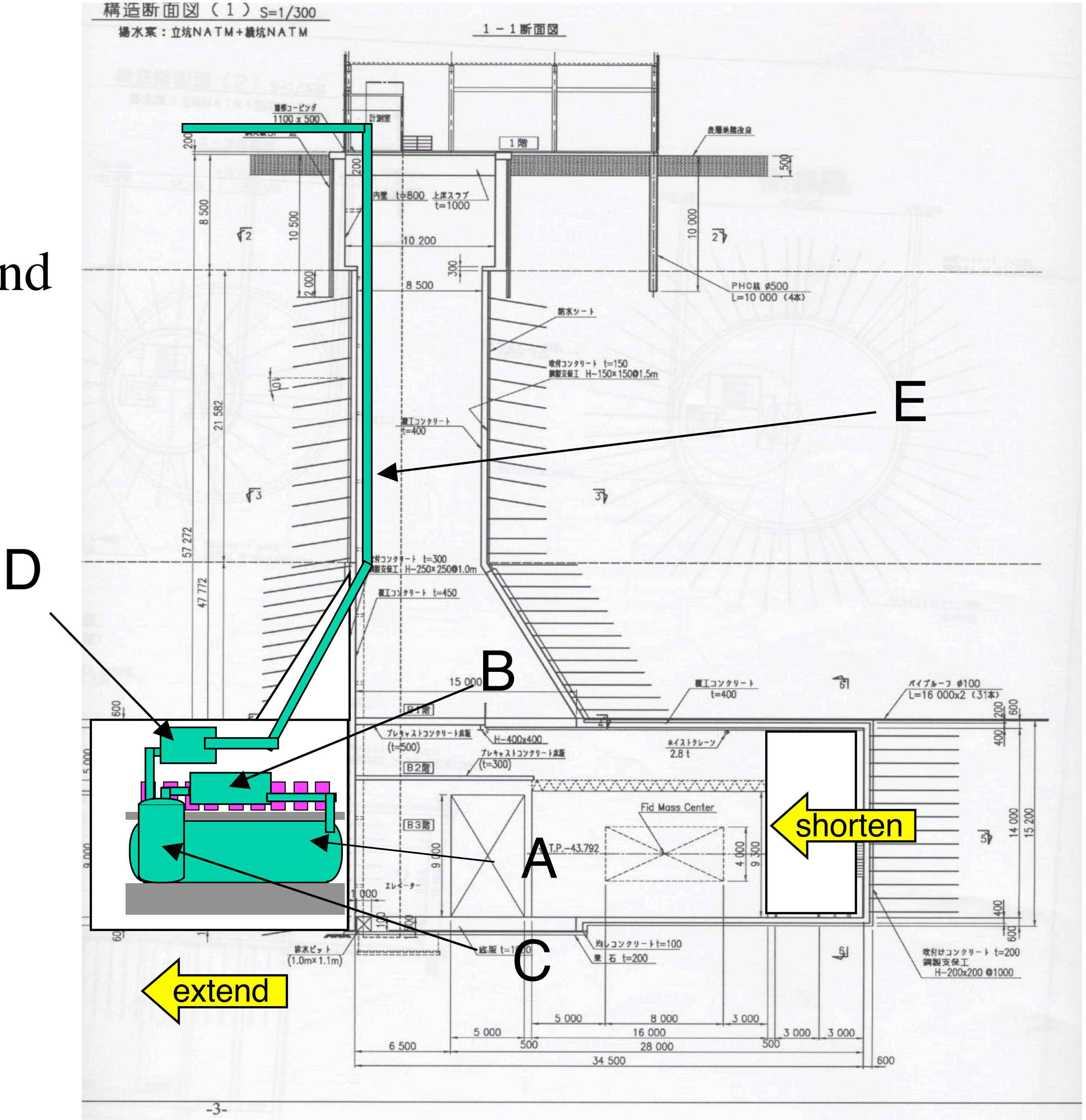
A tentative schematic on space requirement (III)



A tentative schematic on space requirement (IV)

A: Detector dewar
B: LAr Purification
C: Buffer
D: Heat exchanger and expansion valve
E: Argon pipes





Strategy for T2K participation

- There is strong interest in the physics program of T2K
  - ➥ Switzerland has already defined T2K as a point of interest for the step beyond CNGS (wide consensus among Swiss neutrino physicists)
  - ➥ Similar scenarios in other European countries

- The idea of a 100 ton liquid Argon is seen as a way to reinforce the European contribution to T2K
  - ➥ Discussions with funding agencies to officially join the T2K Collaboration

- A support for a participation in T2K would allow to define the necessary steps before the start of the physics program
  - ➥ Finalize physics studies (e.g. LAr “stand-alone” or “embedded” ?)
  - ➥ Optimize detector mass and geometry
  - ➥ Formalize design work
  - ➥ Allow for requests of resources to develop prototype and detector
  - ➥ Allow to consider preliminary measurements in existing beams

Outlook

- The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration.

- There is a strong interest for applications at two different mass scales, with important synergies:
  - ≈ 100 ton: systematic study of neutrino interactions, near detectors at LBL facilities
  - ≈ 100 kton: proton decay, high statistics astrophysical & accelerator neutrinos

- A 100 ton detector in a near-site of the T2K facility is a straight forward and very desirable application of the technique. It would provide clean and independent measurements with complementary systematics at the 2 km position.

- The 100 ton detector has a close synergy with a large 100 kton underground liquid argon detector whose design is being developed based on LNG cryogenic self-refrigerated (boiling) tanker, bi-phase operation for very long drifts with charge imaging, scintillation and Cerenkov light readout. R&D is on-going to ascertain the technical feasibility and performance of this design. A 10% full-scale, cost-effective prototype could be envisaged as an engineering design test with a physics program on its own.