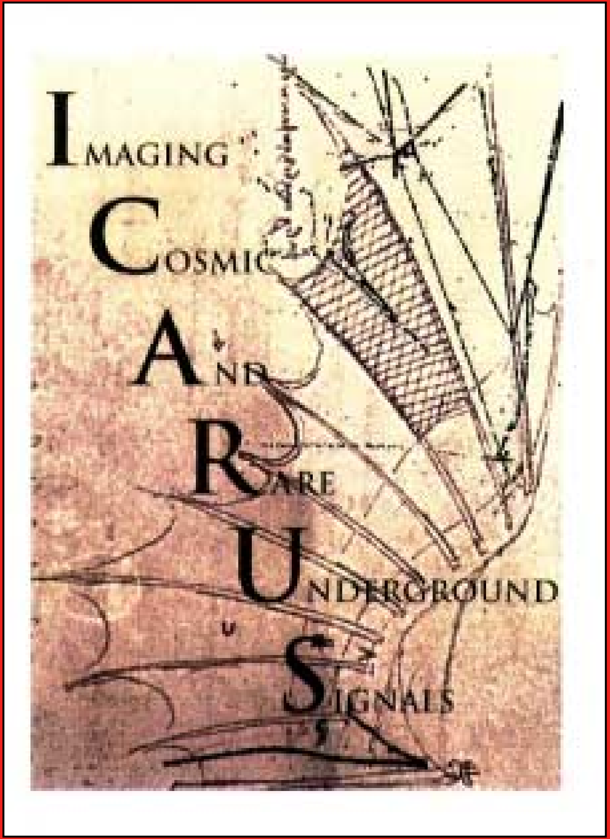

The ICARUS Project

CERN

China
IHEP

Italy
Aquila, LNGS, Milano, Padova, Pavia, Pisa, Torino

Switzerland
ETH/Zurich

Poland
Katowice, Krakow, Warszawa, Wroclaw

USA
UCLA

André Rubbia
ETH Zürich

SNOW in Uppsala

8th-10th February, 2001

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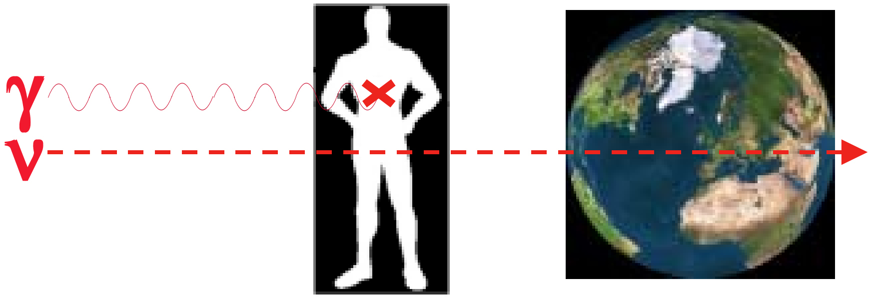
Neutrino and rare process physics

- The performance of a **neutrino detector** is ***proportional*** to its ***total mass*** and also to its ***geometrical granularity*** with which the events can be reconstructed.

What we get for 5 ktons:

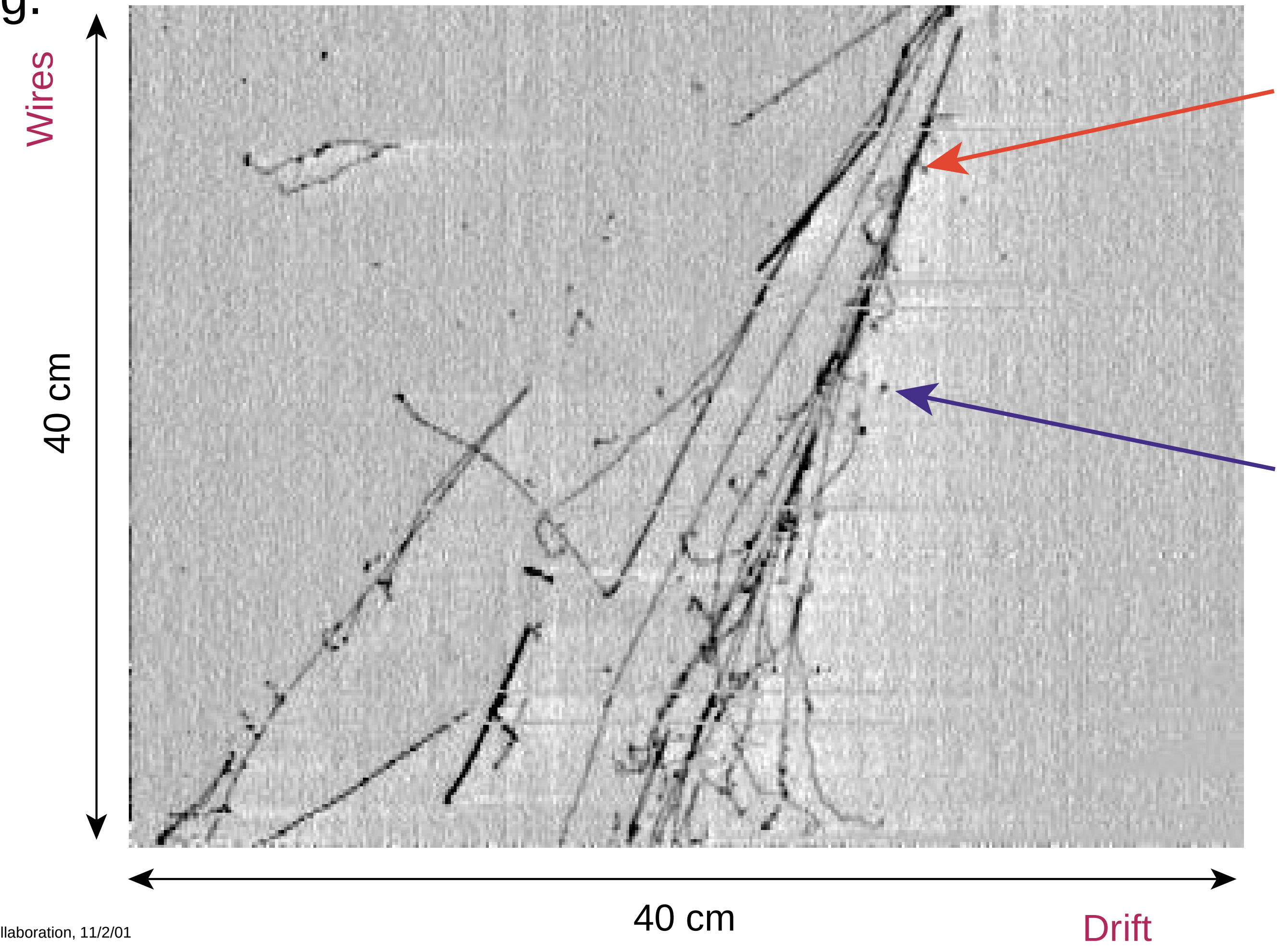


- **Atmospheric neutrinos:**
  - $\approx$**1000** atm CC events / year
  - **≈5** ν_τ CC /year from oscillations
- **Solar neutrinos:**
  - **17500×f_{8B}** solar neutrinos / year @ E > 5 MeV
- **Neutrinos from CERN (CNGS):**
  - **13600** ν_μ CC per 4.5×10^{19} pots @ L = 730 km
- **Neutrino factory:**
  - **1200** ν_μ CC per 10^{20} μ @ L = 7400 km
- **Number of targets for nucleon stability:**
  - 3×10^{33} nucleons $\Rightarrow$ **τ_p (10^{32} years) > 6 × T(yr) × ε** @ 90 C.L.

A bonus!

ICARUS liquid argon imaging TPC (I)

- The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.

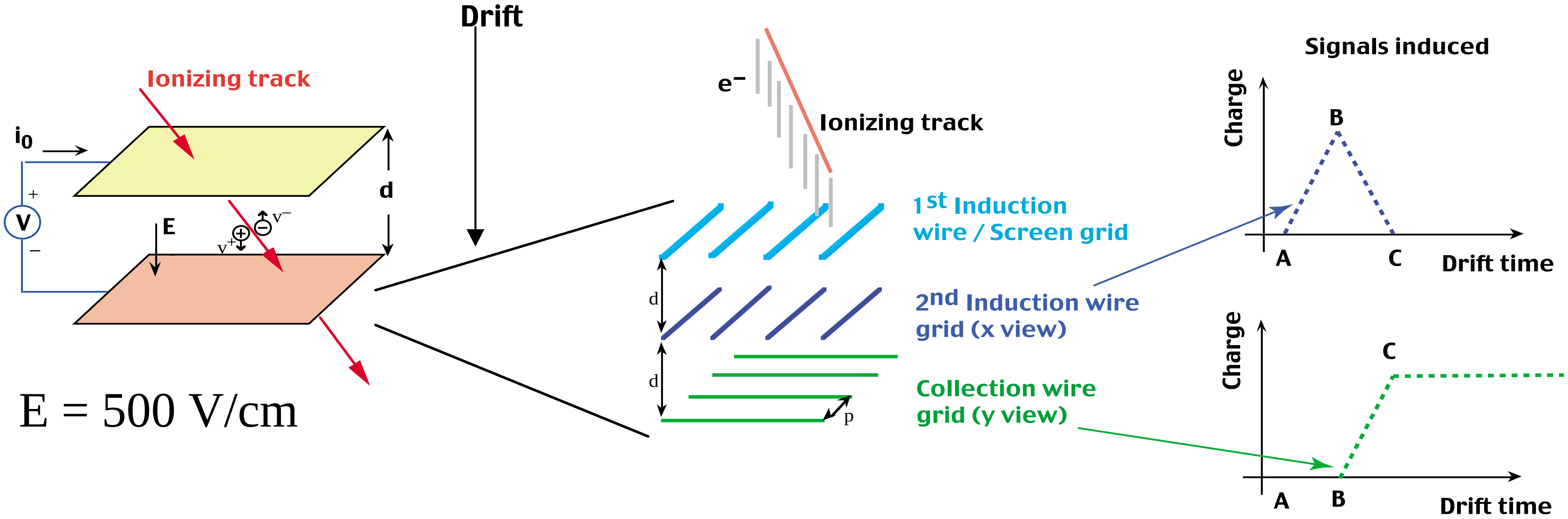


"Bubble" size ≈ 3 x 3 x 0.2 mm^3

Energy deposition measured for each point

ICARUS liquid argon imaging TPC (II)

- Detect electrons produced by ionizing tracks crossing the LAr



E = 500 V/cm

Electron–ion pairs are produced
Electrons give the main contribution to the induced current due to the much larger mobility

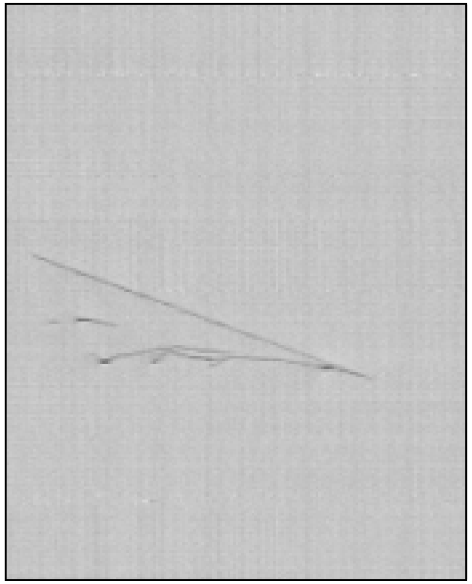
$$I_0 = e(v^+ + v^-)/d$$

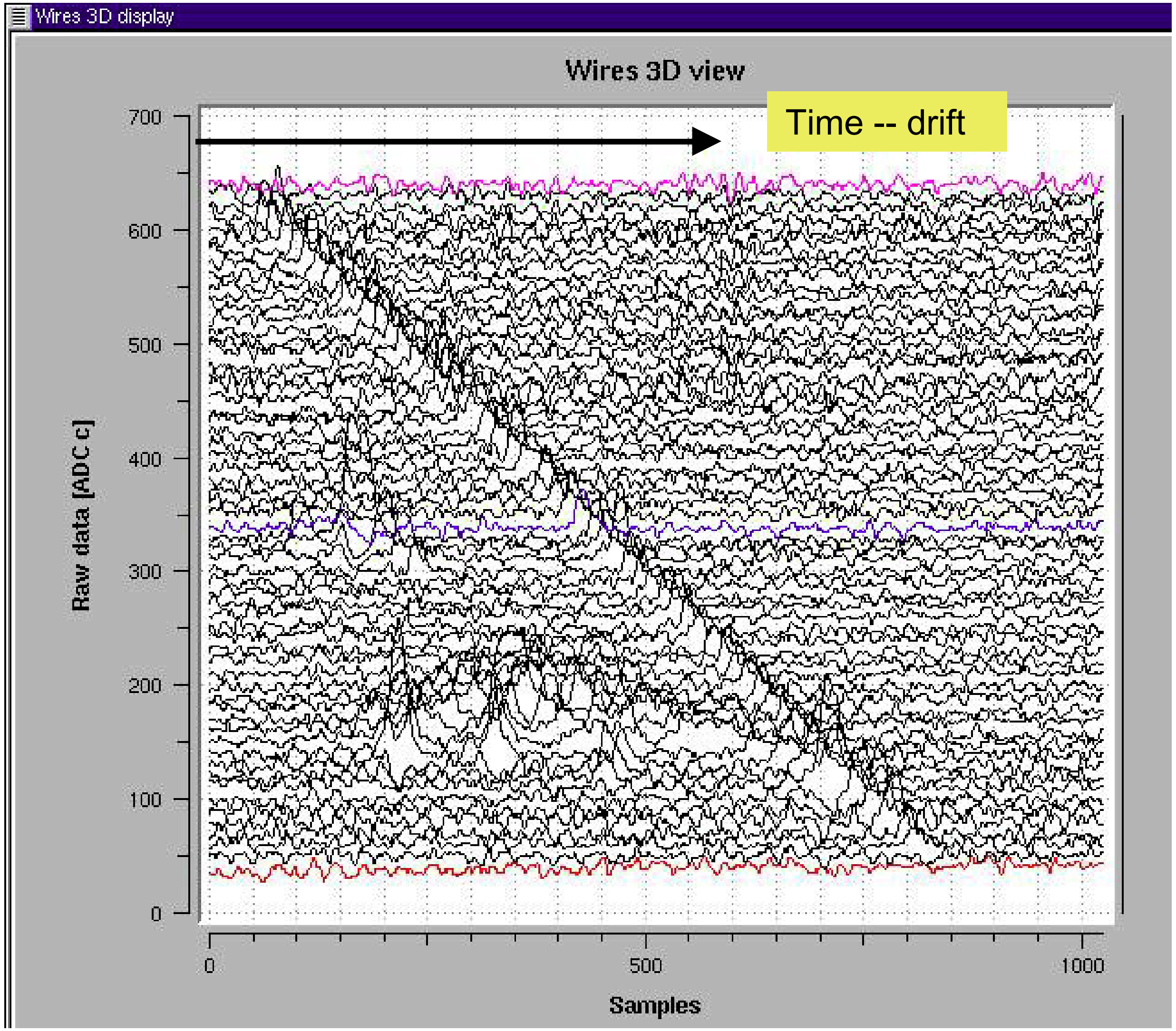
A set of wires at the end of the drift give a sampling of the track
No charge multiplication occurs near the wires Ë electrons can be used to induce signals on subsequent wires planes with different orientations ⇒ 3D imaging

ICARUS liquid argon imaging TPC (III)

Detector is continuously sensitive, thus allowing to easily simultaneously collect atmospheric, CNGS and other rare events...

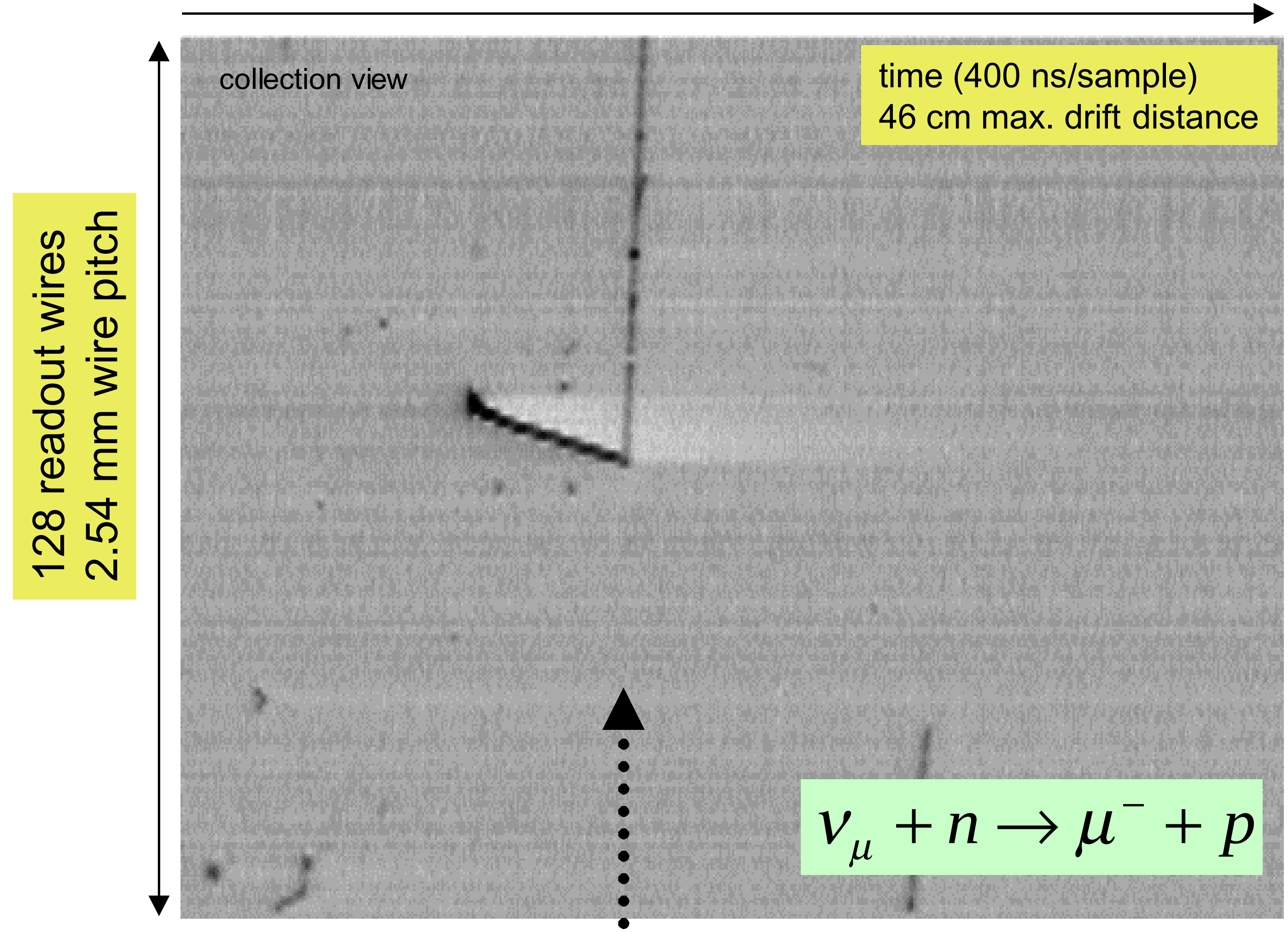
Real event from 15 ton





Neutrino event in 50 liter LAr TPC (1998)

ICARUS-CERN-Milano



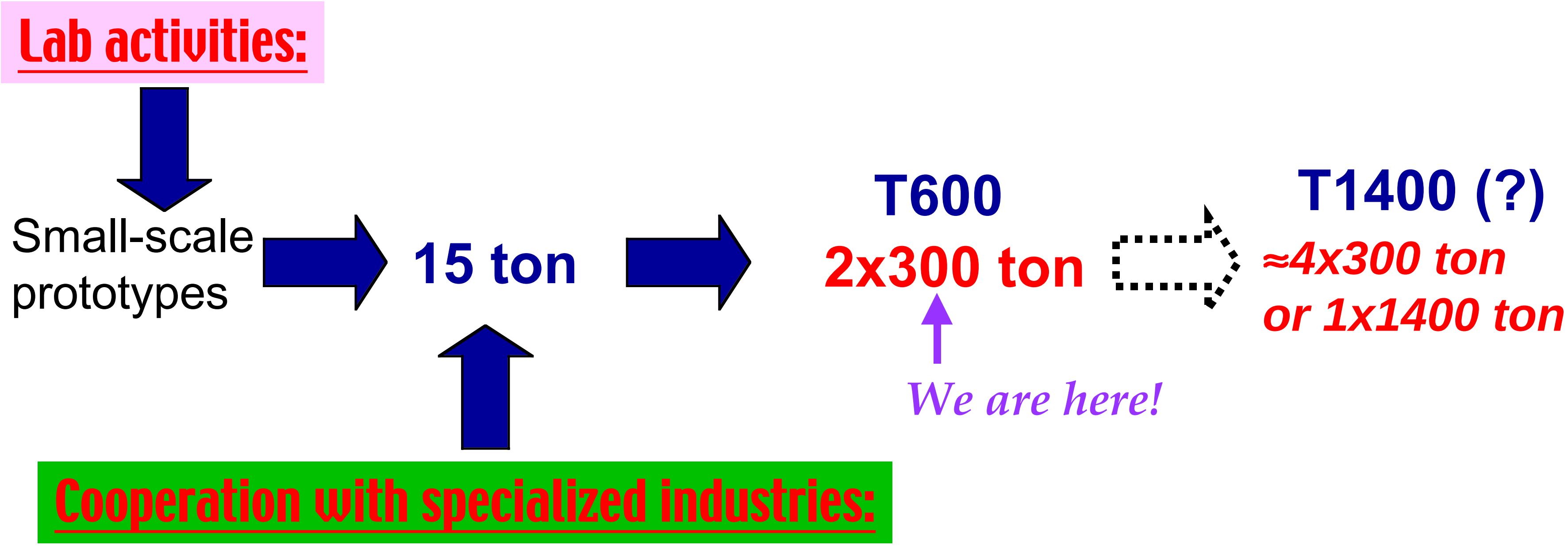
$$\nu_\mu + n \rightarrow \mu^- + p$$

CERN ν-beam

(Chamber located in front of NOMAD detector)

ICARUS: a graded strategy

✓ **After several years of R&D and prototyping, the ICARUS collaboration is now realizing the first 600 ton module, which will be installed at Gran Sasso in the year 2001.**



Lab activities:

Small-scale prototypes

15 ton

T600

2x300 ton

We are here!

T1400 (?)

≈4x300 ton or 1x1400 ton

Cooperation with specialized industries:

→ **Air Liquide** for Cryostat and Argon purification

→ BREME Tecnica for internal detector mechanics

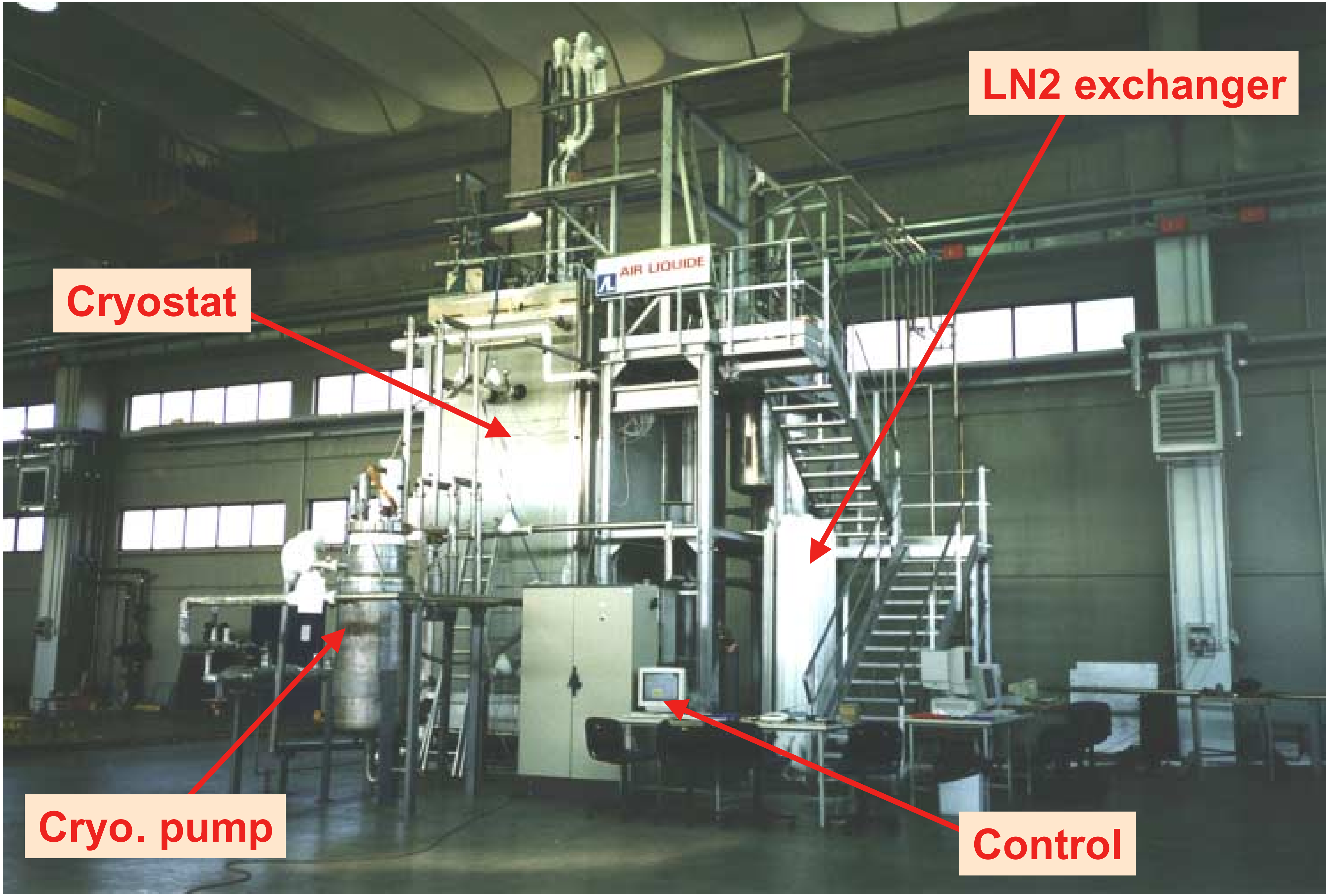
→ CAEN for readout electronics

ICARUS 15 ton (10m^3) prototype (1999-2000)

- A major step of the R&D program has been the construction and operation of a ***10m^3 prototype***
  - ① ***Test of the cryostat technology***
  - ② ***Test of the "variable-geometry" wire chamber***
  - ③ ***Test of the liquid phase purification system***
  - ④ ***Test of trigger via scintillation light***
  - ⑤ ***Large scale test of final readout electronics***

➜ First operation of a 15 ton LAr mass as an actual "detector"

T15 installation @ LNGS (Hall di Montaggio)



LN2 exchanger

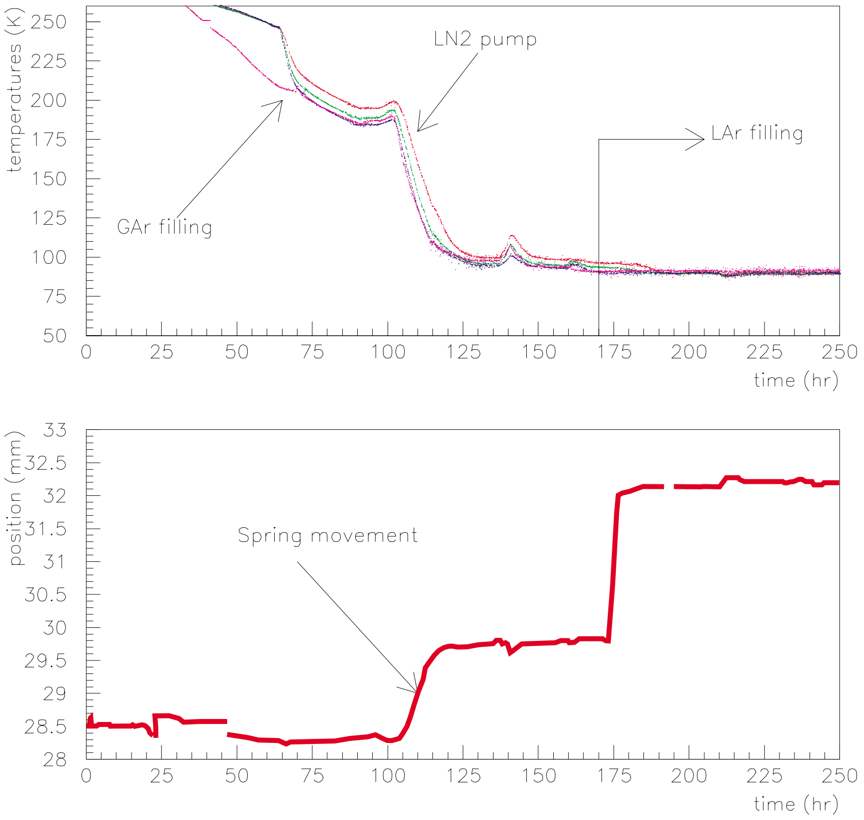
Cryostat

Cryo. pump

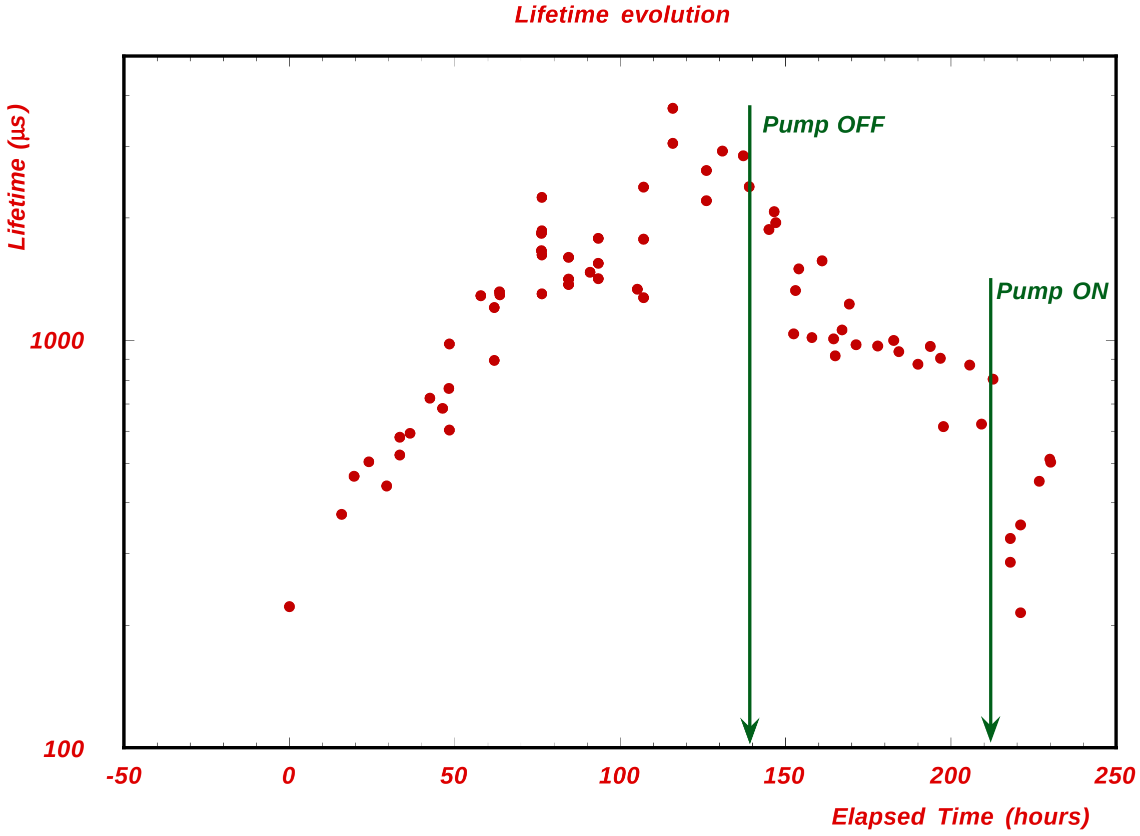
Control

Cooling 15 ton prototype March '99

Temperature / Wire stretching



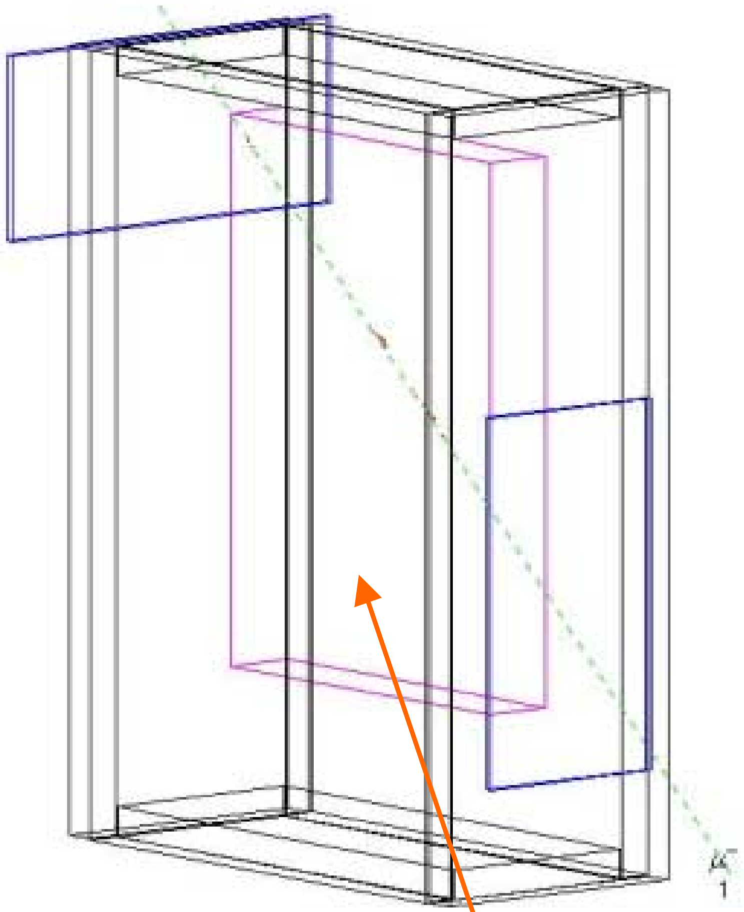
LAr purity



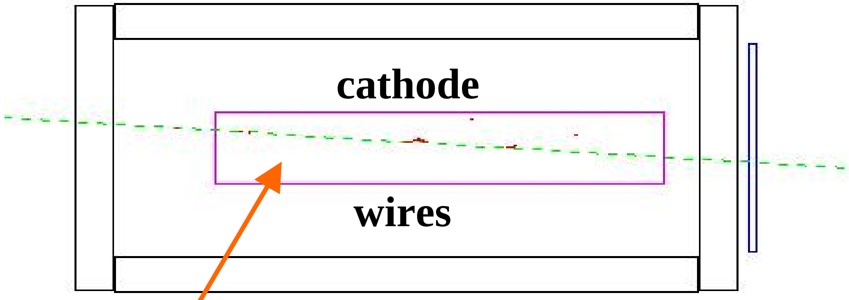
- ✖ Confirmation of the functionality of the *variable geometry* mechanics

- ✖ **The electrons lifetime, after about 4 days of recirculation, was between 2 ms to 3 ms.**

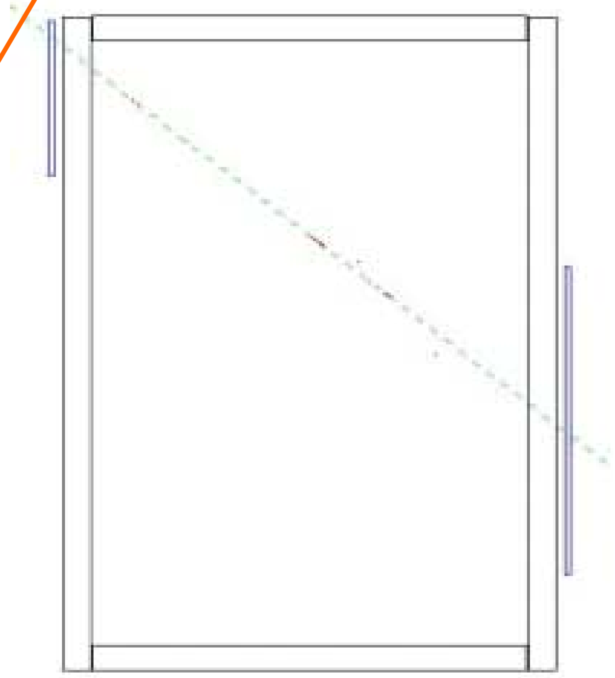
Internal Volumes Layout



Top View



Lateral View

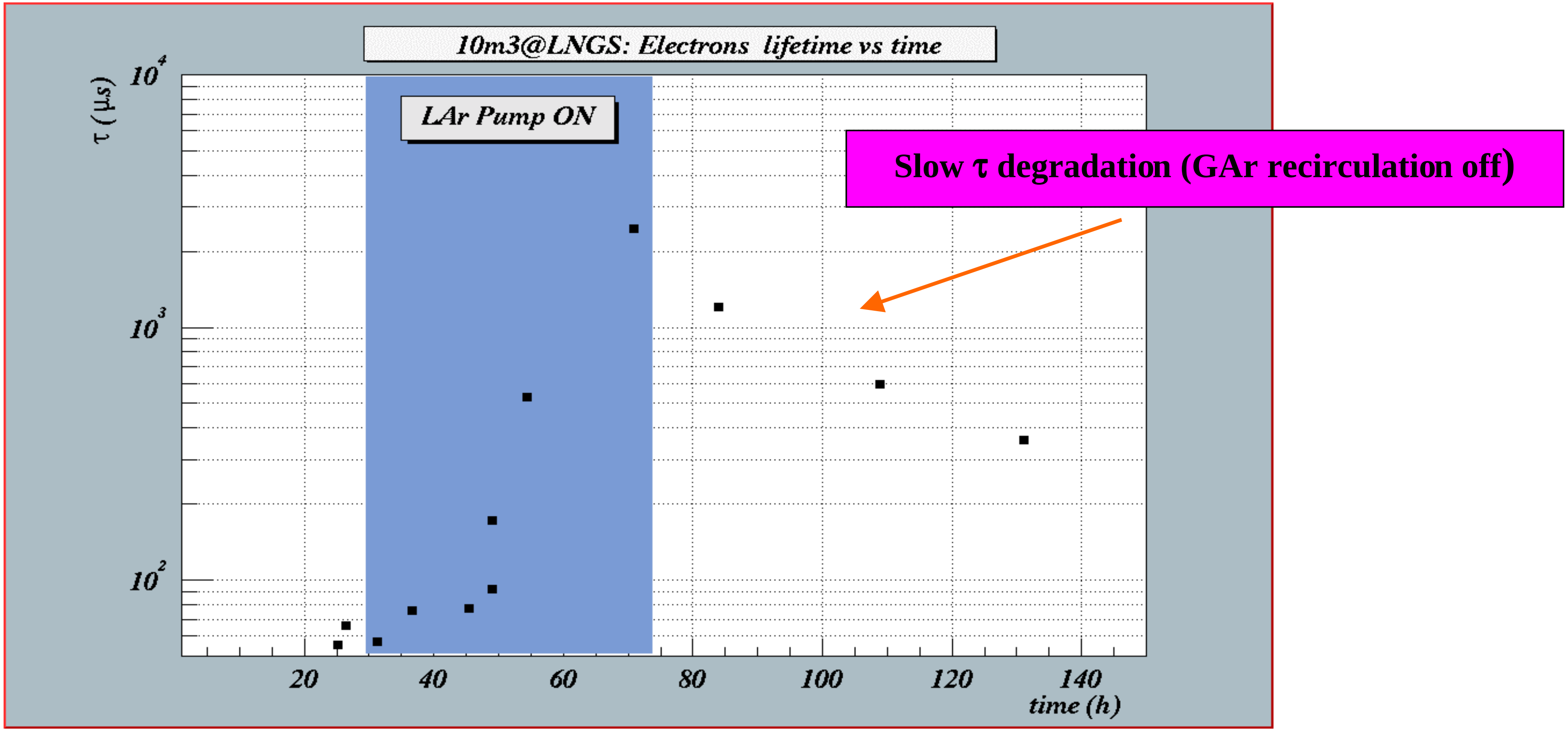


Imaging region (35 cm drift)

External trigger

Electron Lifetime Measurements

- Just after LAr filling: $\tau \sim 100 \mu s$, according to expectations based on residual leak rates (10^{-5} mbar/s).
- In a few days of LAr pump operation: $\tau > 2$ ms

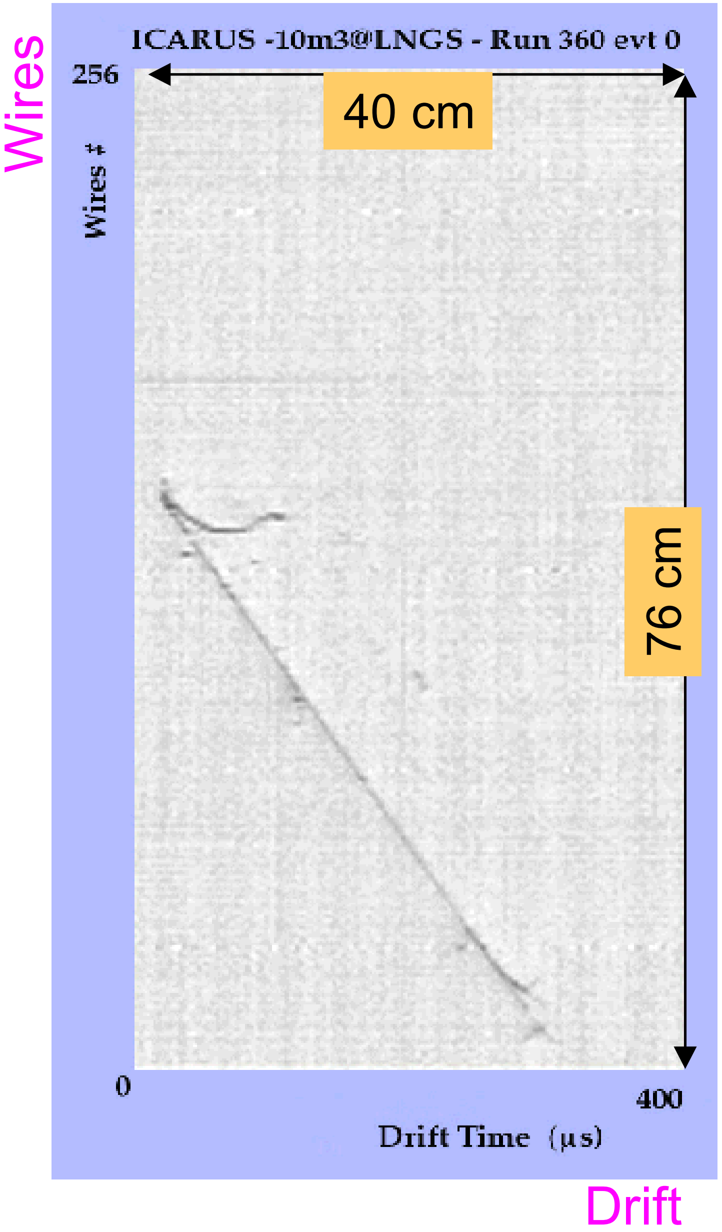


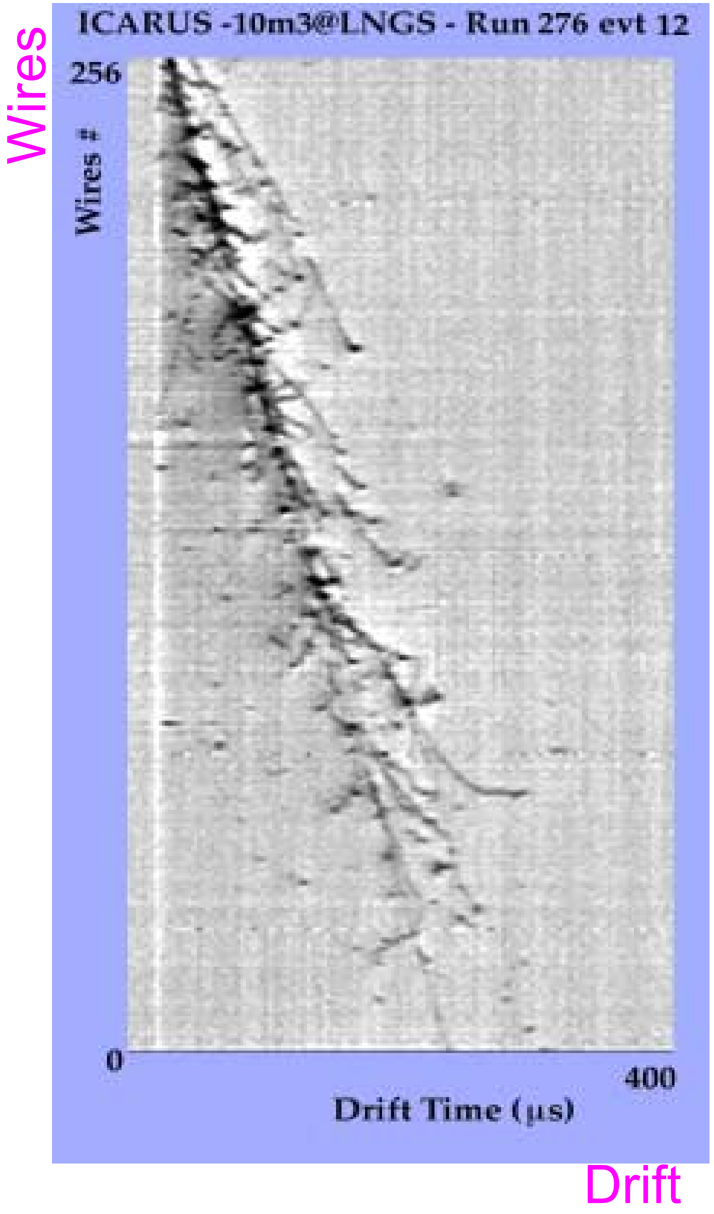
Slow τ degradation (GAr recirculation off)

Tracks in 15 ton prototype

$10m^3$ Module
at LNGS

Cosmic Ray tracks recorded during the $10\ m^3$ operation



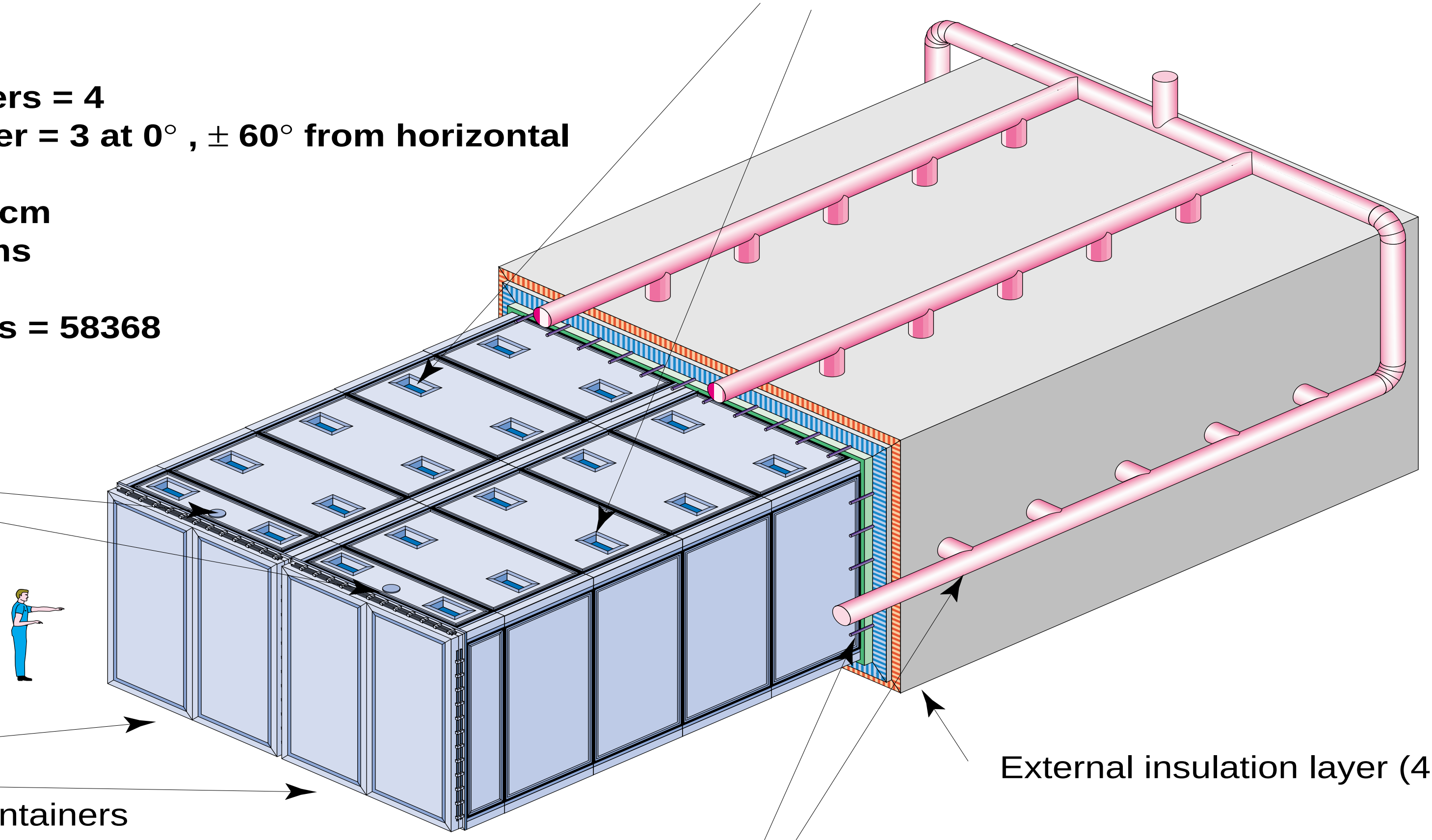


The ICARUS T600 module

Under construction

Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m
Total (cold) Internal Volume = 534 m^3
Sensitive LAr mass = 476 ton

Number of wires chambers = 4
Readout planes / chamber = 3 at 0° , ± 60° from horizontal
Maximum drift = 1.5 m
Operating field = 500 V / cm
Maximum drift time ≈ 1 ms
Wires pitch = 3 mm
Total number of channels = 58368



Signal feedthroughs

HV feedthroughs

2 independent aluminum containers each one transportable inside the GS Laboratory

LN2 cooling circuit

External insulation layer (400 mm)

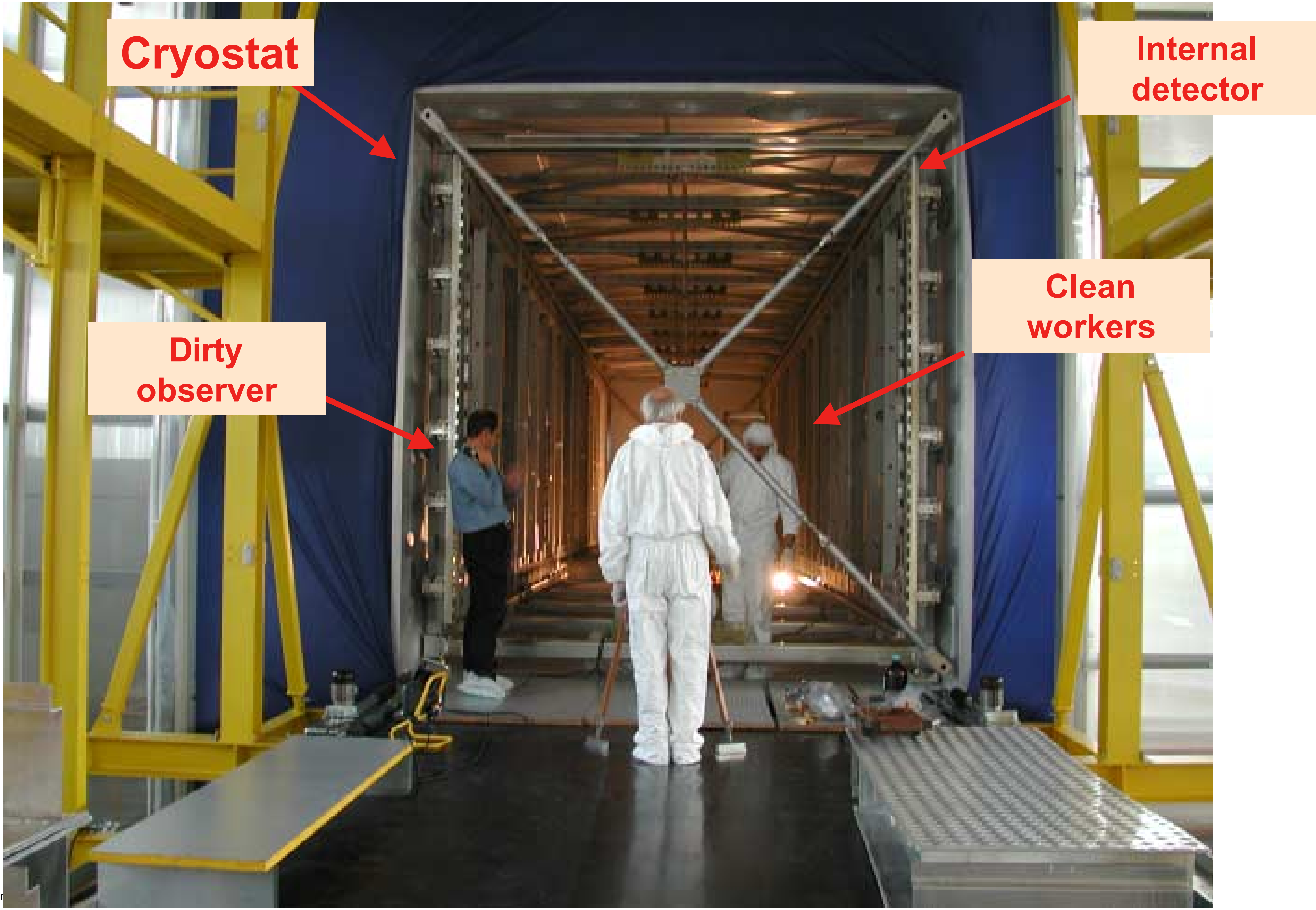
André Rubbia, ETH/Zürich, ICARUS Collaboration, 11/2/01

T600 assembly schedule

- Completed ***site preparation*** in Pavia for the T600 cryostat (***Nov 1999***)
  - → “clean room”, “assembly island”, floor, ...
- Delivery of the ***1st cryostat*** by AirLiquide (***Feb 2000***)
  - → Successful vacuum tightness and mechanical stress tests
- Beginning of ***assembly of the internal detector mechanics*** (***Mar 2000***)
- Completion of assembly and positioning of inner detector frames (***Jul 2000***)
- Installation of ***30000 wires*** + ***signal cables*** (***Jul 2000-Oct 2000***)
- Delivery of the ***2nd cryostat*** of AirLiquide (***Aug 2000***)
  - → Successful vacuum tightness and mechanical stress tests
- Installation of ***scintillation light*** and all ***slow control devices*** (***Jul 2000-Dec 2000***)
- ***H.V. and field electrodes system*** installation (***Oct 2000- Jan 2001***)
- Installation of the ***48 electronic racks*** on top of dewar (***Dec 2000-ongoing***)
- Installation of ***external heat insulation*** (for both dewars) and ***LAr and LN_2 cryogenic circuits*** (***Dec 2000-Jan 2001***)
- Semi-module now ready to be sealed.

First half-module delivery in Pavia (Feb 29, 2000)

Assembly of the T600 internal detector (Mar-Jul 2000)



Cryostat

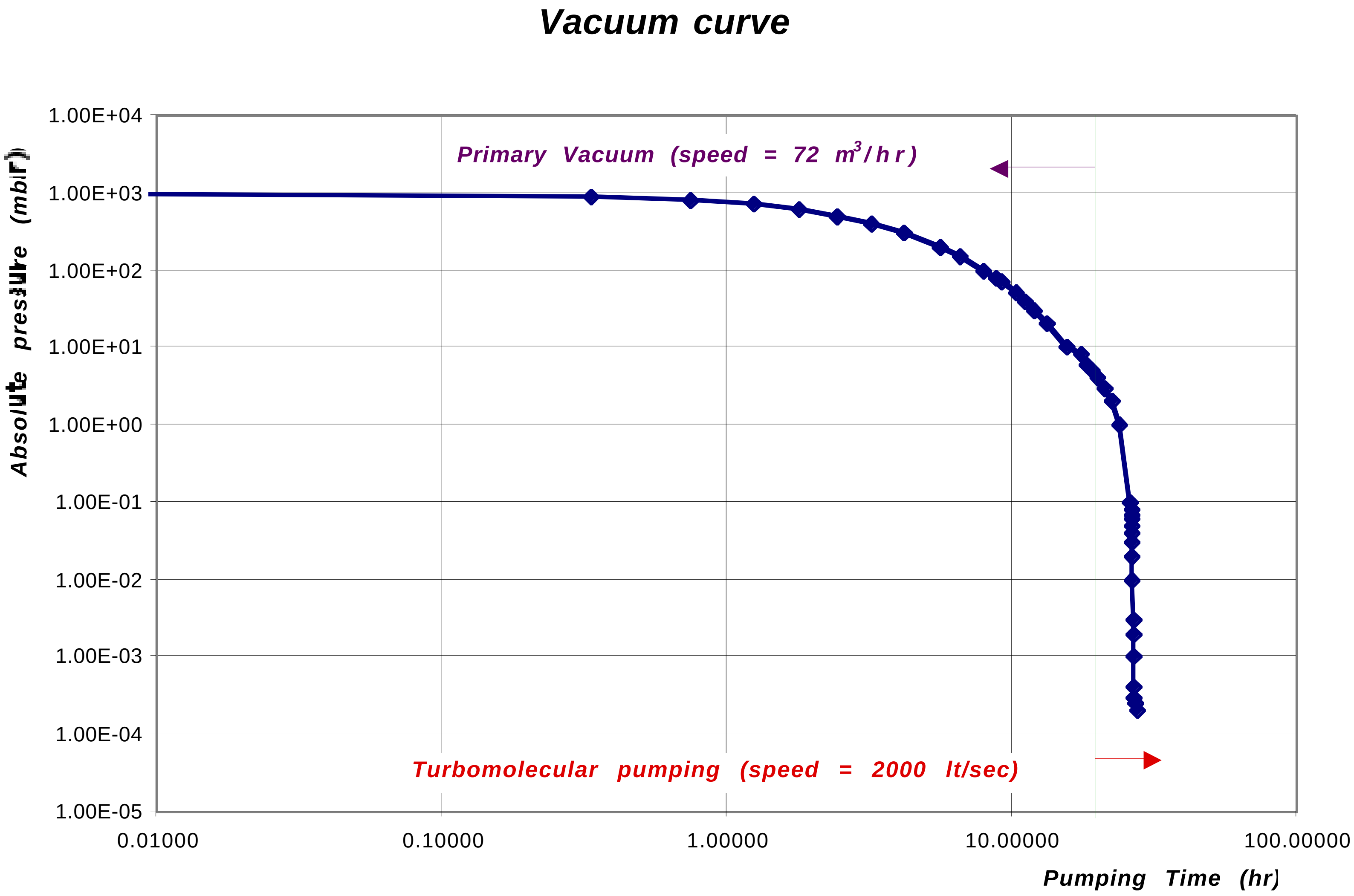
Internal detector

Clean workers

Dirty observer

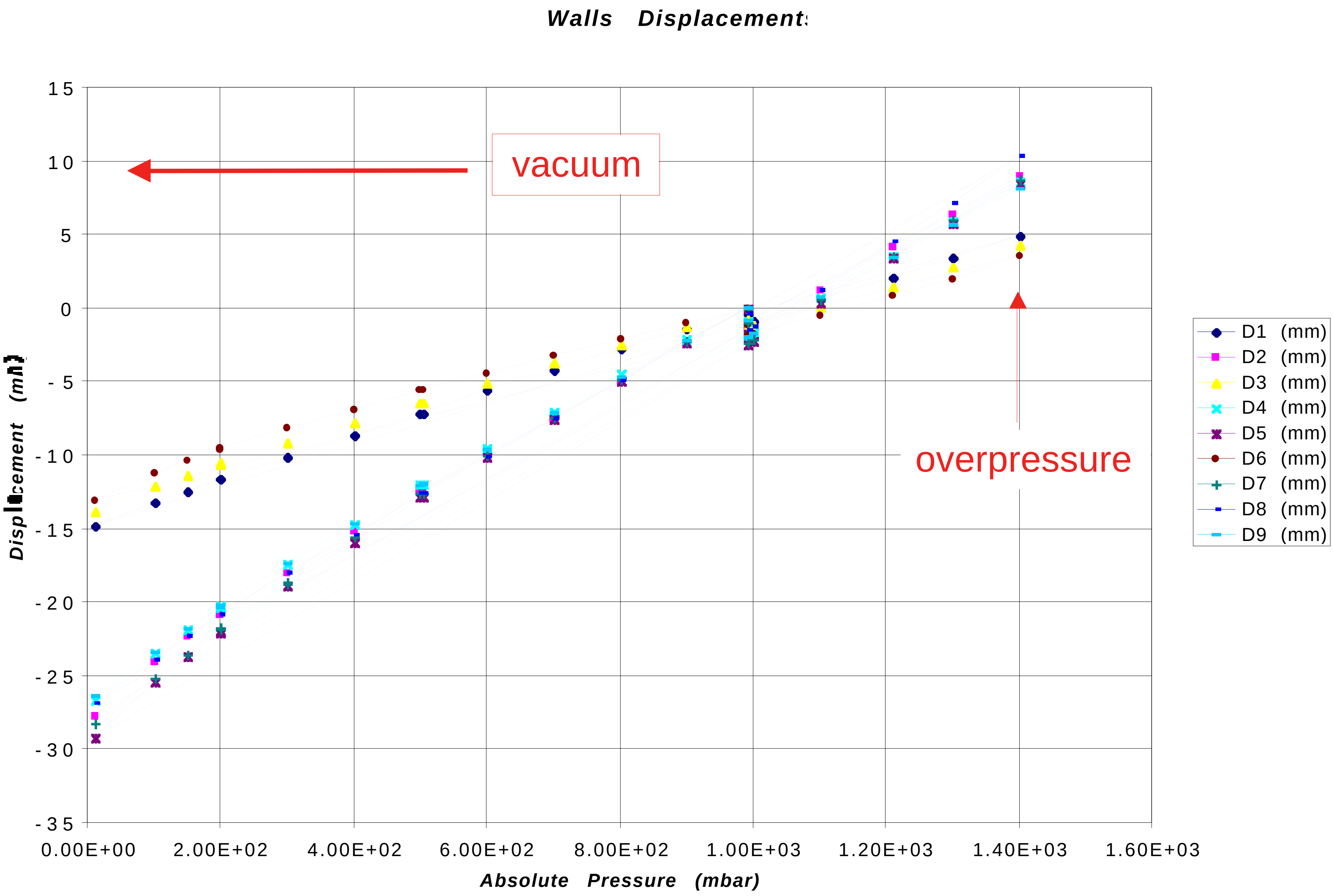
Second half-module during the vacuum test (Jul 2000)

Vacuum Tests - Second half-module

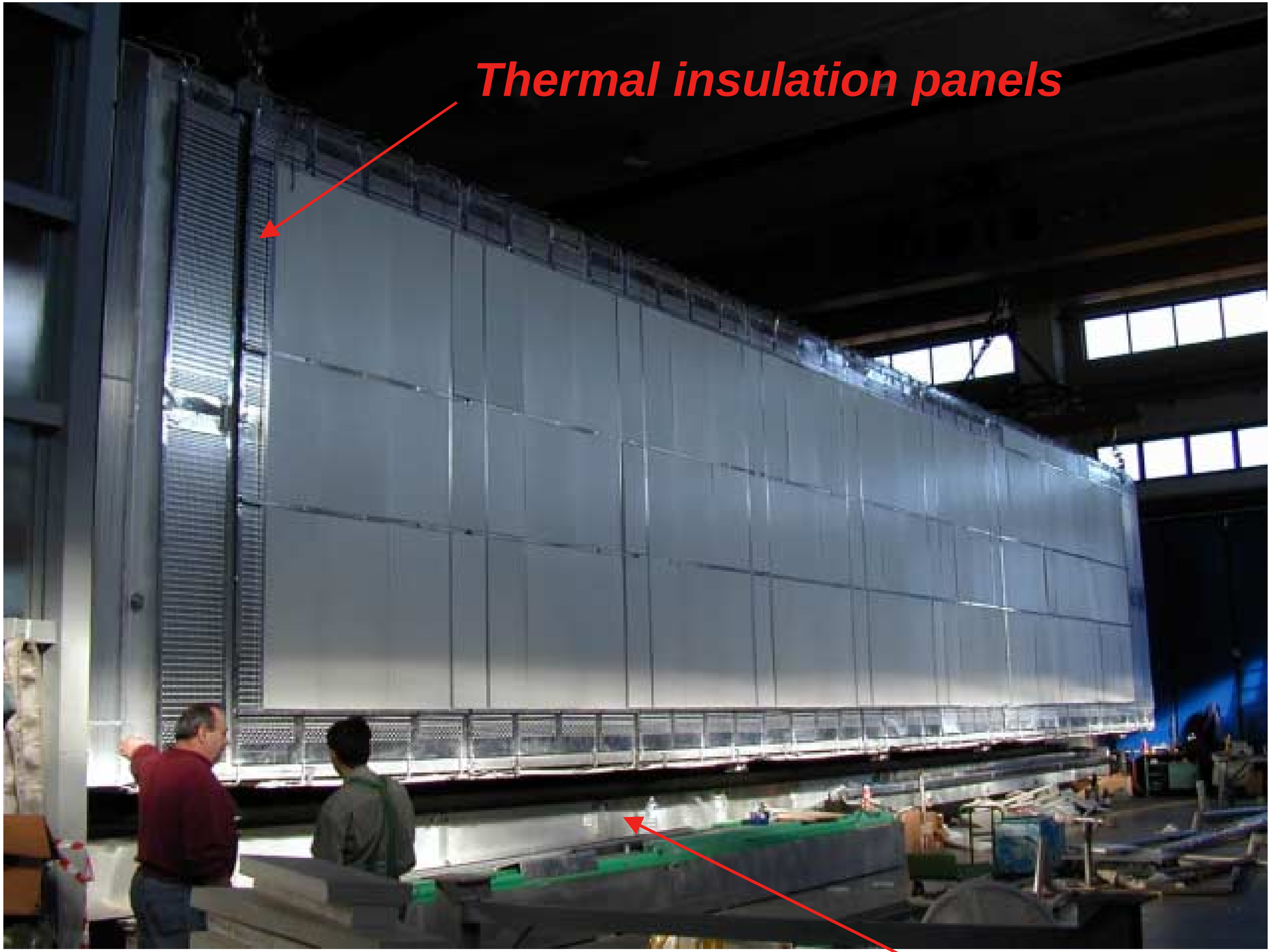


André Rubbia, ETH/Zürich, ICARUS Collaboration, 11/2/01

Dewar behaviour under inner pressure change

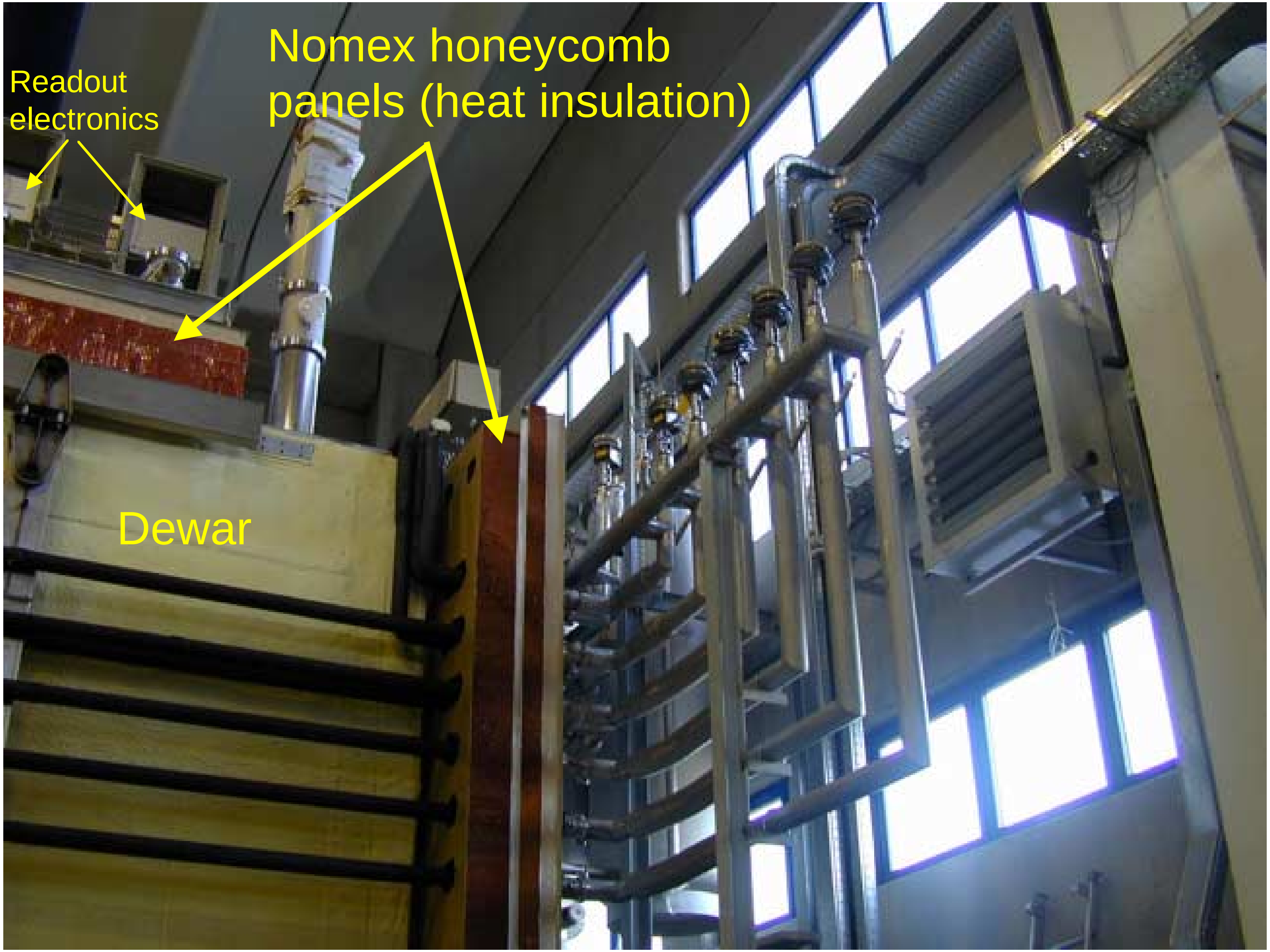


Second half-module (delivered Aug 2000)



Thermal insulation panels

Thermal floor


Readout electronics
Nomex honeycomb panels (heat insulation)
Dewar

Installation slow control devices (Jul 2000)

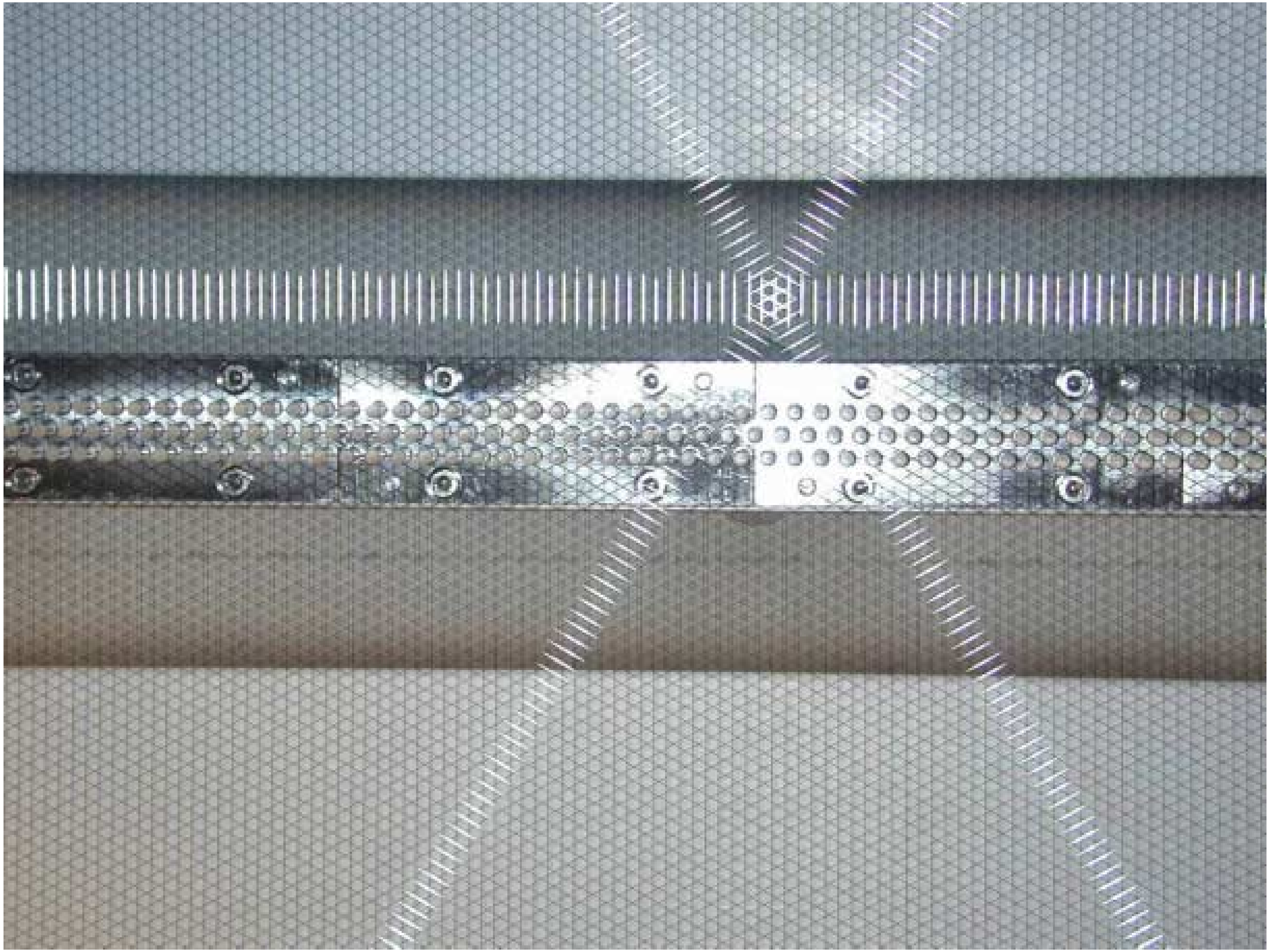
Wire stretching sensor

Wire installation in T600 internal detector (Jul-Oct 2000)

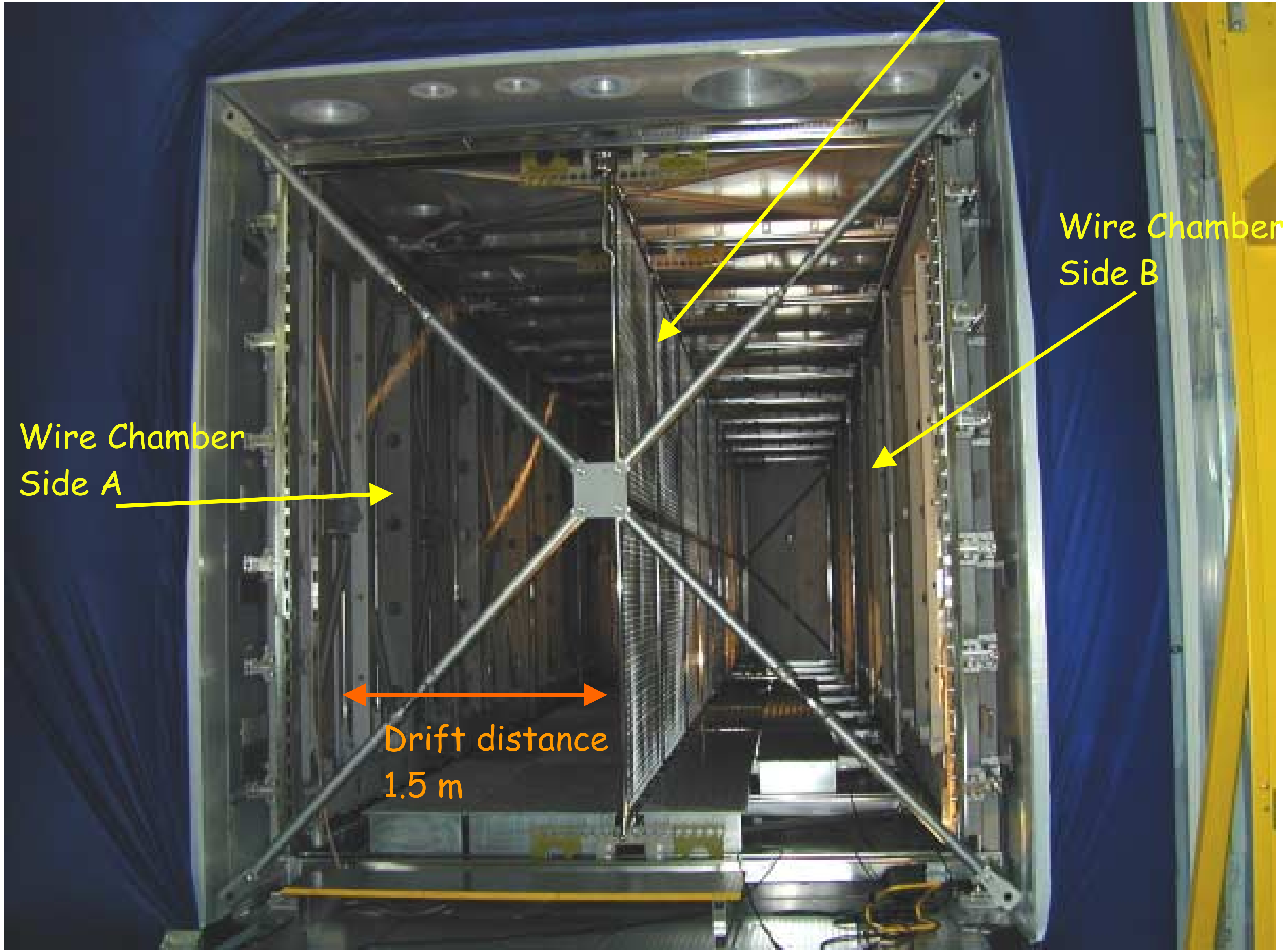
The three wire planes at 0°,±60° (wire pitch = 3mm)

and one PMT

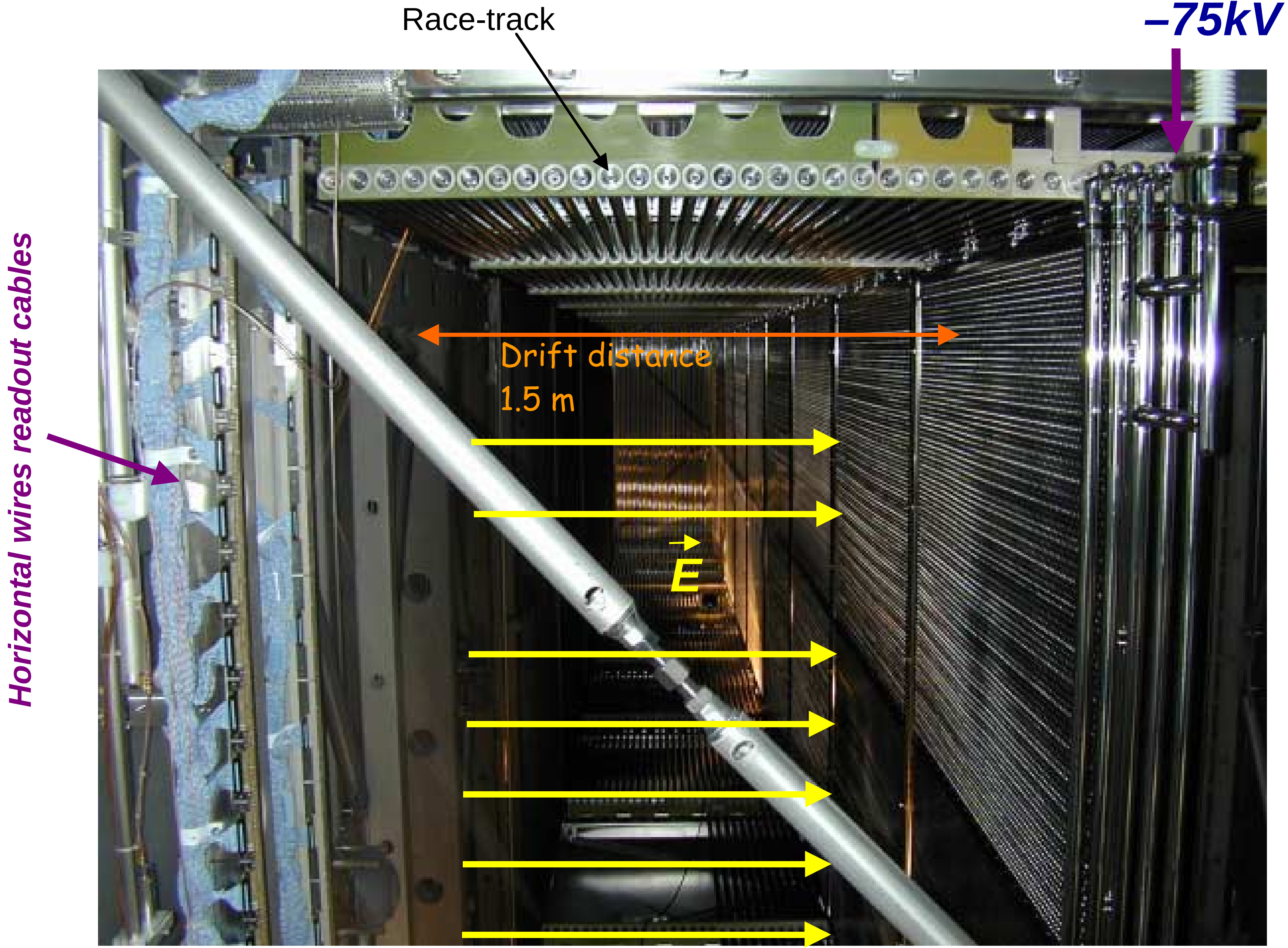
Wires crossing the spacers (wire pitch = 3mm)



T600 - Completed Internal Detector view



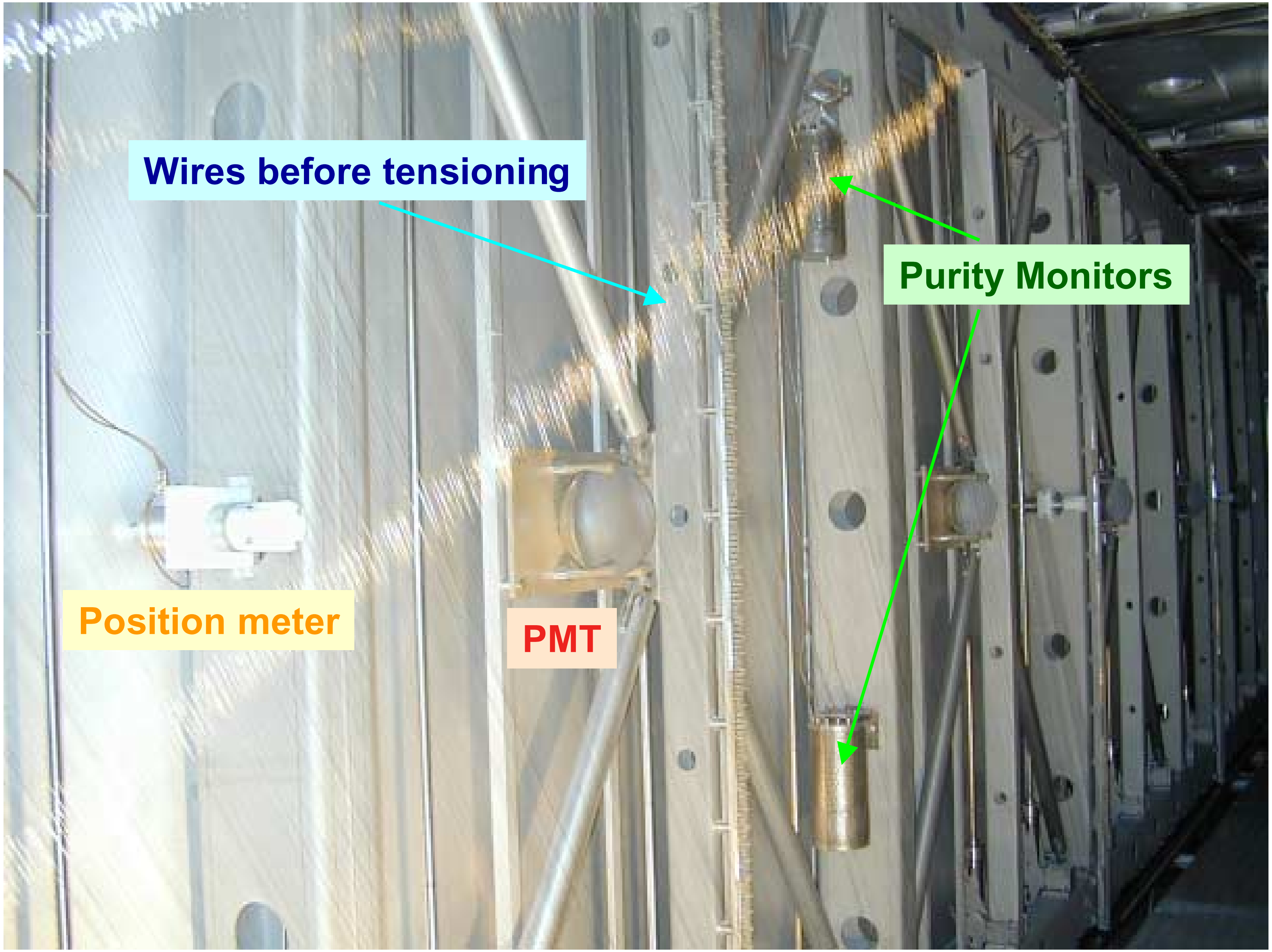
Drift H.V. and field electrodes system



Slow control system and scintillation light detection

- Several ***instrumentation***, most of it custom designed to work at LAr temperature in high purity environment, has been built tested and installed:
  - ➜ LAr Purity monitors
  - ➜ High precision LAr level meters
  - ➜ Position meters for the wires tensioning springs and for the container walls
  - ➜ Temperature probes
- ***Detection of LAr scintillation light*** (VUV λ=128 nm, attenuation length in LAr ≈90cm, $1 \div 2 \times 10^4$ γ per MeV deposited)
  - ➜ Provide ***help for triggering*** and ***T_0 measurement***.
  - ➜ Bare PMT's immersed in LAr with wavelength shifter deposited on the glass window
    - – Test and qualification of PMT at LAr temperature:8 inches EMI PMTs with special treated bialkali photocathode to work at cryogenic temperature.
    - – Choice of most efficient wavelength shifter (***TPB*** = TetraPhenylButadiene), deposition method (spray), aging properties, pollution of LAr, etc.

Slow control sensor (behind wire planes)



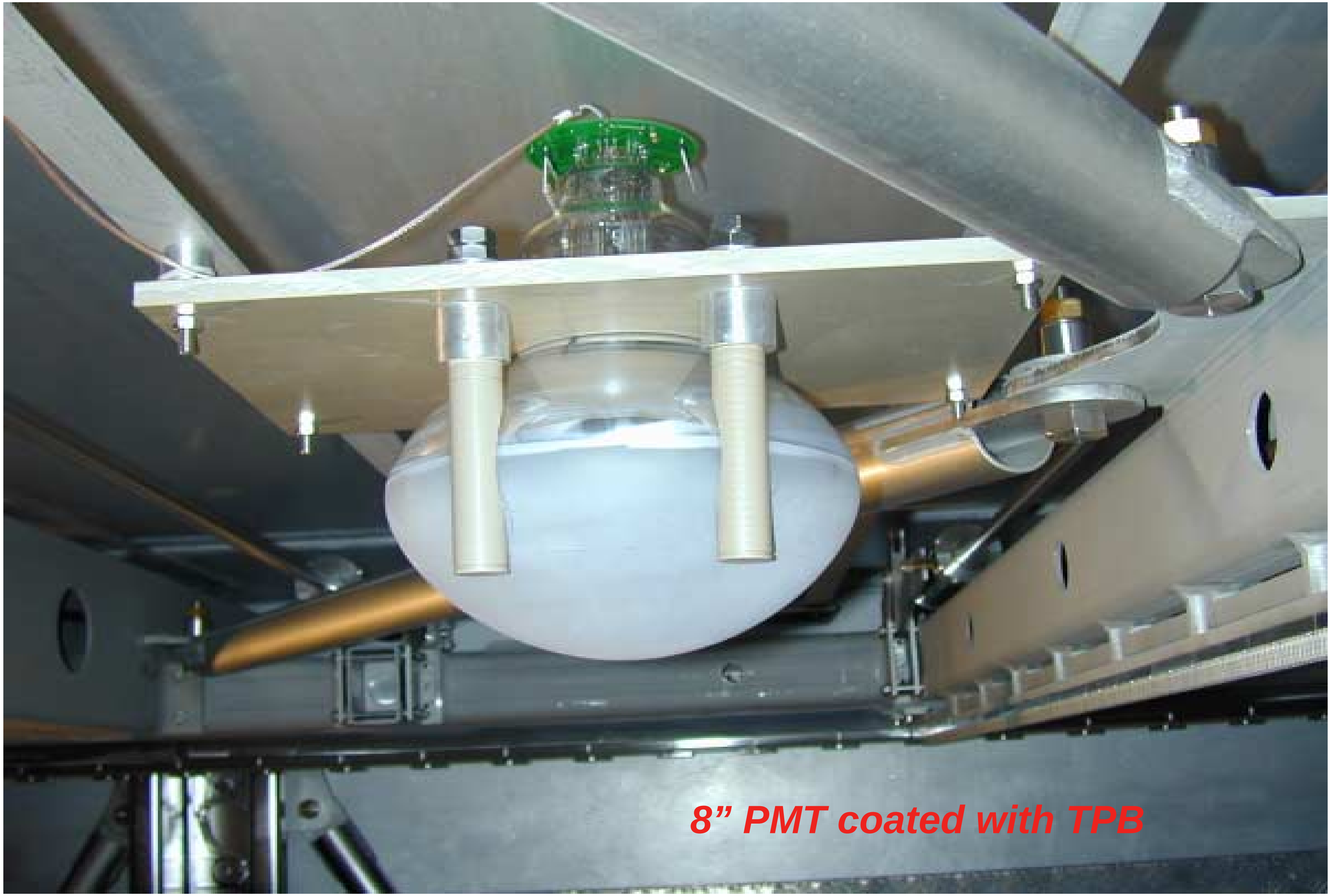
Wires before tensioning

Purity Monitors

Position meter

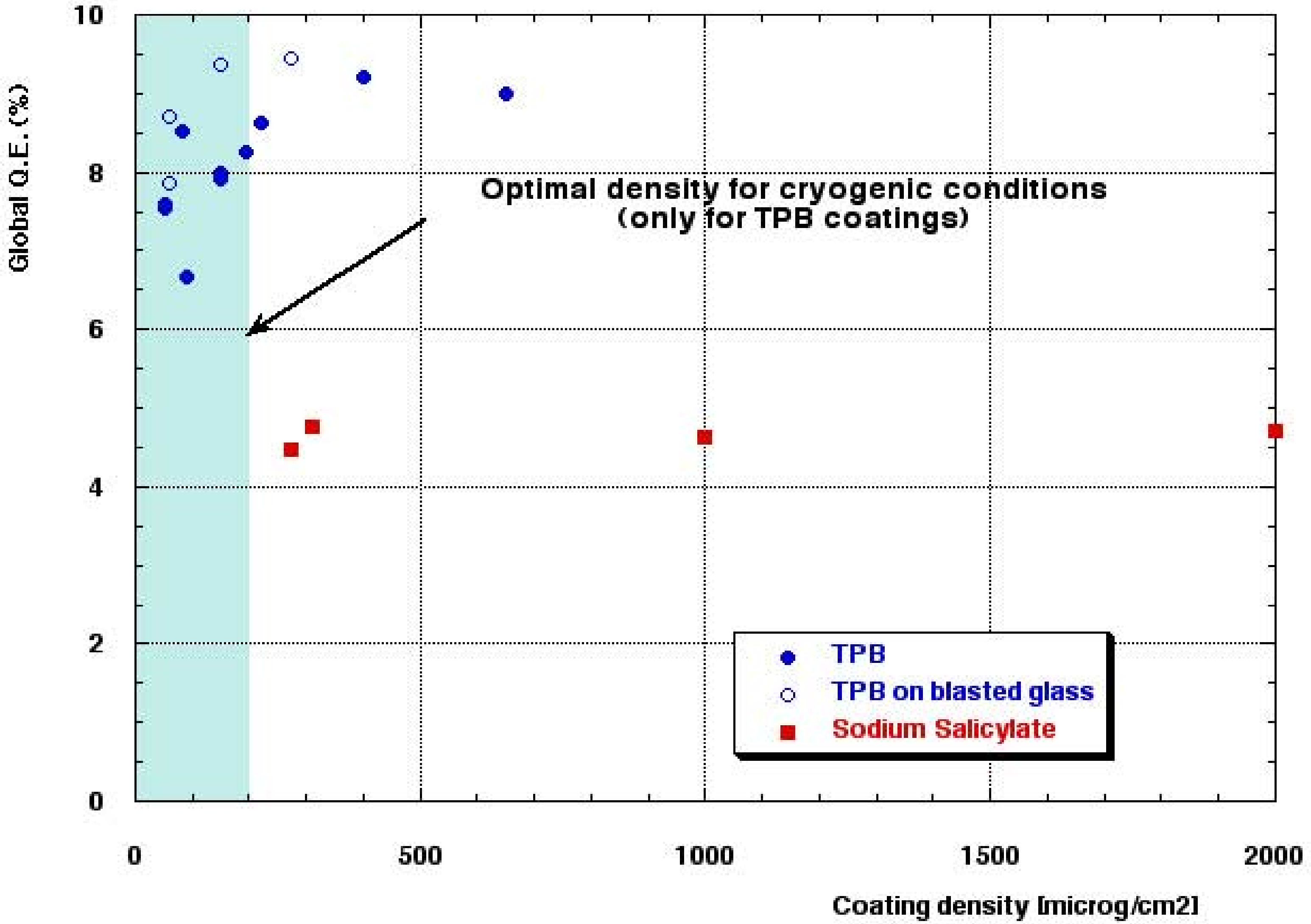
PMT

Scintillation light collection
(in total 20 PMTs on detector walls)



8” PMT coated with TPB

Global Quantum Efficiency
(PMT + wavength-shifter coating)



Optimal density for cryogenic conditions
(only for TPB coatings)

Readout electronic installation on top of dewar (Dec 2000-now)

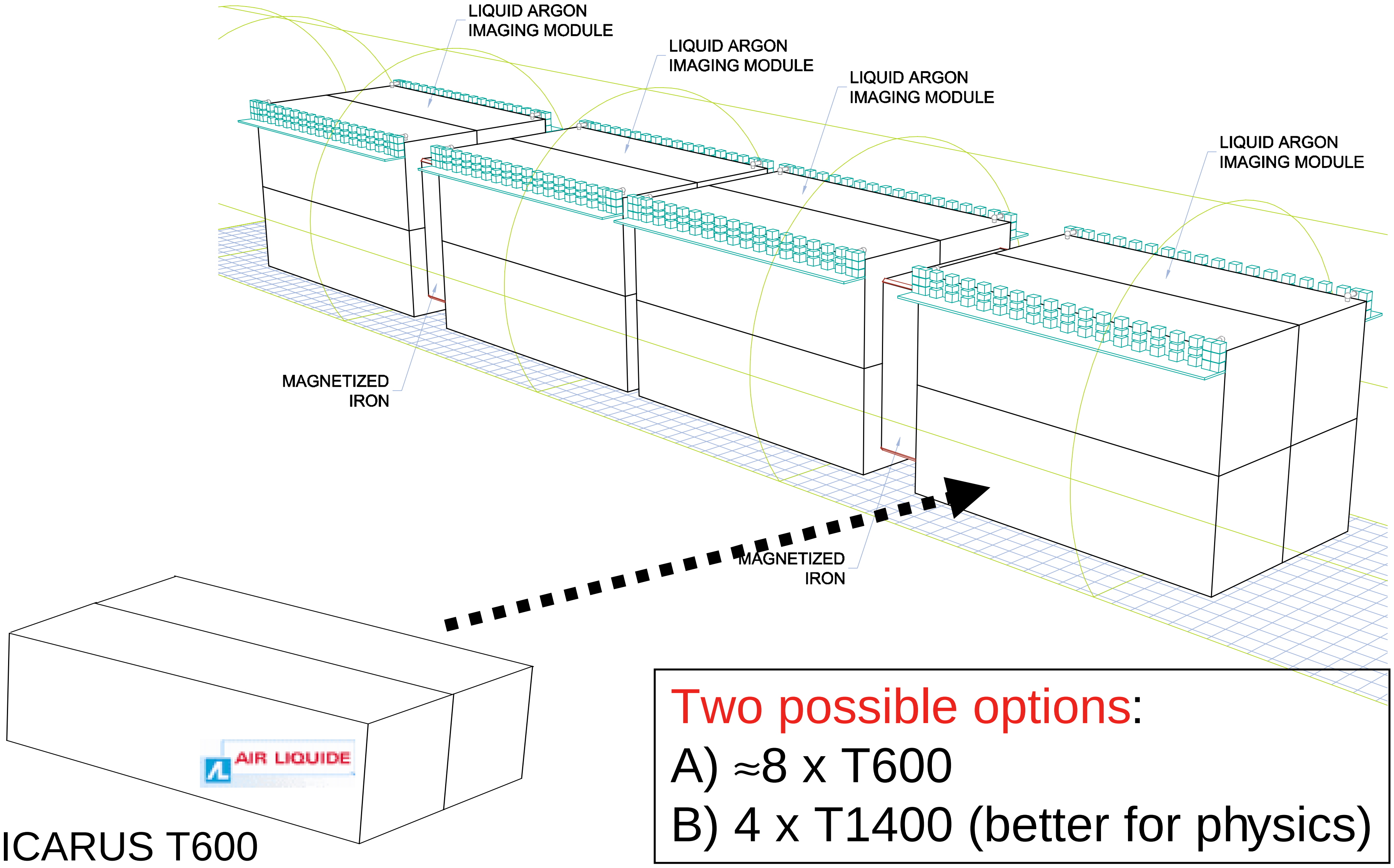
Readout electronic installation on top of dewar (Dec 2000-now)

Man-hole (after sealing, the only way to get inside!)

Perspectives of ICARUS

- The ICARUS T600 detector
  - → has a ***physics program*** of its own, immediately relevant for neutrino oscillation physics: ***solar+SN neutrinos, atmospheric neutrinos***
  - → Though with limited statistics, due its relatively small mass, compared to the standard for underground detectors set by the operating SuperKamiokande.
- However, the T600 should also be considered as one more step towards larger detector masses.
  - → solving technical issues associated with actual operation of a large mass LAr device in an underground site (LNGS Tunnel).
  - → fully establish the imaging, PID, calorimetric energy reconstruction capabilities of REAL events, during steady detector operations
  - → In situ proof of actual physics performance of this novel detector technique, in particular measurement of backgrounds, extrapolable to larger mass detectors
- Physics issues for both present and future LAr detectors:
  - Atmospheric ν
  - Solar+SN ν
  - CNGS+Nufactory ν
  - **p** decay

Proposed setup ICARUS 5kt in LNGS Hall B



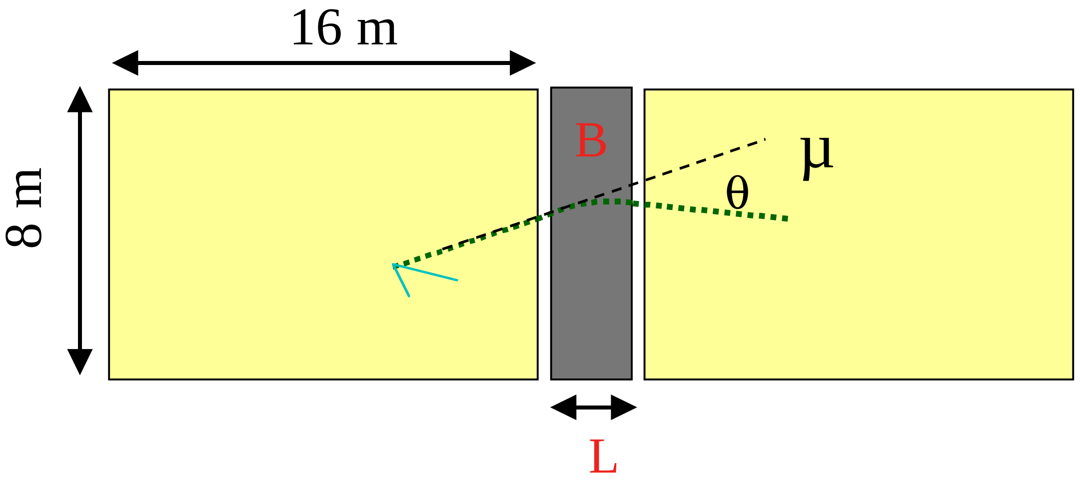
Two possible options:

A) ≈8 x T600

B) 4 x T1400 (better for physics)

Muon bending measurement

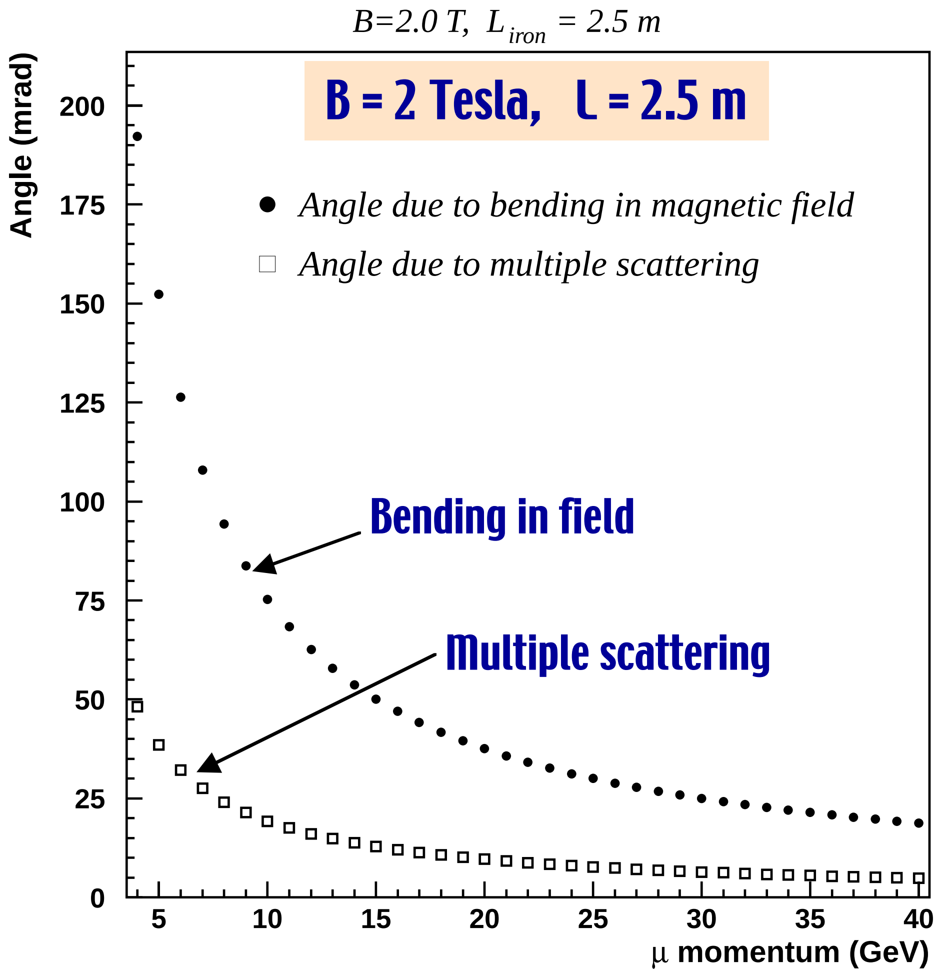
- We consider a design in which the muon escaping the liquid Argon is bent by a magnetized piece of iron



The bending angle θ is measured with the tracks observed in two subsequent liquid argon module

$\Delta p/p \approx 25\%$

Charge confusion: $\sim 10^{-4}$

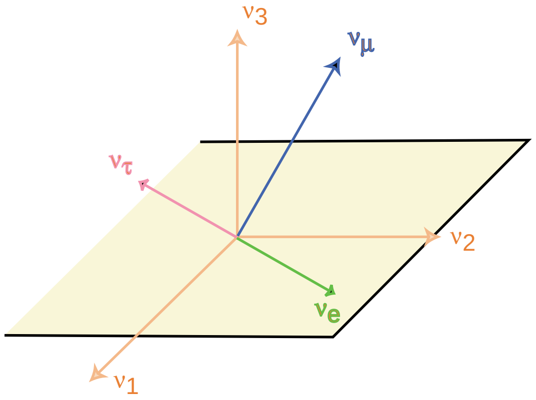


The ν oscillation framework: Three flavor mixing!

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Weak eigenstates

Mass eigenstates



$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = P_{CP}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) \pm P_{\not{C}\not{P}}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta)$$

CP-conserving

$$P_{CP} = \delta_{\alpha\beta} - 4\sum_{j>k} \mathrm{Re}\, J_{\alpha\beta jk} \sin^2 \Delta_{jk}$$

CP-violating

$$P_{\not{C}\not{P}} = 4\sum_{j>k} \mathrm{Im}\, J_{\alpha\beta jk} \sin \Delta_{jk} \cos \Delta_{jk}$$

$$J_{\alpha\beta jk} = U_{\alpha k} U^*_{\beta k} U^*_{\alpha j} U_{\beta j}$$

Mixing strength

$$\Delta_{jk} = \frac{1.27 \;\; \Delta m^2_{jk} L}{E}$$

Oscillatory pattern

Δm^2_{jk} in eV^2, L in km, E in GeV

In general, the oscillation pattern may be complicated and involve **a combination of transitions** to **ν_e, ν_μ, ν_τ** and by symmetry with quark sector **it is natural to expect CP violation** at some level.

Three family oscillations

Parameterization la CKM :

$\boxed{U_{e3}}$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Current standard mass and mixing assignment:

Atmospheric anomaly: $\nu_\mu \to \nu_\tau$

$\Delta m^2_{32} \approx \Delta m^2_{31} \approx 3\text{x}10^{-3}\ \text{eV}^2,\quad \theta_{23} \approx 45°$

$\nu_\mu \to \nu_e \qquad \nu_e \to \nu_\tau$

θ_{13} (small)

Solar deficit: $\nu_e \to \nu_{\mu/\tau}$

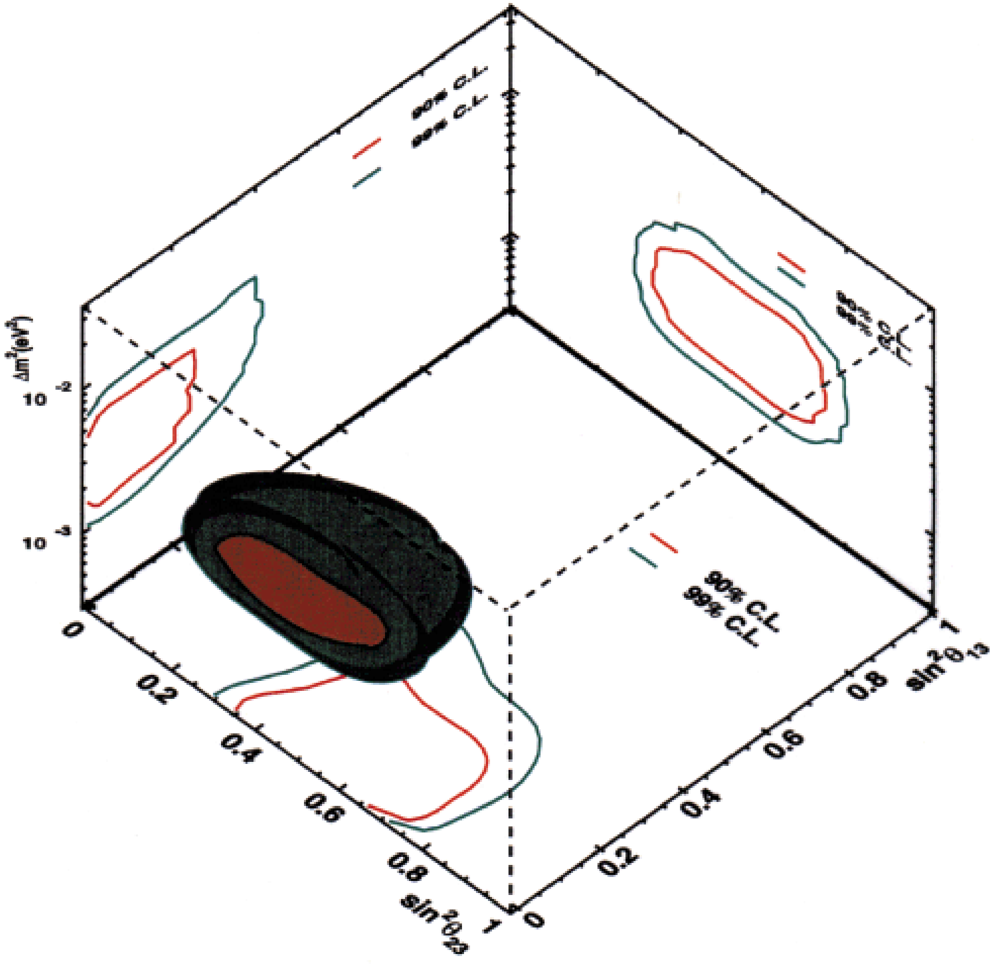
$\Delta m^2_{12},\quad \theta_{12},\quad \theta_{23}$

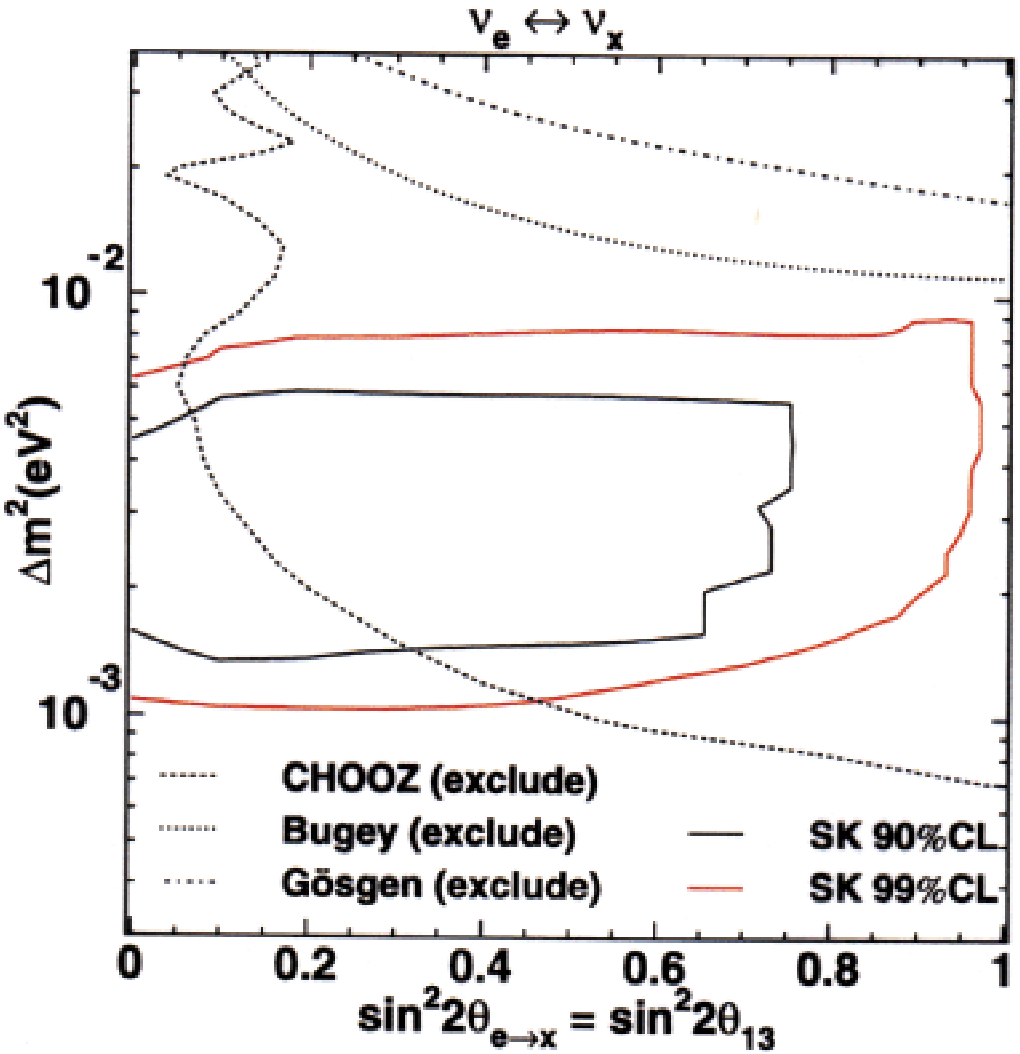
$$P(\nu_\alpha \to \nu_\beta) \overbrace{\neq}^{?} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$\delta \neq 0$?

3 flavor mixing analysis of SuperKamiokande

PRELIMINARY

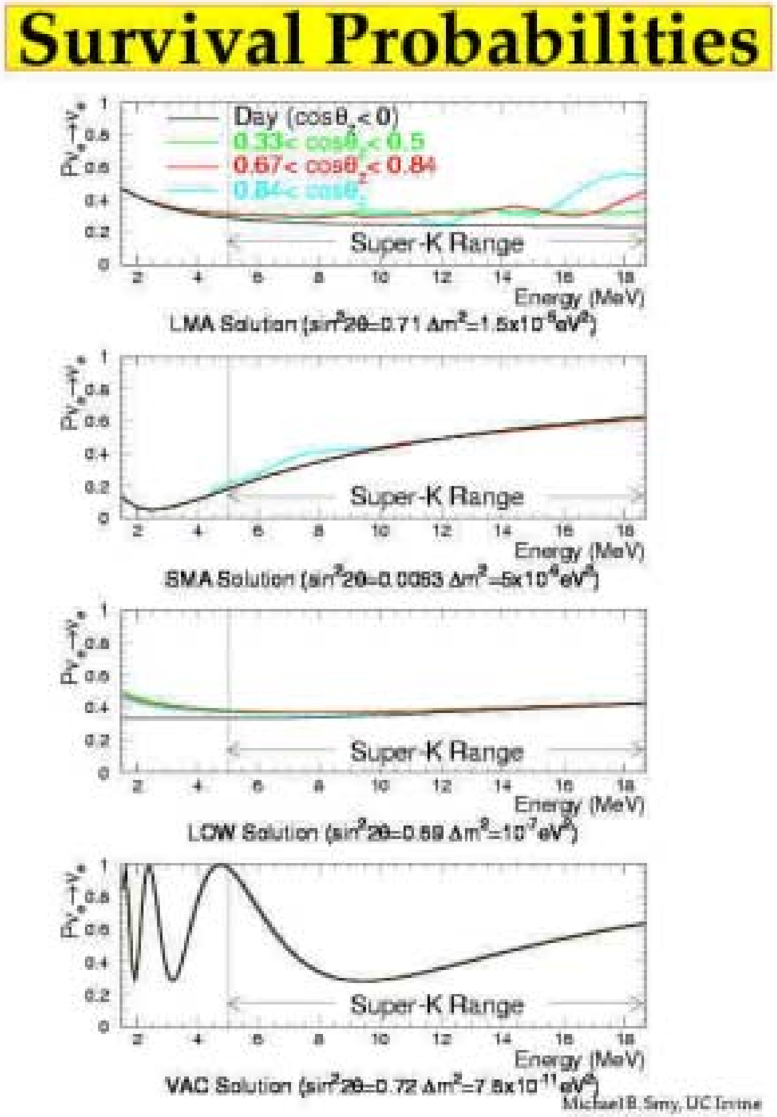


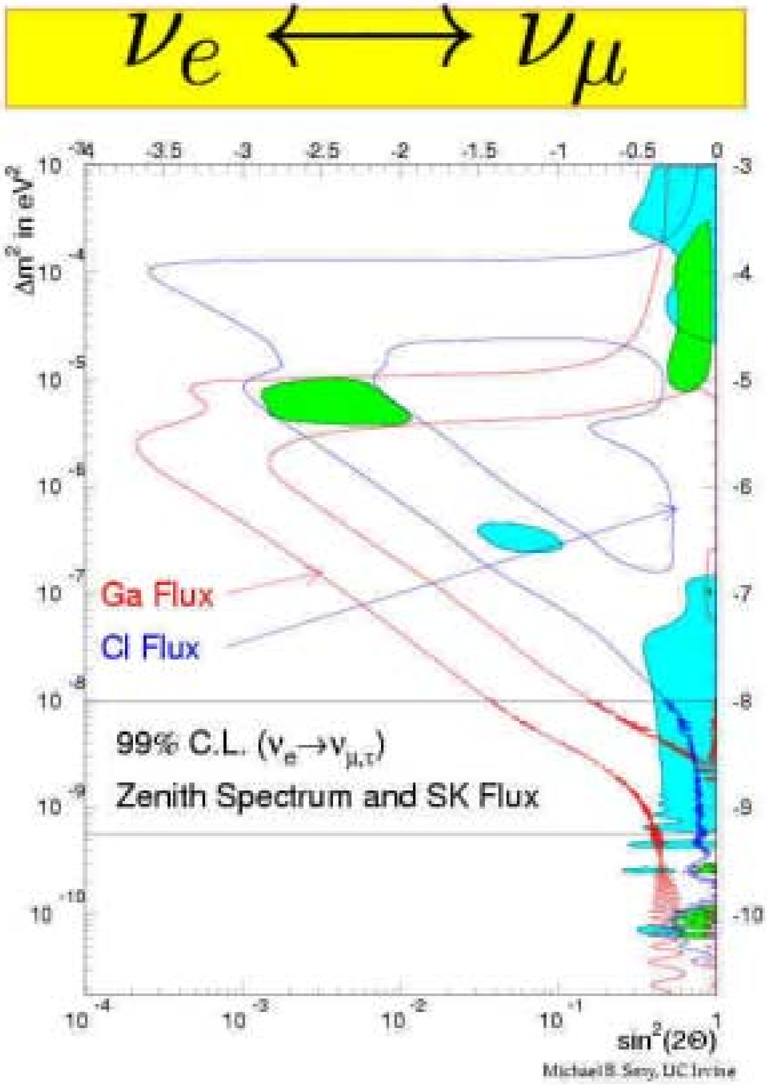


Atmospheric neutrinos analysis

K. Nakamura, NUFACT00, Monterey (USA), May 2000

Solar neutrinos





M.B. Smy, NOON2000, Tokyo (Japan), Dec 2000

No smoking gun ?

ICARUS physics potential (I)

Atmospheric neutrinos

- Improvements over existing detection technique
  - *Detection down to production thresholds*
  - *Complete event final state reconstruction*
  - *Identification all neutrino flavors*
  - *Identification of neutral currents*
- Excellent resolution on L/E reconstruction
- Direct τ appearance search

$\Delta m^2_{32}, \quad \theta_{23}$

Δm^2_{12}

Neutrinos from CERN

- Search for $\nu_\mu \rightarrow \nu_\tau$
- Search for $\nu_\mu \rightarrow \nu_e$

$\Delta m^2_{32}, \quad \theta_{23}, \quad \theta_{13}$

Solar neutrinos

- Energy threshold: 5 MeV
- Large statistics, high precision measurements
- Experimental signal

$\Delta m^2_{12}, \quad \theta_{12}$

$$\nu_e + {}^{40}Ar \rightarrow e + {}^{40}K^*$$

Absorption

$$\nu_e + e \rightarrow \nu_e + e$$

Elastic

André Rubbia, ETH/Zürich, ICARUS Collaboration, 11/2/01

ICARUS physics potential (II)

Proton decay

- **Large variety of decay modes accessible**

  ⇒ *study branching ratios free of systematics*

- **Background free searches**

  ⇒ *linear gain in sensitivity with exposure*

Physics at Unification scales?

$$m_\nu \overbrace{=}^{?} \frac{m}{M_{heavy}}$$

Neutrinos “factory”

- **Precise measurement of Δm^2_{23}, Θ_{23}, Θ_{13}**
- **Matter effects, sign of Δm^2_{23}**
- **First observation of $\nu_e \rightarrow \nu_\tau$**
- **CP violation**

Δm^2_{32}, θ_{23} , θ_{13}

$\Delta m^2_{32}>0$ or $\Delta m^2_{32}<0$?

Unitarity of mixing matrix

$\delta\neq 0$?

Solar neutrinos detection in ICARUS

- Two reactions can be measured independently:

Elastic scattering on atomic electron

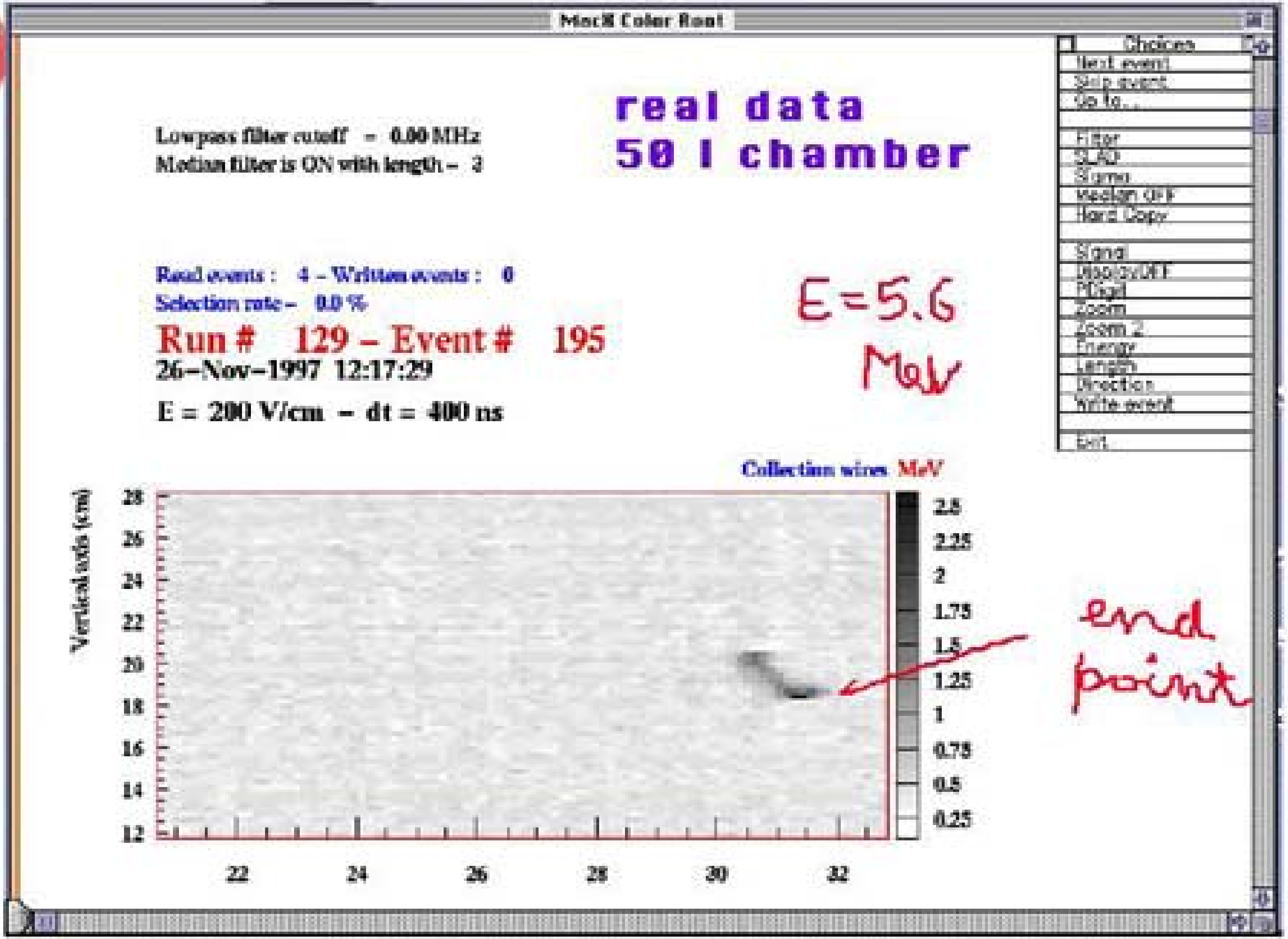
$$\nu_x + e^- \rightarrow \nu_x + \boxed{e^-}$$

ν absorption on Argon nuclei

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + \boxed{e^-}$$

- **Signature**:
  - Primary electron track
  - Absorption: surrounded by low energy secondary tracks ($^{40}K^*$ de-excitation).
- Prototype setup: electron track visible down to kinetic T=150 KeV
- Electron track threshold = 5 MeV (needed to reduce background contribution and to establish the e^- direction in elastic scattering).
- Sensitive to ^8B component of the solar spectrum.

Radioactive source: 6 MeV γ's



Lowpass filter cutoff - 0.00 MHz
Median filter is ON with length - 3

real data
50 l chamber

Read events : 4 - Written events : 0
Selection rate - 0.0 %

Run # 129 - Event # 195
26-Nov-1997 12:17:29

E = 200 V/cm - dt = 400 ns

E=5.6 MeV

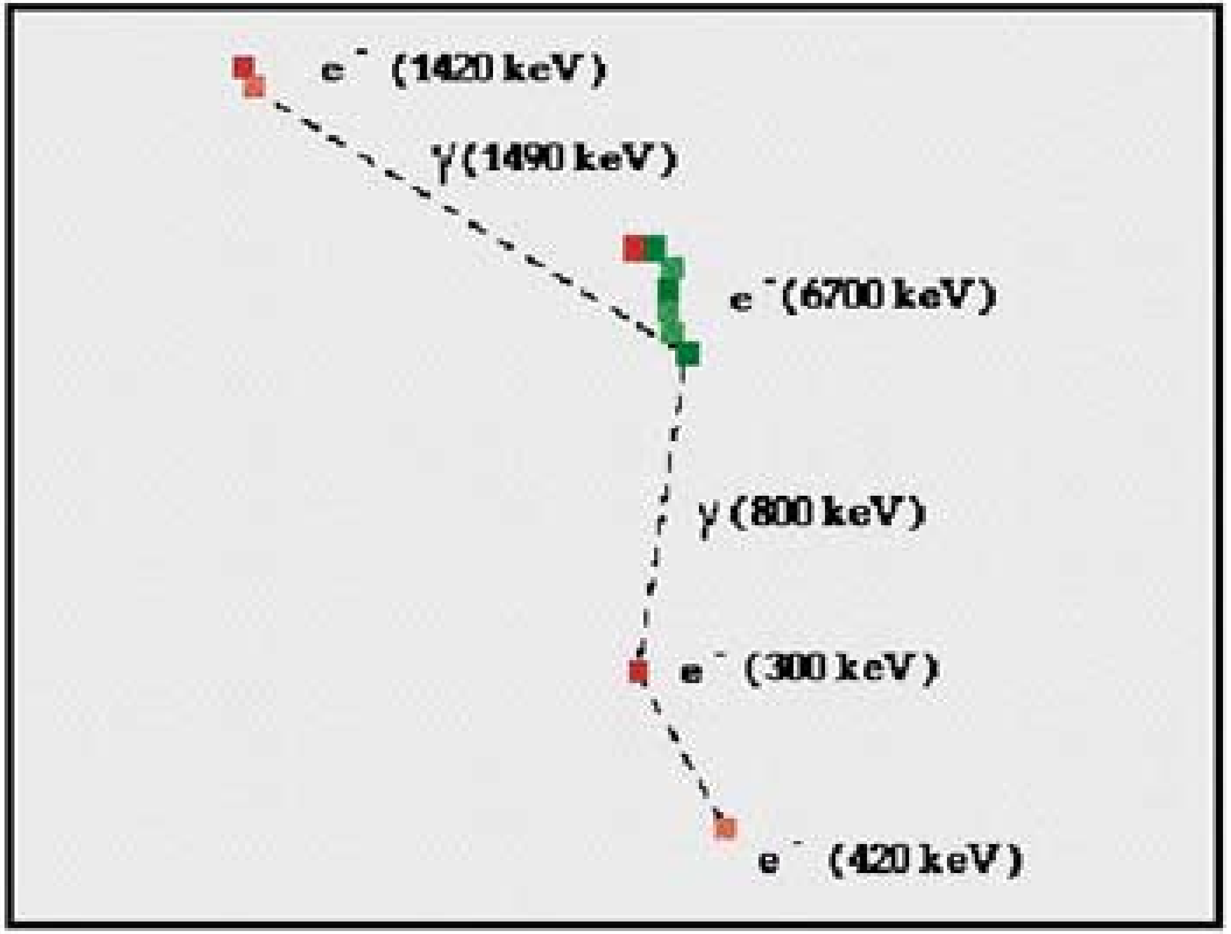
end point

Typical Montecarlo Gamow -Teller digitised event

$E_{\text{main electron}}$ = 6700 keV

Associated compton energy = 2140 keV

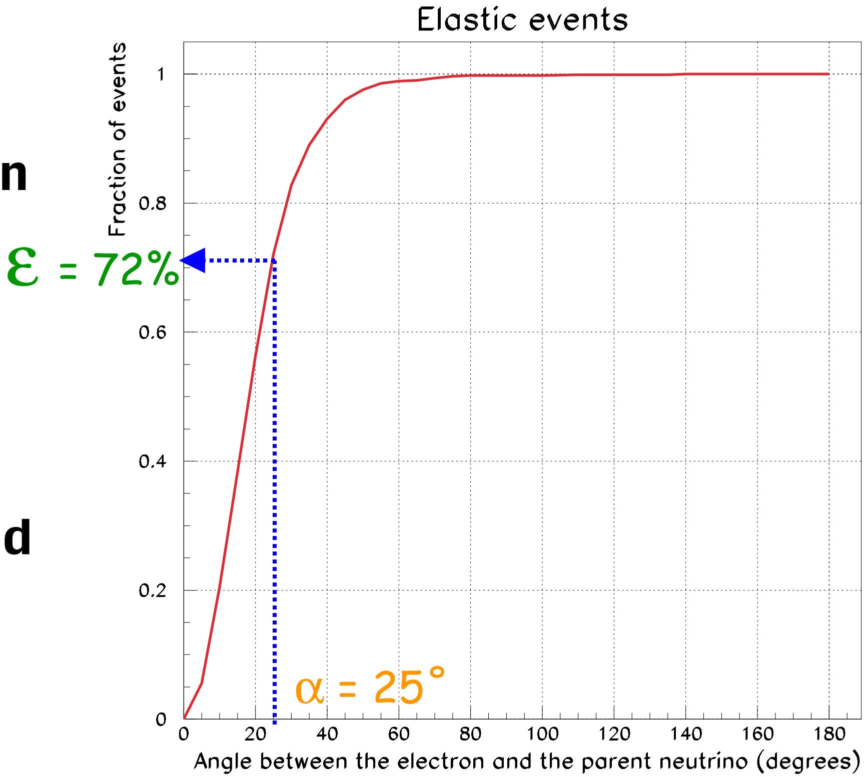
Multiplicity = 3



Signal selection

- **Elastic events:**
  - → **Angular distribution of the electron peaked in the solar ν direction:**

- **Absorption events:**
  - → **Electron track directions can be considered isotropically distributed**



The off–line selection can be done in terms of the energy of the main electron and the correlation between multiplicity and energy of the associated tracks.

Solar ν's background events

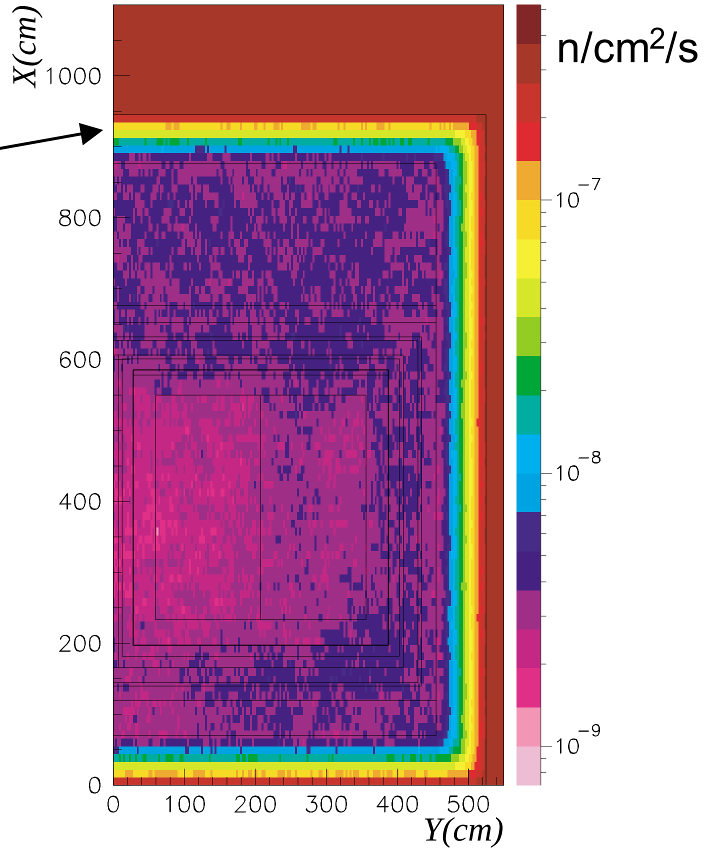
≈7400 captures/year in 500 ton fiducial

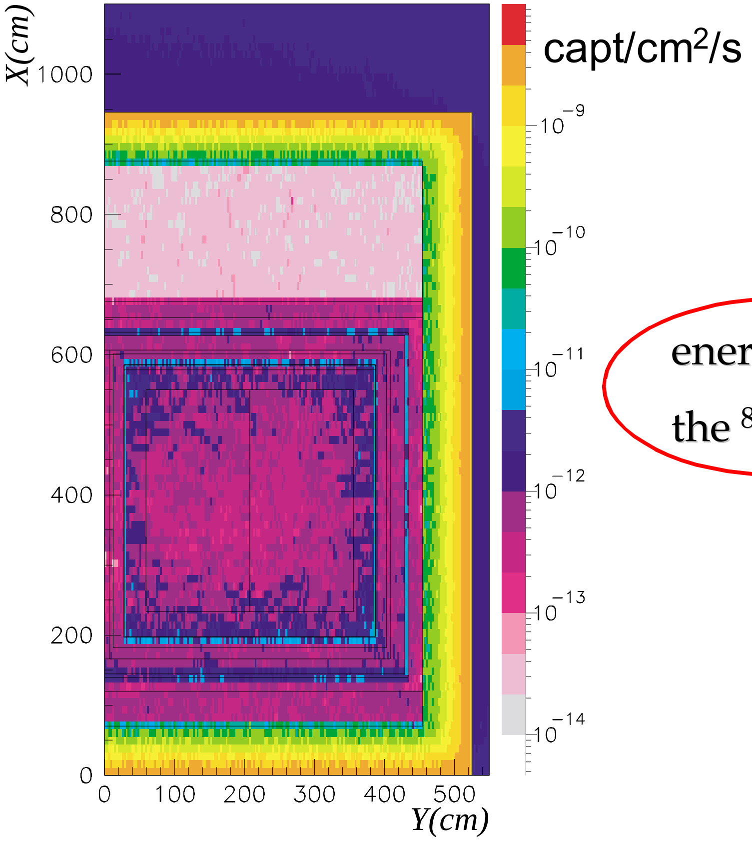
≈150 /year with E_e>5 MeV

Natural radioactivity → Spontaneous fission or (α,n) reactions → **n flux** → Captures in the detector (^{40}Ar, ^{27}Al, ^{56}Fe,…) → **γ-rays** → e^-

energies in the ^{8}B range

Neutron shield





(Full FLUKA simulation)

Solar neutrino rates and sensitivity

470 ton fiducial, all cuts imposed

Events/year

Elastic channel	**212**
Background	**6**
Absorption channels	**759**
Background	**26**

Events per year for a 600 ton detector

Te (MeV)	**Neutrons**
0.0	7400
1.0	3404
2.0	1554
3.0	696
4.0	318
5.0	144
6.0	66
7.0	30
8.0	13

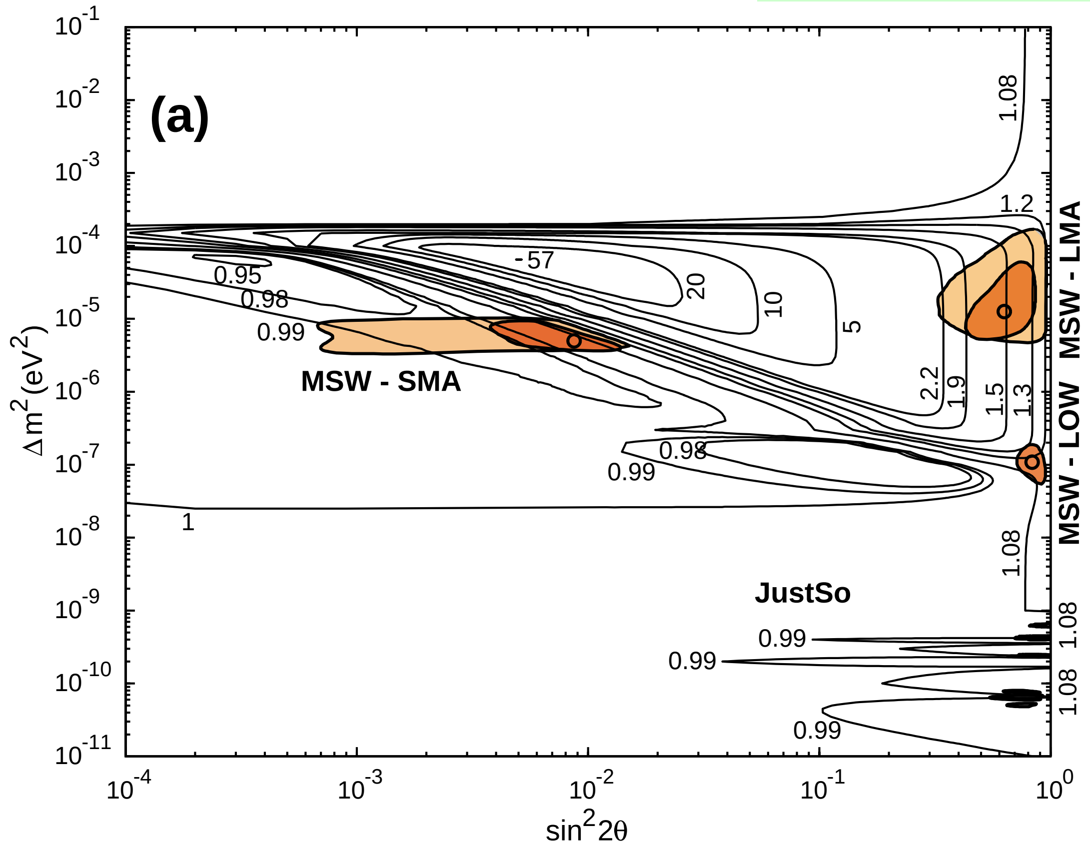
$$R \equiv \frac{N^{ES} / N^{ES}_{theory}}{N^{ABS} / N^{ABS}_{theory}}$$

ES=elastic scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ABS=absorption events

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$



$$\Delta R / R \approx 7\% (1 kt \times yr),\ \ 5\% (2 kt \times yr),\ \ 4\% (4 kt \times yr)$$

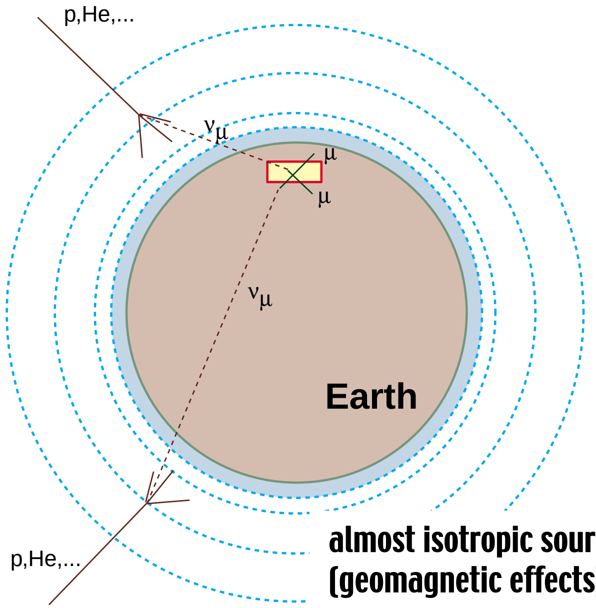
Supernova neutrinos detection in ICARUS

- ✯ **ICARUS can detect neutrinos coming from stellar collapses in our Galaxy via 2 processes:**
  - → Elastic scattering (flavor independent) $\nu_x + e^- \rightarrow \nu_x + e^-$
  - → Absorption on argon $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

Expected events from a stellar collapse occurred at 10 kpc		
600 ton	5 kton	30 kton
8	**70**	**400**

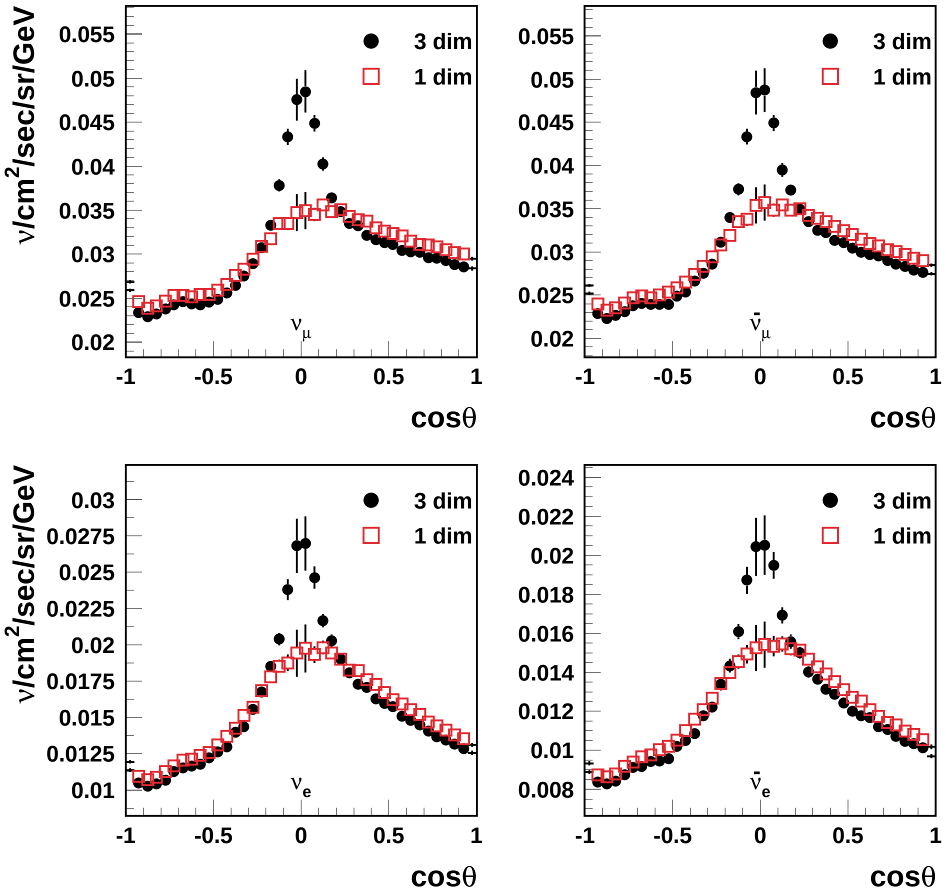
$$N_\nu = 8 \times 10^{57}$$

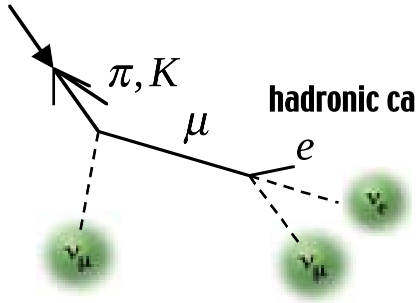
Atmospheric neutrinos



almost isotropic source (geomagnetic effects)

0.4 < E_ν < 1 GeV at Gran Sasso

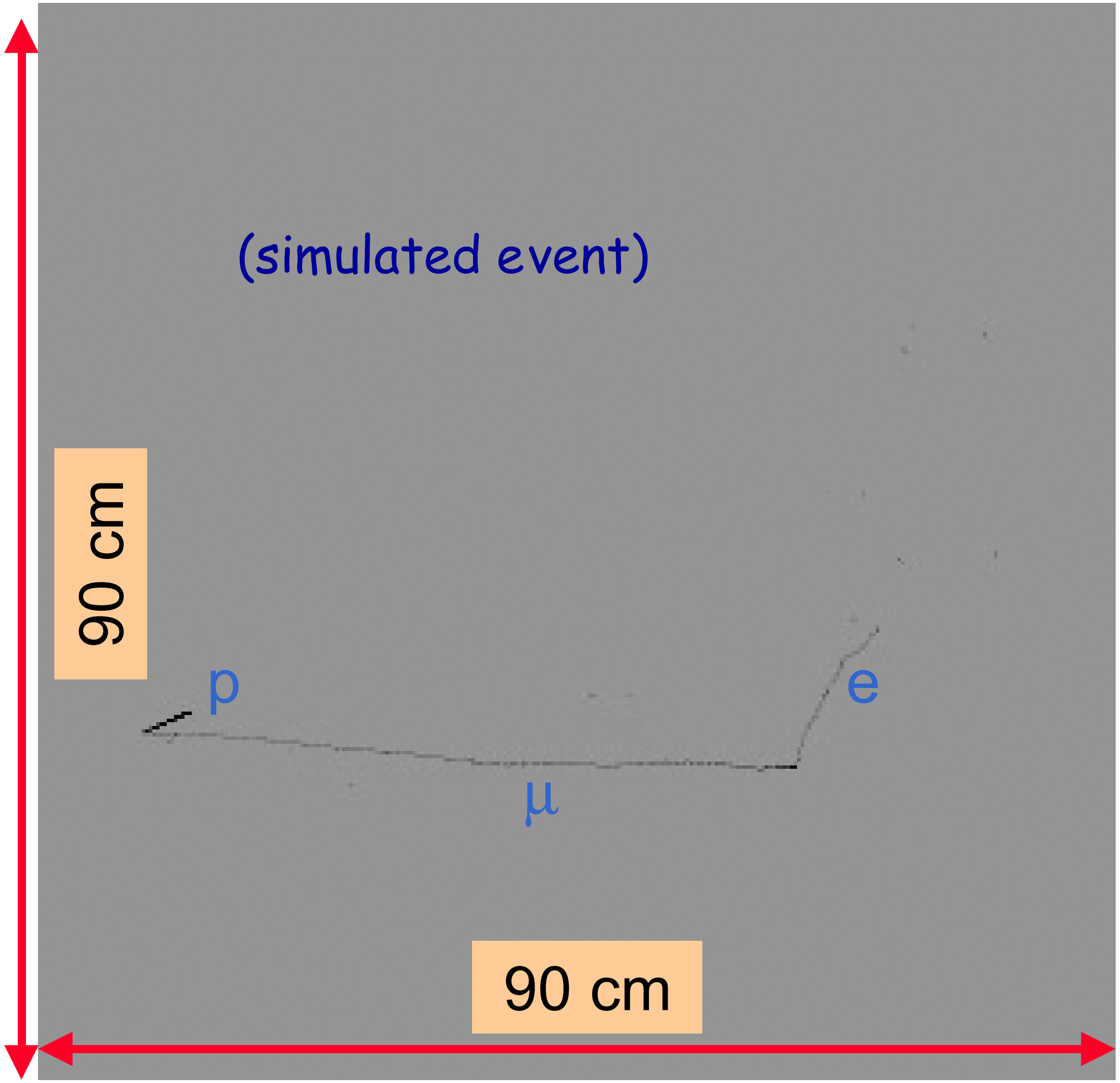




hadronic cascade + decays

Simulation based on FLUKA interaction and transport code (extensively benchmarking against data)
3D representation of Earth and atmosphere
Geomagnetic effects included
All relevant physics taken into account: energy losses, polarized decays

Atmospheric ν_μ CC


(simulated event)

Atmospheric ν's

ν_μ Q-el. interaction

$E_\nu = 370$ MeV

$P_\mu = 250$ MeV

$T_p = 90$ MeV

Atmospheric ν_e CC

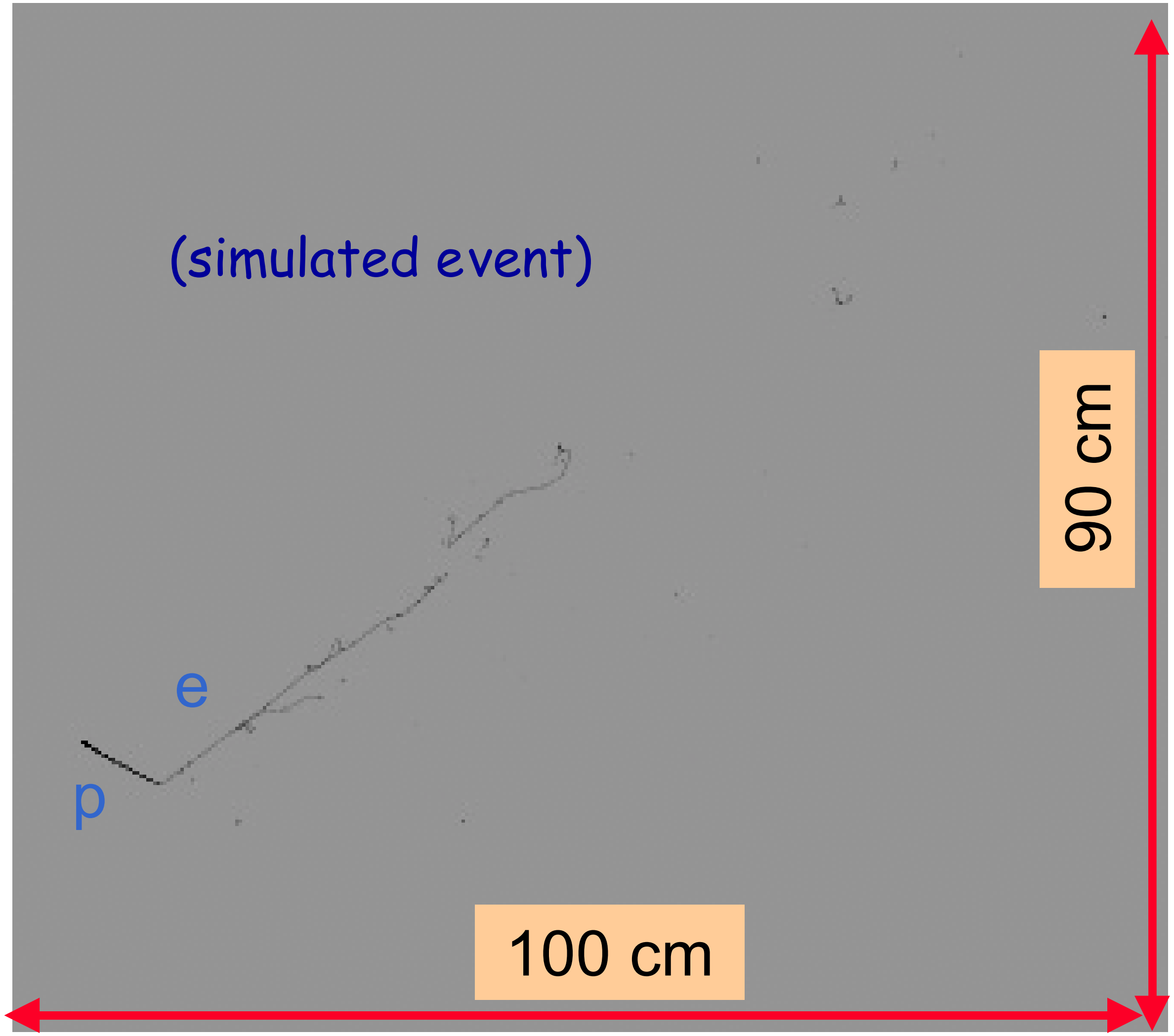
Atmospheric ν

ν_e quasielastic interaction

E_ν = 450 MeV

P_e = 200 MeV

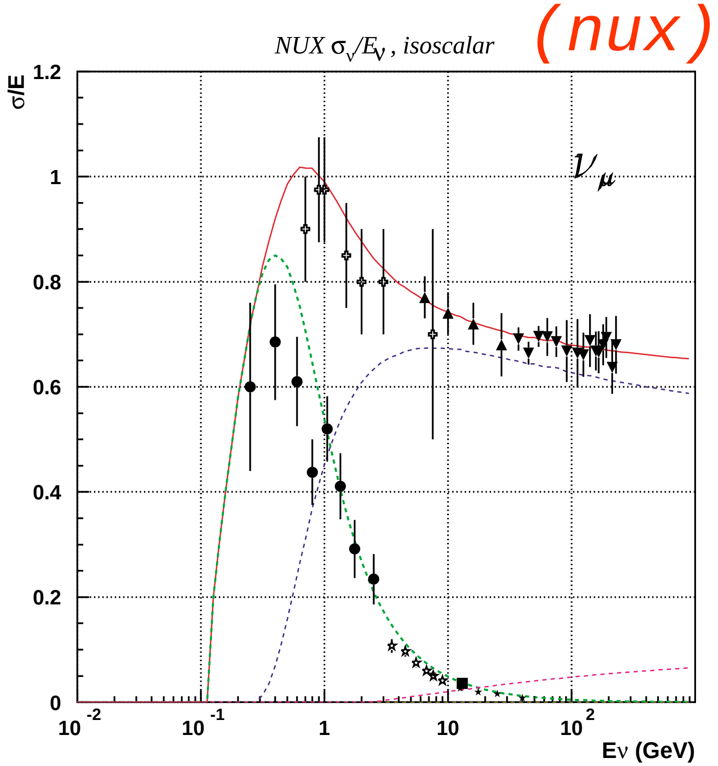
T_p = 240 MeV



André Rubbia, ETH/Zürich, ICARUS Collaboration, 11/2/01

Atmospheric neutrino rates (5 kt x year)

(nux)



——— Total

.... QE

.... DIS

.... Charm

	No osci	Δm^2_{23} (eV^2)			
		5×10^{-4}	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
Muon-like	675 ± 26	515 ± 23	495 ± 22	470 ± 22	455 ± 21
Contained	418 ± 20	319 ± 18	307 ± 18	291 ± 17	282 ± 17
Partially-Contained	257 ± 16	196 ± 14	188 ± 14	179 ± 13	173 ± 13
No proton	260 ± 16	190 ± 14	185 ± 14	170 ± 13	165 ± 13
One proton	205 ± 14	160 ± 13	150 ± 12	145 ± 12	140 ± 12
Multi-prong	210 ± 14	165 ± 13	160 ± 13	155 ± 12	150 ± 12
$P_{lepton} < 400$ MeV	285 ± 17	205 ± 14	200 ± 14	185 ± 14	175 ± 13
$P_{lepton} \geq 400$ MeV	390 ± 20	310 ± 18	295 ± 17	285 ± 17	280 ± 17
Electron-like	380 ± 19	380 ± 19	380 ± 19	380 ± 19	380 ± 19
No proton	160 ± 13	160 ± 13	160 ± 13	160 ± 13	160 ± 13
One proton	120 ± 11	120 ± 11	120 ± 11	120 ± 11	120 ± 11
Multi-prong	100 ± 10	100 ± 10	100 ± 10	100 ± 10	100 ± 10
$P_{lepton} < 400$ MeV	185 ± 14	185 ± 14	185 ± 14	185 ± 14	185 ± 14
$P_{lepton} \geq 400$ MeV	195 ± 14	195 ± 14	195 ± 14	195 ± 14	195 ± 14
NC	480 ± 22	480 ± 22	480 ± 22	480 ± 22	480 ± 22
TOTAL	1535 ± 39				

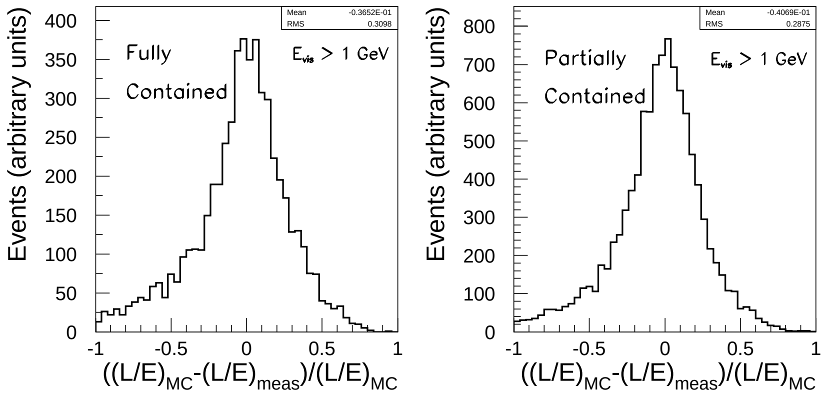
Events/year

Nuclear effects

fully embedded in *FLUKA*
nuclear model

L/E distribution

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

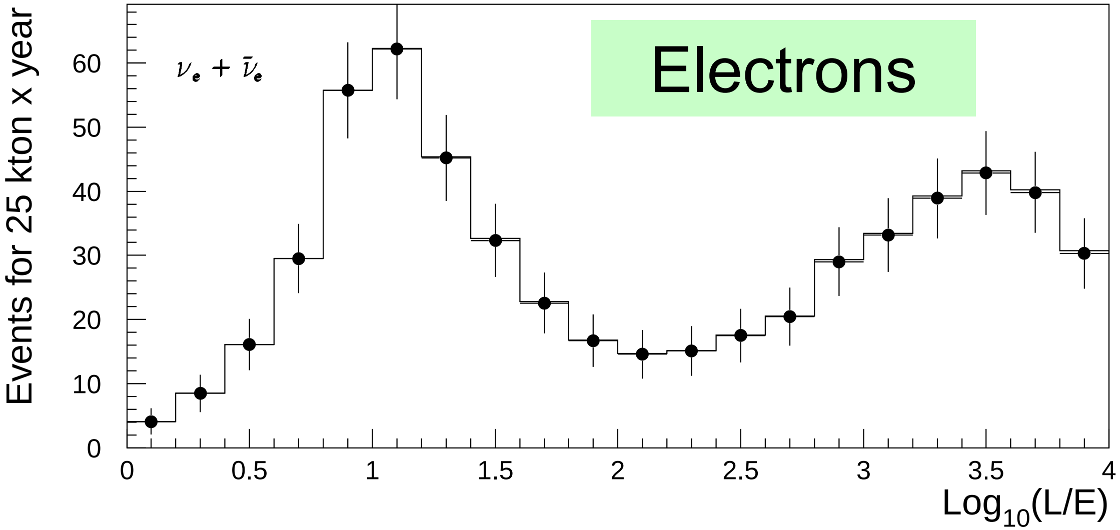


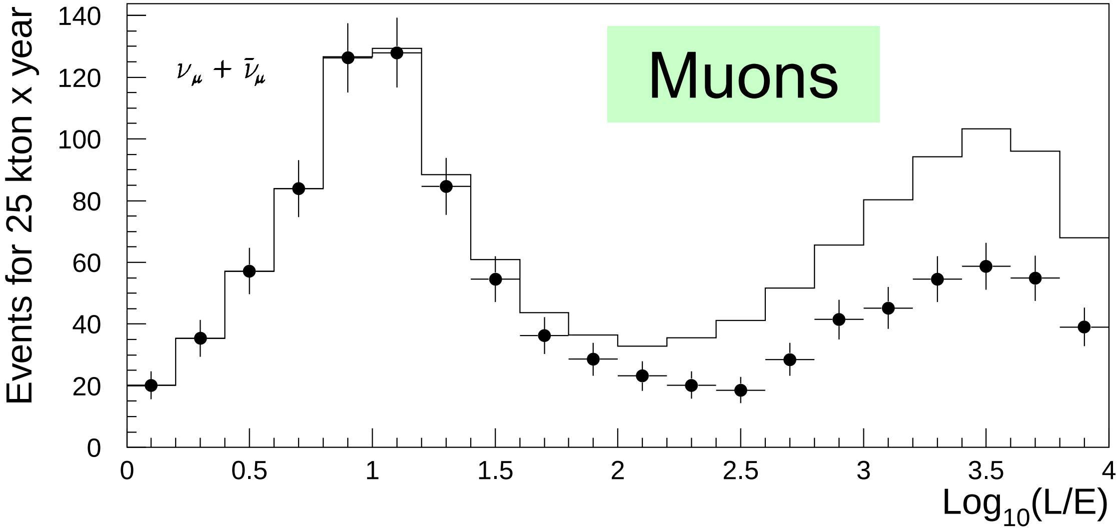
$$\Delta(L/E)_{RMS} \approx 30\%$$

- Oscillation parameters:
  - → ***Δm^2_{32} = 3.5 x 10^{-3} eV^2***
  - → ***sin^2 2Θ_{23} = 0.9***
  - → ***sin^2 2Θ_{13} = 0.1***

- ***Electron sample can be used as a reference for no oscillation case***

25 kt year

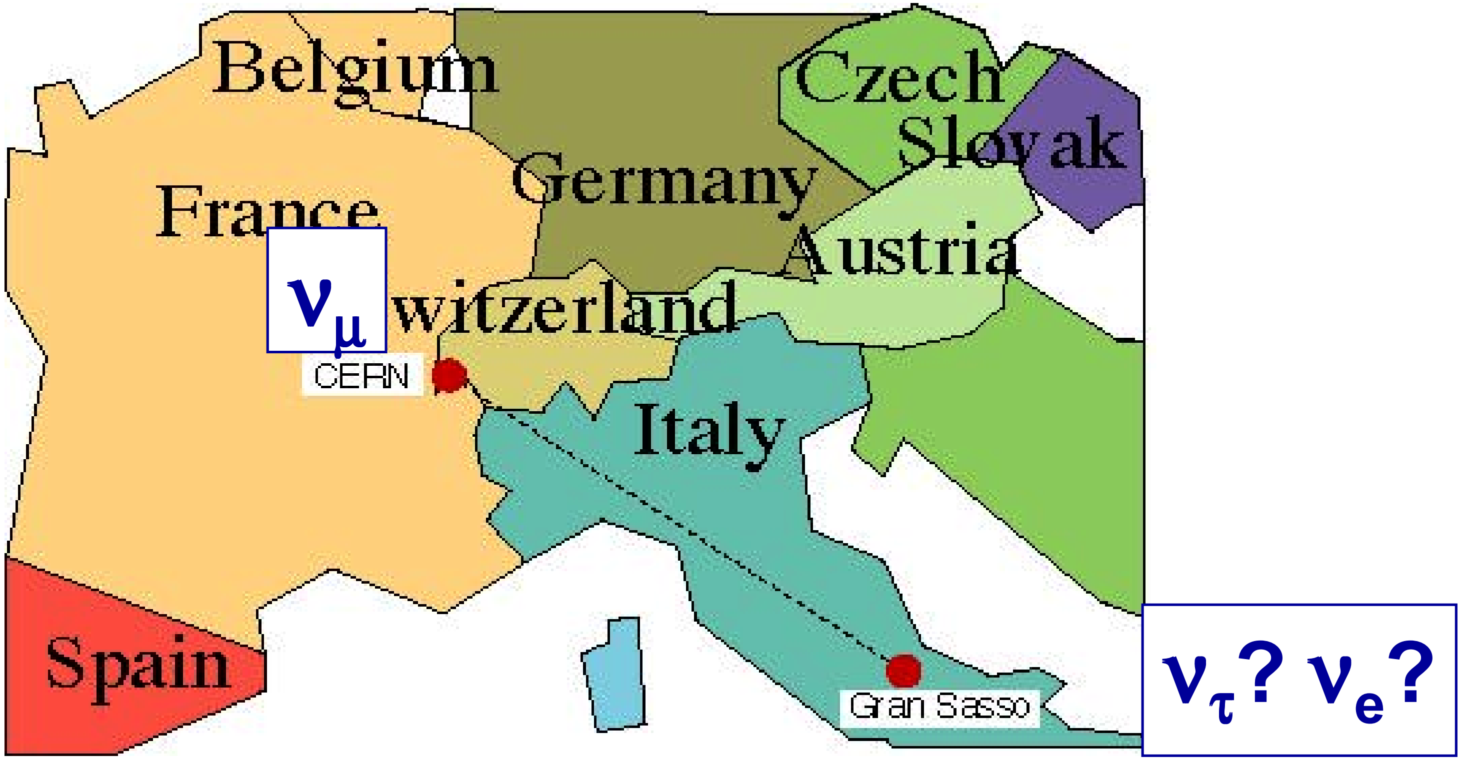


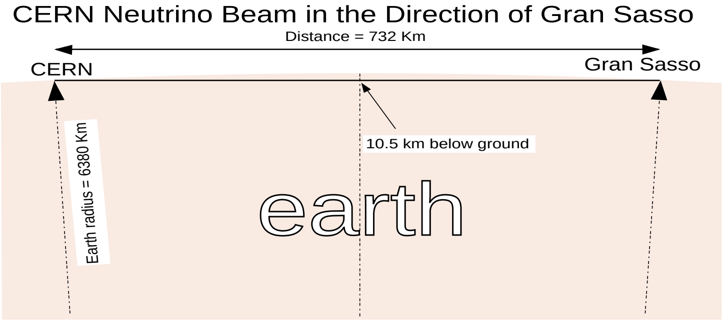


CNGS neutrino beam

The expected ν_e and ν_τ contamination of the CNGS beam are of the order of 10^{-2} and 10^{-7} respect to the dominant ν_μ.

CERN 98-02 - INFN-AE/98-05
CERN-SL/99-034(DI) - INFN/AE-99/05





Planned beam commissioning: May 2005

CNGS event rates

- Primary protons: ***400 GeV; 4x2.3x10^{13} p/cycle; 26.4 s/cycle***
- Pots per year: ***4.5x10^{19} pots*** "shared"; ***200x0.75 days/year***

Process	Rates (events/kton/year)
ν_μ CC	2450
$\bar{\nu}_\mu$ CC	49
ν_e CC	20
$\bar{\nu}_e$ CC	1.2
ν NC	823
$\bar{\nu}$ NC	17

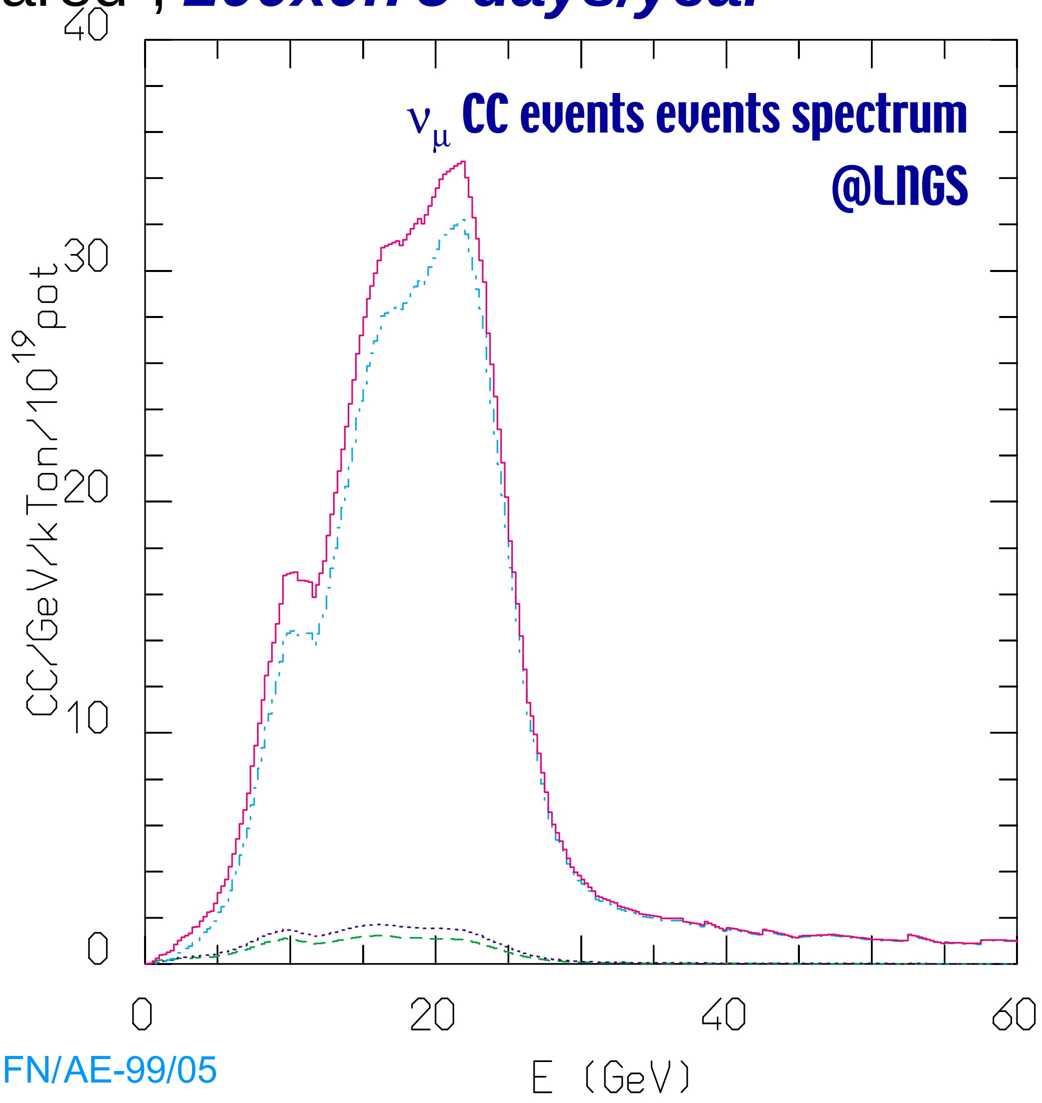
No oscillations

- Optimized for $N_\tau \propto \int \phi_{\nu_\mu}(E)\times\sigma^{CC}_{\nu_\tau}(E)E^{-2}dE$

Δm^2 (eV^2)	Rates (events/kton/year)
1×10^{-3}	2.4
2.5×10^{-3}	15.1
3.5×10^{-3}	29.4
5×10^{-3}	58.6
1×10^{-2}	209.0

ν_τ ***CC event rates***

- 7.6x10^{19} pots/yr "dedicated"



CERN 98-02 - INFN-AE/98-05; CERN-SL/99-034(DI) - INFN/AE-99/05

CNGS events in 5 kton, 4 years running

$\theta_{23} = 45°, \theta_{13} = 7°$

	20 kton×year (4 years running)			
		Δm^2_{23} (eV^2)		
	No osci	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
ν_μ CC	54300	53820	49330	44910
$\bar{\nu}_\mu$ CC	1090	1088	1070	1057
ν_e CC	437	437	437	436
$\bar{\nu}_e$ CC	29	29	29	29
ν NC	17550			
$\bar{\nu}$ NC	410			
$\nu_\mu \to \nu_e$ CC	-	7	74	143
$\nu_\mu \to \nu_\tau$ CC	-	52	620	1250
$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	-	< 1	< 1	1
$\bar{\nu}_\mu \to \bar{\nu}_\tau$ CC	-	< 1	6	13

$\nu_\mu \rightarrow \nu_\tau$ *oscillations (I)*

- Analysis of the electron sample
  - → Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)
  - → Exploit the unique e/π^0 separation

$$\nu_\mu \rightarrow \nu_\tau$$

$$\nu_\tau + N \rightarrow \tau + \text{jet}; \quad \tau \rightarrow e\nu\nu$$

Charged current (CC)

$Br \approx 18\%$

$$\Delta m^2 = 3.5 \times 10^{-3} eV^2 \quad \Rightarrow \quad 110 \;\; events$$

Background:

$$\nu_e + N \rightarrow e + \text{jet}$$

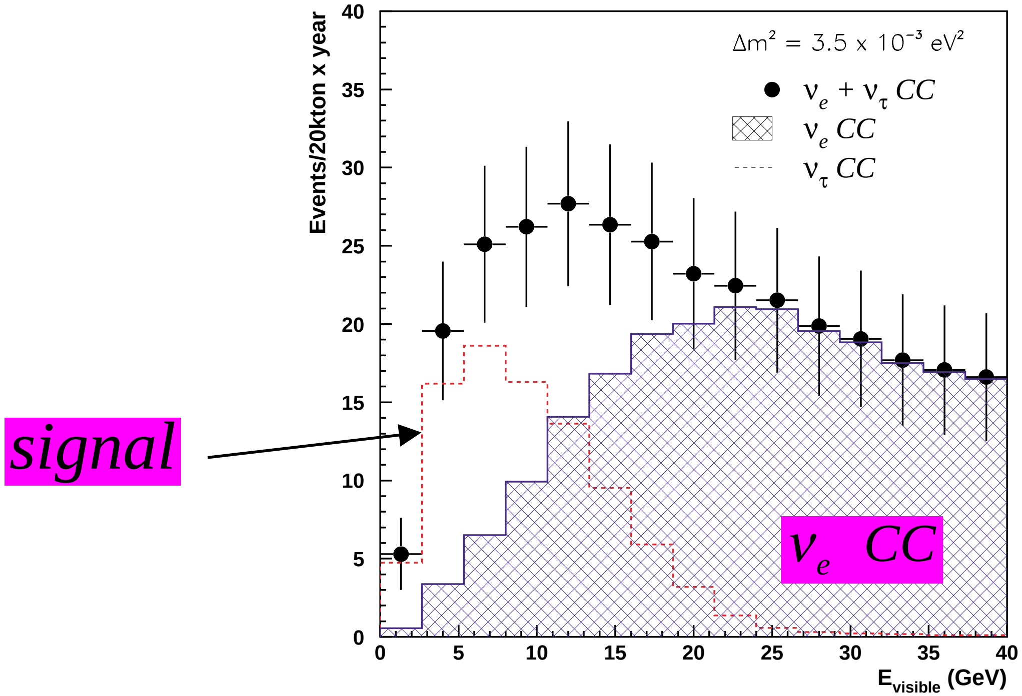
Charged current (CC)

$$470 \;\; \nu_e CC$$

Statistical excess visible before cuts ⇒ this is the main reason for performing this experiment at long baseline !

$\nu_\mu \rightarrow \nu_\tau$ *oscillations (II)*

- Reconstructed visible energy spectrum of electron events clearly evidences excess from oscillations into tau neutrino



signal

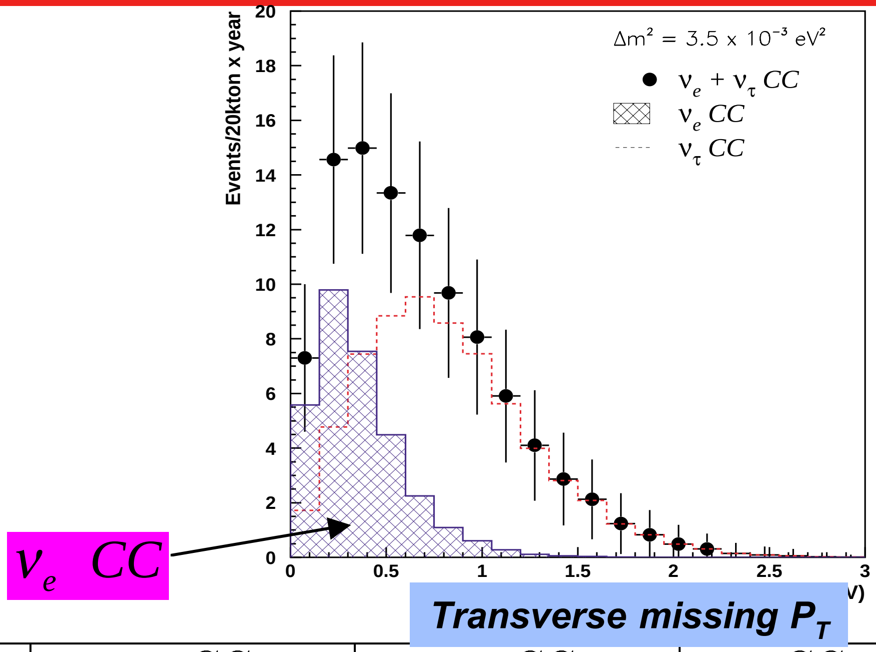
ν_e CC

Reconstructed energy

Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
Initial	100	437	29	9.3	71	111	779
Fiducial volume	88	383	25	8.2	64	97	686
One candidate with momentum > 1 GeV	72	365	25	6.7	50	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522

$\nu_\mu \rightarrow \nu_\tau$ oscillations (III)

- Kinematical selection in order to enhance S/B ratio
- Can be tuned “a posteriori” depending on the actual Δm^2
- For example, with cuts listed below, reduction of background by factor 100 for a signal efficiency 33%



Transverse missing P_T

Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
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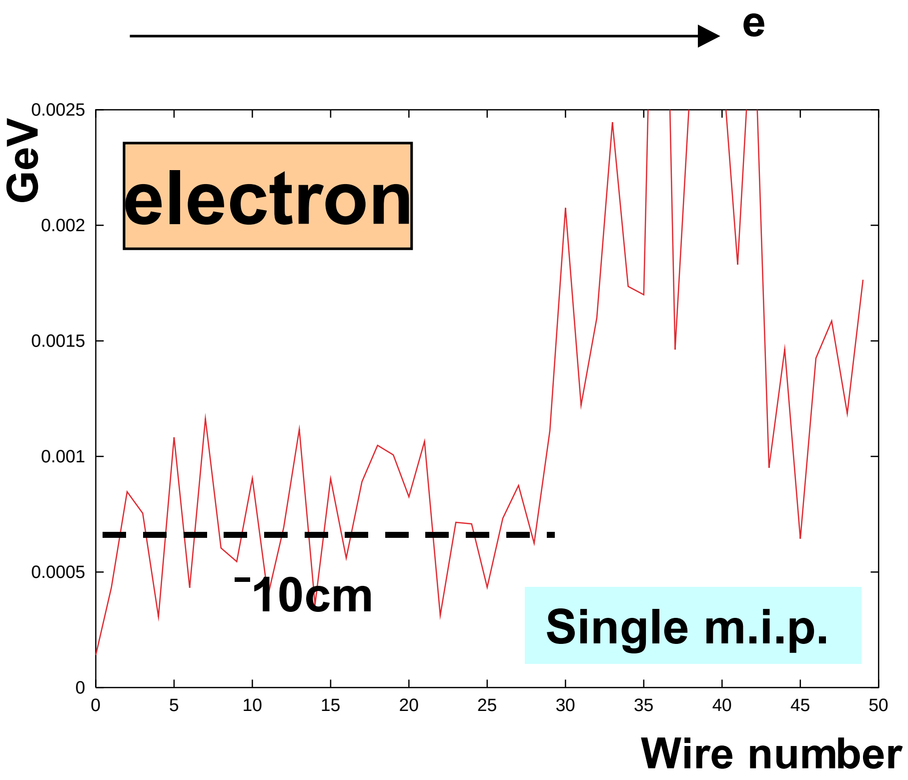
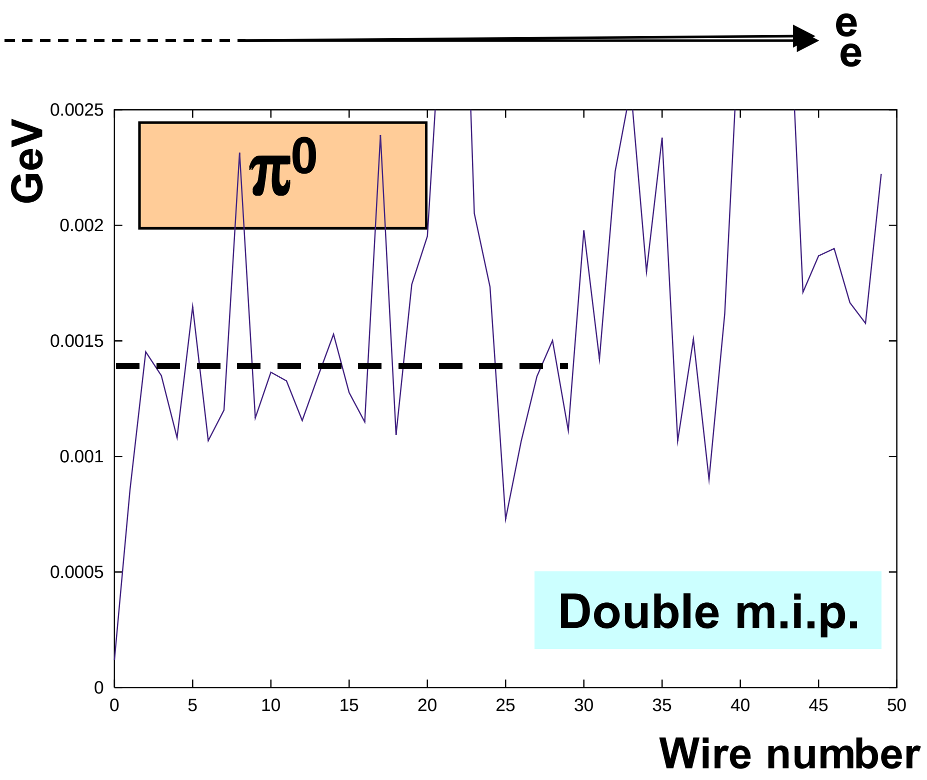
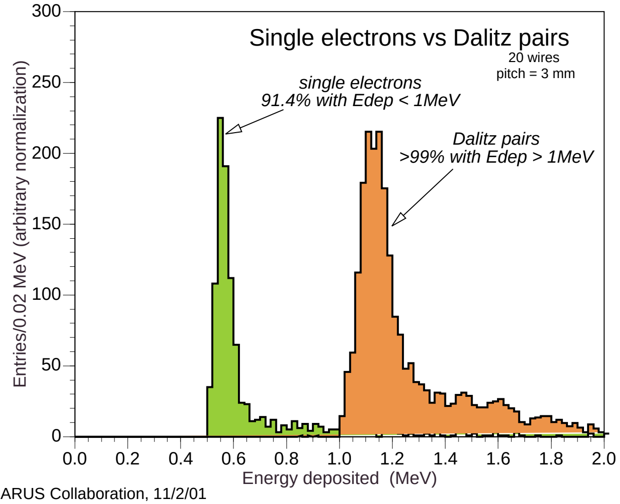
One candidate with momentum > 1 GeV	72	365	25	6.7	50	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522
$P_T^e < 0.9$ GeV	54	31	3	5.0	38	60	421
$P_T^{lep} > 0.3$ GeV	51	29	2	4.7	35	56	397
$P_T^{miss} > 0.6$ GeV	33	4	0.4	3.1	23	37	257

e/π^0 discrimination





Wire pitch = 3 mm ˉ 0 .02 X_0

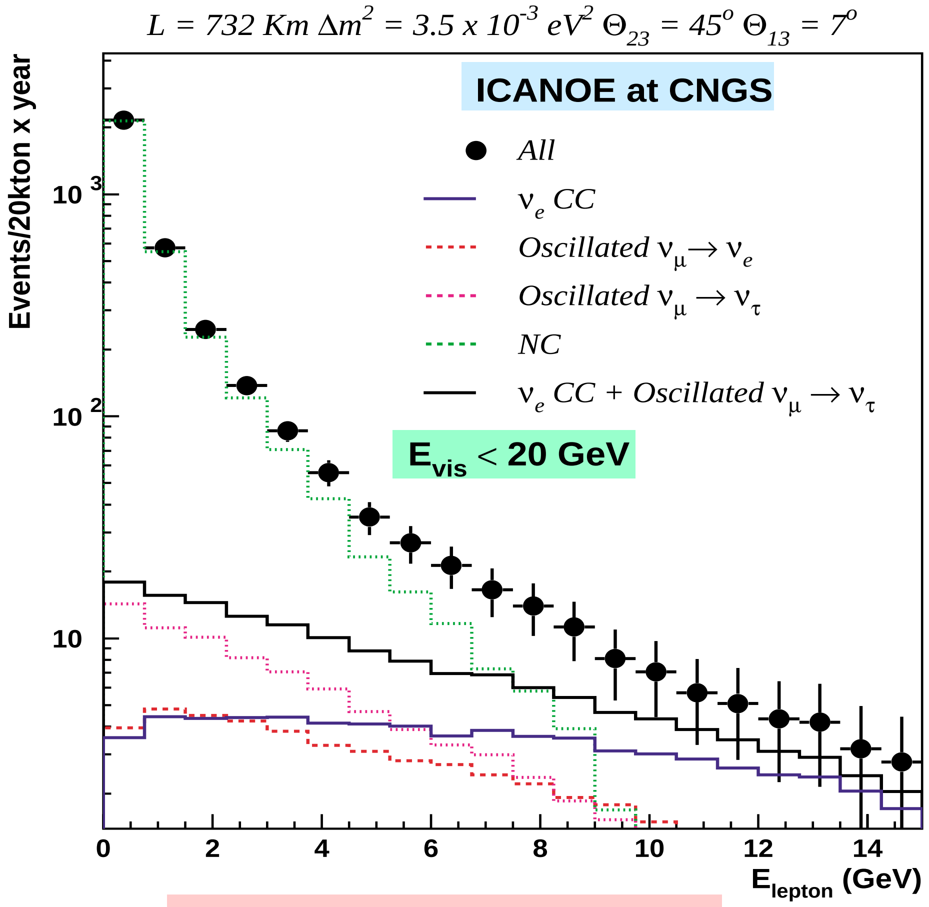


André Rubbia, ETH/Zürich, ICARUS Collaboration, 11/2/01

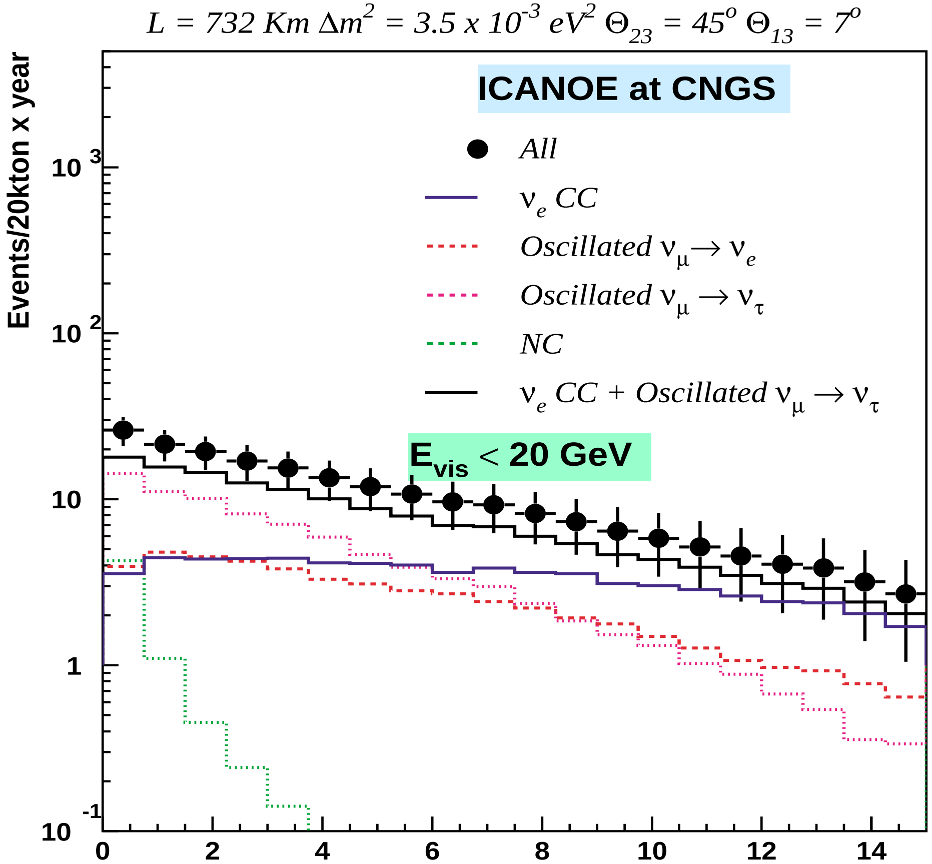
Combined rejection: dE/dx + photon converted within 3 cm of vertex: > 500

ν_e CC versus ν NC discrimination (I)

NC → γ converting within 3 cm (10 samples) from primary vertex considered as electron candidate



NO dE/dx information used

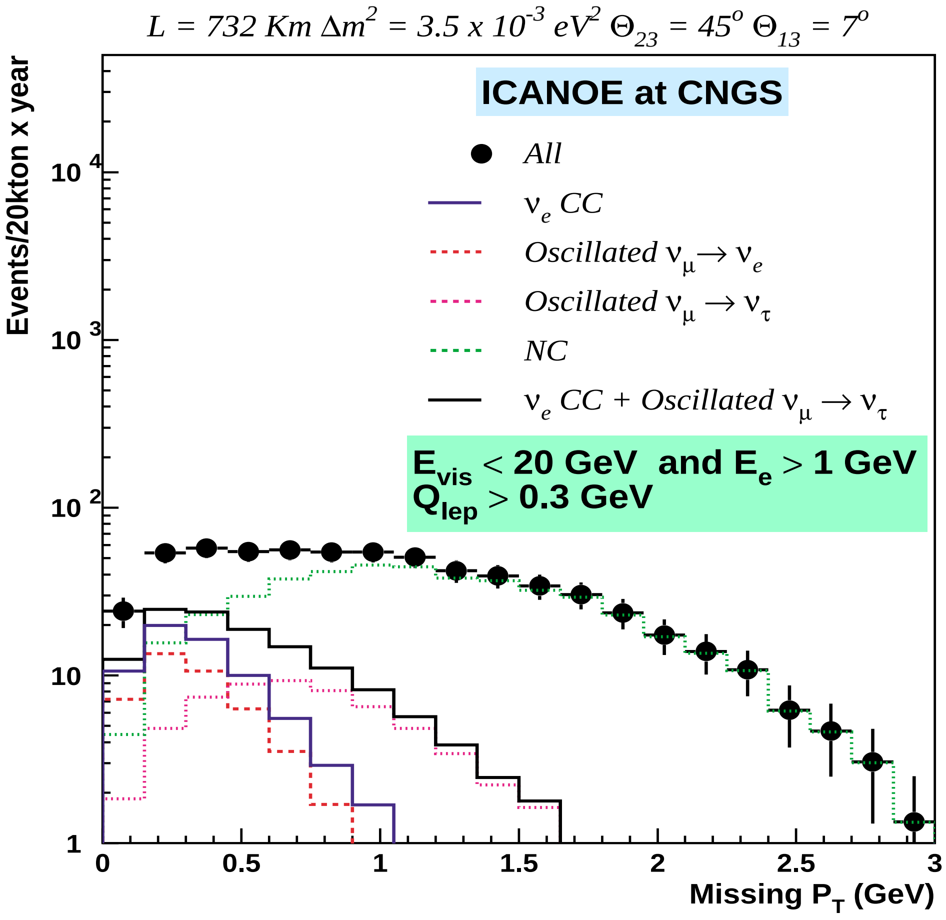


dE/dx information used

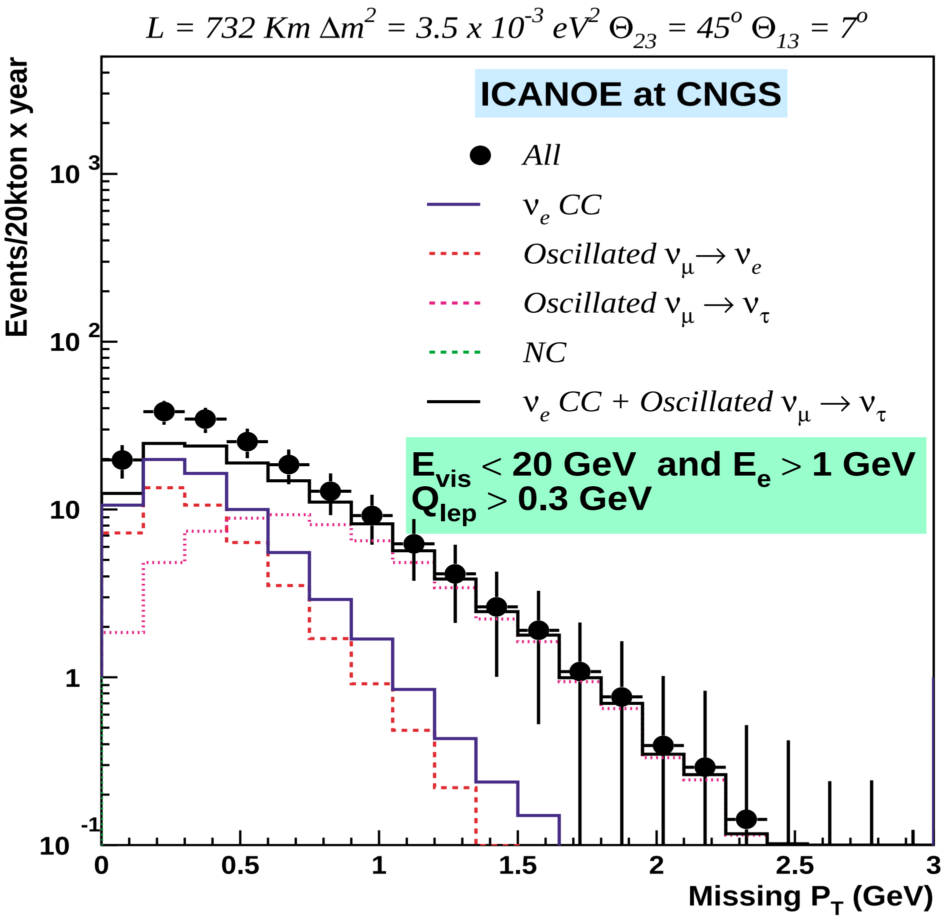
Single vs double m.i.p. algorithm provides **>500 rejection factor**

ν_e CC versus ν NC discrimination (II)

NC rejection → Additional discrimination power provided by event kinematics



NO dE/dx information used



dE/dx information used

Search for $\theta_{13} \neq 0$

ICANOE
4 years

$\Delta m^2_{32} = 3.5\text{x}10^{-3}$ eV^2; $\sin^2 2\theta_{23} = 1$

Cuts: Fiducial, $E_e > 1$ GeV, $E_{vis} < 20$ GeV

$\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV^2, $\theta_{23} = 45^o$

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	Total	Statistical significance
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

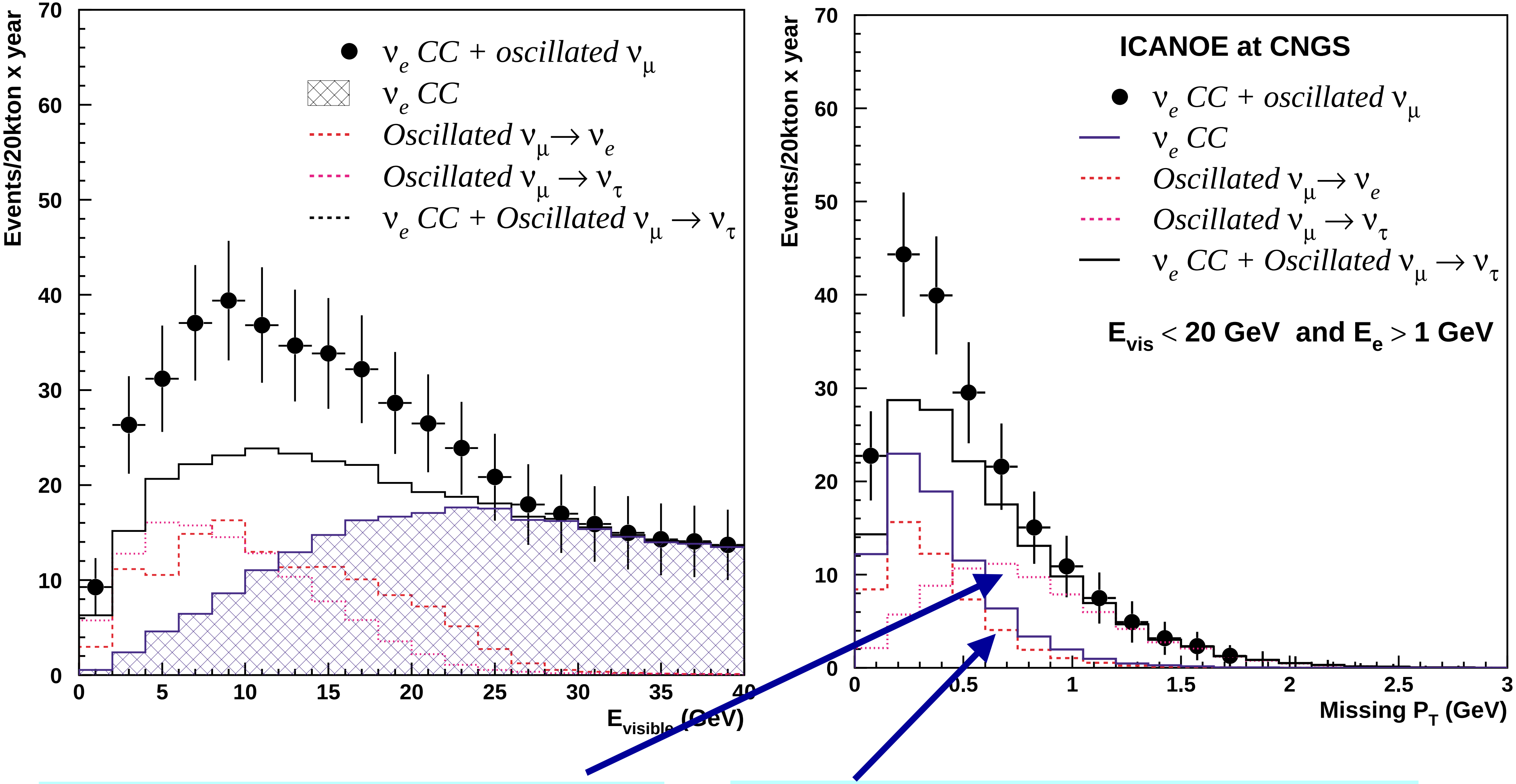
$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2{}_{32}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2{}_{32}$$

$\Delta m^2_{32}=3.5\times10^{-3}\ \mathrm{eV}^2;\ \sin^2 2\theta_{23} = 1\ ;\ \sin^2 2\theta_{13} = 0.05$

Total visible energy

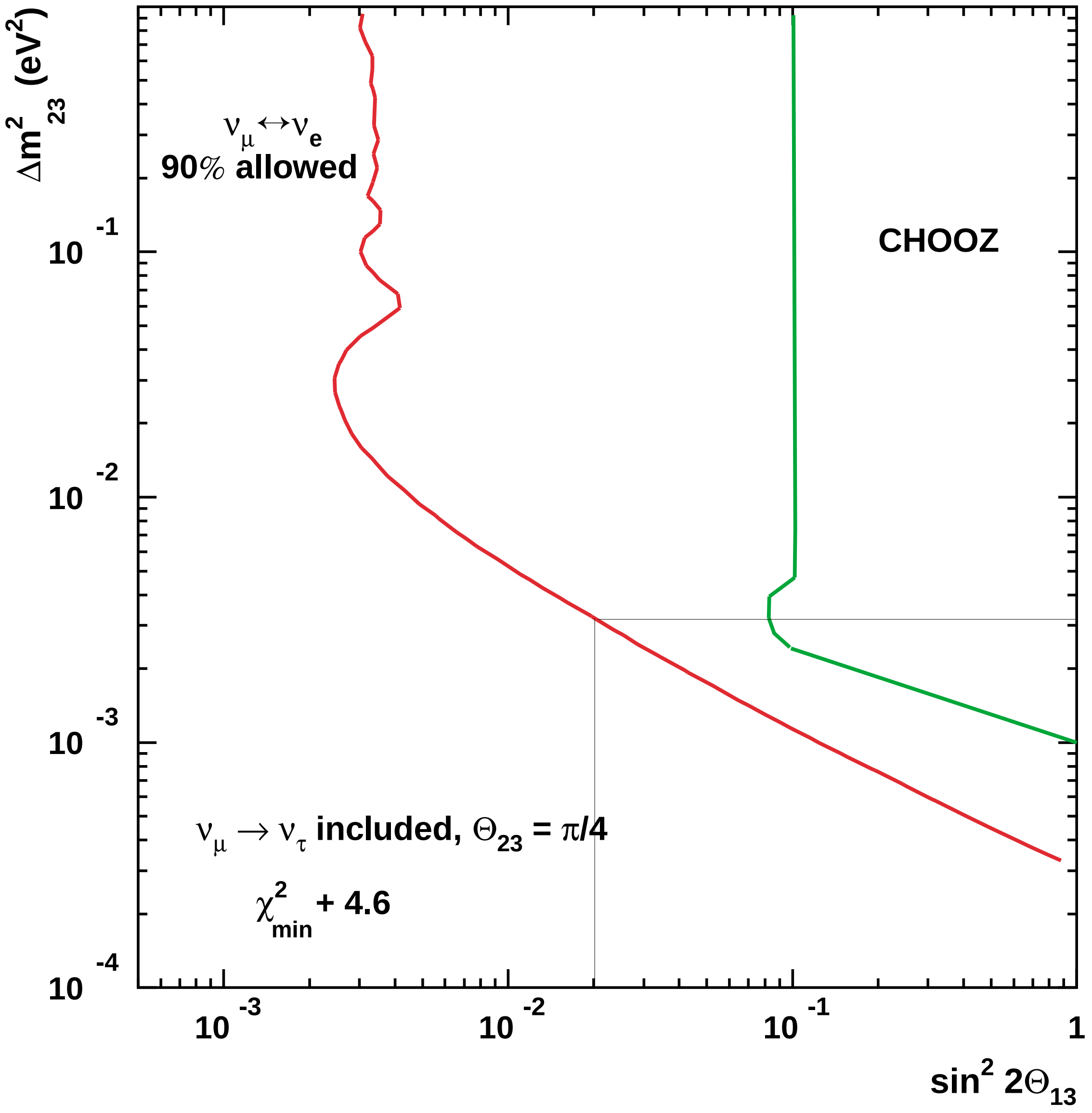
Transverse missing P_T



$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2{}_{32}$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2{}_{32}$$

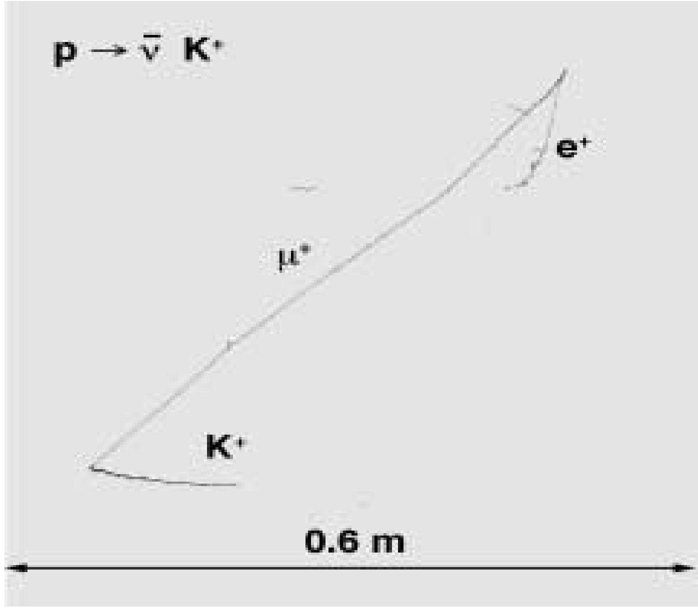
Sensitivity to θ_{13} in three family-mixing



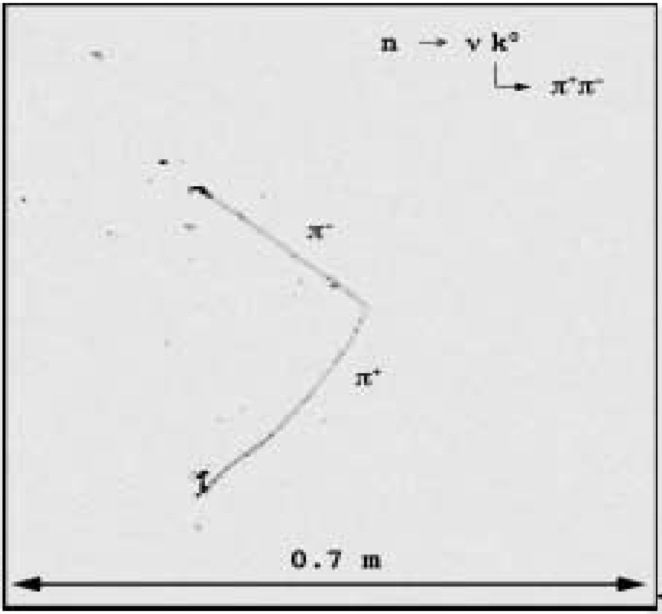
- Sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations in presence of $\nu_\mu \rightarrow \nu_\tau$ (three family mixing)
- Factor 5 improvement on $\sin^2 2\theta_{13}$ at $\Delta m^2 = 3\times10^{-3}$ eV^2
- Almost two-orders of magnitude improvement over existing limit at high Δm^2

Nucleon decay search

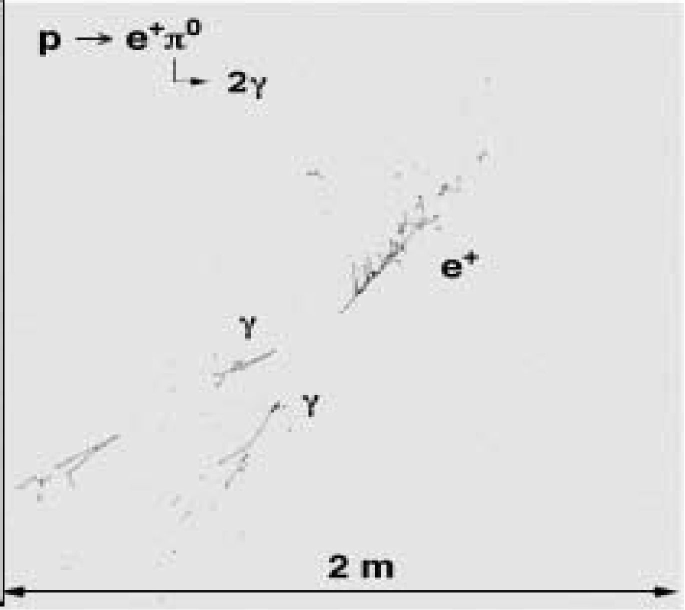
$p \to \nu K^+$ decay



$n \to \nu K^0$ decay



$p \to e^+ \pi^0$ decay



Thanks to excellent tracking and particle *id* capabilities

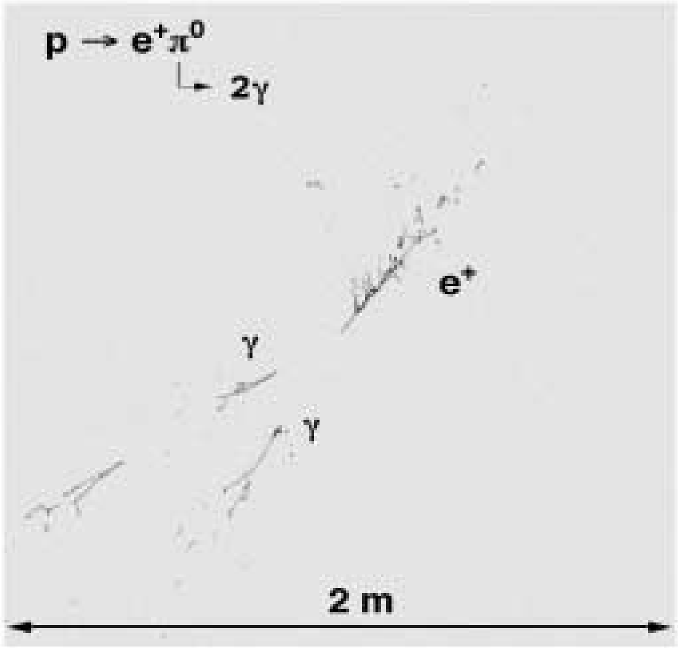
LAr unique tool for

Extremely efficient background rejection

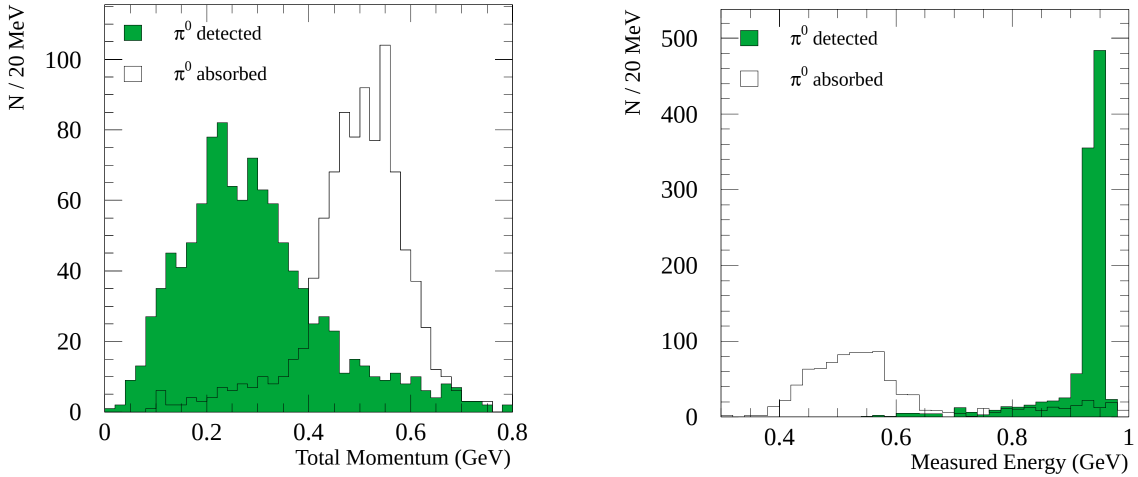
High detection efficiency

Bias-free, fully exclusive channel searches!

$p \to e^+ \pi^0$ decay kinematics



Nuclear effects: pion absorption and rescattering included (FLUKA)

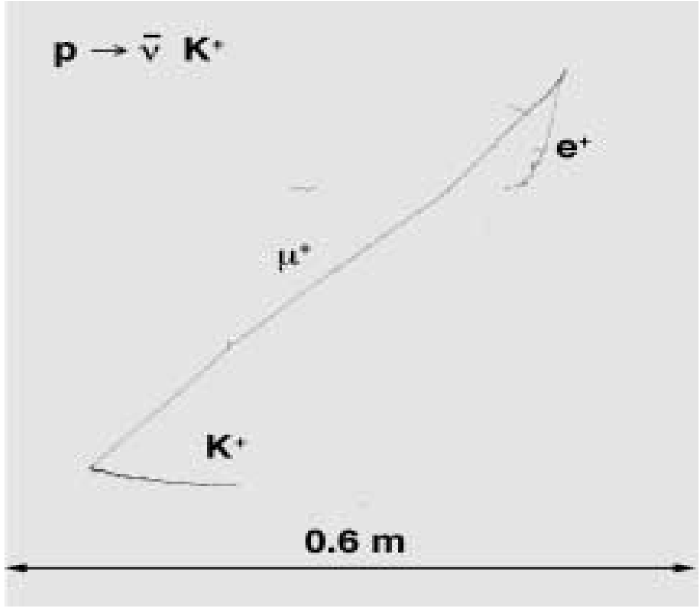


≈45% π^0 absorbed in Ar nucleus

Exclusive Channel Cuts	$p \to e^+ \pi^0$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One π^0	54.00%	6599	2136	15221	5789	8058	3095
One electron	54.00%	6567	2126	19	0	0	0
$T_{proton} < 100$ MeV	52.65%	2715	1448	4	0	0	0
0.93 GeV < Total E < 0.97 GeV	38.30%	28	17	0	0	0	0
Total Momentum < 0.46 GeV	37.50%	2	0	0	0	0	0

Exposure: 1000 kton x year

$p \to K^+\nu$ decay kinematics

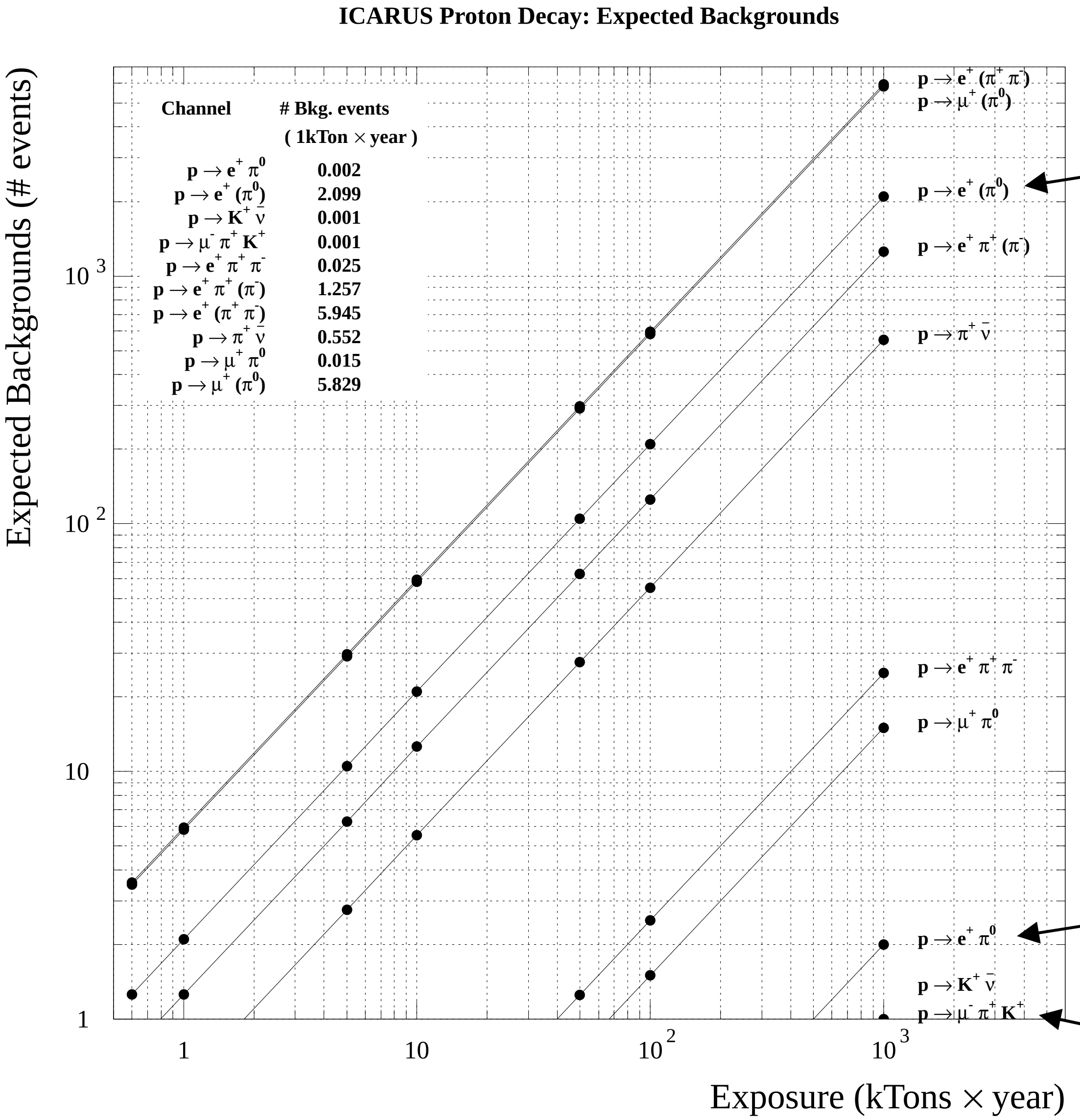


At least we see the kaon!

Cuts	$p \to K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One Kaon	97.30%	310	59	921	214	370	104
No π^0	97.15%	161	30	462	107	197	51
No electrons	97.15%	0	0	455	107	197	51
No muons	97.15%	0	0	0	0	197	51
No charged pions	97.15%	0	0	0	0	109	22
Total Energy < 0.8 GeV	97.15%	0	0	0	0	0	0

Exposure: 1000 kton x year

Proton decay: expected backgrounds vs channel



Channel	# Bkg. events (1kTon × year)
$p \to e^+ \pi^0$	0.002
$p \to e^+ (\pi^0)$	2.099
$p \to K^+ \bar{\nu}$	0.001
$p \to \mu^- \pi^+ K^+$	0.001
$p \to e^+ \pi^+ \pi^-$	0.025
$p \to e^+ \pi^+ (\pi^-)$	1.257
$p \to e^+ (\pi^+ \pi^-)$	5.945
$p \to \pi^+ \bar{\nu}$	0.552
$p \to \mu^+ \pi^0$	0.015
$p \to \mu^+ (\pi^0)$	5.829

$p \to e^+ X$

Extremely good exclusive signal signatures

⇒ Excellent background rejection

Discovery with a single event!

$p \to e^+ \pi^0$

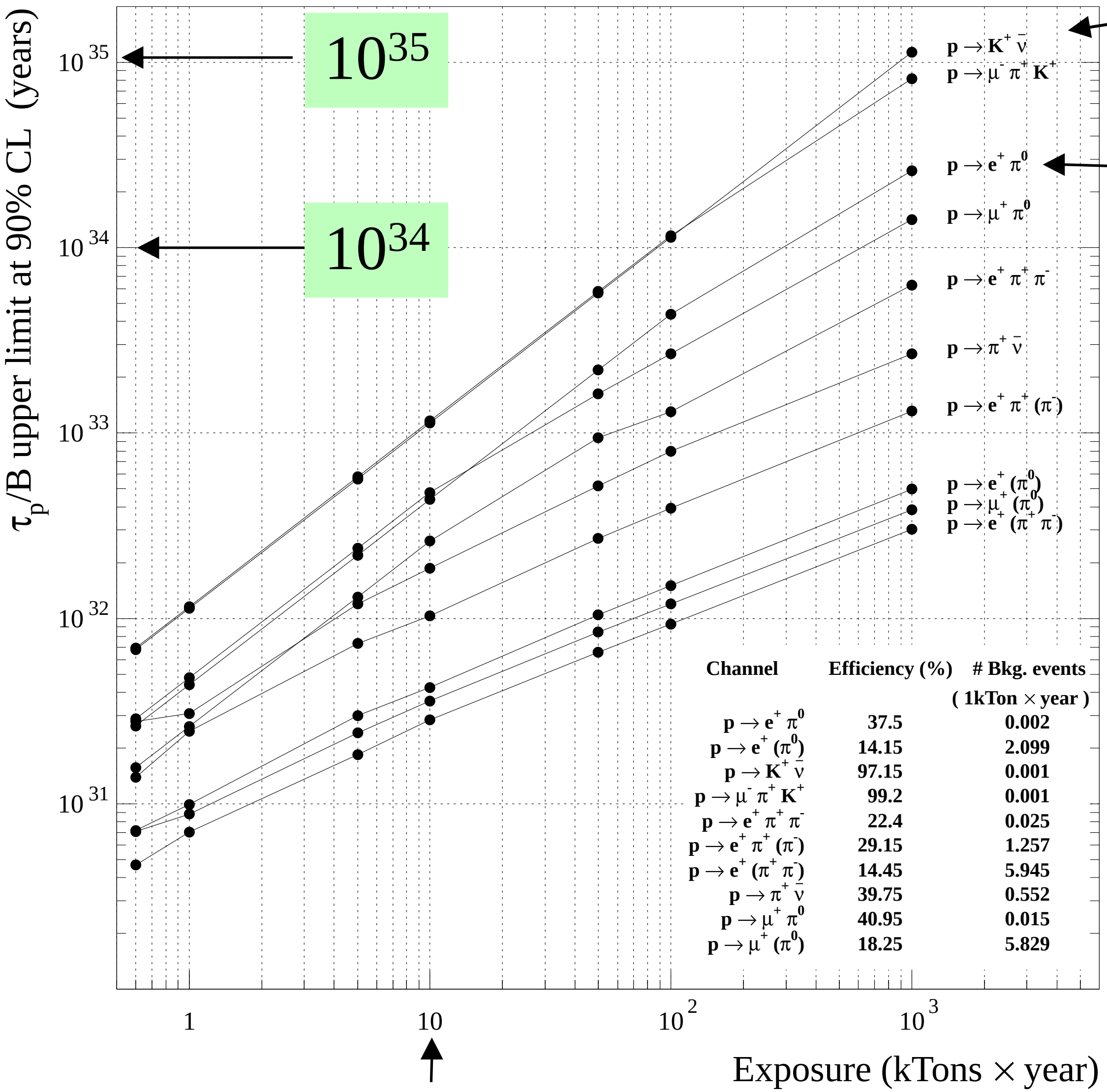
$p \to K^+ \nu$

↑1 Mton x yr

Nuclear effects in backgrounds: fully embedded in *FLUKA* nuclear model

Sensitivity vs exposure

ICARUS: Limits on Proton Decay



Channel	Efficiency (%)	# Bkg. events (1kTon × year)
$p \to e^+ \pi^0$	37.5	0.002
$p \to e^+ (\pi^0)$	14.15	2.099
$p \to K^+ \bar{\nu}$	97.15	0.001
$p \to \mu^- \pi^+ K^+$	99.2	0.001
$p \to e^+ \pi^+ \pi^-$	22.4	0.025
$p \to e^+ \pi^+ (\pi^-)$	29.15	1.257
$p \to e^+ (\pi^+ \pi^-)$	14.45	5.945
$p \to \pi^+ \bar{\nu}$	39.75	0.552
$p \to \mu^+ \pi^0$	40.95	0.015
$p \to \mu^+ (\pi^0)$	18.25	5.829

10^{35}

10^{34}

10 kton x yr

$p \to K^+\nu$

$p \to e^+\pi^0$

Extremely good exclusive signal signatures

⇒ Excellent background rejection

Discovery with a single event!

Nuclear effects in signal: fully embedded in *FLUKA* nuclear model

Exposure needed to reach PDG limit

Channel	Efficiency (%)	Background (1 kton×year)	PDG limit (10^{30} years)	Needed Exposure (in ktons×year)
$p \to e^+ \pi^0$	37.5	<0.1	1600	36.6
$p \to K^+ \bar{\nu}$	97.1	<0.1	670	6.0
$p \to \mu^- \pi^+ K^+$	99.2	<0.1	245	2.2
$p \to e^+ \pi^+ \pi^-$	22.4	<0.1	82	3.2
$p \to \pi^+ \bar{\nu}$	39.7	0.6	25	0.6
$p \to \mu^+ \pi^0$	40.9	<0.1	473	9.9
$n \to e^- K^+$	96.9	<0.1	32	0.3
$n \to e^+ \pi^-$	47.9	<0.1	158	2.3
$n \to \mu^- \pi^+$	48.2	<0.1	100	1.5
$n \to \pi^0 \bar{\nu}$	44.8	0.5	112	2.4

Given our poor knowledge of the physics at the GUT scale, we need to look for all possible channels, in unbiased, free of background searches.

Neutrino factory

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$\nu_\mu \to \nu_e \to e^-$	appearance
ν_μ	disappearance
$\nu_\mu \to \nu_\tau \to \tau^-$	appearance
$\bar{\nu}_e$	disappearance
$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu+$	appearance
$\bar{\nu}_e \to \bar{\nu}_\tau \to \tau+$	appearance

Plus their charge conjugates with μ^+ beam

Ideal detector should be able to measure **12 different processes**

⇨ Detect: μ^+, μ^-, e, NC, τ

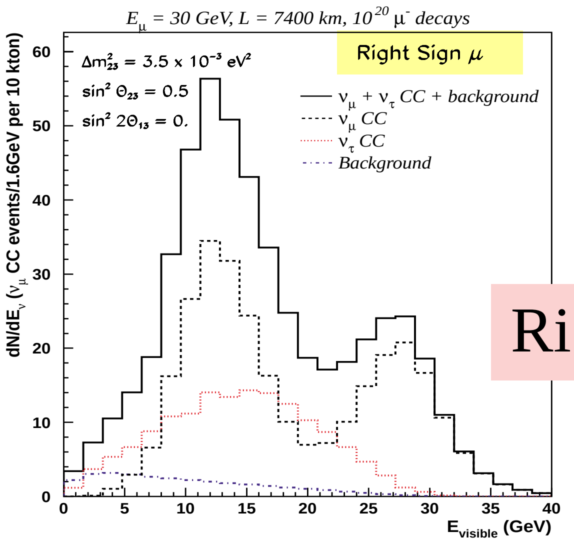
⇨ Various baselines

⇨ Various muon energies

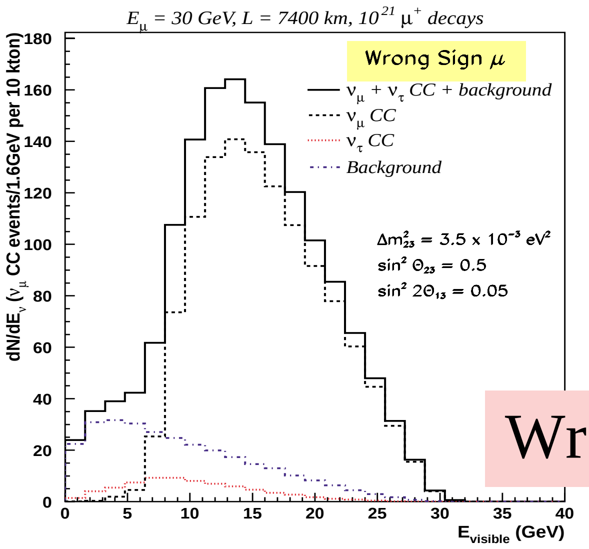
O(10^{21}) μ required

	Baseline →	L=732 km	L=2900 km	L=7400 km
	Muon Energy →	$E_\mu = 5$ GeV	$E_\mu = 30$ GeV	$E_\mu = 30$ GeV
μ^- 10^{21} decays	ν_μ CC	6150	72000	11300
	ν_μ NC	1590	20600	3400
	$\bar{\nu}_e$ CC	2150	27600	4370
	$\bar{\nu}_e$ NC	630	9950	1500
μ^+ 10^{21} decays	$\bar{\nu}_\mu$ CC	2450	31900	5000
	$\bar{\nu}_\mu$ NC	750	11200	1750
	ν_e CC	5550	64500	9900
	ν_e NC	1350	18300	2900

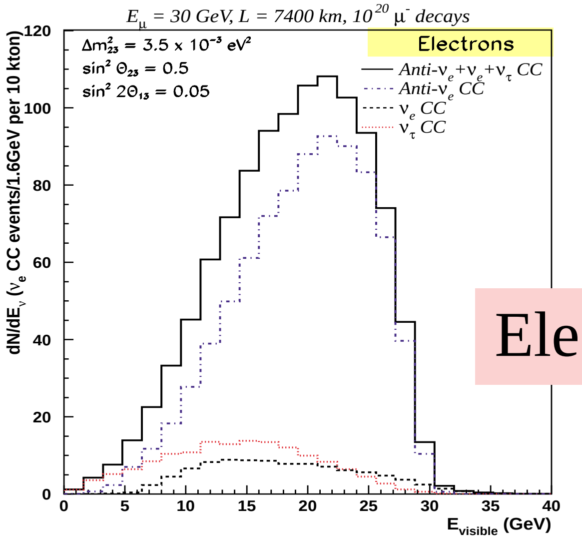
Event classes



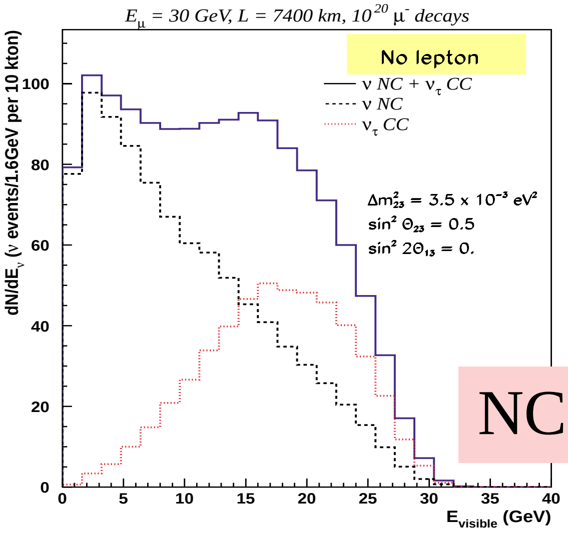
Right sign μ



Wrong sign μ



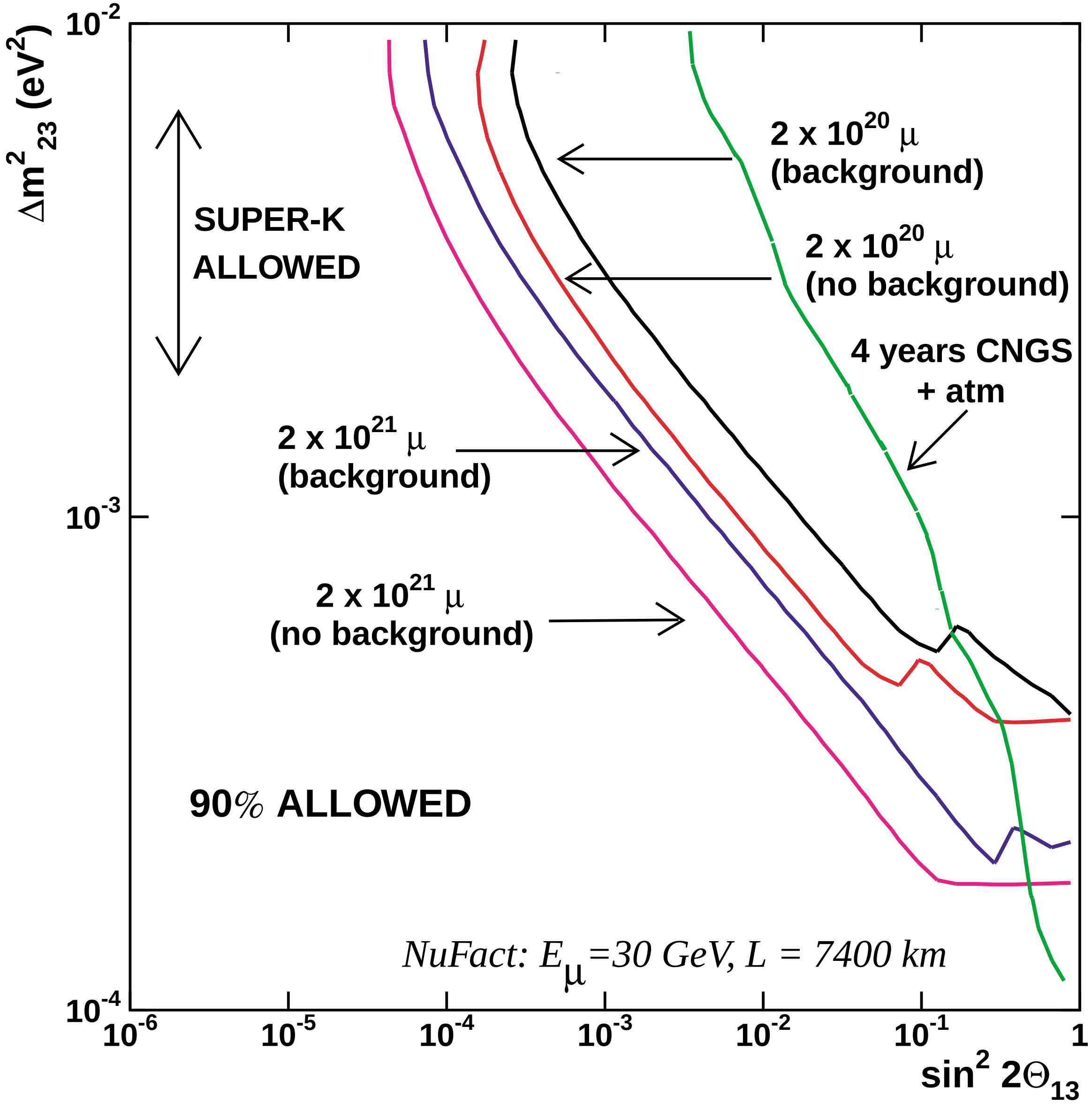
Electrons



NC-like

Combining all classes⇒ (over-constrained) sensitivity to all oscillations!

Expected sensitivity to θ_{13} at a neutrino factory



- ✭ Very long baseline: L=7400 km
- ✭ Search for wrong-sign muons
- o Strongly depends on background level for wrong-sign muons
- o Might be the only way to measure θ_{13}

Conclusion

- The ICARUS T600, based on the novel ICARUS technique, is now almost ready.
- Given the past record with previous prototypes, we are confident that also the T600 will come into operation smoothly…
  - → ***We hope to present the first 20 m long tracks with 3 mm granularity soon!***
  - → It will demonstrate that the ***technique***, even on such large scales, is now ***mature***.
- Then, the first T600 Module should be installed into the Gran Sasso tunnel.
- Operation inside tunnel in the course of next year (2002) should allow an appropriate scaling up for the increase of the mass
- The technology, once it is ***scaled to the "right" size***, will become a powerful tool in particle physics, in particular in order to explore neutrino oscillations from both accelerator and non-accelerator beams and proton decay.