The ICARUS Project

FRONTIERS IN CONTEMPORARY PHYSICS II

Vanderbilt University, March 5-10, 2001

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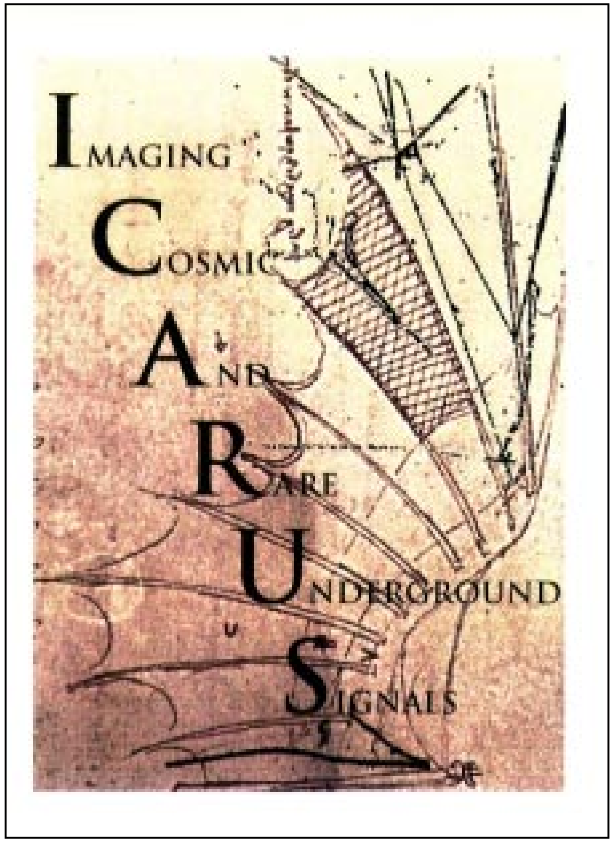
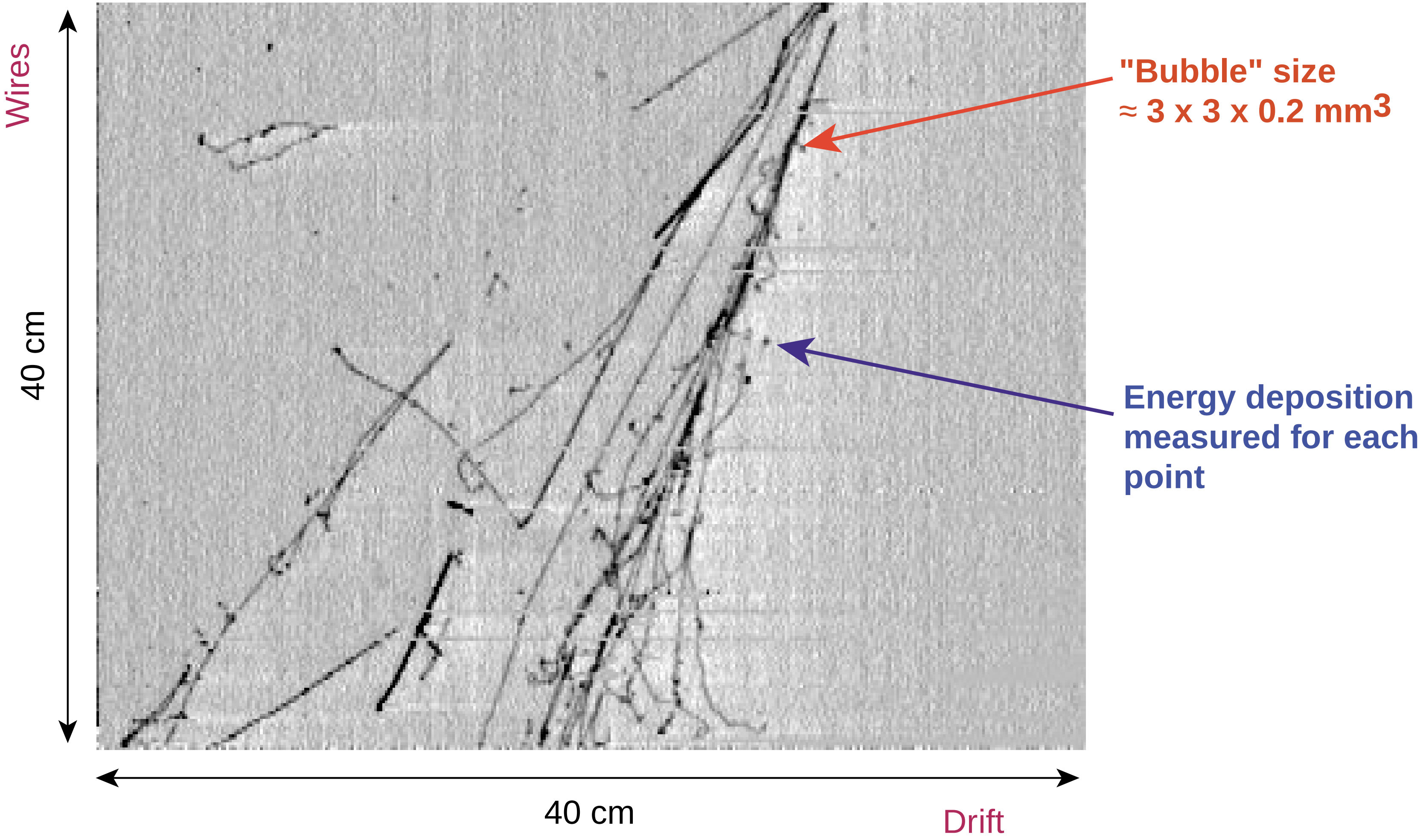


- ✔ Detection Principle
- ✔ The T600 Module
- ✔ Physics Programme:
  - Atmospheric neutrinos
  - Solar and Supernova neutrinos
  - Long Baseline neutrinos
  - Proton decay searches

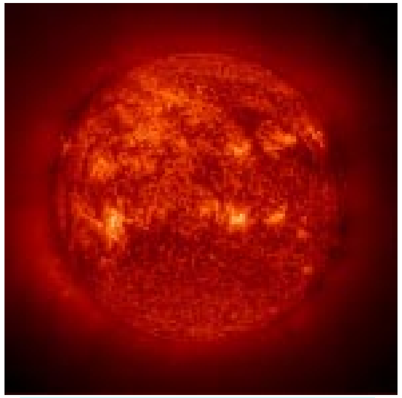
ICARUS liquid argon imaging TPC

- 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.

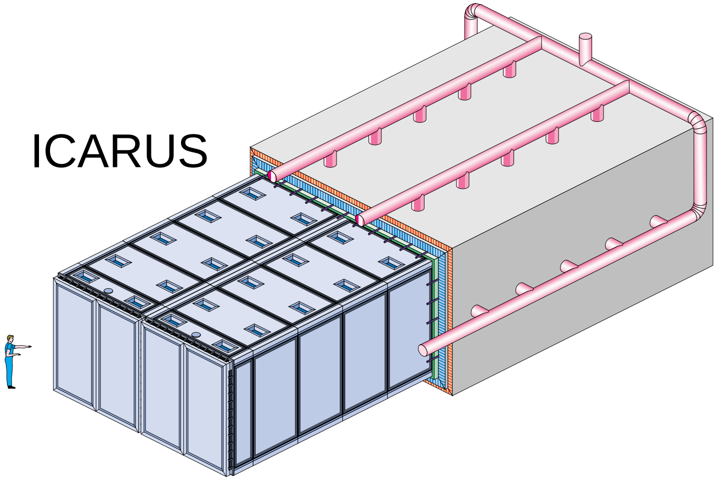


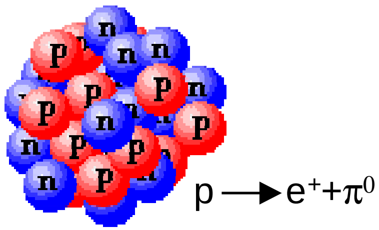
Neutrino and rare process physics with ICARUS

Supernova neutrinos



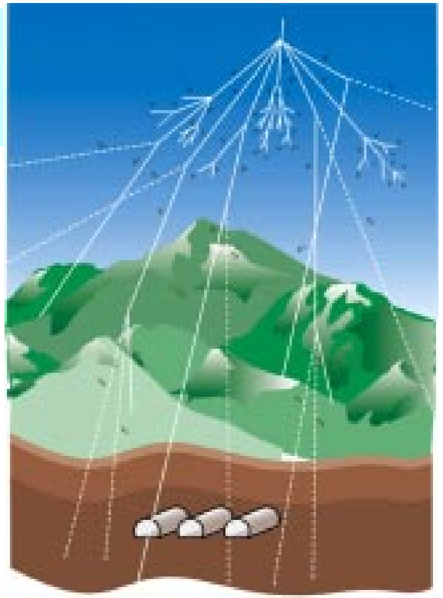
Solar neutrinos





Nucleon stability

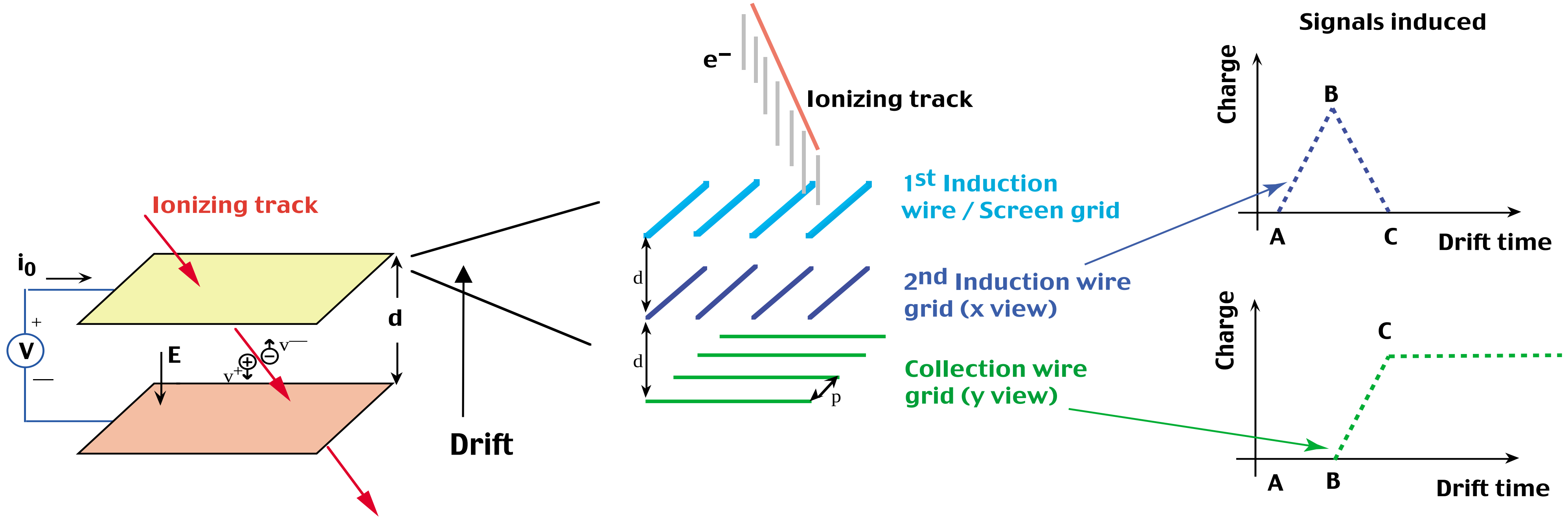
Atmospheric neutrinos



Long Baseline neutrinos

Event imaging in liquid Argon

★ 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.



$E = 500$ V/cm

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

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

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

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 (3 tons, 50 l) → "15 ton" → T600 (2x300 ton) ⇢ ?

We are here! (T600)

Cooperation with specialized industries:

→ **Air Liquide** for Cryostat and Argon purification
→ BREME Tecnica for internal detector mechanics
→ CAEN for readout electronics

ICARUS 15 ton (10m³) prototype (1999-2000)

T15 installation @ LNGS (Hall di Montaggio)

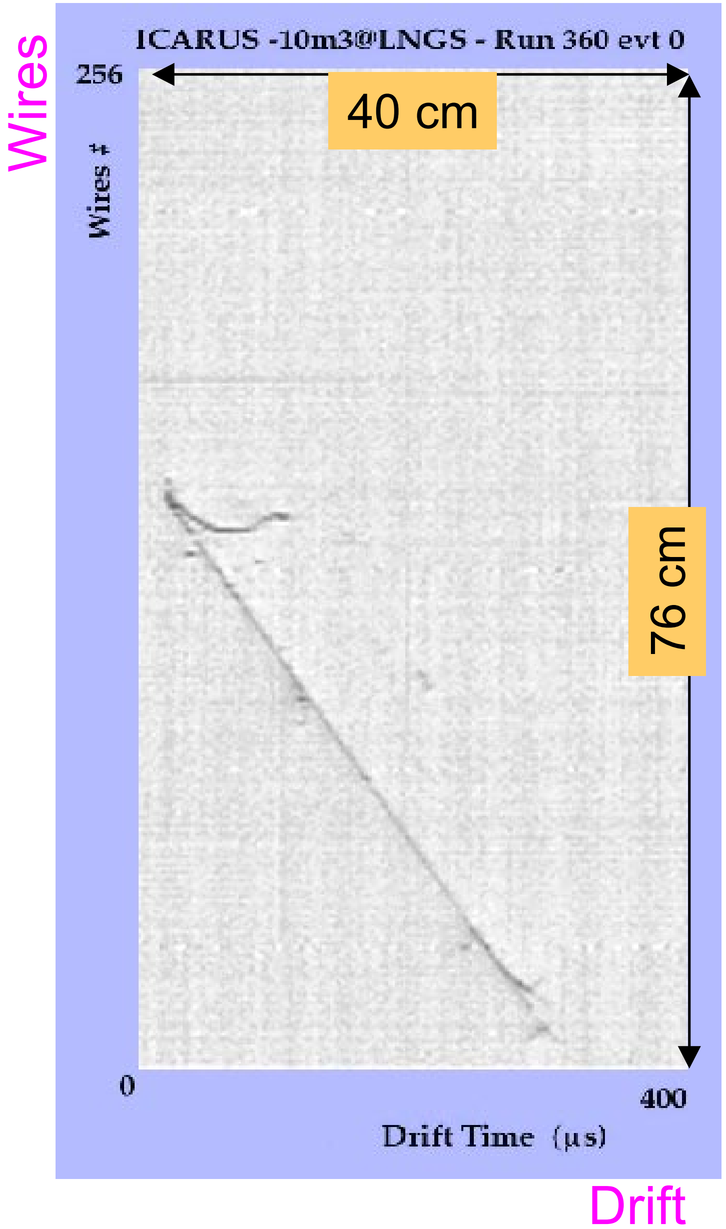
- A major step of the R&D program has been the construction and operation of a **10m³ prototype**
  1. **Test of the cryostat technology**
  2. **Test of the "variable-geometry" wire chamber**
  3. **Test of the liquid phase purification system**
  4. **Test of trigger via scintillation light**
  5. **Large scale test of final readout electronics**

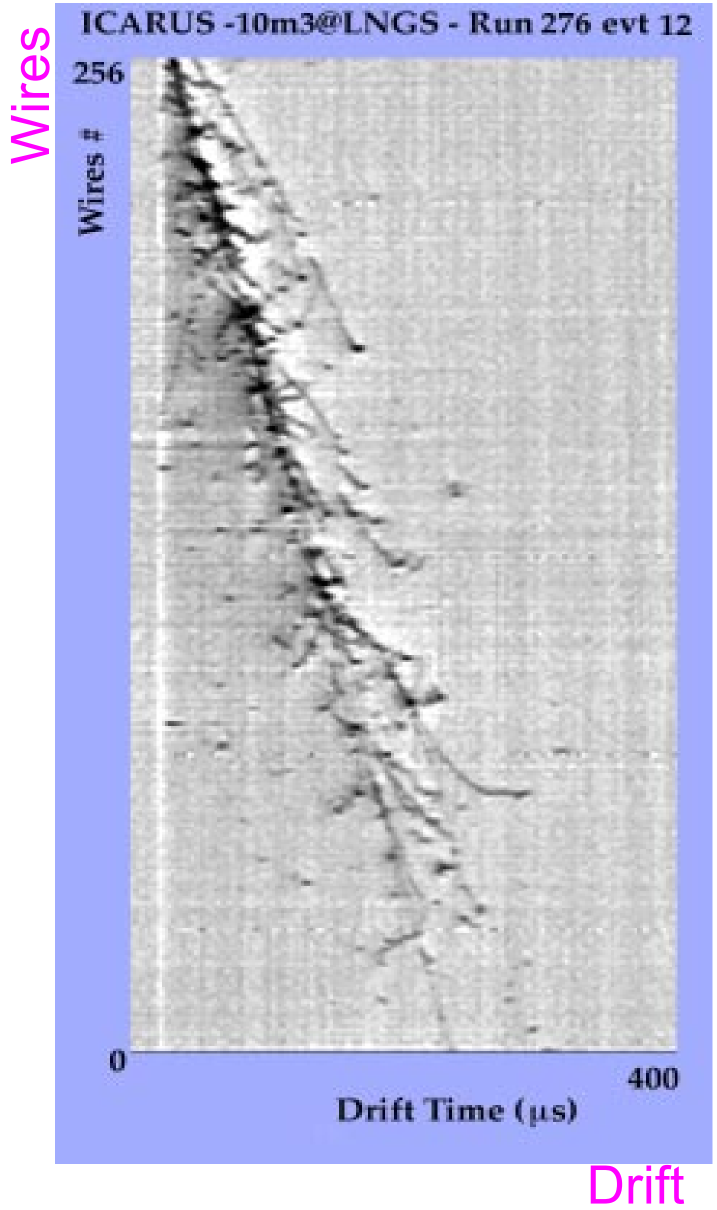
➜ *First operation of a 15 ton LAr mass as an actual "detector"*

Tracks in 15 ton prototype

10m³ Module
at LNGS

Cosmic Ray tracks recorded during the 10 m³ operation



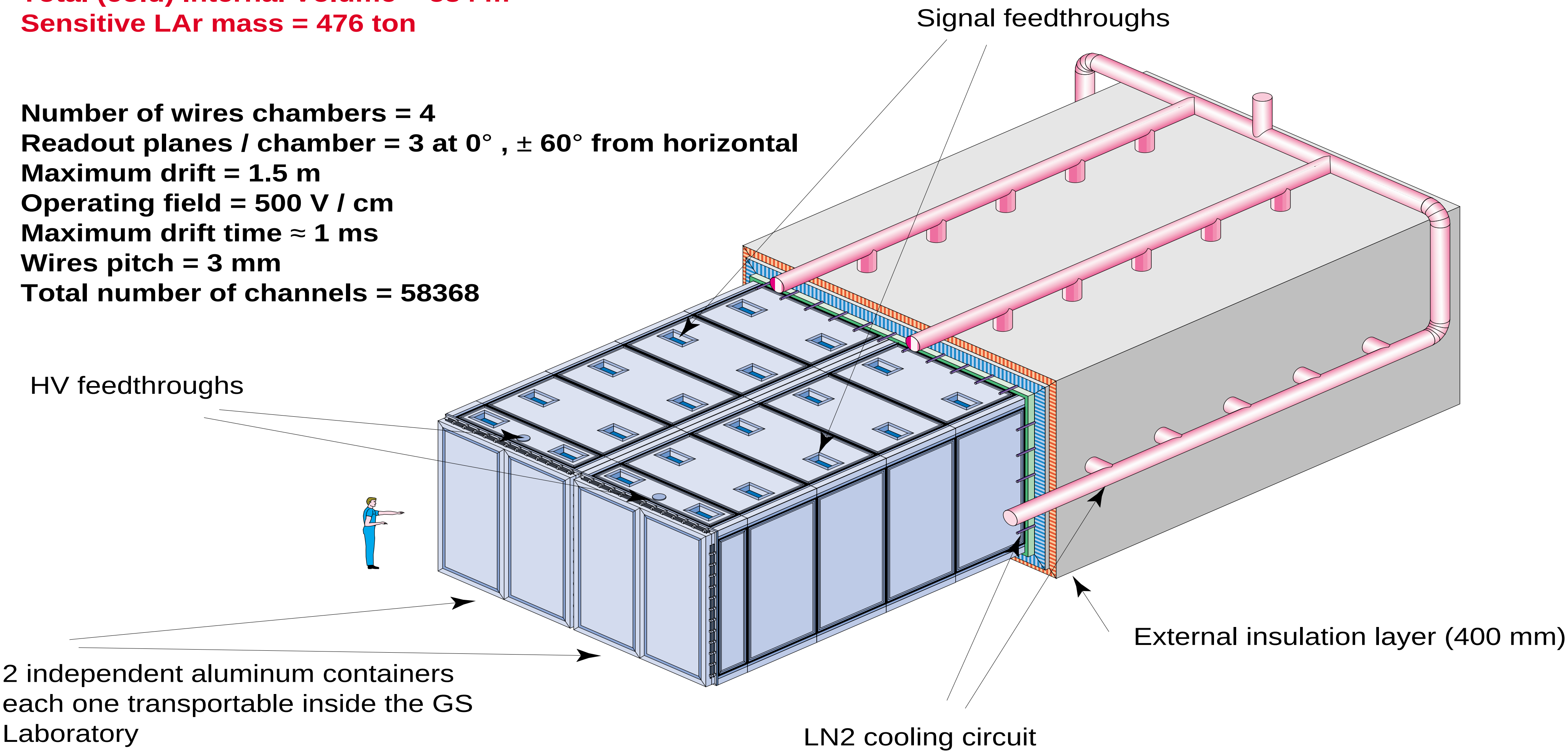


The ICARUS T600 module

Under construction

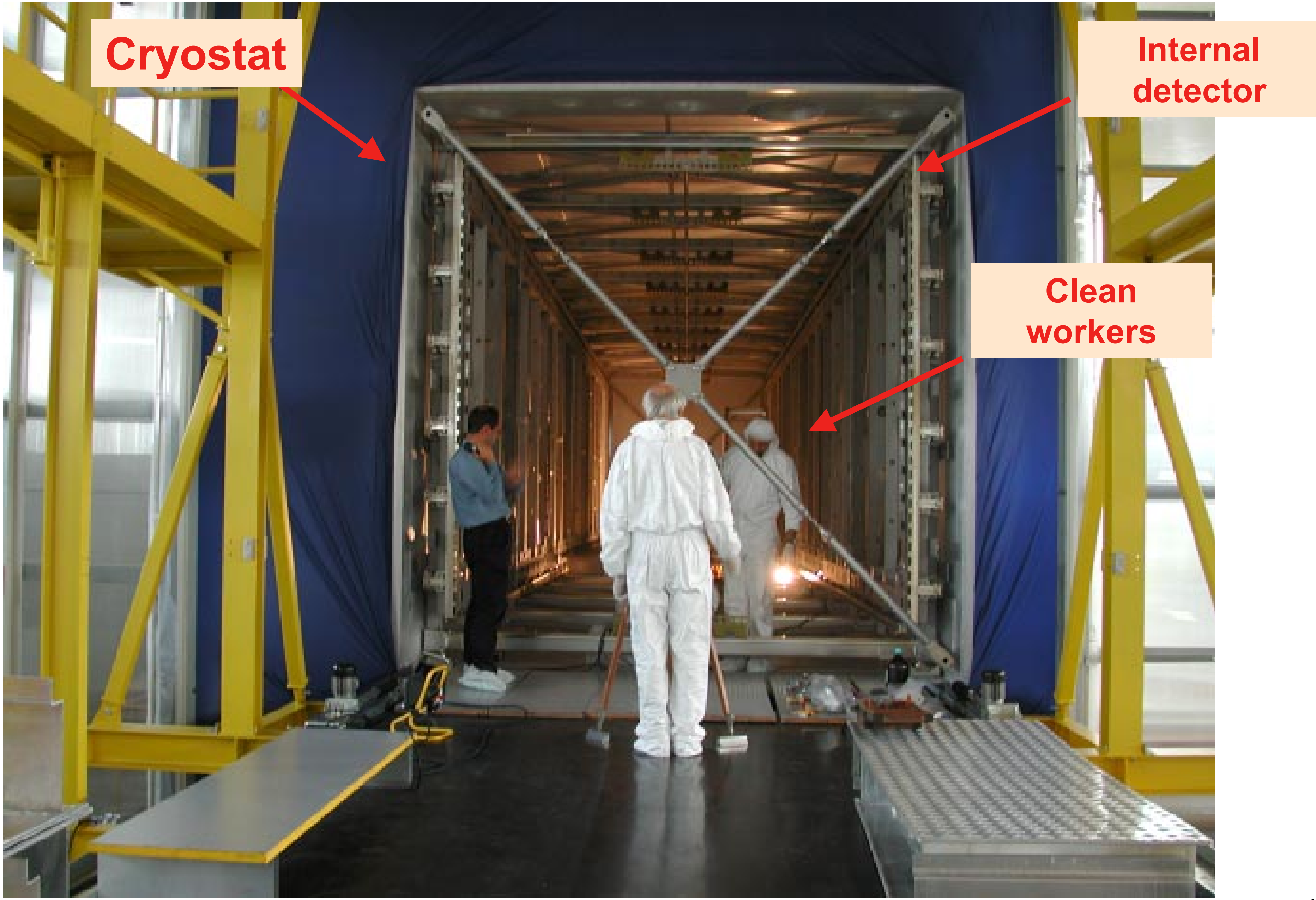
Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m
Total (cold) Internal Volume = 534 m^3
Sensitive LAr mass = 476 ton

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



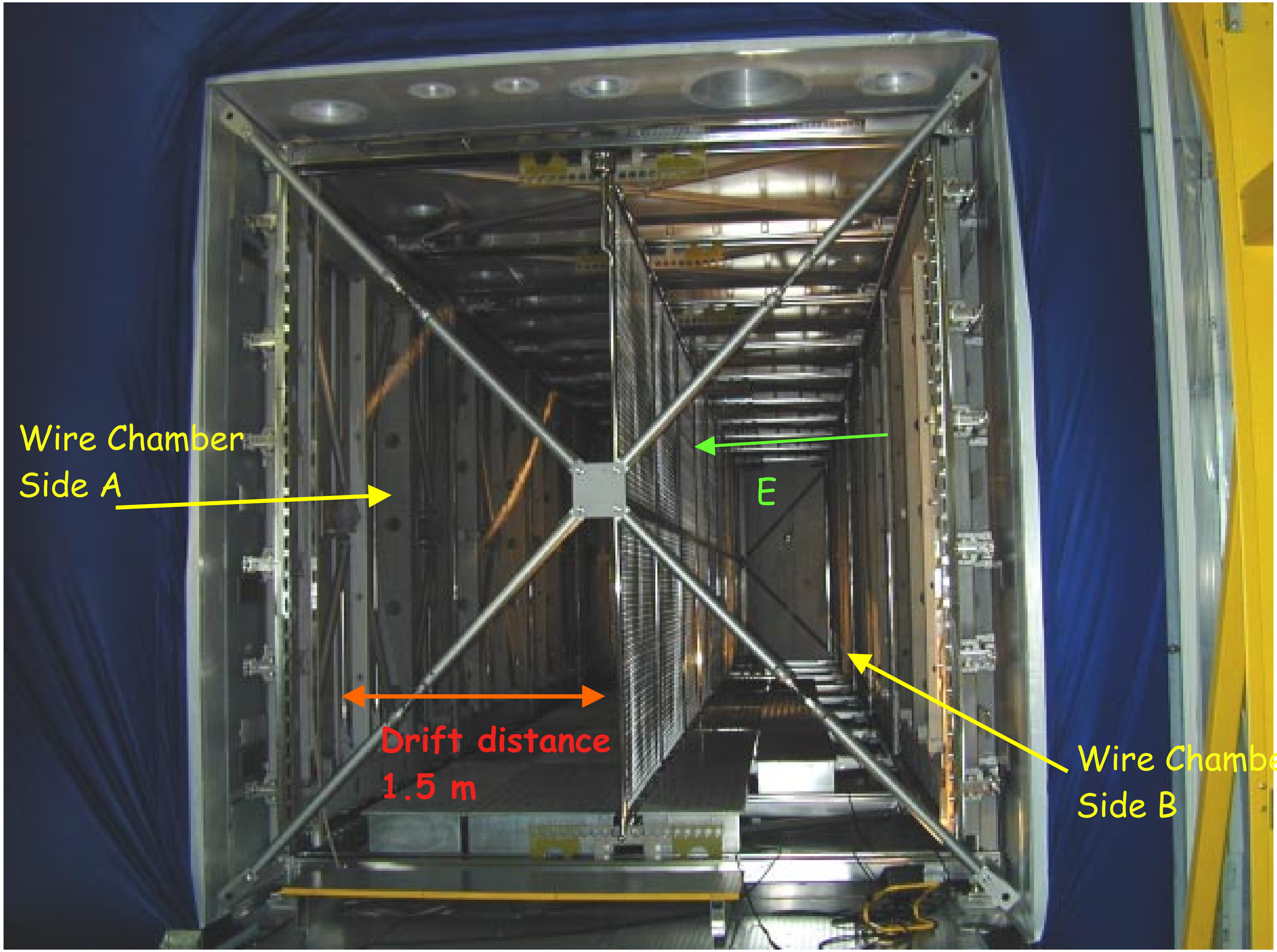
First half-module delivery in Pavia (Feb 29, 2000)

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

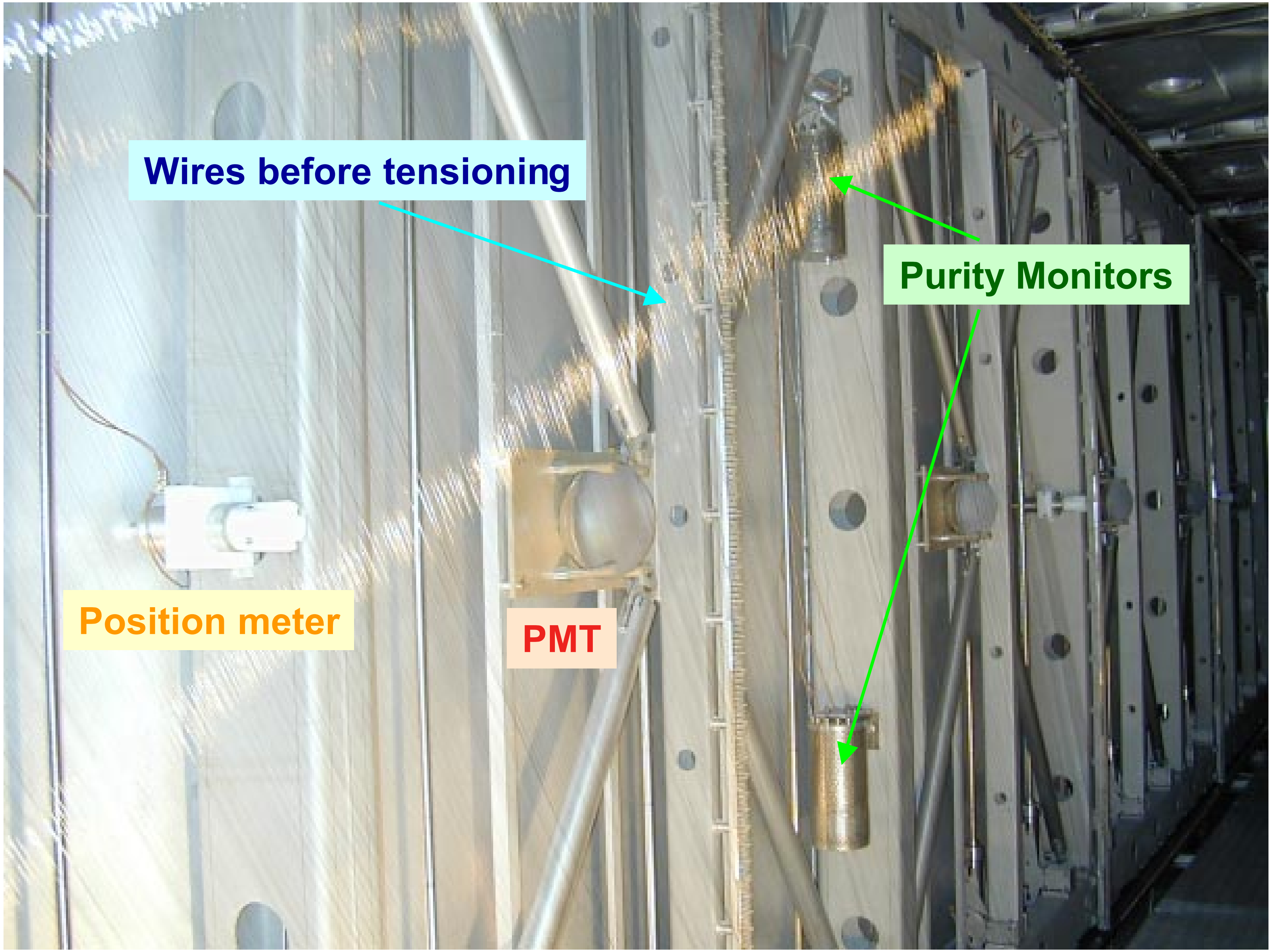


Wire installation in T600 internal detector (Jul-Oct 2000)

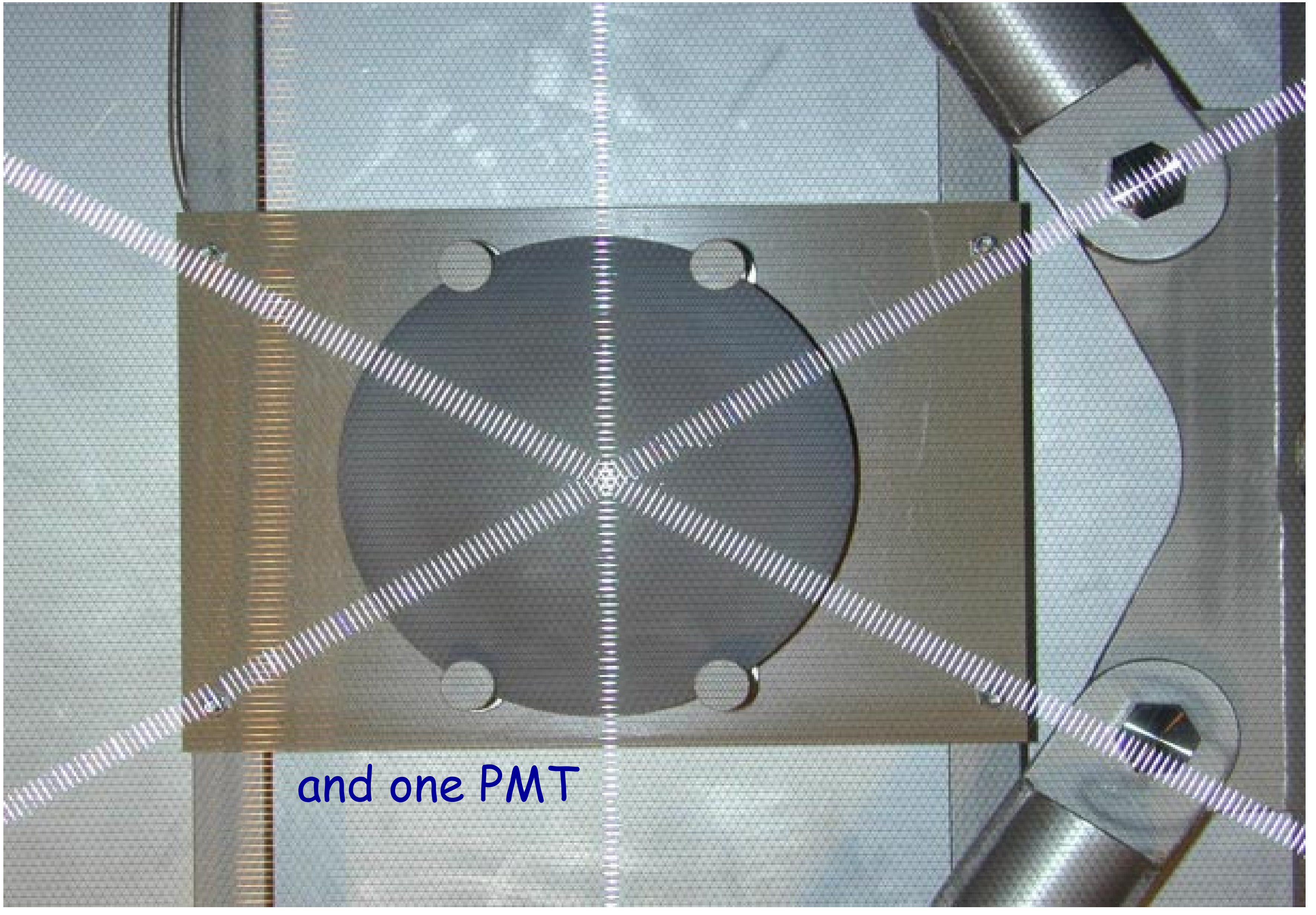
T600 - Completed Internal Detector view



Slow control sensor (behind wire planes)



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



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

Electronic rack

chimneys

Status of the T600 (first half module)

- ✓ Assembly of the internal detector mechanics finished.
- ✓ Wires positioning (3 planes) completed.
- ✓ Central cathode, auxiliary instrumentation, photomultipliers, sensors and signal cables installed and tested.
- ✓ Thermal insulation and cryogenic system proceeded in parallel.
- ✓ Electronics and DAQ system delivered.

Planning

- Next steps:

  1. Vacuum (~3 weeks)
  2. Cooling (~3 weeks) + filling
  3. LAr purification

  → obtain big track (~20 m long)

- The ICARUS T600 detector has a **physics program** of its own, immediately relevant for neutrino oscillation physics: **solar+SN neutrinos, atmospheric neutrinos**
- It should be installed in LNGS tunnel next year.

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

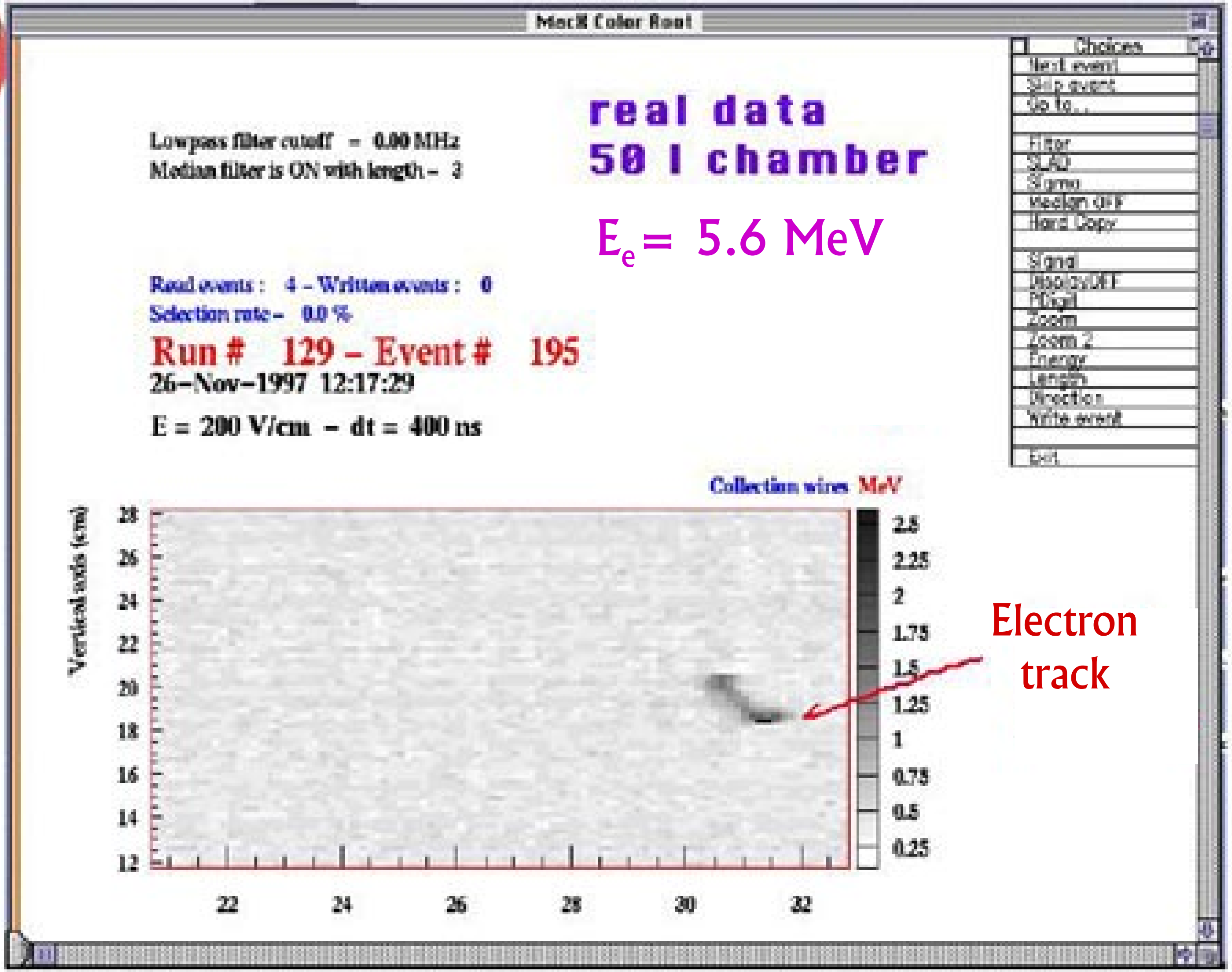
Solar neutrinos detection in ICARUS

- Two reactions can be measured independently:

Elastic scattering on atomic electron	ν absorption on Argon nuclei
$\nu_x + e^- \to \nu_x + e^-$	$\nu_e + {}^{40}Ar \to {}^{40}K^* + e^-$

- **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.

Elastic scattering ν event



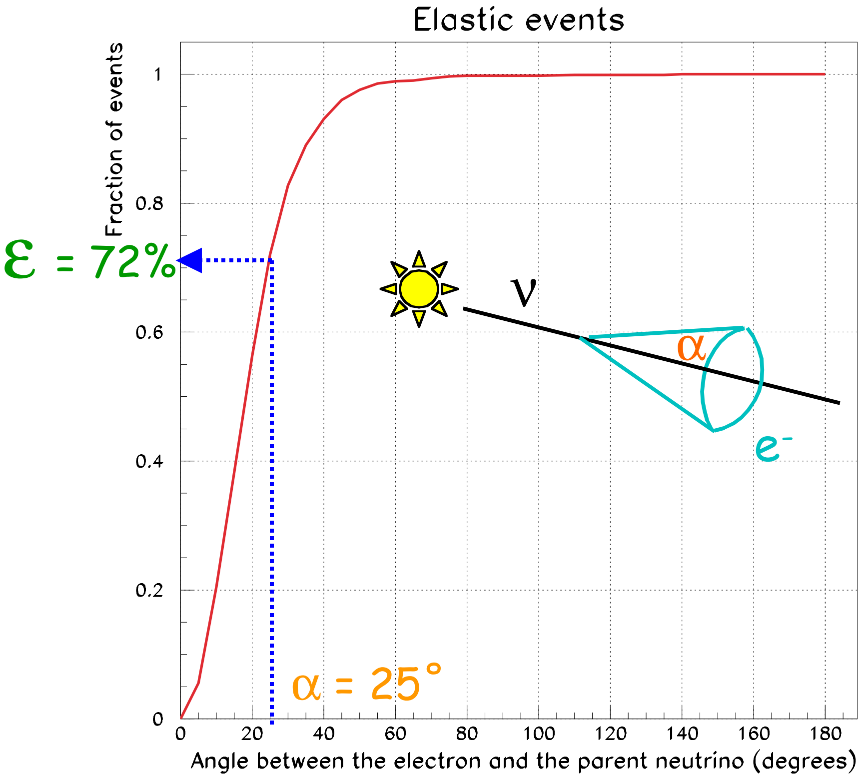
Signal selection

- **Elastic events** :
  - Angular distribution of the electron peaked in the solar ν direction:
- **Absorption events** :
  - Electron track directions can be considered isotropically distributed

For a 600 Ton detector
All cuts imposed

Events/year

Elastic channel	212
Background	6
Absorption channels	759
Background	26



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.

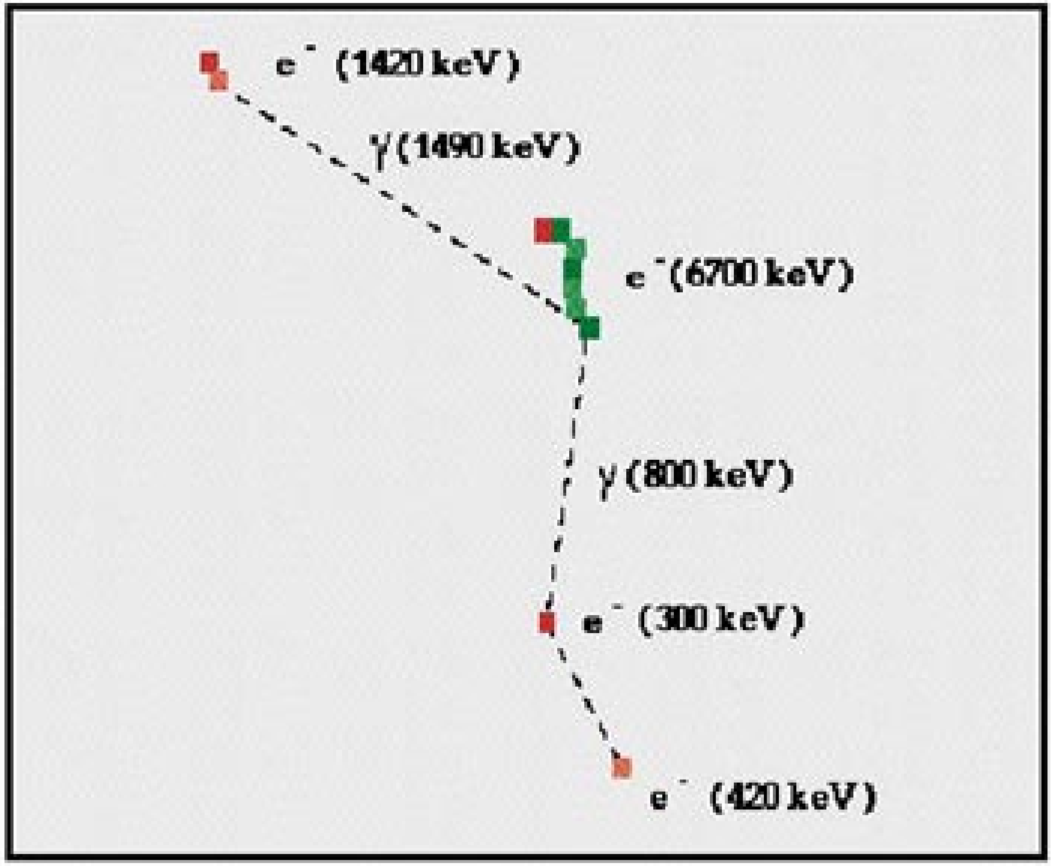
Absorption ν event

Typical Montecarlo Gamow -Teller digitised event

$E_{main\ electron}$ = 6700 keV

Associated compton energy = 2140 keV

Multiplicity = 3



Solar neutrinos sensitivity

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

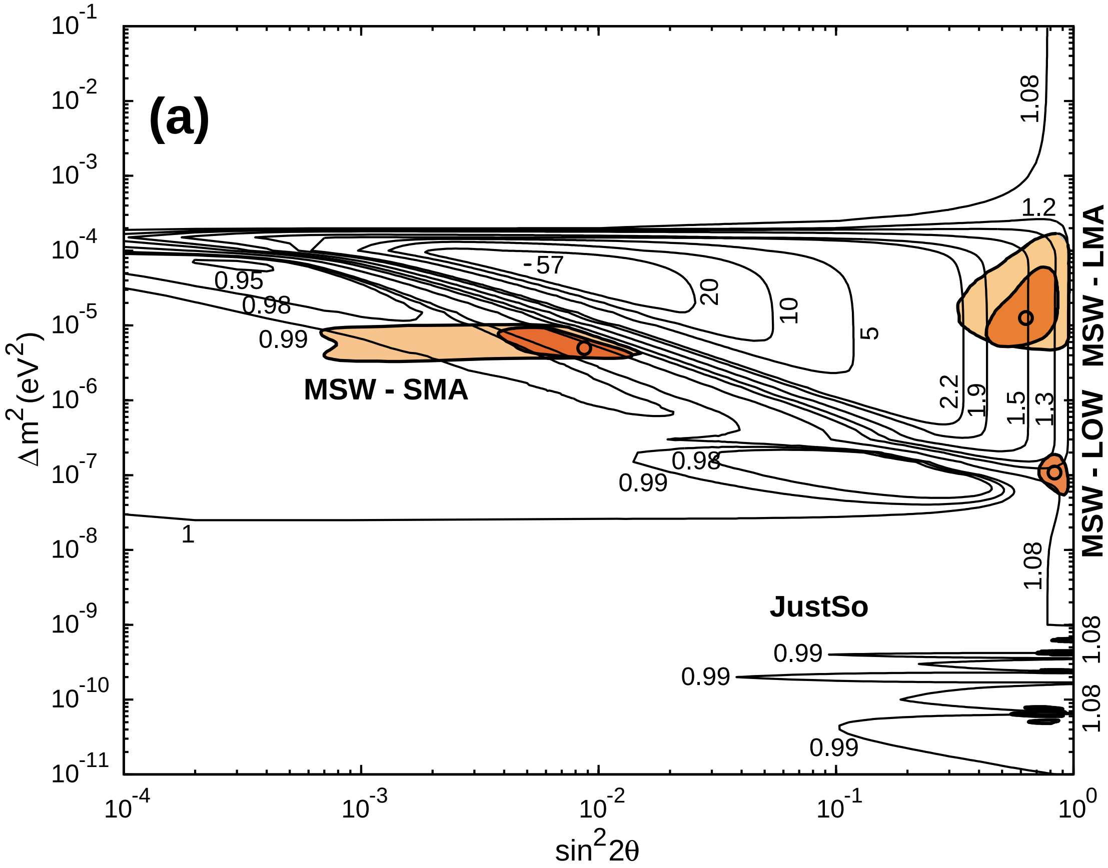
ES=elastic scattering

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

ABS=absorption events

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

- Independent of the ^{8}B total ν flux predicted by solar models..

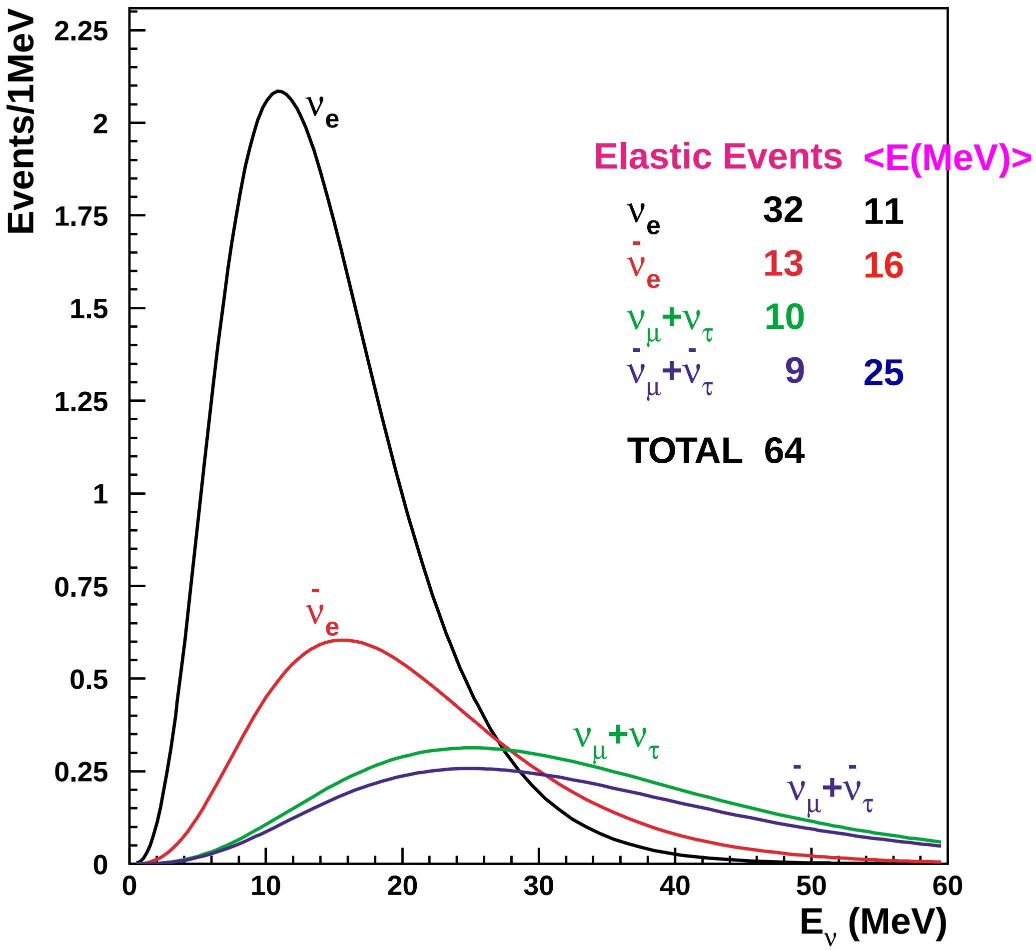


$$\Delta R / R \approx 7\% (1kt \times yr),\ \ 5\% (2kt \times yr),\ \ 4\% (4kt \times yr)$$

Supernova neutrinos expected rates

- ICARUS can detect neutrinos coming from stellar collapses in our Galaxy via the same two processes!

Supernova neutrino rates in 5 KTON ICARUS



Expected events from a stellar collapse ocurred at 10 kpc		
Process	600 ton	5 kton
Elastic scattering	7	64
Absorption events		
Fermi	14	120
GT	28	240
TOTAL	49	424

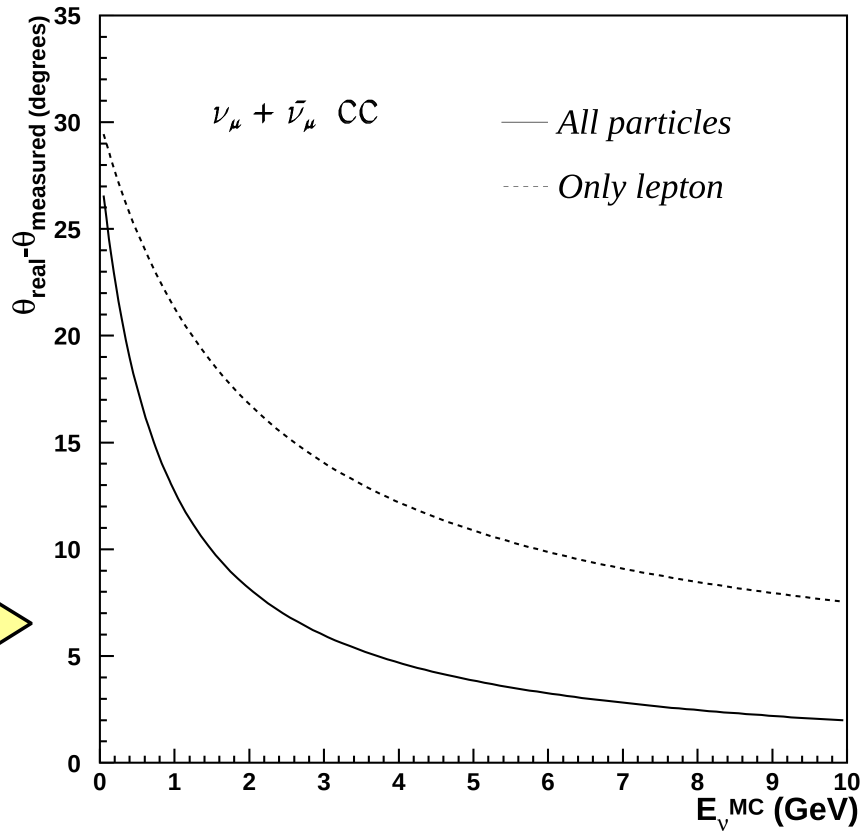
T600 PHYSICS : Atmospheric neutrinos (I)

✻The accumulated statistics will be modest. For a 2 kton x year exposure they will be comparable to first generation water Cerenkov detectors: Kamiokande, IMB

270 $\nu_\mu + \nu_\mu$ CC   150 $\nu_e + \nu_e$ CC 190 ν NC

$\Rightarrow$ 610 events in total

✻Complicated final events with multi-pion products will be completely analyzed and reconstructed $\Rightarrow$ **Zenith angle reconstruction significantly improved!**



✻Events can be fully reconstructed up to kinematics production threshold (50% of the total predicted rate has P_{lepton} < 400 MeV) $\Rightarrow$ **Fundamental contribution to the understanding of the low energy part of the atmospheric neutrino spectrum**

T600 PHYSICS : Atmospheric neutrinos (II)

For a 2 kton x year exposure, we will measure a **significant deficit of upward-going muon-like events**

	2 kton×year				
		Δm^2_{23} (eV^2)			
	No osci	5×10^{-4}	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
Muon-like	270 ± 16	206 ± 14	198 ± 14	188 ± 14	182 ± 13
Downward	102 ± 10	102 ± 10	102 ± 10	98 ± 10	95 ± 10
Upward	94 ± 10	46 ± 7	46 ± 7	47 ± 7	49 ± 7
Electron-like	152 ± 12	152 ± 12	152 ± 12	152 ± 12	152 ± 12
Downward	56 ± 7	56 ± 7	56 ± 7	56 ± 7	56 ± 7
Upward	48 ± 7	48 ± 7	48 ± 7	48 ± 7	48 ± 7

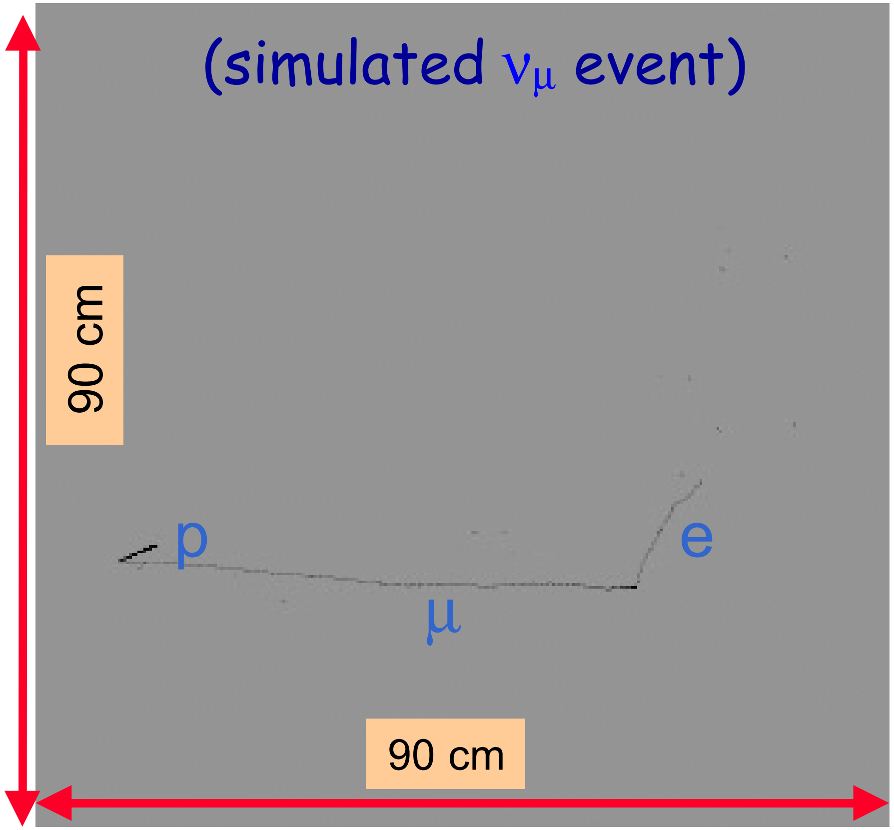
$\nu_\mu\rightarrow\nu_\tau$ or $\nu_\mu\rightarrow\nu_s$ oscillations? The clean NC sample measured allows “indirect” ν_τ appearance search

$$R_{NC/e}=\frac{NC^{data}/\nu_e CC^{data}}{NC^{MC}/\nu_e CC^{MC}}$$

Expected error on $R_{NC/e}$: 15% (22%) for a **2** (1) kton x year

Uncertainty similar to the one obtained by Super-Kamiokande (we are not dominated by systematic uncertainty on poorly known cross sections, e.g. single π^0 production)

Atmospheric CC events

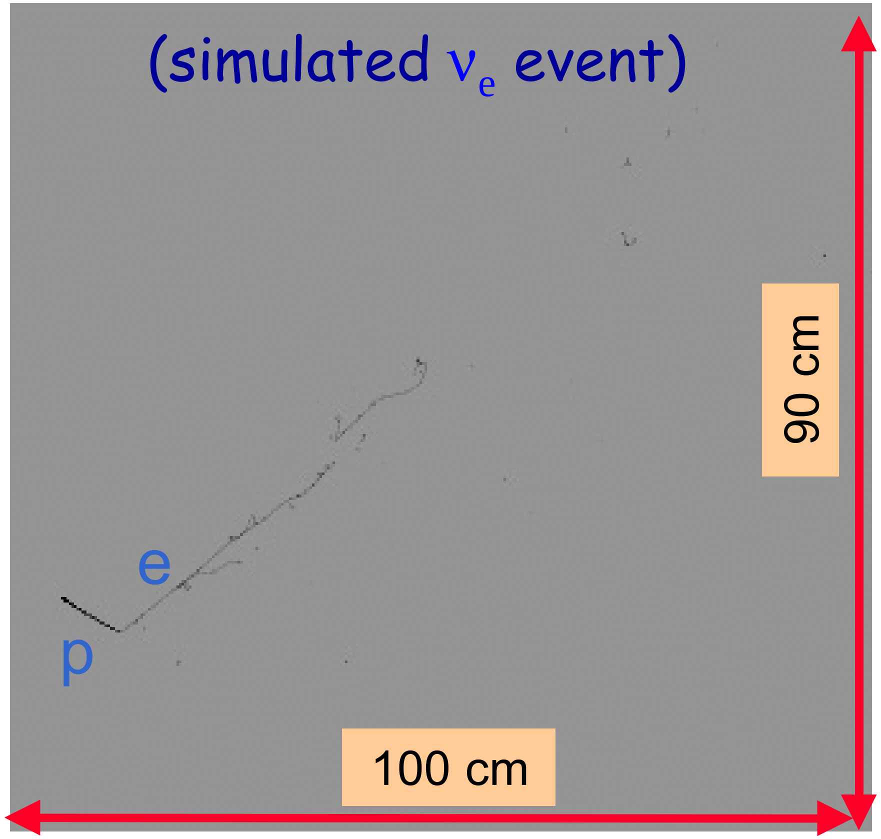


ν_μ Q-el. interaction

E_ν = 370 MeV

P_μ = 250 MeV

T_p = 90 MeV



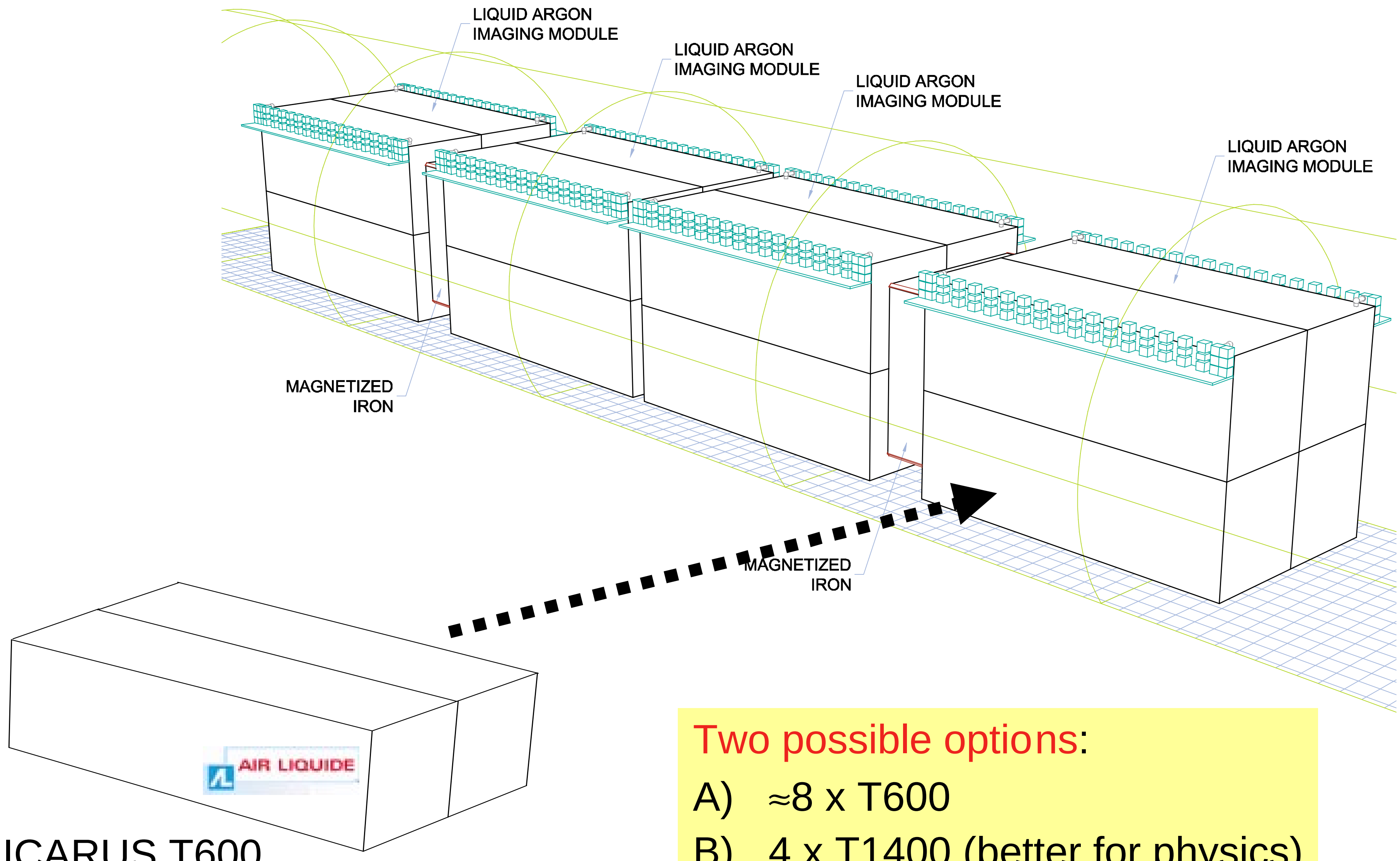
ν_e quasielastic interaction

E_ν = 450 MeV

P_e = 200 MeV

T_p = 240 MeV

Proposed setup ICARUS 5kt in LNGS Hall B



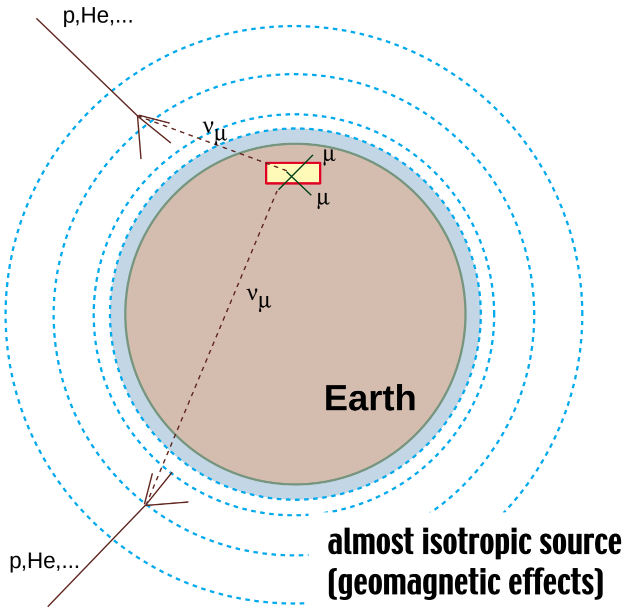
ICARUS T600

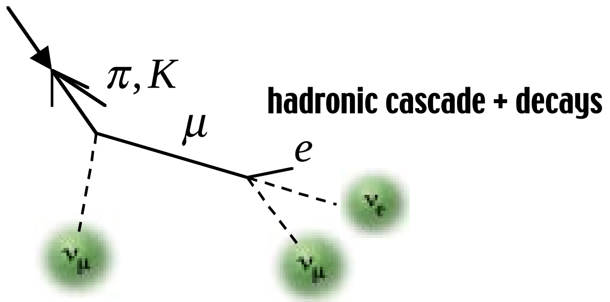
Two possible options:

A) ≈8 x T600

B) 4 x T1400 (better for physics)

Atmospheric neutrinos





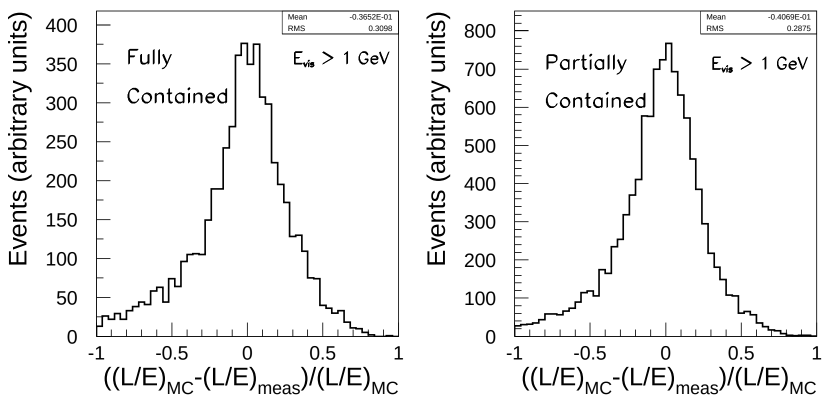
	5 kton×year				
		Δm^2_{23} (eV^2)			
	No osci	5×10^{-4}	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
Muon-like	675 ± 26	515 ± 23	495 ± 22	470 ± 22	455 ± 21
Contained	418 ± 20	319 ± 18	307 ± 18	291 ± 17	282 ± 17
Partially-Contained	257 ± 16	196 ± 14	188 ± 14	179 ± 13	173 ± 13
No proton	260 ± 16	190 ± 14	185 ± 14	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 Events/year

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

ν_μ disapearance: L/E distribution

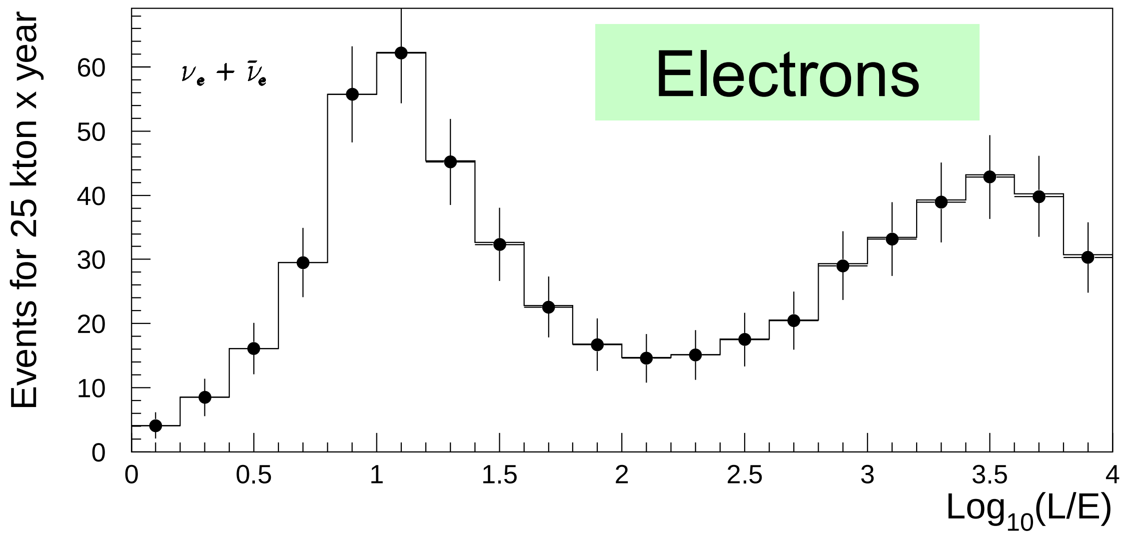
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

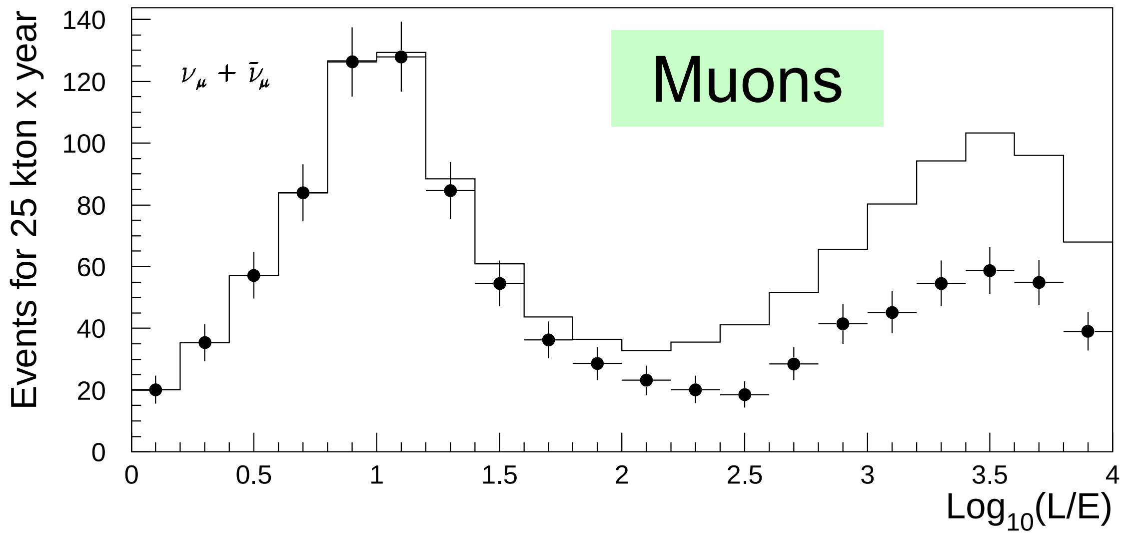


$$\Delta(L/E)_{RMS} \approx 30\%$$

- Oscillation parameters:
  - → $\Delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2
  - → $\sin^2 \Theta_{23} = 0.5$
  - → $\sin^2 2\Theta_{13} = 0.1$
- ***Electron sample can be used as a reference for no oscillation case***

25 kt year

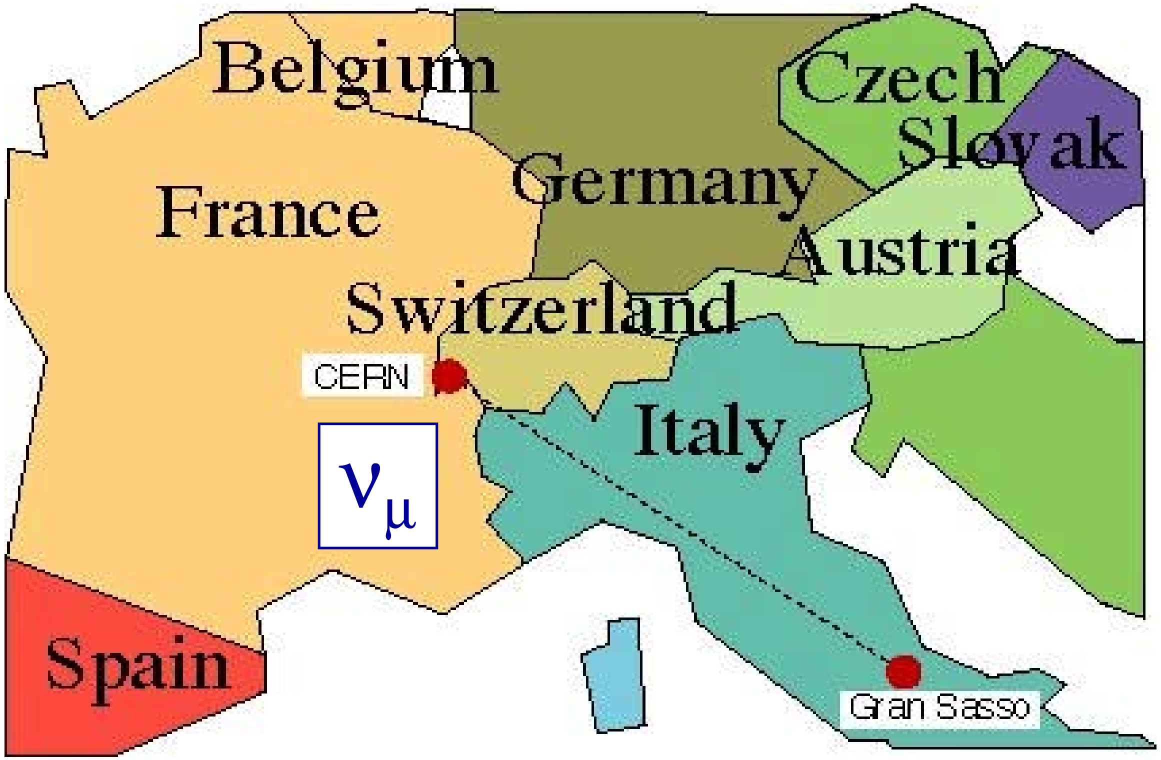




CNGS neutrino beam

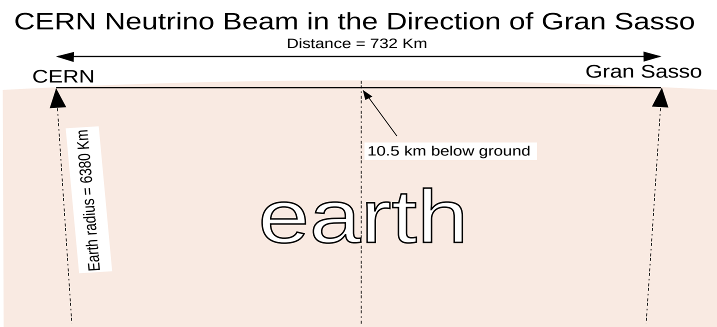
The expected ν_e and ν_τ contamination of the CNGS beam are of the order of 10^{-2} and 10^{-7} respect to the dominant ν_μ.

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



ν_τ? ν_e?

Primary protons: **400 GeV,**
Pots per year: **4.5×10^{19} pots**



Planned beam commissioning: May 2005

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			
$\nu_\mu \rightarrow \nu_e$ CC	-	7	74	143
$\nu_\mu \rightarrow \nu_\tau$ CC	-	52	620	1250
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	-	< 1	< 1	1
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ CC	-	< 1	6	13

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

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

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

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

$\nu_\tau + N \rightarrow \tau + jet\ ;\ \tau \rightarrow e\nu\nu$

Charged current (CC) (Br ≈ 18%)

$\Delta m^2 = 3.5 \times 10^{-3} eV^2$

110 evts

Background:

$\nu_e + N \rightarrow e + jet$

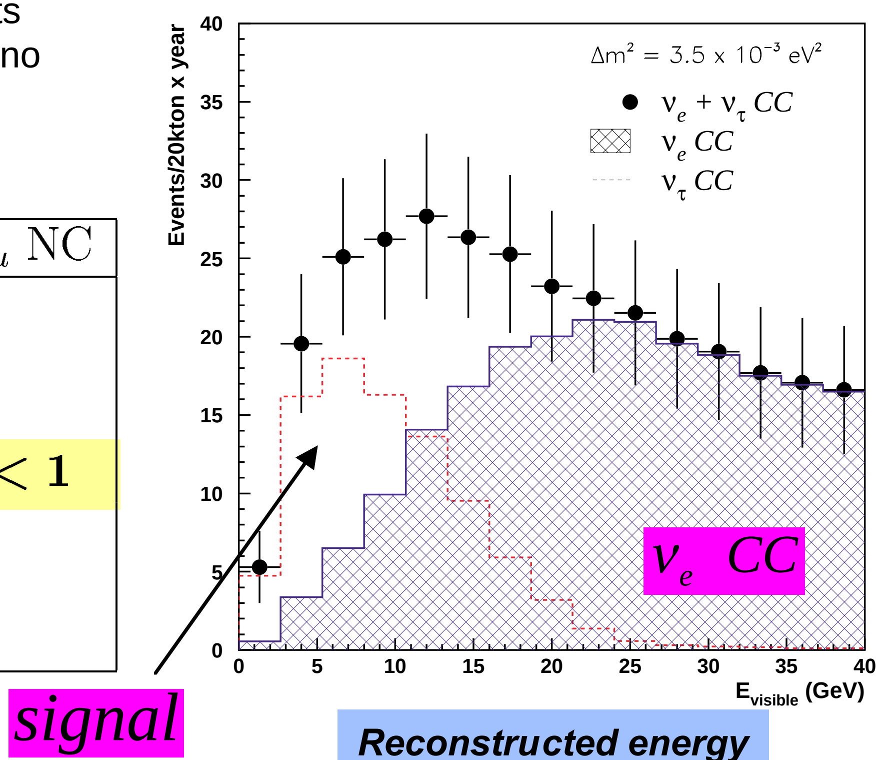
Charged current (CC)

470 ν_e evts

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

ICARUS 4 years (after cuts)

Δm^2 (eV^2)	ν_τ CC	$\nu_e,\ \bar{\nu}_e$ CC	$\nu_\mu,\ \bar{\nu}_\mu$ CC	ν_μ NC
1×10^{-3}	3			
2×10^{-3}	12			
3×10^{-3}	26			
3.5×10^{-3}	**35**	**4.1**	**1.0**	**< 1**
5×10^{-3}	71			
7×10^{-3}	121			
1×10^{-2}	248			



Reconstructed energy

$\nu_\mu \rightarrow \nu_e$ oscillations : Search for $\theta_{13} \neq 0$

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

ICARUS 4 years

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

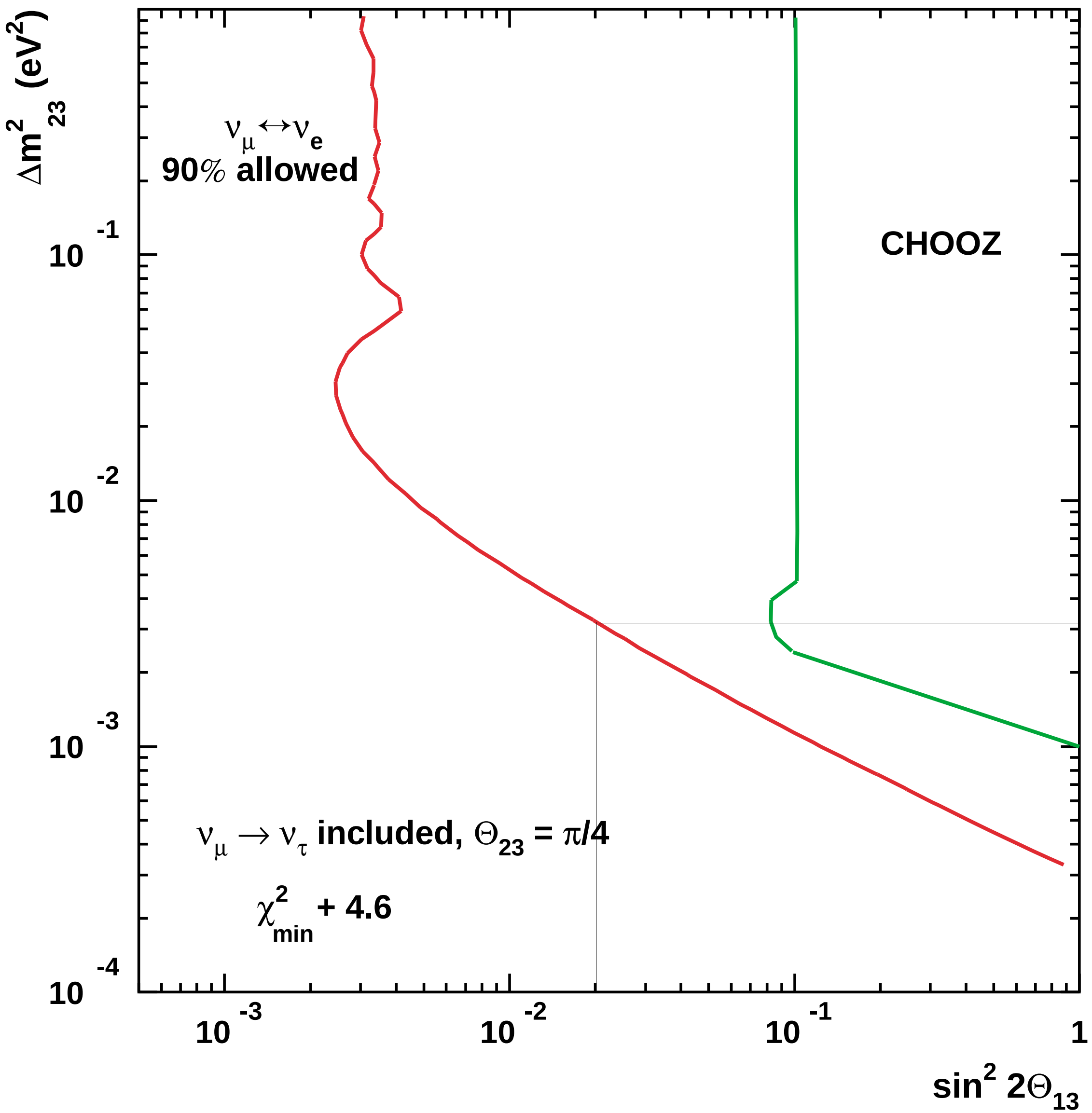
$\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV^2, $\theta_{23} = 45^o$

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \rightarrow \nu_\tau$ $\tau \rightarrow e$	$\nu_\mu \rightarrow \nu_e$	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

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

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

Sensitivity to θ_{13} in three family-mixing



- Sensitivity to $\nu_\mu \to \nu_e$ oscillations in presence of $\nu_\mu \to \nu_\tau$ (three family mixing)
- Factor 5 improvement on $\sin^2 2\theta_{13}$ at $\Delta m^2 = 3\text{x}10^{-3}$ eV^2
- Almost two-orders of magnitude improvement over existing limit at high Δm^2

Nucleon decay search

5 kTons detector ⟹ **3×10^{33} nucleons** $\Rightarrow$ **τ_p (10^{32} years) > $6 \times$ T(yr) $\times \varepsilon$** @ 90 C.L.

Thanks to excellent tracking and particle *id* capabilities

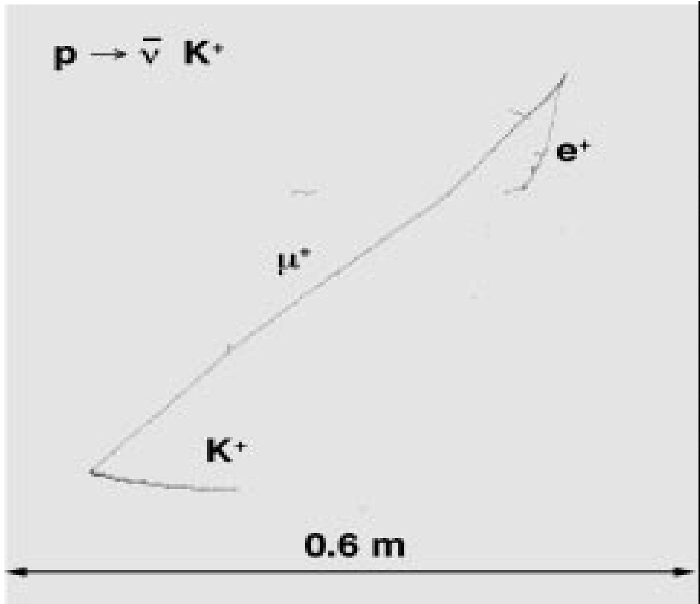
LAr unique tool

Extremely efficient background rejection

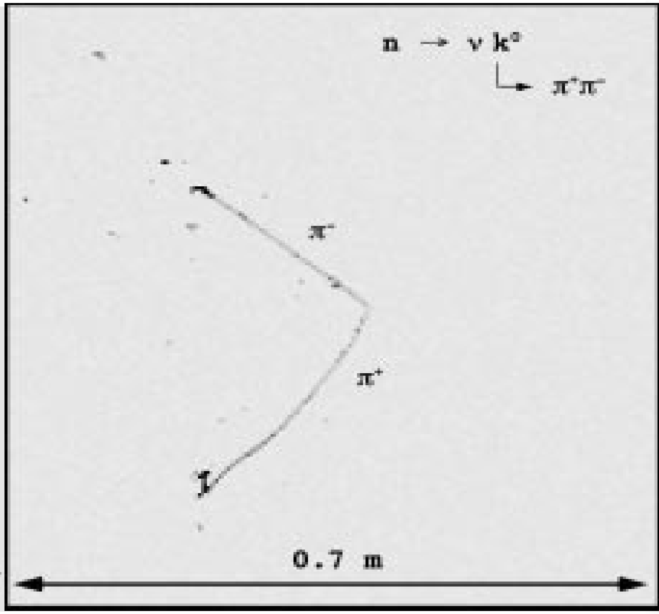
High detection efficiency

Bias-free, fully exclusive channel searches!

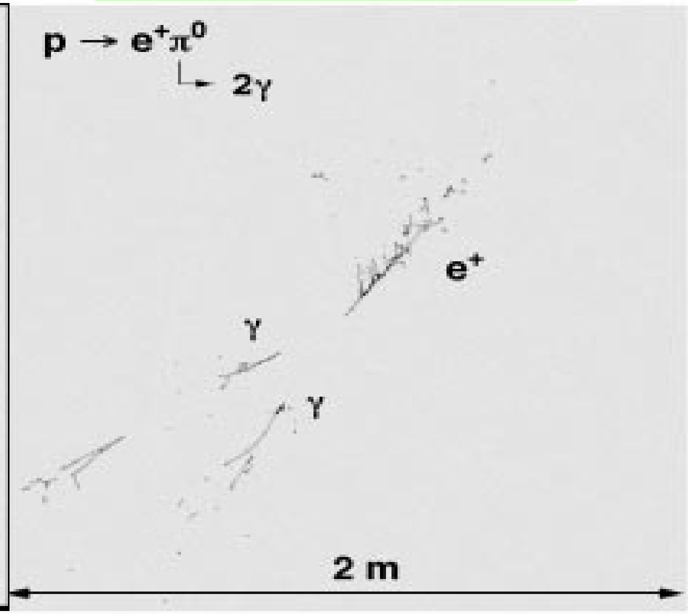
$p \rightarrow \bar{\nu} K^+$ decay



$n \rightarrow \nu K^0$ decay



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



$p \rightarrow e^+ \pi^0$ and $p \rightarrow K^+ \bar{\nu}$ decay kinematics

Nuclear effects: pion absorption and rescattering included (FLUKA)

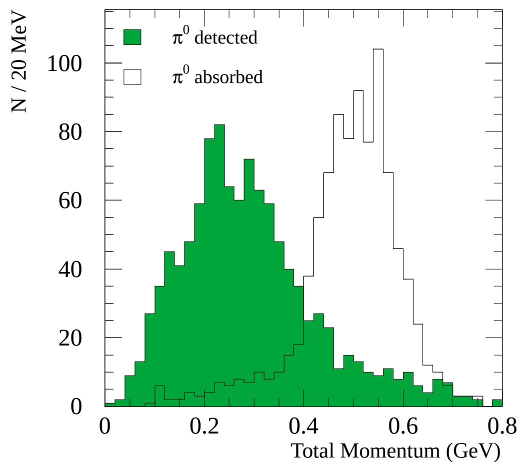
Exposure: 1000 kton x year

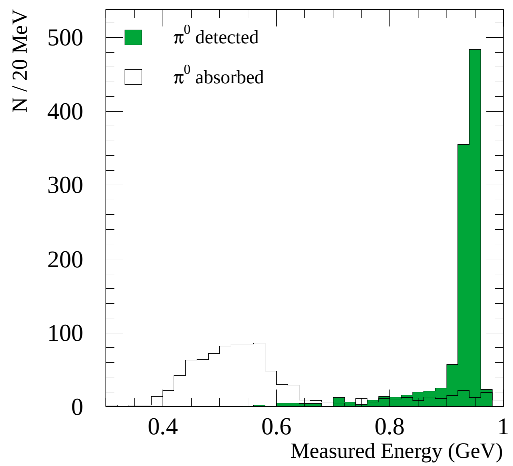
Exclusive Channel Cuts	$p \to e^+ \pi^0$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One π^0	54.00%	6610	2137	15264	5808	8089	3100
One electron	54.00%	6577	2127	20	0	0	0
No $\pi^\pm$, No protons	51.50%	1234	668	2	0	0	0
Total Momentum < 0.4 GeV	46.85%	461	128	0	0	0	0
0.93 GeV < Total E < 0.97 GeV	45.65%	0	0	0	0	0	0

≈ 45% π^0 absorbed in Ar nucleus

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

We see the kaon!





Background free !!

5 kTon x year

$\tau_p (p \rightarrow e^+ \pi^0) > 2.5 \times 10^{32}$ yrs

$\tau_p (p \rightarrow K^+ \bar{\nu}) > 5 \times 10^{32}$ yrs

Conclusions

- The **ICARUS T600**, based on a novel 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**.
- Operation inside the Gran Sasso 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 order to explore
  - ✓ **neutrino oscillations** from both, accelerator and non-accelerator beams
  - ✓ **Solar** and **Supernova neutrinos**
  - ✓ and **nucleon decay** searches.