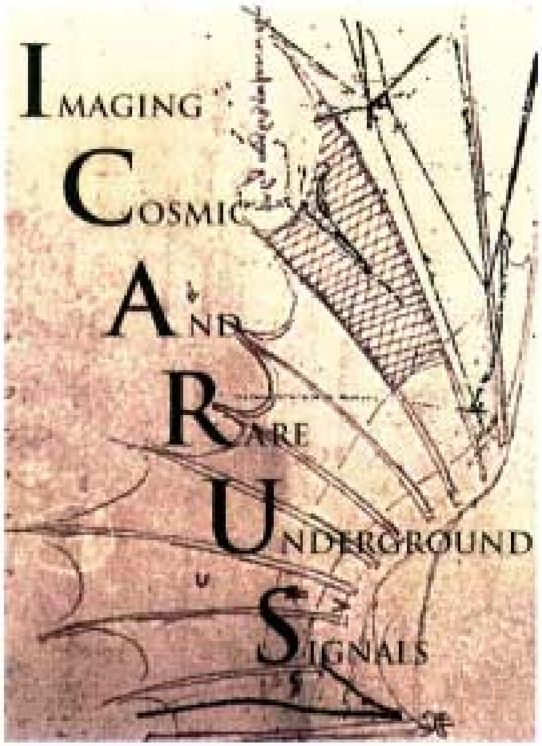

The ICARUS Project

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

Les Houches, June 2001

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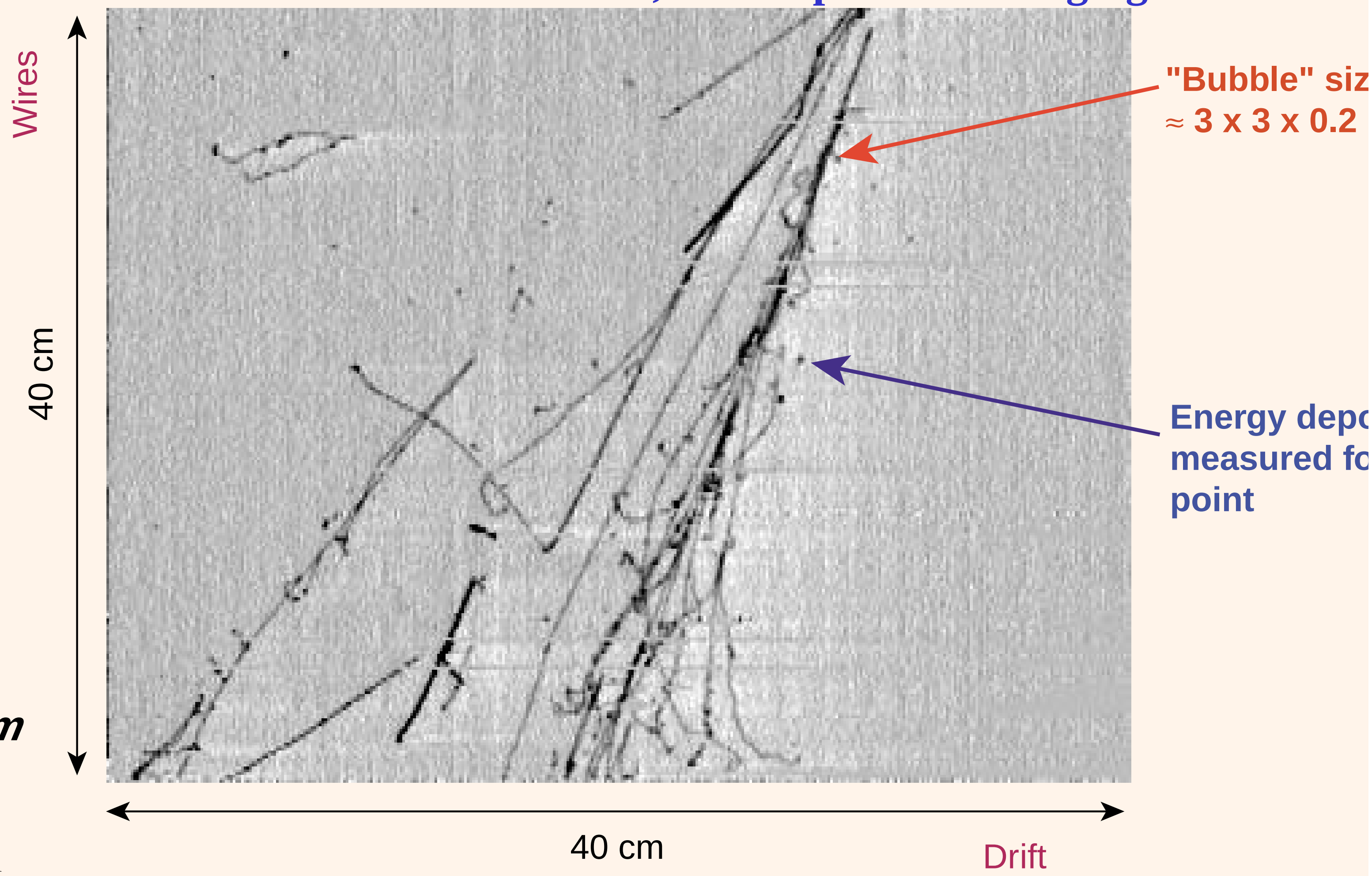
The ICARUS technology

- Traditional bubble-chambers have played a fundamental role in particle physics because they provide non-biased images, in three dimensions and with high resolution.
- ICARUS represents a new generation of bubble-chambers.
- It is based on the novel particle detection technology of liquid argon imaging.
- It offers the advantage over traditional bubble-chambers of being operated over a <u>very large sensitive volume</u>, <u>continuously sensitive</u>, <u>self-triggering</u>, and able to provide <u>3D views</u> with <u>particle ID from dE/dx and range measurements</u>. At the same time <u>excellent calorimetry</u> with very fine granularity and high accuracy is provided for contained events.

ICARUS liquid argon imaging

The ICARUS technique is based on the fact that ionization electrons can drift over larg 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.

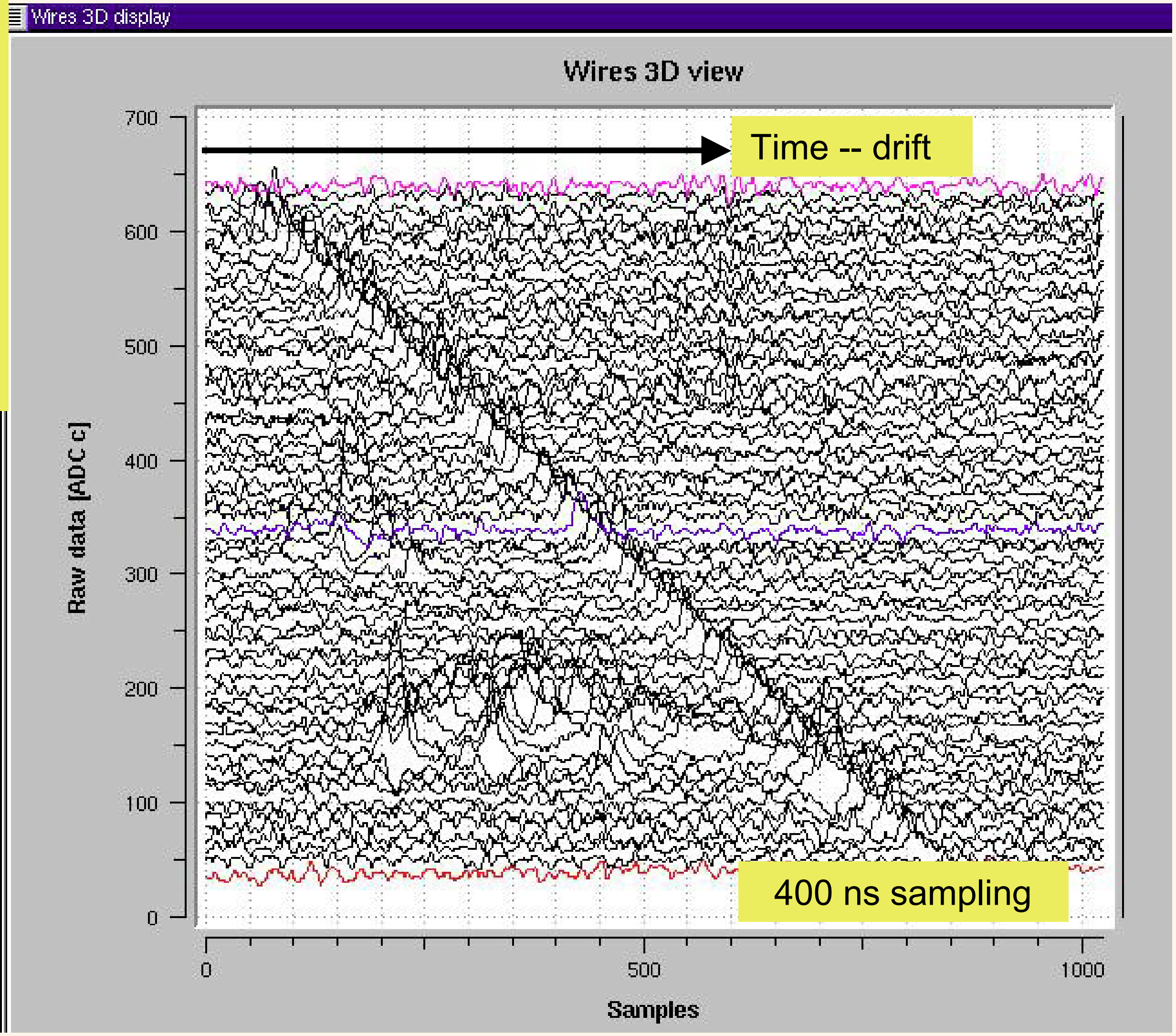


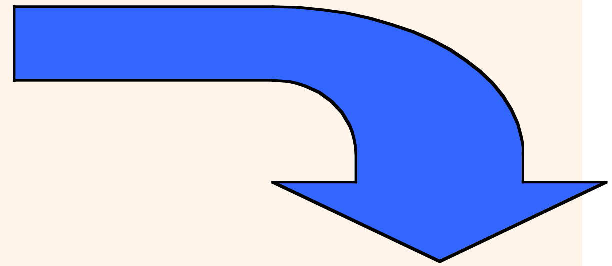
R. shower from
ton prototype

Principle of readout

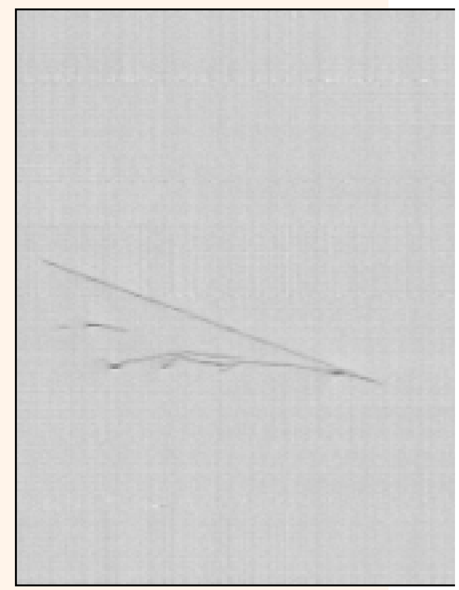
Real event from 15 ton

Raw Data





Reconstructed event



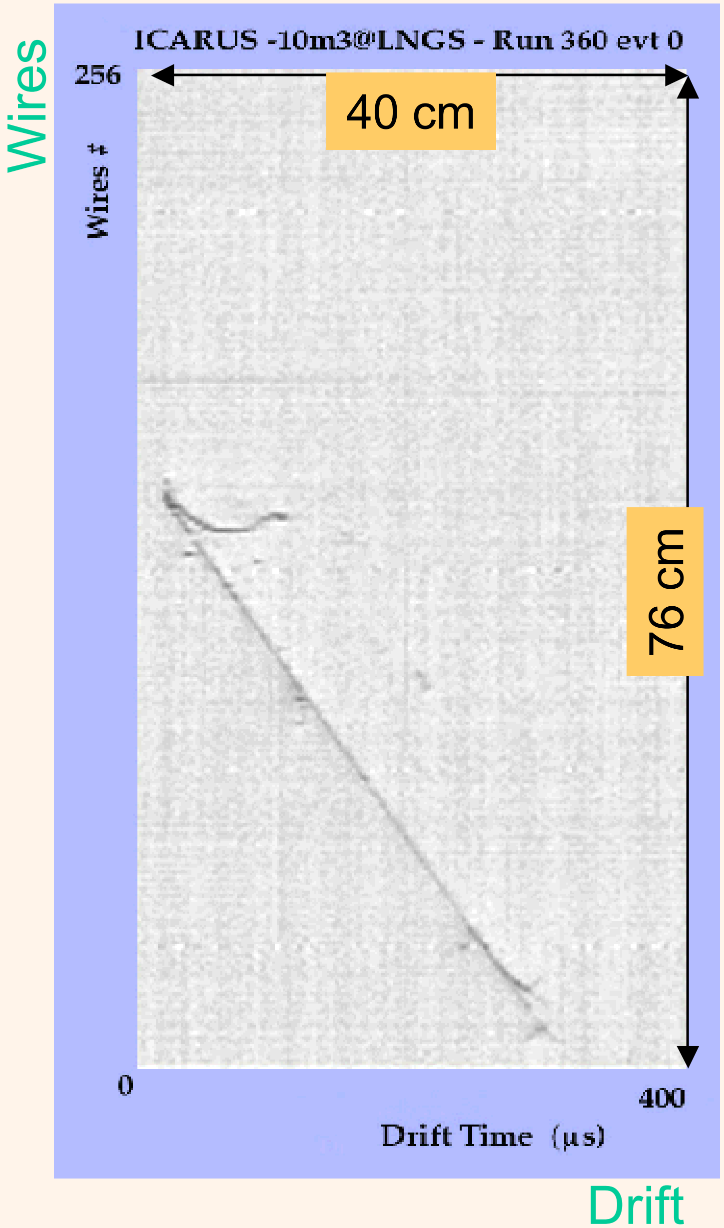
40 cm

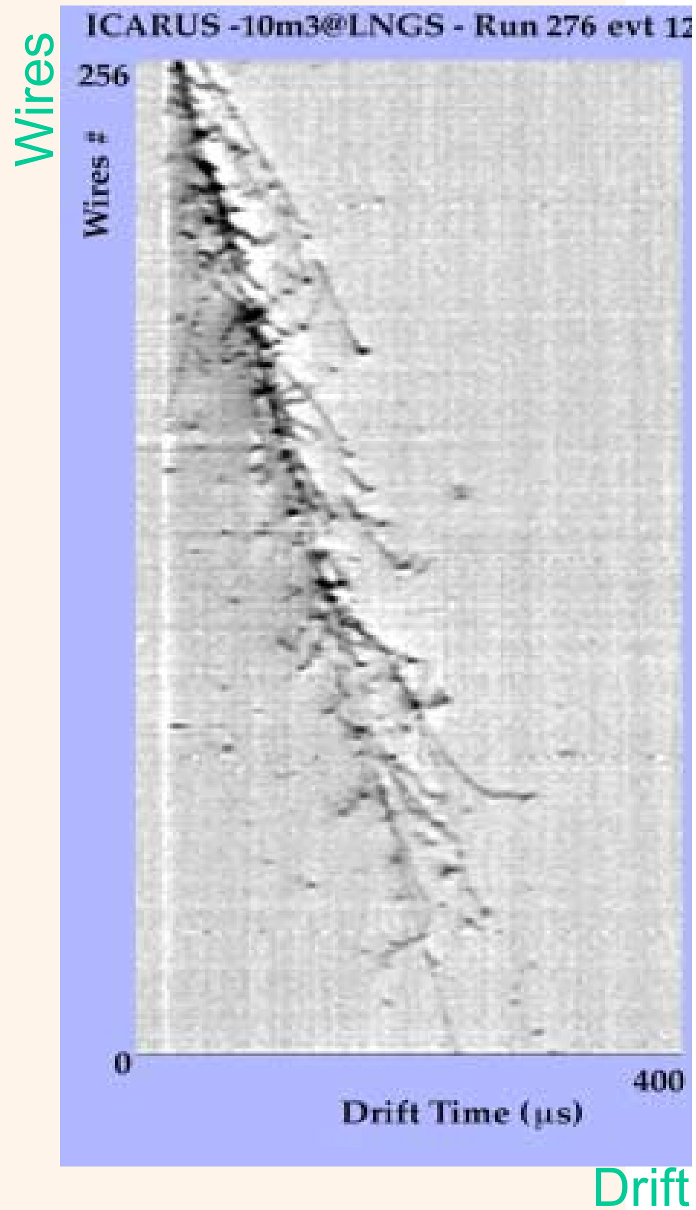
Rubbia, ICARUS Collaboration, May 2001

Liquid Argon imaging on large scales

10m^3 Module at LNGS

Cosmic Ray tracks recorded during the 10 m^3 operation

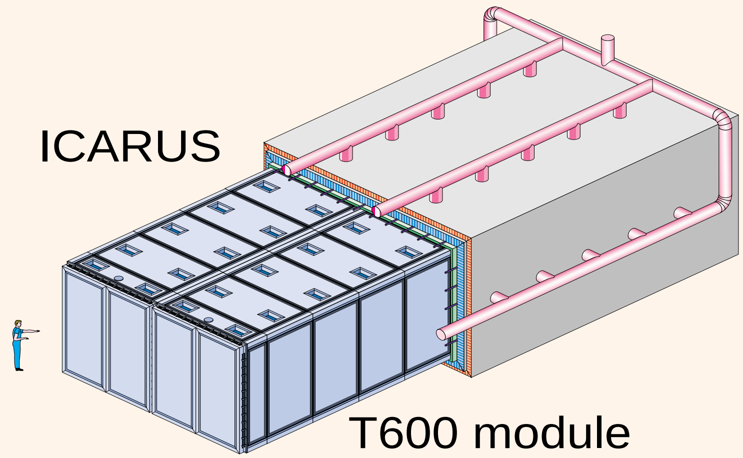




"Big track" in T600 semimodule expected soon...

The first ICARUS T600 prototype

- **The T600 module is to be considered as a <u>fundamental milestone</u> on the road towards a total sensitive mass in the multi-kton range**
  – First piece of the detector to be complemented by further modules of appropriate size and dimension ⇒ *Goal is* ***to reach a multikton mass in LNGS tunnel in a most efficient and rapid way***
- **It has a <u>physics program</u> of its own, immediately relevant to neutrino physics, though limited by statistics (see hep-ex/0103008)**



T600 recent progress

ec 1998 – Jun 1999 Operation of 10 m^3 in Pavia: LAr purification and recirculation tests, cryogenic test of internal detector mechanics, general cryogenics plants performance evaluation.

ep 1999 Completed the site preparation in Pavia for the T600 cryostat.

lov 1999 Completion of the “clean room” and of the “assembly island”.

eb 2000 Operation of the 10 m^3 at LNGS: data taking with a fully functional imaging (up to 4 m tracks), final electronics, cryogenics and purification

eb 2000 – Apr 2000 Successful, 100days test run with cosmic ray trigger at GranSasso.

eb 29, 2000 Acceptance tests and delivery in Pavia of the cryostat by AirLiquide of the first half-module

lar 2000 Beginning of assembly of the internal detector mechanics.

ul 2000 Completion of assembly and positioning of mechanical frames for the first half-module; Begin wiring.

lug 4, 2000 Acceptance tests and delivery in Pavia of the cryostat by AirLiquide of the second half-module

eb 7, 2001 Assembly of first semi-module completed (lasted 11 months)

eb 17, 2001 Semi-module sealed!

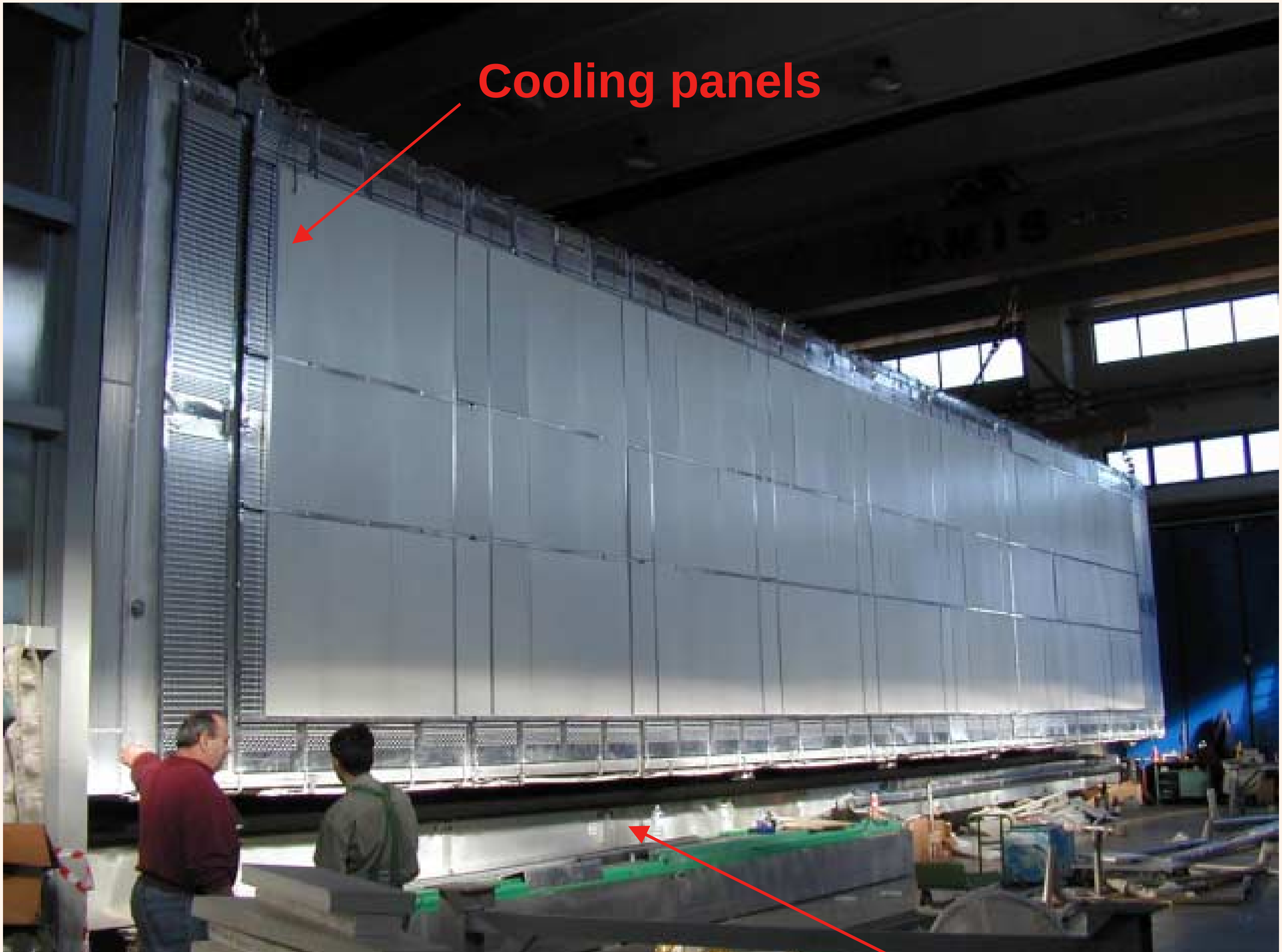
eb 21, 2001 Started leak tests (dewar in overpressure)

lpr 13, 2001 Started vacuum pumping of dewar

lay 1, 2001 <u>Started cooling</u>

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

Second half-module in Pavia (delivered Aug 2000)

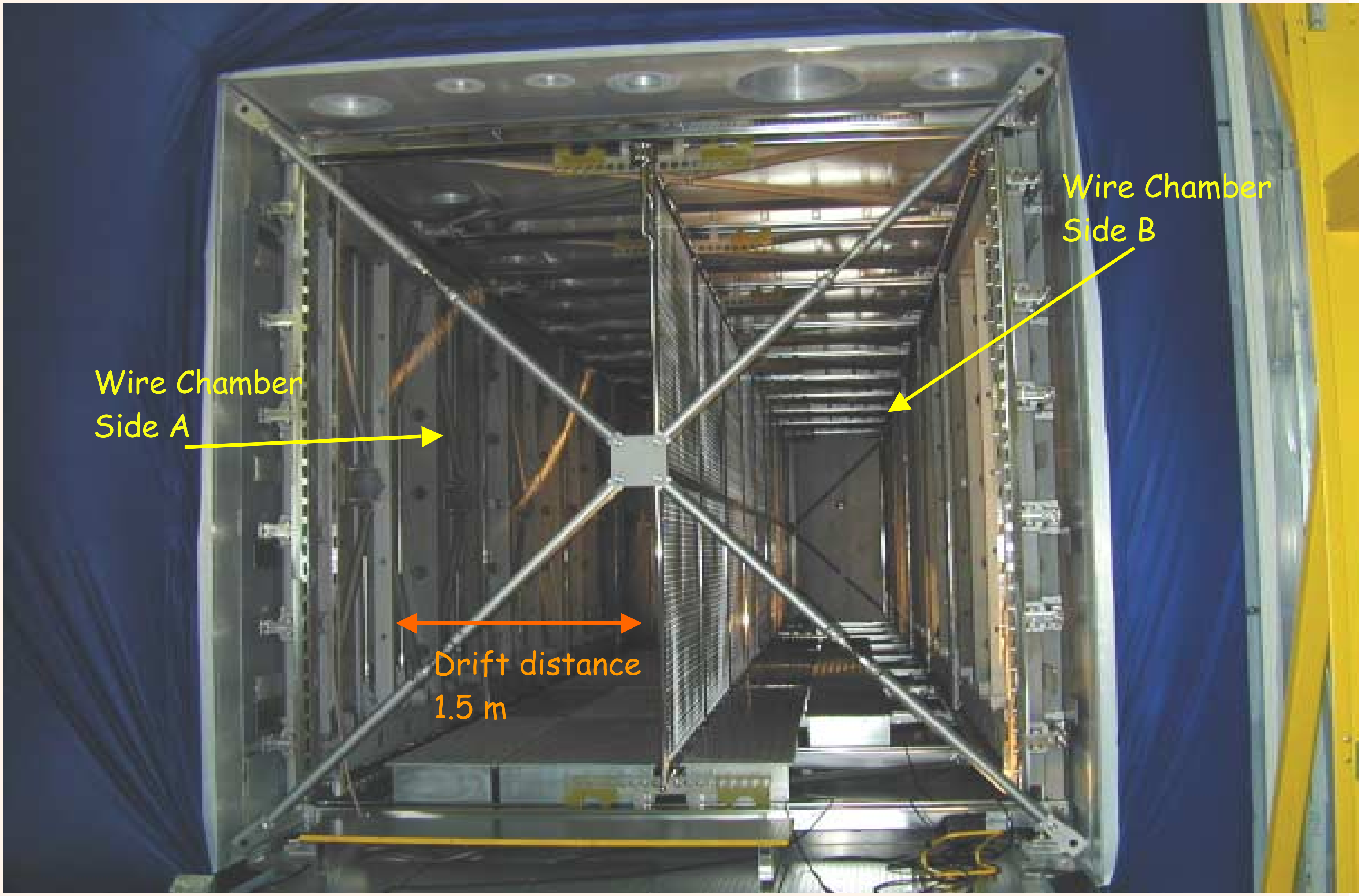


Wire installation in T600 internal detector (Jul-Oct 2000)

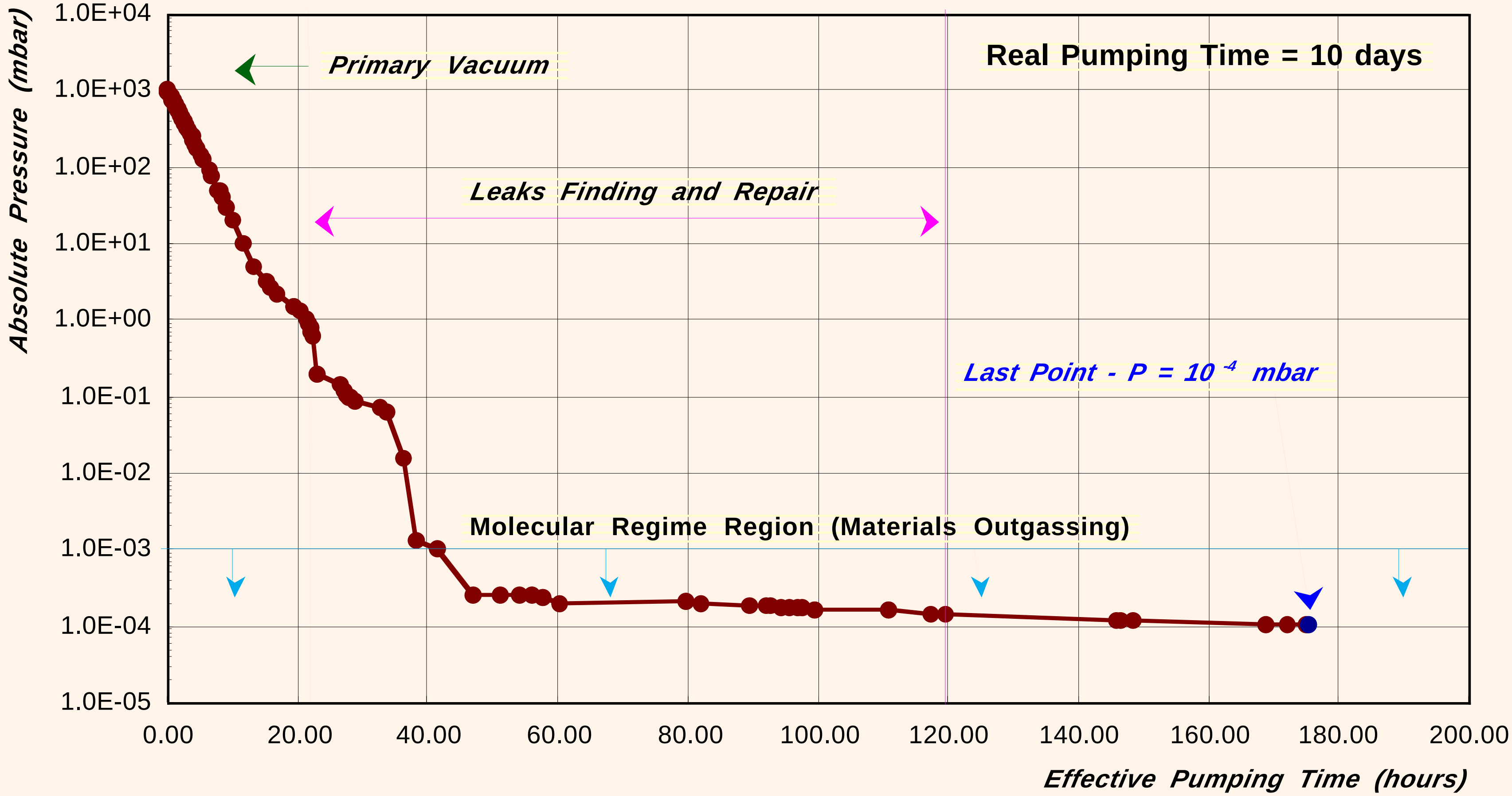
Rubbia, ICARUS Collaboration, May 2001

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

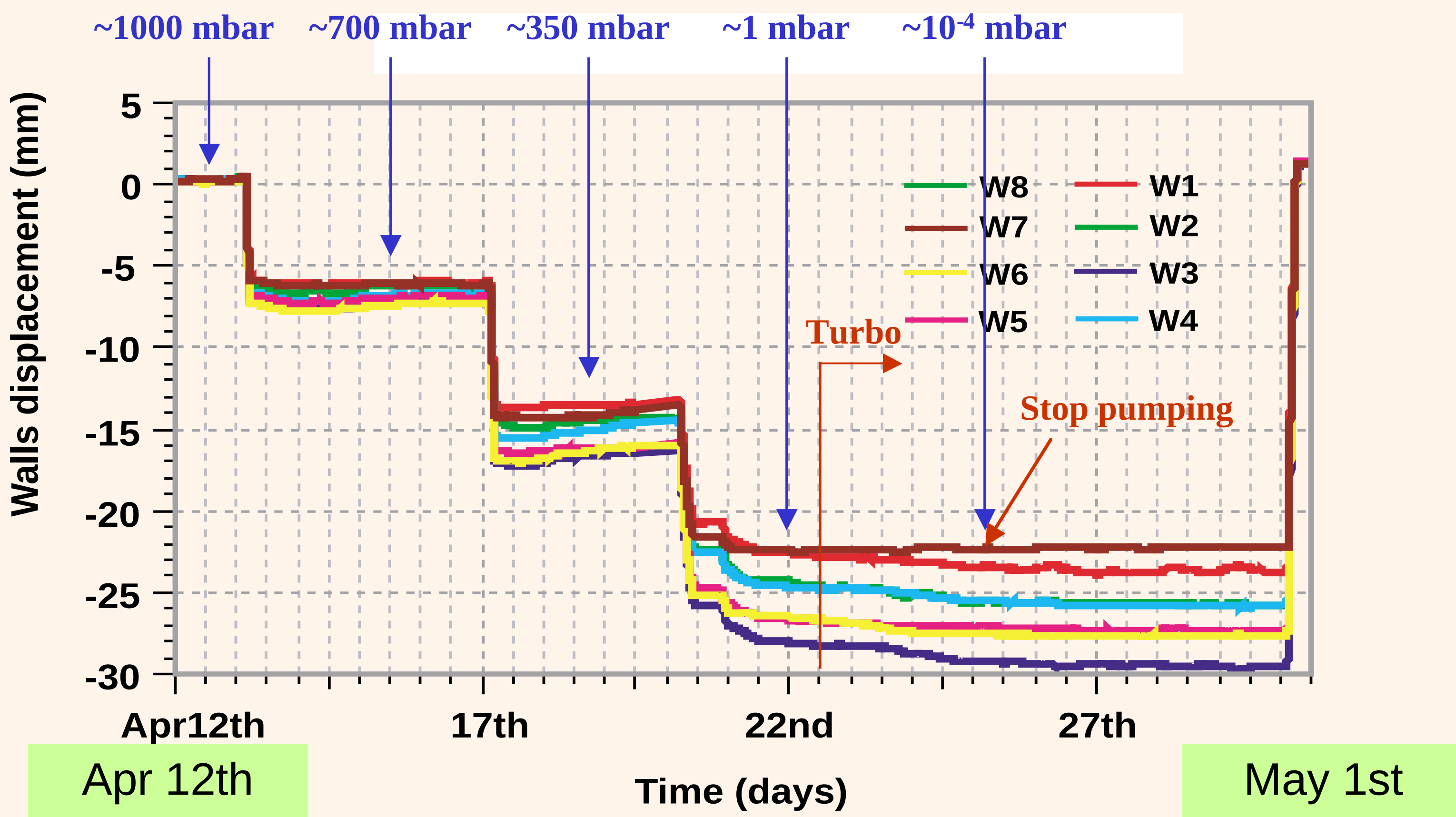
Internal Detector view



Evacuation Curve



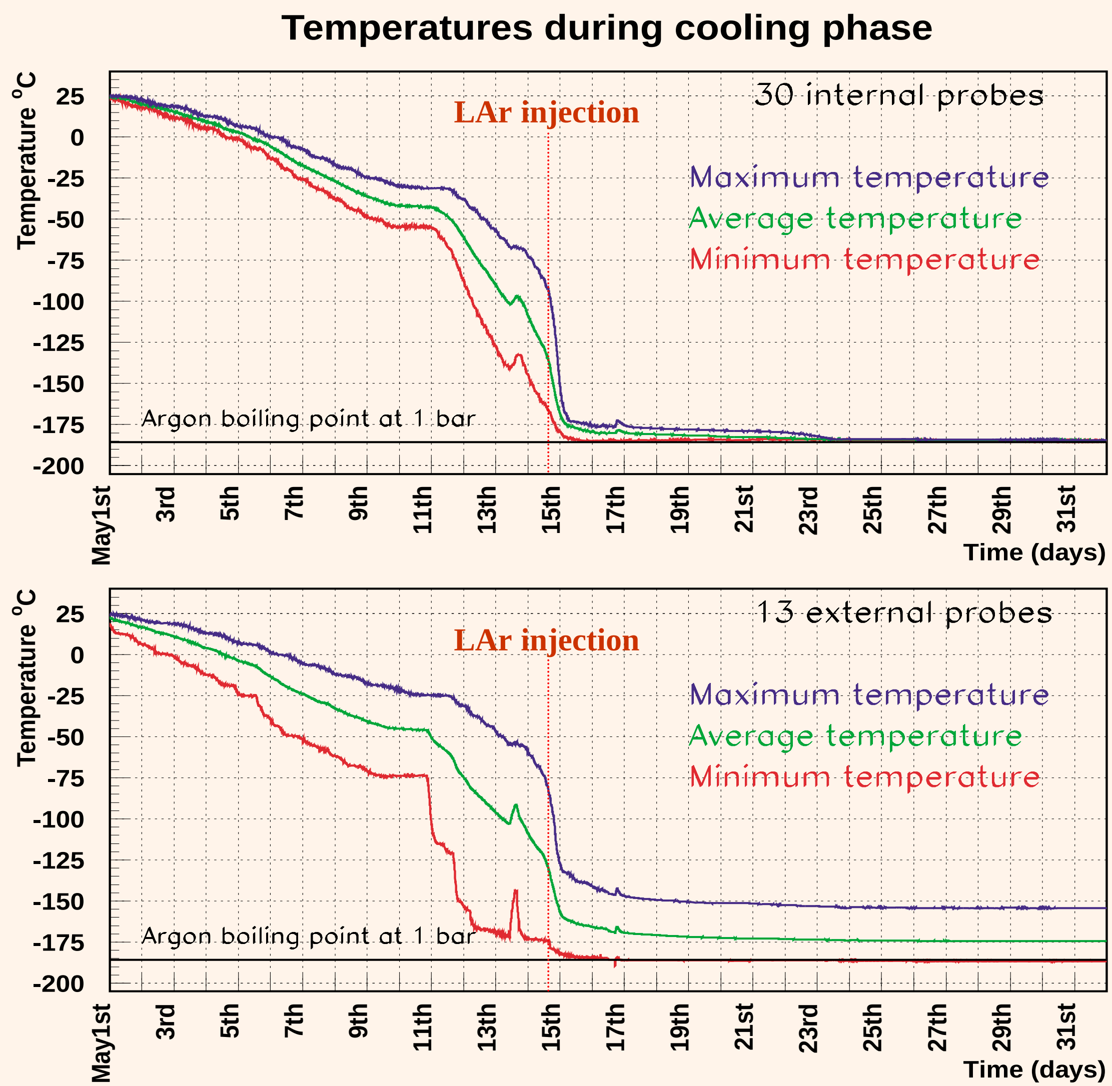
Walls displacement during vacuum phase

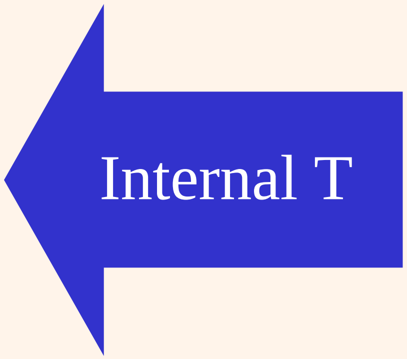


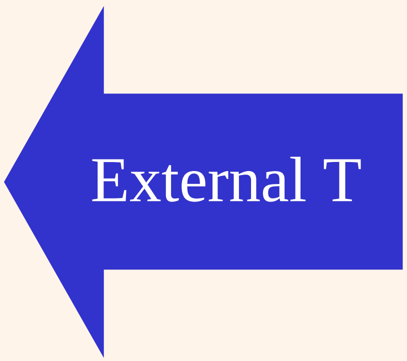
Total spent time: 12 days

Effective time: 47 hours

Temperature during cooling phase



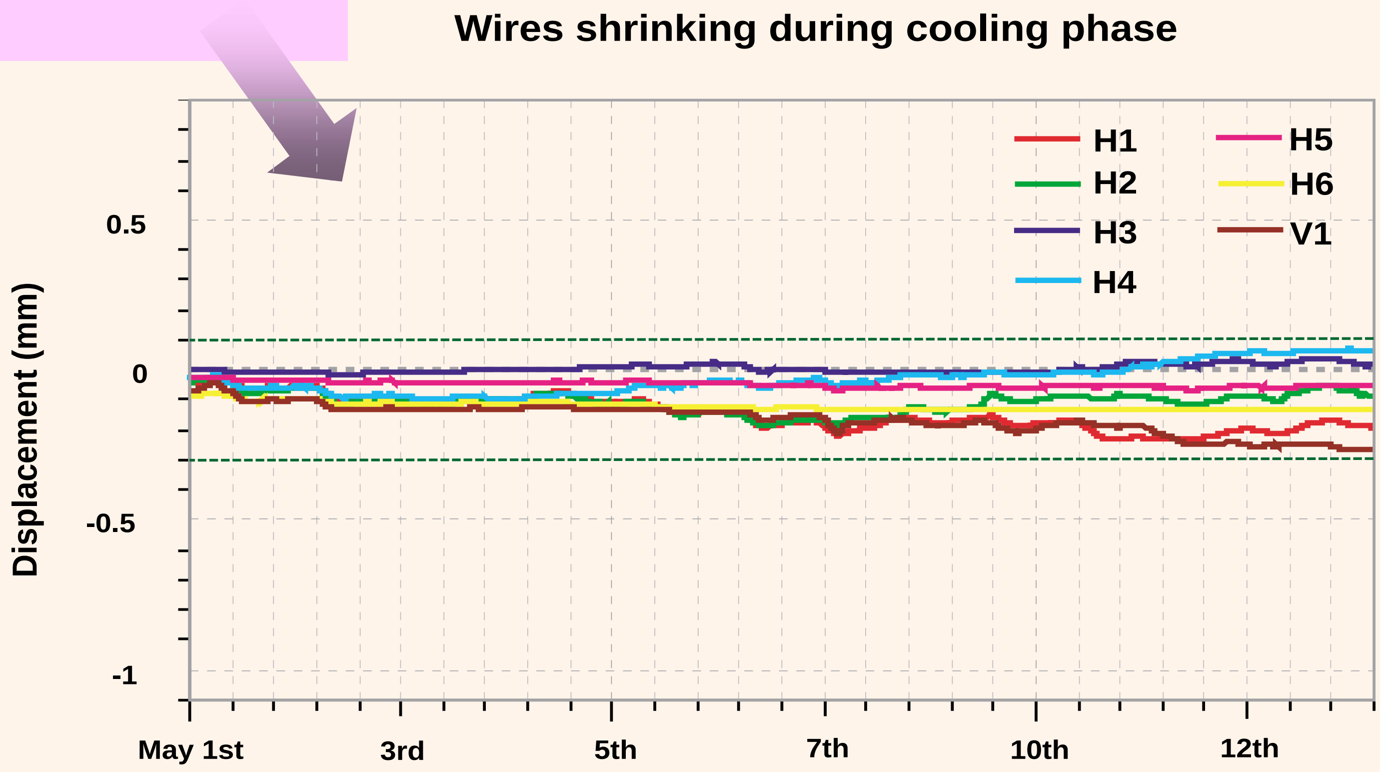




Rubbia, ICARUS Collaboration, May 2001

Wire displacement during the cooling phase

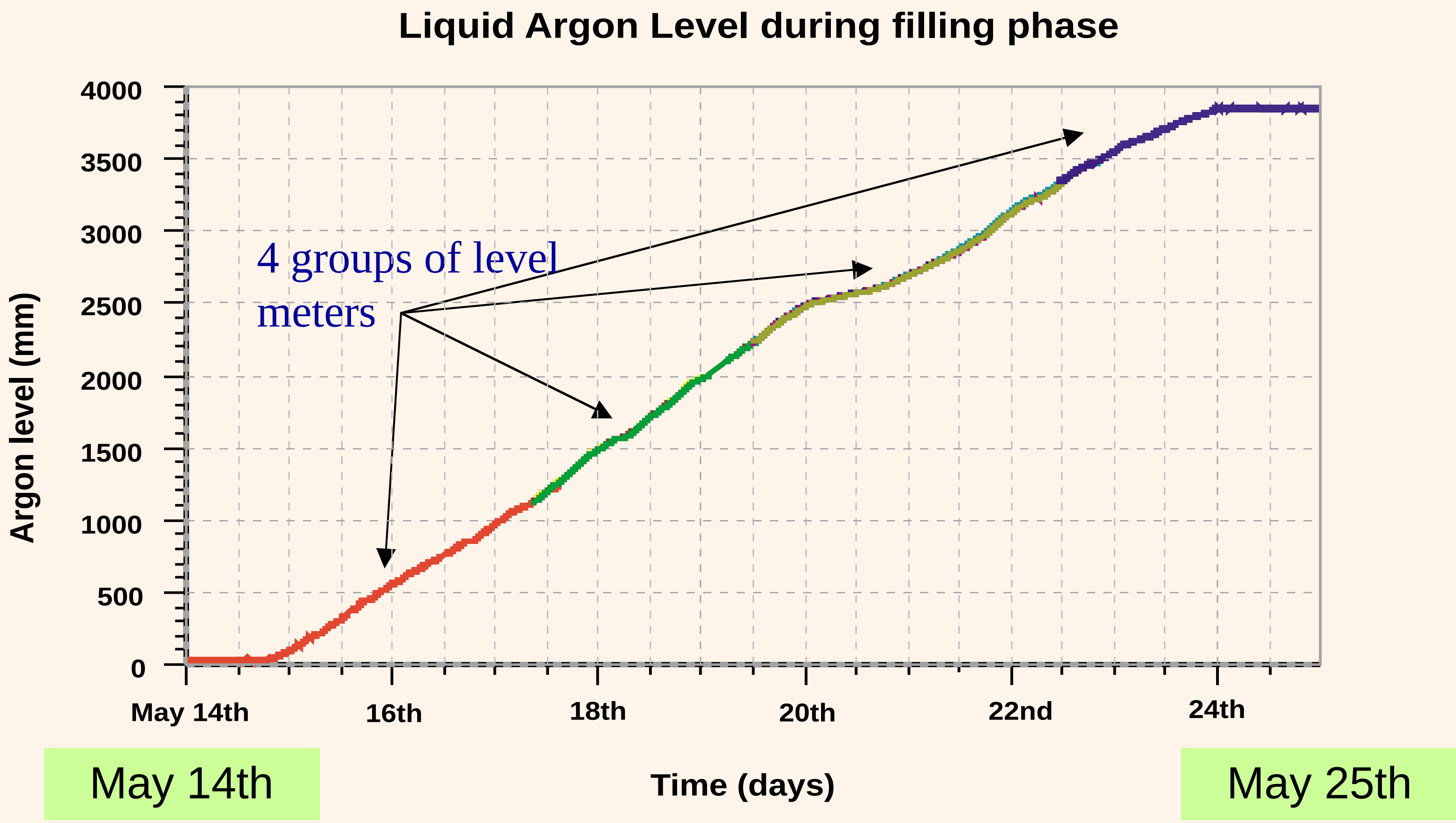
Wires move less than 300μm



May 1st

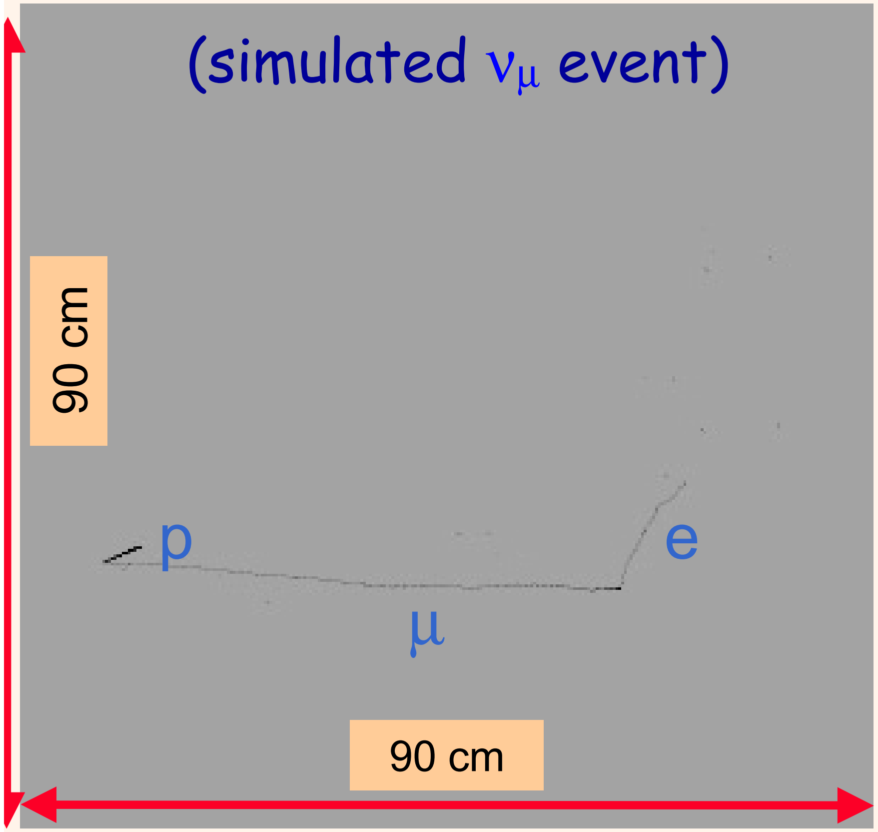
May 15th

Filling phase



10 days were needed to fill up the detector with LAr

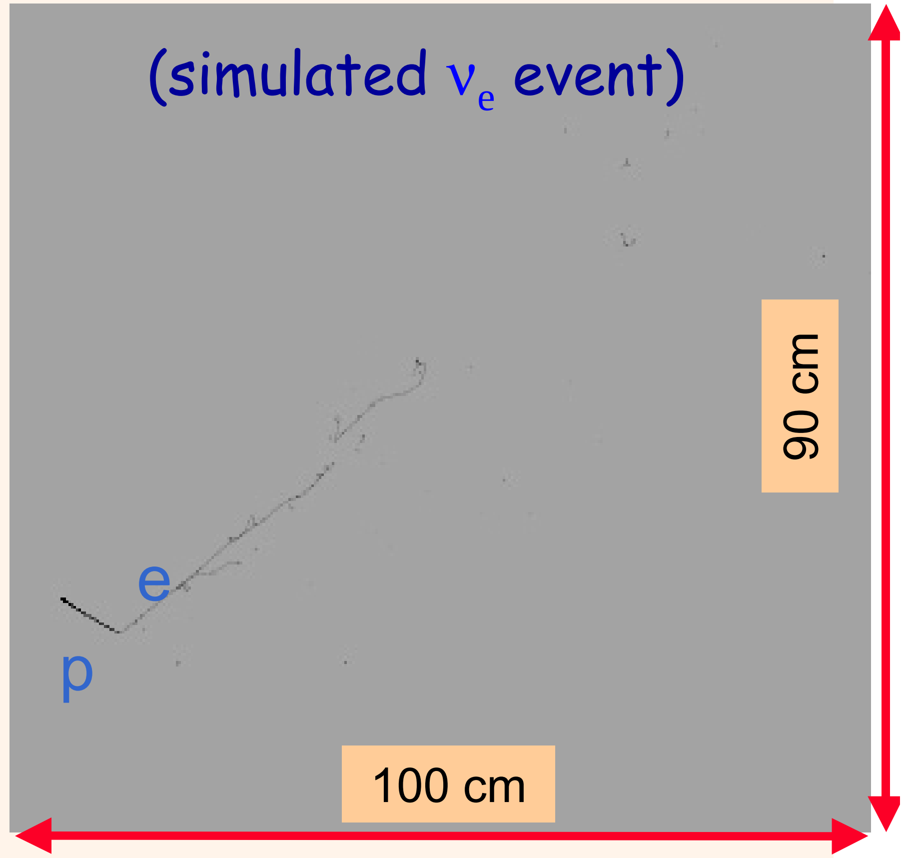
Atmospheric ν events



ν_μ quasi-elastic 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**

Solar neutrino detection

- **Real-time detection of neutrinos through two independent reactions**

Elastic scattering on atomic electron

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

ν absorption on Argon nuclei

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

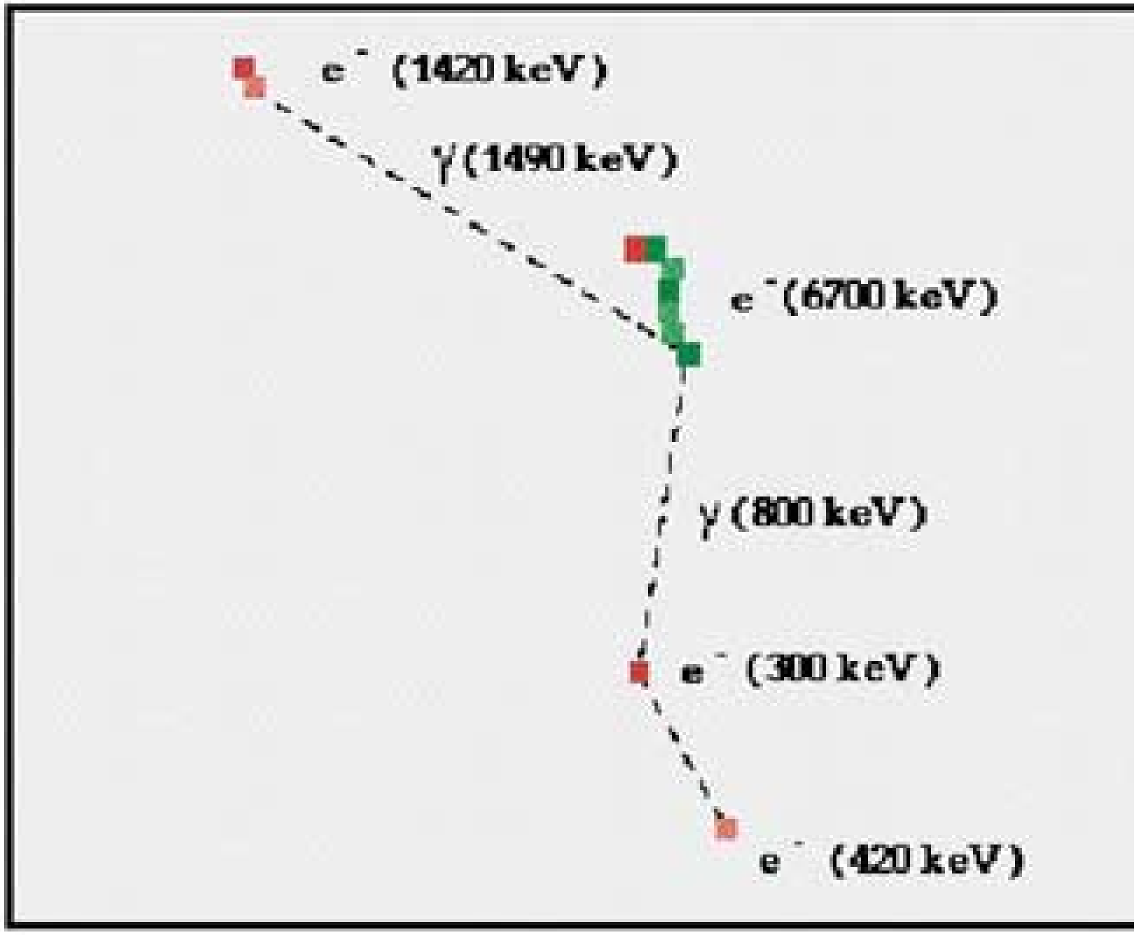
- **Signature: primary electron track**
- **CC/NC separation: (secondary ionization from $^{40}K^*$ de-excitation)**
  - "Smoking gun"
- **Detection threshold: 5 MeV**
- **Sensitive to ^{8}B and *hep* components of the solar neutrino spectrum**

Typical Montecarlo Gamow -Teller digitised event

main electron = 6700 keV

ssociated compton energy = 2140 keV

Iultiplicity = 3



Solar neutrino expected rates

)ff-line event selection done in terms of **energy of the main electron** plus

a) **Elastic:** Angle between electron and solar direction

b) **Absorption:** correlation between multiplicity and energy of the associated tracks

Expected 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

all cuts imposed

Expected events/year (for a 600 ton detector in case of no oscillations)	
Elastic channel	212
Background	6
Absorption channels	759
Background	26

Nucl Instr. And Methods **A455** (2000) 376

Current status

- **Total run duration in Pavia ≈ 3 months (100 days)**
  - √ Day 1 to 10 Vacuum (including leak detection)
  - √ Day 11 to 15 Pre-cooling
  - √ Day 16 to 20 Cooling
  - √ Day 21 to 30 Filling
  - √ Day 31 to 45 Liquid recirculation
  - √ Day 46 to 55 Complete detector start-up
  - √ Day 56 to 65 Data taking with horizontal tracks
    $\Rightarrow$ "***Big track***"
  - √ Day 66 to 70 Data taking with vertical tracks
  - √ Day 71 to 75 Data taking with internal trigger only
  - – Day 76 to 90 Data taking with DEDALUS triggers
  - – Day 91 to 93 Data taking with liquid recirculation on
  - – Day 94 to 100 Data taking with 1 kV / cm drift field

The rationale: “cloning”

- **The T600 module is to be considered as a <u>fundamental milestone</u> on the road towards a total sensitive mass in the multi-kton range**
  - First milestone of a step-wise strategy that allow us **to develop progressively the necessary know-how to build larger detectors**
  - Living proof that **liquid Argon technology can be implemented on large scales**
- **We are now ready to propose the construction of a second T600 “clone” to complete the first 35 meters of the experimental hall at LNGS, with about 1 kton of active liquid argon mass.**
- **The T600 module is hence the first piece of the final detector, to be complemented by further modules of appropriate size and dimension ⇒ *The goal is to reach in a most efficient and rapid way a liquid Argon fiducial mass in the multi-kton range***

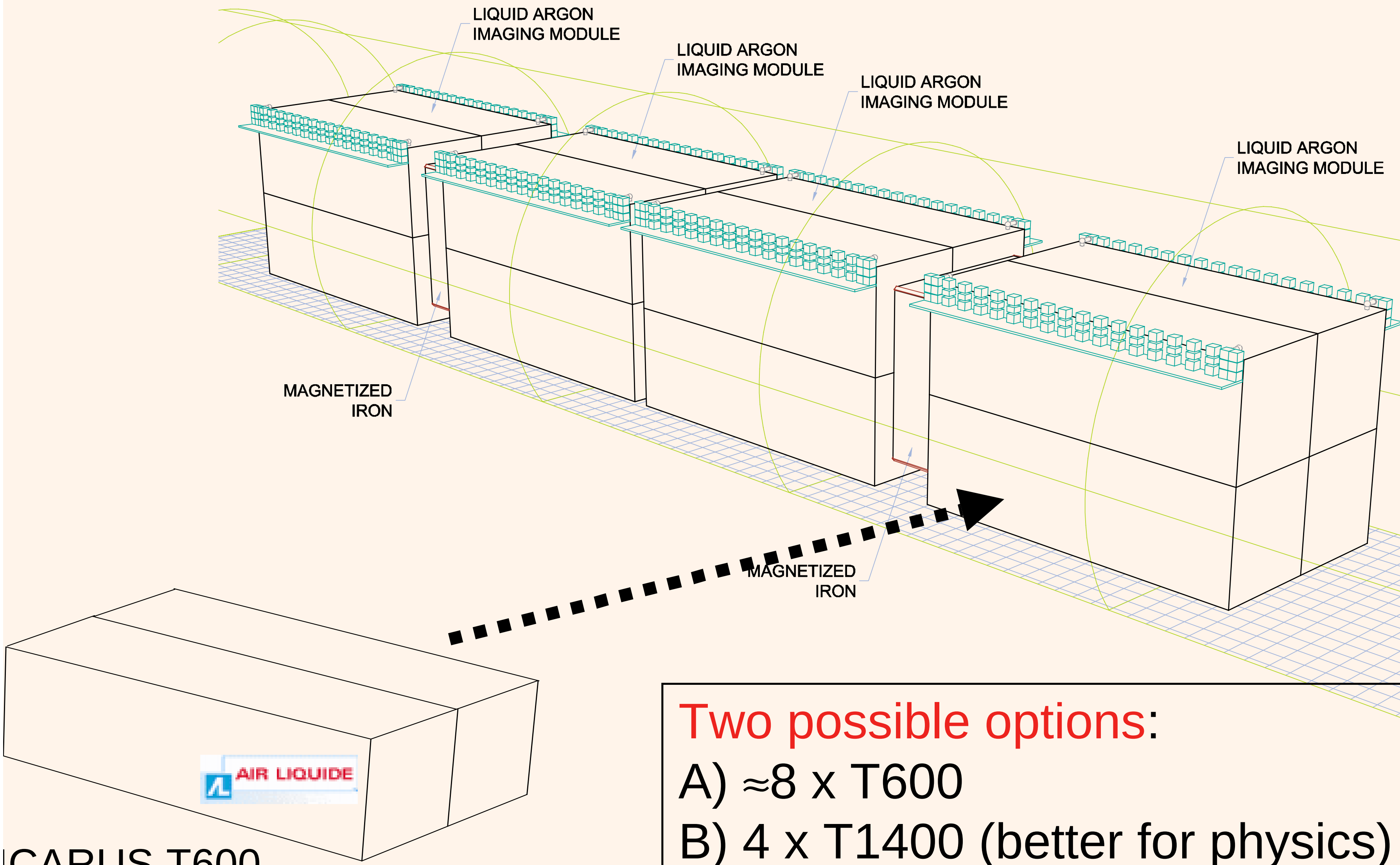
A phased experimental program

At least two different phases:

- **First phase**: atmospheric neutrinos, solar, nucleon decay.
  Exposure ≈ 1-2 kton*year (**hep-ex/0103008**)

- **Second phase**: same + search for τ appearance and $\nu_\mu \rightarrow \nu_e$ oscillations with CERN-Gran Sasso beam.
  Exposure ≈ 20 kton*year
  (LNGS-P21/99 CERN/SPSC 99-25 SPSC/P314 & addendum 1,2)

ICARUS 5kton



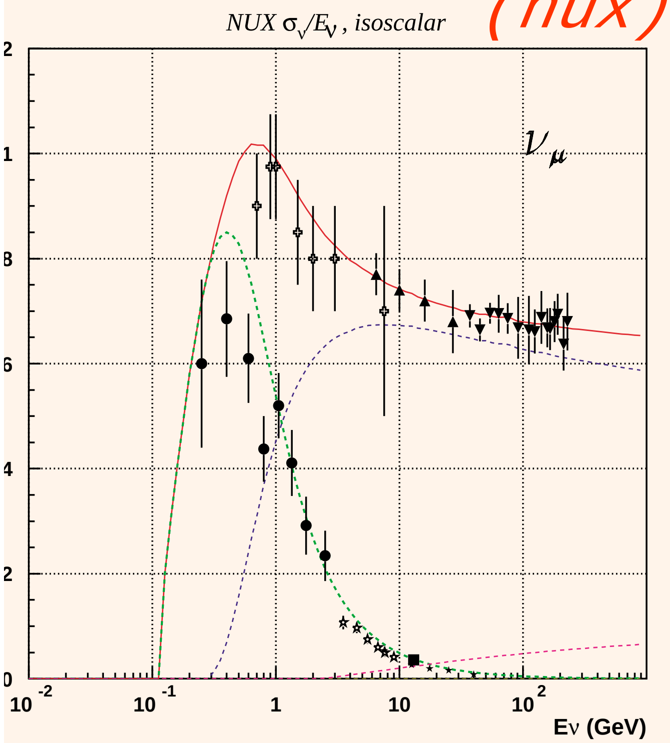
Two possible options:

A) ≈8 x T600

B) 4 x T1400 (better for physics)

Atmospheric neutrino rates (5 kt x year)

(nux)



Total
QE
DIS
Charm

Nuclear effects
fully embedded in *FLUKA* nuclear model

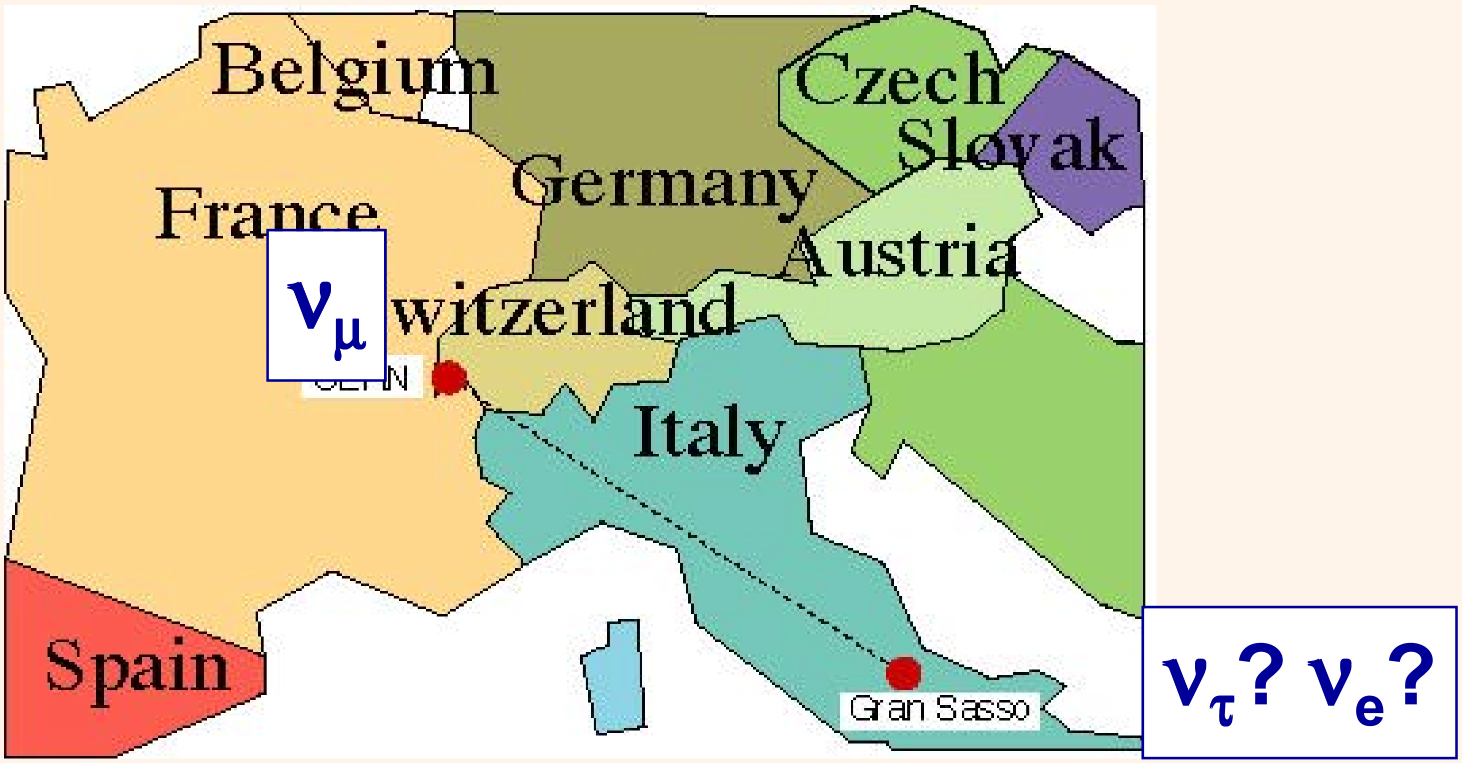
	No osci	Δm^2_{23} (eV^2) 5×10^{-4}	1×10^{-3}	3.5×10^{-3}	5
Muon-like	675 ± 26	515 ± 23	495 ± 22	470 ± 22	4
Contained	418 ± 20	319 ± 18	307 ± 18	291 ± 17	2
Partially-Contained	257 ± 16	196 ± 14	188 ± 14	179 ± 13	1
No proton	260 ± 16	190 ± 14	185 ± 14	170 ± 13	1
One proton	205 ± 14	160 ± 13	150 ± 12	145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

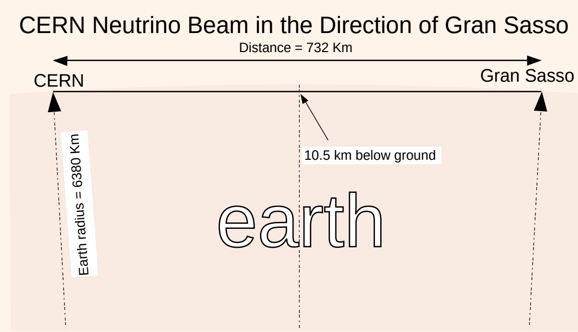
Events/year

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 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

Rubbia, ICARUS Collaboration, May 2001

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

ICARUS
4 years

$\Delta m^2_{32} = 3.5\times 10^{-3}$ 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, $\theta_{23} = 45^o$

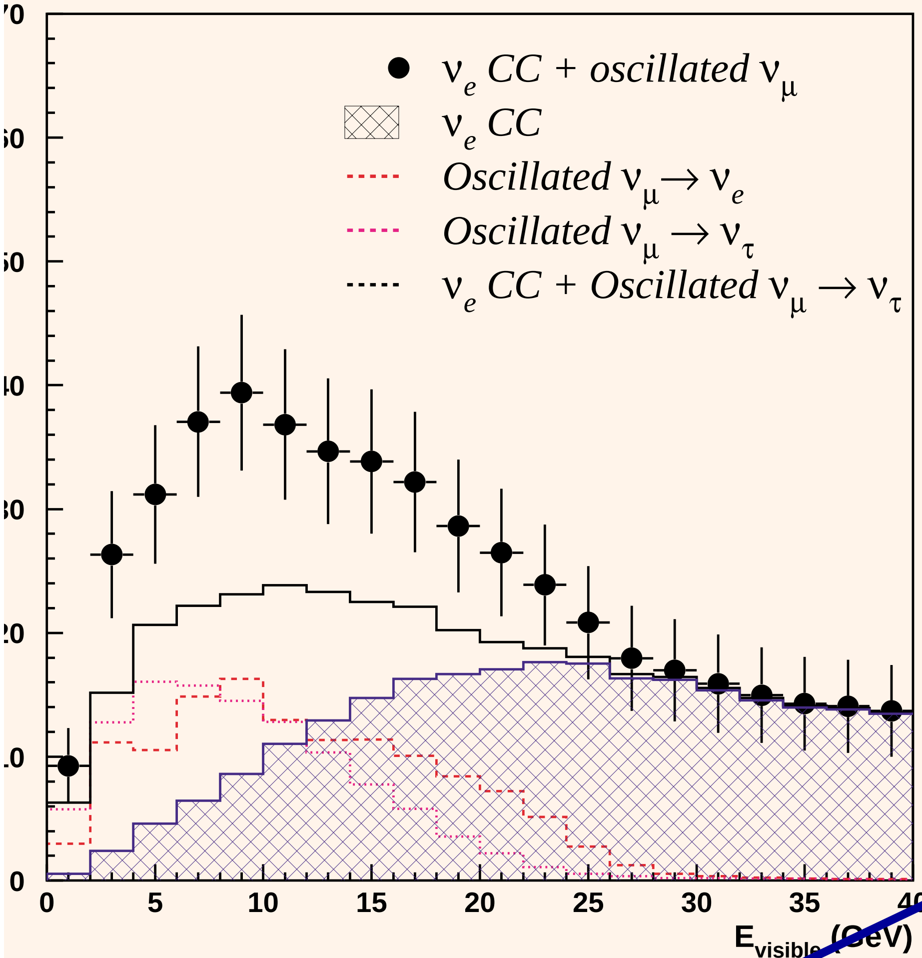
θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	Total	Statistica significan
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

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

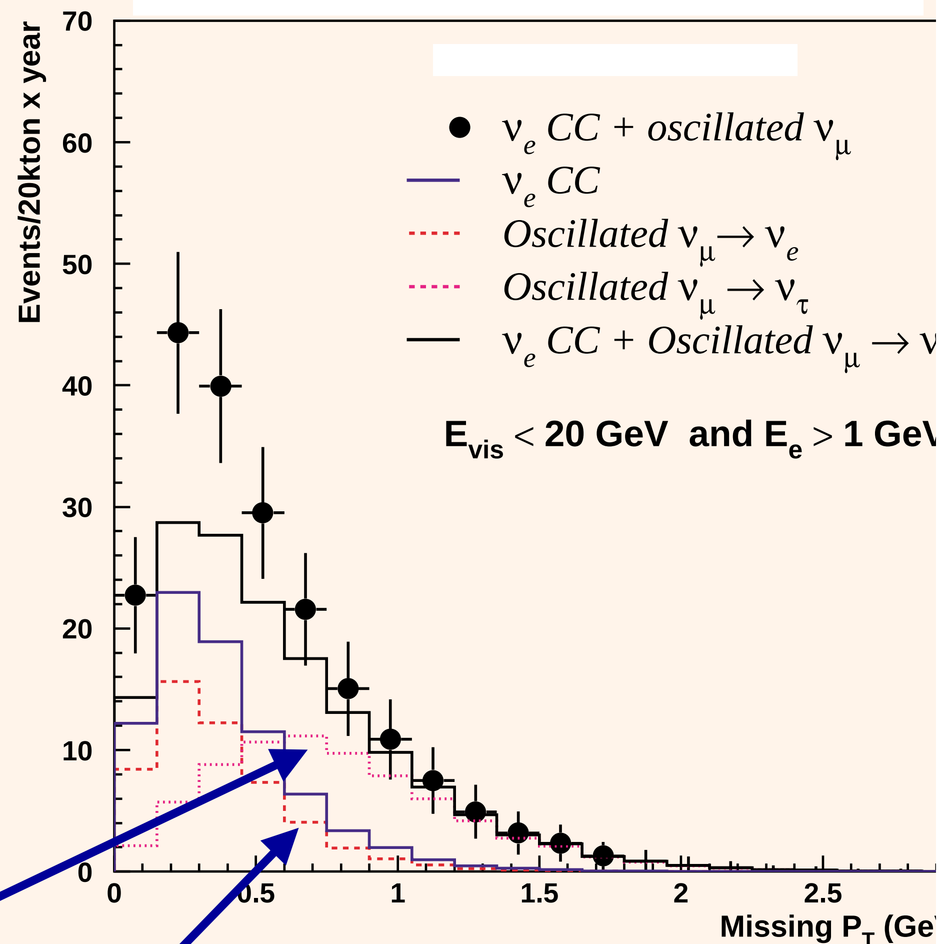
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2_{3}$$

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

Total visible energy



Transverse missing P_T

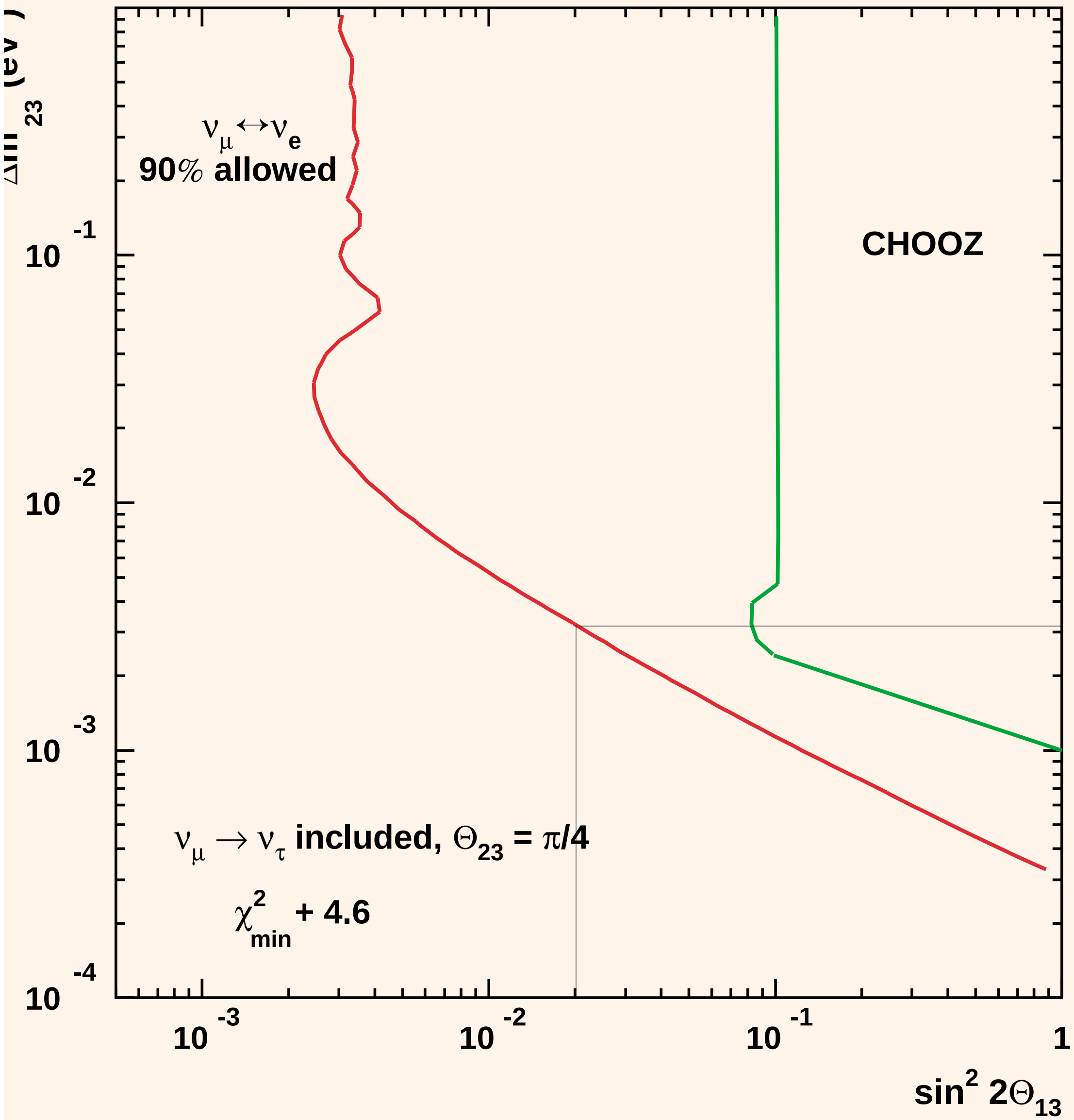


$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2{}_{32}$$

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

Rubbia, ICARUS Collaboration, May 2001

Sensitivity to θ_{13} in three family-mixing



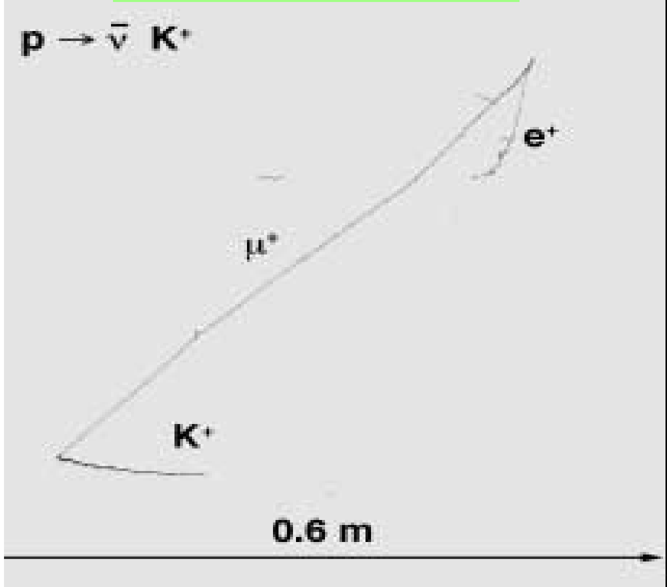
Rubbia, ICARUS Collaboration, May 2001

4 years @ CNGS

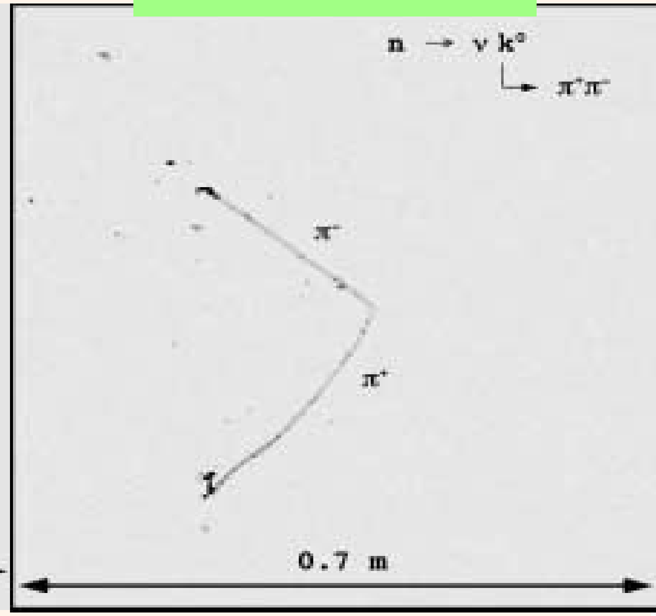
- Estimated sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations in presence of $\nu_\mu \rightarrow \nu_\tau$ (three family mixing)
- Factor 5 improvement on $\sin^2 2\theta_{13}$ at $\Delta m^2 = 3\text{x}10^{-3}$ eV^2
- Almost two-orders of magnitude improvement over existing limit at high Δm^2

Nucleon decay searches

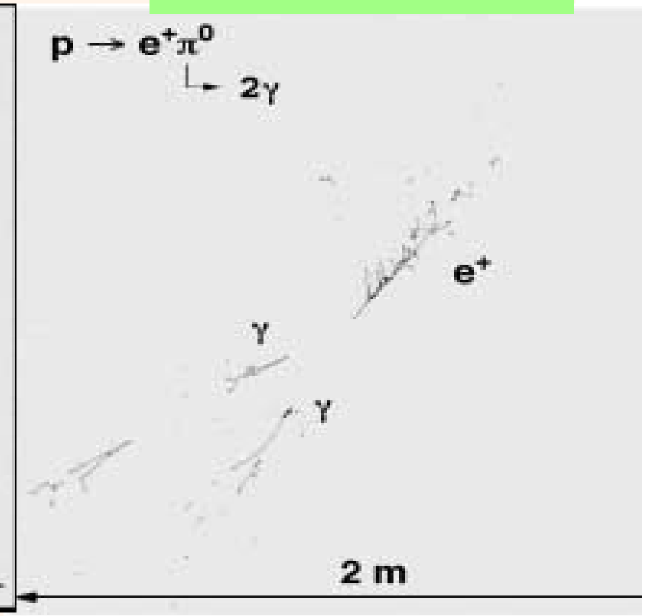
$p \rightarrow \nu K^+$ decay



$n \rightarrow \nu K^0$ decay



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



Thanks to excellent tracking and particle *id* capabilities

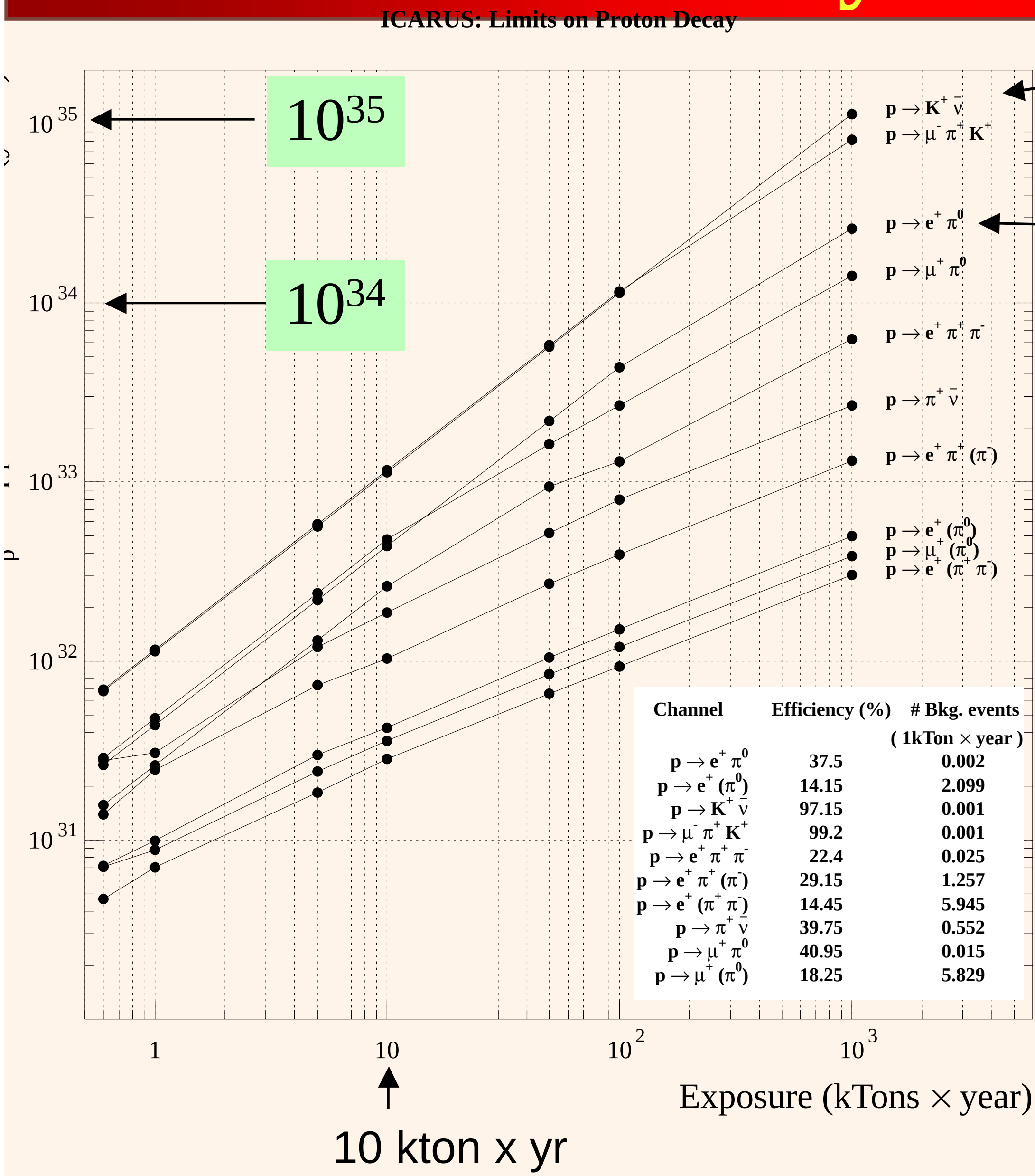
LAr unique tool for

Extremely efficient background rejection

High detection efficiency

Bias-free, fully exclusive channel searches!

Sensitivity vs exposure



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

$p \to K^+ \nu$

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

Extremely good exclusive signal signatures

⇒ Excellent background rejection

Discovery with a single event!

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

Rubbia, ICARUS Collaboration, May 2001

The oscillation physics program at the NF

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

$\nu_\mu \rightarrow \nu_e$	appearance
ν_μ	disappearance
$\nu_\mu \rightarrow \nu_\tau$	appearance
$\bar{\nu}_e$	disappearance
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance
$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	appearance

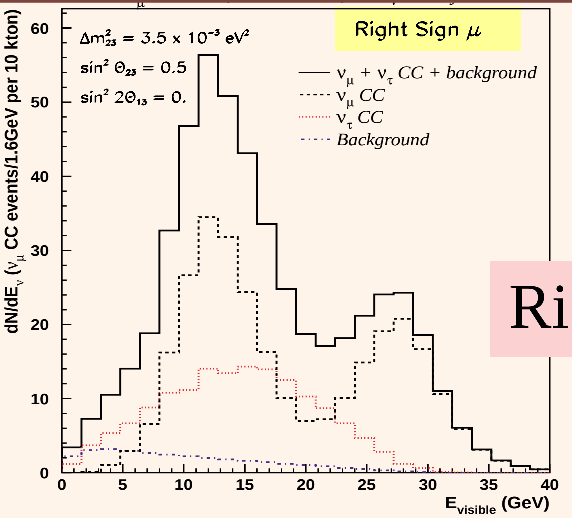
Plus their charge conjugates with μ^+ beam

Ideal detector should be able to measure **12 different processes as a function of L and E_ν**

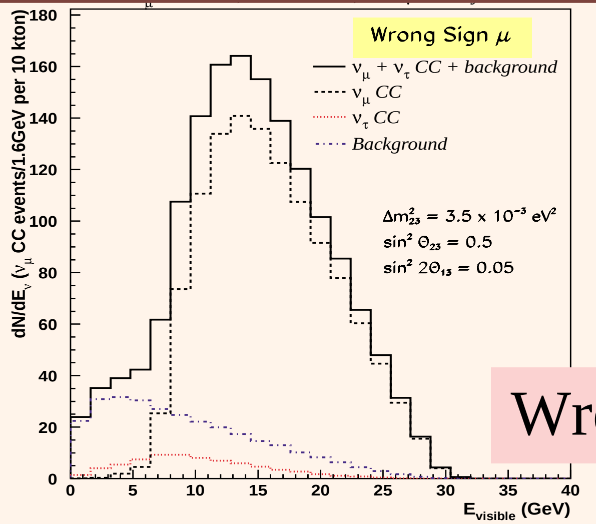
$$\begin{cases} \nu_\ell N \rightarrow \ell^- + hadrons \\ \bar{\nu}_\ell N \rightarrow \ell^+ + hadrons \end{cases} \qquad \begin{cases} \nu_\ell N \rightarrow \nu_\ell + hc \\ \bar{\nu}_\ell N \rightarrow \bar{\nu}_\ell + hc \end{cases}$$

1. ***Particle ID***: *charged lepton tags* ***incoming neutrino flavor***
2. ***Charge ID***: *sign of lepton charge tags* ***helicity*** *of incoming neutrino*
3. ***Energy resolution***: *Reconstructed event energy is* $\boldsymbol{E_\nu = E_l + E_{had}}$
4. ***Various baselines L*** *could help for detector systematics*

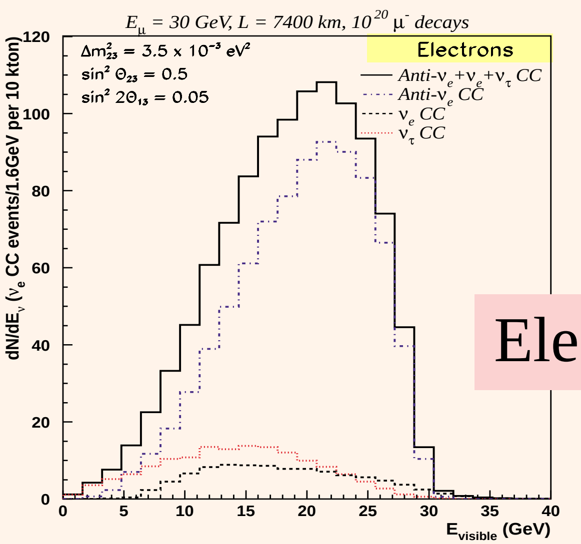
NF event classes with ICARUS



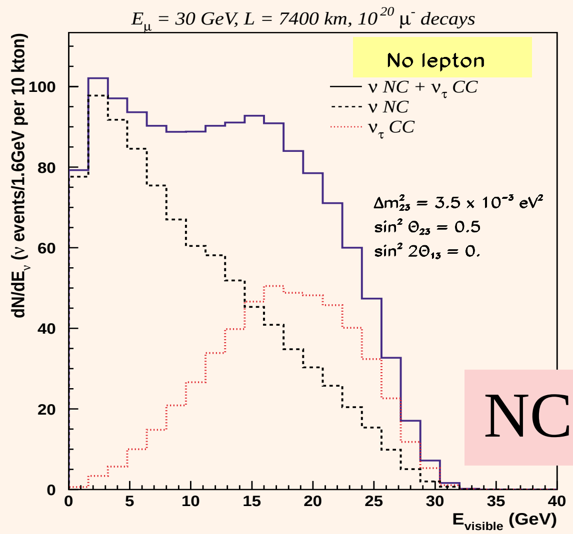
Right sign μ



Wrong sign μ



Electrons



NC-like

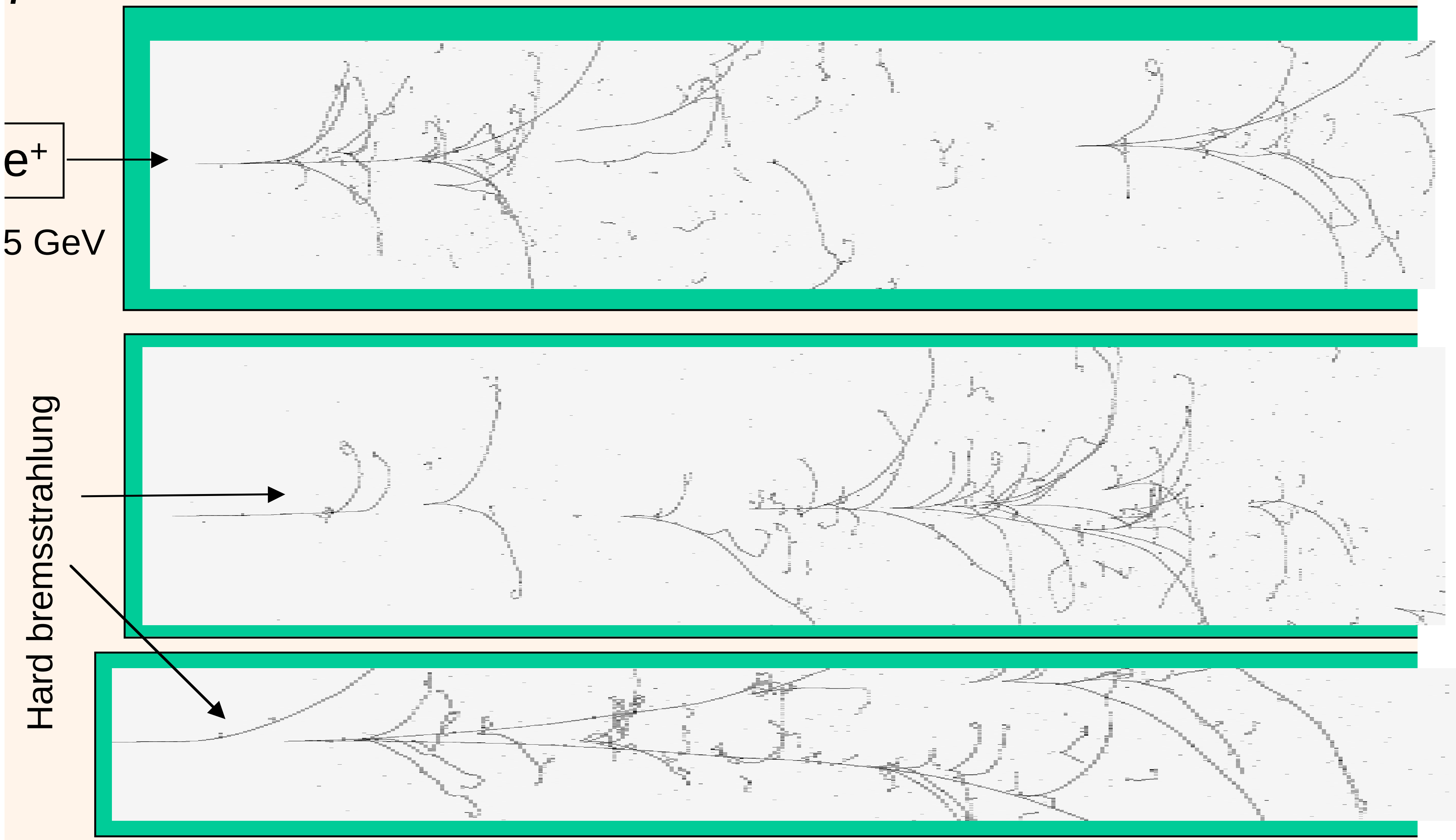
Combining all classes ⇒ (over-constrained) sensitivity to all oscillations!

A.Bueno, M.Campanelli., A.Rubbia Nuc. Phys. B 573 27-39, NIM A 451 176-181, Nuc. Phys. B 589, 577-6

A magnetized ICARUS

The presence of a magnetic field surrounding the LAr should allow to even determine the charge of electrons

B=1T



Conclusion

- **ICARUS T600 experiment will yield information on solar, atmospheric neutrinos and maybe supernova neutrinos.**
- **Thanks to its superior detection technique, it will allow the study of atmospheric neutrino interactions with high quality and resolution, and also in the energy range below 400 MeV.**
- **We expect to transport the ICARUS T600 detector into the LNGS tunnel after successful tests in Pavia.**
- **A strategy to reach the multikton ICARUS in the LNGS tunnel in the most efficient and rapid way is under study. This mass will be required for the first CERN long-baseline beam (CNGS), for sensitive proton decay searches and for possible future neutrino factories.**
- **The ICARUS technology, when scaled to 10's kton masses, holds the potential of a physics of incomparable quality.**
- **A magnetized ICARUS is the only detector that could yield the electron charge.**