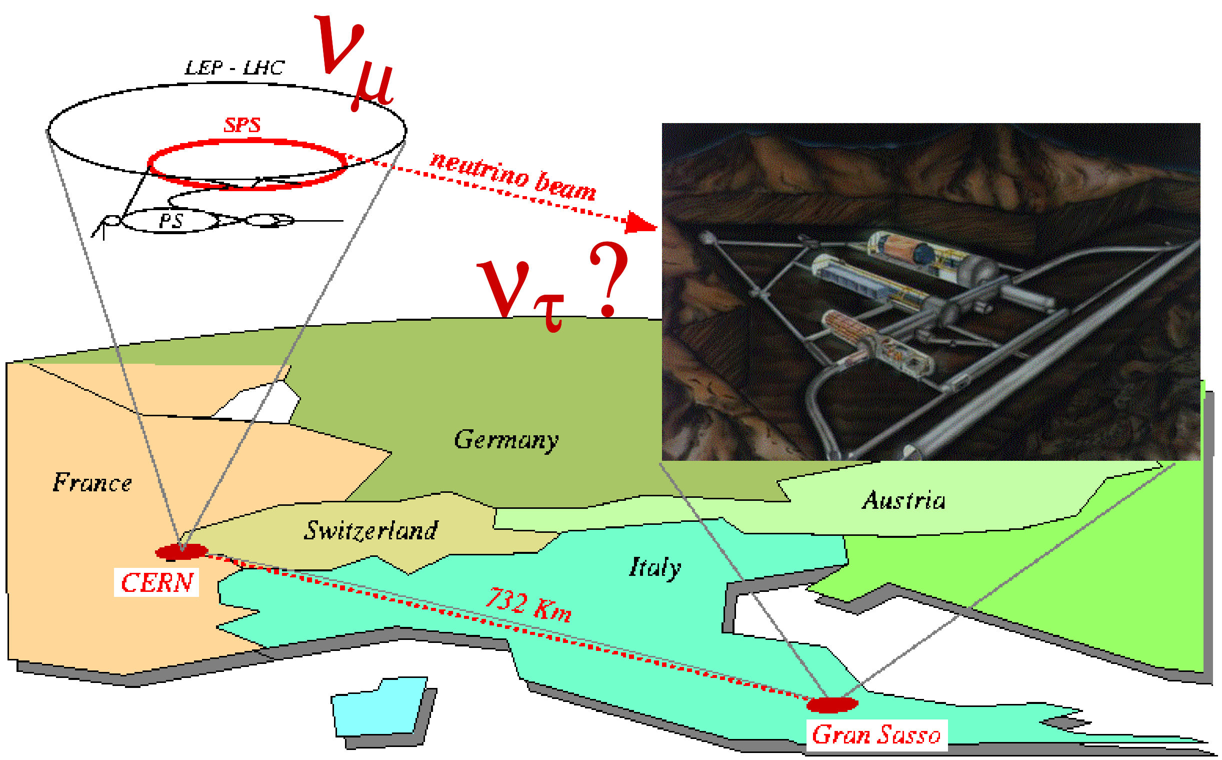
The European Long Baseline Program

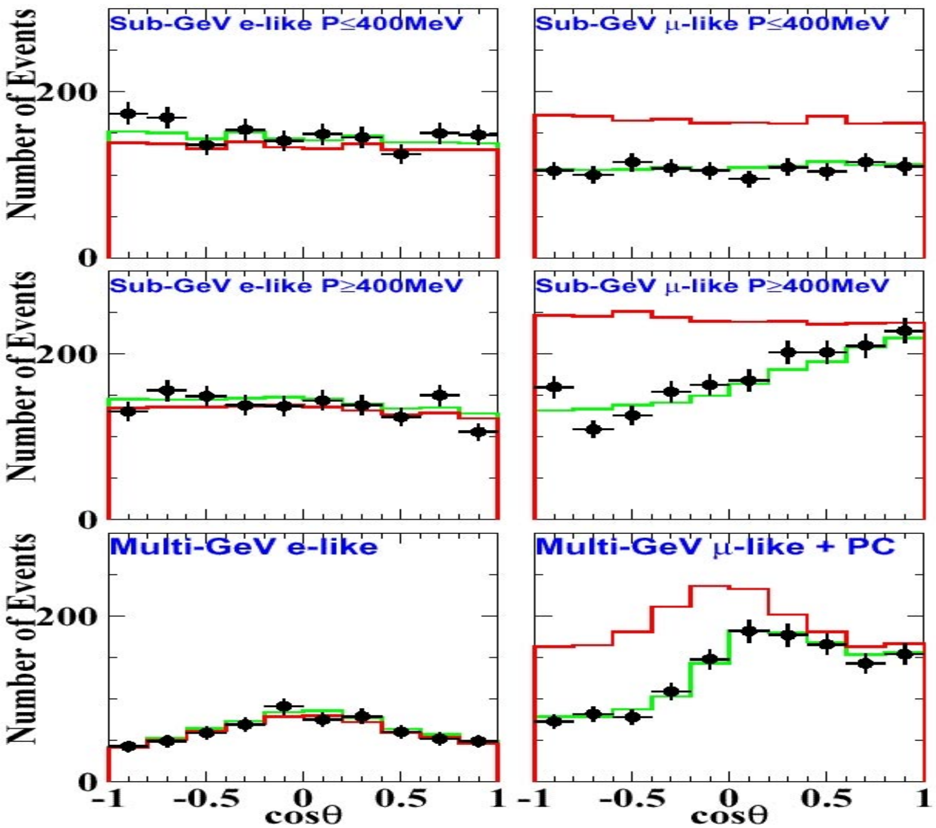
Les Houches, 21 June 2001
Dario Autiero CERN/EP

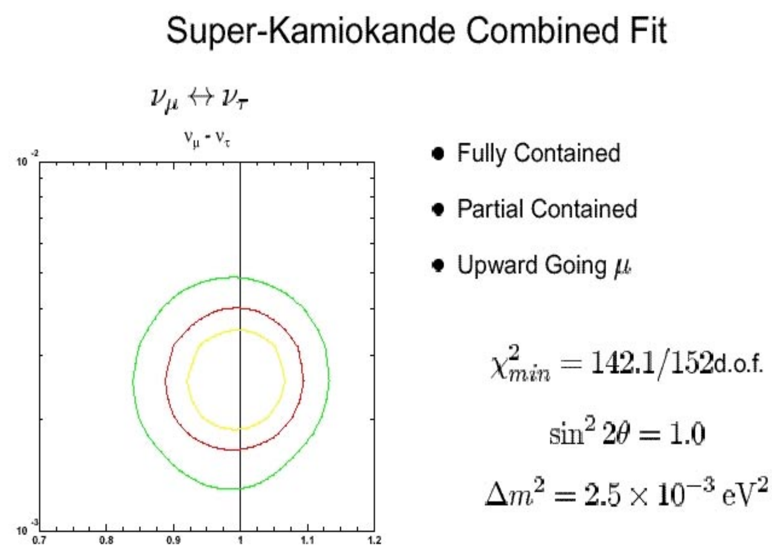
CERN to Gran Sasso Neutrino Beam



Many thanks to A. Rubbia for providing material about ICARUS

The atmospheric neutrino results from SuperKamiokande





There is a clear dependence on L/E but the oscillation behavior (observation of a complete oscillation) is not demonstrated

$\nu_\mu \rightarrow \nu_e$ oscillations are excluded also by CHOOZ
$\nu_\mu \rightarrow \nu_s$ oscillations are already excluded at 99% CL

Motivations

- Study neutrino oscillations at $\Delta m^2 > 10^{-3}$ eV^2 in the region indicated by SuperKamiokande
- Establish unambiguously and definitively that the anomaly is due to $\nu_\mu \rightarrow \nu_\tau$ oscillations by observing ν_τ appearance in a beam containing negligible ν_τ at production
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations with higher sensitivity than CHOOZ

Focussing on ν_τ appearance:

high energy beam optimized for τ appearance,
clear signature, almost background free experiments,
no need for near detectors,
730 Km baseline from CERN to Gran Sasso

Detection of the $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$ signal and background rejection

ν_μ ……………… $\nu_\tau \rightarrow \tau^- + X$

oscillation

CC interaction

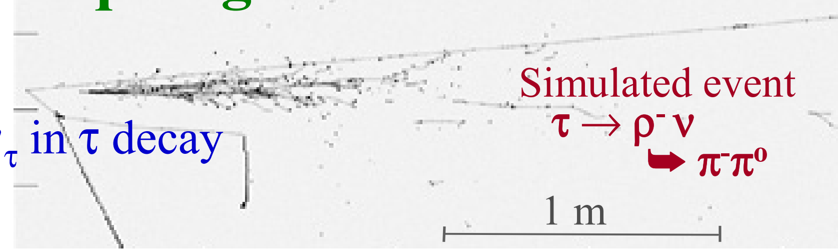
	BR
$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$	BR 18 %
$h^- \ \nu_\tau \ n\pi^o$	50 %
$e^- \ \nu_\tau \ \bar{\nu}_e$	18 %
$\pi^+ \pi^- \pi^- \ \nu_\tau \ n\pi^o$	14 %

ICARUS: Detailed general picture in Liq. Argon

Kinematics ***(à la NOMAD)***

Momentum unbalance from unseen ν_τ in τ decay

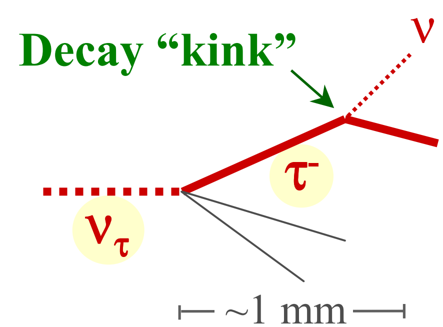
Energy measurement



OPERA: Observation of the decay "signature" at microscopic scale ***(à la CHORUS)***

"nuclear" photographic emulsion

(~ **1μm** granularity)



The Experimental Program

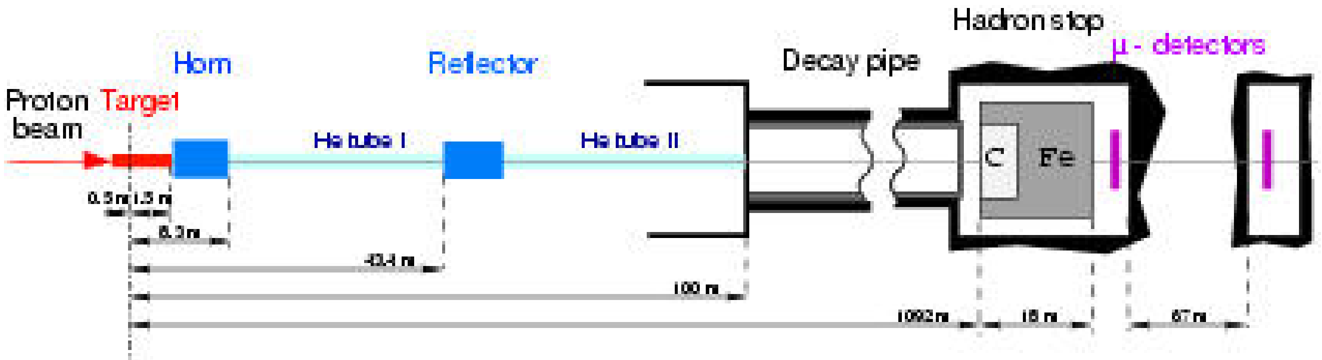
- **CNGS:** Approved at the end of 1999, civil engineering in progress, first neutrinos expected by 2005
- **OPERA:** Approved in February 2001 (CNGS1), observation of the τ^- decay kink in a high resolution detector consisting of emulsion films and lead plates for a mass of 2 Ktons, same technique as the one used by DONUT for the first direct observation of the ν_τ charged current interactions (2000)
- **ICARUS:** Not yet approved. Liquid Argon TPC, kinematic technique a` la NOMAD, total detector mass of about 5 Ktons, 600 Ton demonstration module being completed, first results

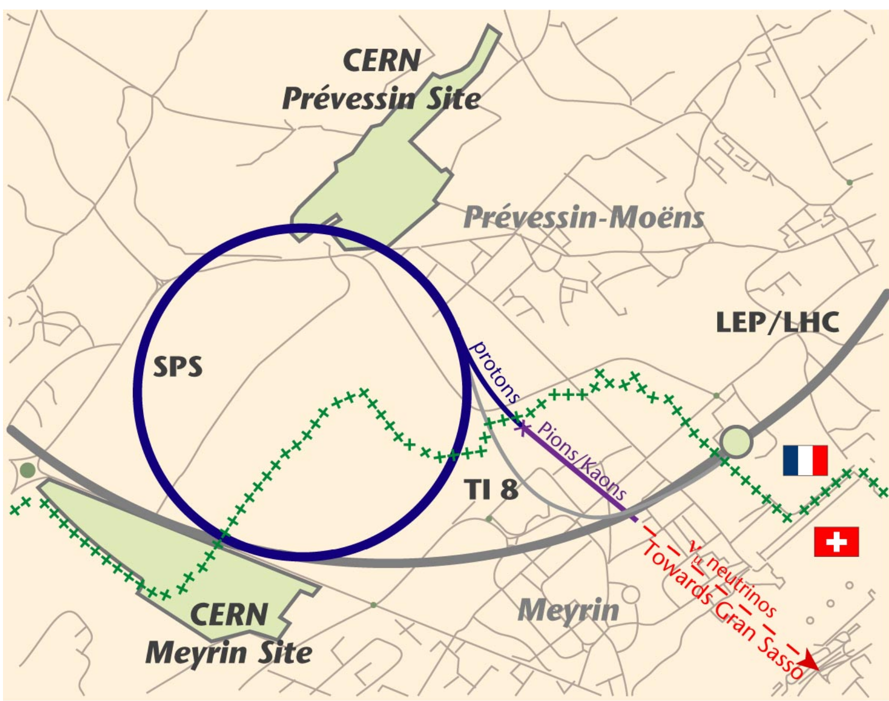
The two experiments are a natural continuation of the CHORUS and NOMAD short baseline experiments at CERN but:

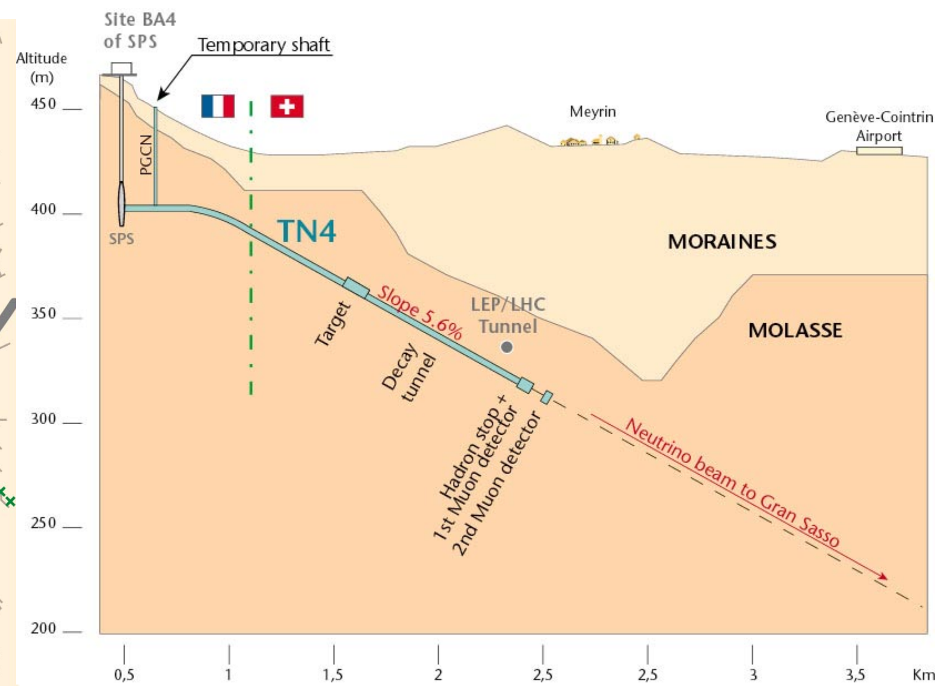
→ **The conflicting requirements of large scale and at the same time very good space/energy resolution represent a big challenge solved by many years of R&D**

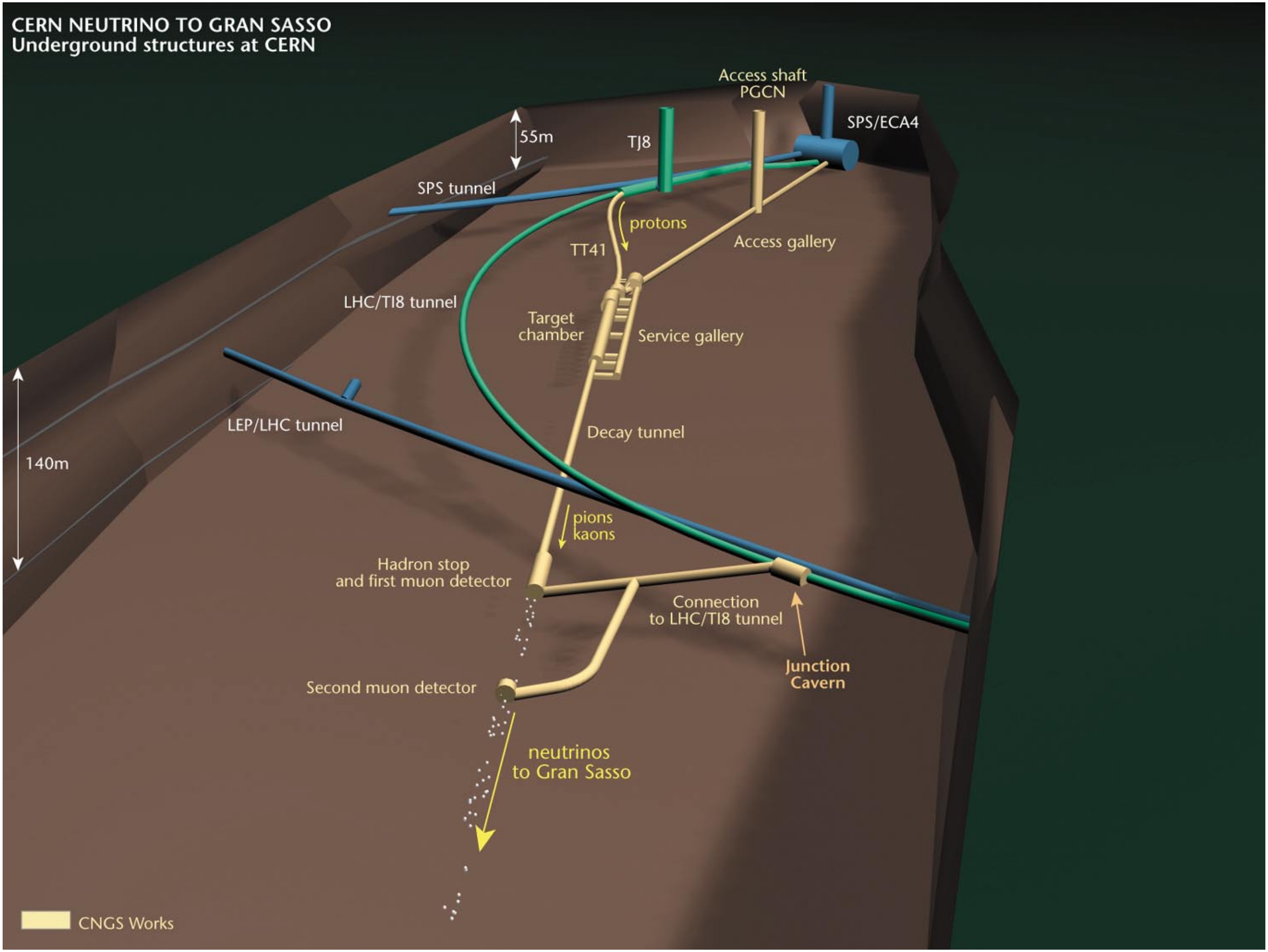
The CERN side

400 GeV/c

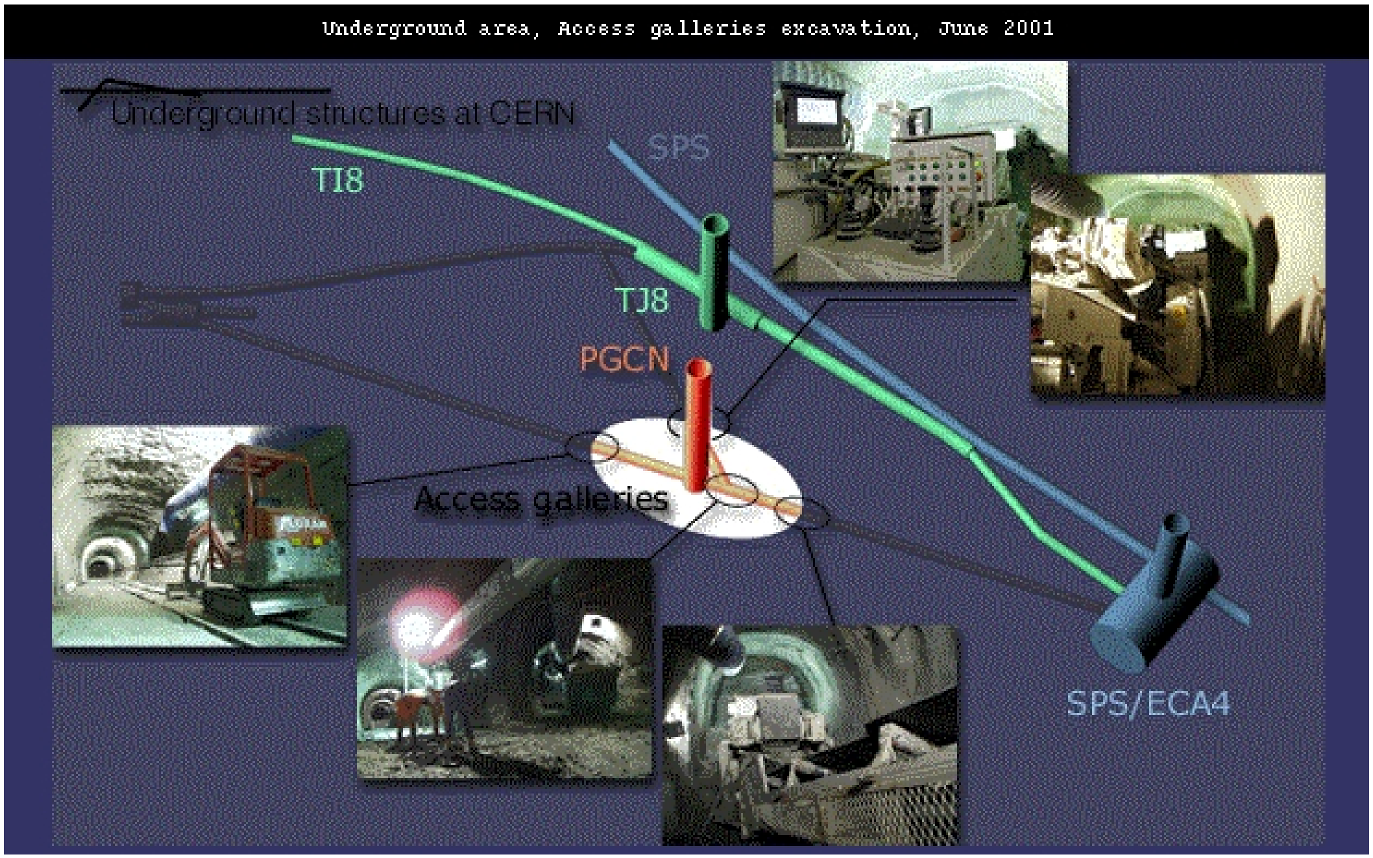







CERN NEUTRINO TO GRAN SASSO
Underground structures at CERN
Access shaft
PGCN
SPS/ECA4
55m
TJ8
SPS tunnel
protons
TT41
Access gallery
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
Decay tunnel
pions
kaons
Hadron stop
and first muon detector
Connection
to LHC/TI8 tunnel
Junction
Cavern
Second muon detector
neutrinos
to Gran Sasso
CNGS Works

Status of the civil engineering work



Excavation is going on smoothly,
very good ground conditions so far ...

CNGS beam characteristics

Nominal ν beam

ν_μ (m^{-2} / pot)	7.78×10^{-9}
ν_μ CC / pot / kton	5.85×10^{-17}
$< E >_\nu$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	negligible

⇒ **Interactions with 1.8 kton target x 5 years**

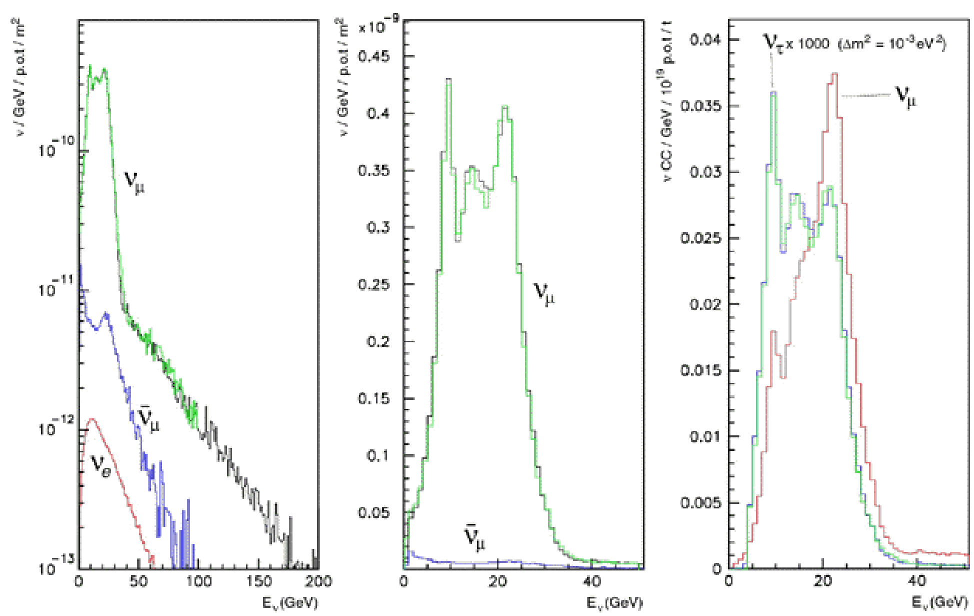
~ 30000 ν NC+CC

~ 140 ν_τ CC (@full mixing, $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

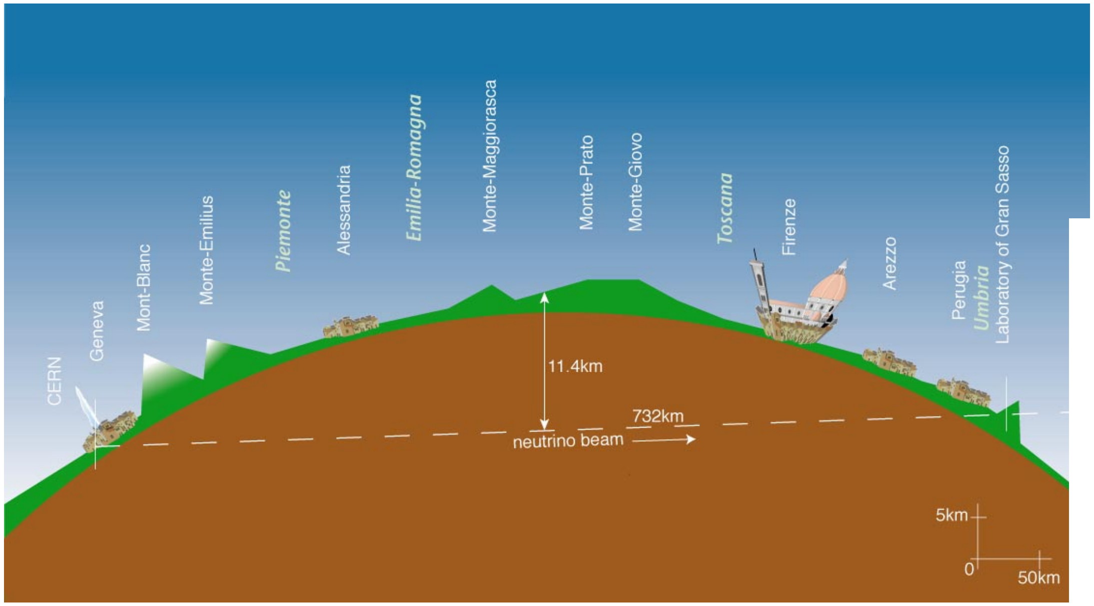
Shared SPS operation

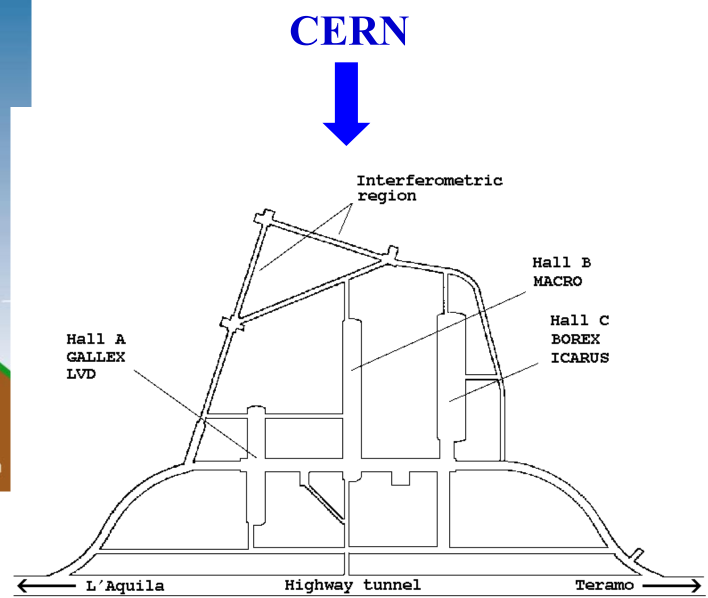
200 days/year

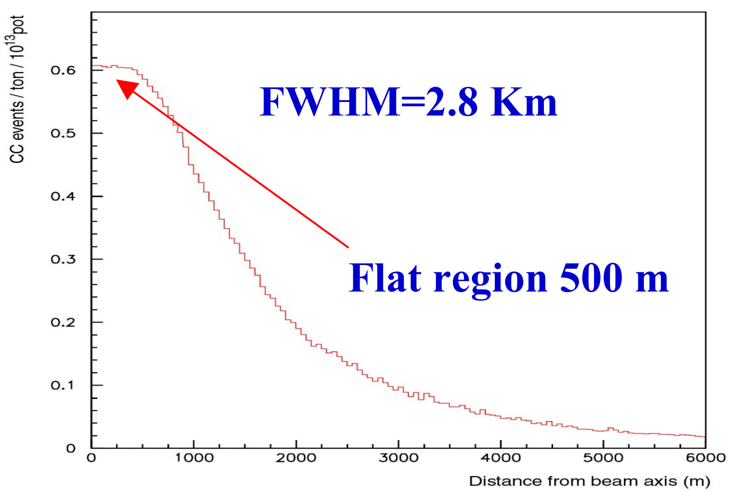
4.5×10^{19} pot / year



The beam at Gran Sasso





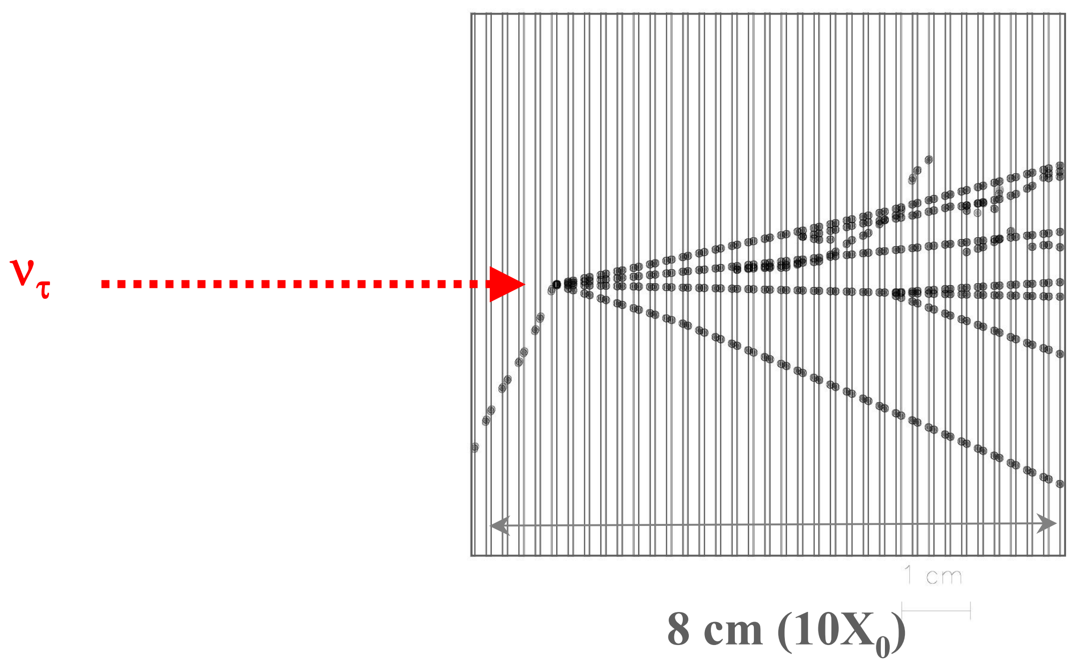


Beam transverse dimensions at Gran Sasso given by $\pi^+ \rightarrow \mu^+ \nu_\mu$ kinematics: max p_T= 30 MeV/c

$\theta_{\nu_\mu} = 0.03/E_{\nu_\mu}$ (GeV)

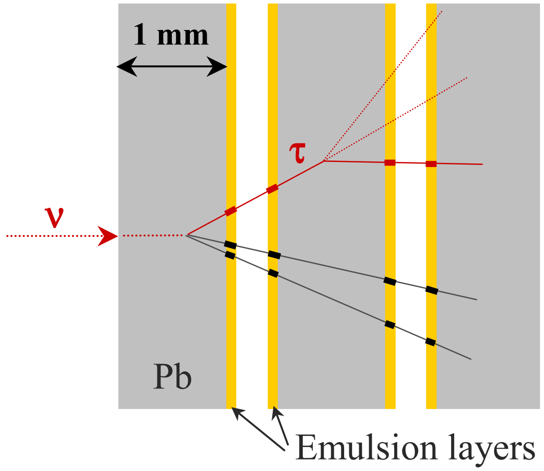
The OPERA experiment

Brick
(56 Pb/Emulsions. “cells”)

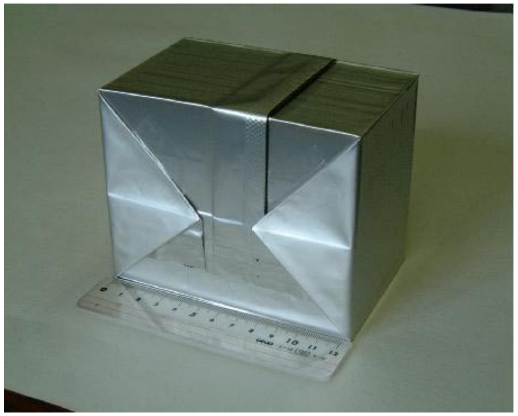


The experimental technique

- **Emulsion Cloud Chamber (ECC)**
  (emulsions for tracking, passive material as target)
  - Basic technique works
    - charmed "X-particle" first observed in cosmic rays (1971)
    - DONUT/FNAL beam-dump experiment: ν_τ events observed



- $\mathbf{\Delta m^2 = (1.6 - 4) \times 10^{-3}\ eV^2}$ (SuperK) → $\mathbf{M_{target} \sim 2\ kton}$ of "compact" ECC (baseline)
  - large detector → sensitivity, complexity
  - modular structure ("bricks"): basic performance is preserved



- **Ongoing developments,** required by the large vertex detector mass:
  - industrially produced emulsion films
  - automatic scanning microscopes with ultra high-speed

Experience with emulsions and/or ν_τ searches : E531, CHORUS, NOMAD and DONUT

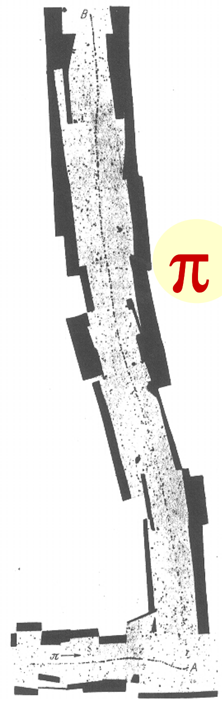
Nuclear Emulsion: unique to "see" the decay of short-lived particles

1947 : π discovery

Sensitivity of ***nuclear*** emulsion

↓

π **discovery** with cosmic rays



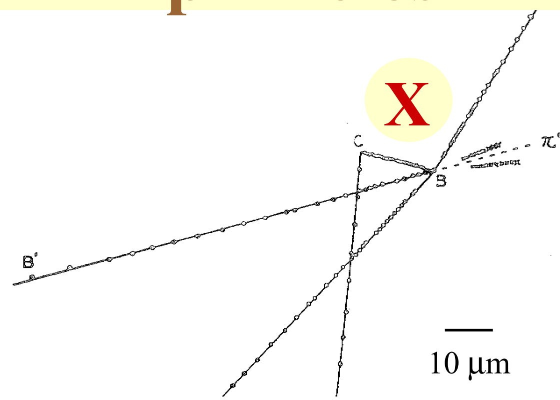
1971 : charm

Emulsion Cloud Chamber

(Pb-emulsion sandwich)

↓

Charm first seen as ***X-particle*** in cosmic ray interactions

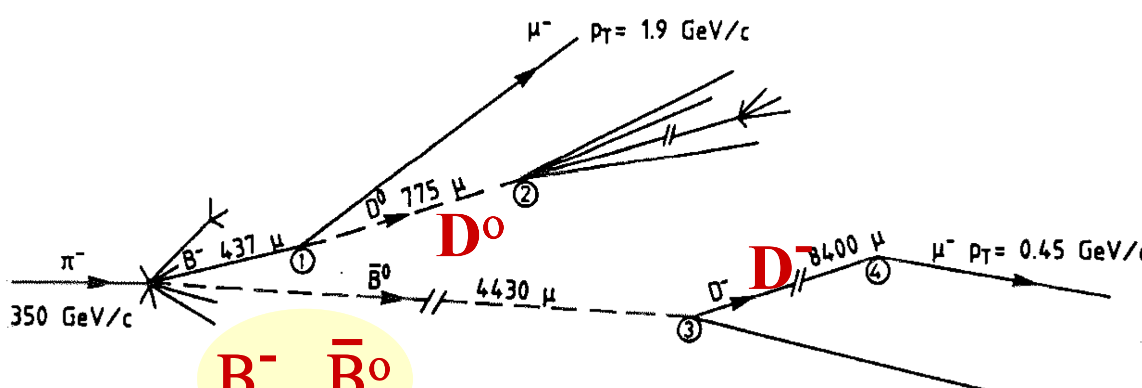


1985 : beauty

WA75 "hybrid" experiment

↓

First observation of beauty production and decay



50 years after π discovery

Automatic scanning, **massive targets**

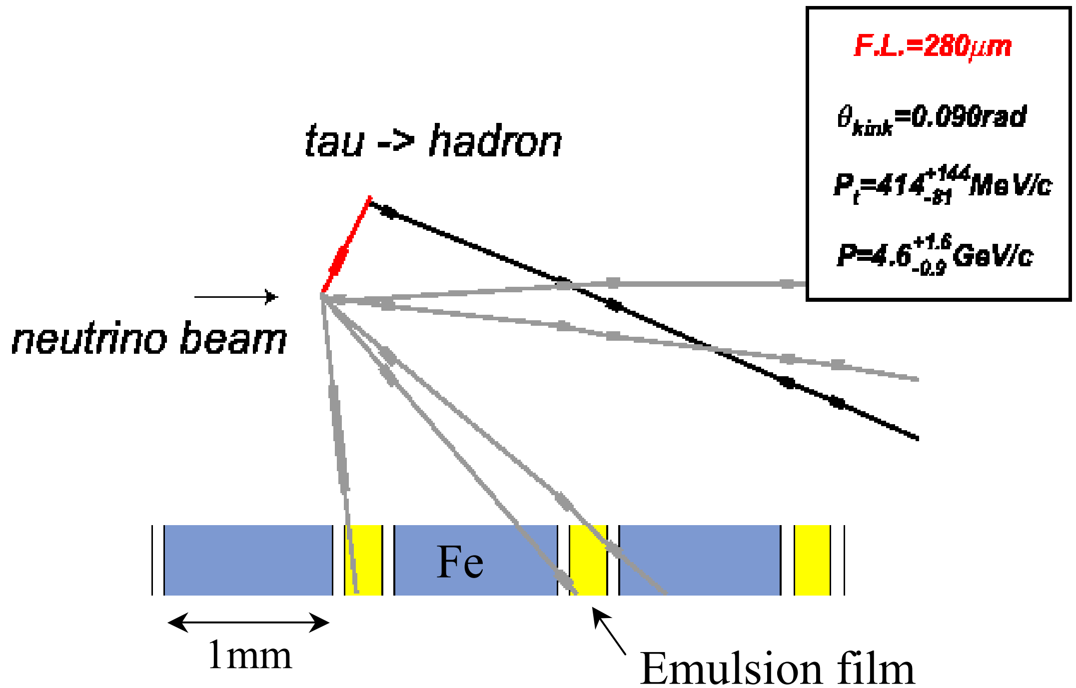
↓

Search for ***τ decay*** from ν_τ interactions

If zero background : 1 event gives a result

Emulsion Cloud Chamber for ν_τ detection
(DONUT → OPERA)

ν_τ detected in the DONUT ECC



Structure	DONUT	=	OPERA	
Material	DONUT Fe	→	OPERA Pb **better for physics analysis** (Fe density : too large or too small)	

ν_τ detection by Emulsion-Counter Hybrid Experiments

	Emulsion gel	Track density In emulsion	Scan area
CHORUS	400 liter	10^4 /cm^2	6×10^4 cm^2
DONUT	50 liter	10^5 /cm^2	2×10^4 cm^2
OPERA	10^4 liter diluted 5000 liter equivalent	10^2 /cm^2	5×10^6 cm^2

10 x CHORUS

100 x CHORUS

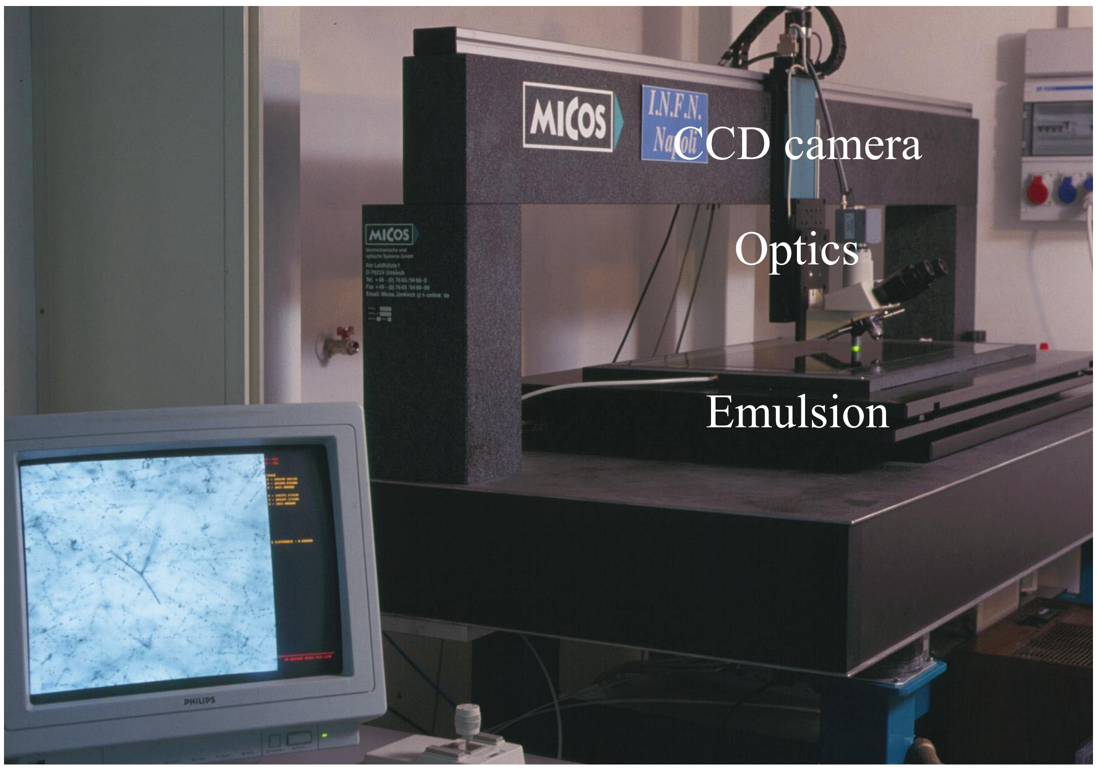
UTS → S-UTS : x 20
# of S-UTS : x 5

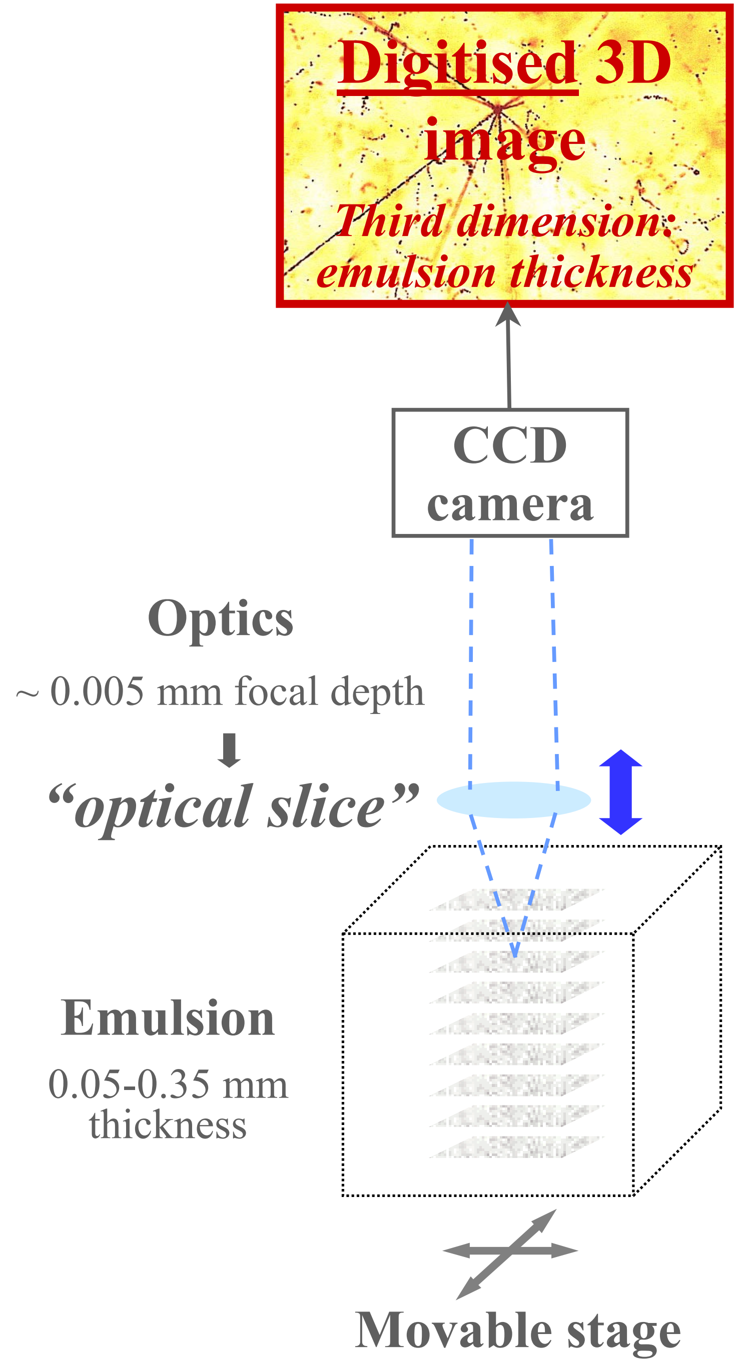
Industrial emulsion films (as for X-rays)

Scanning speed x 10 every few years

Microscope for automatic image analysis

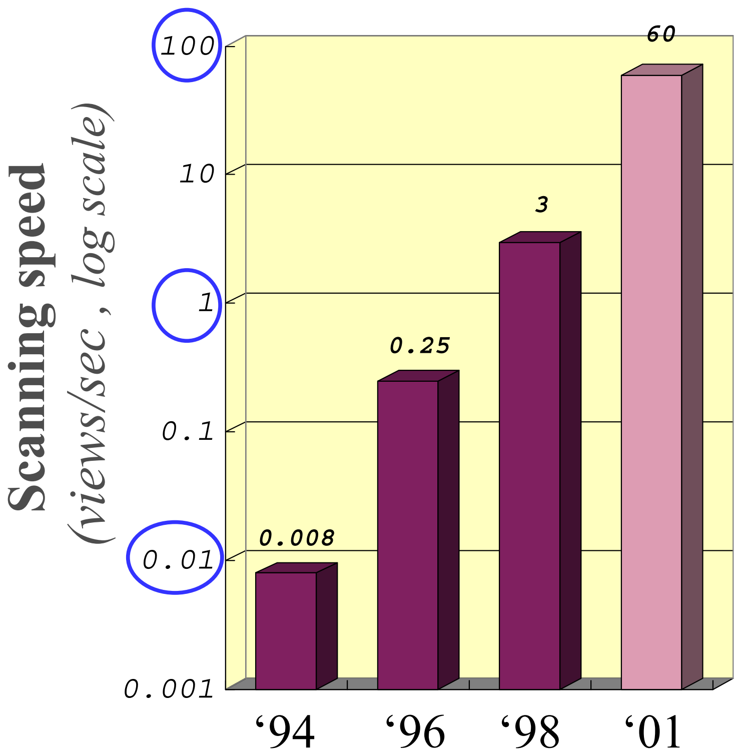
Computer controlled
Multidisciplinary applications: e.g. biophysics





Progress in automatic emulsion scanning

Scanning speed road map
(Nagoya University)



New tools always made a difference !

From B.Kurtén, *Our earliest ancestors*
Columbia University Press (1993)

Aim for OPERA

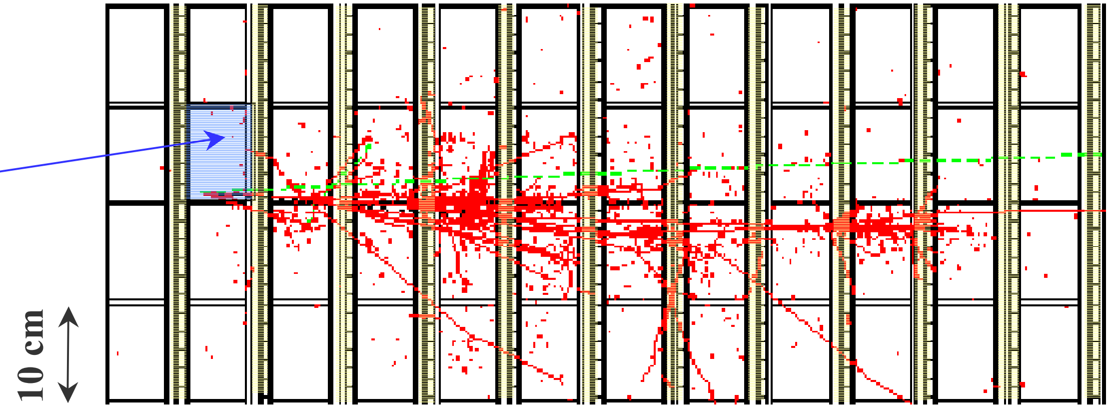
~20 cm^2/hour/system

- Road map : speed x 10 every few years
- At present : Ultra Track Selector ~ 1 cm^2 / h / s

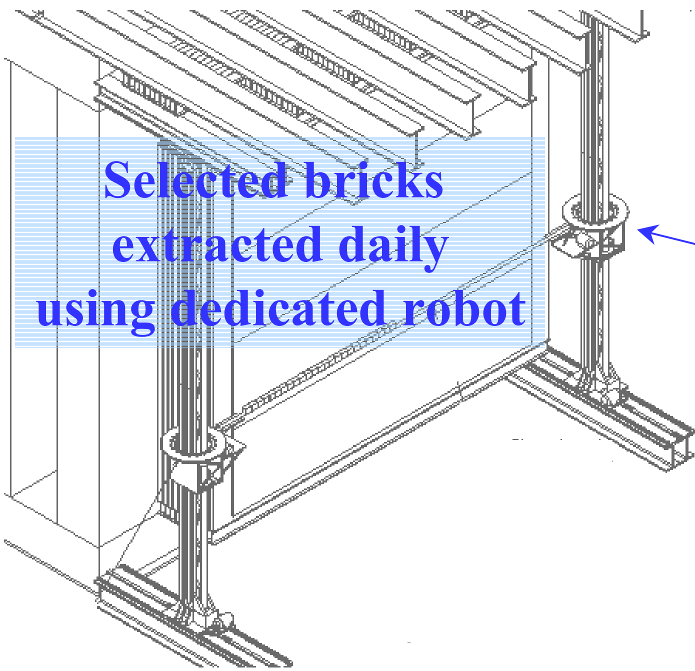
R&D in Japan and in Europe

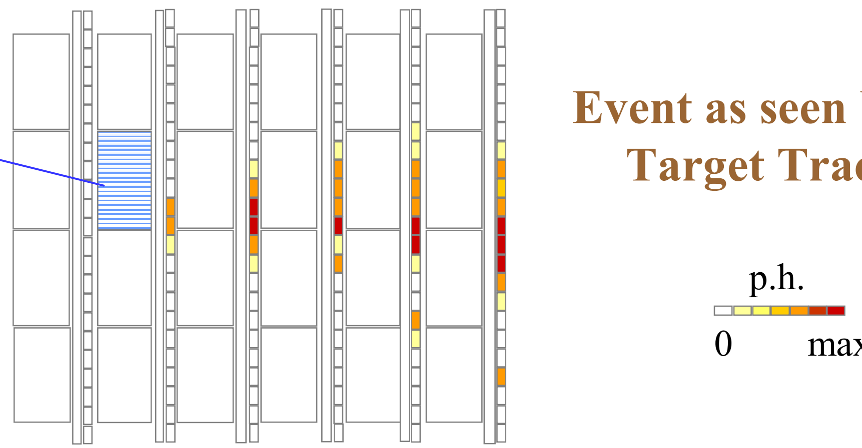
The Bricks are arranged into walls …

- **Target Tracker task :**
  - **a) trigger on neutrino interactions**
  - **b) select bricks efficiently**
  - **c) initiate muon tagging**



Sampling by Target Tracker planes (X,Y) with coarse resolution (1 cm)





Event as seen by the Target Tracker

The target is made of 235,000 bricks !

Muon identification

+ charge and momentum

✸ **Reject charm background**

✍ **Tag and analyse**
$\tau^- \rightarrow \mu^-$ candidates

- **Fe Walls**
  7.1 λ_{int} instrumented with **RPC**

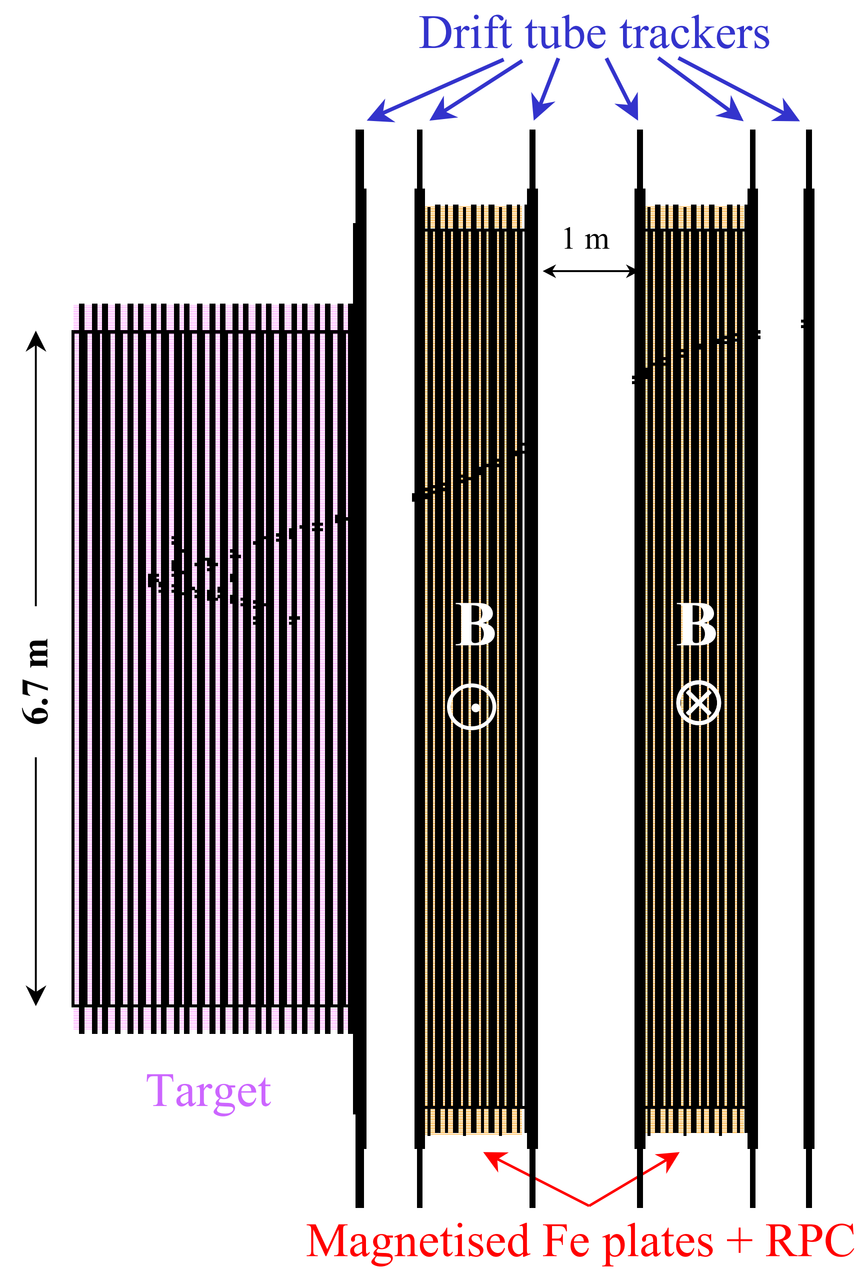
  identify muons by range

  shower energy measurement
  (with p_μ gives E_ν spectrum)

- **Drift Tube trackers**

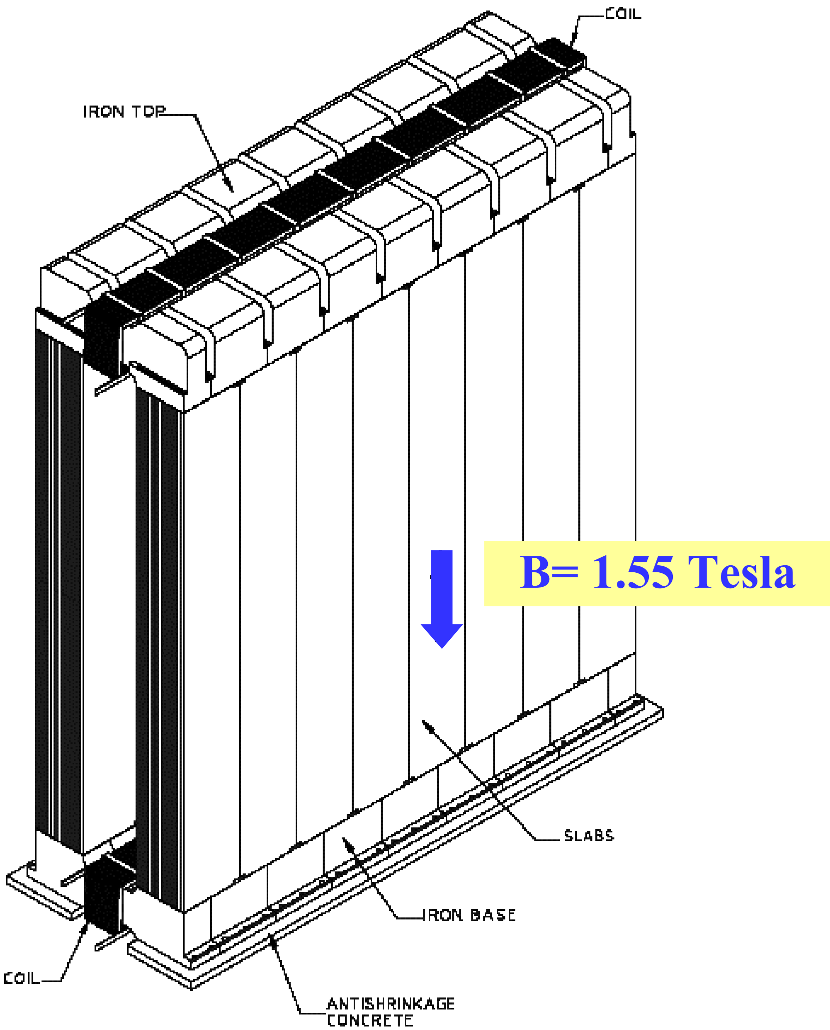
  $$\frac{\sigma_p}{p} < 25\% \quad \text{for } p < 25 GeV/c$$

  Wrong charge < 0.5 %

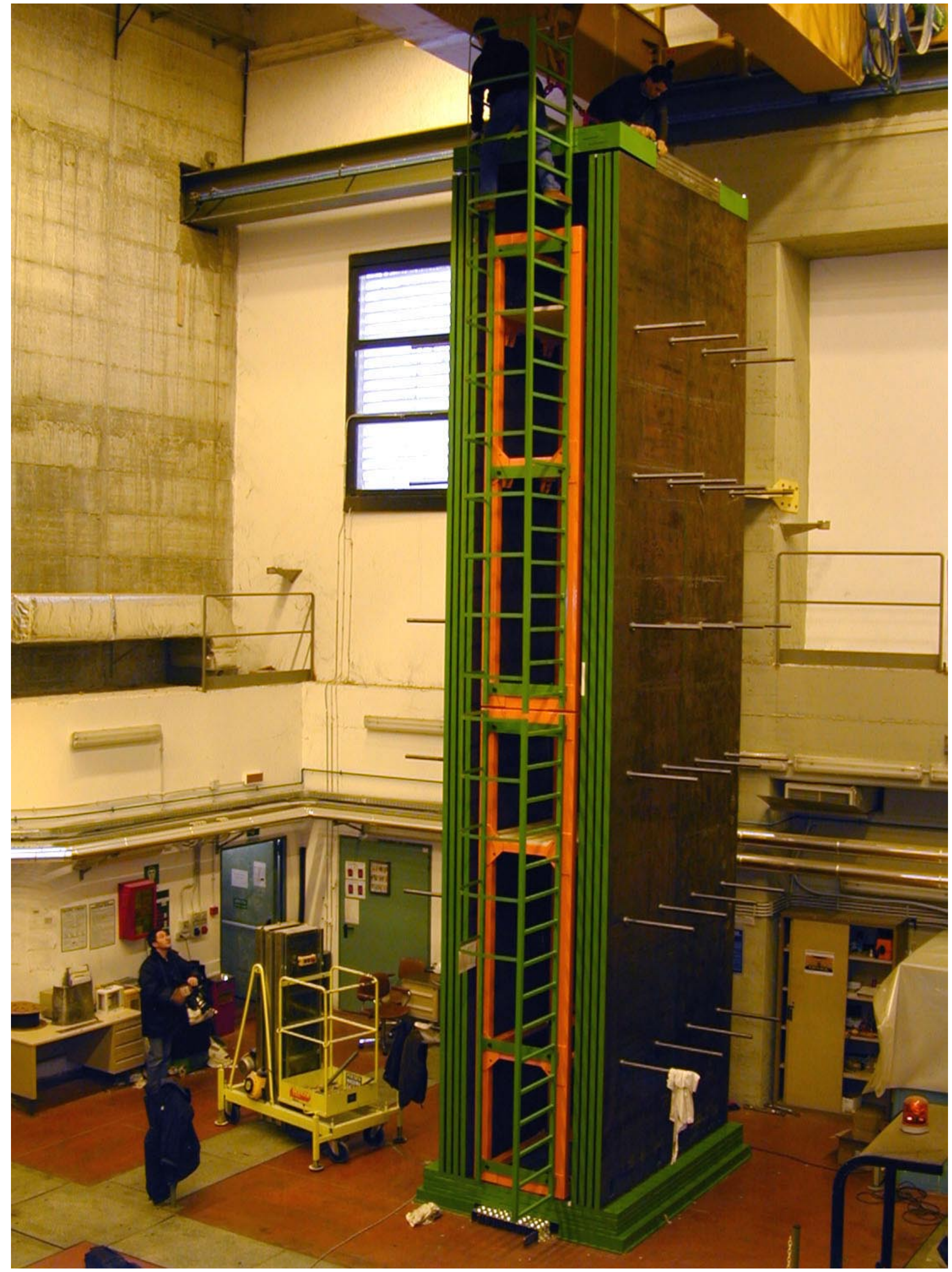


Muon spectrometer
(top view)

Dipolar spectrometer magnet
(weight: ~ 950 ton)

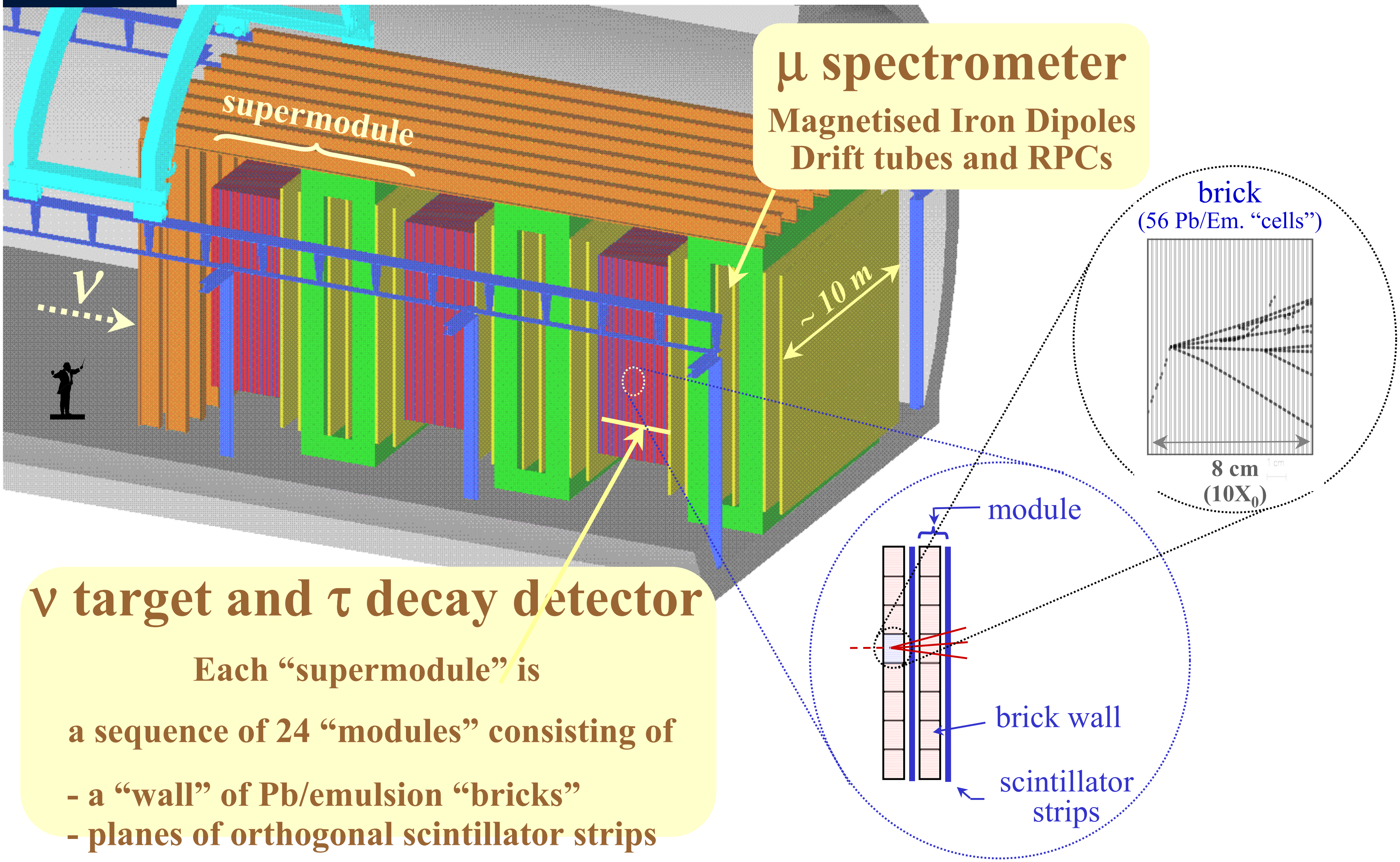


Prototype of magnet section being assembled at Frascati



The detector at Gran Sasso

(modular structure, configuration with three "supermodules")



μ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

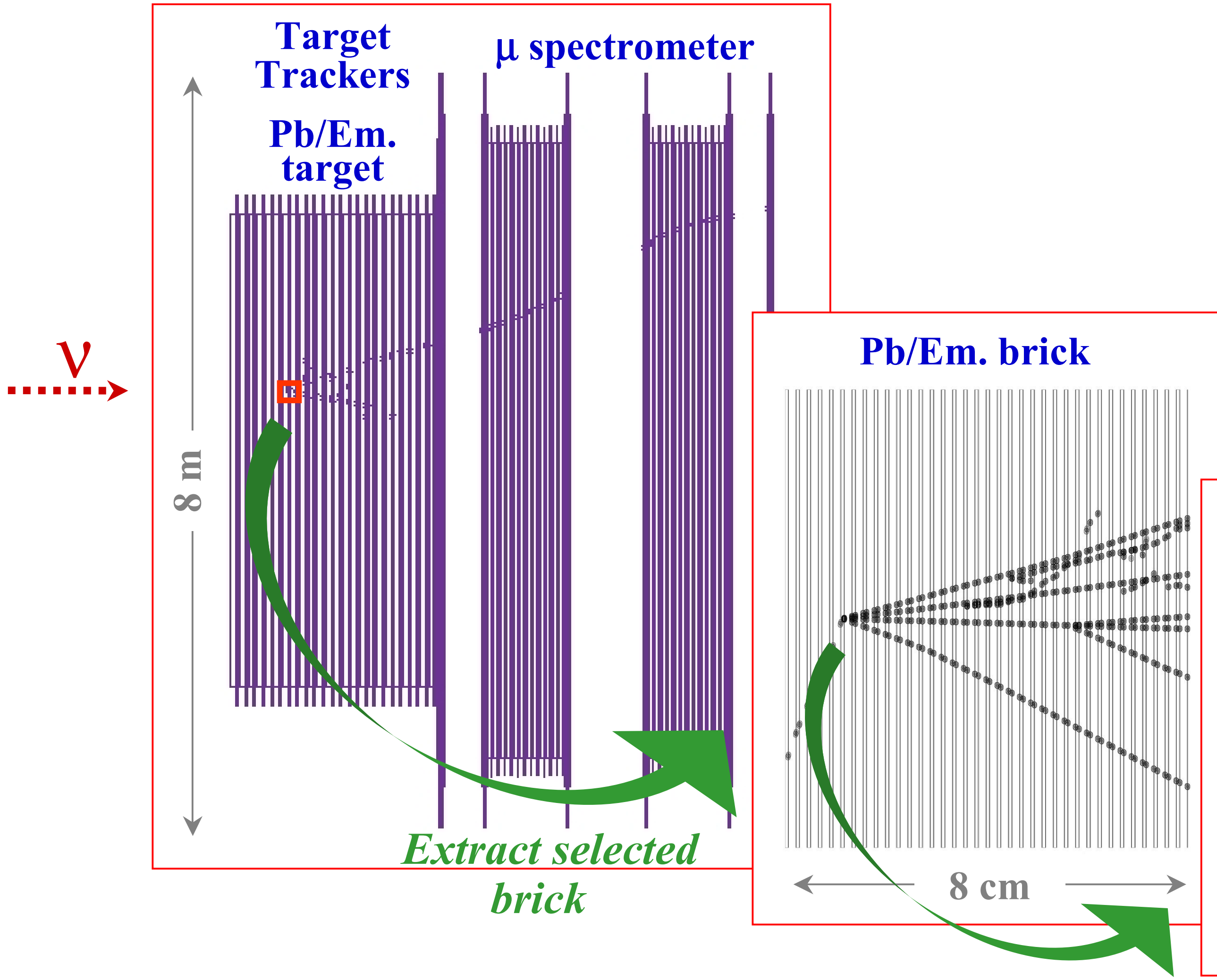
ν target and τ decay detector

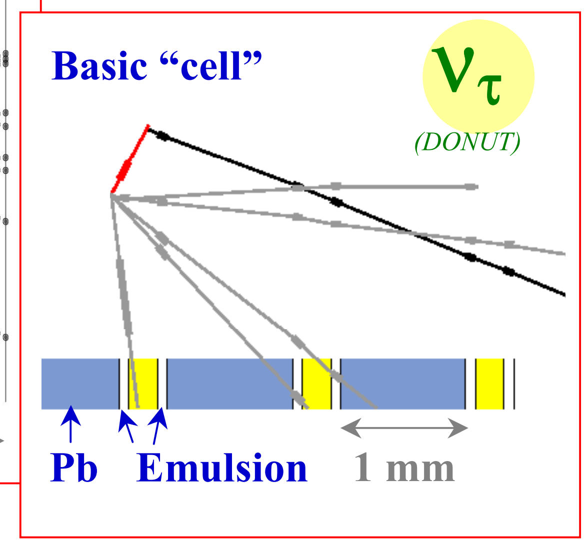
Each "supermodule" is

a sequence of 24 "modules" consisting of

- a "wall" of Pb/emulsion "bricks"
- planes of orthogonal scintillator strips

A "hybrid" experiment at work





Electronic detectors

→ select ν interaction brick

→ μ ID, charge and p

Emulsion analysis

→ vertex search

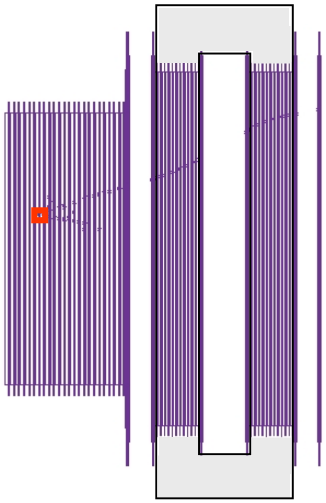
→ decay search

→ e/γ ID, kinematics

From the CNGS to physics

ν

CNGS



brick extraction

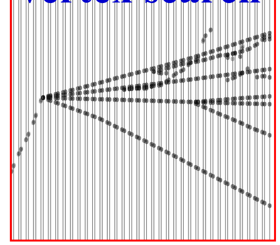
~30/day

cosmic ray exposure

emulsion processing

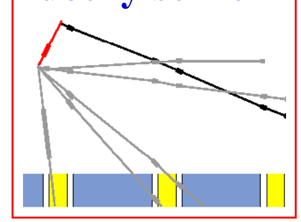
no vertex :
extract other bricks?

vertex search



candidate :
extract other bricks?

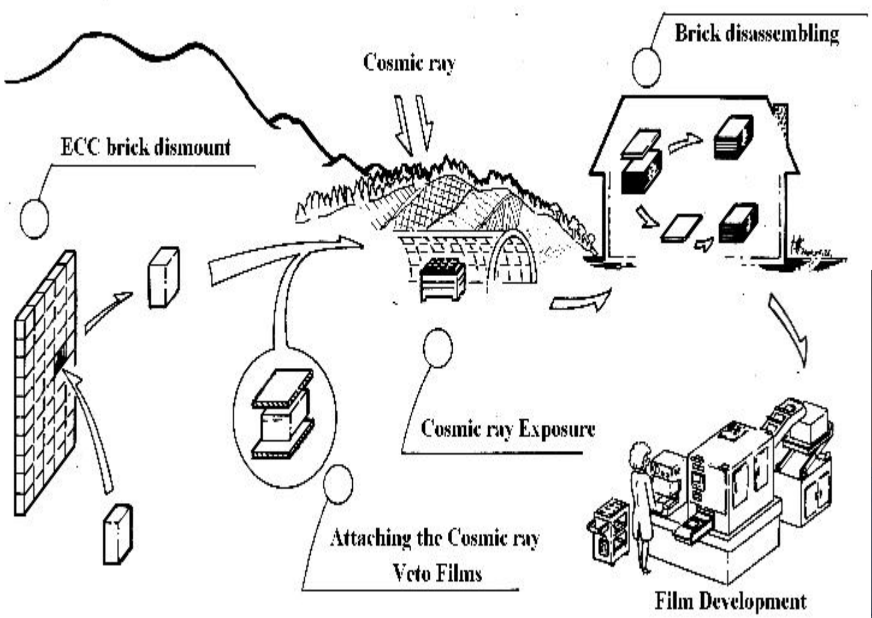
decay search



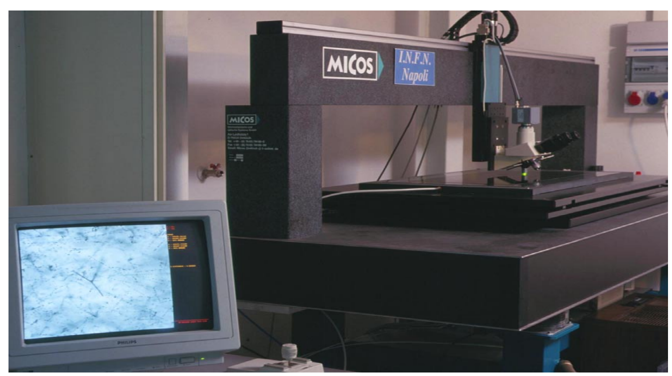
candidate events

~3/day

Gran Sasso



Emulsion read-out facilities
(quasi-online)



FULL emulsion analysis

Scanning Labs

Physics

<u>All Labs</u>

Expected background
(5 years of data taking)

		$\tau \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow h$	Total
Long decays	Charm production	0.15	0.03	0.15	0.33
	ν_e CC and π^0	0.01	-	-	0.01
	Large μ scattering	-	0.10	-	0.10
	Hadron reinteractions	-	-	0.10	0.10
	Total	**0.16**	**0.13**	**0.25**	**0.54**
Short decays	Charm production	0.03	-	-	0.03
	ν_e CC and π^0	«0.01	-	-	«0.01
	Total	**0.03**	-	-	**0.03**
	Total	**0.19**	**0.13**	**0.25**	**0.57**

Sensitivity to $\nu_\mu \rightarrow \nu_\tau$ oscillations

Summary of τ detection efficiencies
(in % and including BR)

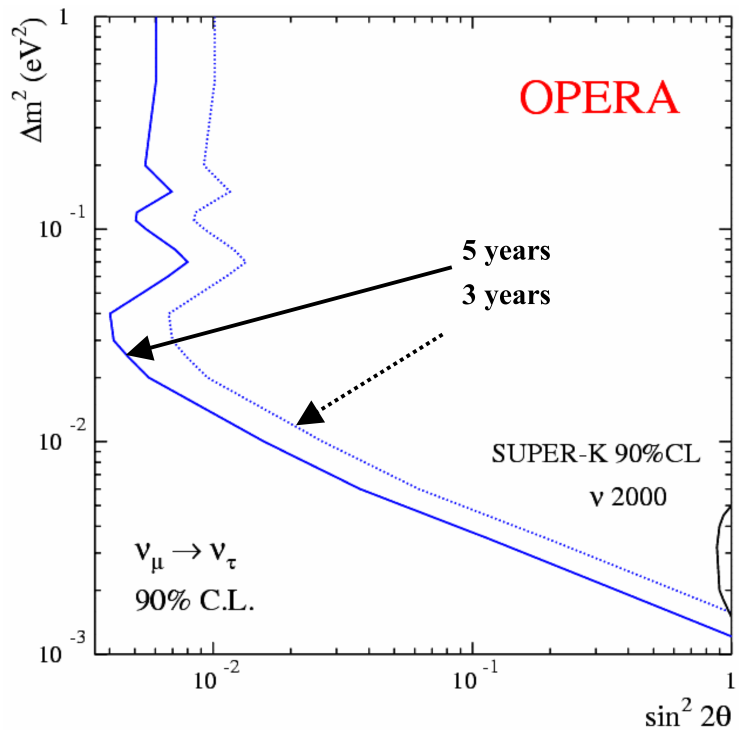
Decay mode	DIS long	QE long	DIS short	Overall
$\tau \rightarrow e$	3.0	2.6	1.3	3.7
$\tau \rightarrow \mu$	2.7	2.8	-	2.7
$\tau \rightarrow h$	2.2	2.8	-	2.3
Total	8.0	8.3	1.3	8.7

Expected ν_τ events (2.25x10[20] pot, 1.8KTon, accounting for removed bricks)

$\Delta m^2 (10^{-3}\ eV^2)$

τ decay	1.6	2.5	4.0	b.g.
e	1.9	4.7	11.8	0.19
μ	1.5	3.5	8.8	0.13
h	1.3	3.0	7.6	0.25
Total	4.7	11.2	28.2	0.57

Events $\propto (\Delta m^2)^2$

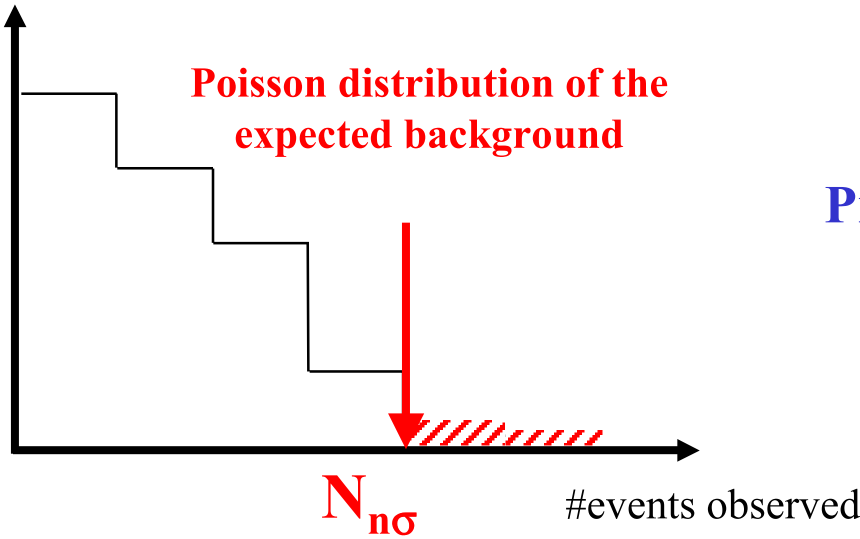


After 5 years data taking

$\Delta m^2 = 1.2 \times 10^{-3}\ eV^2$ at full mixing

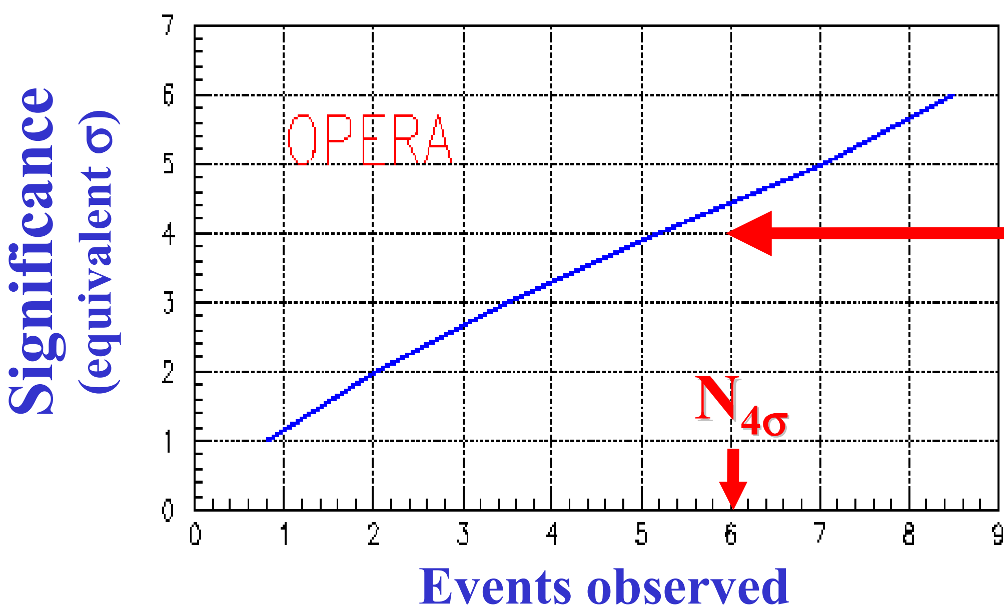
$\sin^2(2\theta) = 6.0 \times 10^{-3}$ at large Δm^2

Statistical significance for discovery



Probability that the b.g. fakes the signal:

$< P_{n\sigma}$ if #observed events $\geq N_{n\sigma}$



$P_{4\sigma} = 6.3 \times 10^{-5}$

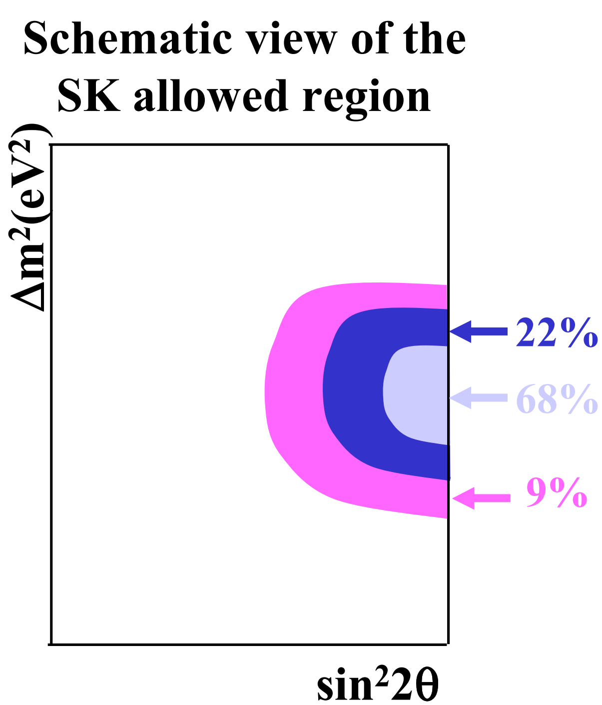
$P_{3\sigma} = 2.7 \times 10^{-3}$

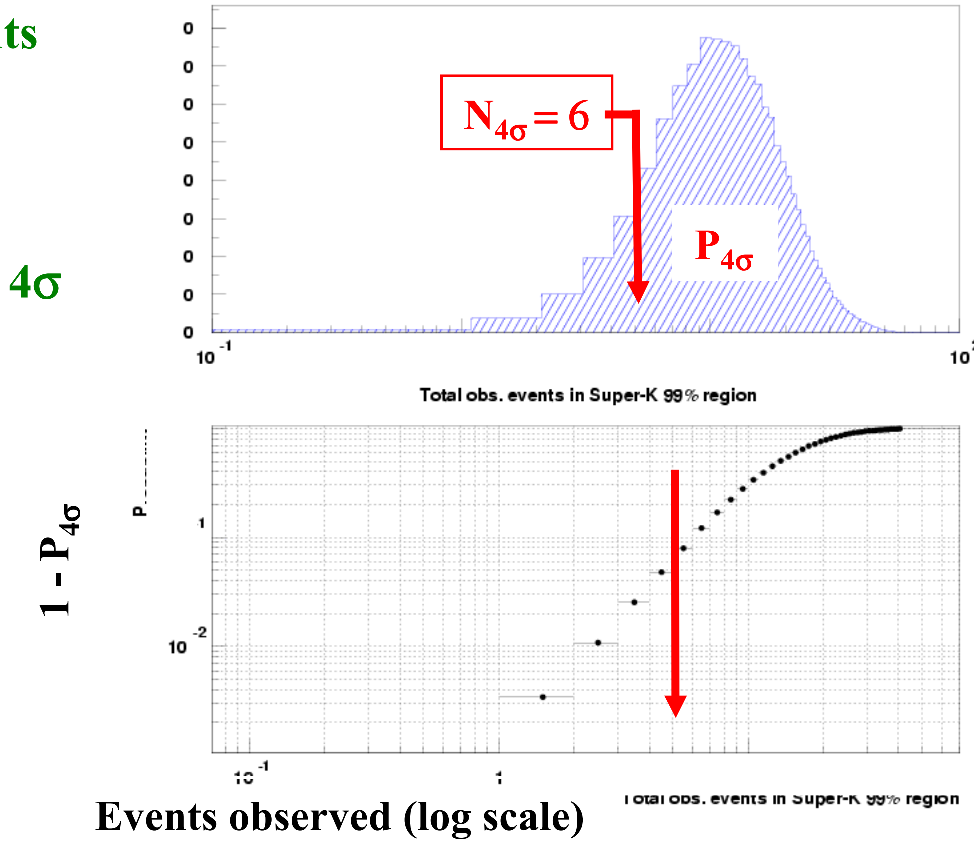
≥ 6 events

4σ "discovery"

Probability of 4σ significance

- Simulate a large number of experiments with oscillation parameters generated according to the SuperK probability distribution
- $N_{4\sigma}$ events required for a discovery at 4σ
- Evaluate fraction $P_{4\sigma}$ of experiments observing ⇩ $N_{4\sigma}$ events



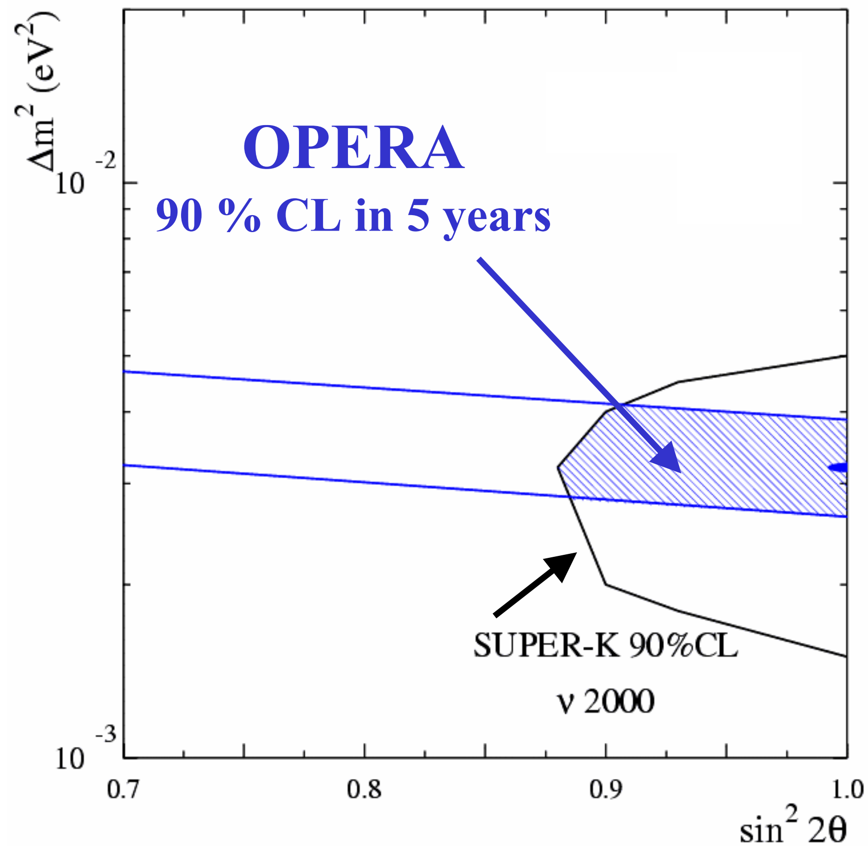


years	$P_{3\sigma}$	$P_{4\sigma}$
3	94%	80%
5	97%	92%

Determination of Δm^2

(mixing constrained by SuperK)

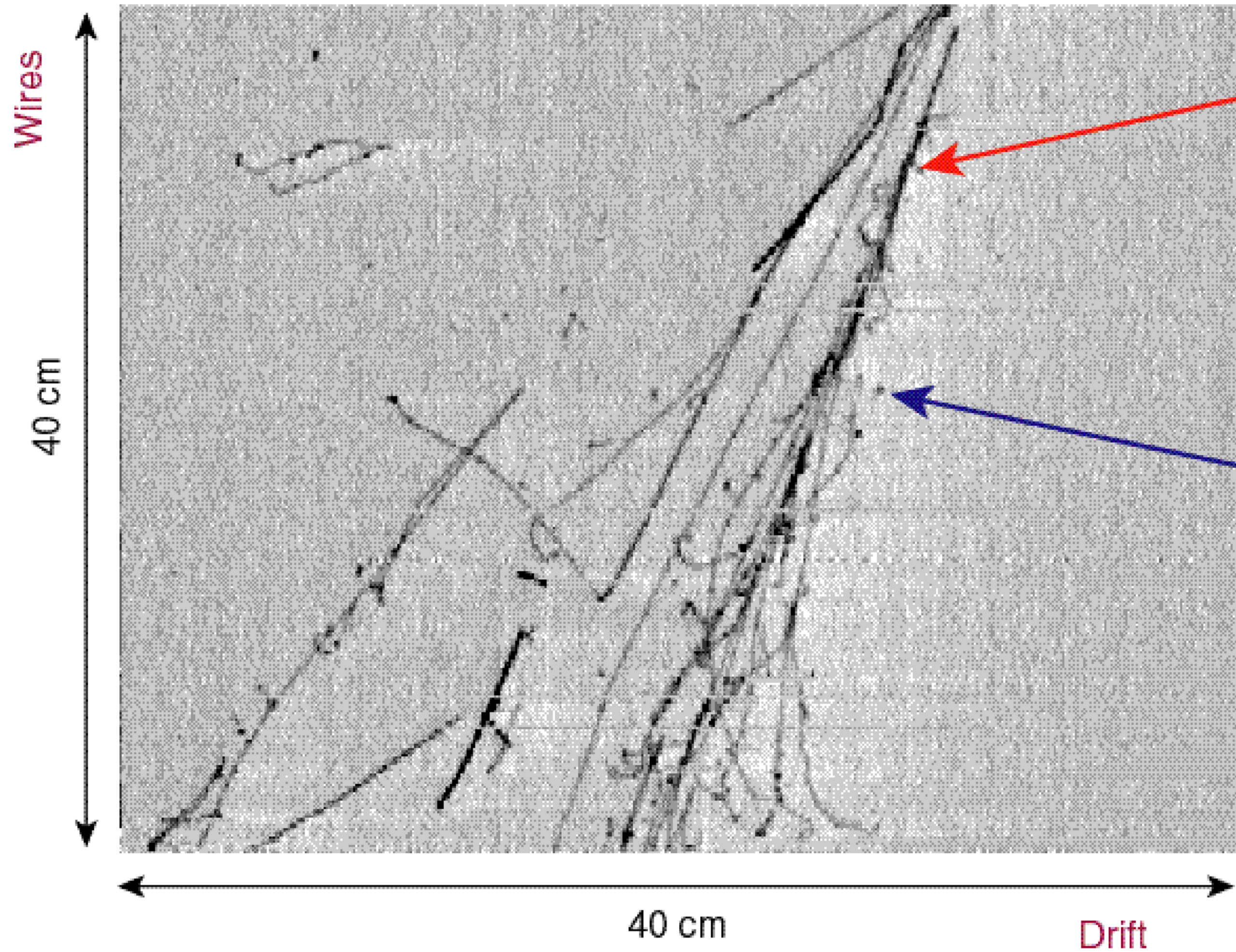
<u>90 % CL limits</u> *	Δm^2 (10^{-3} eV^2)		
	1.5	3.2	5.0
Upper limit	2.1	3.8	5.6
Lower limit	0.8	2.6	4.3
(U - L) / True	41 %	19 %	12 %



* assuming the observation of a number of events corresponding to those expected for the given Δm^2

The ICARUS experiment

C.R. shower from 3 ton prototype



"Bubble" size
≈ 3 x 3 x 0.2 mm^3

Energy deposition measured for each point

The ICARUS Liquid Ar Time Projection Chamber

- **Event reconstruction in 3D with measurement of the primary ionization**
  1. drift time
  2. induction wires
  3. collection wires

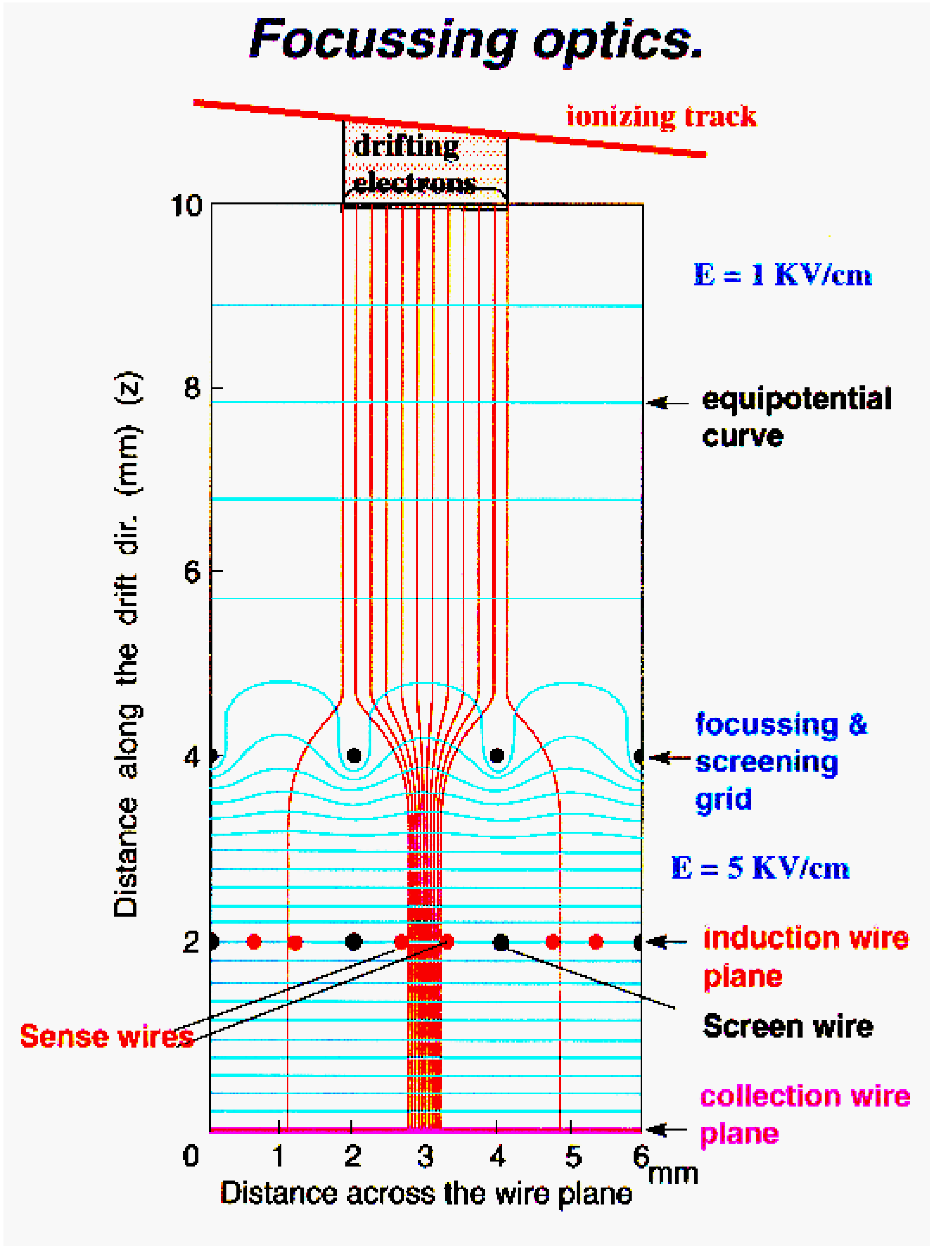
- **Space resolution around 1 mm**

- **Maximum drift length** in the Liq. Ar
  1.5 m in the 600 ton module
  (requiring < 0.1 ppb O_2 equiv. impurities)

- **Calorimetric energy resolution:**

$$\frac{\sigma(E)}{E} \approx \frac{0.03}{\sqrt{E}} (Em.)$$

$$\frac{\sigma(E)}{E} \approx \frac{0.12}{\sqrt{E}} (Hadr.)$$

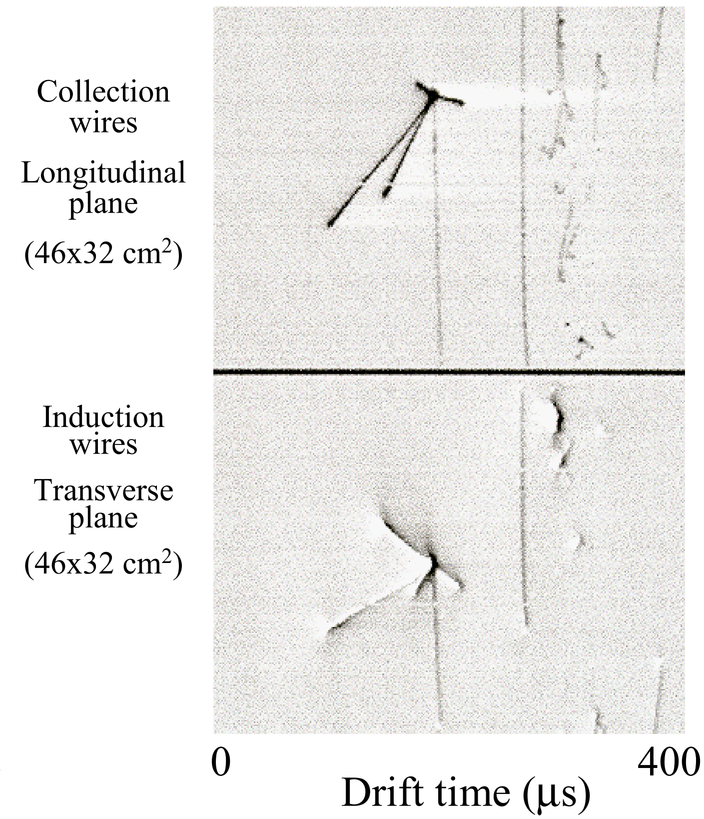


The ICARUS liquid Ar Image TPC

An electronic Bubble Chamber (BC)

- Large sensitive volume (as BC)
- Detector = Target (as BC)
- High spatial granularity (as BC)
- Energy measurement (as BC)
- High energy resolution
- Specific ionisation (dE/dx) measurement
- dE/dx vs. range for particle identification
- Continuous sensitivity
- Self triggering capability

A ν interaction in the 50 liters test TPC



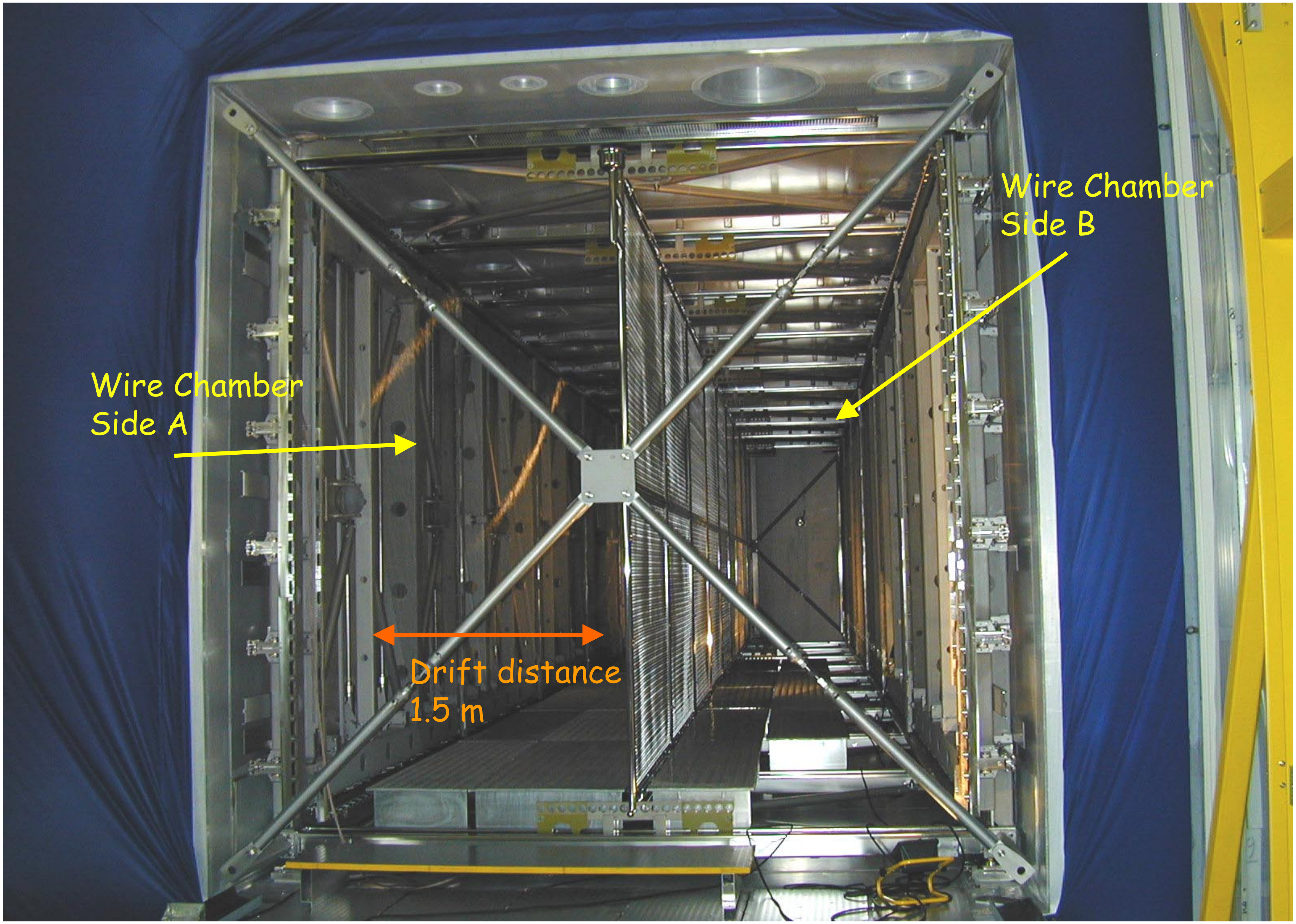
New detector → new physics potentialities

Under construction : 0.6 kton module

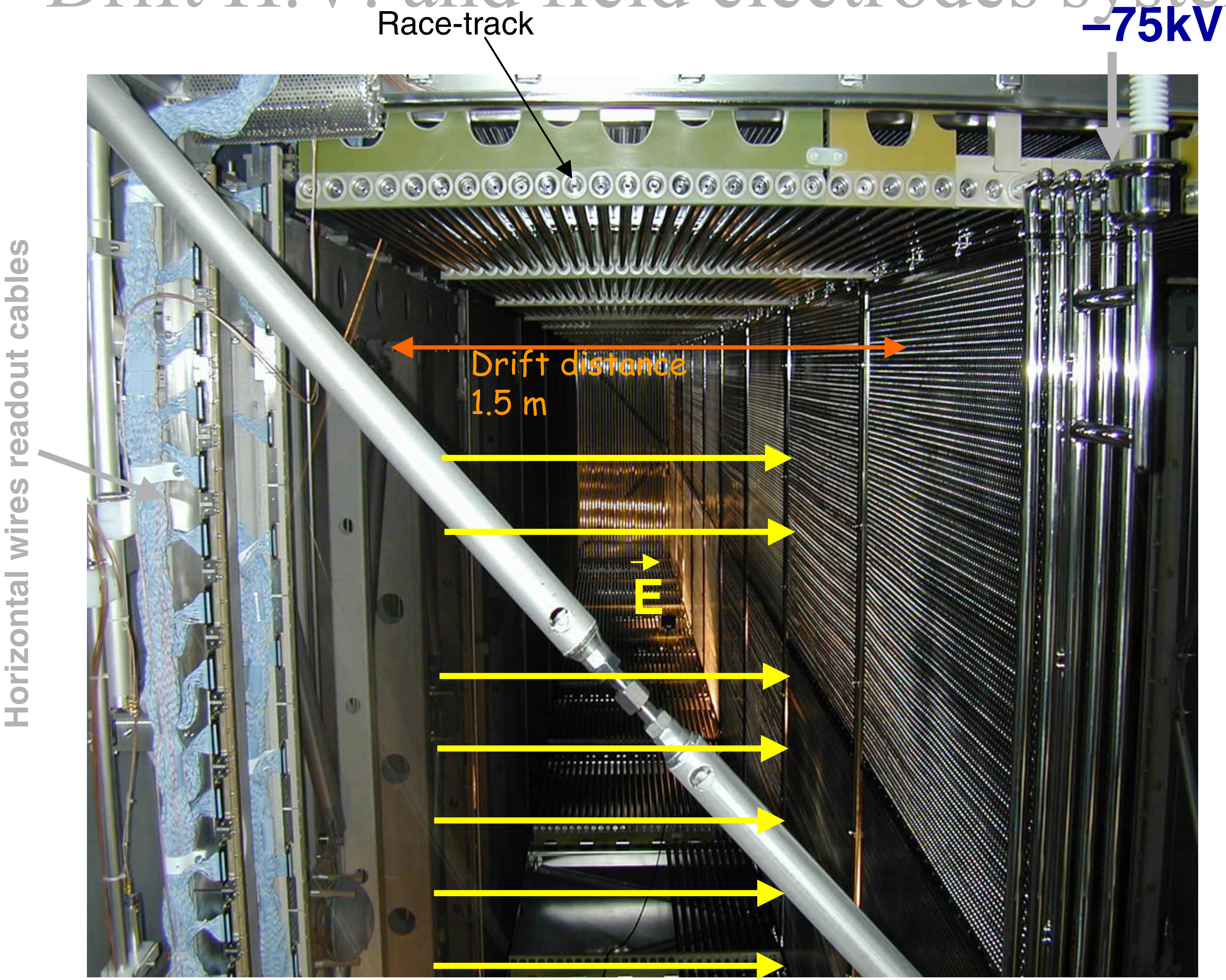
For physics : multi kton ➨
- **proton decay**
- **atmospheric ν**
- **long baseline ν oscillation**
- **solar ν**

The ICARUS 600 Ton module

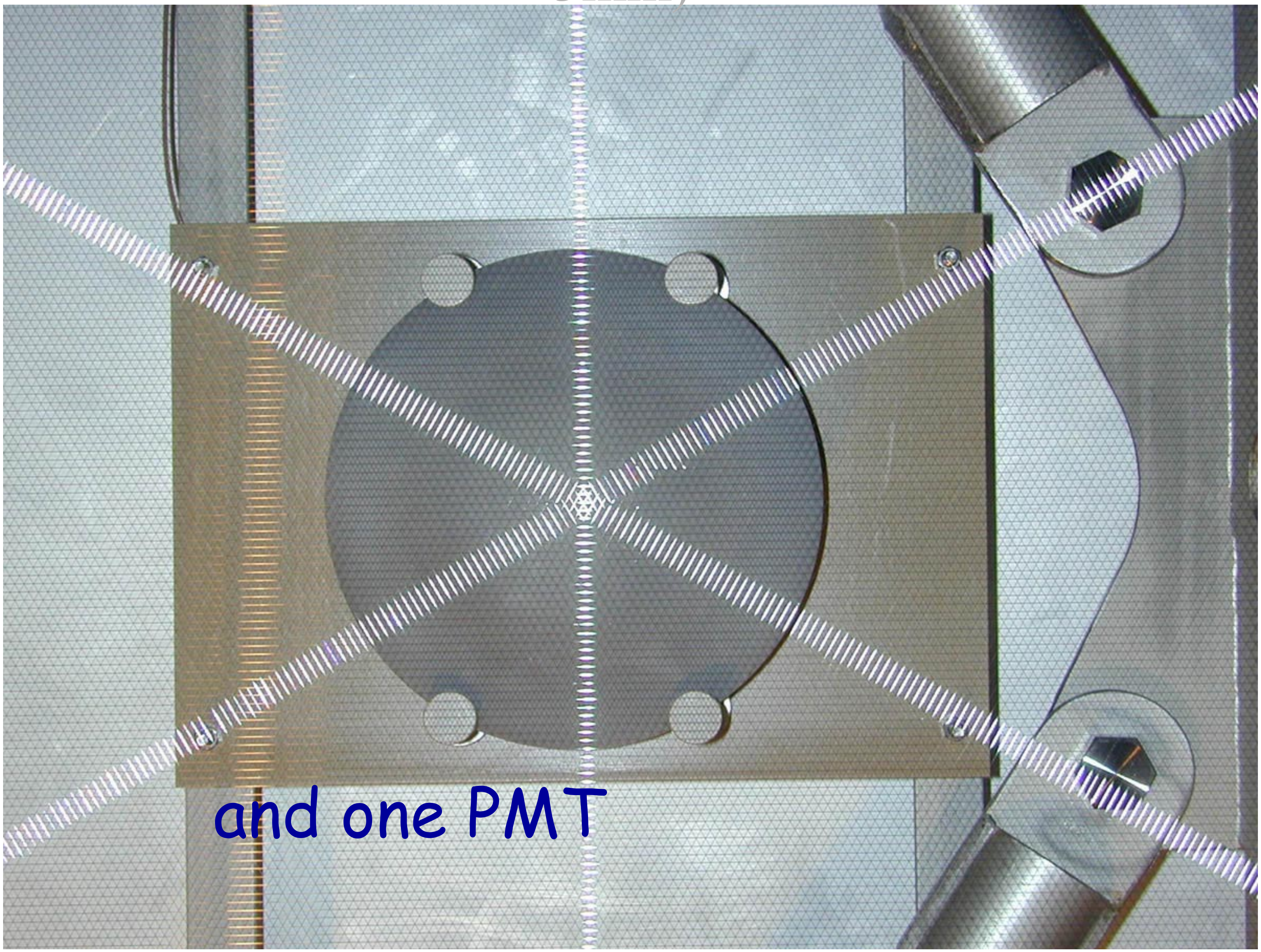
(under construction, first results with half module)


Wire Chamber
Side B
Wire Chamber
Side A
Drift distance
1.5 m

Drift H.V. and field electrodes system



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



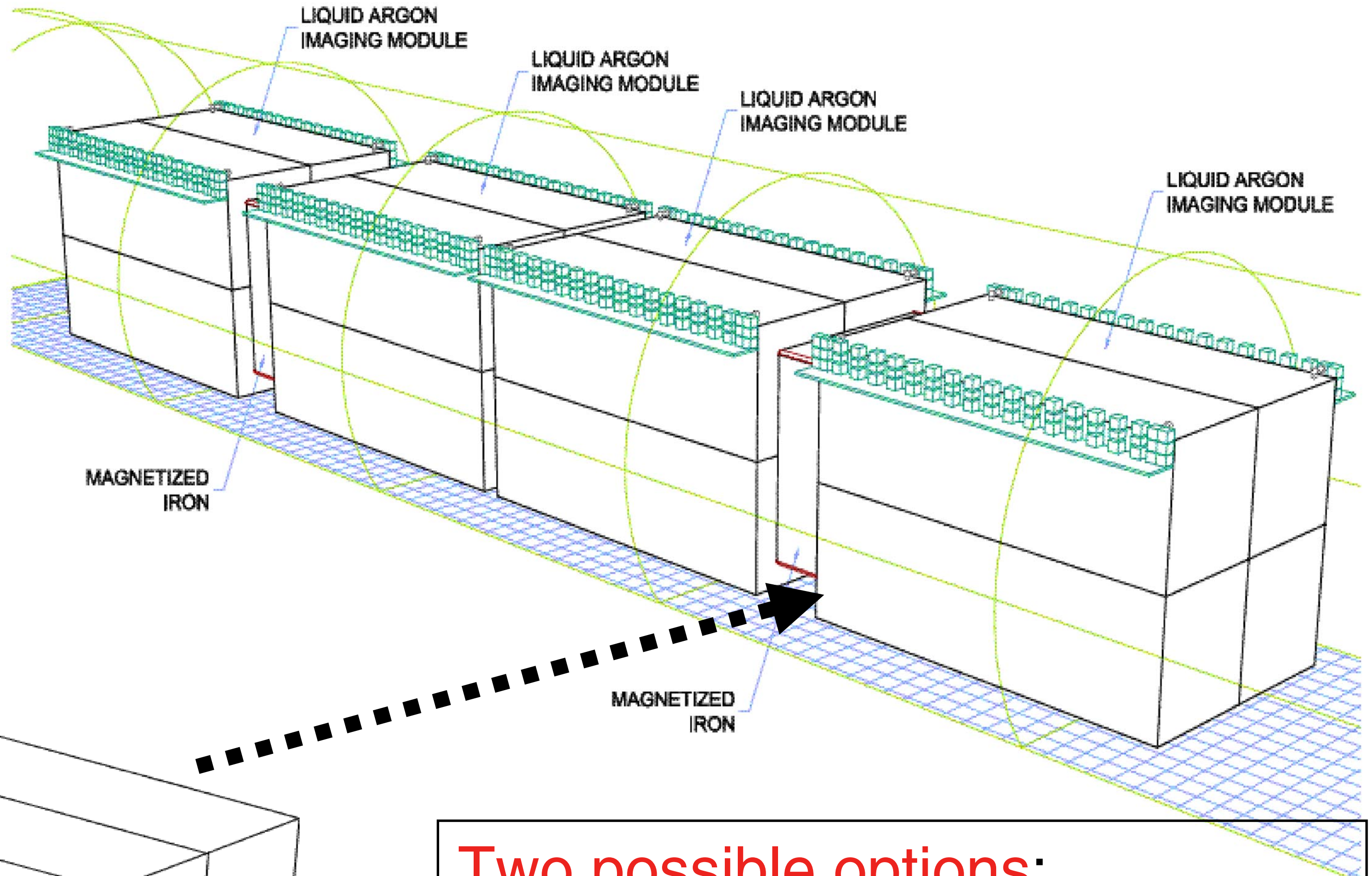
Current T600 status

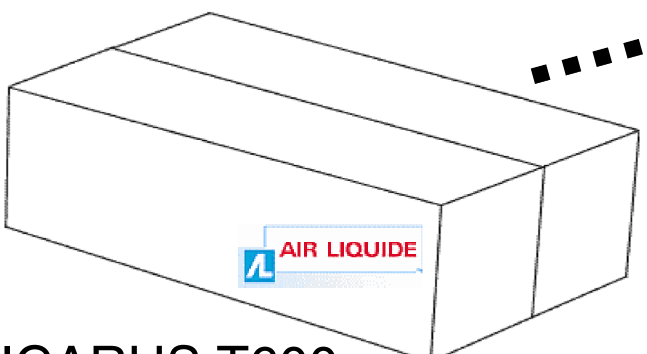
- Total run duration in Pavia□3 months (100 days)
  - √ Day 1 to 10 — Vacuum (including leak detection)
  - √ Day 11 to 15 — Pre-cooling
  - √ Day 16 to 20 — Cooling
  - √ Day 21 to 30 — Filling
  - √ Day 31 to 45 — Liquid recirculation
  - √ Day 46 to 55 — Complete detector start-up
  - √ Day 56 to 65 — Data taking with horizontal tracks
    $\Rightarrow$ ***"Big Track"***

    We are here!
  - – 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

ICARUS 5kton

The T600 is a milestone towards future evolutions. In order not be statistically limited a multi-Kton detector is needed for the CNGS. This could come naturally from a cloning strategy of the T600.





ICARUS T600

Two possible options:

A) □8 x T600

B) 4 x T1400 (better for physics)

CNGS events in 5 kton, 4 years running

$\theta_{23} = 45°, \theta_{13} = 7°$ ← **CHOOZ upper limit**

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

	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

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

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

Charged current (CC) Br ~18%

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

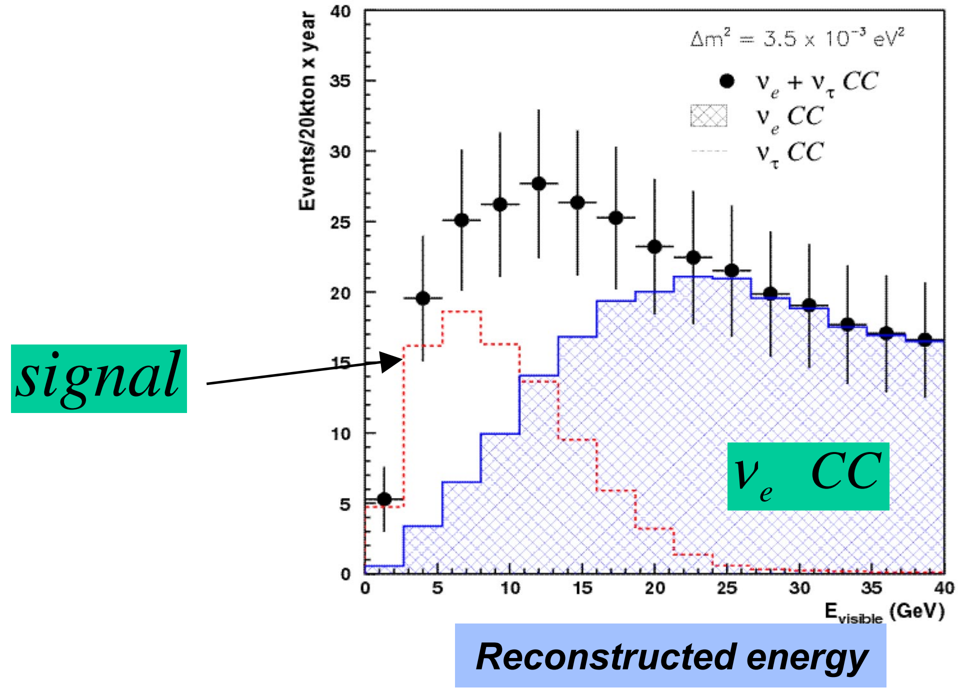
Background: $\nu_e + N \rightarrow e + jet$ Charged current (CC)

$470 \;\; \nu_e CC$

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

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

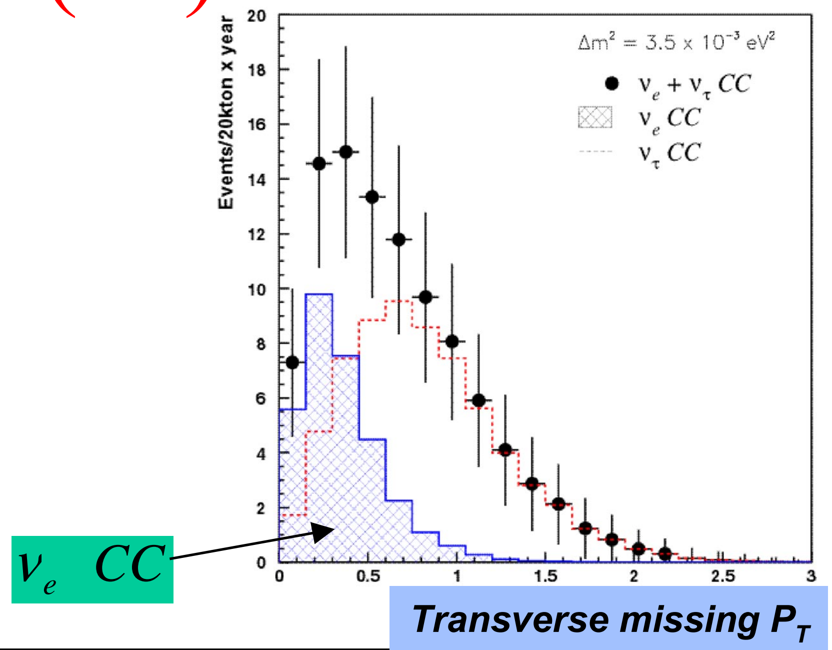
- Reconstructed visible energy spectrum of electron events clearly evidences excess from oscillations into tau neutrino



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%



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

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

Δm^2_{32}=3.5x10^{-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	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	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

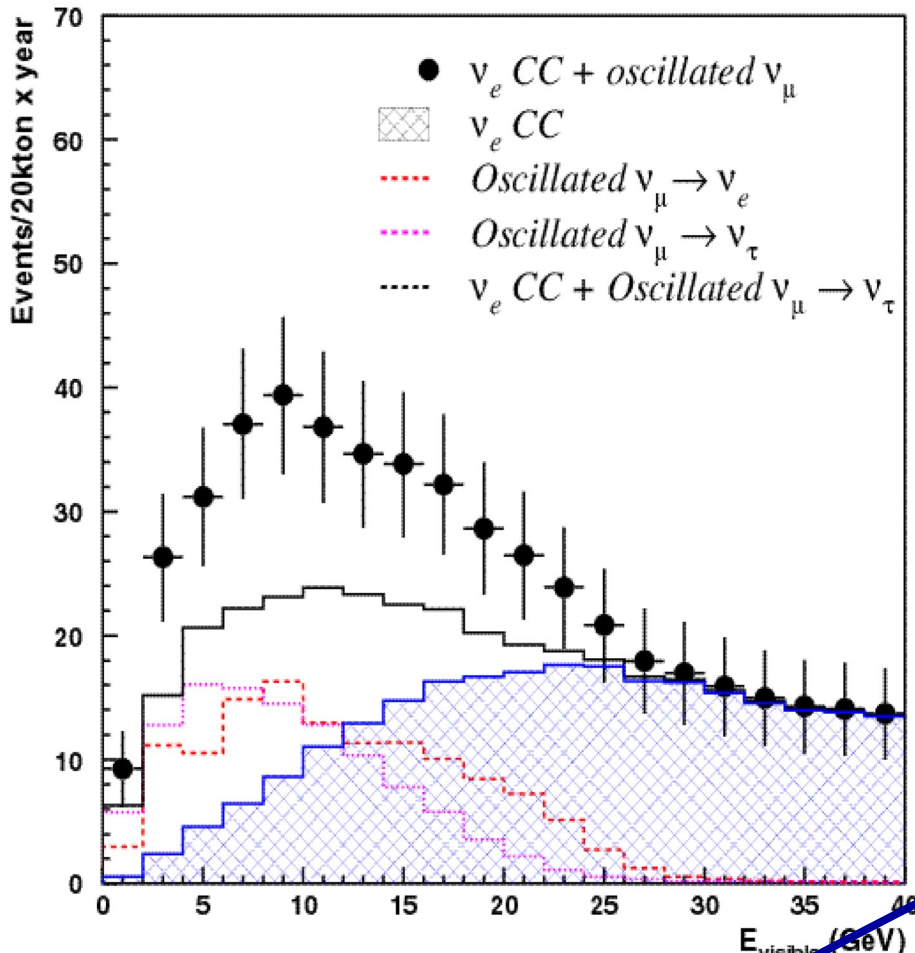
$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2_{32}$$

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

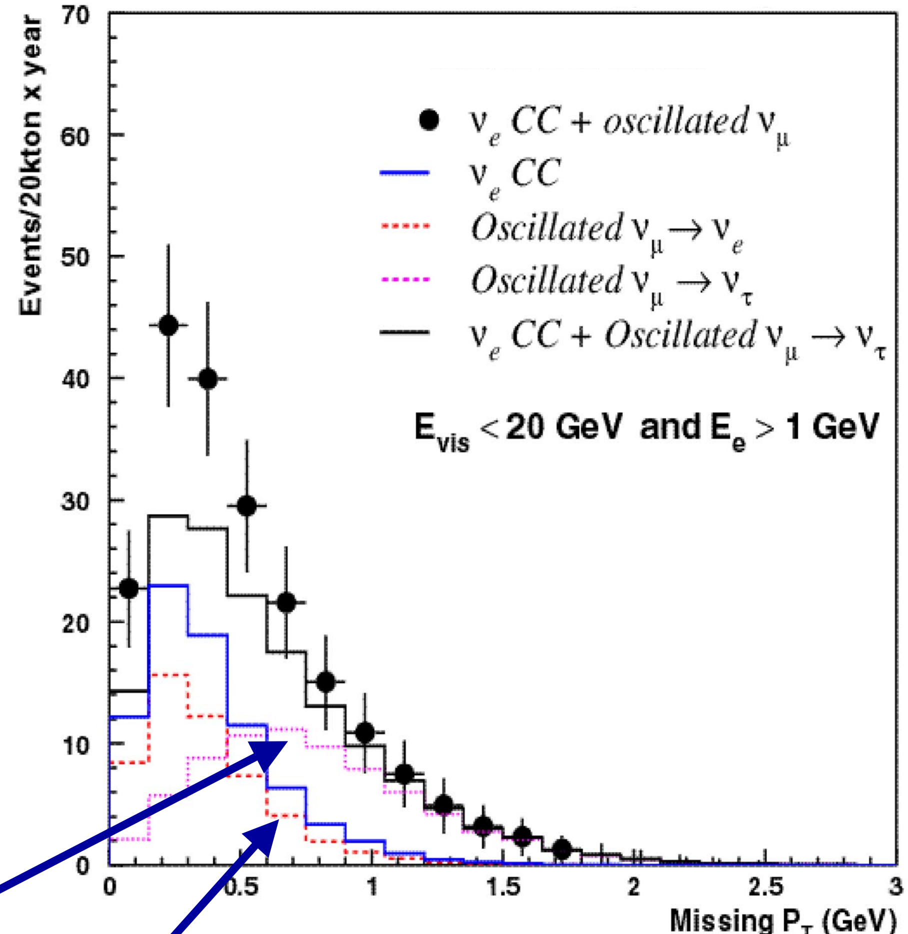
$$\Delta^2_{23} = \sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

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

Total visible energy



Transverse missing P_T

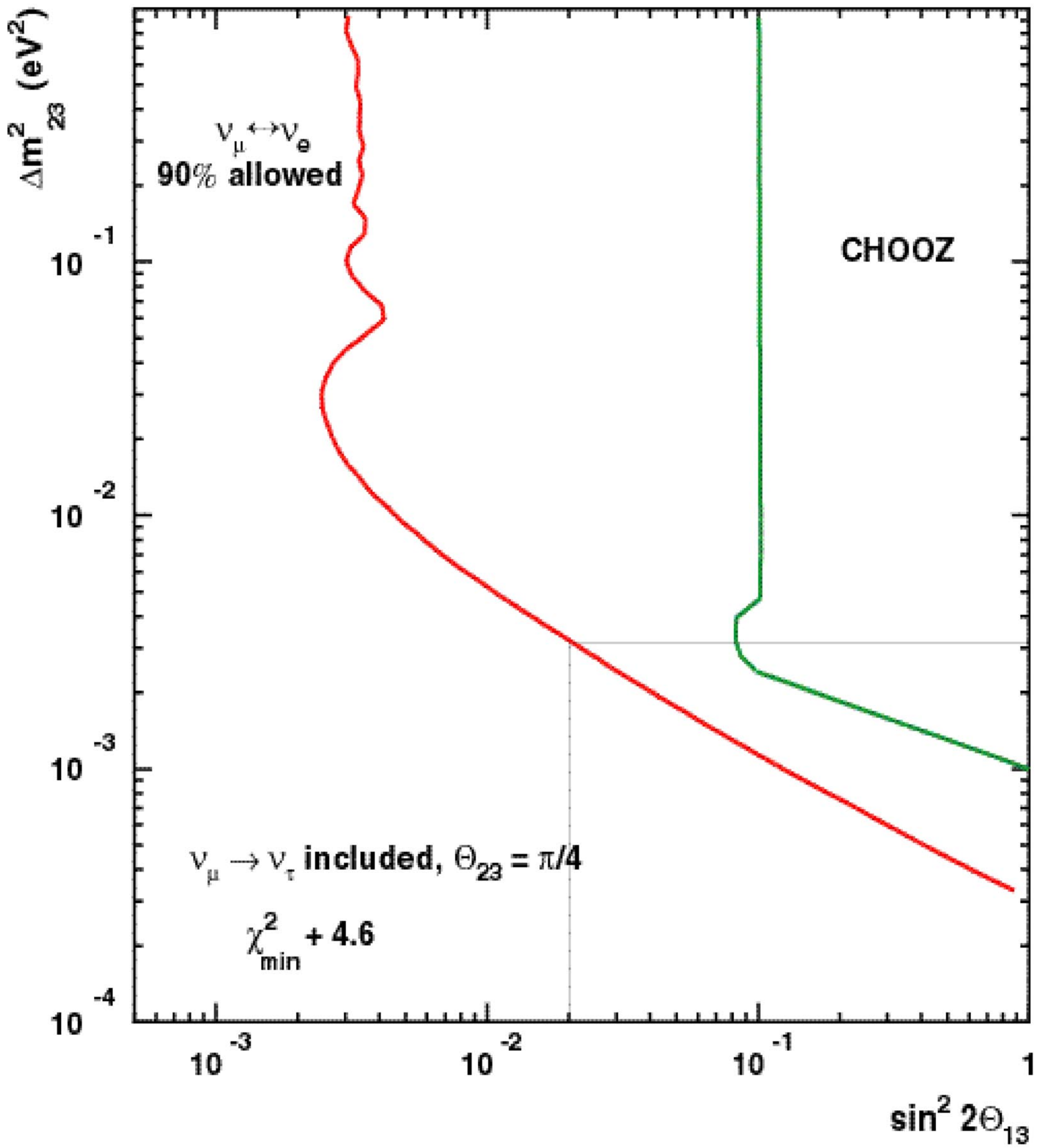


$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2_{32}$$

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

Sensitivity to θ_{13} in three family-mixing

4 years @ CNGS



- Estimated 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

Conclusions

- The European long baseline program has the unique feature of continuing the study of neutrino oscillations in the atmospheric neutrinos region by looking directly for the appearance of ν_τ providing an unambiguous proof of $\nu_\mu \rightarrow \nu_\tau$ oscillations.
- $\nu_\mu \rightarrow \nu_e$ oscillations must also be studied to provide a more precise determination of θ_{13} important for the future neutrino factories
- The European program is clearly complementary to the other long baseline experiments based on ν_μ disappearance (K2K,MINOS,JHF)
- The excavation work for the CNGS beam is on schedule
- The OPERA experiment was approved at the beginning of 2001 and it is now starting the detector construction phase
- There are very encouraging results from the ICARUS T600 module which will hopefully evolve in a multi Kton detector able to exploit at best also the CNGS beam