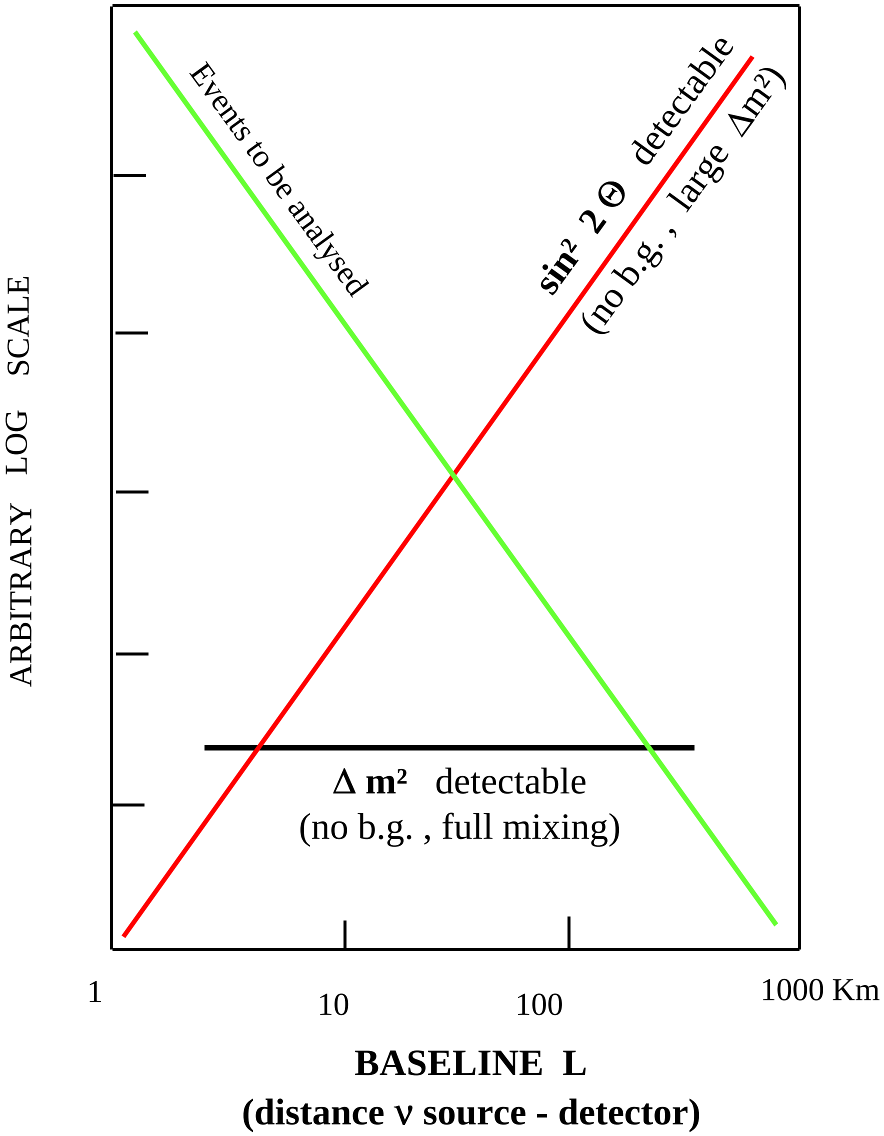
VIII "Neutrino Telescopes"
February 23-26 1999, Venice

LBL neutrino beams and appearance experiments

Antonio Ereditato, INFN Napoli

Baseline "à la carte"



- event rate = P · (ν_μ flux) · σ_τ · M_{target}
- oscill. prob.: $\propto (\Delta m^2 L/E)^2$ for $\Delta m^2 \ll E/L$
- ν_μ flux $\propto L^{-2}$
- background $\propto \nu_\mu$ flux

highest $M_{target}^{1/2}$ → low Δm^2

no BG:	$\sin^2 2\theta_{min} \propto L^2/E$
	$\Delta m^2_{min} \propto E$
BG>0:	$\sin^2 2\theta_{min} \propto L/E$
	$\Delta m^2_{min} \propto E/L^{1/2}$

Optimal baseline: technique dependent

low b.g. technique → can reduce baseline

Aim in sensitivity → baseline, detector

Low $\sin^2 2\theta$

↓

high ν flux

↓

short baseline

↓

Detector: event topology and complete kinematics
(high background rejection)

Low Δm^2

↓

largest possible M_{target}

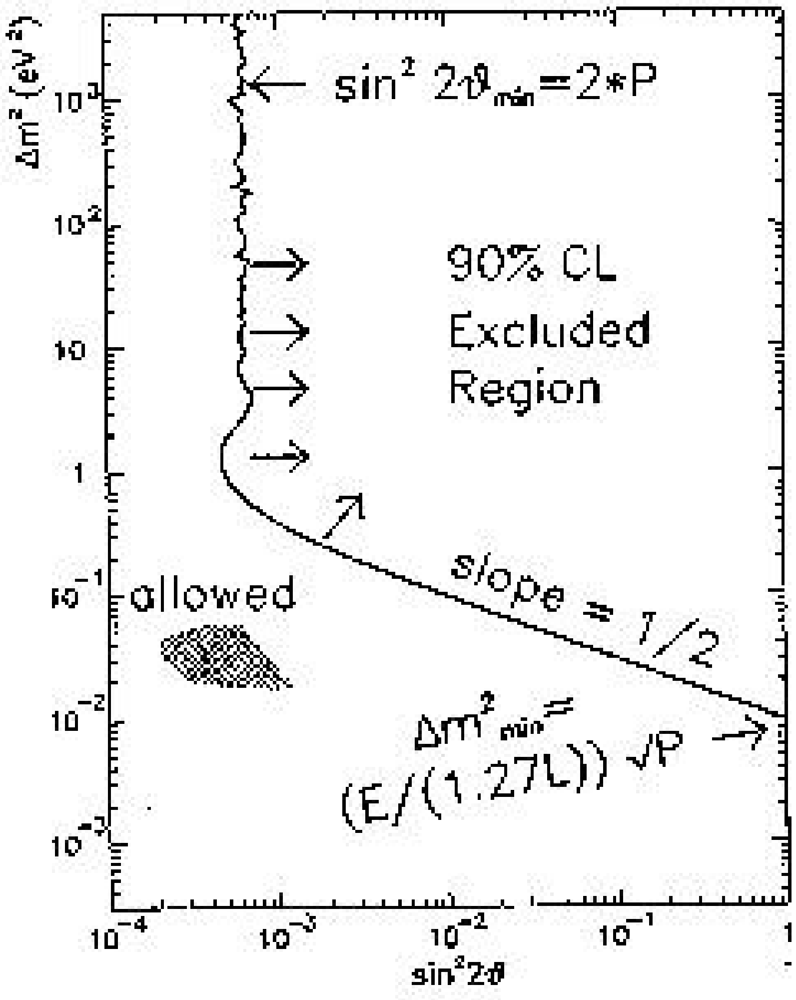
↓

Detector: "low" cost/ton (e.g. no pure emulsion)
(potential background problems)

↓

long baseline
(for acceptable background)

From J.Conrad, ICHEP98



long baseline

short baseline

Experiments:

Disappearance: **observed / expected CC**

(possibly with help of "near detector")

Appearance: **from anomalous "NC"/CC**

ability to discriminate NC and CC

Direct appearance: **present trend , to pinpoint oscillation channels**

$\nu_\mu \rightarrow \nu_e$: e-identification, as for ν_μ-e scattering

$\nu_\mu \rightarrow \nu_\tau$: a new generation of τ detectors

Which atmospheric neutrinos oscillate?

CHOOZ:

ν_e do not disappear in the "atmospheric ν region"

Super Kamiokande:

No evidence of ν_e disappearance

Evidence for ν_μ disappearance

K2K:

Check ν_μ disappearance and no ν_e appearance

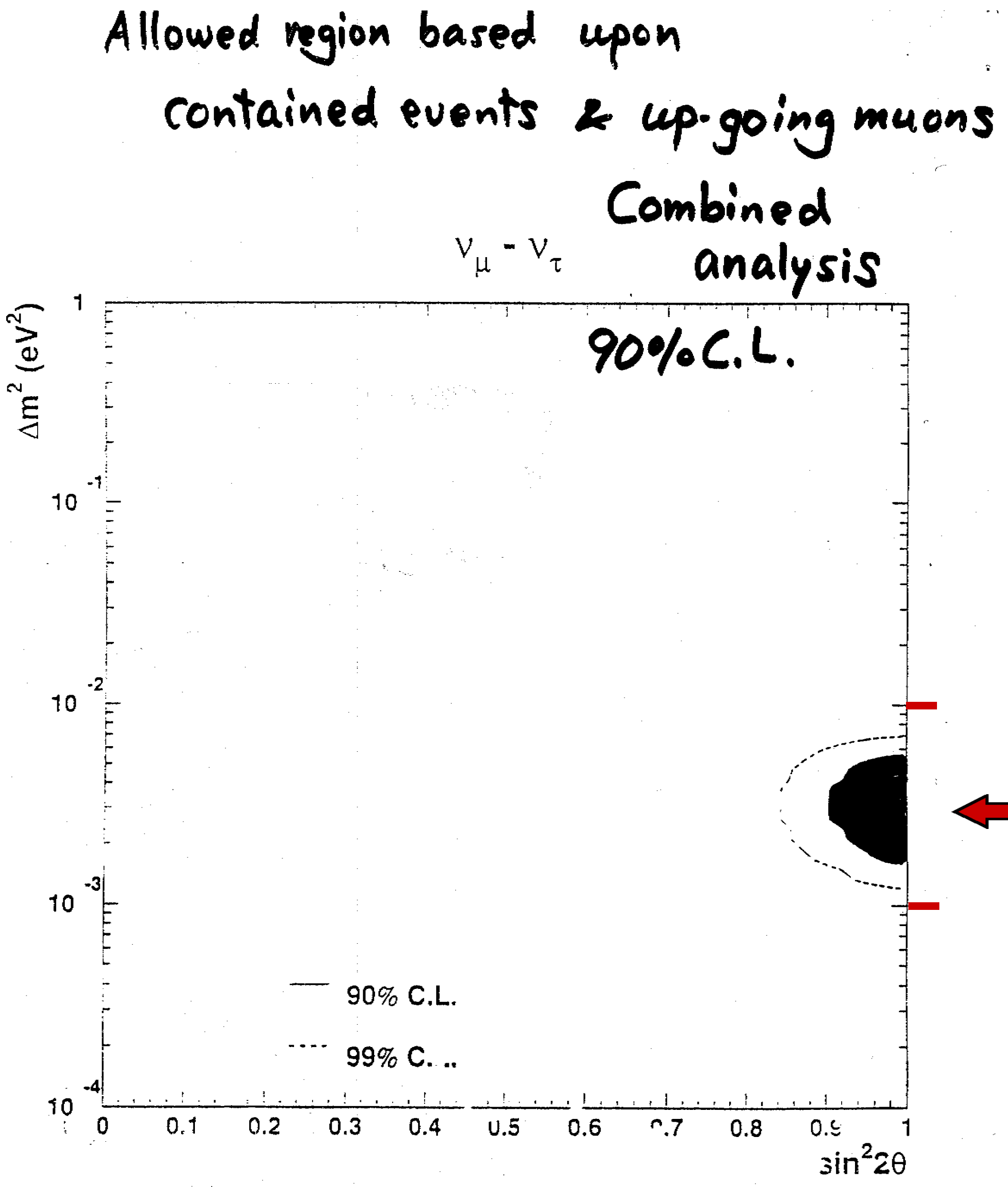
⬇

signal is from $\nu_\mu \to \nu_\tau$ oscillation ?

The issue : "see" $\nu_\mu \to \nu_\tau$ direct appearance

Super Kamiokande

(WIN99 Workshop, Cape Town)



central value: 3.5x10

Discovery potential for $\nu_\mu \rightarrow n_t$ appearance experiments

Atmospheric ν issues and next steps

“measure” Δm^2

⬍

“see” oscillation pattern

⬍

L/E resolution

feasible with **atmospheric ν**

$M_{target} \sim 30$ kton

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

⬍

“see” $\nu_\mu \rightarrow \nu_\tau$ appearance

⬍

τ detection

high energy, **long** baseline **beam**

($E_{CM} >> m_\tau$ L ~ 1000 km)

$\mathbf{M_{target}} \gtrsim 1$ kton ⇔ b.g. rejection

Oscillation pattern and L/E$_\nu$ spectra

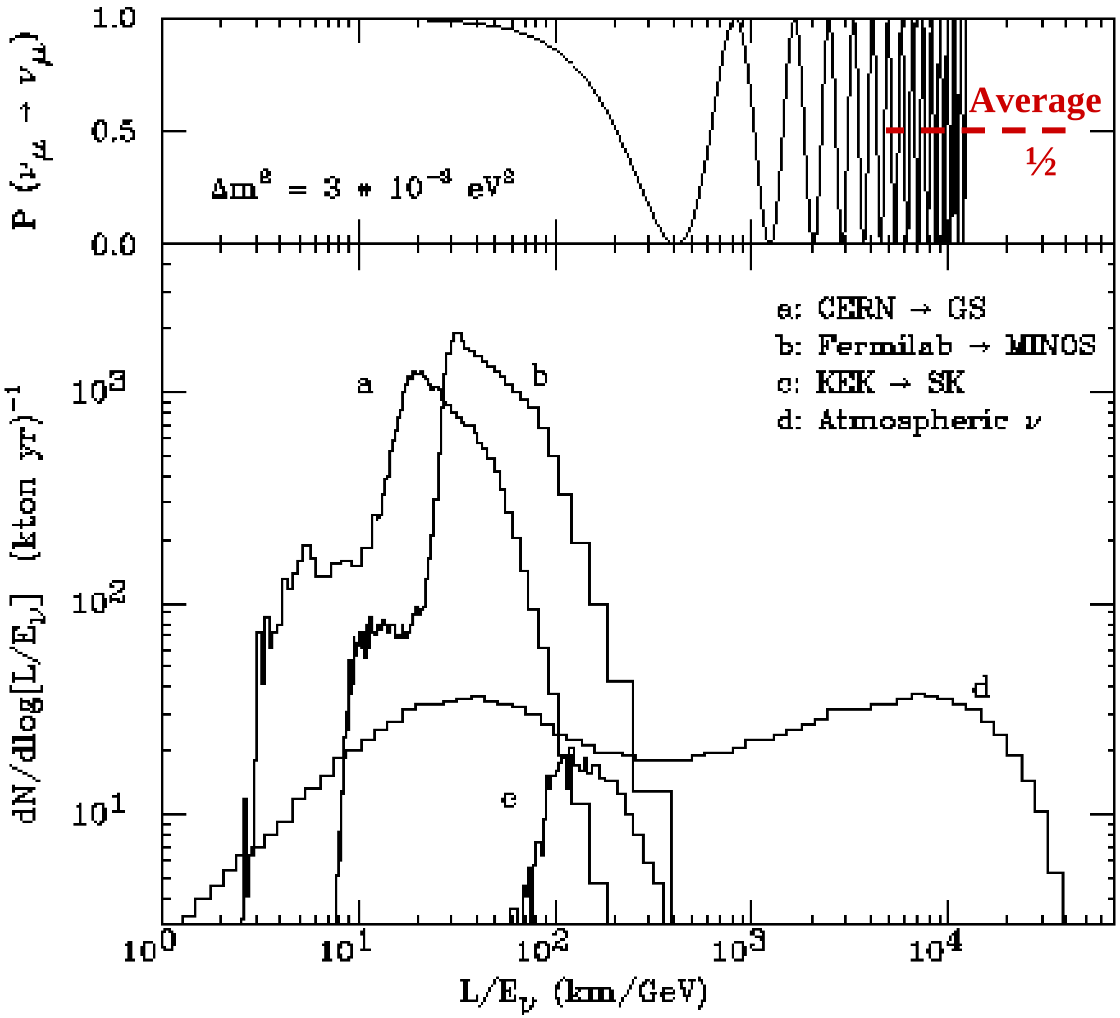
Disappearance probability

$P = 1- \sin^2 2\theta \ \sin^2(\Delta m^2 L / 4E)$

oscillation pattern

(shown for "full" mixing)

L/E$_\nu$ distribution of ν_μ CC events (no osc.) with accelerator and atm. ν



From G.Battistoni and P.Lipari, 1998 Vulcano Workshop on Astrophysics and Particle Physics

"High energy" long baseline projects

($E_{CM} >> m_\tau$, detector at ~ 730 km from ν_μ source)

CERN - Gran Sasso: **NGS beam**

FNAL - Soudan mine: **NuMI beam**

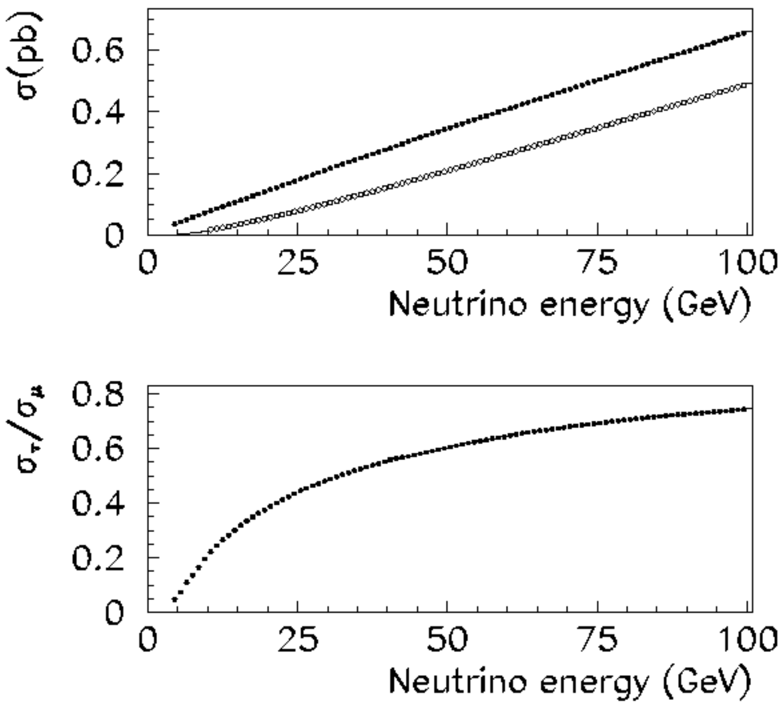
very appealing for $\nu_\mu \rightarrow \nu_\tau$ appearance

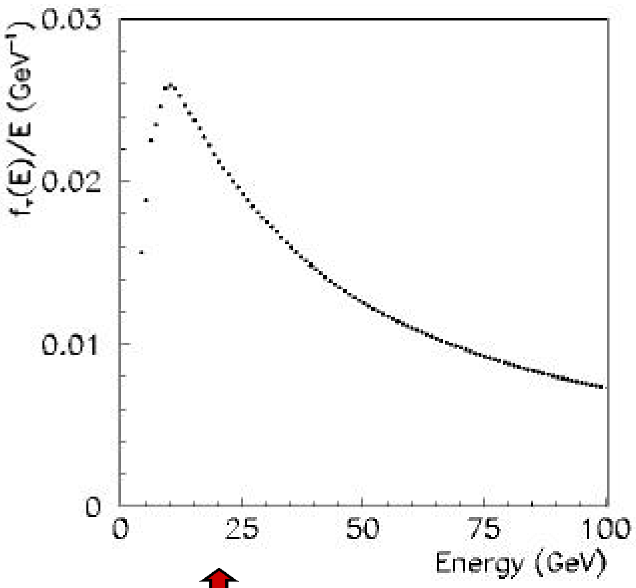
M $\gtrsim$ 1 kton and low background required

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

Conflicting requirements.....

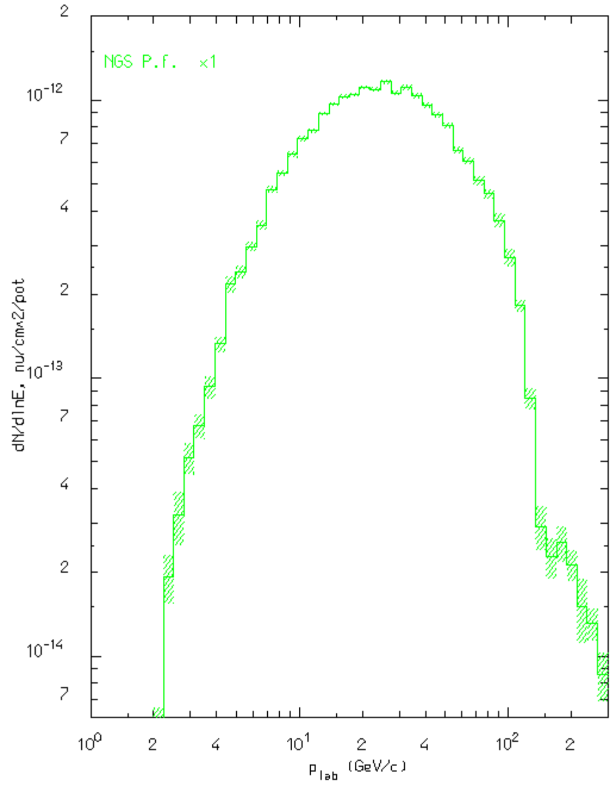
due to the τ threshold σ_τ/σ_μ increases with the energy



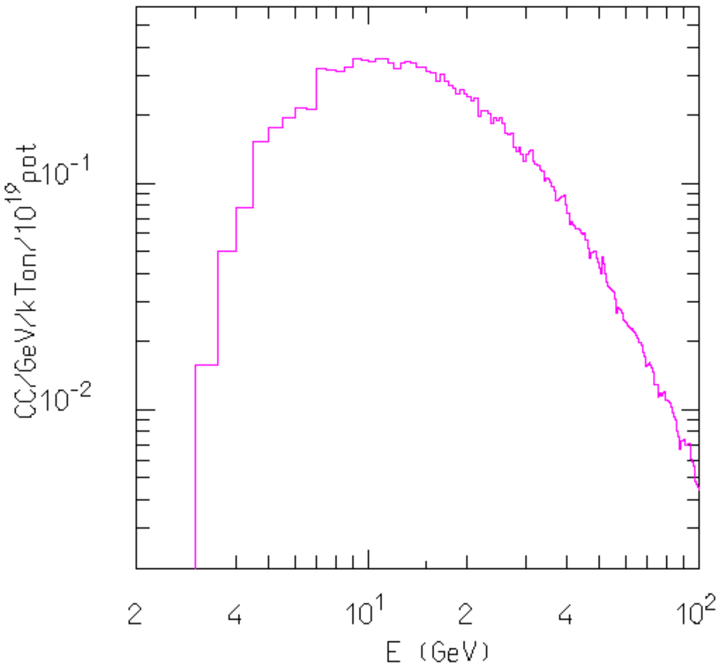


τ yield

X

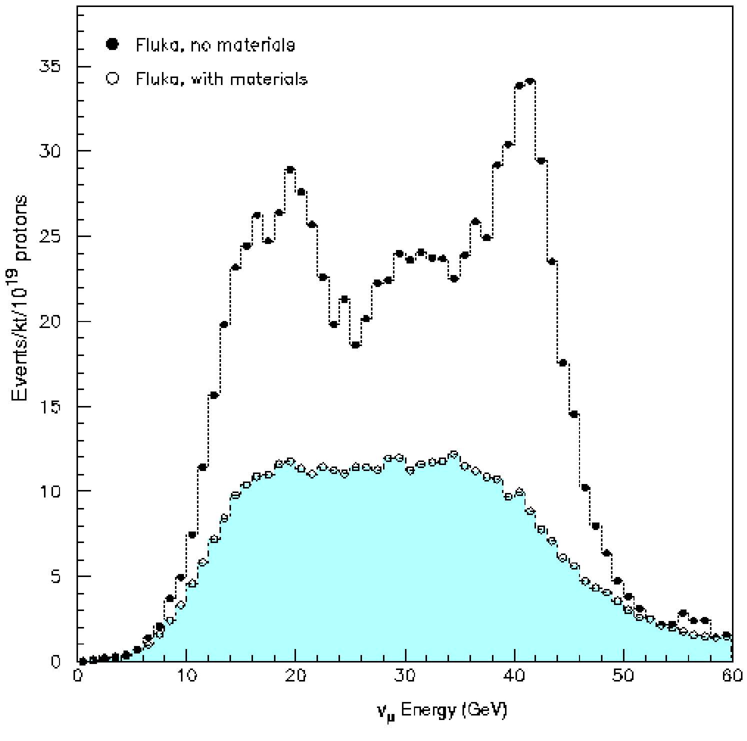


perfect focusing

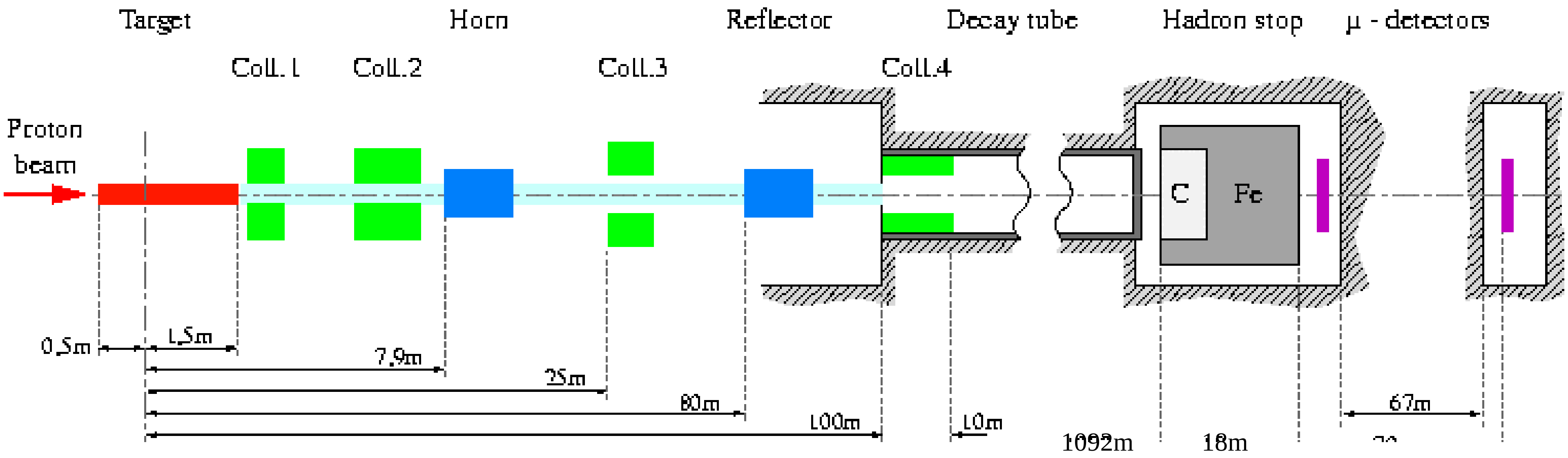


overall optimization

Reduce losses due to material in the beam line...



The NGS beam line



Features of the NGS beam

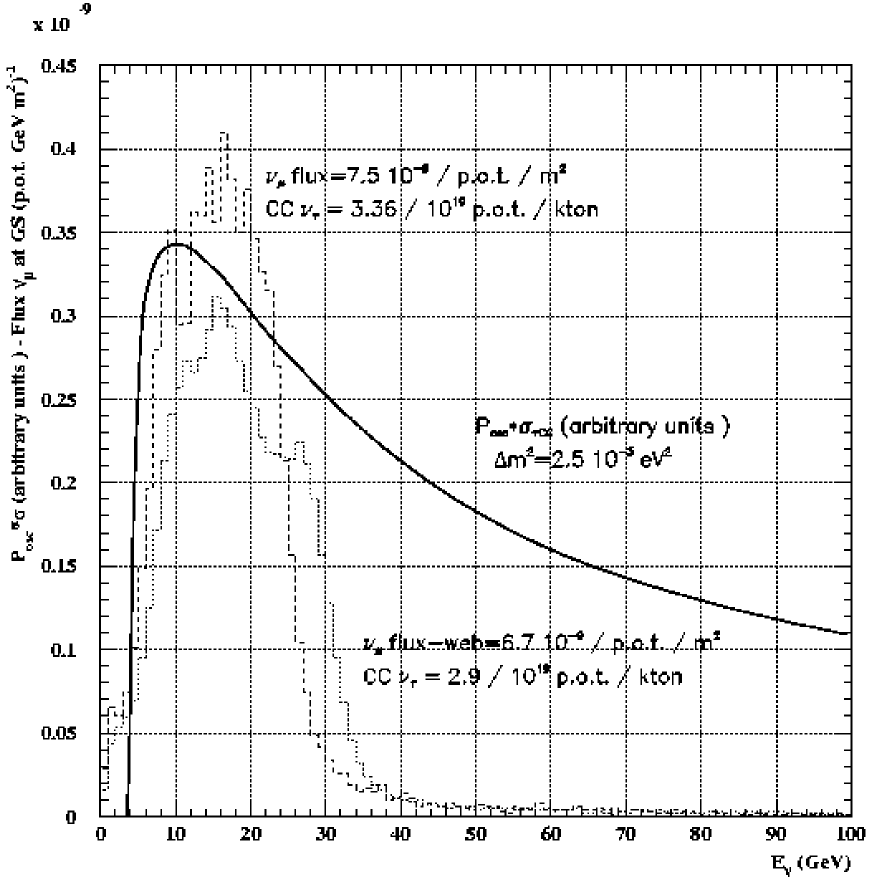
400 GeV proton beam:
4 x 10^{19} protons/year (x2 in dedicated running mode)
200 days/year, ε=55%
τ yield: 2.84/(10^{19} pot x kton)

	ν_μ	antiν_μ	ν_e	antiν_e
ν/(10^{19}pot/m^2)	**6.7 x 10^{10}**	**2.5 x 10^{9}**	**3.8 x 10^{8}**	**5.9 x 10^{7}**
Relative interaction rate	**1**	**0.02**	**0.008**	**6.0 x 10^{-4}**
Mean neutrino energy (GeV)	**20.4**	**21.0**	**31.5**	**26.3**
DIS events /(10^{19}pot/kton)	**540**	**10.4**	**4.7**	**0.3**
QE events /(10^{19}pot/kton)	**50**	**1.3**	**0.3**	**—**

Possible performance improvements

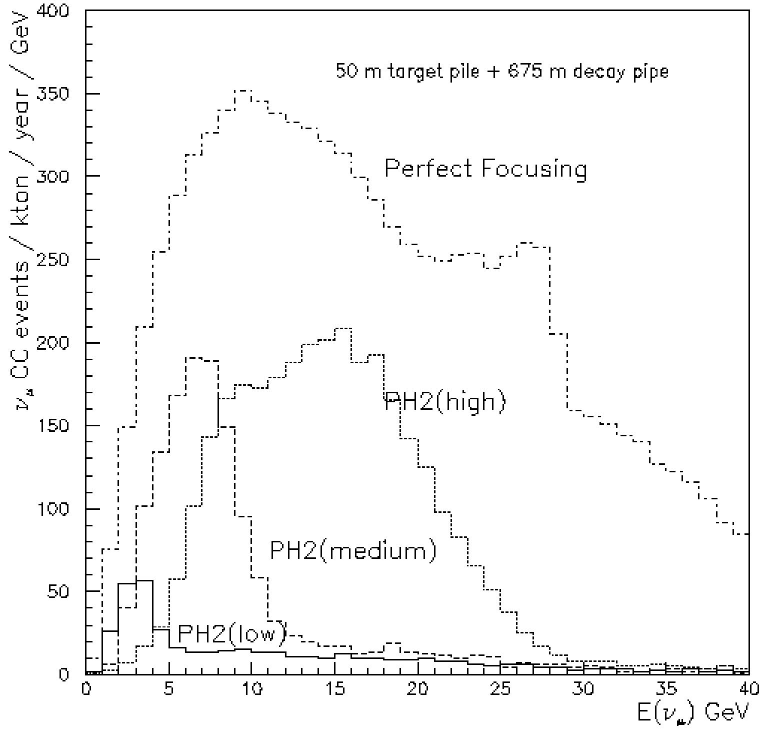
higher Horn current: 150 kA
(CERN/INFN Techn. Comm.)

+15% τ yield
+10% CC events



Beam spectra for the NuMI beam

first run: low energy ⟶ disappearance



Detection of τ from ν_τ CC

$\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau \xrightarrow{\text{CC}} \tau^- + X$

$\mu^- \nu_\tau \bar{\nu}_\mu$	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 %

Tools for background rejection

kinematics:

Requires good particle identification and resolution in momentum unbalance (unseen ν)

(NOMAD)

direct observation of decay topology "signature":

$\gamma c\tau$ = 0.5-1 mm

Requires **emulsion** : ~ 1μm granularity

(**CHORUS**)

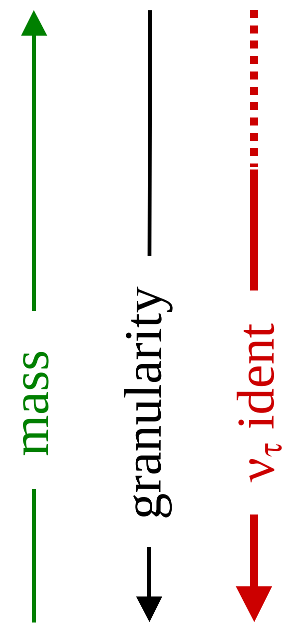
Long baseline experiments for τ appearance

Èerenkov

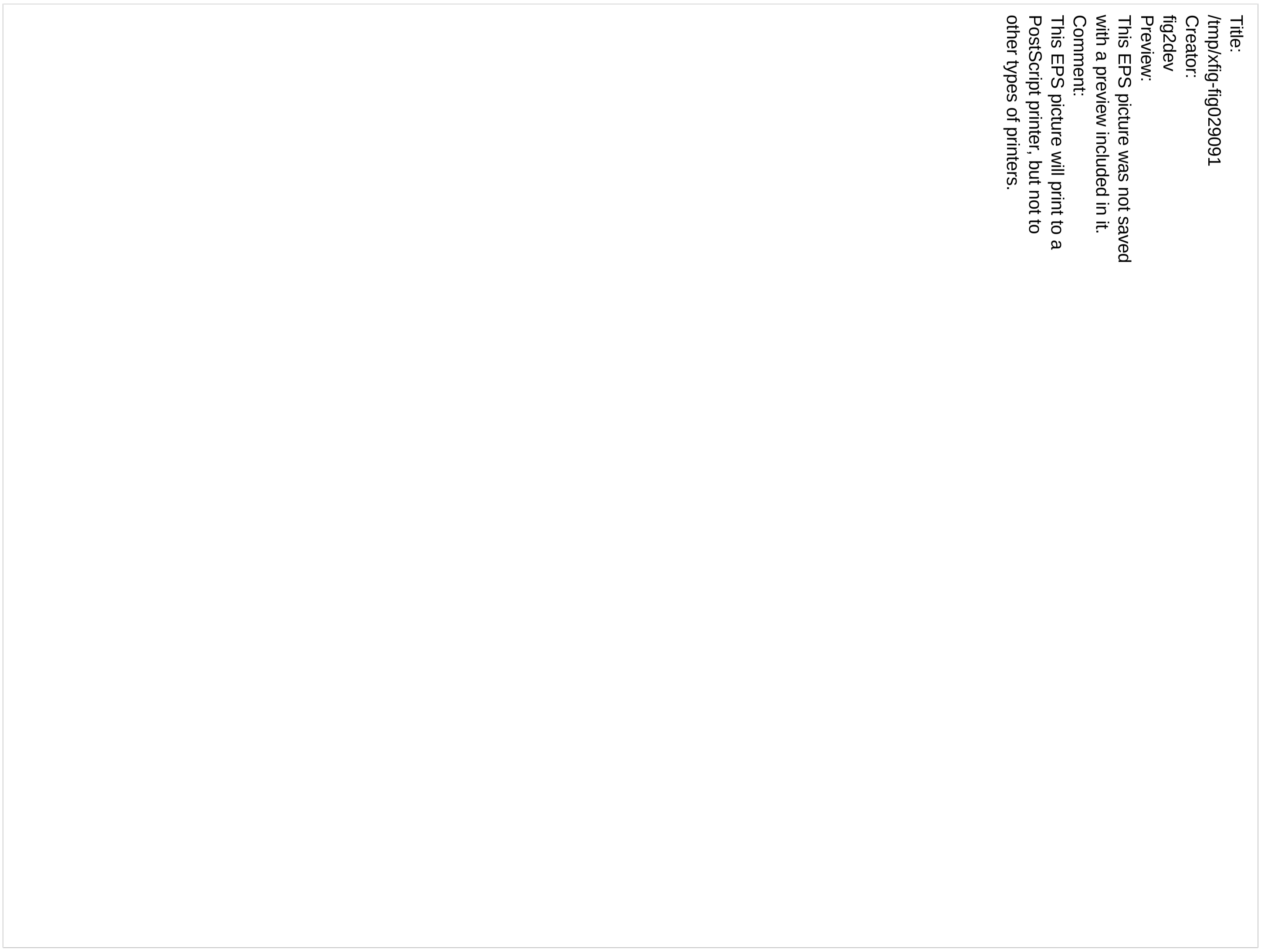
ACQUARICH	125 kton	H_2O + focusing mirror	ν_τ by kin

Tracking

MINOS	10	Magnetised Fe / Scint	kin
NOE'	7-8	Fine grain calorimeter + TRD	kin
ICARUS	0.6 .. 30	Liquid Argon TPC	kin
OPERA	0.8	Pb-emulsion	decay (+kin)



FNAL - Soudan beam



ν_μ disappearance with Near Detector for "reference"

(beam divergence gives very different beams near and far)

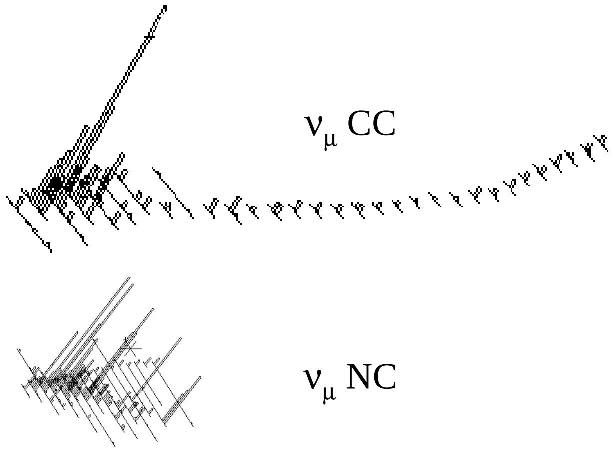
ν_μ-ν_x from "NC"/ ν_μ CC

MINOS : best for ν_μ disappearance

A “technologically revisited”

conventional detector with mass x *O*(10)

(HPWF, CDHS, CHARM, CCFR, … MINOS)



Coarse event reconstruction

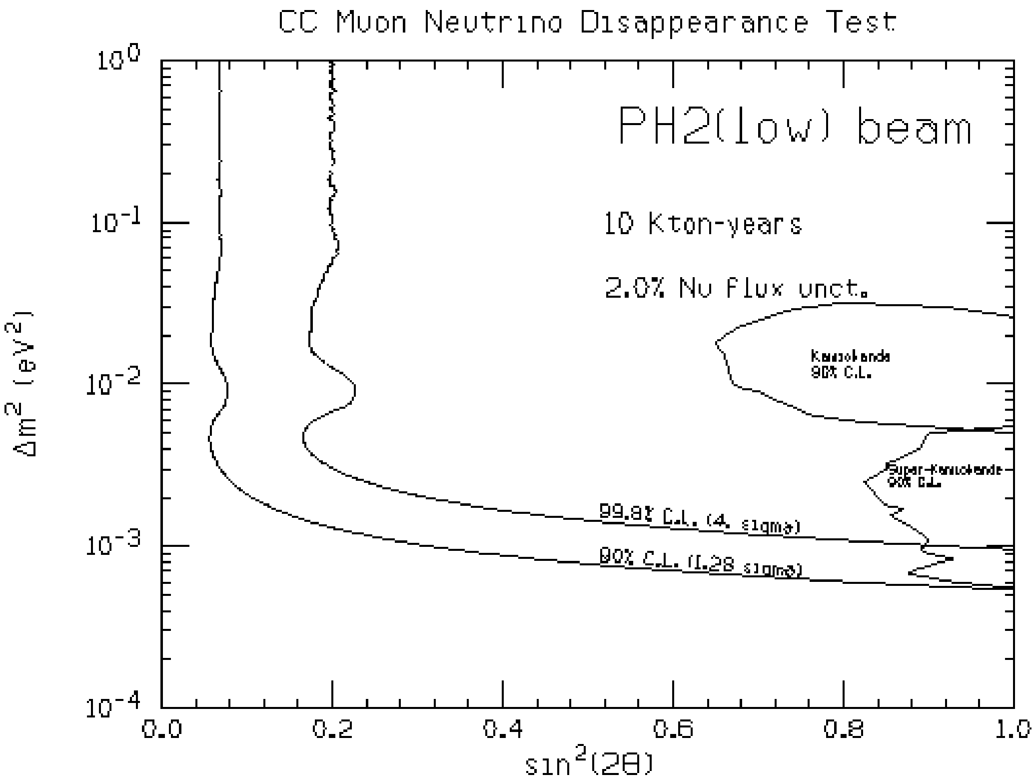
μ tracking, e/h from shower features

ν_μ disappearance search (at low E_ν)

ν_e appearance

appearance from “NC”/ ν_μ CC

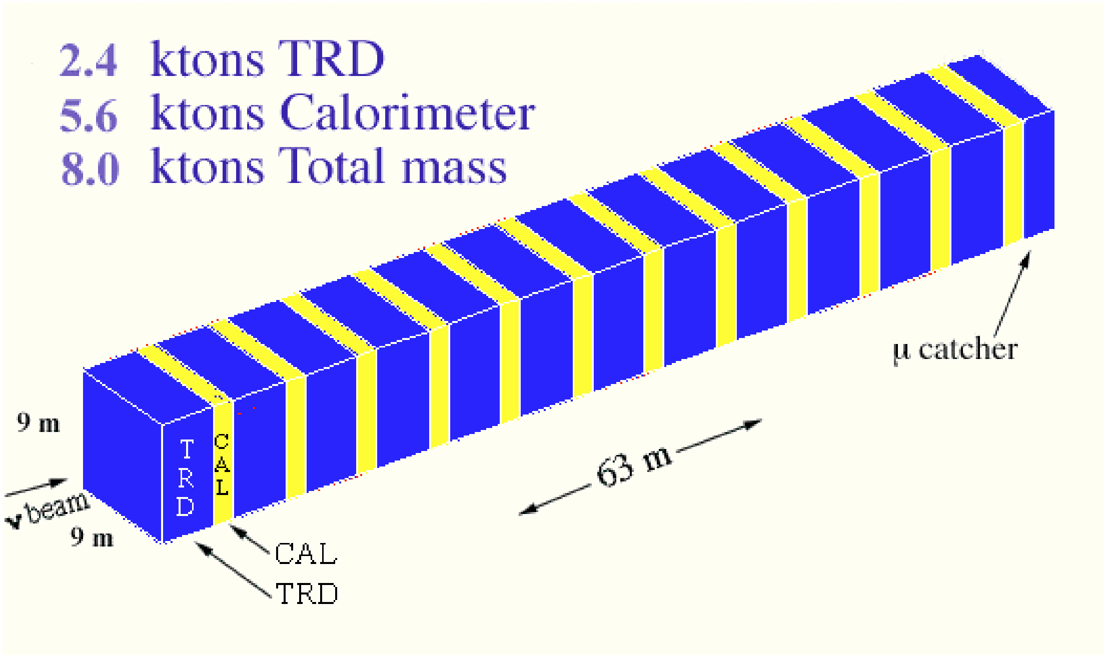
<u>no</u> ν_μ-*n$_t$* direct appearance**

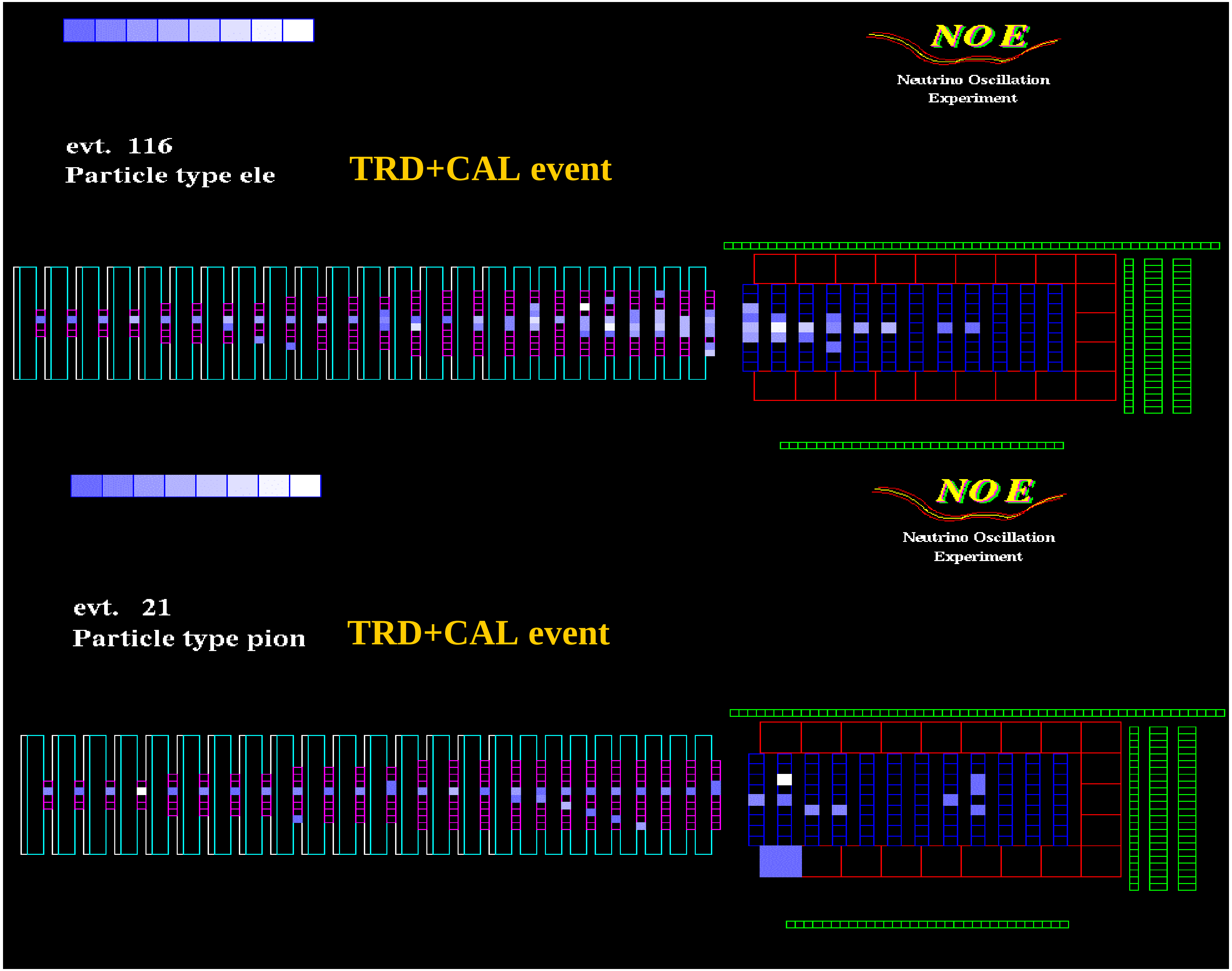


The Noe detector

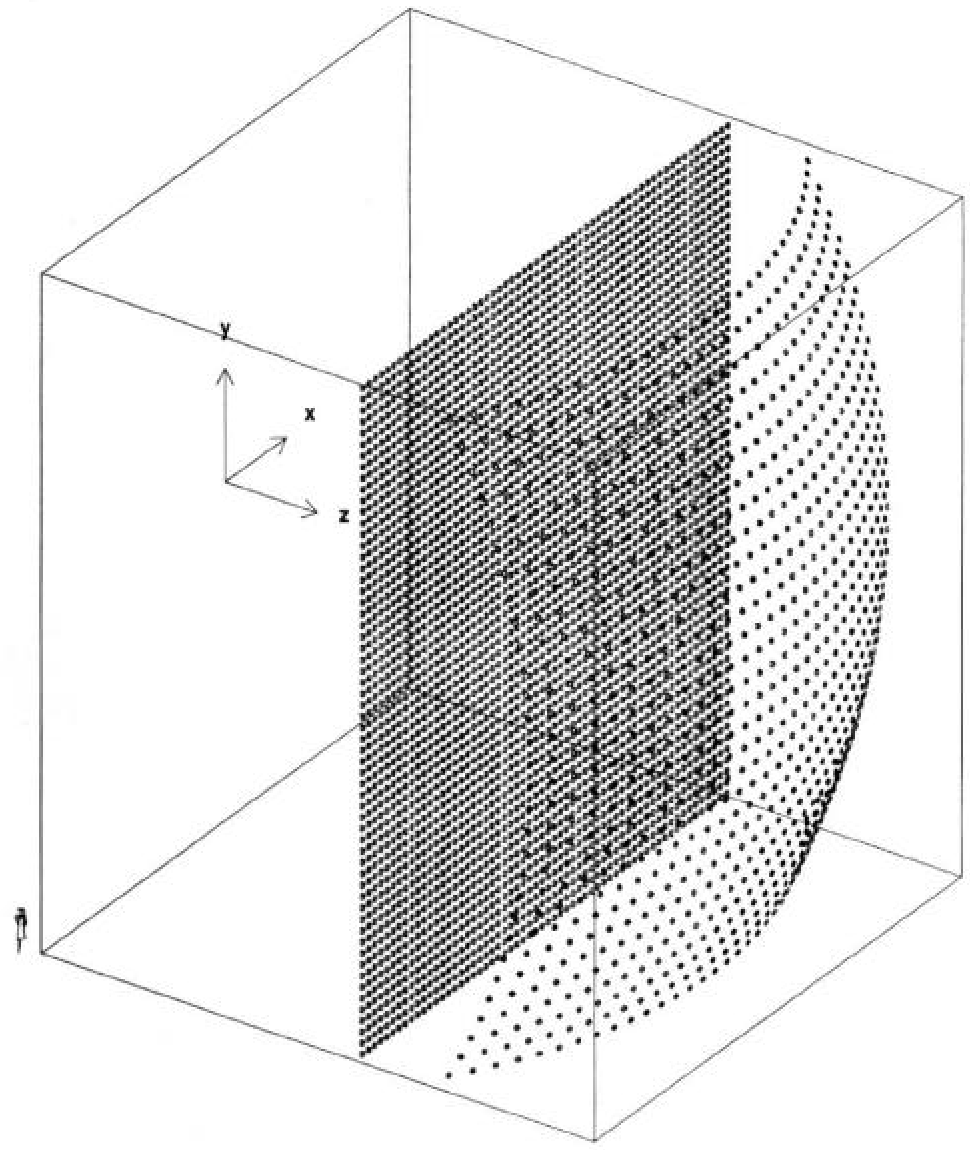
e ID by **TRD** and **CAL** combination.
clean τ e-channel.

E_e, E_π measurement in **CAL.**
E_μ by multiple **dE/dx** in the **TRD** prop. tubes.




NOE
Neutrino Oscillation Experiment
evt. 116
Particle type ele
TRD+CAL event
NOE
Neutrino Oscillation Experiment
evt. 21
Particle type pion
TRD+CAL event

The ACQUARICH detector (125 kton)



ACQUARICH rings

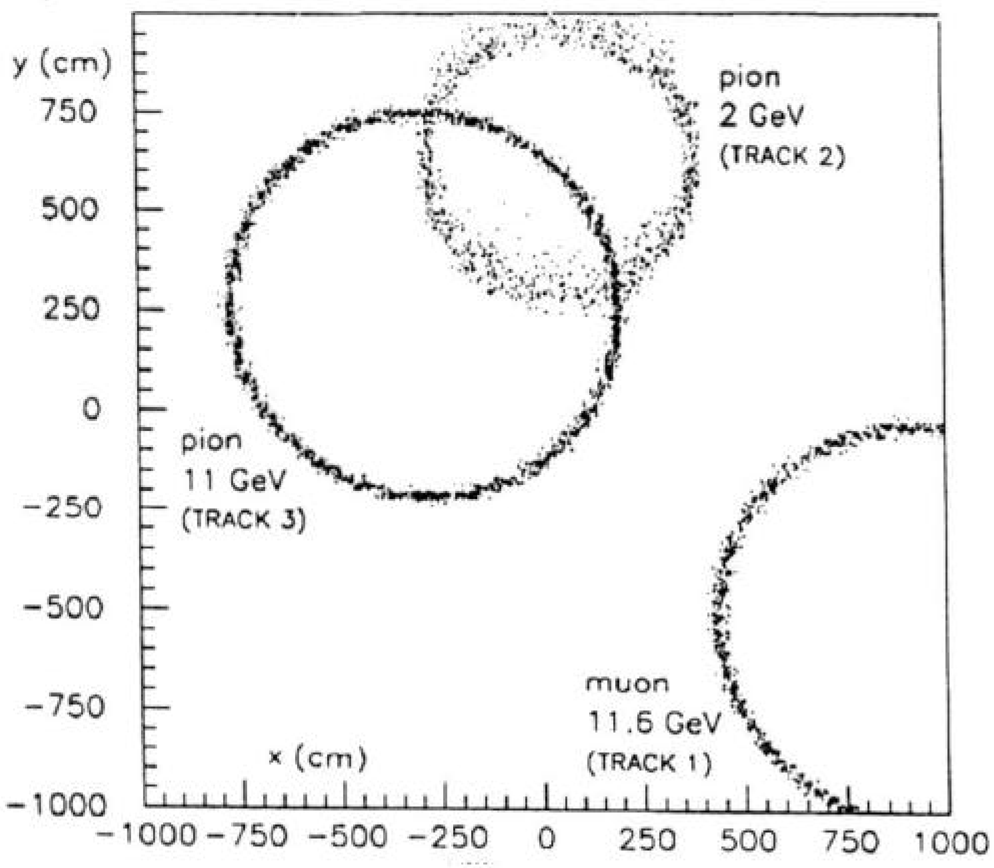
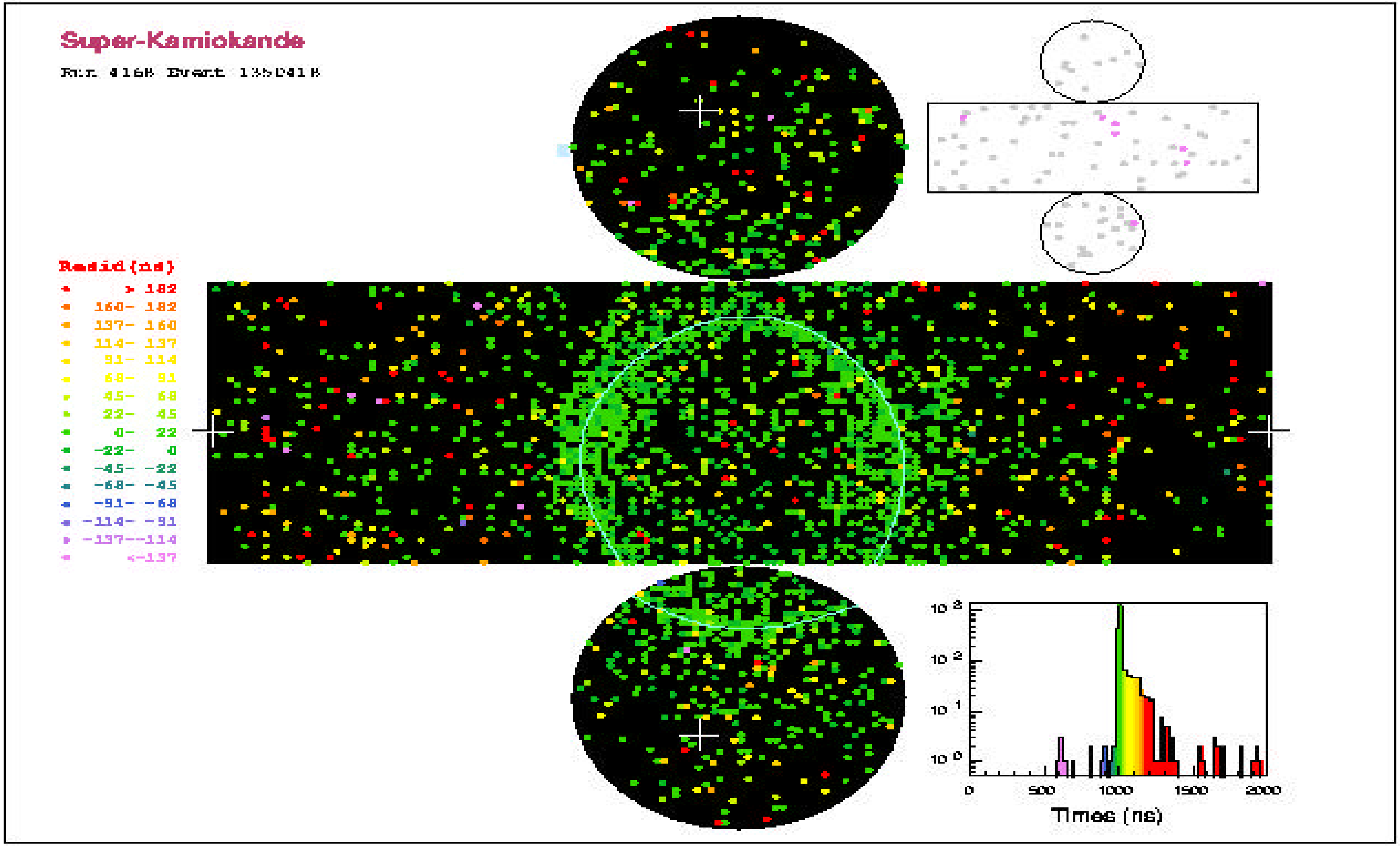


Fig. 3. Images of a 40 GeV neutrino interaction $\nu_\mu p \rightarrow \mu^- \rho^+ \eta' \Delta^+ \pi^o$, $\rho^+ \rightarrow \pi^+ \pi^o$, $\Delta^+ \rightarrow \pi^+ \pi^o$, $\eta' \rightarrow \gamma \rho^o \rightarrow \gamma \pi^+ \pi^-$ in 25 m of an Argon gas radiator with γ_t=10. The three above thresold tracks are labeled 1, 2, 3 with their identity and energy.

...compare with a SuperKamiokande event



The liquid Ar Image TPC Chamber of ICARUS: 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

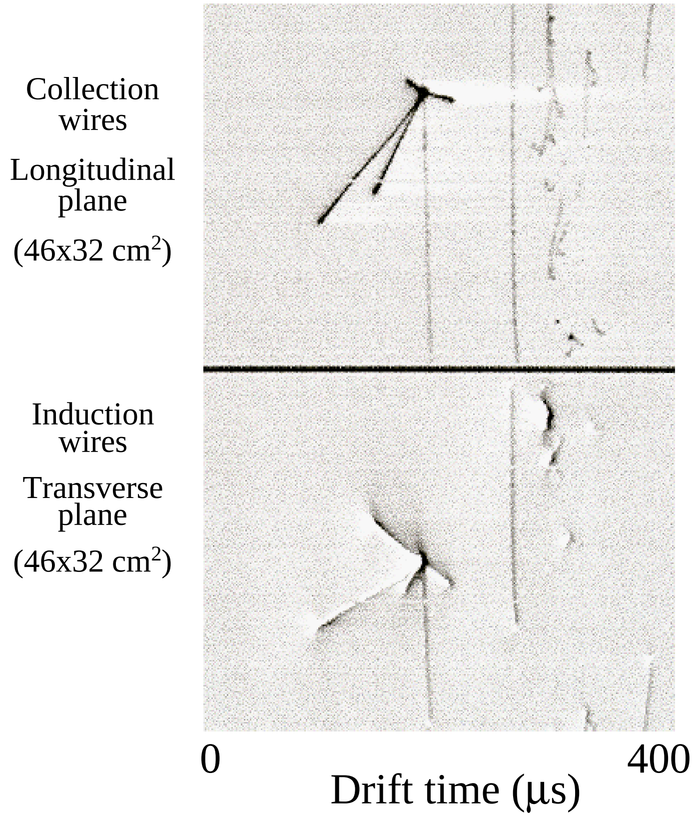
• Specific ionisation (dE/dx) measurement

• dE/dx vs. range for particle identification

• Continuous sensitivity

• Self triggering capability

A ν interaction in the 50 liters test TPC



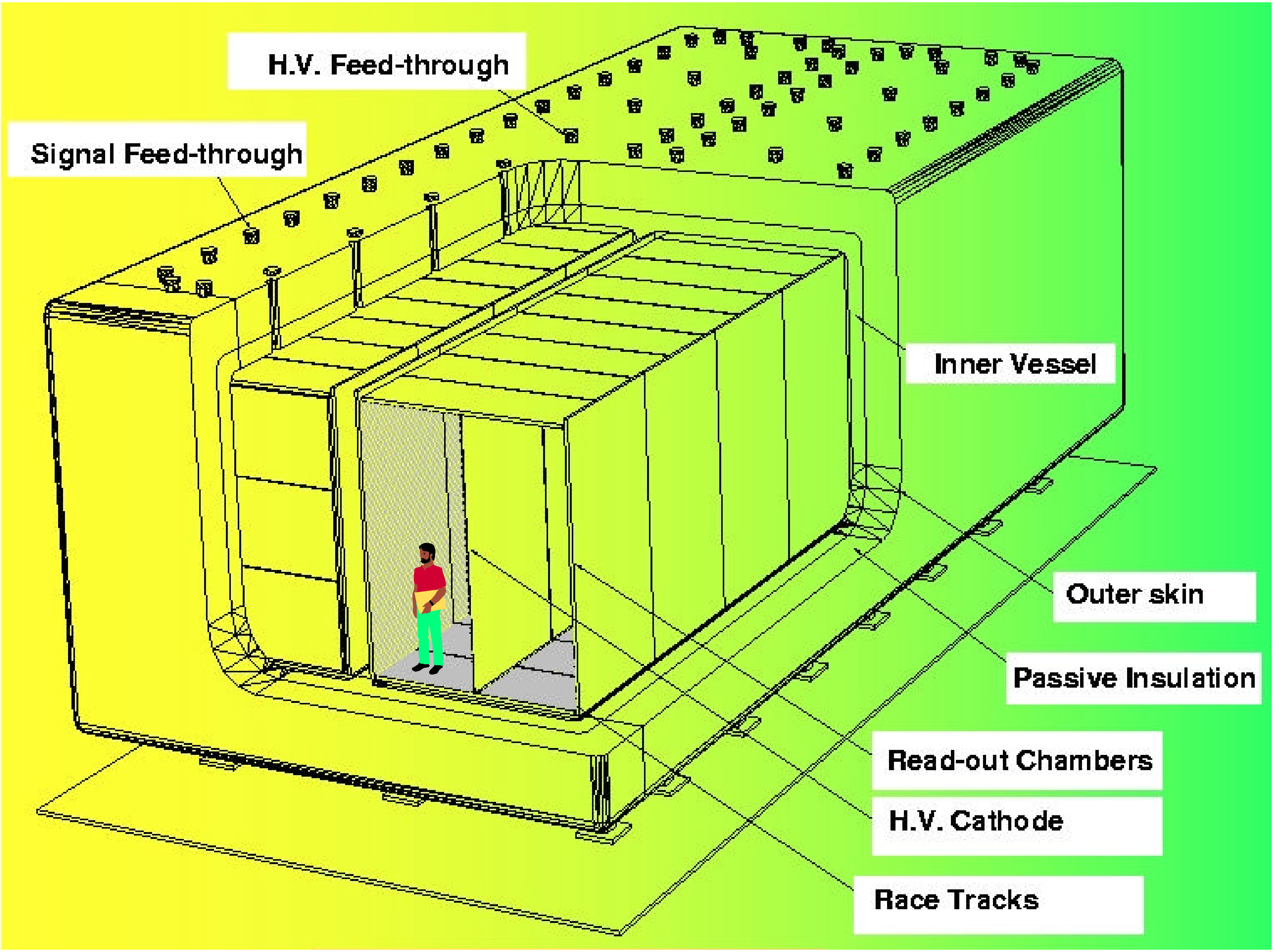
New detector → new physics capabilities

Under construction : 600 ton module

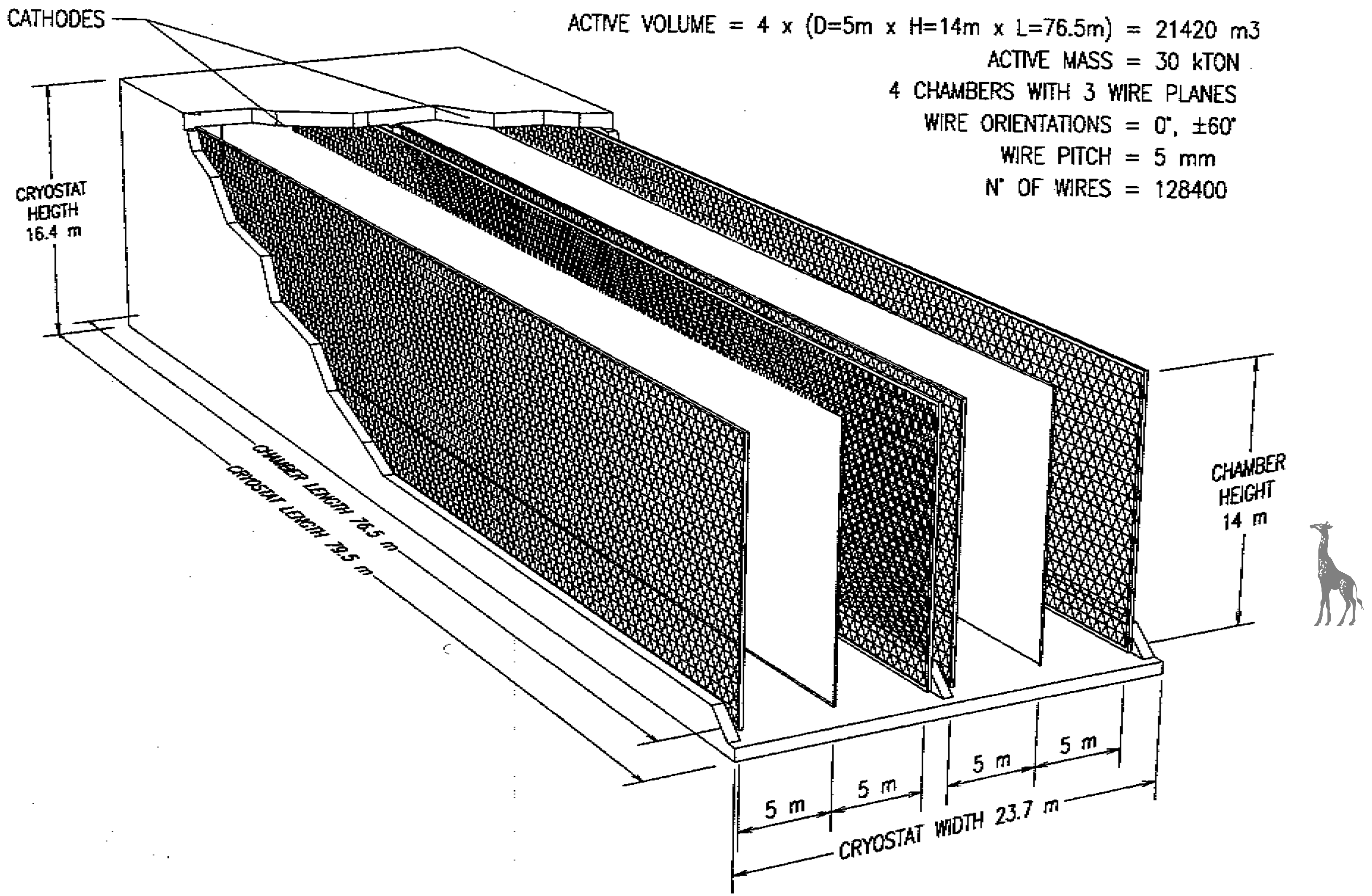
For physics : 2.4 , …. tons

proton decay
atmospheric ν
long baseline ν oscillation
solar ν

The ICARUS 600 ton module



A 30 kton Super-ICARUS
for long baseline and atm. ν experiments
(to be situated at shallow depth)



Only kinematics or decay "signature" ?

Only kinematics

NOMAD	(M_{target} ~ 1 ton)	10^4-10^5	}	required b.g. rejection
Long baseline	(M_{target} ~ **10** kton !)	10^2-10^3		

Massive (long baseline) AND sophisticated electronic detector

Non gaussian tails : ways-in for background

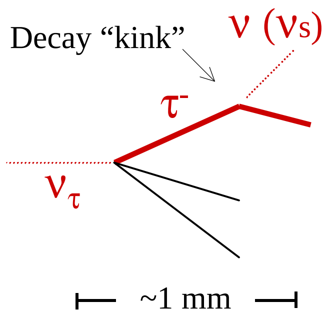
Losses of final state particles (acceptance, inefficiencies, neutrons, …)
Tails of **Fermi momentum** of target nucleons
Nuclear effects (rescattering, absorption, …)

Emulsion: topology as decay "signature"

Modest rejection by kinematics is adequate

(e.g. against charm decays , with similar lifetime)

Very low background



Automatic emulsion scanning

- **Pioneered by Nagoya: *Track Selector***
  → speed x 100 w.r.t. semi-automatic systems
- ***New Track Selector*** → speed x 10
  routine scanning in Nagoya and other laboratories
- **Important investments** in old and new scanning laboratories : Nagoya, Toho, Utsunomiya, Korea, Ankara, Bari, CERN/NIKHEF, Münster, Napoli, Roma, Salerno, USA
- **R&D** → … even faster systems, general scanning: ***UTS, S-UTS***

↓

Automatic scanning of large number of events
Semi-automatic scanning only for candidate events
Event pre-selection by kinematics cuts not required → higher ε

a revolution :
Rebirth of the emulsion technique

New tools always made a difference...

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

Microscope event view

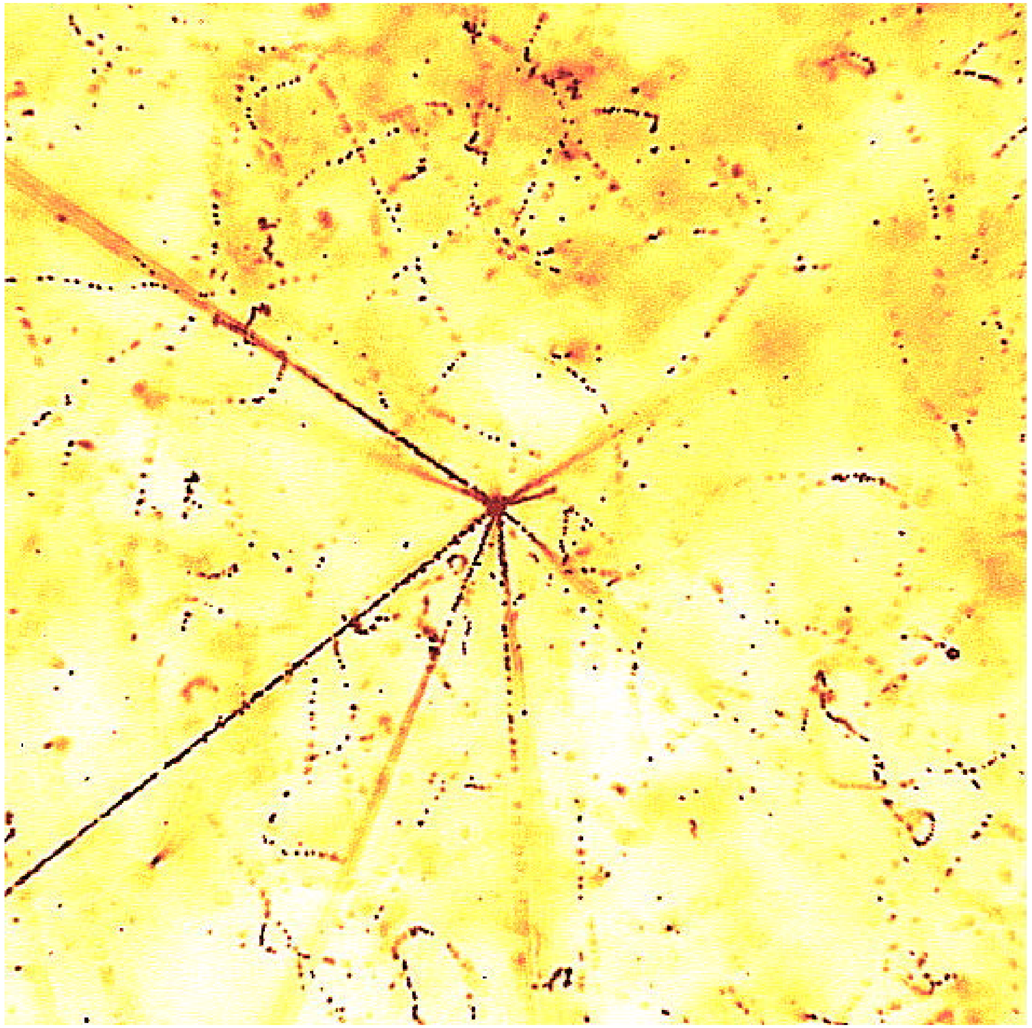
Emulsion
⊥
to beam

↓

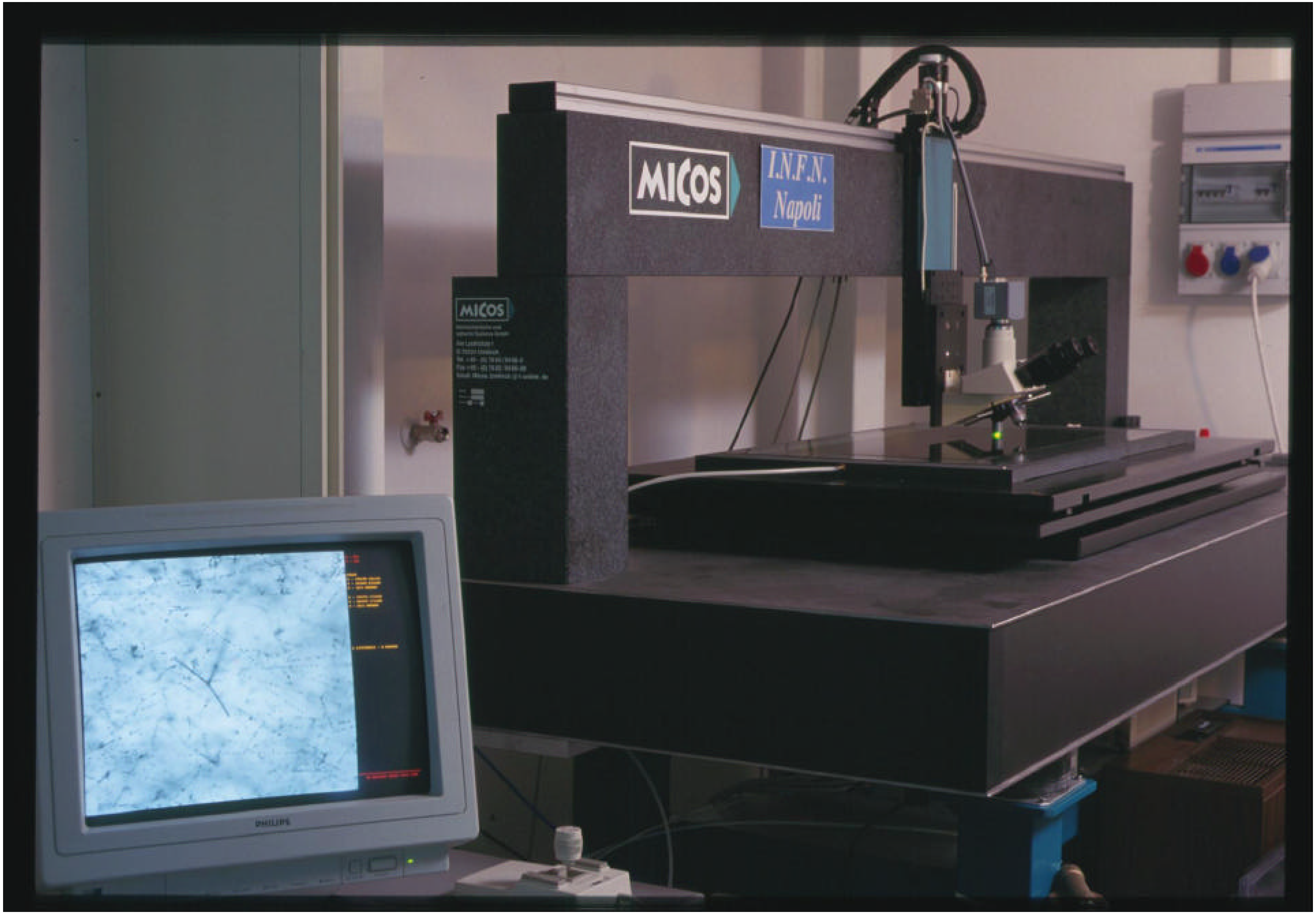
Good tracks
appear as
dots

↓

Tracking
implies
connection of
dots
in different
layers



~100 μm


MICOS
I.N.F.N.
Napoli
MICOS
PHILIPS

Aim, target mass and experimental technique

- Atmospheric neutrino signal — $\Delta m^2 = 10^{-2} - 10^{-3}\ eV^2$
- On planned long baseline beams — $M_{target} = O\ (1000)$ ton
- Impossible with **pure** emulsion target (CHORUS ~ 0.8 ton)
- Different approach required — passive target material - emulsion **sandwich** (emulsion only for tracking)
- Starting point : the **E**mulsion **C**loud **C**hamber (ECC)

  used in cosmic rays (charmed “X-particle” observed in 1971!) and accelerator experiments

The OPERA ν_τ appearance experiment in the CERN-Gran Sasso NGS beam

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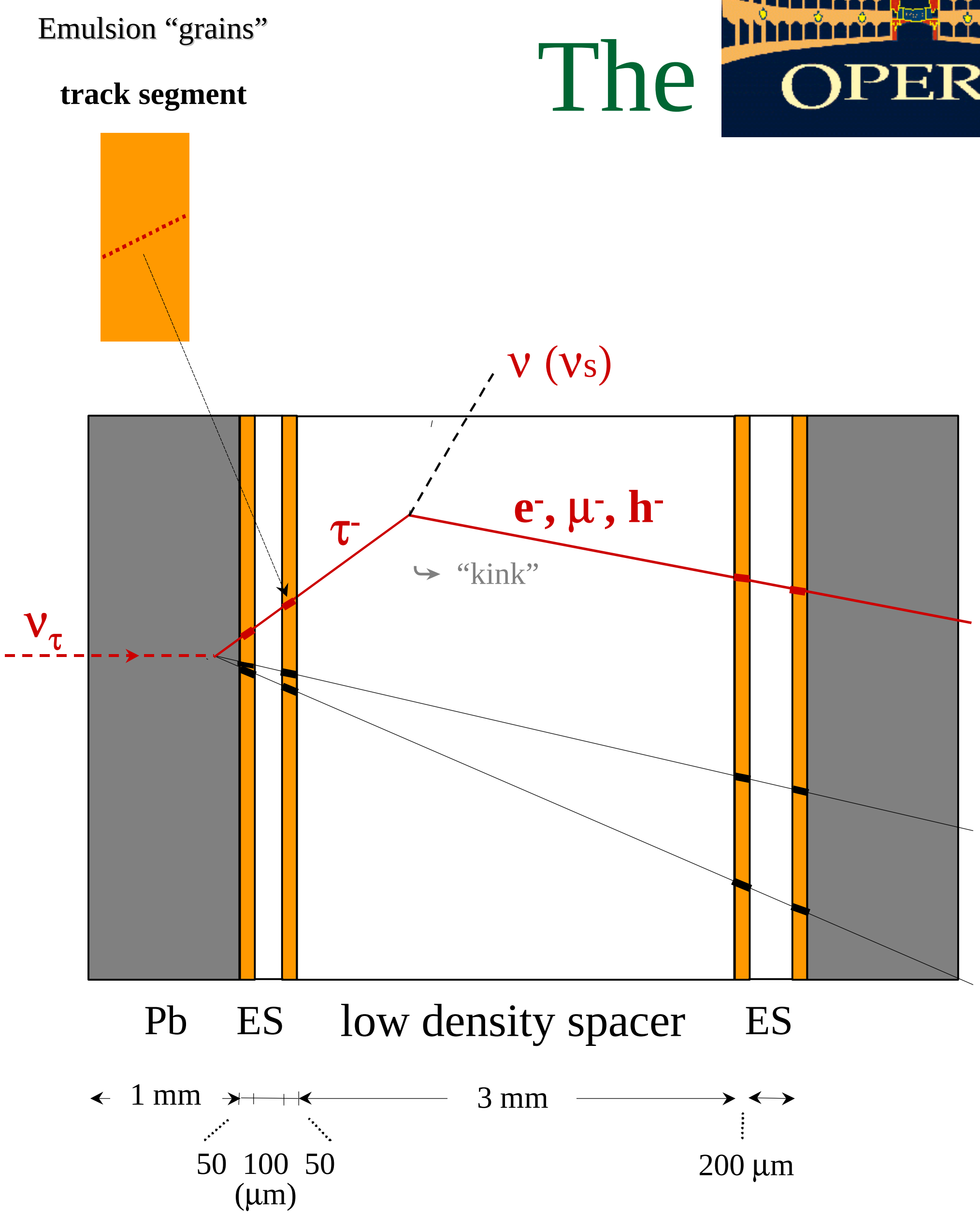
LNGS-LOI 8/97 and SPSC 97-24/I218,
SPSC 98-25/M612

The OPERA concept



- Pb → **large M_{target}**
- Emulsion sheets (ES)

  → **tracking in space**
- Each of the two (double-sided) ES
  - 50 μm emulsion layers on both sides of 100 (200) μm plastic base
  - μm detection granularity

  → two **high quality track segments**
- τ decays in the spacer
  - no reinteractions or charm decays in Pb
  - $\gamma c\tau > 1$ mm Pb → $\varepsilon_\tau \sim 0.4$

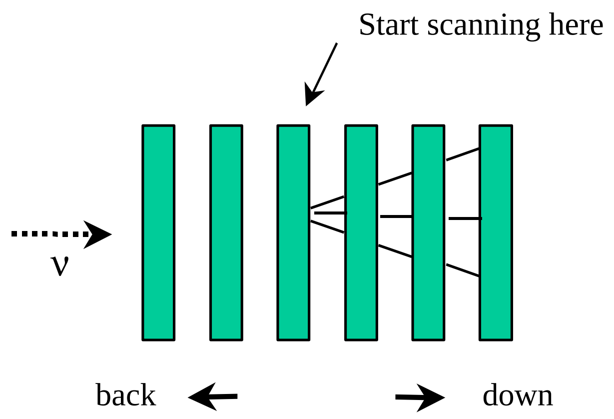
Decay topology directly observed

Low background

Event reconstruction

- Study all τ decay channels $\rightarrow e^-$, μ^-, h^-, (possibly into 3π)
- Event localization by electronic detectors
- Start scanning from ES upstream of event in electronic detector
- General scanning
- Find vertex plate (Pb) and neutrino vertex
- Follow down tracks from vertex
- Kink search (in gaps between Pb)
- Kinematics of candidate events

  (few % of total)

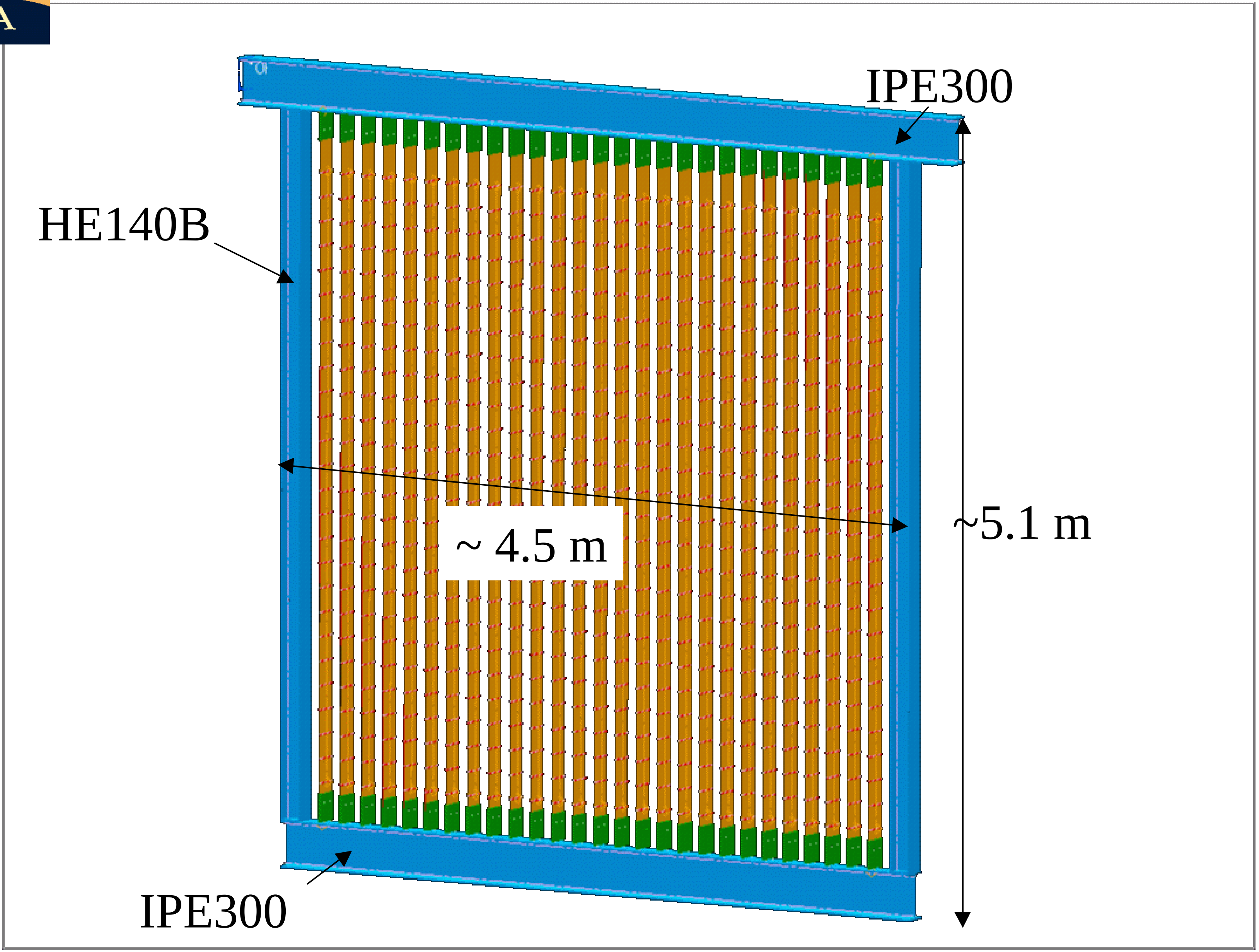


The detector

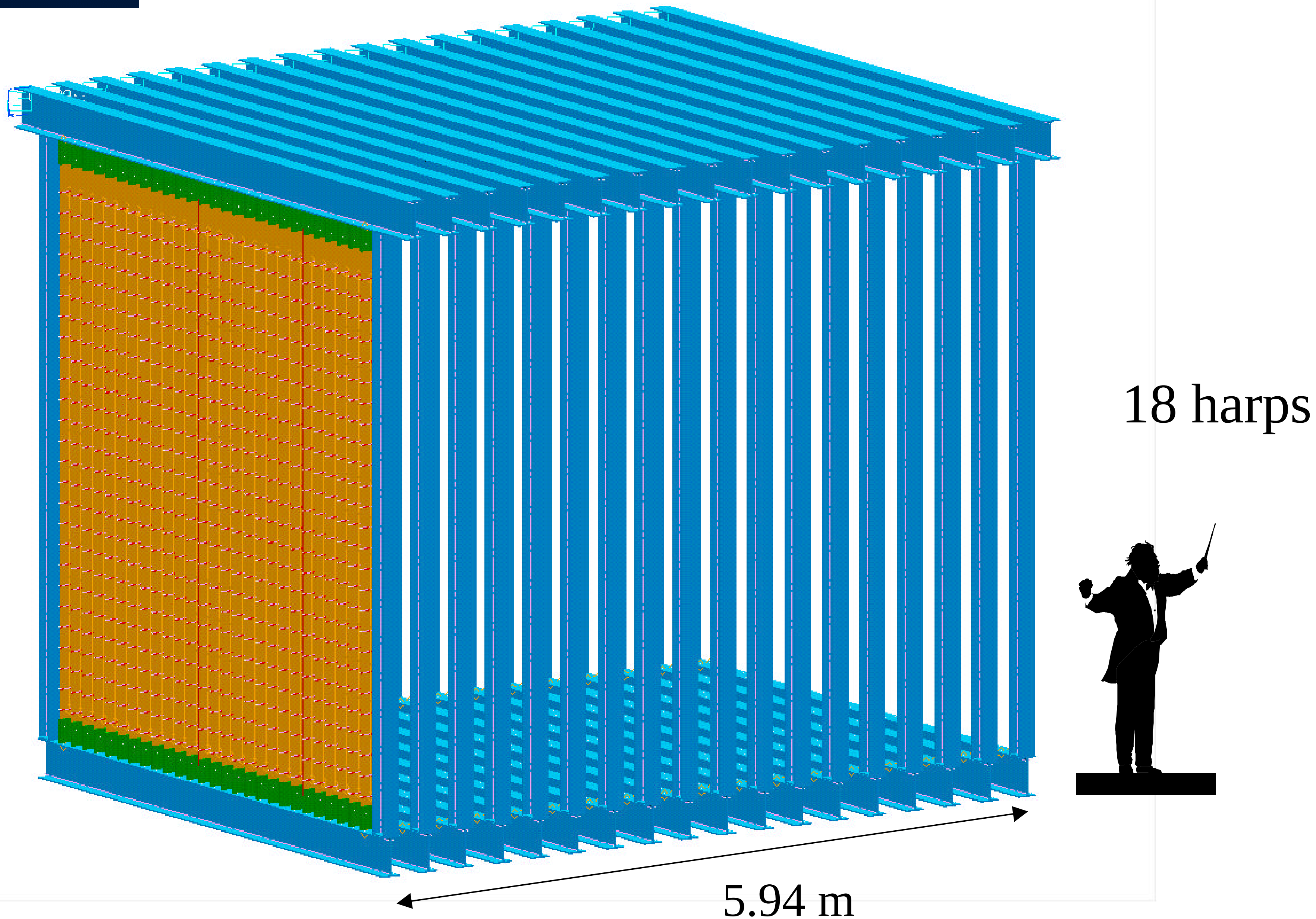
Present design

- **Lead-emulsion target**
  - cell: 1 mm Pb, ES, 3 mm gap, ES
  - brick: stack of 30 elements (~ 13 cm thick, 15 x 15 cm^2 X-sect.)
  - module: matrix of bricks (~ 5 x 5 m^2)
  - electronic detector planes following each module
  - total mass: ~ 800 ton, subdivided into supermodules
  - maximum detector length ~ 40 m
  - detector mass is scalable (number of supermodules)
- **Muon detection**
  - tracking in the target (electronic detectors)
  - magnetised iron μ-spectrometer downstream: sign of charge (momentum)
- **Calorimetry**
  - in the target: Pb (each module ~ 5 X_0) + electronic det. (Scintillator strips)
- **Momentum measurement** from multiple scattering in emulsion
- **Electron ID** from emulsion measurements (EM interactions in lead plates)

“Harp” support



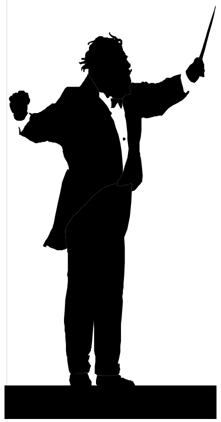
Target supermodule support

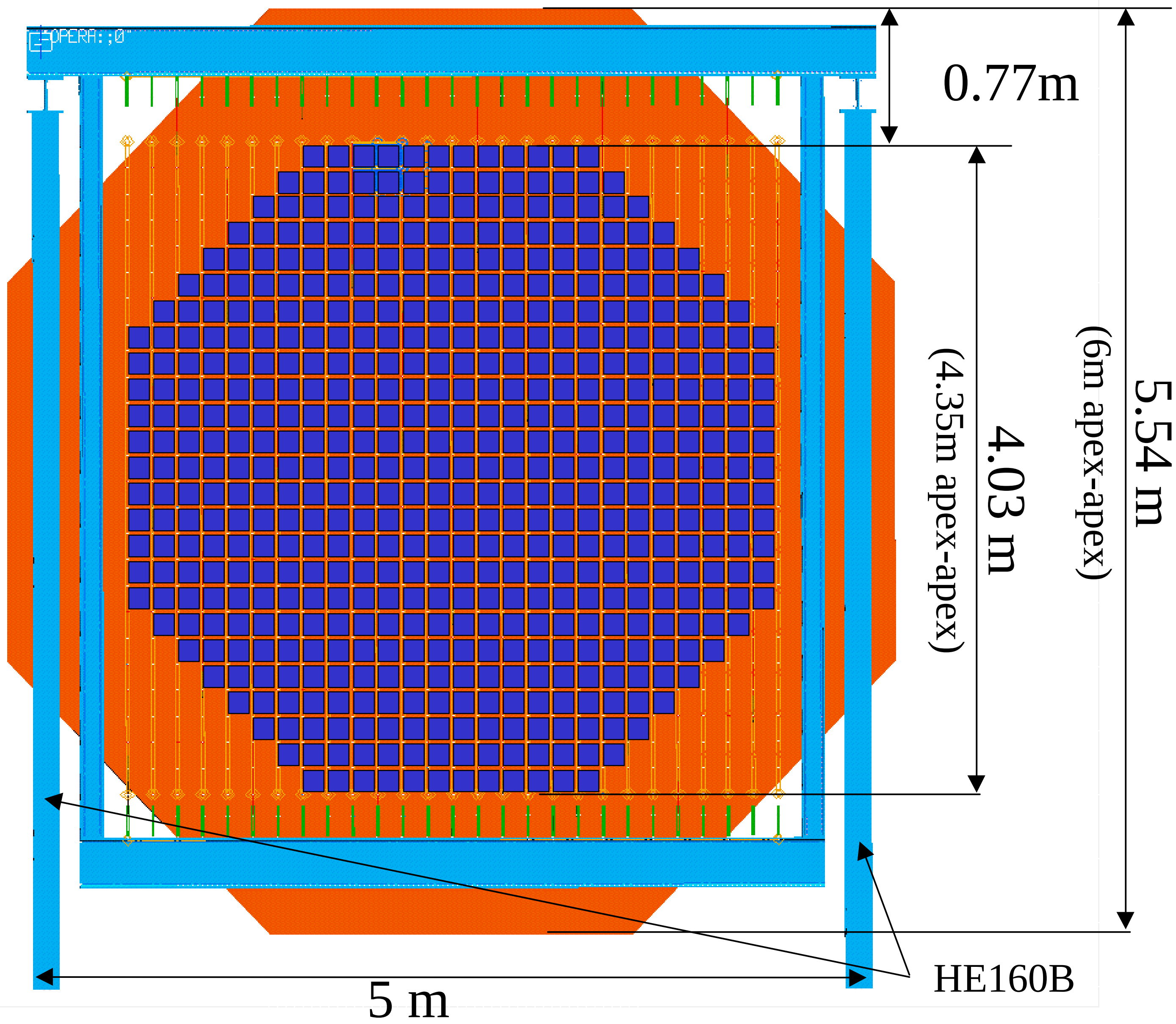


Supermodule (front view)

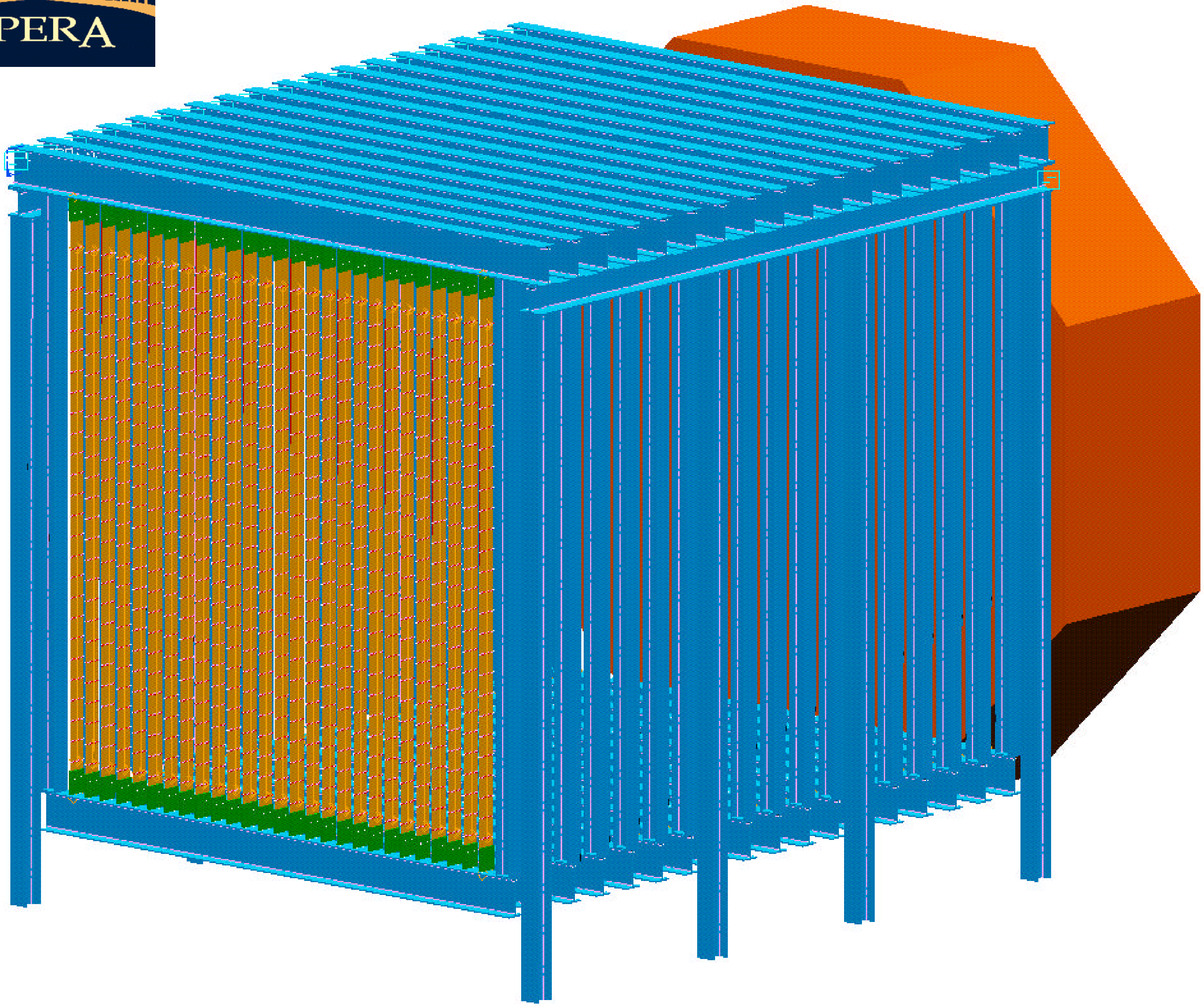
564 bricks/plane
(26x26 - 4x28)

18 planes
(10152 bricks)

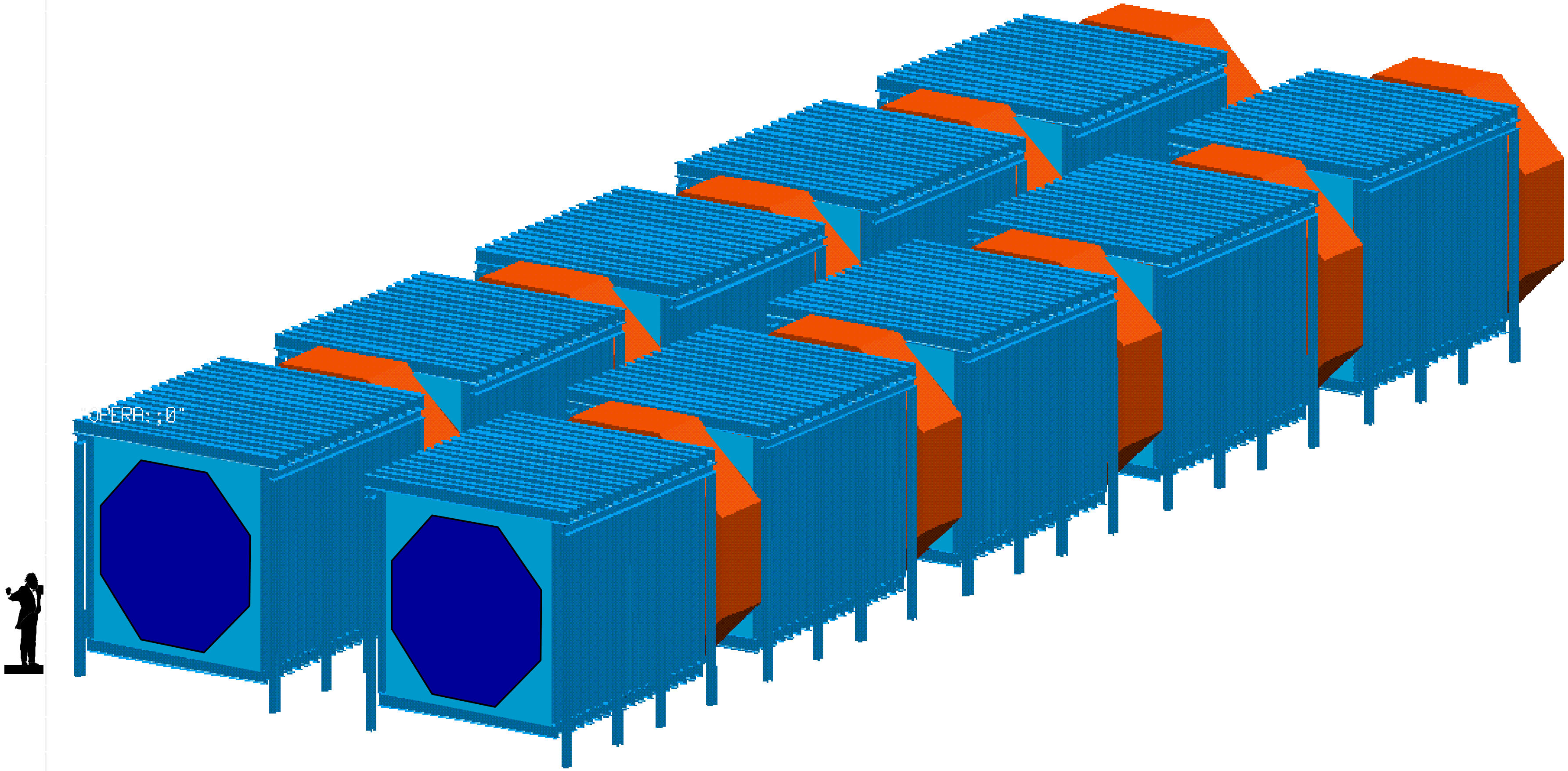




Supermodule (perspective)



The apparatus (perspective)



Emulsion

- No target ("bulk") emulsion, but still:
  ~ 13 m^3 of emulsion layers
- Diluted emulsion: AgBr content 1/2-1/3 w.r.t. short baseline experiments: cost scales down
  (lower grain density allowed by automatic scanning and b.g. level)
- Industrial production: time schedule, lower cost
- Thin emulsion layers: allow special development and good sensitivity (# of grains)
- Recent achievement: industrially produced ES in Japan
- European companies could also be involved

τ detection efficiency

Detection efficiency depends on Δm^2: below assume 2.5×10^{-3} eV^2

- Decays outside Pb (1 mm) → $\varepsilon_{gap} \sim 0.42$

  (ε_{gap} depends on beam features)

- Kink finding efficiency ε_{kink} →
  - 0.88 ($\tau \to \mu$)
  - 0.83 ($\tau \to e$)
  - 0.91 ($\tau \to h$)

  determined by the angular cuts:

  (5 mrad resolution) → $20 < \theta_{kink} < 500$ mrad ← (scanning & bg rejection)

- BR $\tau \to \mu$, e, h → 0.174 , 0.178 , 0.5

- Fiducial volume cut → $\varepsilon \sim 0.90$

Total efficiency for the 1-prong channels: ~ **0.29**

Charm b.g. to $\tau^- \rightarrow h^-, \mu^-, e^-$

(before vertex kinematics of candidate events)

$N_{bg}(h^-)$ =	0.05	charm / CC	
	x 0.5	D production probability	
	x 0.22	BR ($D \rightarrow$ h + neutrals)	
	x 0.45	D decay outside Pb	
	x 0.91	ε_{kink}	
	x 0.90	fiducial volume cuts	
	x 0.04	μ^- CC not identified	
	x 6900	DIS events →	**~ 0.55 events (h^-)**

BR (charged $D \rightarrow l$ + neutrals) ~ 0.065
μ charge measured by the downstream spectrometer (1-ε ~ 0.3) →

~ 0.05 events (μ^-)

~ 0.15 events (e^-)

Total: 0.75 events from single charm (“realistic” running scheme)

Other backgrounds

- Prompt ν_τ in the beam: negligible (**<0.02** events)
- Reinteractions (spacer) : negligible (**<0.07** events)
- π , K decays (CC and NC) : 0.2 events (eliminated by momentum cut)
- CC+NC associated charm production : double decay topology: **0.15** events before the vertex kinematics

Sensitivity and discovery potential

$\sin^2 2\theta_{\mu\tau}$ (large Δm^2) **< 3.8 x 10^{-3}**

Δm^2 (full mixing) **< 1.1 x 10^{-3} eV^2**

(90% CL)

NO OBSERVED EVENTS (0.41 expected BG)

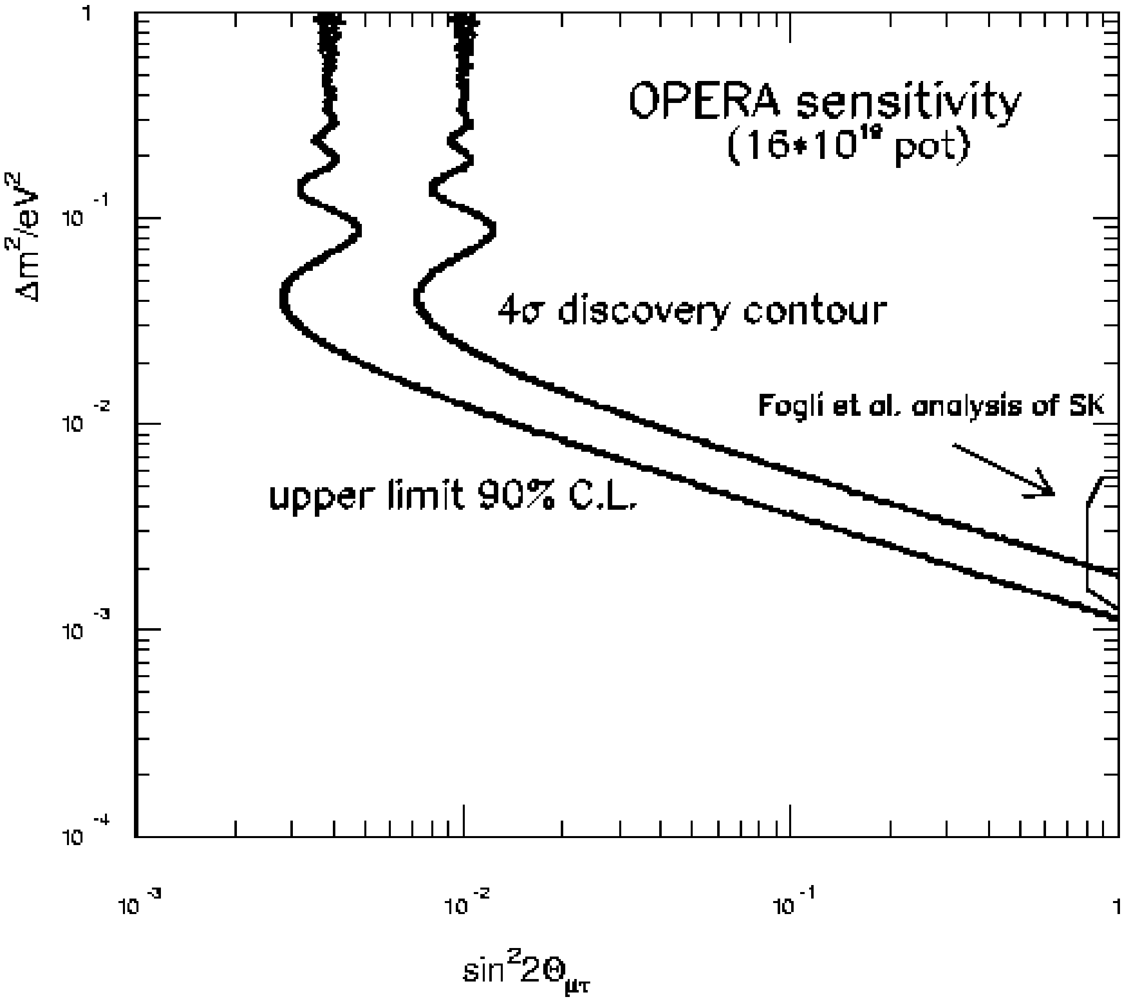
If oscillation occurs @ :

Δm^2 = 2.5 x 10^{-3} eV^2	**~ 10 detected τ events**
Δm^2 = 3.5 x 10^{-3} eV^2	**~ 20 " "**
Δm^2 = 8 x 10^{-3} eV^2	**~ 90 " "**

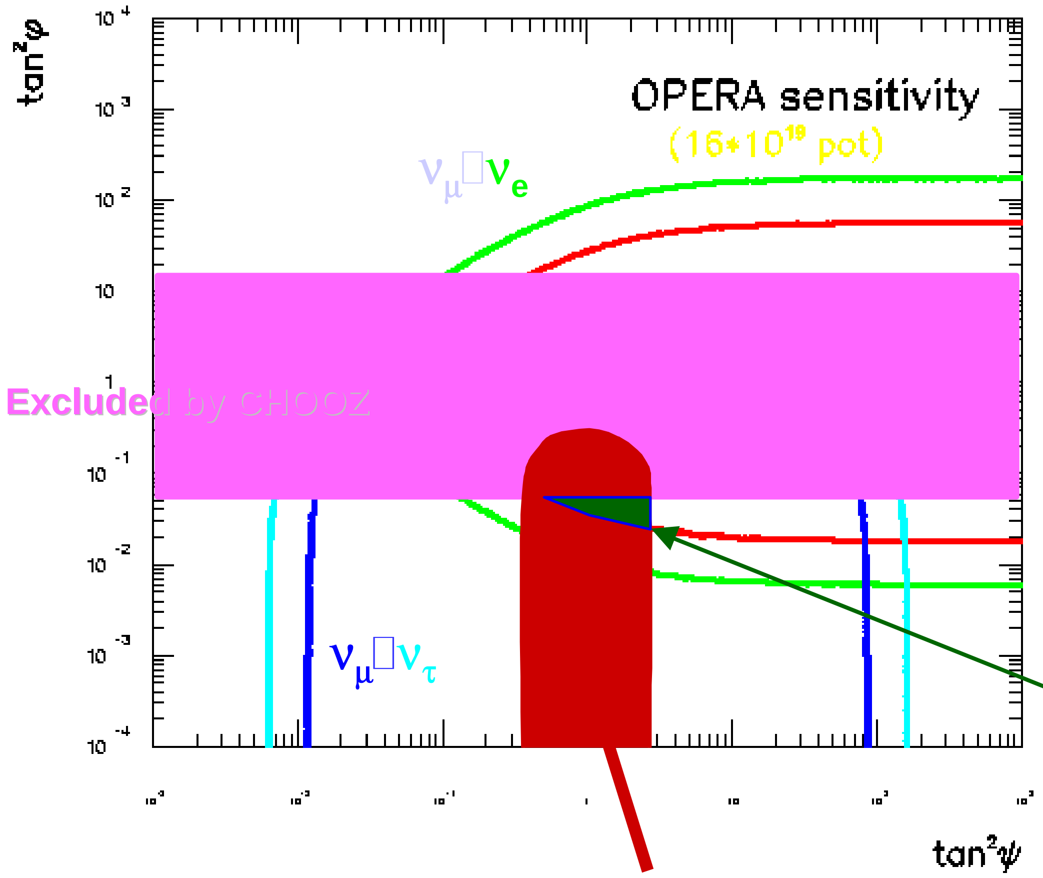
4 σ discovery potential: **1.8 x 10^{-3} eV^2 (full mixing)**

(5 detected events)

Sensitivity and discovery potential



Three flavour analysis

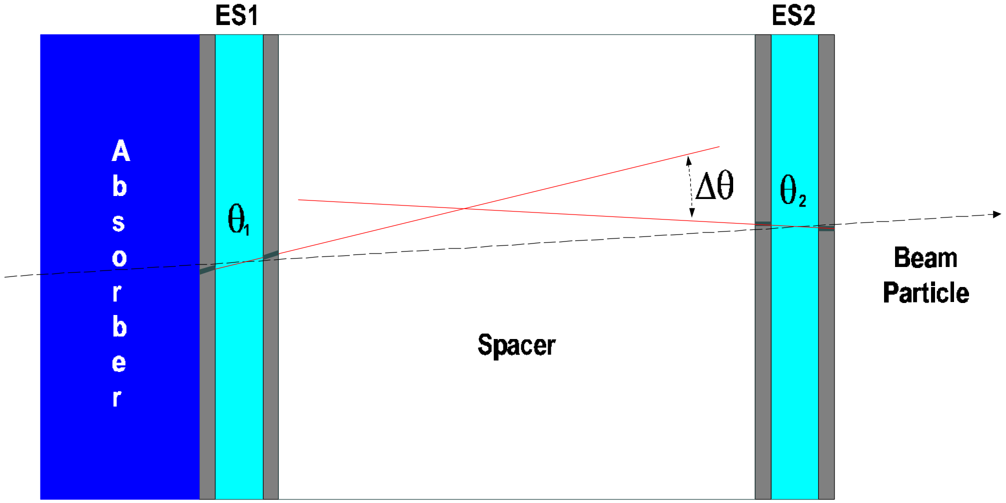


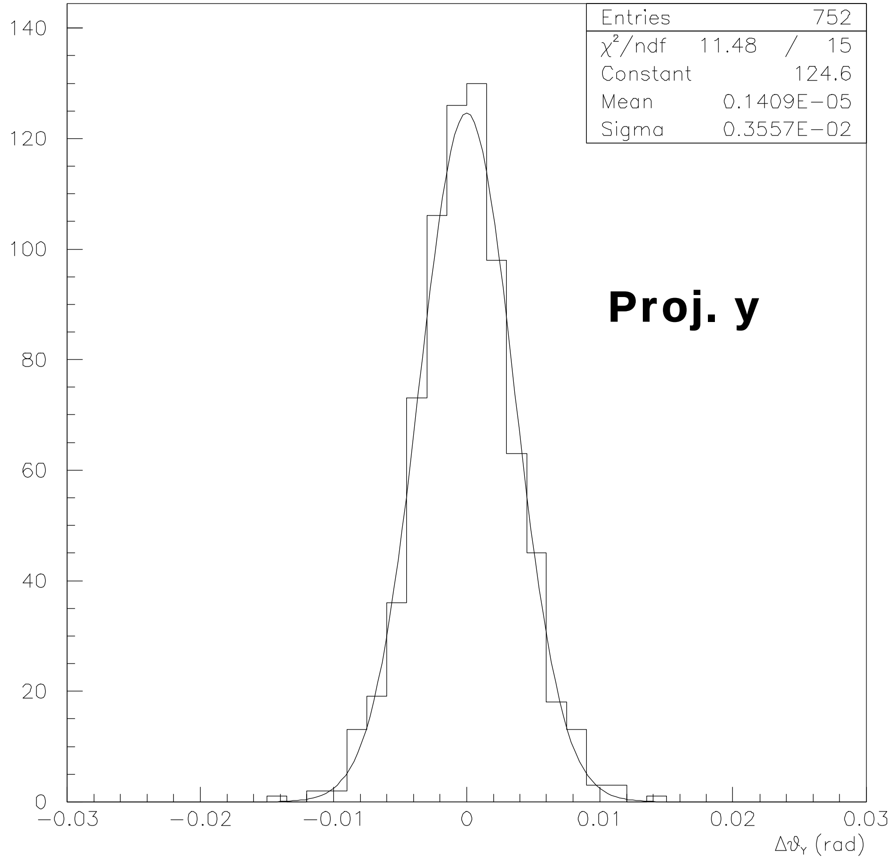
Excluded region (90% C.L.) and discovery potential (4σ) assuming: $\Delta m^2 = 8 \times 10^{-3}$ eV^2

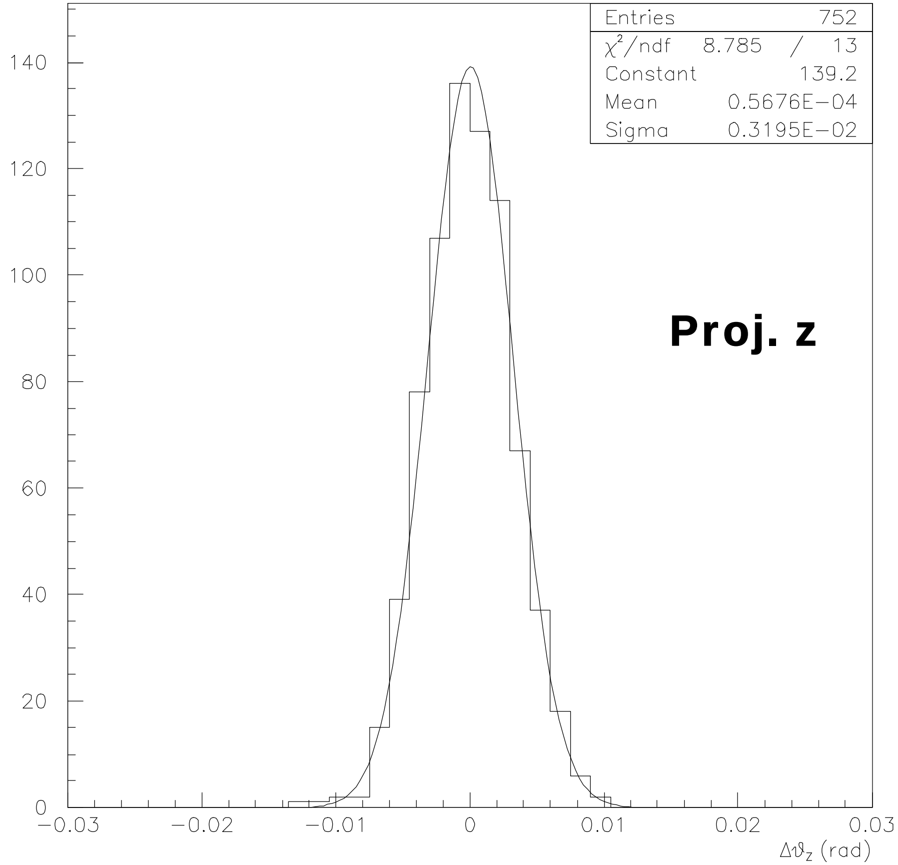
Region constrained by OPERA

Allowed region by the SK combined analysis

OPERA test beam results on the ES angular resolution







OPERA ...at the Gran Sasso

- Present design: **~800 ton , 1.6 x 10^{20} pot** (4 years)

  → **~10000** ν_μ CC+NC events

- Discovery potential: small bg, a few events are meaningful:

  @ **Δm^2 = 3.5 x 10^{-3} eV^2** → ~ **20** τ events (~**0.4** b.g.)

- Negative search: **Δm^2 ~ 10^{-3} eV^2 ; $\sin^2 2\theta_{\mu\tau}$ < ~ 4 x 10^{-3}**

  → covers ν_{atm} (Super Kamiokande)

- Modular structure: scalable detector mass

↓

High sensitivity ν_μ-ν_τ search

↓

explore the atmospheric neutrino signal

ν_τ appearance experiments at the Gran Sasso

(expected performance in 4 years running)

Exp/ Δm^2	BG (events)	$2x10^{-3}$	$3.5x10^{-3}$	$5x10^{-3}$	10^{-2}	Δm^2 discovery limit (4 σ)
ICARUS (2.4 kton)	2.5	13	40	85	340	$1.8x10^{-3}$
SUPER ICARUS (30 kton)	3.7	70	200	420	1700	$0.9x10^{-3}$
NOE (8 kton)	3.7	2	7	15	60	$4.7x10^{-3}$
OPERA (0.8 kton)	0.4	6	20	40	150	$1.8x10^{-3}$

Number of BG and detected τ events as a function of Δm^2
The 4-sigma discovery limit is also shown.

Tr. KHL

Scientific Policy Committee of CERN 6/7 Dec. 1998

Excerpt of Chairman's Summary of Conclusions

Item 7: Report from the Joint SPSC/LNGSC Meeting
(K. Königsman - Oral)

At its September meeting, the SPC heard first presentations and had first discussions on the possible CERN contribution to a broad international ν programme which had been stimulated by the recent evidence of atmospheric ν oscillation presented by the SuperKamiokande experiment.

The SPC heard, at this present meeting, a further report on the proposed programme, as discussed at the SPSC-LNGS Committee meeting, and at the CERN Research Board.

The SPC wished to stress the importance of the programme of ν oscillation, which had an impact on two of the most important questions in our field: the existence and origin of neutrino masses and the relations between lepton families.

The SPC recognized the important contribution that a CERN-Gran Sasso ντ appearance experiment could make. Such an experiment could explore, in a large fraction of the Δm^2 region indicated by the SuperKamiokande experiment, the most favored explanation for the observed √μ disappearance (i.e. a νμ–ντ oscillation)

The SPC therefore urged CERN to proceed in the coming year to all necessary studies and work preparation on the ν beam so as to be able to start its construction as soon as possible when a decision can be taken.

The SPC supports the Management in its request for pledges of special financial contributions, from Member and non-Member States, which are necessary to make such a programme possible.

The SPC wished to be informed throughout the coming year on progress on the first two above points, and on further clarification of the capabilities of a proposed detector. The existing expressions of interest on the construction of such a detector, had to be transformed through the year in a proposal for a √τ appearance apparatus with a precise assessment of its level of background and Δm^2 reach.

The SPC also wished to be informed during the year on the development of strategy of the CERN Management on how to reach a final decision at the earliest possible date, hopefully before the end of 1999.

Concluding remarks

long baseline beams

⬇

- Identify the source of the atmospheric neutrino deficit
- Strong interest of the international community
- **K2K**, **NuMI** and **NGS** beams: complete programme, complementary explorations
- τ appearance: **NGS** is an excellent tool
- Detectors: several approaches exist. Aim at high sensitivity, low background: discovery potential
- Important results expected: very exciting time!