NUMI MINOS

Long Baseline Accelerator Experiments in US and Europe

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Outline

- Overall Picture
  - What we have learned
  - What we want to know
- The US Program – NuMI/MINOS
  - Description and Current Status
  - Physics Goals and Sensitivity
- The European Program – CNGS
  - The OPERA Program
  - Other Possibilities

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Historical Perspective on the $\Delta m^2 \sim 10^{-2} - 10^{-3}\ eV^2$ region

- The Initial Non-Accelerator Experiments
  - Atmospheric ν interactions: IMB, Kamiokande, Soudan2
  - Upward going μ's: MACRO + others
  - Reactor Experiments: CHOOZ, Palo Verde
- Second Generation Non-Accelerator Expts
  - SuperKamiokande
  - Krasnoyarsk (?)
- Accelerator Long Baseline Experiments
  - K2K Experiment
  - US and European Programs
- The Future: SuperHot Beams and ν Factories

Summary of Experiments

Assuming pure $\nu_\mu \rightarrow \nu_\tau$
Super-K measures:

$0.0015 < \Delta m^2 < 0.005$ eV^2

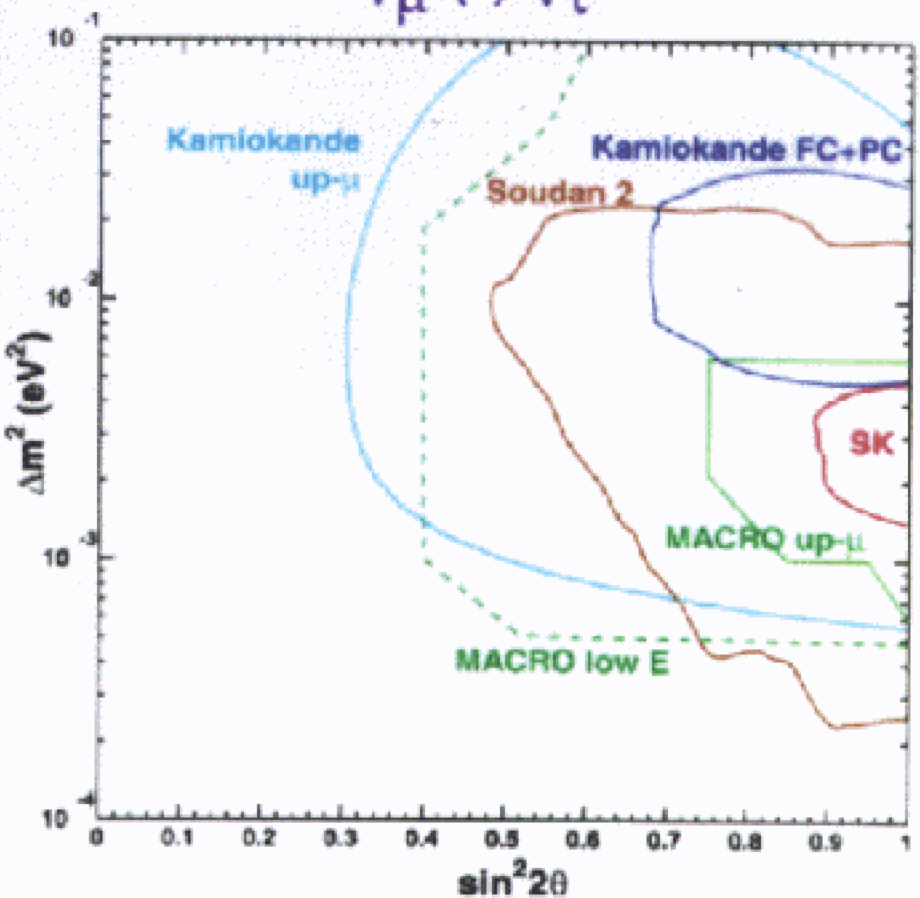
$0.88 < \sin^2 2\theta$

at 90% confidence limit

Other experiments are consistent with Super-K: Soudan 2 and MACRO see similar effects but with much less statistical precision.

90% C.L. Contours

$\nu_\mu \leftrightarrow \nu_\tau$



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Likely Situation in 2003/4

- Neutrino Anomaly well established
- Oscillations Hypothesis consistent with data
- Oscillations parameters well constrained:
  - Dominant mode is $\nu_\mu \rightarrow \nu_\tau$
  - Mode $\nu_\mu \rightarrow \nu_e$ is small (CHOOZ limit)
  - $1.5 < \Delta m^2 < 5$ eV^2 or better
  - Dominant mode consistent with maximum mixing
- Alternative (to oscillation) hypotheses unlikely but possible

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What will we want to know

- What is precise value of Δm^2
- What is the sign of Δm^2
- What is the magnitude of $\nu_\mu \rightarrow \nu_e$ mode
- What is the maximum possible contribution of $\nu_\mu \rightarrow \nu_{sterile}$ mode
- How well can contributions from non-oscillation mechanisms be excluded
- Are matter effects as expected
- Is there CP violation in lepton sector

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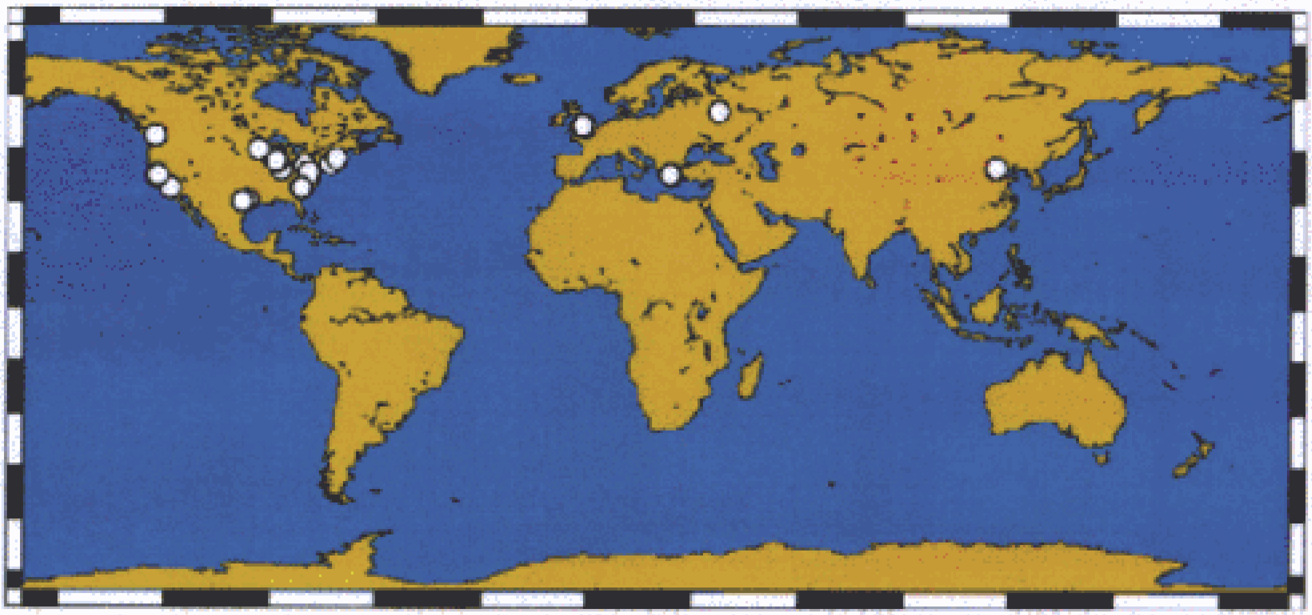
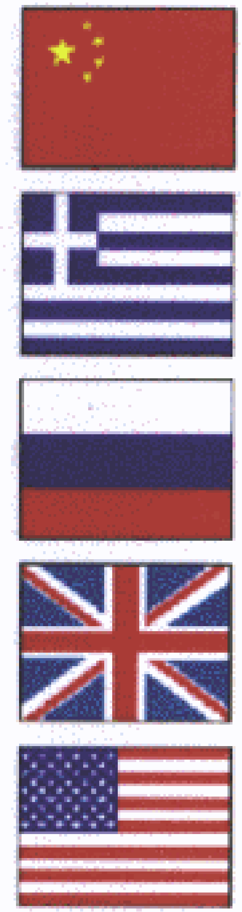
The MINOS Collaboration





About 200 Physicists and Engineers

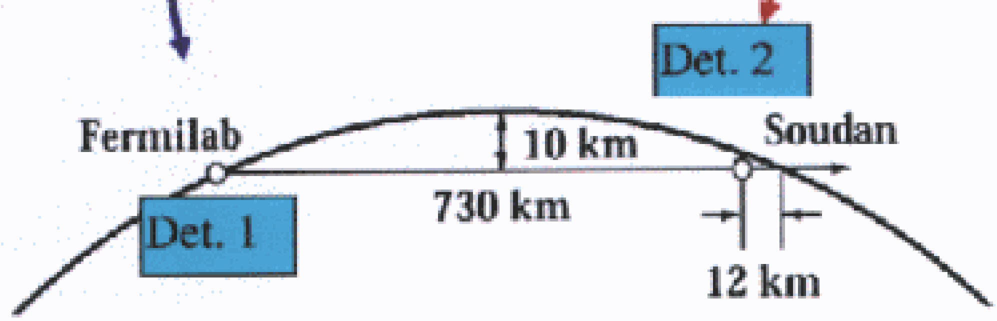
Athens • IHEP-Beijing • Cambridge • Dubna • ITEP-Moscow • Lebedev • Protvino • Oxford • Rutherford • Sussex • University College London • Argonne • Brookhaven • Caltech • Chicago • Elmhurst • Fermilab • James Madison • Harvard • Indiana • Livermore • Minnesota • Minnesota/Duluth • Northwestern • Pittsburgh • South Carolina • Stanford • Texas-Austin • Texas A&M • Tufts • Western Washington • Wisconsin

MINOS Experiment

Two Detector Neutrino
Oscillation Experiment
(Start 2003)

Near Detector: 980 tons

Far Detector: 5400 tons



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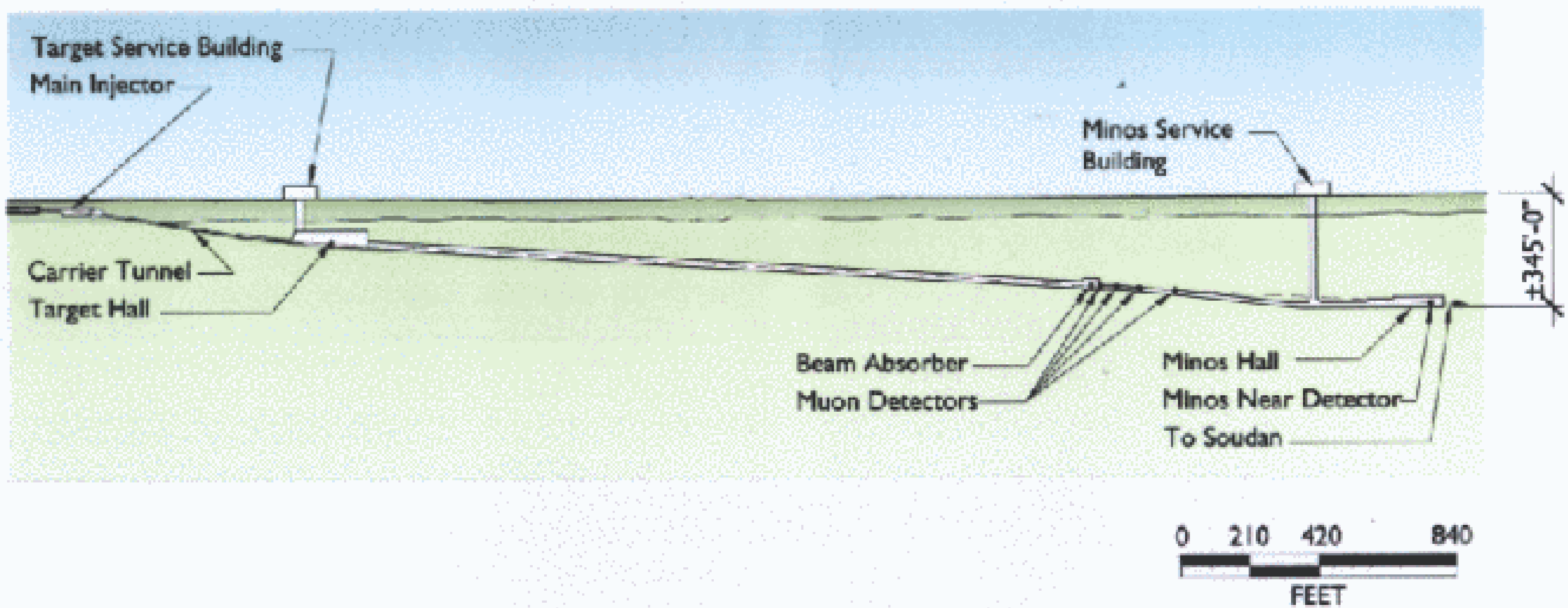
Overview of NuMI Beamline at Fermilab



NuMI - LONGITUDINAL SECTION

NuMI

FERMILAB NATIONAL ACCELERATOR LABORATORY

200

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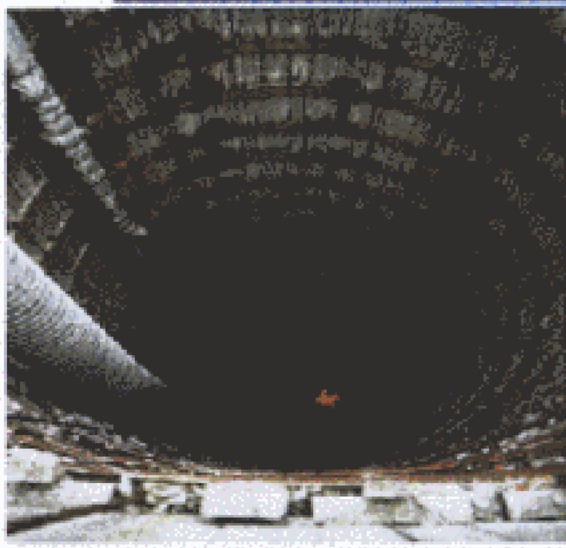
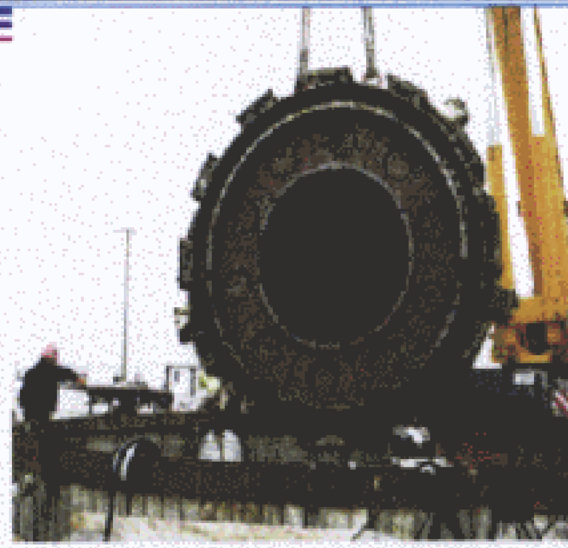
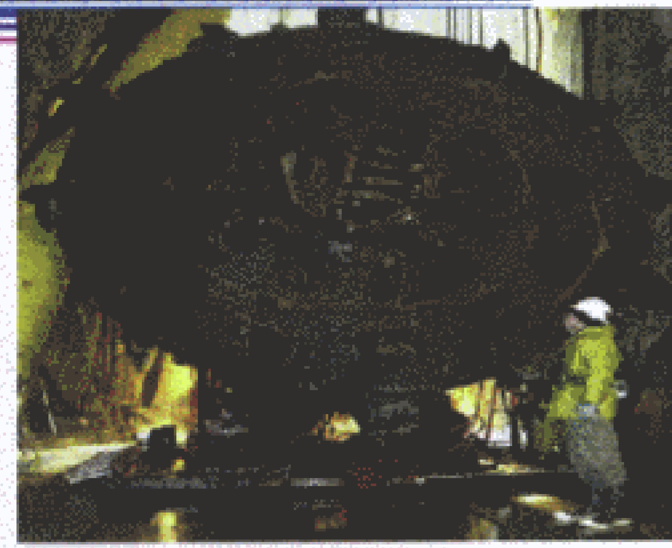
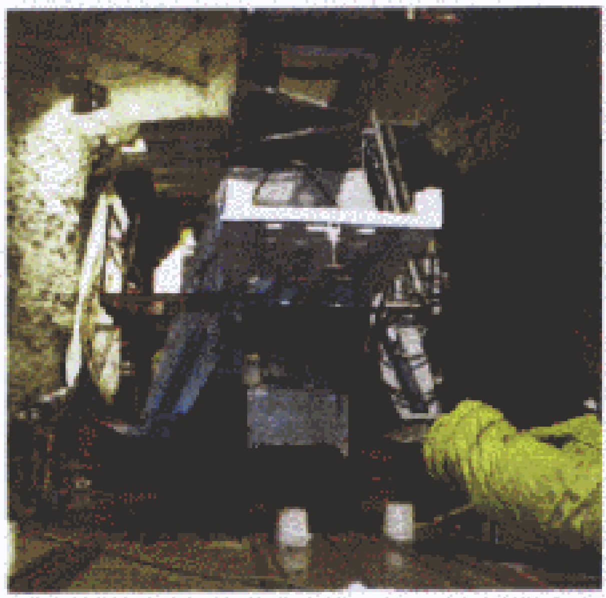
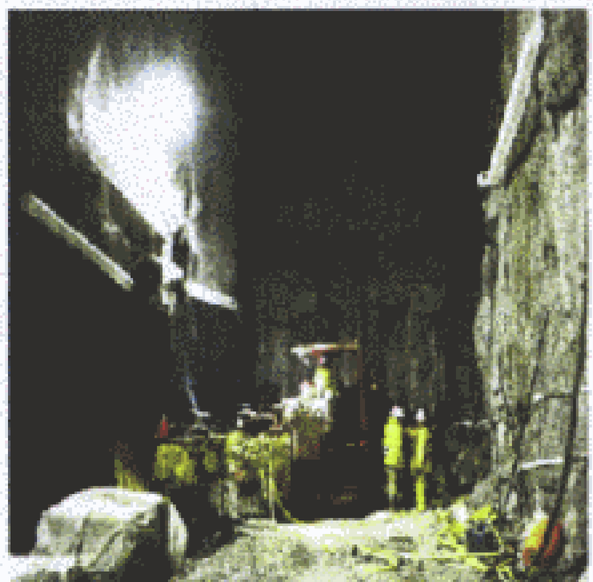
Excavation at Fermilab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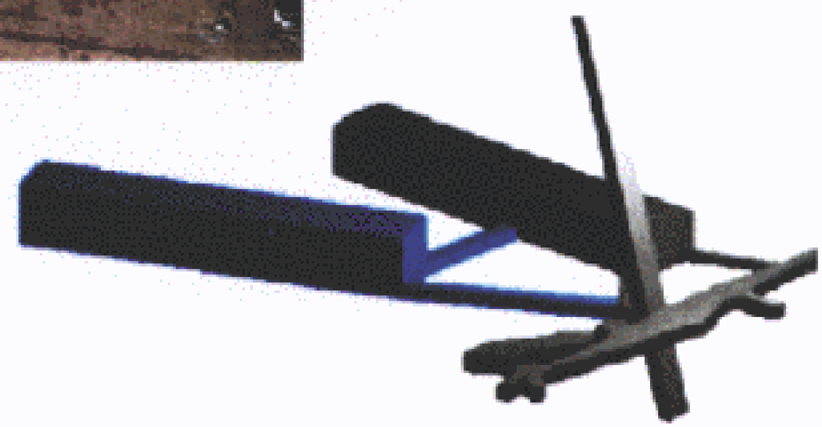
Soudan Underground Laboratory

The Soudan shaft limits objects to a maximum size of 1m by 2m by 9m



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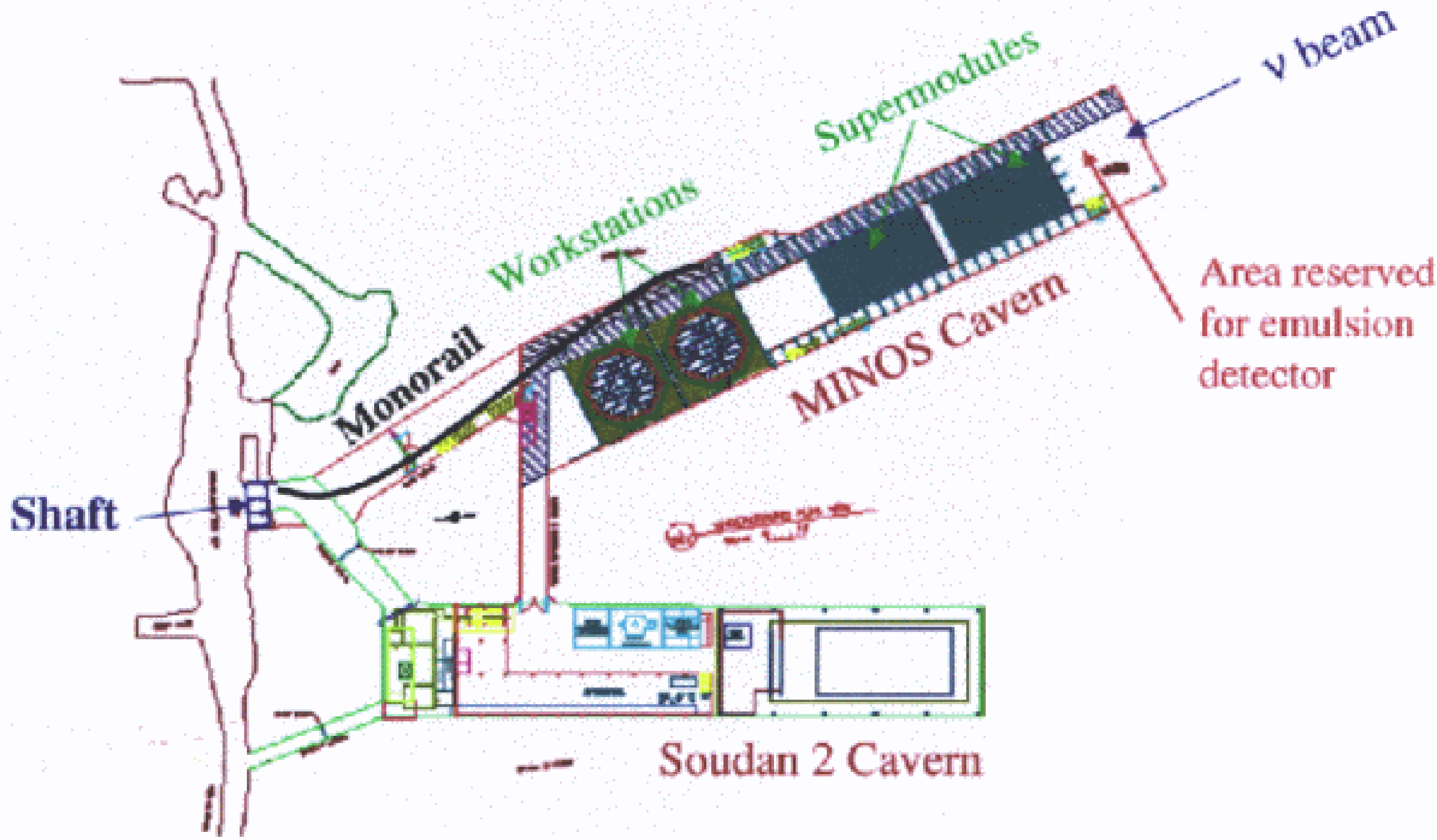
Far Detector Cavern Layout



Construction at Soudan

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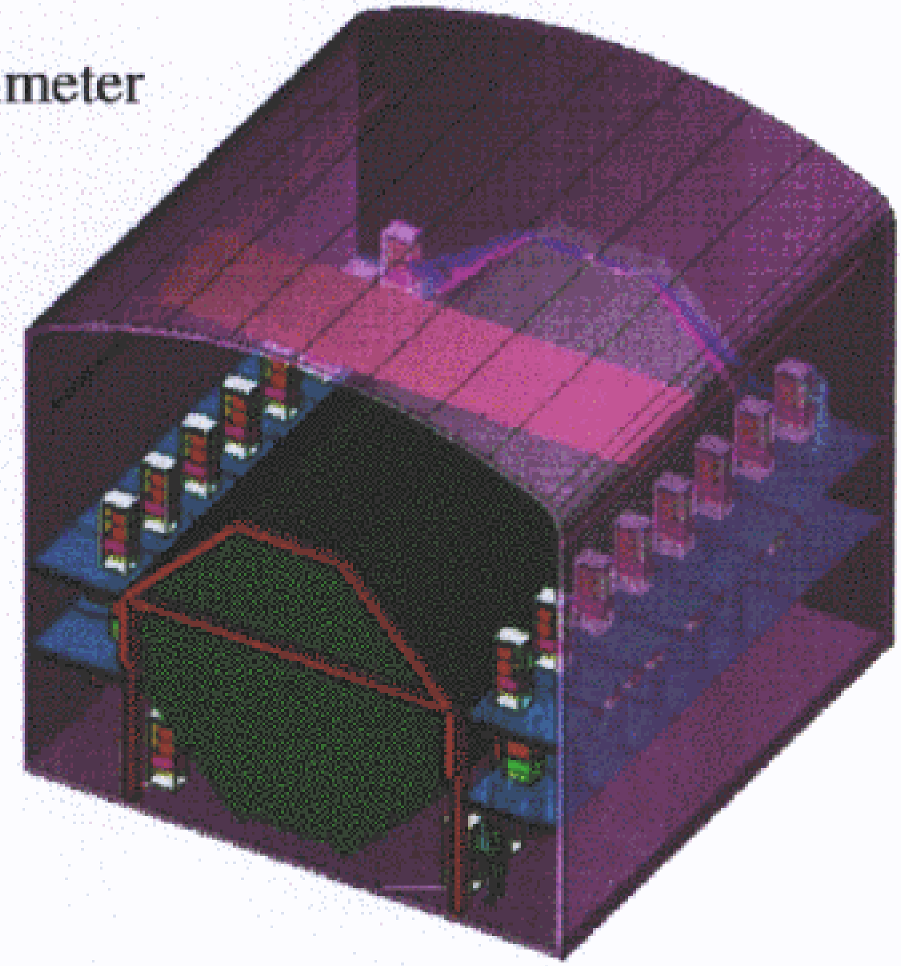
MINOS Far Detector

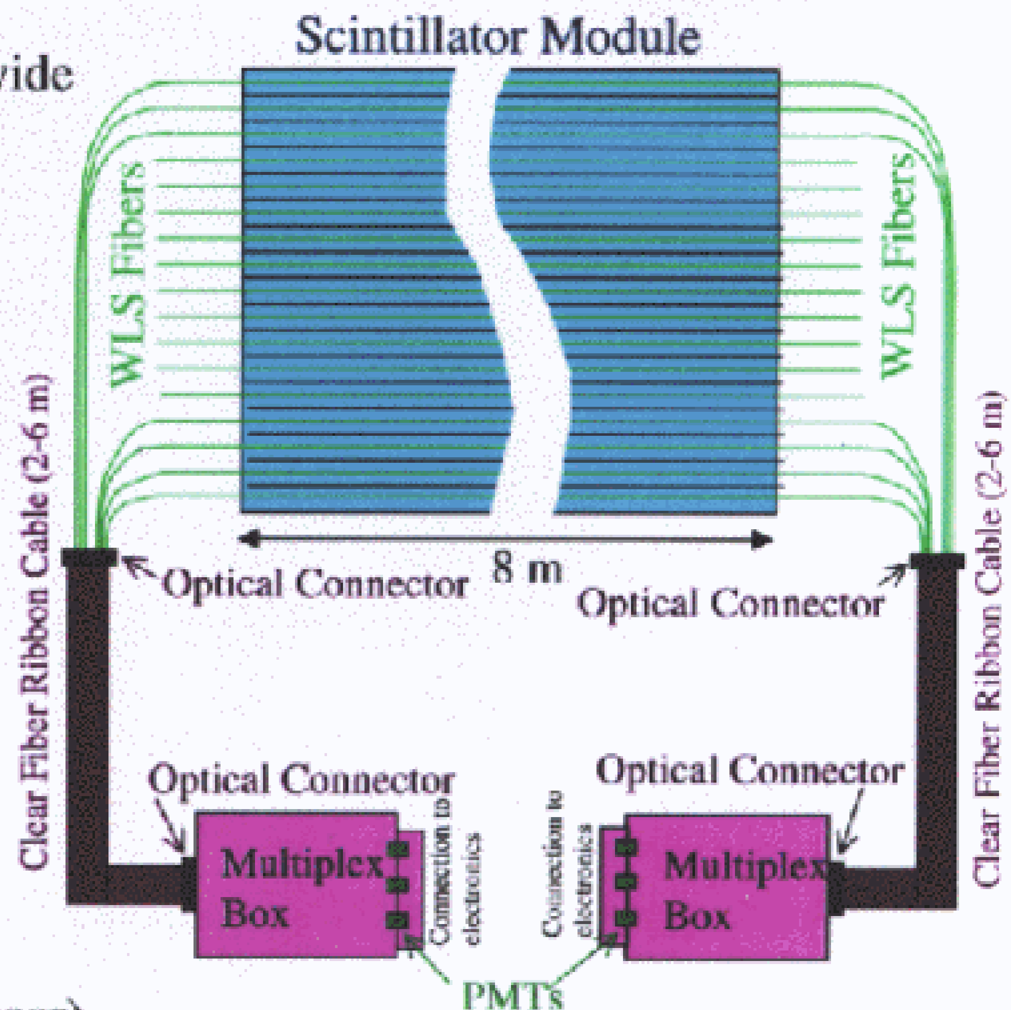
- 8m Octagonal Tracking Calorimeter
- 486 layers of 2.54cm Fe
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readout
- 25,800 m^2 active detector planes
- Magnet coil provides $\langle B \rangle \approx 1.3T$
- 5.4kt total mass



Half of the MINOS Far Detector

Schematic View of the MINOS Scintillator System

- Extruded scintillator, 4.1 cm wide
- Two-ended WLS fiber readout.
- Strips assembled into 20 or 28-wide modules.
- WLS fibers routed to optical connectors.
- Light routed from modules to PMTs via clear fibers.
- 8 Fibers/PMT pixel in far detector. (Fibers separated by ~1m in a single plane.)
- 1 Fiber/PMT pixel in near detector (avoids overlaps).
- Multi-pixel PMTs
  Hamamatsu M16 (far), M64 (near)

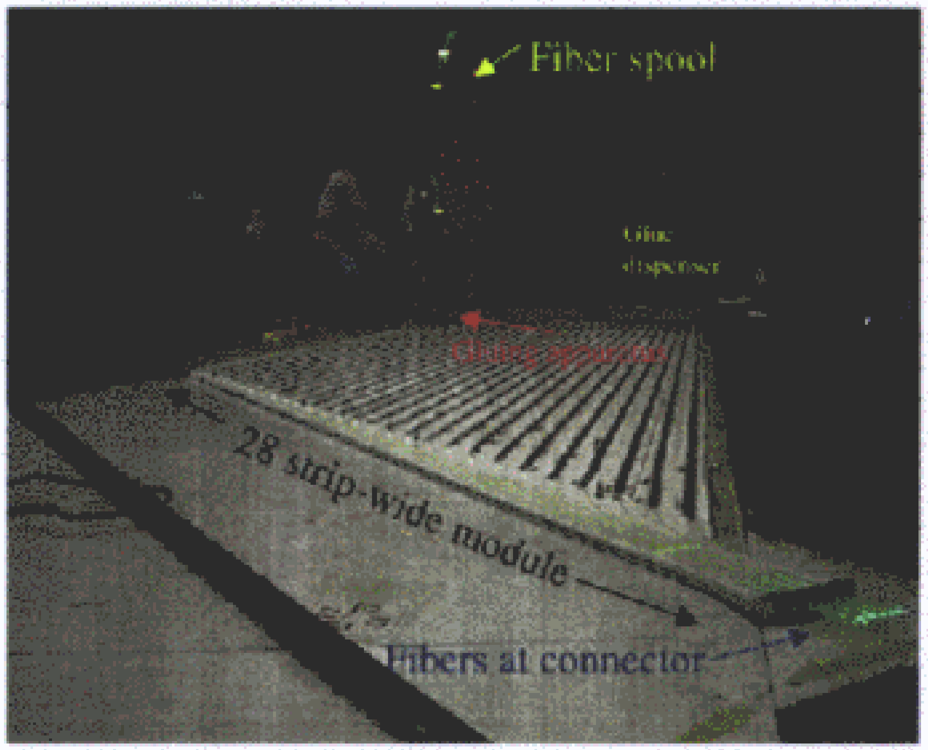


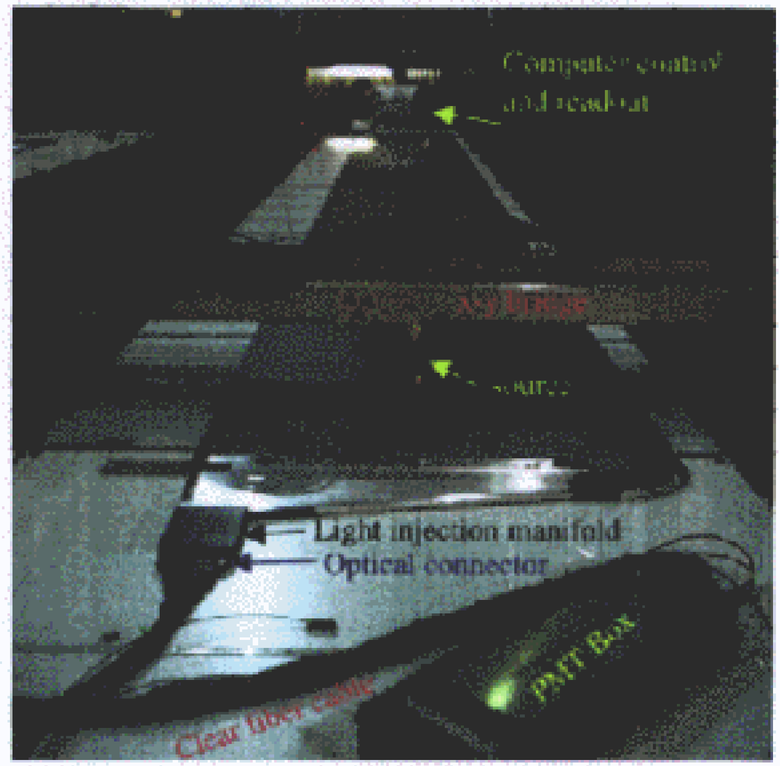
Objects not to scale

Automated Production Equipment at CalTech Factory

Automatic Fiber Gluing Machine: Lays down bead of glue, unrolls fiber from spool, pushes fiber into glue in groove and covers the groove with a reflector.

Automated Module Mapper with 28 strip-wide module (8m x 1.2 m). Uses computer driven x-y scanning table with ^{137}Cs source.





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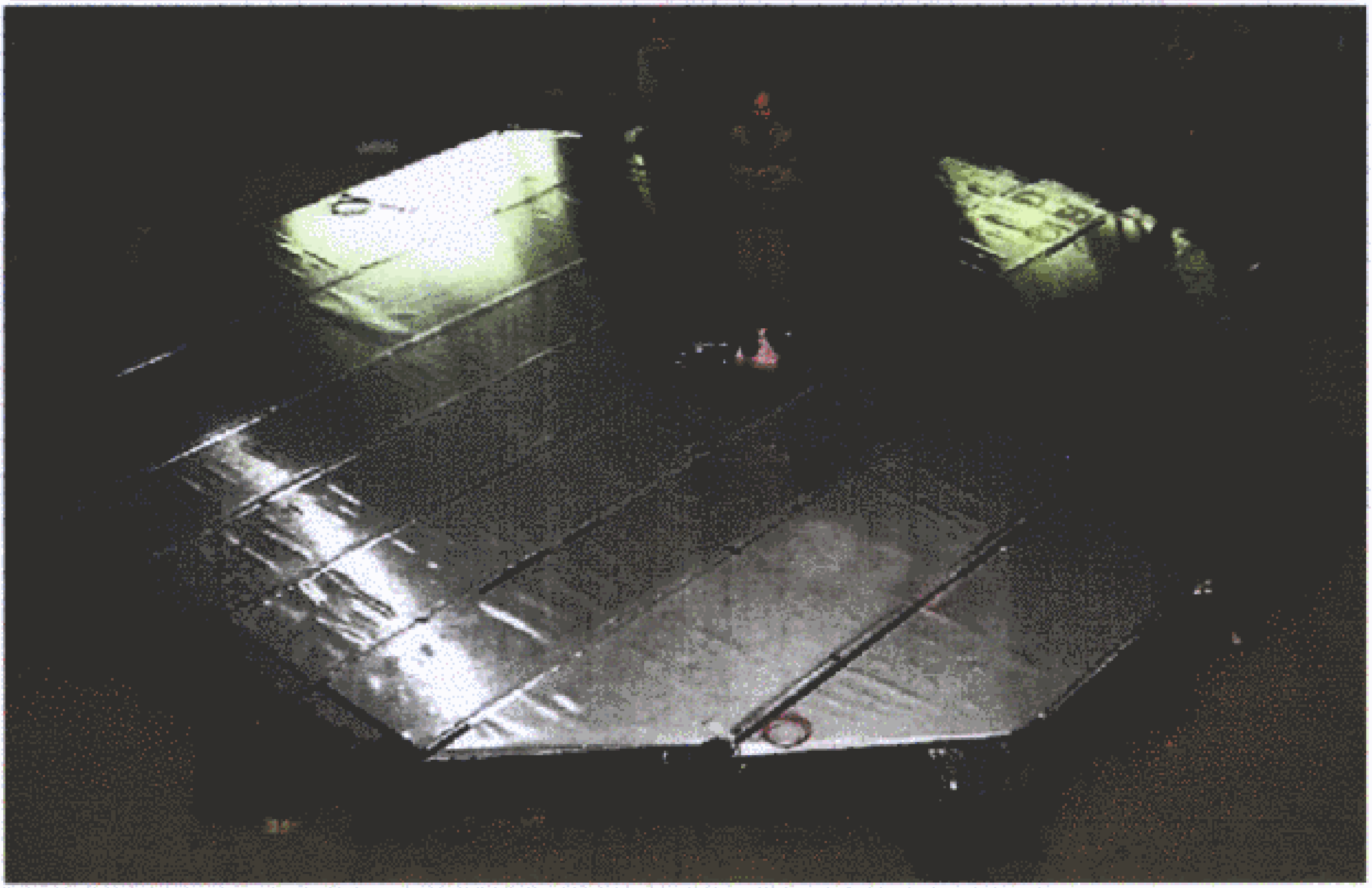
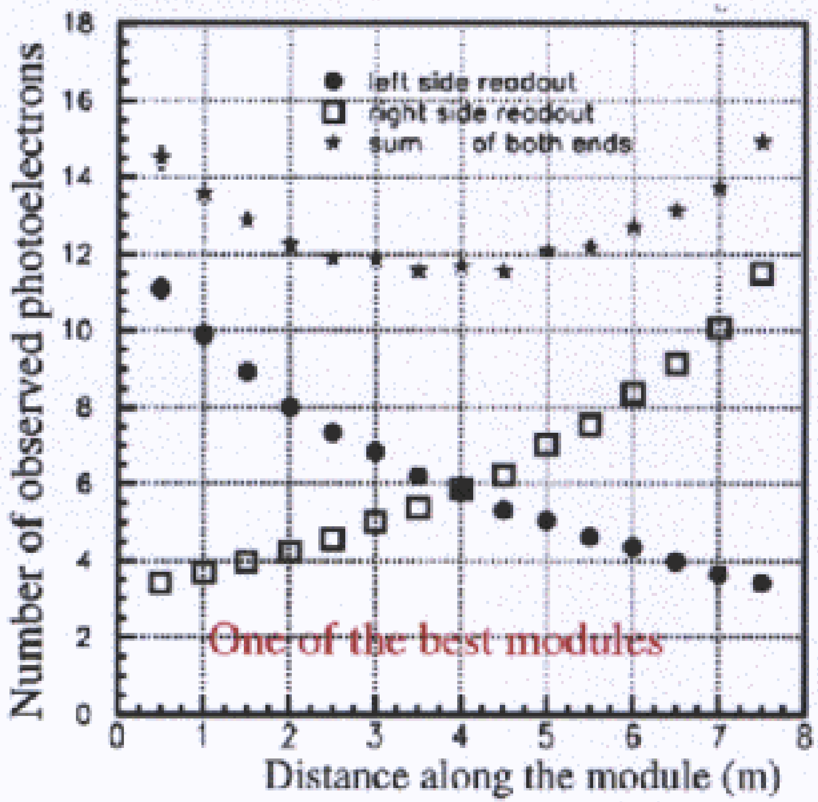
Assembled Scintillator Plane



Light Output Measurements



Light output vs position of cosmic ray muons passing nearly perpendicularly through a scintillator module averaged over all strips within a module. The light output is measured using the full MINOS readout apparatus (connectors, clear fibers, PMTs…). The light read from each end of a module is shown along with the sum of light from each end.

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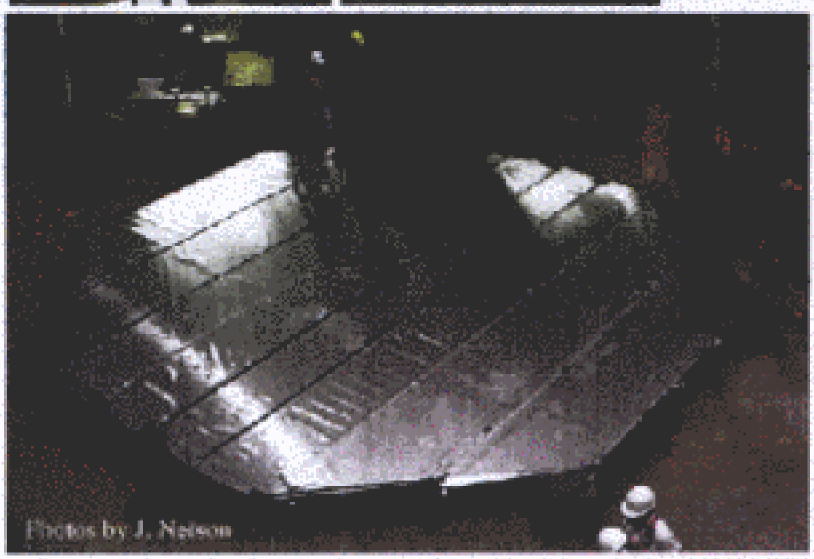
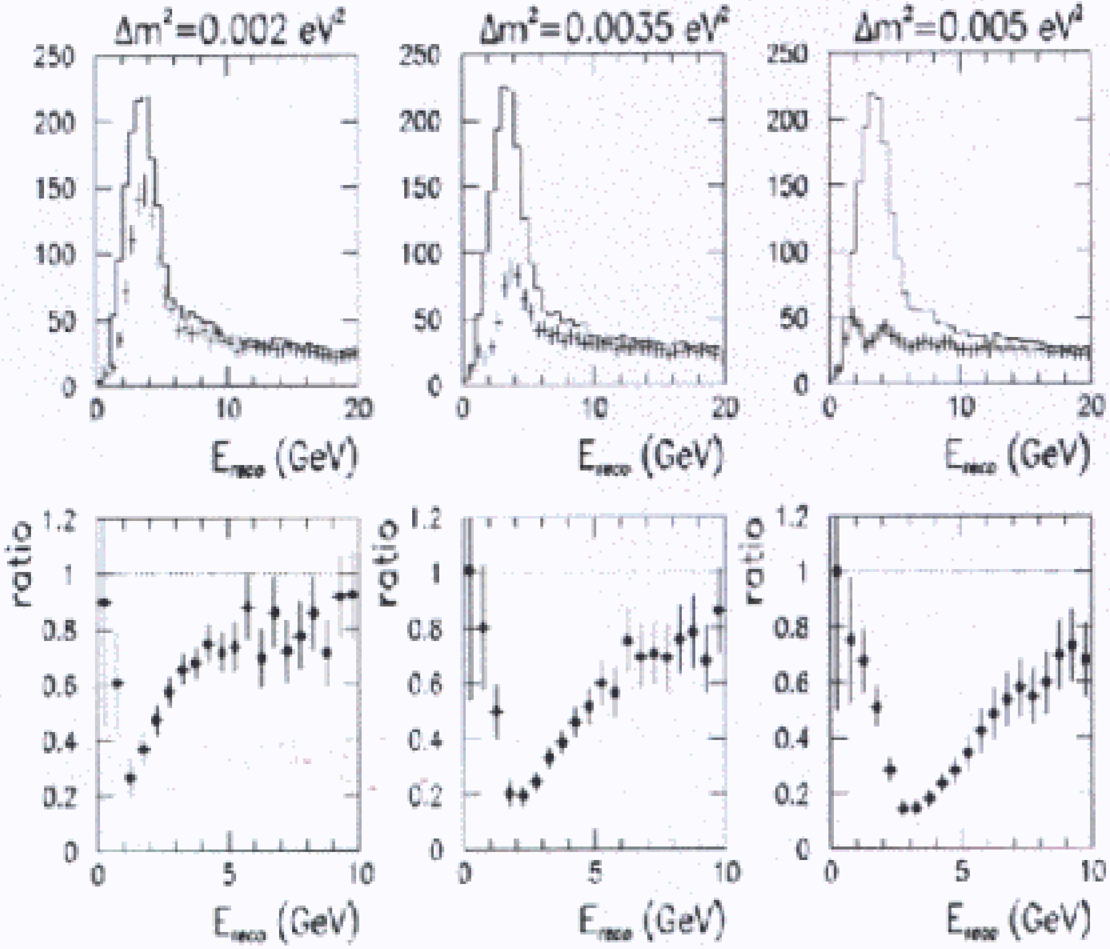
4 Plane Prototype

Built Summer of 1999 at Fermilab



MINOS Energy Spectra

CC energy distributions – Ph2le, 10 kt.yr., $\sin^2(2\vartheta)=0.9$



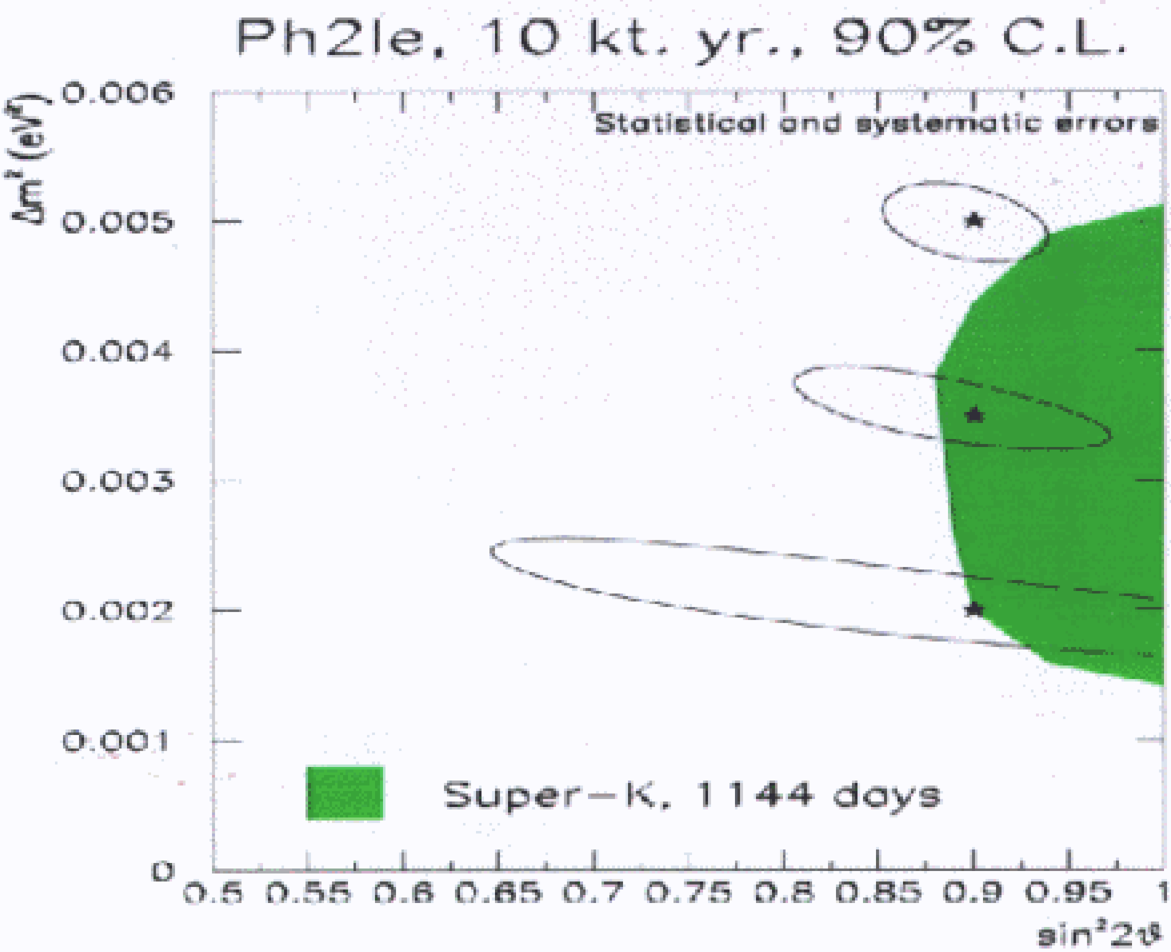
10 kt-yr Exposure

Solid lines - energy spectrum without oscillations

Points with error bars - spectrum in presence of oscillations

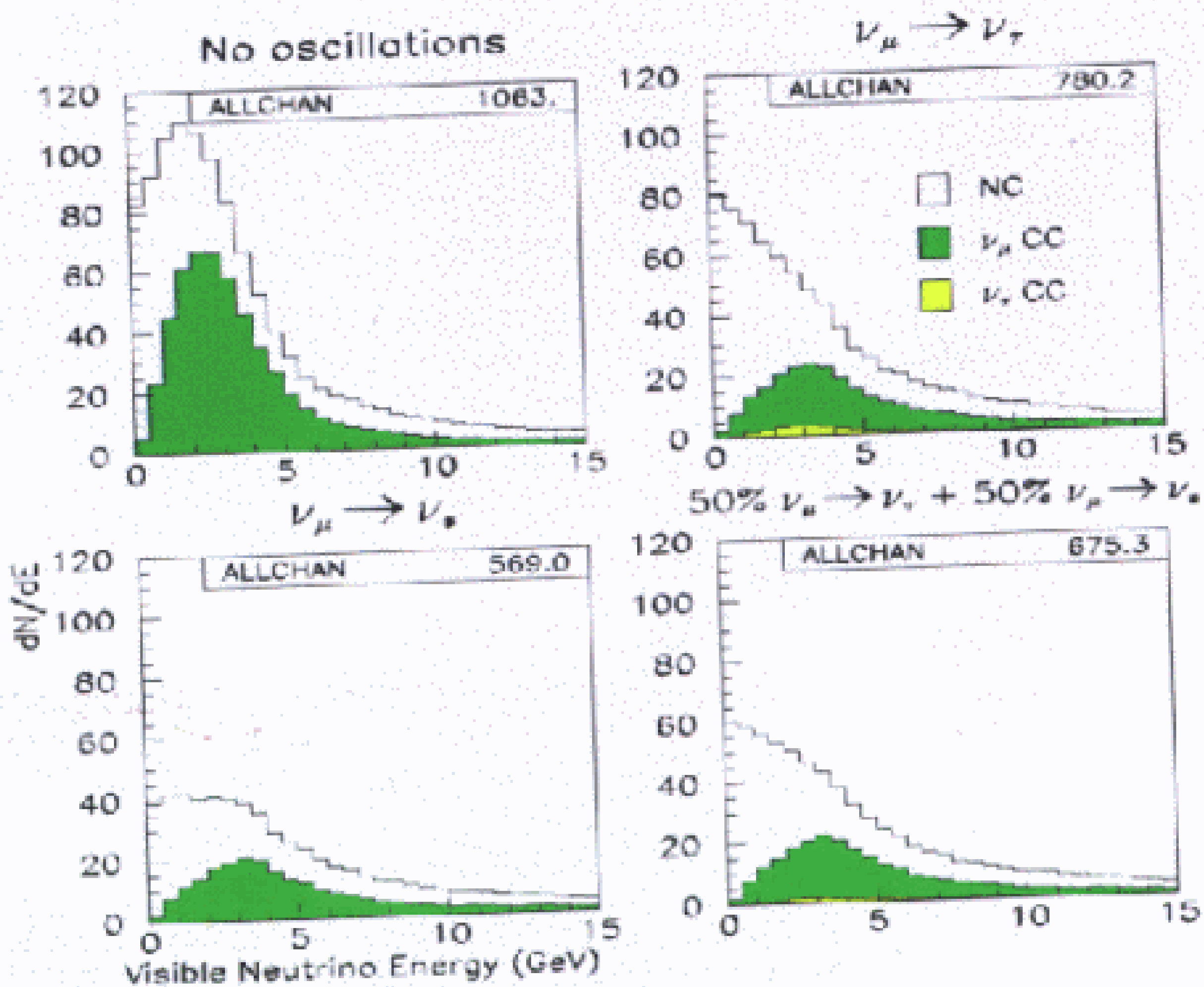
Lower plots – ratio of oscillation spectrum to no-oscillation spectrum

MINOS Sensitivity from CC



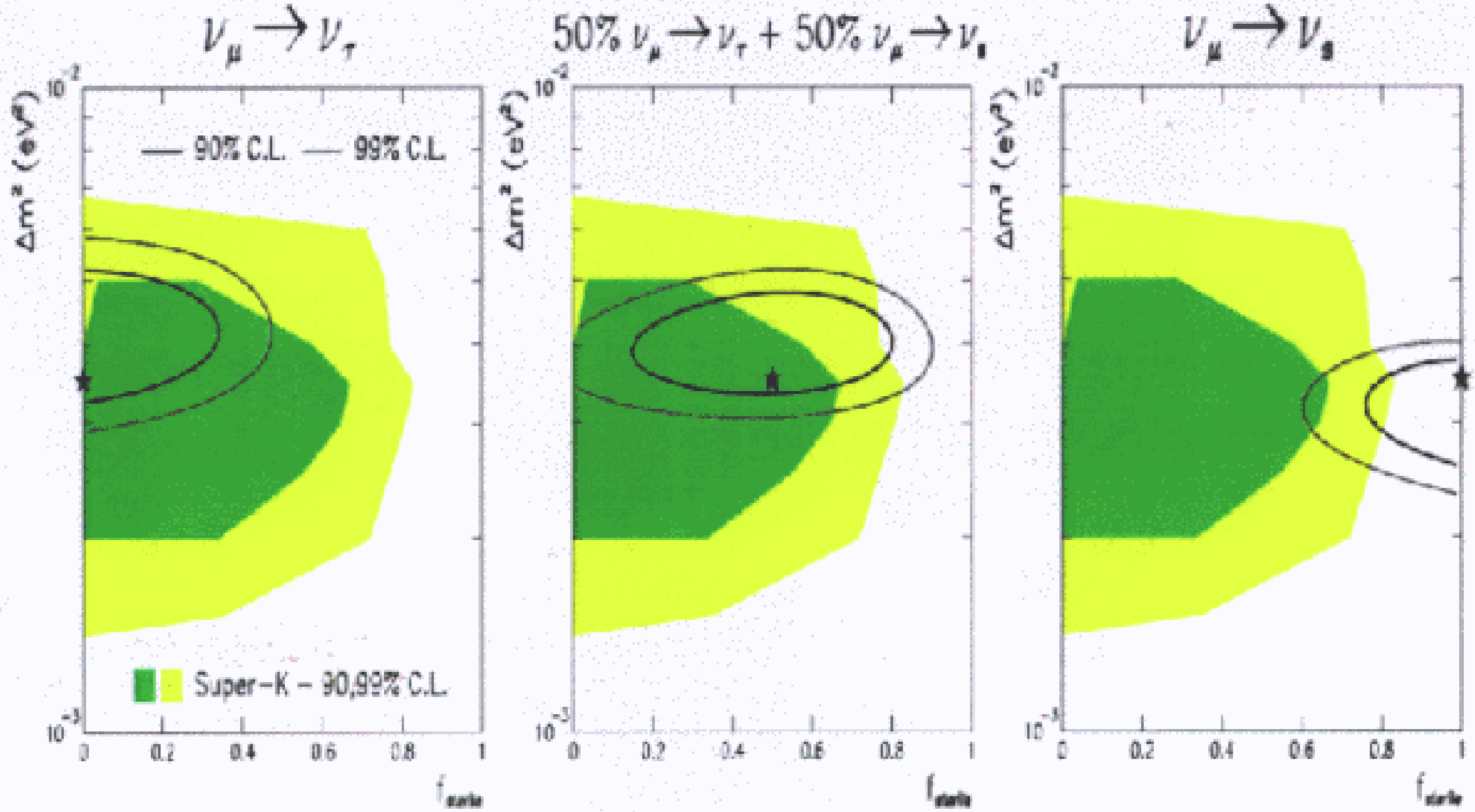
NC Energy Spectra

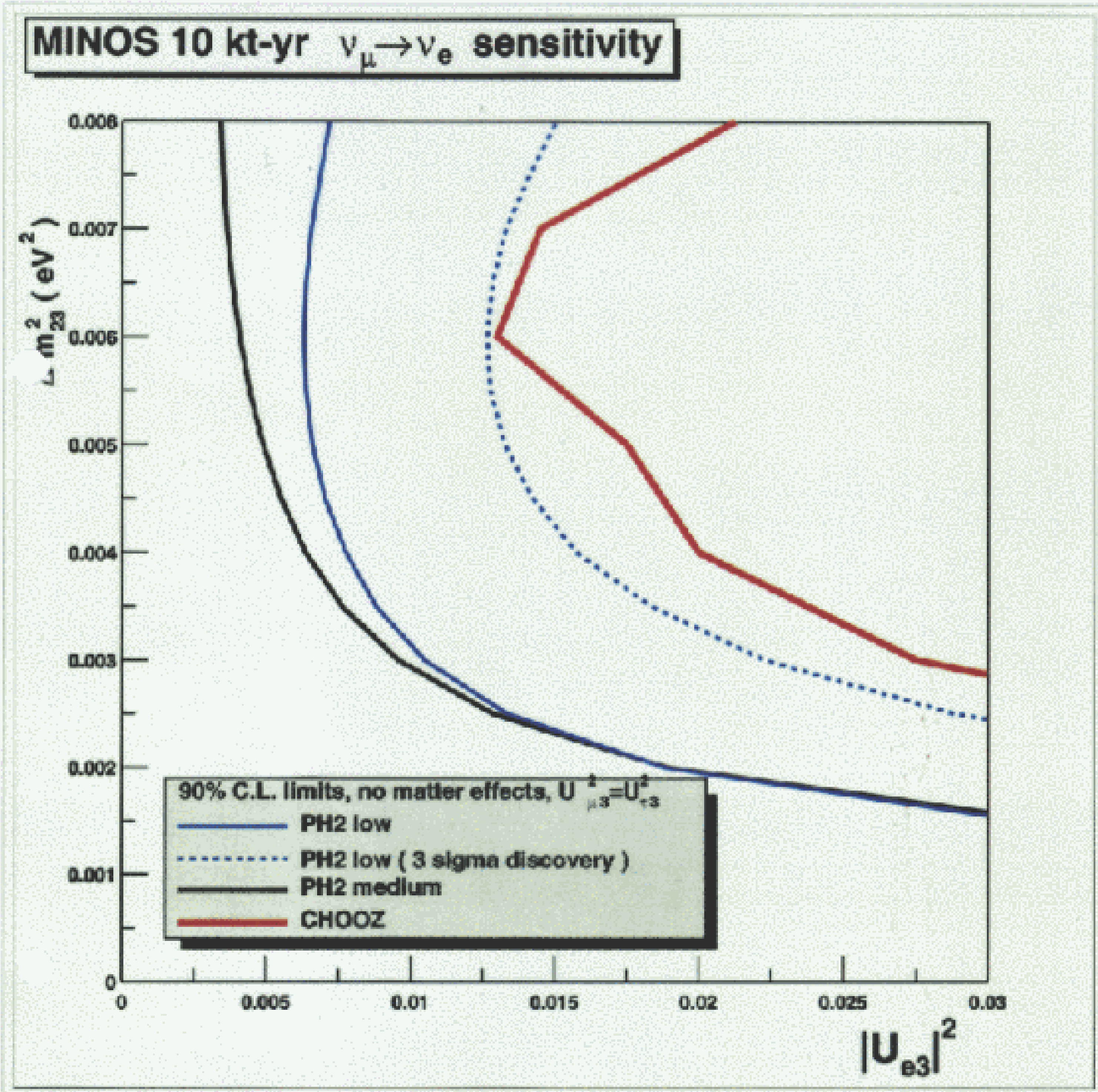
NC energy distributions, Ph2le, $\Delta m^2=0.0035\ eV^2$



$\nu_{sterile}$ Sensitivity

Ph2le, 10 kt. yr., $\Delta m^2 = 0.0035\ eV^2$



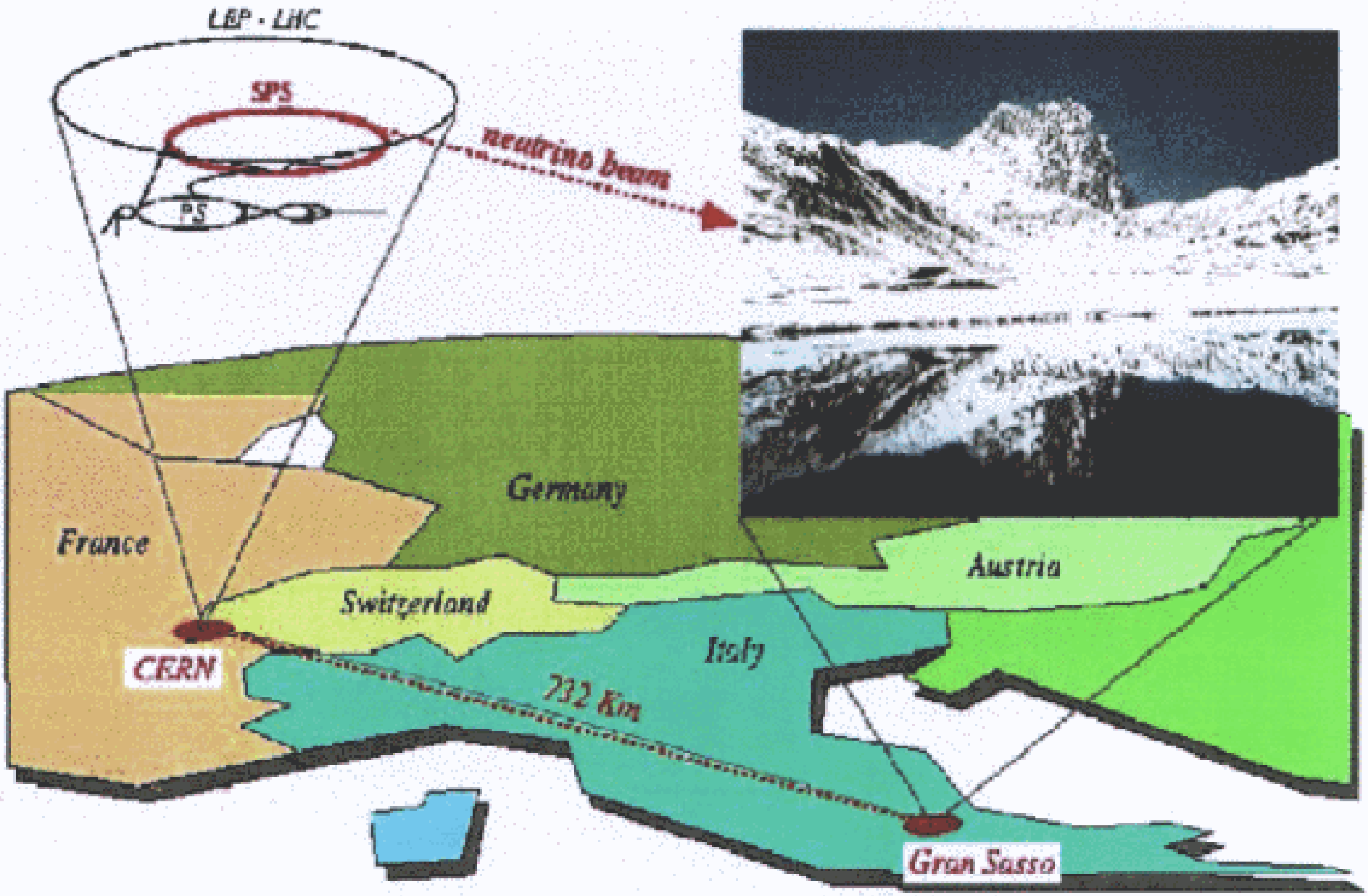


MINOS 10 kt-yr $\nu_\mu \rightarrow \nu_e$ sensitivity
Δm^2_{23} (eV^2)
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0.005
0.01
0.015
0.02
0.025
0.03
$|U_{e3}|^2$
90% C.L. limits, no matter effects, $U^2_{\mu 3}=U^2_{\tau 3}$
PH2 low
PH2 low (3 sigma discovery)
PH2 medium
CHOOZ

Schedule (assuming full funding in 2002 and 2003)

- October, 2000 – Start of Scintillator Module Production
- December, 2000 – Soudan Cavern Excavation Complete
- August, 2001 - Start of Far Detector Installation
- September, 2002 – Completion of 1st MINOS SuperModule
- October, 2002 –Start of Installation of Beam Components and Near Detector
- June, 2003 – Start of System Commissioning
- August, 2003 – Completion of Detector Installation
- April, 2004 – Start of Physics Data Taking

CERN to Gran Sasso Neutrino Beam



OPERA

An appearance experiment to search for ν_μ -ν_τ oscillations in the CNGS beam

MINOS/OPERA Complementarity

- MINOS studies characteristics of the neutrino beam after it traversed a long distance
  - It requires a Near Detector similar to Far Detector
  - It requires knowledge of the beam at these two locations
  - The beam energy is optimized for maximum disappearance effect
- OPERA searches for ν_τ appearance
  - It tries to have a background free experiment
  - It optimizes the beam energy for a maximum ν_τ signal

OPERA Beam Optimization

- The number of τ's produced and detected is proportional to:
  - Number of neutrinos produced
  - Charged current (CC) ν_τ cross section
  - Tau detection efficiency
  - Oscillation probability
- The optimum energy is a compromise between the first 3 (pushing for higher energy) and the fourth factor

The CNGS beam

Nominal ν beam

ν_μ (m^{-2} / pot)	7.45×10^{-9}
ν_μ CC / pot / kton	5.44×10^{-17}
$\langle E \rangle_\nu$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.85 %
$\bar{\nu}_\mu / \nu_\mu$	2.0 %
ν_τ prompt	negligible

Interactions with 1.8 kton target x 5 years

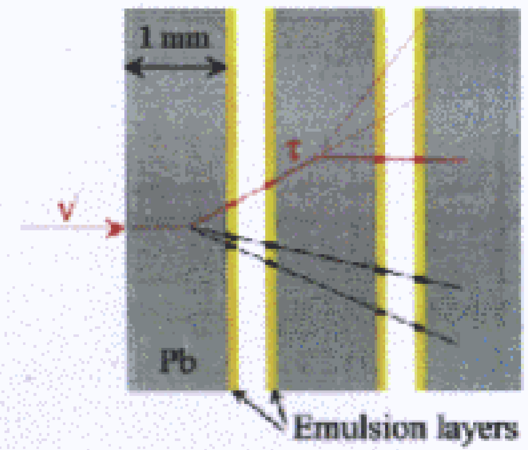
~ 32000 ν NC+CC

~ 240 ν_τ CC

Shared SPS operation
200 days/year
4.5×10^{19} pot / year

for SuperK best fit :
$\sin^2 2\theta = 1$
$\Delta m^2 = 3.2 \times 10^{-3}\ eV^2$

The experimental technique



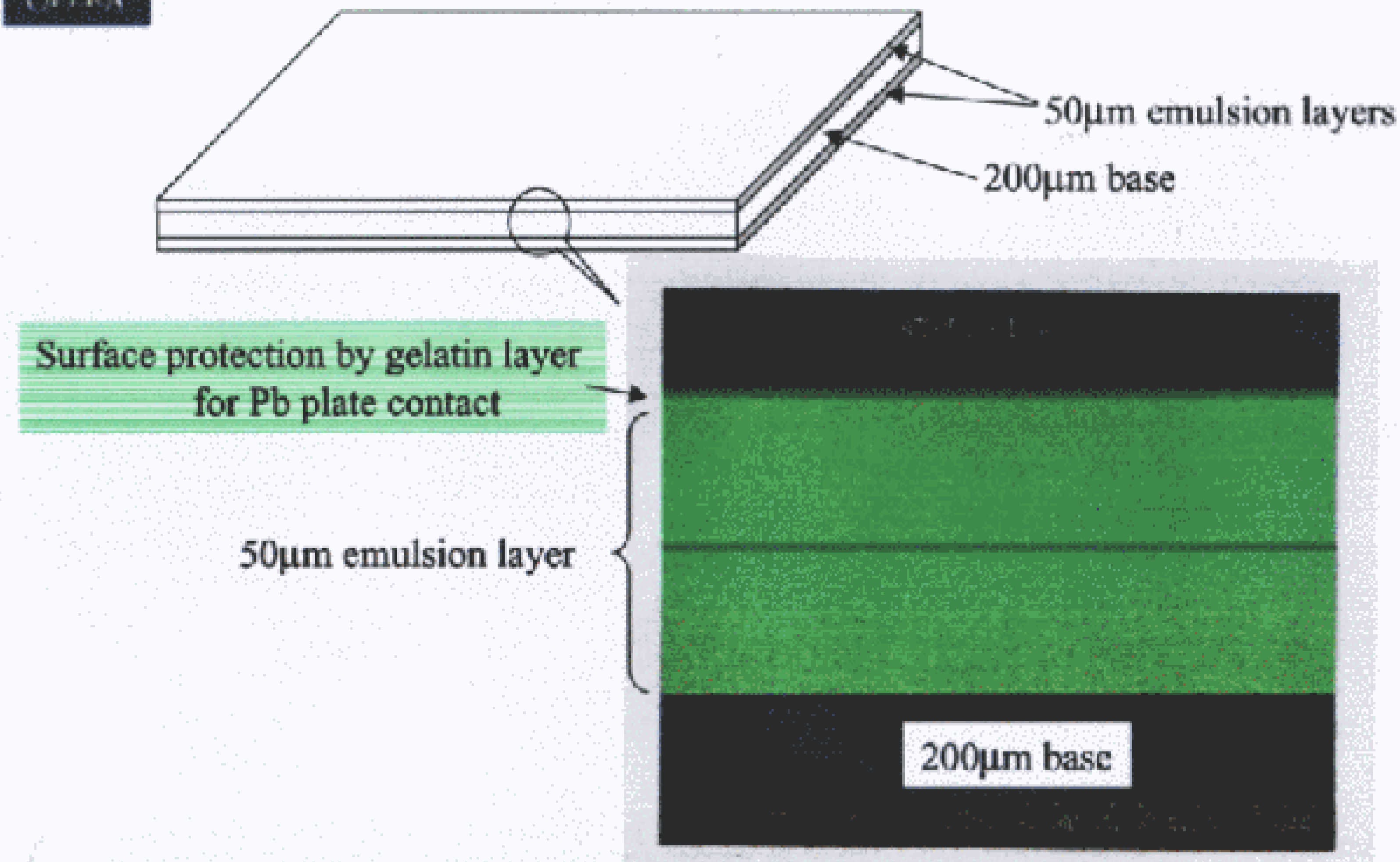
- **Emulsion Cloud Chamber (ECC)**
  - Emulsions for tracking, passive material as target
  - Basic technique works
    - charmed "X-particle" first observed in cosmic rays (1971)
    - DONUT/FNAL beam-dump experiment: ν_τ events observed

- $\Delta m^2 = (1.5 - 5) \times 10^{-3}\ eV^2$ (SuperK) → $M_{target} \sim 2$ **kton** of "compact" ECC (baseline)
  - large detector → sensitivity, complexity
  - modular structure ("bricks"): basic performance is preserved

- **Ongoing developments** in the emulsion technique, 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

Industrially mass-produced emulsion film

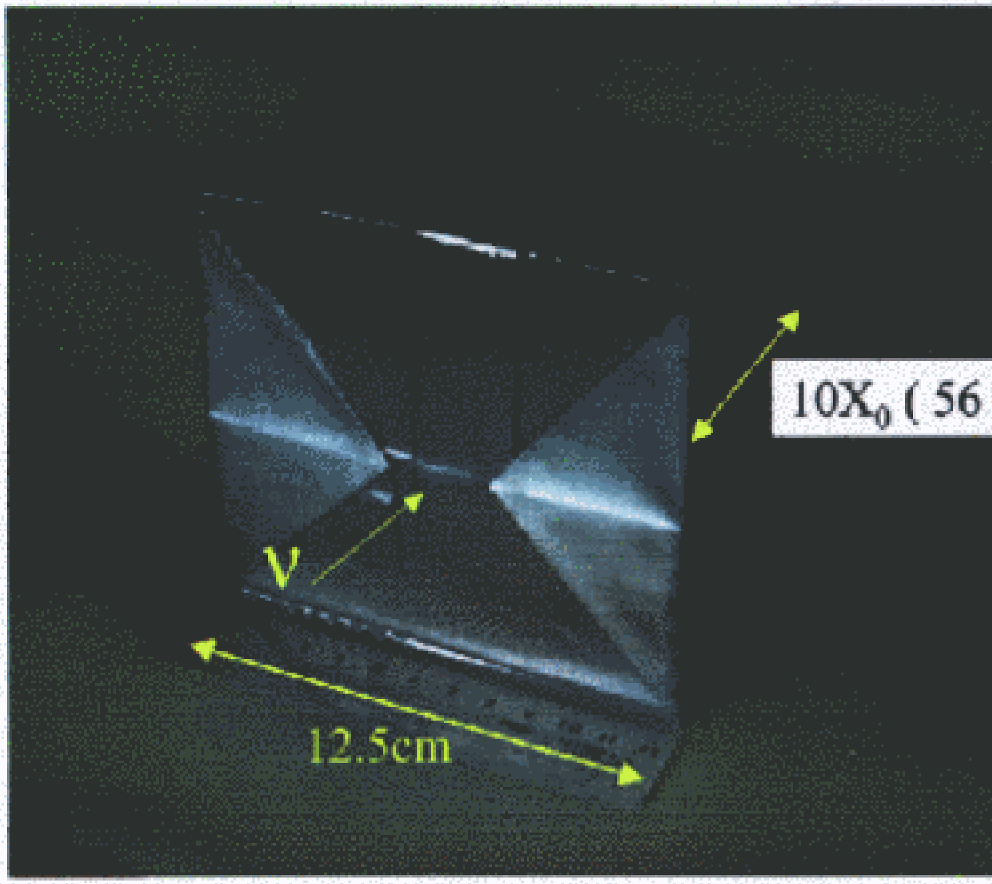


Products by Fuji Film Co.

Suitable for mass production: < 2 years for production for OPERA (13.6M films)

Precise mechanical size : emulsion layer thickness (~ 1 μm accuracy)

Origami packed ECC brick for OPERA



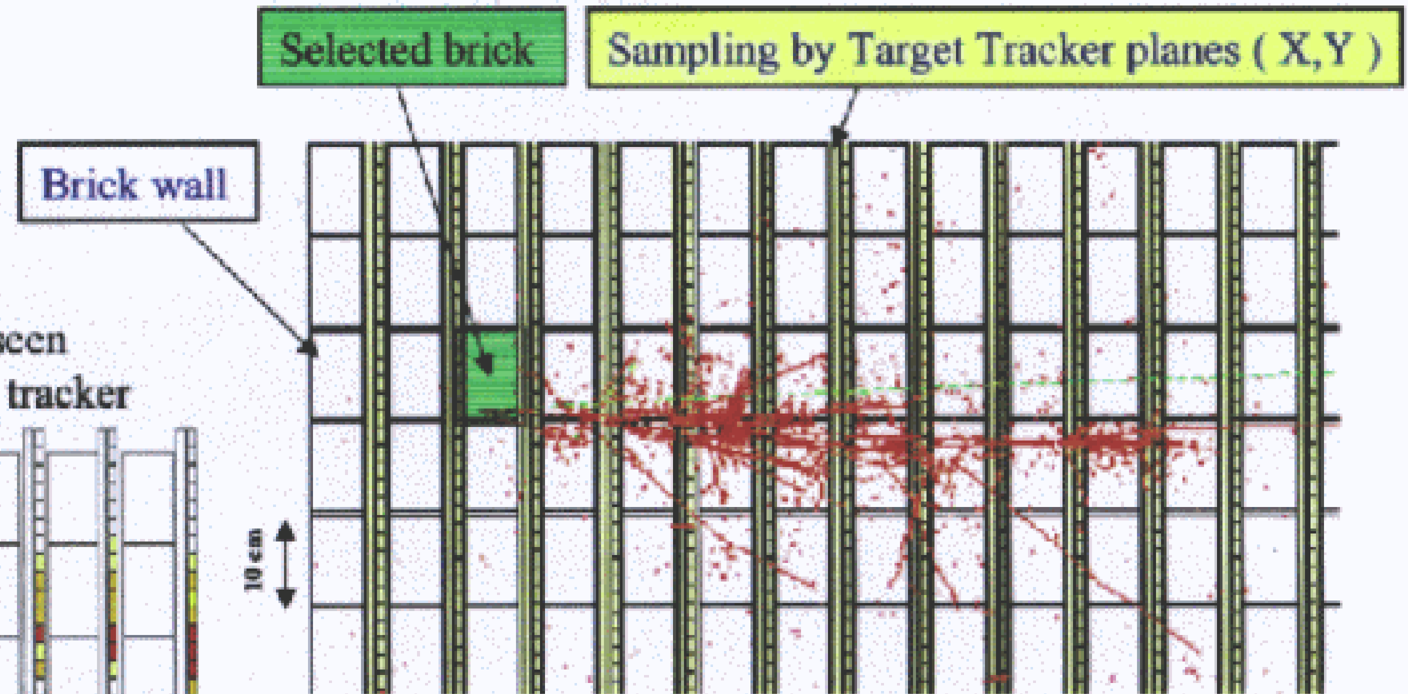
$10X_0$ (56 emulsion films)

235k bricks
for 3 supermodules

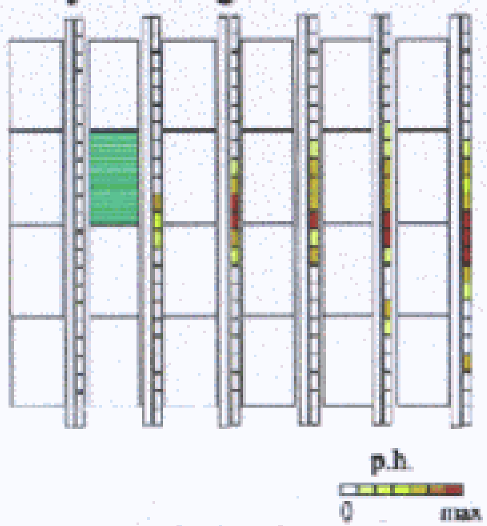
Origami packing = vacuum packing

(1) Protection against light and humidity variations.
(2) Keep the position between films and Pb plates.
(3) Vacuum preserved over 10 years

How to select the ν interaction brick ?



Event as seen
by the target tracker



Selected bricks extracted daily
using dedicated robot

Emulsion-Scintillator strip Hybrid Target

- Tracker task
  - select bricks efficiently
- High scanning power + low background
  - allow coarse tracking

Muon identification
and the measurement of its charge and momentum

- Reject charm background
- Tag and analyze $\tau^- \rightarrow \mu^-$ candidates

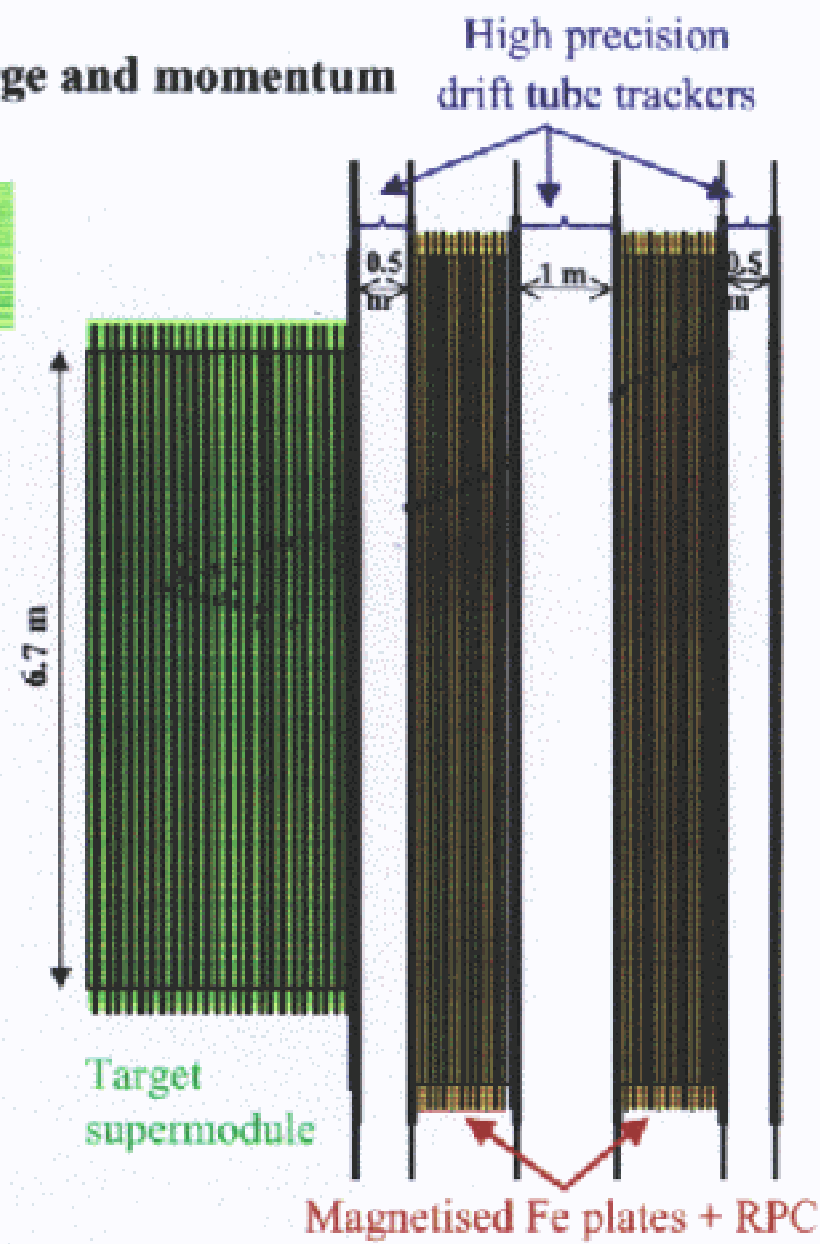
with target + spectro as calorimeter:
measure E_ν spectrum

- Fe Walls: $7.1\lambda_{int}$ instrumented with RPC
  identify muons
  shower energy measurement

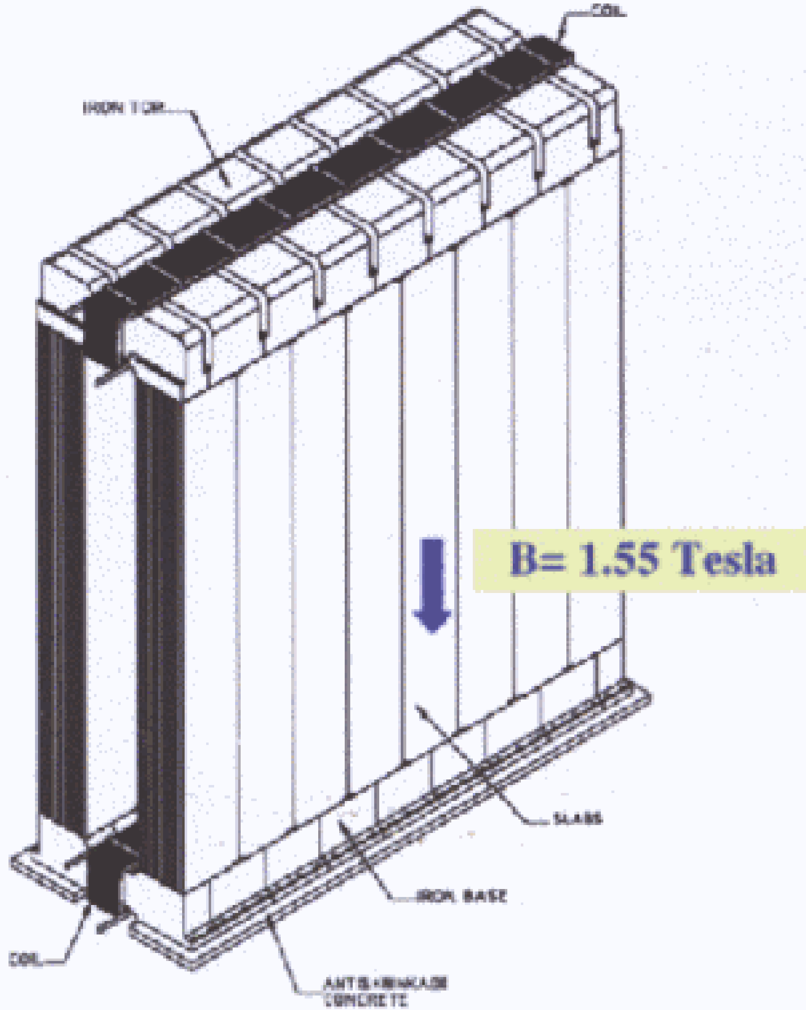
- Spectrometer: 3 external high resolution drift tubes

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

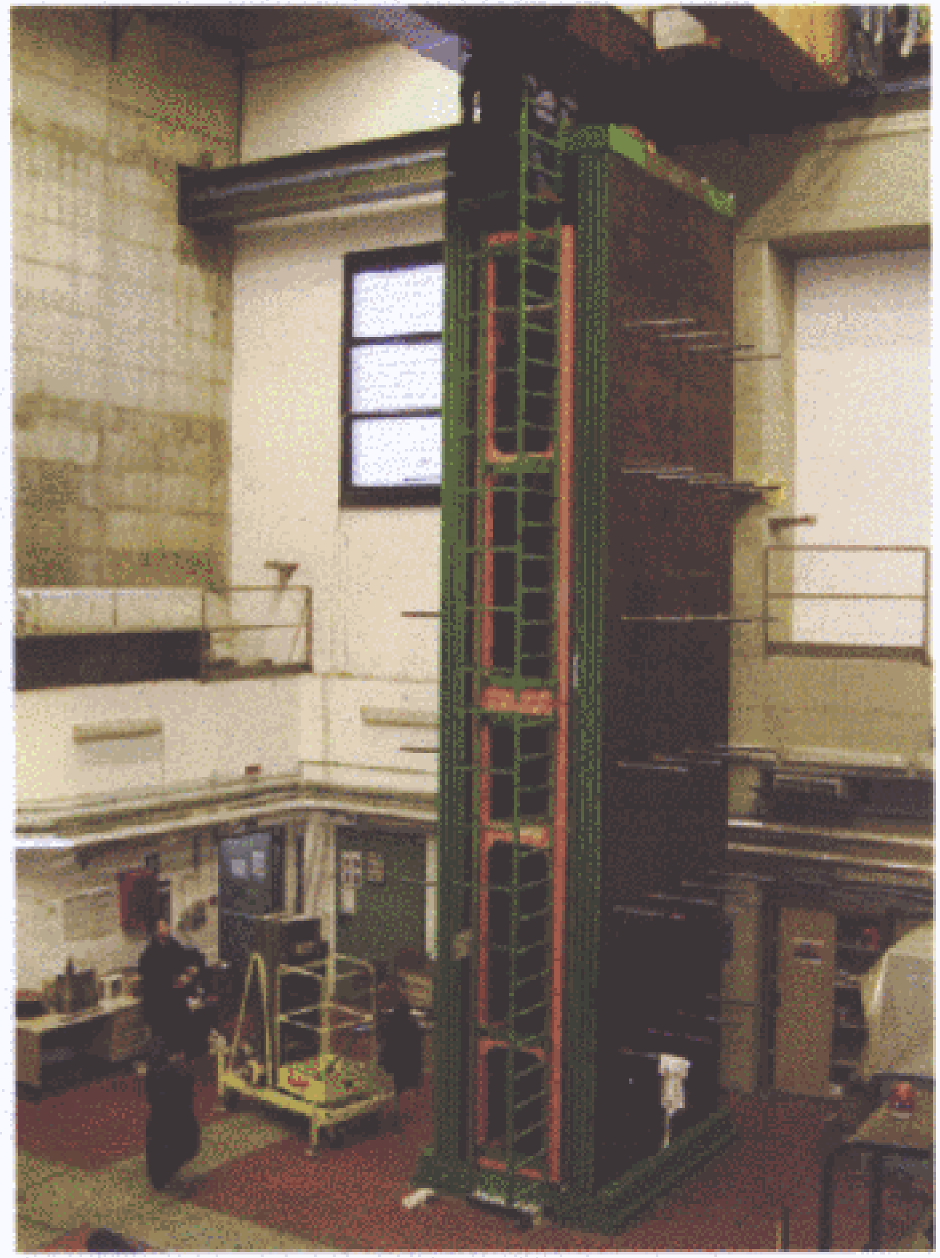
Wrong charge < 0.5 %



Dipolar spectrometer magnet
(weight: ~ 950 ton)

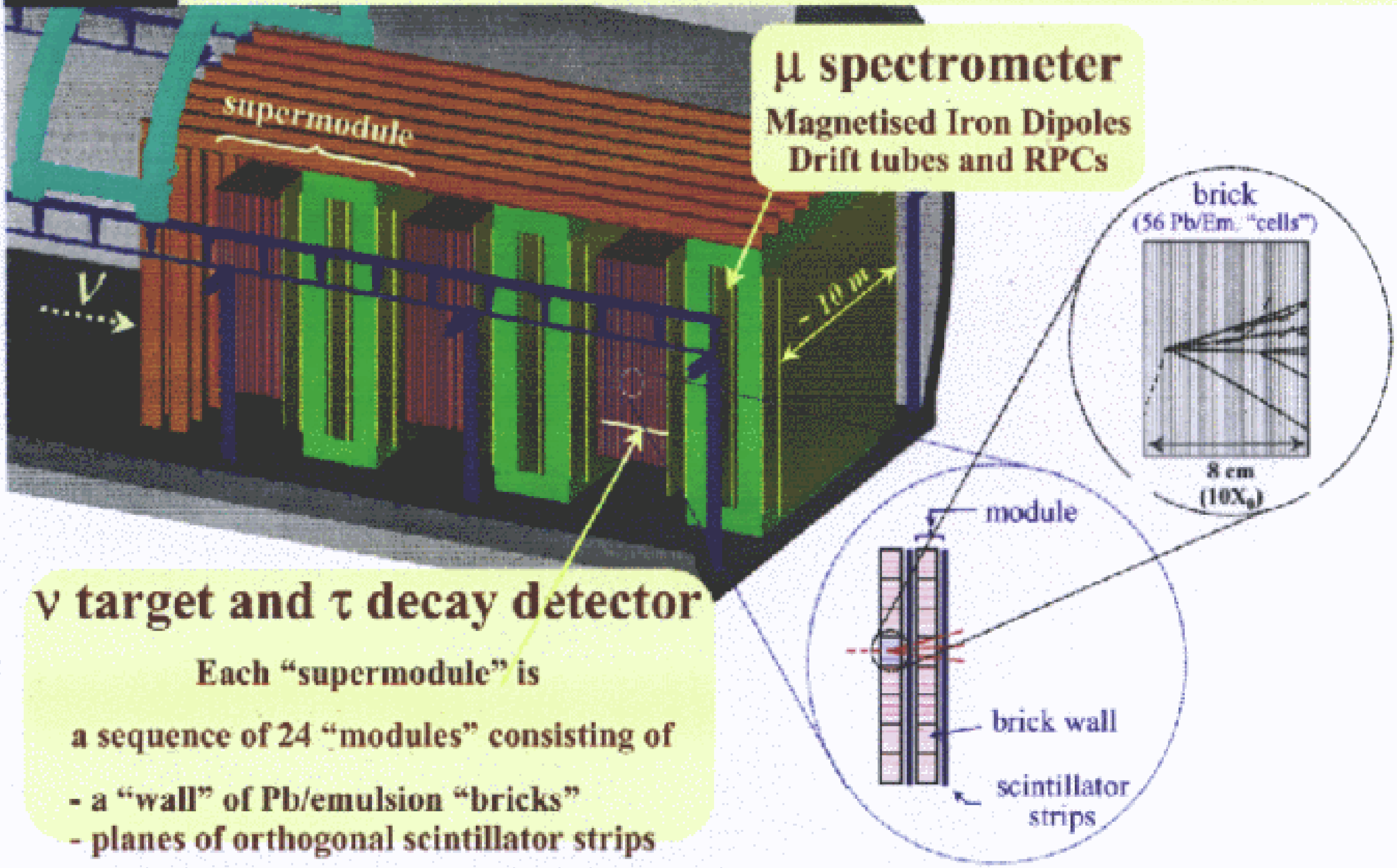


Prototype of magnet section being assembled at Frascati



The detector at Gran Sasso

(modular structure, configuration with three "supermodules")



μ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

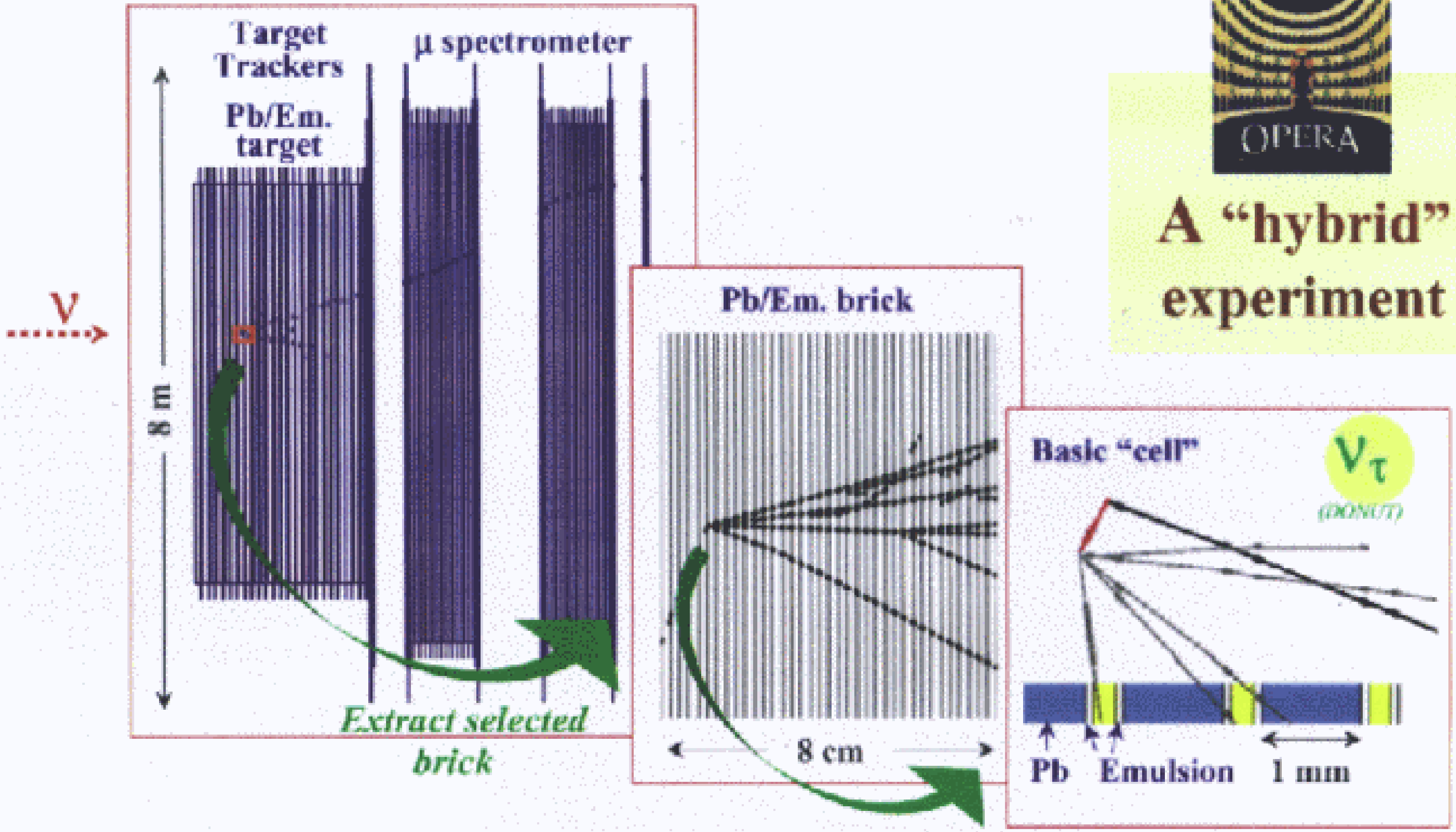
ν target and τ decay detector

Each "supermodule" is

a sequence of 24 "modules" consisting of

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

A "hybrid" experiment



Electronic detectors

→ select ν interaction brick

→ μ ID, charge and p

Emulsion scanning

→ vertex search

→ decay search

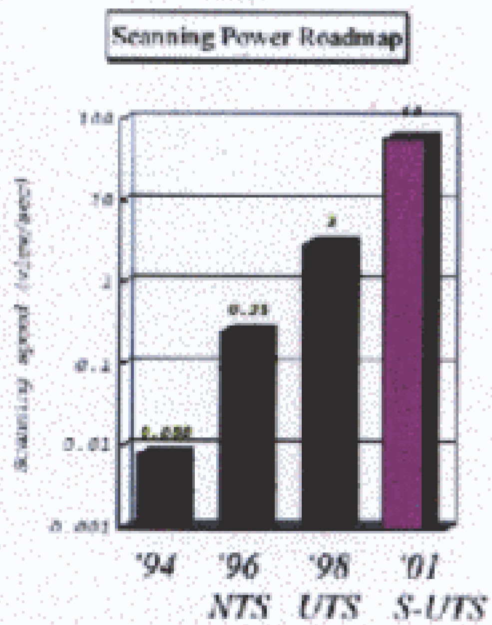
→ e/γ ID, kinematics

S-UTS

S-UTS Scanning speed: 20cm^2/h
×20 faster than the current system (UTS)

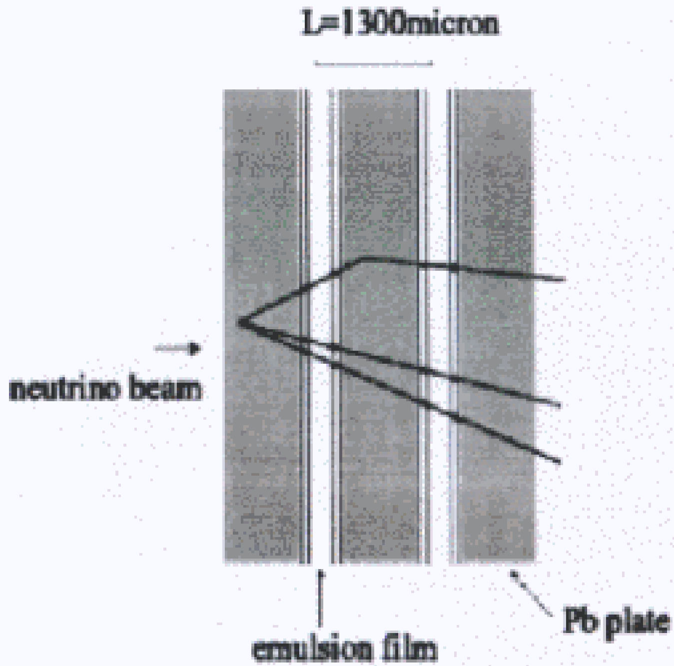
10^5 data reduction from pixels to base tracks

Will be realized by
- Fast CCD camera (3 k frames/sec)
- Continuous movement of the X-Y stage
  Z movement controlled by piezo actuator

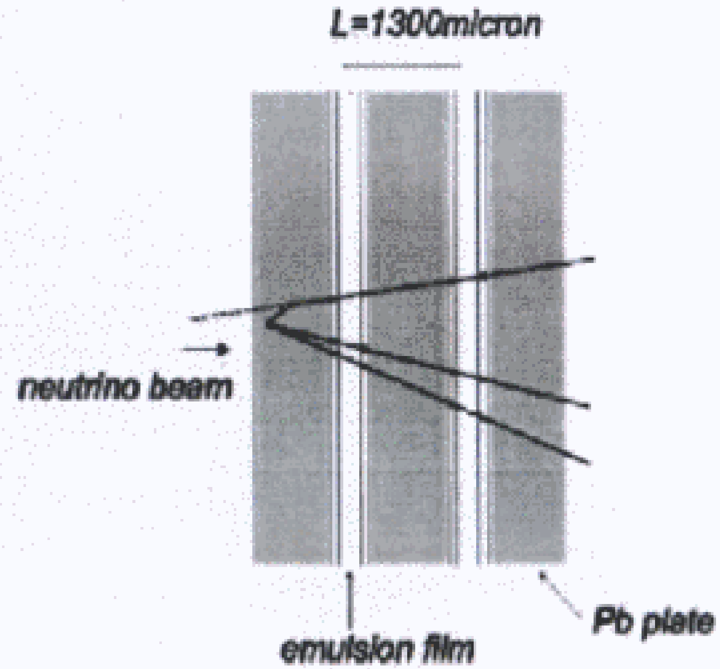


late summer 2001 → first S-UTS

Select ν_τ candidates to be passed to the FULL data taking



" Long decays"
reconstruct kink topology



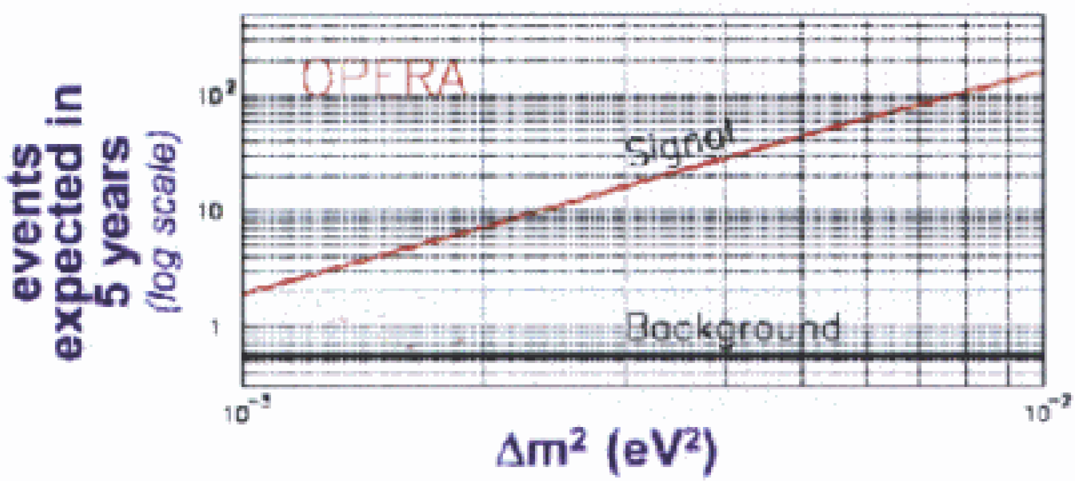
" Short decays "
detect large impact parameter track

Loose cut to reject low momentum tracks

Small fraction of the located events are passed to the FULL DAQ

Expected events

τ decay	ν_τ events Δm^2 (10^{-3} eV^2) 1.5	3.2	5.0	b.g.
e	1.7	7.7	18.5	0.19
μ	1.3	5.7	13.8	0.13
h	1.1	4.9	11.8	0.25
Total	**4.1**	**18.3**	**44.1**	**0.57**



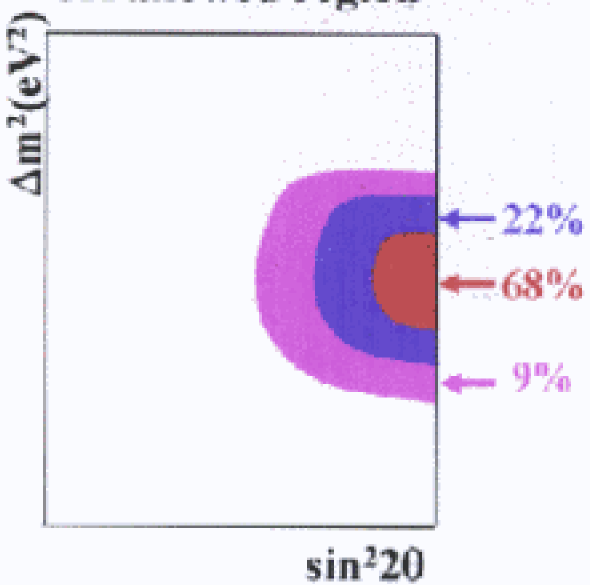
- Full mixing
- 5 years with shared SPS operation (2.25×10^{20} pot)
- Average target mass = 1.8 kton

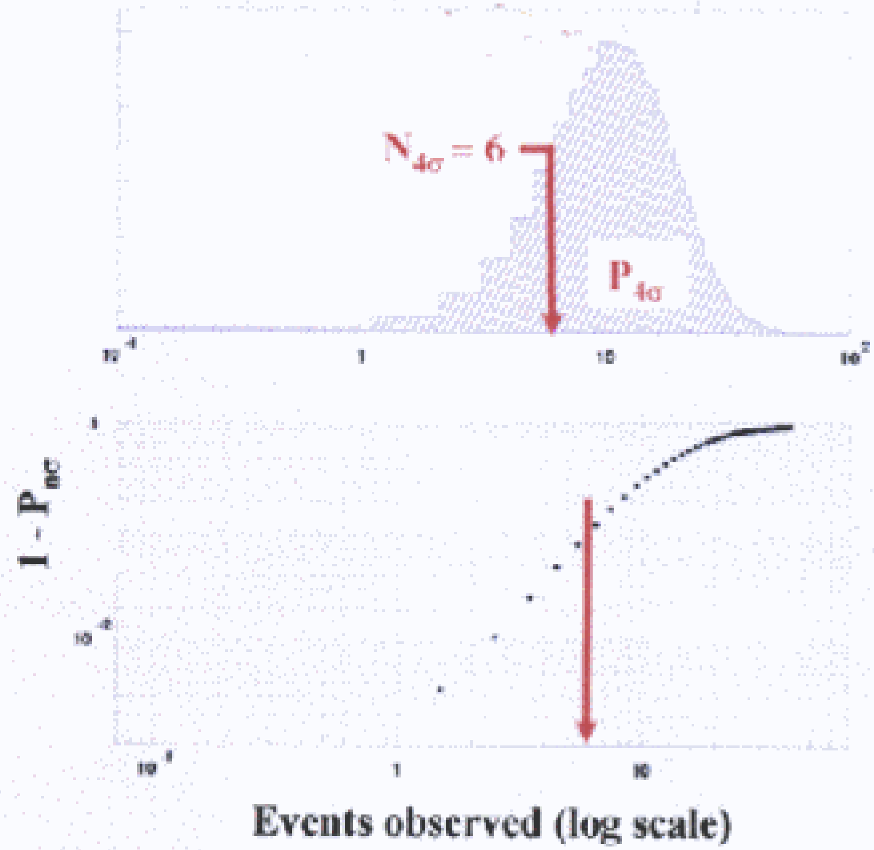
  (accounting for mass reduction with time, due to brick removal for analysis)
- Uncertainties on background and efficiencies accounted for in the following

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 $\geq N_{4\sigma}$ events

Schematic view of the SK allowed region

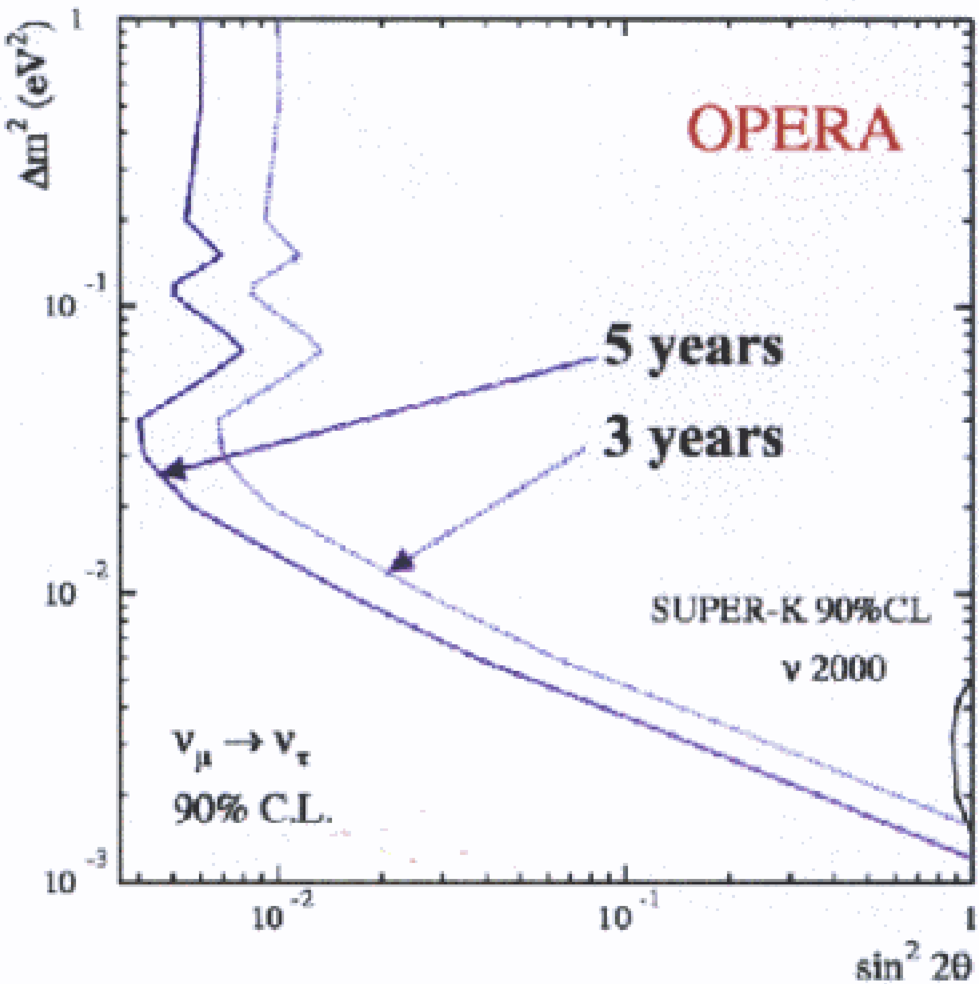




years	$P_{3\sigma}$	$P_{4\sigma}$
3	94%	80%
5	97%	92%

Sensitivity

(average 90 % CL upper limit for a large number of exp.[ts] in the absence of a signal)



5 years data taking

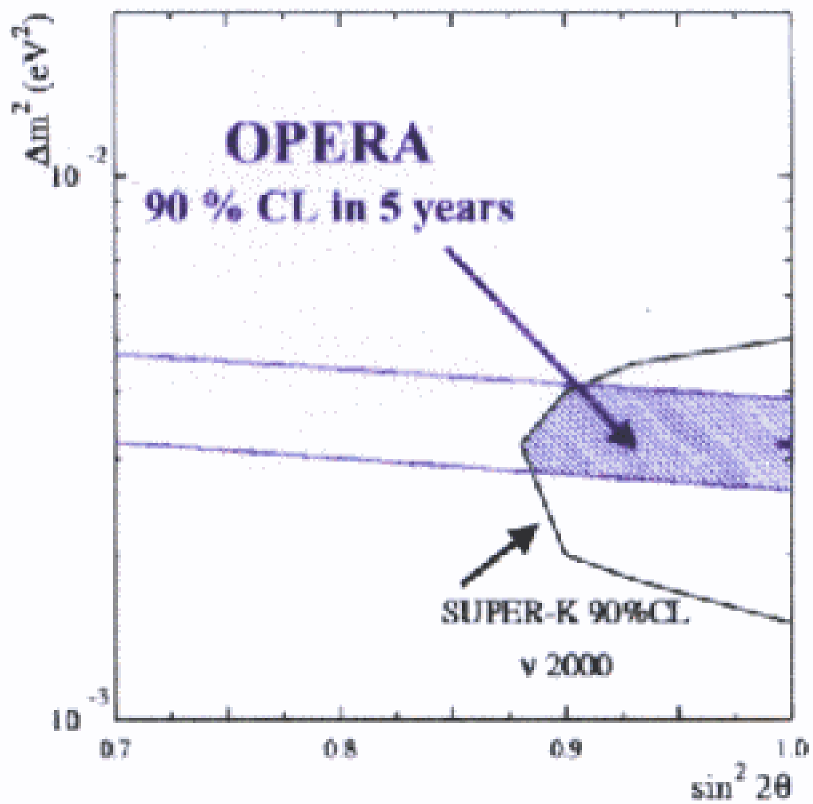
$\Delta m^2 = 1.2 \times 10^{-3}$ eV^2 at full mixing

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

Determination of Δm^2

(mixing constrained by SuperK)

90 % CL limits *	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

Electron identification in ECC brick

(1) Different energy loss by multiple scattering

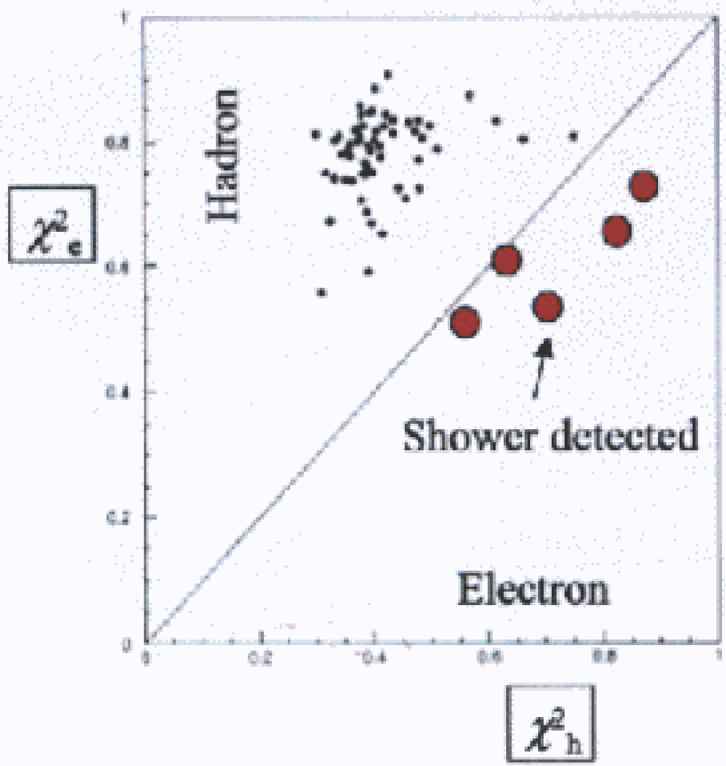
$E(x)=E_0 e^{(-x/X0)}$ for electrons χ^2_e

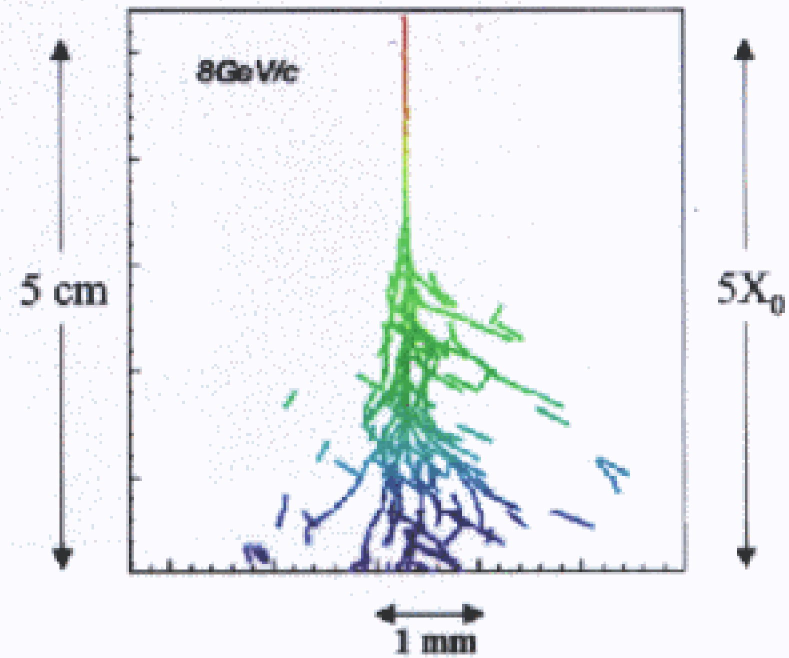
$E(x)=E_0(1-(dE/dx)x)$ for hadrons χ^2_h

(2) Detection of electromagnetic shower

Requires low background track density → controlled fading

Sensitive to electrons close to the Pb critical energy



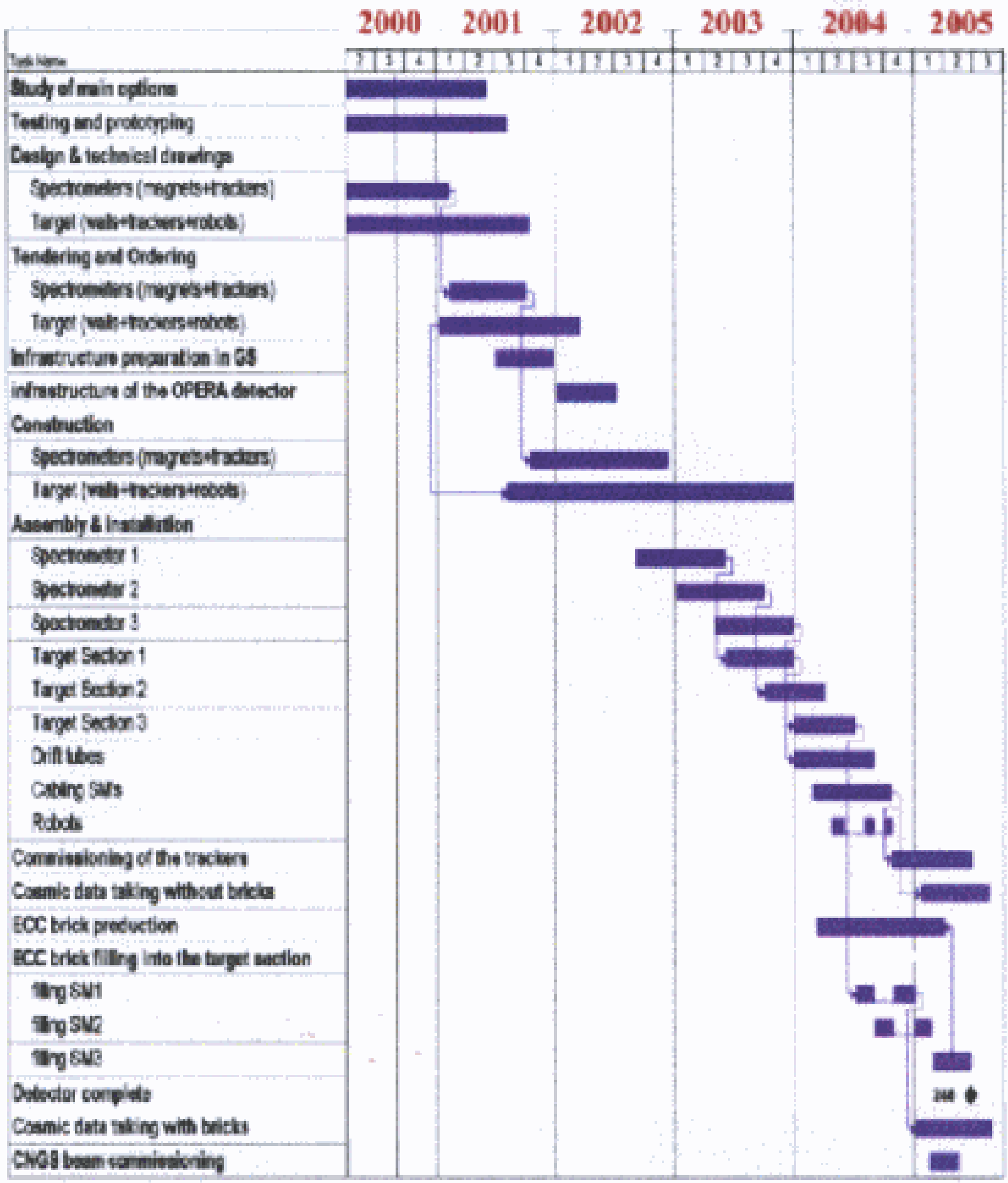


TEST experiment at CERN PS

Schedule

(3 supermodules)

Large parallelism in the mounting of supermodules: tight schedule



Strategy

⇕

Resources

Technical and practical issues

K2K and **SuperK**

Starting dates

2001 Construction

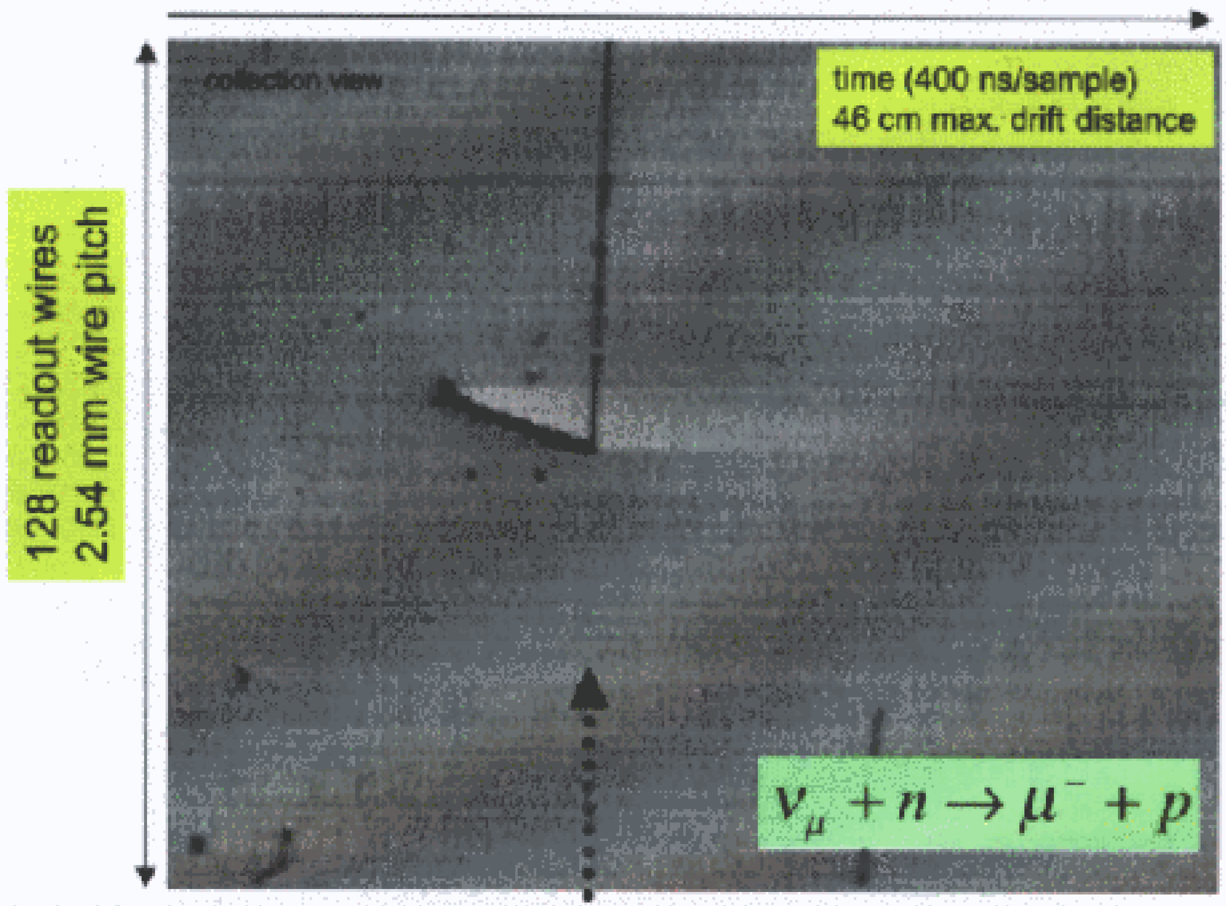
2002 Installation

2004 Filling with emulsion bricks

2005 Data taking

Neutrino event in 50 liter LAr TPC (1998)

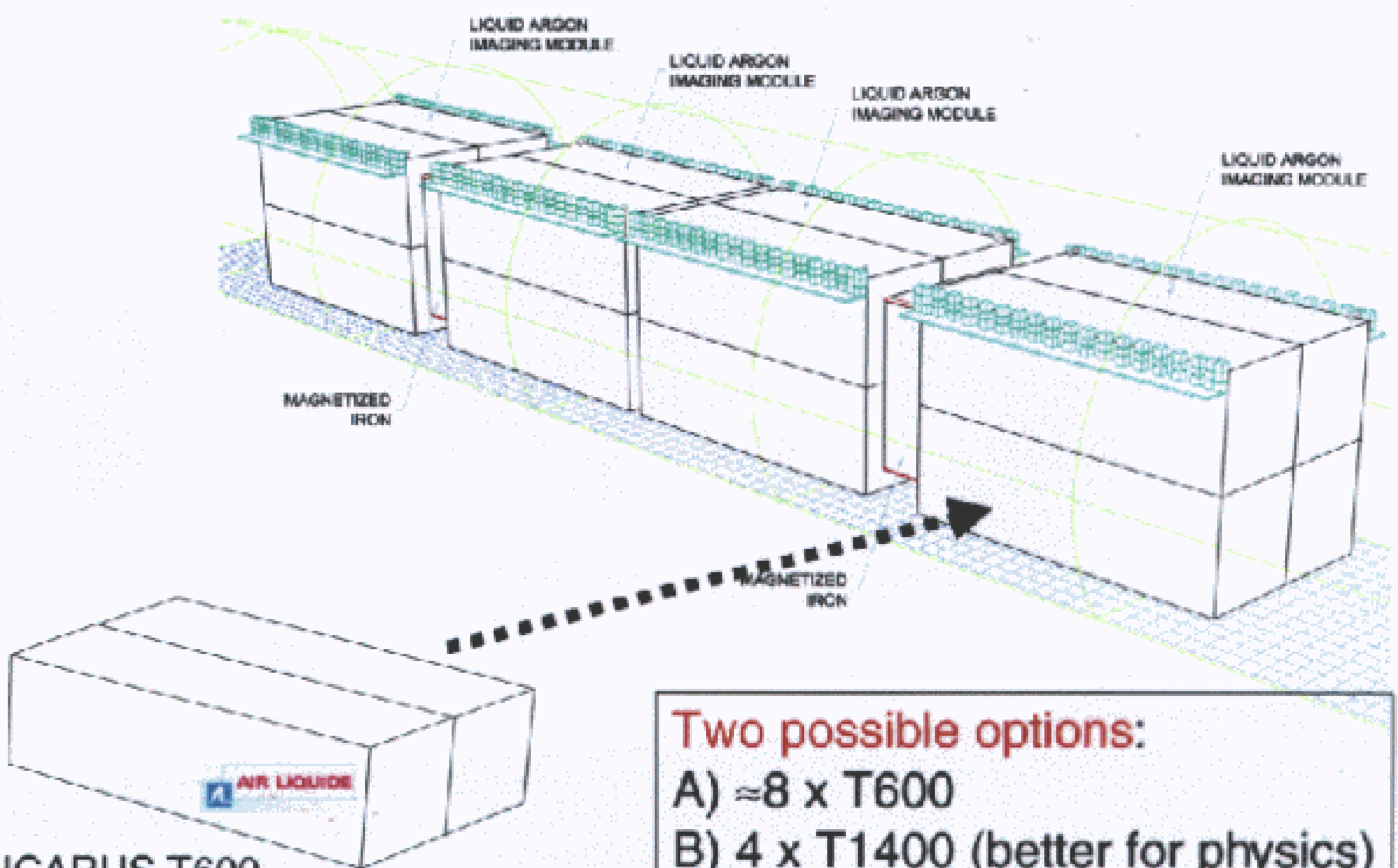
ICARUS-CERN-Milano



CERN ν-beam

(Chamber located in front of NOMAD detector)

Proposed setup ICARUS 5kt in LNGS Hall B



ICARUS T600

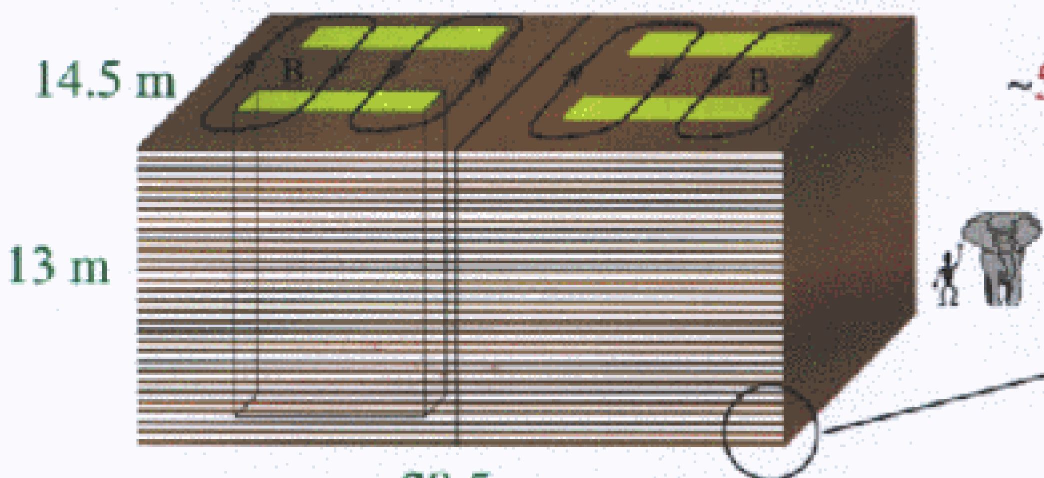
Two possible options:

A) ≈8 x T600

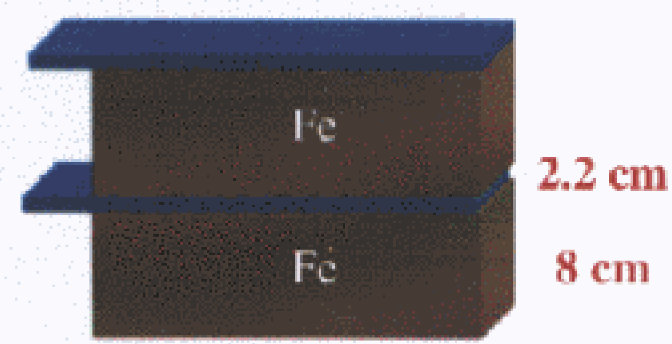
B) 4 x T1400 (better for physics)

The Monolith Detector

Large mass	34 kton
Magnetized Fe spectrometer	B = 1.3 Tesla
Time resolution	~ 1 ns (for up/down discrimination)
Space resolution	~ 1 cm (rms on X-Y coordinates)
Momentum resolution σ_p/p	~ 20% from track curvature for outgoing mu
	~ 6% from range for stopping muons
Hadron E resolution σ_{E_h}/E_h	~ $90\%/\sqrt{E_h} \oplus 30\%$



~52000 m^2 of detector : Glass Spark Coun



XIVth GSSC, September 2000

Final Comments

- Neutrino physics continues to be a fascinating field with many unanswered questions
- Within the next few years we shall embark on the next phase of the neutrino oscillation experiments using accelerator beams
- We can have strong expectations of obtaining then important new information