CERN-Gran Sasso Neutrino Program

D.Duchesneau
LAPP, Annecy

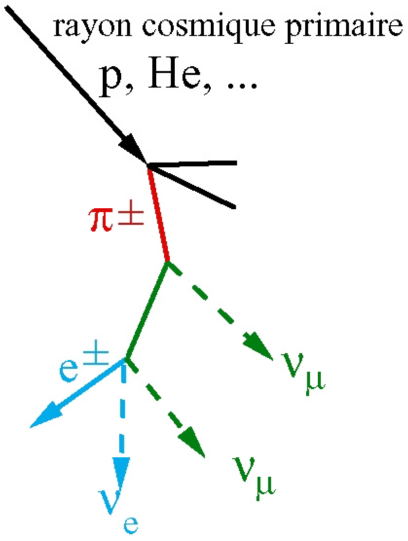
- Introduction
- CNGS beam-line
- OPERA experiment
- ICARUS experiment
- Conclusion

Université de Montréal
September 11th 2003

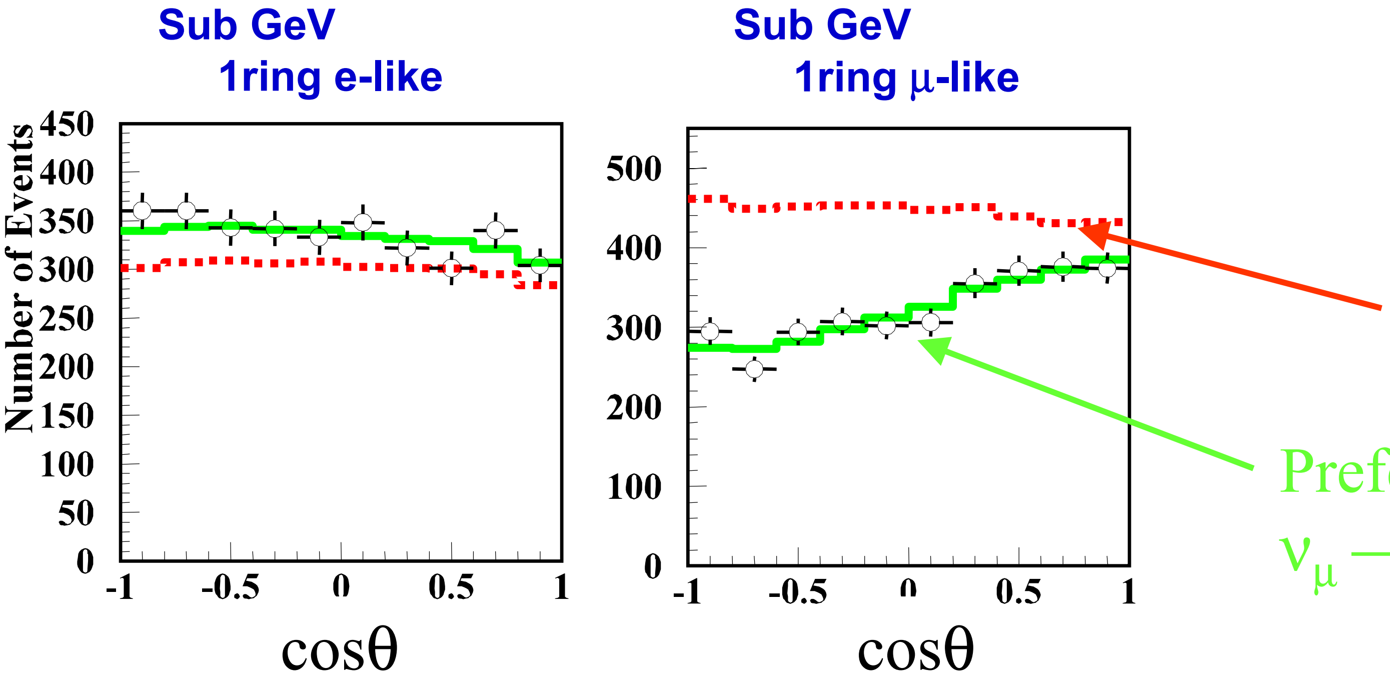
Introduction: Experimental facts (EPS-Aachen 2003):

Atmospheric results: clear ν_μ disappearance

(SK, Soudan II, MACRO)



Super-K: Atmospheric ν zenith angle distribution



No oscillation (Honda)

Preferred explanation is $\nu_\mu \to \nu_\tau$ oscillation

Best fit: $\Delta m^2 = 2.0\ 10^{-3}\ \mathrm{eV}^{-2}$ and $\sin^2 2\theta = 1.0$

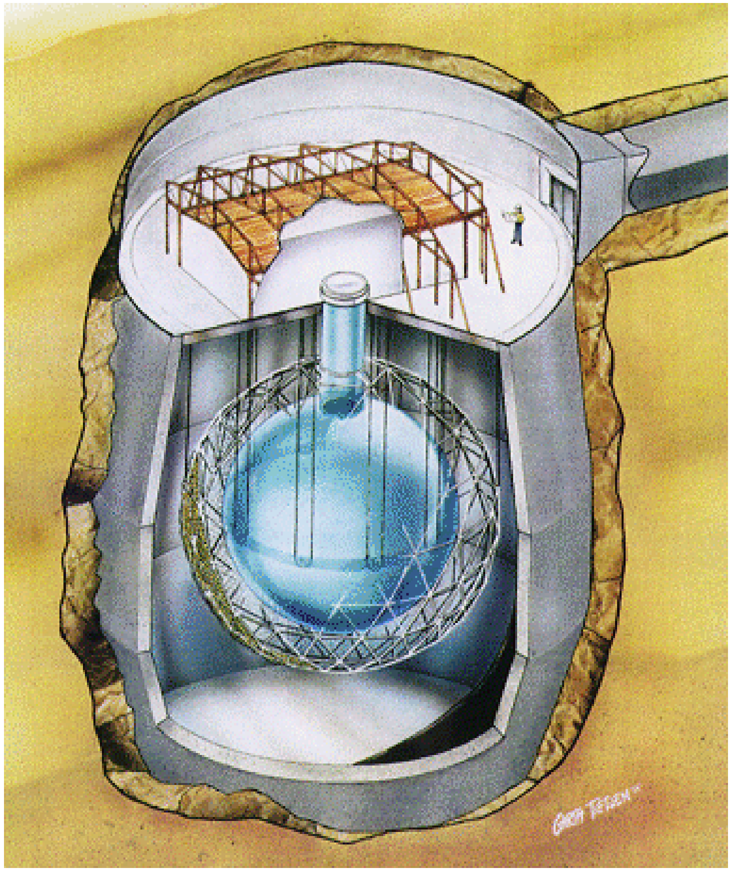
$1.3 < \Delta m^2 < 3.0 \times 10^{-3}\ \mathrm{eV}^2$ at 90% CL

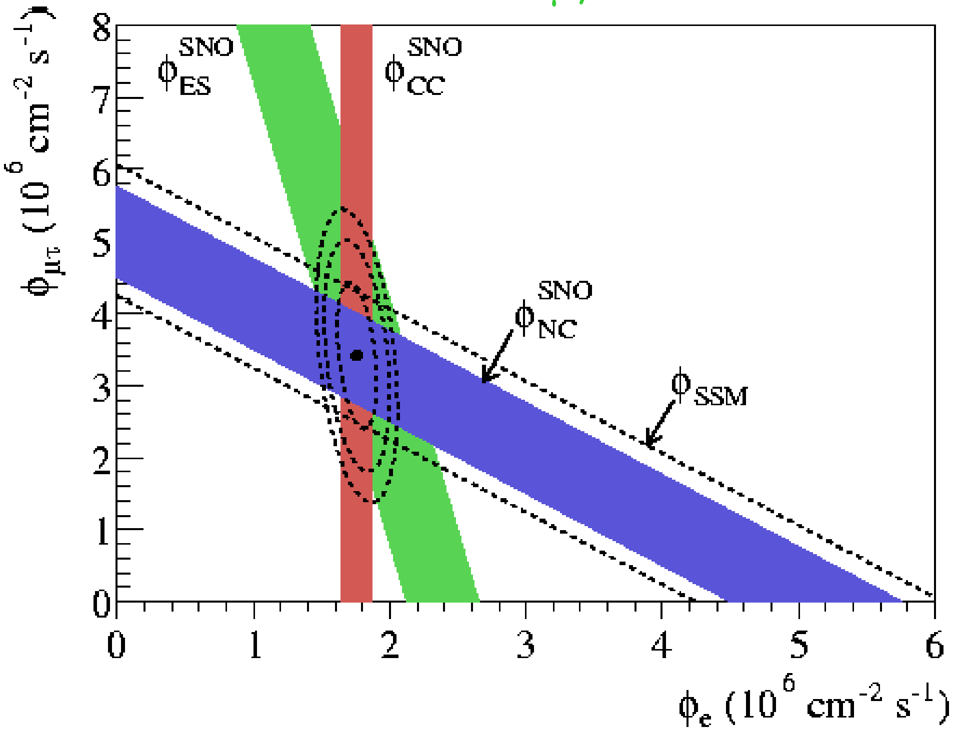
Solar results:

SNO: deficit of solar ν_e + strong evidence of flavour change

$\Phi_{CC} = \Phi_e$ $\Phi_{NC} = \Phi_e + \Phi_{\mu,\tau}$

$\Phi_{ES} = \Phi_e + 1/6\ \Phi_{\mu,\tau}$





$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.})\times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}(\text{syst.})\times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

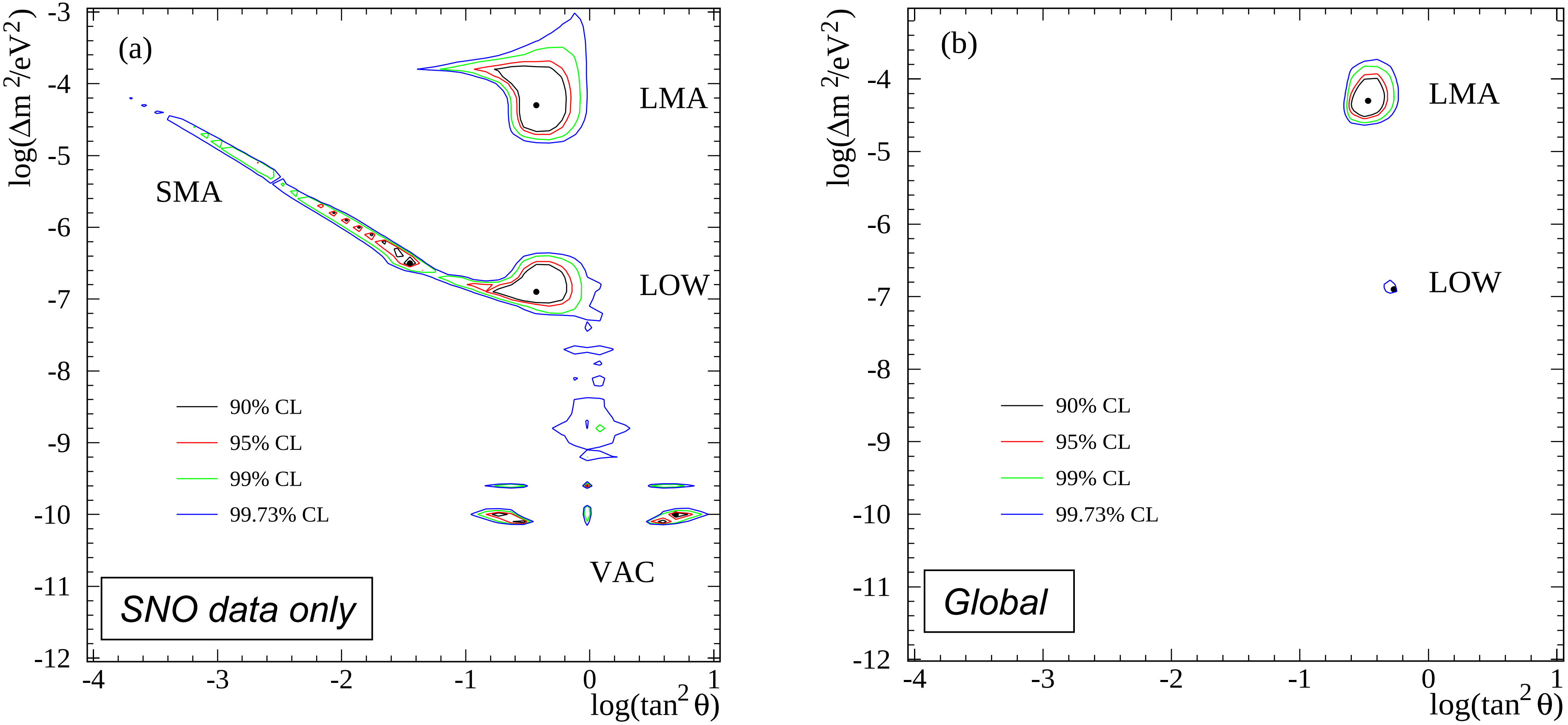
No flavor transformation hypothesis ($\Phi_{\mu,\tau} = 0$) rejected at 5.3 σ

Compatible with oscillation hypothesis favouring LMA solution

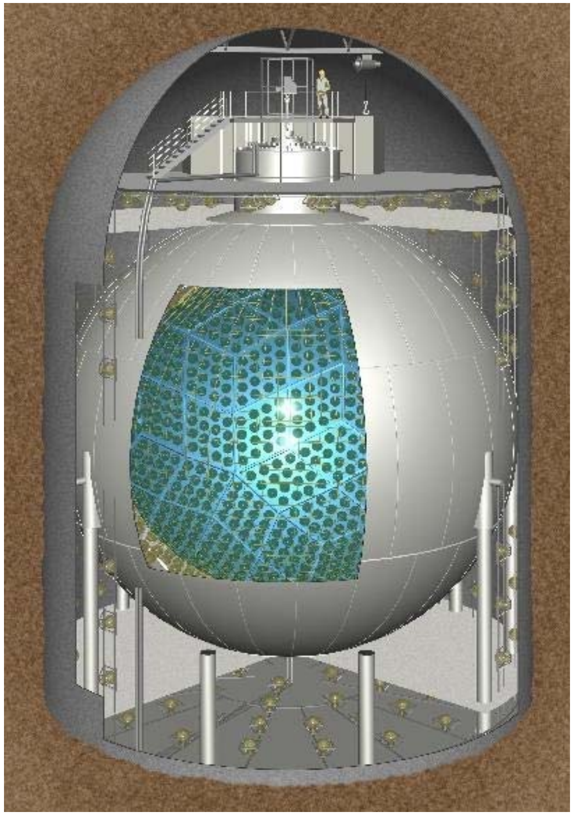
Phys.Rev.Lett. 89 (2002) 011301; Phys.Rev.Lett. 89 (2002) 011302

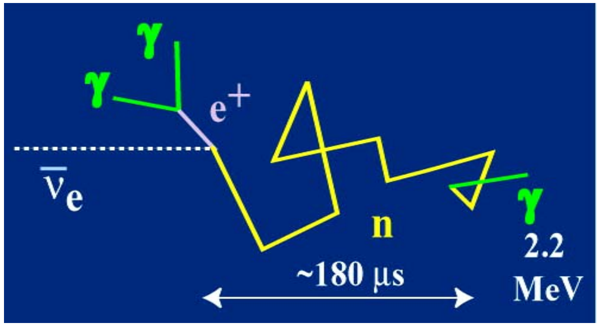
Global Solar ν Analysis

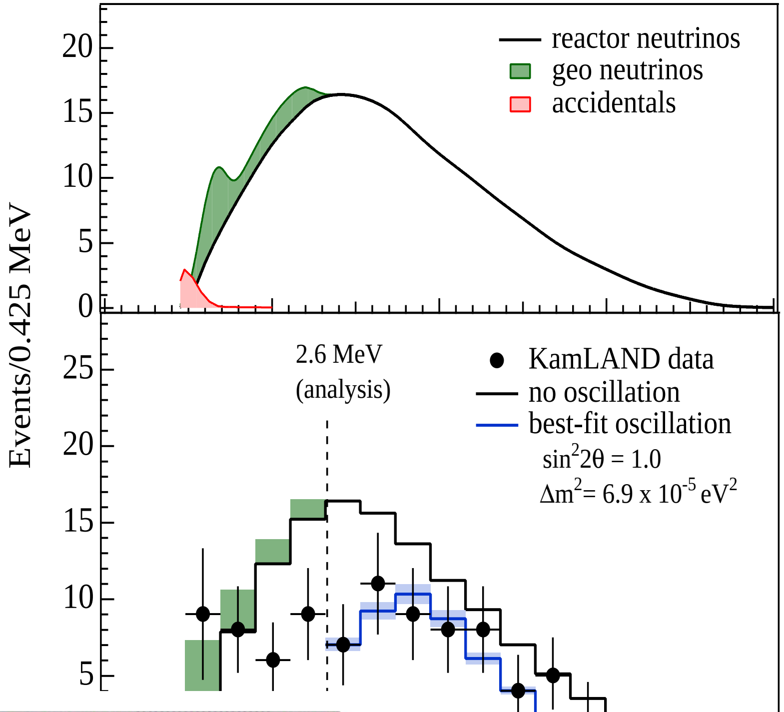
Inputs:
- ^{37}Cl, latest Gallex/GNO, new SAGE, SK 1258-day day & night spectra
- SNO day spectrum (total: CC+NC+ES+background)
- SNO night spectrum (total: CC+NC+ES+background)
- ^{8}B floats free in fit, hep ν at 1 SSM

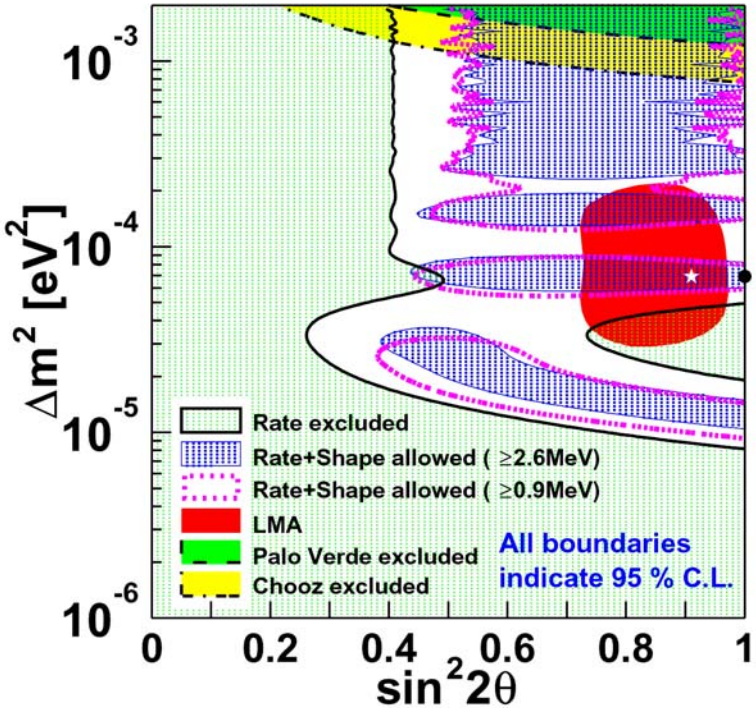


Reactor result: KAMLAND deficit of anti-ν_e observed compatible with LMA









→ No doubt that neutrinos undergo a flavour changing mechanism and that $m_\nu > 0$

MNSP matrix and 3 ν oscillations

(MNSP: Maki-Nakagawa-Sakata-Pontecorvo)

$$\nu_\alpha = \sum_{j=1}^{3} U_{\alpha j} \nu_j$$ $U_{\alpha j}$ is the mixing matrix

$$U_{\alpha j} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

6 parameters to determine:

- 3 angles, 2 mass differences,
- 1 CP violation phase

1st generation of Long Base-line ν projects:

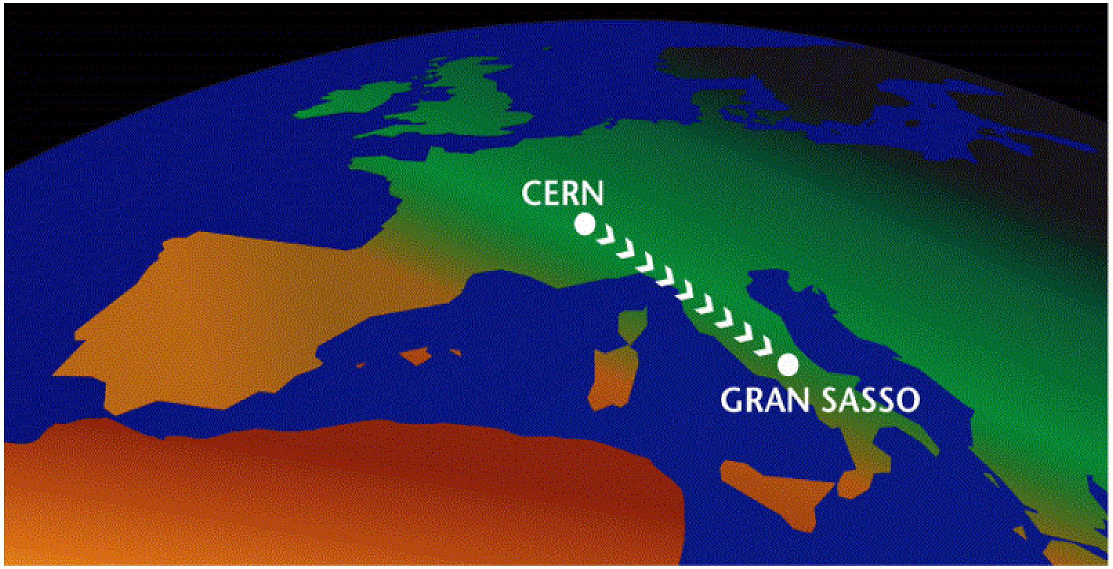
- confirm the atmospheric ν result and the oscillation hypothesis
- verify the nature of these oscillations (ν_μ-$\nu_?$)
- measure more precisely Δm_{23}^2 and θ_{23}
- observe $\nu_\mu \rightarrow \nu_e$ and constrain θ_{13}

3 projects using "home-made" ν_μ:

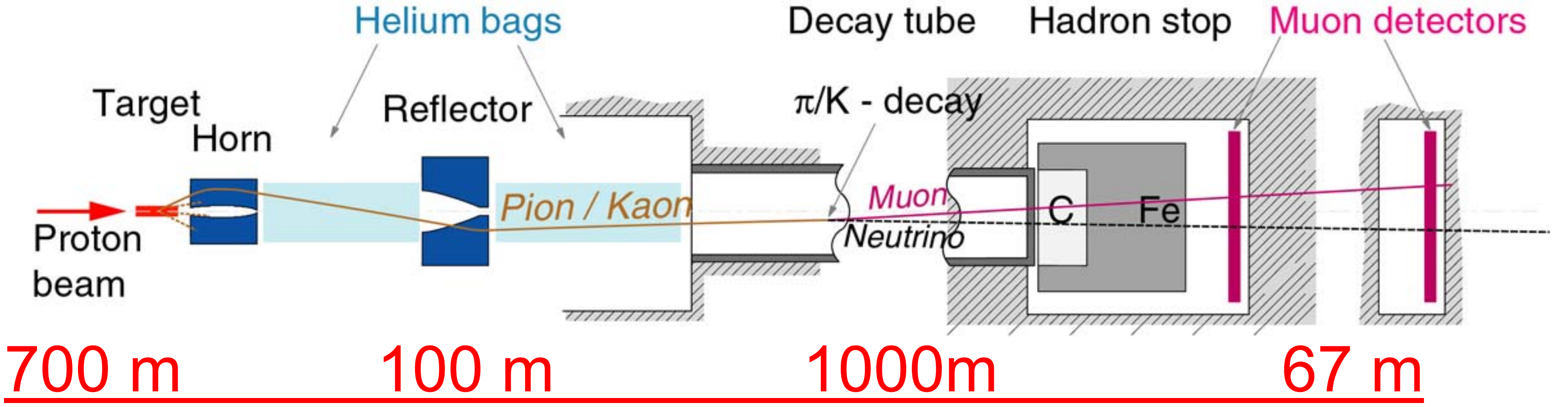
K2K and NUMI/MINOS looking primarily at ν_μ disappearance

and CNGS:

searching for ν_τ appearance at Gran Sasso laboratory (732 km from CERN) in a ν_μ beam produced at CERN



CNGS main characteristics



400 GeV protons on graphite

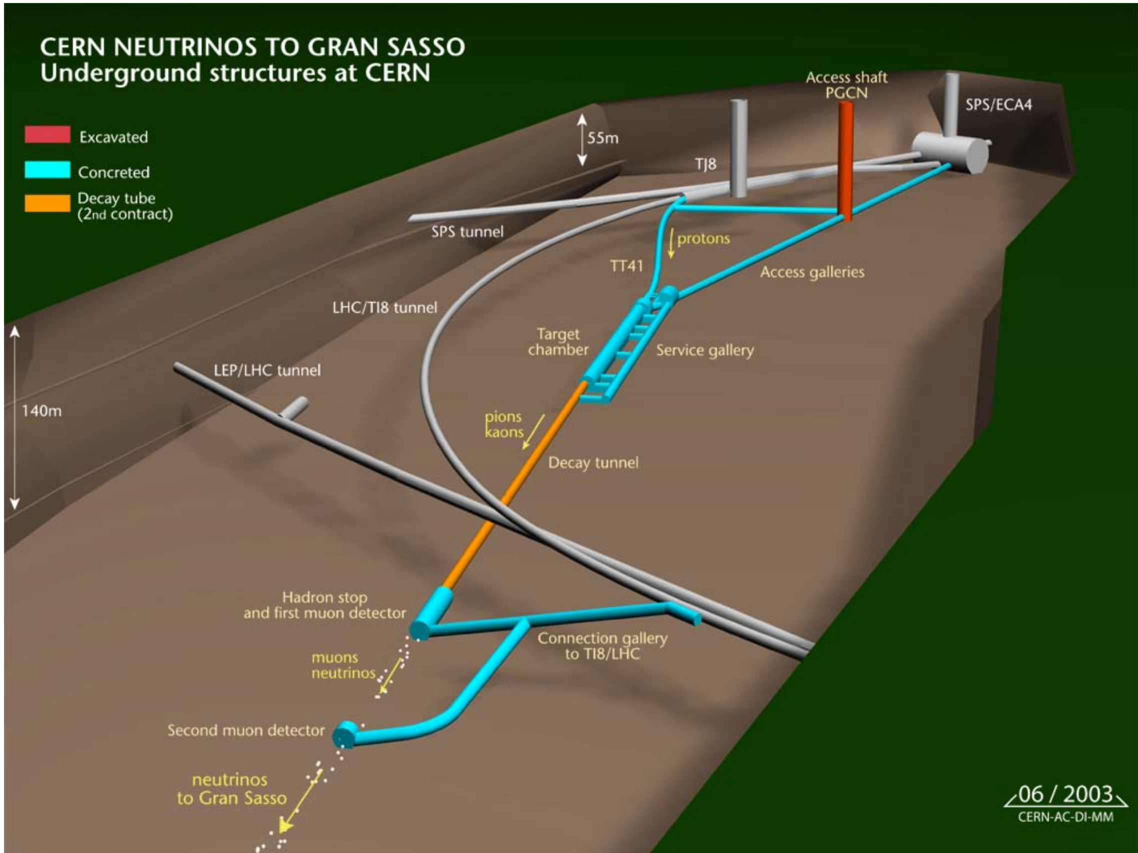
Beam Intensity increase:
(approved and financed)
expect 1.5x original design

7.0 x 10^{13} pot/spill

200 days/year ; **ε = 55%**

6.76 x 10^{19} pot/year

(shared mode)

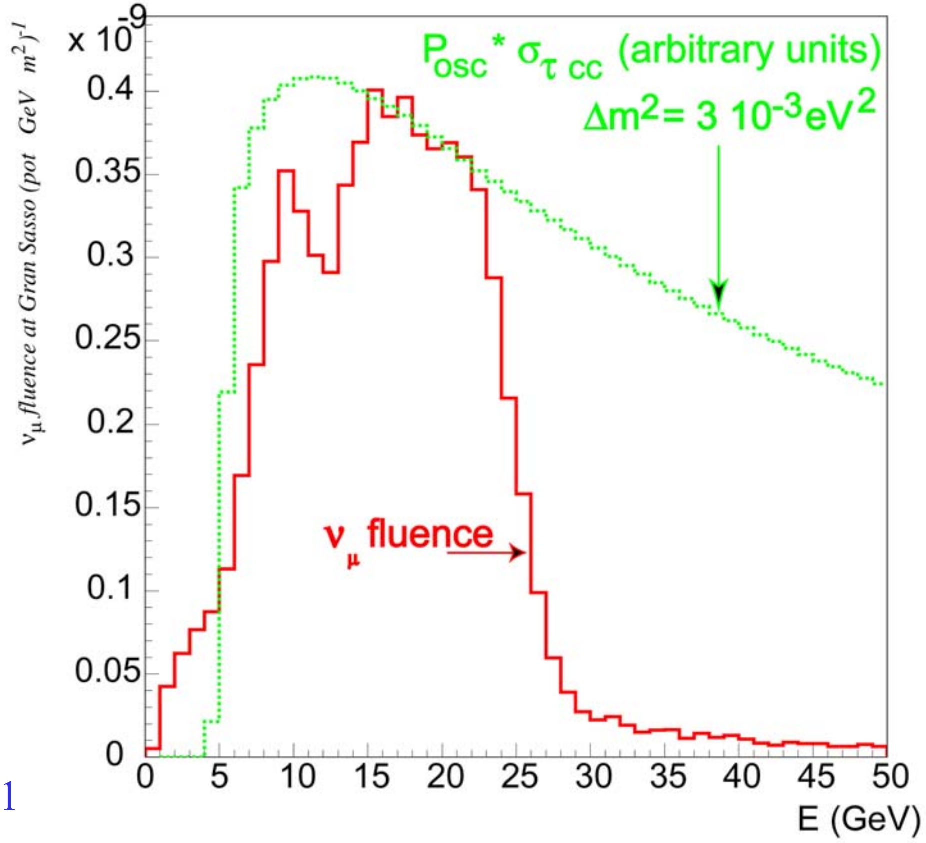


Beam optimized for ν_τ appearance

For 1 year of CNGS operation with the expected intensity upgrade:

ν_μ (m^{-2} / pot)	**7.78×10^{-9}**
ν_μ CC / kton	**4000**
ν_μ NC / kton	**1240**
$< E >_\nu$ (GeV)	**17**
$(\nu_e + \overline{\nu}_e) / \nu_\mu$	**0.8 %**
$\overline{\nu}_\mu / \nu_\mu$	**2.1 %**
ν_τ prompt	**negligible**

ν_μ per m^2 at Gran Sasso 5.25×10^{11}



For $\Delta m^2 = 2.5\times10^{-3}$ and maximal mixing

expect 25 ν_τ CC/kton/year at Gran Sasso

Status of the project:

- Civil engineering is completed (june 2003)
- Upgrade of the beam intensity (factor 1.5) is well under way
- Start the installation of hadron stopper and decay tube

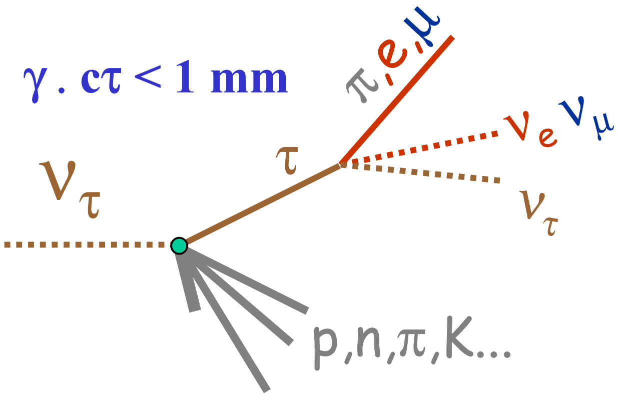
Target chamber: june 20th 2003

Inner Conductor of the Horn

Assembled with the Outer Conductor by end 2003

➡ First beam to Gran Sasso in spring 2006

Experimental signature for ν_τ appearance:



τ decay modes:

$\mu^- \nu_\tau \bar{\nu}_\mu$	BR 17.4 %
$h^- \nu_\tau n\pi^o$	49.5 %
$e^- \nu_\tau \bar{\nu}_e$	17.8 %
$\pi^+ \pi^- \pi^- \nu_\tau n\pi^o$	15.2 %

The detectors should be able to detect and identify the ν_τ CC events

- Two massive detectors are under preparation

OPERA: direct observation of τ decay topology

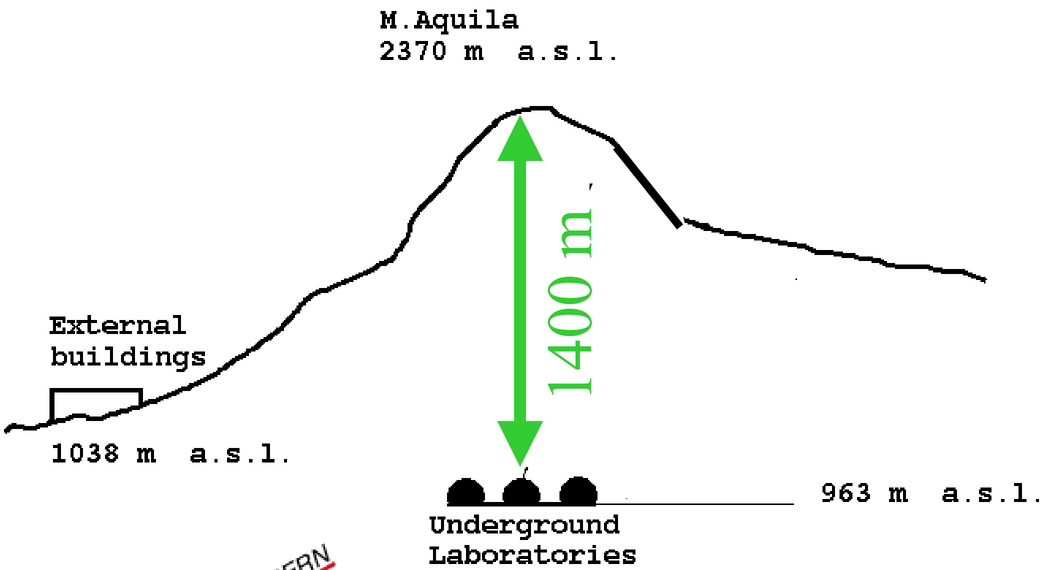
requires nuclear emulsions: ~ μm granularity
needs large target mass: Emulsion Cloud Chamber technique

ICARUS: ν_τ CC events identified through kinematic criteria

requires particle-ID, momentum and angular resolution
large electronic bubble chamber capabilities: ~ mm granularity

Gran Sasso National Laboratory: (Italy, 120 km from Rome)

Underground laboratory:



good cosmic ray shielding

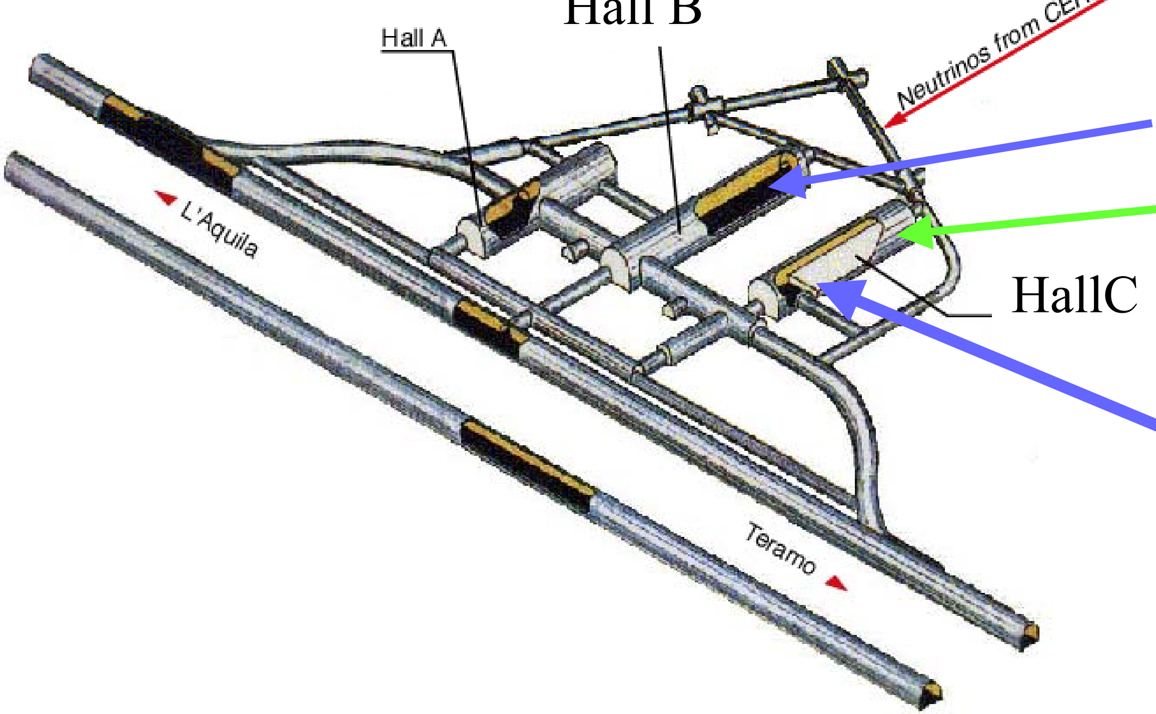
1 cosmic/m^2/hr

3 large experimental halls

(100m x 18m x 18m)

directed towards CERN

Hall B



ICARUS

Borexino

HallC

OPERA

OPERA
COLLABORATION

Belgium
IIHE(ULB-VUB) Brussels

Bulgaria
Sofia University

China
IHEP Beijing, Shandong

Croatia
Zagreb University

France
LAPP Annecy, IPNL Lyon, LAL Orsay, IRES Strasbourg

Germany
Berlin, Hagen, Hamburg, Münster, Rostock

Israel
Technion Haifa

Italy
Bari, Bologna, LNF Frascati, L'Aquila, LNGS, Naples, Padova, Rome, Salerno

Japan
Aichi, Toho, Kobe, Nagoya, Utsunomiya

Russia
INR Moscow, ITEP Moscow, JINR Dubna, Obninsk

Switzerland
Bern, Neuchâtel
Turkey
METU Ankara

36 groups
~ 165 physicists

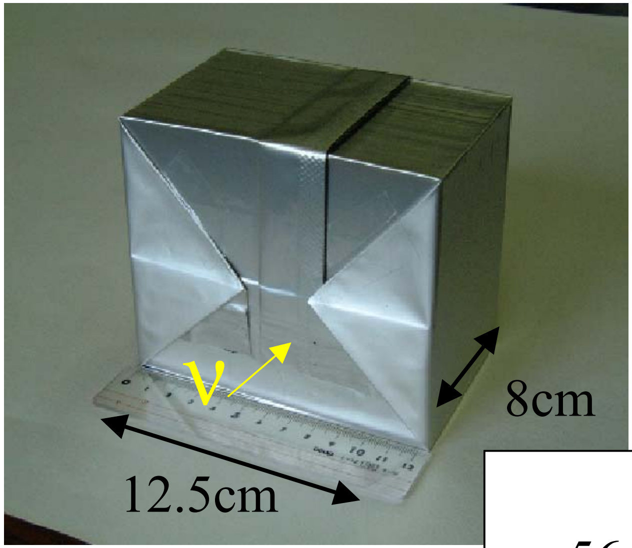
OPERA: approved CERN experiment CNGS1

Principle: direct observation of τ decay topologies in ν_τ CC events

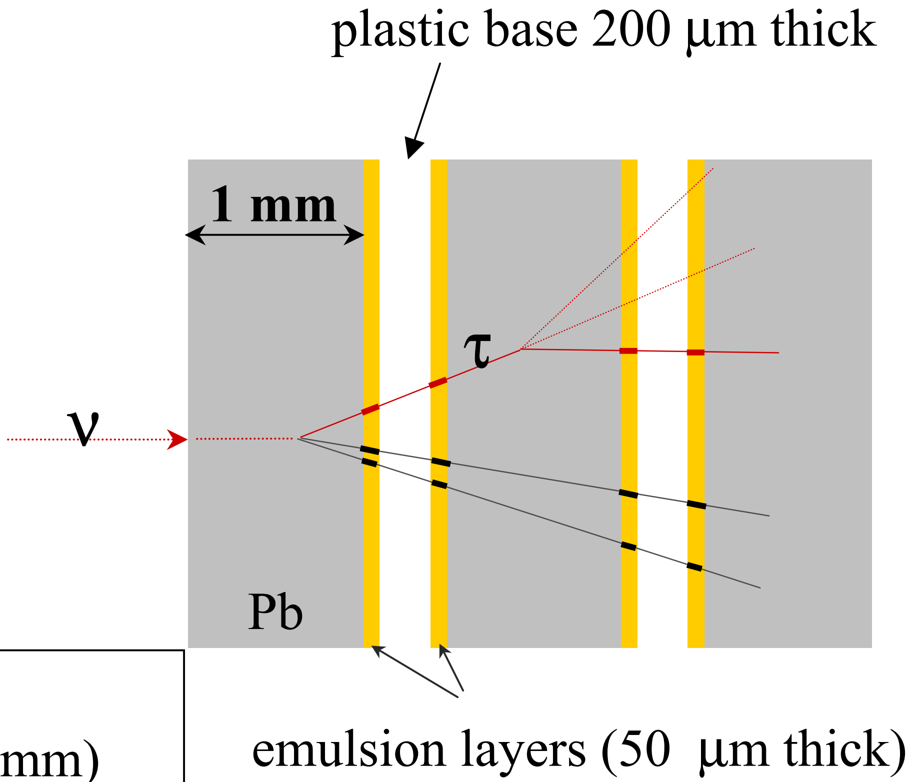
→ requires μm resolution: use photographic emulsions

→ needs large target mass: alternate emulsion films with lead sheets (ECC concept)

Modular detector: basic unit **brick**

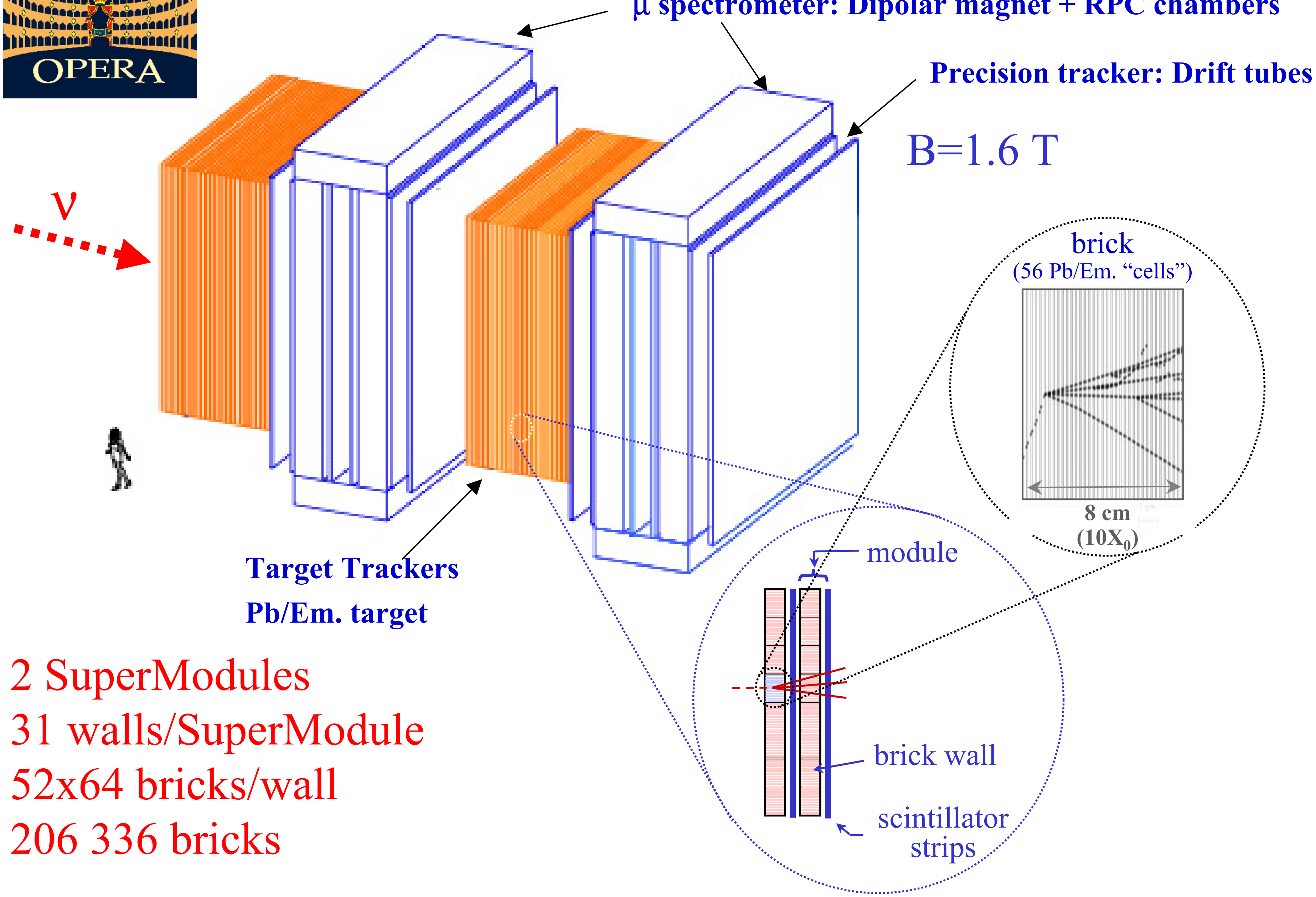


10X_0
56 Pb sheets (1mm)
57 FUJI emulsion films
1 changeable sheet



206 336 bricks are needed → target mass: 1.8 ktons

1.8 kton detector at Gran Sasso (Hall C)



μ spectrometer: Dipolar magnet + RPC chambers

Precision tracker: Drift tubes

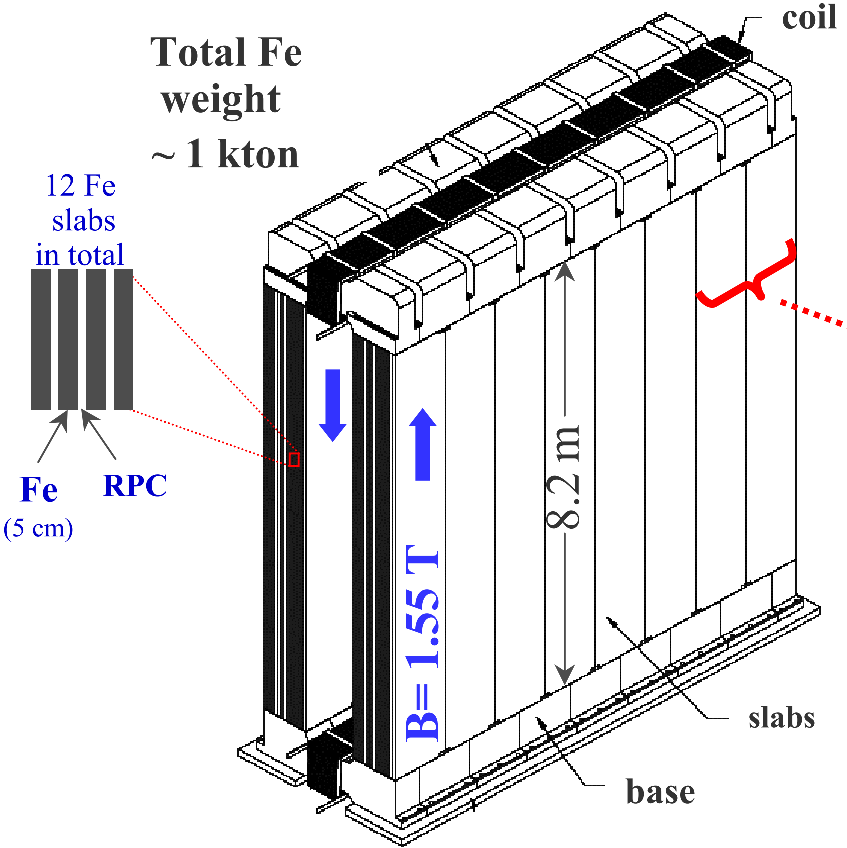
B=1.6 T

Target Trackers

Pb/Em. target

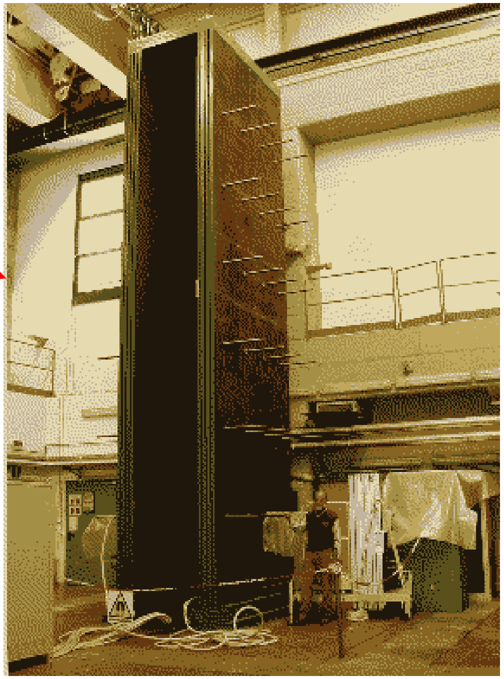
- 2 SuperModules
- 31 walls/SuperModule
- 52x64 bricks/wall
- 206 336 bricks

Muon spectrometer



Total Fe weight ~ 1 kton

Full scale prototype magnet
Constructed and tested at Frascati



Precision tracker

- **Tube :** vertical , ϕ = 38 mm, length 8 m , wire ϕ = 50 μm
- **Plane:** 4 staggered layers, each with 168 tubes

full size prototype (Hamburg)

- **Iron slabs, Yokes, coils, supplies ordered**
- **installation started: may 2003**

$$\varepsilon^{\text{miss}}_{\text{charge}} \approx (0.1 \div 0.3)\%$$

$\Delta p/p < 20\%$ for p<50 GeV

μId > 95%

(with Target Tracker)

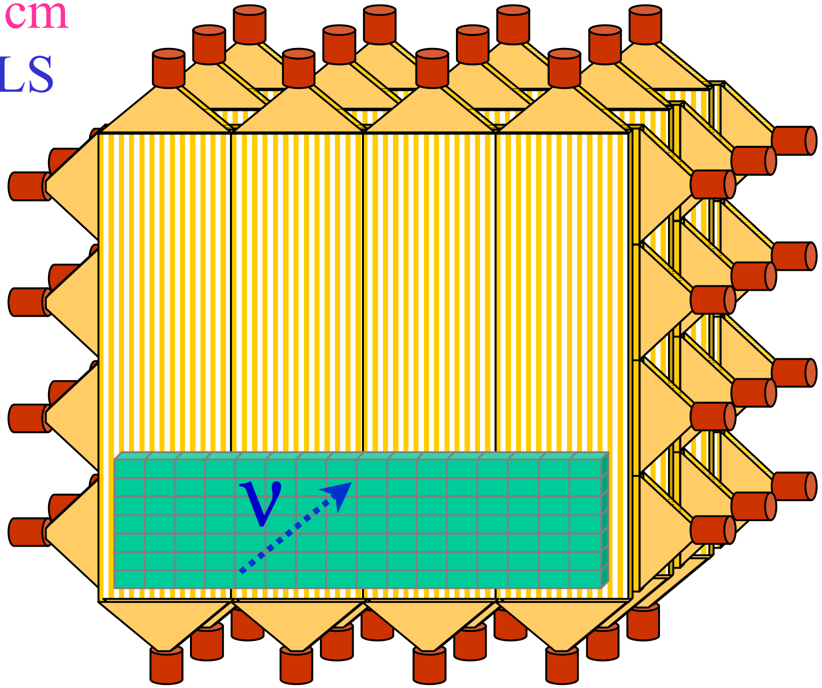
Hall C in Gran Sasso:

ne

July 2003

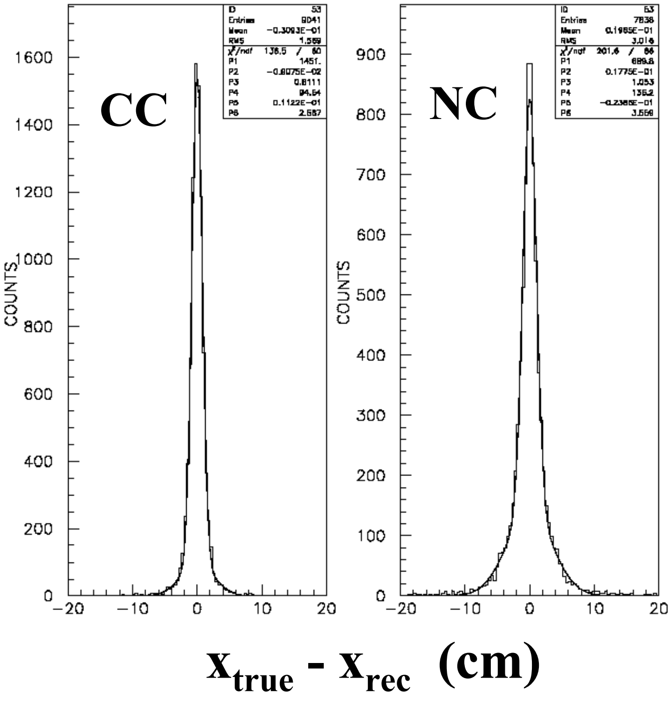
Target tracker:

- Plastic scintillator strips: 6.7 m x 2.5 cm x 1 cm
- AMCRYS-H (Kharkov) readout by Kuraray WLS optical fibres + Hamamatsu PMT 64 channels
- X and Y planes of 256 strips



- Target Tracker tasks :
  - trigger (ε=99%)
  - select bricks efficiently
  - initiate muon tagging

10 cm

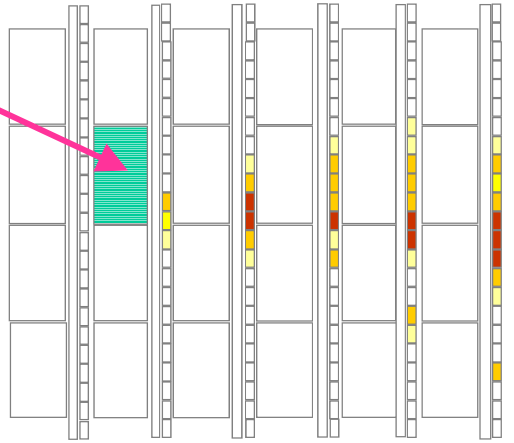


$x_{true} - x_{rec}$ (cm)

Selected bricks are extracted daily using robots

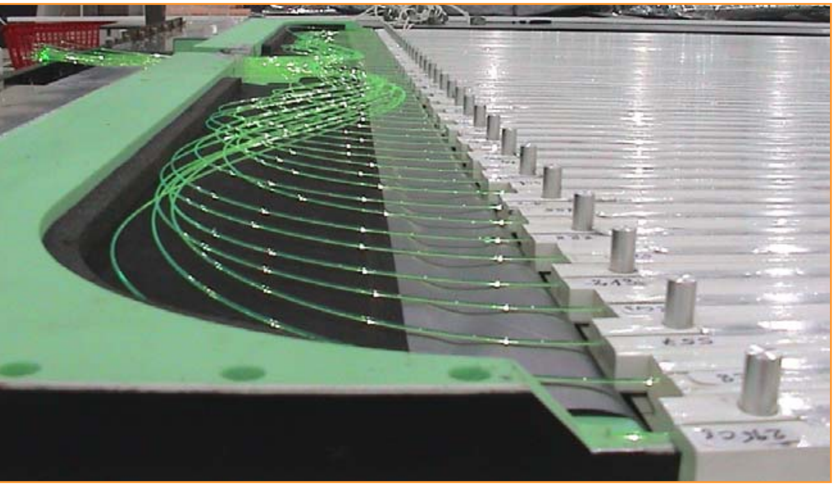
σ = 1.5 cm CC
3.0 cm NC

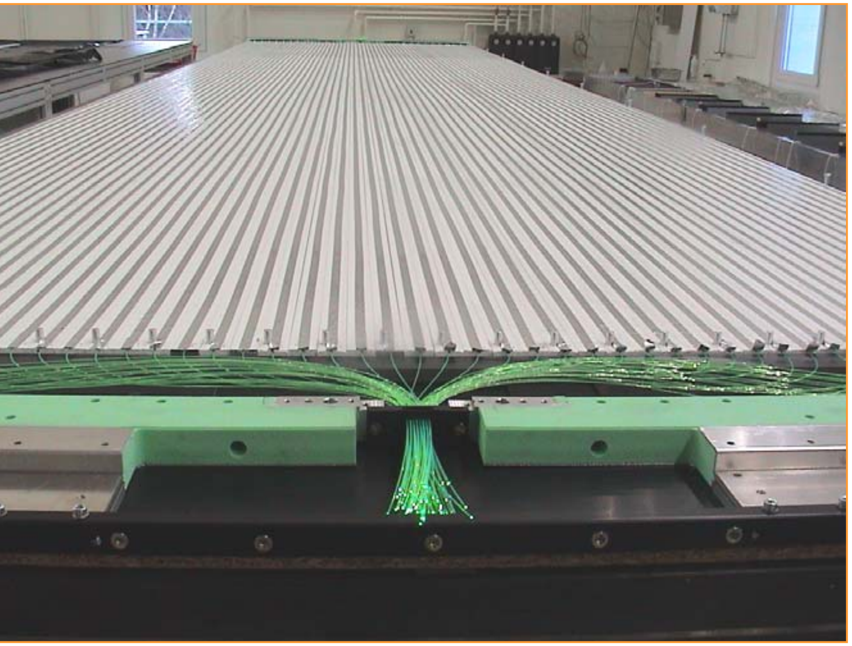
ε_{brick} = 70-80%



Scintillator signals

Target tracker Wall 0 construction at Strasbourg



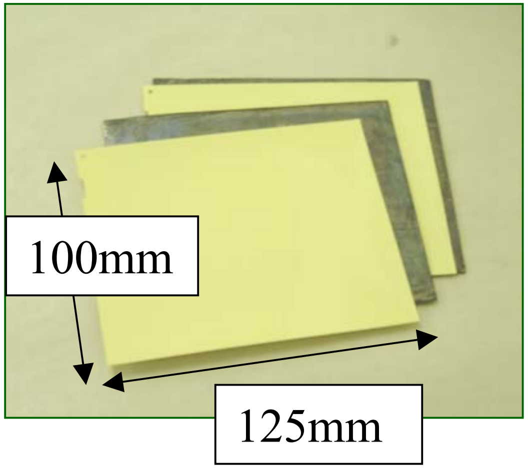


First TT vertical plane

production: 8 modules / week
Delivery and installation at LNGS:
starts february 2004

Fuji Emulsion Films

- **Mass production started April 2003 (~150 000 m^2)** rate: 8000 m^2/month
- Refreshing done in the Tono Mine in Japan to erase cosmic ray tracks before transportation
- One batch sent to LNGS every 2 months starting august 2003



Lead

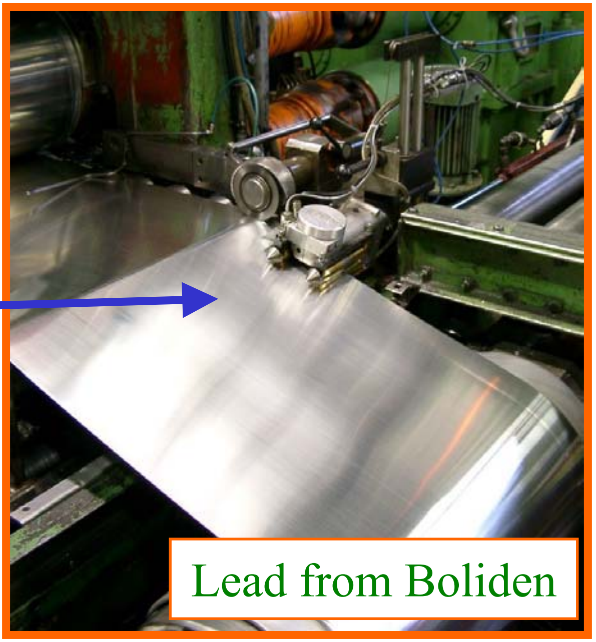
Low radioactivity lead (Boliden) Pb +0.7 % Ca

•No surface treatment needed : emulsion compatible with lubricant traces

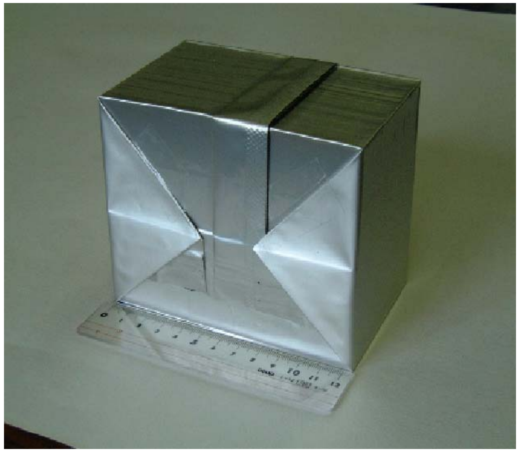
•Thickness control: 1030 µm +– 10µm)

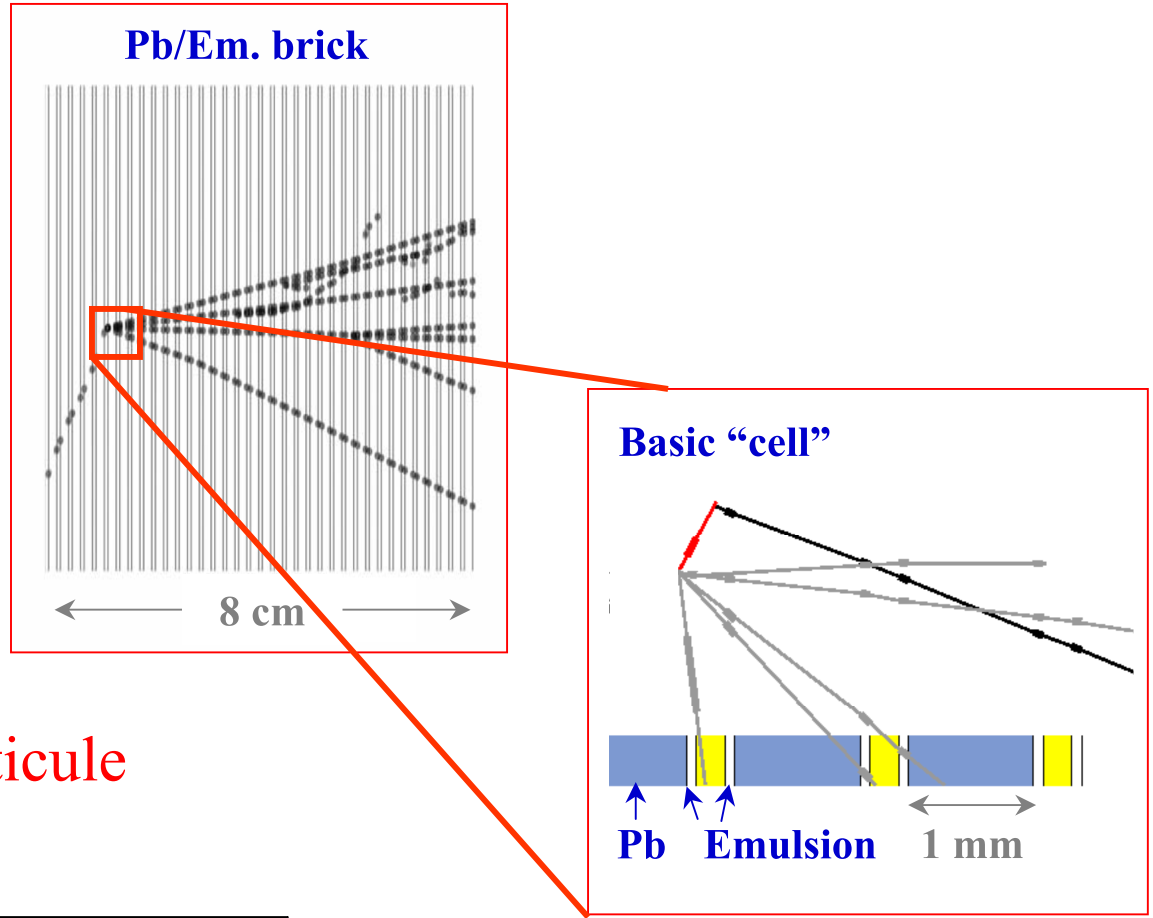
ready for prototype mass production in Goslar (Germany)

(~10^7 plates to be produced for OPERA)



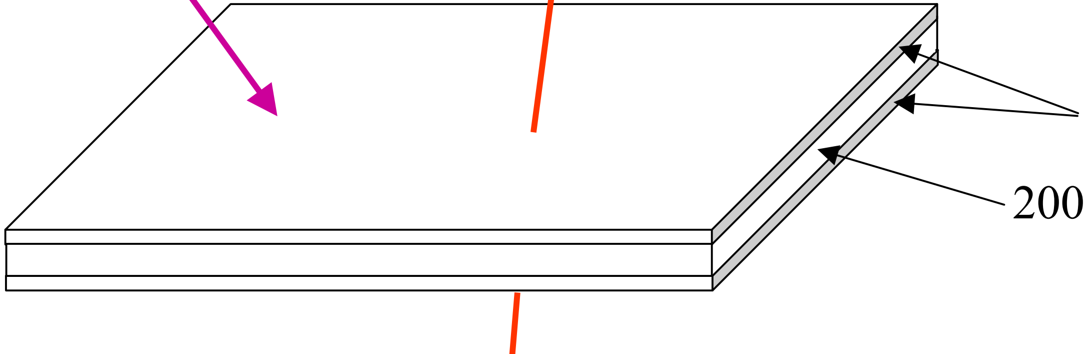
L’analyse des briques et des émulsions:





particule

1 film d’émulsion:

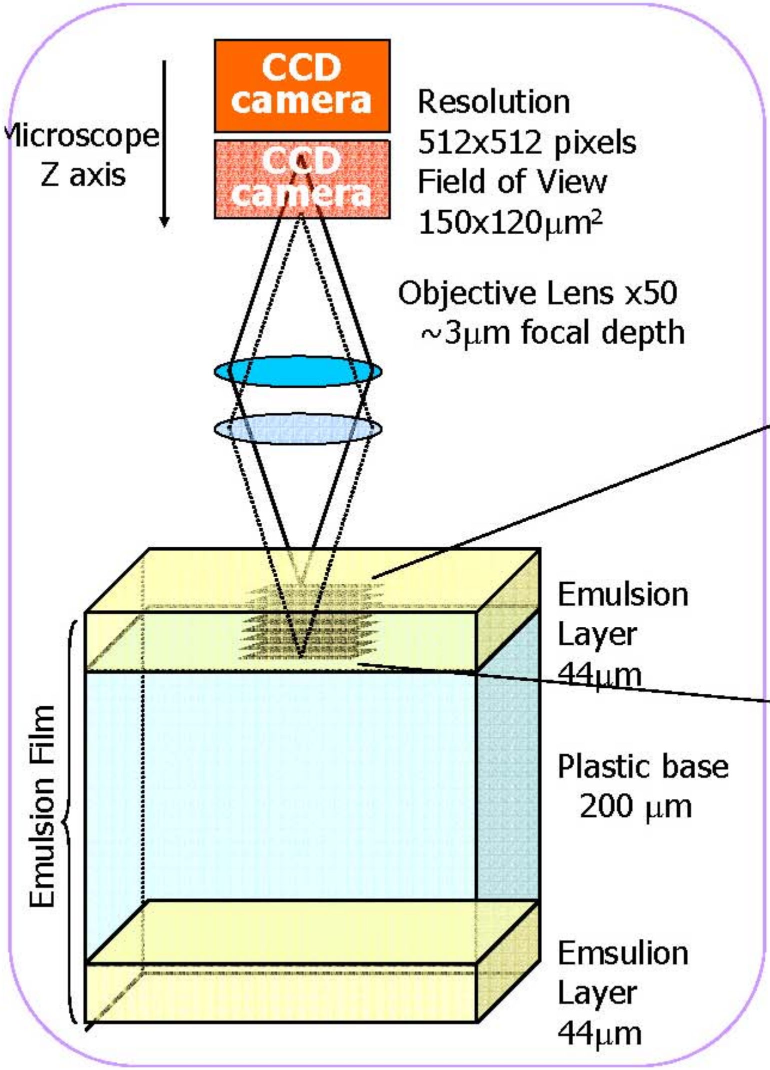


50µm couches emulsion

200µm base plastique

T.Nakano(Nagoya Univ.
R&D @ Nagoya

Film Read-out **Principle**



Microscope
Z axis

CCD camera

CCD camera

Resolution
512x512 pixels
Field of View
150x120µm²

Objective Lens x50
~3µm focal depth

Emulsion Film

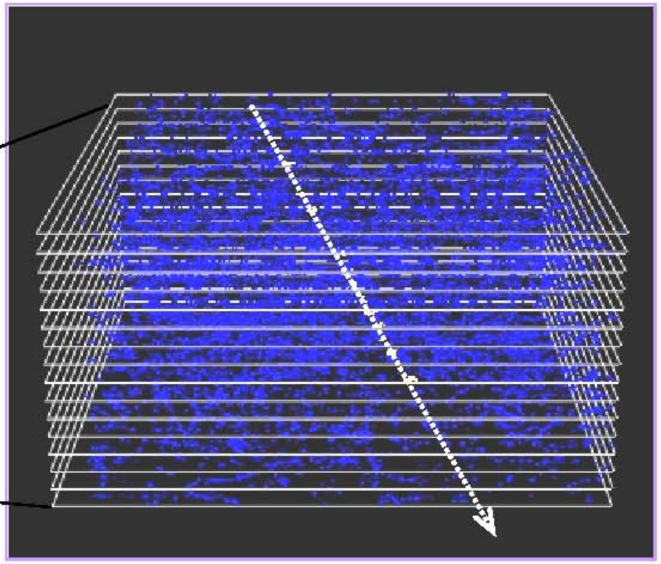
Emulsion
Layer
44µm

Plastic base
200 µm

Emsulion
Layer
44µm

3D digitised Emulsion layer image

(16 two-dimensional images
of different focal positions.)



Search for aligned grains

(straight-lines) .

⇩ output

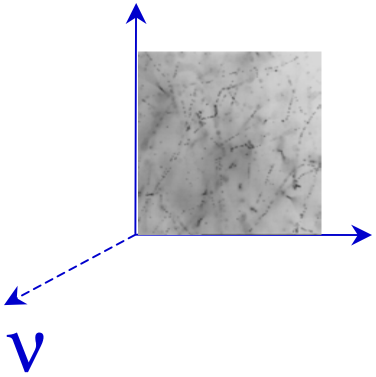
Track info: Position and Angle

Slide from M. Nakamura @ NOON2003

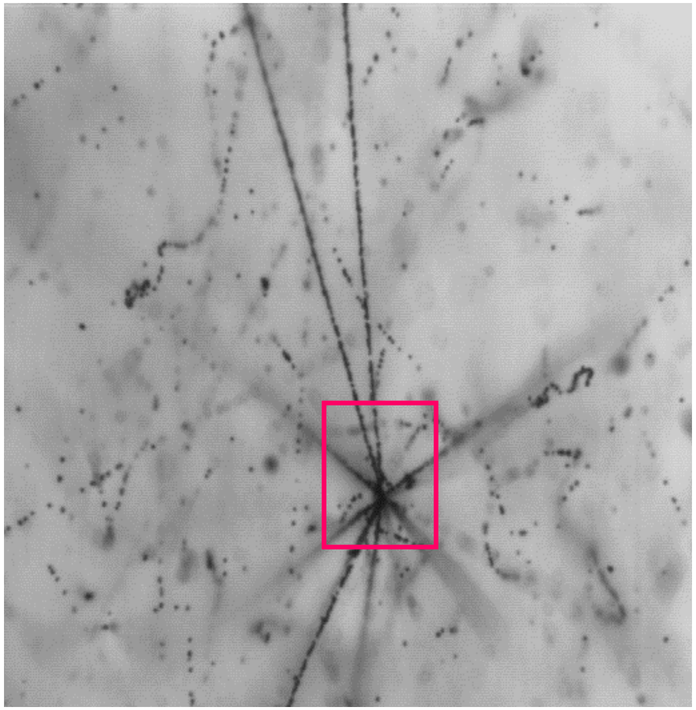
Principe: déplacé le plan focal jusqu’au vertex d’interaction ν

Les particules produites dans les interactions ν sortent de l’image

Les traces intéressantes apparaissent comme des points



Le déplacement du plan focal a travers l’épaisseur de l’émulsion donne la 3eme dimension.

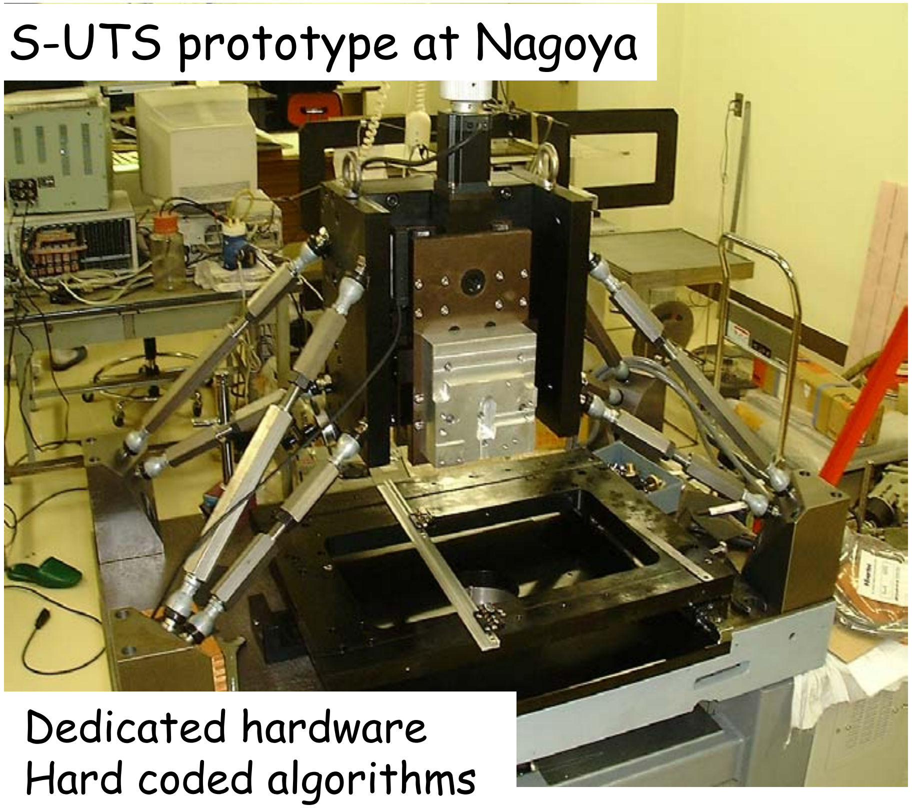


← 0.1 mm →

“tranches tomographiques” de profondeur focale ~ 0.005 mm

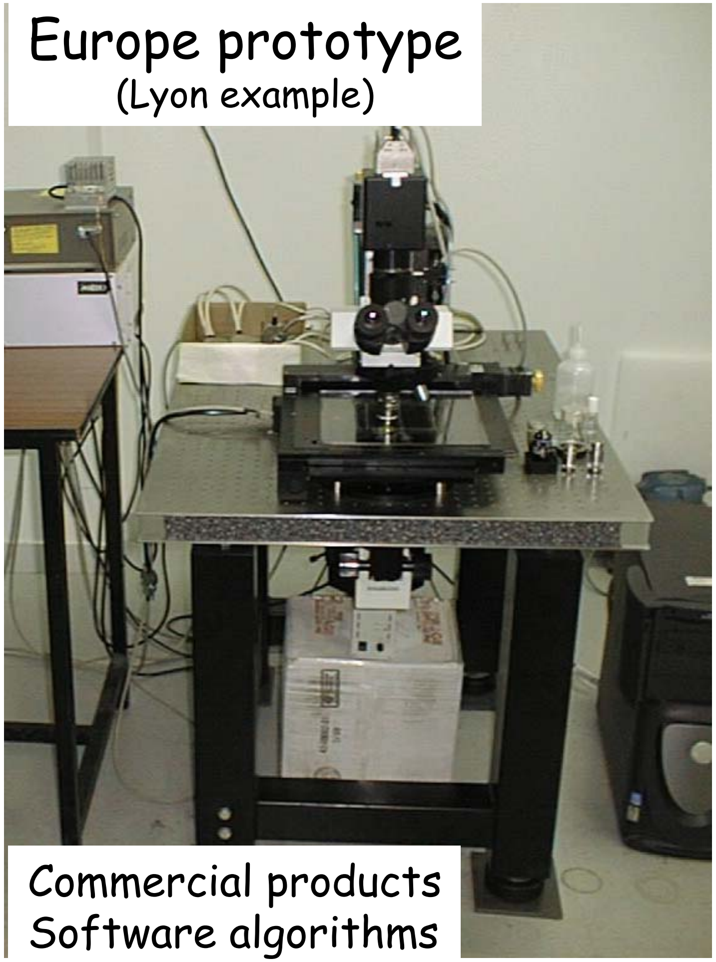
Automatic Scanning: Nagoya and Europe R&D efforts

Bari, Bern, Bologna, Lyon, Münster, Napoli, Roma, Salerno



S-UTS prototype at Nagoya

Dedicated hardware
Hard coded algorithms



Europe prototype
(Lyon example)

Commercial products
Software algorithms

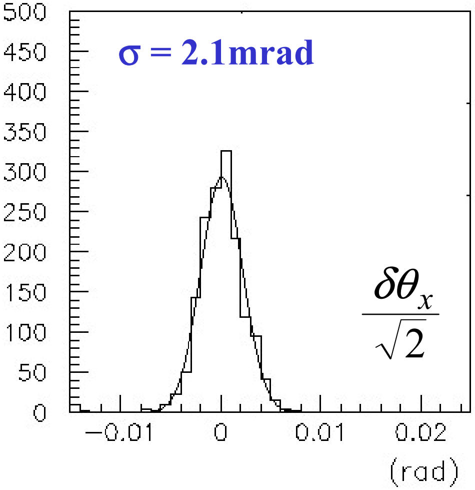
Actual speed $\geq 5\ \mathrm{cm}^2/\mathrm{hr}$; Near future $\geq 20\ \mathrm{cm}^2/\mathrm{hr}$

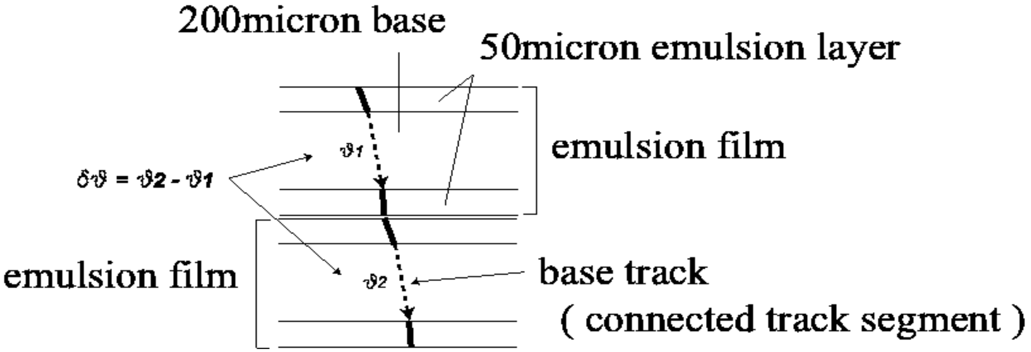
Emulsion bricks: 3-d tracker with sub-micron accuracy

Flow: Brick removal → cosmic exposure → development → scanning →analysis: vertex search → decay search → e/γ ID, kinematics

Tracking resolution:

intrinsic tracking accuracy: σ = 0.06 μm





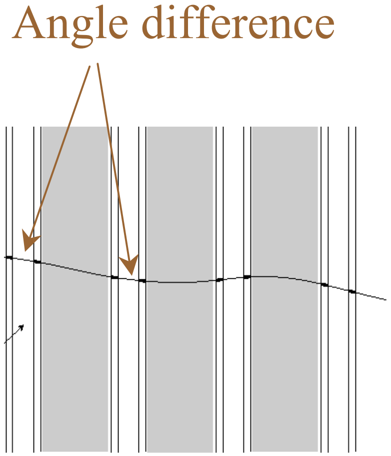
σ (angle) = 2.1 mrad σ (position) = 0.3 μm

(limited by digitisation error in image processing)

Momentum measurement:

by Multiple Coulomb Scattering in lead sheets:

$\Delta p/p < 0.2$ after $5X_0$ up to 4 GeV

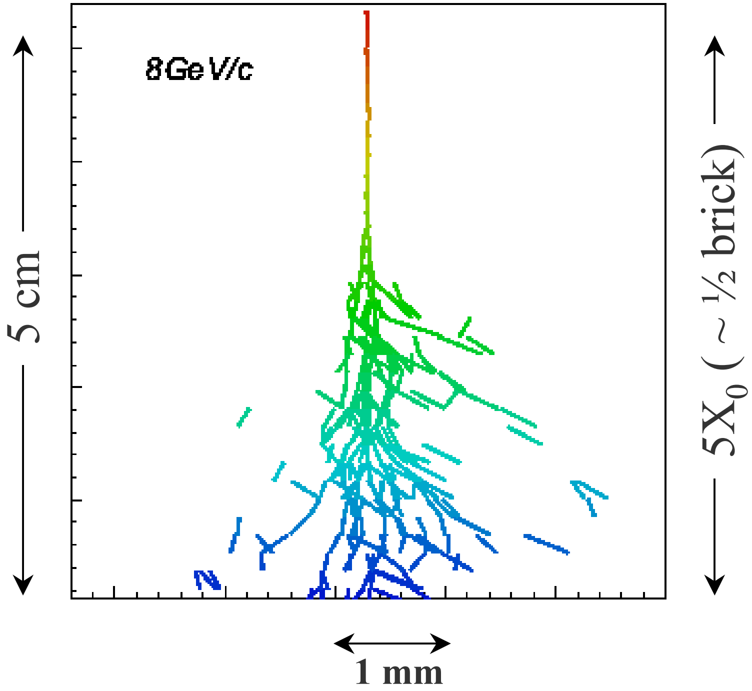


Emulsion bricks:

Electron Identification

- Method based on shower identification and on MCS of the track (e and π losses different)
- $\varepsilon_e \sim 90\ \%$,

TEST experiment at CERN PS



Energy measurement

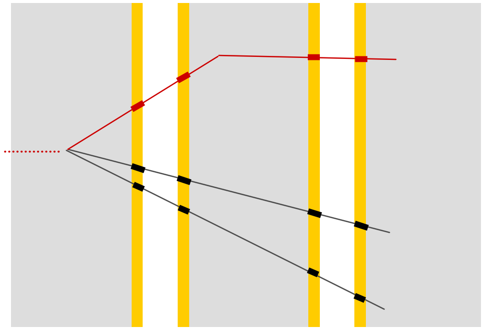
- count the number of track segments into a cone of 50 mrad along the electron track
- Resolution $\boxed{\frac{\sigma}{E} = \frac{40\%}{\sqrt{E}}}$ @ few GeV

→ Excellent capabilities for $\tau \rightarrow e$ decays and search for $\nu_\mu \rightarrow \nu_e$ appearance

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

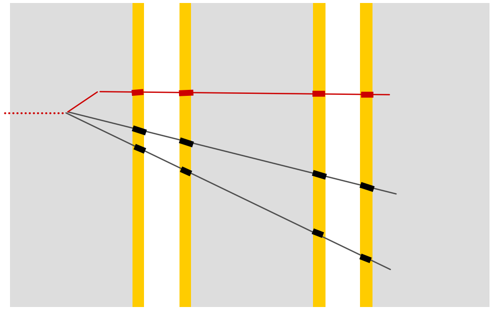
Exploited τ decay channels

τ → e “ long decays ”
τ → μ “ long decays ”
τ → h “ long decays ”
ε.BR = 2.8-3.5%



kink angle
$\theta_{kink} > 20$
mrad

τ→ e “ short decays ”
τ → μ “ short decays ”
ε.BR = 0.7-1%



impact
parameter
I.P. > 5 to
20 μm

Expected number of background events after 5 years:

	τ→e	τ→μ	τ→h	total
Charm background	.313	.017	.243	.573
Large angle μ scattering		.174		.174
Hadronic background		.139	.174	.313
Total per channel	.313	.330	.417	1.060

$\nu_\mu \to \nu_\tau$ search

full mixing, 5 years run @ 6.76x10^{19} pot / year

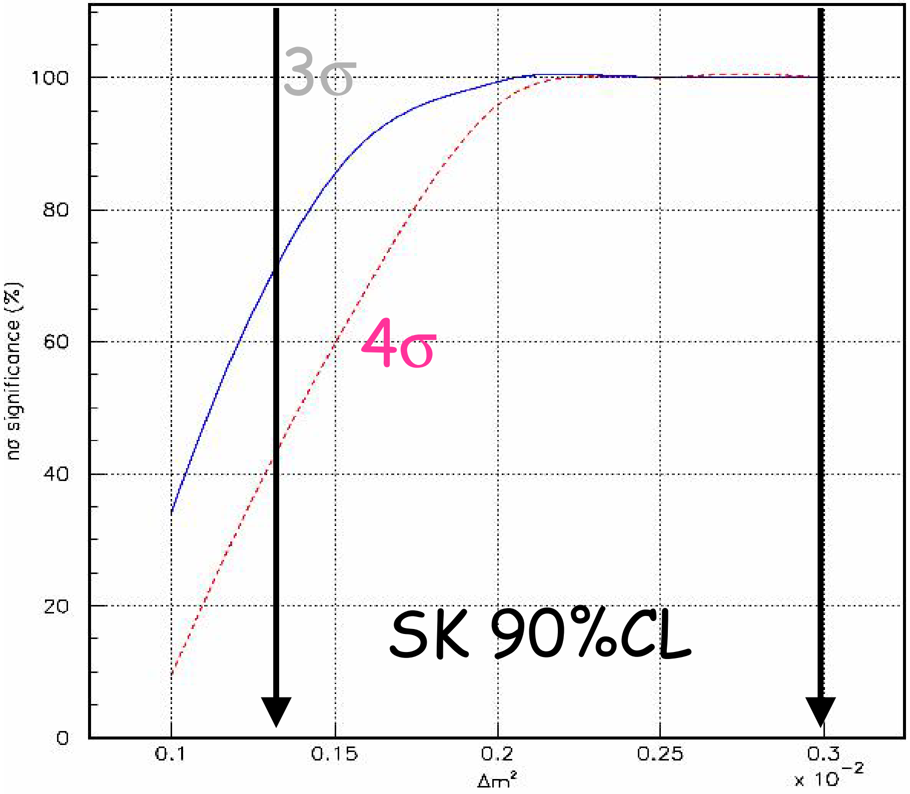
channel	Signal (Δm^2 (eV^2))			ε.BR	Background
	1.3 10^{-3}	2.0 10^{-3}	3.0 10^{-3}		
e	1.8	4.1	9.2	3.4%	0.31
μ	1.4	3.4	7.6	2.8%	0.33
h	1.5	3.5	7.8	2.9%	0.42
total	4.7	11.0	24.6	9.1%	1.06

5 YEARS

Nσ significance probability as a function of Δm^2

Possible future improvements:

- Changeable sheet: increase efficiency by 10-15%
- improve π/μ id. (low p) using dE/dx vs range: reduce the charm background by 40%



$\nu_\mu \rightarrow \nu_e$ search:

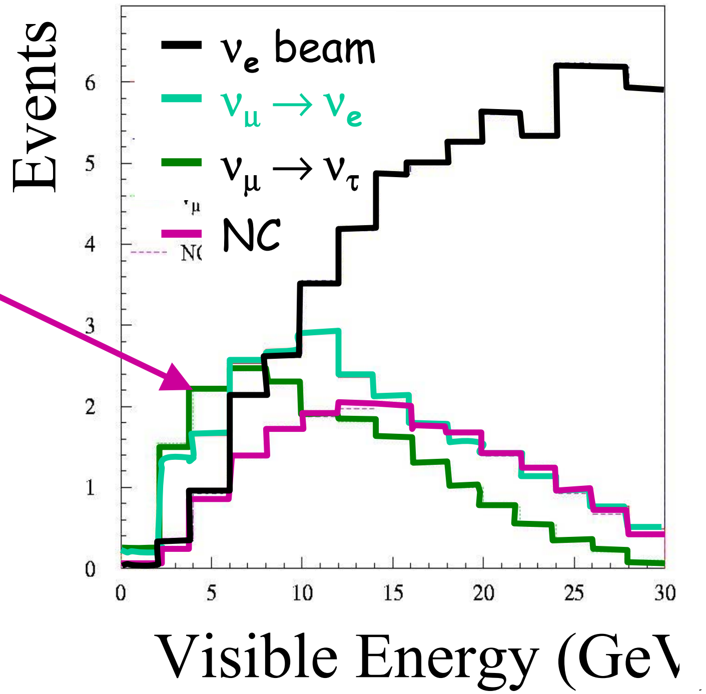
Assuming $\Delta m_{12}^2 << \Delta m_{23}^2 = \Delta m_{13}^2 = \Delta m^2$, in the 3 flavour ν oscillation framework

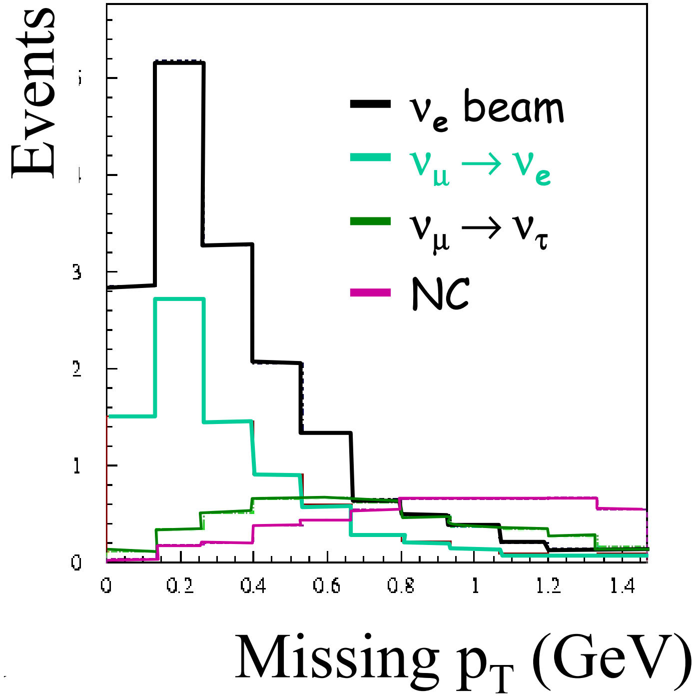
$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\, \Delta m^2\, L/E)$

$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\, \Delta m^2\, L/E)$ ← subleading transition

- look for an excess of ν_e CC events
- take into account electron event from $\nu_\mu \rightarrow \nu_\tau$, $\tau \rightarrow e \nu_\tau \nu_e$

Both oscillations distort E_{vis} at low energy





Fit oscillation components simultaneously

→ $\sin^2 2\theta_{13}$

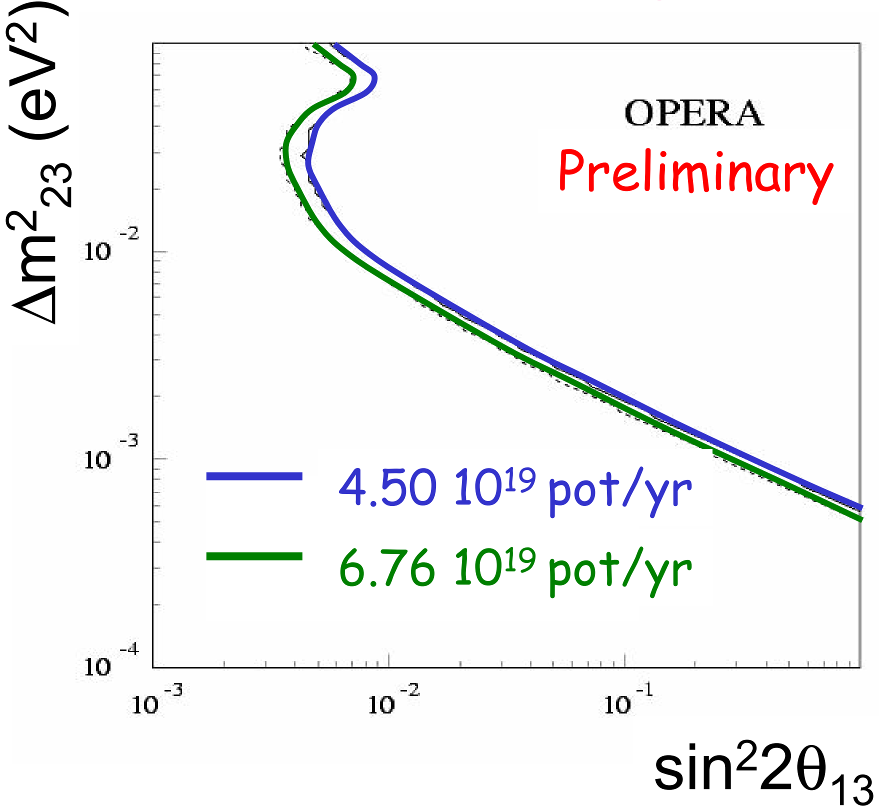
use E_{vis}, P_T^{miss}, E_{el}

$\nu_\mu \rightarrow \nu_e$ expected signal and background 5 years: 2.25×10^{20} pot

θ_{13} (deg)	$\sin^2 2\theta_{13}$	Signal $\nu_\mu \to \nu_e$	$\nu_\mu \to \nu\tau$, $\tau \to e\nu_\tau\nu_e$	ν_μ CC	ν_μ NC	ν_e CC
9	0.095	9.3	4.5	1.0	5.2	18
7	0.058	5.8	4.6	1.0	5.2	18
5	0.030	3.0	4.6	1.0	5.2	18

syst. on the ν_e contamination up to 10%

OPERA sensitivity to θ_{13}



Limits at 90% CL for
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 full mixing

	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	**<0.14**	**11^0**
OPERA	**<0.06**	**7.1^0**

Improve the CHOOZ limit

The ICARUS Collaboration

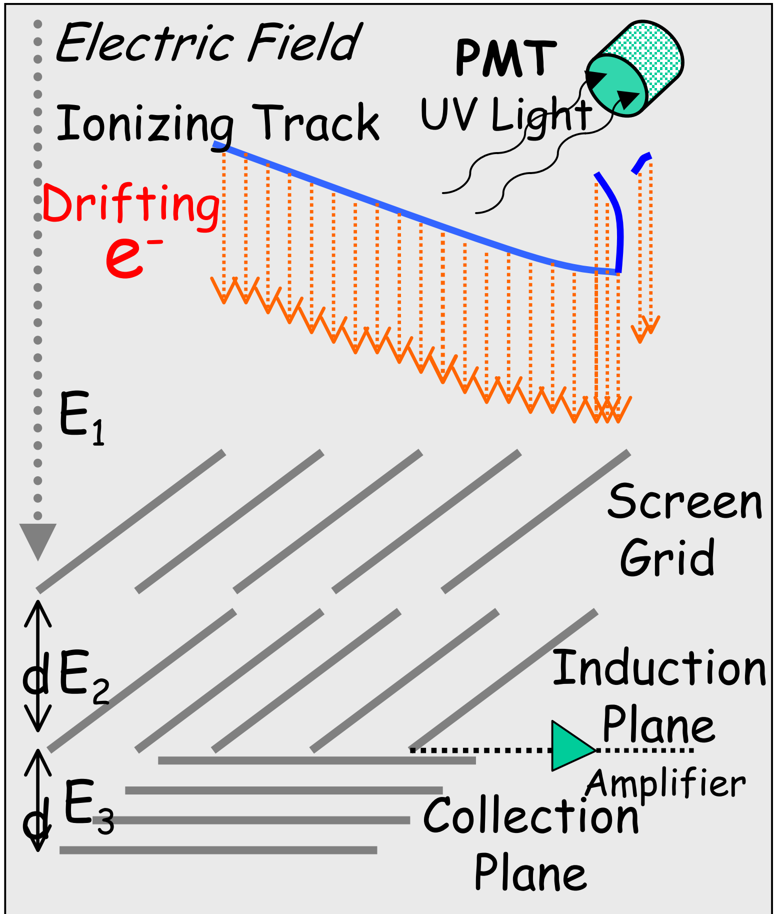
S. Amoruso, P. Aprili, F. Arneodo, B. Babussinov, B. Badelek, A. Badertscher, M. Baldo-Ceolin, G. Battistoni, B. Bekman, P. Benetti, A. Borio di Tigliole, M. Bischofberger,
R. Brunetti, R. Bruzzese, A. Bueno, E. Calligarich,D. Cavalli, F. Cavanna, F. Carbonara,
P. Cennini, S. Centro, A. Cesana, C. Chen, Y. Chen, D. Cline, P. Crivelli,A.G. Cocco,
A. Dabrowska, Z. Dai, M. Daszkiewicz, A. Di Cicco, R. Dolfini, A. Ereditato, M. Felcini,
A. Ferrari, F. Ferri, G. Fiorillo, S. Galli, Y. Ge, D. Gibin, A. Gigli Berzolari, I. Gil-Botella,
A. Guglielmi, K. Graczyk, L. Grandi, X. He, J. Holeczek, C. Juszczak, D. Kielczewska,
J. Kisiel, L. Knecht, T. Kozlowski, H. Kuna-Ciskal, M. Laffranchi, J. Lagoda, B. Lisowski,
F. Lu, G. Mangano, G. Mannocchi, M. Markiewicz, F. Mauri, C. Matthey, G. Meng,
M. Messina, C. Montanari, S. Muraro, G. Natterer, S. Navas-Concha, M. Nicoletto,
S. Otwinowski, Q. Ouyang, O. Palamara, D. Pascoli, L. Periale, G. Piano Mortari,
A. Piazzoli, P. Picchi, F. Pietropaolo, W. Polchlopek, T. Rancati, A. Rappoldi, G.L. Raselli, J. Rico, E. Rondio, M. Rossella, A. Rubbia, C. Rubbia, P. Sala, R. Santorelli,
D. Scannicchio, E. Segreto, Y. Seo, F. Sergiampietri, J. Sobczyk, N. Spinelli, J. Stepaniak, M. Stodulski,
M. Szarska, M. Szeptycka, M. Terrani, R. Velotta, S. Ventura, C. Vignoli,
H. Wang, X. Wang, M. Wojcik, X. Yang, A. Zalewska, J. Zalipska, P. Zhao, W. Zipper.

ITALY: L'Aquila, LNF, LNGS, Milano, Napoli, Padova, Pavia, Pisa, CNR Torino, Pol. Milano.
SWITZERLAND: ETHZ Zürich.
CHINA: Academia Sinica Beijing.
POLAND: Univ. of Silesia Katowice, Univ. of Mining and Metallurgy Krakow, Inst. of Nucl. Phys. Krakow, Jagellonian Univ. Krakow, Univ. of Technology Krakow, A.Soltan Inst. for Nucl. Studies Warszawa, Warsaw Univ., Wroclaw Univ.
USA: UCLA Los Angeles.
SPAIN: Univ. of Granada.

ICARUS:

Principle: 3D imaging in a large volume Liquid Argon TPC

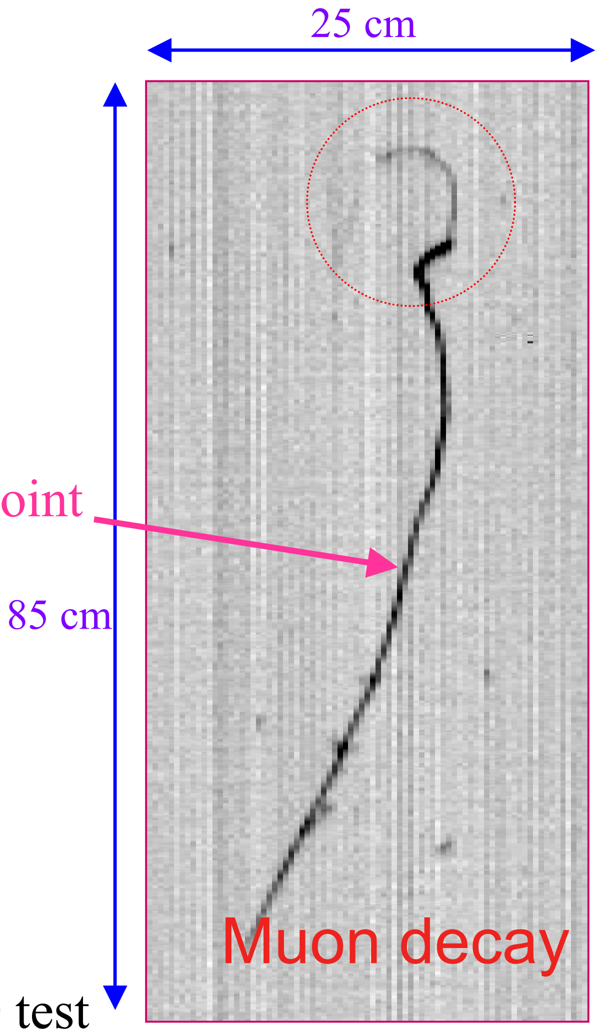
- very pure LAr (<0.1ppb) → electrons can drift over large distances (>1.5 m)
- scintillation light for t_0
- 3 wire planes at 0,+60,-60° with 3mm pitch
- → 3D reconstruction with high resolution



$\sigma_z = 150\,\mu m$

$\sigma_{xy} = 1\,mm$

Energy deposition measured for each point (400 ns sampling)

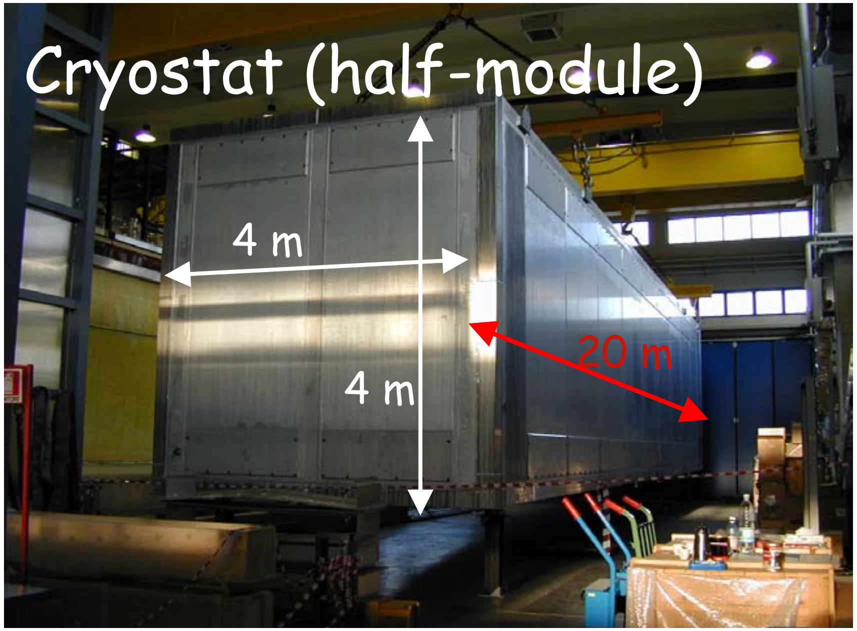


T600 test

Run 960, Event 4 Collection Left

ICARUS design: multi kton device in modular structure

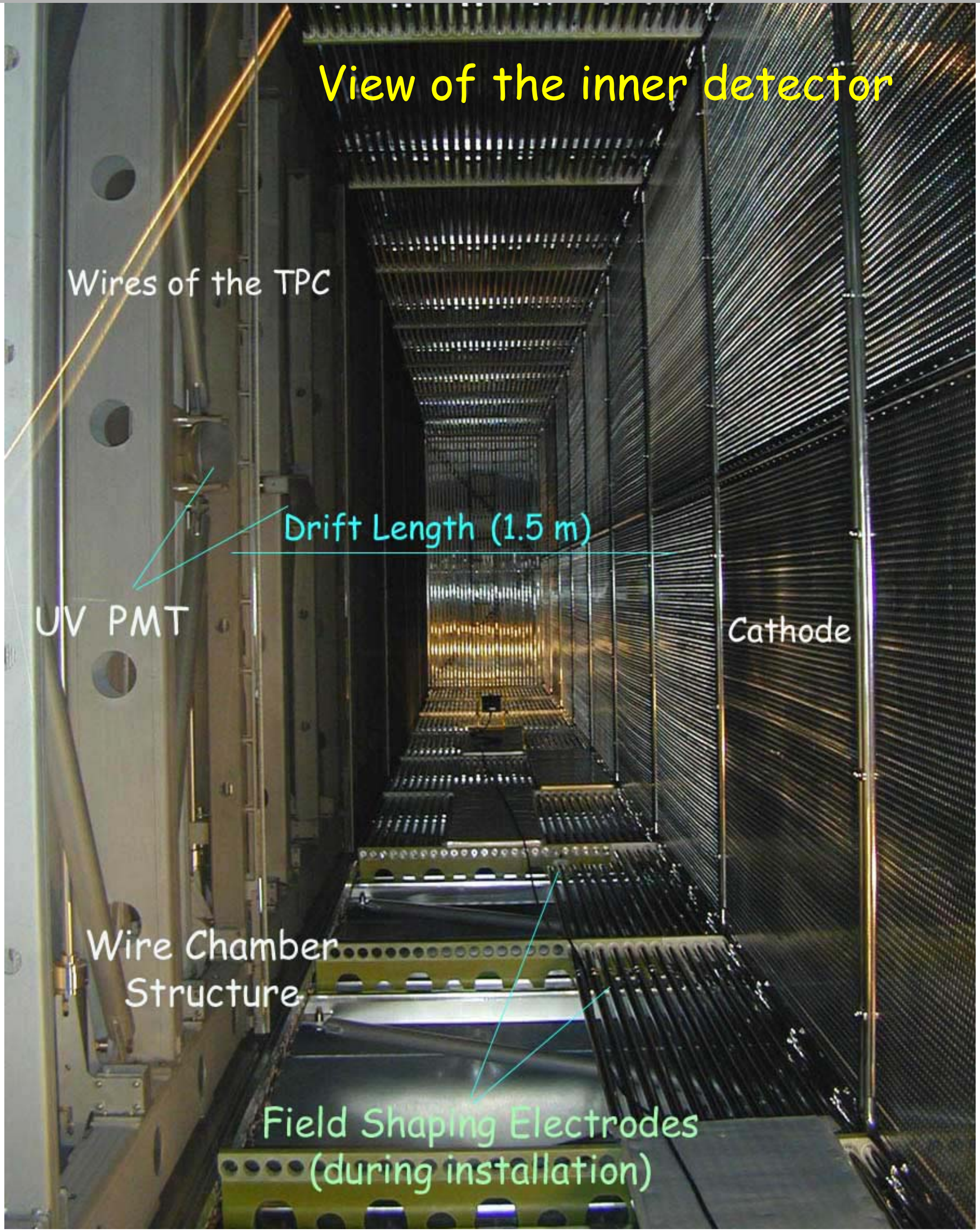
Smallest detector unit: 300 tons (T600 half-module)



1st half T600 succesfully tested during 2001 in Pavia

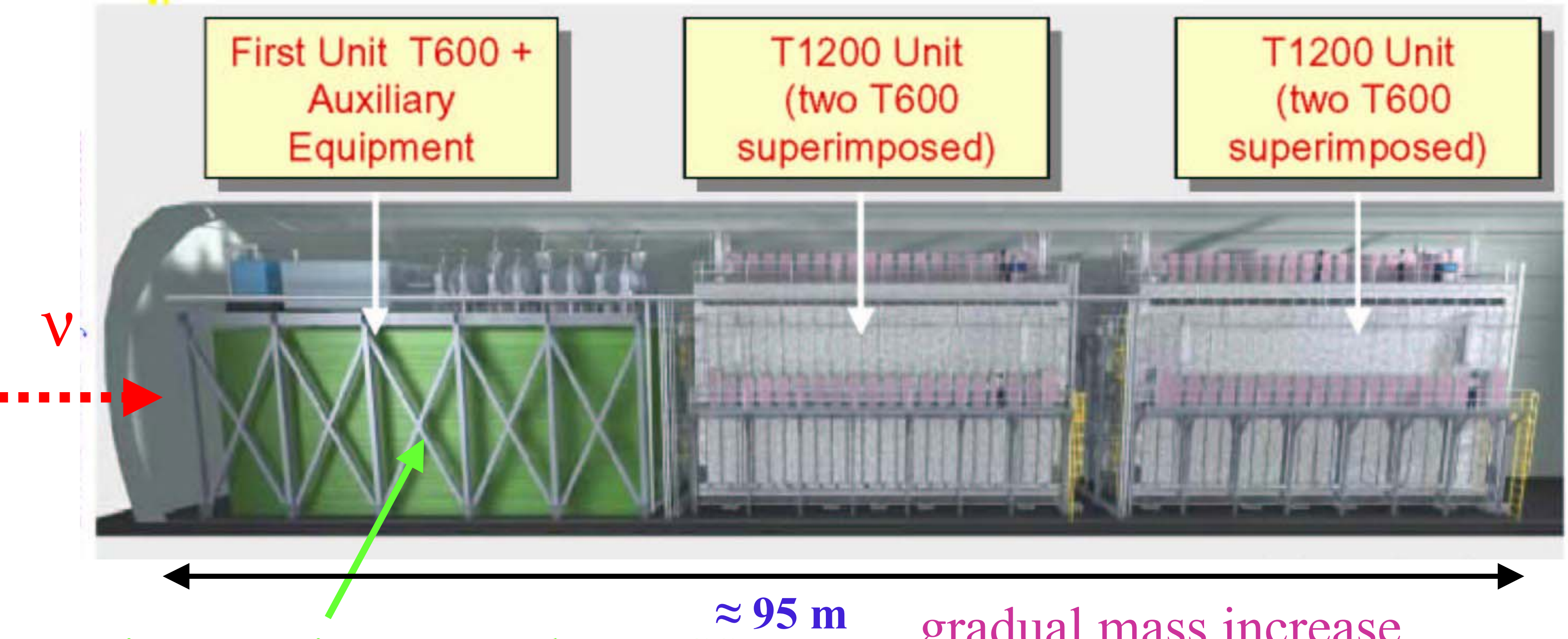
Validate the technology for these large scales

ICARUS T600 prototype



ICARUS T3000 in Gran Sasso (Hall B)

Cloning T600 module to reach a sensitive mass of 2.35ktons



First T600 is transported to LNGS:
to be installed in 2004

collect atmospheric and solar ν
starting from 2004

gradual mass increase

Complete setup should be operational by summer 2006

Physics program: CNGS, solar and atm. ν,
Supernova ν, proton decay

(2.35 kton active, 1.5 kton fiducial)

Detector performance:

EM and hadronic showers are identified and fully sampled

Total energy obtained from charge integration

➡ Excellent calorimeter with very good E resolution

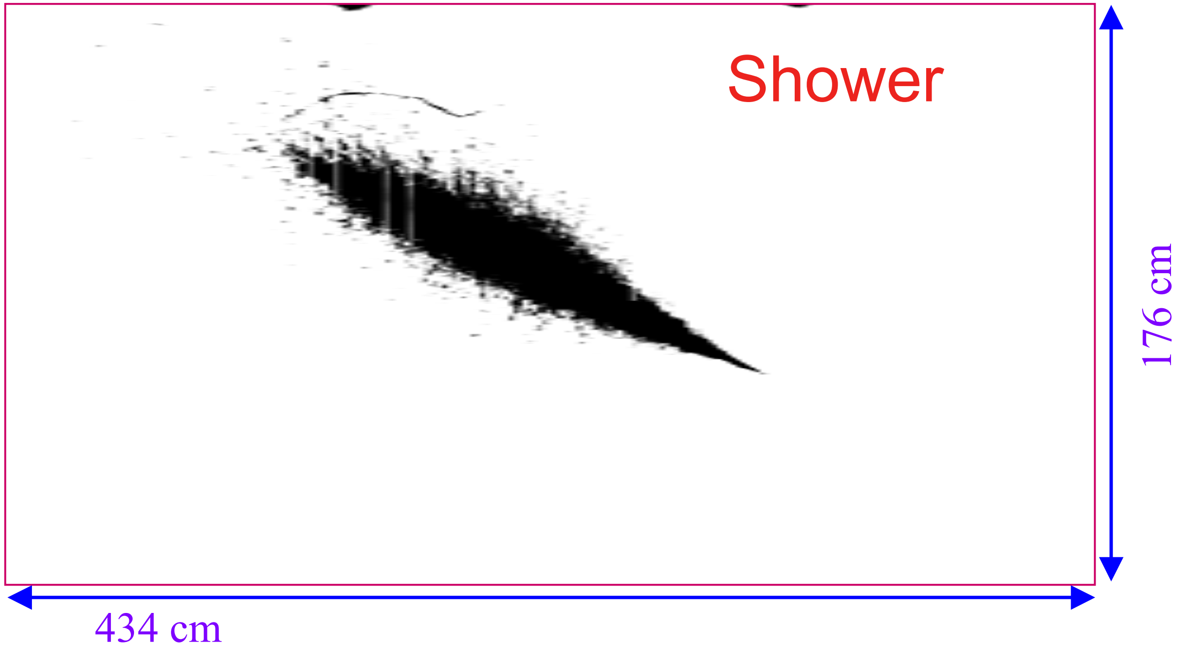
EM showers:

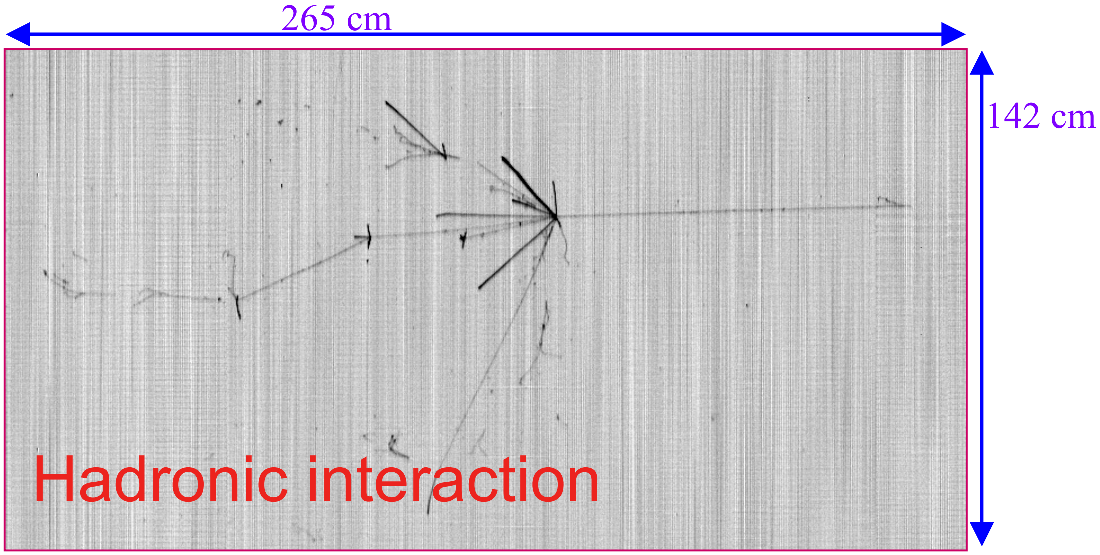
$$\boxed{\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} + 1\%}$$

Hadronic showers:

$$\boxed{\frac{\sigma(E)}{E} = \frac{17\%}{\sqrt{E}} + 1\%}$$

Pictures from T600 technical run:

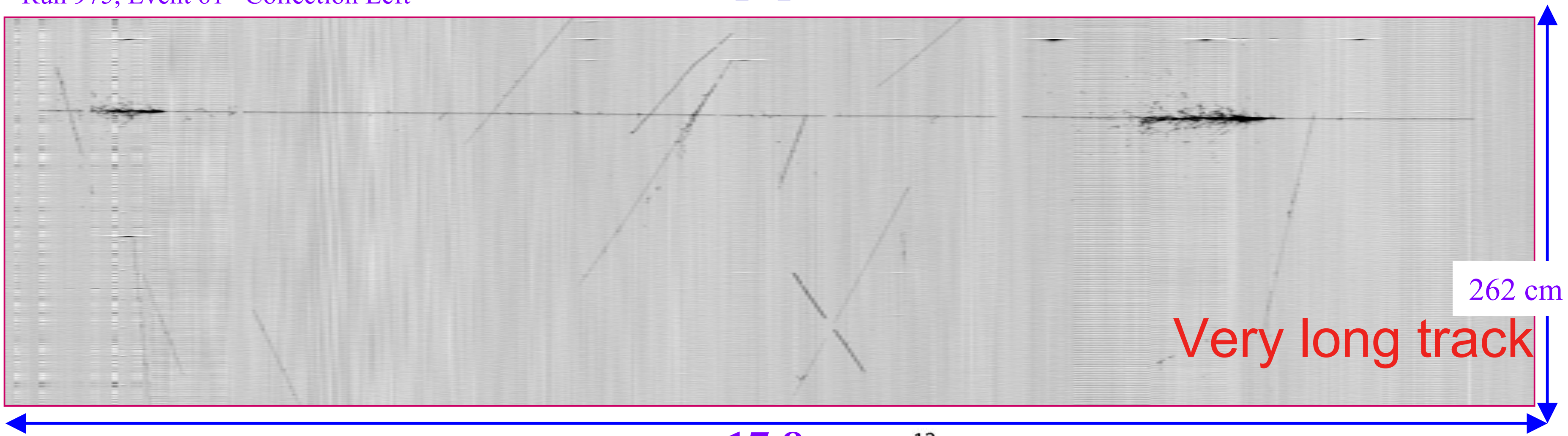




Run 308, Event 160 Collection Left

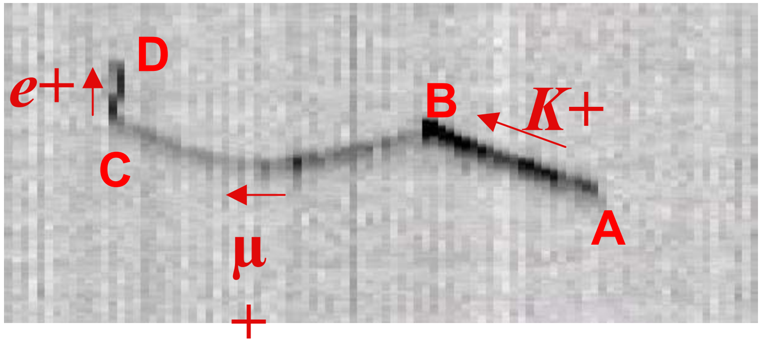
Detector performance:

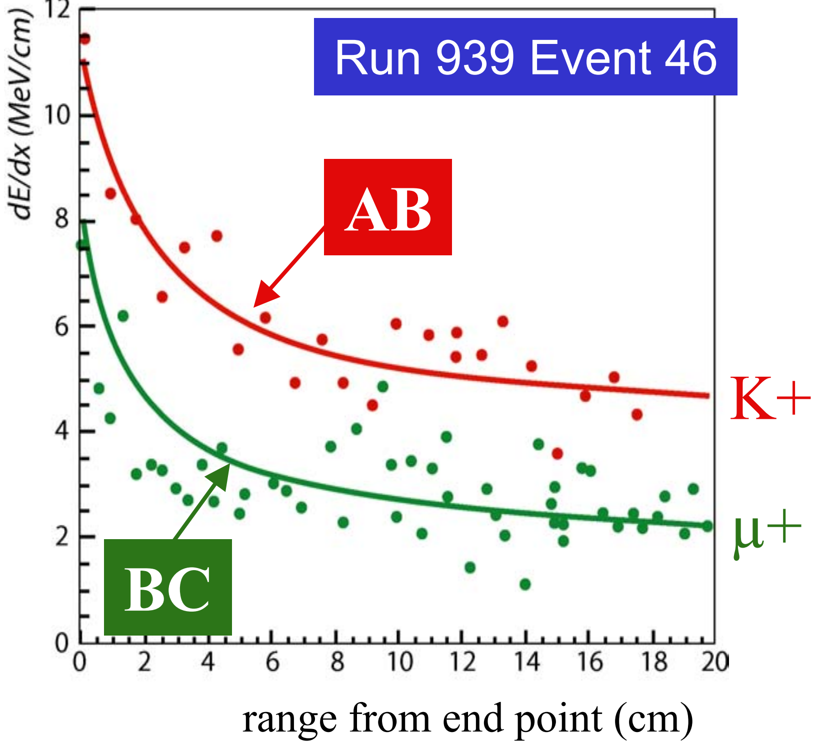
μ momentum measurement by MCS
Δp/p=20% at 10 GeV



Particle identification:
by means of dE/dx vs range

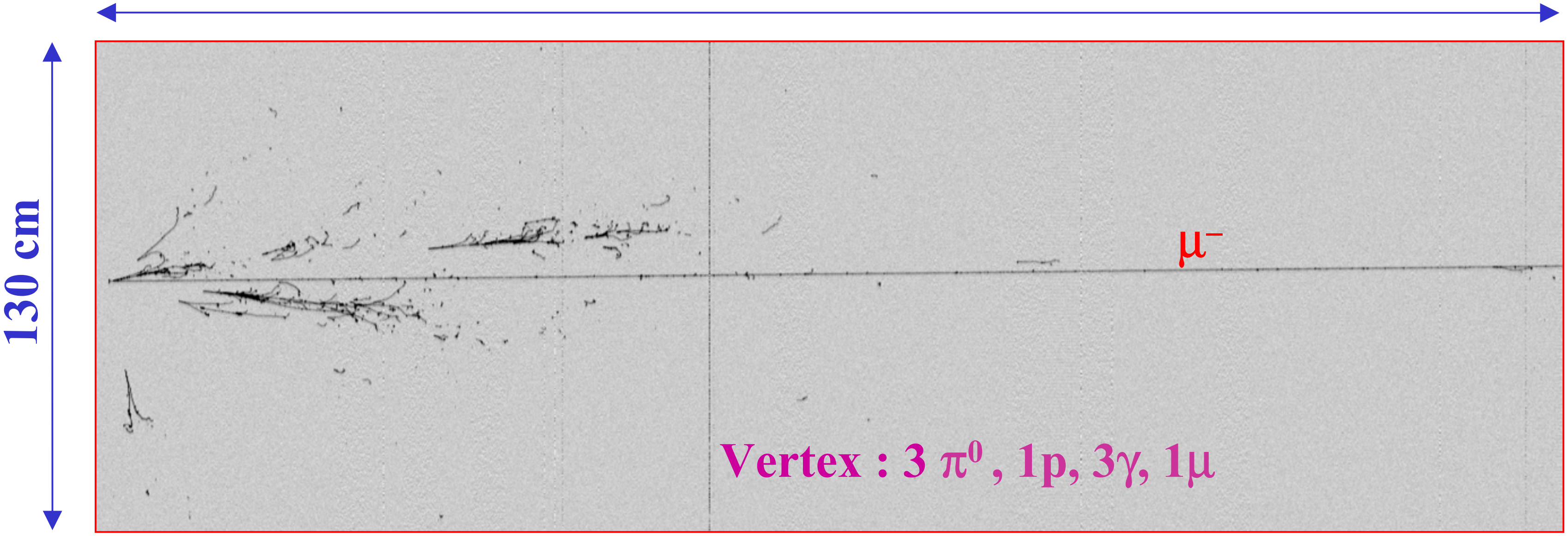
$$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$$





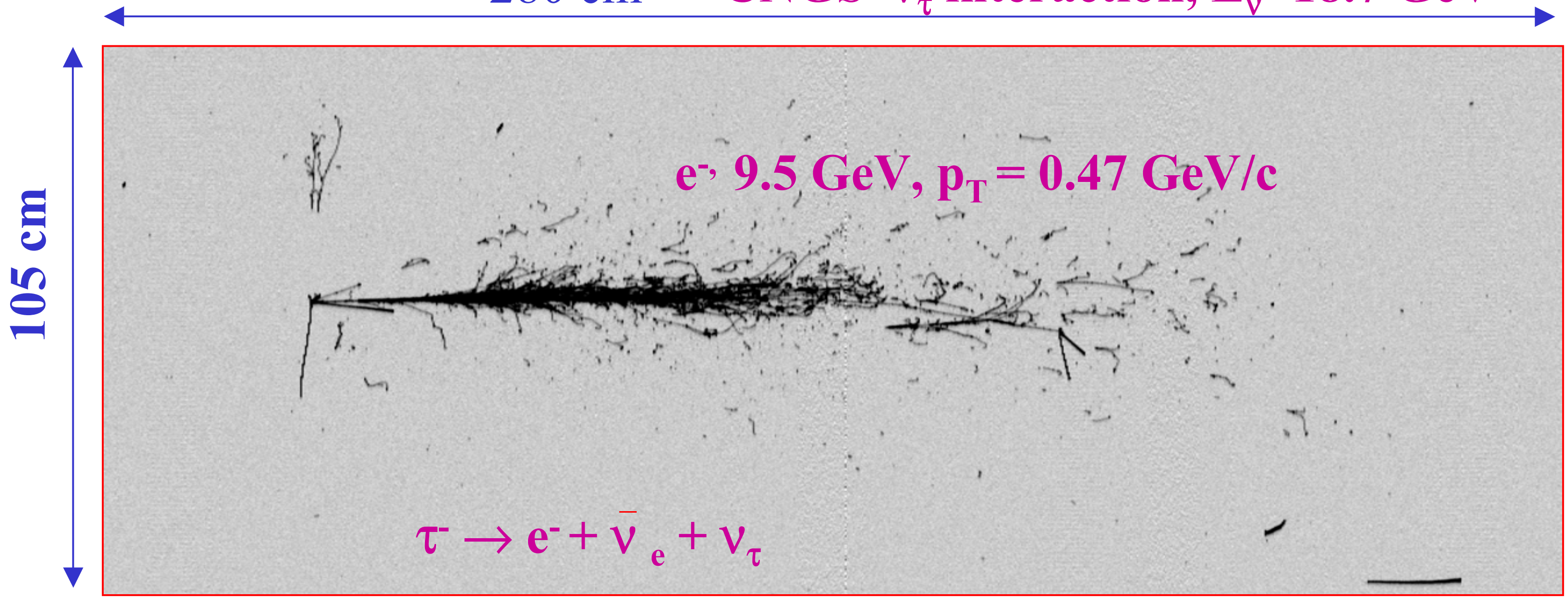
CNGS studies

CNGS ν_μ interaction, E_ν=26 GeV



Vertex : 3 π^0, 1p, 3γ, 1μ

CNGS ν_τ interaction, E_ν=18.7 GeV



e^-, 9.5 GeV, p_T = 0.47 GeV/c

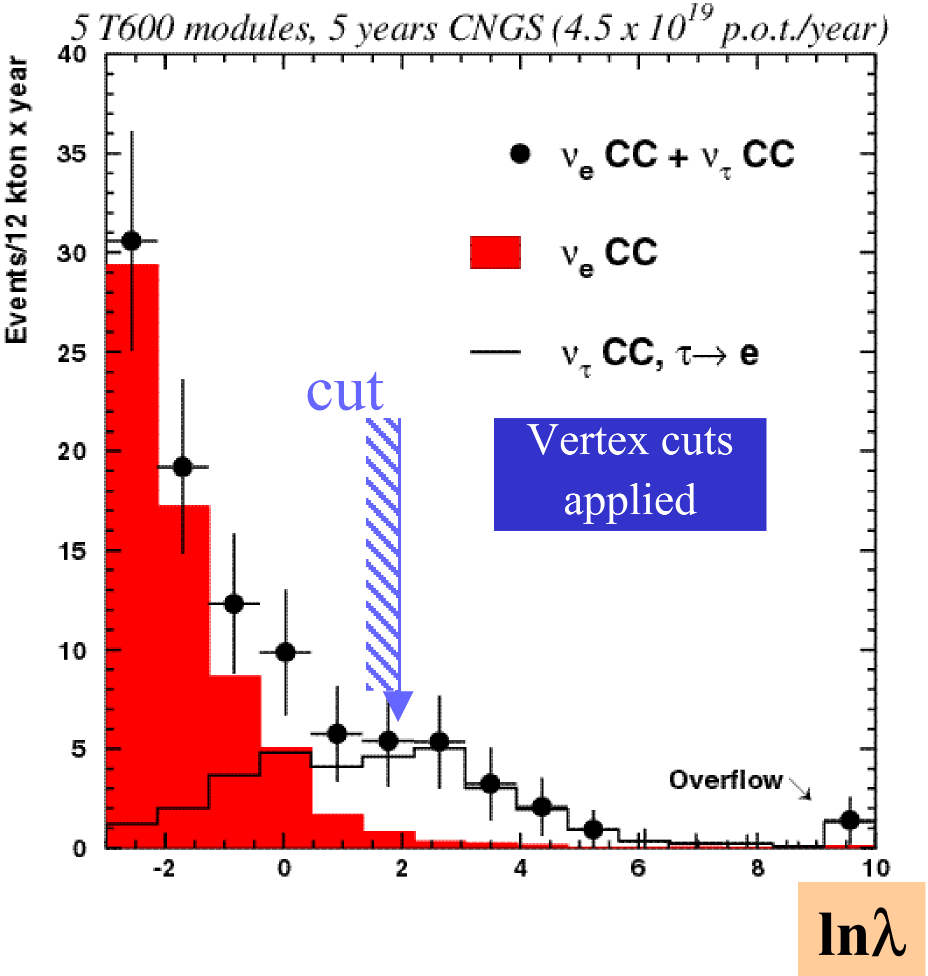
$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$

ICARUS: $\nu_\mu \rightarrow \nu_\tau$ search

golden channel: $\tau \rightarrow e\nu_e\nu_\tau$

Kinematical suppression of the background: ν_eCC from beam

- Analysis based on 3 dimensional likelihood
  - **$E_{visible}$,**
  - **P_T^{miss},** **$\rho_l \equiv P_T^{lep}/(P_T^{lep}+P_T^{had}+P_T^{miss})$**
  - **Exploit correlation between variables**
  - Two functions built:
    - L_S ([Evisible, P_T^{miss}, ρ_l]) (signal)
    - L_B ([Evisible, P_T^{miss}, ρ_l]) (ν_e CC background)
  - Discrimination given by



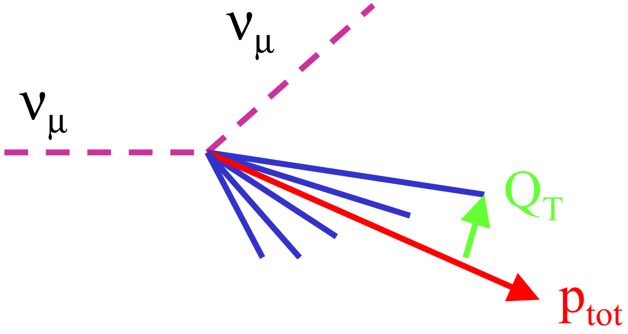
$$\ln\lambda \equiv L([\text{Evisible}, P_T^{miss}, \rho_l]) = L_S / L_B$$

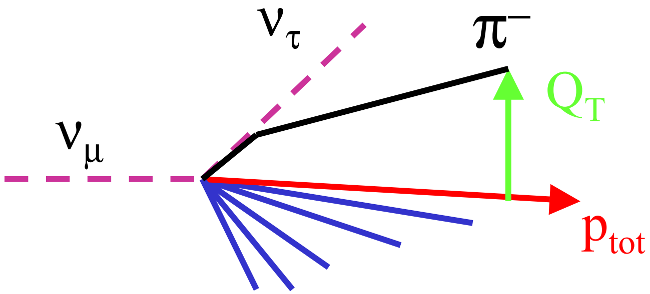
ICARUS: $\nu_\mu \rightarrow \nu_\tau$ search

other channel: $\tau \rightarrow \rho\nu_\tau$ with $\rho^- \rightarrow \pi^-\pi^o$

main background: ν_μ NC → missing p_t

use isolation criteria: Q_T





T3000 detector (2.35 kton active LAr)

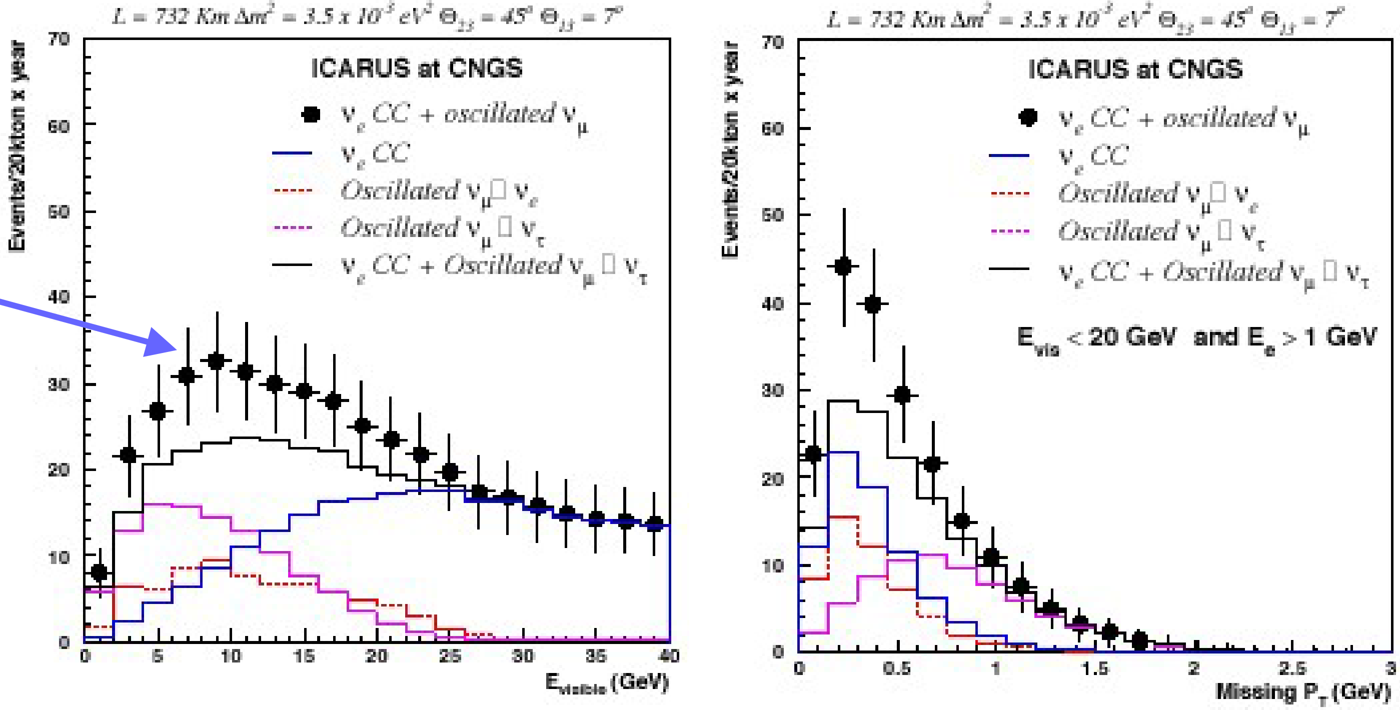
5 years: 2.25×10^{20} pot

channel	Signal (Δm^2 (eV^2))			ε.BR	Background
	$1.6\ 10^{-3}$	$2.5\ 10^{-3}$	$4.0\ 10^{-3}$		
e	3.7	9.0	23	4.4%	0.7
ρ DIS	0.6	1.5	3.9	0.8%	<0.1
ρ QE	0.6	1.4	3.9	0.7%	<0.1
total	4.9	11.9	30.5	5.9%	0.7

SIMILAR SENSITIVITY AS OPERA

$\nu_\mu \rightarrow \nu_e$ search:

- look for an excess of ν_e CC events
- take into account electron event from $\nu_\mu \rightarrow \nu_\tau$, $\tau \rightarrow e\nu_\tau\nu_e$



Both oscillations distort E_{vis} at low energy

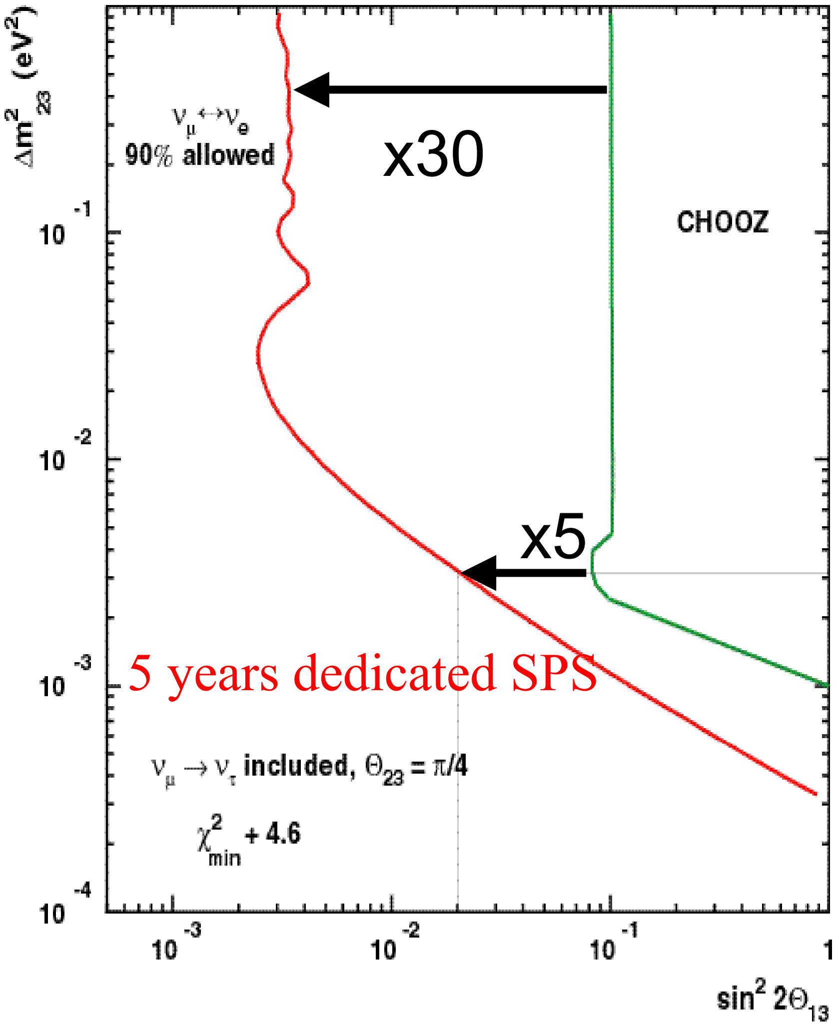
Fit 2 oscillation components simultaneously

$\sin^2 2\theta_{13}$

use E_{vis}, P_T^{miss}, P_T^{el}

Expected sensitivity to θ_{13}

ICARUS T3000



Preliminary studies from OPERA

5 years: 2.25×10^{20} pot

θ_{13} (deg)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu\tau$, $\tau \to e\nu_\tau\nu_e$	Signal $\nu_\mu \to \nu_e$
9	0.095	50	24	27
7	0.058	50	24	16
5	0.030	50	25	8.4

Limits at 90% CL for
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 full mixing

	$\sin^2 2\theta_{13}$	θ_{13}
ICARUS	**<0.04**	**5.8^0**
OPERA	**<0.06**	**7.1^0**
CHOOZ	**<0.14**	**11^0**

Improve the CHOOZ limit

LNGS Hall B: where is ICARUS ?

Conclusions

CNGS beam: on schedule → expect to start in june 2006

OPERA: work in progress to be ready by 2006

ICARUS: successful demonstration of the principle withT600
T3000 version estimated for 2006

Physics with CNGS:

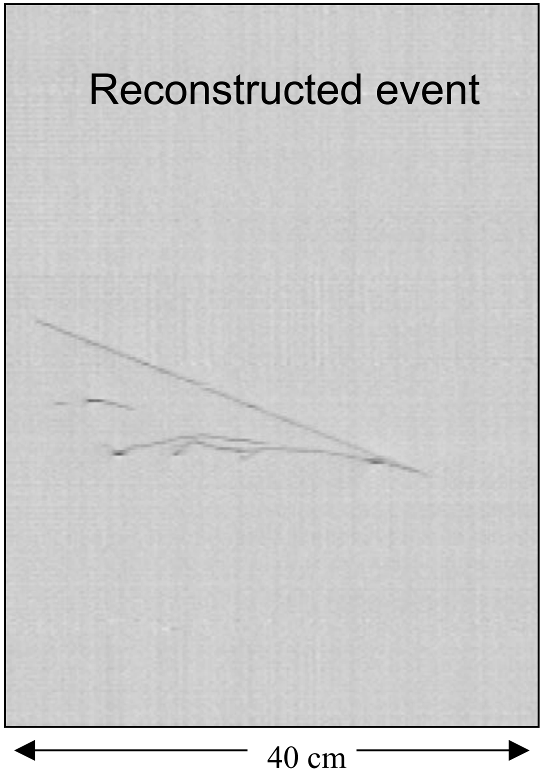
$\nu_\mu \rightarrow \nu_\tau$:

- unambiguous appearance signal after a few years
- expect 20-25 τ events after 5 years with very small background at $\Delta m^2 \sim 2.0\ 10^{-3}\ eV^2$
- precision on Δm^2 of the order of 10%

$\nu_\mu \rightarrow \nu_e$:

- high detector capabilities to explore this channel
- θ_{13} limit down to 6^0-7^0
- best sensitivity until the JHF-SK turns on

Detector Characteristics



- High density fully imaged target
- Completely homogeneous
- High granularity
  - Wire pitch ➔ few mm
  - Time sampling ➔ few hundreds ns
- Self-triggering with no dead time
- Very good calorimetry
  - Local energy deposition detection
  - Very good energy resolution
    - $\sigma(E)/E = 7\% / \sqrt{E(\mathrm{MeV})}$ low energy el.
    - $\sigma(E)/E = 3\% / \sqrt{E(\mathrm{GeV})}$ e.m. showers
    - $\sigma(E)/E = 16\% / \sqrt{E(\mathrm{GeV})} + 1\%$ hadr. show.
- Particle ID capability

	Density (g/cm^3)	**dE/dx (MeV/cm)**	**Radiation Length (cm)**	**Nucl. Coll. Length (cm)**	**Boiling Point (°C)**	**El. Mobility (cm^2 / V s)**	**W_{ion} (eV)**	**W_{ph} (eV)**
Argon	**1.394**	**2.10**	**14.0**	**54.8**	**-185.7**	**500**	**23.6**	**19.5**