Long baseline neutrino oscillations experiments: why and how

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Neutrino News from the Lab and the Cosmos,
October 18 2002

- Introduction
- Long baseline neutrino oscillation experiments:
  - What exists: K2K (KEK to SuperK)
  - In preparation: MINOS and the CNGS program
- For the future: a wealthy collection of long baseline proposals

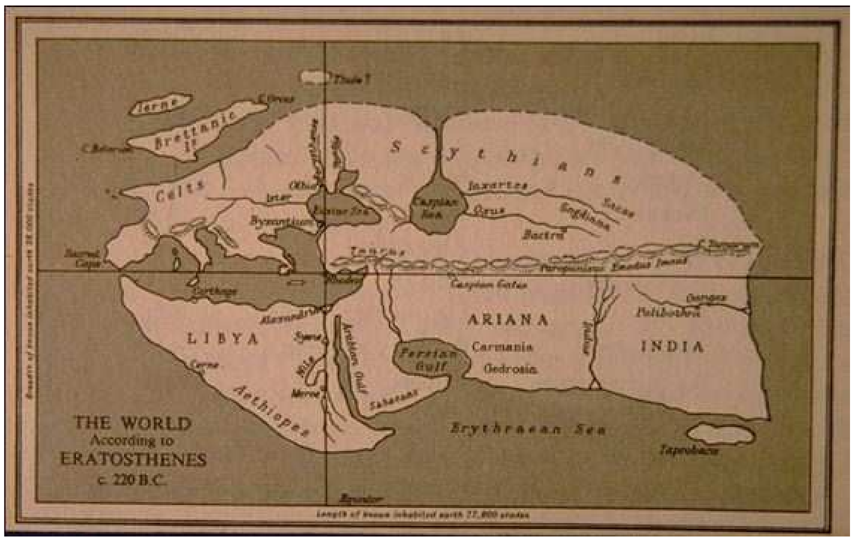
The early map of neutrino oscillations

For 3 ν's:

Atm. ν — Reactor, accel. — solar

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Where $c_{ij}=\cos_{\theta ij}$, $s_{ij}=\sin\theta_{ij}$, δ = CP viol. phase



Eratosthenes of Cyrene, 194 B.C.

$\Delta m_{12}^2 = \Delta m^2_{sol} \simeq 2\text{-}20\times 10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\theta_{12} \sim 0.8$

$\Delta m_{23}^2 \simeq 1.6\text{-}3.9\times 10^{-3}\ \mathrm{eV}^2$, $\sin^2 2\theta_{23} > 0.92$

$\sin^2 2\theta_{13} < 0.12$ ($\theta_{13} < 10°$) @ $\Delta m^2 = 3\times 10^{-3}\ \mathrm{eV}^2$

At the atmospheric scale, neglecting matter effects and CP violation:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\Delta m^2_{23} L/E_\nu)$$

$\sin^2 2\theta_{13}\sin^2\theta_{23} \rightarrow \sin^2 2\theta_{\mu e}$

$$\sin^2 2\theta_{\mu e} \cong \frac{1}{2}\sin^2 2\theta_{13} \cong 2|U_{e3}|^2$$

Caveat: we might miss a continent (LSND signal !)

Long baseline experiments

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\vartheta)\sin^2(1.27\Delta m^2 L / E)$$

where $\Delta m^2 = m_1^2 - m_2^2$ eV^2, L/E in m/MeV

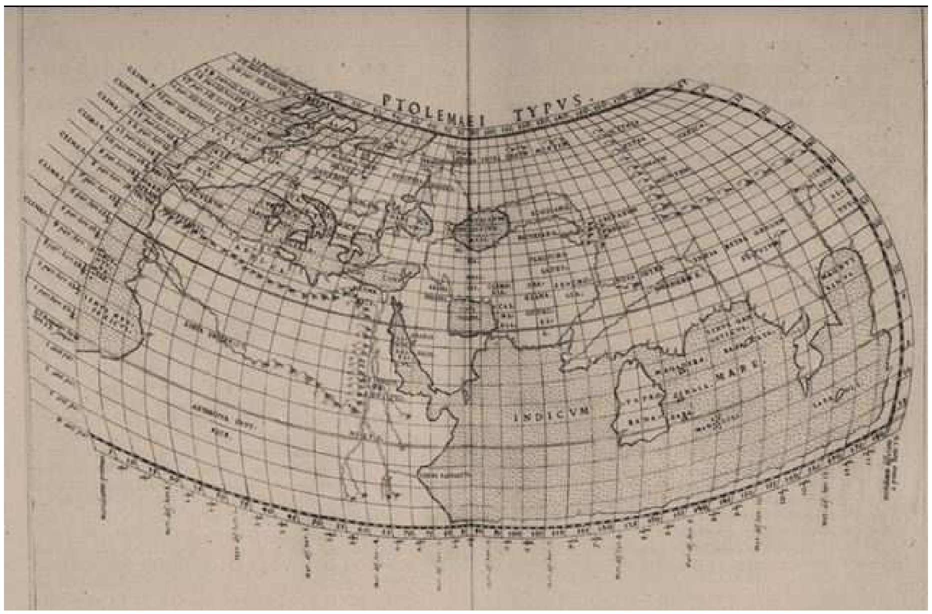
$\Delta m^2 \approx 2\times10^{-3}$ $eV^2 \Rightarrow$ Investigate L/E ~ 500 Km/GeV

➔ use a ~ GeV ν_μ beam over a distance of ~ 1000 Km

- Intensity must be as high as possible
- Beam transport, target, decay tunnel are underground
- Proper pointing of the beam

➔ Look for ν_μ spectra distortion in a far detector and/or ν_τ appearance

Towards a quantitative understanding of neutrino oscillations

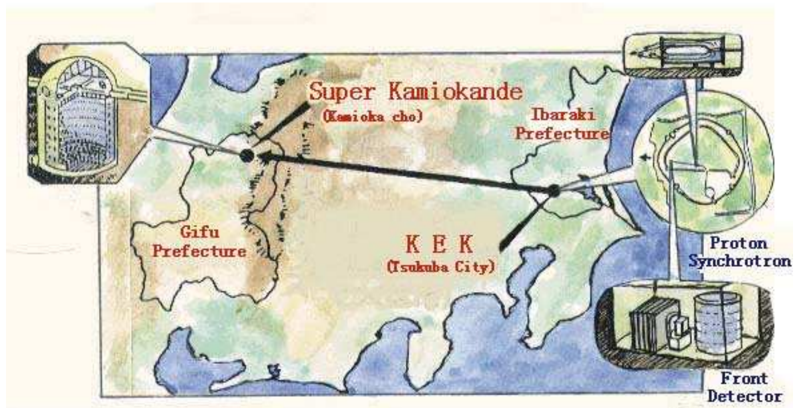


Claudius Ptolemy, A.D. 200

☛ **Long baseline programs**

- Neutrino oscillations or some **other effect** (decay ?...)
- Make sure that we see the oscillation signature: $\sin^2(1.27\Delta m^2 L/E)$ dependence
- Measure accurately the oscillation parameters Δm^2 and $\sin^2 2\theta$
- Measure, if any, $\nu_\mu \to \nu_{sterile}$
- Measure θ_{13} (search for $\nu_\mu \to \nu_e$ at the atmospheric Δm^2)
- Leptonic CP violation ?

K2K (KEK to SuperK)



- The first long baseline neutrino experiment
  - with a near and a far detector (SuperKamiokande)
- Neutrino beam with $\langle E_\nu \rangle = 1.3\,\mathrm{GeV}$ over a baseline of 250 Km
  - L/E $\approx$ 200 Km/GeV, sensitive for $\Delta m^2 \geq 2\ 10^{-3}\ eV^2$
- Proton intensity: 6×10^{12} protons of 12 GeV kinetic energy on an Al target every 2.2 s
  - accumulated 4.8×10^{19} protons, aim to 10^{20} pot

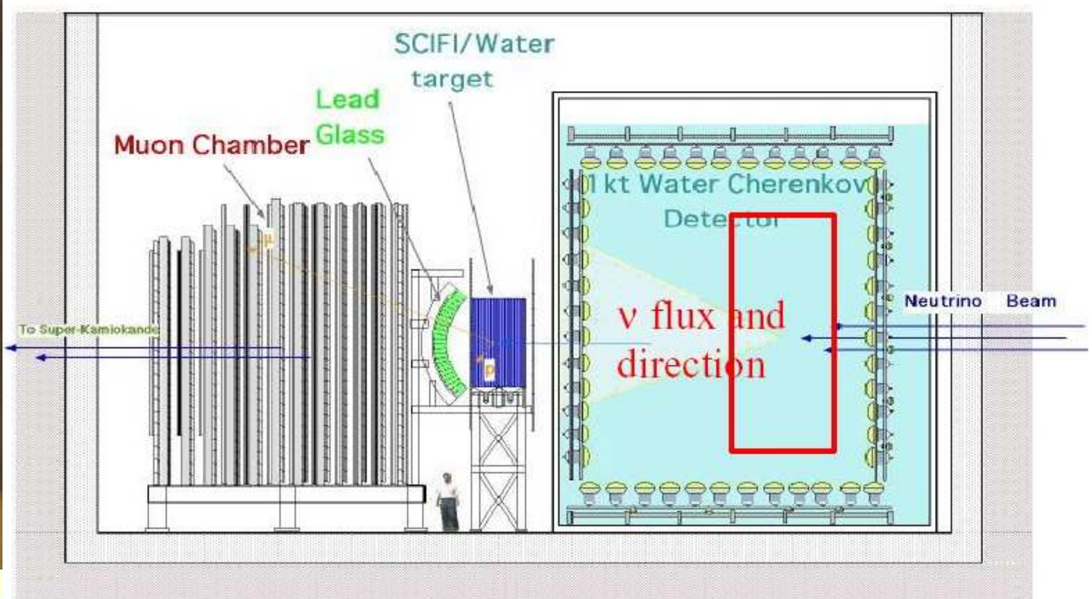
K2K Collaboration

High Energy Accelerator Research Organization(KEK)
Institute for Cosmic Ray Research(ICRR), University of Tokyo
Kobe University
Kyoto University
Niigata University
Okayama University
Tokyo University of Science
Tohoku University

Chonnam National University
Dongshin University
Korea University
Seoul National University

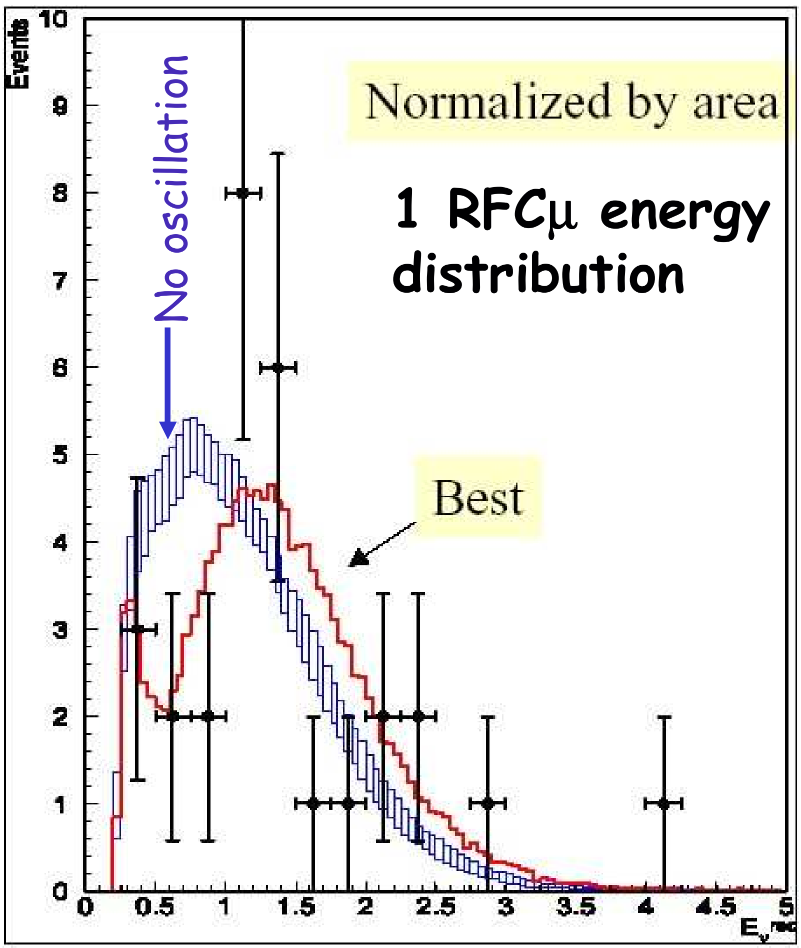
Boston University
University of California, Irvine
University of Hawaii, Manoa
Massachusetts Institute of Technology
State University of New York at Stony Brook
University of Washington at Seattle

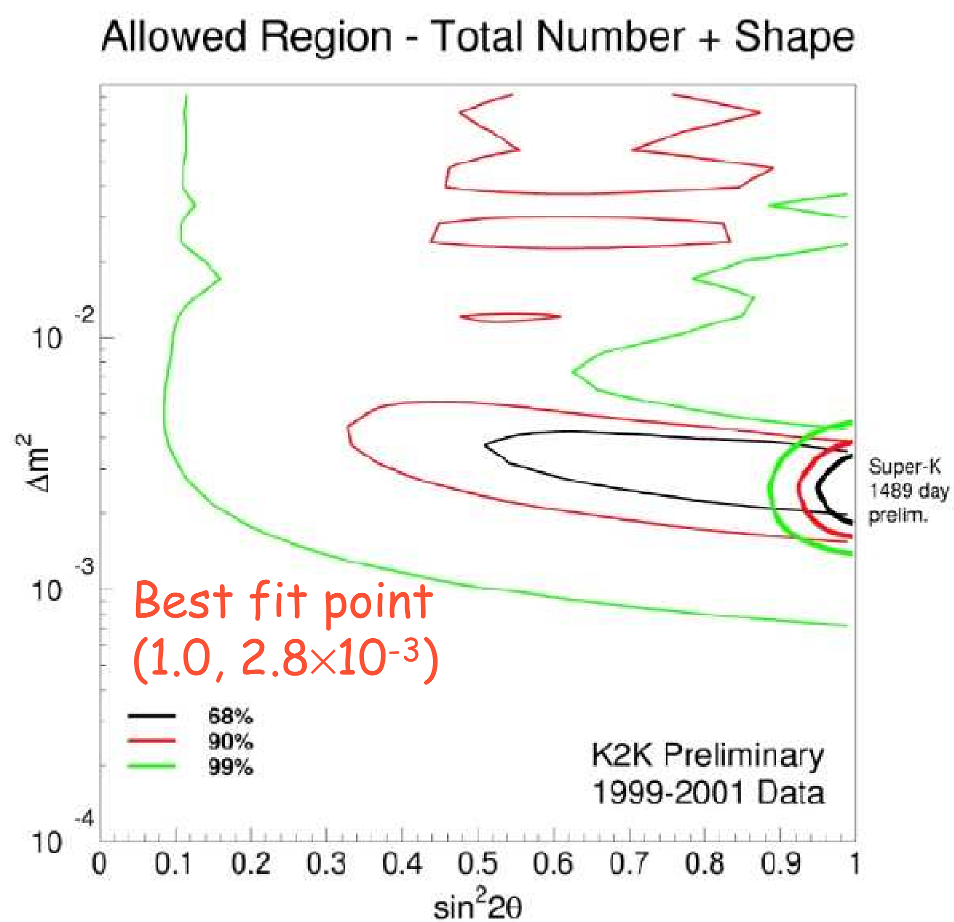
Warsaw University
Solton Institute forNnuclear Study



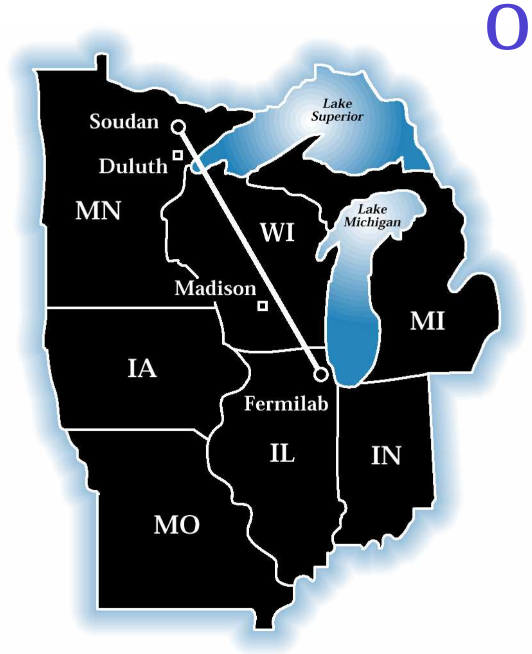
K2K present results

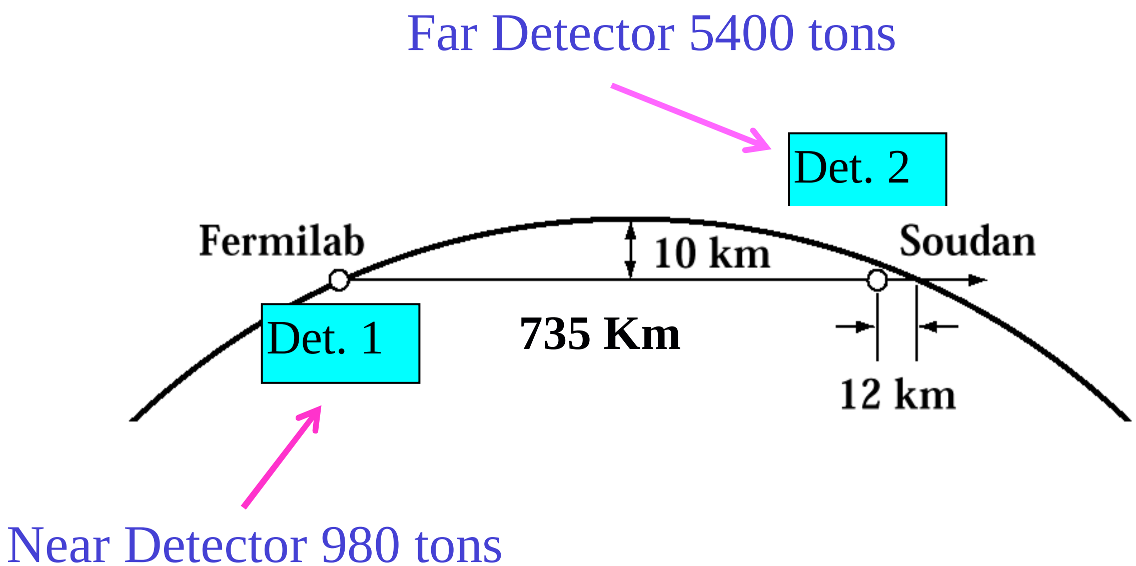
- The result: $80.1^{+6.2}_{-5.4}$ events expected, 56 events observed in SuperK
  - null oscillation probability: < 1%
  - 52.4 events predicted for $\Delta m^2 = 3\times10^{-3}$ eV^2





MINOS: a two detector neutrino oscillation experiment





- shoot a neutrino beam from Fermilab to Soudan mine (Minnesota) over a baseline of 735 km
- 120 GeV protons from the Main Injector on a C target
- flexible configuration of 2 parabolic horns, to get “low”, “medium” and “high” energy neutrino beams
- measure produced neutrino spectrum in a Near location and predict it at the Far site

Start data taking by Jan 2005

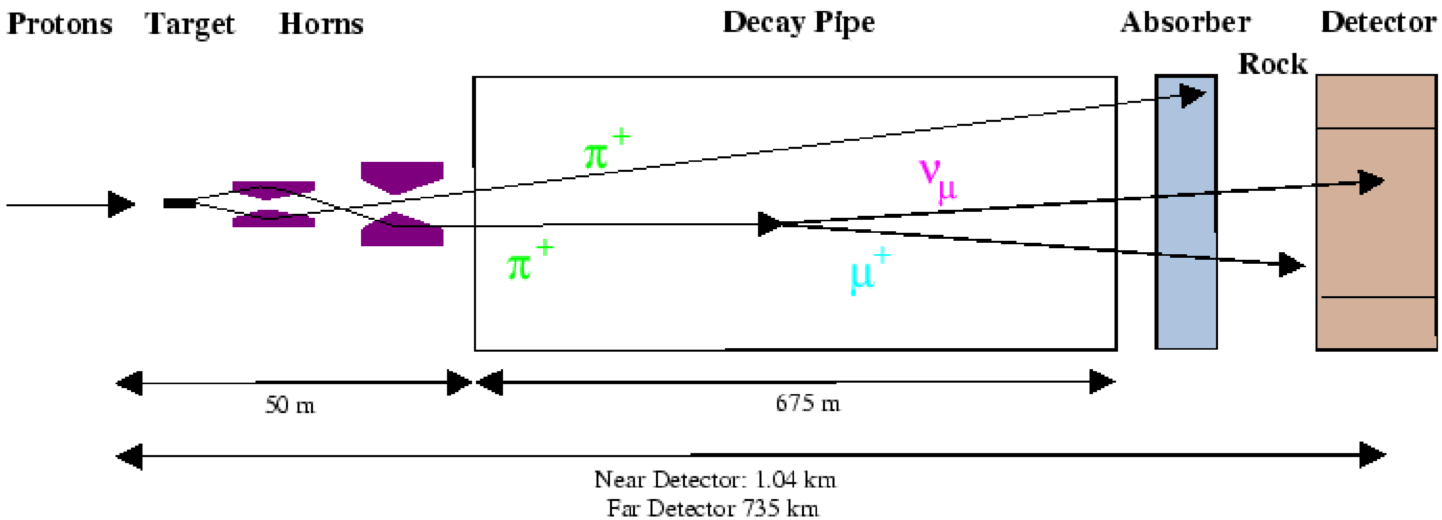
MINOS experiment

The Collaboration

Over 250 physicists and Engineers

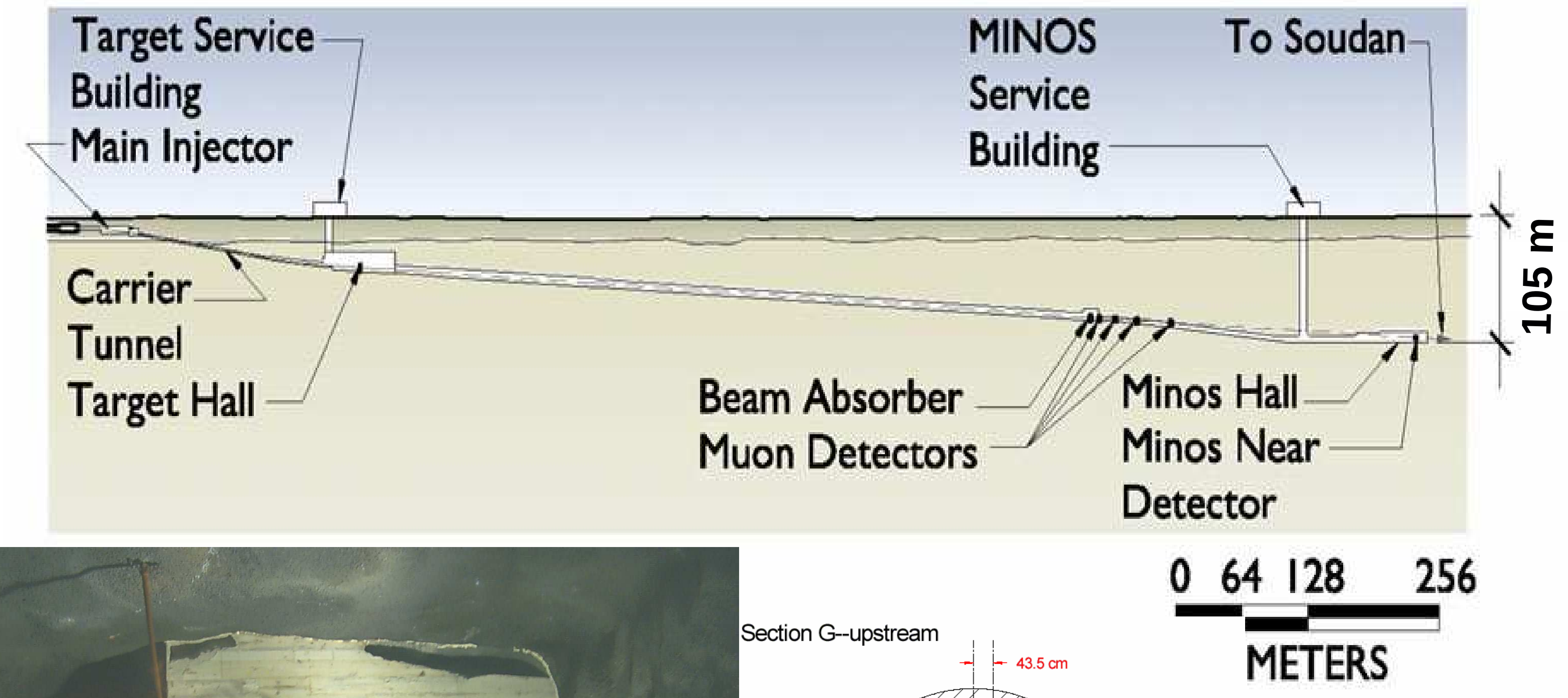
Argonne • Athens • Brookhaven • Caltech • Cambridge • College de France • Fermilab • Harvard • IIT • Indiana • ITEP-Moscow • James Madison • Livermore • Lebedev • Macalester • Minnesota - Twin Cities • Minnesota - Duluth • Northwestern • Oxford • Pittsburgh • Protvino • Rutherford • South Carolina • Stanford • Sussex • Texas-Austin • Texas A&M • Tufts • University College London • Western Washington • Wisconsin

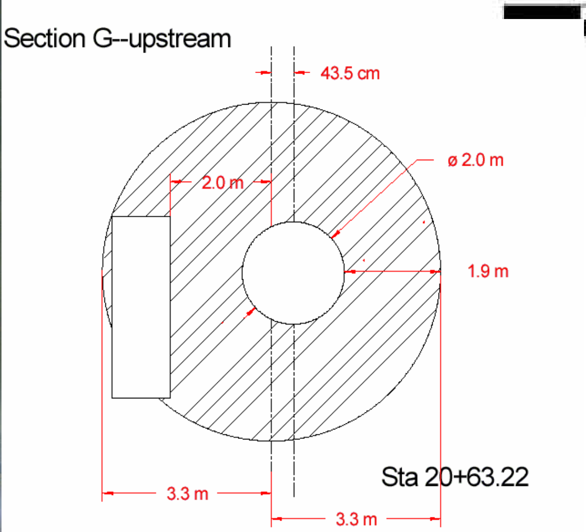
The NuMI beamline



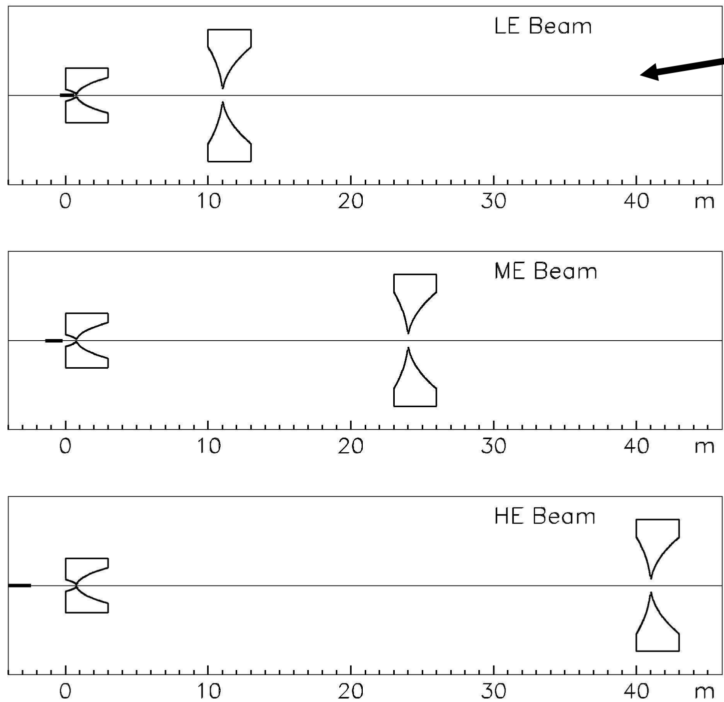
- 120 GeV protons from the Main Injector (up to 4x10[13] ppp in 8 μs every 1.9 sec, i.e. beam power of 0.4 MW, 3.7×10^{20} protons/year)
  - at start up 2.25×10^{13} protons/cycle
- water cooled graphite target, 2.0-2.4 interaction length, which provides absorption of ~ 90% of the primary protons
- flexible configuration of 2 parabolic magnetic horns, water cooled, pulsed with a 2.6 ms half-sine wave pulse of 200 kA
- 675 m long decay pipe with a radius of 1 m

NuMI civil construction





NuMI Horn system

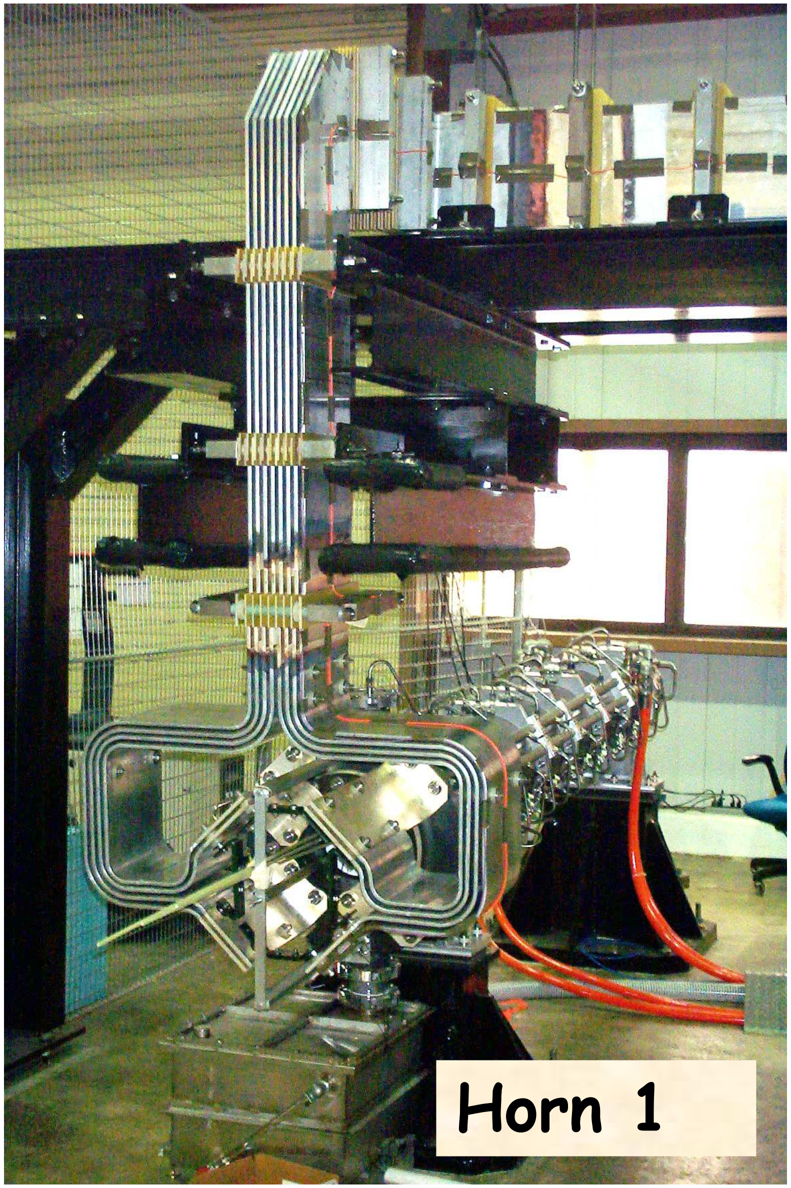


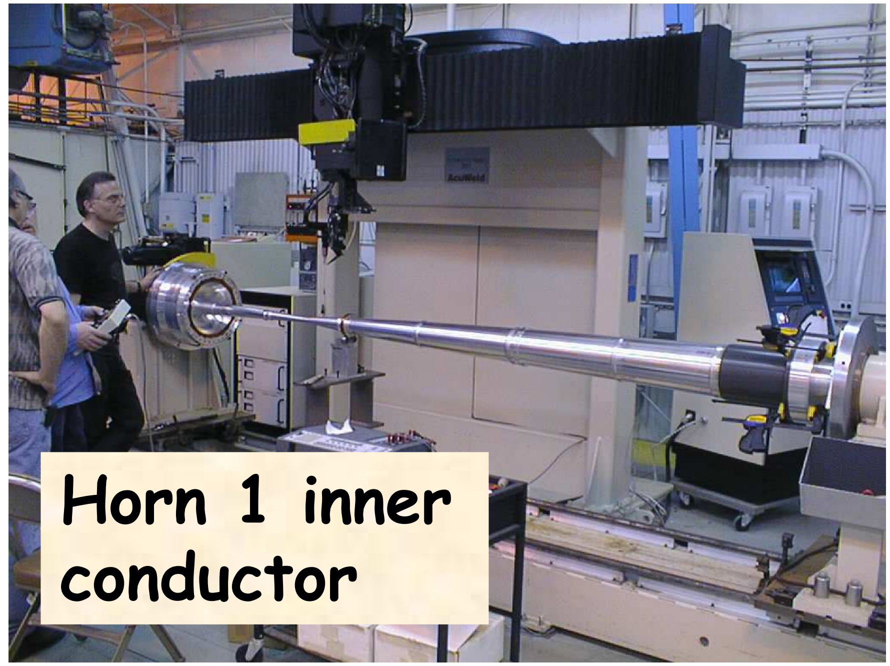
Baseline solution

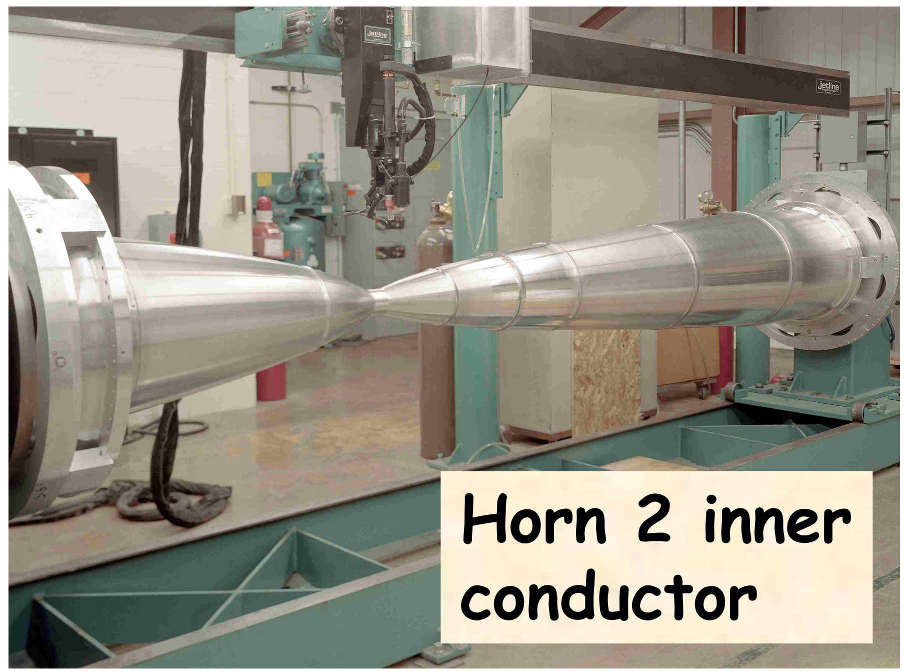
In order to focus different momentum intervals, change target position with respect to horn 1 and the relative distance of the two horns

- With a parabolic shaped horn inner conductor, the horn behaves like a lens (p_t kick proportional to the distance from the axis), with a focal length proportional to the momentum
- π's focused parallel by horn 1 go through hole of horn 2, while those somewhat overfocused or underfocused are finally focused by horn 2

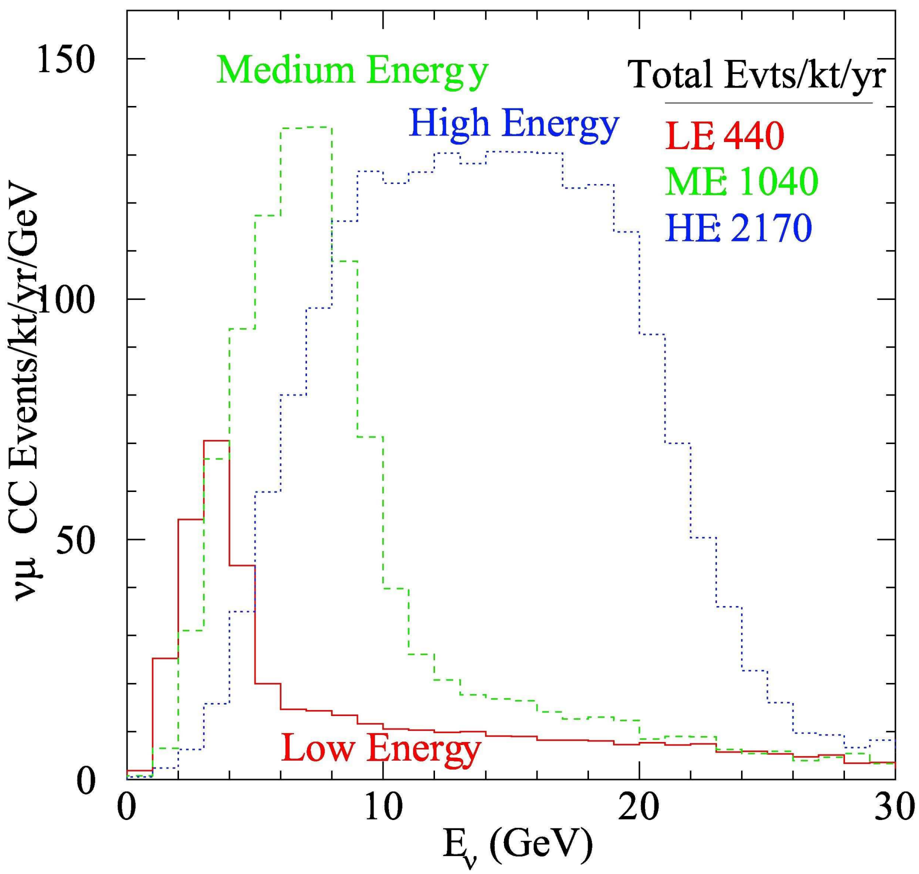
NuMI horns







Neutrino spectra in the Far Detector

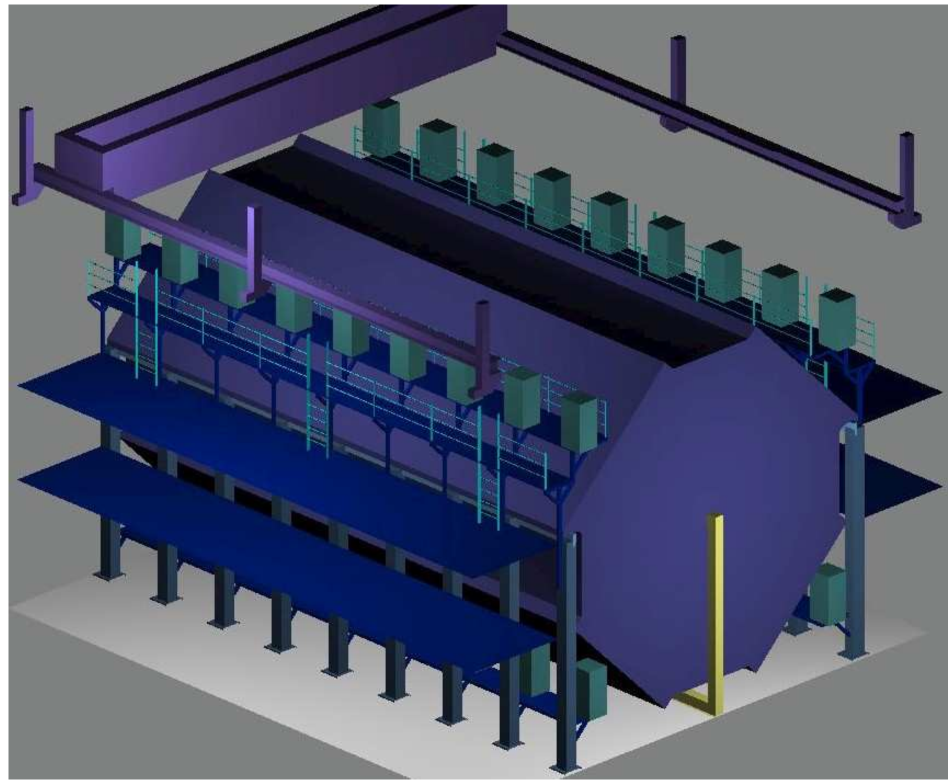


With 3.7×10^{20} pot/year :

- LE beam
  - ~ 440 events/kton/year
- ME beam
  - ~ 1040 events/kton/year
- HE beam
  - ~ 2170 events/kton/year

MINOS Far Detector

- 2 sections, each 15m long
- 8m Octagonal Tracking Calorimeter
  - 486 layers of 2.54cm Fe
  - 4cm wide solid scintillator strips with WLS fiber readout
  - 25,800 m^2 active detector planes
- Magnet coil provides <B> $\approx$ 1.3T
- 5.4kt total mass

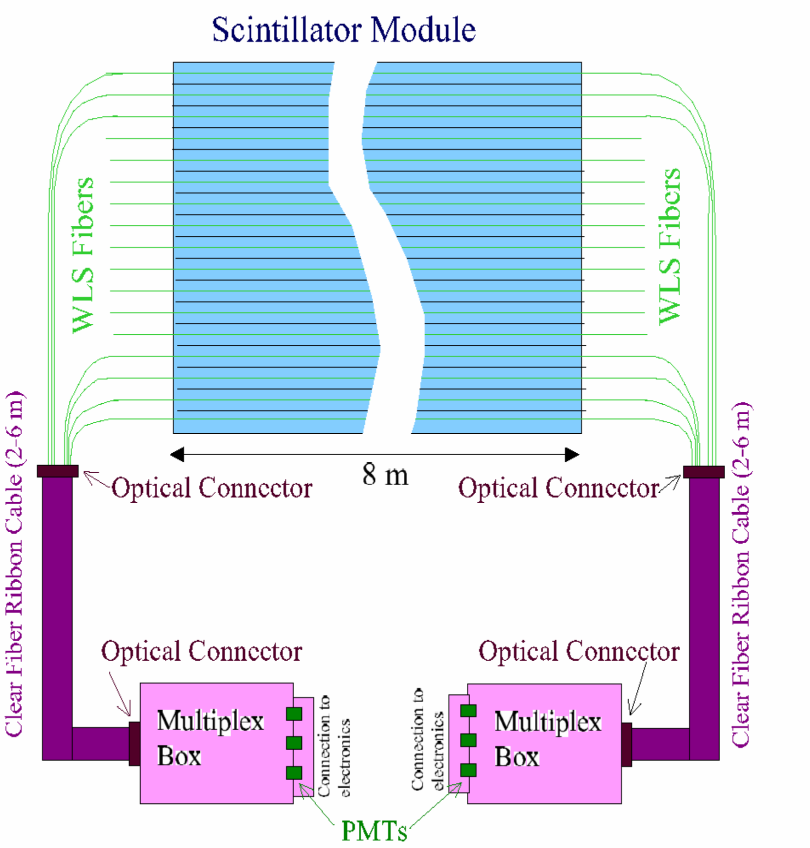


Half of the MINOS Detector

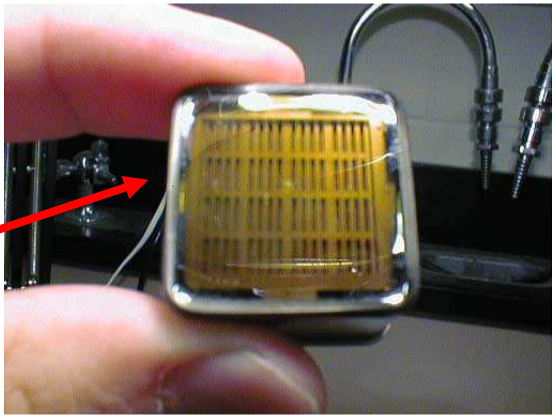
8 m$\times$8 m $\times$15 m

Detector Technology

Detector module with 20 scintillator strips



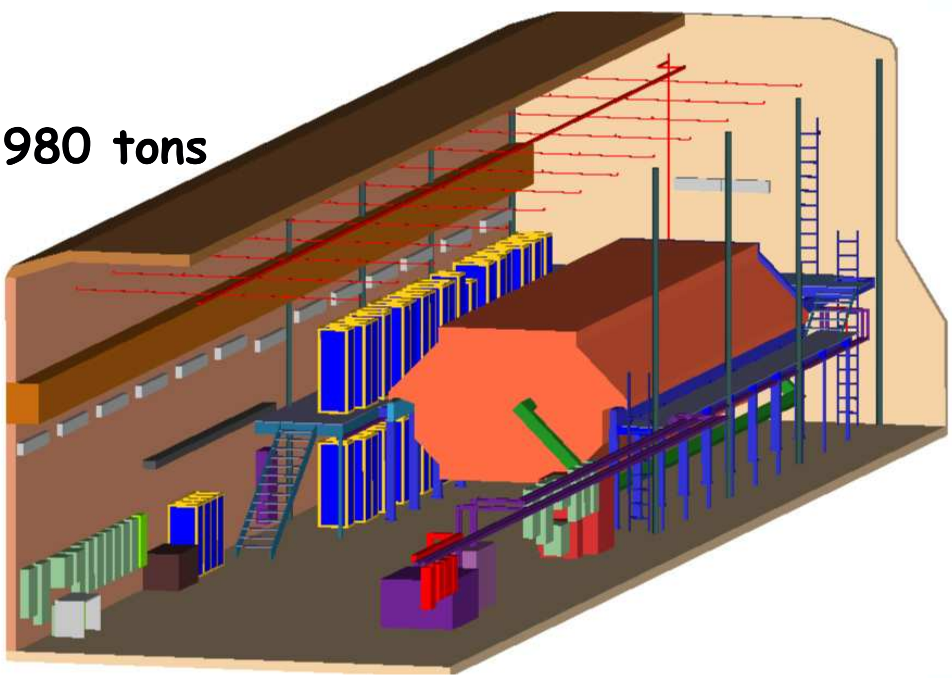
MUX boxes route 8 (1 in Near Detector) fibers to one MAPMT pixel



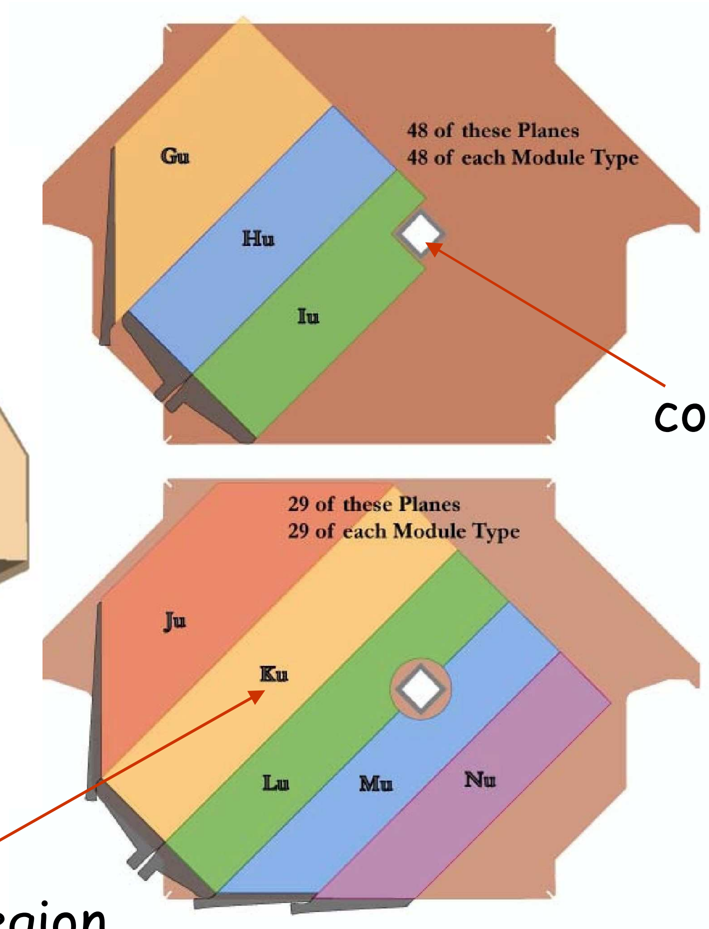
MINOS Near Detector

- an essential part of the experiment
- built to be as similar as possible to the far detector, it will be used to predict the far spectrum
- provides high statistics, about 700,000 times as many interactions as in the far detector (per kton)

980 tons



4.8 m × 3.8 m × 16.6 m



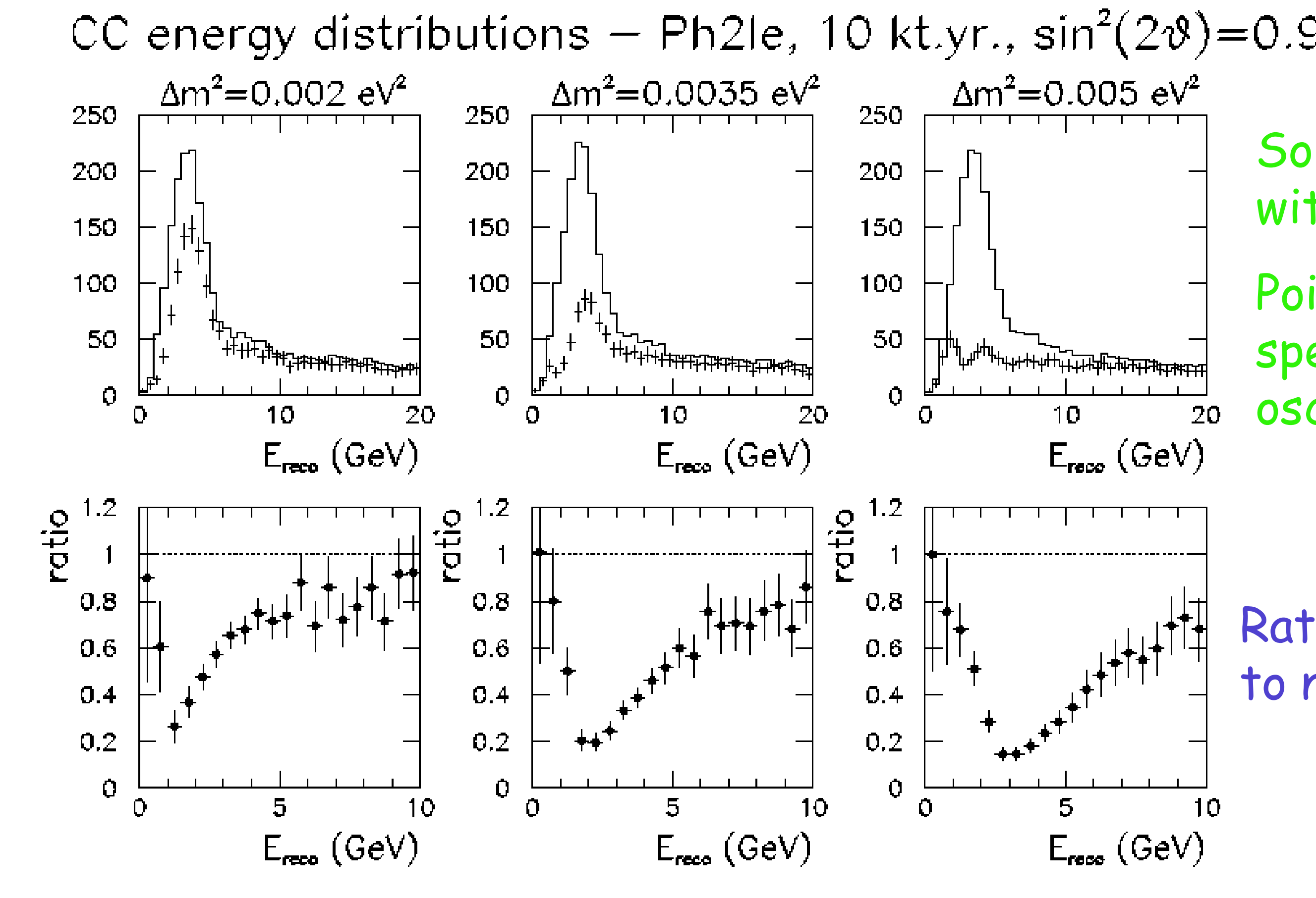
coil hole

Beam central region

Far Detector ν_μ CC distributions

10 kt-year exposure

3.7×10^{20} prot/year



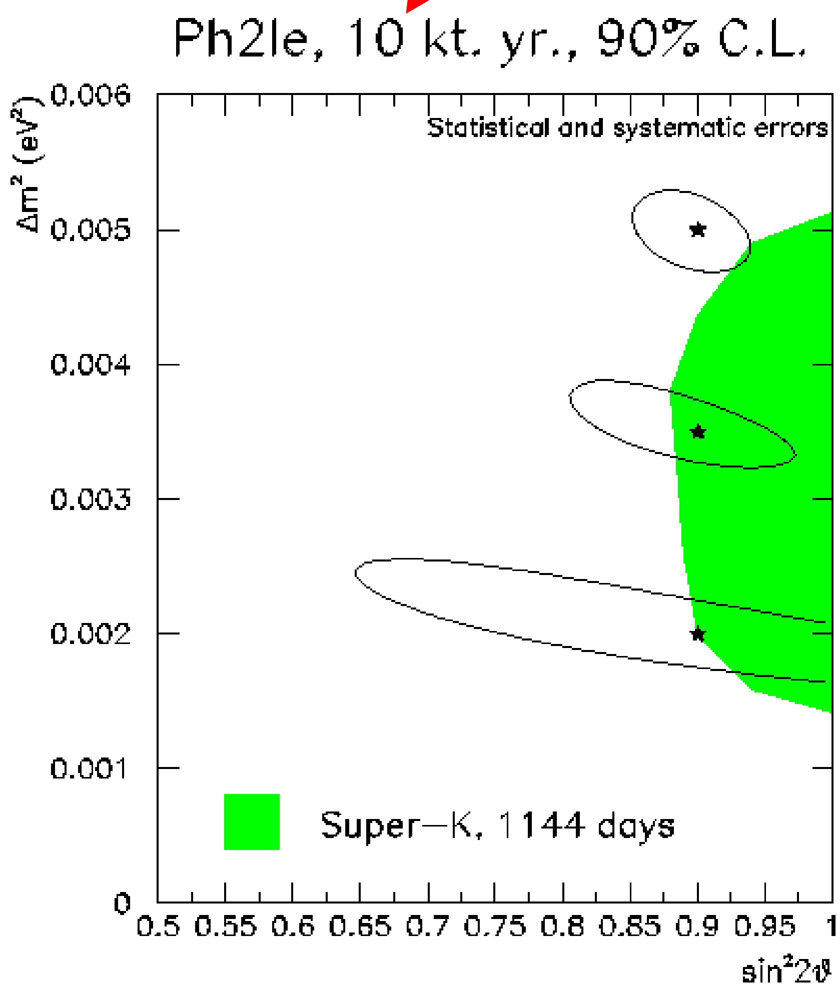
Solid lines: energy spectrum without oscillations

Points with error bars: spectrum in presence of oscillations

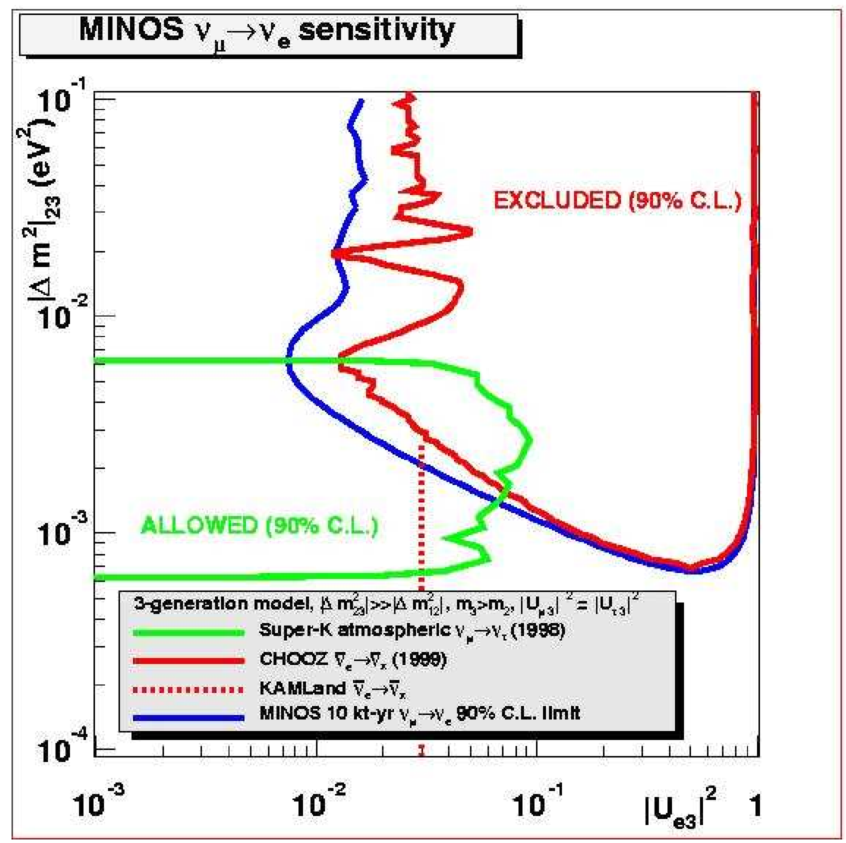
Ratio of oscillation spectrum to no-oscillation spectrum

MINOS sensitivity

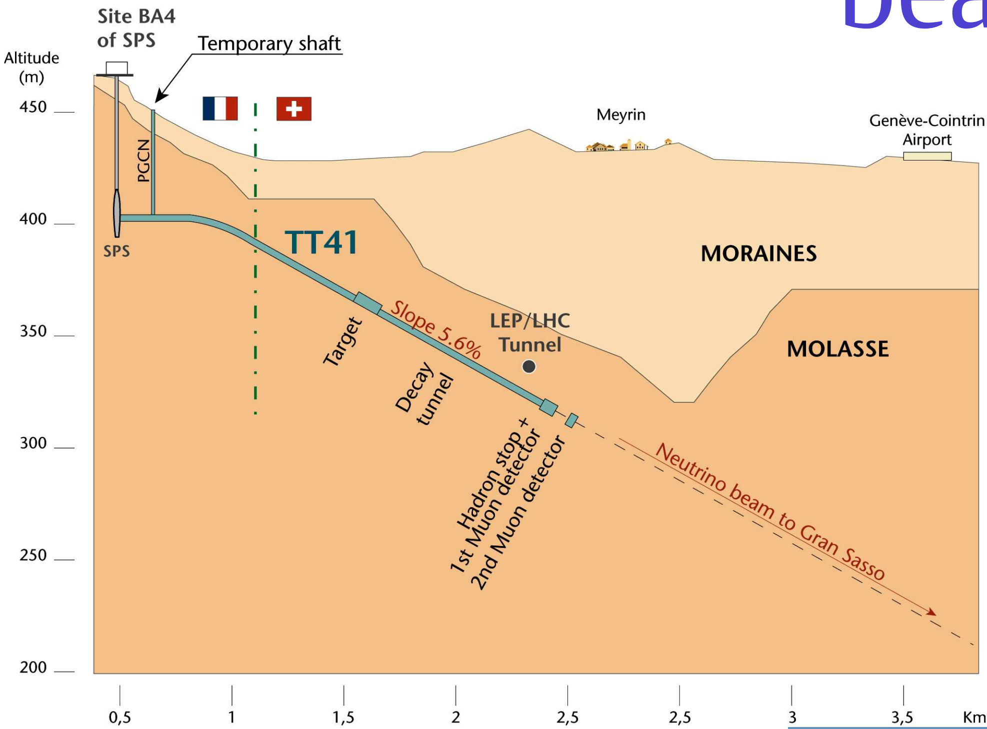
Δm_{23}^2, $\sin^2 2\theta_{23}$

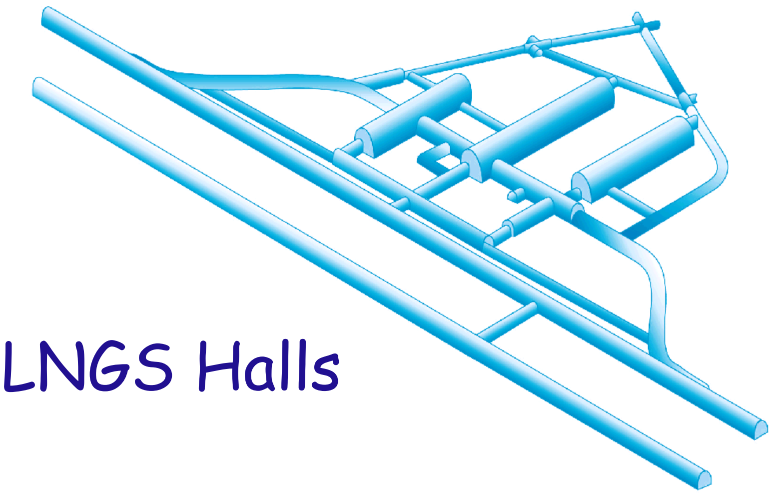


$\sin^2 2\theta_{13}$

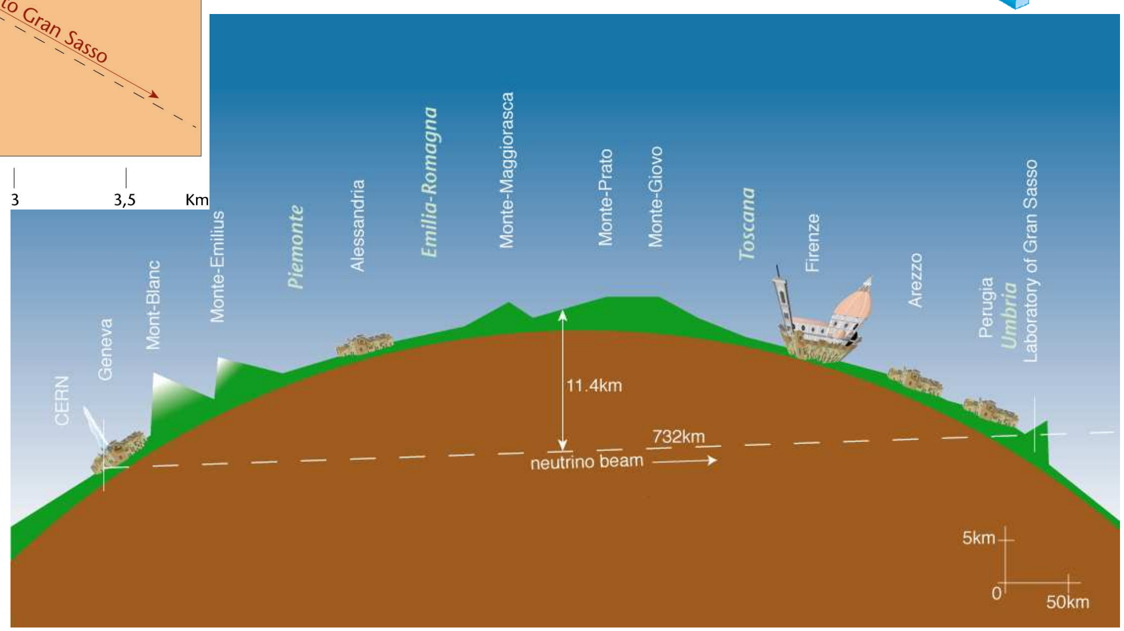


CNGS, CERN to Gran Sasso neutrino beam





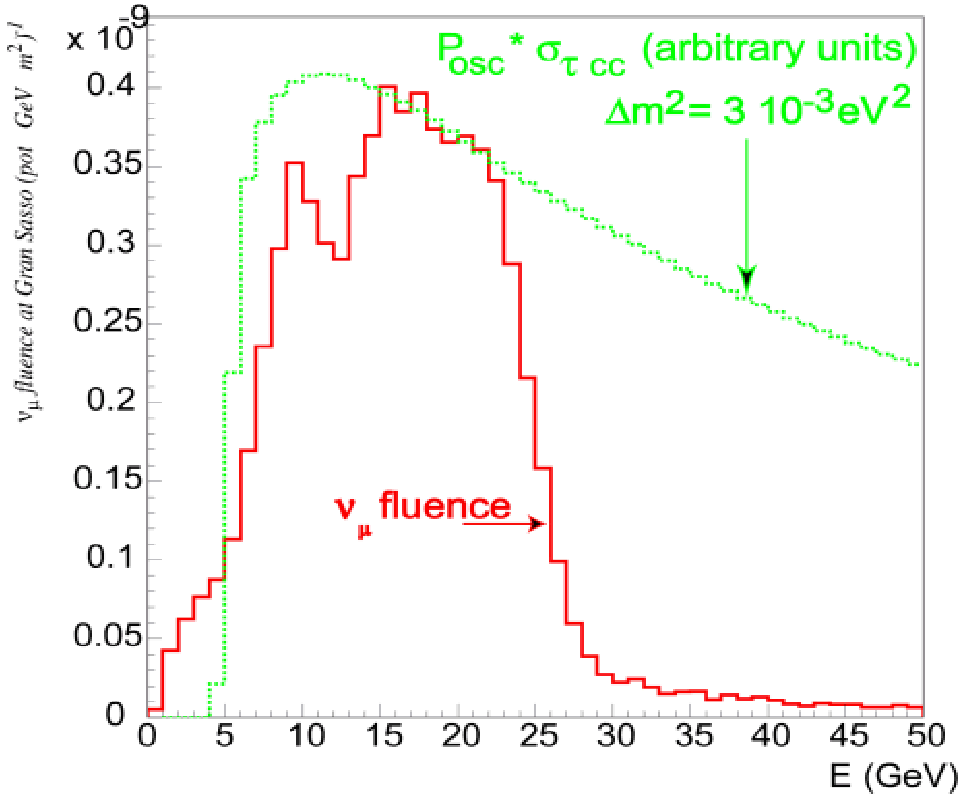
LNGS Halls



neutrino beam to Gran Sasso by the 3rd quarter of 2006

CNGS: a ν_τ appearance program

- over a distance of 732 Km
- energy matched for $\nu_\mu \rightarrow \nu_\tau$ appearance experiment



- **400 GeV protons from SPS**
- **200 days, sharing with other users (LHC,…) $\Rightarrow$ 4.5$\times$10^{19} prot/year**
- **# ν interactions in 5 years**
  - **18300 NC+CC/kton**
  - **67 ν_τ /kton for Δm^2=2.4 10^{-3} eV^2 and maximum mixing**

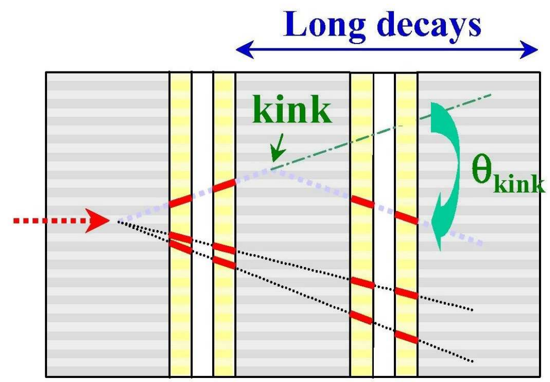
OPERA: direct observation of ν_τ appearance from $\nu_\mu \rightarrow \nu_\tau$ oscillations

$$\nu_\tau \xrightarrow[\text{CC}]{} \tau^- + X$$

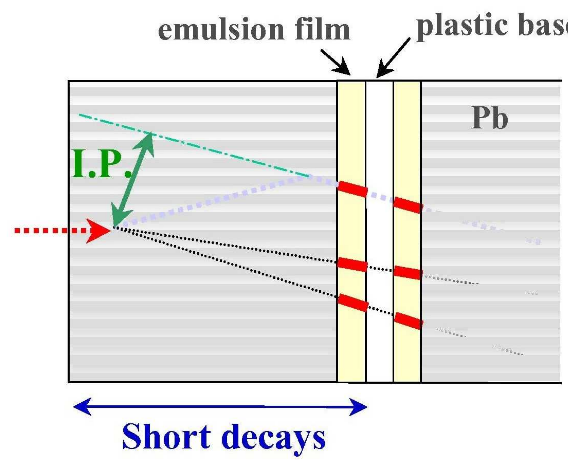
interaction

~ 1 mm

Decay mode	BR
$\mu^-\nu_\tau\bar{\nu}_\mu$	18%
$h^-\nu_\tau n\pi^0$	50%
$e^-\nu_\tau\bar{\nu}_e$	18%
$\pi^+\pi^-\pi^-\nu_\tau n\pi^0$	14%



- Observation of the decay topology of τ in an Emulsion Cloud Chamber
  - a modular structure made of a sandwich of 1 mm Pb plates interspaced with photographic emulsion layers



OPERA

COLLABORATION

35 groups
~ 160 physicists

Belgium
IIHE(ULB-VUB) Brussels

China
IHEP Beijing, Shandong

Croatia
Zagreb

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

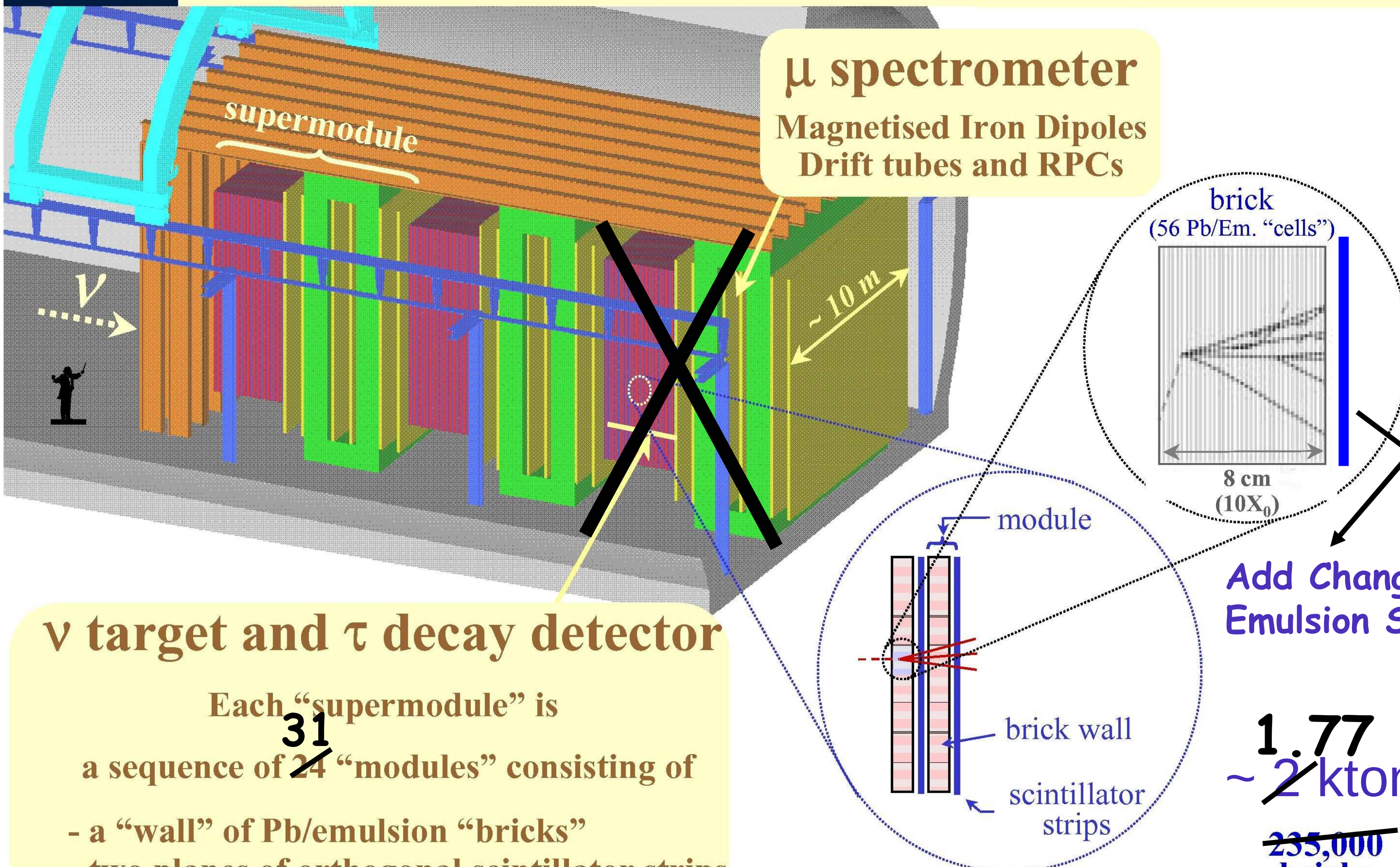
Turkey
METU Ankara

Interest for participation from Sofia

Underlined : groups having joined since last year

The detector at Gran Sasso

(modular structure, ~~three~~ 2 "supermodules")



ν target and τ decay detector

Each "supermodule" is

a sequence of ~~24~~ 31 "modules" consisting of

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

Add Changeable Emulsion Sheets

~ ~~2~~ 1.77 kton

~~235,000~~ 206336 bricks

OPERA sensitivity

$\nu_\mu \rightarrow \nu_\tau$ appearance sensitivity

5 years run @ 4.5×10^{19} pot/year

Signal $\Delta m^2=1.6\times10^{-3}$ eV^2	**Signal** $\Delta m^2=2.5\times10^{-3}$ eV^2	**Signal** $\Delta m^2=4.0\times10^{-3}$ eV^2	Background
4.3	**10.3**	**26.3**	**0.65**

Sensitivity to θ_{13}

Good electron identification in emulsion, but what about systematics ?

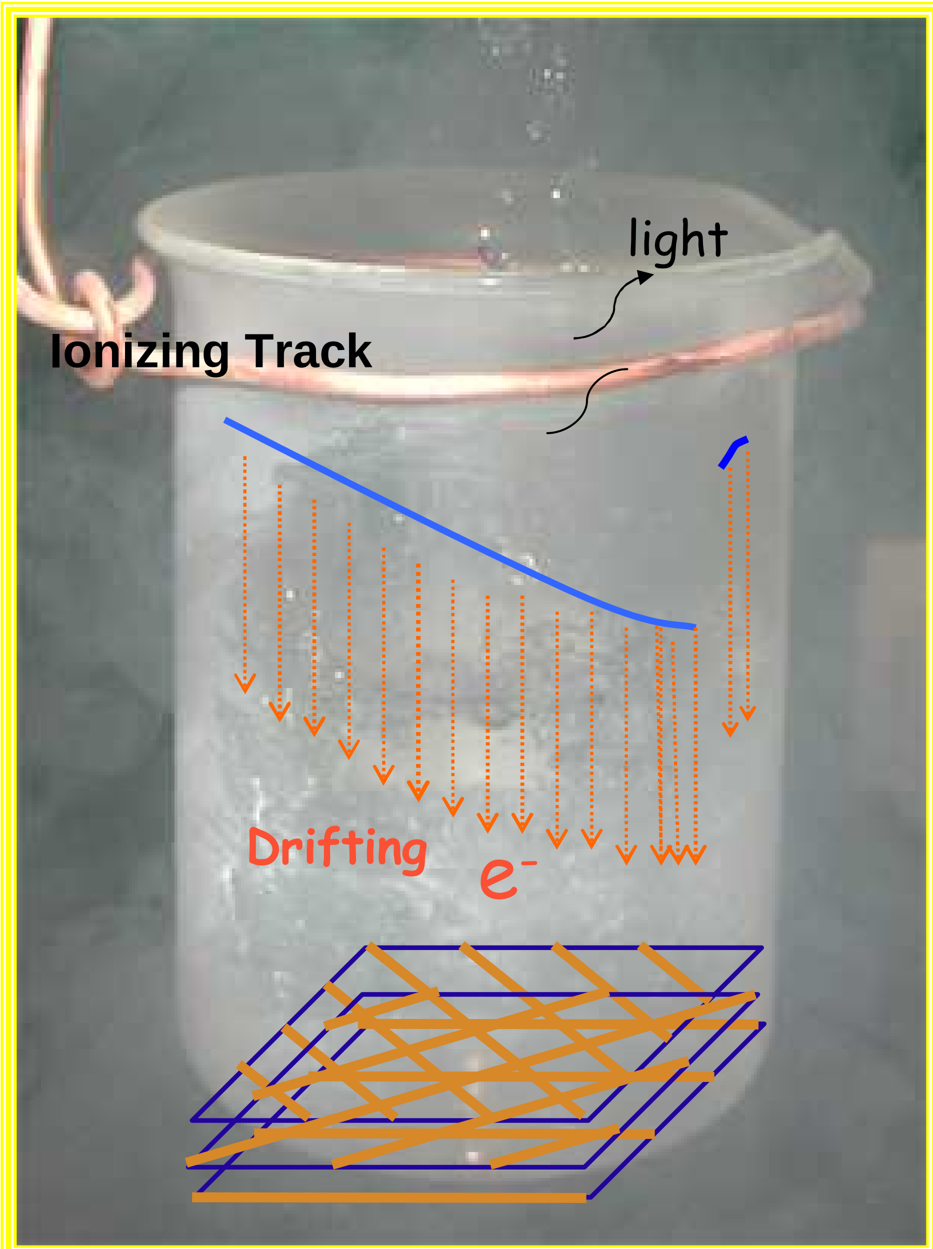
Expected signal and background

Θ_{13}	signal	$\tau\rightarrow e$	ν_μCC	ν_μNC	ν_eCC beam
7°	5.8	4.6	1.0	5.2	18

@ 90% C.L.

$\sin^2 2\theta_{13} < 0.06$

$\theta_{13} < 7.1°$



ICARUS: a Liquid Argon Imaging Detector

Working principle:

- **Ionization chamber filled with LAr, equipped with sophisticated electronic read-out system (TPC) for 3D imaging reconstruction, calorimetric measurement, particle ID.**
- **Absolute timing definition and internal trigger from LAr scintillation light detection**

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. Dabrowska, Z. Dai, M. Daszkiewicz, 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, K. He, J. Holeczek, X. Huang, C. Juszczak, D. Kielczewska, J. Kisiel, L. Knecht, T. Kozlowski, H. Kuna-Ciskal, M. Laffranchi, J. Lagoda, Z. Li, B. Lisowski, F. Lu, J. Ma, G. Mangano, G. Mannocchi, M. Markiewicz, F. Mauri, C. Matthey, G. Meng, C. Montanari, S. Muraro, G. Natterer, S. Navas-Concha, M. Nicoletto, S. Otwinowski, 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, 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, G. Xu, X. Yang, A. Zalewska, J. Zalipska, C. Zhang, Q. Zhang, S. Zhen, W. Zipper.

University and INFN of: L'Aquila, LNF, LNGS, Milano, Naples, Padova, Pavia, Pisa - Italy
ETH Hönggerberg, Zürich - Switzerland
CNR Istitute of cosmogeophysics, Torino - Italy
University of Silesia, Katowice - Poland
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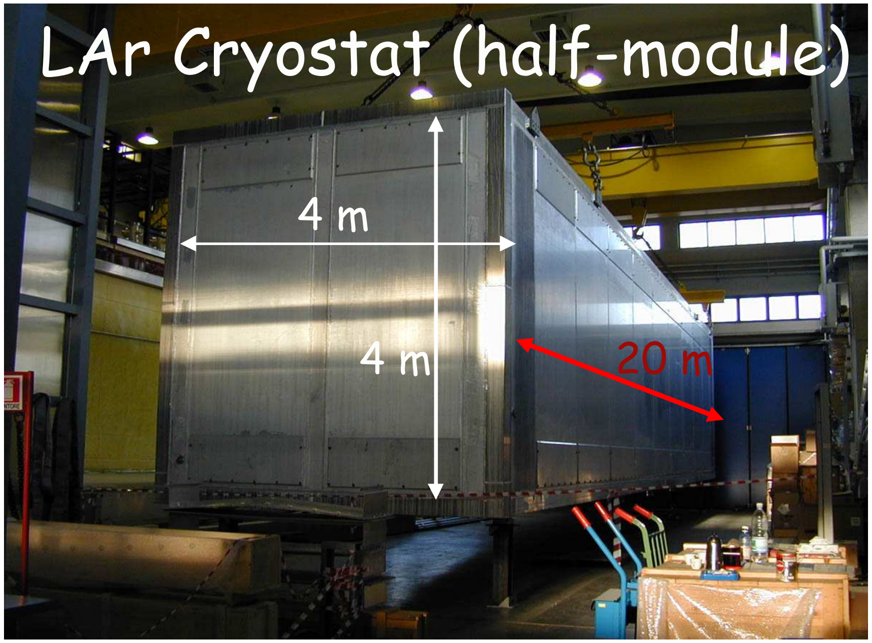
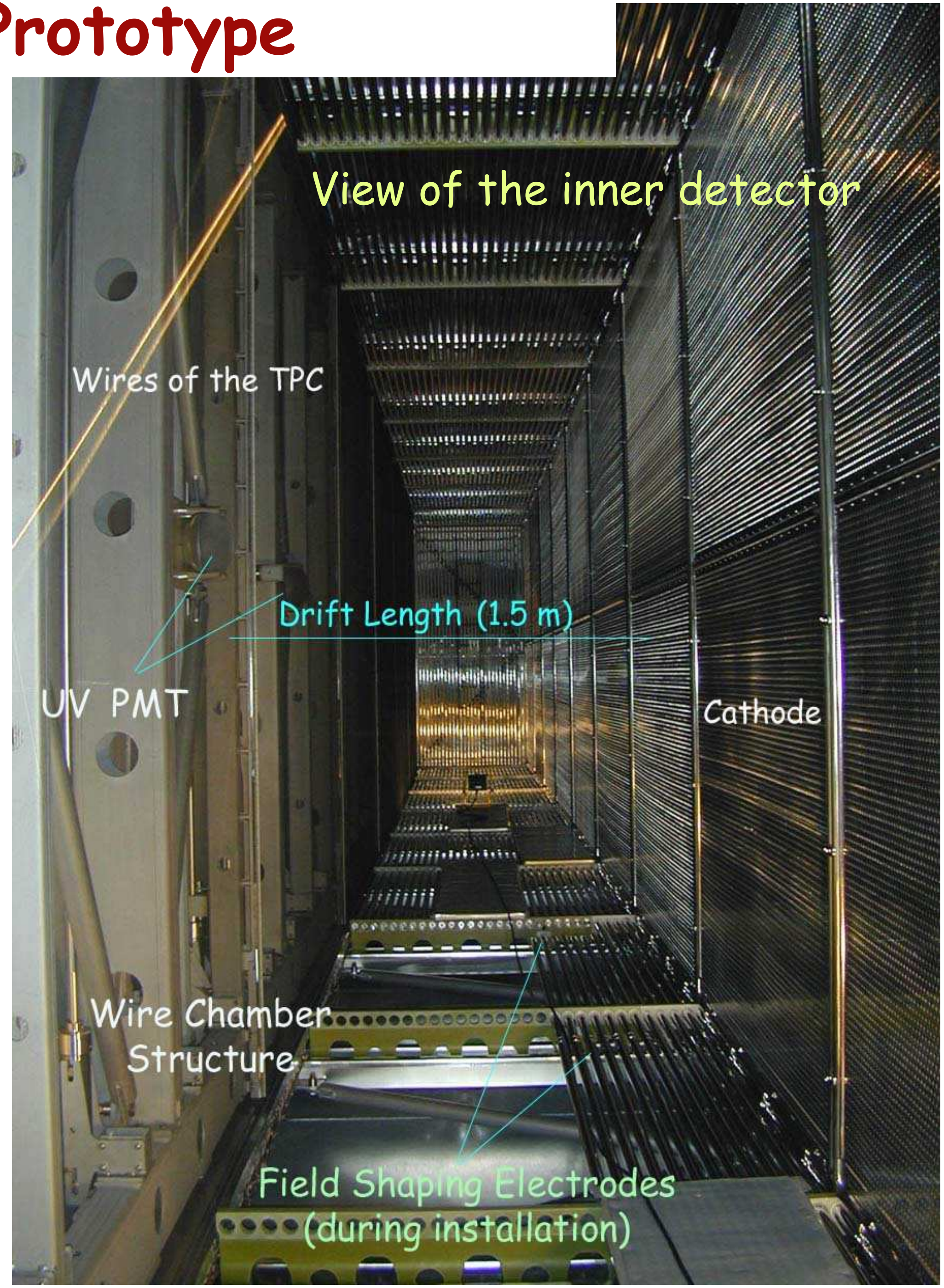
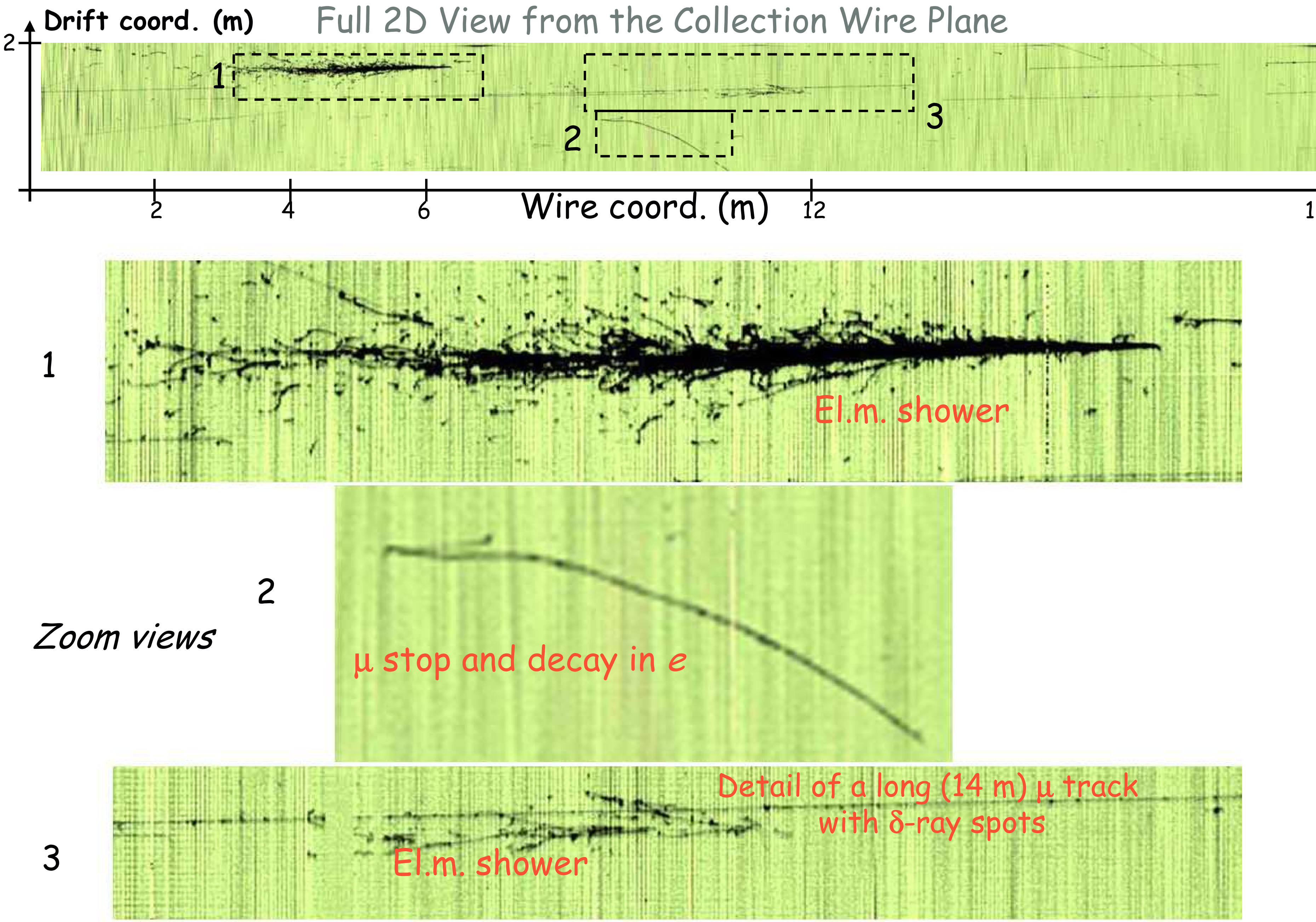
Warsaw University, Warszawa - Poland
UCLA, Los Angeles - USA
IHEP, Academia Sinica, Beijing - China
Politecnico di Milano - Italy
University of Mining and Metallurgy, Krakow – Poland
Jagellonian University, Krakow - Poland
A.Soltan Inst. for Nucl. Studies, Warszawa - Poland
Wroclaw University, Wroclaw - Poland
University of Granada - Spain

ICARUS T300 Prototype

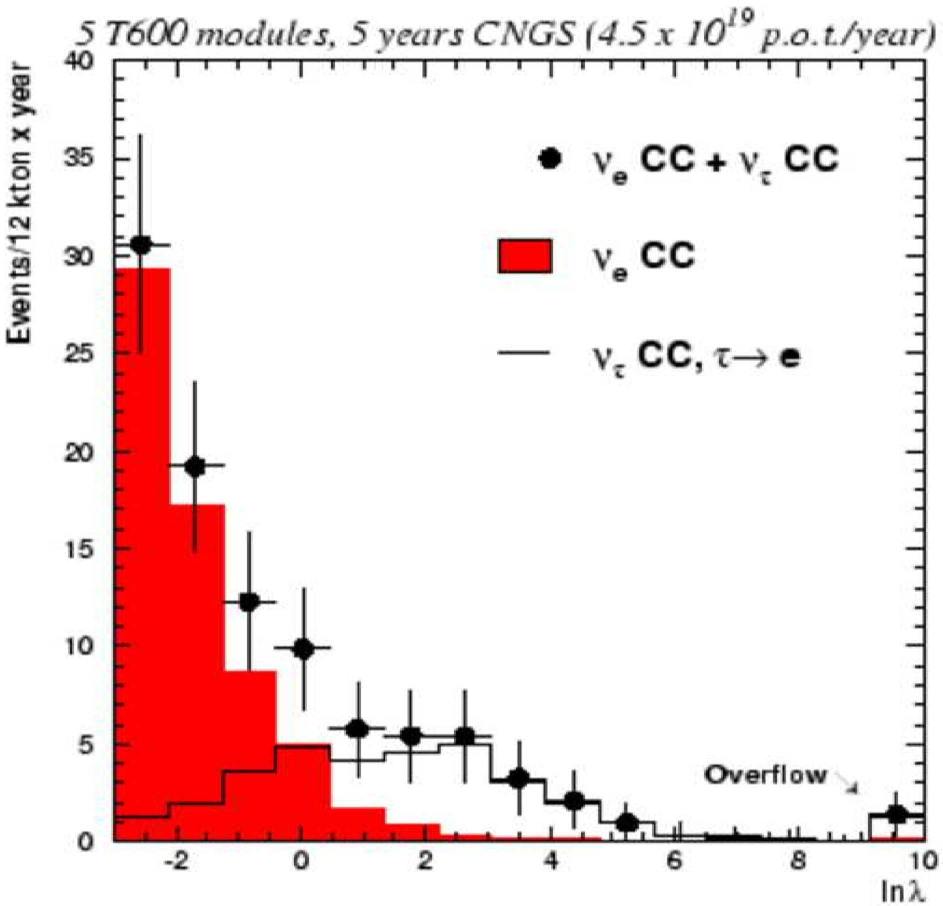






T600 test @ Pv: Run 201 - Evt 12

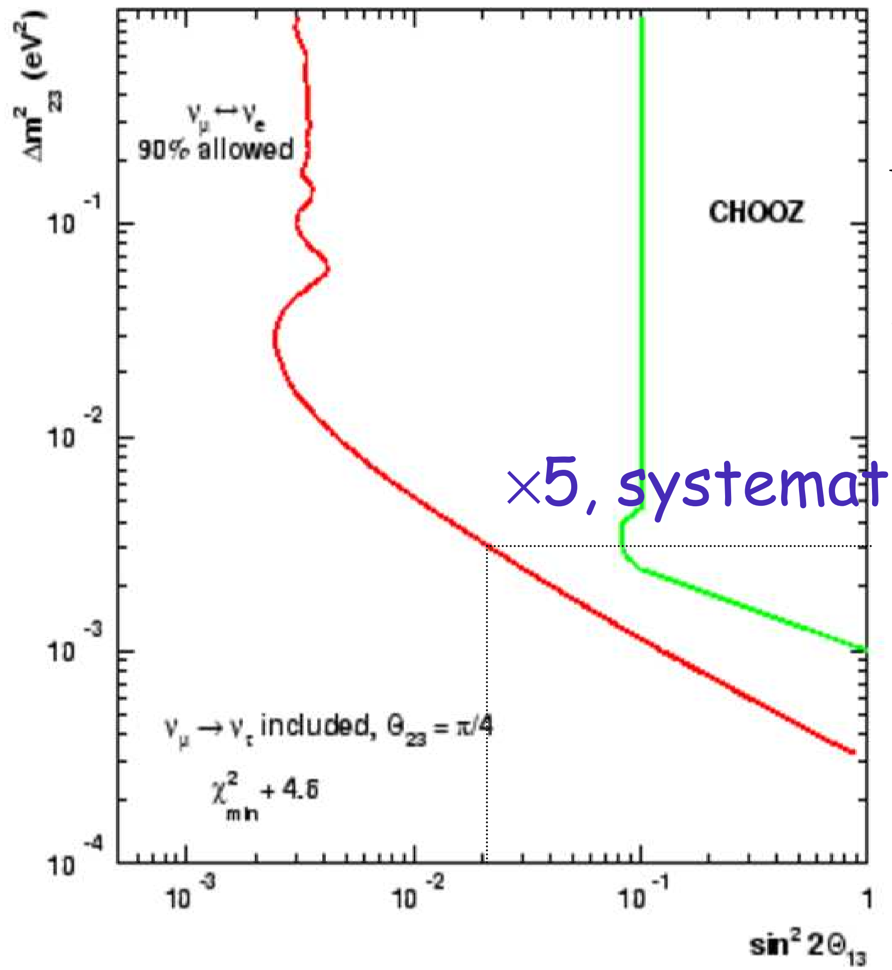
ICARUS is … a long baseline tau and electron appearance experiment



- **Detector configuration: 5 T600 modules, with 2.35 kton of active LAr**
- Oscillations $\nu_\mu \rightarrow \nu_\tau$: golden channel $\tau \rightarrow e$ (good e/π^0 separation), but also $\tau \rightarrow \rho$
- **5 years: 11.9 events with 0.7 background events @ $\Delta m^2 = 2.5 \times 10^{-3}$**

Analysis based on a 3-dimensional Likelihood:
$E_{visible}$, P_T^{miss}, $\rho_l = P_T^{lep} / (P_T^{lep} + P_T^{had} + P_T miss)$

ICARUS $\nu_\mu \rightarrow \nu_e$ sensitivity



$\times$5, systematics ?

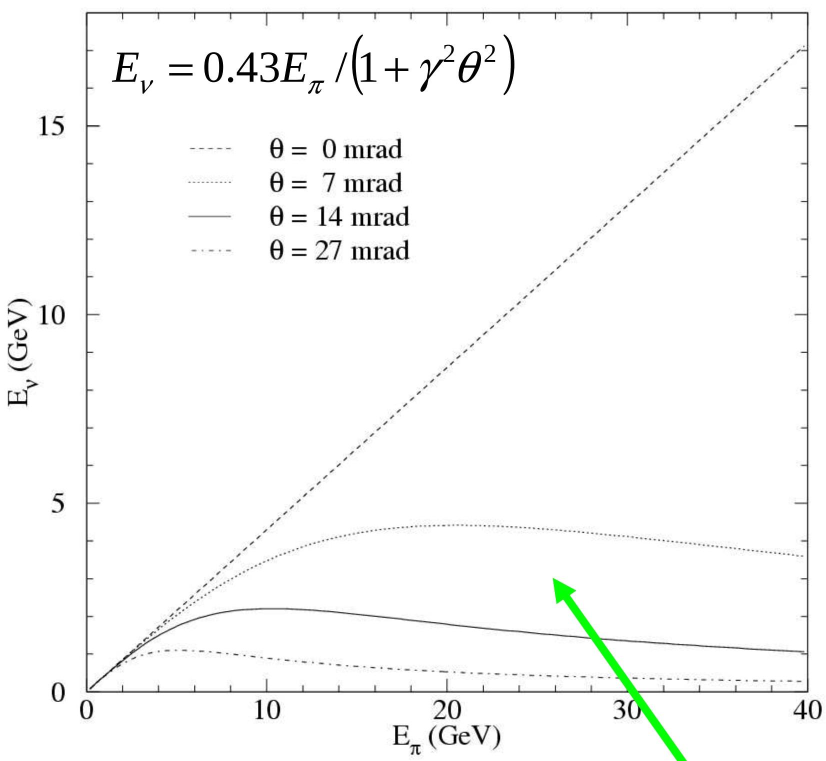
$\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ disentangled by the use of missing transverse momentum

Next Proposals for Long Baseline Experiments: θ_{13} ?

- JHF-I (0.75 MW, 22.5 kton) & JHF-2 (4 MW, 1Mton) with 50 GeV PS, 0.8 GeV ν's over a baseline of 295 Km from JAERI to Kamioka
- NuMI off-axis (20 kton surface detector @ 700-1000 Km from FNAL, 5-10 km off axis)
- BNL beams possibly to Lansing (350 km), Soudan (1770 km), NUSL (2540 km), WIPP (2880 km) … with upgraded AGS (0.5-1.3 MW), $E_\nu \simeq 1$ GeV
- CNGS off-axis to off-shore under water Č detector in Golfo di Taranto (1200 km from CERN, 0.8 GeV ν's)
- CERN beam to Frejus with SPL (2 GeV, 4 MW proton linac, 300 MeV ν's, over a baseline of 130 km)
- Beta-beam to Frejus (300 MeV ν_e and $\overline{\nu_e}$ from ^{18}Ne and ^{6}He ions)
- FNAL proton driver, neutrino factories …

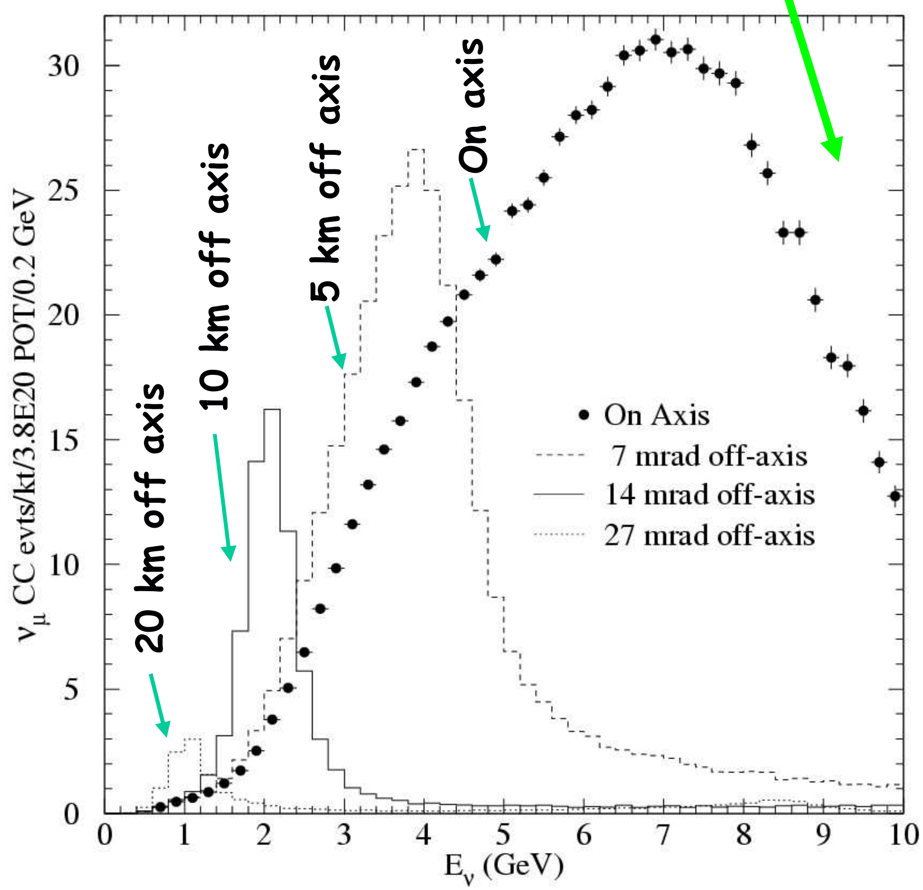
The Off-Axis concept

(D. Beavis et al. BNL Proposal E-889)



For a given θ≠0, a large range of pion energies contributes to a small range of neutrino energies

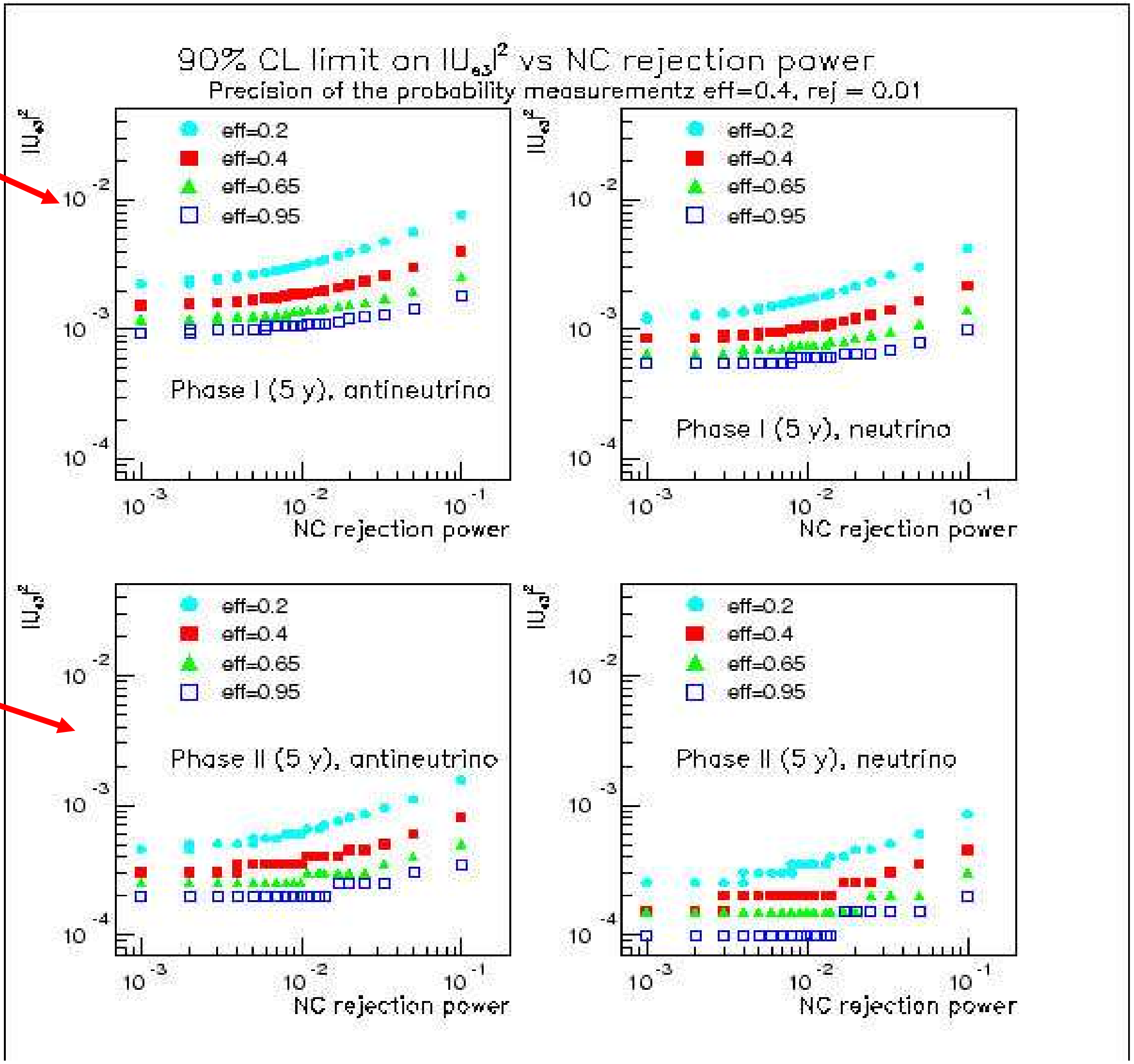
Off-axis beam from NuMI ME configuration



NuMI off-axis detector

LOI, Fermilab P929 submitted

- ~ 20 kton fiducial volume detector
  - Low Z target with RPC's, drift tubes or scintillator
    - absorber medium can be recycled plastic pellets
  - Liquid Argon, Water Cherenkov
- Phase II with 25 times higher POT×Detector mass
- Sensitivity to 'nominal' $|U_{e3}|^2$ (i.e. neglecting CP phase δ) at the level 0.001 (phase I) and 0.0002 (phase II)



JHF for a neutrino beam

Overview of experiment

1st Phase

- $\nu_\mu \rightarrow \nu_x$ disappearance
- $\nu_\mu \rightarrow \nu_e$ **appearance**
- NC measurement

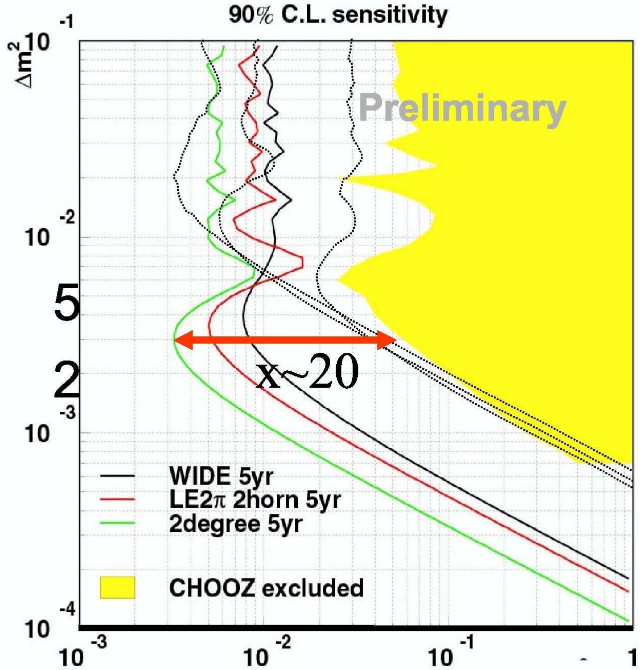
2nd Phase

- **CPV**
- **proton decay**

JHF: the physics reach

Sensitivities in first phase(5yrs)

Search for ν_e appearance

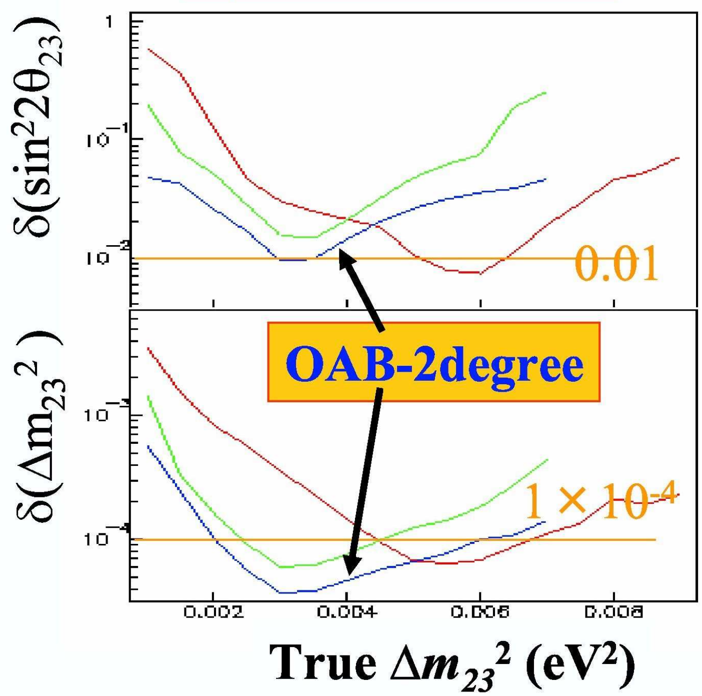


$$\sin^2 2\theta_{\mu e} \equiv \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13}$$

~0.5

Sensitive $\sin^2 2\theta_{13} > 0.006$ (90%)
$\sin^2 2\theta_{13} > 0.018$ (3σ)

ν_μ disappearance



$\delta(\sin^2 2\theta)$~0.01 in 5 years
$\delta(\Delta m^2)$ ~<1×10^{-4} in 5 years

w/ beam MC sim, & full SK det. sim.

Conclusions

☺ **An exciting future is ahead of Long Baseline neutrino oscillation experiments**

MINOS to start by the 1st quarter 2005, CNGS by the 3rd quarter 2006

Learn how to efficiently produce and operate high power proton beams to make neutrino beams

The detectors

- large masses needed: from few ktons (now) up to hundreds of ktons (in the future), and it had better be cheap !
- a rich spectrum of experimental techniques

Lots of room for realistic creativity !