The MINOS Experiment & Long Baseline ν Oscillation Programs in Europe and U.S.

Jon Urheim, U. of Minnesota

ICHEP 2002, Amsterdam, 27 July 2002

- Introduction
- MINOS Experiment Overview
- Status of MINOS – Construction & First Data
- Status of CNGS – [thanks to S. Katsanevas]
- Near-Future Initiatives in Europe and US

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Introduction

- **picture emerging from existing data**
  - **Large effect at "atmospheric" Δm^2**
    - oscillation hypothesis very strong **[Super K]**
    - effect now seen at accelerator expt. **[K2K]**
    - dominant mode likely to be $\nu_\mu \rightarrow \nu_\tau$ **[Super K]**
  - **Also large effect at "solar" Δm^2** **[Davis]**
    - could be the LMA solution !! **[Ga + SNO + SK]**
  - **Questions:**
    - two angles large, what about the third θ_{13} ?
    - complex phase in MNS matrix → CPV ?
    - what about CPT ? sterile neutrinos ? Extra dimensions ? where does LSND fit ?

Goals of 1st generation of Long Baseline Experiments

Confront emerging picture with precision data

- confirm deficit of ν_μ in accelerator-based exp't
- confirm oscillation hypothesis:

  must measure/know E & L precisely to see osc'ns in L/E

  pin down oscillation parameters

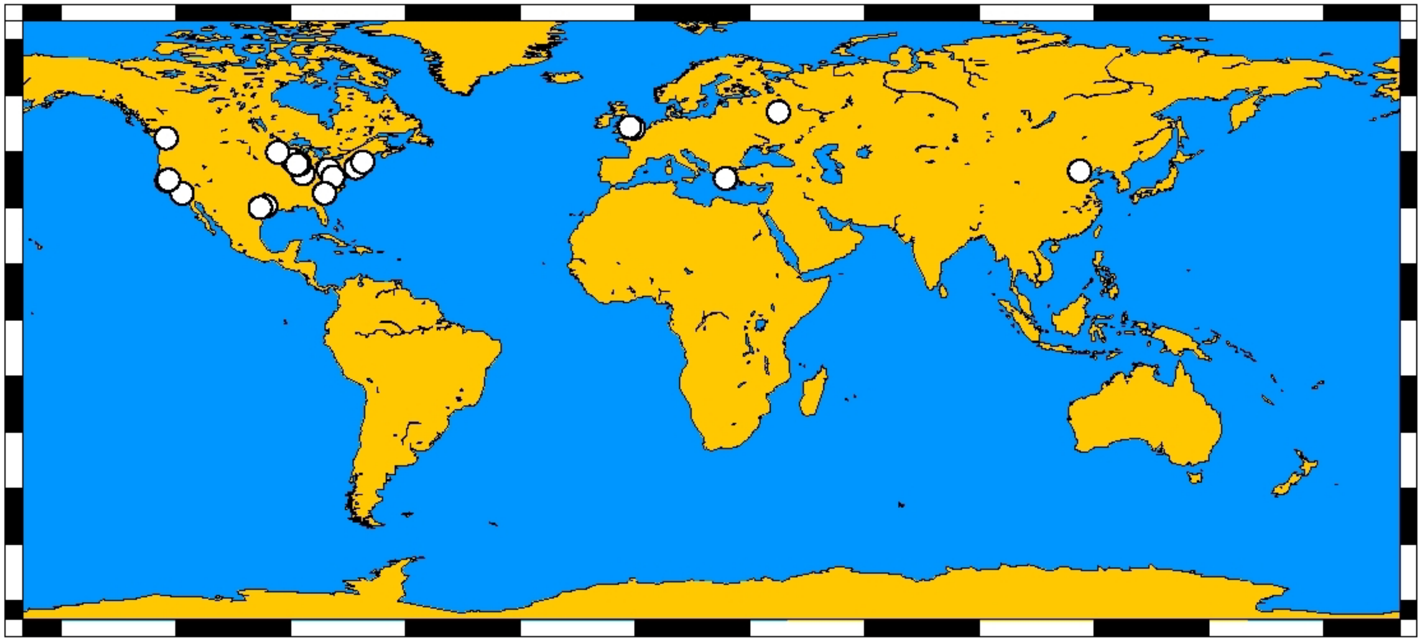
- demonstrate $\nu_\mu \rightarrow \nu_\tau$ is dominant mode:

  Tau appearance ! (CNGS → direct, MINOS → NC/CC)

Look for new phenomena

- evidence for non-zero θ_{13} : → detection of ν_e
- test for possible CPT violation ?
- etc….

The MINOS Collaboration



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

~30 Institutions   ~250 physicists & engineers

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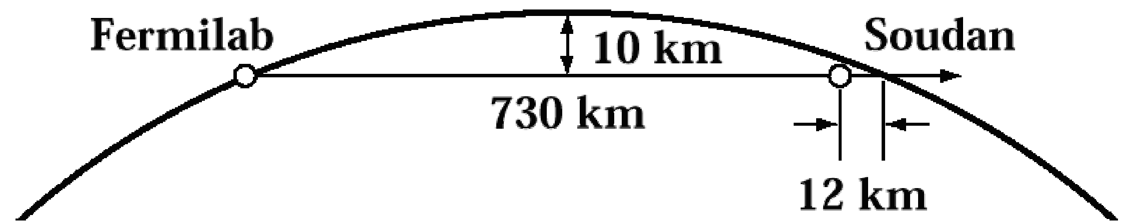
NuMI / MINOS Concept



ν_μ source: (NuMI)

120 GeV protons from FNAL Main Injector

detectors: (MINOS)

1) 'Far' detector:

5.4 kT magnetized iron/scintillator tracker/calorimeter in Soudan mine

2) 'Near' detector:

980 T version of far detector at FNAL

3) Also:
'Calibration' detector in test beams at CERN

NuMI & The Main Injector

Fermilab Main Injector:

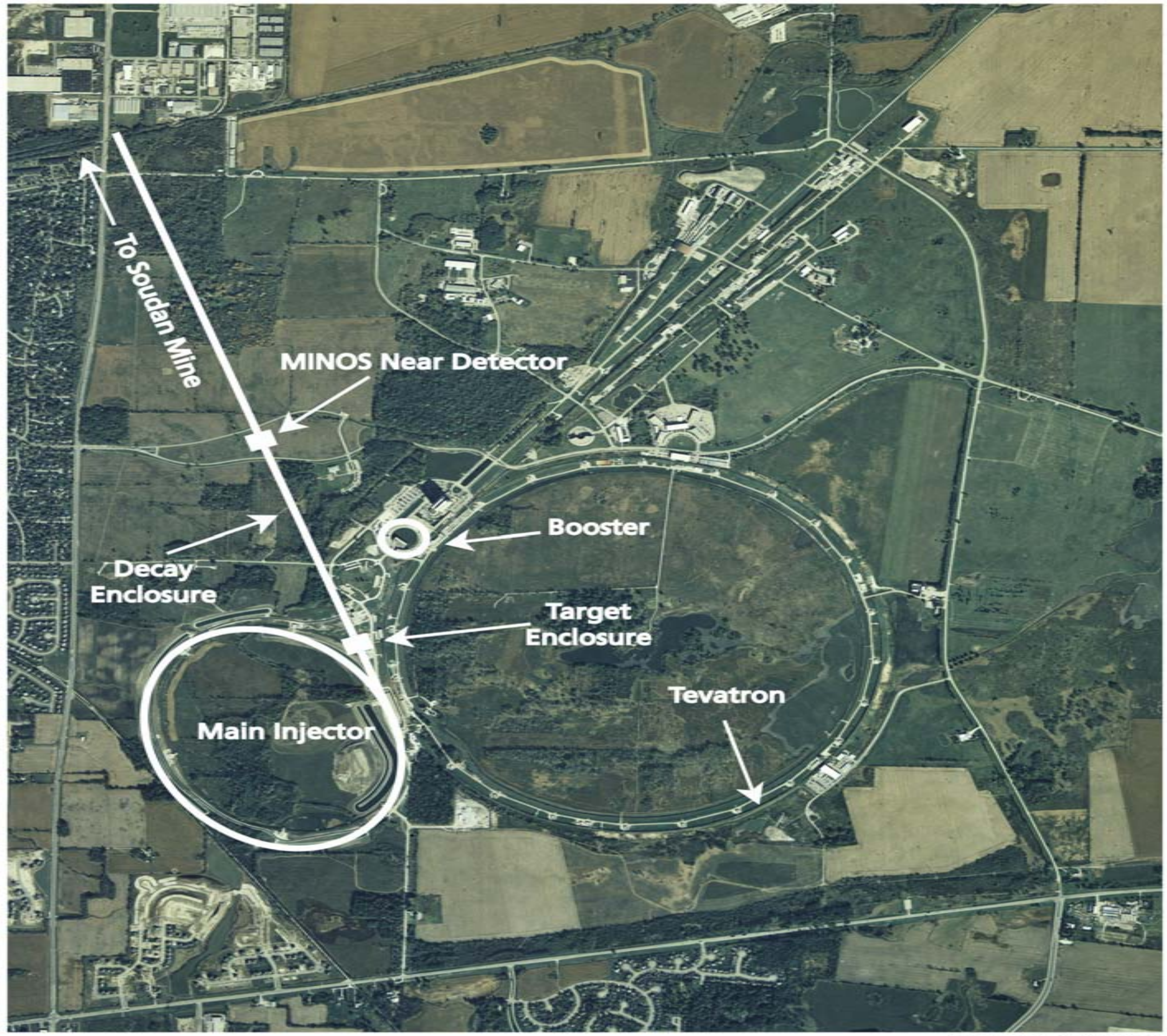
120 GeV protons
4×10^{13} protons/pulse
1.9 sec rep rate
(~8 μsec spill)
→ 0.4 MW

NuMI Beam:

Graphite target
Two magnetic horns
675 m. vac. decay pipe
hadron absorber

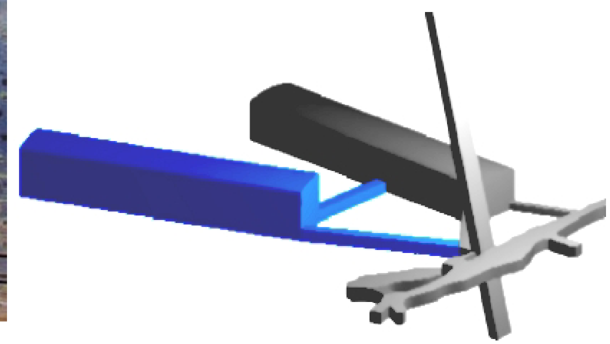
Beam Monitoring:

muon detectors
hadron detectors
+ Near Detector !



FERMILAB #98-765D

Soudan Underground Laboratory



- **former iron mine, now a state park,**
  - **home of: Soudan-1 & 2 , CDMS-II , and MINOS expts**

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The MINOS Far Detector

Steel / Scintillator :

2.5 cm thick steel

4 cm x 1 cm polystyrene
– encased in Al cover

15,000 Amp-turn coil

486 Layers → 5.4 kTon !

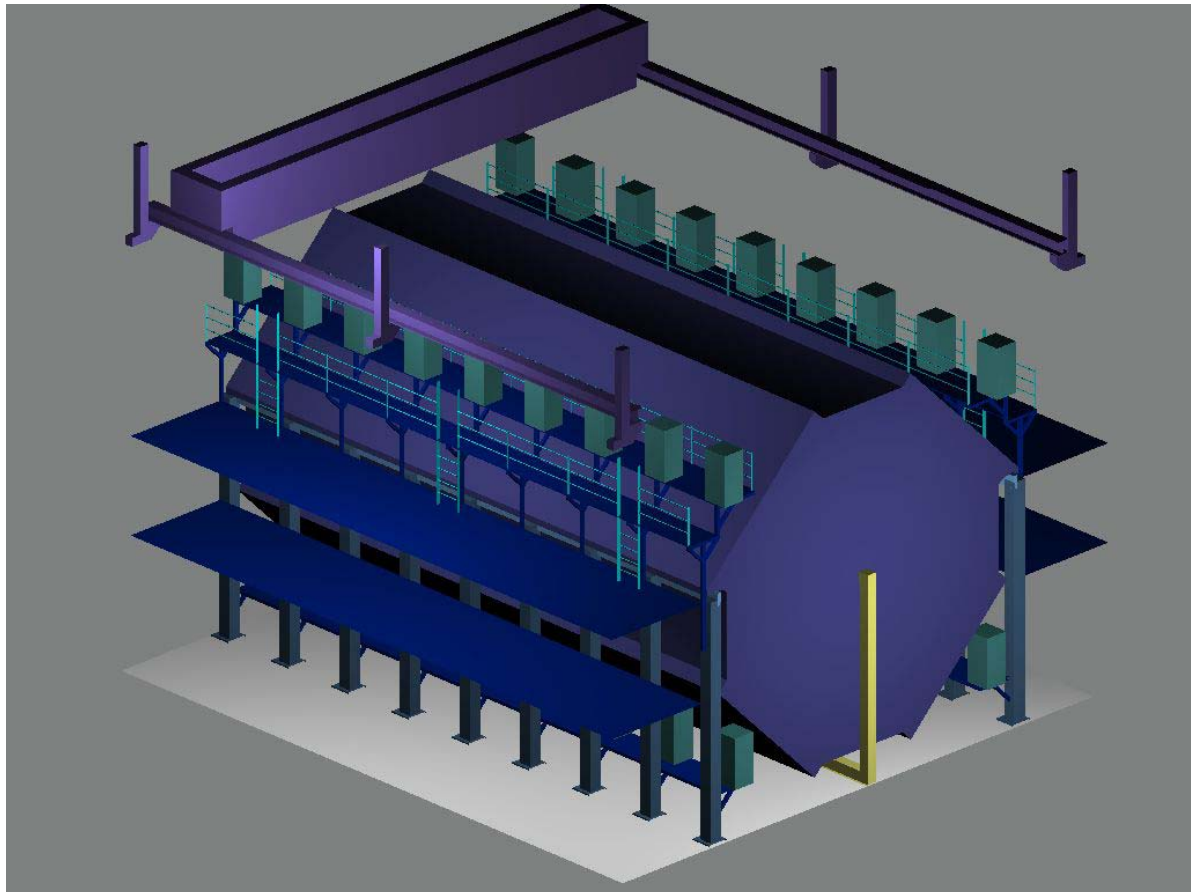
Readout:

WLS fibers glued into groove in scintillator
– double-ended readout

Hamamatsu M16 pmt's
– 8-fold optical summing

IDE 'VA' front-end chips pulseheight & time

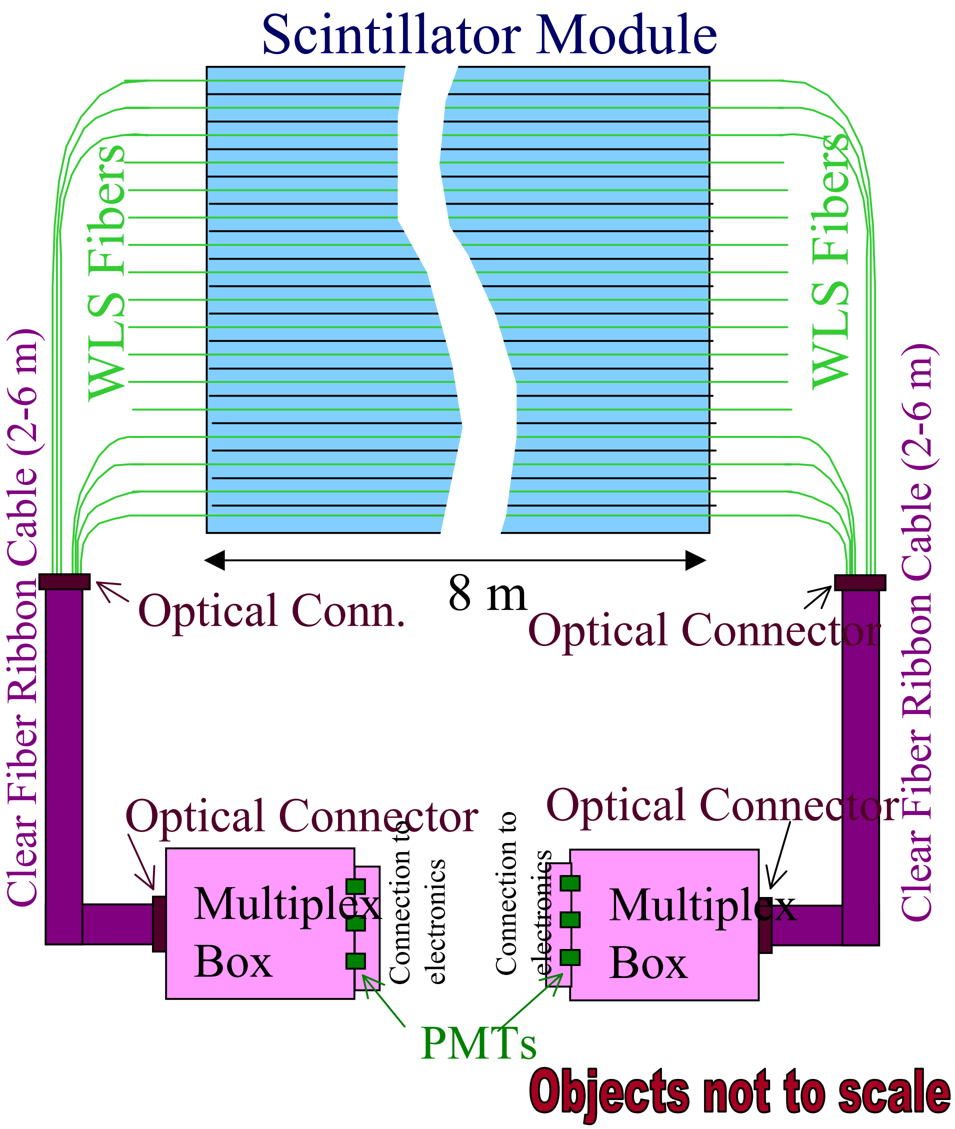
GPS to synch to MI spill

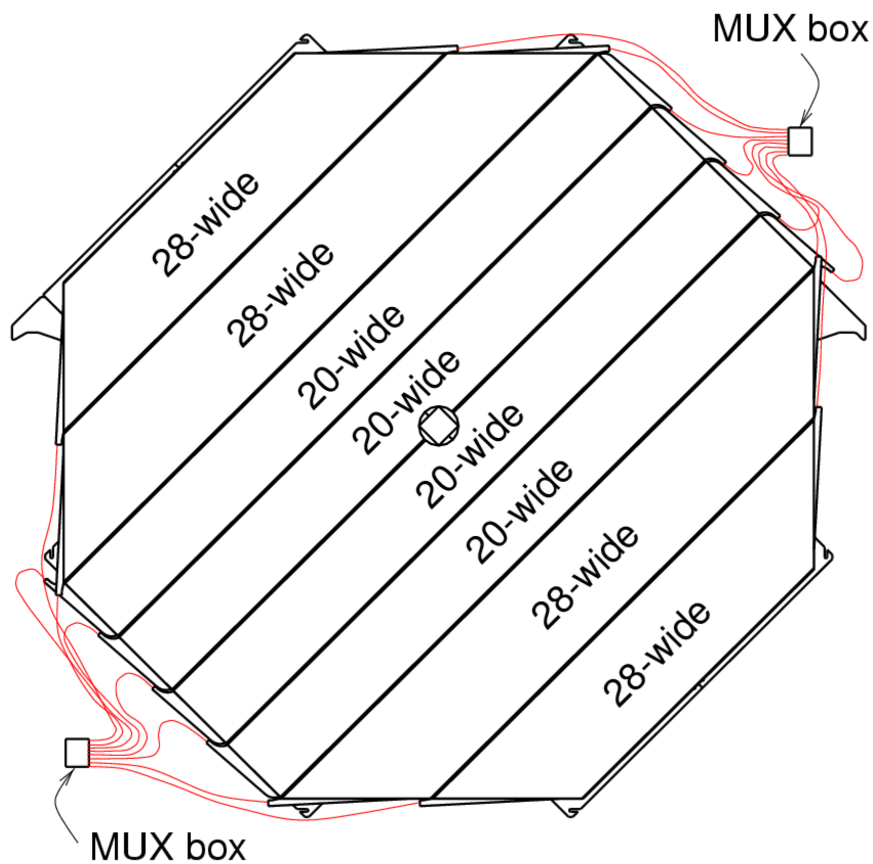


Shown here: 1 (of 2) super modules

– **248 planes: 8m x 8m x 15m !**

Far Detector Module Layout

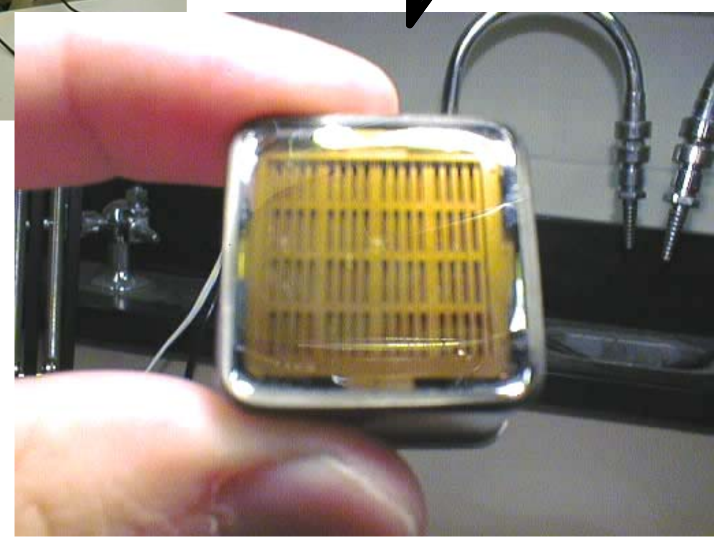




Scintillator Detectors & PMTs

Spool of 1.2 mm WLS fiber being glued into groove

Hamamatsu M16 16-channel PMT (8 fibers per pixel)



4.1 cm x 1 cm polystyrene strips
– coextruded with TiO_2 coating
& groove for WLS fiber

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The MINOS Near Detector

1 Ton version of far det.

290 m d/s of hadron absorber
→ beam is small !

→ 4 regions:
'veto' + 'target' + 'shower'
+ 'spectrometer' (sparse)

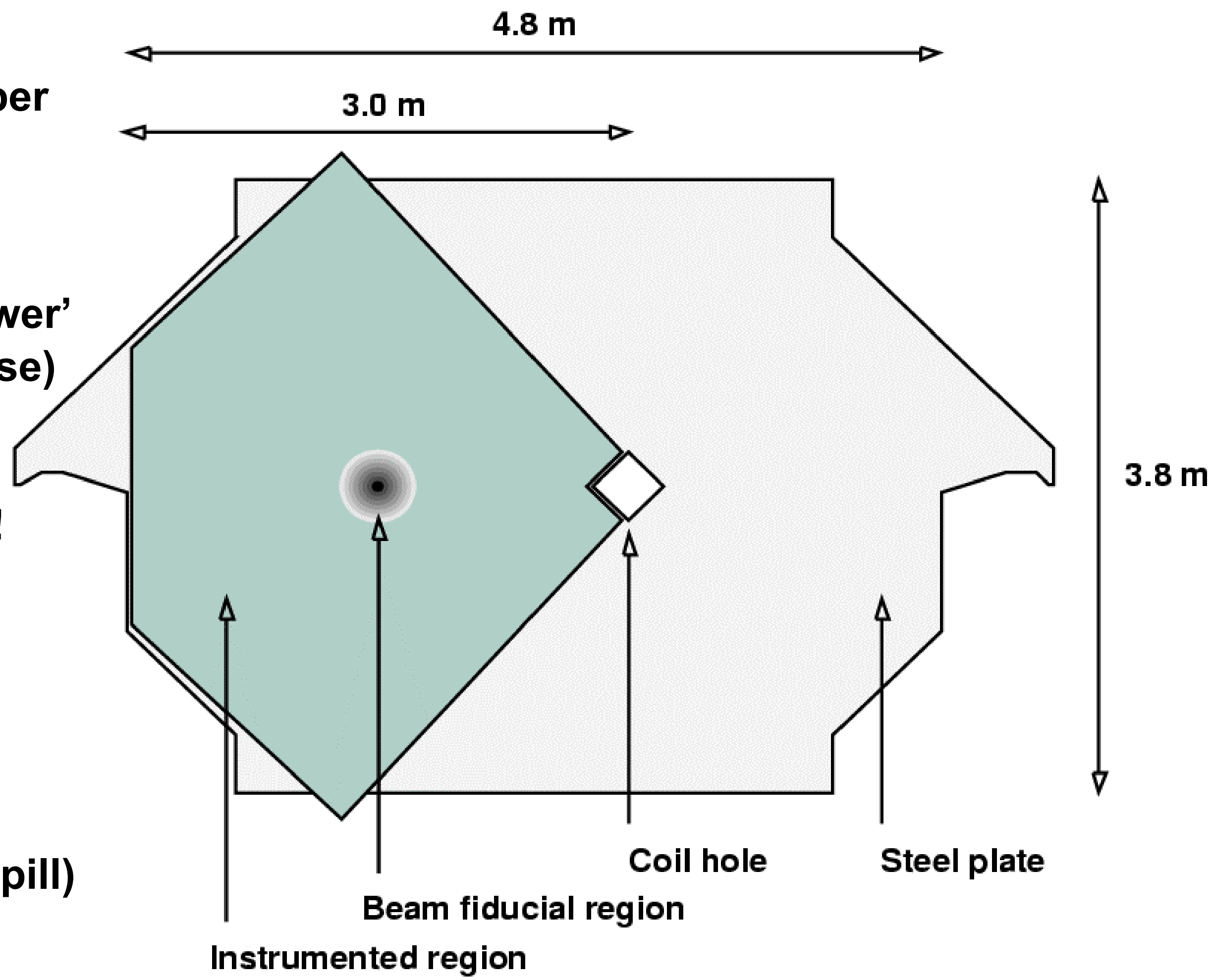
make as similar to
far detector as possible !

Readout:

Hamamatsu M64 pmt's

High instantaneous rates
(~50 ν events / 8 μsec spill)
→ fast front ends needed

→ use FNAL QIE chips
(based on KTeV version)



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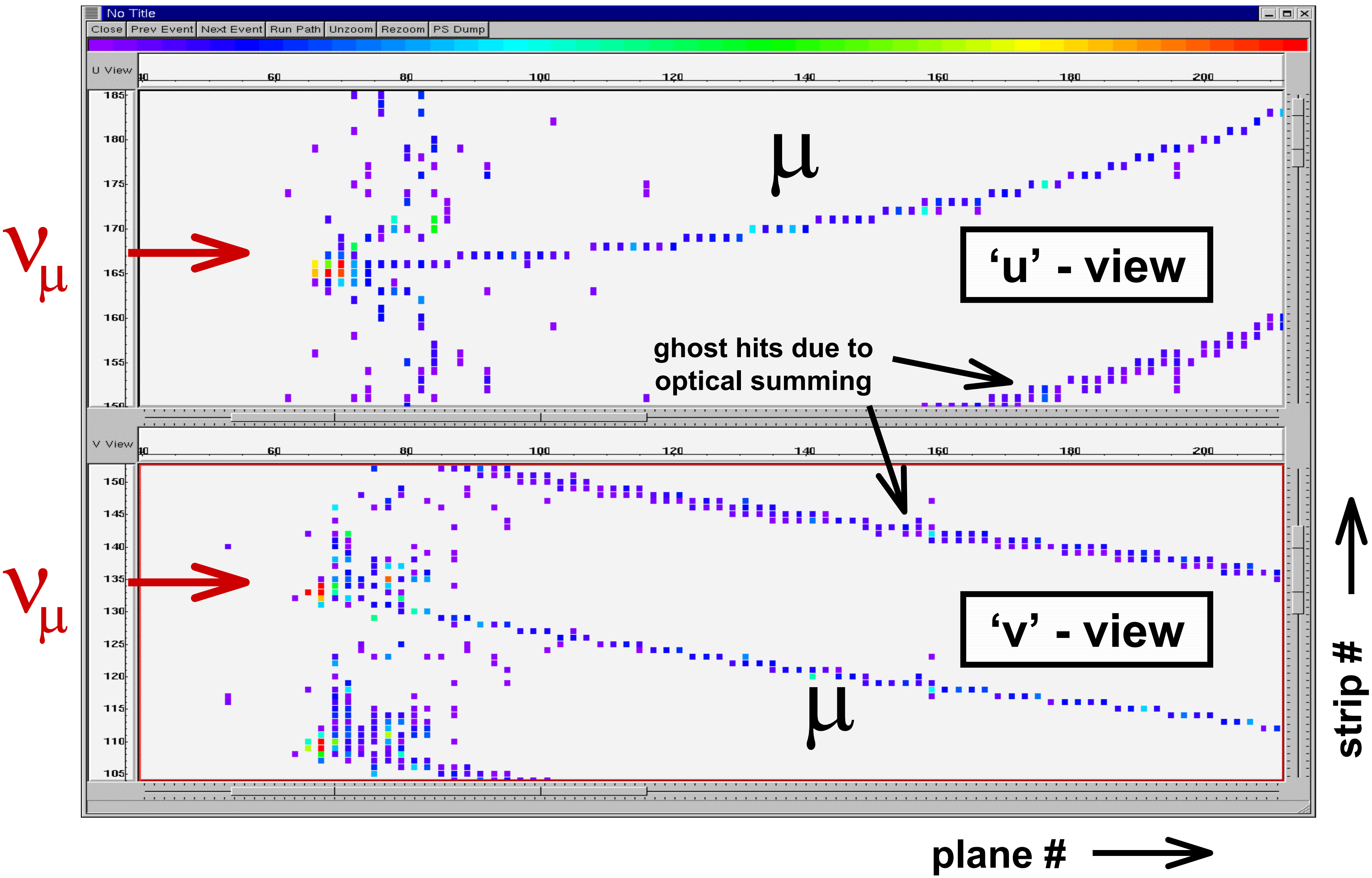
Simulated Neutrino Interaction



Beam Energy Considerations

Pre – Super K:

$\Delta m^2 \sim 0.01\ eV^2$ (IMB,Kam..)

→ NuMI 'high energy beam' gives best sensitivity

→ good prospects for observation of ν_τ

Post – Super K:

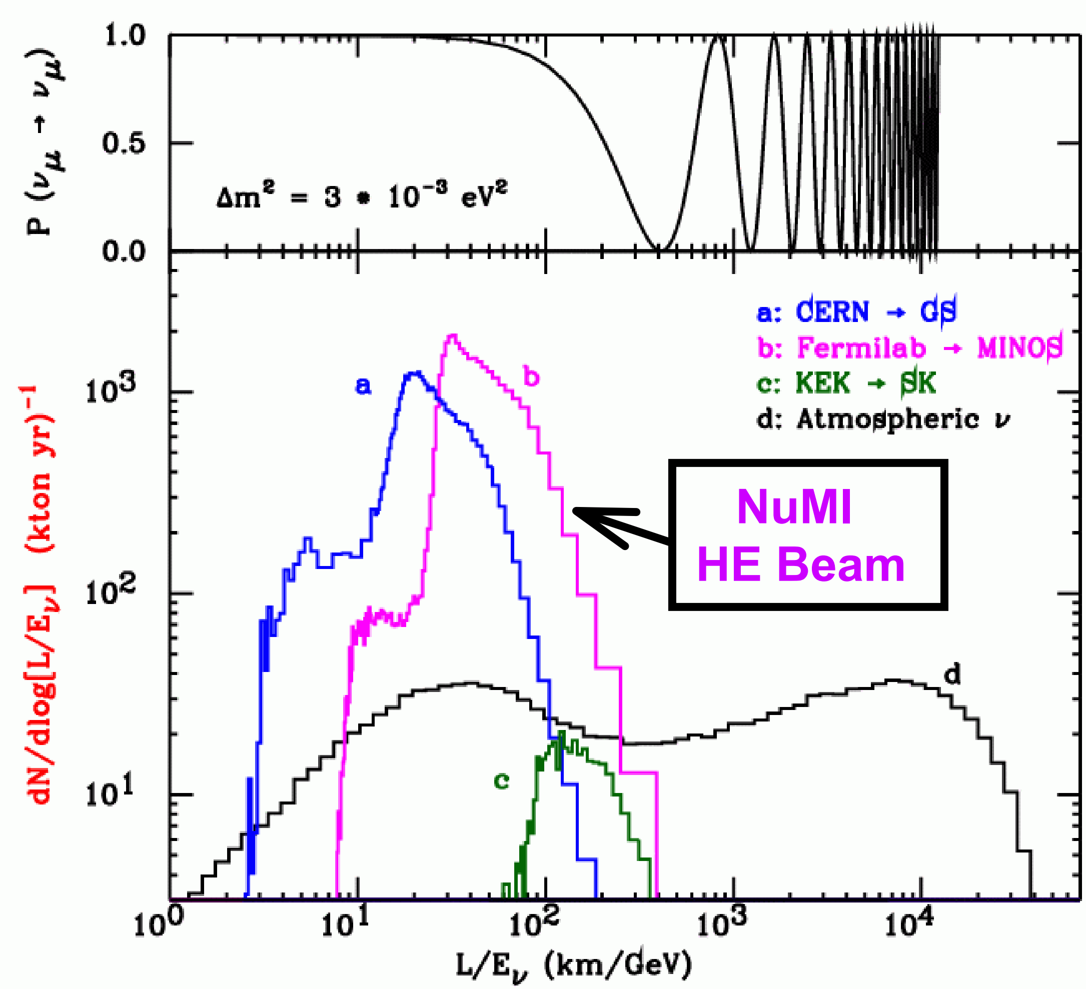
$\Delta m^2 \sim 0.001 – 0.004\ eV^2$

Can't increase "L"

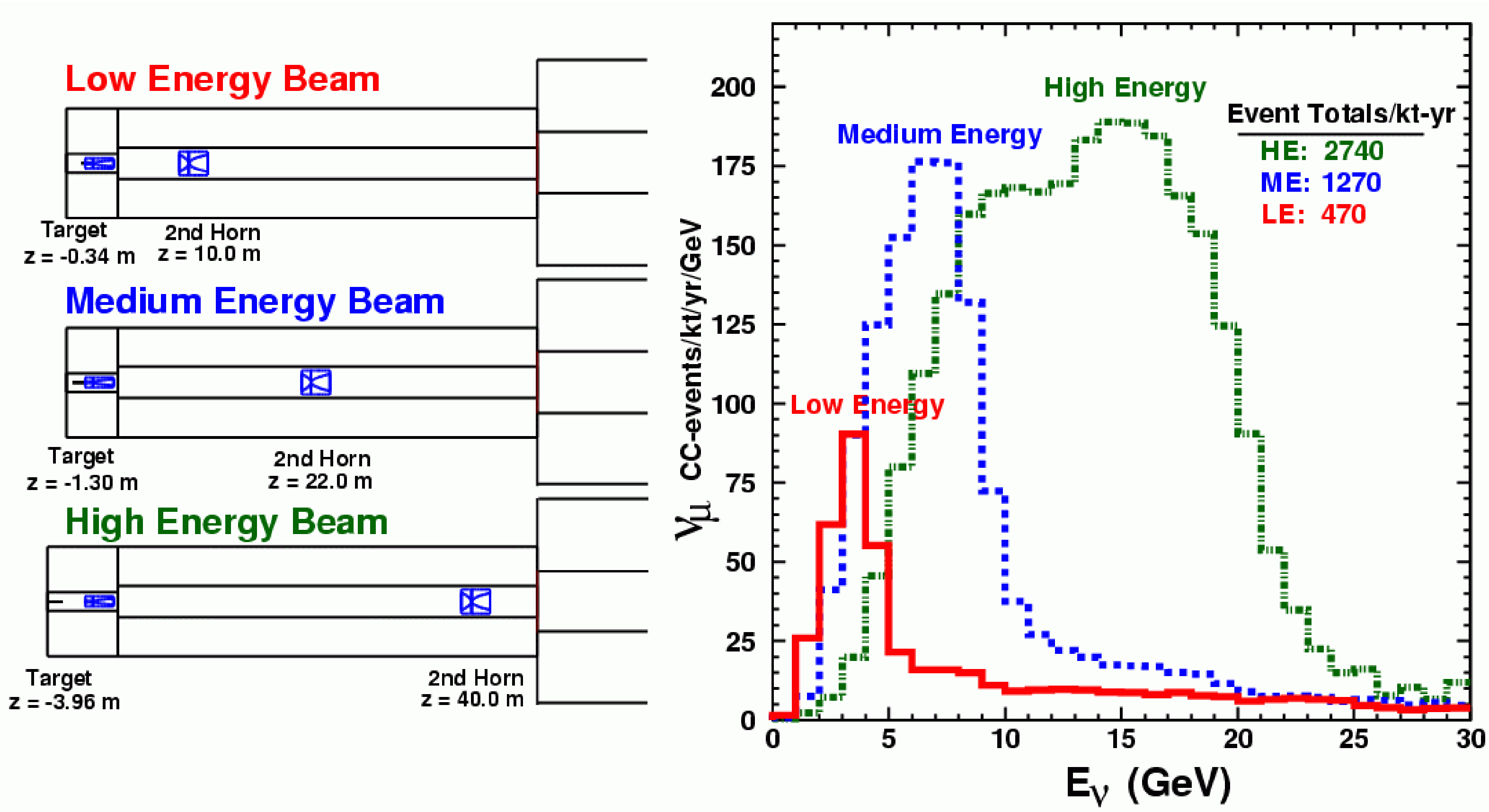
→ High energy beam no longer desirable !

→ But NuMI beam was designed to be tunable !

From: Battistoni & Lipari, hep-ph / 9807475



Configurable 2-Horn Design



– **Low energy beam: less flux, but better match to Δm^2**

– **Still plenty of events: ~ 5000 ν_μ CC events in 2 yrs**

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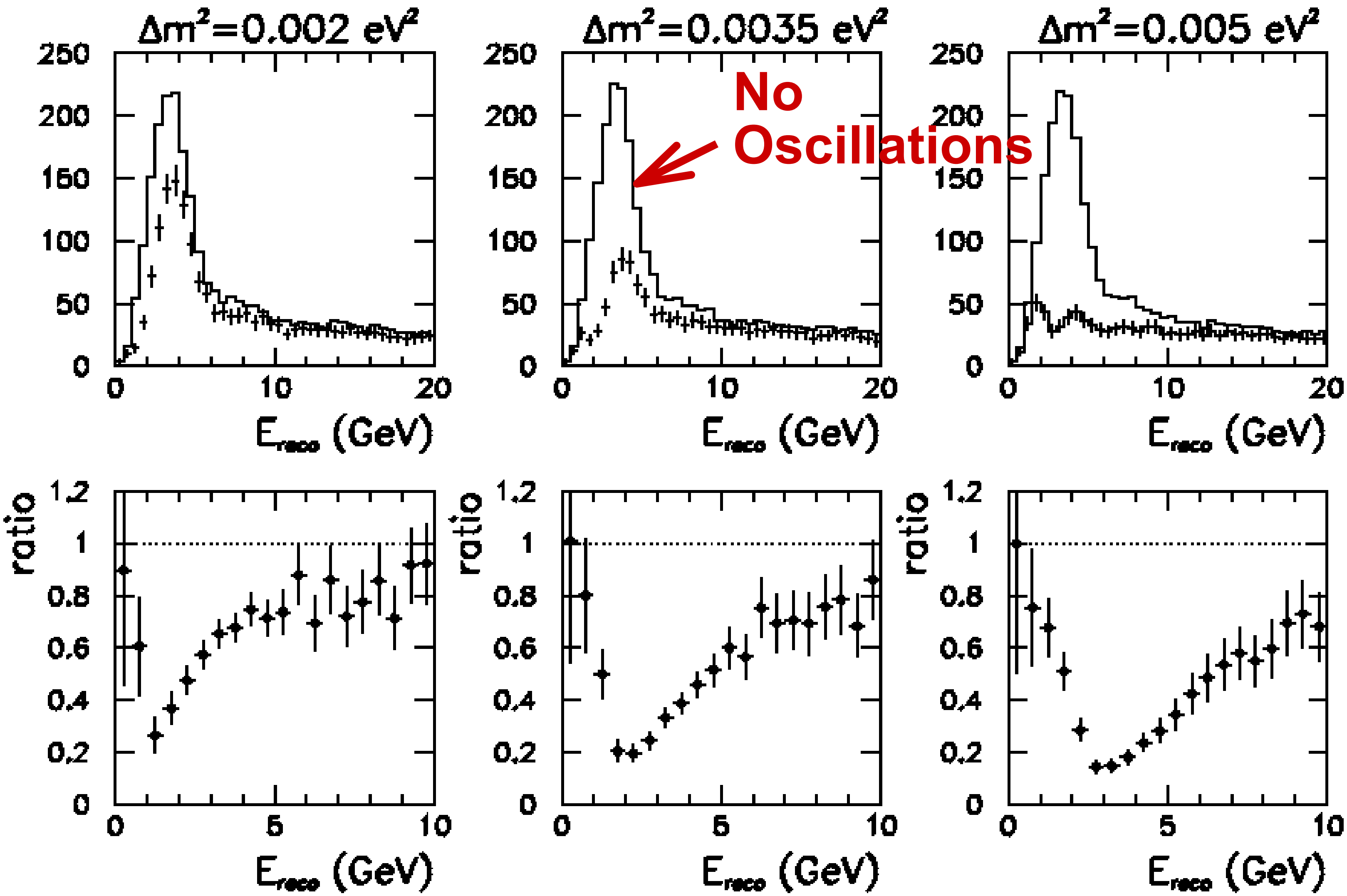
Expected Neutrino Energy Dist'ns



- **What we might see in 2 yrs of running**

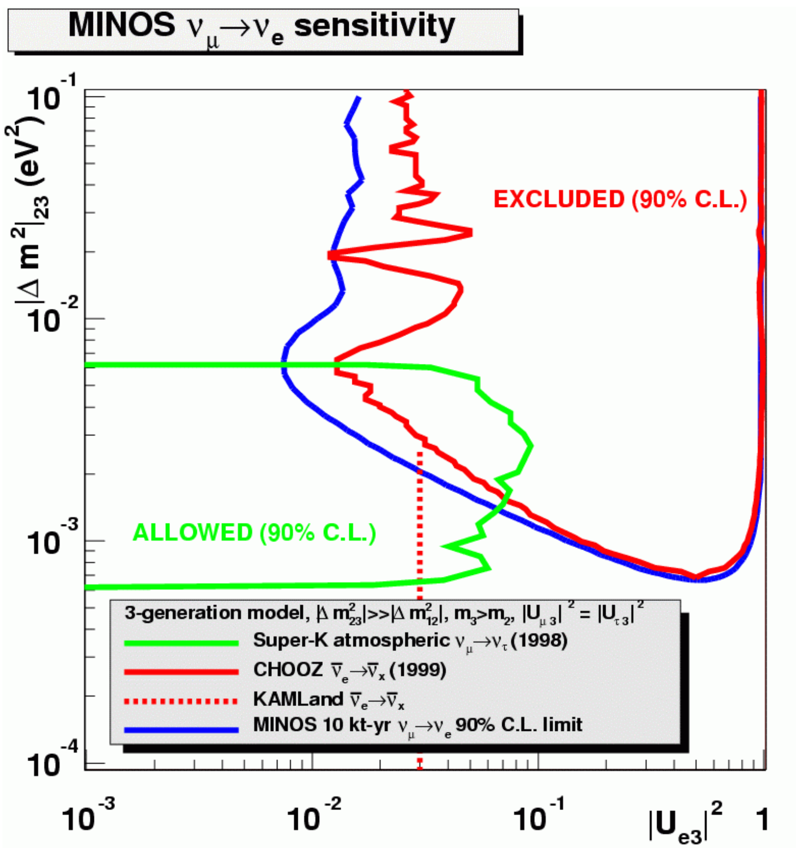
MINOS sensitivity to Oscillations

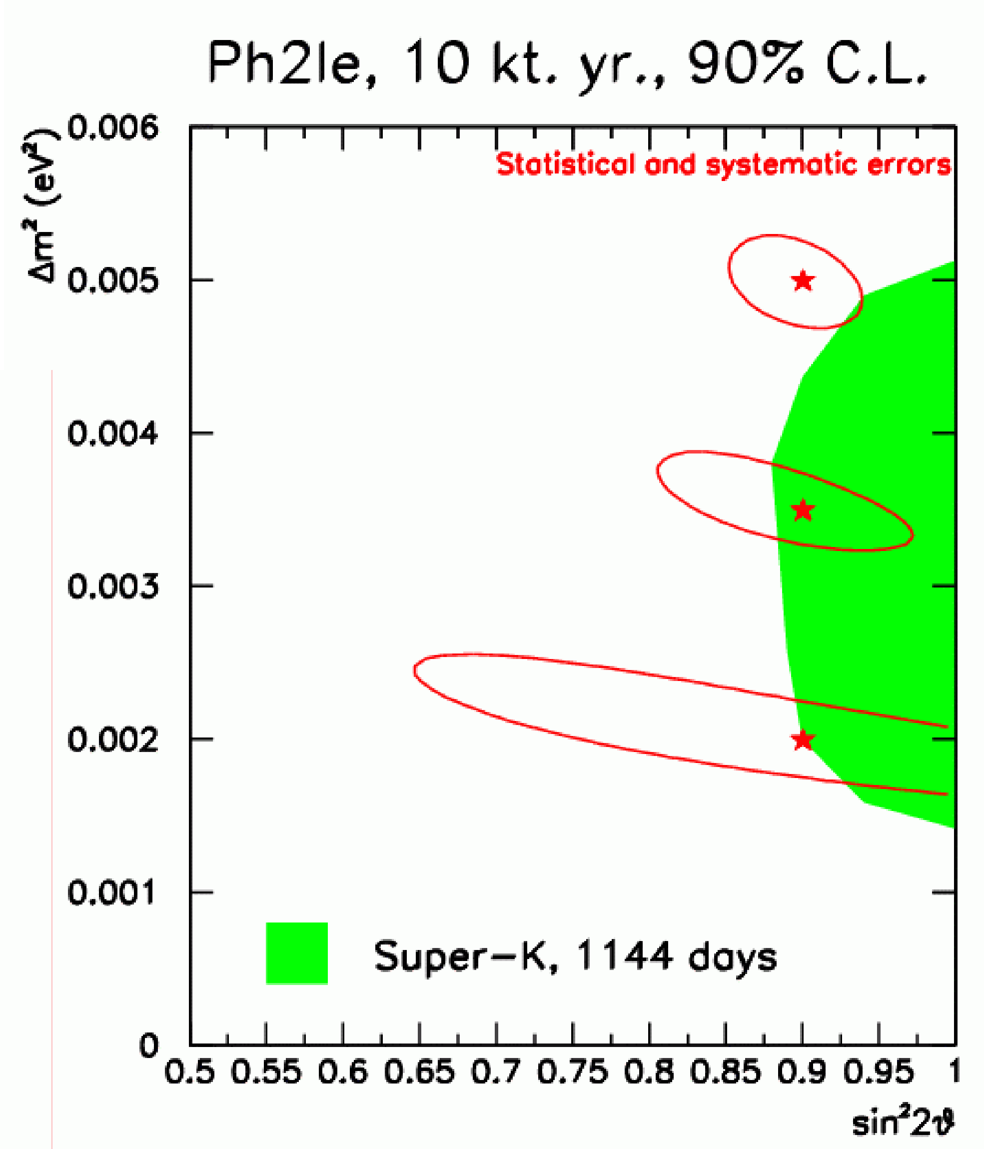
Two–neutrino mixing:

see figure at right → 2 yrs

note: we expect to run longer !

Search for ν_e appearance:





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Status of Far Detector Construction

27 July 2002

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Status of Detector & Beam Construction (cont'd)

– **Far Detector Supermodule 1 completed, 24 June**

- **248 planes, (~7 planes per week since Aug, '01)**
- **Coil now installed, to be energized this week !**
- **Supermodule 2 already being assembled → finish in April '03**

– **Near Det. Plane Assembly ongoing at FNAL**

- **Being done on surface while expt'l hall is outfitted**
- **Excellent progress so far**

– **Excavation of Beam Line & Near Det. Hall is done**

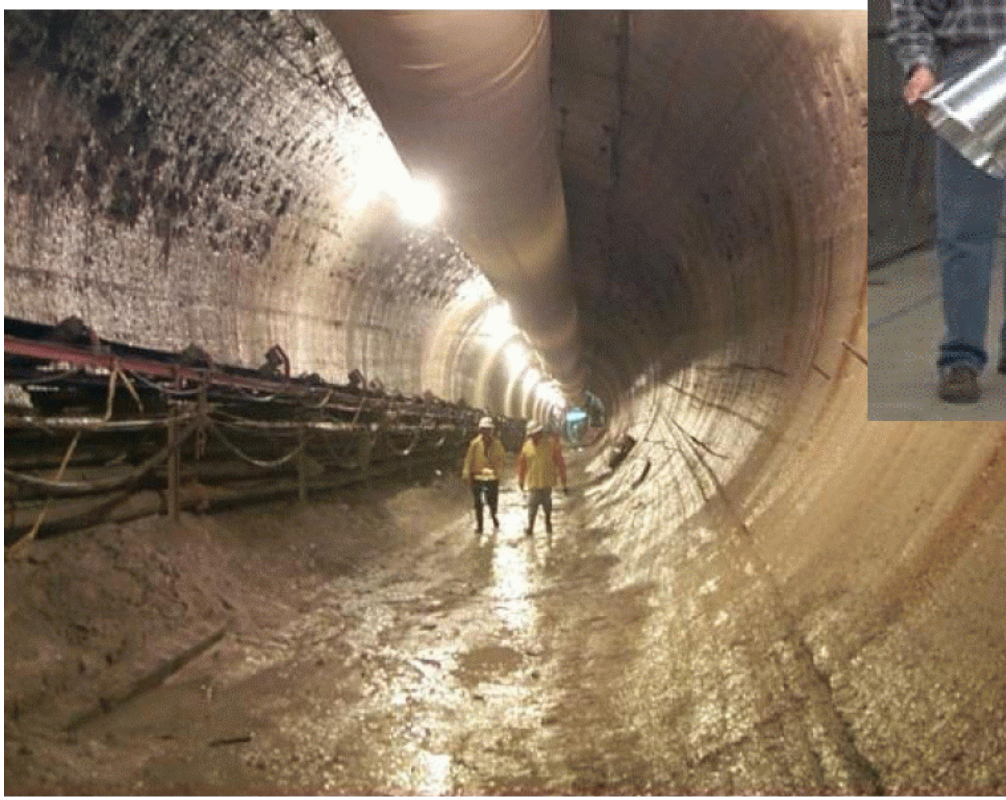
- **Installation of 2-m diameter, 675-m long decay pipe under way**
- **Prototype horn 1 tested, production horns being fabricated**
- **Design of target pile nearly complete**

– **NuMI Beam commissioning in late 2004 !!**

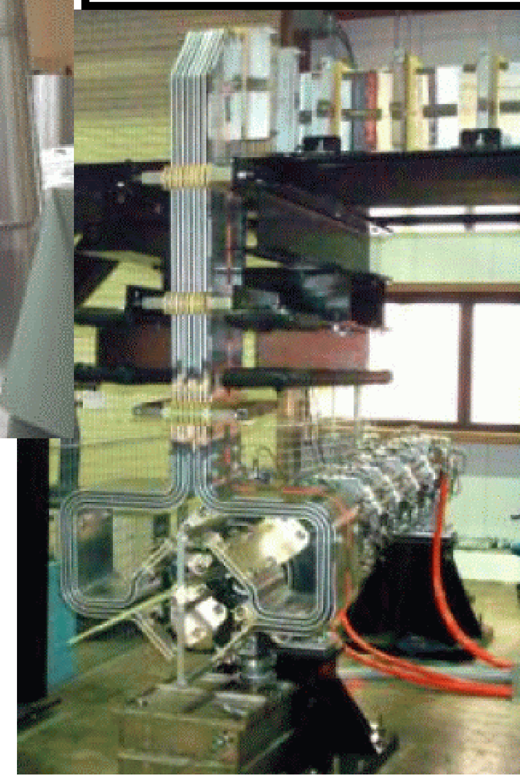
NuMI Construction

Horn 2 inner conductor →

NuMI 675-meter decay pipe segment being installed…



Horn 1 prototype, being tested…



First Look at Far Detector Data

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Detector commissioned as construction proceeds:

cosmic ray / atm neutrino data taken mainly nights & weekends

→ exposure measured in kton–months so far !

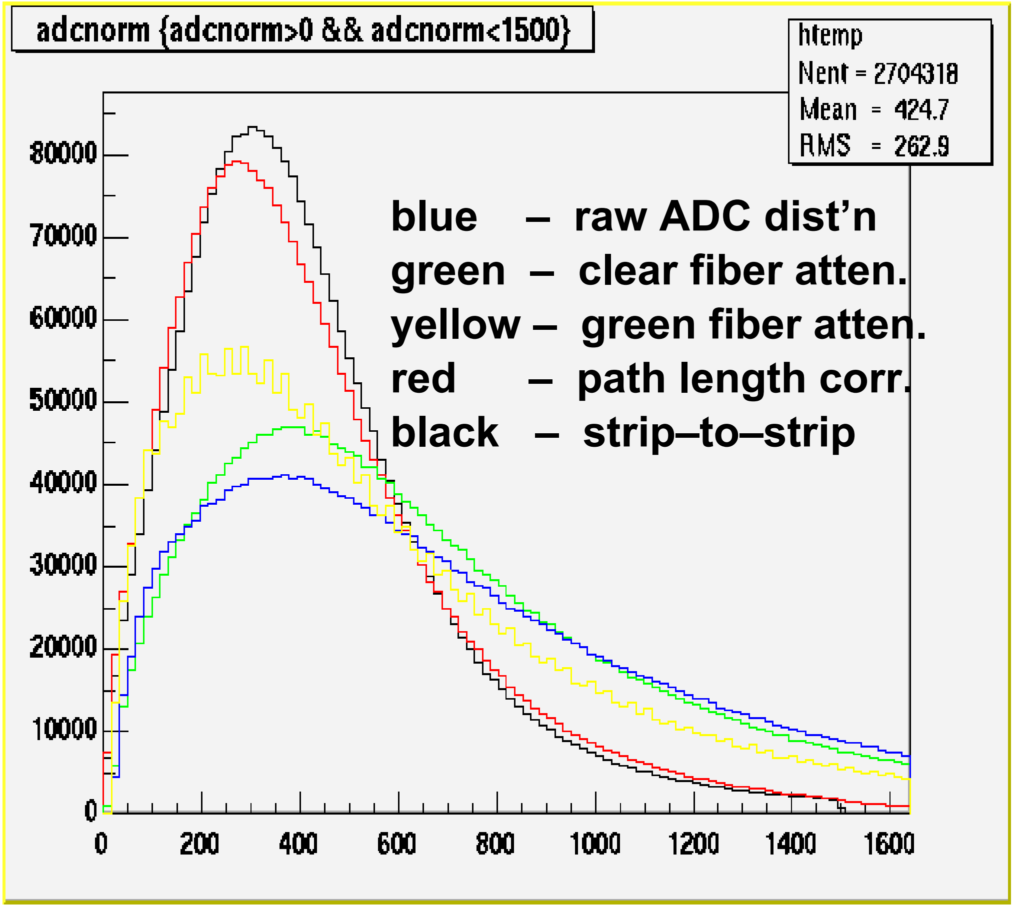
→ but will run SM 1 ~full-time during construction of SM 2

First attempts to calibrate !

note: 192 strips/plane X 248 planes X 2 ends/strip = ~ 95,000 strip-ends in SM 1

pulse height (min-I) & timing

Calibration Detector at CERN:
relates hadron/em shower energy to min-I depos'n.



ADC value

Pulseheight Calibration

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First upward-going muon !

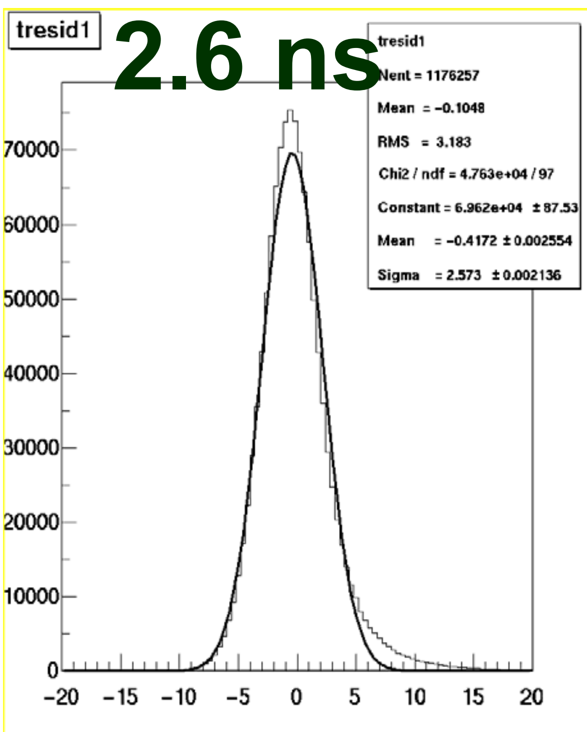
Muon entered at front face (plane 0),

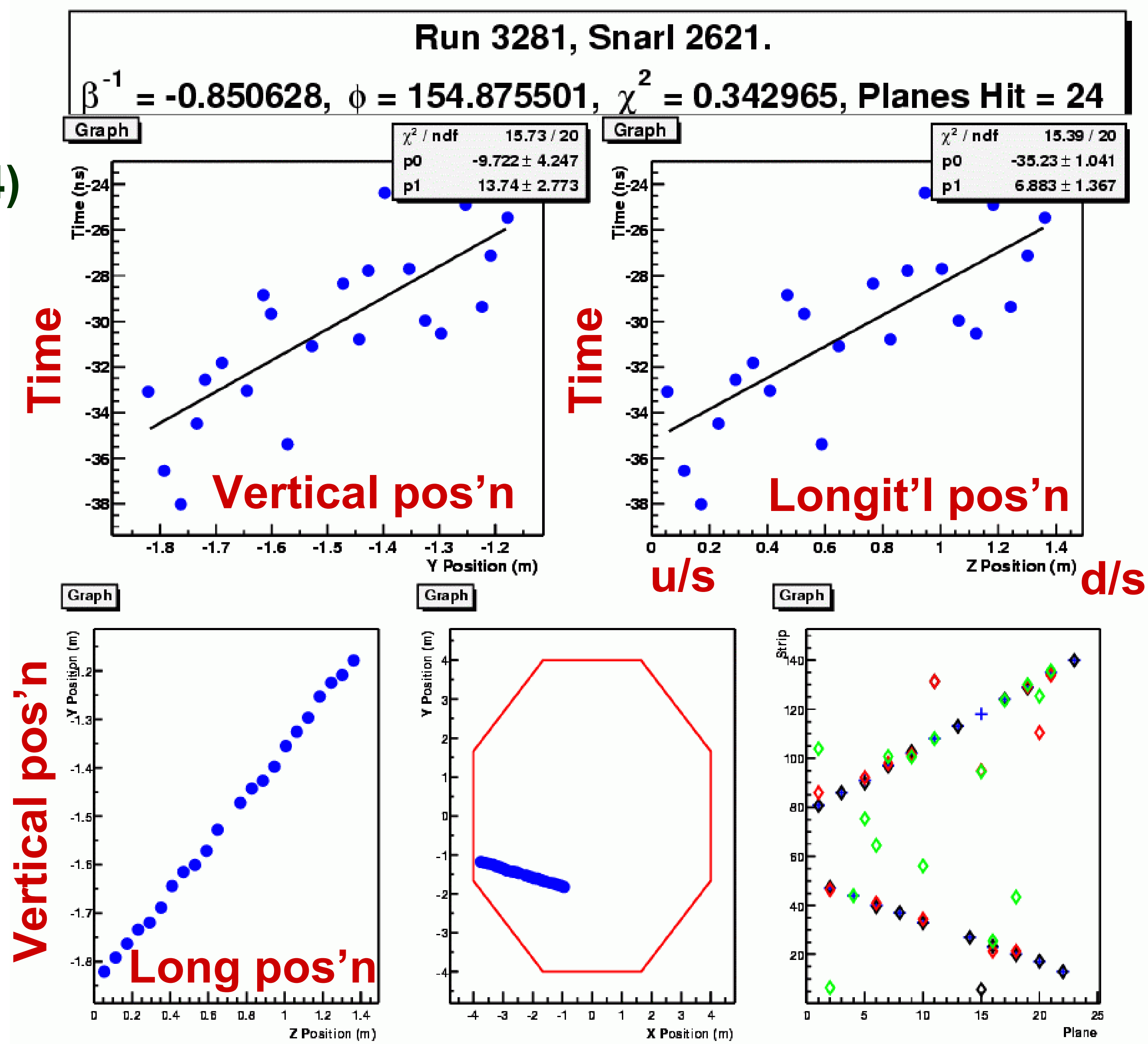
exited at side (plane 24)

Good timing is key !

Single strip timing resol'n:

2.6 ns





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(Downward-going) Candidate: Partially Contained ν_μ Event ?

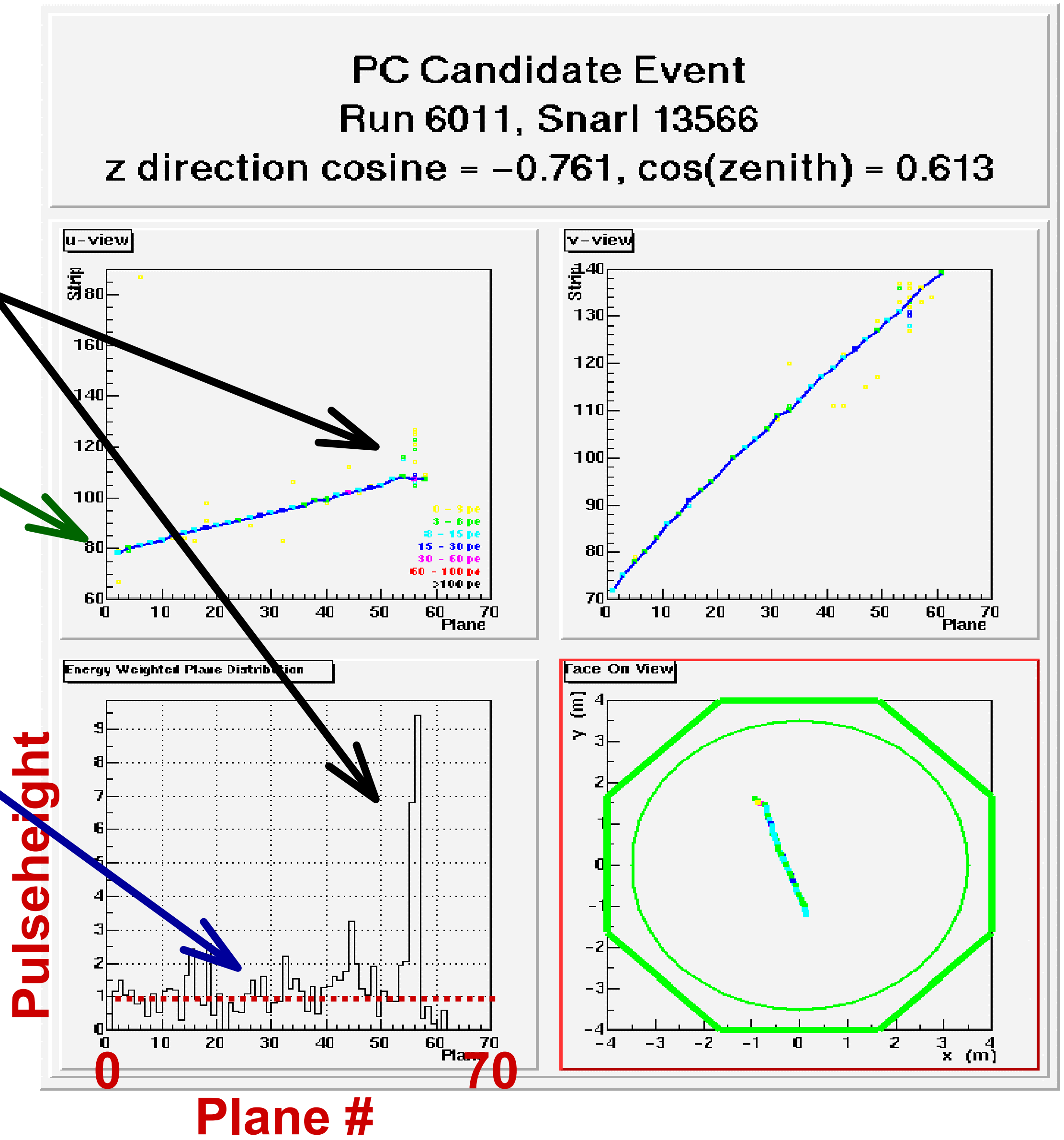
Neutrino interaction around plane 60 (large energy deposit)

muon exited through front face of detector (plane 0)

Note energy deposited by muon consistent w/ minimum ionizing

Cosmic ray muon backgrounds are non-trivial !

→ veto shield needed?



Summary of MINOS

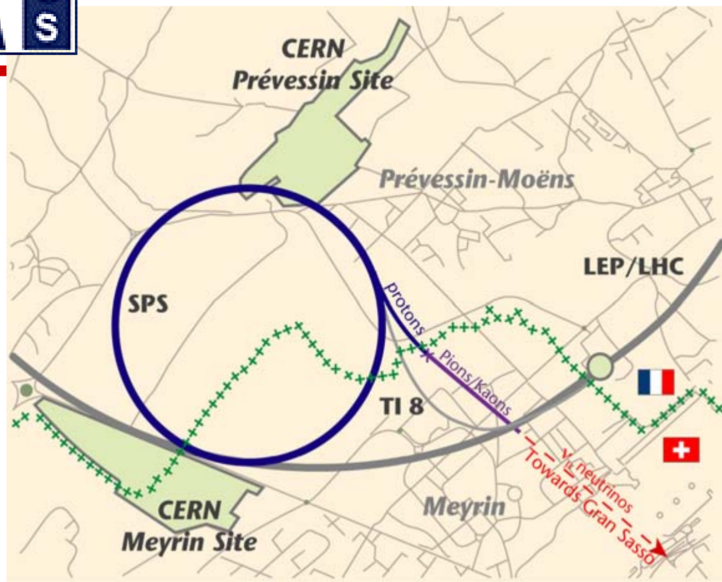
– **Data-taking w/ NuMI beam will begin in late 2004**
  - **Far & Near detector on schedule, Far det. already ½ complete**
    (detector very stable: < 1 ns timing drifts, ~ 1% pulseheight drifts)
  - **Calibration detector running & data analysis will be complete**
  - **much progress on NuMI: civil & technical components**

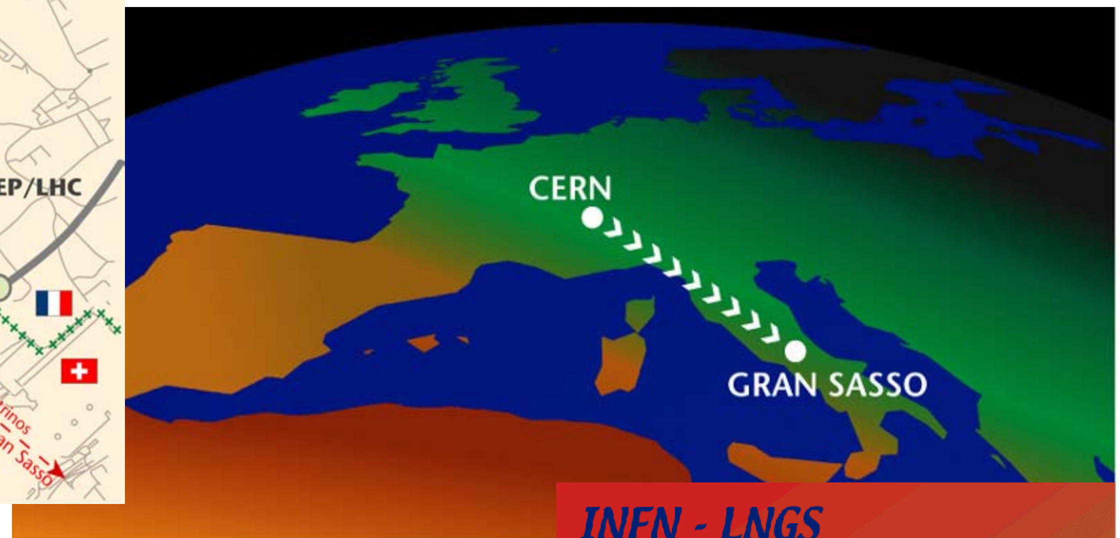
– **By 2007, will have precise measurements:**
  - **osc'n parameters**: $\nu_\mu \rightarrow \nu_\tau$ **case**; (NC/CC ratio for mode id)
  - **search for subdominant** $\nu_\mu \rightarrow \nu_e$

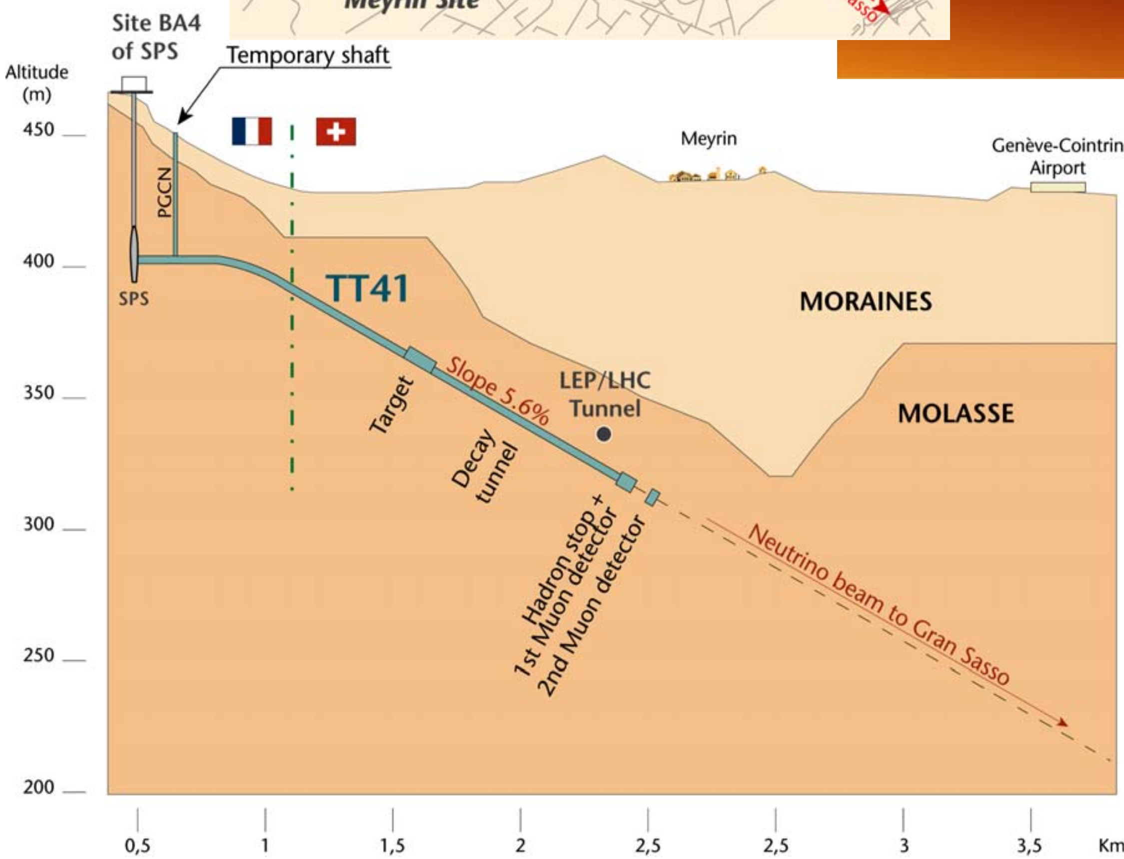
– **Will also have ~ 24 kiloton-year exposure to atm. ν's**
  - **energy, direction resol'n → Minos competitive on** $\nu_\mu \rightarrow \nu_\tau$
  - **1st direct search for CPT non-cons.** ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ vs $\nu_\mu \rightarrow \nu_\mu$)

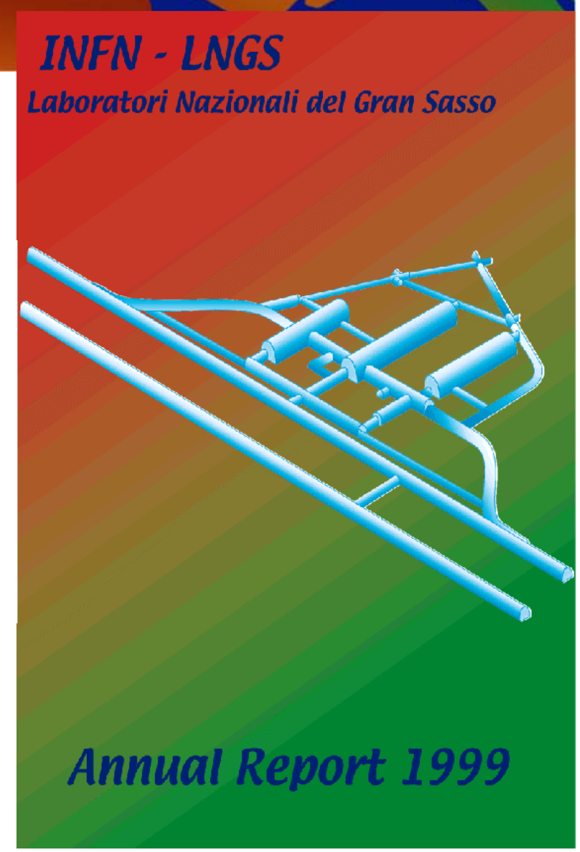
– **'conventional' neutrino physics w/ near detector**

The CNGS project









The CNGS Project

- Targeting direct observation of $\nu_\mu \rightarrow \nu_\tau$
- High energy beam from 400 GeV CERN SPS
  - needed to produce tau's
- Fine-grained detectors: OPERA & ICARUS
  - needed to identify tau decays !
- Excellent capabilities for electron detection
  - can do well on $\nu_\mu \rightarrow \nu_e$ search
  - high energy beam a handicap here, unless Δm^2 is large
- CNGS civil construction far along !!
  - current projection to deliver neutrinos in 2006 (?)
  - [exact date may depend on CERN schedule for SPS running]

The CNGS Neutrino Beam

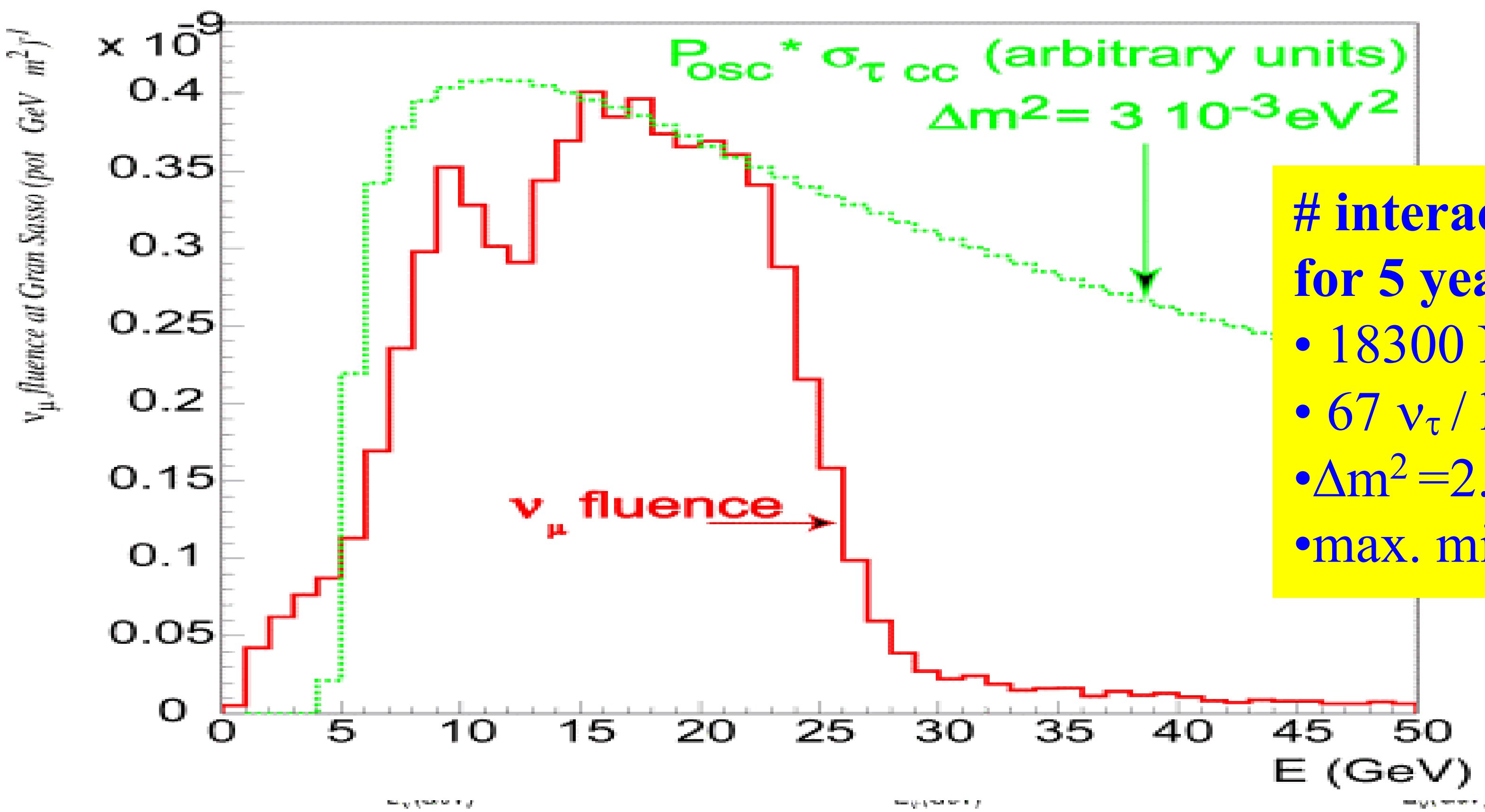
Shared SPS operation

200 days/year

4.5×10^{19} pot / year

$<E>_\nu$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	negligible

Slide courtesy S. Katsanevas



 # interactions ν for 5 years :

- 18300 NC+CC / kt
- 67 ν_τ / kt
- $\Delta m^2 = 2.4\times10^{-3}$ eV^2
- max. mixing

OPERA

COLLABORATION

The OPERA Experiment

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, Naples, Padova, Rome, Salerno

Japan
Aichi, Toho, Kobe, Nagoya, Utsunomiya

Switzerland
Bern, Neuchâtel

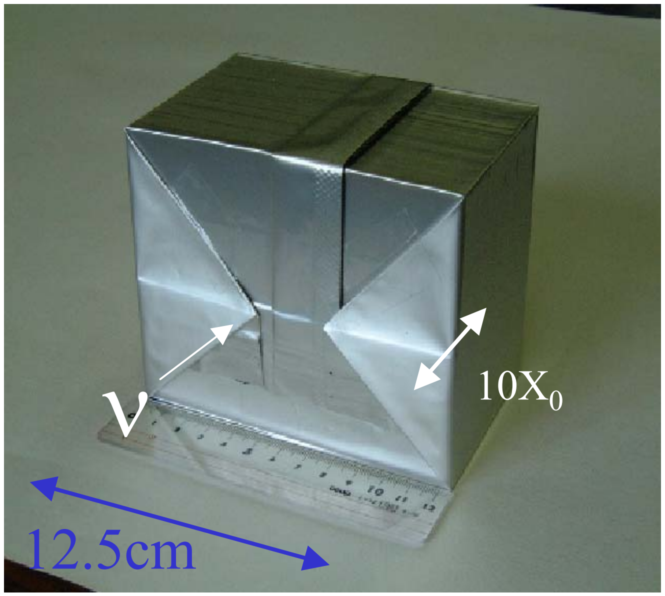
Russia
INR Moscow, ITEP Moscow, JINR Dubna, Obninsk

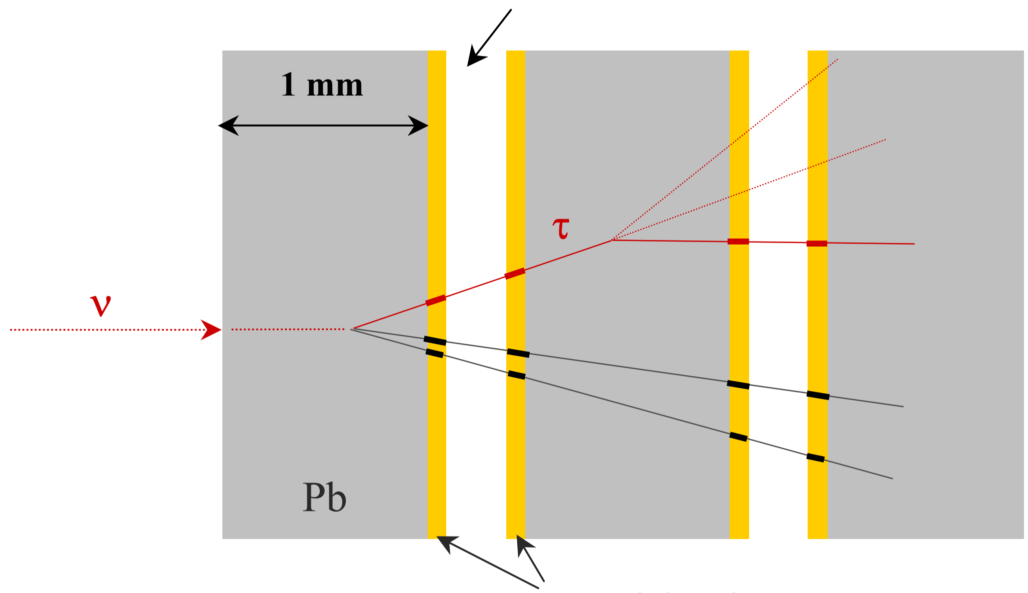
Turkey
METU Ankara

34 groups
~ 170 physicists

OPERA = CNGS1
Approved

OPERA Detector: Emulsion





56 emulsion films / brick

- To the full detector:
  2 supermodules
  31 walls / supermodule
  52 x 64 bricks /wall
  200 000 bricks

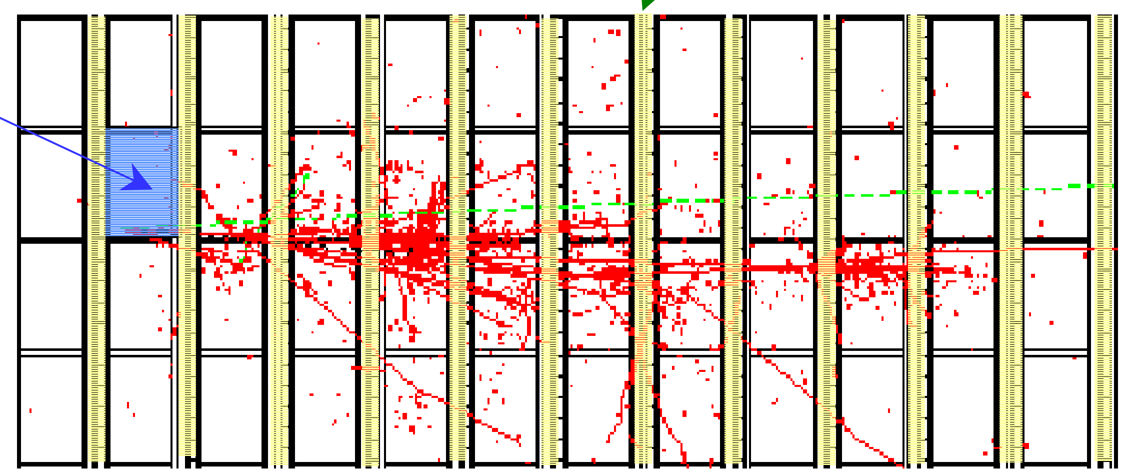
~2 kTon (Pb)
0.04 kTon emulsion

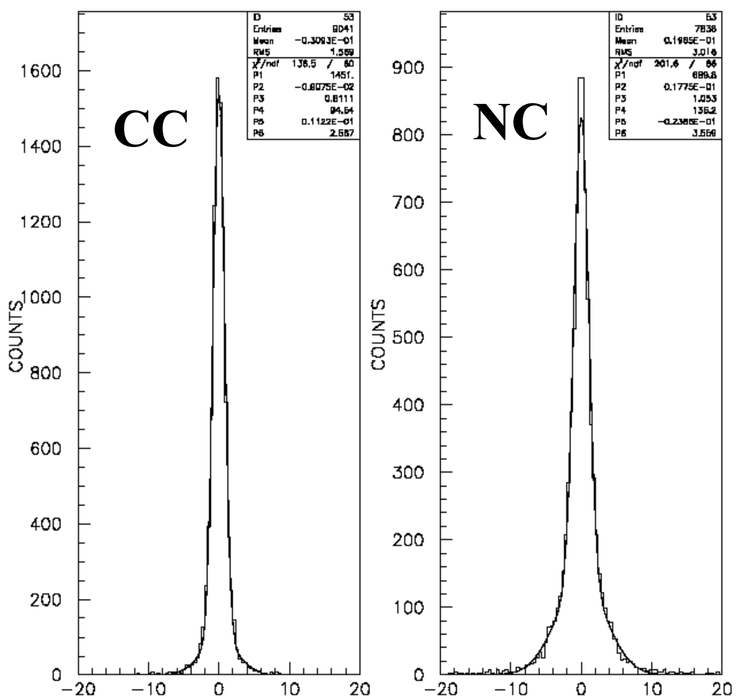
Slide courtesy S. Katsanevas

Electronic detectors to select bricks with ν interactions
(plastic scintillator strips)

- **Target Tracker tasks** :
  - select bricks efficiently
  - initiate muon tagging

Sampling by Target Tracker planes (X,Y)



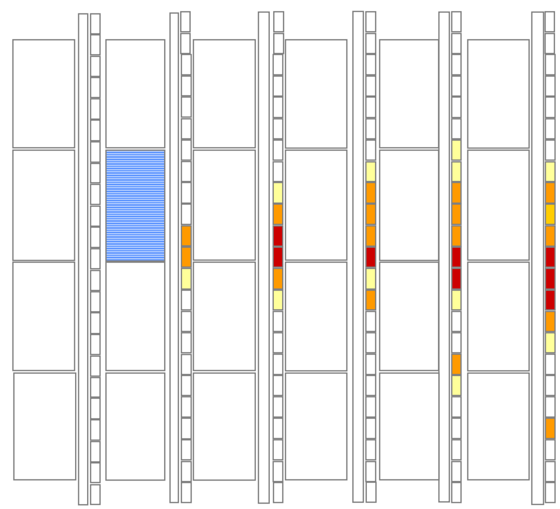


$x_{true} - x_{rec}$ **(cm)**

σ **= 1.5 cm CC**

3.0 cm NC

Slide courtesy S. Katsanevas



Event as seen by the Target Tracker

p.h.

0 max

OPERA Experiment Sensitivity

- Sensitivity to many decay modes of tau lepton
- Expect to take data for 5 yrs → 9 kTon-yrs.
- Low Backgrounds (0.75 events)

- Expected event yields:
  - $\Delta m^2 = 1.2 \times 10^{-3}\ eV^2$: 2.7 events
  - $\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$: 11 events
  - $\Delta m^2 = 5.4 \times 10^{-3}\ eV^2$: 54 events

The ICARUS Collaboration

F. Arneodo, B. Babussinov, B. Badelek, A. Badertscher, M. Baldo-Ceolin, G. Battistoni, B. Bekman, P. Benetti, E. Bernardini, A. Borio di Tigliole, M. Bischofberger, R. Brunetti, A. Bueno, E. Calligarich, D. Cavalli, F. Cavanna, P. Cennini, S. Centro, A. Cesana, C. Chen, Y. Chen, D. Cline, P. Crivelli, A. Dabrowska, M. Daszkiewicz, C. De Vecchi R. Dolfini, M. Felcini, A. Ferrari F. Ferri, A. Gigli Berzolari, I. Gil-Botella, 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, M. Markiewicz, F. Mauri, C. Matthey, G. Meng, C. Montanari, S. Muraro, G. Natterer, S. Navas-Concha, G. Nurzia, 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 J. Stepaniak, M. Stodulski, M. Szarska, M. Szeptycka, M. Terrani, S. Ventura, C. Vignoli, H. 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, Padova, Pavia, Pisa - Italy
ETH Hönggerberg, Zürich - Switzerland
CNR Istitute of cosmogeophysics, Torino - Italy
University of Silesia, Katowice - Poland
H.Niewodniczanski Inst. of Nucl. Phys., Krakow - Poland
Cracow University of Technology, Krakow - Poland
Warsaw University, Warszawa - Poland
UCLA, Los Angeles - USA
IHEP, Academia Sinica, Beijeing - 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

This is an "open" collaboration: new teams welcome !

The Icarus Detector

Large Volume, liquid Argon TPC

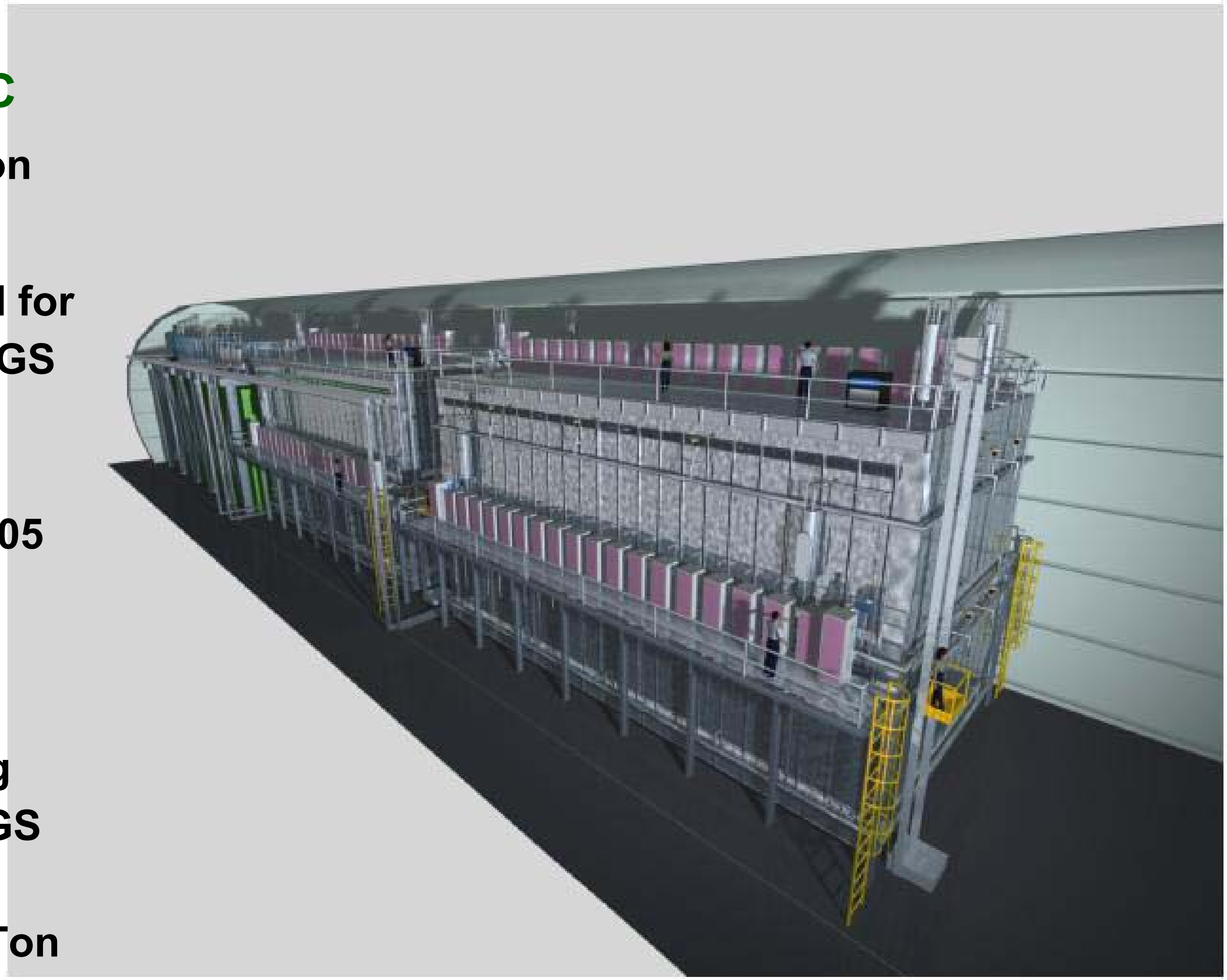
total mass ~ 3 kTon

recently approved for installation in LNGS Hall B:

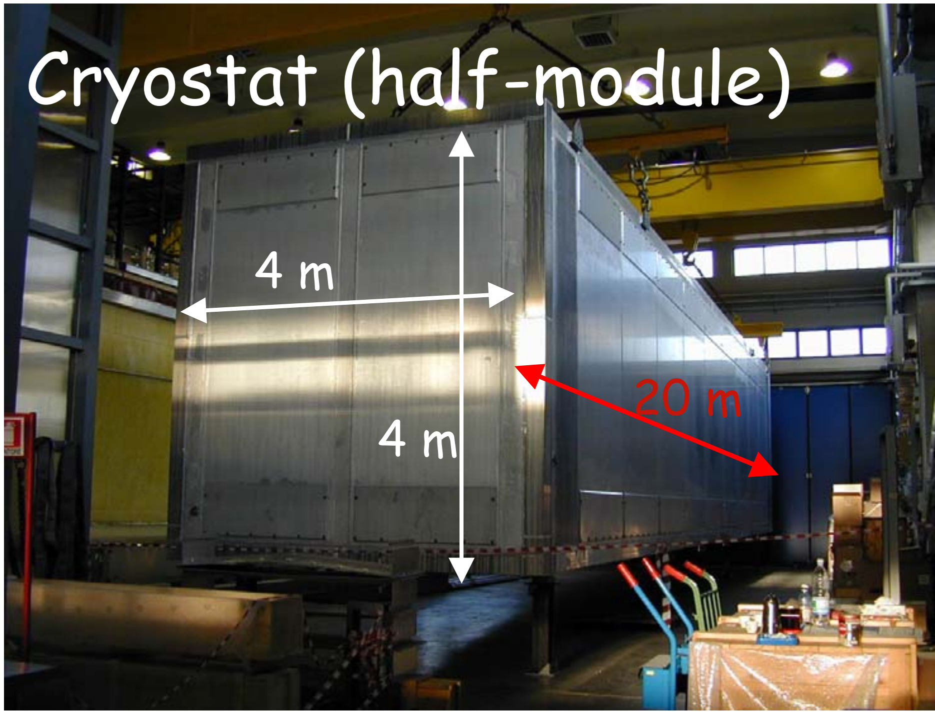
expected date: 2005

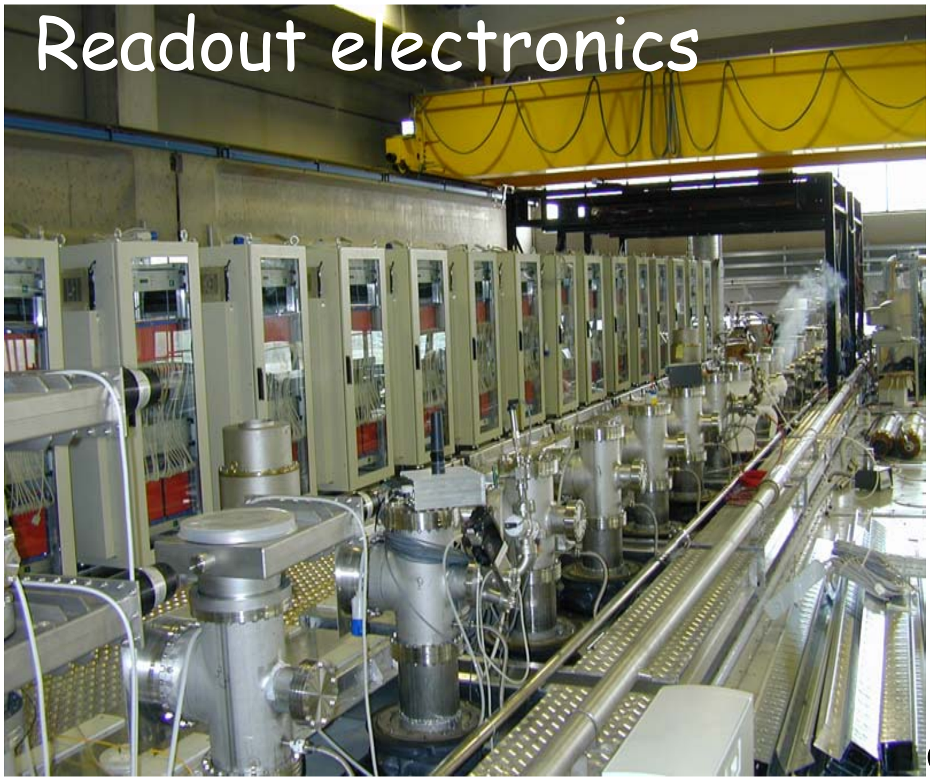
Currently 600 Ton prototype being installed at LNGS

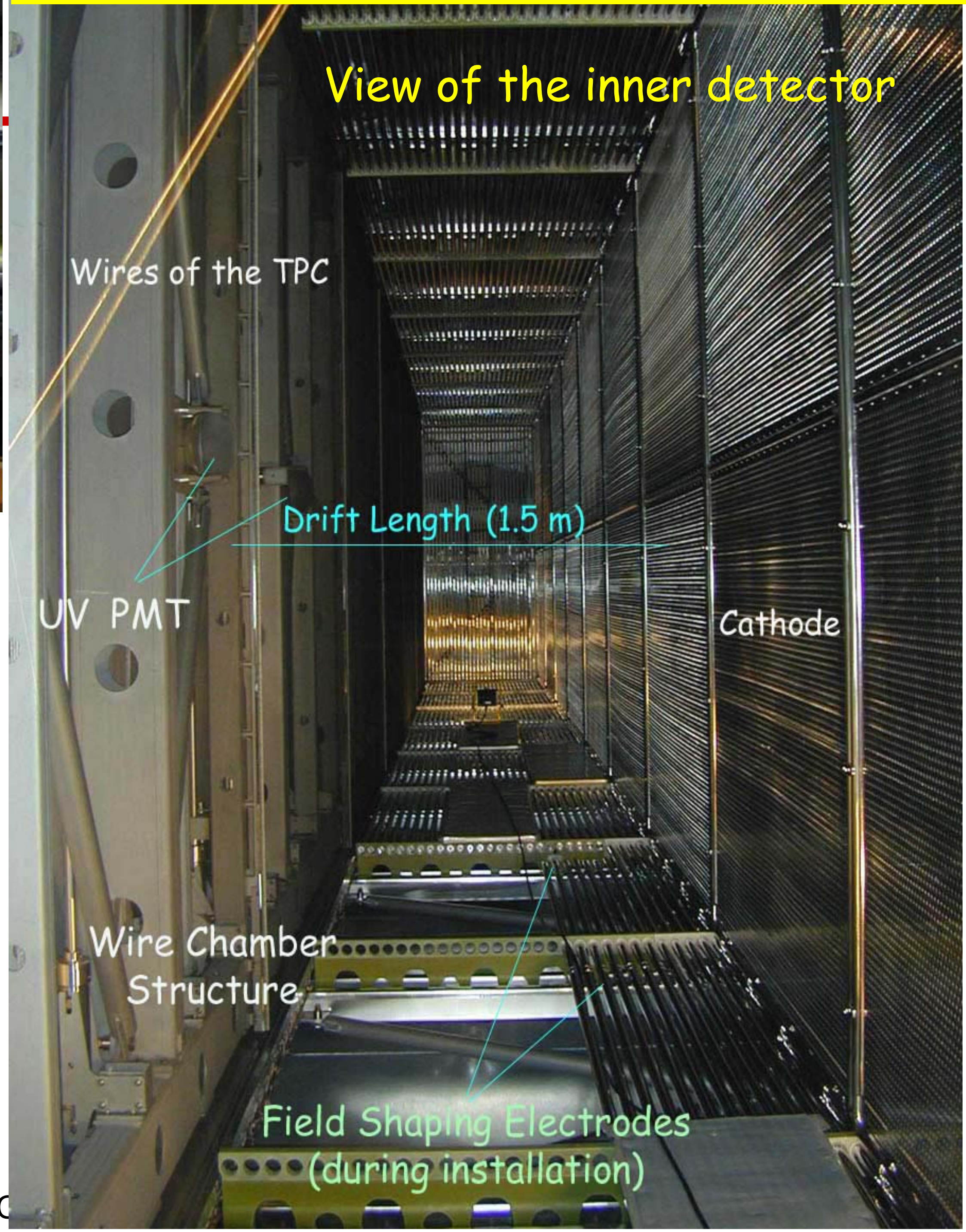
Results from 300 Ton module



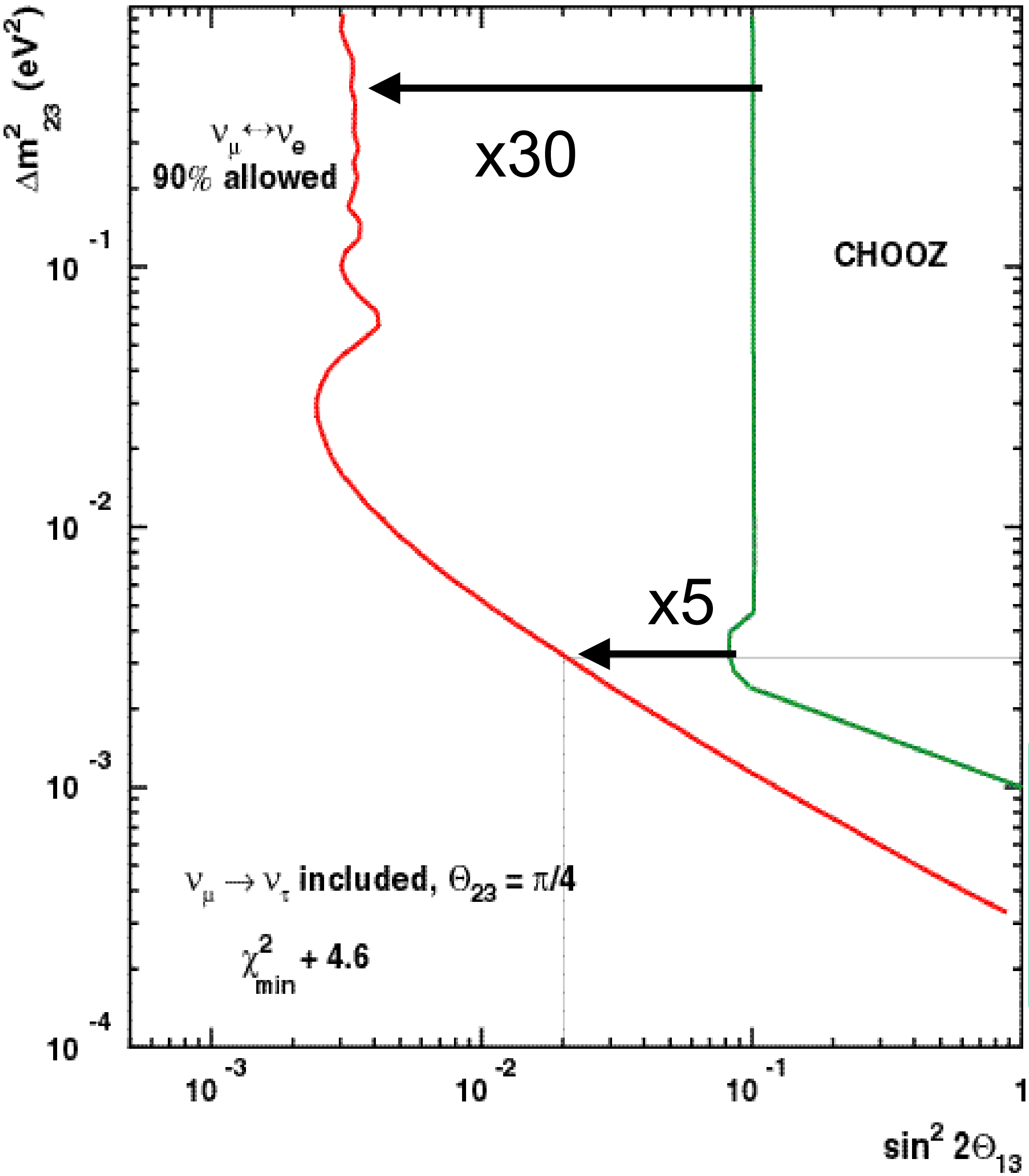
ICARUS T300 prototype







Expected sensitivity to θ_{13}



ICARUS
5 years dedicated SPS
2.35 kton fid. mass

Sensitivity assuming both $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ at the same Δm^2 (three family mixing)

$$\sin^2 2\theta_{13} > 2 \times 10^{-2}$$
$$for\ \ \Delta m^2_{32} = 3 \times 10^{-3} eV^2$$

Θ_{13} limit from 9 to 5^0

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Long Baseline Experiments: The Next Generation

- Geared toward observation of $\nu_\mu \rightarrow \nu_e$ at Δm^2_{atm}

- Off-Axis (2^0) CNGS beam to off-shore detector
  - Under-water Č detector 1200 km from CERN in G. of Taranto
  - Low energy beam config. @ 0.8 GeV (2^{nd} osc. max.)
  - EOI: http://home.cern.ch/dydak/oscexp.ps

- Off-Axis ($0.5\text{-}1^0$) NuMI beam to surface detector
  - sites in Minnesota (~700+ km) & Canada (~900 km) possible
  - 20 kTon detector, possibly H_20, possibly RPC, possibly scint.
  - Sensitivity to θ_{13} at 1.5×10^{-3} level
  - LOI (Fermilab P929):

    http://www-numi.fnal.gov/fnal_minos/new_initiatives/
  - Note: 1-Day meeting at UC London, Monday September 16

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Long Baseline Experiments: More Ideas for future

– **BNL beams to NUSL, Upstate NY, Soudan…**
  - **Upgrades to AGS: 0.5 – 1.3 MW**
  - **Letter of Intent: hep-ex/0205040**

– **CERN beam to Frejus**
  - **New low-energy proton synchrotron (2 GeV) re-using LEP RF**
  - **300 MeV neutrino energy, H_20 detector**

– **"Beta-Beam" to Frejus**
  - **ν_e and $\bar{\nu}_e$ from accelerated ^{18}Ne and ^{6}He ions**
  - **300 MeV neutrino energy, H_20 detector**

– **Krasnoyarsk reactor experiment – ν_e disappearance**
  - **Improve on Chooz sensitivity by factor of ~8**

- **Haven't mentioned FNAL proton driver, or ν factories**

Summary

- **Exciting time for Long Baseline experiments**
  - MINOS construction far along— first look at cosmics
  - Significant progress in CNGS program
  - Interesting ideas for next generation:
    - **NuMI off-axis, CNGS off-axis, BNL beams, beta beams…**

- **Far future will depend on what current and next generation exp'ts turn up!**
  - If θ_{13} is not so small, possibility of seeing CP violation will be too good to pass up.
  - This will require a significant international project

Backup Slides

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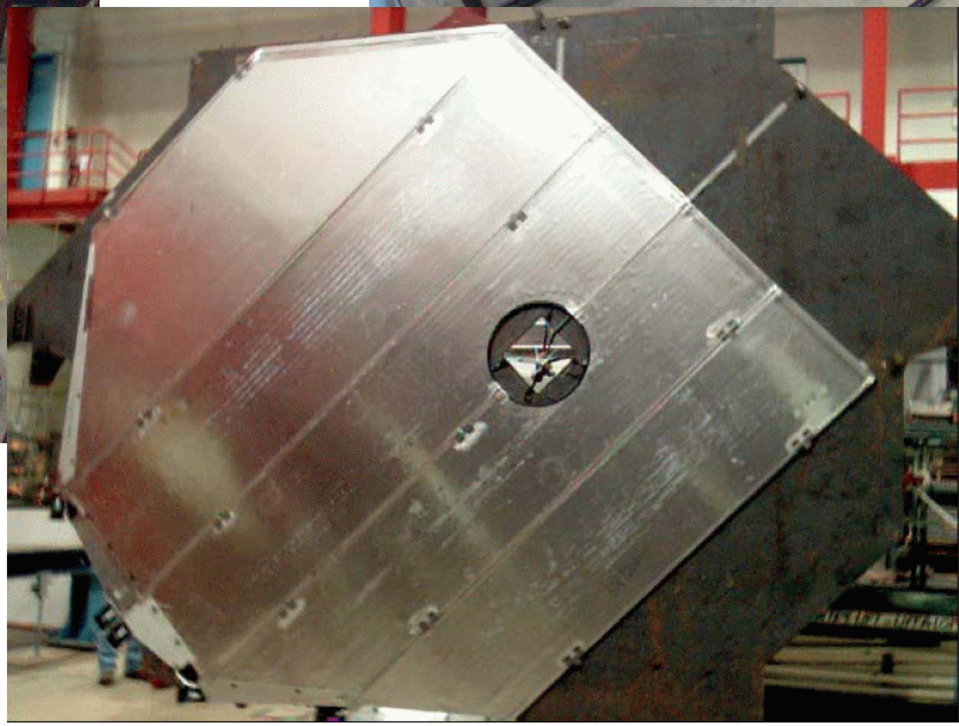
Near Detector Assembly



Calibration Detector