Sensitive Measurement of $Sin^2 2\,\theta_{13}$ with Accelerator Neutrino Beams

David B. Cline
UCLA

1. Methods to Observe $Sin^2 2\,\theta_{13}$
   - Accelerator Neutrinos
   - Backgrounds for $\nu_\mu \rightarrow \nu_e$
2. CERN and FNAL Neutrino Beams
3. Reach of Projects in Constructions
   - MINOS at NUMI
   - ICARUS at LGNS/CNGC and possible Reconfigured CNGS Beam
4. Possible Future Programs in USA and Japan
5. Brief Comparison of Astrophysical Methods Using SuperNova Detection

--- Summary ---

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KITP/UCSB CONFERENCE
MARCH 2003

OVERVIEW

With the following facts:

1. The Solar Neutrino Effect is now resolved $\nu_e \rightarrow \nu_x$
   (Solar Neutrino Experiments, KamLand)
2. The Atmospheric Neutrino Effect is likely $\nu_\mu \rightarrow \nu_\tau$
   (K2K Data Consistent) and Super K most recent data

We now know that θ_{12} and θ_{23} are fairly large angles - possibly maximal

The key question for future Neutrino Oscillation Studies: Is the value of θ_{13} near the chooz limit? The future is Bright. Possible CP violation observation.

If $\theta_{13} \sim 0$, there is no hope to observe CP violation.

THE OBSERVATION OF θ_{13} IS THE KEY ISSUE IN NEUTRINO PHYSICS!

BNL

Neutrino Physics: the difficult stuff

Bill Marciano, hep-ph/0108181

Very long baselines with a superbeam

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_1c_3 & s_1c_3 & s_3e^{-i\delta} \\ -s_1c_2 - c_1s_2s_3e^{i\delta} & c_1c_2 - s_1s_2s_3e^{i\delta} & s_2c_3 \\ s_1s_2 - c_1c_2s_3e^{i\delta} & -c_1s_2 - s_1c_2s_3e^{i\delta} & c_2c_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (3)$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4(s_2^2s_3^2c_3^2 + J_{CP}\sin\Delta_{21})\sin^2\frac{\Delta_{31}}{2} \\ & +2(s_1s_2s_3c_1c_2c_3^2\cos\delta - s_1^2s_2^2s_3^2c_3^2)\sin\Delta_{31}\sin\Delta_{21} \\ & +4(s_1^2c_1^2c_2^2c_3^2 + s_1^4s_2^2s_3^2c_3^2 - 2s_1^3s_2s_3c_1c_2c_3^2\cos\delta \\ & \quad - J_{CP}\sin\Delta_{31})\sin^2\frac{\Delta_{21}}{2} \\ & +8(s_1s_2s_3c_1c_2c_3^2\cos\delta - s_1^2s_2^2s_3^2c_3^2)\sin^2\frac{\Delta_{31}}{2}\sin^2\frac{\Delta_{21}}{2} \end{aligned} \quad (4)$$

We ignore CP from now on in this talk

Note Terms with Δ_{21}

Milind Diwan

UCLA

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NEW FUTURE EXPERIMENTS

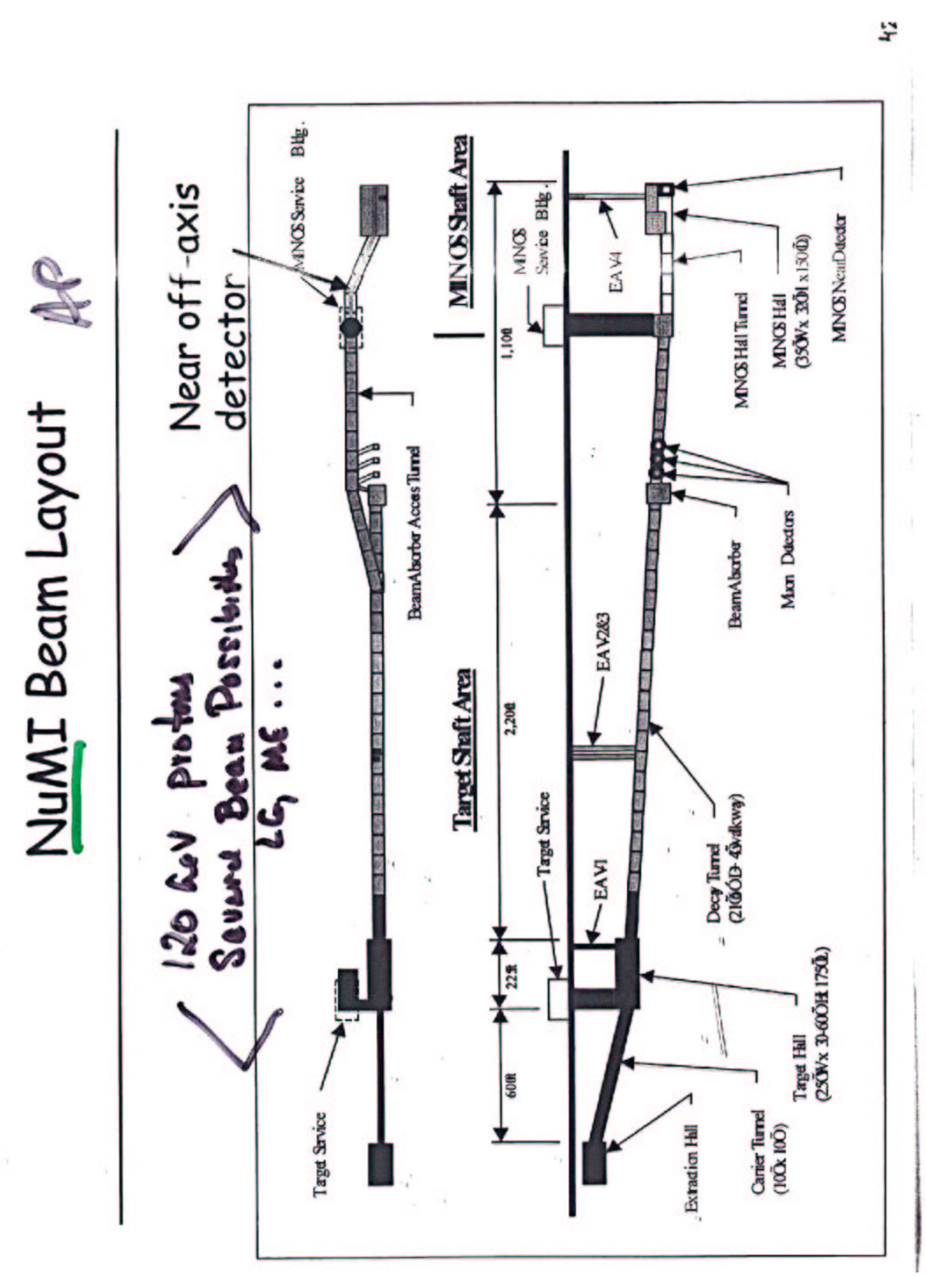
1. MINOS will be able to confirm the $\nu_\mu \to \nu_x$ from Super K and measure Δm^2_{23} well (if not very small)
2. ICARUS and OPERA will be able to provide conclusive proof that $\nu_\mu \to \nu_\tau$ by detecting τ events
3. MINOS and ICARUS will be able to search for a non-zero $\sin^2 2\theta_{13}$ below CHOOZ – LIMIT. My estimate:

MINOS $\sin^2 2\theta_{13} \sim 0.06$

ICARUS $\sin^2 2\theta_{13} \sim 0.03$

TO GO BELOW THESE VALUES, A NEW GENERATION OF DETECTORS AND/OR NEUTRINO BEAMS WILL BE NEEDED.

GOAL : TO DETECT NO ZERO $\sin^2 2\theta_{13}$



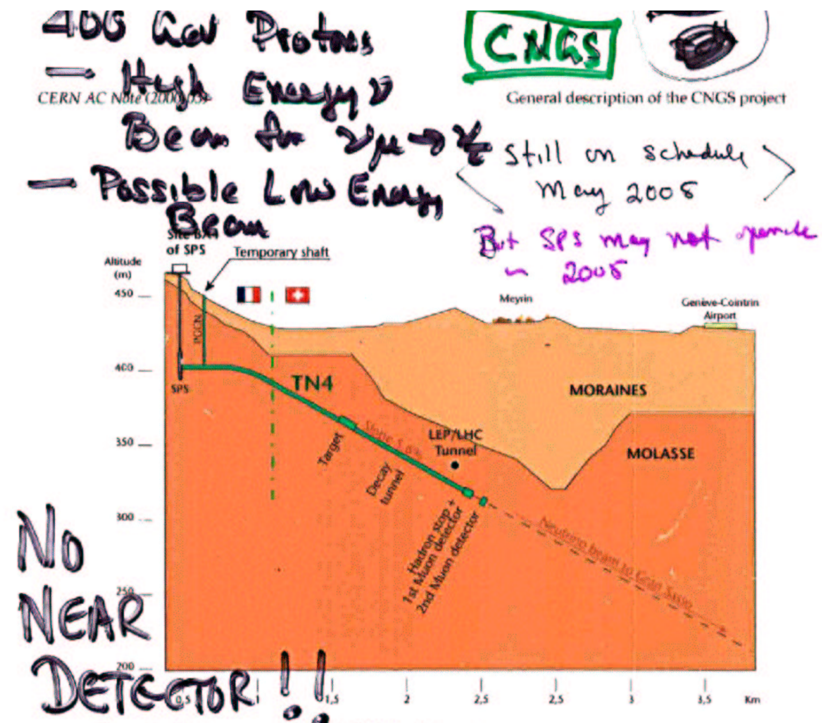


Figure 11: Works connected with the CNGS project: section

Logic – While LHC operating SPS available for CNGS

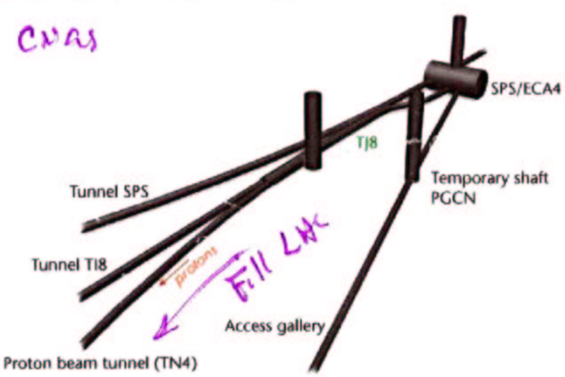


Figure 12: Underground work-sites at Point BA4 of the SPS. Tunnel TI8, under construction, will connect the SPS to the LHC.

Backgrounds for
$\nu_\mu \to \nu_e$

Table 2. Optimal $sin^2(2\cdot\theta_{13})$ determination in ν_e background

(1) "ν_e flux issue"

$$\frac{R(\nu_\mu \to \nu_e)}{R(\nu_e)} = \frac{A}{B} sin^2 2\theta_{13}$$

A = function of [θ_{23}, osc. prob. (4_E)]

B = Ratio $\frac{(\nu_e)}{(\nu_\mu)}$ in beam

$$\frac{R(\nu_\mu \to \nu_e)}{R(\nu_e)} \approx 1 \to \text{Signal} \approx \text{Bkg}$$

Difficult to go far below this level. Must know Bkg very well!

ν_e flux in key to $\sin^2 2\theta_{13}$ Reach

A ~ ½ optimal oscillation distance

B ~ ½ $10^{-2} \to (0.4 - 0.8) \times 10^{-2}$

NuMi CNGS??

$sin^2(2\theta_{13}) \sim 10^{-2}$ is optimal: to go below this, the value of Bkg should be well known.

UCLA Note: Mini LANNDD May 2002

(2) Neutral Current Bg
if $\sin^2 2\theta_{13} \sim 5\times10^{-3}$
NC BG ~ 10^2 Larger
make cuts – segment detector – Liquid Argon TPC

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HOW TO DETECT A VERY SMALL $Sin^2 2\theta_{13}$

There are three possibilities:

1. Detect $\nu_\mu \to \nu_e$ down to and below the background in the Beam from ν_e Flux
2. Detect $\nu_e \to \nu_\mu$ with a Neutrino Factory (S. Geer Talk)
3. Detect $\nu_{\tau,\mu} \to \nu_e$ in a SUPERNOVA II Event (C Lunardini Talk)

The reach of these three methods is:

1. $Sin^2 2\theta_{13} \sim 0.004$ (Depending on ν_e Flux)
2. $Sin^2 2\theta_{13} \lesssim 10^{-3}$
3. $Sin^2 2\theta_{13} \sim 10^{-4}$??

FNAL DETECTOR STUDY
D. Harris

Detector R& D for future Neutrino Experiments with the NuMI Beamline

October 21, 2002

A report the Fermilab Directorate from the Study Group on Future Neutrino Experiments at Fermilab.

G. Barenboim,[1] A. Bodek,[2] A. Bross,[1] L. Buckley-Geer,[1] B. Choudhary,[1] D. Cline,[3] F. DeJongh,[1] G. Drake,[4] S. Geer,[1] M. Goodman*,[4] A. deGouvea,[1] D. A. Harris*,[1] K. Heller,[5] J. Huston,[7] J. Johnstone,[1] M. Kostin,[1] J. Learned,[6], P. Litchfield,[5], M. Marshak,[5], K. McDonald,[8] K. S. McFarland,[3] S. Menary,[9] M. Messier,[1]0 D. Michael,[11] R. Miller,[6] N. Mokhov,[1] J. K. Nelson,[1] E. Peterson,[5], R. Richards,[6], K. Ruddick,[5], F. Sergiamepietri,[3] P. Shanahan,[1] R. Shrock,[12] Y. Soo,[3] R. Stefanski,[1] M. Szleper,[13] K. Tollefson[7]

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1. Fermilab National Laboratory
2. University of California at Los Angeles
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6. University of Hawaii
7. Michigan State University
8. Princeton University
9. York University
10. University of Indiana
11. California Institute of Technology
12. State University of New York at Stonybrook
13. Northwestern University

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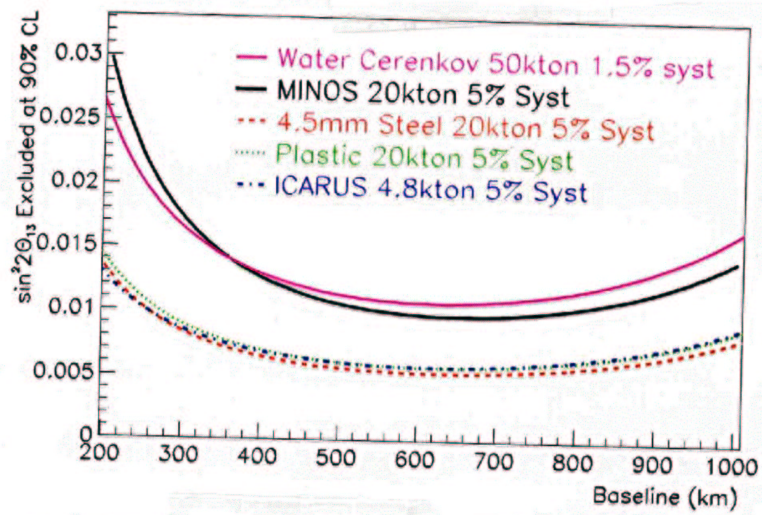
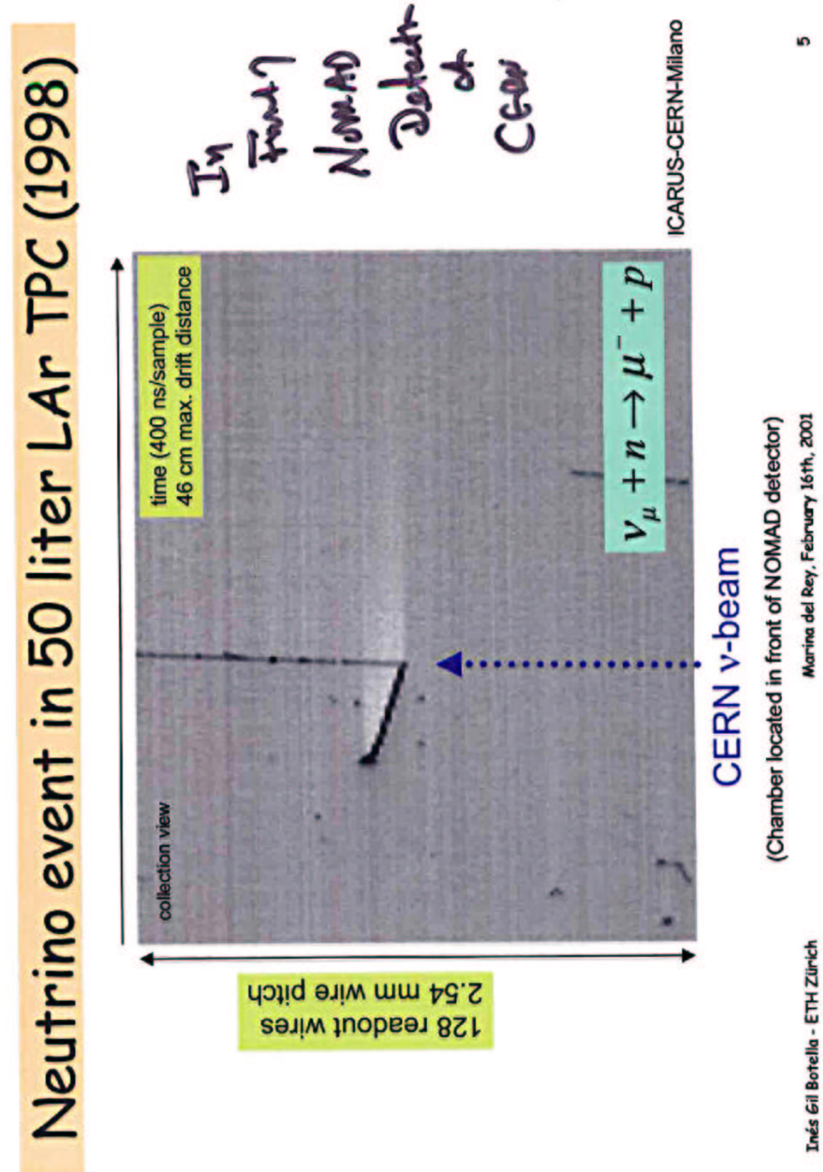
FNAL STUDY
FOR DIRECTOR
D. Harris



Liquid Argon ~ 4 X Better Than other methods from the FNAL Study


LIQUID ARGON METHOD
The ICARUS Project
CERN
Italy
Aquila, LNGS, Milano, Padova, Pavia, Pisa, Torino
China
IHEP
Switzerland
ETH/Zurich
Poland
Katowice, Krakow, Warszawa, Wroclaw
USA
UCLA
Imaging Cosmic And Rare Underground Signals


Neutrino event in 50 liter LAr TPC (1998)
In Front? NOMAD Detector at CERN
collection view
time (400 ns/sample)
46 cm max. drift distance
128 readout wires
2.54 mm wire pitch
$\nu_\mu + n \rightarrow \mu^- + p$
CERN ν-beam
(Chamber located in front of NOMAD detector)
ICARUS-CERN-Milano
Marina del Rey, February 16th, 2001
Inés Gil Botella - ETH Zürich
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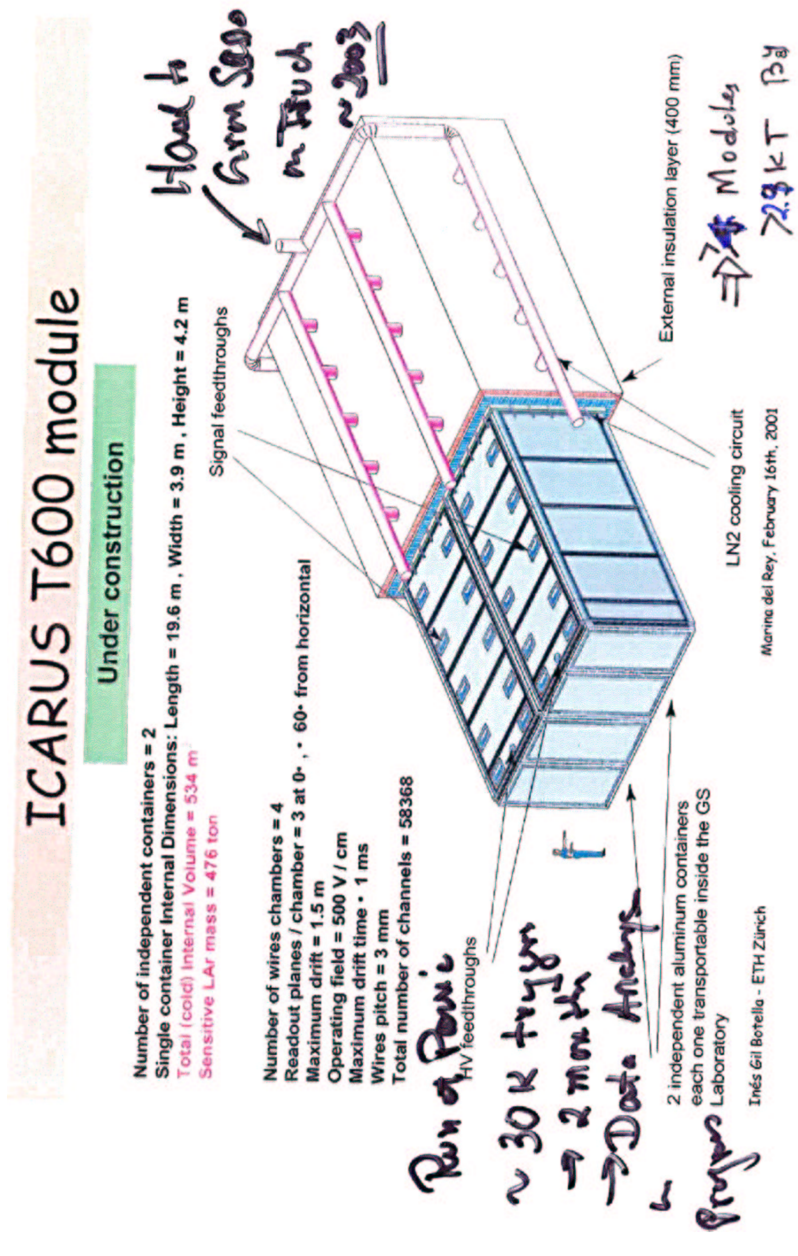
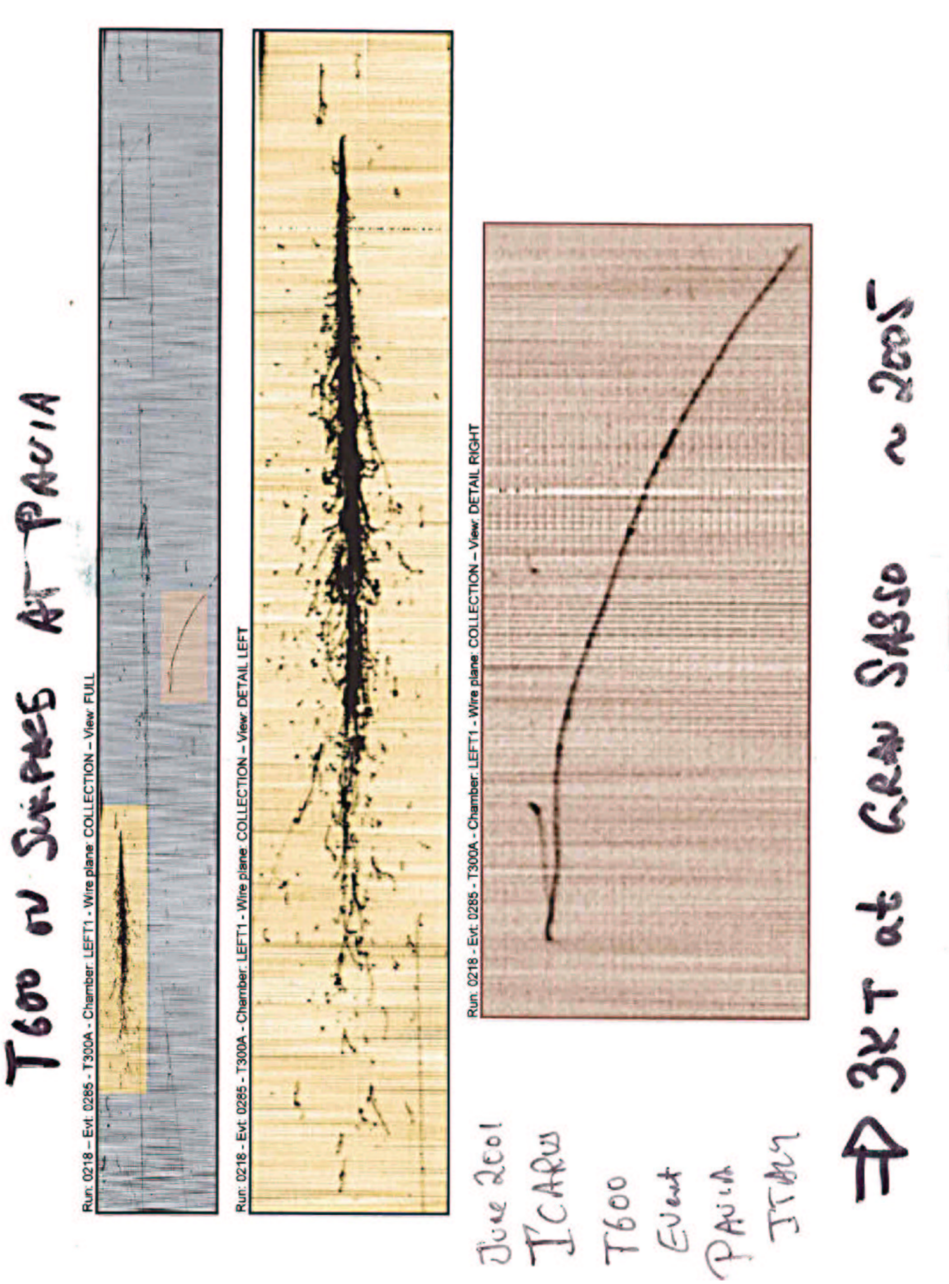
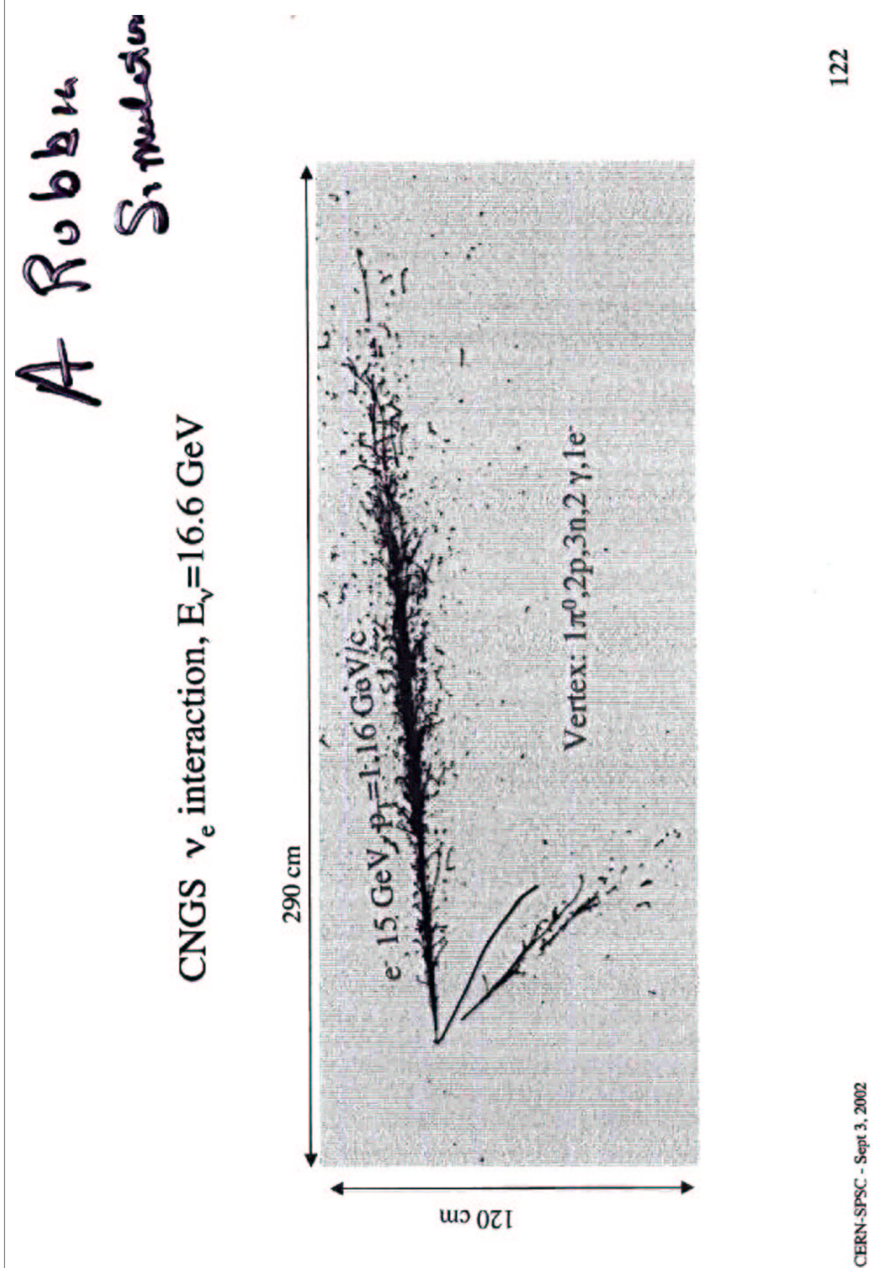

ICARUS T600 module
Under construction
Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m
Total (cold) internal Volume = 534 m³
Sensitive LAr mass = 476 ton
Number of wires chambers = 4
Readout planes / chamber = 3 at 0°, ± 60° from horizontal
Maximum drift = 1.5 m
Operating field = 500 V / cm
Maximum drift time ≈ 1 ms
Wires pitch = 3 mm
Total number of channels = 58368
Signal feedthroughs
External insulation layer (400 mm)
LN2 cooling circuit
HV feedthroughs
2 independent aluminum containers each one transportable inside the GS Laboratory
Marina del Rey, February 16th, 2001
Inés Gil Botella - ETH Zürich
Run at Pavia
~ 30 K triggers
→ 2 months
→ Data Analysis
Hauled to Gran Sasso
2005

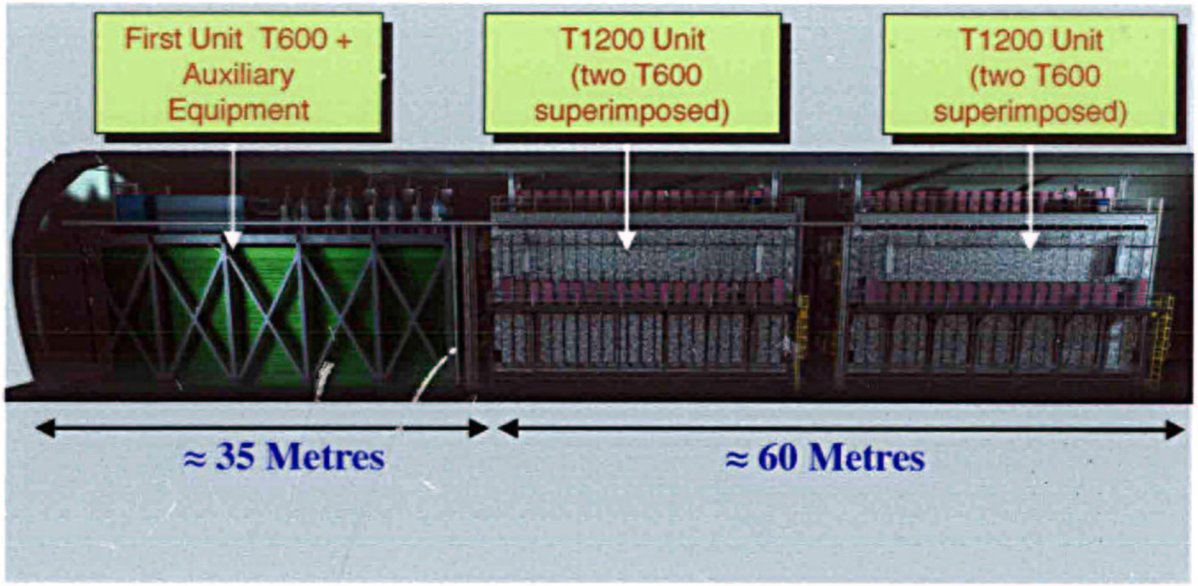

ICARUS T300 prototype
View of the inner detector
Wires of the TPC
Drift Length (1.5 m)
Cathode
UV PMT
Wire Chamber Structure
Field Shaping Electrodes (during installation)
Cryostat (half-module)
4 m
4 m
20 m
Readout electronics
CERN-SPSC - Sept 3, 2002


T600 ν Surprises At Pavia
Run: 0218 - Evt: 0285 - Chamber: LEFT1 - Wire plane: COLLECTION - View: FULL
Run: 0218 - Evt: 0285 - T300A - Chamber: LEFT1 - Wire plane: COLLECTION - View: DETAIL LEFT
Run: 0218 - Evt: 0285 - T300A - Chamber: LEFT1 - Wire plane: COLLECTION - View: DETAIL RIGHT
June 2001
ICARUS
T600
Event
PAVIA
ITALY
⇒ 3KT at Gran Sasso ~ 2005


A Rubbia Simulation
CNGS ν_e interaction, E_ν=16.6 GeV
122
290 cm
e 15 GeV, p_T=1.16 GeV/c
Vertex: 1π0,2p,3n,2γ,1e
120 cm
CERN-SPSC - Sept 3, 2002

~ 2006

ICARUS detector configuration in LNGS Hall B (T3000)



CERN-SPSC - Sept 3, 2002

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Possible Neutrino Beams In The World

	DISTANCE
Near Future (~ 2005-2007)	
1. NUMI - FNAL to SOUDAN	~700km
2. CNGS - CERN to GRAN SASSO	~700km
Next Step (2010 ??)	
A. JHF NEUTRINO Beam to SUPER K ~ 2008 ?	~250km
B. Low Energy Option for CNGS to GRAN SASSO	~700km
C. Off Axis NUMI Beam to Canada	~1000km
D. BNL Beam to NUSL	~1500-3000km

SUPER BEAMS (A) is a super beam

(B, C, D) BEAMS COULD BE UPGRADED TO SUPER BEAM STATUS WITH NEW PROTON DRIVERS!

Reconfigure CNGS Beam to Low Energy

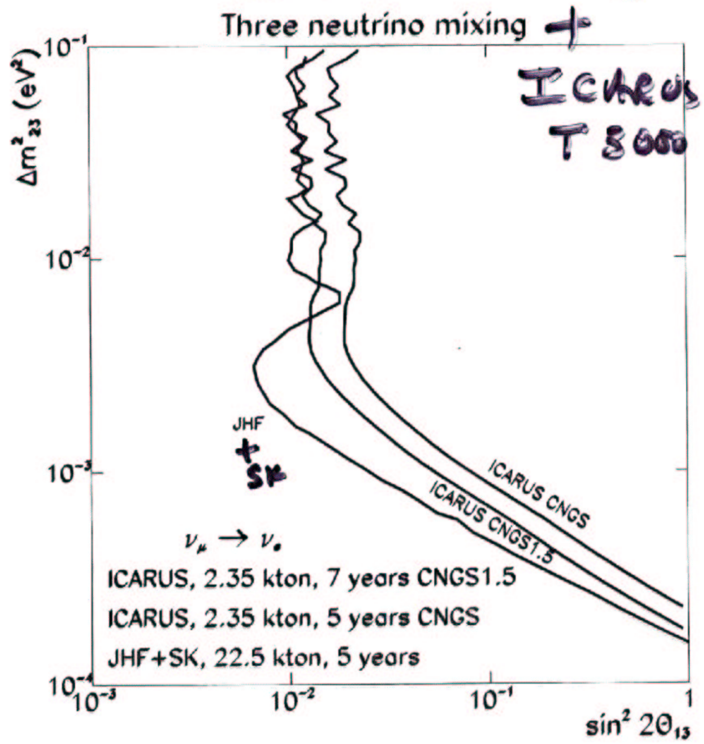

Figure 7: Comparison of expected sensitivity to $\sin^2 2\theta_{13}$ mixing angle with an improved CNGS×1.5[16] and 7 years of running.

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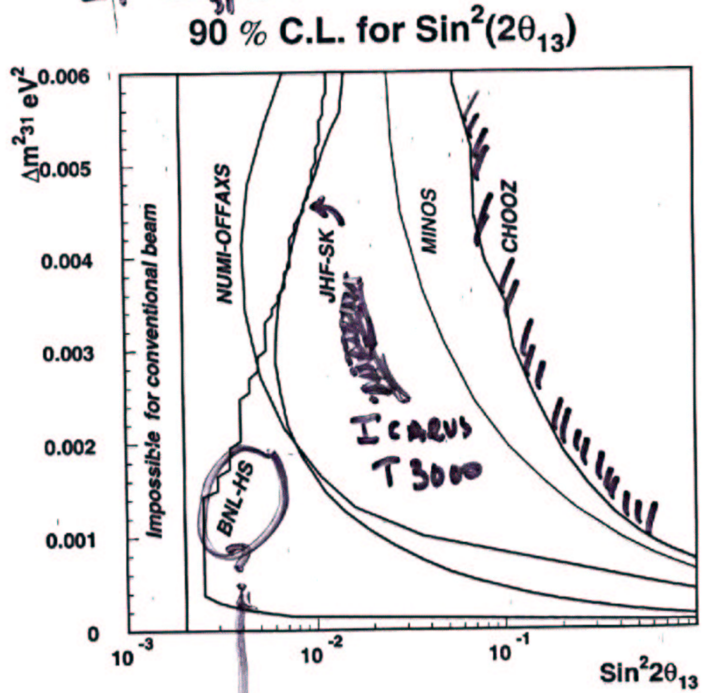
Very long baselines with a superbeam

BNL View Point

Measurement of $\sin^2 2\theta_{13}$ 90% C.L.

If Δm^2_{31} Small

M. Diwan



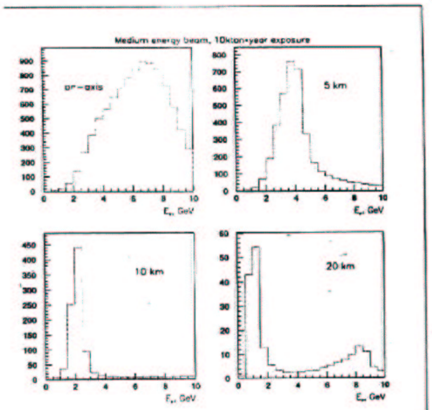
Distinctive signature with multiple oscillations above 0.001 eV^2

Super Beam
~ 1/2 Mega Ton Detector
~ 2000 KM

Milind Diwan

(A. Para)

NuMI Neutrino Beam: Off-axis detectors



Choice of experimental conditions:

- Baseline
- Beam energy (control of matter effects as an amplifier of physics)

Figures of merit, take 15 mrad angle and 735 km:

- ~ 100 CC ν_μ ev/kton/year (== 4×10^{20} pot)
- ~ 0.25 CC ν_e ev/kton/year (@ 50% ID efficiency)
- ~ 0.25 NC background event
- ~ 33 CC anti ν_μ ev/kton/year

NuMI OFF AXIS DETECTOR PROJECT

Project Evolution I (so far)

LOI to FNAL for Off Axis Experiment (AP)

- May 2002: Workshop at Fermilab, 140 people
- June 2002: LOI submitted
- September 2002: All about NuMI – UCL London, 27 participants
- Now: Argonne- Athens - Berkeley - Boston - Caltech - Chicago - College de France - Fermilab -Harvard - ITEP - Lebedev - UC-London - LSU - MIT - MSU – Minnesota-Crookstone - Minnesota-Duluth -Minnesota-Minneapolis - TUM-Munchen - NIU - Ohio-Athens - Oxford - Pittsburgh - Princeton (*) - Rochester - Rutherford - Sao Paulo - Stanford - Stony Brook - Sussex- Texas-Austin - TMU-Tokyo - Tufts - UCLA (*) - Virginia Tech - York-Toronto(115 physicists) (red – joined since PAC submission)
- Expression of interest from several more institutions

(*) Lead Liquid Argon Option

NuMI Beam: wide range of possible sites

AP

Current NuMI → MINOS

Off Axis Detector

~ 1000 km for off Axis

- Collection of possible sites, baselines, beam energies
- Physcis/results driven experiment optimization
- Complementarity with other measurements (Cluster of detectors? JHF? ⇒K. Whisnant's talk)

Two phase program

FUTURE

AP

Phase I (~ \$50-100 M, running 2007 - 2014)

- 20 kton (fiducial) detector with ε~35-40%
- $4x10^{20}$ protons per year
- 1.5 years neutrino (2400 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (2600 ν_μ CC, 70-80% 'oscillated')

$\sin^2 2\theta_{13} \lesssim 5\times10^{-3}$
Goal
CP??

Phase II (~ \$500M, running 2014-2020)

- 100 kton (fiducial) detector with ε~35-40%
- $20x10^{20}$ protons per year (new proton source?)
- 1.5 years neutrino (60000 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (65000 ν_μ CC, 70-80% 'oscillated')

CP ? Study
Mass Hierarchy ?

NuMI Off-axis Detector

AP.

- Different detector possibilities are currently being studied ([redacted])
- The goal is an eventual 20 kt fiducial volume detector
- The possibilities are:
  - ⊙ Low Z imaging calorimeter with RPC's, drift tubes or scintillator
  - ⊙ Liquid Argon (a large version of ICARUS) ← No longer considered
  - ~~Water Cherenkov counter~~
  - Neutrino detectors is not a rocket science. Scaleable, can be built to cost.
- Phase I vs Phase II
  - The same/different technology? Too early to tell
  - The same/different location?

UCLA
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Department of Physics & Astronomy

D. B. Cline
S. Otwinowski
F. Sergiampietri

INFN Sezione di Pisa

EXAMPLE- A 5KT LIQUID ARGON DETECTOR IN NUMI BEAM

3. Mini-LANNDD.

We have made a very preliminary design of a 5 kt LANNDD like detector to use in a NuMi like beam (or off axis CNGS beam).Fig. 3 shows the one design including the Cryostat whereas Fig.4 shows a cut through of the detector. We assume 5 m drift length. In Table 5 we give some preliminary parameters of the detector.

4. The reach of Mini-LANNDD.

Using some value given to us by Adam Para [6] [7] we show the signal and background for Mini-LANNDD with 20 ktxy exposure – Table 3 and Table 4. Neutral current will be unimportant. Mini-LANNDD can reach ultimate limit possible in the NuMi beam (or off axis CNGS) of 0.005.

Table 3. Mini-LANNDD in NuMi medium energy beam. (≈730 km). Rates from $\nu_\mu \to \nu_e$ oscillations in three family mixing (for $\Delta m^2_{23} = 3.5\times10^{-3}$ eV² and $\theta_{23} = 45°$). Rates are normalised to 20 ktxy. (4 years running on beam of 3.8×10^{20} pot).

θ_{13} (degrees)	$\sin^2(2\theta_{13})$	ν_e CC	$\nu_\mu \to \nu_\tau$, $\tau \to e$	$\nu_\mu \to \nu_e$	Total	$S/\sqrt{B}$
9	0.095	60	-	382	442	49σ
8	0.076	60	-	304	364	32σ
7	0.058	60	-	234	294	30σ
5	0.030	60	-	121	181	23σ
3	0.011	60	-	44	104	5.7σ
1.5	0.003	60	-	11	71	1.4σ

A 5 KT Detector (Li Ar) in the Numi Beam Can reach $\sin^2 2\theta_{13} \sim 5\times10^{-3}$

~0.005 to 90% C.L.

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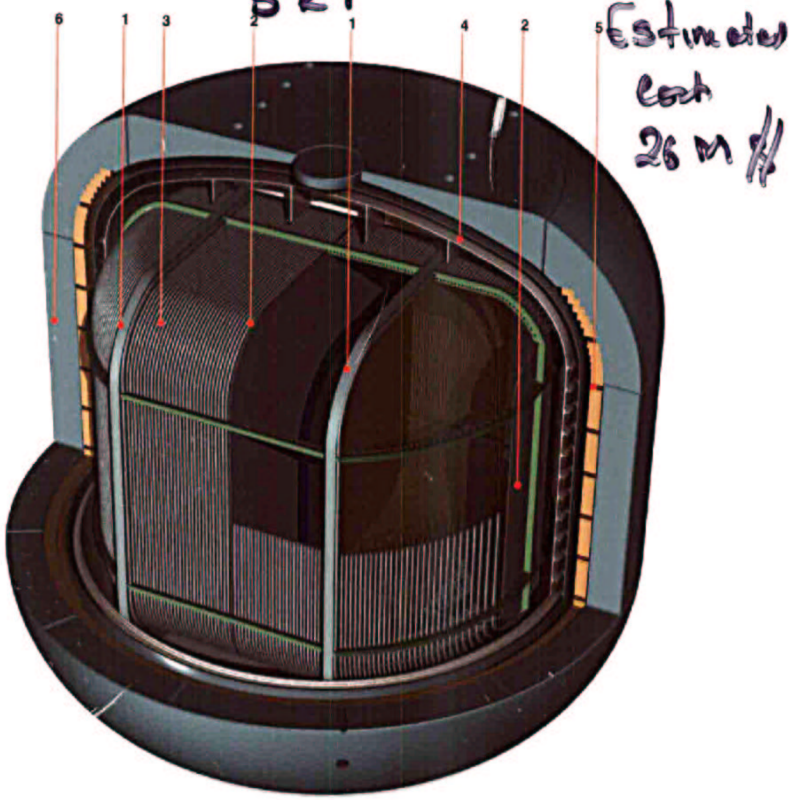


Figure 3. Mini LANNDD: 5,000 Tons Magnetised Liquid Argon Time Projection Chamber. Preliminary sketch:

1) Wire chambers
2) Cathode planes
3) Drift field electrodes
4) Cryostat
5) Solenoid coil
6) Iron yoke.

K. MacDonald
Princeton

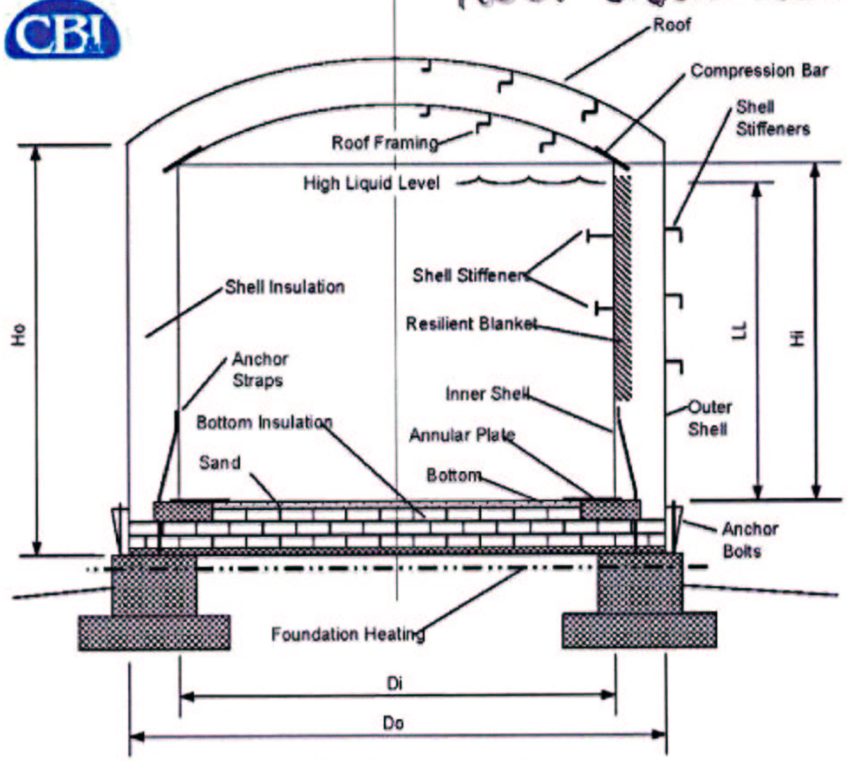
Is a 100-kton Liquid Argon Detector Feasible?

- Use mature, low-cost technology of liquid methane storage tanks (up to 300 kton based on existing structures).
  Preliminary budget estimate from industry of < \$20M for a 100-kton tank, IF built on the SURFACE.
- 100 kton of liquid argon = 10% of USA annual production.
  ⇒ Deliver one trailer-load every 2 hours from Chicago,....
  Only 5 ppm O_2 grade available in large quantities,
  ⇒ On-site liquid-phase purification via Oxisorb (MG).
  Raw material, delivery + purification ⇒ \$0.8M/kton.
- ICARUS electronics from CAEN @ \$100/channel.
  3 mm wire spacing ⇒ 300k ch ⇒ \$30M.
  9 mm wire spacing ⇒ 100k ch ⇒ \$10M.
  High capacity of long wires ⇒ signal may be too weak to use 3 mm spacing.
- With neutrino beam, record every pulse (10^{-3} duty factor).
  Cosmic rays occupy ≈ 10^{-3} of active volume,
  ⇒ ≈ 10 MB data per trigger.
  ⇒ Modest (< \$10M) DAQ/computer system.

TO STUDY $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ IN NUMI BEAM

200-kton Cryogenic Tanks Used for LNG Storage

100 KT LIQUID ARGON



Double Wall & Double Roof Tank

	Feet
Di =	165
Hi =	117.9803
LL =	117.7303
Do =	173
Ho =	118.0443

Chicago Bridge & Iron: can build 100-kton LAr tank for < \$20M.

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CRYOGENIC TANKS THE SIZE OF A KM

LANNDD DETECTOR

Cryogenic LNG Storage Tanks

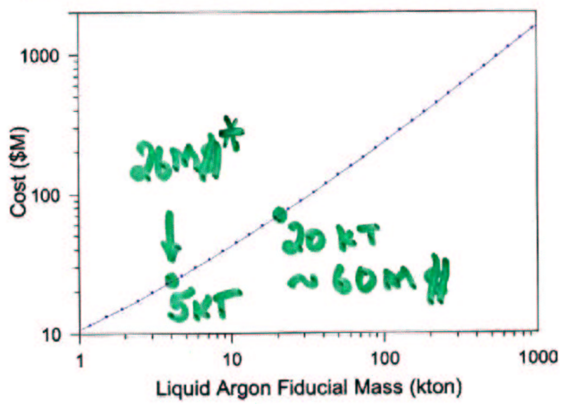
12

KM.

Budget Estimate (Very Rough)

For a 100-kton detector at the surface:

Component	Cost
Liquid argon (industrial grade)	$70M
Cryo plant, including Oxisorb purifiers	$10M
Surface site preparation	$10M
Cryogenic storage tank	$20M
Electronics (300k channels)	$30M
Computer systems	$10M
Subtotal	$150M
Contingency	$50M
Total	$200M



* Detailed Cost Estimate by UCLA/Pisa Group

Proposed to Measure ν_e Background Flux in NuMI Beam

Mini-LANNDD T40: A detector to measure the neutrino-argon cross section and the ν_e contamination in the off-axis NuMI beam

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[a]Department of Physics and Astronomy, University of California, Los Angeles, California 90095-1547, USA

[b]INFN-Sezione di Pisa, via Livornese 1291, San Piero a Grado (PI), Italy

Abstract

We describe a preliminary study of a 40-ton liquid argon TPC based on the ICARUS method to use in the NuMI near region in line with the LANNDD project [1,2]. This reduced-scale detector, called "Mini-LANNDD T40", is designed for R&D purposes and systematic measures on its response. Safety concerns are a key issue, which will be discussed as well as a preliminary design of the detector. Adapted as a near or vertex detector in a neutrino beam, the Mini-LANNDD T40 is capable of observing the ν_e flux in the off-axis beam, a key to use for measuring $\sin^2 2\theta_{13}$ in the future, and measuring the low energy neutrino-argon cross-section, an important piece of information for future long baseline experiments.

+ We could learn the liquid Argon Technology in the USA with this Small Detector

Possible Detector at NuMI Near Hall to measure ν_e flux

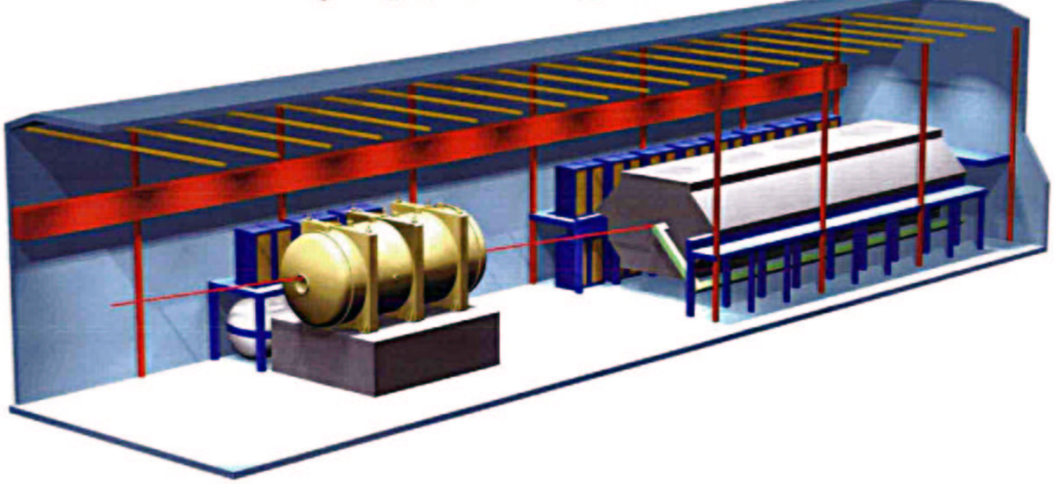


Figure 1: The Mini-LANNDD T40 detector situated inside the NuMI near hall (The drawing of the NuMI near hall is freely extracted from J. Morfin [6]).

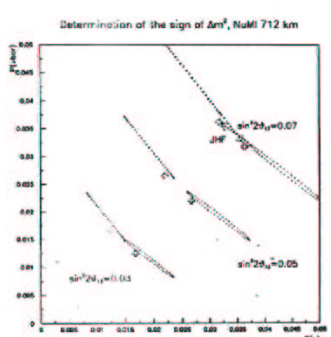
Next Off Axis General mtg at ANL April 25 - 27

Presented at SLAC mtg Jan 28

⇒ Next mtg FNAL T40 April 11/12

Determination of mass hierarchy: complementarity of JHF and NuMI

Key Issue Mass levels m_1 m_2 m_3



Combination of different baselines: NuMI + JHF extends the range of mixing angles

May Require 2 Sites

JHF	NuMI (20 kt) 0.4 MW $\sin^2 2\theta_{13}$ (θ_{OA})	1.6 MW $\sin^2 2\theta_{13}$ (θ_{OA})
no JHF data	0.09 (0.7-1.0°)	0.05 (0.8-1.0°)
22.5 kt, 0.8 MW	0.07 (0.8-1.0°)	0.04 (0.9-1.0°)
22.5 kt, 4.0 MW	0.06 (0.7-1.0°)	0.03 (0.7-1.0°)
450 kt, 4.0 MW	0.05 (0.6-1.0°)	0.02 (0.7-0.9°)

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SUMMARY

Progress on the observation of a Non Zero $\mathrm{Sin}^2 2\theta_{13}$ will follow this:

- **2005 – 2008**

  MINOS AND ICARUS CAN SEARCH: $\mathrm{Sin}^2 2\theta_{13} \gtrsim 0.03$
  Possible Reactor Experiments?

- **2008 – 2012**

  JHF to Super K – Possible Low Energy CNGS Search
  Initial NUMI Off Axis Experiment $\mathrm{Sin}^2 2\theta_{13} \sim 0.03 \rightarrow 0.005$

- **All other projects (Hyper K, UNO, Phase II; NUMI Off Axis) likely to depend on these observations.**

- **Future CP Violation Search, Neutrino Factories will also depend on this.**

  ➢ **OBSERVATION OF $\mathrm{Sin}^2 2\theta_{13}$ IS CRUCIAL!**