Current and Future Neutrino Experiments

Martin Hierholzer

Students' Seminar, Universität Hamburg

2008-07-03

- introduction
- neutrino sources
- detector types
- experimental performance
- summary

Introduction

- here only neutrino oscillation physics covered
- most oscillation parameters known:
  $\sin^2\Theta_{23} > 0.90$ (90% C.L.)
  $|\Delta m^2_{23}| = (2.43 \pm 0.13) \cdot 10^{-3}\,\mathrm{eV}^2$
  $\tan^2\Theta_{12} = 0.45 \pm 0.08$
  $\Delta m^2_{21} = (8 \pm 0.5) \cdot 10^{-5}\,\mathrm{eV}^2$
- missing: Θ_{13}, δ_{CP}, mass hierarchy
- goals of current and future experiments:
  - determination of remaining parameters
  - precision measurement of known parameters (MINOS...)

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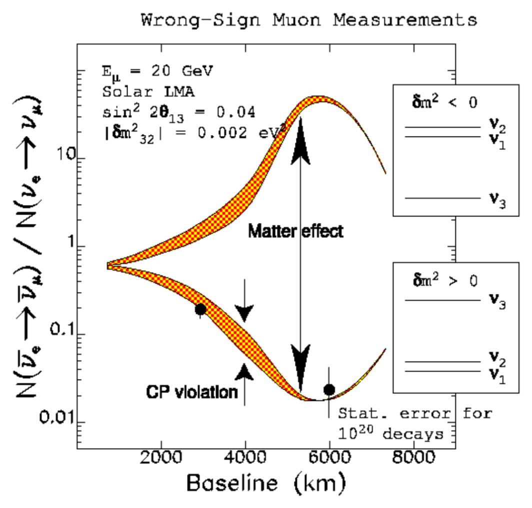
"precision era of neutrino physics"

Physics Motivation

- Hierarchy: matter effect (long baseline)
- CP-phase: precise measurement (medium baseline)
- Θ_{13}: "vacuum" oscillations ("short" baselines)



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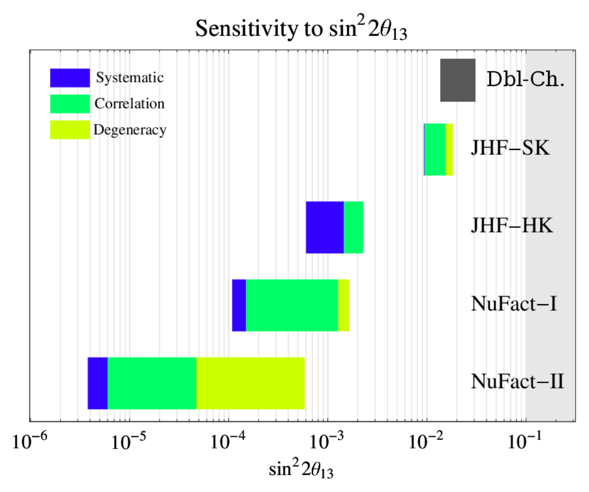


| ← reached ∼ 2012

Folgi & al: hint for $\sin^2 \Theta_{13} = 0.016 \pm 0.010 (1\sigma) \Rightarrow \sin^2 2\Theta_{13} = 0.06$ (arXiv:0806.2649v1)

Requirements for Future Experiments

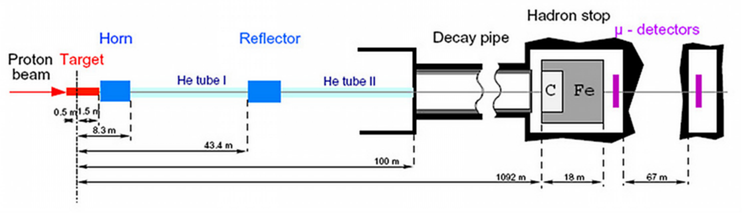
- requirements to the neutrino sources:
  - higher intensities
  - smaller energy distributions
  - purer or better known composition (flavours and $\nu/\overline{\nu}$)
- requirements to the detectors:
  - higher target masses ("Megaton" detectors required)
  - purer flavour separation, higher energy resolution
  - better shielding or separation from background
- new technologies required

Neutrino Sources

- Super Beams
- Beta Beams
- Neutrino Factories
- not covered here:
  - reactor neutrinos
  - solar and atmospheric neutrinos
  - geo-neutrinos
  - astronomical neutrino sources

Super Beams

- conventional beams: π/K decay: $\nu_\mu/\overline{\nu}_\mu$
- high intensity (e.g. upgraded existing beams)



- on axis: wide energy distribution
- off axis: narrow energy distribution
- high intensity needed for off axis operation

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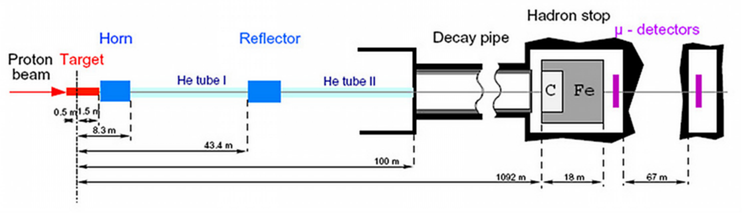

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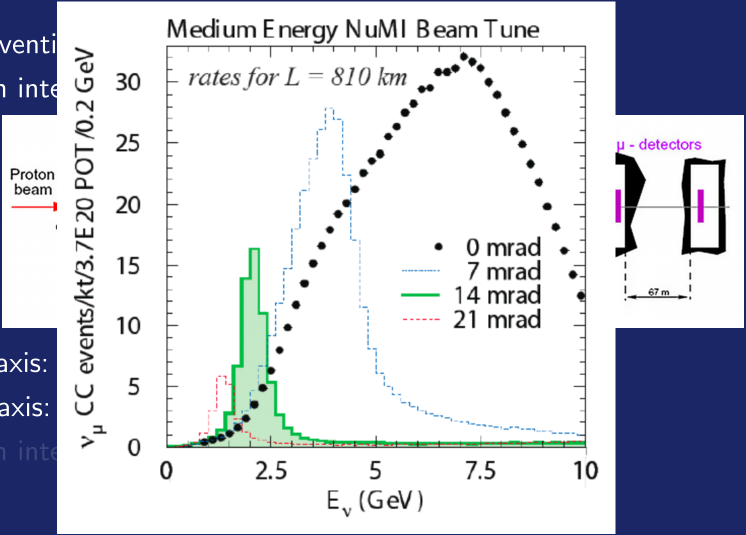

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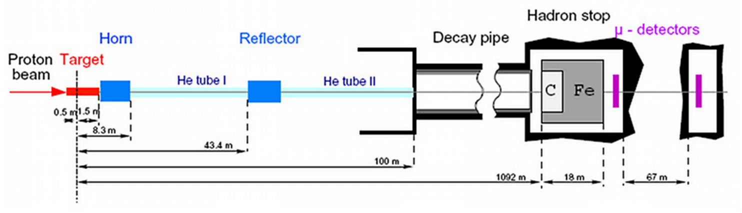

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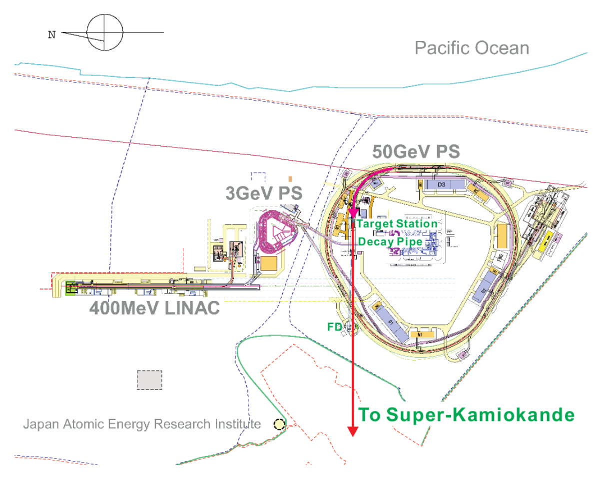
J-PARC (T2K)

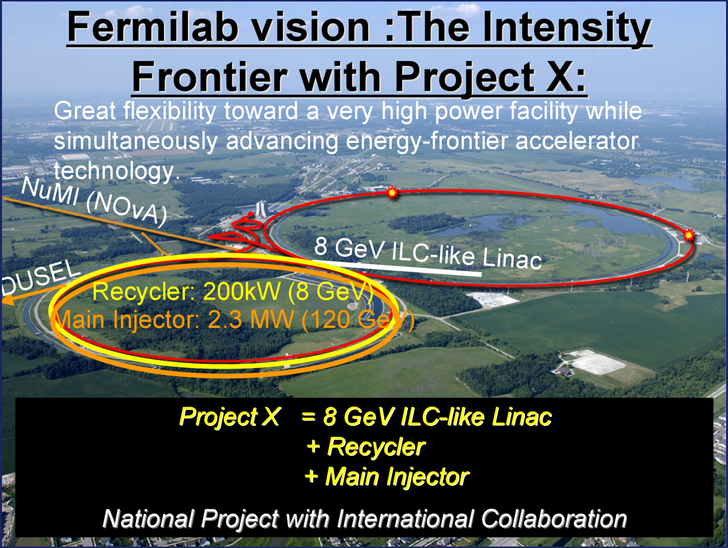
- J-PARC (Tokai, Japan): $50\,\mathrm{GeV}$ proton synchrotron



J-PARC (T2K)

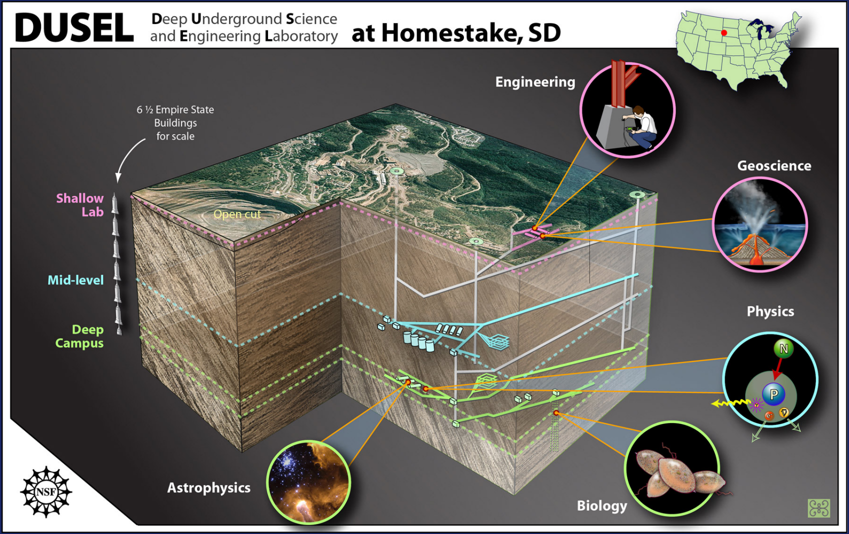
- J-PARC (Tokai, Japan): $50\,\mathrm{GeV}$ proton synchrotron
- beam power: $0.75\,\mathrm{MW}$, $10^{21}\,\mathrm{POT/year}$
- neutrino energy $0.7\,\mathrm{GeV}$ (2° OA) or $0.55\,\mathrm{GeV}$ (3° OA)
- energy tuneable by bending magnet after the horn (?)
- main PS under construction (LINAC and RCS finished)
- will start in early 2009

Project X



Gina Rameika, P5 Meeting at SLAC, February 21, 2008

DUSEL


DUSEL
Deep Underground Science and Engineering Laboratory
at Homestake, SD
6 ½ Empire State Buildings for scale
Shallow Lab
Mid-level
Deep Campus
Open cut
Engineering
Geoscience
Physics
Astrophysics
Biology
NSF

Neutrino Factories

- muon storage/decay ring
- $50\%\ \overline{\nu}_\mu$ and $50\%\ \nu_e$ or $50\%\ \nu_\mu$ and $50\%\ \overline{\nu}_e$
- "golden channel": $\nu_e \longmapsto \nu_\mu$
- required components:
  - proton driver (special requirements: short bunches, ...)
  - target for muon production
  - buncher and cooler
  - acceleration to $20\,\mathrm{GeV}$ (recirculating linac and synchrotrons)
  - storage ring (35% muon decays in downward-going straight)
- R&D in progress (also to create muon colliders...)
- cooling of muons: demonstration experiment in 2006 (MANX)
- challenge: short muon life time

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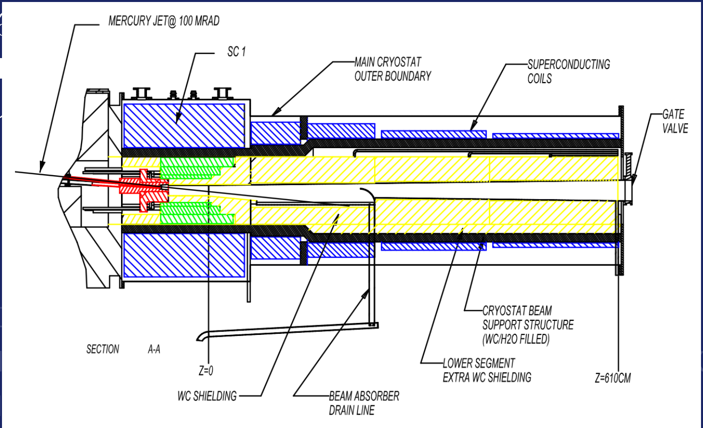

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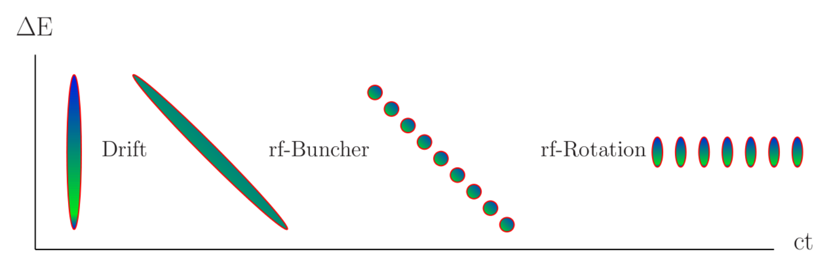

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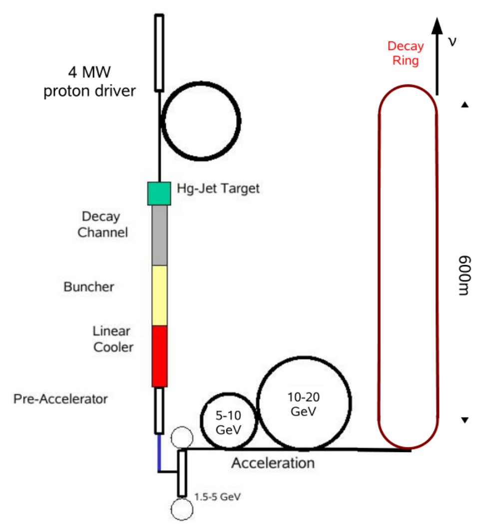

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Beta Beams

- first proposed in 2002 by P. Zucchelli ("easier" than NuFact)
- beta-decay of stored ions: pure beam of $\nu_e/\overline{\nu}_e$
- ion choice:
  - $^{6}He^{2+}$ to produce $\overline{\nu}_e$
  - $^{18}Ne^{10+}$ to produce ν_e
  - rare earth nucleai for monochromatic beams
  - half-lives $\mathscr{O}(1\,\mathrm{s})$
- required components:
  - proton driver (2 GeV)
  - ISOL Target and Ion Source
  - accelerators: LINAC (to $20-100\,\mathrm{MeV/u}$), then RCS (to $300\,\mathrm{MeV/u}$)
  - further acceleration to $\gamma \sim 150$ (e.g. SPS)
  - decay ring: long straight sections ($\approx 2500\,\mathrm{m}$)

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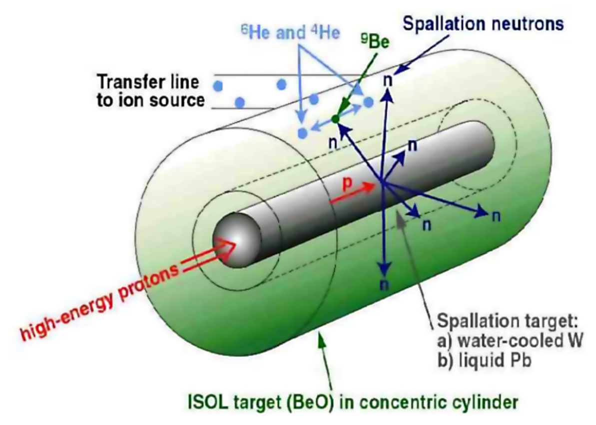

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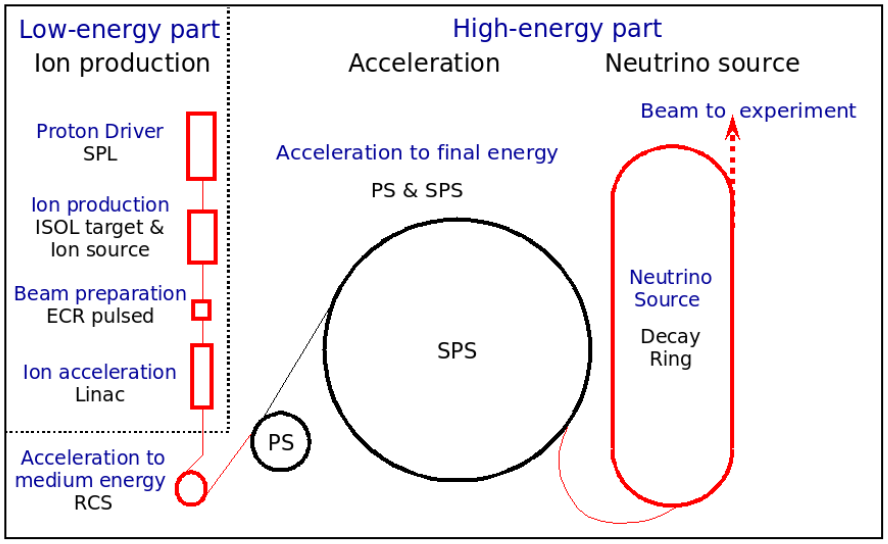
Beta Beam Example: EURISOL Design Study



Detector Types

- Water Čherenkov
- Liquid Scintillator
- Tracking Calorimeters
- Liquid Argon Time Projection Chambers

Water Čherenkov

- active target material: water (or ice)
- detection of secondary particle by Čherenkov light
- Čherenkov light detected by PMTs
- proven technology, successfully used in many experiments
- very good scaleable to large target masses
- cheap (or free) target material
- angular resolution: $< 2^\circ$
- caveats:
  - big volume, large cavernes needed (if underground)
  - bad energy resolution ($\Delta L/E \sim 70\%$)
  - low background rejection
  - no magnetization possible (no charge measurement)

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- ν_e and ν_μ can be distinguished on a statistical basis
- energy threshold for detection: $5\,\mathrm{MeV}$ ($3.5\,\mathrm{MeV}$ for D_2O)
- suitable for:
    - solar neutrinos (only ^8B)
    - atmospheric neutrinos
    - accelerator neutrinos
    - super novae
- present examples: Super-Kamiokande, SNO (D_2O), Antares, IceCube

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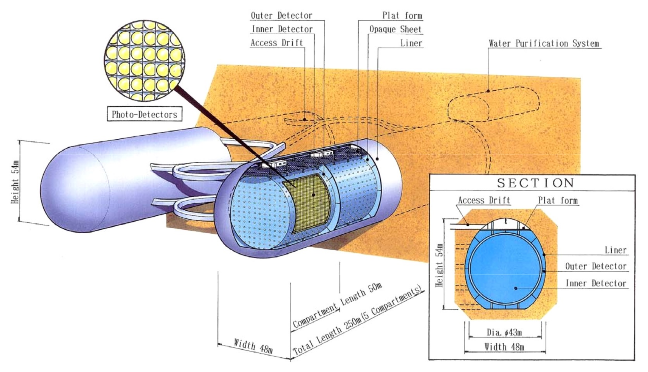
Hyper-Kamiokande

- total target mass: $\sim 1\,\mathrm{Mt}$, fiducial mass $0.54\,\mathrm{Mt}$
- two independent detectors, each devided into 5 compartments
- located Tochibora mine (Kamioka, $500\,\mathrm{m.w.e.}$)



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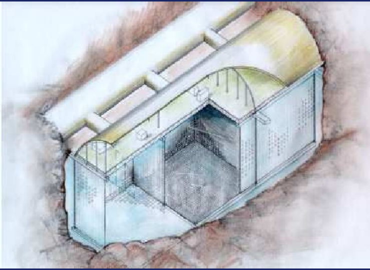
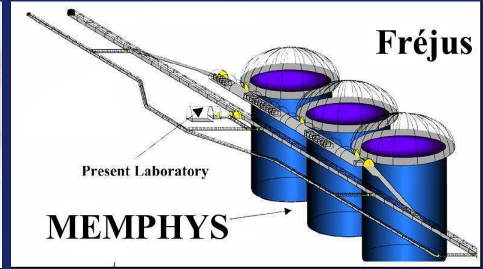
- located Tochibora mine (Kamioka, $500\,\mathrm{m.w.e.}$)
- PMT coverage: 40%
- T2K long baseline (J-PARC, $290\,\mathrm{km}$)
- atmospheric and super nova neutrinos
- 10 years of construction (starting $\sim$ 2010, if funded)

UNO and MEMPHYS

- both $440\,\mathrm{kt}$ fiducial mass
- UNO: probably located in DUSEL, base lines: $\sim 1280\,\mathrm{km}$ (Fermilab) or $\sim 2530\,\mathrm{km}$ (BNL)
- MEMPHYS: located in Frejus ($130\,\mathrm{km}$ to CERN, beta beam!?)
- alternatives to Hyper-Kamiokande





Liquid Scintillator

- detection of secondary particle by scintillation light
- active target material: liquid scintillator, e.g.
  - PC (Pseudocumene = 1,2,4-Trimethylbenzene)
  - PXE (Phenylxylylethane)
- scintillation light detection by PMTs
- proven technology at large target masses
- good efficiency and good energy resolution (6% at $1\,\mathrm{MeV}$)
- clean signatures, good background rejection
- almost no angular information
- low energy threshold (few $100\,\mathrm{keV}$, depending on scintillator)
  important for solar and reactor, but not for accelerator neutrinos
- examples: (Double) Chooz, Borexino, KamLAND

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Tracking Calorimeters

- target and active area seperated:
  - segmented solid target (iron, lead)
  - active components (e.g. scintillator strips) between target segments
- suitable for "golden channel" of neutrino factories ($\nu_e \longmapsto \nu_\mu$):
  - identification of "wrong signed" muons
  - muon charge identification with high purity ($< 10^{-5}$)
- but: high density target prevents detection of low-energy neutrinos

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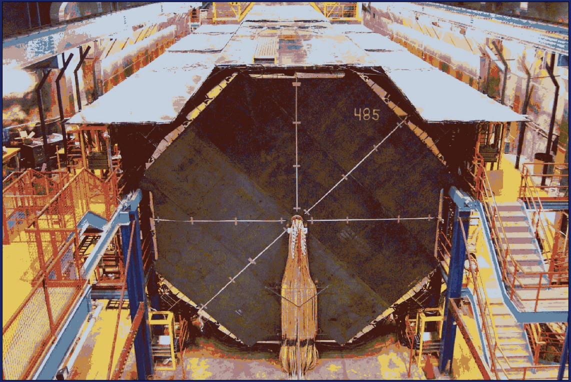
Tracking Calorimeters

- known technology: e.g. MINOS uses it successfully
- MINOS has a target mass of $5\,\mathrm{kt}$ ($3\,\mathrm{kt}$ fiducial)
- future experiments will be larger by 1 order of magnitude
- NOνA: $30\,\mathrm{kt}$ TCal with liquid scintillator (delayed funding)



Liquid Argon Time Projection Chamber

- detection of secondary particle by ionization
- active target material: liquid argon
- TPC: measurement of electron drift, readout wires
- drift distances of some meters possible in liquid argon
- trigger: Fluorescence light detected by PMTs
- low energy threshold, high efficiency
- full 3D reconstruction:
  - high spatial resolution ($\mathcal{O}(1\,\mathrm{cm})$)
  - energy measurement with magnetic field (?)
  - high background rejection
- caveats:
  - technology not proven to work at large scales
  - safety concerns in underground operation (!)

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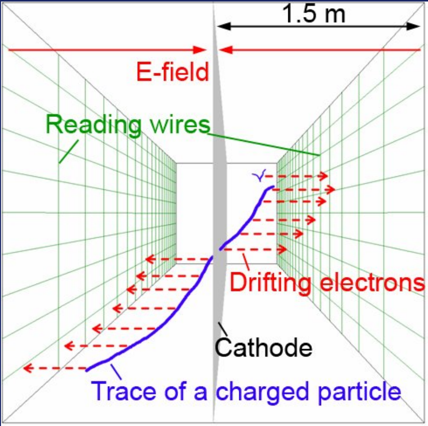
Liquid Argon Time Projection Chamber

- detection of secondary particle by ionization
- active target material: liquid argon
- TPC: measurement of electron drift, readout wires
- drift distances of some meters possible in liquid argon
- trigger: Fluorescence light detected by PMTs
- low energy threshold, high efficiency
- full 3D reconstruction:
  - high spatial resolution ($\mathcal{O}(1\,\mathrm{cm})$)
  - energy measurement with magnetic field (?)
  - high background rejection
- caveats:
  - technology not proven to work at large scales
  - safety concerns in underground operation (!)

ICARUS T600

- $600\,\mathrm{t}$ module, consisting of 2 identical $300\,\mathrm{t}$ half-modules
- the originally planned T3000 (5xT600) will not be built (safety)



ICARUS T600

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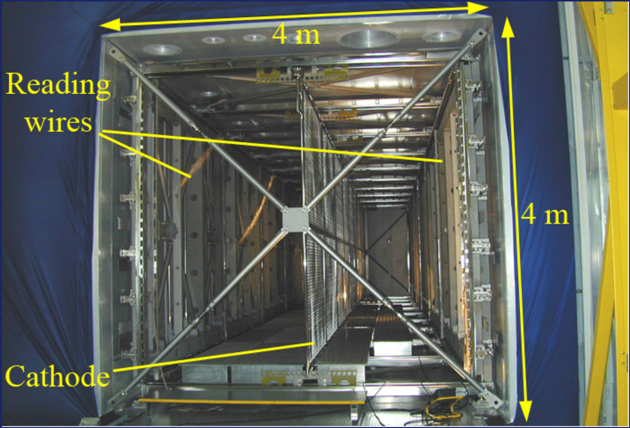
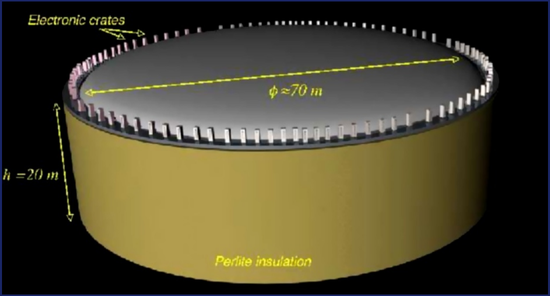


ICARUS T600

- $600\,\mathrm{t}$ module, consisting of 2 identical $300\,\mathrm{t}$ half-modules
- the originally planned T3000 (5xT600) will not be built (safety)
- both half modules share the same cryostat
- each half module has two TPCs
- nominal voltage: $75\,\mathrm{kV}$ ($500\,\mathrm{V/cm}$)
- maximum drift distance and time: $1.5\,\mathrm{m}$ / $1\,\mathrm{ms}$
- total active volume: $170\,\mathrm{m}^3$
- total number of wires: 53248 ($\varnothing\,150\,\mu\mathrm{m}$)
- current status: construction at LNGS (Italy)
- Physics opportunity: $\nu_\mu \to \nu_e$ (CNGS beam)

GLACIER

- $100\,\mathrm{kt}$ LAr TPC
- using industrial available tanks (no R&D)
- new readout techniques for very long drift times (e.g. LEM)
- magnetized volume (under study)
- sensitive to CP-phase



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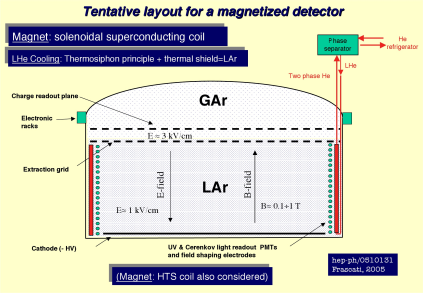
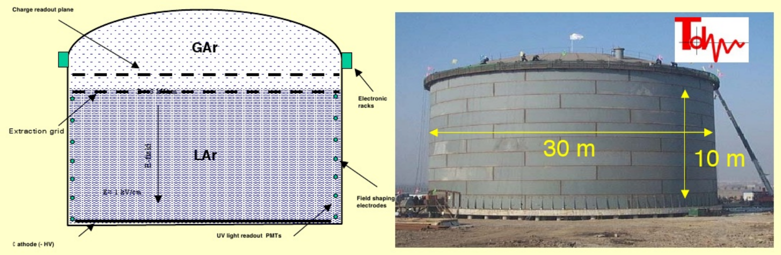
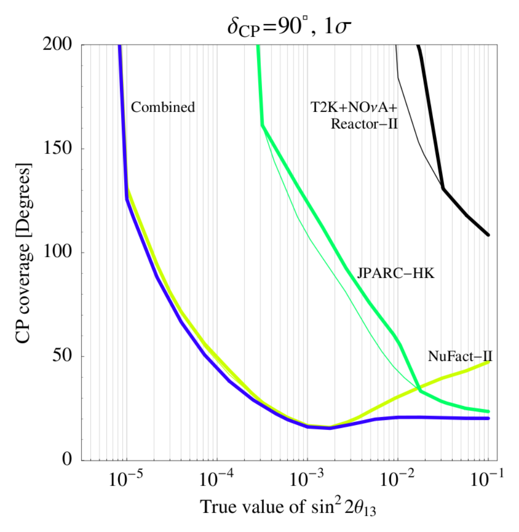


GLACIER

- 100 kt LAr TPC
- using industrial available tanks (no R&D)
- new readout techniques for very long drift times (e.g. LEM)
- magnetized volume (under study)
- sensitive to CP-phase
- 10 kt prototype with own physics program (proton decay)

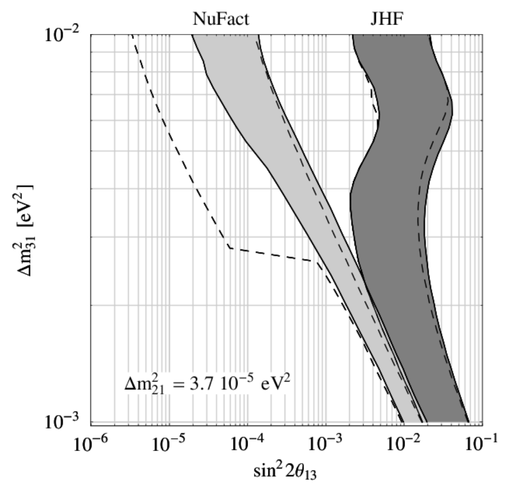


CP Phase



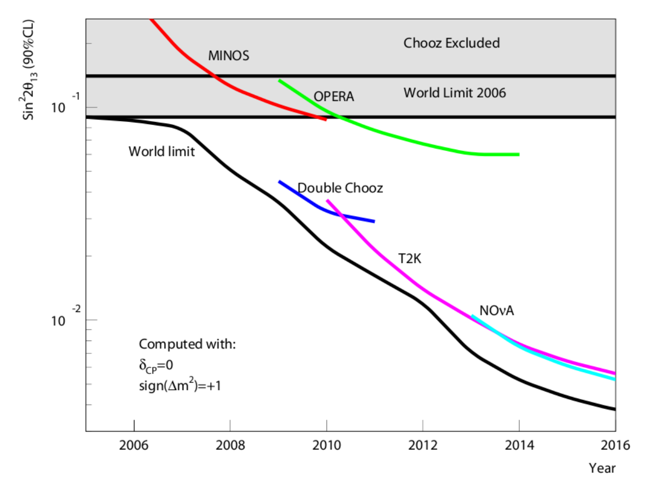
physics/0411123v2

Θ_{13} vs Δm^2_{31}



90% c.l., hep-ph/0204352v2

Θ_{13}

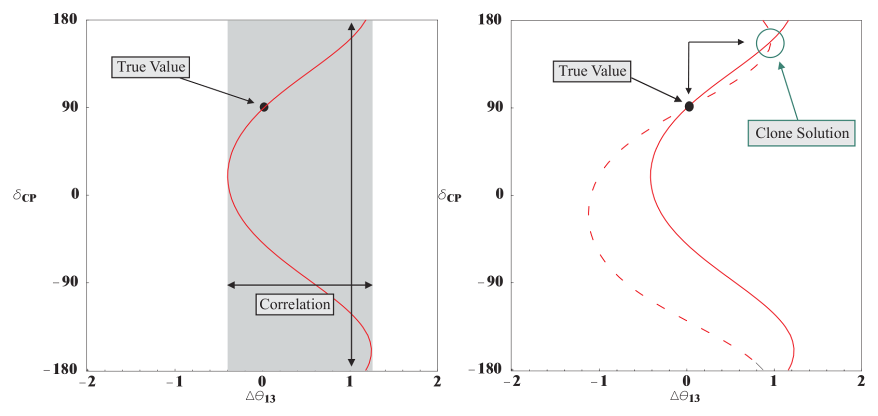


90% c.l., hep-ph/0710.4947v2 (international scoping study)

Summary

Det. ╲ Src.	(Super) Beam	NuFact	Beta Beam	Reactor
WC	Hyper-K UNO MEMPHYS			
LScint				DblChooz
TCal	MINOS	MIND *(golden ch.)* mag. ECC *(all ch.)*		
LAr TPC	ICARUS GLACIER LArTPC@NuMI	GLACIER	GLACIER	

Correlation



Correlation

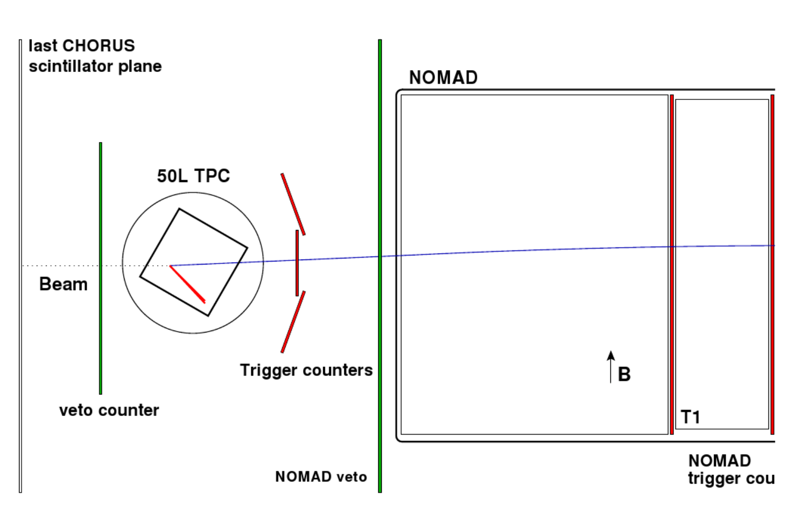
$$
\begin{aligned}
P(\nu_\mu \to \nu_\mu) \quad = \quad & 1 - \left[\sin^2 2\theta_{23} - s_{23}^2 \sin^2 2\theta_{13} \cos 2\theta_{23}\right] \sin^2\left(\frac{\Delta_{23} L}{2}\right) \\
& - \left(\frac{\Delta_{12} L}{2}\right) \left[s_{12}^2 \sin^2 2\theta_{23} + \tilde{J} s_{23}^2 \cos\delta\right] \sin(\Delta_{23} L) \\
& - \left(\frac{\Delta_{12} L}{2}\right)^2 \left[c_{23}^4 \sin^2 2\theta_{12} + s_{12}^2 \sin^2 2\theta_{23} \cos(\Delta_{23} L)\right],
\end{aligned}
$$

where $\tilde{J} = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$ and $\Delta_{23} = \Delta m_{23}^2/2E$, $\Delta_{12} = \Delta m_{12}^2/2E$.

ICARUS WANF test setup

- $50\,l$ LAr TPC module
- high beam energy and modest detector volume: external muon spectrometer
- coincidence with NOMAD DAQ, using NOMAD dipole magnet as spectrometer
- first 3D reconstruction of neutrino events with a LAr TPC

ICARUS WANF test setup



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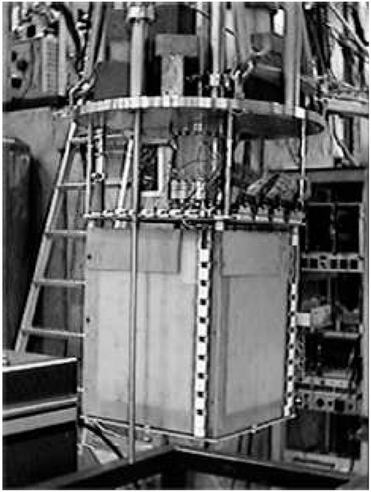

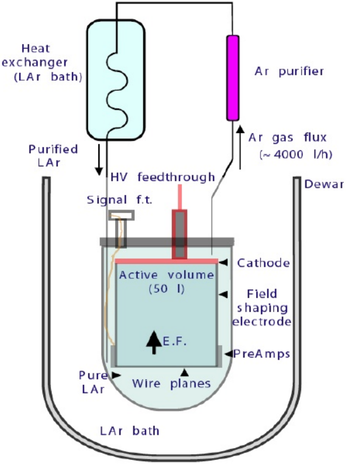

ICARUS WANF test setup