Completing the Neutrino Mixing Matrix

Gordon Research Conferences, Nuclear Physics, July 13, 2009

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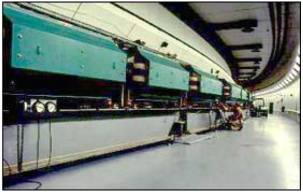
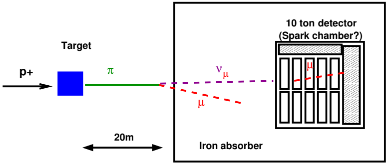
Outline

Neutrinos have flavors

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi^+ \longrightarrow \mu^+\nu_x$



The AGS



Making ν's

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

The first accelerator neutrino experiment was at the AGS.

Neutrino oscillations

1957,1967: B. Pontecorvo proposes that neutrinos could oscillate:

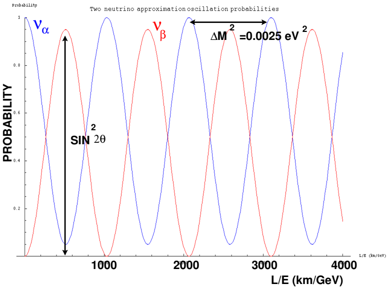
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).

If flavor eigenstates mix with mass eigenstates ⇒ neutrinos have mass



The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

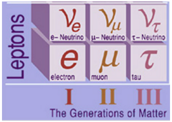
Ray Davis

1. $\nu_e^{sun} + {}^{37}\text{CL} \rightarrow e^- + {}^{37}\text{Ar}$, $\tau({}^{37}\text{Ar}) = 35$ days.
2. Number of Ar atoms = number of ν_e^{sun} interactions.

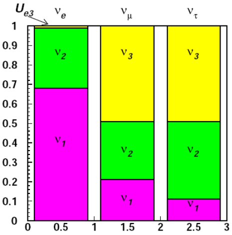
Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Neutrino Mixing: 3 flavours

We know now of 3 flavours of neutrinos: **The 3 flavour PMNS mixing matrix was developed in 1962 by Maki-Nakagawa-Sakata based on Pontecorvo's earlier work:**



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



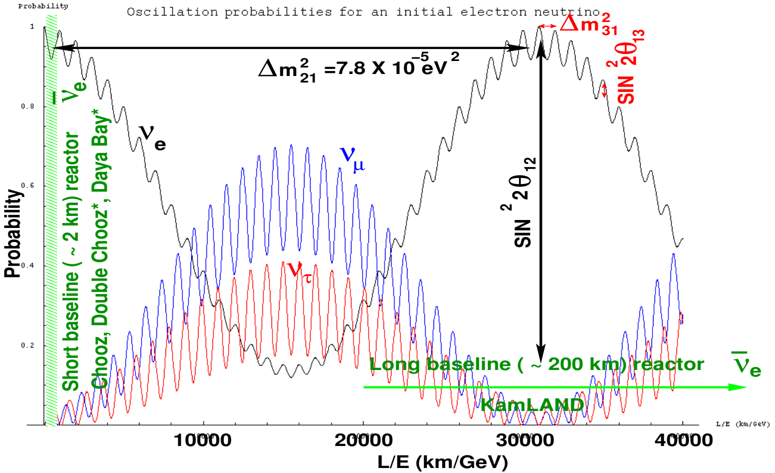
In the past 10 yrs we have measured most of the U_{PMNS} parameters

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & < 0.20\ ?? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}, \quad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

In contrast to CKM, large off diagonal terms:

Measuring neutrino mixing - ν_e oscillations

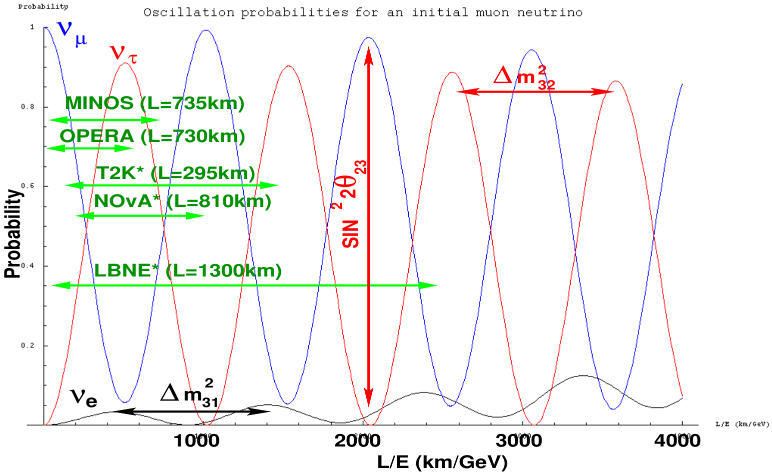
Solar ν_e disappearance constrained 1 $\longrightarrow$ 2 mixing. Precision from reactor $\bar{\nu}_e$ experiments:



$*$ = future reactor $\bar{\nu}_e$ experiments

Measuring neutrino mixing - ν_μ oscillations

SuperK atmospheric ν_μ disappearance (L/E $3 \rightarrow 30,000$) demonstrated $2 \rightarrow 3$ oscillations. Accelerator expts followed at smaller L/E:

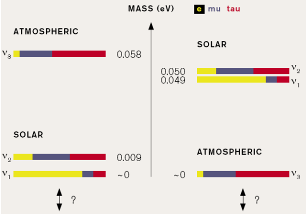


*** = future accelerator ν_μ experiments**

Neutrino Matrix Parameterization

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\nu_\mu \text{ disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\nu_\mu \to \nu_e,\ \text{reactor } \bar{\nu_e} \text{ disappear}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu_e,\ \bar{\nu_e} \text{ disappear}}$$

where $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$ and $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$ and δ_{CP} is the CP phase.



Normal Inverted

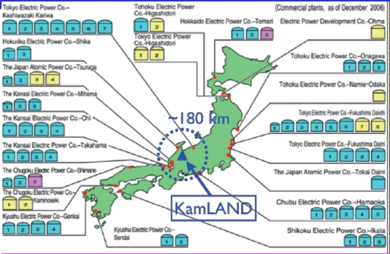
$\sin^2\theta_{13}$: Amount of ν_e in ν_3

$\tan^2\theta_{23}$: Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

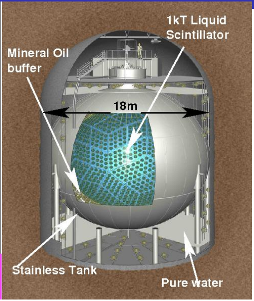
WE DONT KNOW: $\sin^2 2\theta_{13}, \delta_{cp}, \mathrm{sign}(\Delta m^2_{31})$

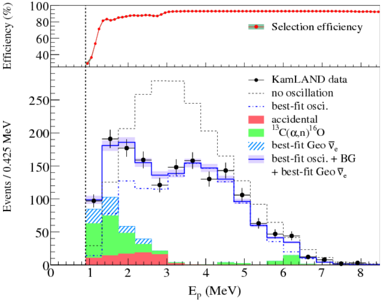
The KamLAND $\bar{\nu}_e$ Reactor Experiment

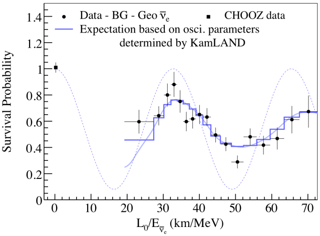


World reactors + Research reactors : 0.96%

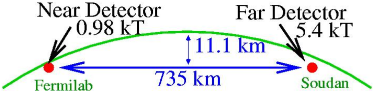
Korean reactors : 3.2%



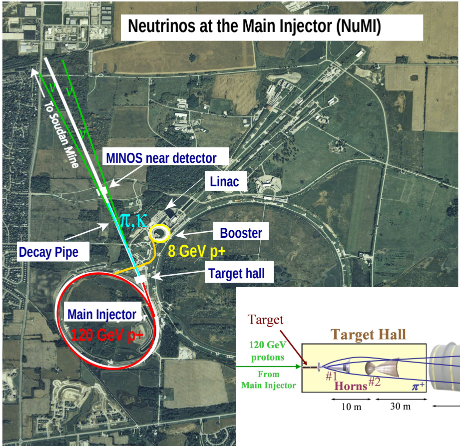




The NuMI/MINOS Accelerator ν_μ Experiment

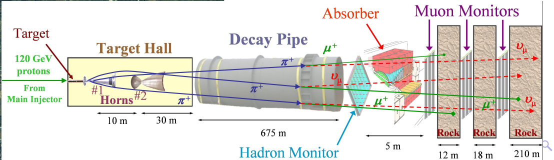


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**



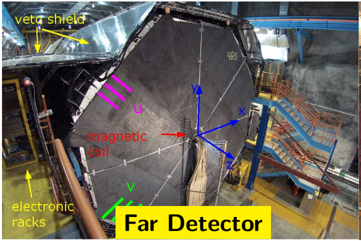
NuMI Horn 2 inner conductor
Radial field, B $\propto$ 1/r

3T at 200 kA



The MINOS Detectors

Magnetized iron calorimeters with 2.54 cm thick Fe plates sandwiched with scintillator strips readout by WLS fiber.



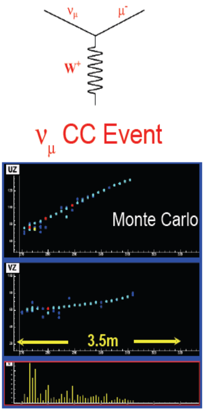
The Far Detector

- 484 octogonal steel/scintillator plates 8m wide, $\Rightarrow$ 5.4kTon and 30 m in length.
- Toroidal B-field, 1.3 T at r = 2m
- Cosmic μ veto shield

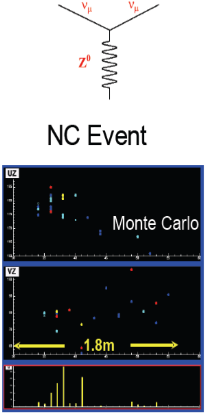
The Near Detector

- 282 "squashed" octagonal steel plates, 153 scintillator planes. $\Rightarrow$ 1kTon and 16 m in length.
- Toroidal B-field, 1.3 T at r = 2m

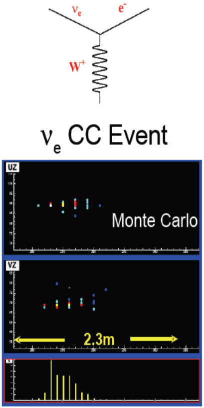
Event Topologies



Clear track + activity at vertex



Diffuse, shorter events



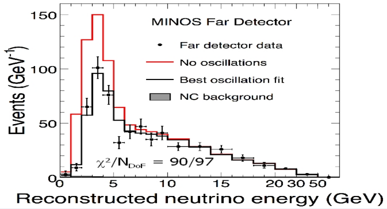
Short with EM shower profile

$$E_\nu^{CC} = \underbrace{E_\mu}_{\sigma_P \sim 10\%} + \underbrace{E_{shower}}_{\sigma_{had} = 55\%/\sqrt{E}}$$

MINOS Data (2009)

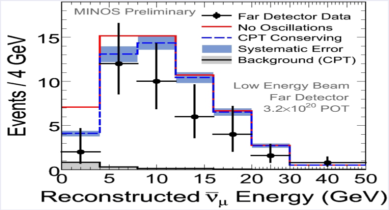
The NuMI beam contains 91.5% ν_μ, 7 % $\bar{\nu}_\mu$ and 1.5% $\nu_e + \bar{\nu}_e$

ν_μ disappearance



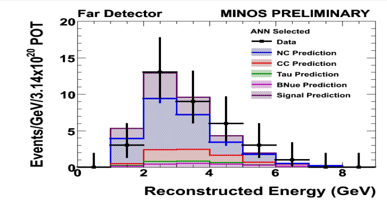
Expected no-osc 1065 $\pm$ 60.
Observe 848.

$\bar{\nu}_\mu$ disappearance



Expected (with osc) 58.3 $\pm$ 7.6$_{stat}$ $\pm$ 3.6$_{sys}$.
Observe 42.

ν_e appearance



Expected FD background: 27 $\pm$ 5$_{stat}$ $\pm$ 2$_{sys}$.
Observe 37.

MINOS results 2009

ν_μ Disappearance:

$\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3} eV^2$

$\sin^2 2\theta_{23} > 0.90 (90\% C.L.)$

$\bar{\nu}_\mu$ Disappearance:

Fraction $\nu_\mu \rightarrow \bar{\nu}_\mu < 0.026 (90\% C.L.)$

ν_e appearance:

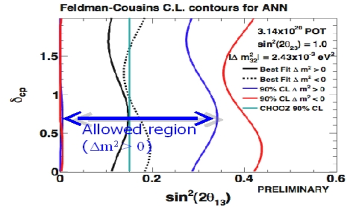
$\sin^2 2\theta_{13} < 0.29 (90\% C.L.)$; $\Delta m^2 > 0$, $\delta_{cp} = 0$

$\sin^2 2\theta_{13} < 0.49 (90\% C.L.)$; $\Delta m^2 < 0$, $\delta_{cp} = 0$

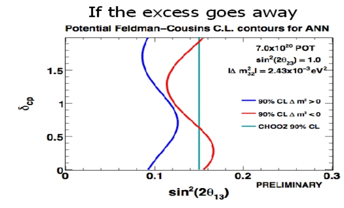
MINOS Results 2009 and Future

Search for ν_e appearance

Current results

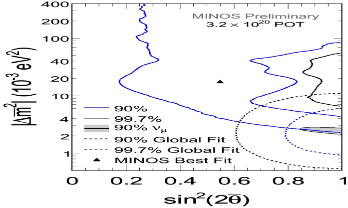


Expected by 2010

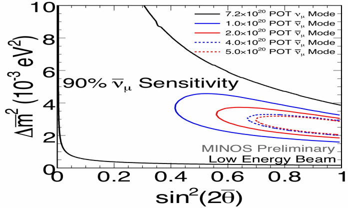


$\bar{\nu}_\mu$ disappearance

Current results



Future dedicated $\bar{\nu}_\mu$ running

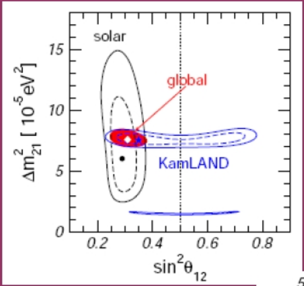


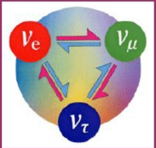
The mixing matrix - 2009

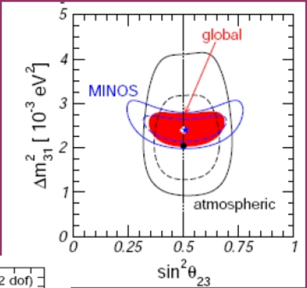
J. Valle, TAUP '09

Maltoni et al, NJP 6 (2004) 122

Schwetz et al, NJP 10 (2008) 113011



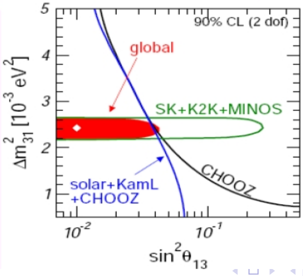




Homestake, SAGE+ GALLEX/GNO, Super-K, SNO
Borexino

KamLAND (180 Km)

Valle@TAUP09



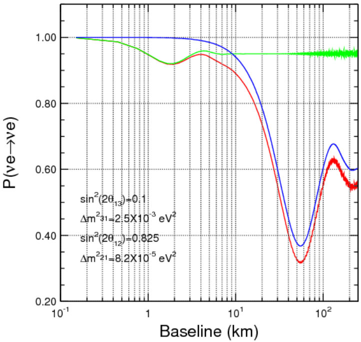
... Super-K

K2K (250 Km)
MINOS (735 Km)

Short Baseline Reactor $\bar{\nu}_e$ oscillations

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

Osc prob. (integrated over E) vs distance



Unambiguous measurement of $\sin^2 2\theta_{13}$

Getting to $\sin^2 2\theta_{13} < 0.01$

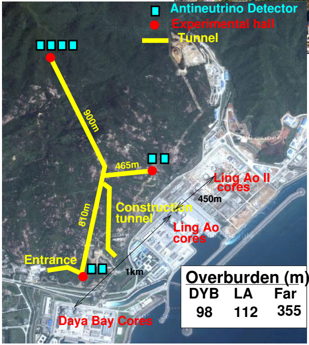
Lots of statistics: -Powerful nuclear reactors + more massive detectors

Supress cosmic backgrounds:
-Increase overburden = go deeper underground.

Reduce systematic uncertainties:
-Deploy near detectors as close as possible to reactor to minimize reactor flux uncertainties.
-Use multiple, “identical” detector pairs to reduce near/far detector uncertainties.
-Calibration, calibration, calibration...

The Daya Bay Reactor Complex

see Kevin Zhang's talk



Overburden (m)

DYB	LA	Far
98	112	355

Reactor Specs:

Located 55km north-east of Hong Kong.

Current: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 $\mathrm{GW_{th}}$

By 2011: 2 more cores at Ling Ao II site = 17.4 $\mathrm{GW_{th}}$ $\Rightarrow$ top five worldwide

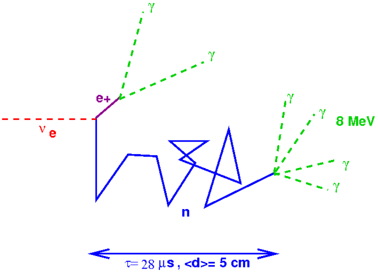
1 $\mathrm{GW_{th}} = 2 \times 10^{20} \bar{\nu}_e/\mathrm{second}$

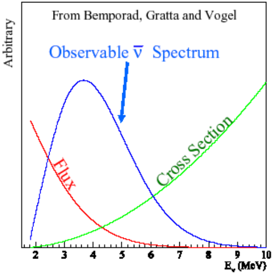
Deploy multiple near and far detectors $\Rightarrow$

Reactor power uncertainties $< 0.1\%$

Detecting $\bar{\nu}_e$ using GD-loaded LS.

The active target in each detector module is liquid scintillator loaded with 0.1% Gd



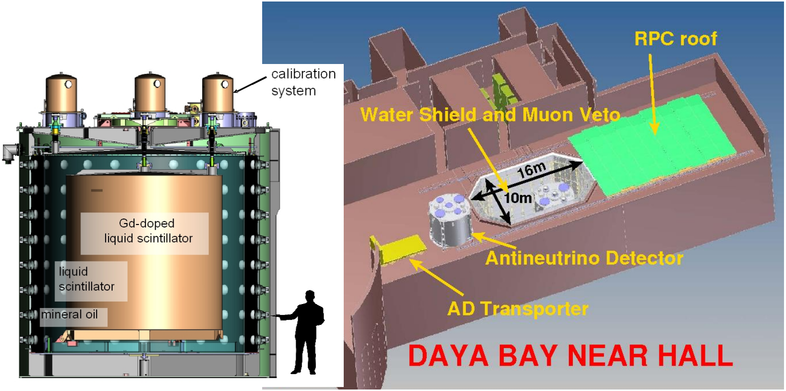


The detection sequence is as follows: $\bar{\nu}_e + p \rightarrow n + e^+$ THEN
$e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV $+T_{e+}$, prompt)
$n + p \rightarrow D + \gamma$ (2.2 MeV, $\tau \sim 180\mu s$, $\sigma = 0.3b$). OR
$n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$'s (8 MeV, $\tau \sim 28\mu s$, $\sigma = 5 \times 10^4 b$).

$\Rightarrow$ delayed co-incidence of e^+ conversion and n-capture (> 6 MeV)

with a specfic energy signature

The Daya Bay Experiment



- Multiple "identical" detectors at each site.
- Manual and multiple automated calibration systems per detector.
- Thick water shield to reduce cosmogenic and radiation bkgds.

	DYB	LA	Far
Event rates/20T/day	840	740	90

Daya Bay Sensitivity

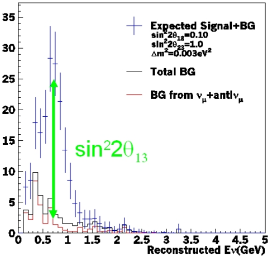
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)	Strategy
# protons	H/C ratio	0.8	$<$ 0.1	Fill in pairs/calib
	Mass	-	$<$ 0.3	Load cells and mass flowmeters
Detector Efficiency	Energy cuts	0.8	0.2	lower threshold/calib
	Position cuts	0.32	0.0	3-zone
	Time cuts	0.4	0.1	Common clock $\sim$ 10ns
	H/Gd ratio	1.0	0.1	fill in pairs/calib
	n multiplicity	0.5	0.05	Deeper/muon veto
	Trigger	0	0.01	Redundant triggers
	Live time	0	$<$ 0.01	Common GPS clock
Total detector-related uncertainty		1.7%	0.38%	

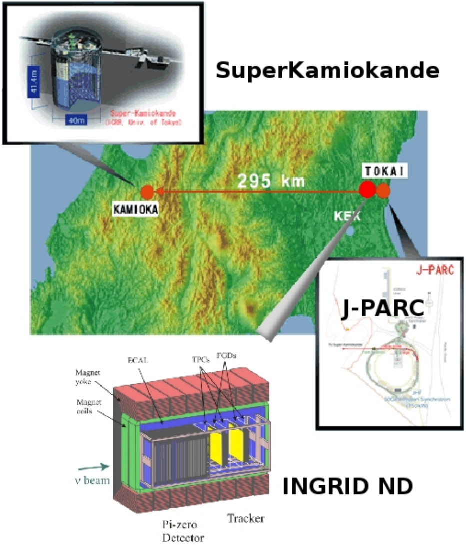
Reach sensitivity to $\sin^2 2\theta_{13} < 0.01$ @ 90% C.L. by 2014

Off-axis high intensity ν_μ beams: T2K

First proposed for BNL E-889 (1995): A narrow beam of ν can be achieved by going off-axis to the π beam. Better S:B at oscillation max.

Signal at $\sin^2 2\theta_{13} = 0.1$:

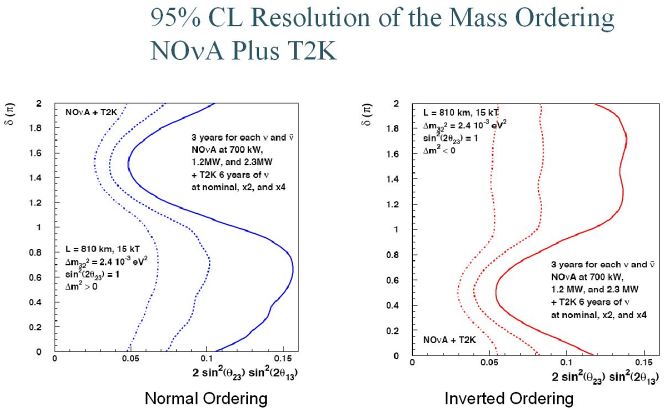




T2K is almost ready - proton beam down beamline June, 2009

NOνA and T2K

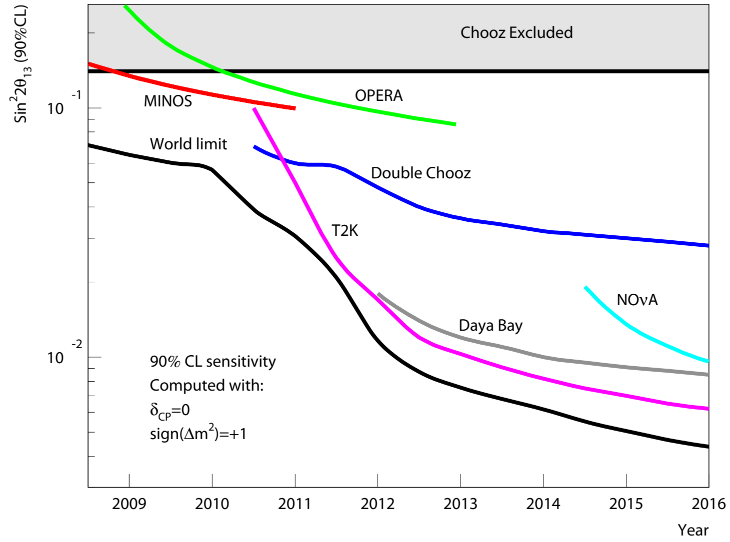
The NOνA experiment is at a baseline of 810km off-axis to the NuMI beam. Detector is 15kT of active scintillator on the surface. Operational by 2013. **From G. Feldman:**



Some sensitivity to mass hierarchy at large θ_{13}

θ_{13} by 2016

J. Valle TAUP'09



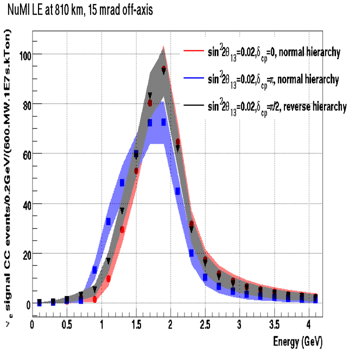
Measuring δ_{cp} and the Mass Hierarchy

Long baseline accelerator $\nu_\mu \rightarrow \nu_e$ appearance. 300 kT. MW. yr:

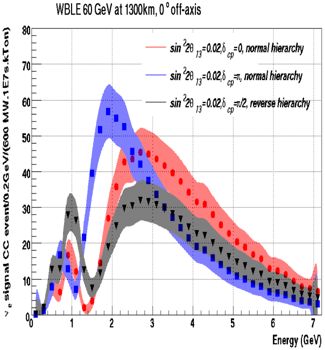
—- $\sin^2 2\theta_{13} = 0.02$, $\delta_{cp} = 0$, normal hierarchy

—- $\sin^2 2\theta_{13} = 0.02$, $\delta_{cp} = \pi$, normal hierarchy

—- $\sin^2 2\theta_{13} = 0.02$, $\delta_{cp} = -\pi/2$, reverse hierarchy



Off axis NuMI beam at 810 km

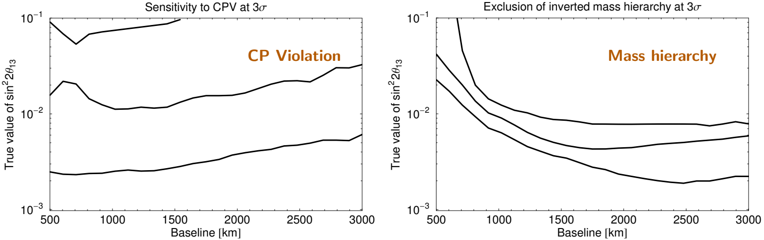


A wide-band beam at 1300km

Wide-band beam spectral information = resolves degeneracies

Physics sensitivity vs baseline

Using a broad-band beam with a peak interaction rate at 2 GeV, FWHM=3 GeV, a parameterized water Cerenkov detector and exposure of 5MW.yr (ν) + 10 MW.yr ($\bar{\nu}$) (V. Barger *et al.*. Phys. Rev. D 74, 073004 2006)**:**



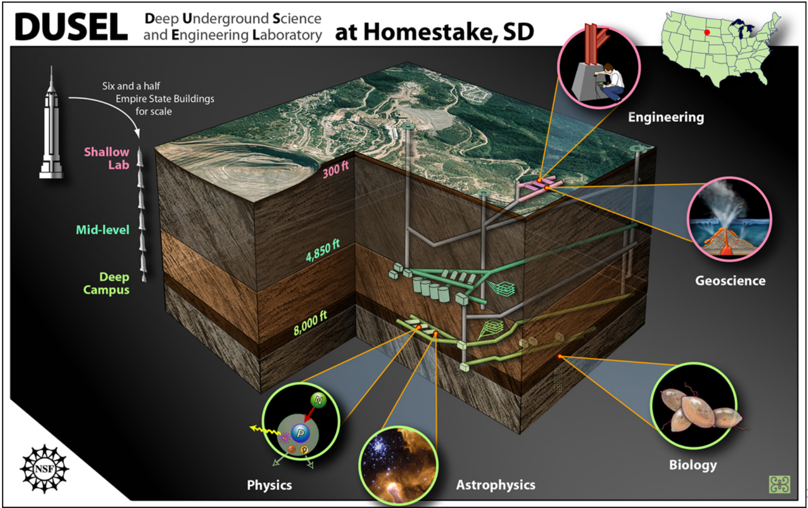
Minimum value of $\sin^2(2\theta_{13})$ for which the sensitivity is $> 3\sigma$ for (best,50%, worst) of δ_{cp} values

Longer baselines = larger mass effects

Best sensitivity is for baselines 1200 - 2500km

Deep Underground Science and Engineering Laboratory

July 10, 2007: the National Science Foundation (NSF) selected the University California-Berkeley to produce a techincal design for DUSEL at Homestake Mine, SD



DUSEL Timeline

J. Dehmer HEPAP Feb, 2009

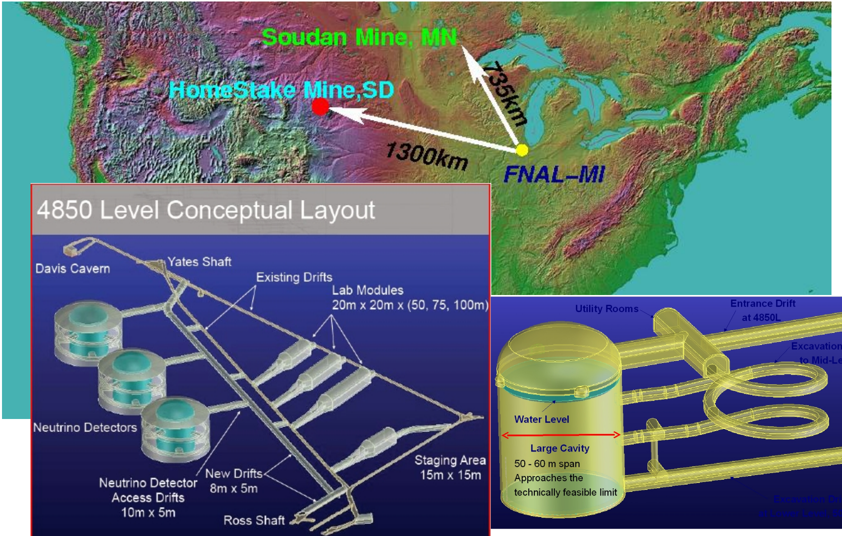
DUSEL Working Timeline

- July '08: Internal project review of facility & infrastructure.
- January '09: NSF Project Review #1.
- January '10: NSF Project Review #2.
- December '10: NSF Preliminary Design Review (PDR).
  - Project readiness, plan will be assessed at this milestone.
- Spring '11: Presentation of DUSEL MREFC package to NSB.
- FY13: Earliest construction funding (MREFC) start, if approved.

Planning with potential partners (DOE, international, etc.) being integrated into above schedule.

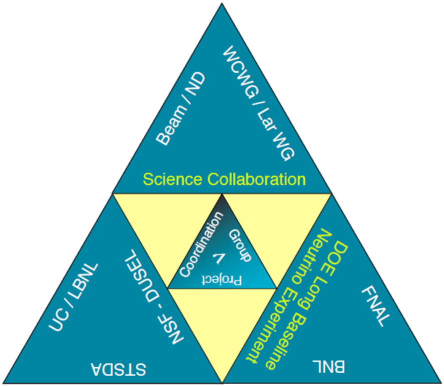
The Long Baseline Neutrino Experiment

A Long Baseline Neutrino Experiment (LBNE) from Fermilab to megaton scale detectors at Homestake is now being designed. CDR late 2010.



DUSEL-LBNE is supported by DOE and NSF

- Two DOE project offices have now been established to organize efforts and support university groups: FNAL LBNE Project Office and the BNL Detector Project Office.
- UC-Berkeley manages DUSEL (NSF) and oversees the efforts needed for DUSEL construction within NSF's MREFC Account.



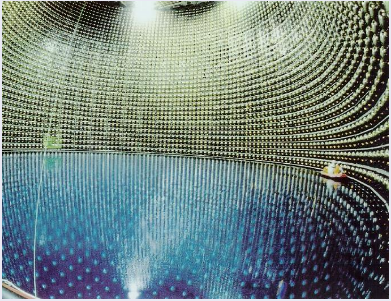
The LBNE Collaboration

Institutions: ANL, Boston, BNL, Caltech, UC Davis, UC Irvine, UCLA, Chicago, Colorado State, Columbia, Drexel, Duke, FNAL, Indiana, INFN(Catania), Kansas State, LANL, LLNL, LBL, LSU, Maryland, MIT, Minnesota, Minnesota (Duluth), Penn, Princeton, RPI, S. Carolina, Tennessee, Texas, Tufts, Wisconsin, Yale

Collaboration meeting 2/26-2/28, 2009 at UC Davis, CA

DUSEL Detectors

Water Cerenkov: 300kT

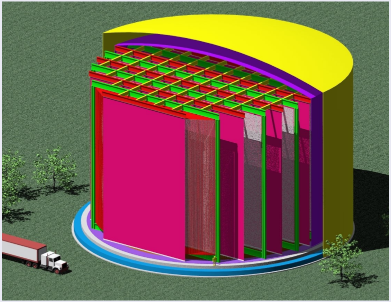


3 100kT models
≈ 55m diameter, ≈ 60m height
60K 10" PMTs/module (25% coverage)

Known technology 2 − 3× SuperK

Higher backgrounds, low efficiency

Liquid Argon TPC: 50kT



Small prototype in the NuMI beam. Hand scanning and prelim automated MC studies (Tufts U., Yale).

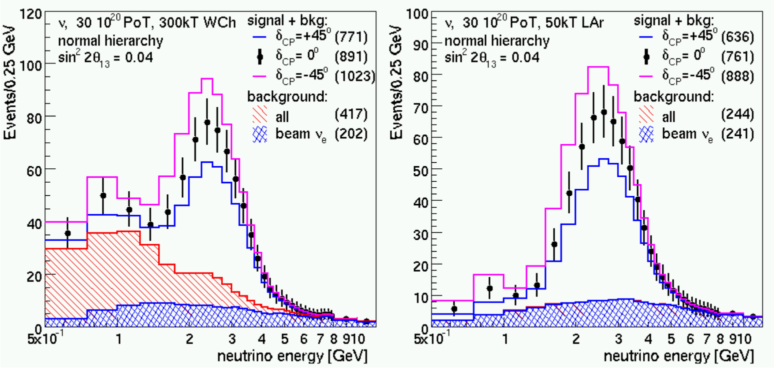
High efficiency and purity

Requires 100× scale-up - unproven.

DUSEL spectra

A preliminary on-axis wide-band beam for LBNE based on the NuMI focusing system has been developed. Water Cerenkov response is based on the SuperK MC. LAr is modeled as a near-perfect detector.

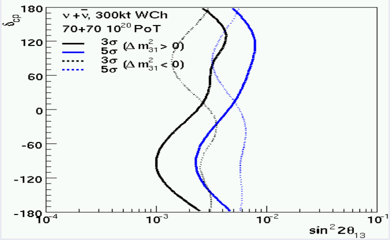
300 kT WCe, 3 yrs 1MW beam | **50 KT LAr, 3 yrs, 1MW beam**



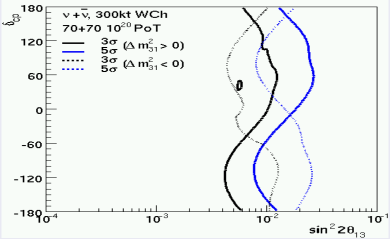
DUSEL Sensitivities

WCe, 2.3MW beam, 3 yrs ν + 3 yrs $\bar{\nu}$

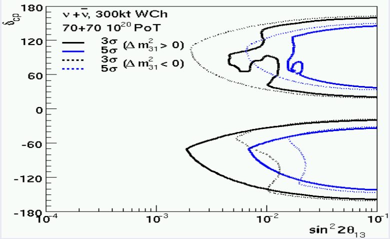
θ_{13} @ 3,5 σ



Mass hierarchy @ 3,5 σ



CP violation @ 3,5 σ



Summary of sensitivities

The smallest value of $\sin^2 2\theta_{13}$ @ 3σ:

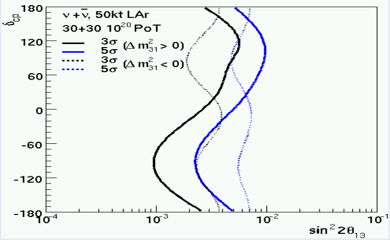
$\theta_{13} \neq 0$	sign(Δm^2) all δ_{cp}	CPV $50\%\delta_{cp}$
0.004	0.014	0.012

Mark Dierckxsens, APS 09

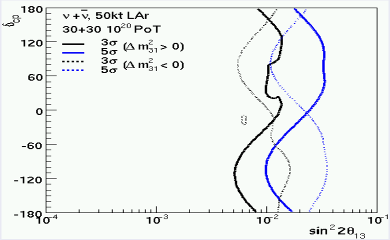
DUSEL Sensitivities

LAr, 2.3MW beam, 3 yrs ν + 3 yrs $\bar{\nu}$

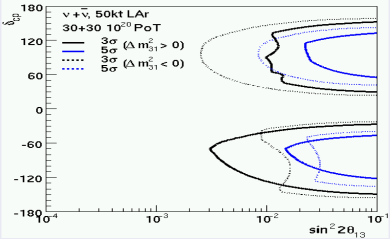
θ_{13} @ 3,5 σ



Mass hierarchy @ 3,5 σ



CP violation @ 3,5 σ



Summary of sensitivities

The smallest value of $\sin^2 2\theta_{13}$ @ 3σ:

$\theta_{13} \neq 0$	sign(Δm^2) all δ_{cp}	CPV 50% δ_{cp}
0.005	0.012	0.013

Mark Dierckxsens, APS 09

Summary and Conclusions

3 flavor neutrino mixing is now well established, but STRANGE. Large off diagonal terms and almost maximal mixing.

BUT- what we dont know is even more important:

- **How small is $\sin^2 2\theta_{13}$? Is it close to the current limit (0.1) or is it very small? Is it 0?**
- **Is there CP violation (and LFV) in the lepton sector?**
- **What is the mass hierarchy?**
- **Are there only 3 generations of leptons?**

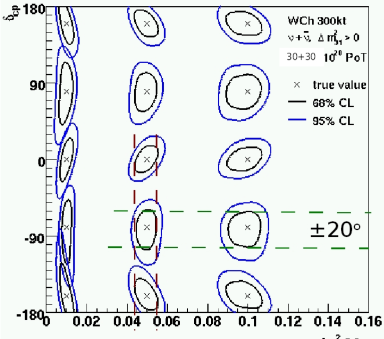
The next decade of reactor and conventional accelerator neutrino experiments will push the sensitivity limits of $\mathbf{\sin^2 2\theta_{13}}$ *to* $< \mathbf{0.005}$ *and can see evidence for CPV and the mass hierarchy down to* $\mathbf{\sin^2 2\theta_{13}}$ *of* $\mathbf{0.01}$.

TO BE CONTINUED: neutrino factories - see Steve Geer's talk!

EXTRA SLIDES FOR DISCUSSION

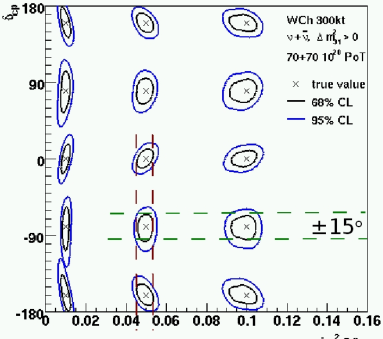
$(\theta_{13}, \delta_{cp})$ Measurement

1 MW



±10%

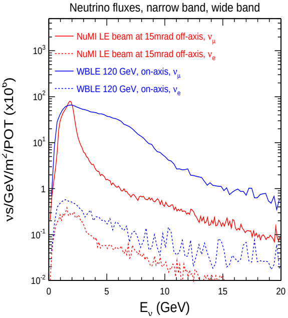
2.3 MW



±5%

Sensitivity vs Exposure

The potential physics reach from studies with the 120 GeV WBLE-DUSEL at 1300km using a LAr detector, the NOνA experiment and the T2KK experiment:*



From hep-ph/0703029: