Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

Summary

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

ACS 2009, Neutrino Symposium, Aug 16-18, Washington DC

Mary Bishai
Brookhaven National Laboratory

August 13, 2009

Outline

1 Neutrino mixing: A brief overview

2 CP violation and the mass hierarchy

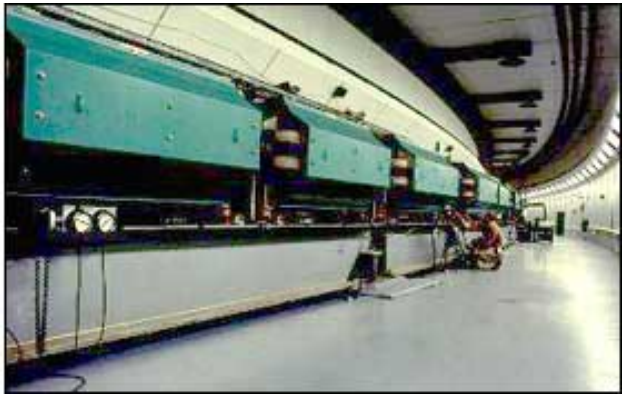
3 DUSEL and LBNE

4 Summary

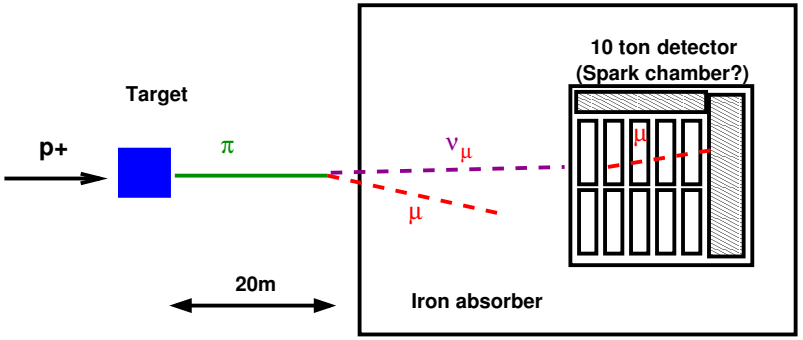
Neutrinos have flavors

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary

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

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

Summary

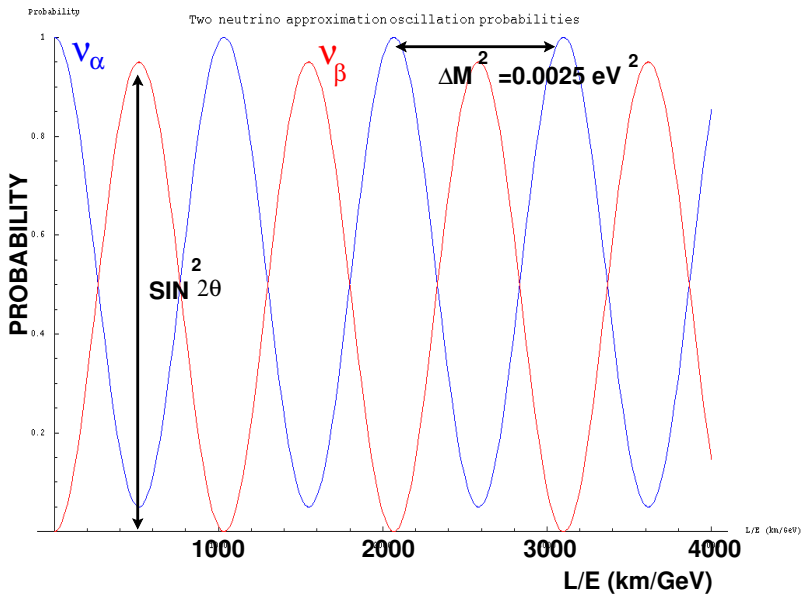
1957,1967: B. Pontecorvo proposes that neutrinos could oscillate:

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

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

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

where $\Delta m^2_{21} = (m_2^2 - m_1^2)$ in eV^2, L (km) and E (GeV).



If flavor eigenstates mix with mass eigenstates ⇒ neutrinos have mass

The Homestake Experiment

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary

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.

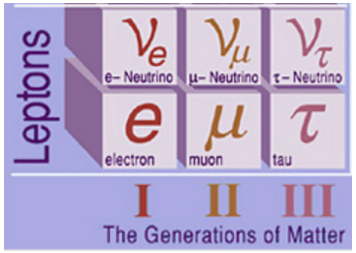
Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Solar ν_e and atmospheric ν_μ disappearance $\Rightarrow$ experimental proof of oscillations (R. Wendell's talk next)

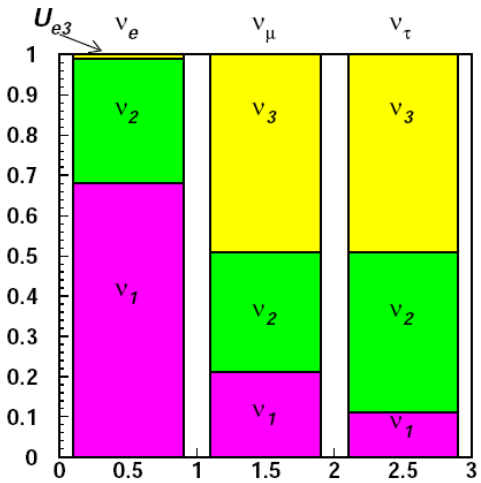
Neutrino Mixing: 3 flavours

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary

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

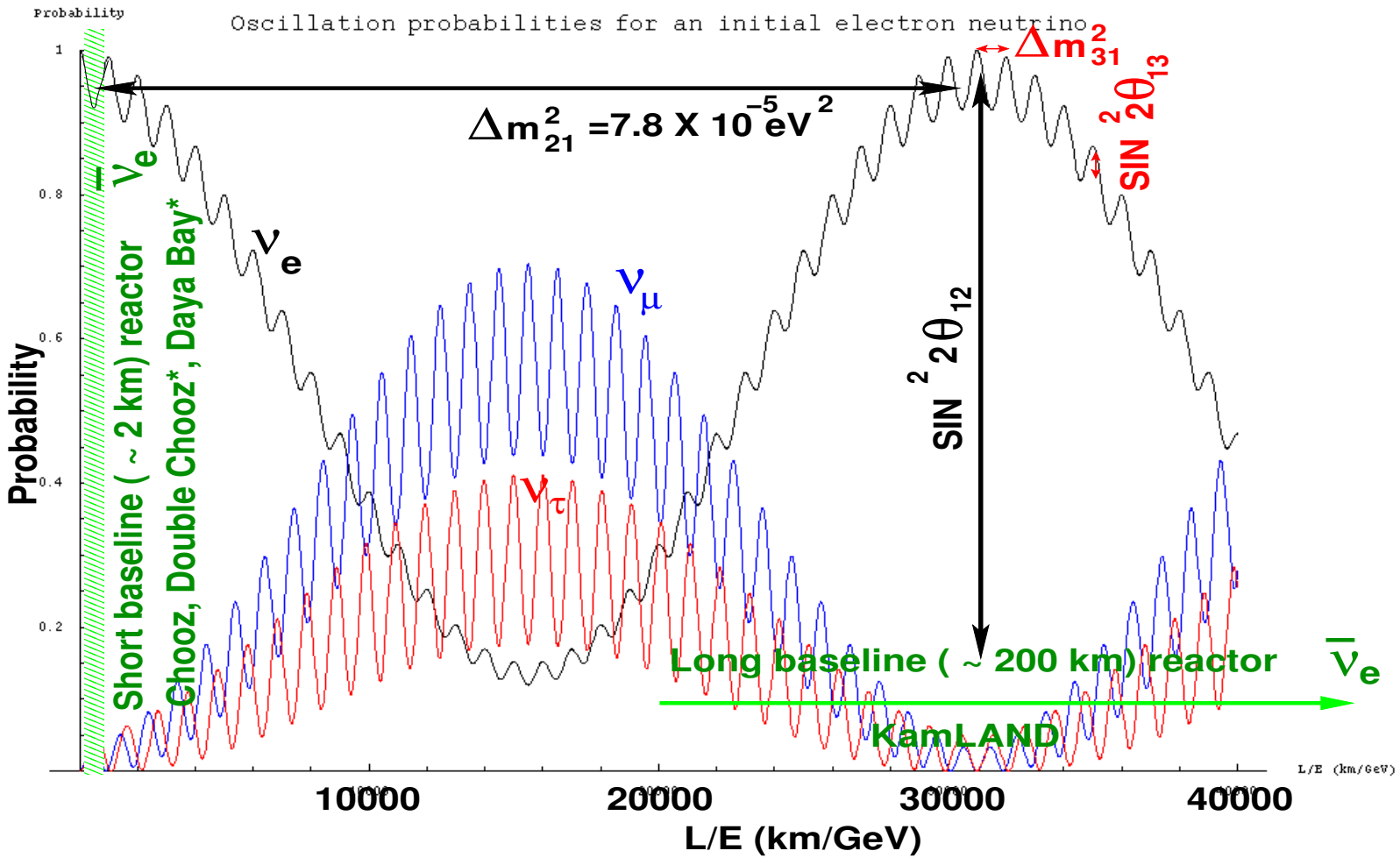
$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & < 0.20\ ?? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}, V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

In contrast to CKM, large off diagonal terms:

Measuring neutrino mixing - ν_e oscillations

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary

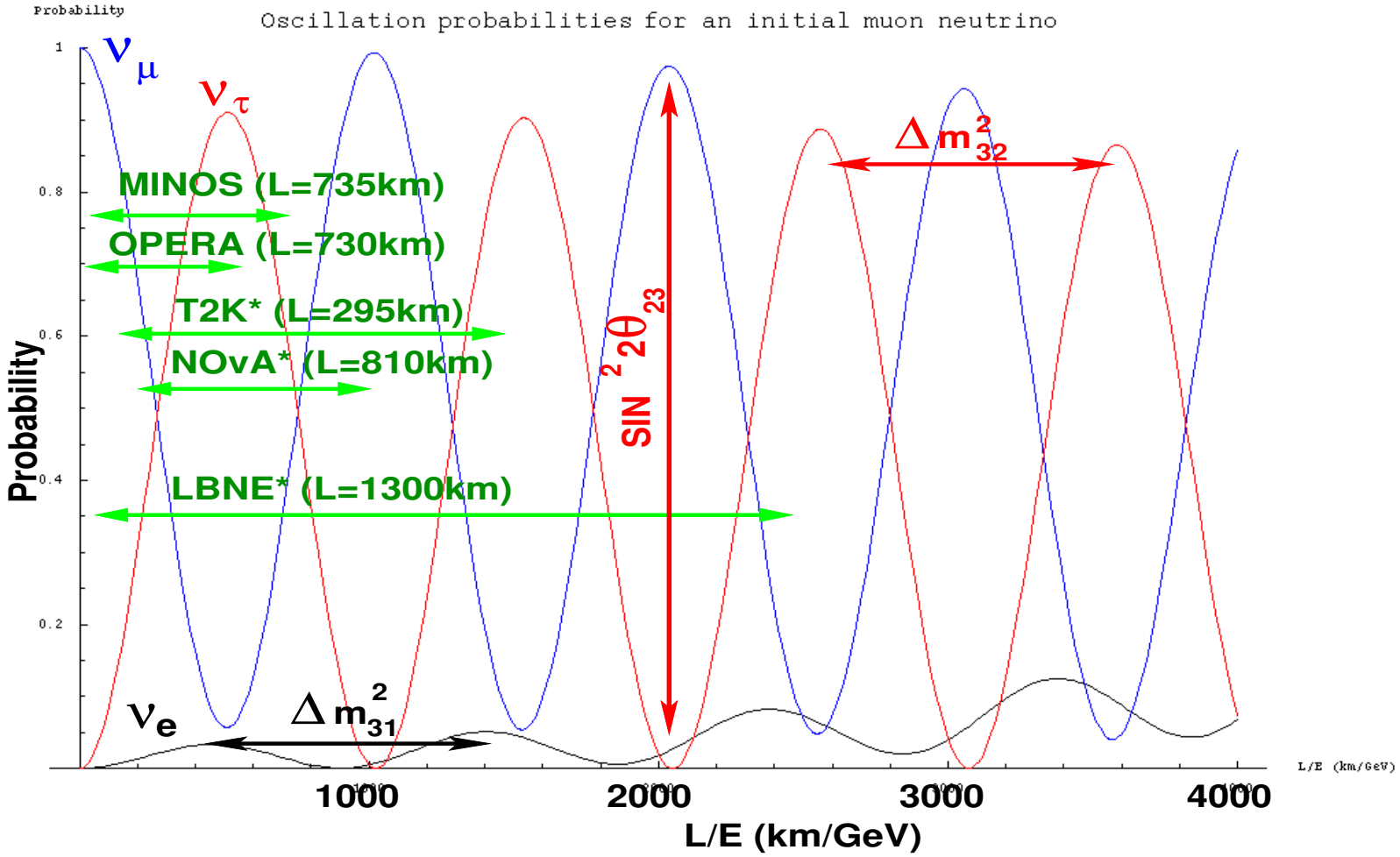
Solar ν_e disappearance constrained $1 \rightarrow 2$ mixing. Precision from reactor $\bar{\nu}_e$ experiments:



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

Measuring neutrino mixing - ν_μ oscillations

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary



* = future accelerator ν_μ experiments

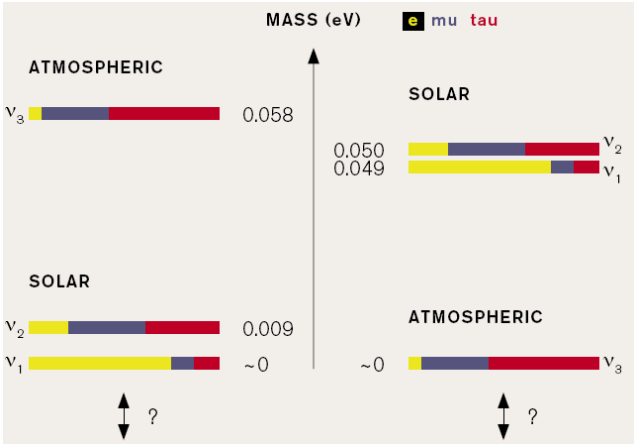
SuperK atmospheric ν_μ disappearance (L/E 3 $\rightarrow$ 30,000) probes 2 $\rightarrow$ 3 oscillations (talks by Yang, Raaf).

Neutrino Matrix Parameterization

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary

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

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

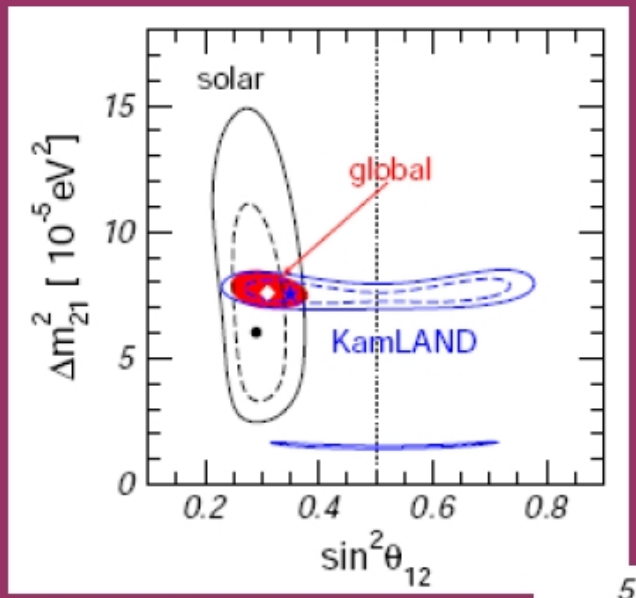
The mixing matrix - 2009

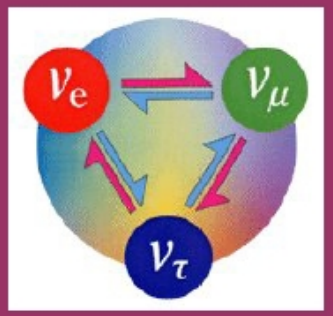
J. Valle, TAUP '09

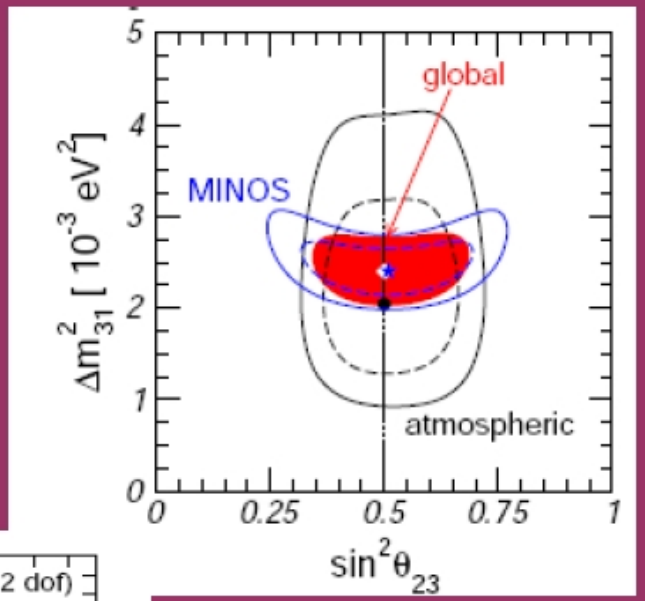
Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary

Maltoni et al, NJP 6 (2004) 122

Schwetz et al, NJP 10 (2008) 113011

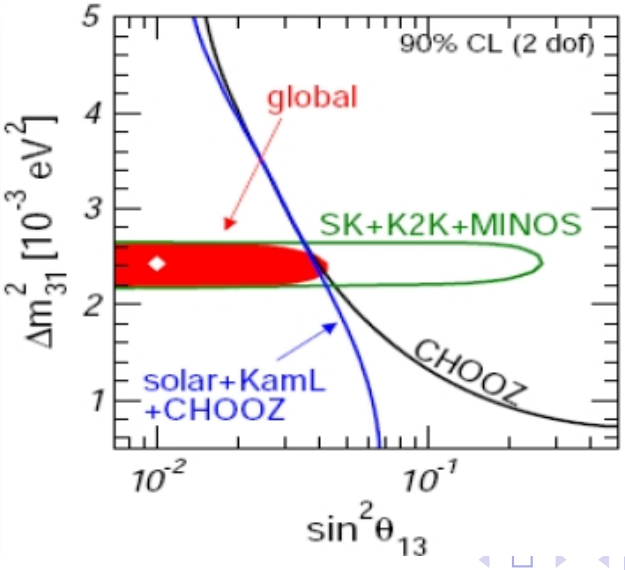






Homestake, SAGE+ GALLEX/GNO, Super-K, SNO
Borexino

KamLAND (180 Km)



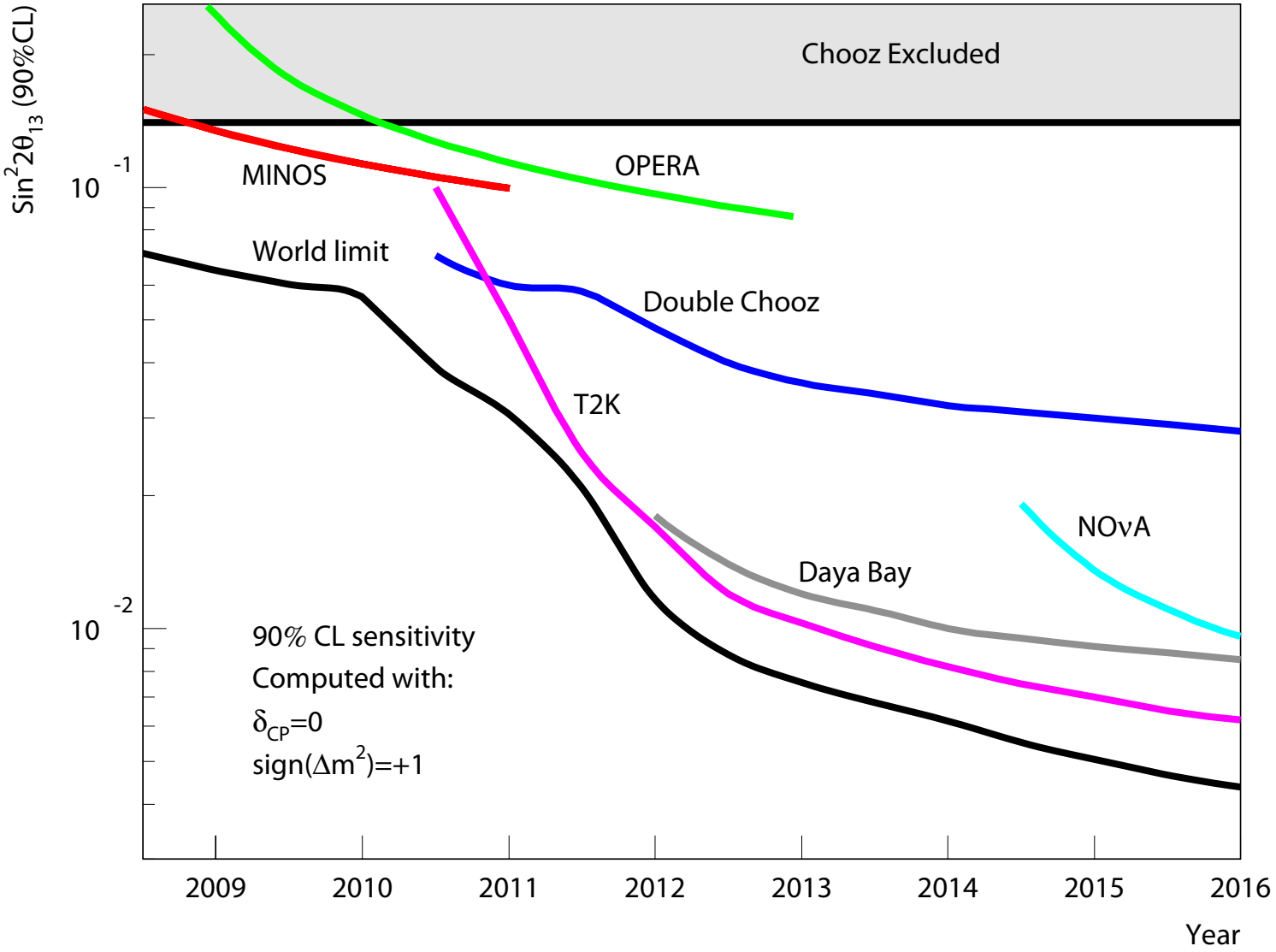
... Super-K

K2K (250 Km)
MINOS (735 Km)

θ_{13} by 2016

M. Mezzetto, arXiv:0905.2842

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary



CP Violation, Mass Hierarchy and $\nu_\mu \longrightarrow \nu_e$

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

Neutrino mixing: A brief overview

CP violation and the mass hierarchy

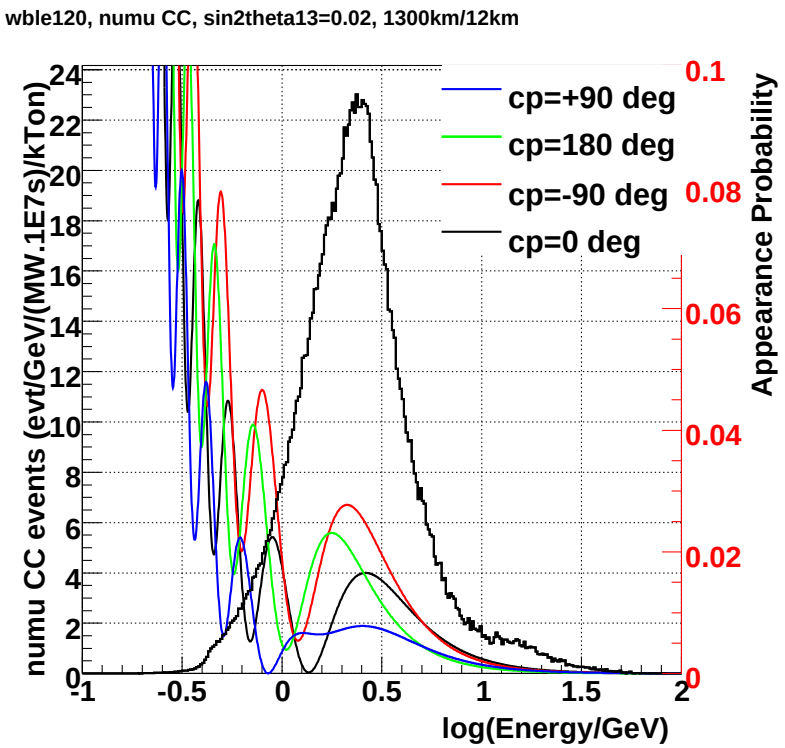
DUSEL and LBNE

Summary

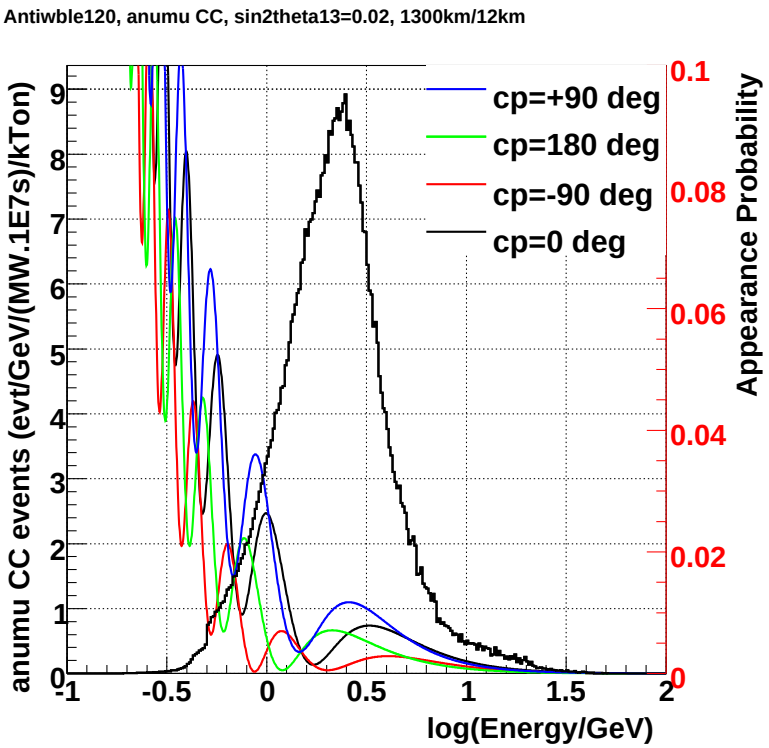
Appearance probabilities of $\nu_\mu \longrightarrow \nu_e$ for different values of the CP phase. A CP phase $\neq 0, \pi$ implies CP is violated in the lepton sector.

Normal Hierarchy

ν



$\bar{\nu}$



CP effects largest $E_\nu < 3$ GeV.

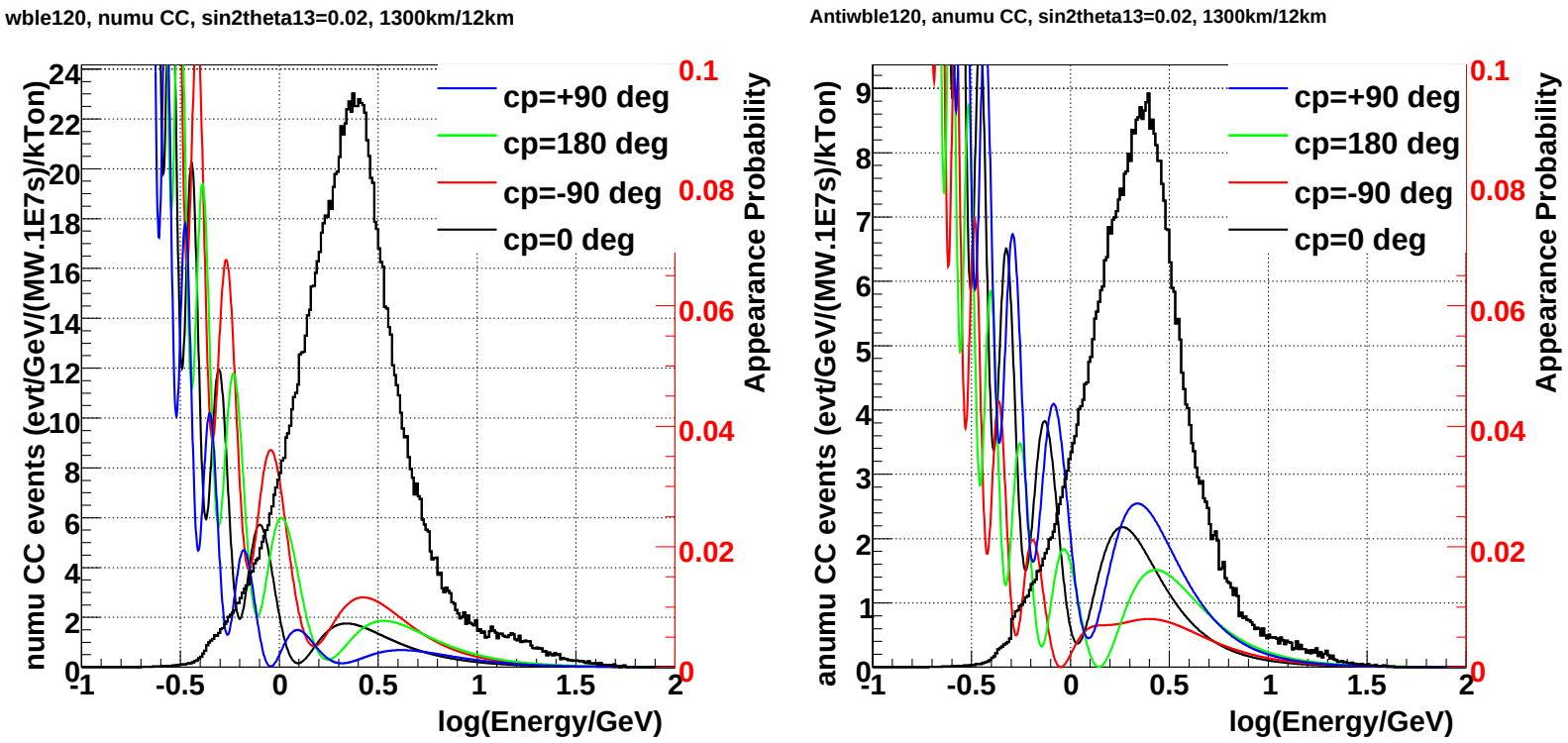
CP Violation, Mass Hierarchy and $\nu_\mu \longrightarrow \nu_e$

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL
Mary Bishai Brookhaven National Laboratory
Neutrino mixing: A brief overview
CP violation and the mass hierarchy
DUSEL and LBNE
Summary

Appearance probabilities of $\nu_\mu \longrightarrow \nu_e$ for different values of the CP phase. A CP phase $\neq 0, \pi$ implies CP is violated in the lepton sector.

Reversed Hierarchy

ν $\bar{\nu}$



Matter effects large $E_\nu > 1.5$ GeV.

Strategies for Measuring δ_{cp} and the Mass Hierarchy

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

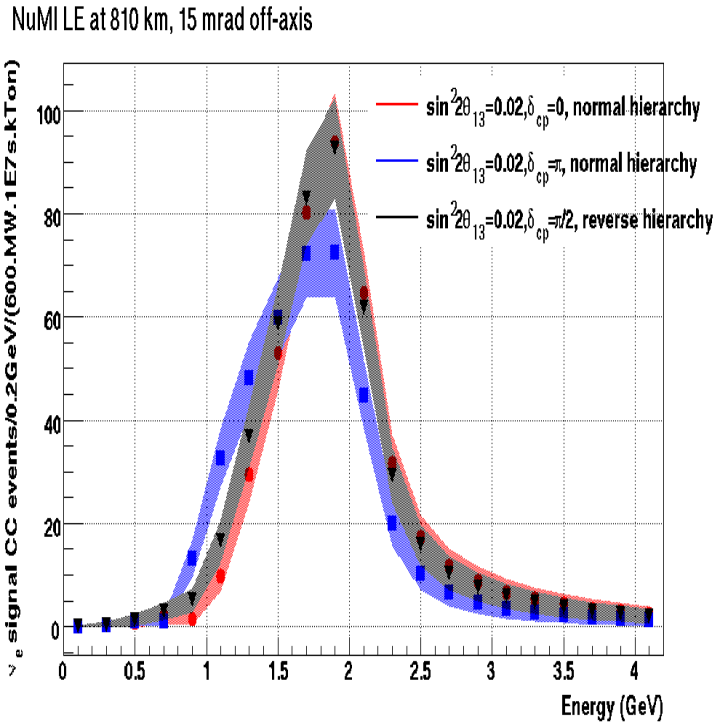
Summary

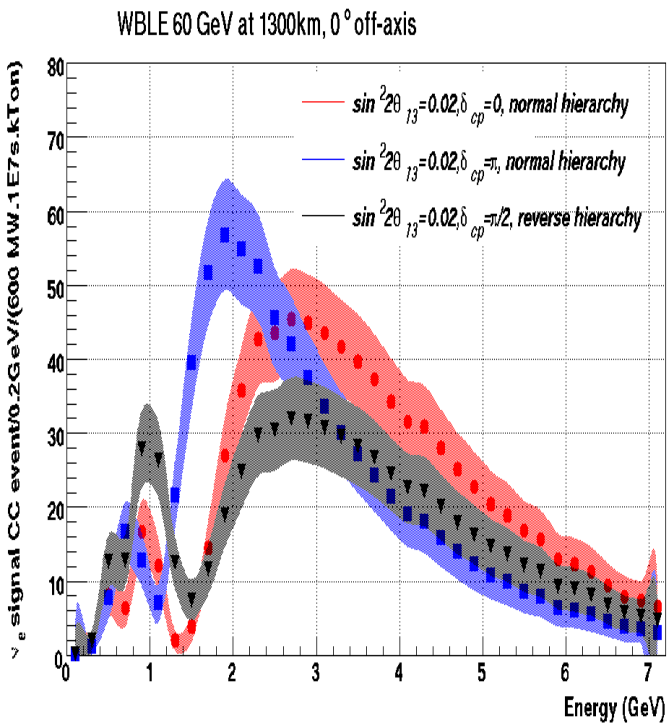
Long baseline accelerator $\nu_\mu \rightarrow \nu_e$ appearance. 300 kT. MW. yr:

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

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

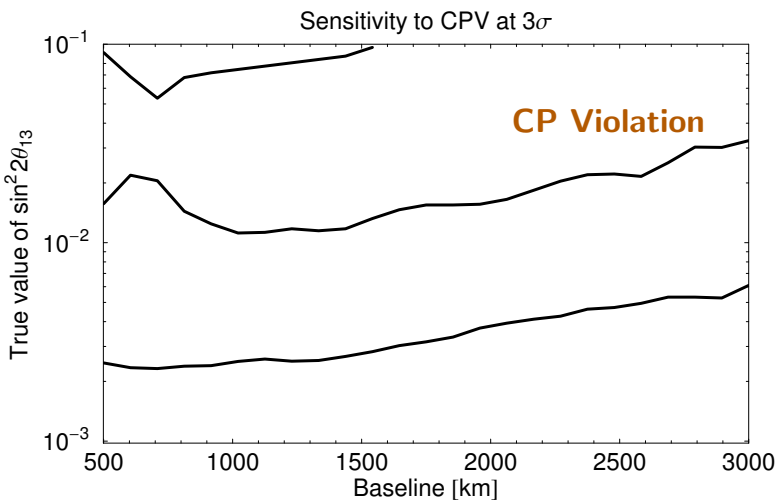
Neutrino mixing: A brief overview

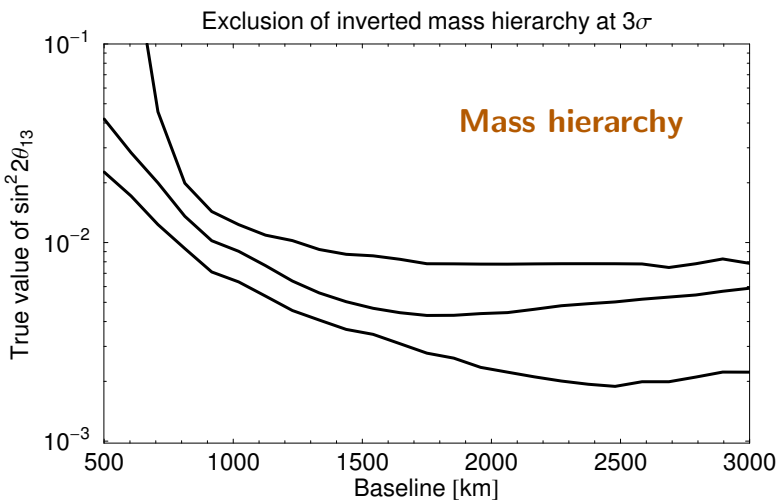
CP violation and the mass hierarchy

DUSEL and LBNE

Summary

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

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

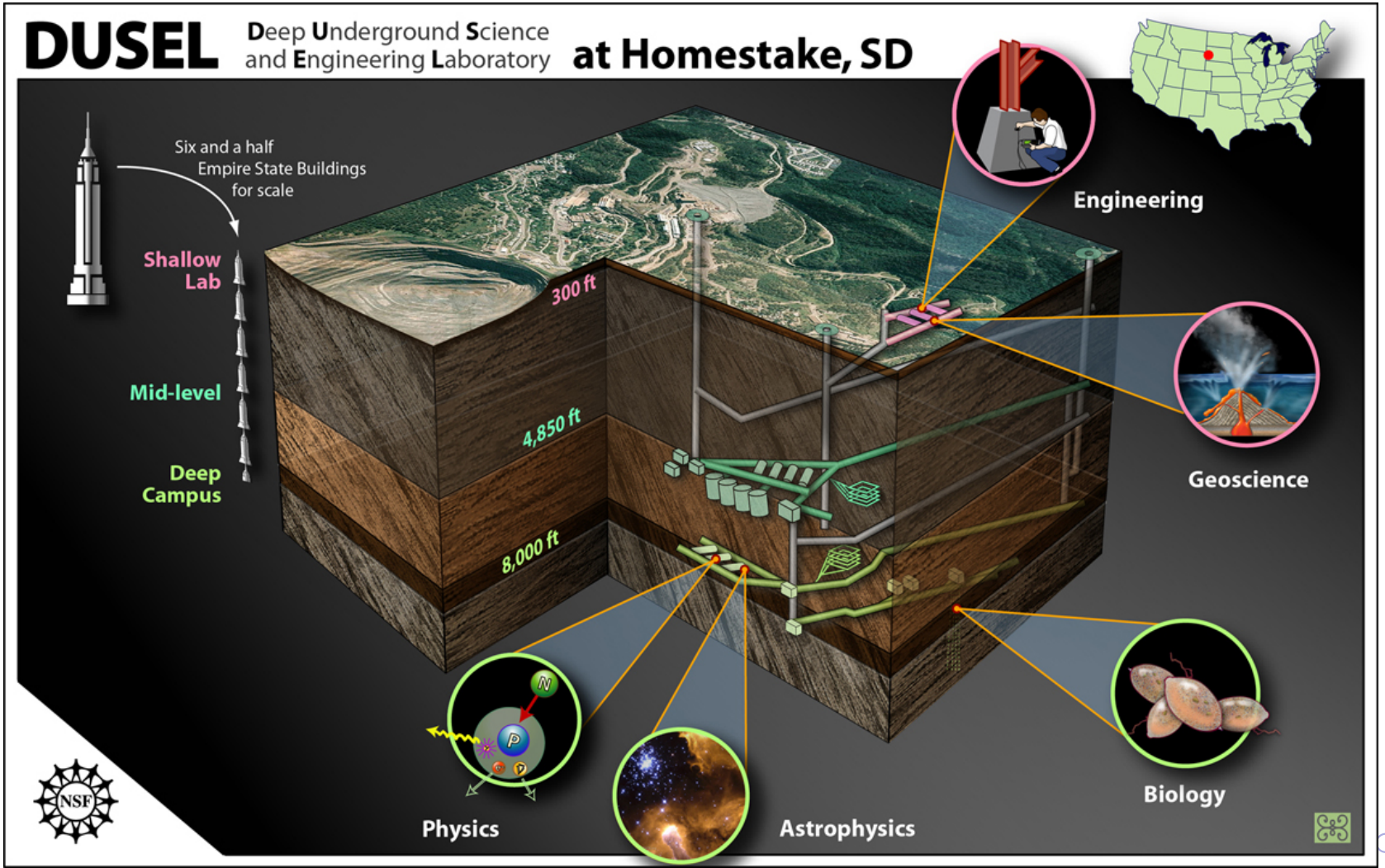
Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

Summary

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

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

Summary

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 Fermilab NuMI Beamline

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

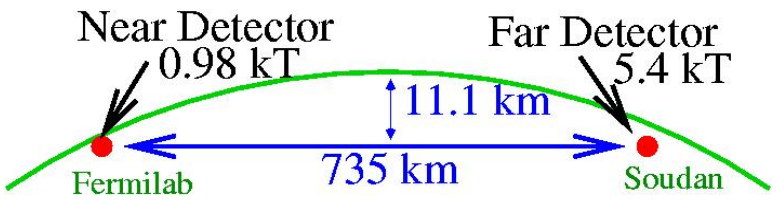
Mary Bishai Brookhaven National Laboratory

Neutrino mixing: A brief overview

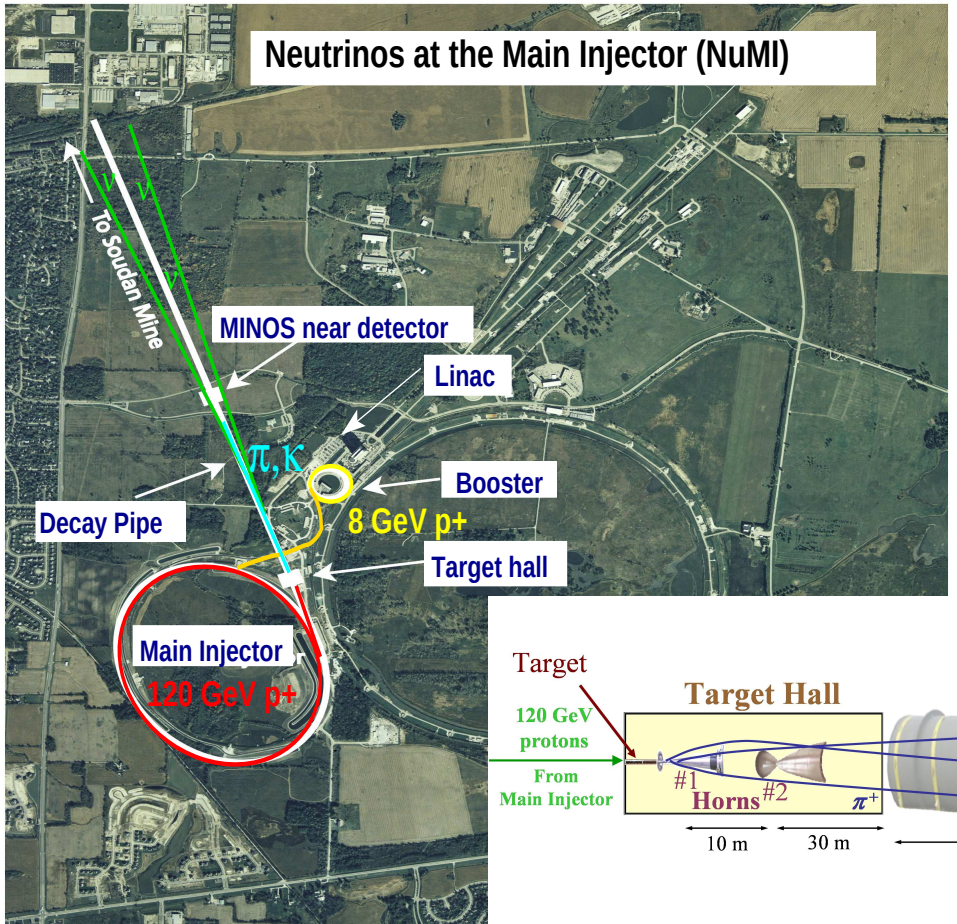
CP violation and the mass hierarchy

DUSEL and LBNE

Summary

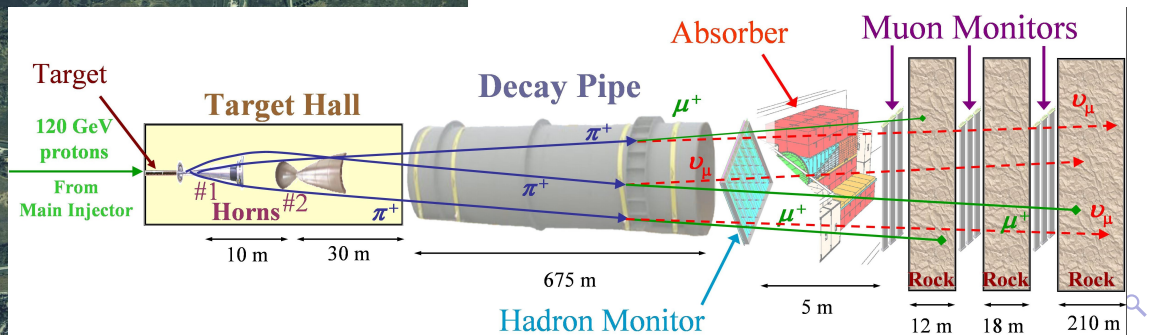


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**



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

3T at 200 kA



Fermilab Neutrino Beams: Future

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

Neutrino mixing: A brief overview

CP violation and the mass hierarchy

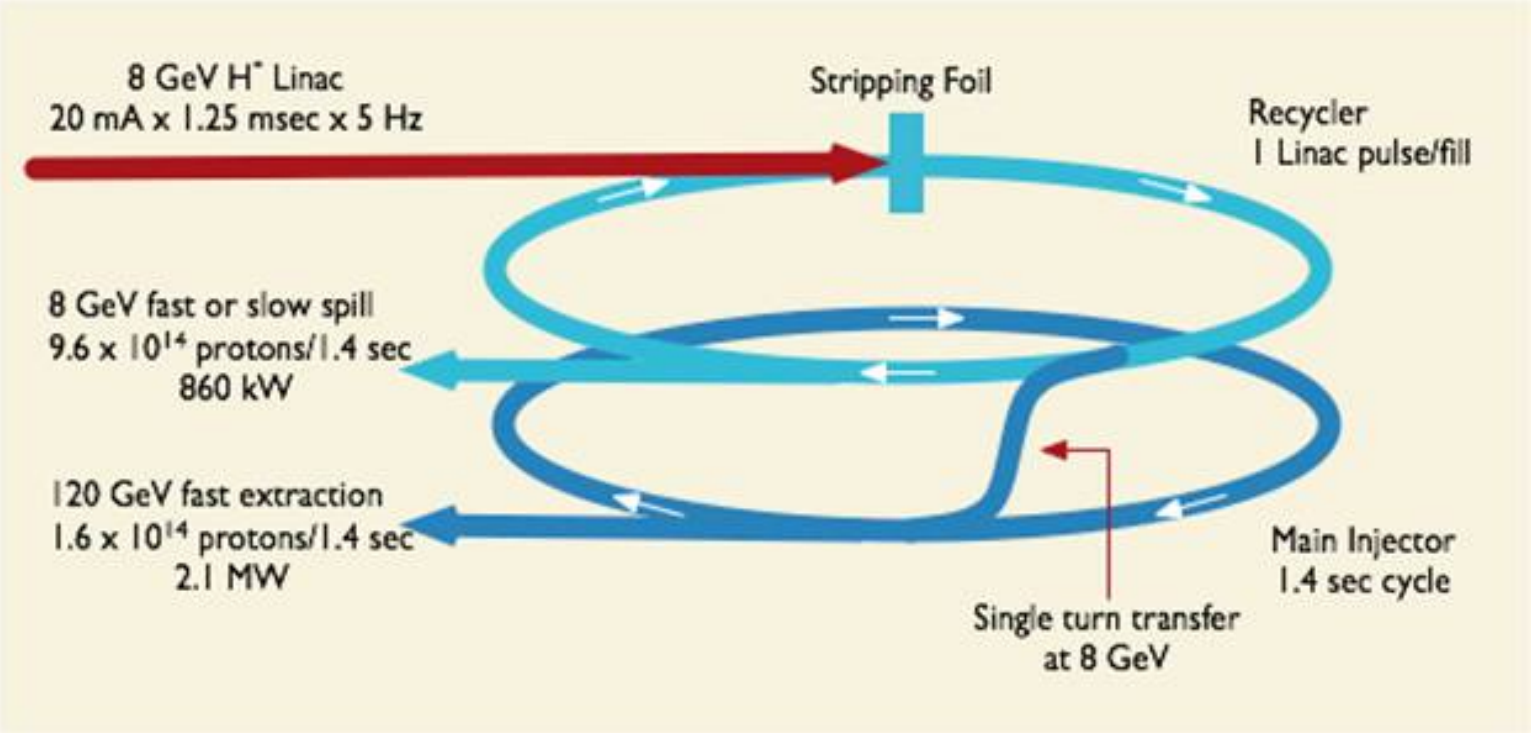
DUSEL and LBNE

Summary

The NuMI beamline currently uses 300kW sustained power from the Main Injector.

NuMI is the most powerful neutrino beamline in operation today .

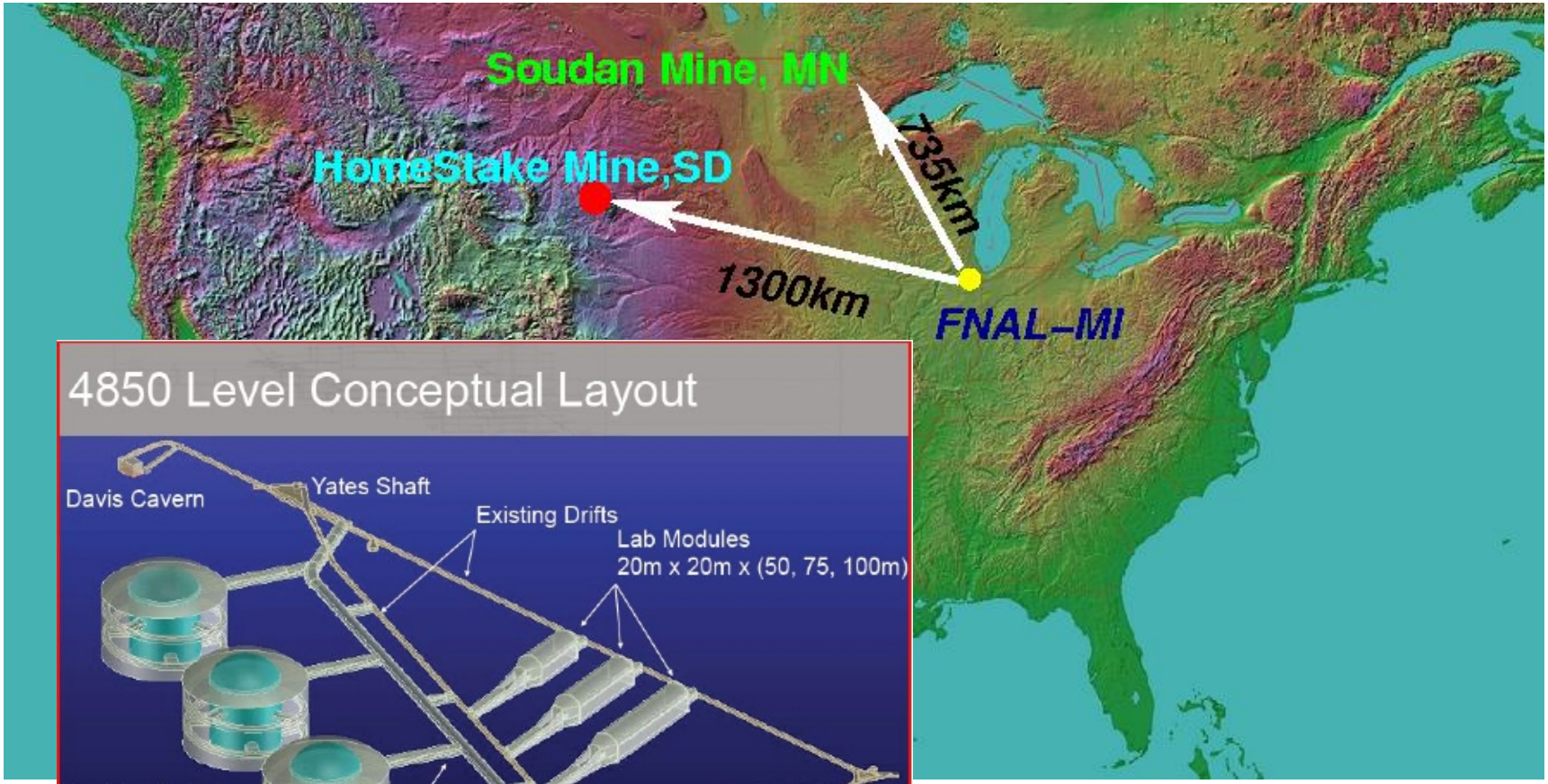
Planned upgrades to NuMI and the Main Injector → 700 kW by 2012.

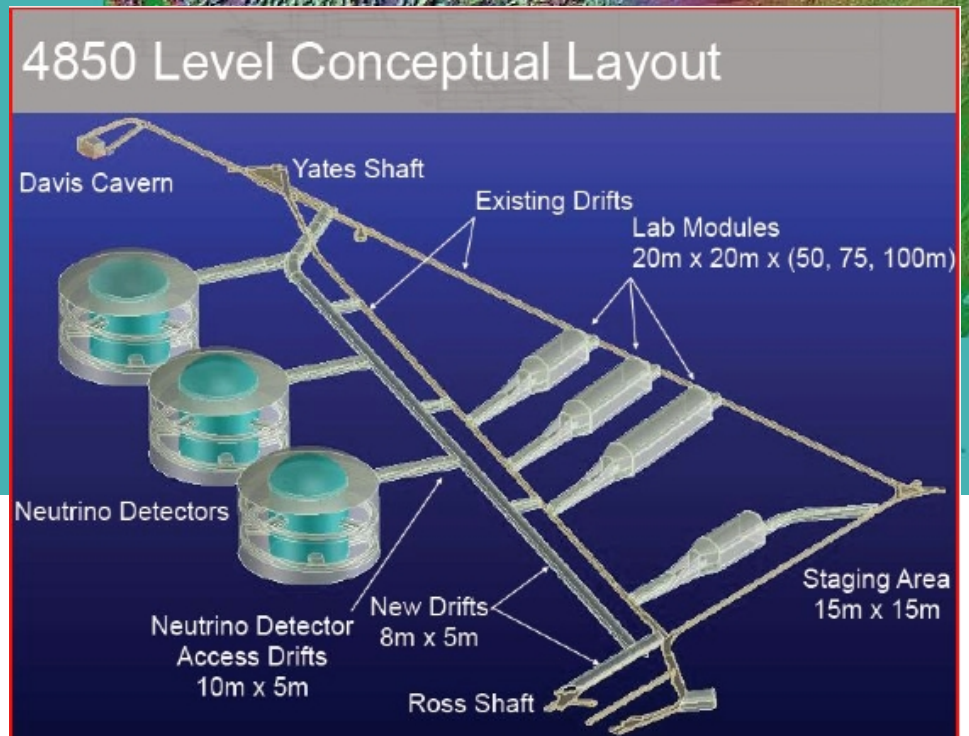


The proposed Project X at FNAL can produce 2MW

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.





The LBNE Collaboration

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

Summary

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

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

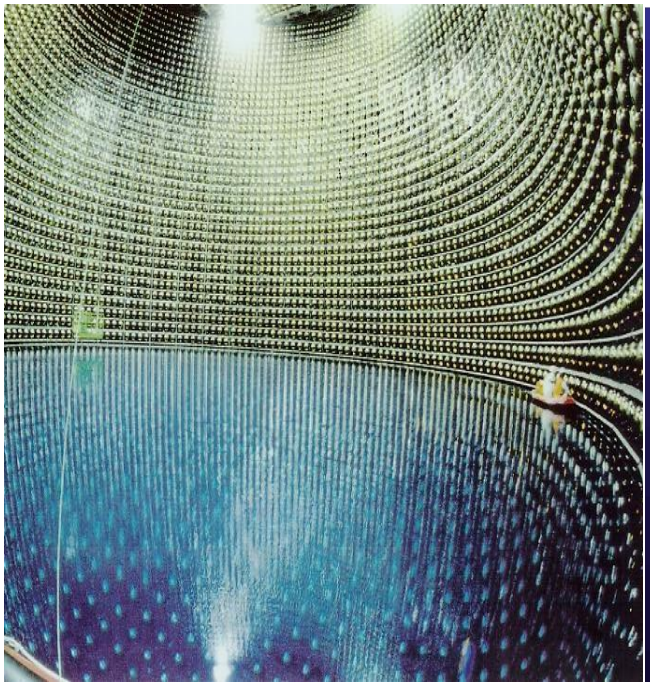
Neutrino mixing: A brief overview

CP violation and the mass hierarchy

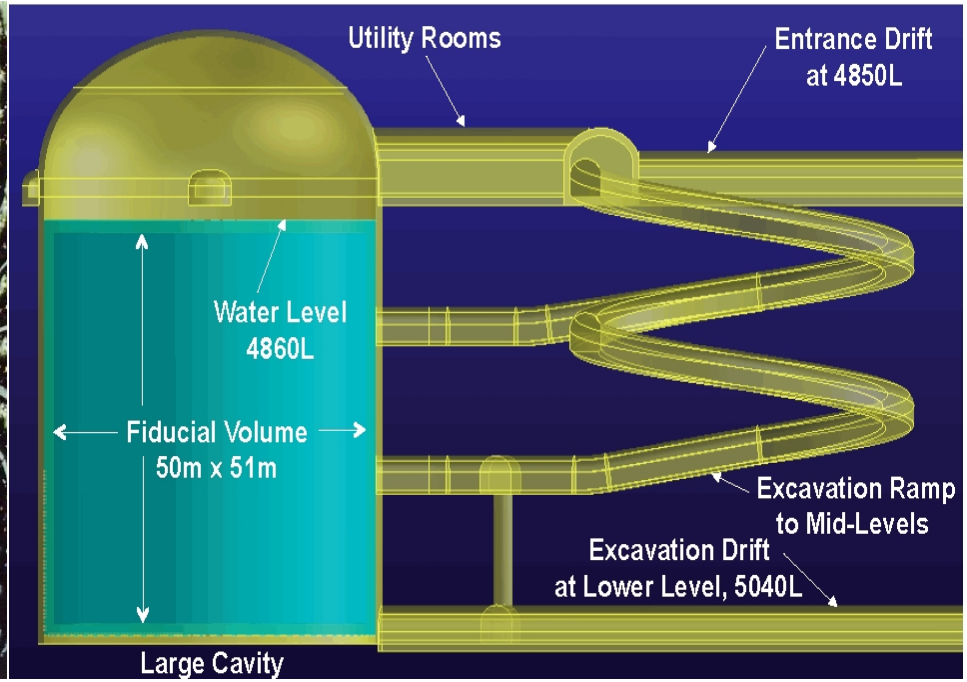
DUSEL and LBNE

Summary

SuperKamiokande : 50kT



DUSEL WCe Module : 120 kT



3 100kT (fiducial) modules, $\approx$ 55m diameter, $\approx$ 60m height, 60K 10" PMTs/module (25% coverage)

Known technology $2-3\times$ SuperK

Higher backgrounds, low efficiency

DUSEL Detectors: Liquid Argon TPC

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

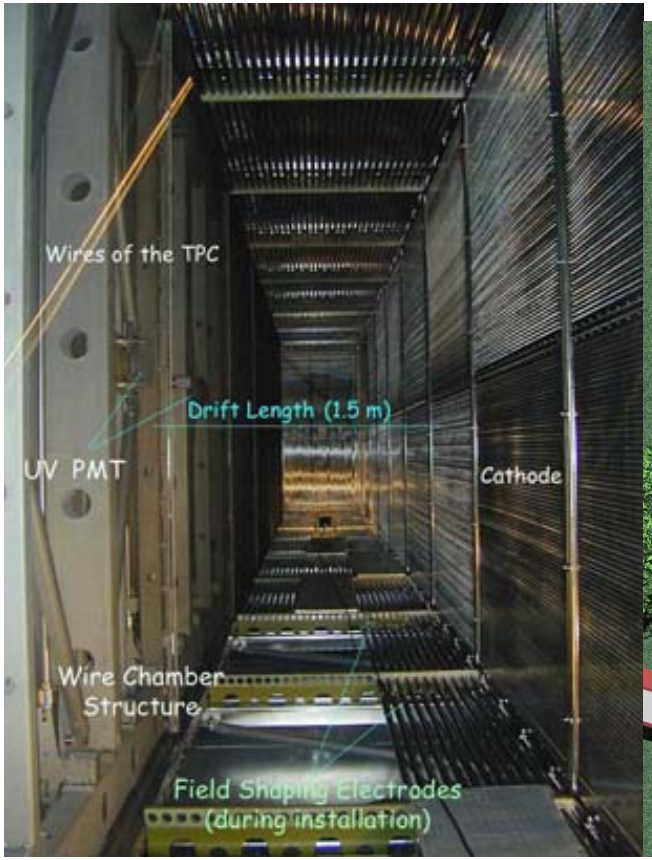
Neutrino mixing: A brief overview

CP violation and the mass hierarchy

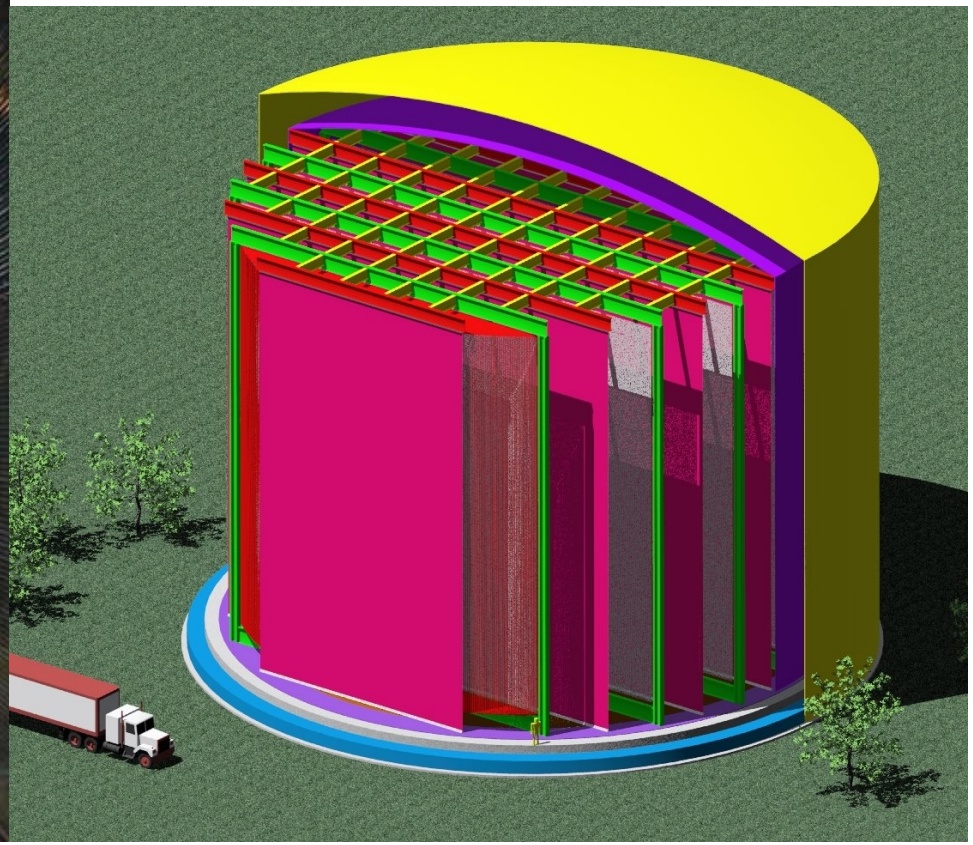
DUSEL and LBNE

Summary

ICARUS module : 0.3kT



DUSEL LAr : 50 kT



Small 175 litre prototype in the NuMI beam. Hand scanning and prelim automated MC studies (Tufts U., Yale)

High efficiency and purity

Requires 100× scale-up - unproven.

LBNE/DUSEL spectra

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

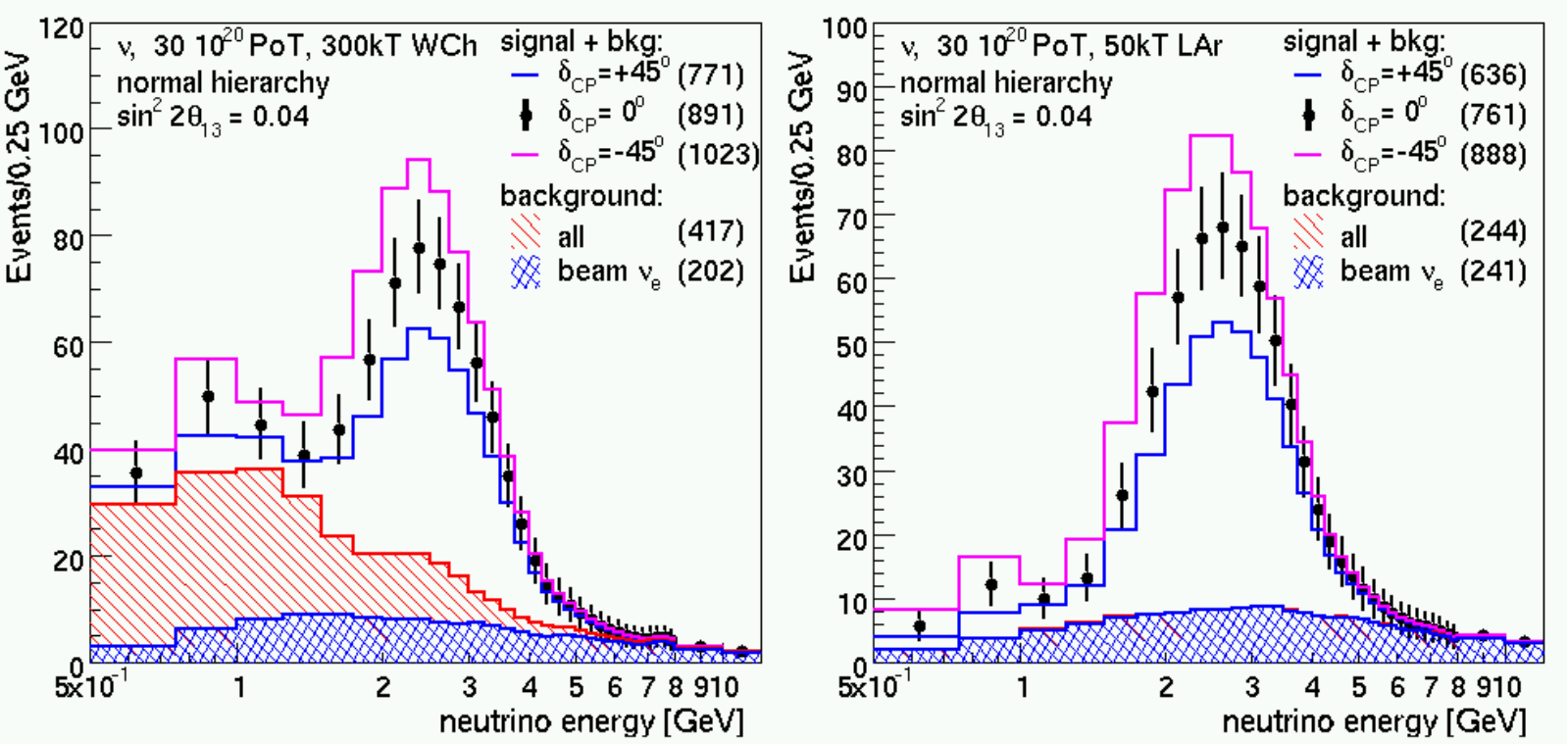
Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

Summary

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.



Measurements of δ_{cp} in LBNE

Mark Dierckxsens

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

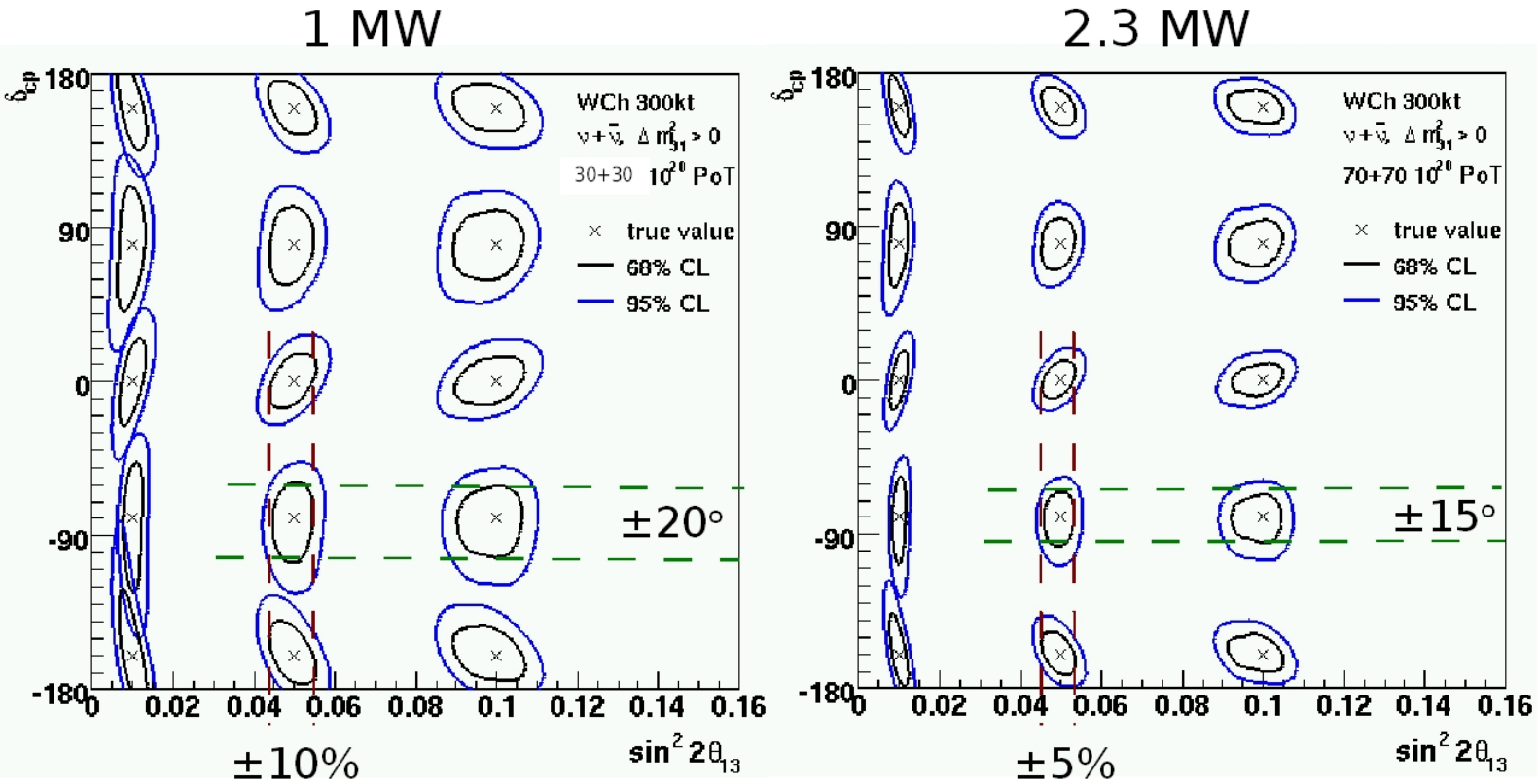
Neutrino mixing: A brief overview

CP violation and the mass hierarchy

DUSEL and LBNE

Summary

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



DUSEL Sensitivities

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

Future Neutrino Physics Prospects Using Massive Detectors at DUSEL

Mary Bishai Brookhaven National Laboratory

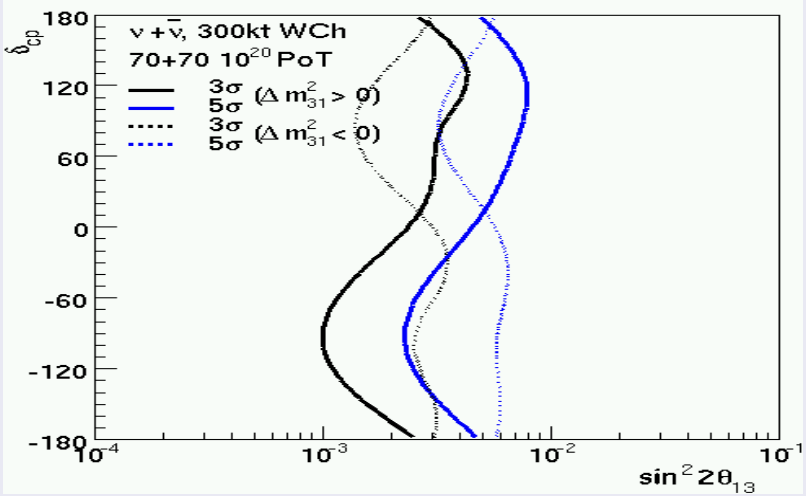
Neutrino mixing: A brief overview

CP violation and the mass hierarchy

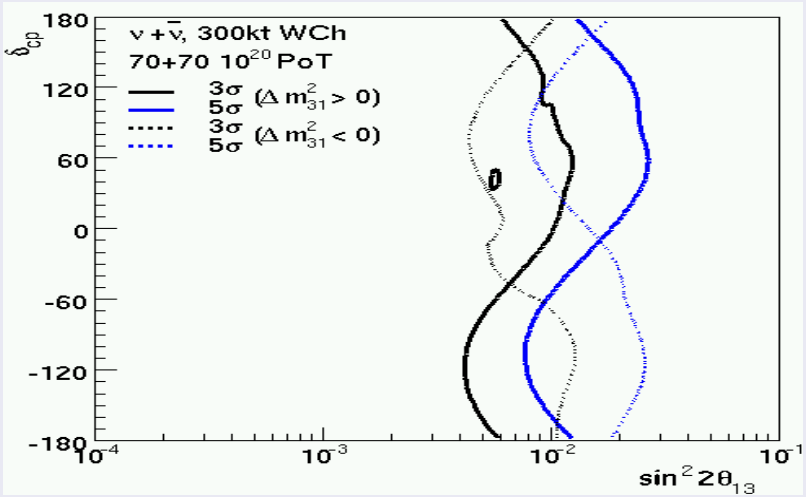
DUSEL and LBNE

Summary

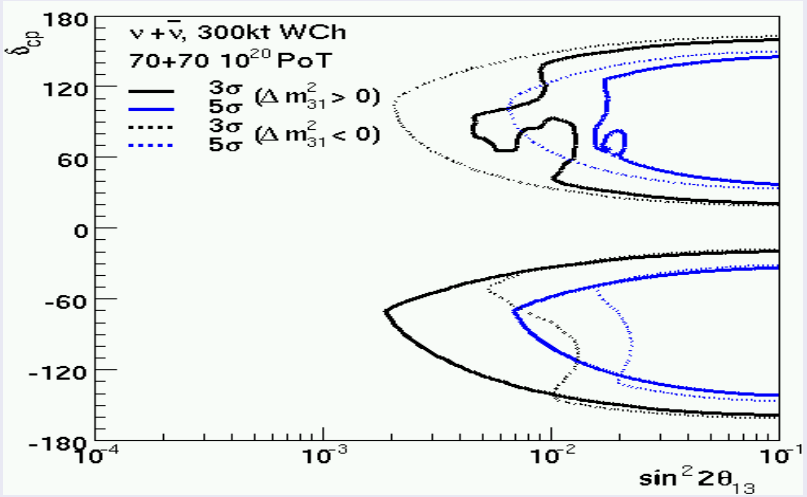
θ_{13} @ 3,5 σ



Mass hierarchy @ 3,5 σ



CP violation @ 3,5 σ



Summary of sensitivities

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

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

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 LBNE project will determine if $\sin^2 2\theta_{13} > 0.005$ *and can measure* δ_{cp} *and the mass hierarchy for* $\sin^2 2\theta_{13} \geq 0.01$.

There is a goldmine of scientific discoveries at the end of this rainbow