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Neutrino mixing matrix 2009

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DUSEL and LBNE

Summary

Neutrino Oscillations: Beams and Reactors

BUE CTP Seminar, Cairo, Sept 15, 2009

Mary Bishai
Brookhaven National Laboratory

September 14, 2009

Outline

1 Neutrino mixing: A brief overview

2 Neutrino mixing matrix 2009

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Neutrinos first detected with reactors

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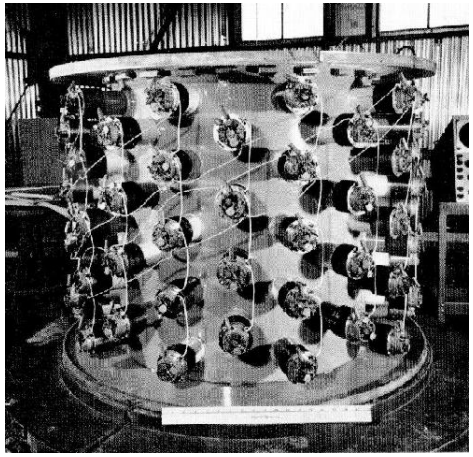
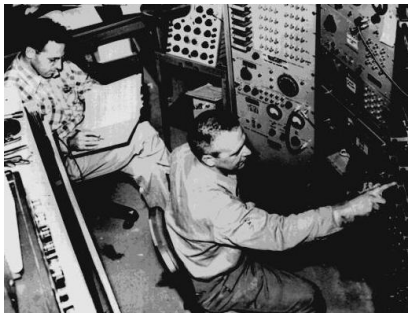
1950's: Fred Reines at Los Alamos and Clyde Cowan mounted an experiment at the Hanford nuclear reactor in 1953 and in 1955 at the new Savannah River nuclear reactor. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV + T_e^+)
3. $n + {}^{108}Cd \rightarrow {}^{109}Cd* \rightarrow {}^{109}Cd + \gamma$ ($\tau = 5\mu s$).



Neutrinos first detected from a reactor!

Neutrinos have flavors

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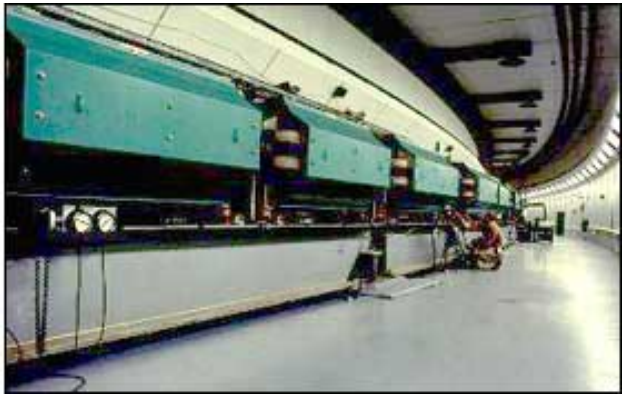
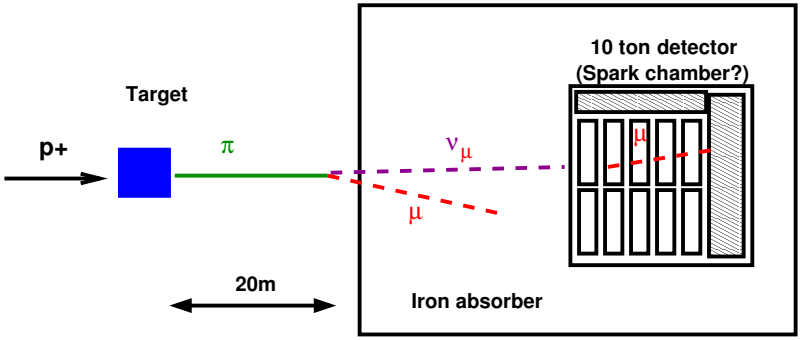
1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi^+ \longrightarrow \mu^+ \nu_x$



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

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

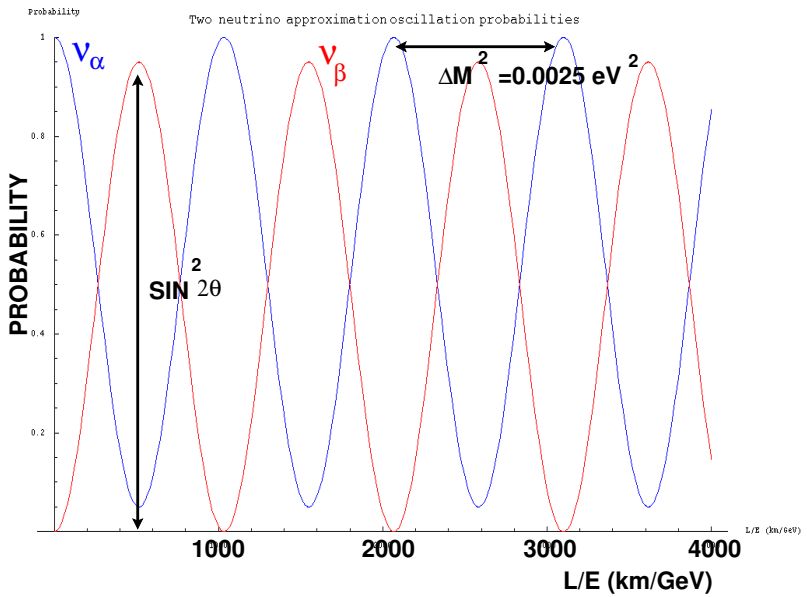
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

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

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

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 $\Rightarrow$ neutrinos have mass



The Homestake Experiment

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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

Neutrino Mixing: 3 flavours

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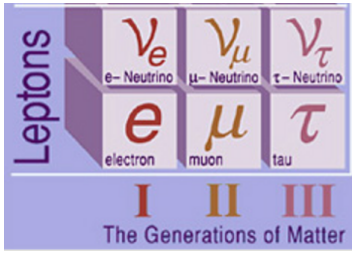
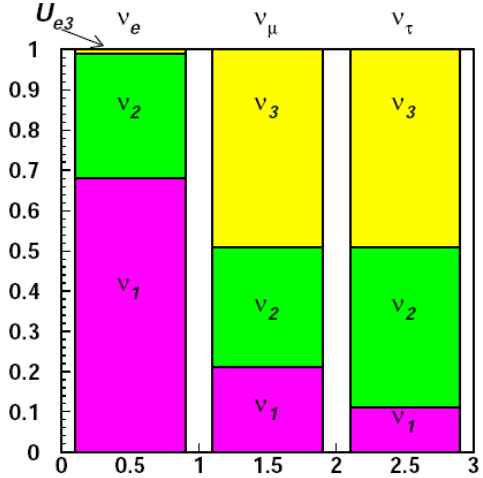
We know now of 3 flavours of neutrinos: The 3 flavour PMNS mixing matrix was developed in 1962 by Maki-Nakagawa-Sakata based on Pontecorvo's earlier work:



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



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

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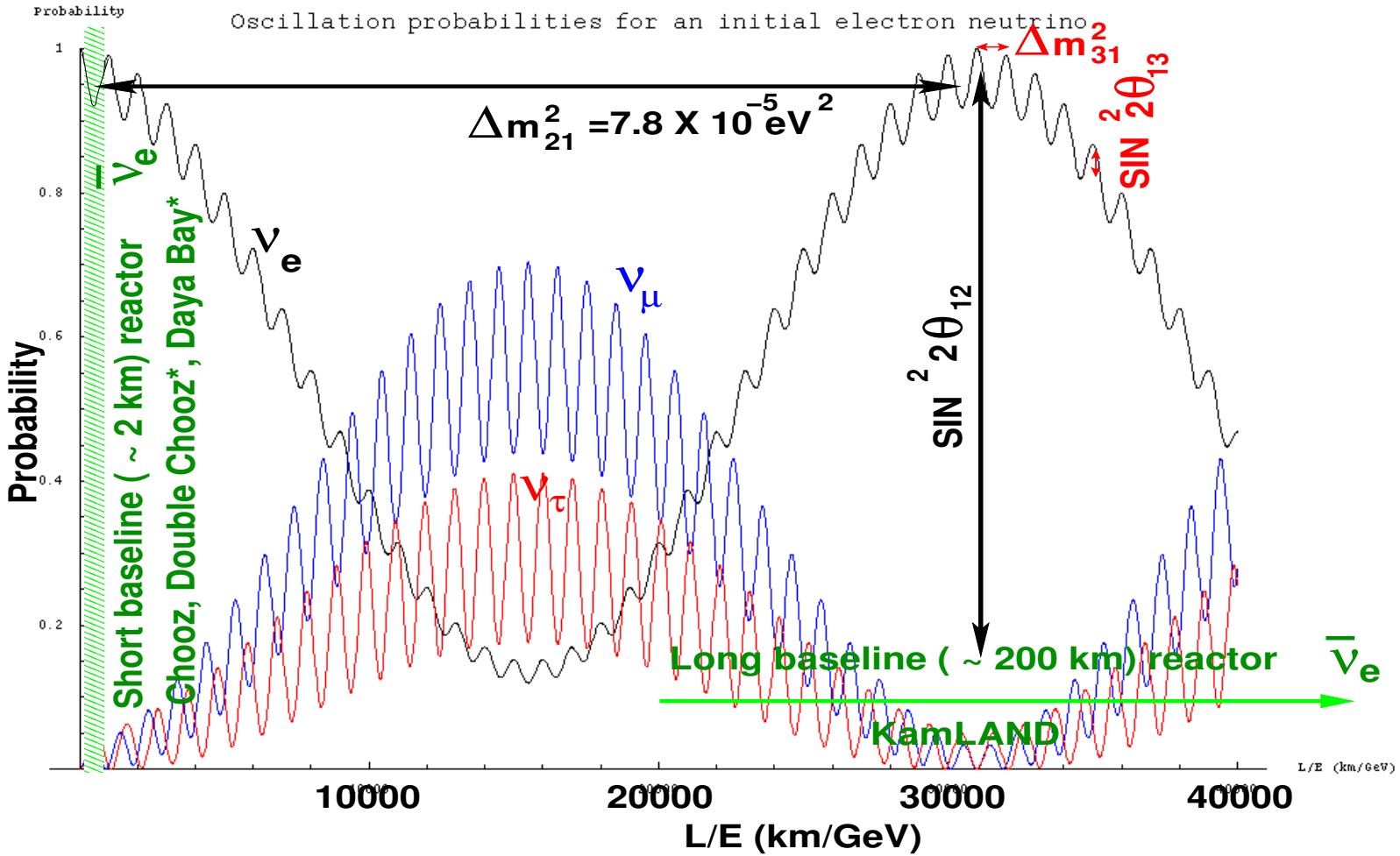
Solar ν_e disappearance constrained $1 \rightarrow 2$ mixing. Precision from reactor $\bar{\nu}_e$ experiments:



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

Measuring neutrino mixing - ν_μ oscillations

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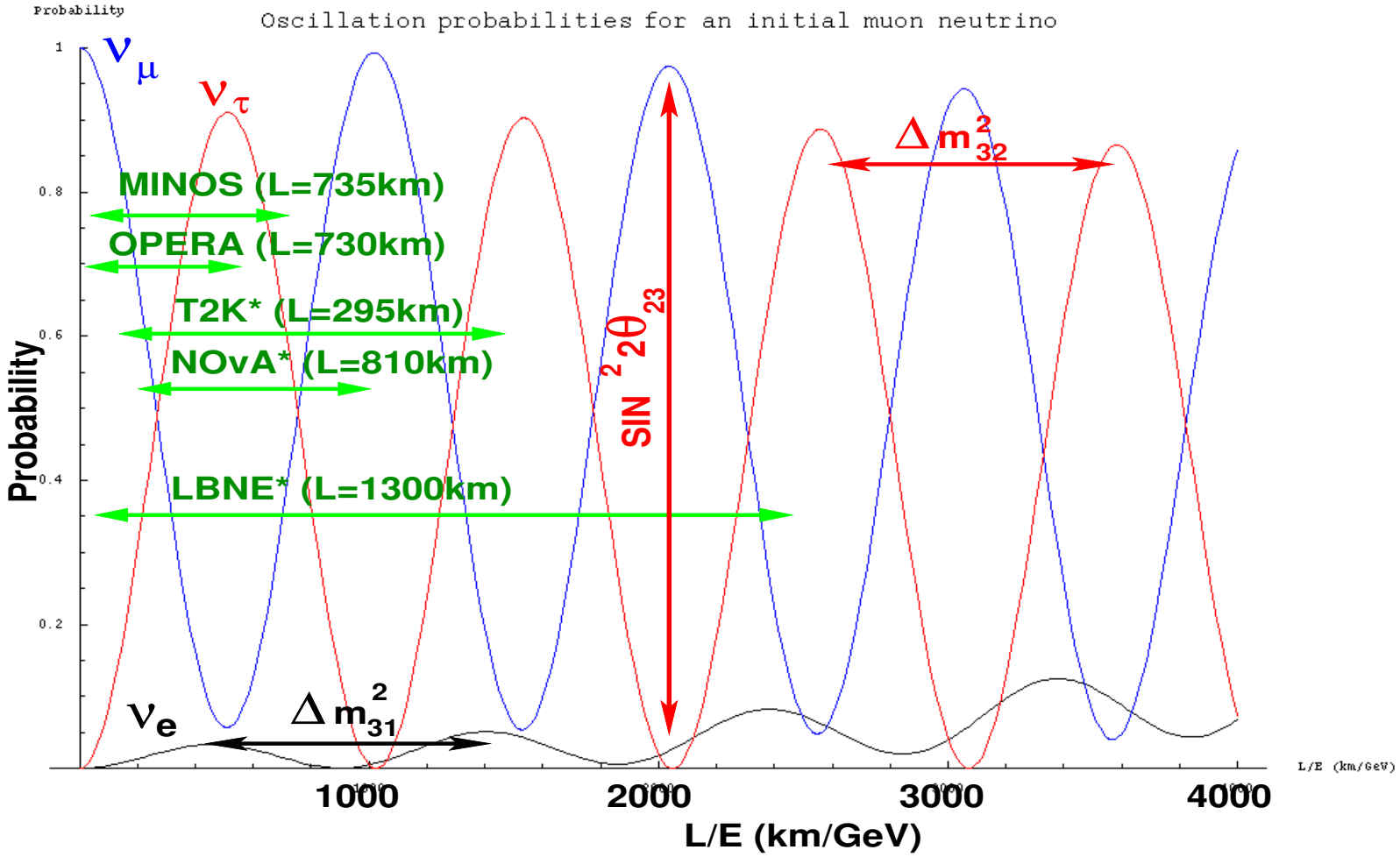

* = future accelerator ν_μ experiments

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

Neutrino Matrix Parameterization

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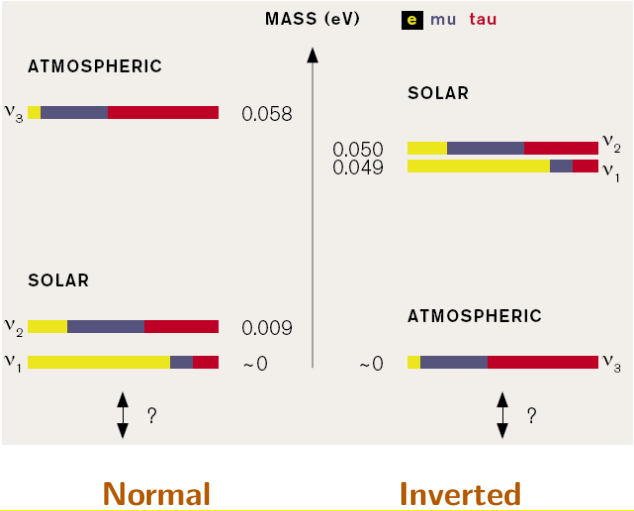
$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\nu_\mu \text{ disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\nu_\mu \to \nu_e,\ \text{reactor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

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



$\sin^2\theta_{13}$: 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

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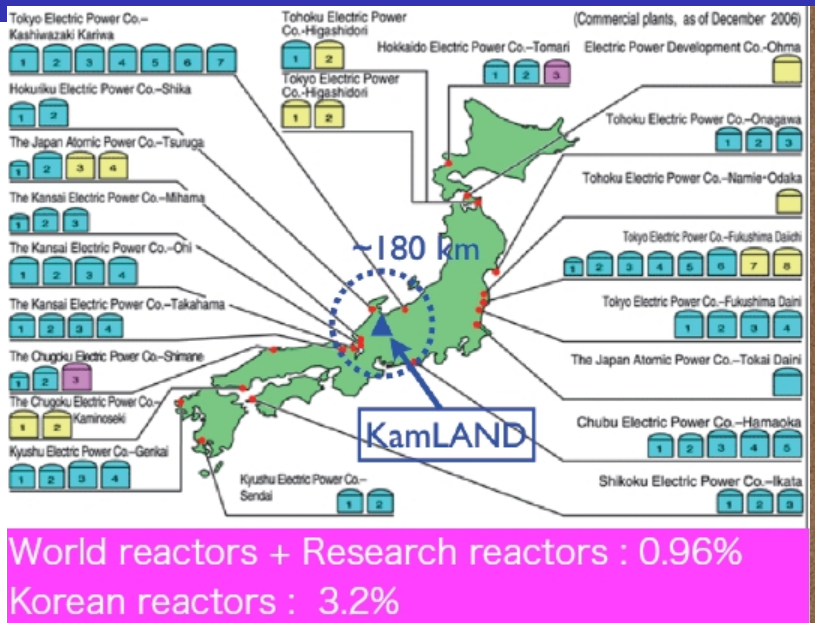

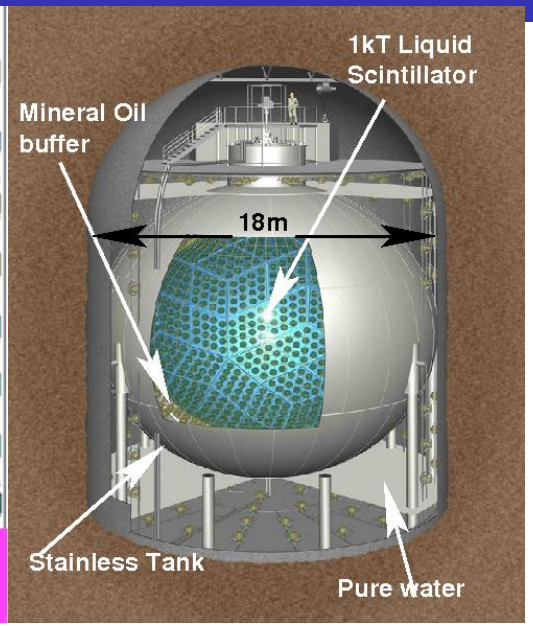

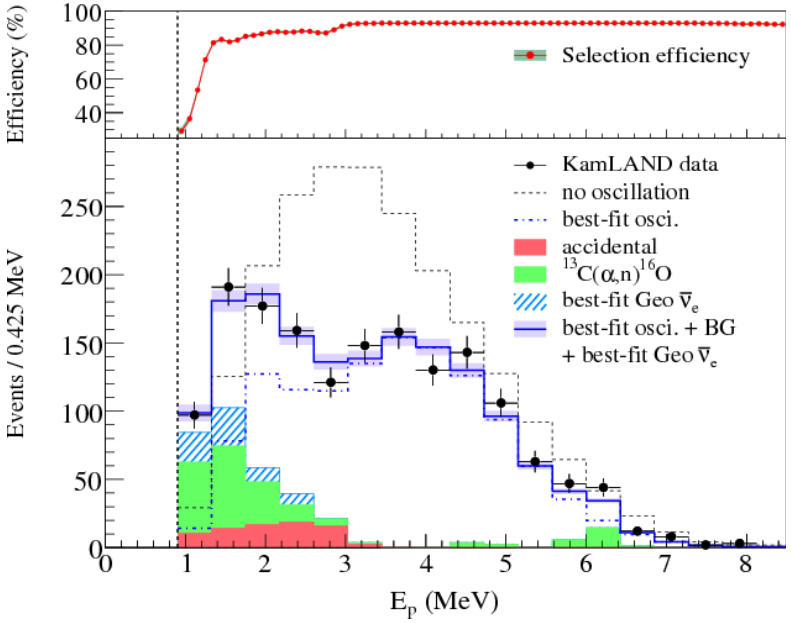

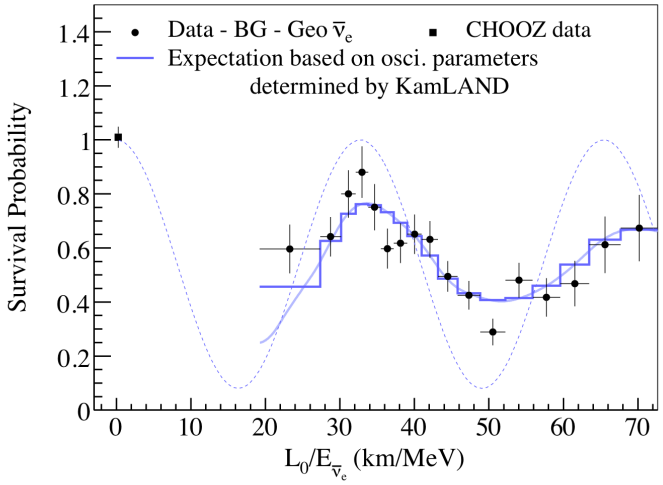

The NuMI/MINOS Accelerator ν_μ Experiment

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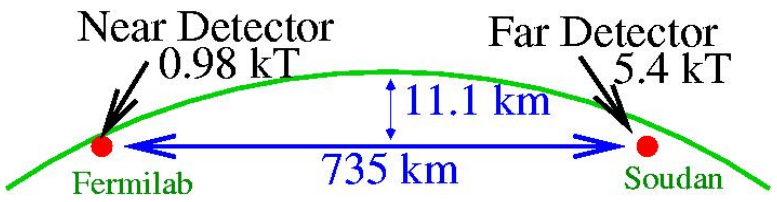
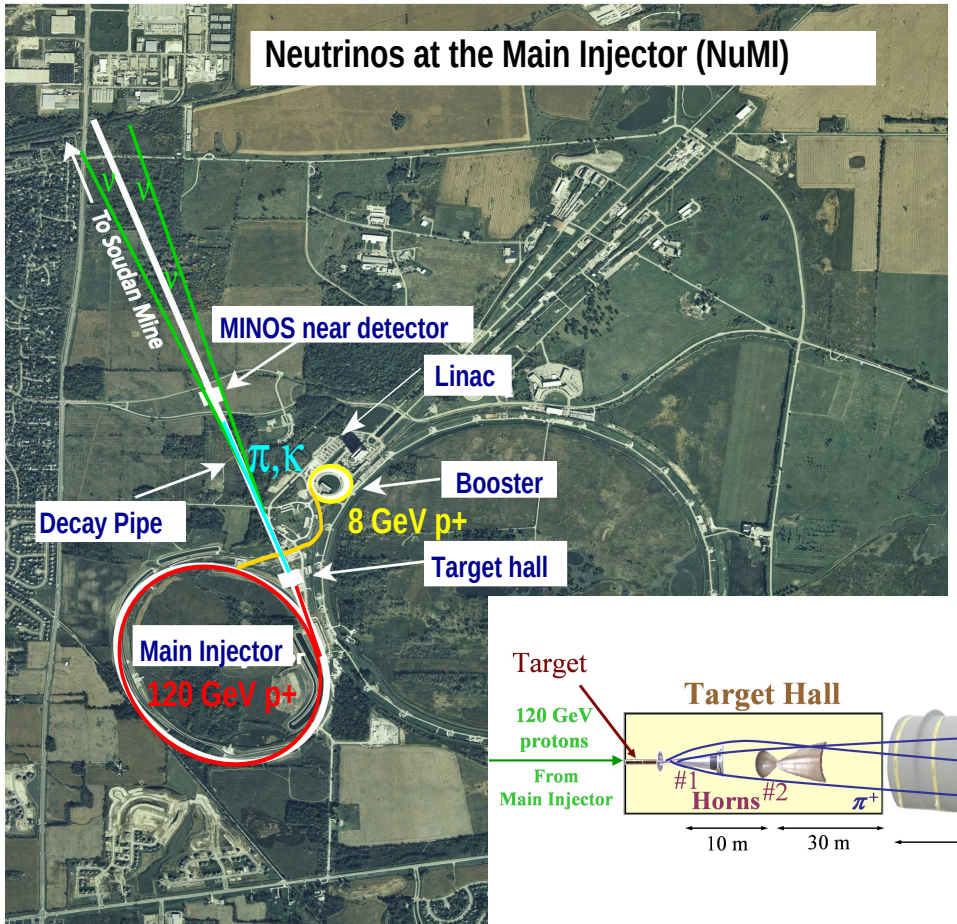
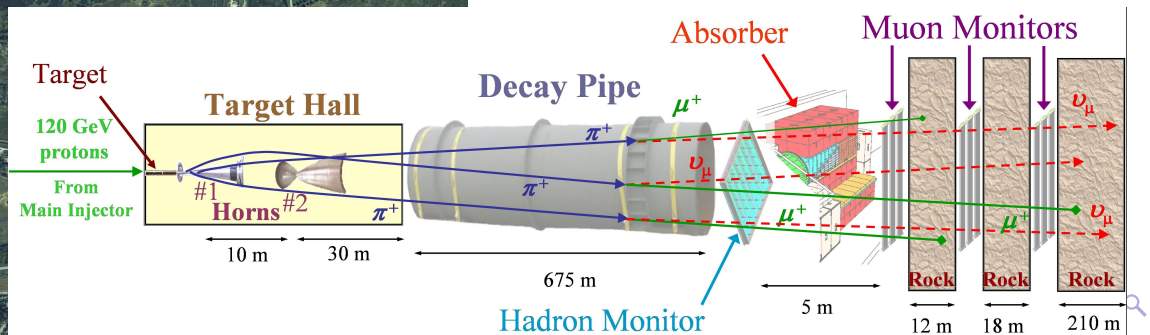


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**



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

3T at 200 kA



The MINOS Detectors

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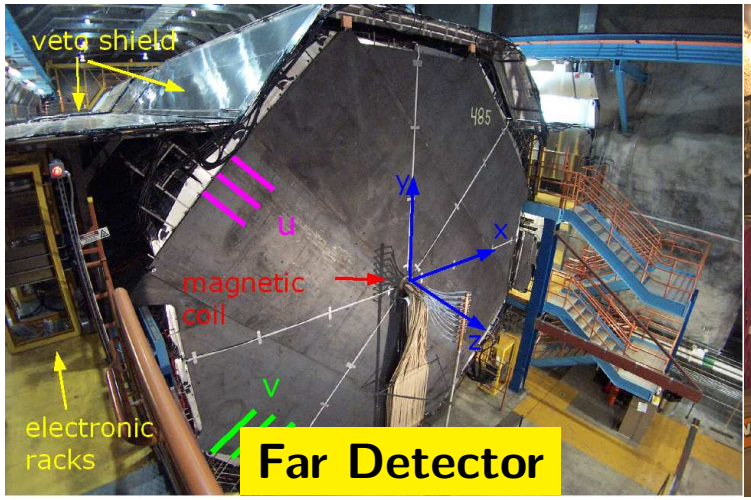
Magnetized iron calorimeters with 2.54 cm thick Fe plates sandwiched with scintillator strips (1 cm thick, 4.1 cm wide) readout by WLS fiber.



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

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

Interactions in MINOS

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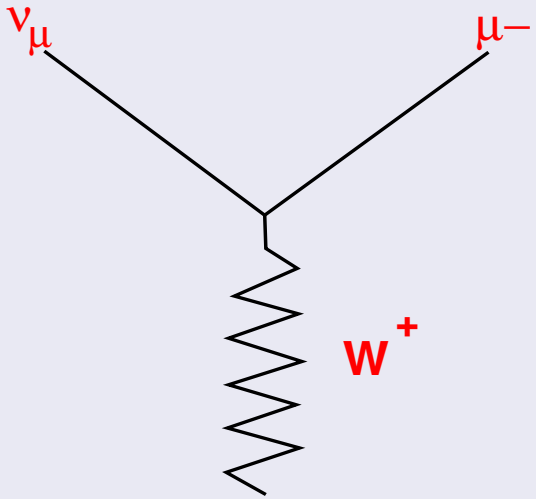
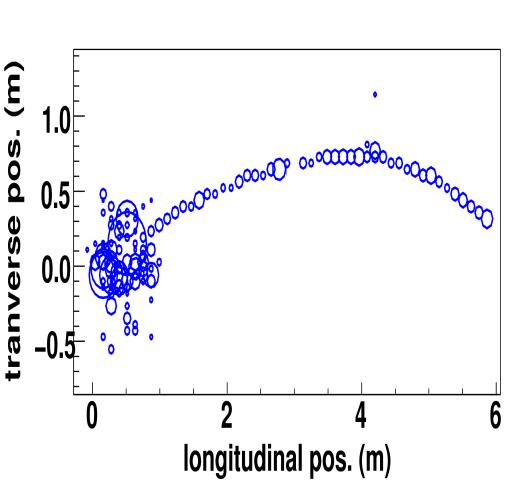
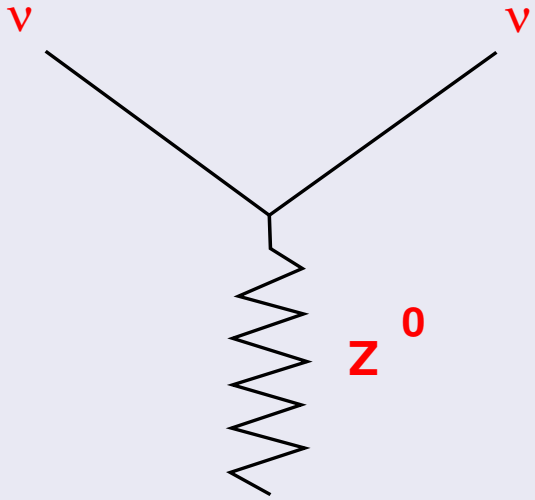
ν_μ CC Event

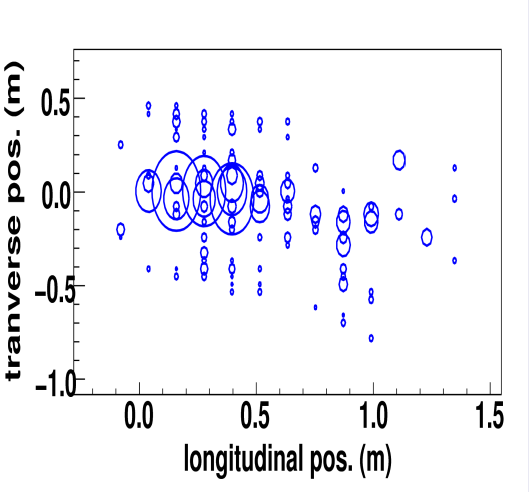




Curved track w/ shower

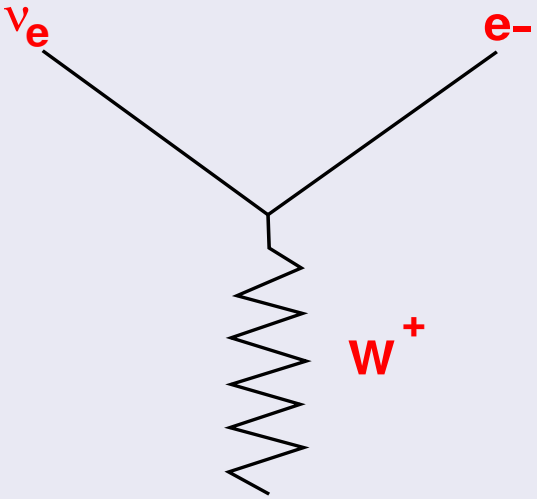
ν NC Event

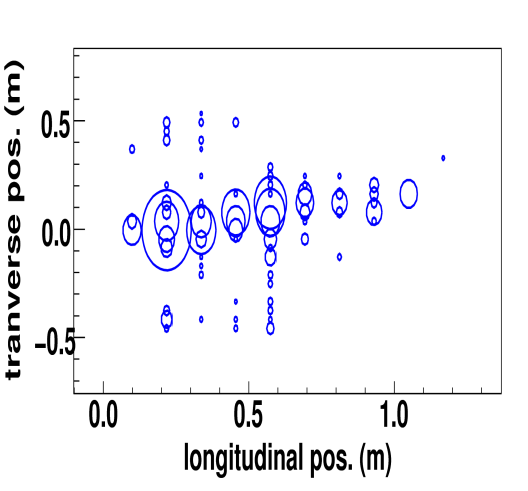




Diffuse shower

ν_e CC Event





Compact shower

MINOS Data (2009)

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

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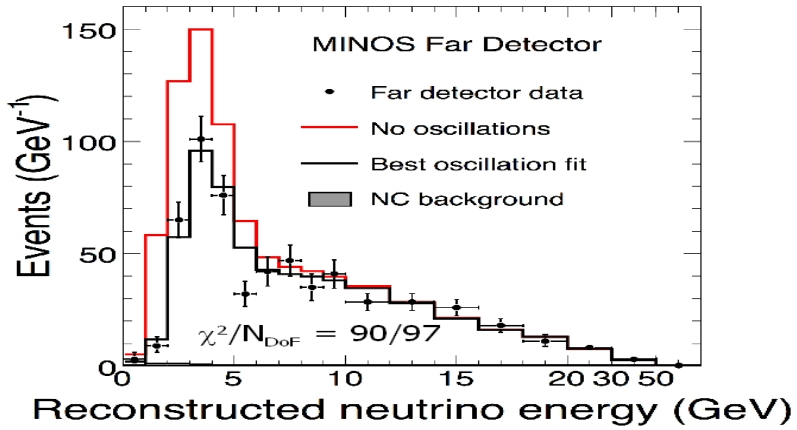
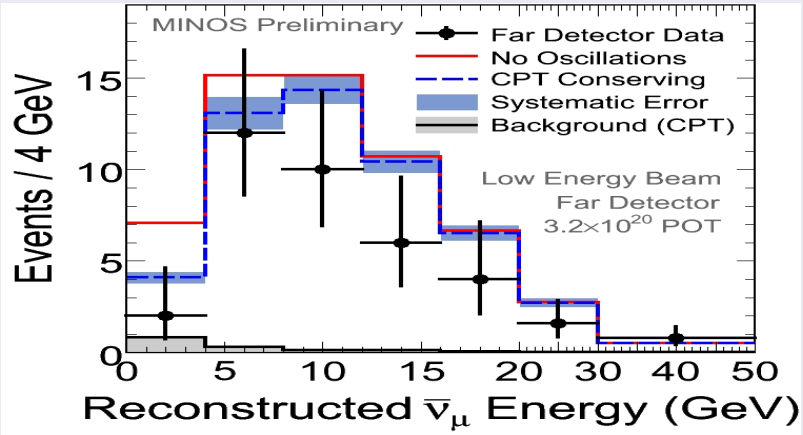
ν_μ disappearance — PRL 101, 2008



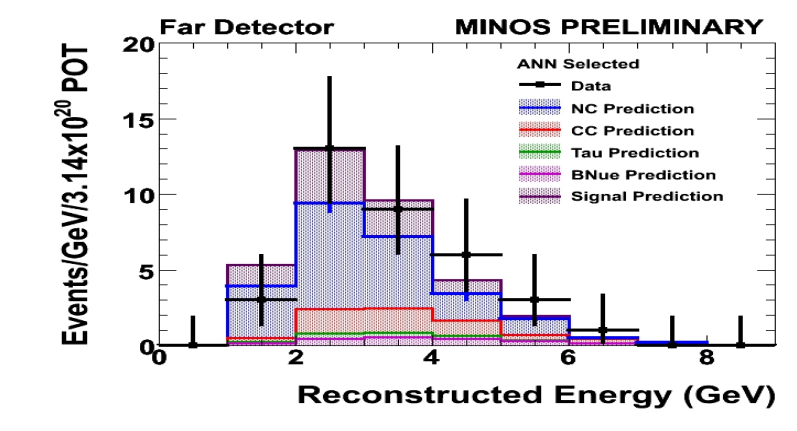
Expected no-osc 1065 $\pm$ 60.
Observe 848.

$\bar{\nu}_\mu$ disappearance — PRL in preparation



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

ν_e appearance — PRL in preparation



Expected FD background: 27 $\pm$ 5$_{stat}$ $\pm$ 2$_{sys}$.
Observe 35.

MINOS results 2009:

ν_μ Disappearance:

$\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3} eV^2$ **5% accuracy**

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

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

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

ν_e appearance:

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

$\sin^2 2\theta_{13} < 0.42(90\%C.L.); \Delta m^2 < 0, \delta_{cp} = 0$

Search for ν_s

MINOS Results 2009 and Future

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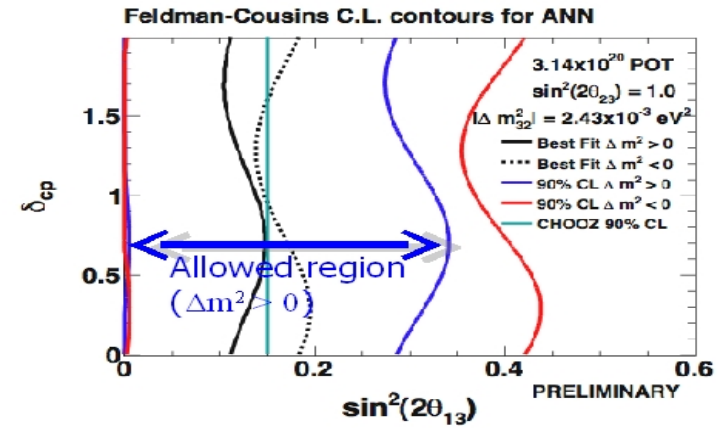
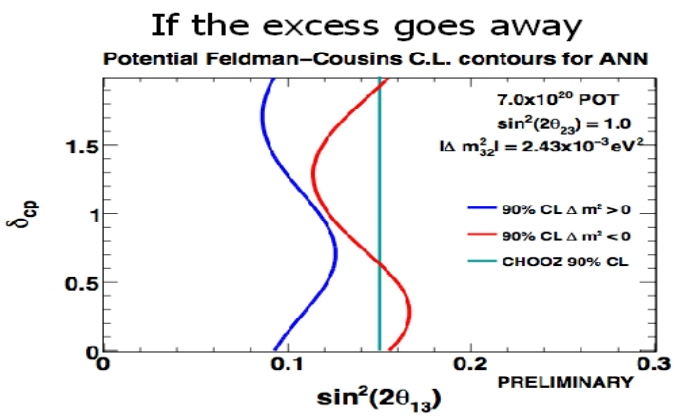
Search for ν_e appearance

Current results

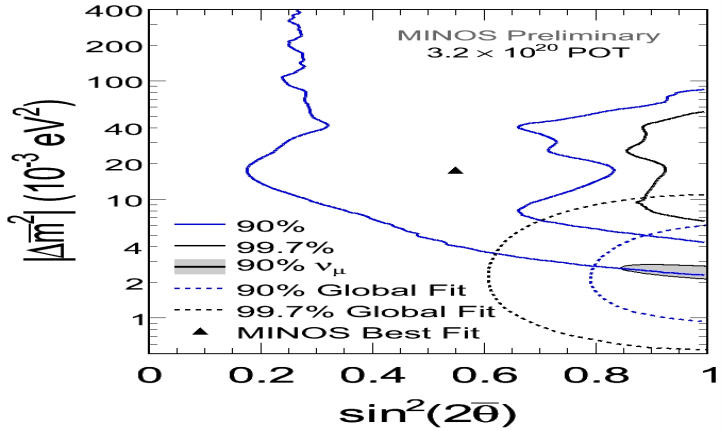


Expected by 2010

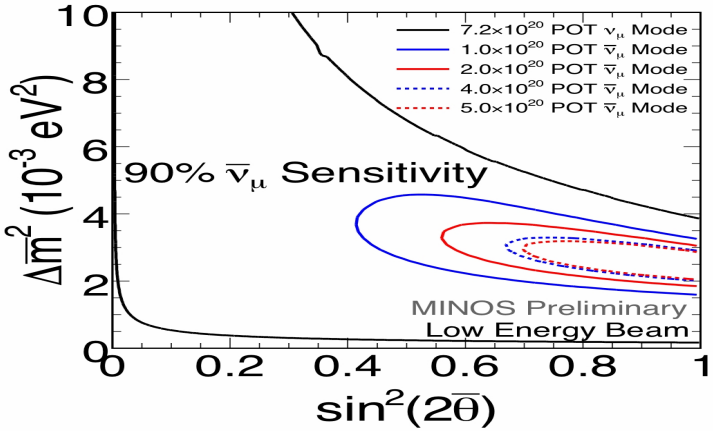


$\bar{\nu}_\mu$ disappearance

Current results



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



The mixing matrix - 2009

J. Valle, TAUP '09

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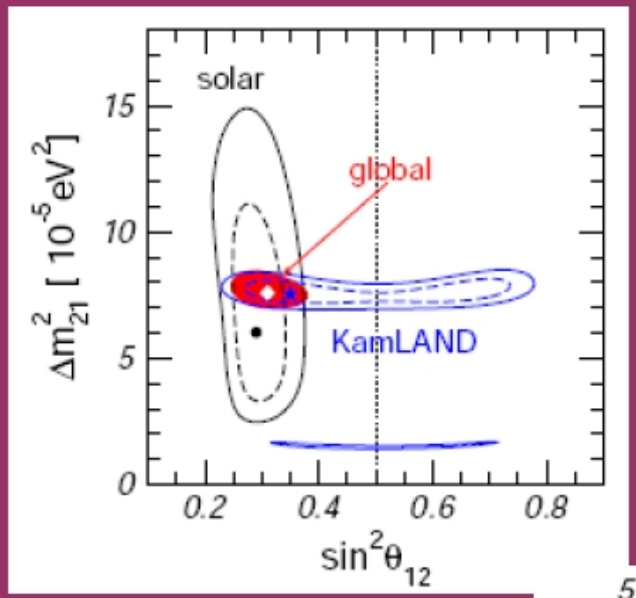
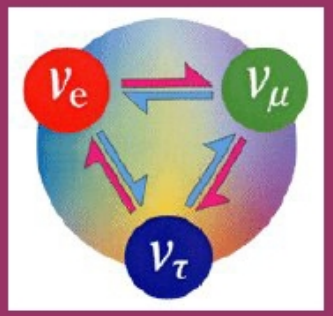
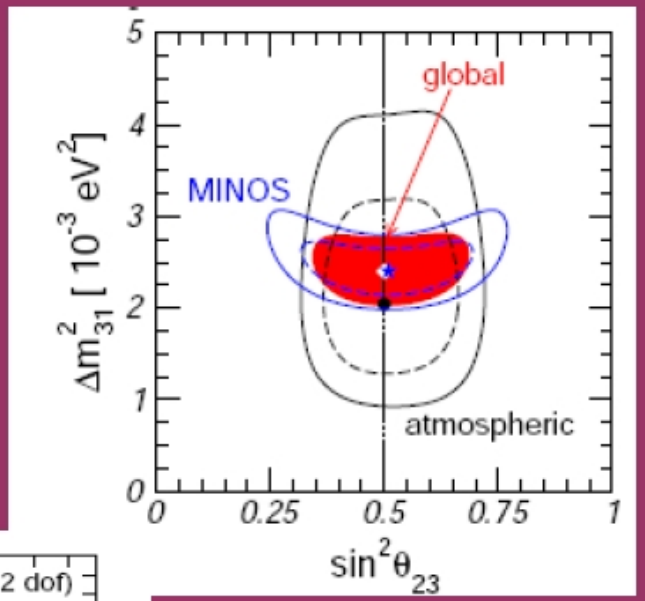
Maltoni et al, NJP 6 (2004) 122

Schwetz et al, NJP 10 (2008) 113011

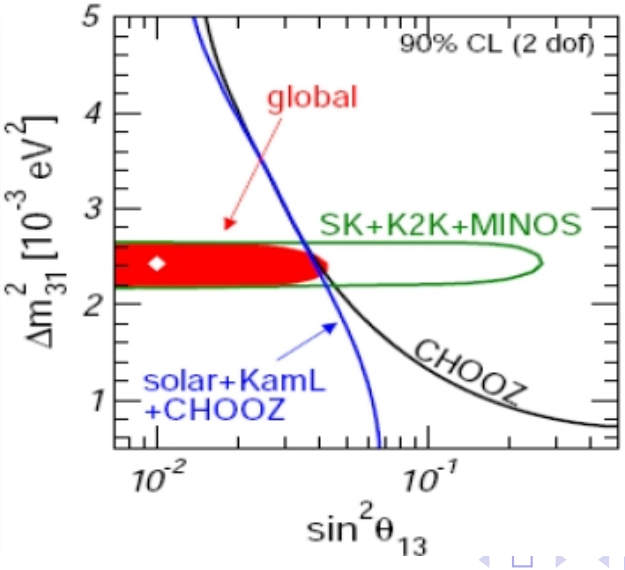






Homestake, SAGE+ GALLEX/GNO, Super-K, SNO
Borexino

KamLAND (180 Km)



... Super-K

K2K (250 Km)
MINOS (735 Km)

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

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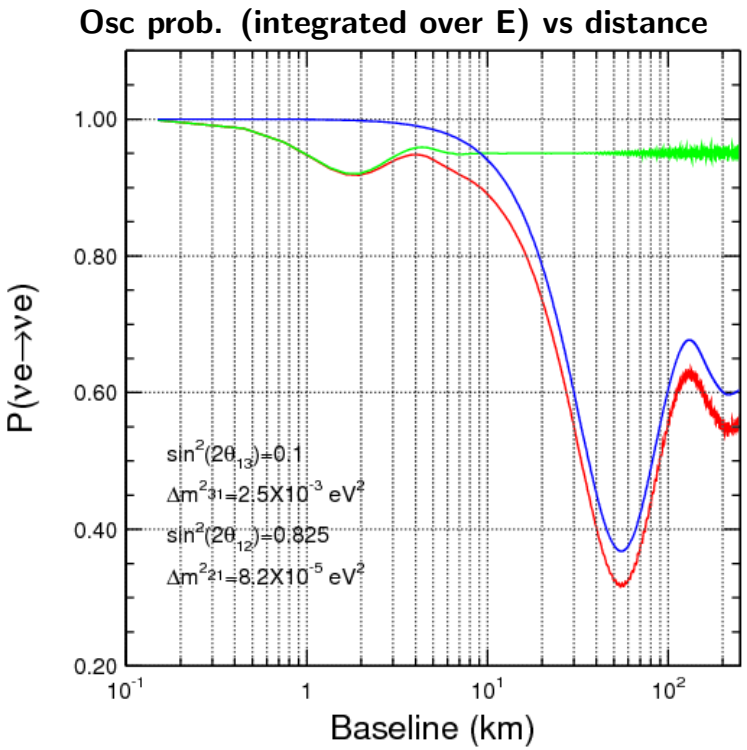
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$



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 "identical" N/F detectors to reduce near/far detector uncertainties.
-Calibration, calibration, calibration...

The Double Chooz Experiment

M. Dierckxsens, TAUP'09

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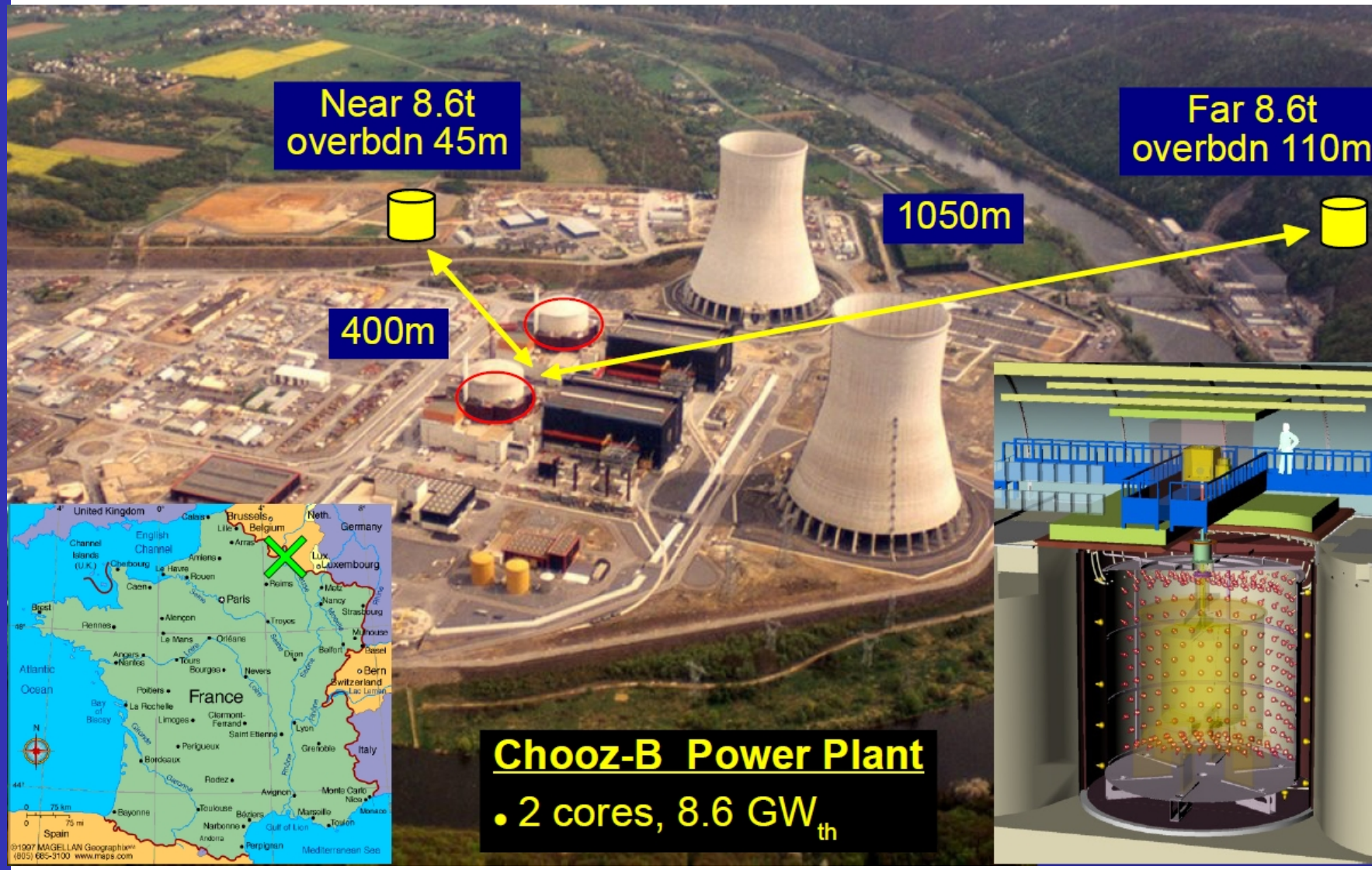
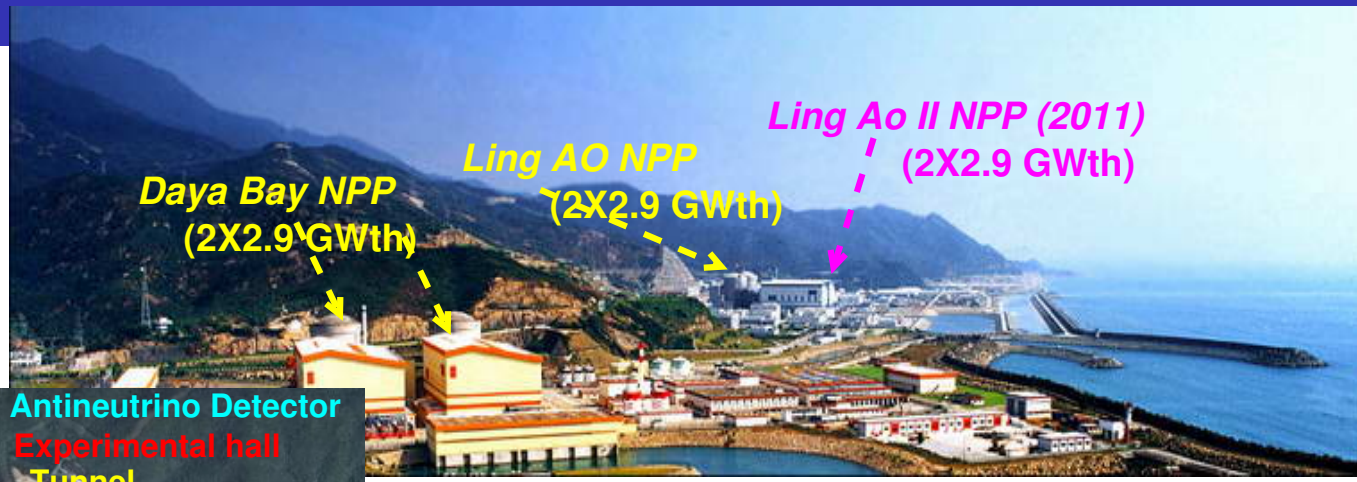


Spring 2010: Far detector ready. End 2010: near detector ready

The Daya Bay Reactor Complex



Reactor Specs:

Located 55km north-east of Hong Kong.

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

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

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

Deploy multiple near and far detectors

Reactor power uncertainties $< 0.1\%$

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

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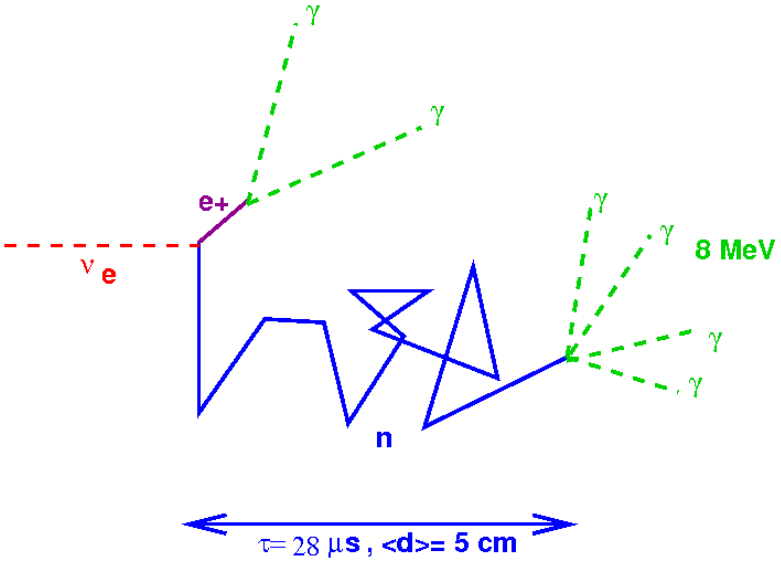
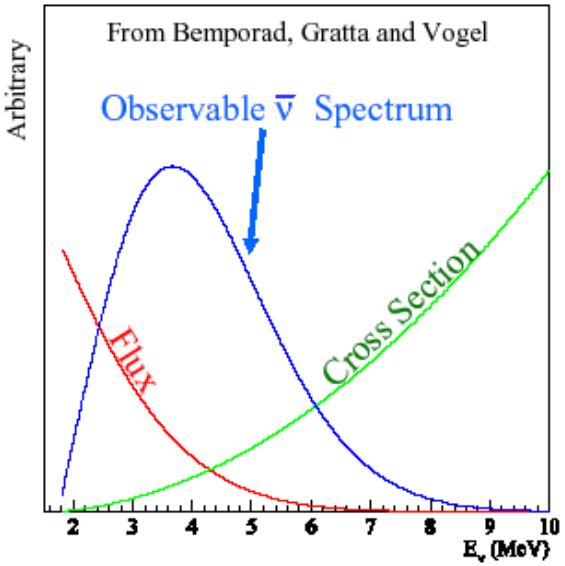
The active target in each detector module is liquid scintillator loaded with 0.1% Gd





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,** $\tau \sim 28\mu s$**,** $\sigma = 5 \times 10^4 b$**).**

⇒ delayed co-incidence of e^+ **conversion and n-capture (> 6 MeV)**

with a specfic energy signature

The Daya Bay Experiment

D. Mohapatra's talk tomorrow

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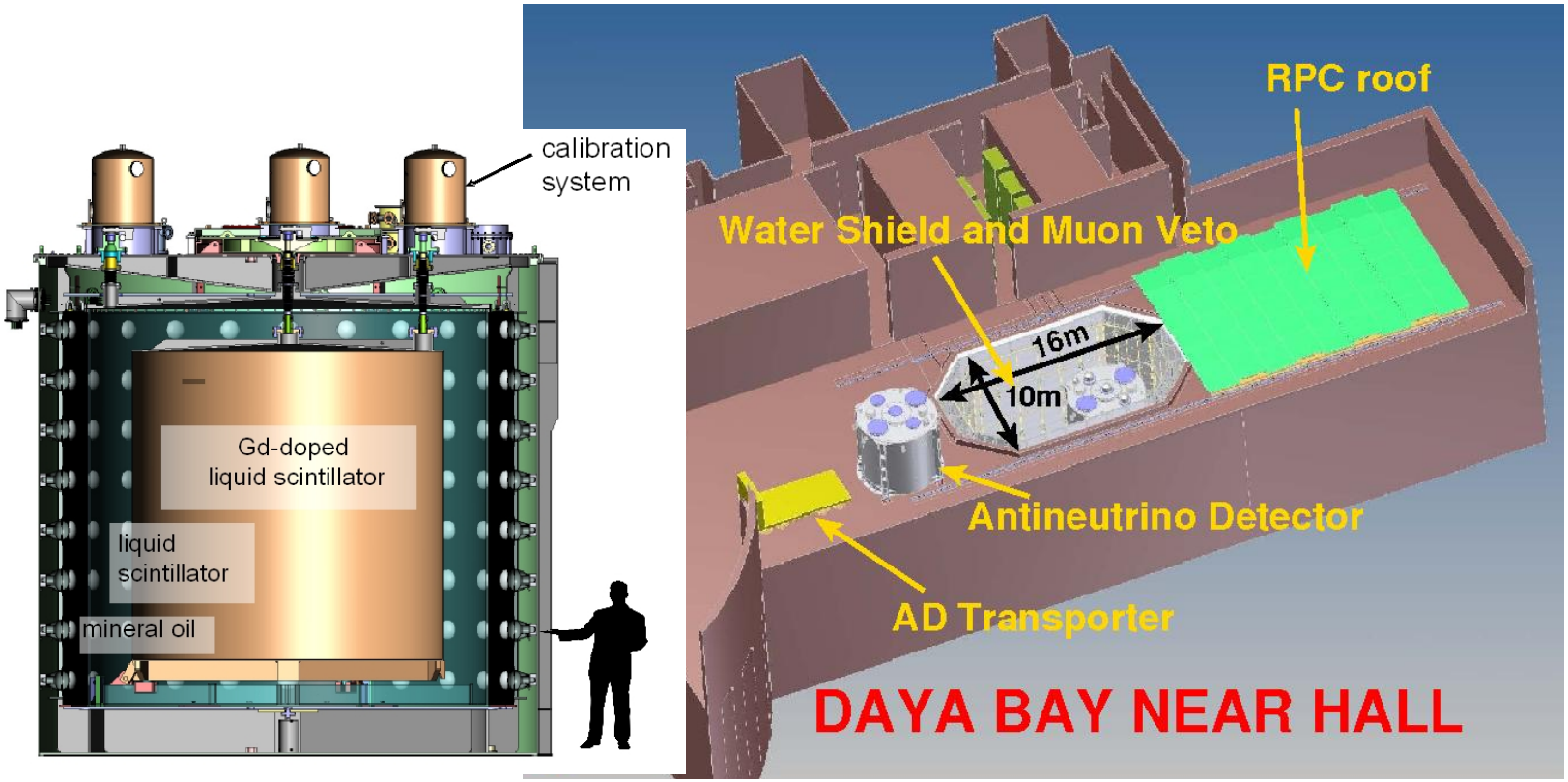

- **Multiple "identical" detectors at each site.**
- **Manual and multiple automated calibration systems per detector.**
- **Thick water shield to reduce cosmogenic and radiation bkgds.**

	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%	

Summer 2010: Near detector ready. Summer 2011: far detector ready

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

Off-axis high intensity ν_μ beams: T2K

T. Le's talk

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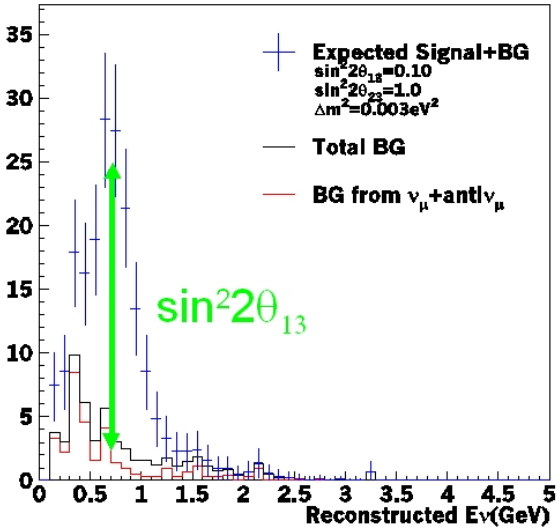
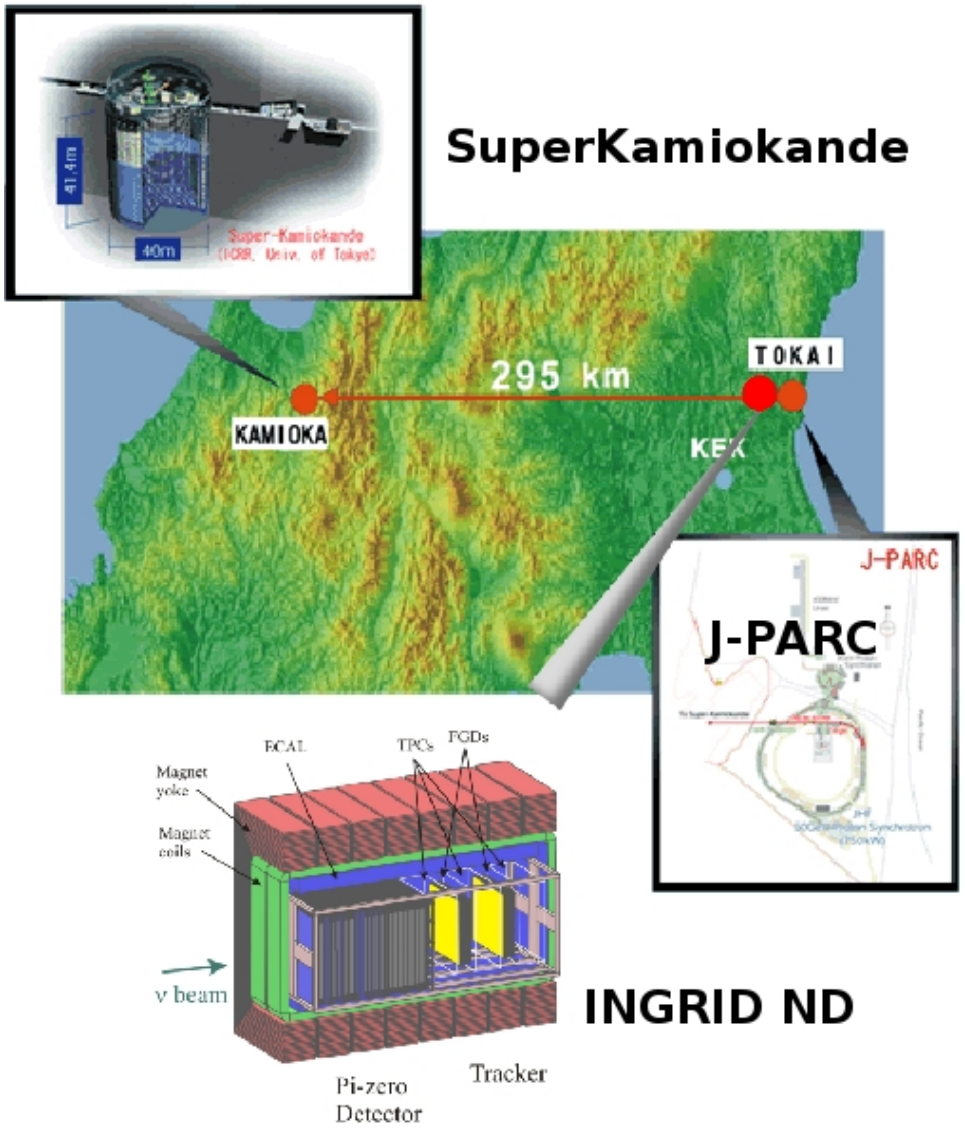
First proposed for BNL E-889 (1995): A narrow beam of ν can be achieved by going off-axis to the π beam. Better S:B at oscillation max.

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





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

NOνA and T2K

A. Norman's talk

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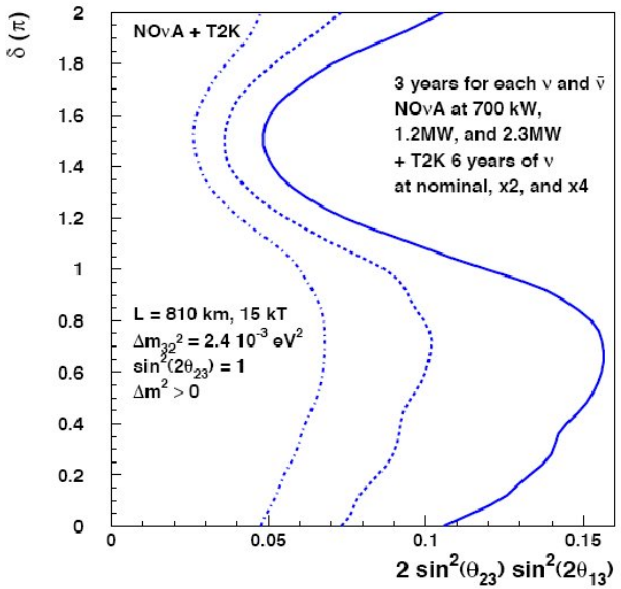
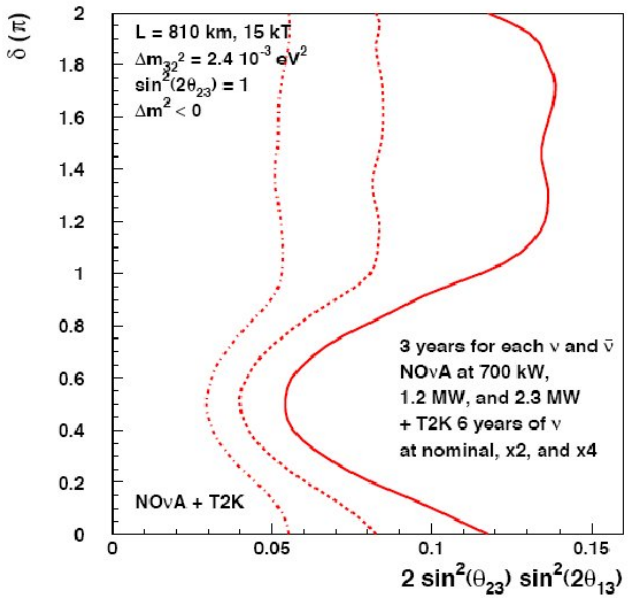
The NOνA experiment is at a baseline of 810km off-axis to the NuMI beam. Detector is 15kT of active scintillator on the surface. Operational by 2013. From G. Feldman:

95% CL Resolution of the Mass Ordering
NOνA Plus T2K



Normal Ordering



Inverted Ordering

Some sensitivity to mass hierarchy at large θ_{13}

θ_{13} by 2016

M. Mezzetto, arXiv:0905.2842

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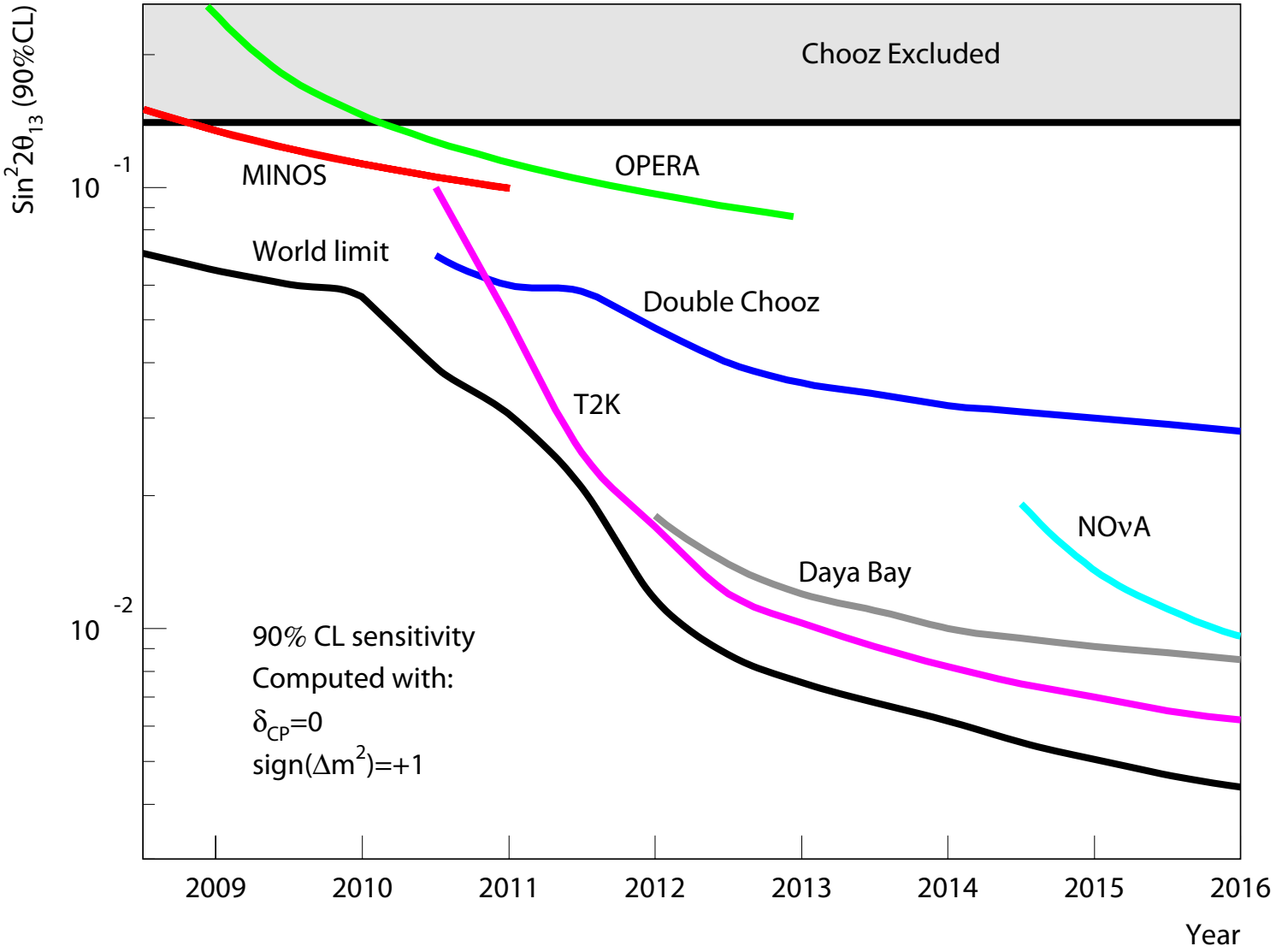

CP Violation, Mass Hierarchy and $\nu_\mu \longrightarrow \nu_e$

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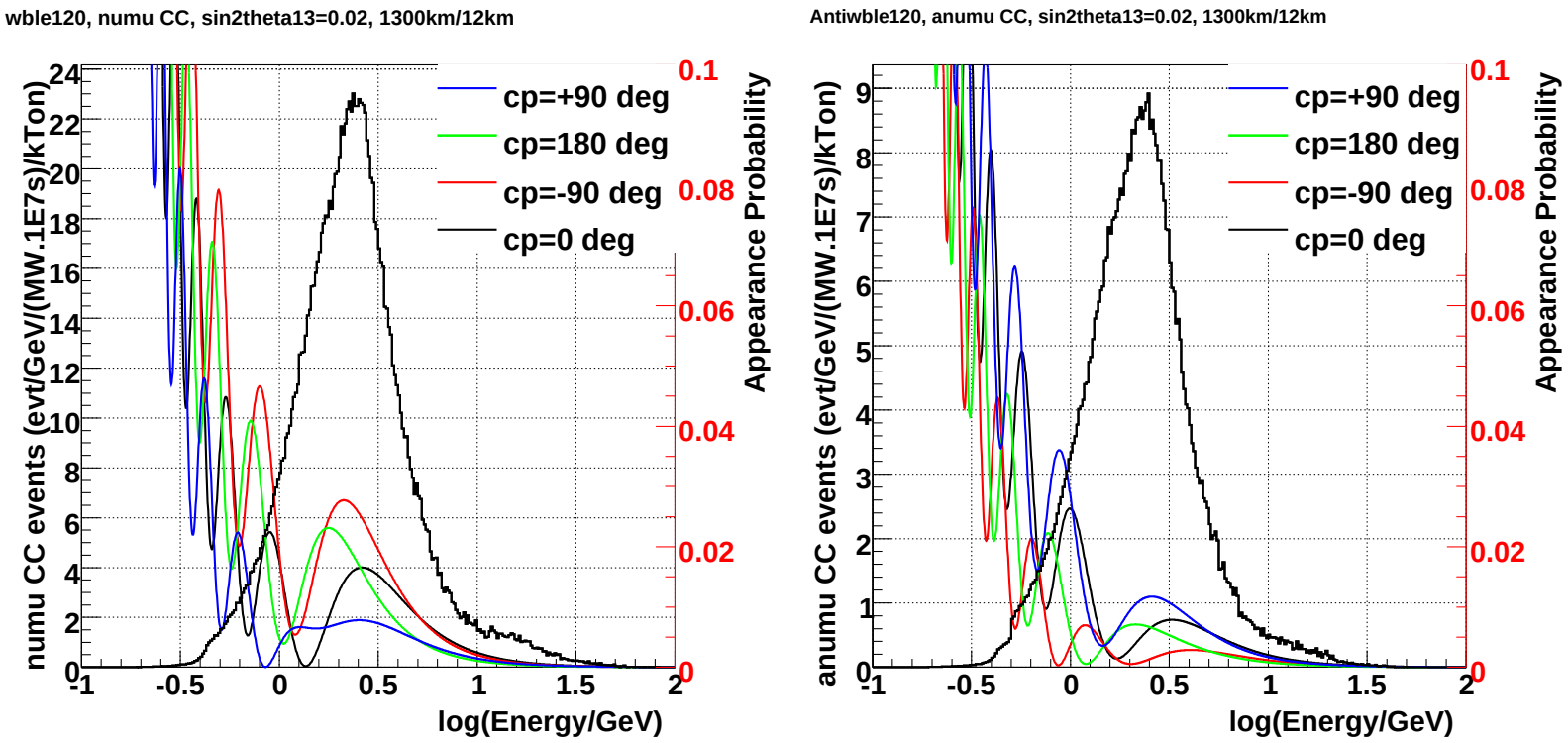
Appearance probabilities of $\nu_\mu \longrightarrow \nu_e$ for different values of the CP phase. A CP phase $\neq 0, \pi$ implies CP is violated in the lepton sector.

Normal Hierarchy

ν $\bar{\nu}$



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

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

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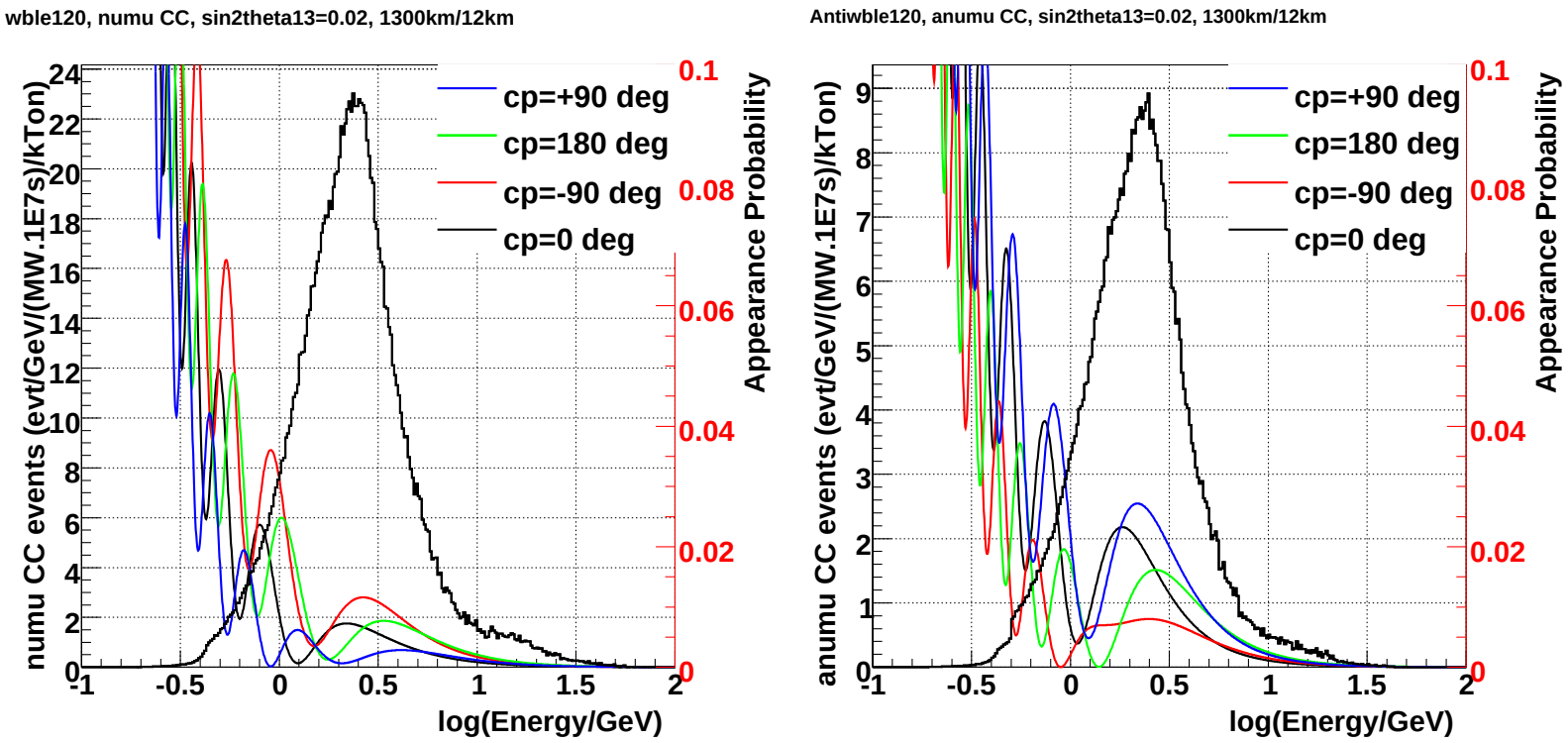
Reversed Hierarchy

ν $\bar{\nu}$



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

Measuring δ_{cp} and the Mass Hierarchy

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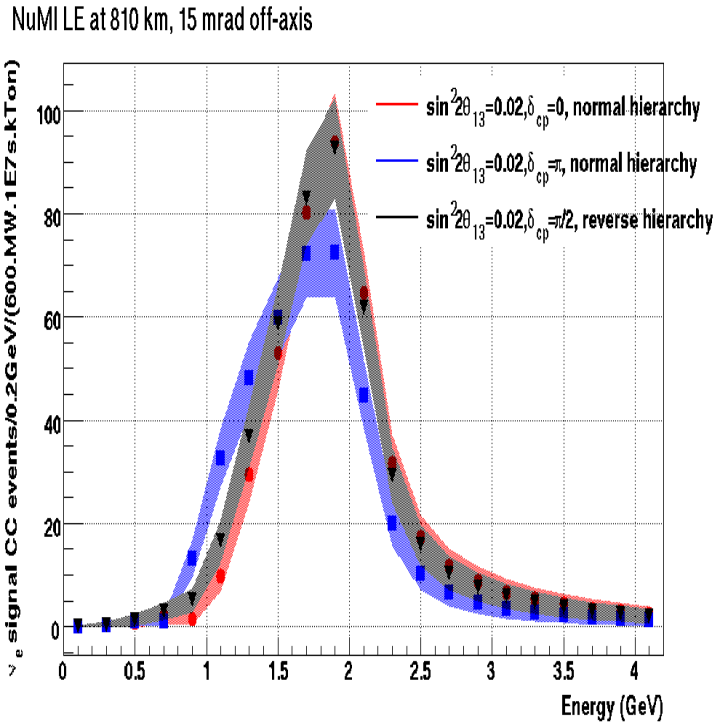
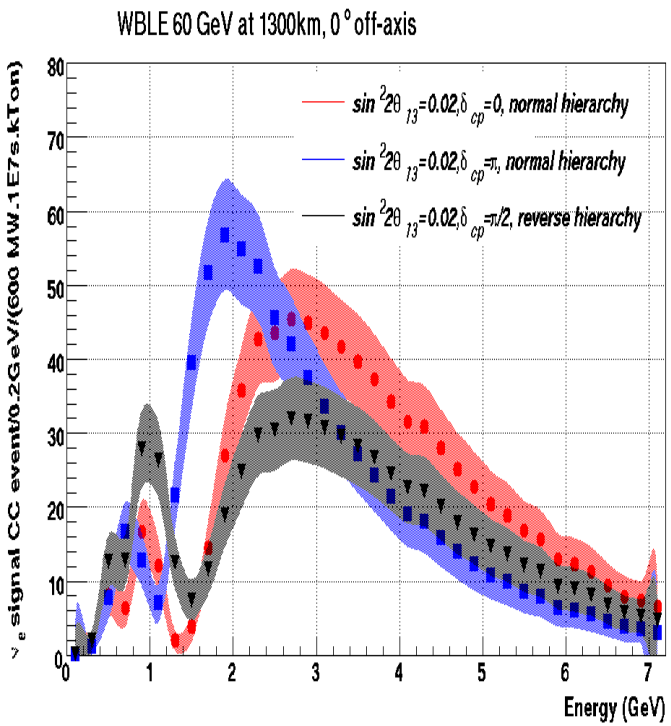
Long baseline accelerator $\nu_\mu \rightarrow \nu_e$ appearance. 300 kT. MW. yr:

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

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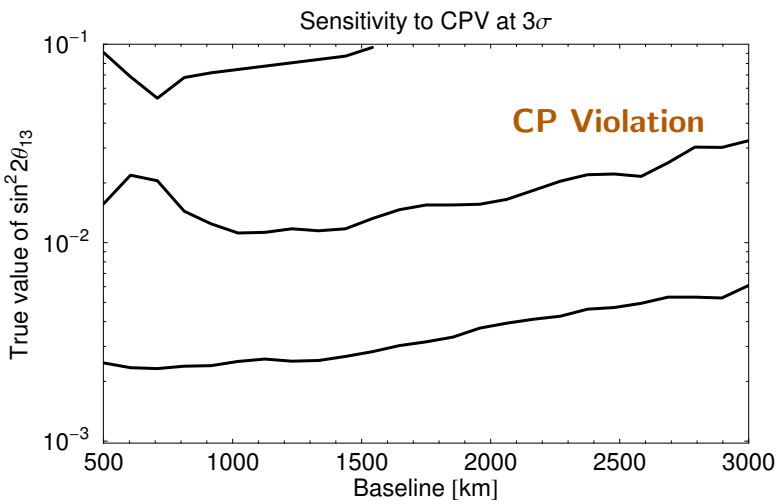
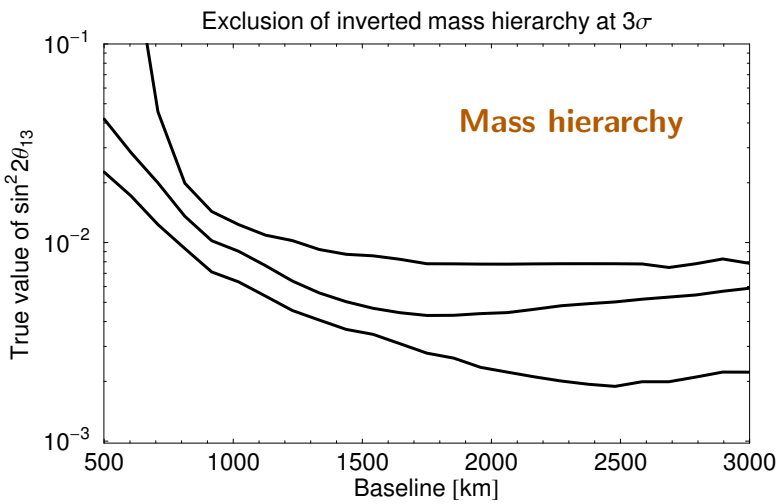
Using a broad-band beam with a peak interaction rate at 2 GeV, FWHM=3 GeV, a parameterized water Cerenkov detector and exposure of 5MW.yr (ν) + 10 MW.yr ($\bar{\nu}$) (V. Barger *et al.*. Phys. Rev. D 74, 073004 2006):





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

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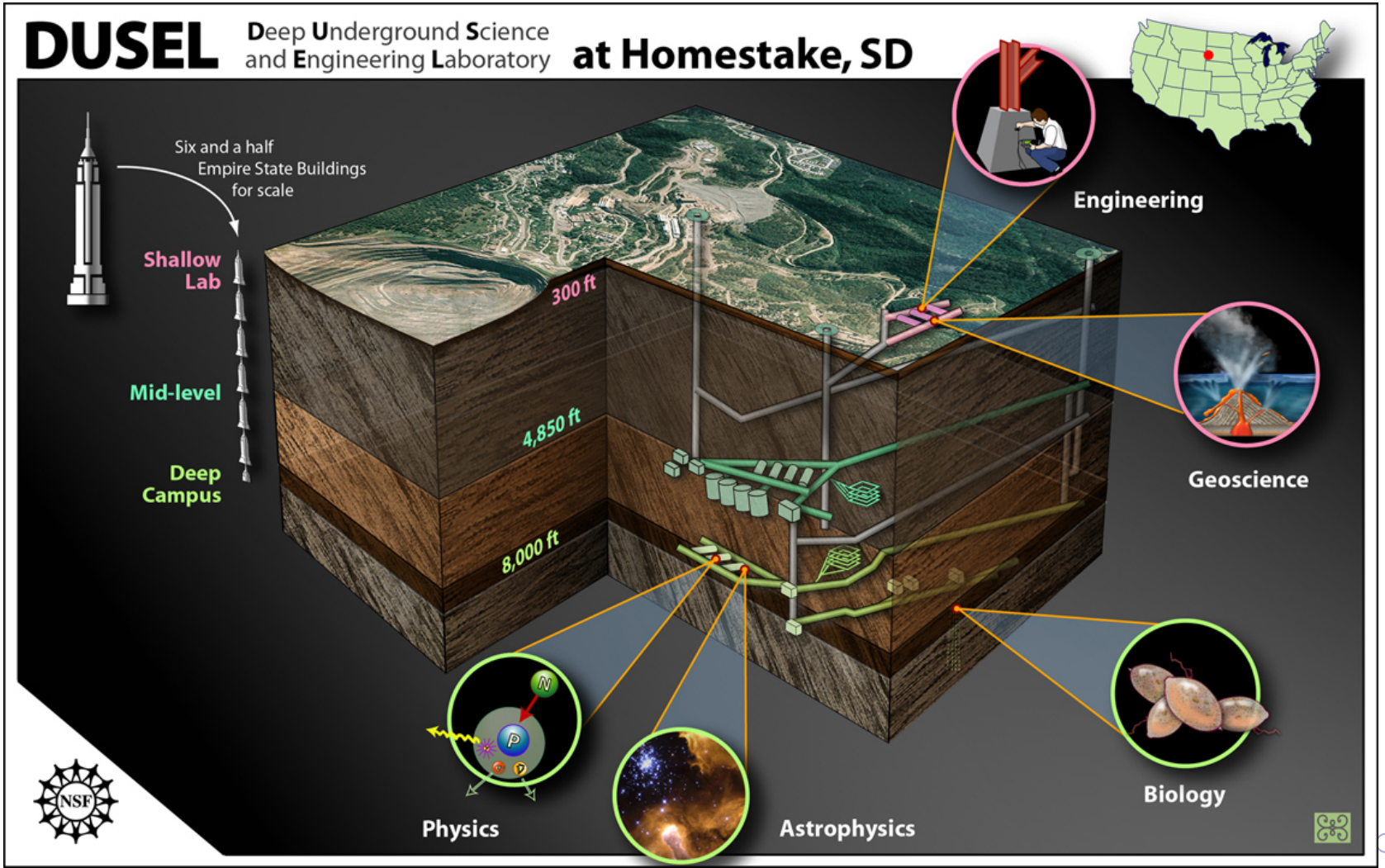
July 10, 2007: the National Science Foundation (NSF) selected the University California-Berkeley to produce a techincal design for DUSEL at Homestake Mine, SD



DUSEL Timeline

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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

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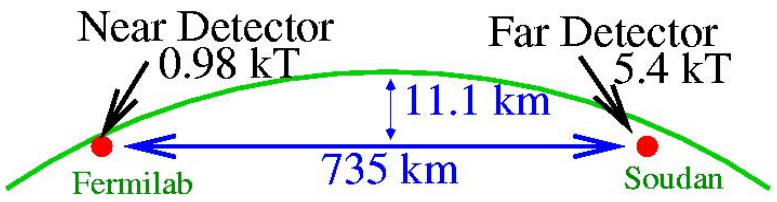
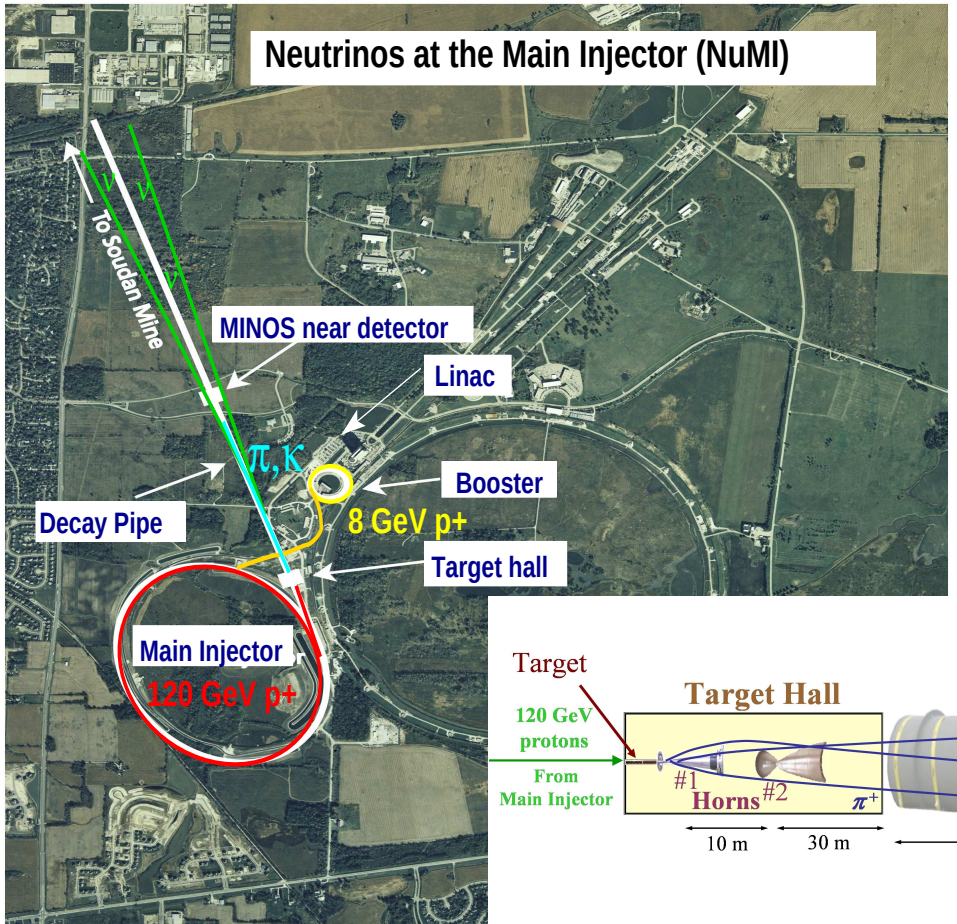
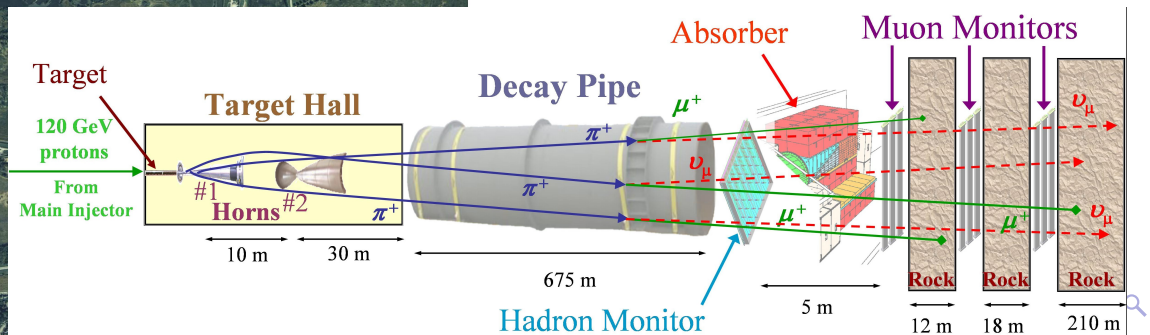


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**



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

3T at 200 kA

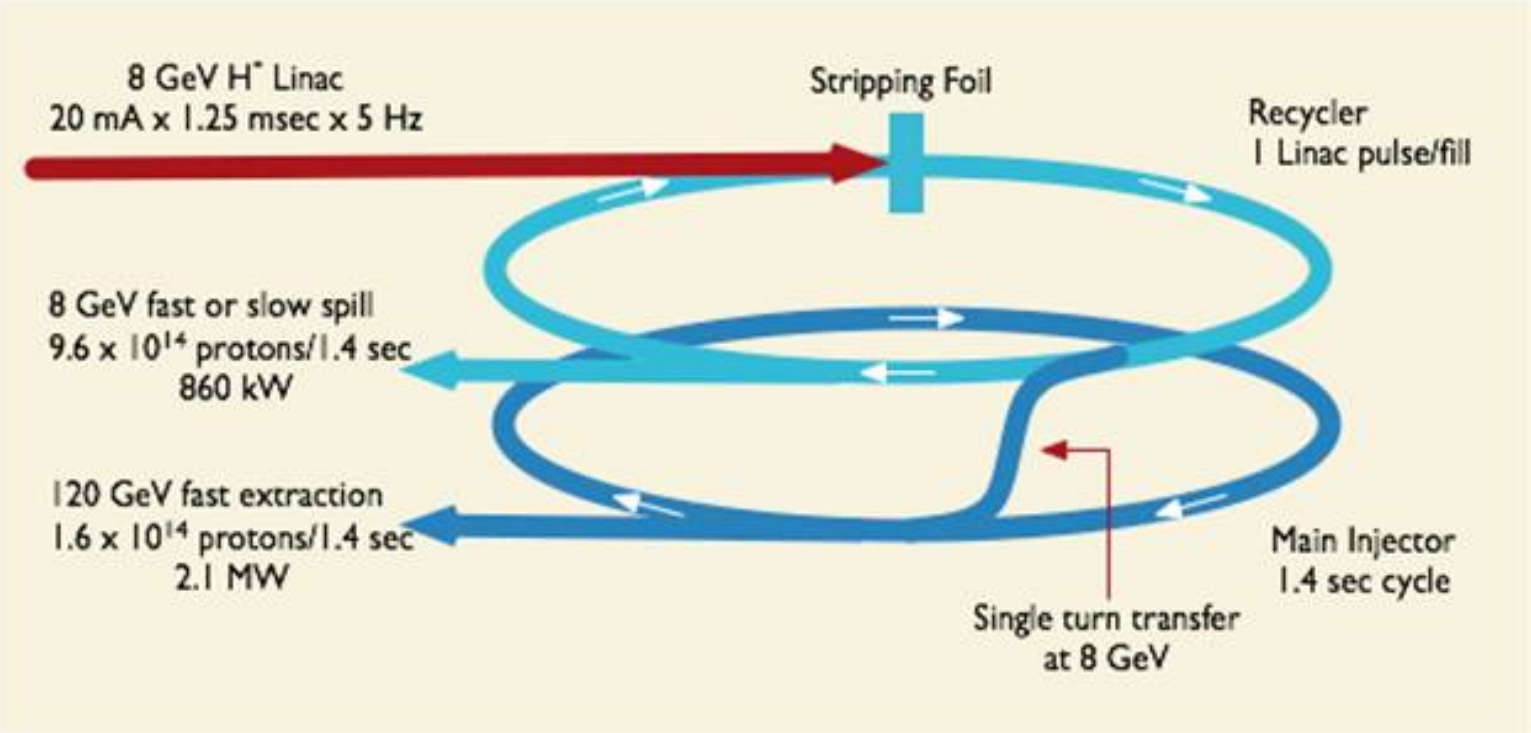


Fermilab Neutrino Beams: Future

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

NuMI is the most powerful neutrino beamline in operation today .

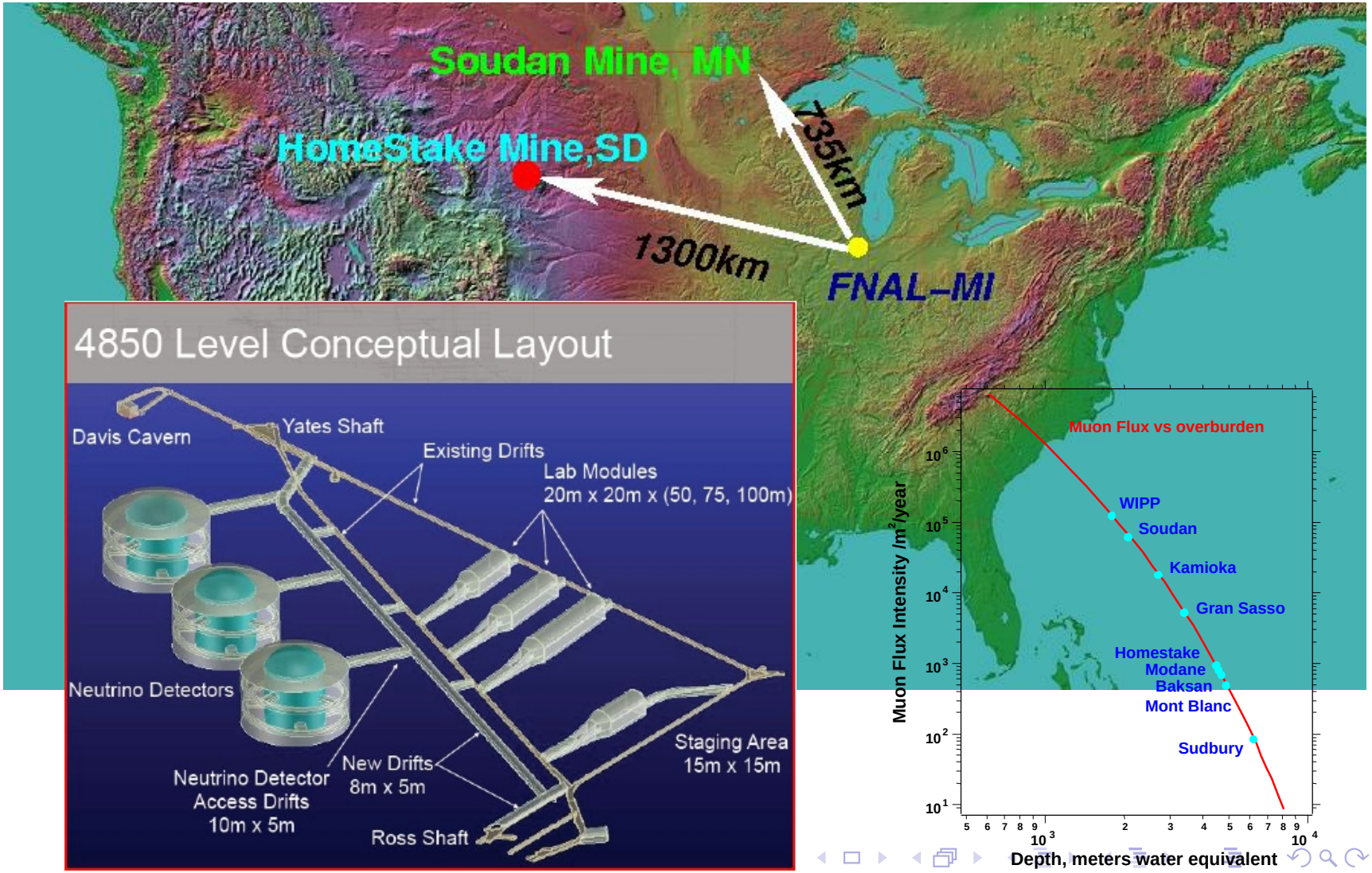
Planned upgrades to NuMI and the Main Injector → 700 kW by 2012.



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

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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

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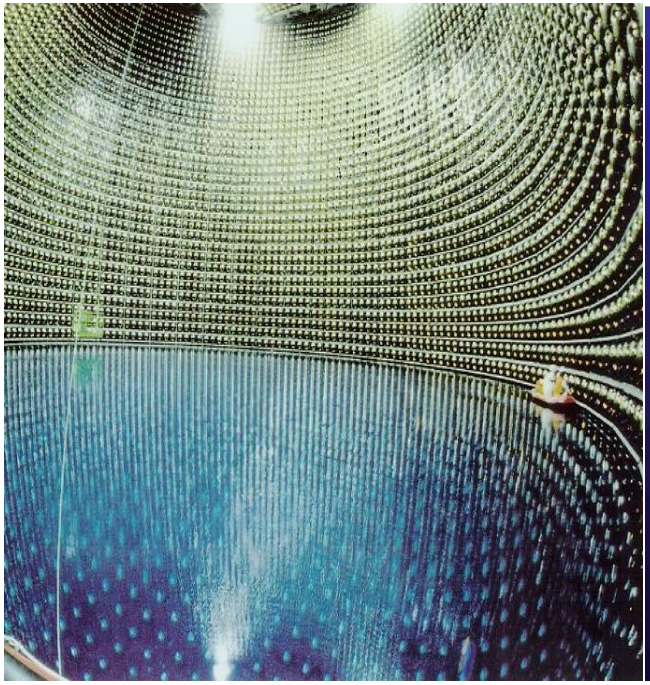
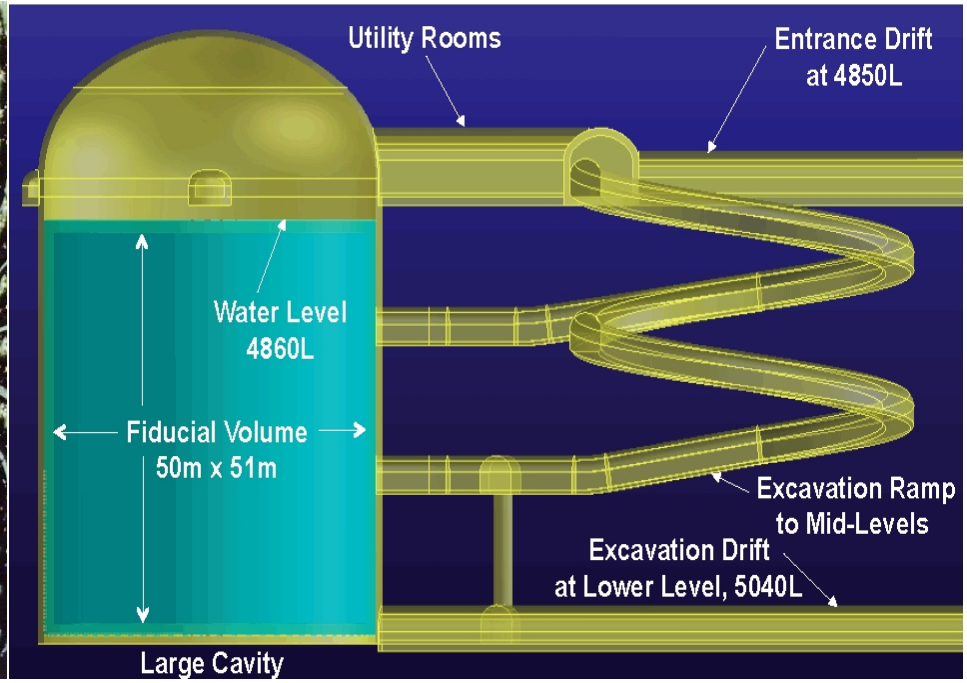
SuperKamiokande : 50kT



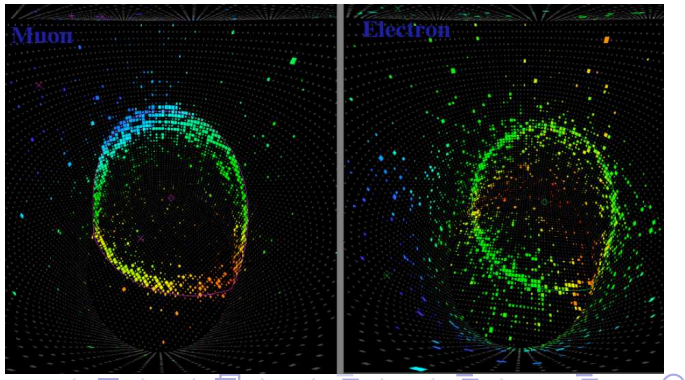
DUSEL WCe Module : $\sim$ 120 kT



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

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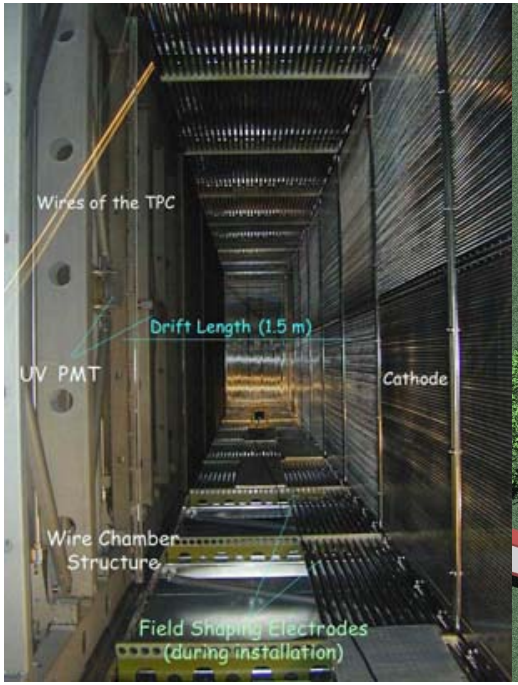
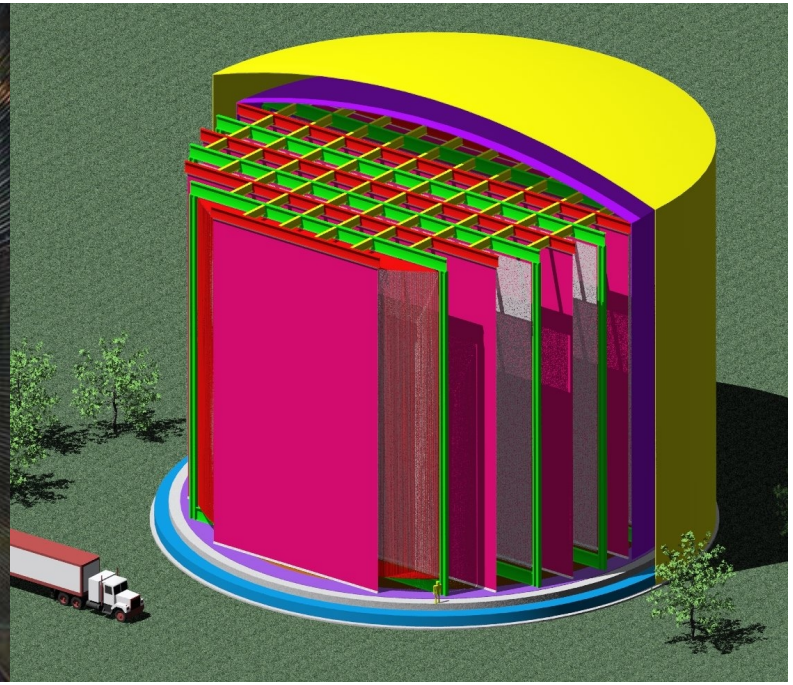
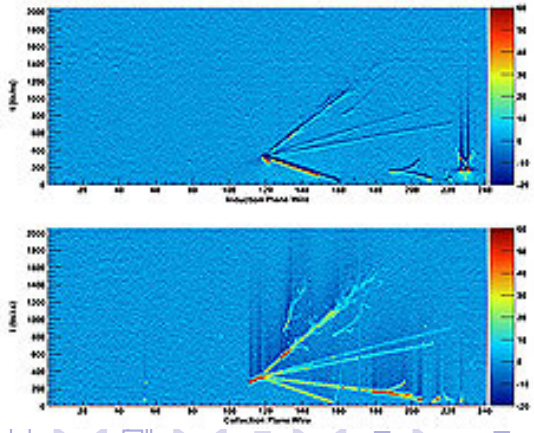
ICARUS module : 0.3kT



DUSEL LAr : 50 kT



ArgoNeuT (175 litre) prototype in the NuMI beam →



High efficiency and purity

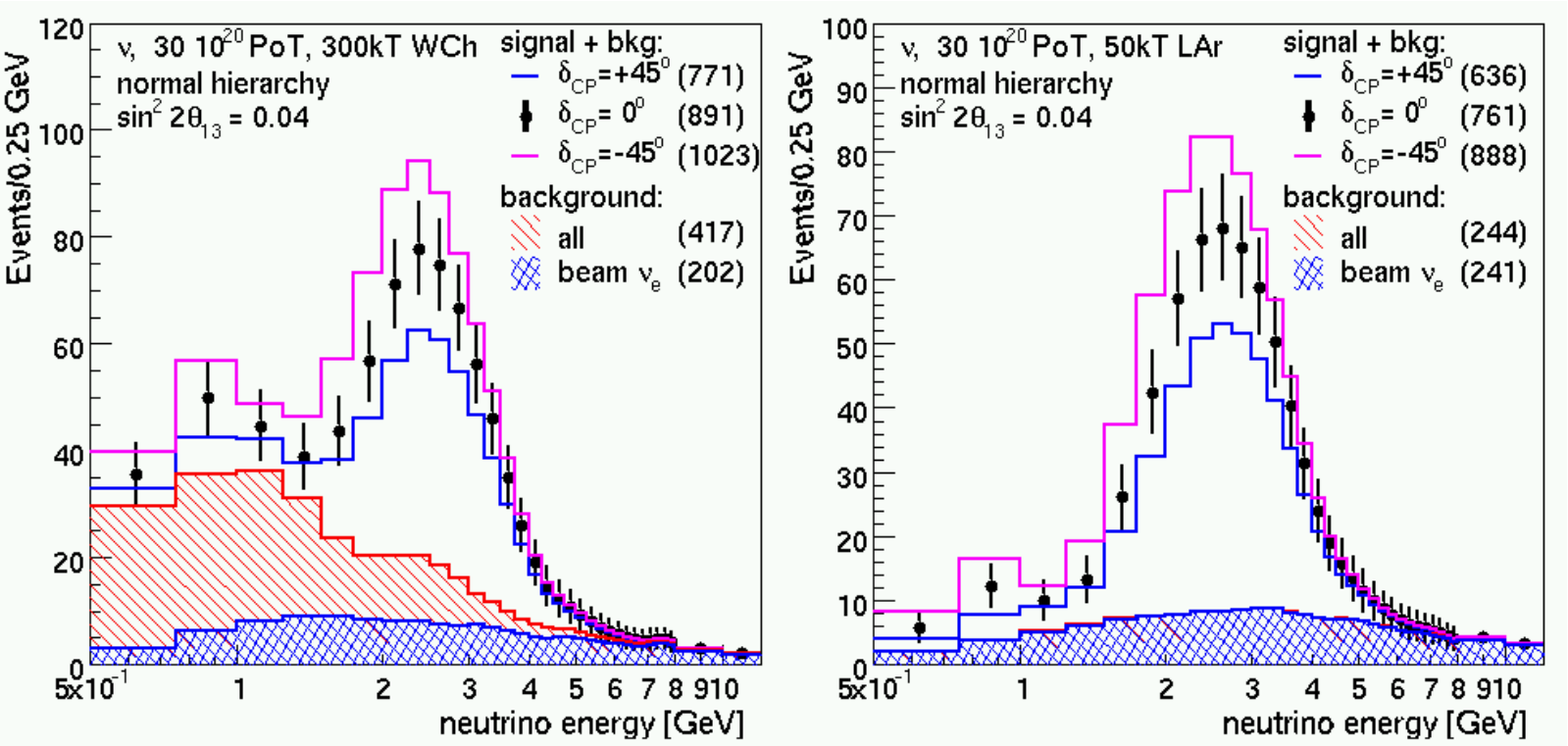
Requires 100× scale-up - unproven.

LBNE/DUSEL spectra and event rates

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.

Exposure is 3 MW. yr ν with $\sin^2 2\theta_{13} = 0.04,\ \delta_{cp} > 0,\ m_3 > m_1$

300 kT WCe **50 kT LAr**



Measurements of δ_{cp} in LBNE

Mark Dierckxsens

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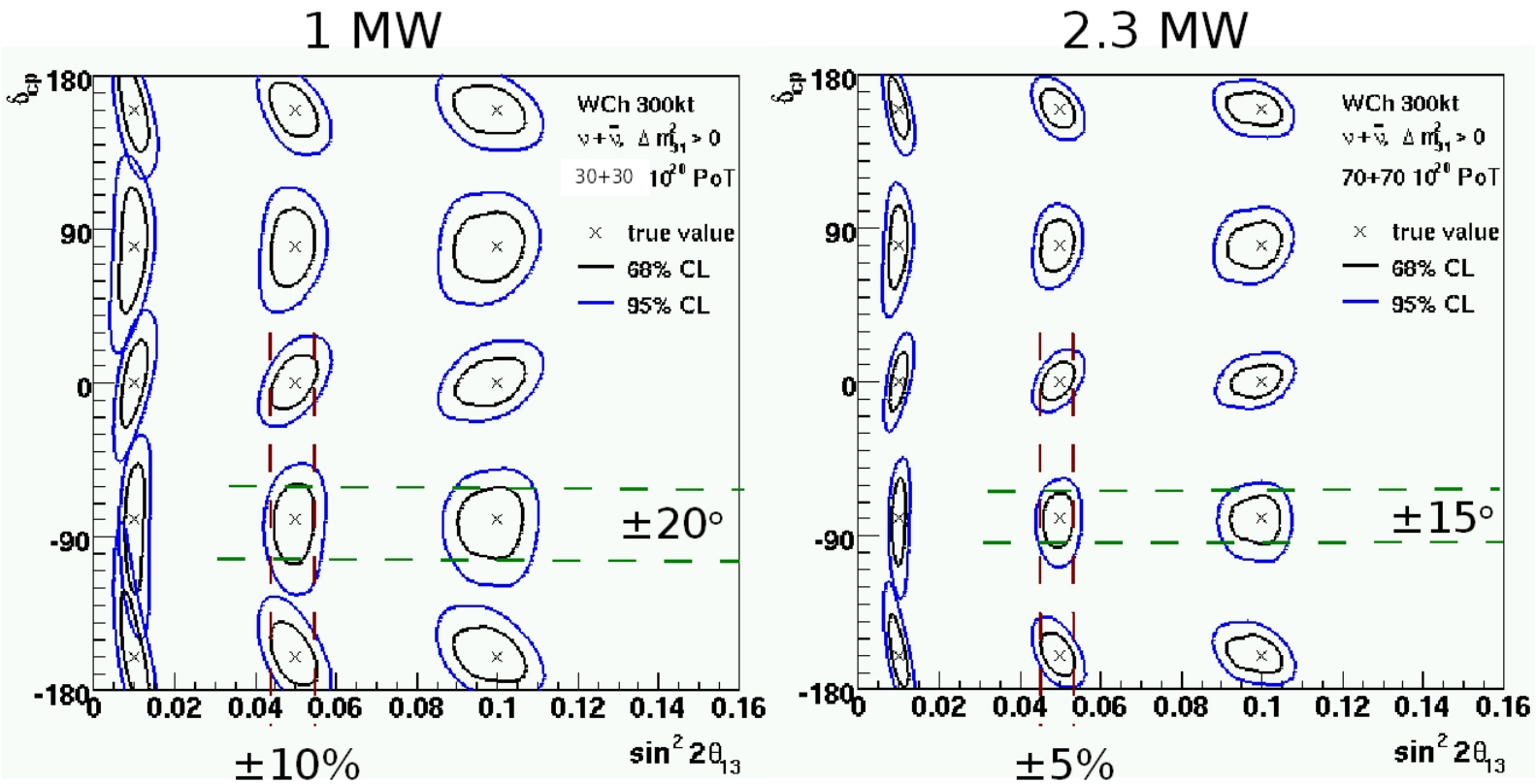
with a 300 kT WCe detector and 3 yrs of ν + 3 yrs of $\bar{\nu}$ running:

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



Precision measurement of δ_{cp} for $\sin^2 2\theta_{13} \geq 0.01$

DUSEL Sensitivities

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

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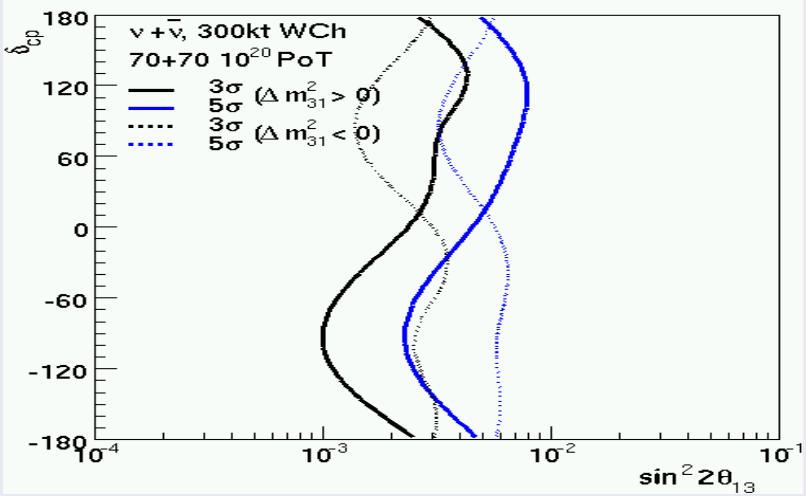
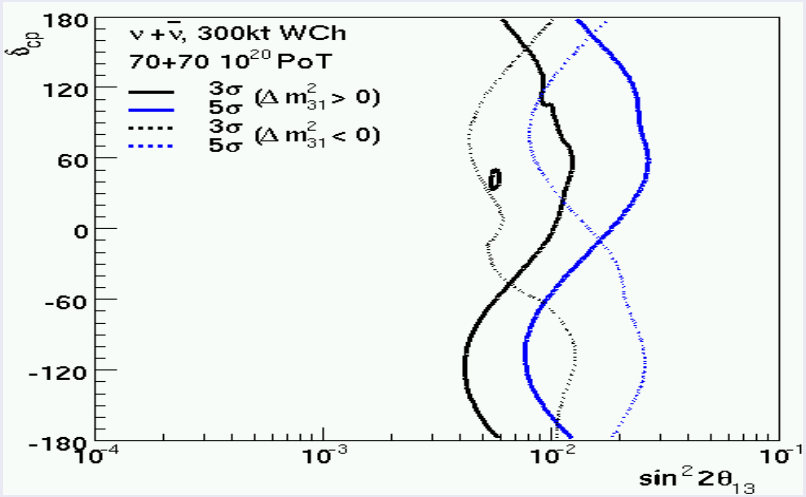
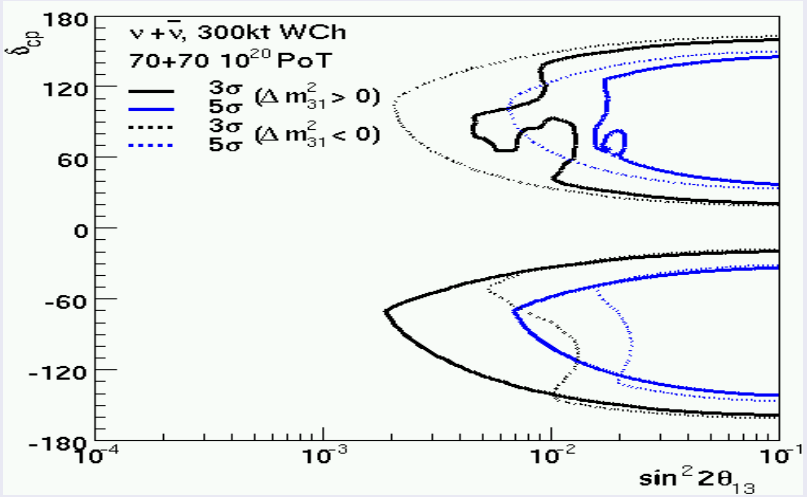
θ_{13} @ 3,5 σ



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)	CPV
	all δ_{cp}	50% δ_{cp}
0.004	0.014	0.012

Mark Dierckxsens, APS 09

Summary and Conclusions

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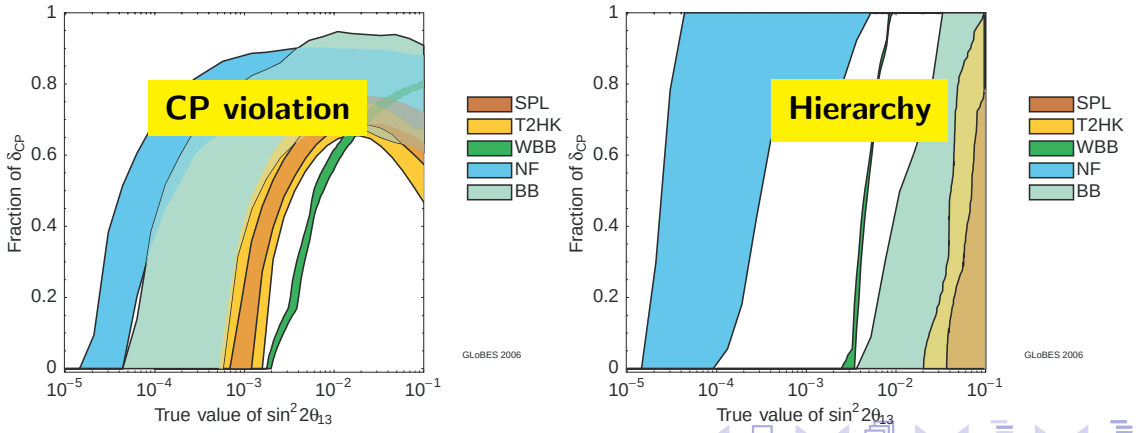
3 flavor neutrino mixing is now well established, but STRANGE. Large off diagonal terms and almost maximal mixing.

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?**

Next. gen. reactor and accelerator ν expts determine if $\sin^2 2\theta_{13} > 0.005$ *and can measure δ_{cp} and the mass hierarchy for* $\sin^2 2\theta_{13} \geq 0.01$.

Neutrino factories and beta beams can push further, arXiv:0712.0909 :



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EXTRA SLIDES FOR DISCUSSION

Sensitivity vs Exposure

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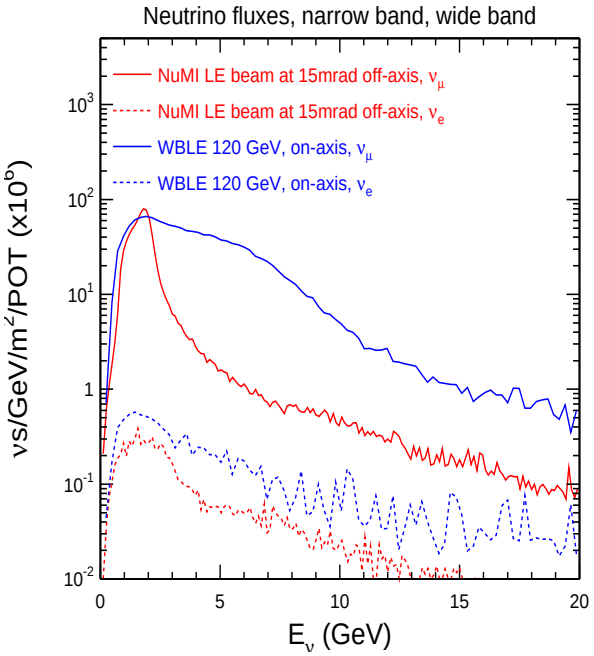
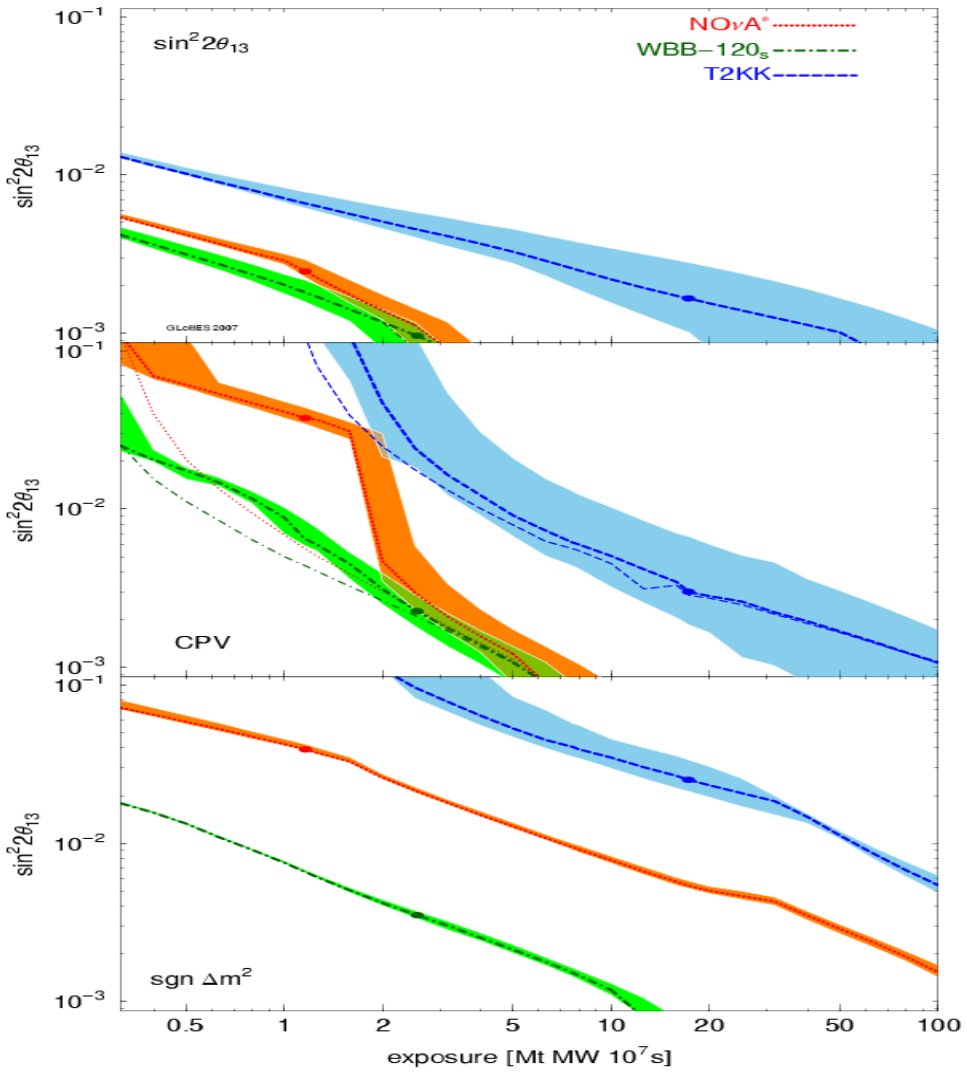
The potential physics reach from studies with the 120 GeV WBLE-DUSEL at 1300km using a LAr detector, the NOνA experiment and the T2KK experiment:*



From hep-ph/0703029: