Long Baseline Accelerator Neutrino Experiments and the Neutrino Mass Hierarchy

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April 26, 2012

Mass, Energy, and Length Scales

$\sin^2 2\theta_{12}$	0.857 ± 0.024
$\sin^2 2\theta_{23}$	> 0.95
$\sin^2 2\theta_{13}$	0.098 ± 0.013
Δm^2_{21}	$7.50 \pm 0.20 \times 10^{-5}\,\mathrm{eV}^2$
$\lvert\Delta m^2_{32}\rvert$	$2.32^{+0.12}_{-0.008} \times 10^{-3}\,\mathrm{eV}^2$

Solar

Atmospheric

Maximal mixing condition:

$$\Delta = 1.27\frac{\Delta M^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})} = \frac{\pi}{2}$$

At peak mixing:

Solar

$$L(\mathrm{km}) = 16 \times 10^3 E(\mathrm{GeV}) = 16\ E(\mathrm{MeV})$$

$$L(\mathrm{km}) = 540\ E(\mathrm{GeV})$$

Atmospheric

ν_m to ν_e is small in long base line

$$\langle \nu_e | \nu_\mu(t) \rangle = \Delta_{21} \sin 2\theta_{12} \cos\theta_{23} + e^{-i(\Delta_{31}+\delta)} \sin\Delta_{31} \sin 2\theta_{13} \sin\theta_{23}$$

small

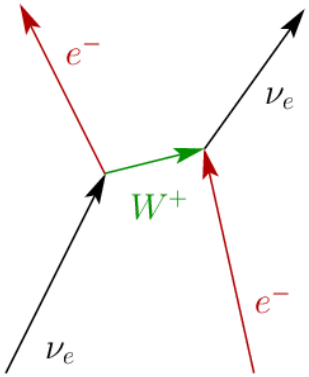
$$\Delta_{31} \approx \frac{\pi}{2}; \quad \Delta_{21} \approx \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \frac{\pi}{2} \approx \frac{1}{30} \frac{\pi}{2}$$

Sort of small

For anti-neutrinos, the sign of δ is reversed. The goal is to determine the sign of Δ_{31}. We can't tell the difference between (Δ_{31}, δ) and ($-\Delta_{31}$, $\pi-\delta$).

$$\begin{aligned} P(\nu_\mu \to \nu_e) \quad = \quad & \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\Delta_{31} \\ & + \Delta_{21} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta_{31} \cos(\Delta_{31}+\delta) \\ & + \Delta^2_{21} \cos^2\theta_{23} \sin^2 2\theta_{12} \end{aligned}$$

Matter Effect



- ν_es interact differently in matter from ν_μs because they scatter from electrons by W exchange.
- Analogous to K_S regeneration.
- Key parameter: $x = 2\sqrt{2}G_F N_e E / \Delta m^2_{31} \approx E(\mathrm{GeV})/14$

A circle in polar coordinates:

$$r = \sin 2\theta_{13}; \quad \phi = \delta$$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(1-x)\Delta_{31}}{(1-x)^2}$$
$$+\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{13}\sin 2\theta_{12}\,\sin 2\theta_{23}\frac{\sin[(1-x)\Delta_{31}]}{1-x}\frac{\sin x\Delta_{31}}{x}\cos(\Delta_{31}+\delta)$$
$$+\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(x\Delta_{31})}{x^2}$$

x changes sign with Δm^2_{31}

δ changes sign with $\upsilon \to \bar{\upsilon}$

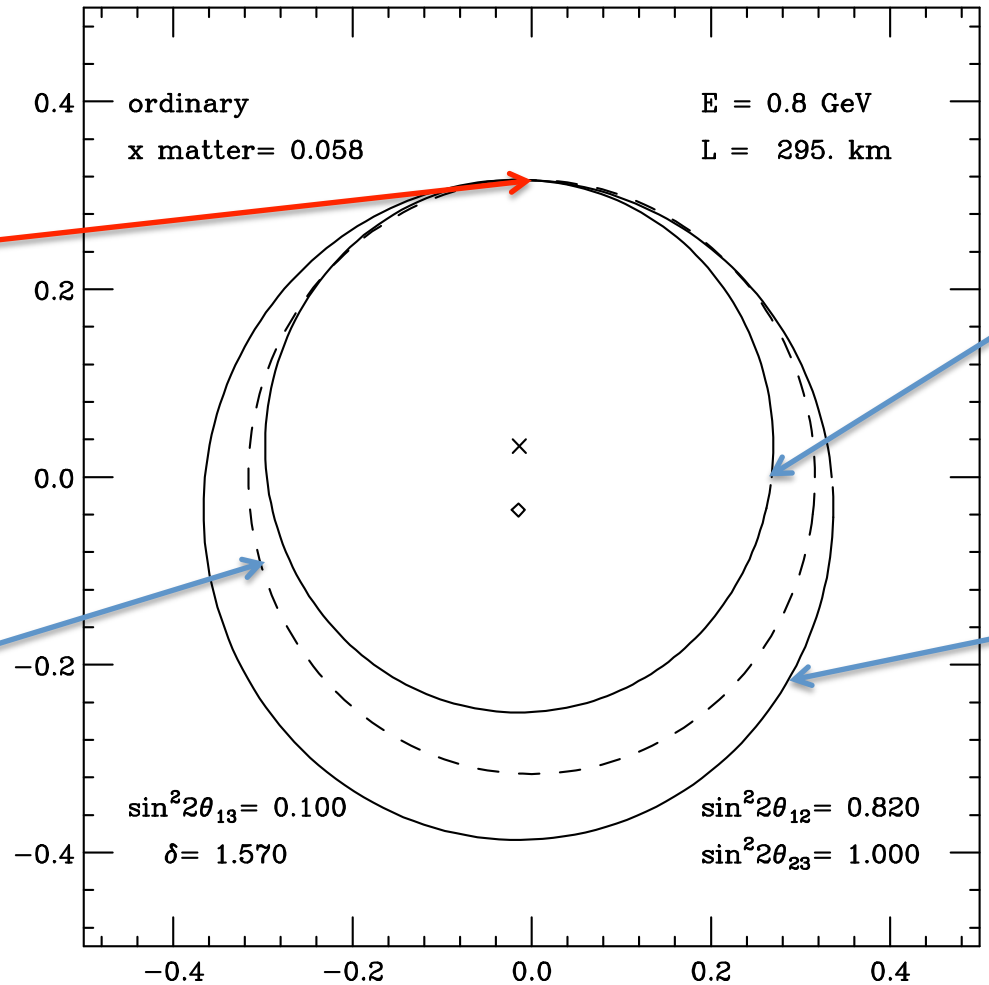
Example: T2K

Answer:

$\sin 2\theta_{13} = \sqrt{0.10}$

$\delta = \pi / 2$

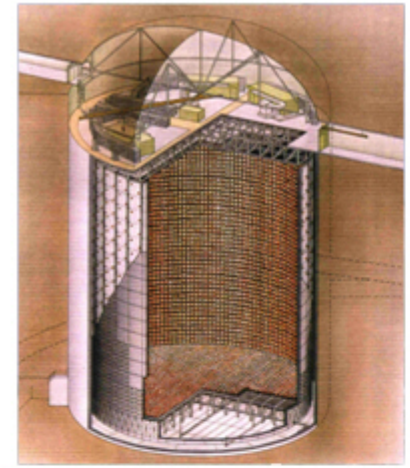
Reactor experiment

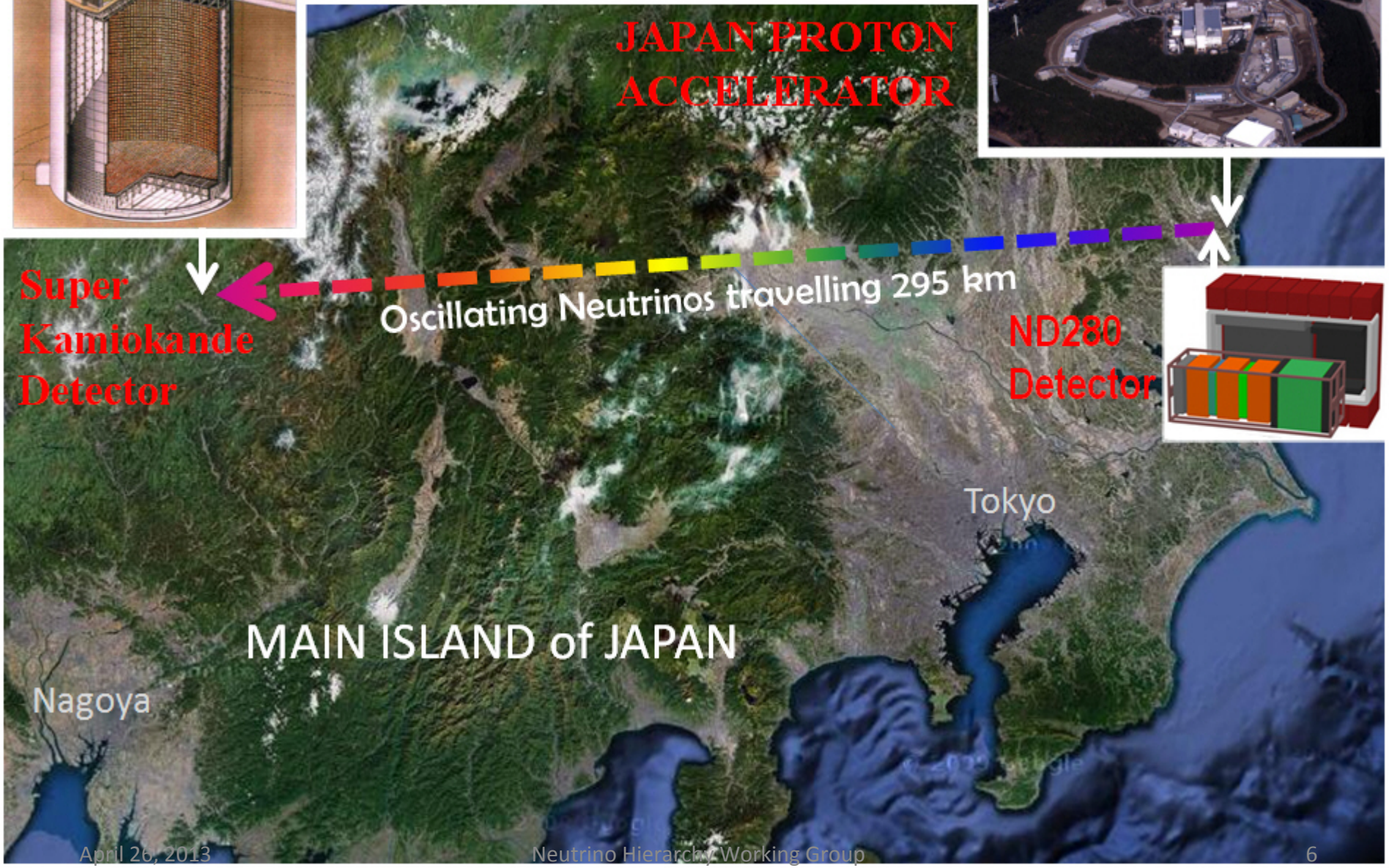


P_{υ}

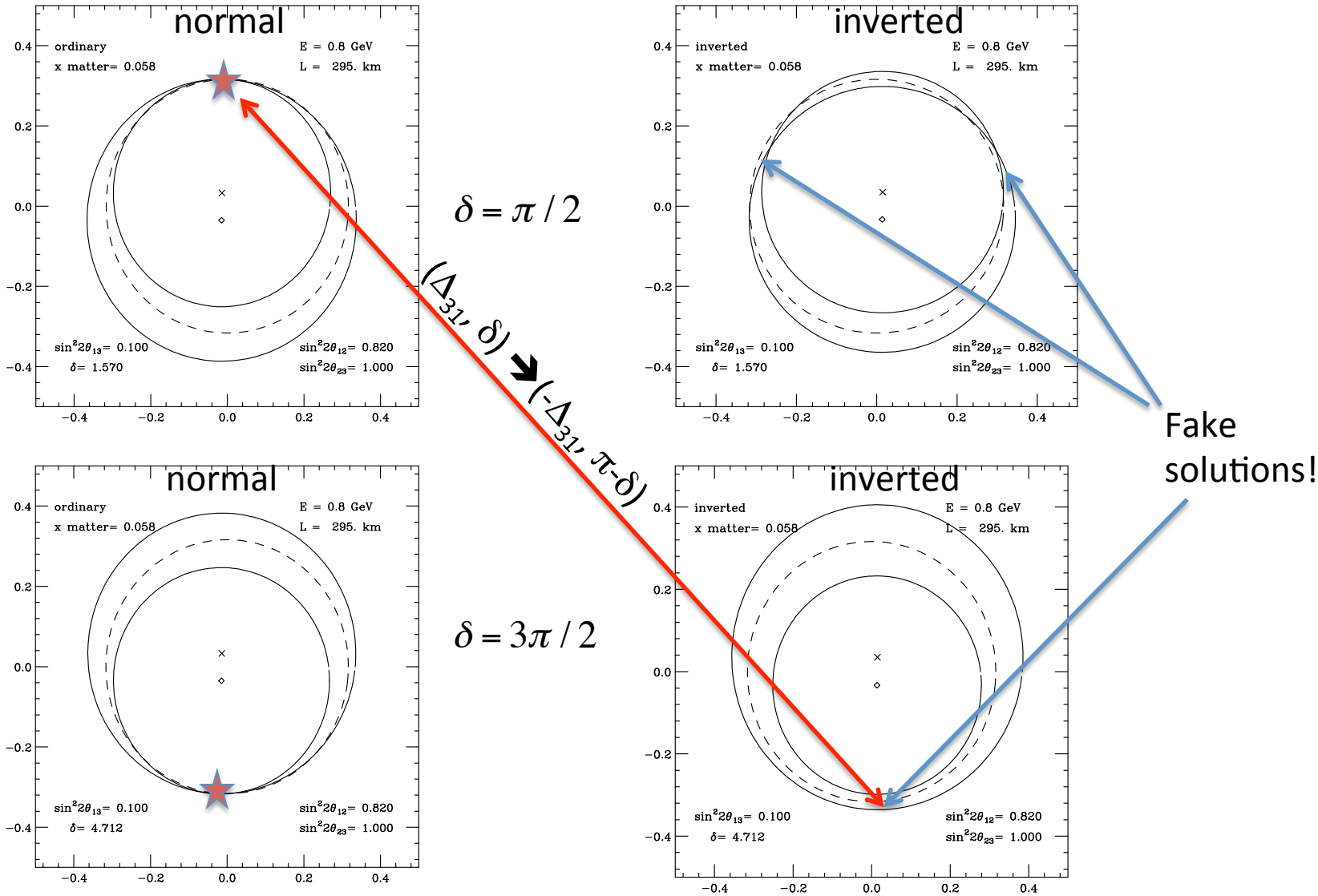
$P_{\bar{\upsilon}}$

T2K EXPERIMENT





T2K Hierarchy Plots



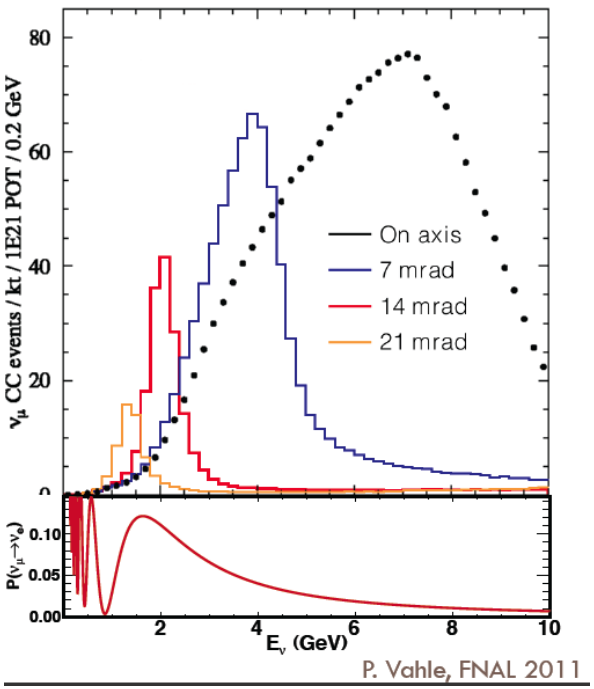
NOvA

Off-axis beam at 810 km.

15 kt detector.

Liquid scintillator.

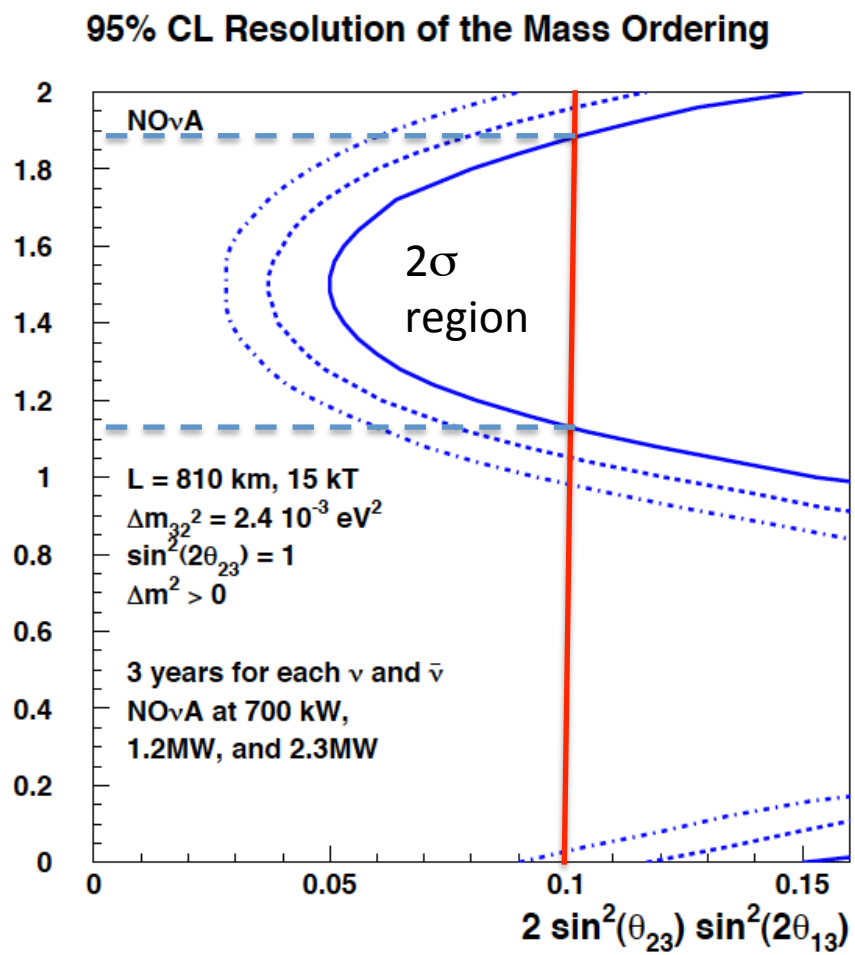
220 t near detector at 1 km.



NOvA Sensitivity

From NOvA website:

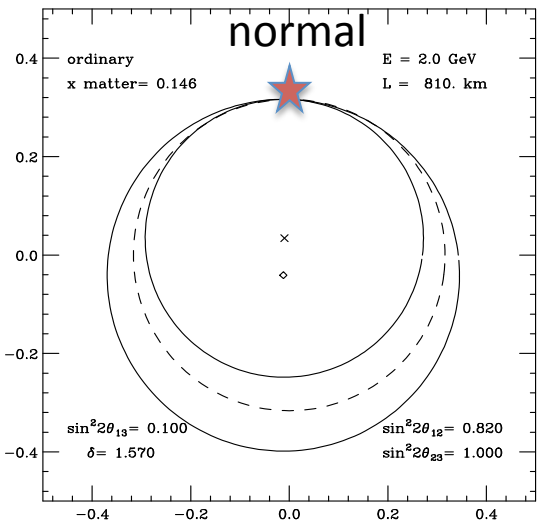
The experiment will begin taking data in 2013 and construction will be complete in January 2014. The first run will last six years.



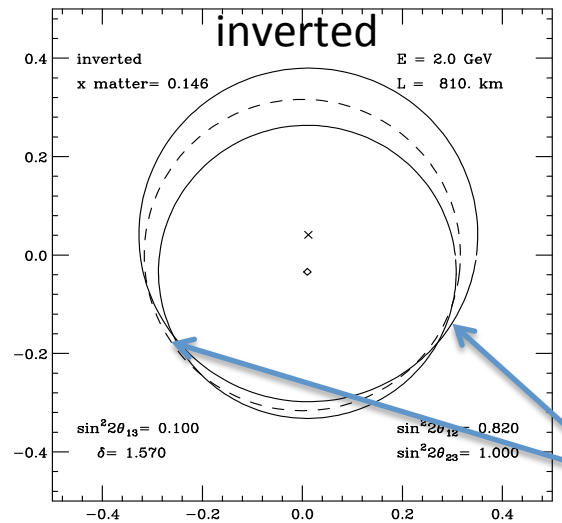
- Sensitivity to mass hierarchy

P. Vahle, FNAL 2011

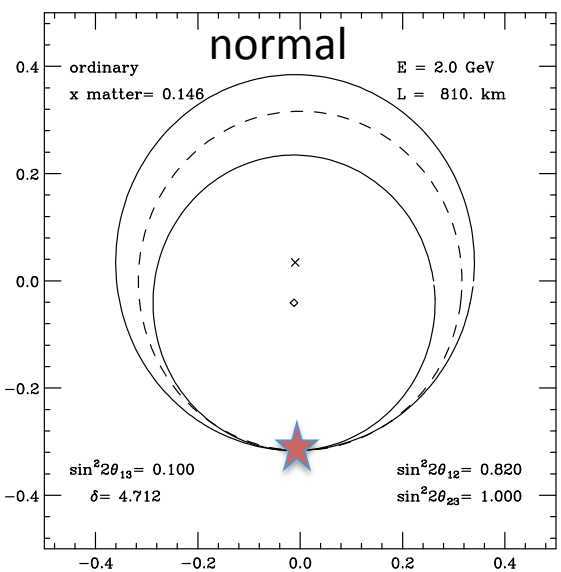
NOvA Hierarchy Plots



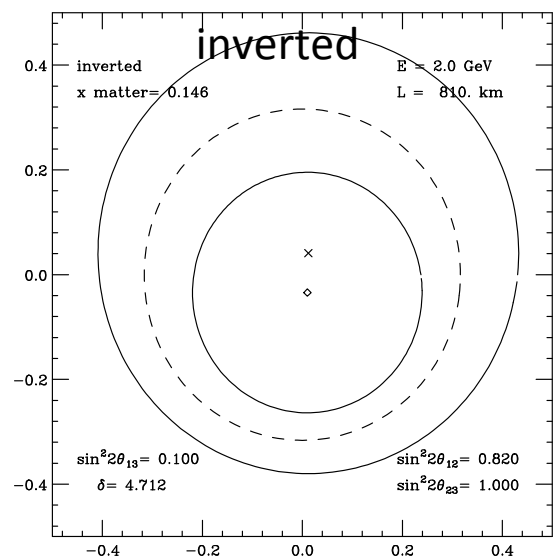
$\delta = \pi / 2$



Fake solutions!



$\delta = 3\pi / 2$



LBNE Project Scope

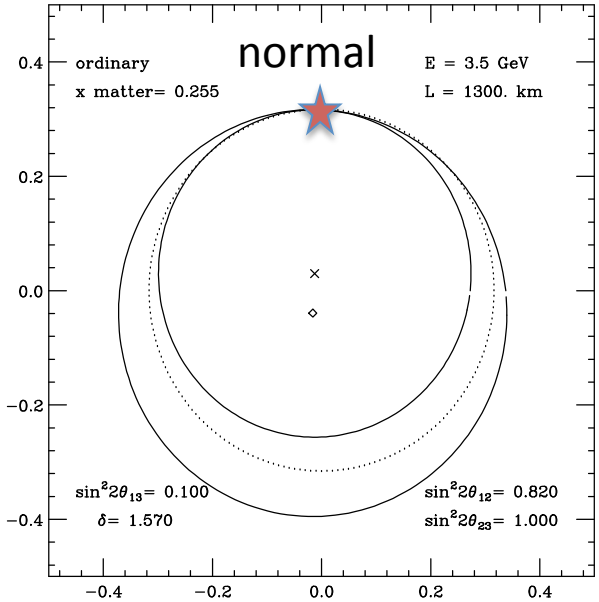
New Neutrino Beam at Fermilab…

Directed towards a distant detector at the Sanford Underground Research Facility (SURF) in Lead, SD

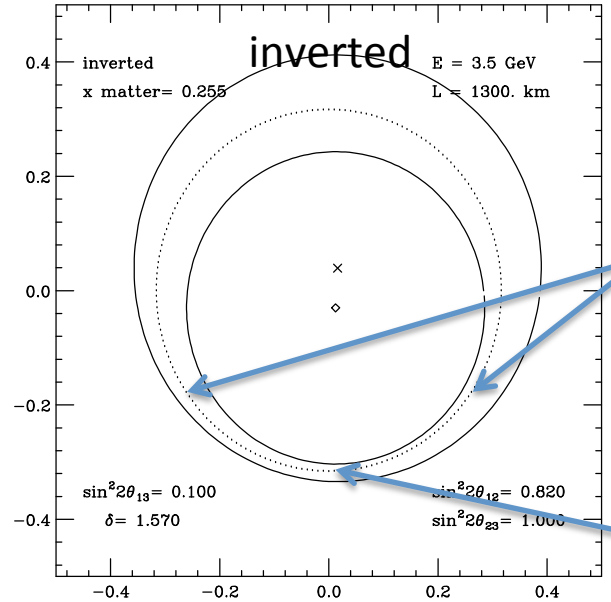
10 kton Liquid Argon TPC Far Detector just below the surface

All the Conventional Facilities at Fermilab and SURF required to support the beam and detectors.

LBNE Hierarchy Plots

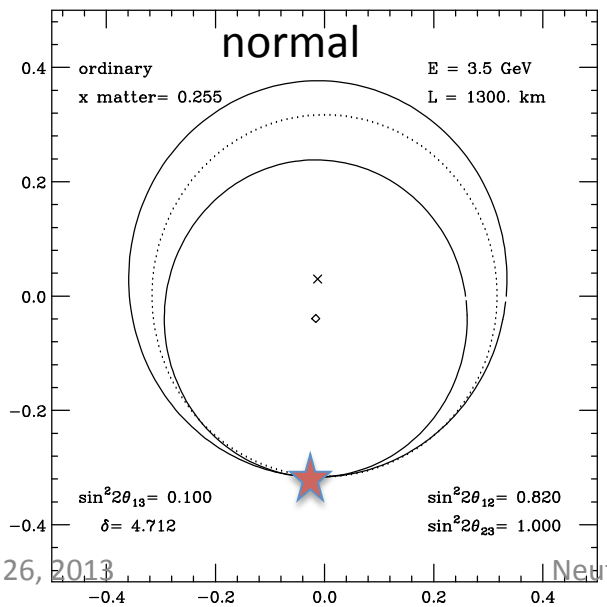


$\delta = \pi / 2$

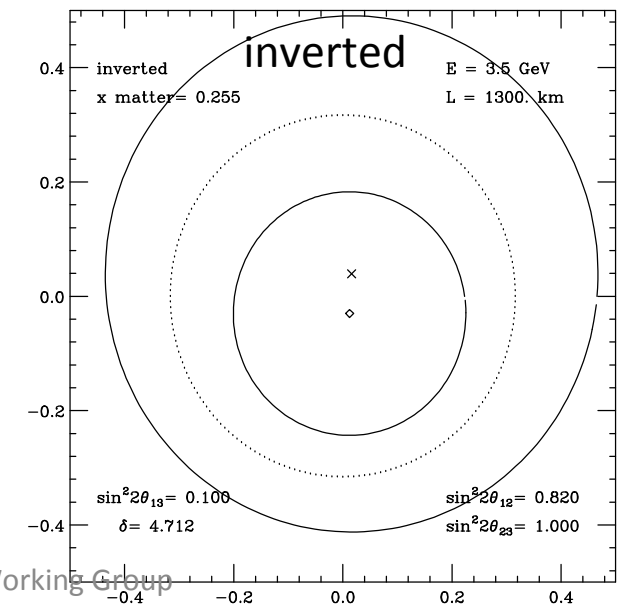


NOvA fakes

LBNE Fake solution!



$\delta = 3\pi / 2$

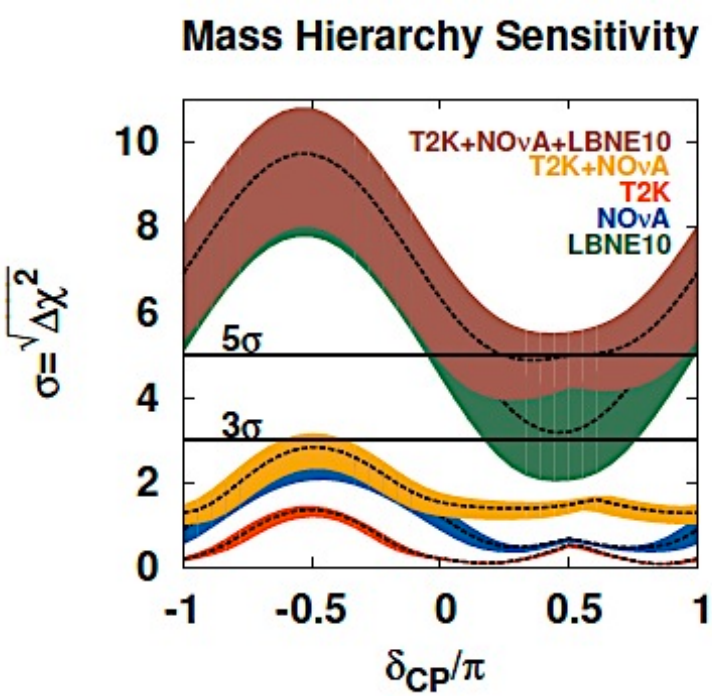


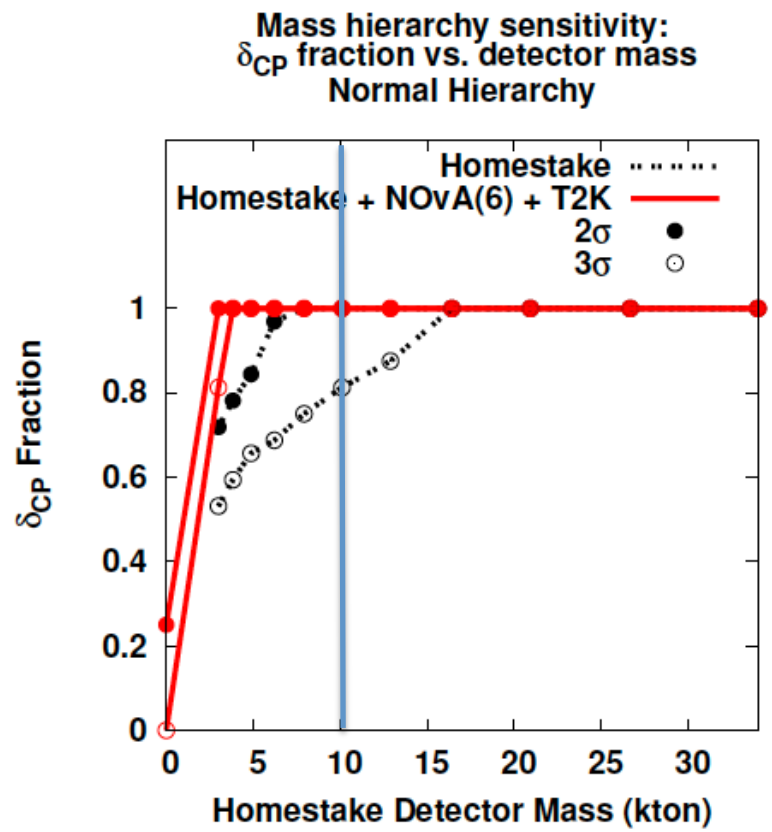
LBNE 10kt Mass Hierarchy Reach

10 kt LBNE performance:

80% 3σ coverage in 5+5 years alone

100% 3σ coverage with NOvA+T2K





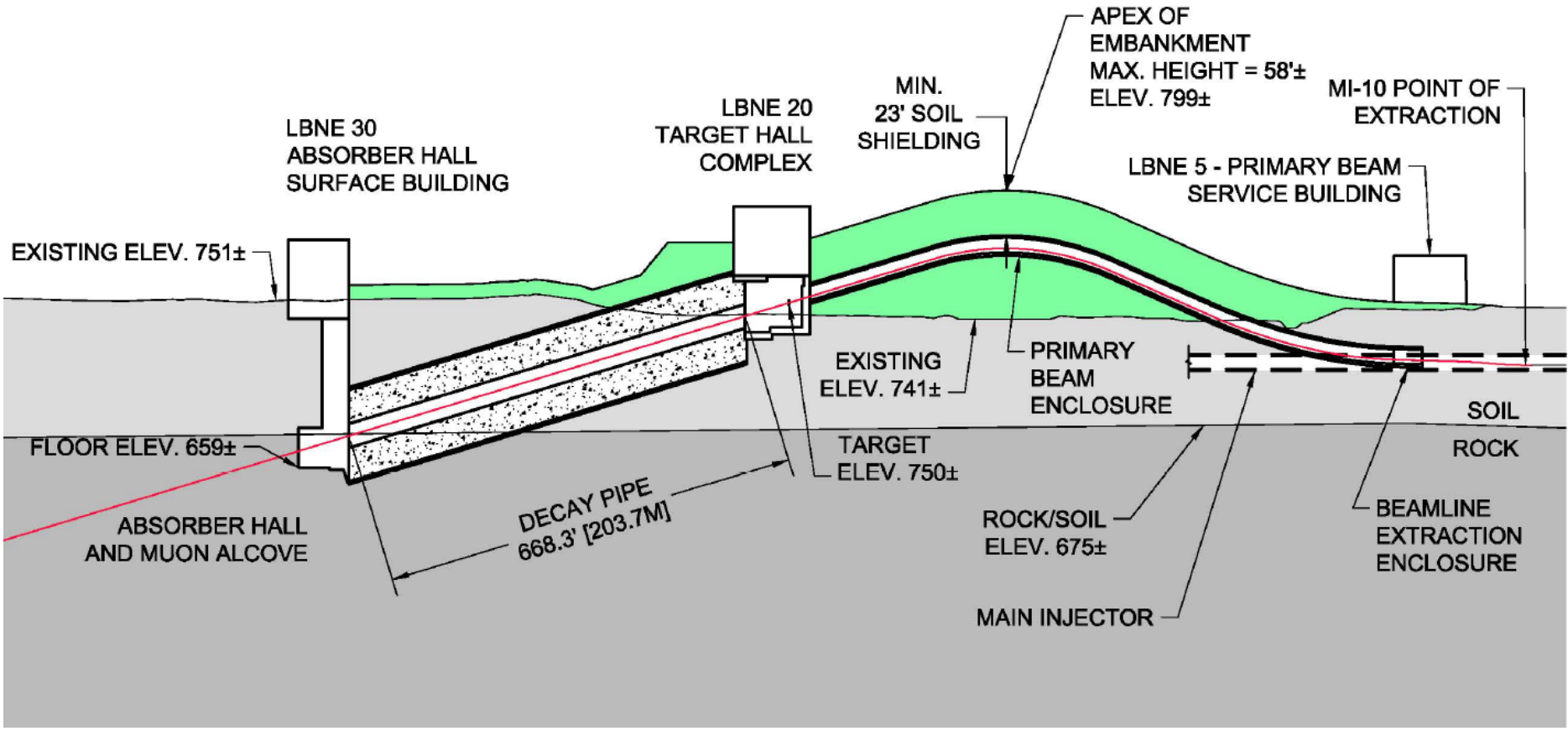
Costs at 'Reconfiguration' June 6, 2012 DOE Briefing

Scope	Cost (TPC)
LBNE 34 kTon@4850L and near detector	$1.440B
LBNE Phase I, 10 kTon surface	$0.789B
+Place Underground	$0.924B
+ Near Detector	$1.054B

Milind Diwan, LBNE Houston Meeting, December 1, 2012

CF Critical path Item

- Embankment is on critical path.
- Takes 2 years for earth to settle prior to construction



LBNL Involvement

- Richard Kadel
  - Exec Board Member 2010- Jan 2013
  - Member, Water Cherenkov Technical Board through Jan 2012
- Victor Gehman
  - Co Convener (with Xinhua Bai SDSMT) of detector cleanliness group (both LAr and formerly WCD)
- Trigger Scintillator R&D for the LAr detector
  - Baseline proposal has sensitivity of 2 photo electrons for 20 MeV neutrino interaction with 800,000 photons generated. Efficiency = 2.5×10^{-6}
- Low energy behavior of LAr detector via cleanliness group
  - Low threshold for supernova physics
- Slow controls and/or Slow monitoring for entire experiment

New Area of Involvement: Offline Analysis

- Anticipate that much of the detector "hardware" will be sold off to non-DOE funding agencies.
- Current LBNE Software package is based on "LArSoft," meant to serve all possible LAr detectors in all possible configurations (ie Argonut, MicroBoone,…)
- We have been encouraged to develop an alternative, easily portable software package.
- Working on Offline proposal involving LBNL, LLNL, Davis LLNL, Stonybrook, Cambridge (…SLAC not yet signed on)
- Leverage experience of LBNL on software management/execution in ATLAS, DayaBay, etc. Includes Craig Tull from Computer Science Div.
- Provides early entry into physics analysis
- Could test software against data from CAPTAIN, a 2 m diameter x 1 meter high (vertical drift) TPC being built at LANL.

Challenge of Energy Measurement in Liquid Argon

- If the scattering is quasi-elastic, measuring the charged lepton determines neutrino energy, but there are other processes:

$$\upsilon_e n \rightarrow ep$$

$$\upsilon_e n \rightarrow e\Delta^+$$

$$\upsilon_e p \rightarrow e\Delta^{++}$$

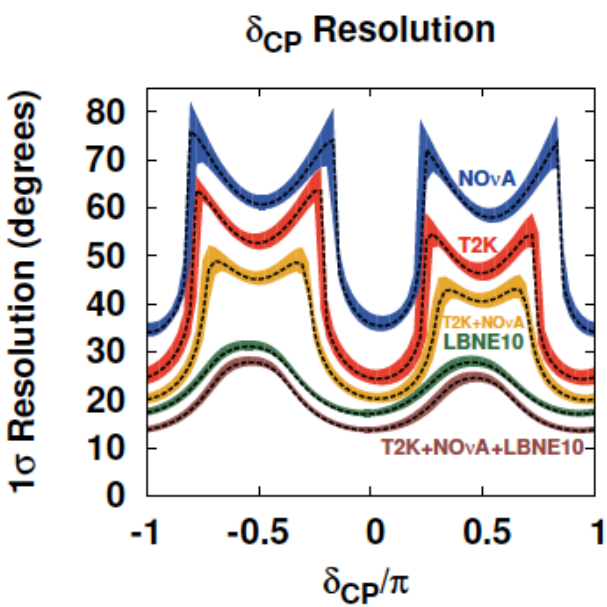
Other effects that obscure the energy measurement:

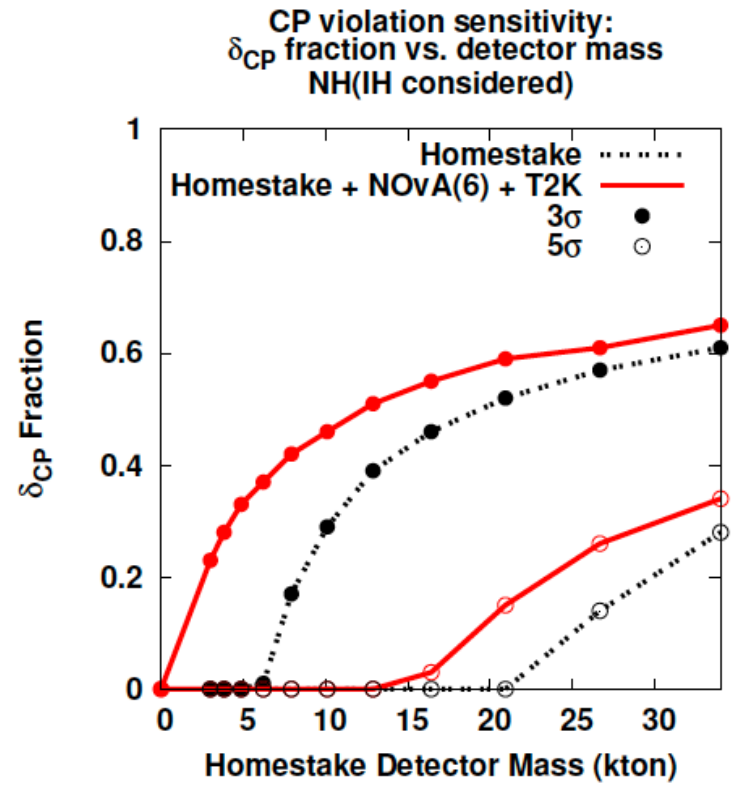
Fermi motion
Neutrons from nucleus
Pion absorption in nucleus
Scattering from correlated nucleons

Progress will require joint experimental and theoretical effort.

Beyond Mass Hierarchy at LBNE

- Involvement in LBNE would likely mean pushing for Phase II, in particular measuring δ_{CP}.
- Task force did not address LBNE capability for measuring δ_{CP} or assess the importance of the measurement.





Summary

- The ability of long base line neutrino experiments to determine the hierarchy depends critically on the neutrino energy, which is in practice proportional to the distance.
- T2K is too short to be effective.
- NOvA could get a 2σ result with a fortuitous value of δ_{CP}.
- Detailed studies for Phase I LBNE show that alone it has an a priori 80% chance of a 3σ determination of the hierarchy, which increases to 100% with NOvA and T2K added in.
- This is based on 10kt LA with 5+5 years of running. With a favorable value of δ_{CP}, the hierarchy could be known sooner.
- However, in the intervening 15 years or so, some other experiment could scoop LBNE, or, more probably, find an indication that was less than definitive.

Offline software: Possible Model

- Diagram shows one possible implementation of software package
- Looking at CAPTAIN LAr detector being built at LANL for Jan, 2014 as hardware test bed for software.