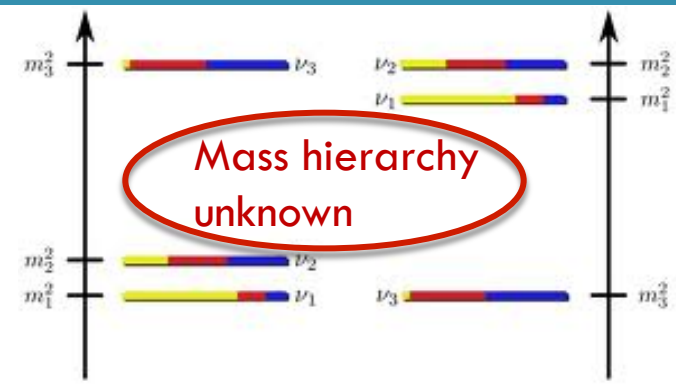
LBNE IN THE PRECISION ERA OF NEUTRINO OSCILLATION

Elizabeth Worcester (BNL) for the LBNE Collaboration

EPS HEP, Stockholm, Sweden, July 19, 2013

3 Neutrino Model

- $|\nu_i\rangle = \sum_\alpha U^*_{\alpha i} \nu_\alpha\rangle$
- Flavor composition of neutrinos change as they propagate



$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- $\theta_{23} \approx 45°$
- Atmospheric, Accelerator
- Octant unknown

- $\theta_{13} \approx 10°$
- Short-Baseline Reactor, Accelerator
- δ_{CP} unknown

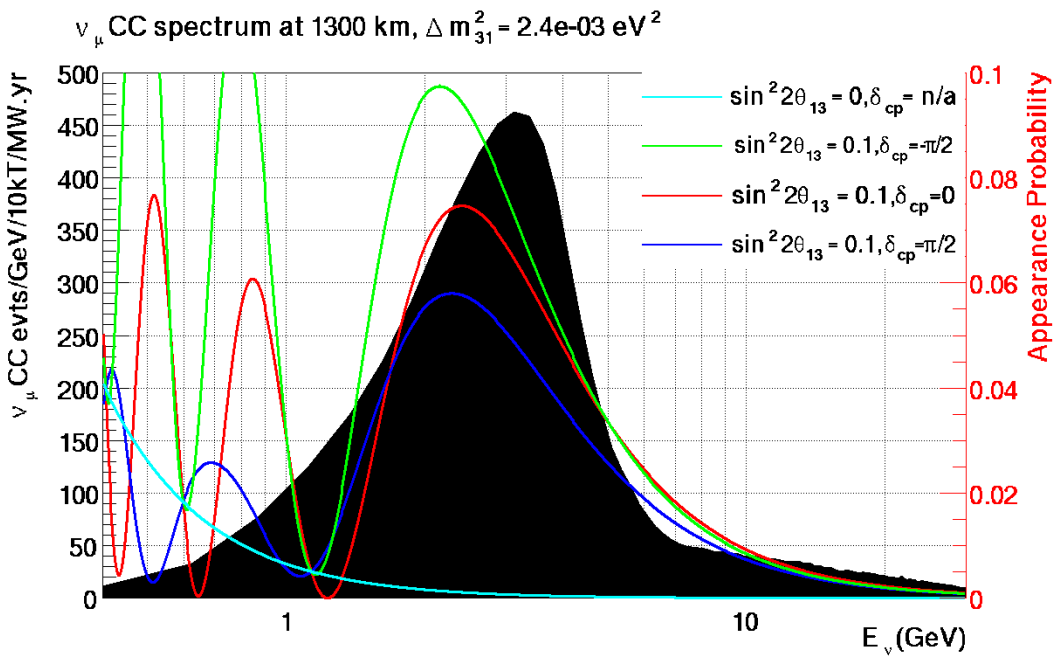
- $\theta_{12} \approx 35°$
- Solar, Long-Baseline Reactor

ν_e Appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} - \alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

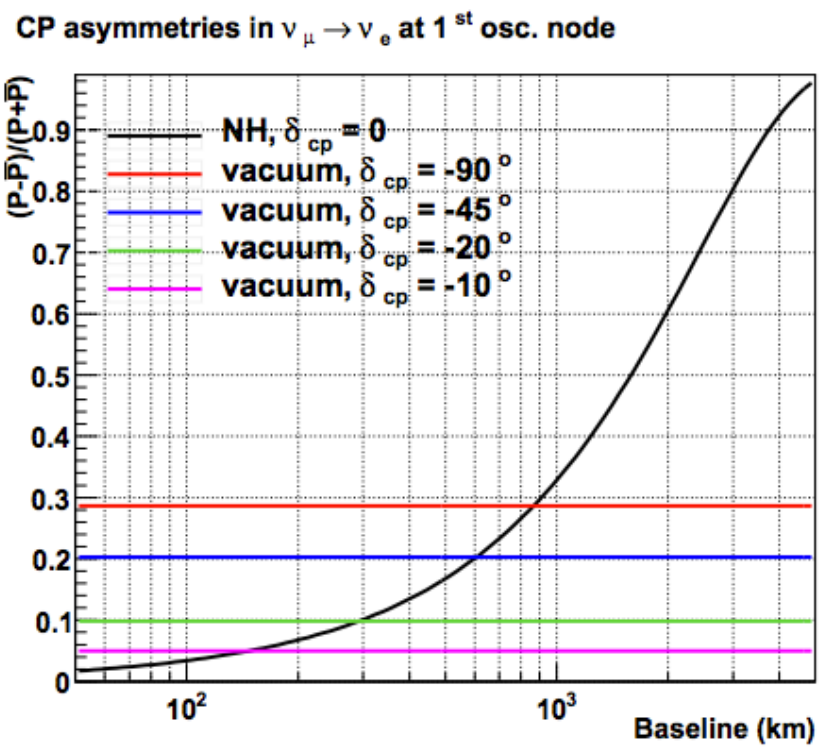
$$a = G_F N_e \sqrt{2}$$

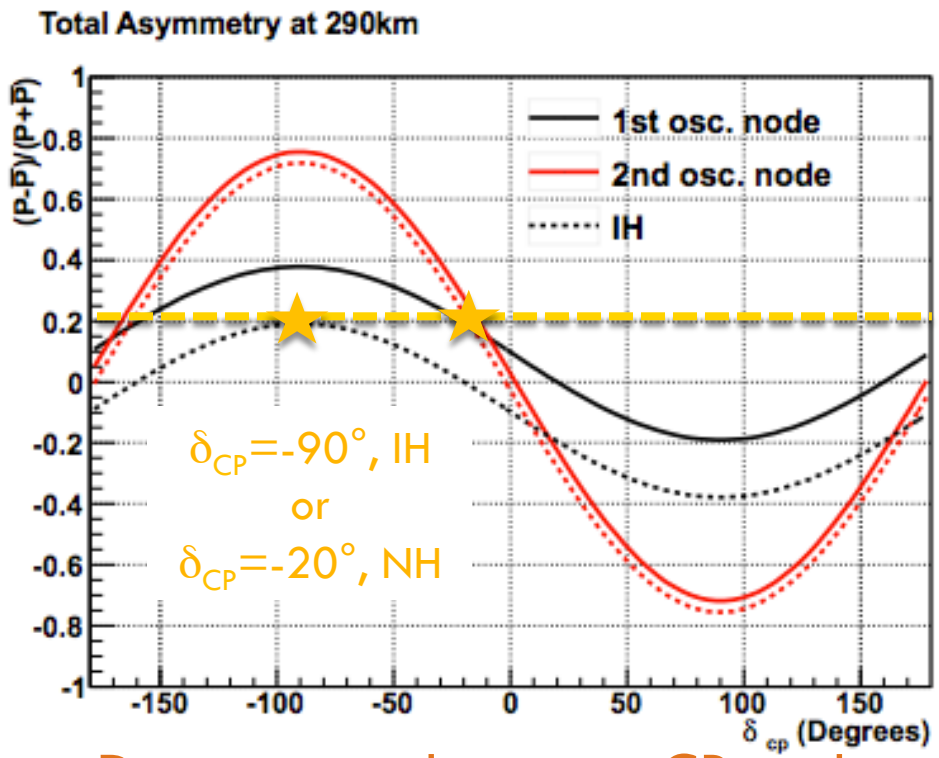
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- $\sin^2(2\theta_{13})$ determines size of event sample
- δ_{CP} affects amplitude of oscillation
- Δ_{31} affects frequency of oscillation
- MH affects both amplitude and frequency

Matter and CP Asymmetry

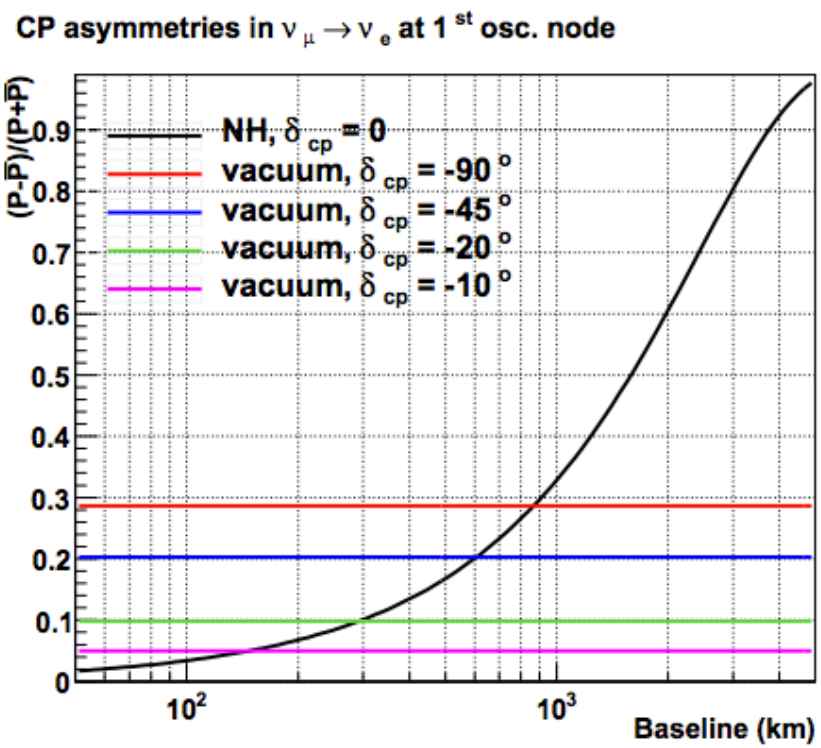


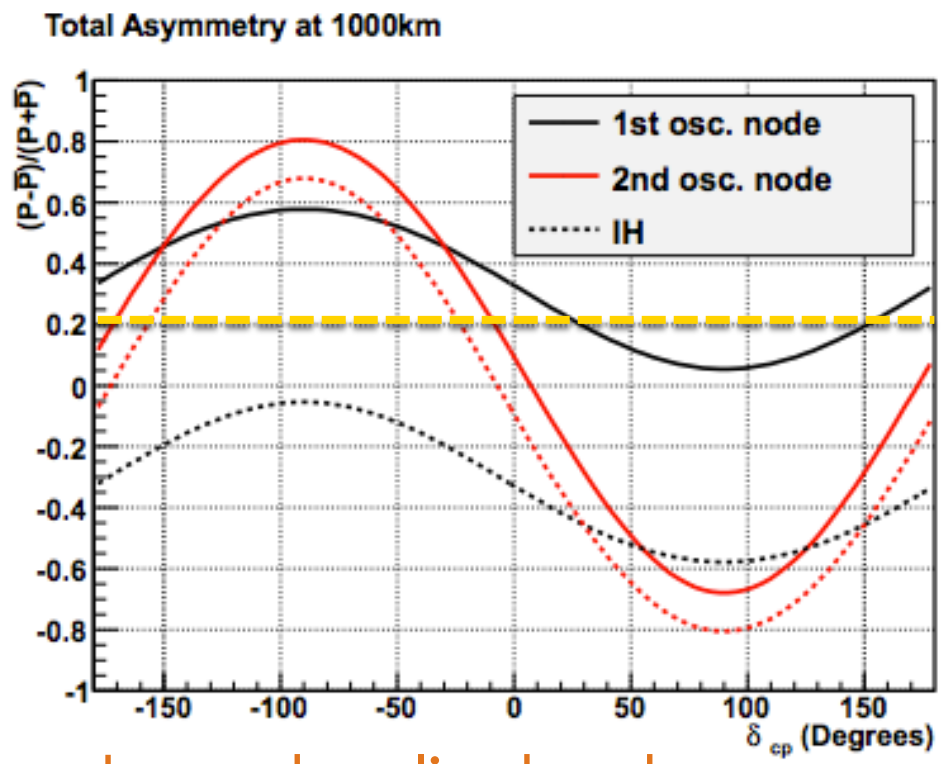


Matter asymmetry very important for long-baseline experiments!

Degeneracy between CP and matter asymmetry for 1st oscillation node at short baseline

Matter and CP Asymmetry



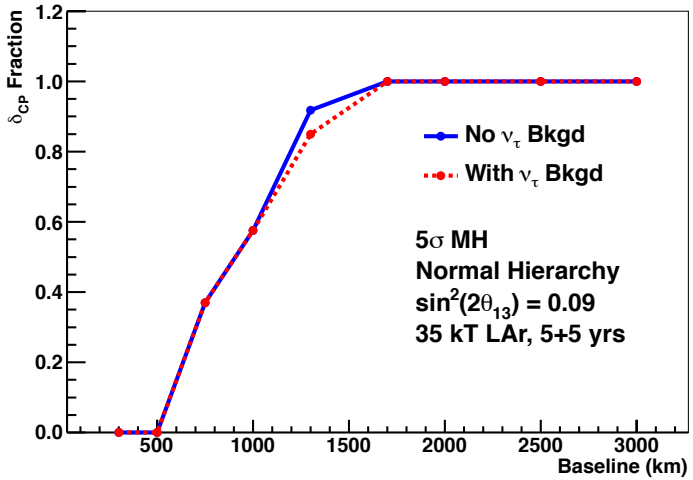


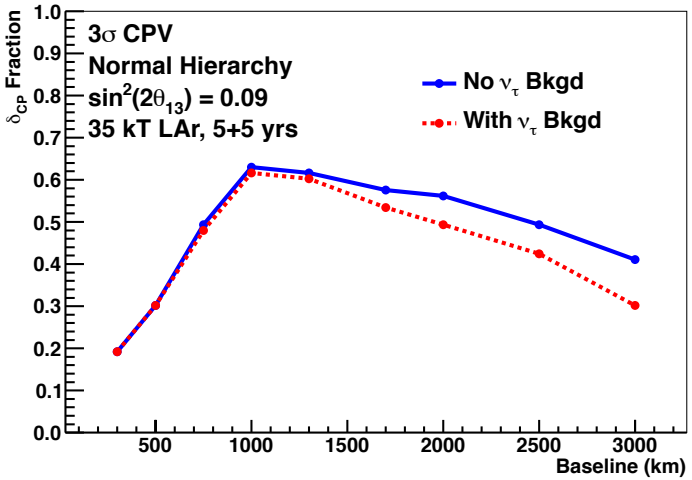
Matter asymmetry very important for long-baseline experiments!

Longer baseline breaks degeneracy between CP and matter asymmetry

Optimum Baseline

- Qualitative summary
  - MH: Longer baseline is better
  - CPV: Balancing act between long enough baseline to resolve degeneracy with MH and short enough baseline to accumulate statistics
- Study with optimized beam design

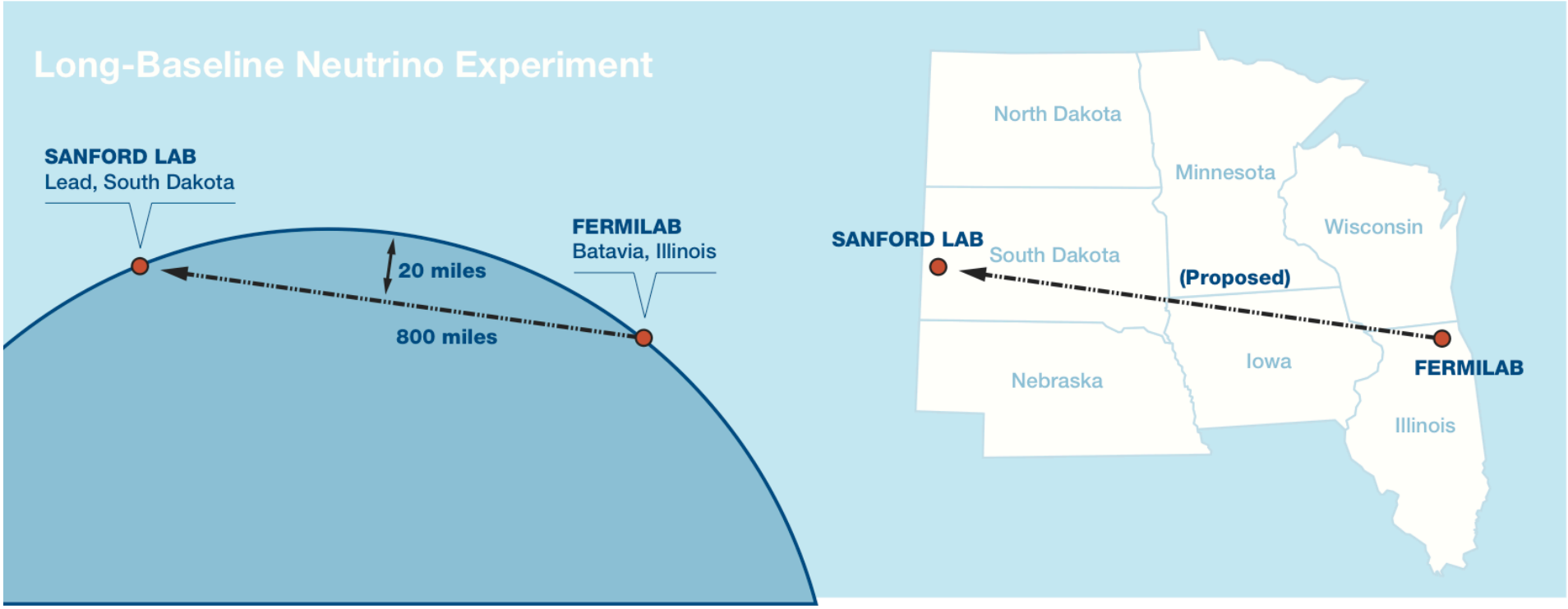




- 1300 km a near optimal baseline

Long-Baseline Neutrino Experiment

- Neutrino beam from FNAL to SURF (1300 km baseline)
  - Protons from Main Injector
  - New μ-neutrino beam line
- Massive underground far detector
  - LAr TPC
  - Integrated photon detection system



Sanford Underground Research Facility

Sanford Underground Research Facility

LBNE Collaboration

- 372 members, 61 institutions, 5 countries (April 2013)
- Co-spokespersons: Milind Diwan (BNL), Bob Wilson (CSU)

Alabama
Argonne
Boston
Brookhaven NL
Cambridge
Catania
Columbia
Chicago
Colorado
Colorado State
Columbia
Dakota State
Davis
Drexel
Duke
Duluth
Fermilab
Hawai
Indian Group
Indiana
Iowa State

Irvine
Kansas State

London UCL
Los Alamos NL

New Mexico
Northwestern

Princeton
Rensselaer

Kavli/IPMU-Tokyo
Lawrence Berkeley NL
Livermore NL

Louisiana State
Maryland
Michigan State
NGA

Notre Dame
Oxford
Pennsylvania
Pittsburgh

Rochester
Sanford Lab
Sheffield
SLAC

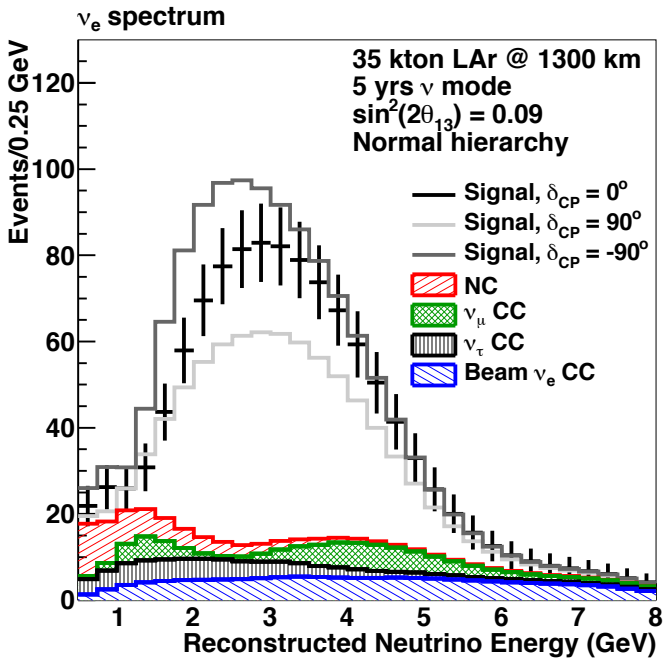
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arllington
Texas, Austin
Tufts
UCLA
Virginia Tech
Washington
William & Mary
Wisconsin
Yale

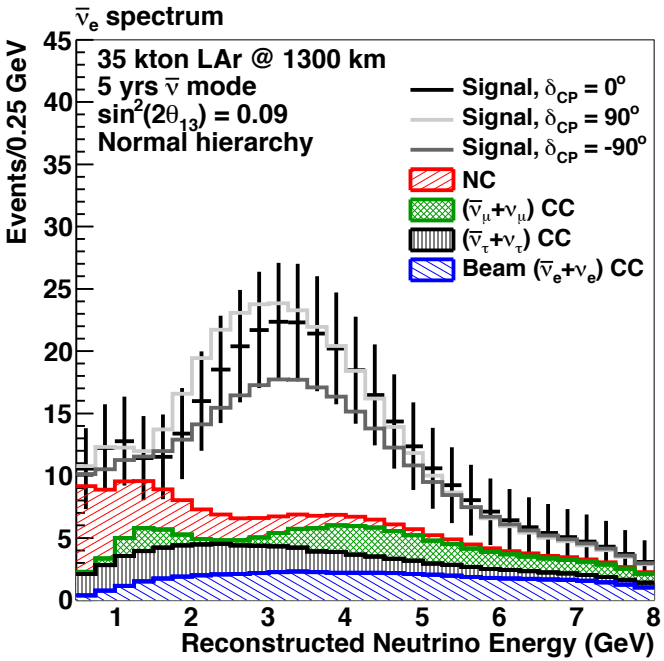
LBNE Staging

- LBNE10
  - 10 kt LAr TPC
  - 700 kW, 120 GeV proton beam (6×10^{20} POT/year)
  - US DOE scope/cost approved, with the expectation that the scope of experiment will expand as the collaboration grows
- Higher exposure
  - Goal to have >10 kt LAr TPC in first phase of experiment
  - Proton beam upgradeable to 2.3 MW
- Underground physics
  - Goal to build first phase of experiment at 4850L - engineering/design efforts focusing on 4850L only

ν_e Appearance Events

35 kt:





10 kt:

	Signal Events	Background Events				
	ν_e	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC	Total
Neutrino Normal Hierarchy	222	19	24	42	14	99
Neutrino Inverted Hierarchy	98	19	23	44	15	100
Anti-neutrino Normal Hierarchy	54	11	11	23	9	54
Anti-neutrino Inverted Hierarchy	80	11	11	23	9	54

ν_e Appearance Events

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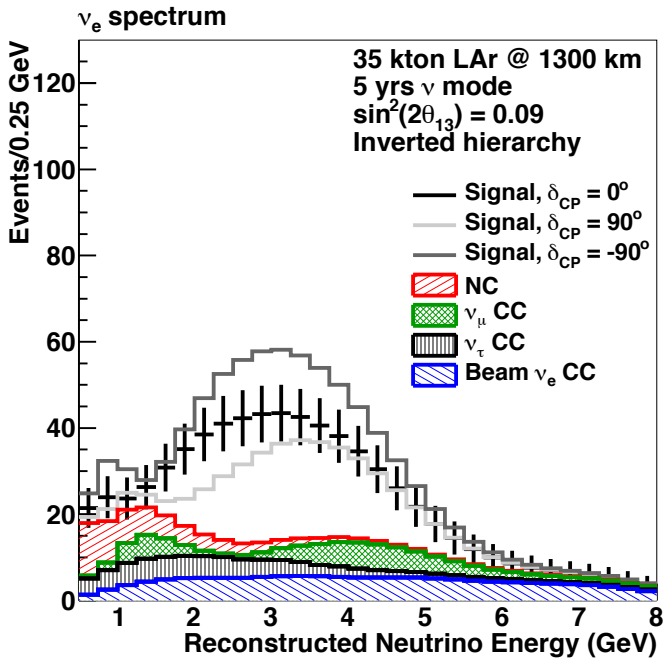

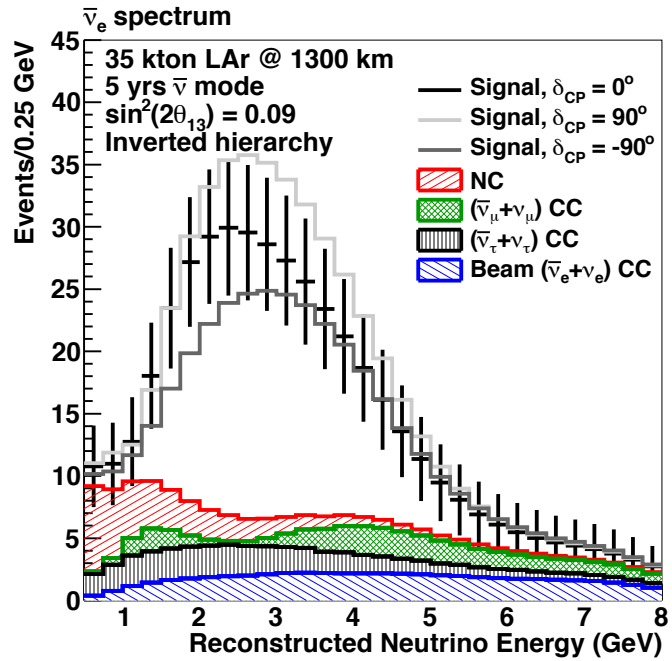

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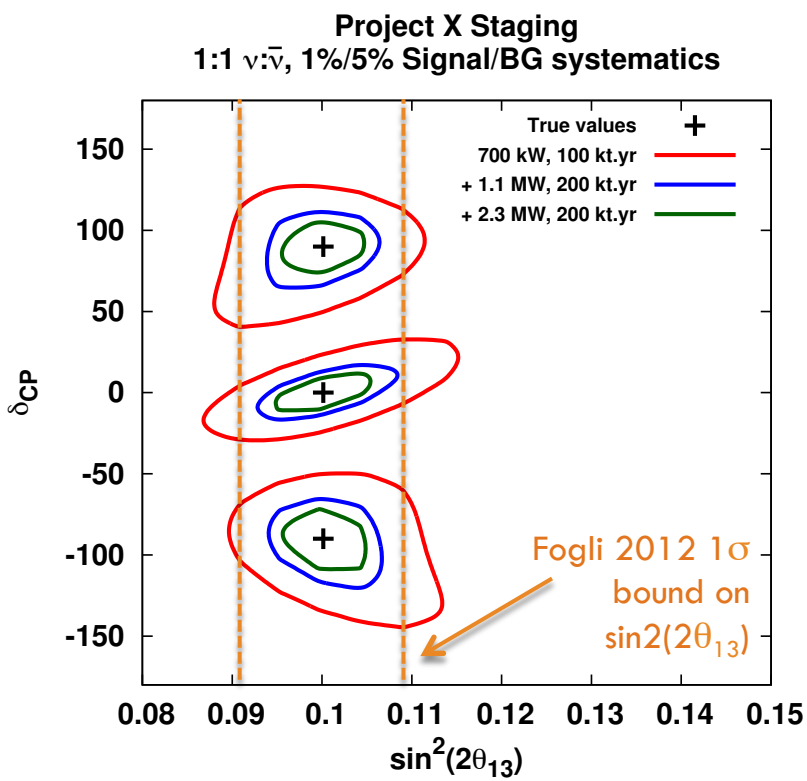
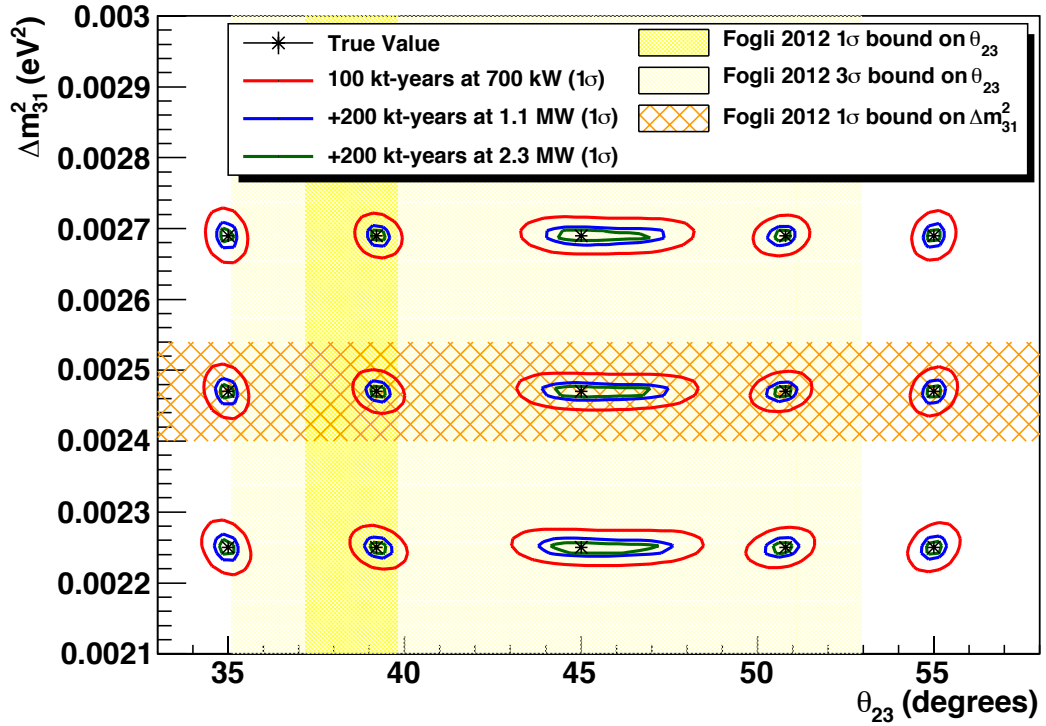
Parameter Measurements

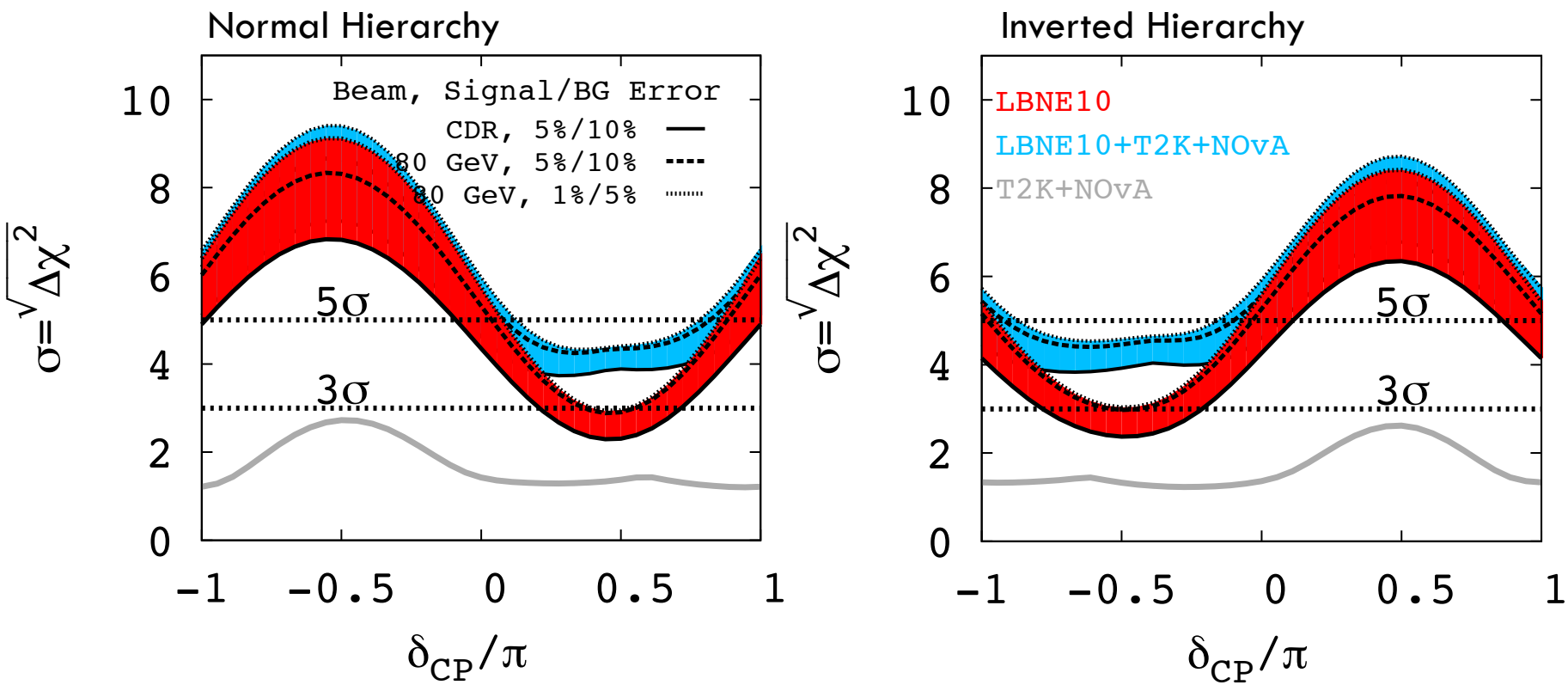
δ_{CP} vs. $\sin^2(2\theta_{13})$



Δm^2_{31} vs. θ_{23}

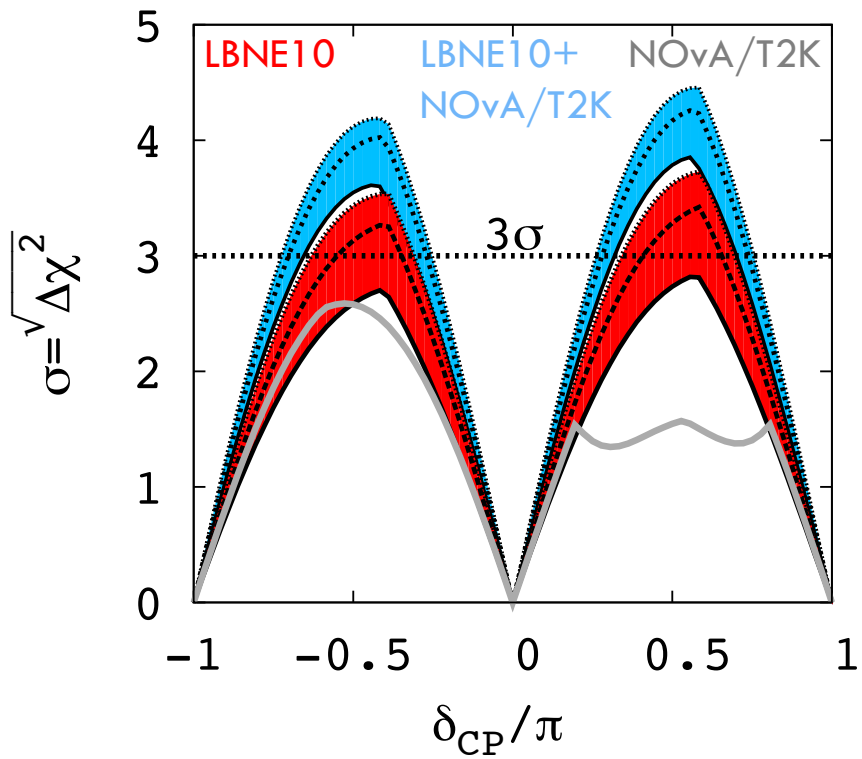


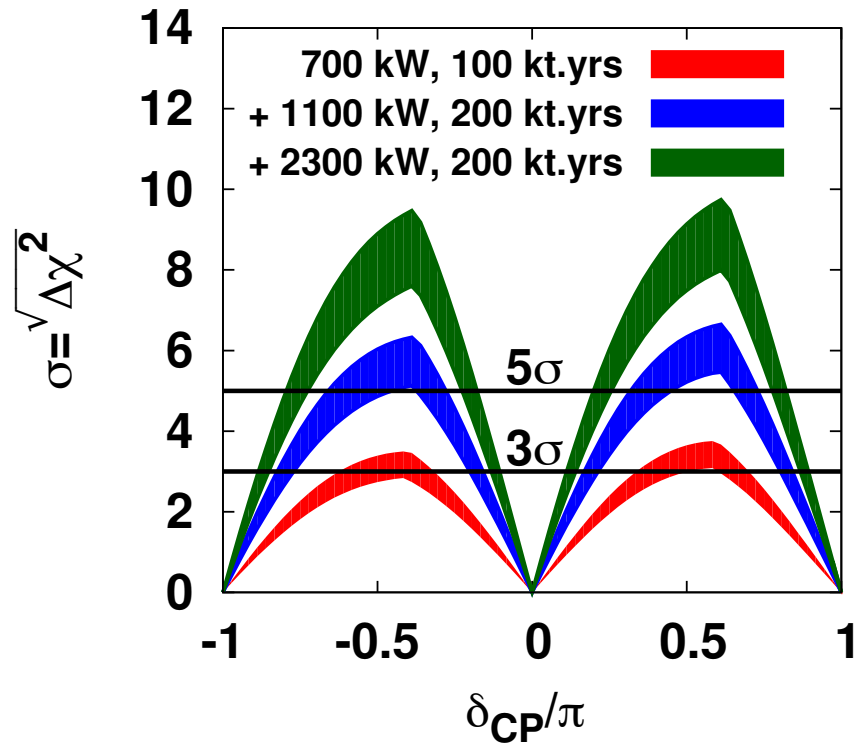
Mass Hierarchy Determination



LBNE10, in combination with NOvA and T2K, will determine the mass hierarchy to >3σ for all values of δ_{CP}, for either hierarchy.

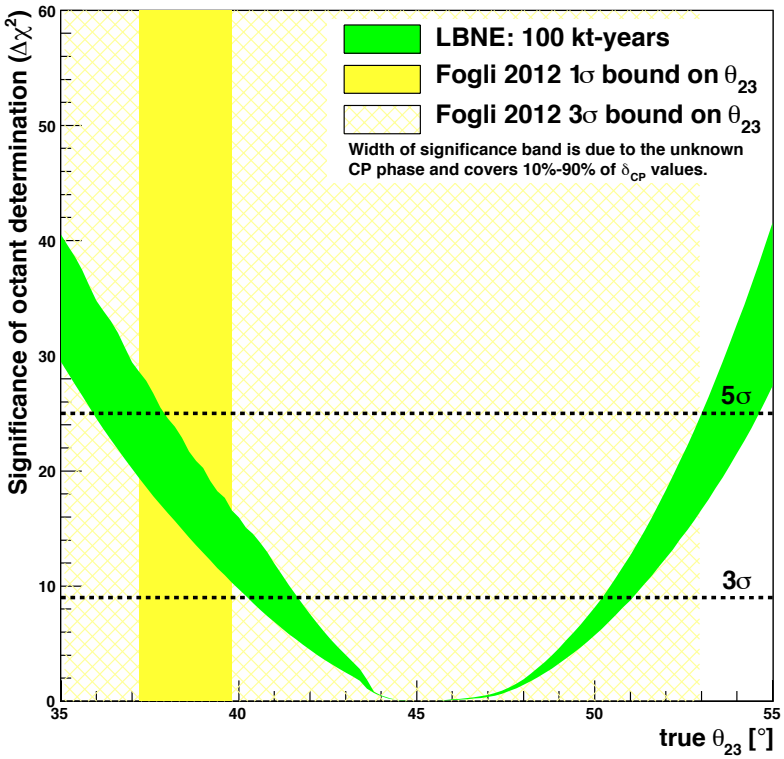
CP Violation Sensitivity

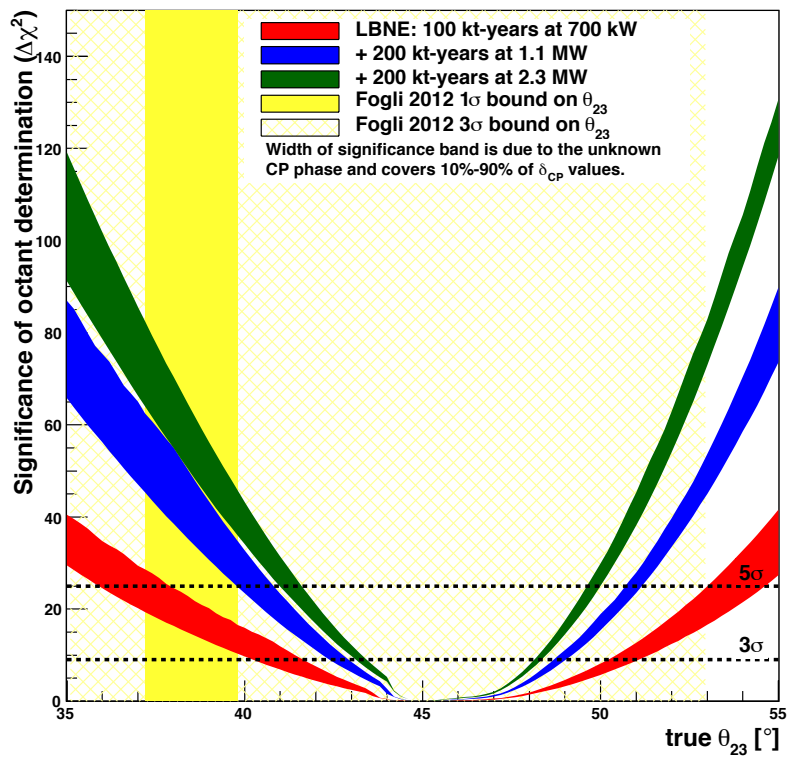




LBNE10 represents a major step forward in the search for leptonic CP violation. 3σ evidence for CPV could be found for many values of δ_{CP}. A larger detector and higher beam power will accelerate >5σ sensitivity.

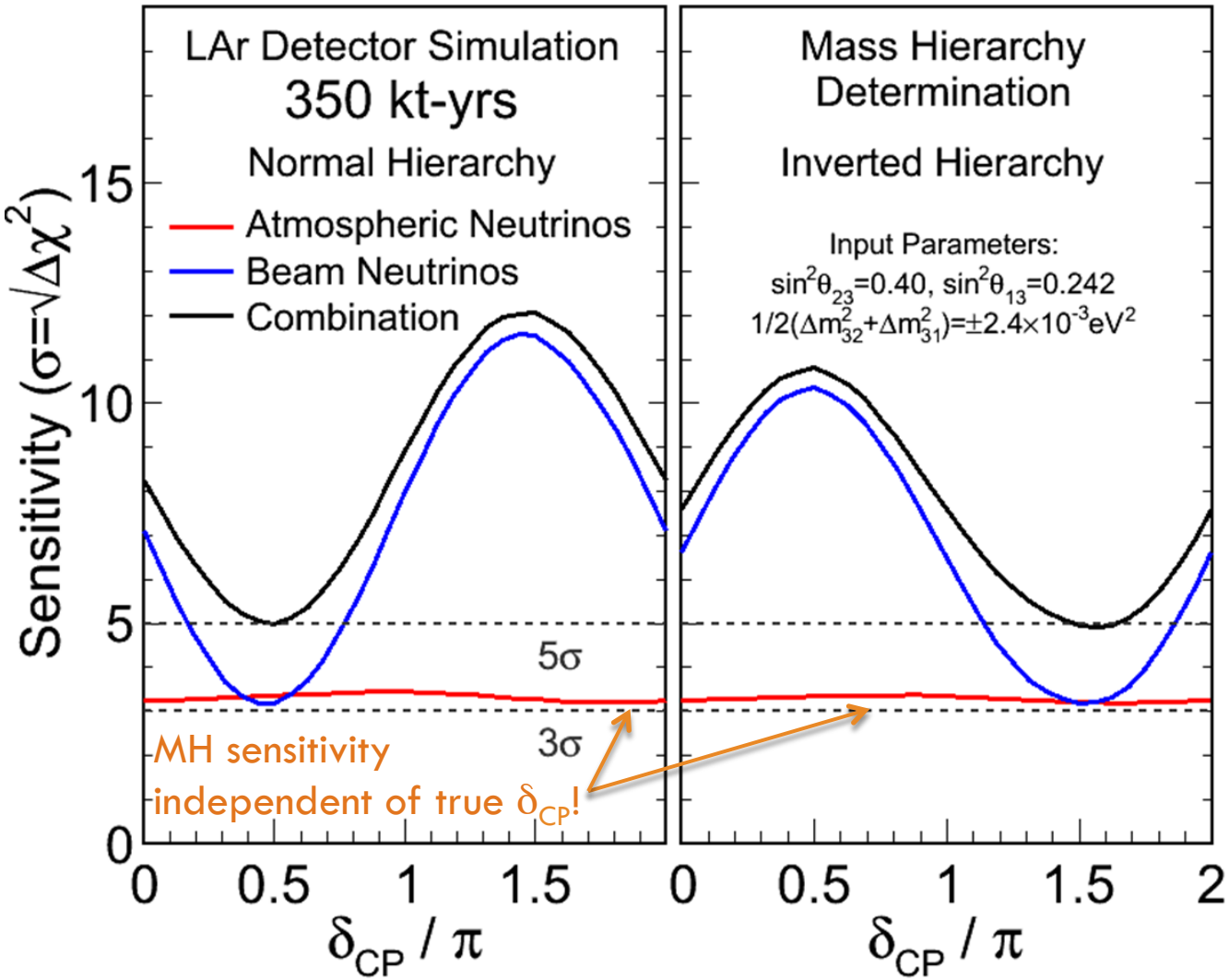
θ_{23} Octant Determination

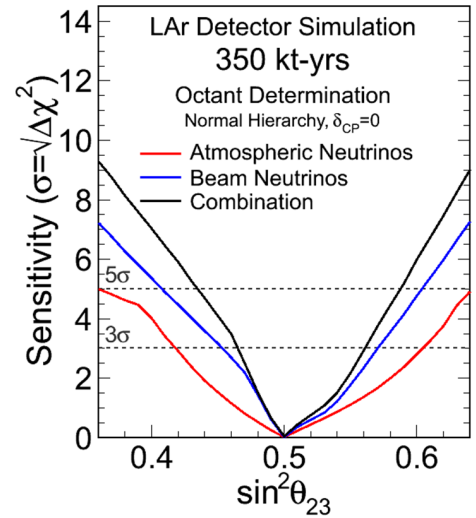


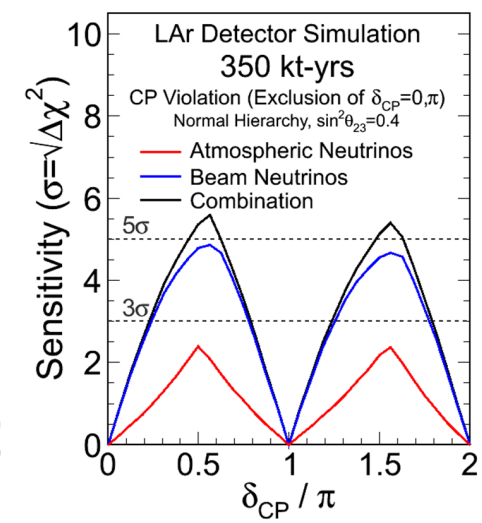


LBNE10 could determine the θ_{23} octant at >3σ if the true value of θ_{23} is within the 1σ Fogli 2012 bound. With higher exposure, it will be possible to determine the θ_{23} octant at >3σ for true values of θ_{23} within a few degrees of 45°.

Atmospheric Neutrinos



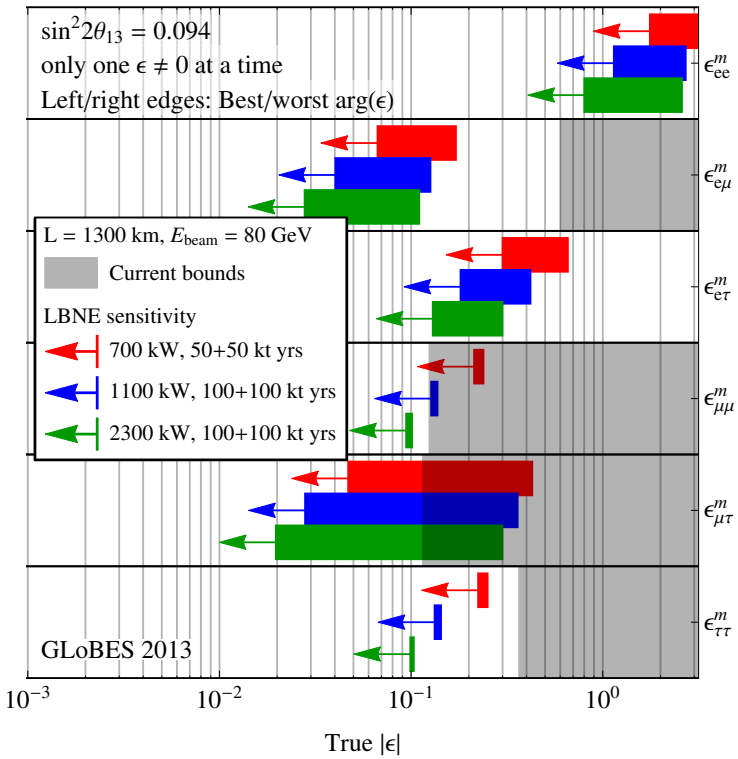




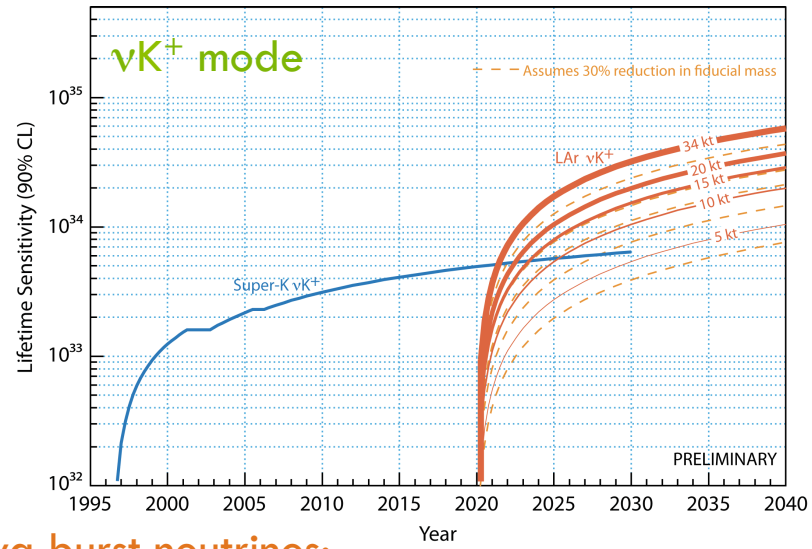
More LBNE Physics

Non-standard interactions:

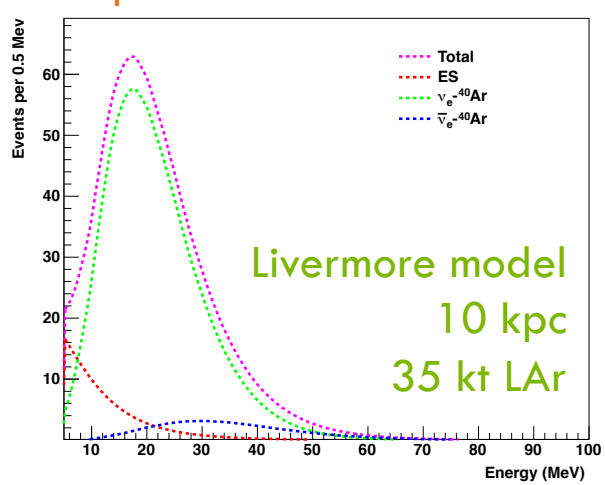
NC NSI discovery reach (3σ C.L.)



Proton decay:



Supernova burst neutrinos:



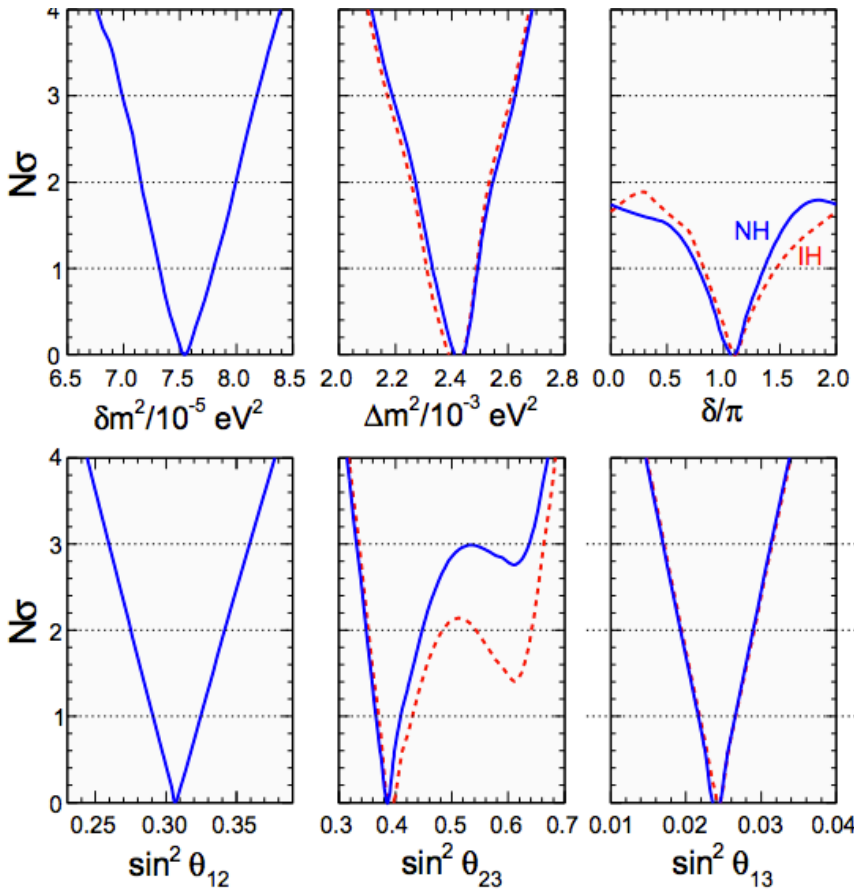
Summary

- FNAL & SURF provide an ideal baseline and excellent facilities to address many of the unanswered questions in neutrino physics
- LBNE10:
  - MH determined at $>3\sigma$ for all values of δ_{CP}
  - CP violation detected at $>3\sigma$ for ~40% of δ_{CP} values
  - θ_{23} octant determined at $>3\sigma$ (θ_{23} within 1σ of Fogli 2012 best fit)
  - LBNE has approval to begin this program
- Clear path forward for detector and accelerator upgrades
- Potential to significantly expand LBNE physics reach in first phase of the experiment
  - Building an international collaboration
  - Good experiment can become great experiment
- Long-term program: decades of precision neutrino oscillation measurements to come!

Extra Slides

Best-fit Neutrino Parameters

Fogli 2012: arXiv:1205.5254



- $\delta m^2 = 7.5\times10^{-5}$ eV^2 (3%)
- $\Delta m^2 = 2.4\times10^{-3}$ eV^2 (3%)
- $\sin^2(\theta_{12}) = 0.31$ (5%)
- $\sin^2(\theta_{23}) = 0.39$ (14%)
- $\sin^2(\theta_{13}) = 0.02$ (10%)
- $\delta_{CP} = ?$
- MH = ?

Fit shows some preference for δ_{CP} near $-\pi$ and no MH preference.