Future Neutrino Oscillation Sensitivities for LBNE

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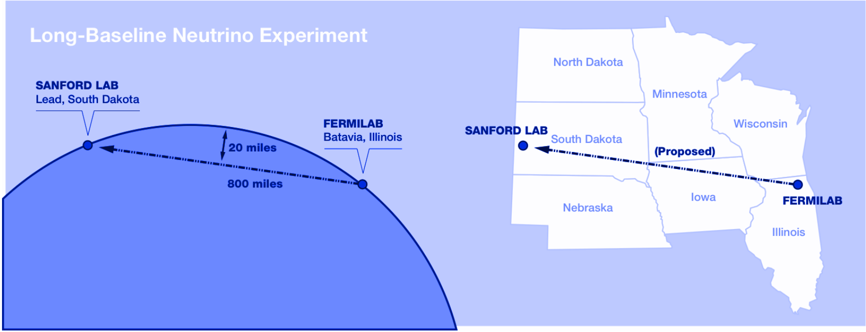
Overview

- What is LBNE?
- Neutrino oscillation parameters
- Method for estimating sensitivity
- LBNE neutrino oscillation parameter sensitivities

Long-Baseline Neutrino Experiment

- New **neutrino beam** (700 kW) from Fermilab
- **Near detector** at Fermilab (see previous talk)
- Optimal **1300 km baseline** from Fermilab to Sanford Lab
- **Large underground detector** (34 kt Liquid Argon TPC) at Sanford Lab



LBNE Staging

- DOE asked LBNE to plan for staged construction
- **LBNE10** (first stage, DOE CD-1 approval):
  - 10 kt (fiducial mass) LAr TPC
  - 700 kW, 120 GeV beam (6×10^{21} POT/year)
- **LBNE** (ultimate goal):
  - 34 kt (fiducial mass) LAr TPC, underground
  - 700-2300 kW beam (Project X)
  - Near detector

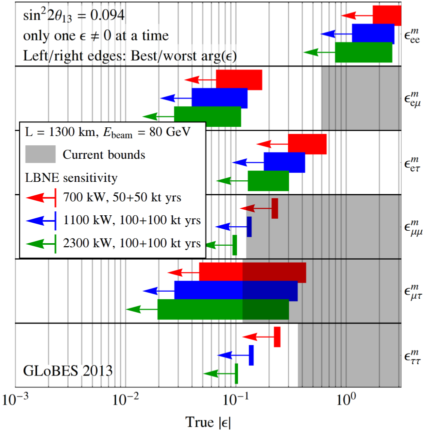
- **Sensitivity studies presented assume either LBNE10 or LBNE**

Detector mass	10 kt (**LBNE10**), or 34 kt (**LBNE**)
Beam	80 GeV, 700 kW
Systematics	1%, 5% normalization error on signal, background
Baseline	1300 km

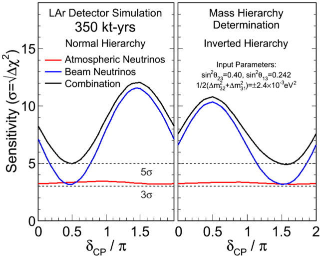
Other physics

- Focusing on ν_e **appearance** here, but there is much more to LBNE

Non-Standard Interactions



Atmospheric ν



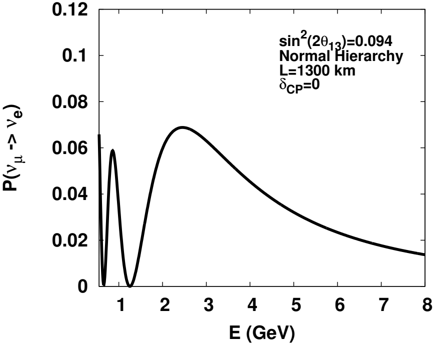
- Proton decay, Sterile ν(s)
- See "Scientic Opportunities with the Long-Baseline Neutrino Experiment" (arXiv:1307.7335)

ν_e appearance

$$P_{\nu_\mu\to\nu_e} \approx \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2((1-x)\Delta)}{(1-x)^2}$$
$$- \alpha\sin 2\theta_{13}\sin\delta\sin 2\theta_{12}\sin 2\theta_{23}\sin\Delta\frac{\sin(x\Delta)}{x}\frac{\sin((1-x)\Delta)}{(1-x)}$$
$$+ \alpha\sin 2\theta_{13}\cos\delta\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\frac{\sin(x\Delta)}{x}\frac{\sin((1-x)\Delta)}{(1-x)}$$
$$+ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(x\Delta)}{x^2}$$

$$x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$
$$\Delta = \frac{\Delta m^2_{31}L}{4E}$$
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

- $P_{\nu_\mu\to\nu_e}$ oscillation probability including matter effects
- LBNE will look for ν_e **appearance** to measure:



ν_e appearance

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} \quad \approx \quad & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-x)\Delta)}{(1-x)^2} \\
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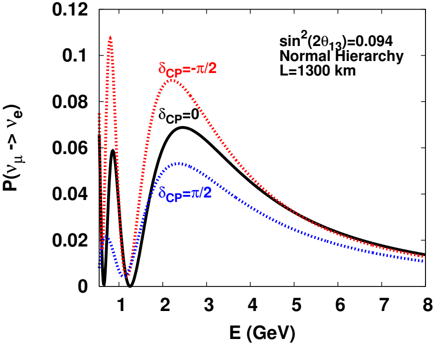
  - δ_{CP} and CP violation ($\sin\delta_{CP} \neq 0$)



ν_e appearance

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$$x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$
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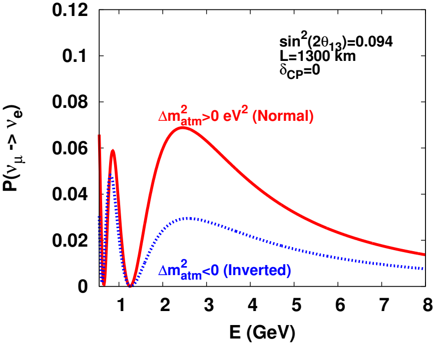
- $P_{\nu_\mu \to \nu_e}$ oscillation probability including matter effects
- LBNE will look for **ν_e appearance** to measure:
  - **δ_{CP}** and CP violation ($\sin \delta_{CP} \neq 0$)
  - **Mass hierarchy**: is $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} < 0$?



ν_e appearance

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$$x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

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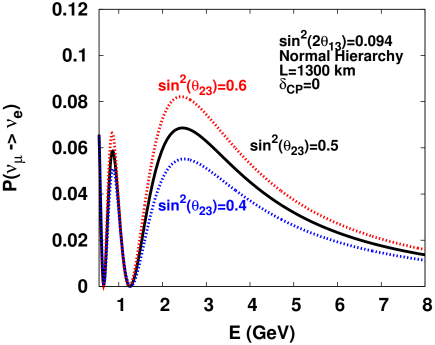
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

- $P_{\nu_\mu\to\nu_e}$ oscillation probability including matter effects
- LBNE will look for $\boldsymbol{\nu_e}$ **appearance** to measure:
  - $\boldsymbol{\delta_{CP}}$ and CP violation ($\sin\delta_{CP} \neq 0$)
  - **Mass hierarchy**: is $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} < 0$?
  - $\boldsymbol{\theta_{23}}$ **octant**: is $\sin^2(\theta_{23}) > 0.5, = 0.5, < 0.5$?



Sensitivity overview

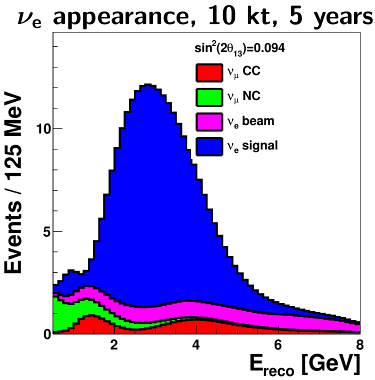
- Sensitivities are computed using the **GLoBES* library**
- **Event Spectra** are simulated
  $N(E_{reco})$ = (Flux) x (Oscillation Probability) x (Cross Section)
  x (Detector Smearing & Efficiencies)
- **Compute $\Delta\chi^2$** comparing a true event spectrum with test spectra
  - **Profiles oscillation parameters** to incorporate uncertainties in oscillation parameters
- Incorporates simple **systematics**
  - Assuming 1%, 5% normalization uncertainty on signal, background

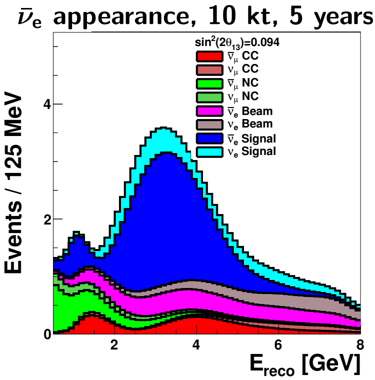
***General Long Baseline Experiment Simulator**

P. Huber, M. Lindner and W. Winter, Simulation of long baseline neutrino oscillation experiments with GLoBES, Comput. Phys. Commun. 167 (2005) 195, arXiv:hep-ph/0407333

P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, New features in the simulation of neutrino oscillation experiments with GLoBES 3.0, Comput. Phys. Commun. 177 (2007) 432, arXiv:hep-ph/0701187

LBNE10 expected event spectra

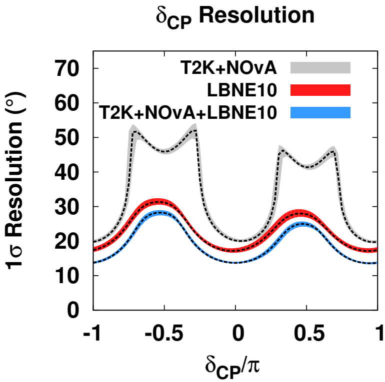




Normal Hierarchy LBNE10 Total Events	ν	$\bar{\nu}$
ν_e signal	220	66
ν_μ CC BG	35	23
ν_e beam BG	77	63
NC BG	17	12

LBNE10 δ_{CP} resolutions

- Estimated 1σ Resolutions on δ_{CP}
- **Bands represent current 1σ bounds** on θ_{13}, θ_{23}, and Δm^2_{31} from Fogli et al 2012
- **LBNE10**: 17° to 31°
- **T2K+NOvA+LBNE10**: 15° to 28°



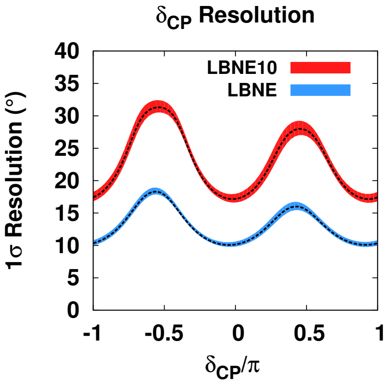
Normal hierarchy

$\sin^2(2\theta_{13}^{true}) = 0.094^{+0.009}_{-0.010}$

$\sin^2(\theta_{23}^{true}) = 0.39^{+0.021}_{-0.024}$

LBNE δ_{CP} resolutions

- Estimated 1σ Resolutions on δ_{CP}
- **Bands represent current 1σ bounds** on θ_{13}, θ_{23}, and Δm^2_{31} from Fogli et al 2012
- **LBNE10**: 17° to 31°
- **LBNE**: 10° to 17°



Normal hierarchy

$\sin^2(2\theta_{13}^{true}) = 0.094^{+0.009}_{-0.010}$

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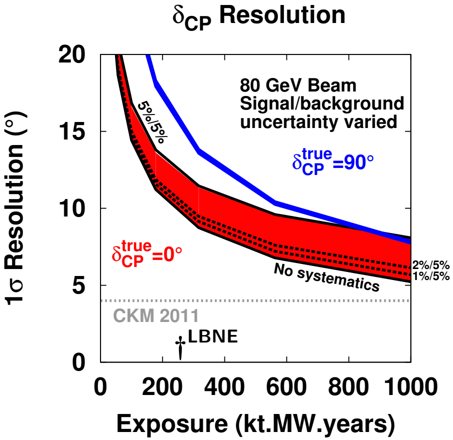
and beyond...

- Estimated 1σ Resolutions on δ_{CP} vs Exposure
- Assumes 50% neutrino, 50% anti-neutrino running



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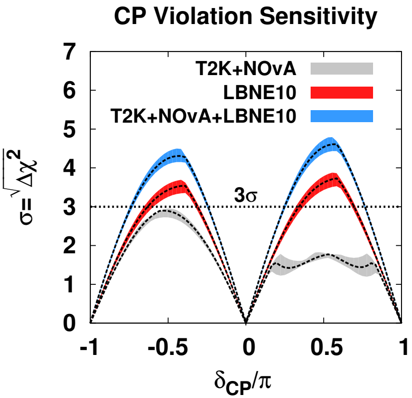
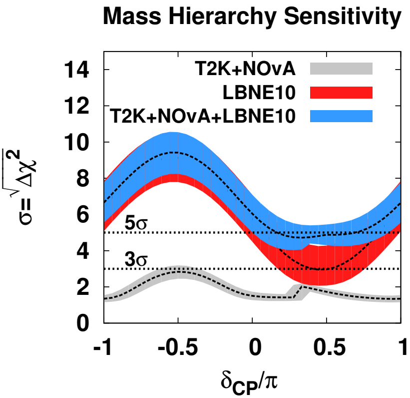
LBNE10 sensitivity





- **Bands represent current 1σ bounds** on θ_{13}, θ_{23}, and Δm^2_{31} from Fogli et al 2012 global fit
- **CPV** detected at 3σ for 40% of δ_{CP} values for **LBNE10 + T2K + NOvA**
- **Mass hierarchy** determined at $\sim 5\sigma$ for 100% of δ_{CP} values (100% for 3σ)

Normal hierarchy

$\sin^2(2\theta_{13}^{true}) = 0.094^{+0.009}_{-0.010}$

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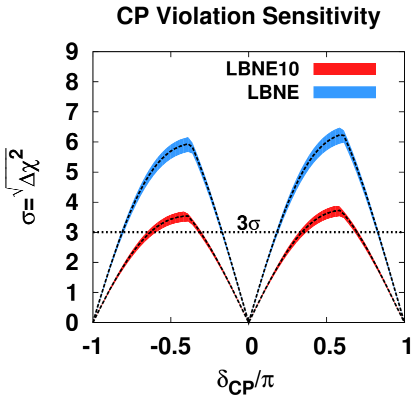
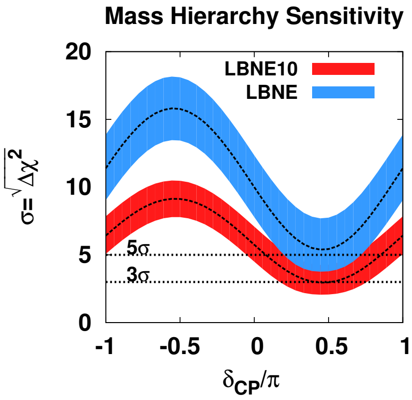
LBNE sensitivity





- **Bands represent current 1σ bounds** on θ_{13}, θ_{23}, and Δm^2_{31} from Fogli et al 2012 global fit
- **CPV** detected at 3σ for 67% of δ_{CP} values for **LBNE**
- **Mass hierarchy** determined at 5σ for 100% of δ_{CP} values

Normal hierarchy

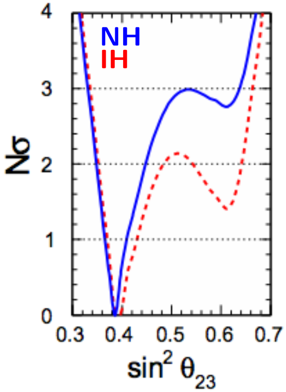
$\sin^2(2\theta_{13}^{true}) = 0.094^{+0.009}_{-0.010}$

$\mathbf{\sin^2(\theta_{23}^{true}) = 0.39^{+0.021}_{-0.024}}$

Effects of uncertainty in $\sin^2(\theta_{23})$

- Previous sensitivities assumed central values and 1σ errors from Fogli 2012 global fit

$$\sin^2(\theta_{23}^{true}) = 0.39^{+0.021}_{-0.024}$$



Fogli et al, arXiv:1205.5254v3

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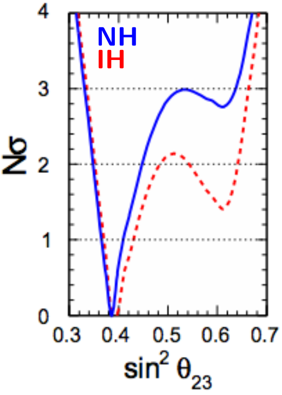
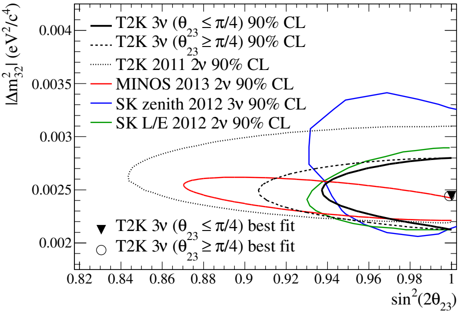


Fogli et al, arXiv:1205.5254v3

- Other (more recent) results to consider:



Abe et al, arXiv:1308.0465v1

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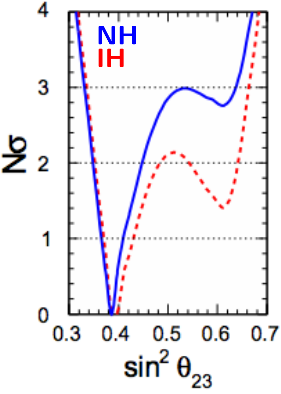

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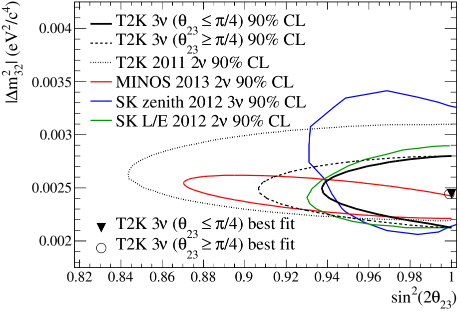
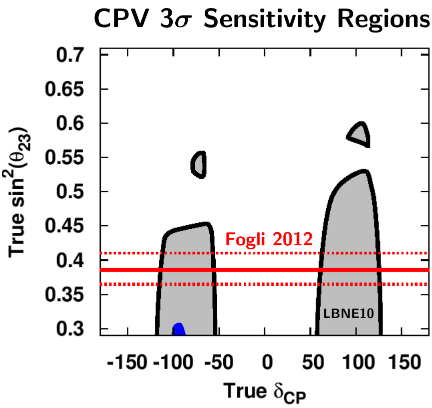
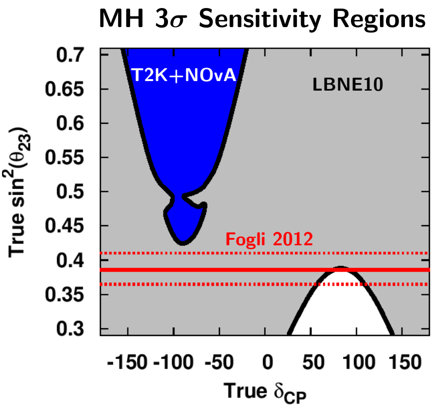


Abe et al, arXiv:1308.0465v1

Evaluate sensitivity to CPV and MH in terms of $\sin^2(\theta_{23})$ vs δ_{CP}!

LBNE10 3σ sensitivity regions





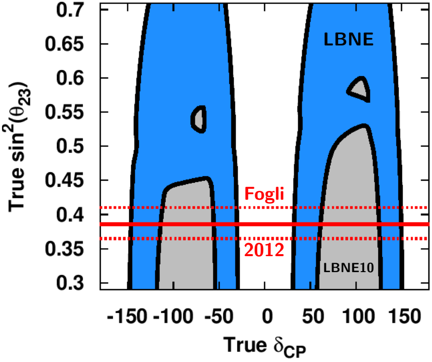
- Shaded regions are where CPV and MH can be determined at 3σ for **T2K+NOvA** and **LBNE10**
  - Mass hierarchy, octant, and δ_{CP} are profiled where appropriate
- The 1σ width from **Fogli 2012** is marked

Normal hierarchy

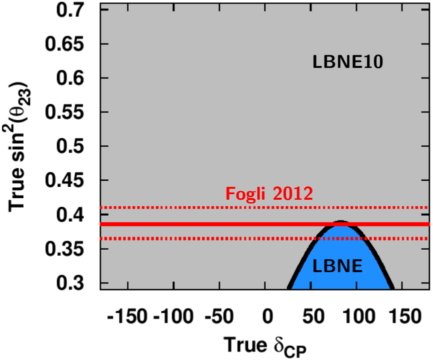
$\sin^2(2\theta_{13}^{true}) = 0.094^{+0.009}_{-0.010}$

LBNE 3σ sensitivity regions

CPV 3σ Sensitivity Regions



MH 3σ Sensitivity Regions



- Shaded regions are where CPV and MH can be determined at 3σ for **LBNE** and **LBNE10**
  - Mass hierarchy, octant, and δ_{CP} are considered unknown
- The 1σ width from **Fogli 2012** is marked

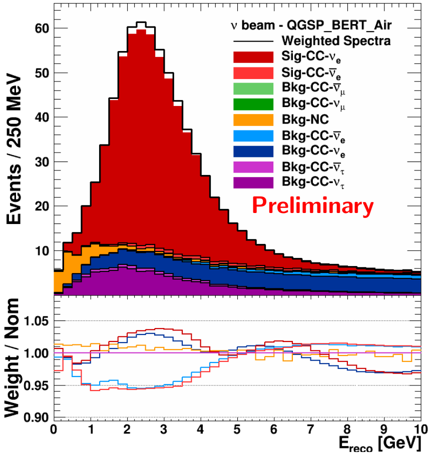
Normal hierarchy

$\sin^2(2\theta_{13}^{true}) = 0.094^{+0.009}_{-0.010}$

LBNE Fast Monte Carlo

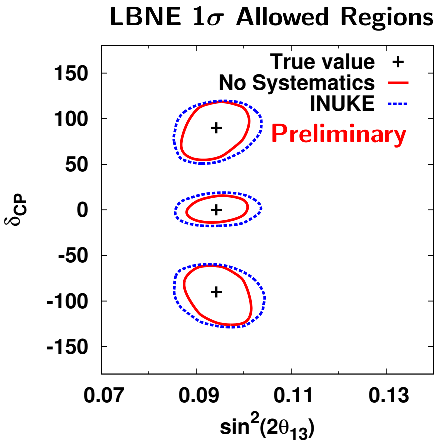
- Simulates (almost) every aspect of the experiment
- Full MC chain
  - Flux (GEANT/FLUKA)
  - Cross sections (GENIE)
  - **Parameterized** detector response
  - Reconstruction
- Event-by-event systematics weights
- Study effects of realistic systematic uncertainties
- Generate **analysis samples** for more advanced sensitivity studies in GLoBES, e.g.
  - Propagated flux uncertainties (e.g. right)
  - ν_τ selection/rejection

ν_e Event Spectra
Flux Uncertainties Example



Preliminary Fast MC Sensitivity

- **LBNE Fast MC** generates **GLoBES friendly** outputs
- Extending GLoBES' custom $\Delta\chi^2$ implementation to incorporate more advanced systematic treatments
- Preliminary **example** (right)
  - Effects of uncertainty in GENIE intranuclear rescattering model
  - Propagated to allowed regions in δ_{CP} vs $\sin^2(2\theta_{13})$
  - Future **data constraints not included**
  - Fast MC highlights models in need of constraint
- Will study each systematic individually and in combination

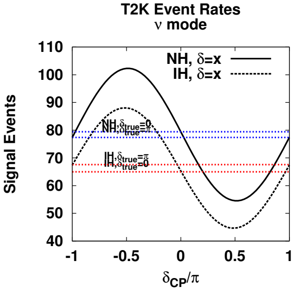


Summary

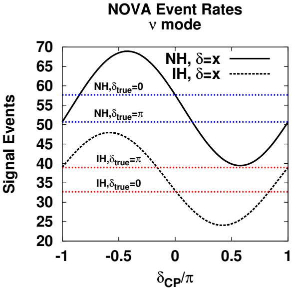
- LBNE is a major step forward in terms of ability to measure the neutrino oscillation parameters
  - $\boldsymbol{\delta_{CP}}$ will be measured to between 10 and 20 degrees
  - **3σ CPV** discovery for 67% of δ_{CP} values
  - **Mass hierarchy** will be determined at 5σ for 100% of δ_{CP} values
  - Robust measurements regardless of $\sin^2(\theta_{23})$ value
- Even in early stages (e.g. LBNE 10 kt), it will be a large improvement on current and near future measurements
  - **Mass hierarchy** will be discovered for 100% of δ_{CP} values
  - **3σ CPV** discovery for 40% of δ_{CP} values
- A **Fast Monte Carlo** simulation is being developed to:
  - Study realistic systematic uncertainties
  - Propagate uncertainties to sensitivity studies

Backup Slides

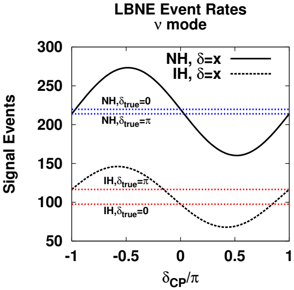
Sensitivity from event rates vs δ_{CP}



L=295 km



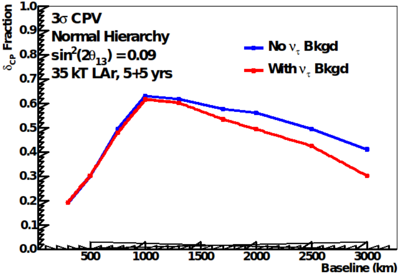
L=810 km



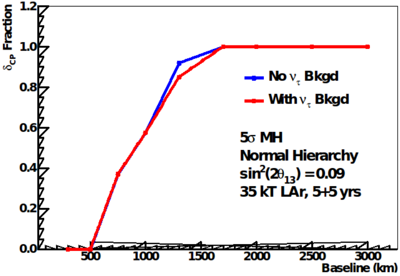
L=1300 km

Baseline Optimization Study

CPV δ_{CP} Coverage vs Baseline



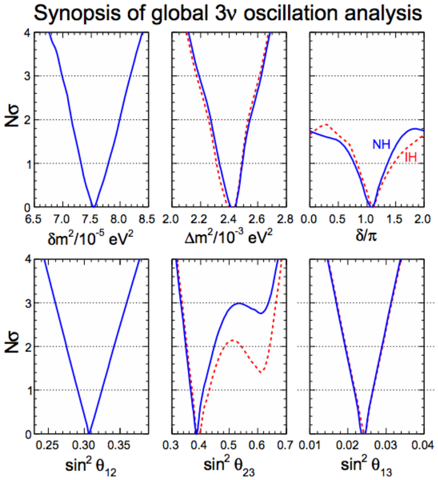
MH δ_{CP} Coverage vs Baseline



- **CP violation**: need a long enough baseline to resolve the mass hierarchy and short enough for adequate statistics
- **Mass hierarchy**: a longer baseline is better
- This study optimizes the beam for each baseline
- **1300 km** is an optimal baseline when both effects are considered

Oscillation parameter values

- Oscillation parameter values based on Fogli 2012 global fit
  - $\sin^2(\theta_{12}) = 0.307$
  - $\sin^2(2\theta_{13}) = 0.094$ (1σ range: $0.0845 - 0.1036$)
  - $\sin^2(\theta_{23}) = 0.386$ (1σ range: $0.370 - 0.431$)
  - $\Delta m^2_{21} = 7.54 \times 10^{-5}\ eV^2$
  - $\Delta m^2_{31} = 2.47 \times 10^{-3}\ eV^2$ (1σ range: $2.37 - 2.53$)



Fogli et al, arXiv:1205.5254v3

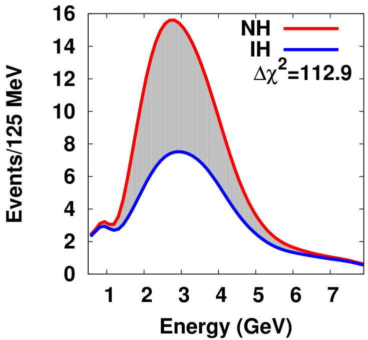
Computing sensitivity: $\Delta\chi^2$

- Using the GLoBES* software package, a $\Delta\chi^2$ is computed

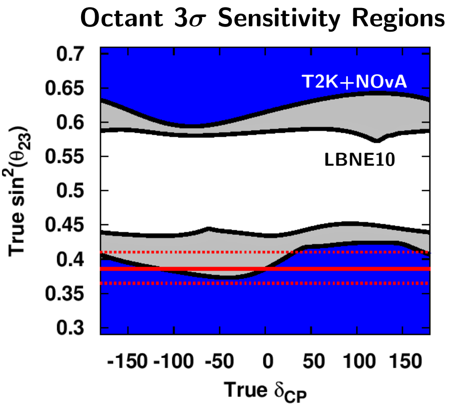
$$\Delta\chi^2(\boldsymbol{\theta}_{\mathbf{true}}, \boldsymbol{\theta}_{\mathbf{test}}, f) = 2 \cdot \sum_{i}^{N} \left(n_i^{true} \cdot ln \frac{n_i^{true}}{(1+f) \cdot n_i^{test}}) + (1+f) \cdot n_i^{test} - n_i^{true} \right) + \frac{f^2}{\sigma_f^2}$$

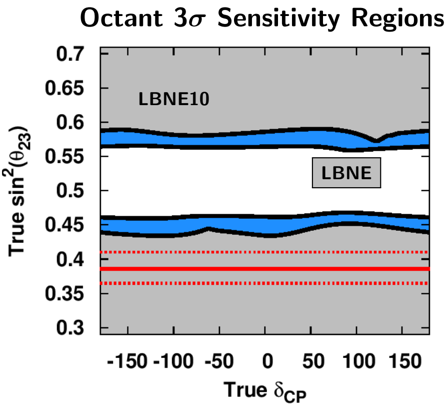
- Determines ability to distinguish between **test spectra** and assumed **true spectra**
- For example (right), mass hierarchy sensitivity is computed as $\Delta\chi^2(\boldsymbol{\theta}_{\mathbf{NH}}, \boldsymbol{\theta}_{\mathbf{IH}})$ that compares two event spectra
  - true spectra: Normal hierarchy
  - test spectra: Inverted hierarchy
- Also profiled with respect to oscillation parameters, $\boldsymbol{\theta}_{\mathbf{test}}$, and systematic normalization, f

Mass hierarchy sensitivity in LBNE



LBNE 3σ octant sensitivity regions



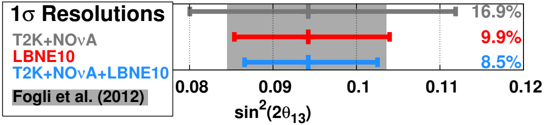


- Shaded regions are where the octant can be determined at 3σ
  - Mass hierarchy and δ_{CP} are considered unknown
- The 1σ width from **Fogli 2012** is marked

Normal hierarchy

$\sin^2(2\theta_{13}^{true}) = 0.094^{+0.009}_{-0.010}$

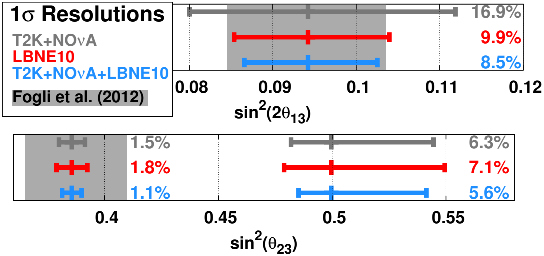
LBNE10 oscillation parameter resolutions



- Estimated 1σ resolutions from 1D $\Delta\chi^2$
- All other parameters profiled
- Normal mass hierarchy
- $\delta_{CP} = 0$
- Gray regions represent Fogli 2012 global fit regions

*T2K+NOvA based on publicly available GLoBES configuations.

LBNE10 oscillation parameter resolutions



- Estimated 1σ resolutions from 1D $\Delta\chi^2$
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- Normal mass hierarchy
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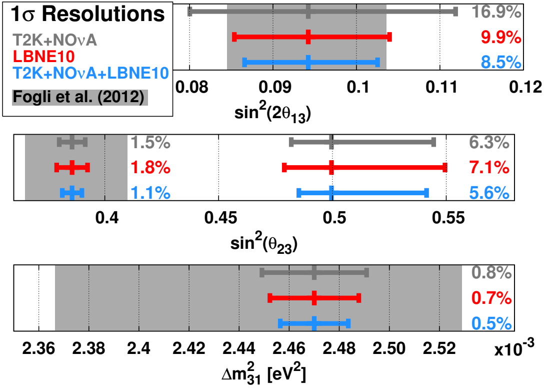

*T2K+NOvA based on publicly available GLoBES configuations.