Science Goals

Oscillation Basics

Experimental Assumptions

Spectra and Event Rates

Sensitivities

Beyond PMNS

Summary

Long Baseline Physics with LBNE-Homestake and Alternatives

Fermilab Steering Committee Mtg, 4/25/2012

Mary Bishai, Sam Zeller (for the Steering Committee Physics Working Group)

April 25, 2012

Outline

Science Goals

Oscillation Basics

Experimental Assumptions

Spectra and Event Rates

Sensitivities

Beyond PMNS

Summary

1 Science Goals

2 Oscillation Basics

3 Experimental Assumptions

4 Spectra and Event Rates

5 Sensitivities

6 Beyond PMNS

7 Summary

P5 Report 2008

The Intensity Frontier

Recent striking discoveries make the study of the properties of neutrinos a vitally important area of research. Measurements of the properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for the evolution of the universe. The latest developments in accelerator and detector technology make possible promising new scientific opportunities in neutrino science as well as in experiments to measure rare processes. The US can build on the unique capabilities and infrastructure at Fermilab, together with DUSEL, the Deep Underground Science and Engineering Laboratory proposed for the Homestake Mine in South Dakota, to develop a world-leading program of neutrino science. Such a program will require a multi-megawatt-powered neutrino source at Fermilab.

> **The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL and a high-intensity neutrino source at Fermilab.**
>
> **The panel recommends an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technologies for a large multi-purpose neutrino and proton decay detector.**

Construction of these facilities could start within the 10-year period considered by this report.

LBNE is a multi-stage, long term, *world-class* project with a broad physics program - not a single stage to measure one parameter.

Neutrino oscillations

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

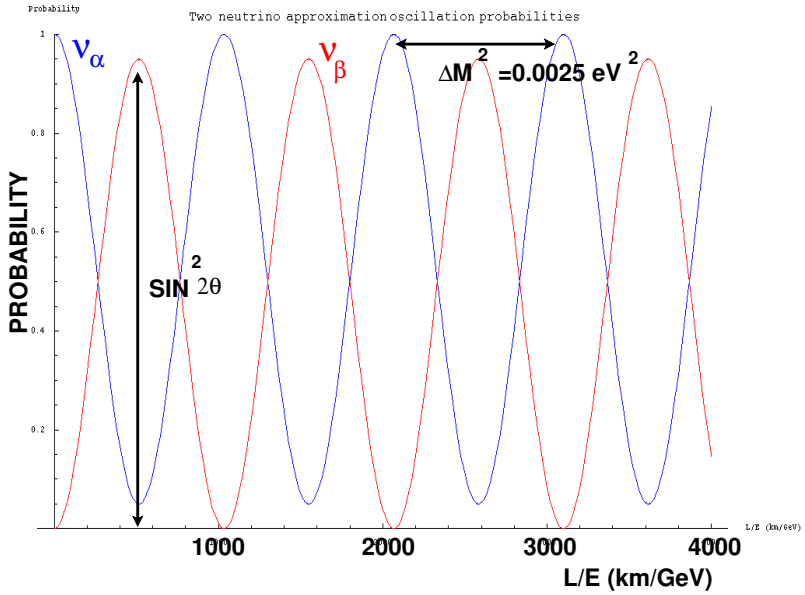
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

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

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

where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates



The Implications of 3-Neutrino Mixing

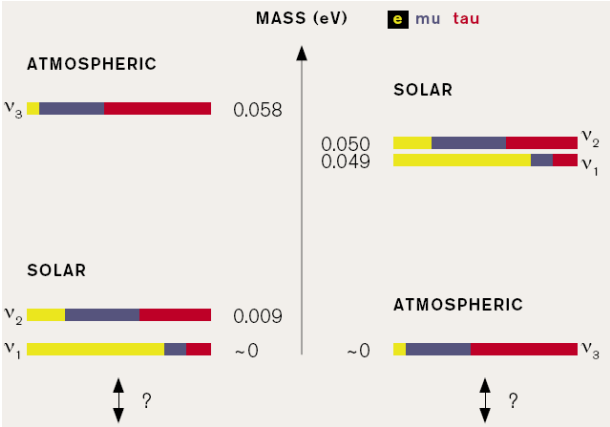
$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\nu_\mu \text{ disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\nu_\mu \to \nu_e,\ \text{reactor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

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

$\sin^2\theta_{13}$: Amount of ν_e in ν_3

$\tan^2\theta_{12}$: $\dfrac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

$\tan^2\theta_{23}$: Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3



Normal (NH) Inverted (IH)

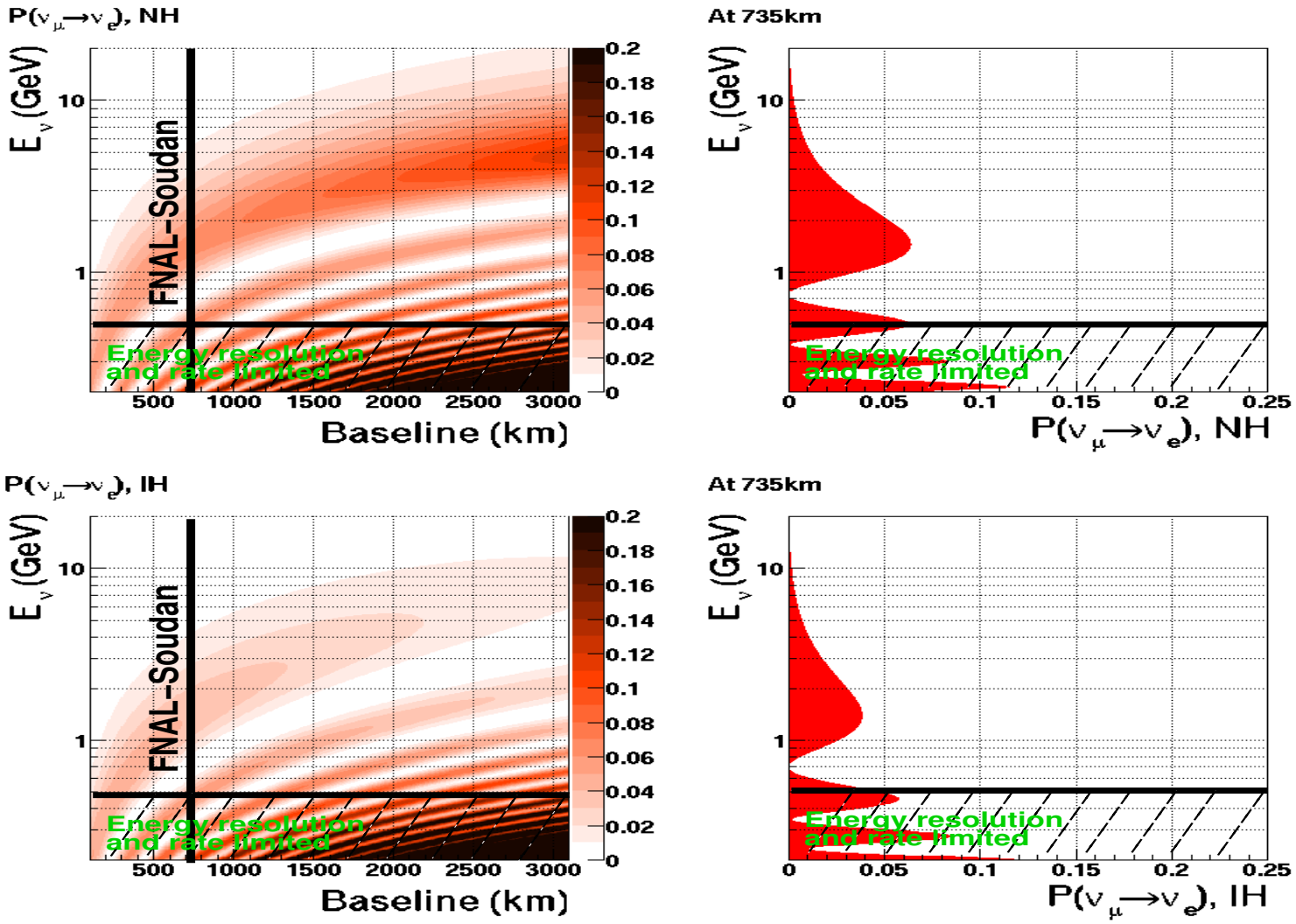
There are 3 quantum states mixing $\Rightarrow$ there is an overall phase: δ_{CP}.

If $\delta_{CP} \neq 0$ or π, charge-parity (CP) is violated and there is a $\nu/\bar{\nu}$ asymmetry.

Could this explain the origin of matter?

What is the value of δ_{CP}, sign(Δm^2_{31})?

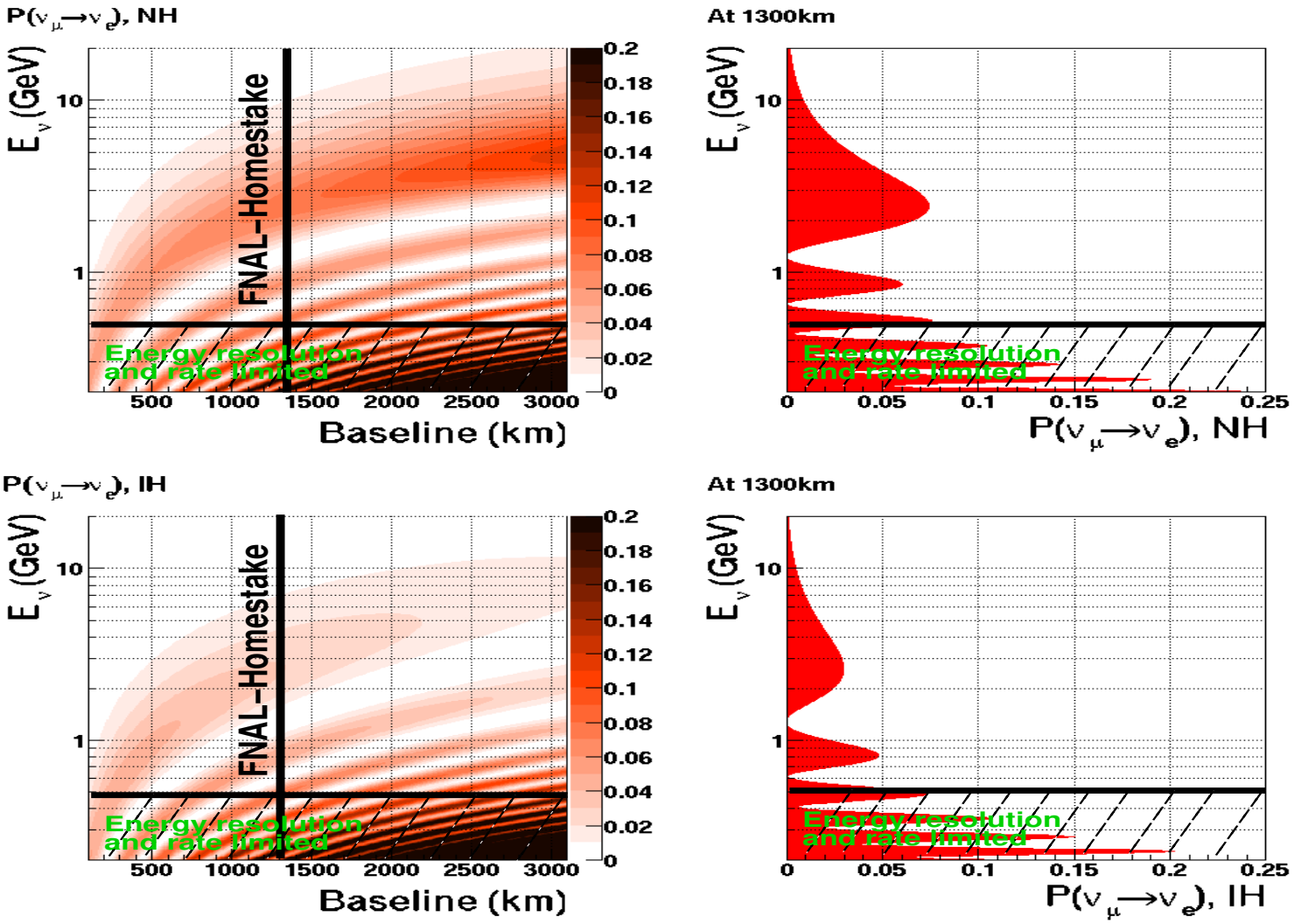
Oscillations of $\nu_\mu \longrightarrow \nu_e$ at different baselines



$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E_\nu^n(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$

for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

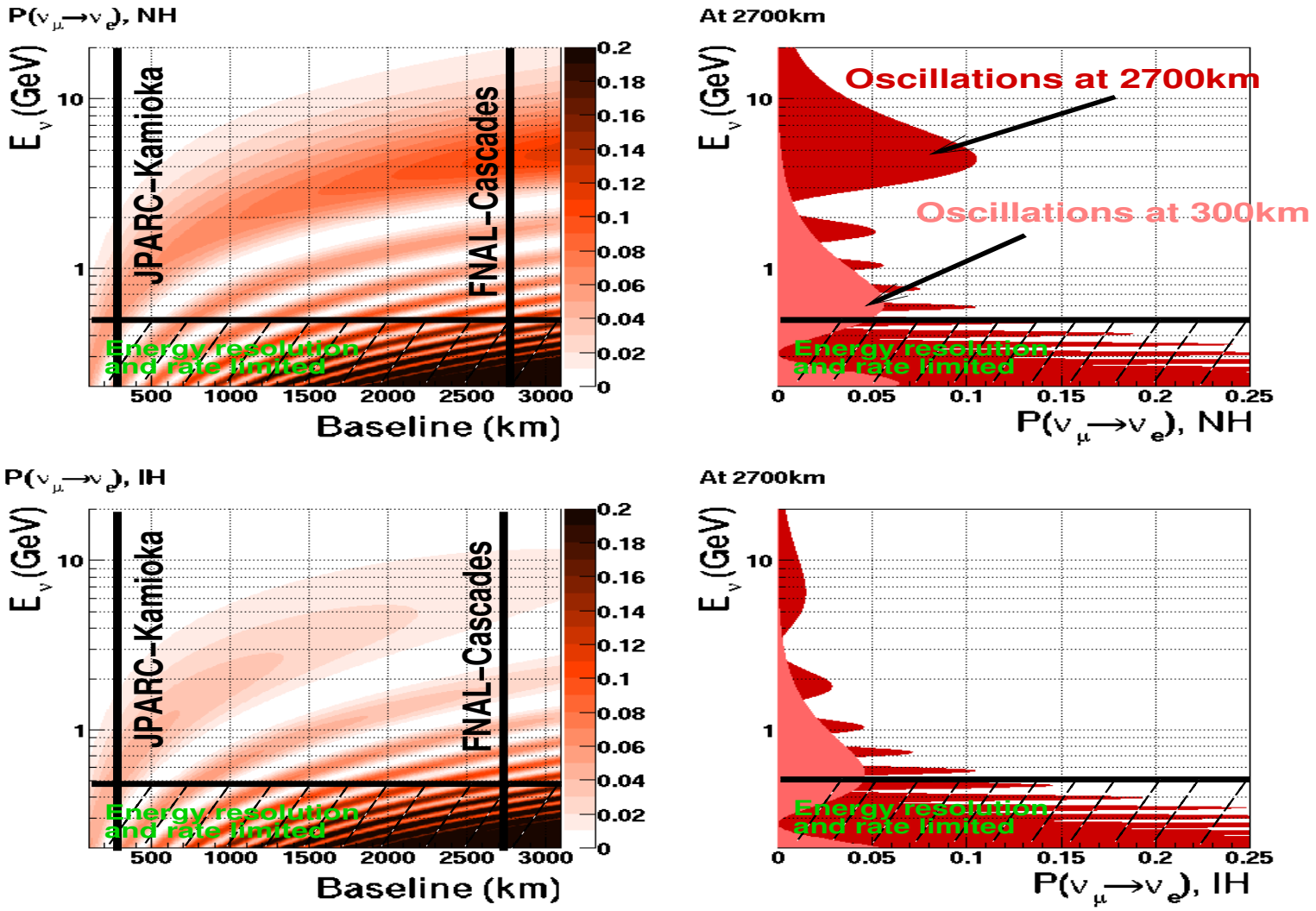
Oscillations of $\nu_\mu \longrightarrow \nu_e$ at different baselines



$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E_\nu^n(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$

for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

Oscillations of $\nu_\mu \longrightarrow \nu_e$ at different baselines



$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E^n_\nu(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$

for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

CP and Matter Asymmetries vs Baselines

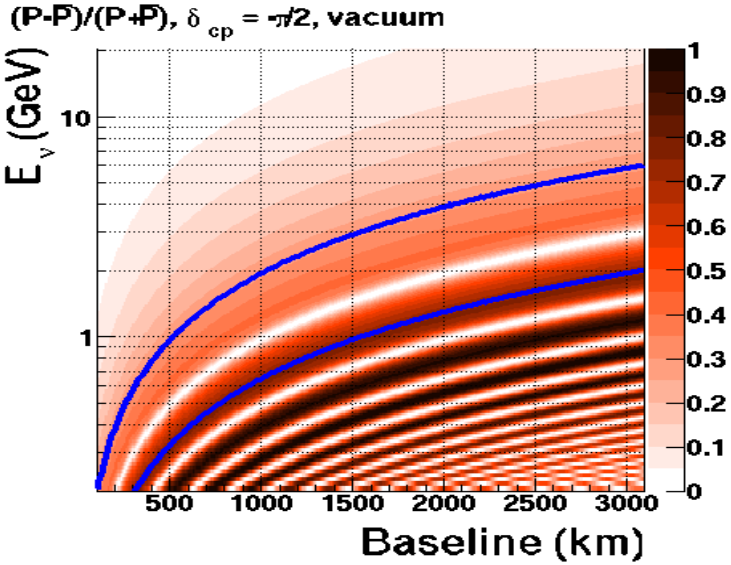
The CP asymmetry is defined as

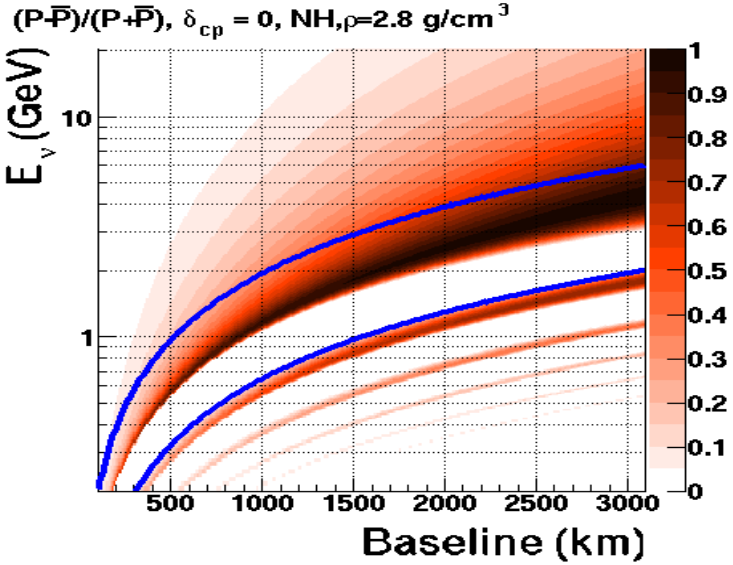
$$\mathcal{A}(E_\nu) = \left[\frac{P(\nu_\mu \to \nu_e) - \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$

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

Maximal CP asymmetry in vacuum $\delta_{cp} = -\pi/2$

Matter asymmetry with no CPV





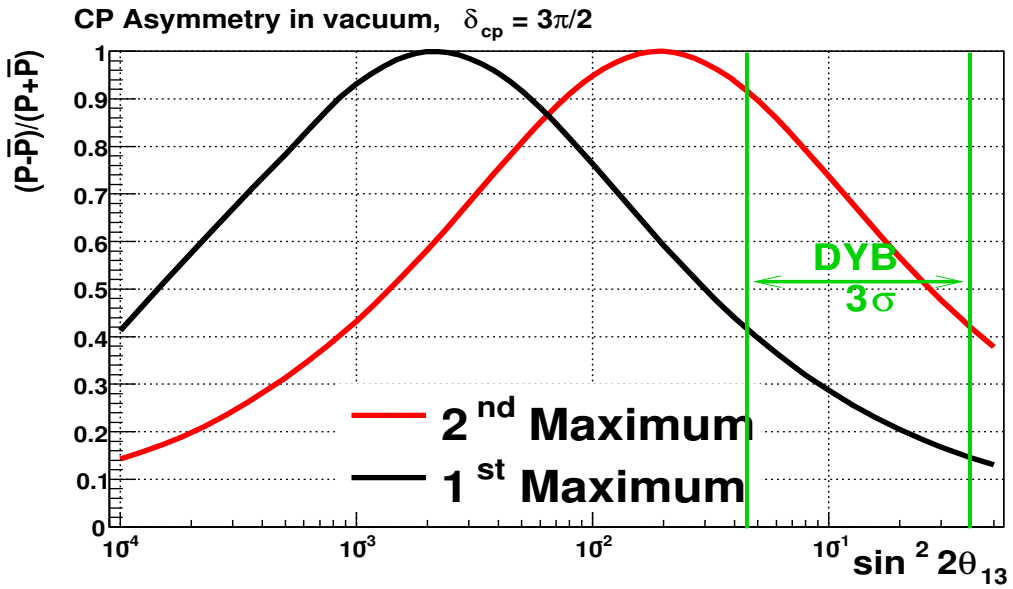
CP asymmetries are largest at the secondary nodes.

Matter asymmetry dominates at the 1st node

Longer baselines, wide-band beams to resolve degeneracies.

CP Asymmetries vs θ_{13}

MAXIMAL CP asymmetry in vacuum ($\delta_{cp} = -\pi/2$)



Large values of θ_{13} = SMALLER CP asymmetries

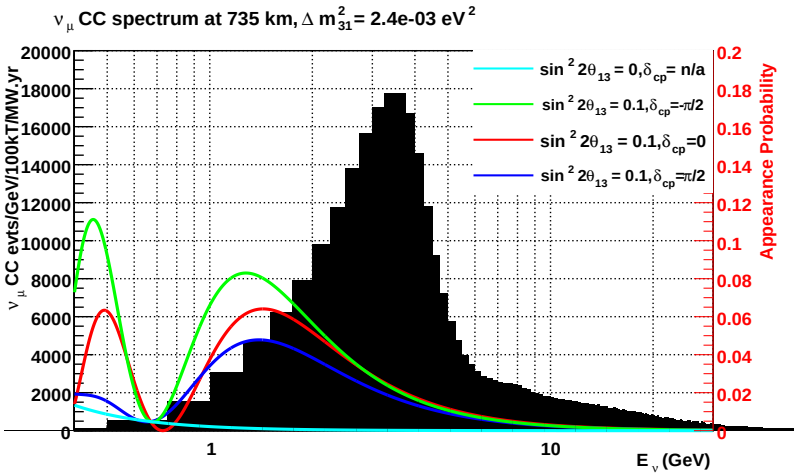
CC event rates per 100kT.MW.yrs (1 MW.yr= 1×10^{21} p.o.t) for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$, NH:

Expt	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e beam	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
Soudan 735km	73K	49K	1.3K	820	1500	166
Ash River 810km	18K	7.3K	360	330	710	38
Hmstk 1300km	29K	11K	500	280	1300	130

Need exposures of 100kt.MW.yrs INDEPENDENT of baseline

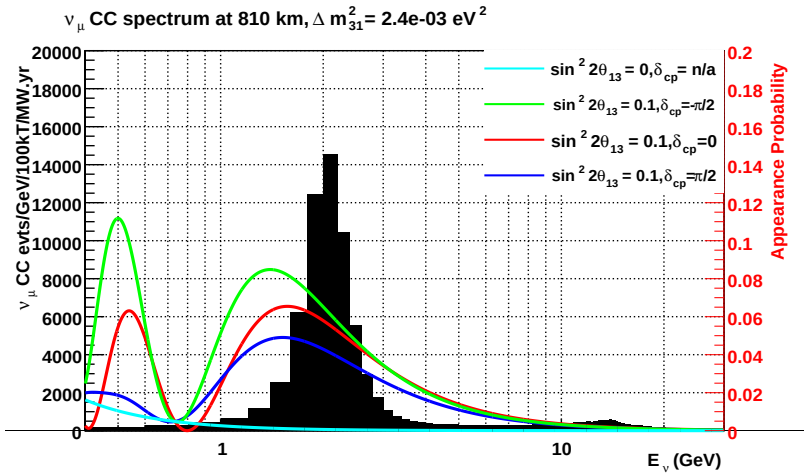
Beams vs Baselines. Neutrinos, NH

735km, NuMI LE at Soudan



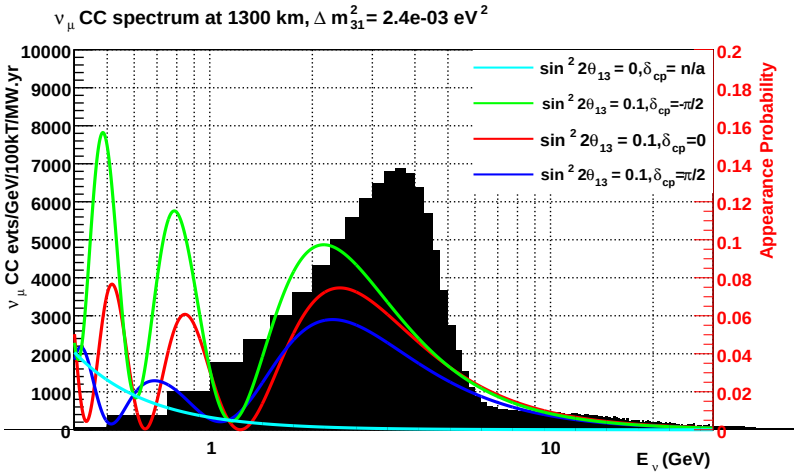
Beam energy too high

810km, NuMI ME at Ash River



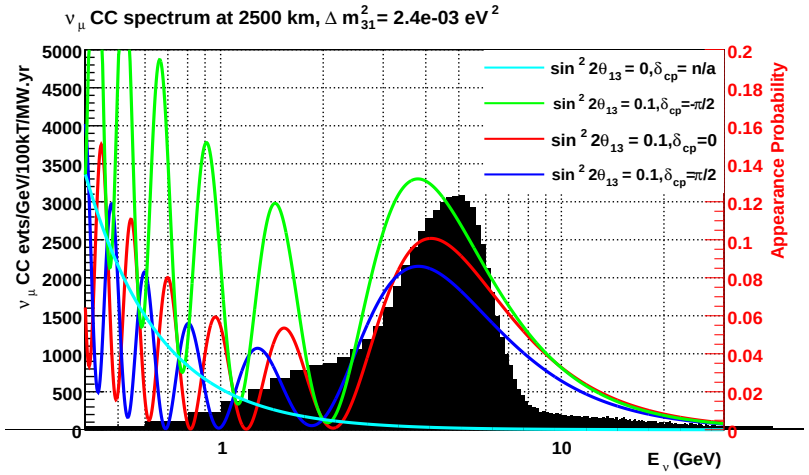
Narrow-band beam

1300km, LBNE LE at Hmstk



Partial coverage of node 2

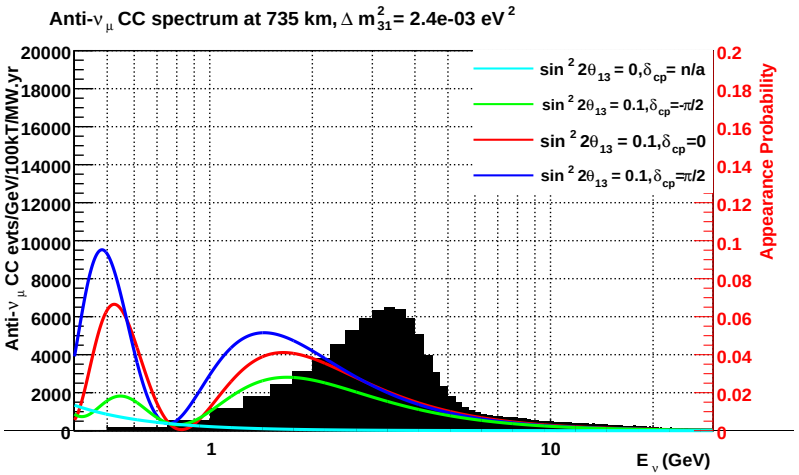
2500km, LBNE pME (580m DP)



Multiple nodes covered

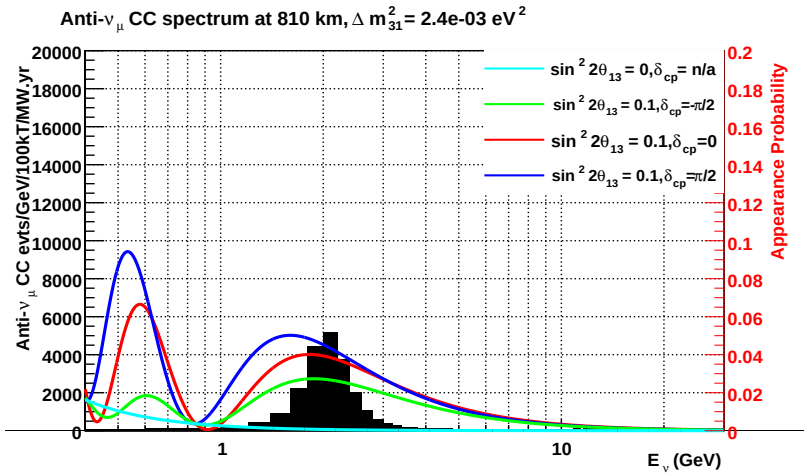
Beams vs Baselines. Anti-neutrinos, NH

735km, NuMI LE at Soudan



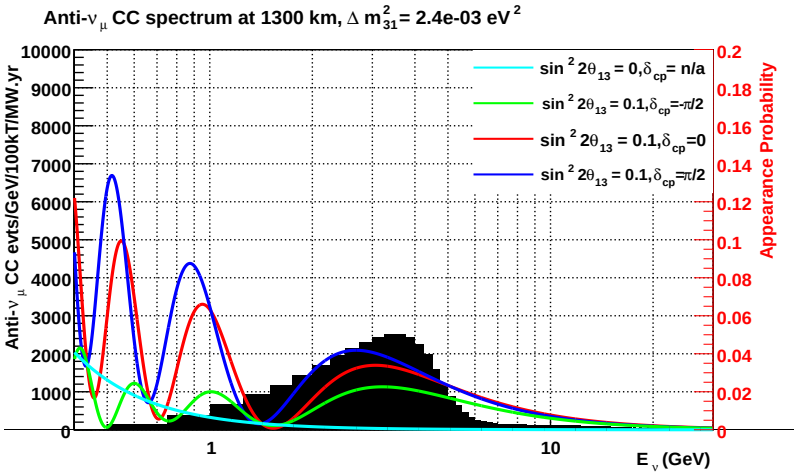
Beam energy too high

810km, NuMI ME at Ash River



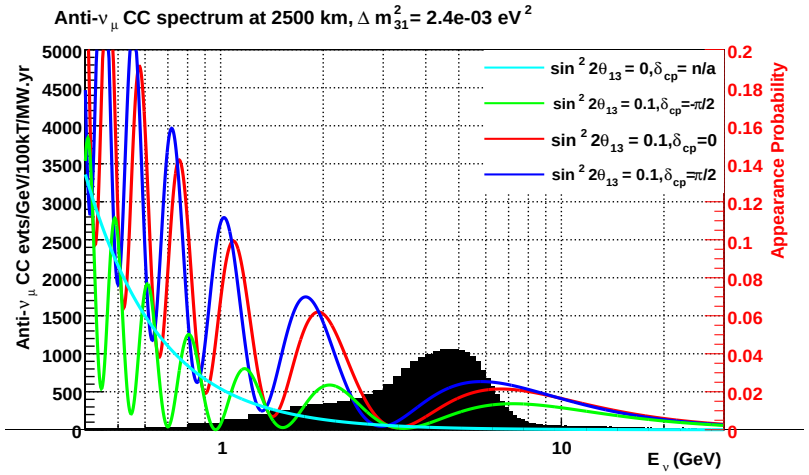
Narrow-band beam

1300km, LBNE LE at Hmstk



Partial coverage of node 2

2500km, LBNE pME (580m DP)



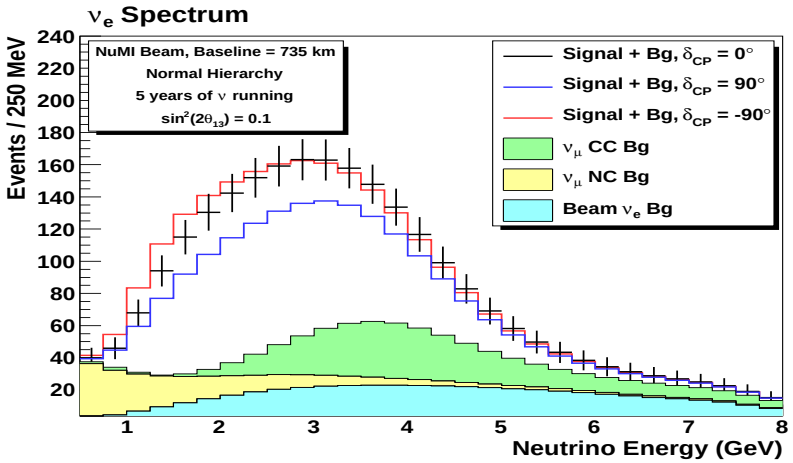
Multiple nodes covered

LAr Detector Performance Parameters

Parameter	Range of Values	Value Used for LBNE Sensitivities
For ν_e CC appearance studies		
ν_e CC efficiency	70-95%	80%
ν_μ NC mis-identification rate	0.4-2.0%	1%
ν_μ CC mis-identification rate	0.5-2.0%	1%
Other background	0%	0%
Signal normalization error	1-5%	1%
Background normalization error	2-10%	5%
For ν_μ CC disappearance studies		
ν_μ CC efficiency	80-95%	85%
ν_μ NC mis-identification rate	0.5-10%	0.5%
Other background	0%	0%
Signal normalization error	1-5%	5%
Background normalization error	2-10%	10%

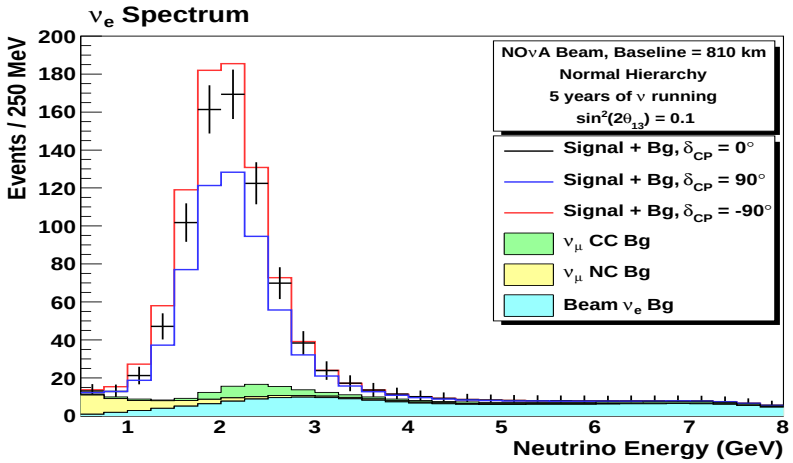
With a 34 kT LAr-TPC. 700kW 5yrs, ν, NH

735km, NuMI LE at Soudan



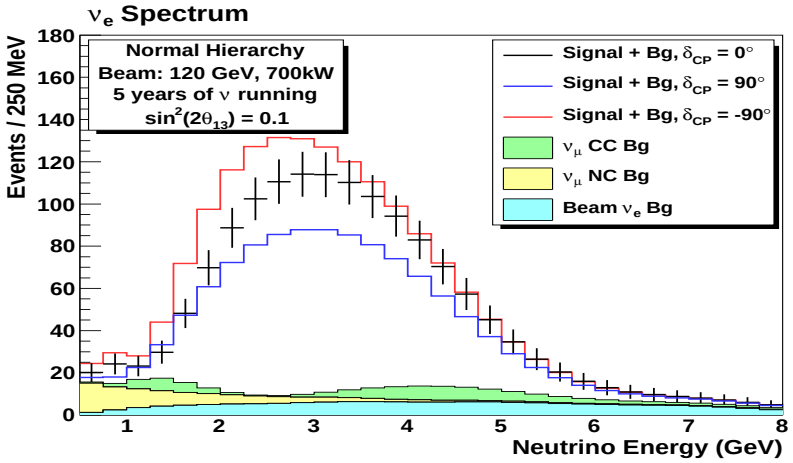
SG: (1386,1338,1011), BG: 1135

810km, NuMI ME at Ash River



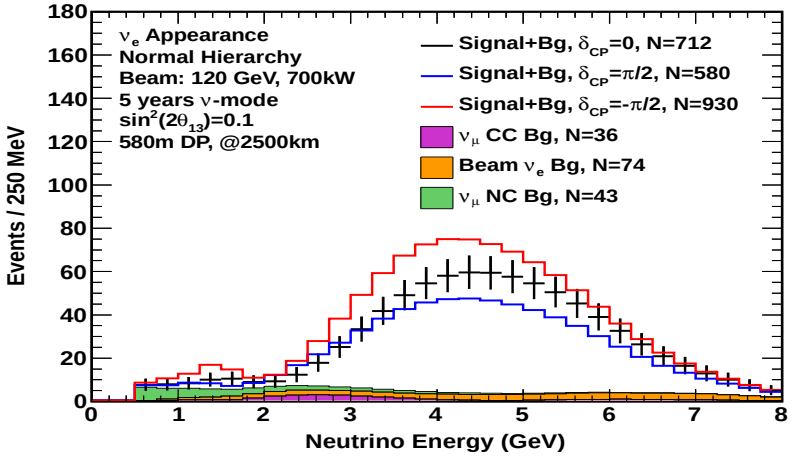
SG: (758,673,497), BG: 278

1300km, LBNE LE at Hmstk



SG: (1366,1157,889), BG: 317

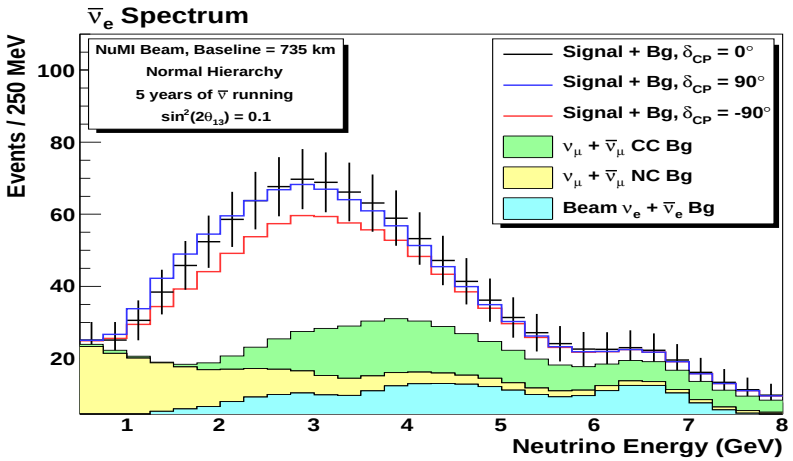
2500km, LBNE pME (580m DP)



SG: (777,559,427), BG: 153

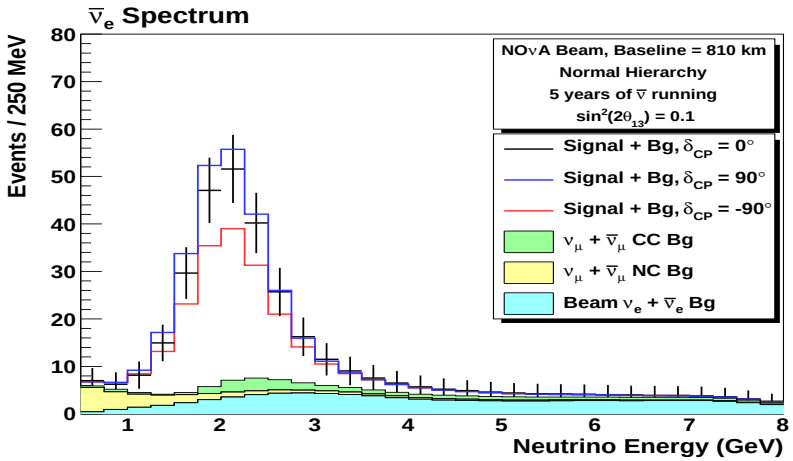
With a 34 kT LAr-TPC. 700kW 5yrs, $\bar{\nu}$, NH

735km, NuMI LE at Soudan



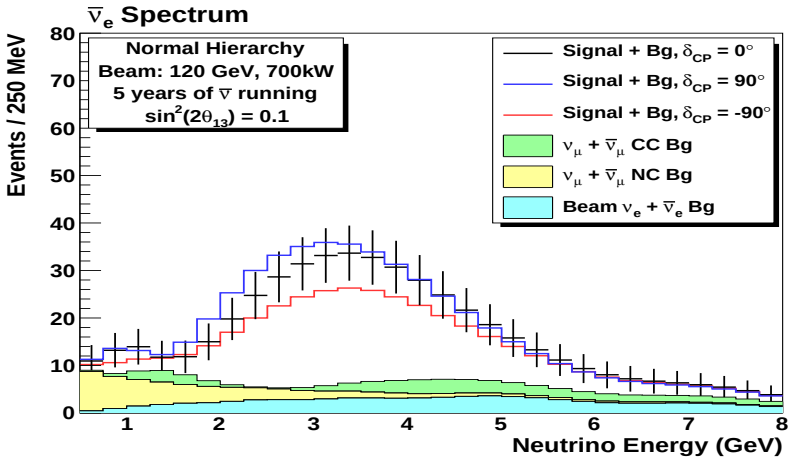
SG: (398,512,502), BG: 644

810km, NuMI ME at Ash River



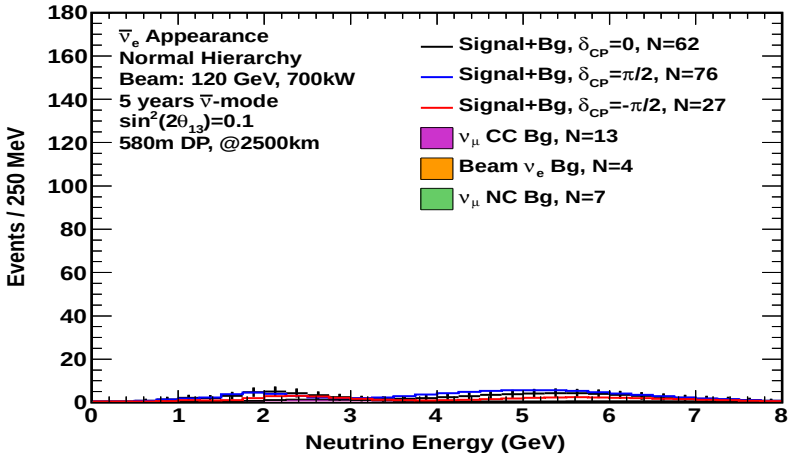
SG: (161,213,228), BG: 136

1300km, LBNE LE at Hmstk



SG: (250,327,353), BG: 176

2500km, LBNE pME (580m DP)



SG: (3,38,52), BG: 24

Estimation of MH and CPV Sensitivities using GLoBeS

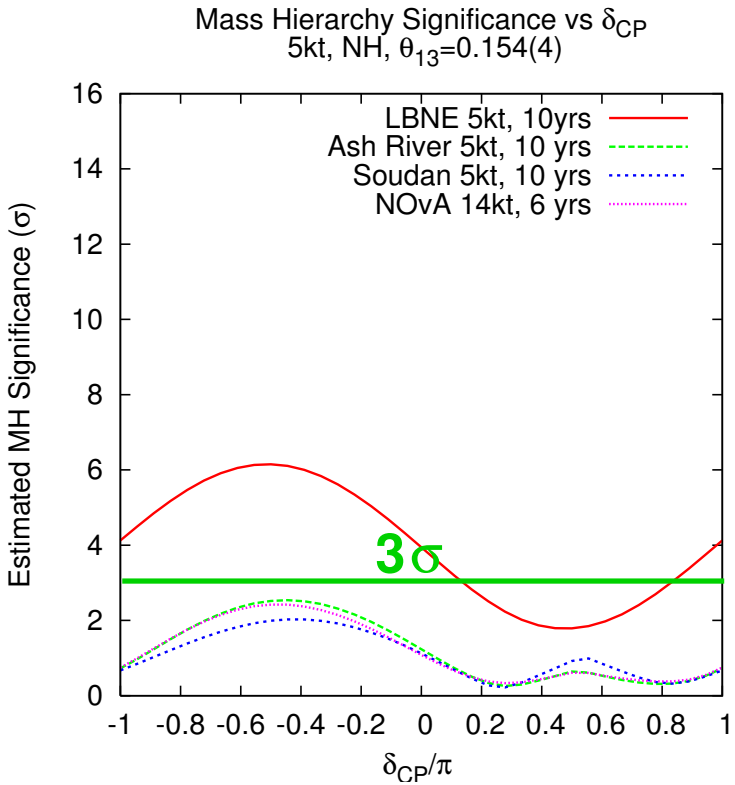
- **We estimate the significance σ with which we can**
  1) exclude the opposite mass hierarchy and
  2) exclude $\delta_{cp} = 0$ or π (CPV)
- **A True appearance event spectrum is generated for a given value of δ_{cp}, sign(Δm^2_{31}).**
- **$\sigma = \sqrt{\chi^2}$, where χ^2 is the smallest value we get comparing the True event spectrum with several Test event spectra. The Test spectra are minimized w.r.t to the known 3-flavor oscillations and the nuisance parameters using Gaussian constraints.**
- **For MH significance the Test spectrum is generated with $\pm|\Delta m^2_{31}|$ and all values of δ_{cp}.**
- **For CPV significance the Test spectrum is generated with $\delta_{cp} = 0, \pi$ and $\pm|\Delta m^2_{31}|$.**

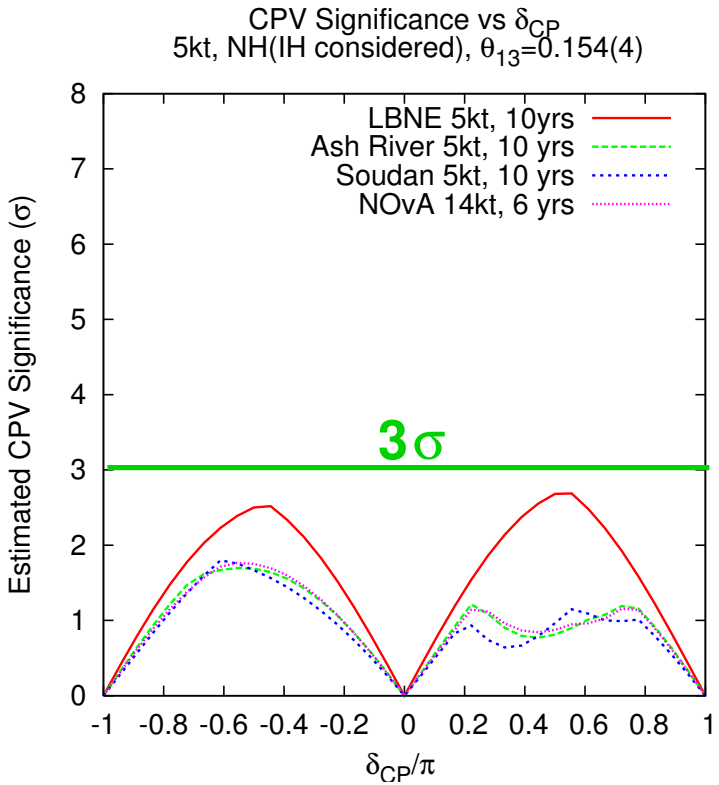
Oscillation and nuisance parameters and uncertainties used:
$\theta_{12} = 0.593 \pm 0.018$, $\theta_{23} = 0.705 \pm 0.078$, $\theta_{13} = 0.154 \pm 0.005$
$\Delta m^2_{21} = 7.58 \pm 0.23 \times 10^{-5}$ eV^2, $\Delta m^2_{32} = 2.35 \pm 0.12 \times 10^{-3}$ eV^2
Matter density: PREM model with 2% uncertainty

1% signal and 5% background normalization uncertainties

Resolution of the Mass Hierarchy and CPV with $\sin^2 2\theta_{13} = 0.092 \pm 0.005$ constraint (M. Bass)

5kt LAr



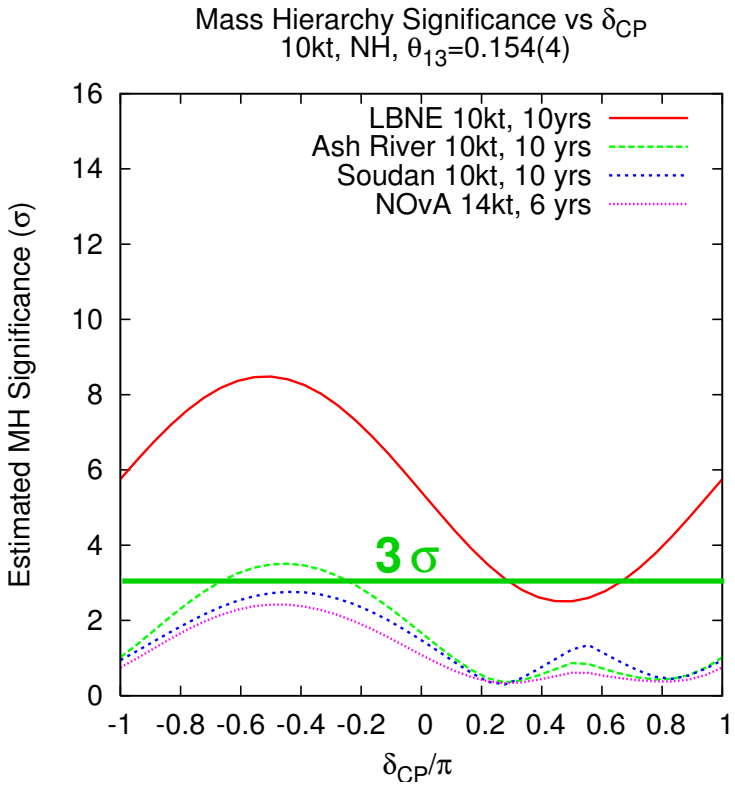


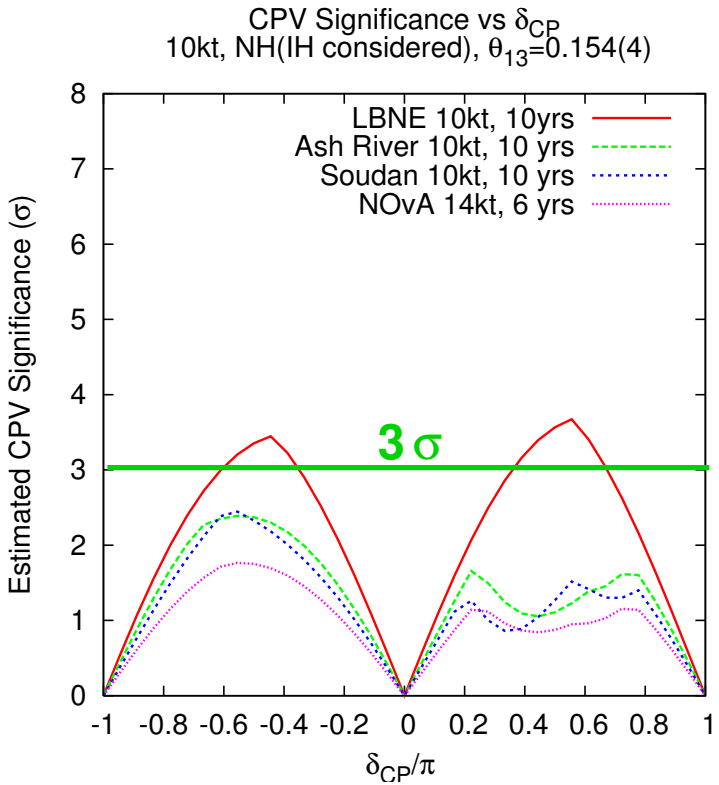
Sensitivities are calculated for each experiment independently.

No constraints from NOνA or T2K **14kt NOνA $\equiv$ 5kt LAr at A.R.**

Resolution of the Mass Hierarchy and CPV with $\sin^2 2\theta_{13} = 0.092 \pm 0.005$ constraint (M. Bass)

10kt LAr



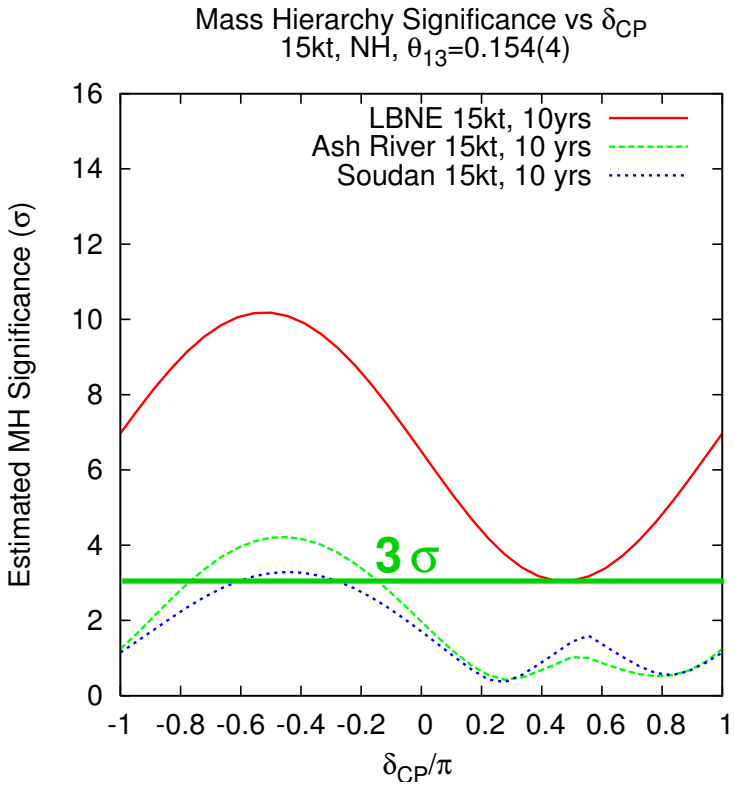


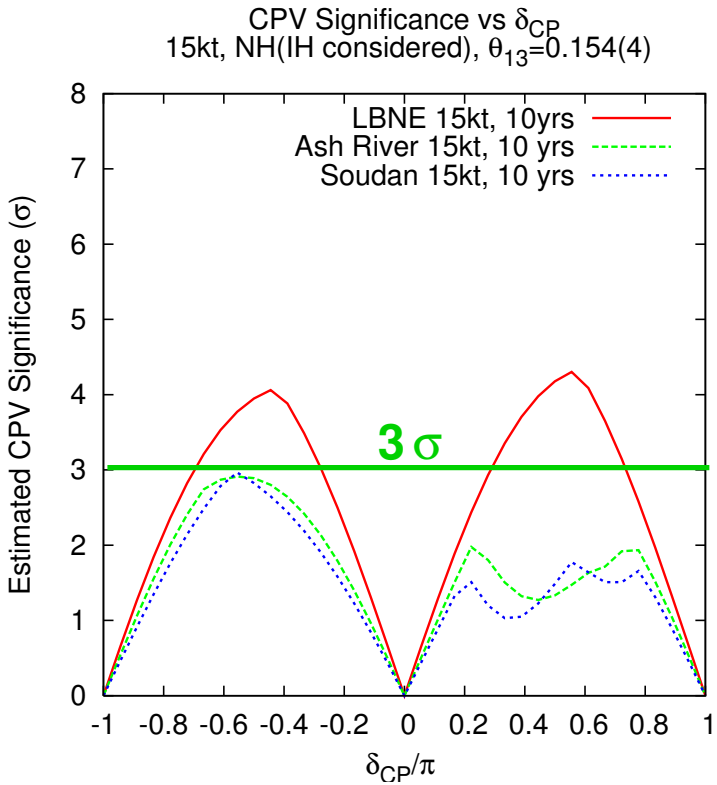
Sensitivities are calculated for each experiment independently.

No constraints from NOνA or T2K **14kt NOνA $\equiv$ 5kt LAr at A.R.**

Resolution of the Mass Hierarchy and CPV with $\sin^2 2\theta_{13} = 0.092 \pm 0.005$ constraint (M. Bass)

15kt LAr



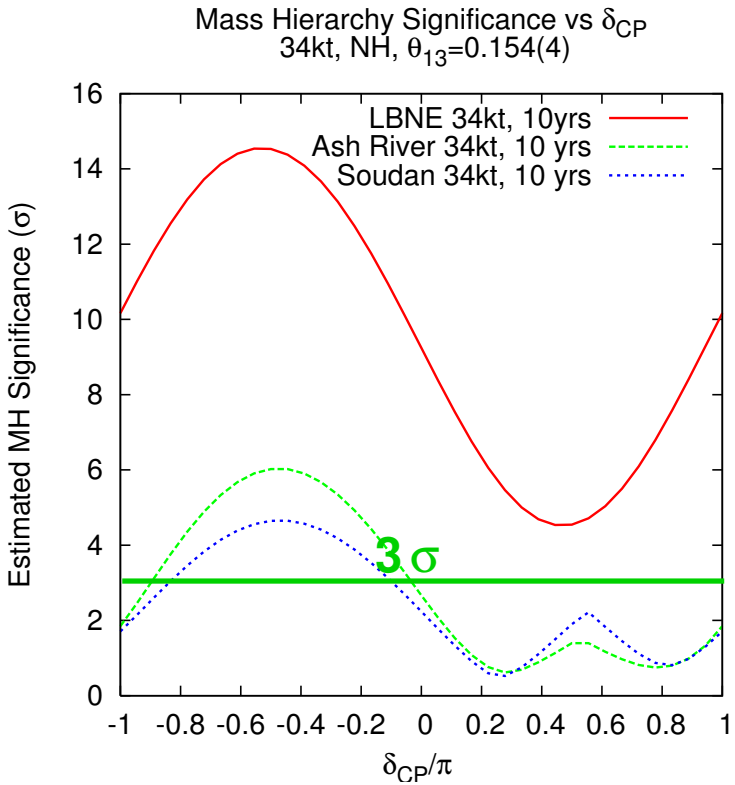


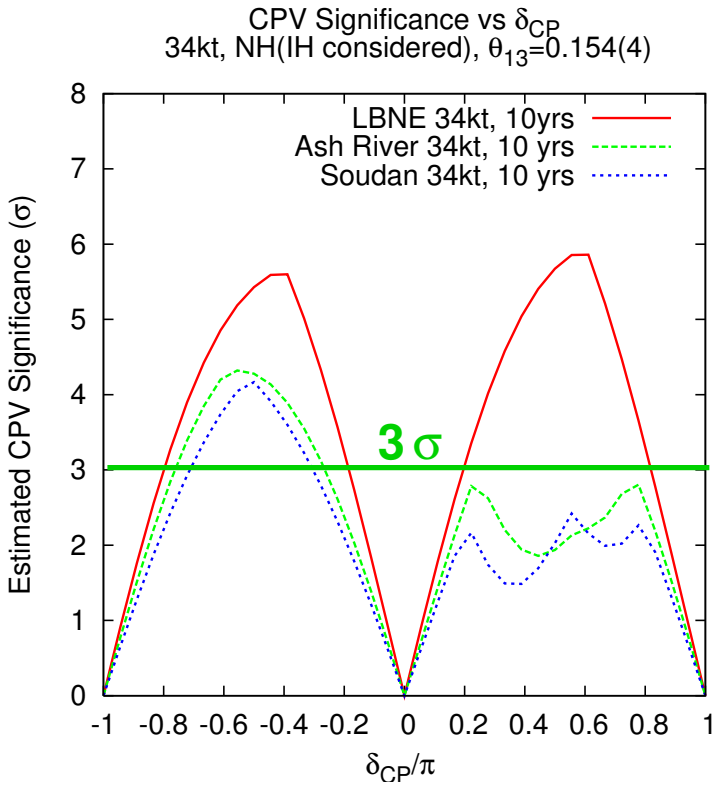
Sensitivities are calculated for each experiment independently.

No constraints from NOνA or T2K **14kt NOνA $\equiv$ 5kt LAr at A.R.**

Resolution of the Mass Hierarchy and CPV with $\sin^2 2\theta_{13} = 0.092 \pm 0.005$ constraint (M. Bass)

34kt LAr



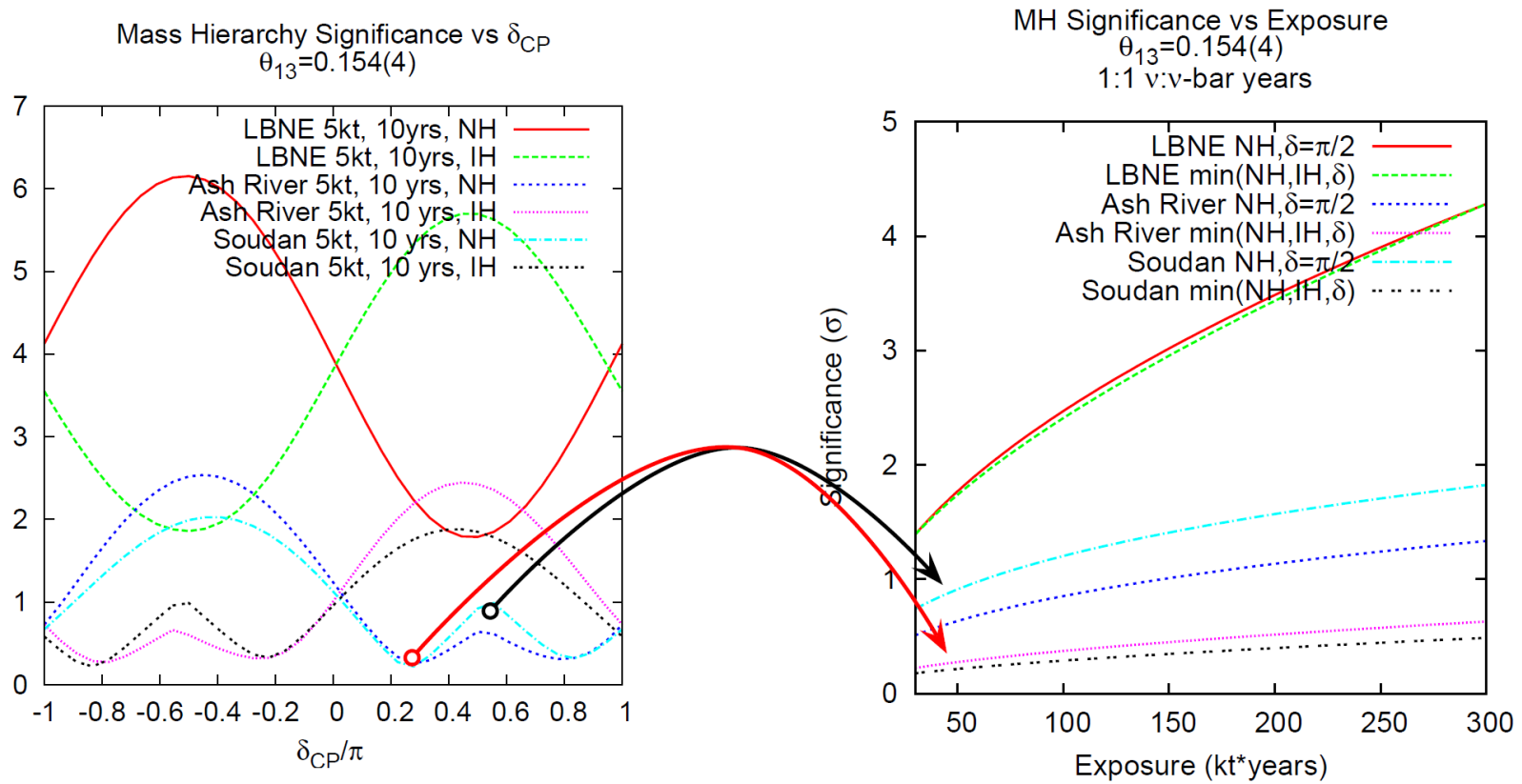


Sensitivities are calculated for each experiment independently.

No constraints from NOνA or T2K **14kt NOνA $\equiv$ 5kt LAr at A.R.**

MH vs Exposure with $\sin^2 2\theta_{13} = 0.092 \pm 0.005$ constraint (M. Bass)

Assumes 6.0×10^{20} p.o.t/yr:



Ability to resolve MH for $(\mathrm{NH/IH}, \delta_{cp} > 0/ < 0)$ is limited with NuMI

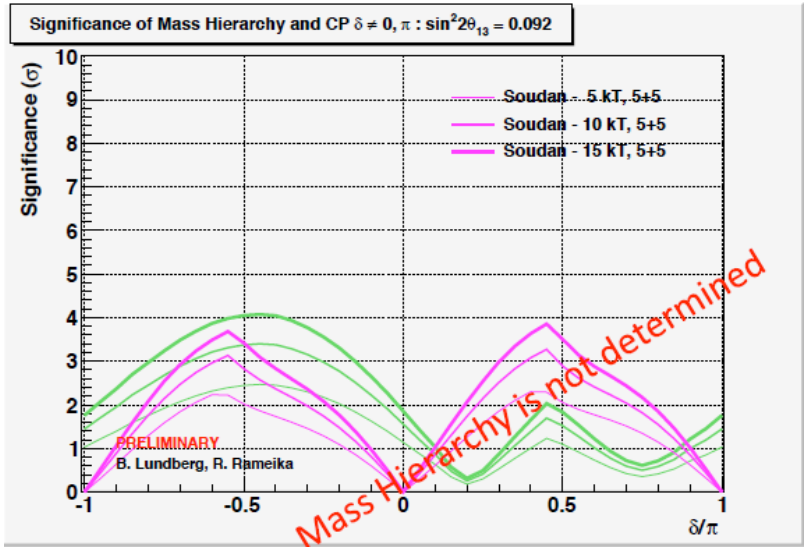
LBNE resolves MH at 3σ <u>unambigously</u> for exposures $\geq$ 150 kt. yrs.

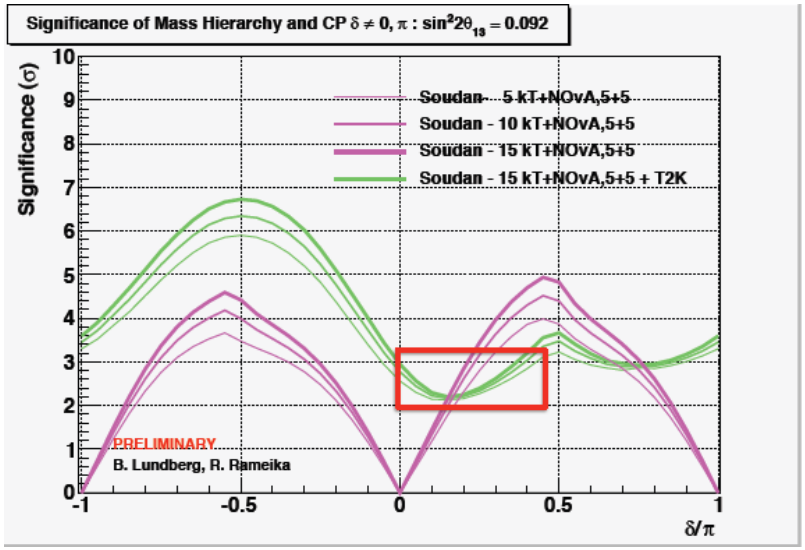
Combination of NOνA, T2K and NuMI LAr. (G. Rameika)

NOνA: NuMI ME (3+3yrs) + NuMI LE (5+5) yrs
T2K: 7yrs at 300 kW.

MH and CPV sensitivies

With no T2K or NOνA **with T2K and NOνA**





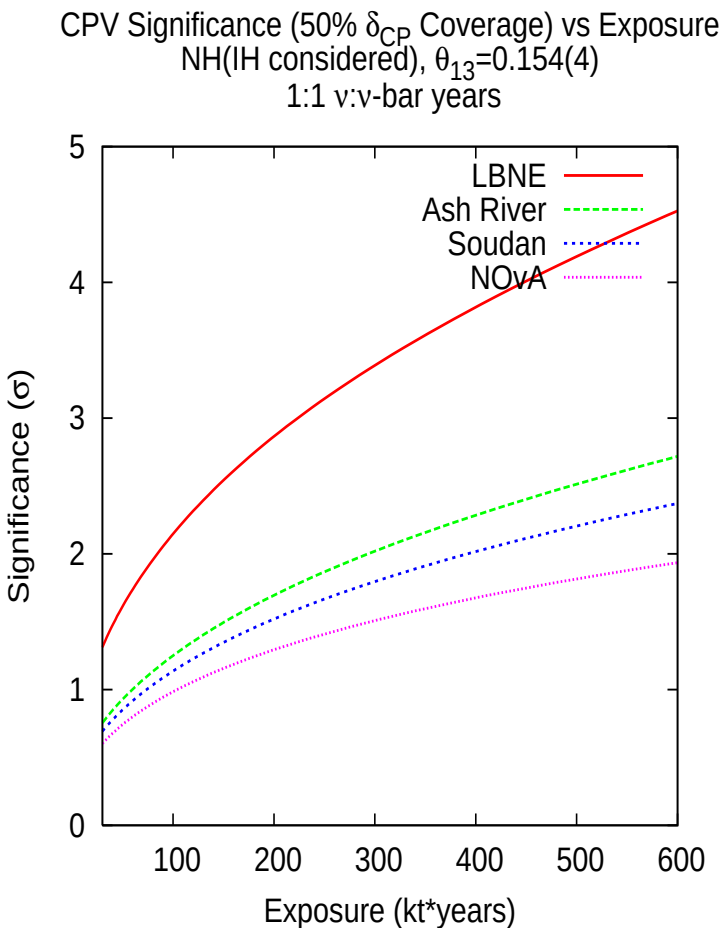
MH could be resolved at 3σ for 75% δ_{cp} with T2K+NOνA .

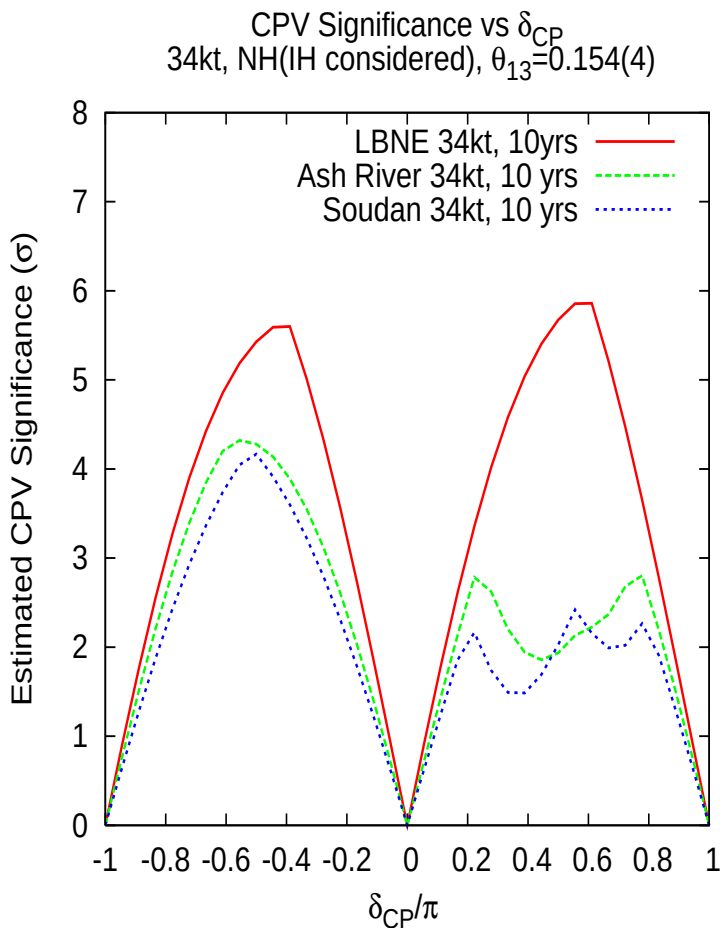
14kt NOνA $\equiv$ 5kt LAr at A.R.

NB: Gina's significance $\sim$ 1.25$\times$ LBNE significance

CPV vs Exposure with $\sin^2 2\theta_{13} = 0.092 \pm 0.005$ constraint (M. Bass)

Opposite hierarchy is considered in χ^2



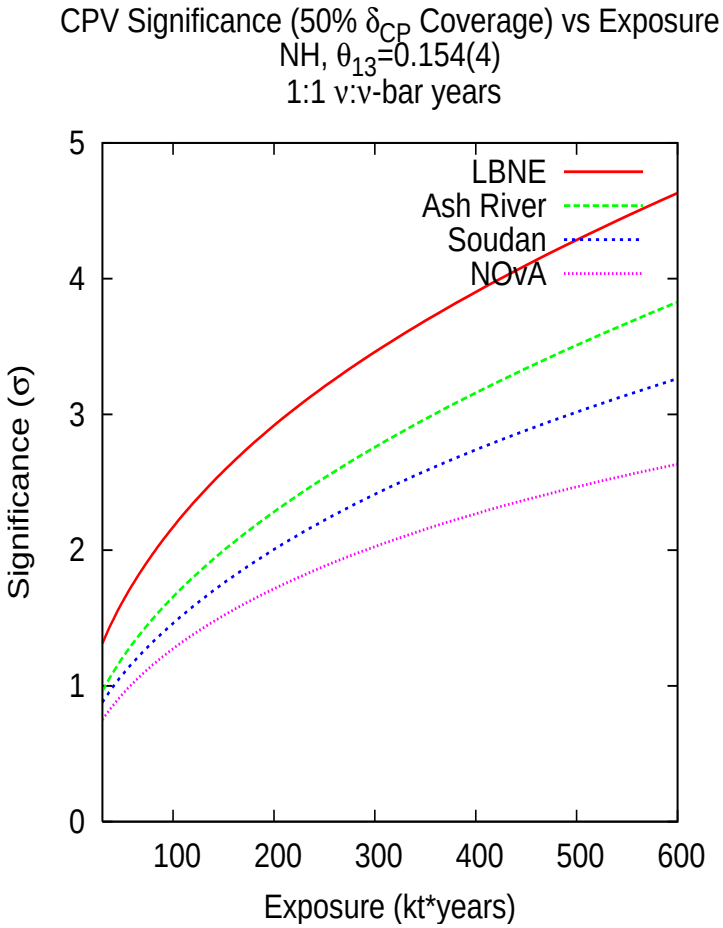


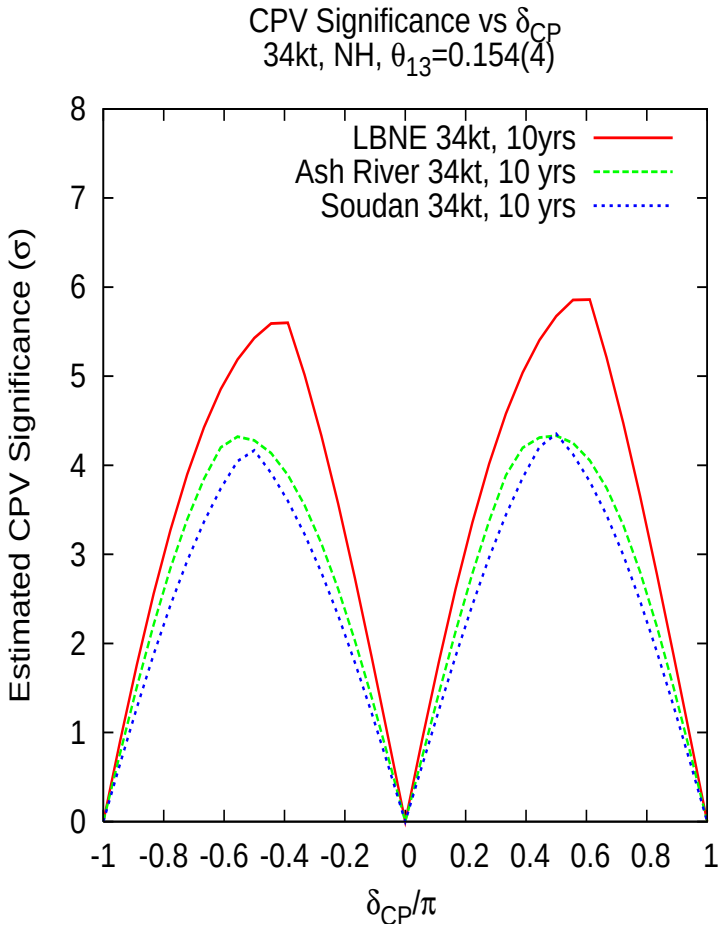
To resolve CPV at $\geq 3\sigma$ for 50% of δ_{cp}

LBNE: 200 kt.yrs. Soudan: 1200 kt.yrs. Ash River: 800 kt.yrs

CPV vs Exposure with $\sin^2 2\theta_{13} = 0.092 \pm 0.005$ constraint (M. Bass)

Assume MH is resolved for all δ_{cp}

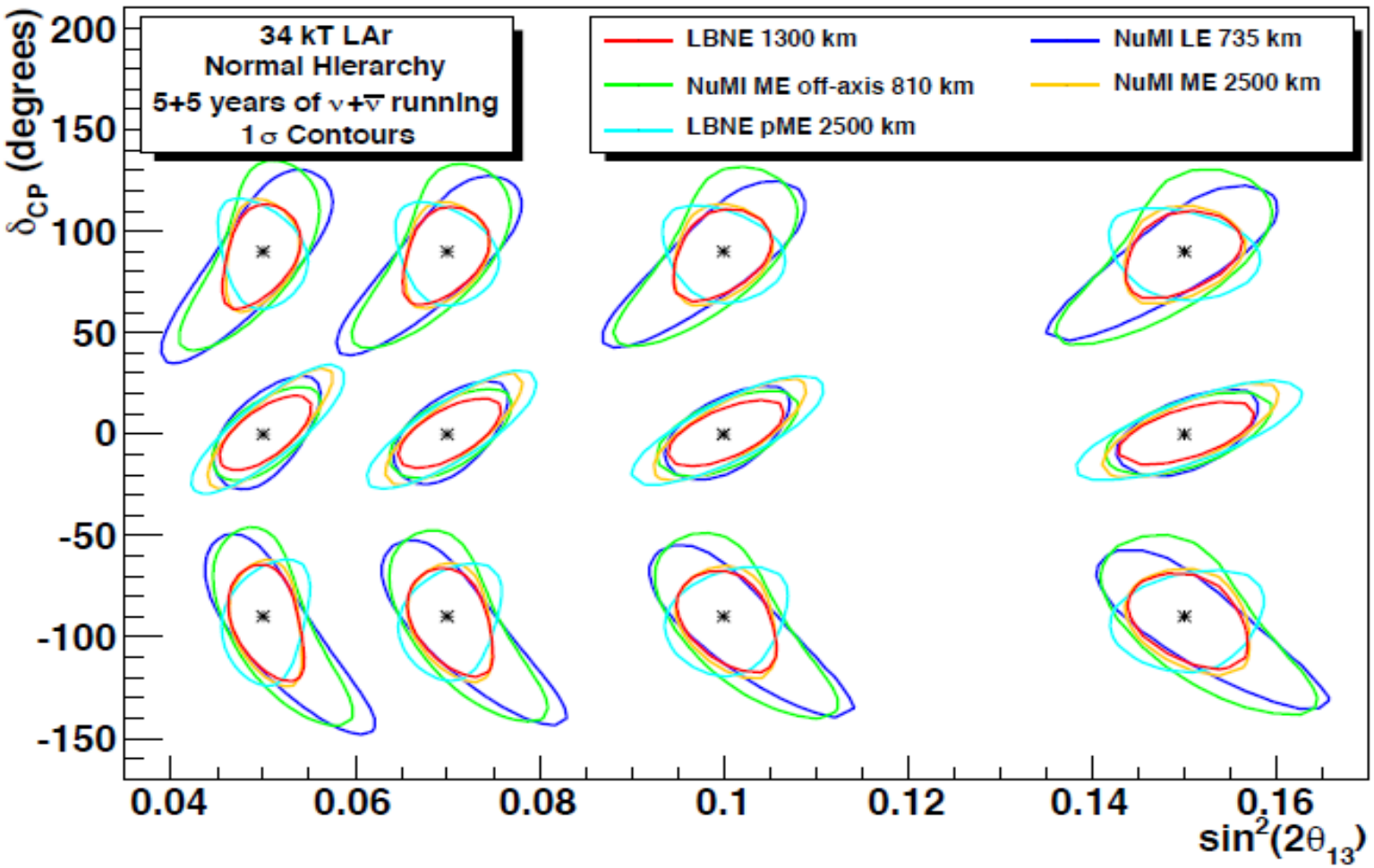




To resolve CPV at $\geq 3\sigma$ for 50% of δ_{cp}

LBNE: 200 kt.yrs. Soudan: 500 kt.yrs. Ash River: 400 kt.yrs

δ_{cp} and θ_{13} resolutions (E. Worcester)

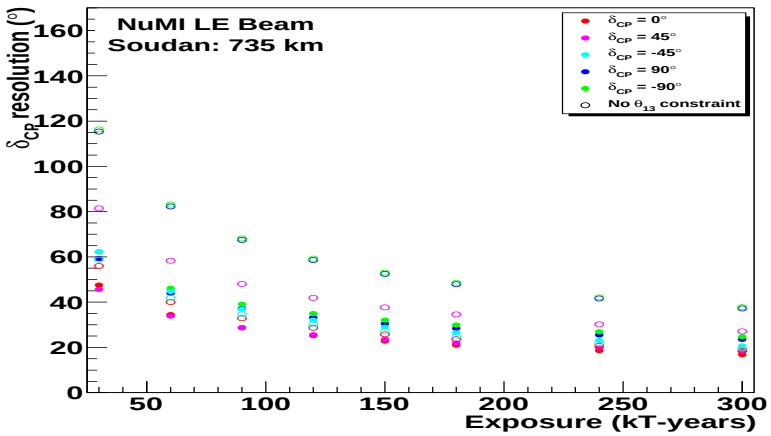


Independent measurement of θ_{13} with similar accuracy to Daya Bay

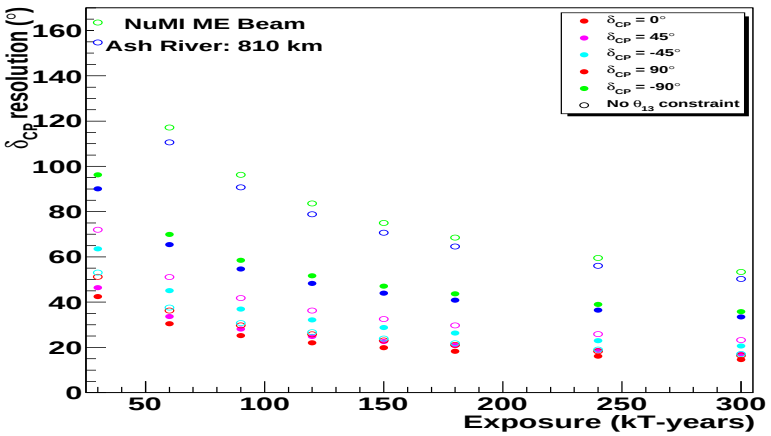
Requires baselines $\geq$ 1300 km

CP and θ_{13} Resolutions vs Exposure (E. Worcester)

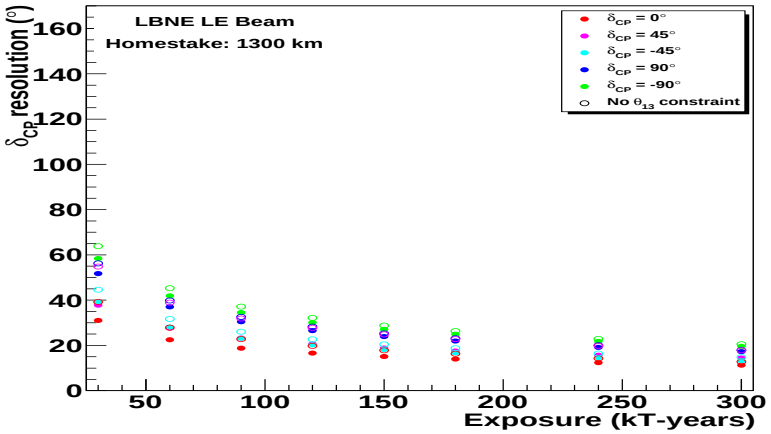
735km, NuMI LE at Soudan



810km, NuMI ME at Ash River



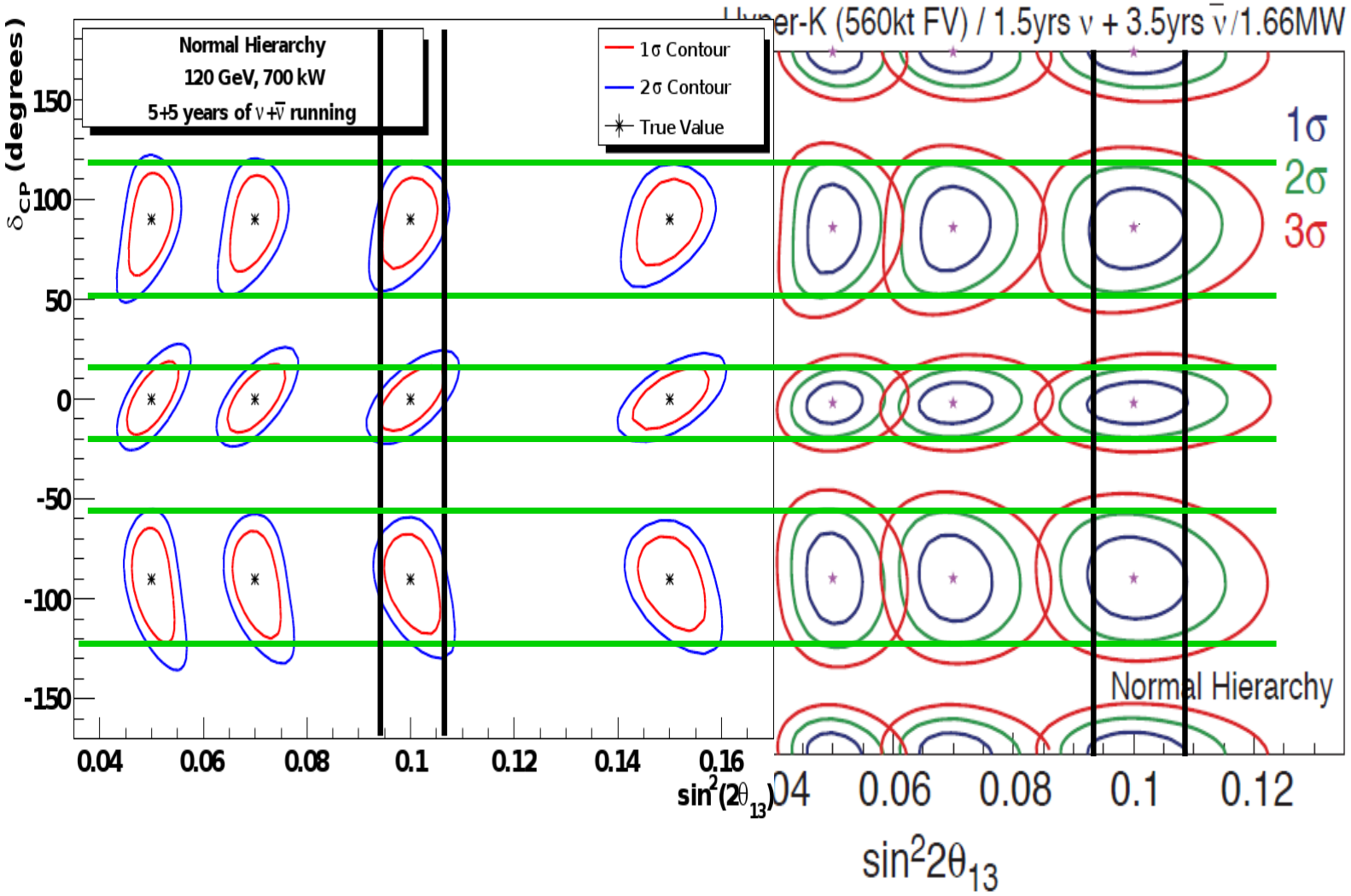
1300km, LBNE LE at Hmstk



LBNE does NOT need external constraints for exposures $\geq$ 60 kt yrs.

Comparisons of LBNE with T2HK

LBNE: 34kT LAr 700kW 10yrs. T2HK: 560kT WCD, 1.66 MW, 10yrs

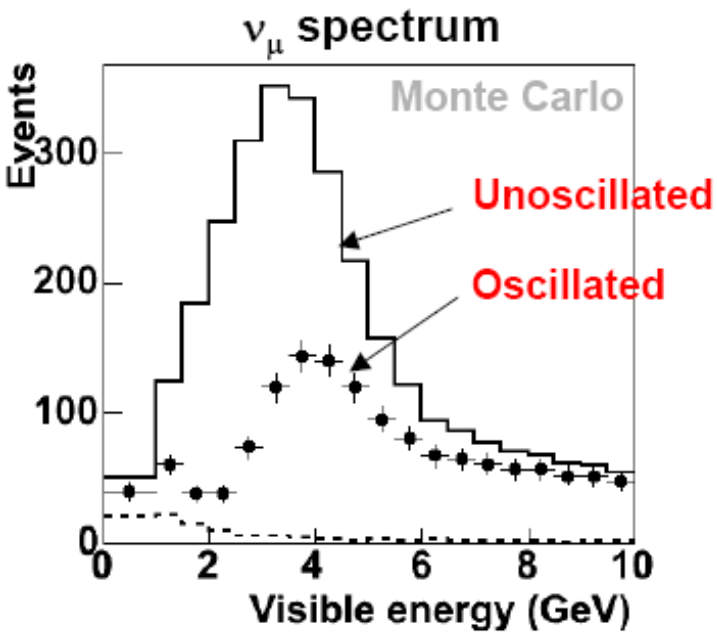


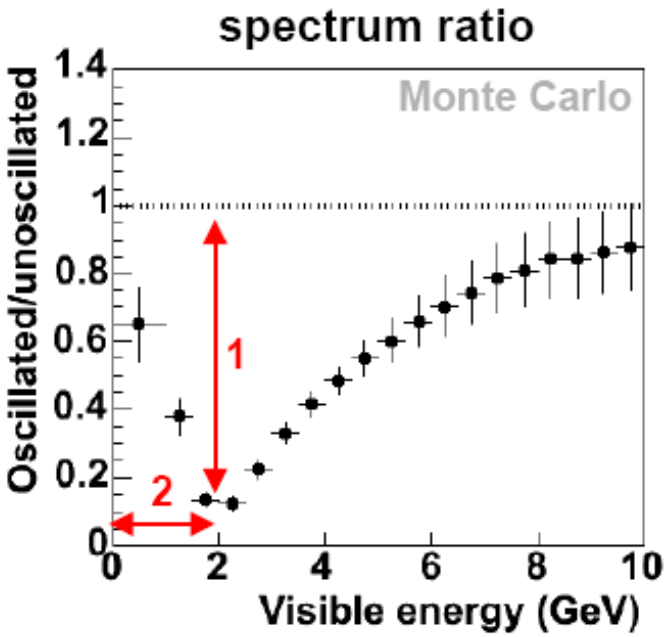
Final phase of LBNE is competitive with T2HK

Measuring Δm^2_{23}, $\sin^2 2\theta_{23}$

ν_μ and $\bar{\nu}_\mu$ disappearance measurements.

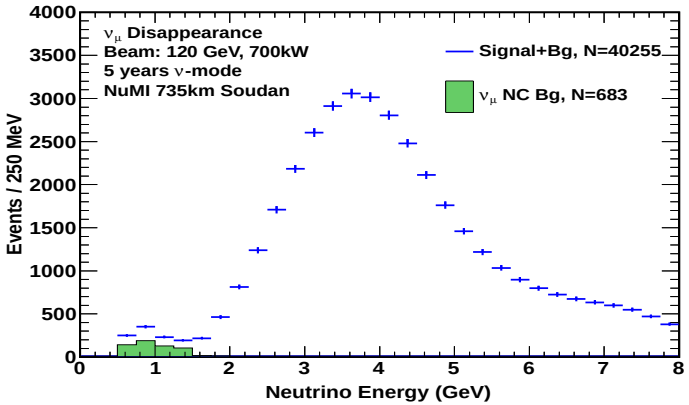
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \underbrace{\sin^2 2\theta_{23}}_{1} \sin^2(1.267\, \underbrace{\Delta m^2_{32}}_{2}\, L/E)$$



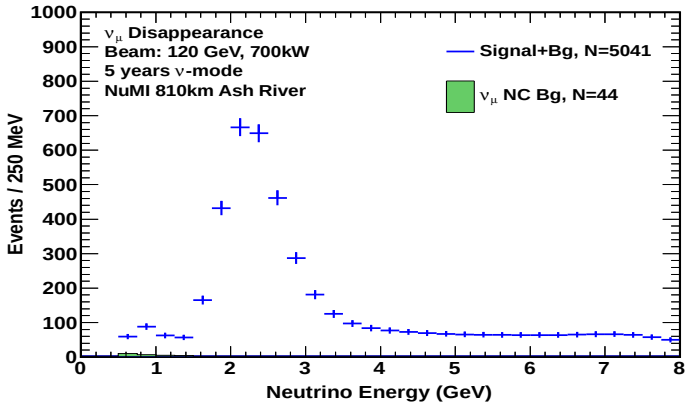


Disappearance Spectra - Neutrinos (Z. Isvan)

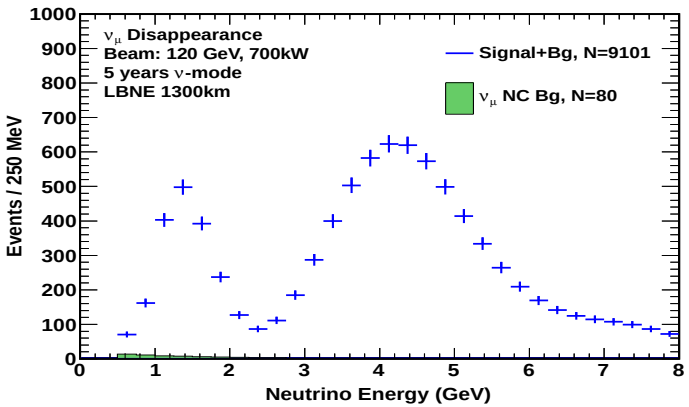
735km, NuMI LE at Soudan



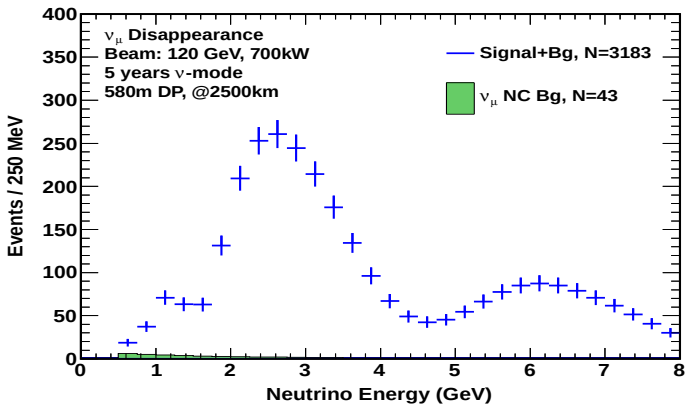
810km, NuMI ME at Ash River



1300km, LBNE LE at Hmstk



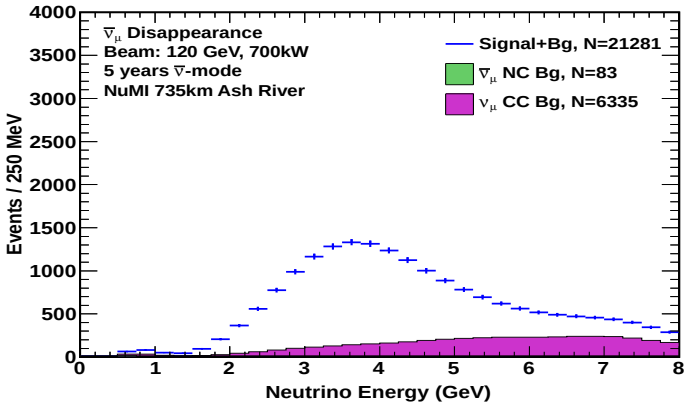
2500km, LBNE pME (580m DP)



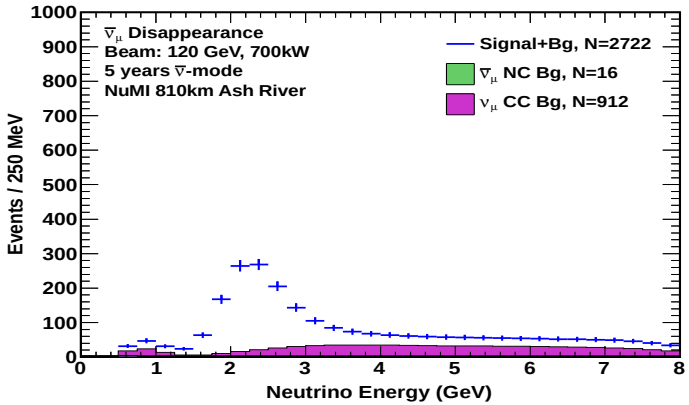
Observe detailed oscillation structure at baselines $\geq$ 1300km .

Disappearance Spectra - Anti-Neutrinos (Z. Isvan)

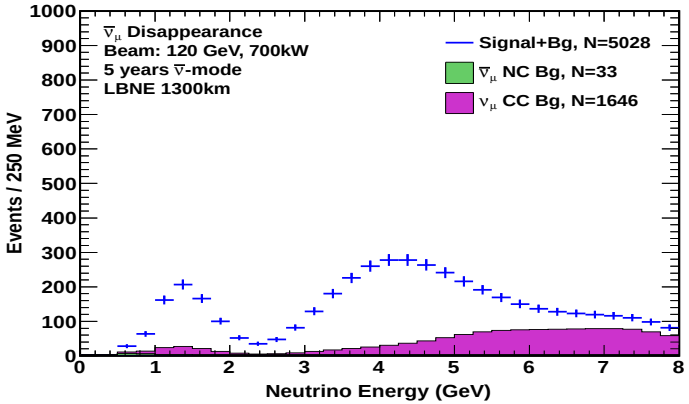
735km, NuMI LE at Soudan



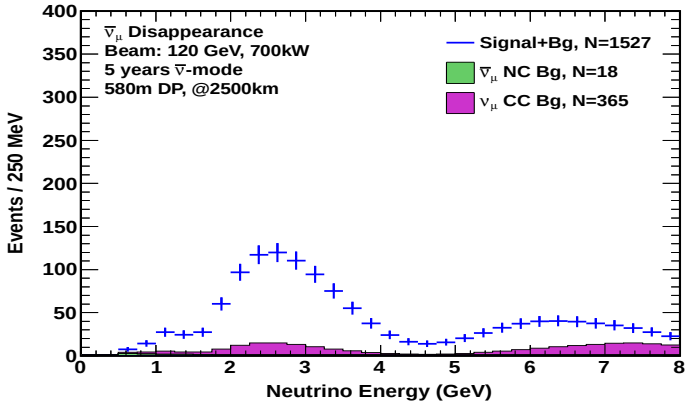
810km, NuMI ME at Ash River



1300km, LBNE LE at Hmstk



2500km, LBNE pME (580m DP)



Observe detailed oscillation structure at baselines $\geq$ 1300km .

LBNE measurement of atmospheric parameters (R. Guenette)

Assumes 7.3 e20 p.o.t/yr:

MINOS 2012

$\Delta m^2_{32}(\nu) = 2.32^{+0.12}0.08(\mathrm{stat.} + \mathrm{syst.})10^3\mathrm{eV}^2$, $\sin^2(2\theta) > 0.90(90\%\mathrm{CL})$

$\Delta m^2_{32}(\bar{\nu}) = 2.62^{+0.31}_{-0.28}(\mathrm{stat.}) \pm 0.09(\mathrm{syst})10^3\mathrm{eV}^2$, $\sin^2(2\bar{\theta}) > 0.75(90\%\mathrm{CL})$

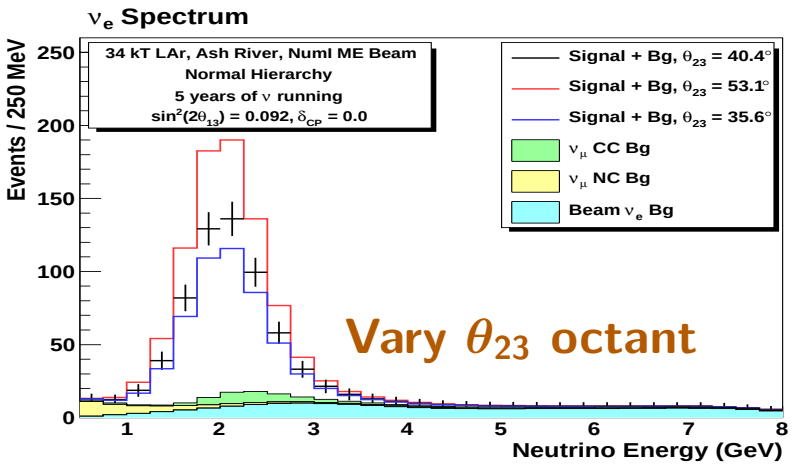
LBNE-Hmstk: $\sin^2 2\theta_{23} = 1.0, \Delta m^2_{32} = 2.41 \times 10^{-3}\ \mathrm{eV}^2$:

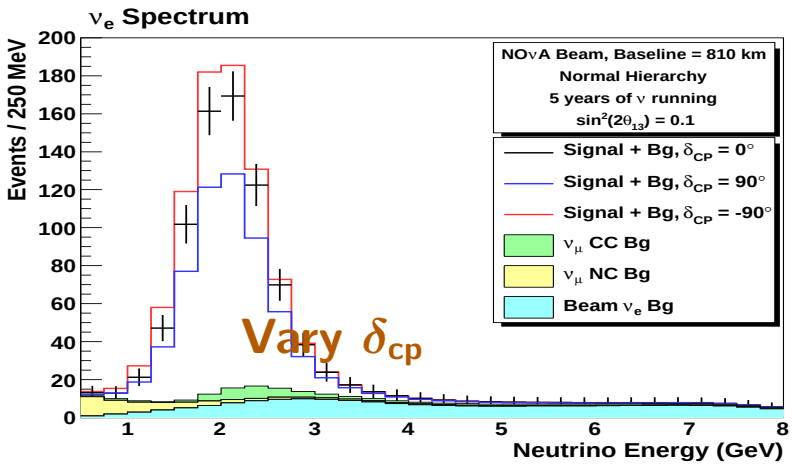
	ν		$\bar{\nu}$	
	$\delta(\sin^2 2\theta_{23})$	$\delta(\Delta m^2_{32}) \times 10^{-3}\ \mathrm{eV}^2$	$\delta(\sin^2 2\theta_{23})$	$\delta(\Delta m^2_{32}) \times 10^{-3}\ \mathrm{eV}^2$
30 kt-yrs LAr	0.012	0.034	0.018	0.054
50 kt-yrs LAr	0.010	0.028	0.015	0.045
75 kt-yrs LAr	0.008	0.023	0.012	0.035
170 kt-yrs LAr	0.005	0.016	0.008	0.024

Measurements with sub-percent precision in final phases

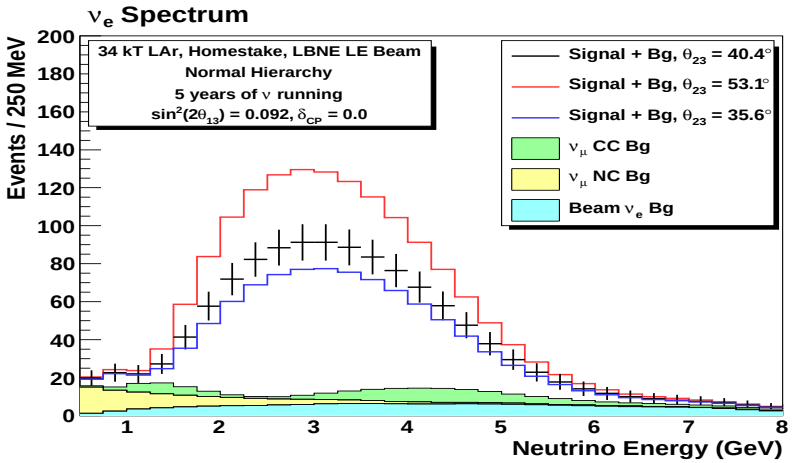
Impact of the θ_{23} Octant. (E Worcester)

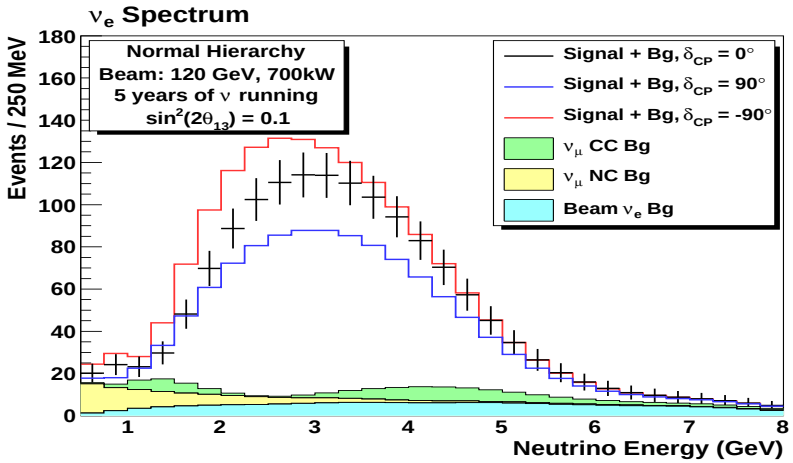
L=810km, NuMI ME 14mrad off-axis





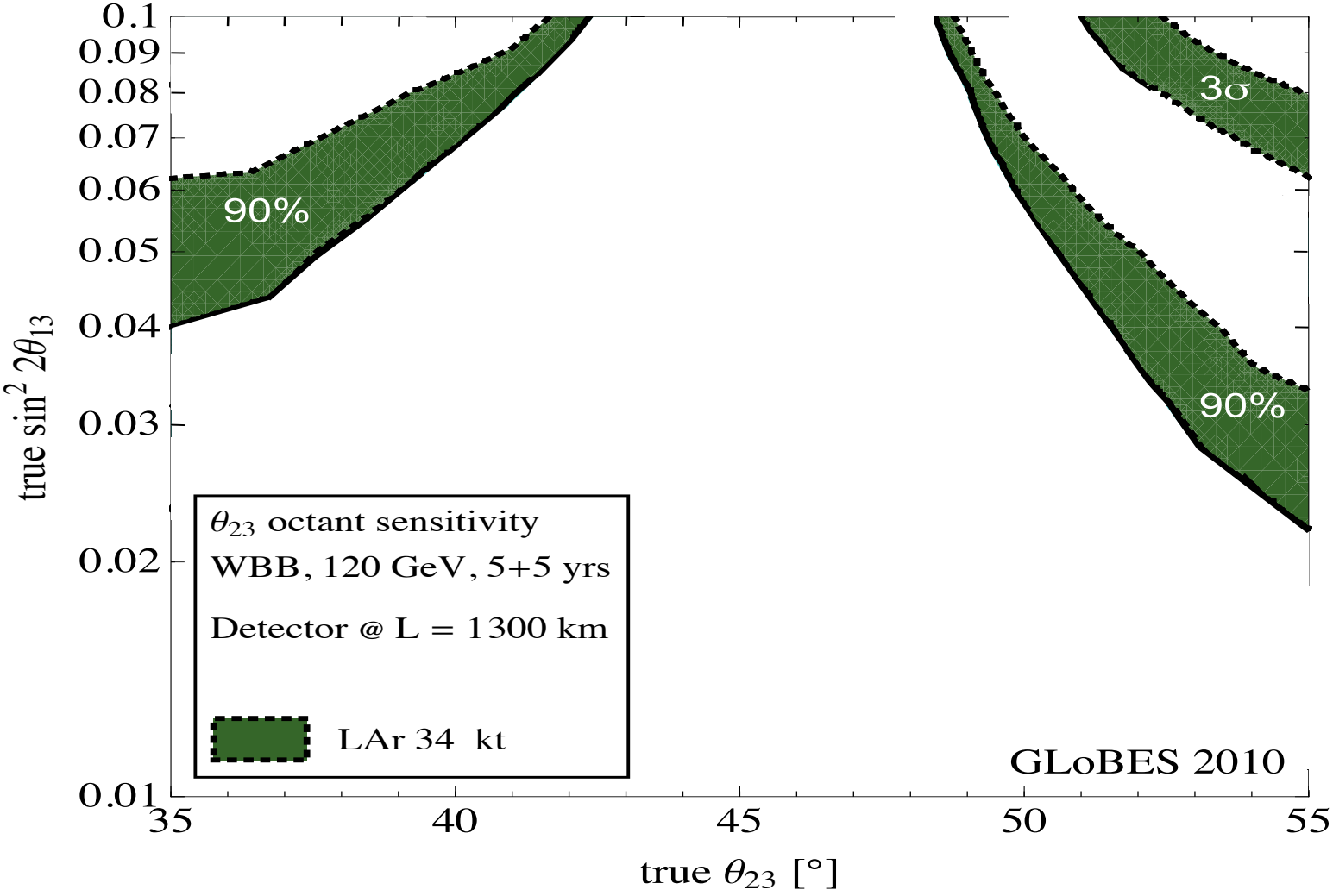
L=1300km, LBNE LE





Larger spectral differences on-axis help break degeneracies

Resolution of the θ_{23} Octant - LBNE 34 kT

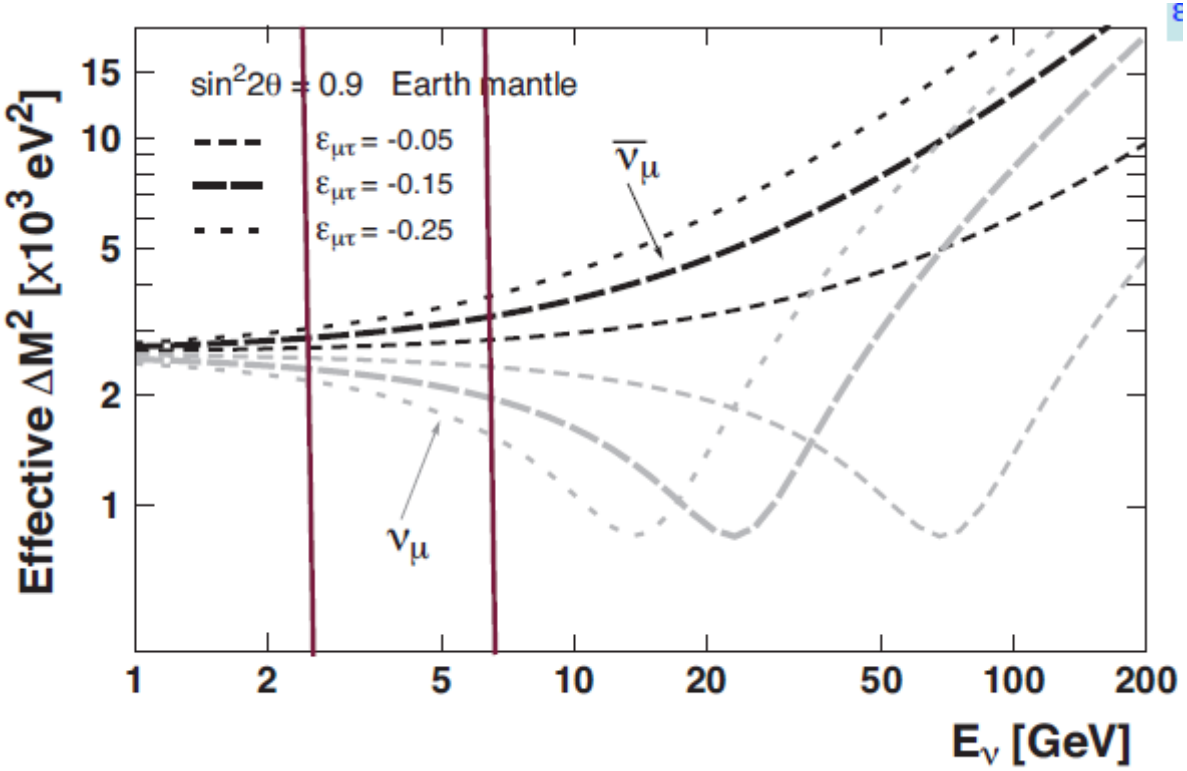


New Physics in $\nu_\mu/\bar{\nu}_\mu$ Disappearance

Phys.Rev. D82 (2010) 113010:

$$\mathcal{P}\left({}^{(}\overline{\nu}_\mu \to {}^{(}\overline{\nu}_\mu\right) \simeq 1 - \sin^2\left(\left|\frac{\Delta m^2_{32}}{4E_\nu} \mp \epsilon_{\mu\tau}|V_e|\right| L\right). \quad (10)$$

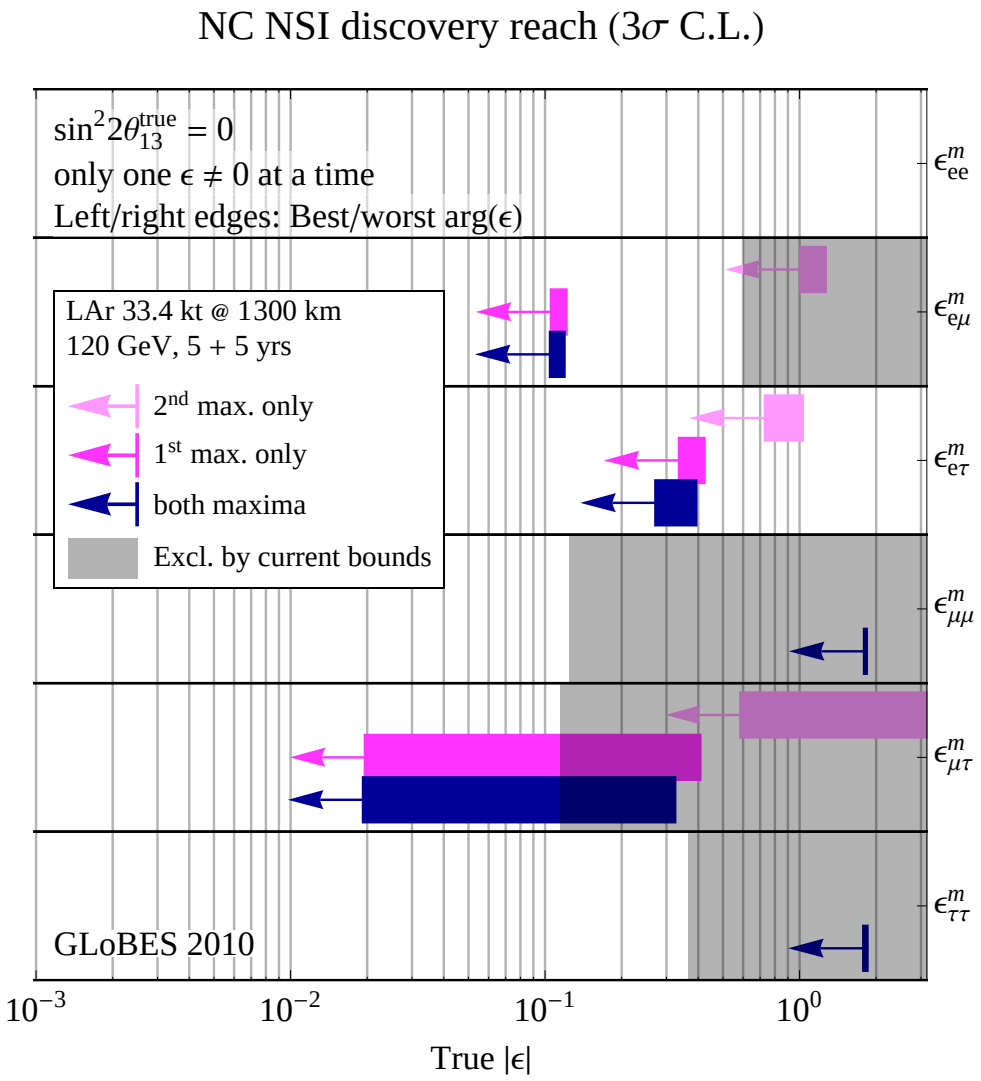
$$\Delta M^2_{\rm eff} = \Delta m^2_{32}\Big\{1 \mp \sin 2\theta\, \epsilon_{\mu\tau}\, |V_e|\, (4E_\nu/\Delta m^2_{32}) + (\epsilon_{\mu\tau}V_e)^2 \cdot (4E_\nu/\Delta m^2_{32})^2\Big\}^{1/2}. \quad (11)$$



Mann A.W. et al., arxiv 1006.5720

Oscillations at larger E_ν (longer baselines) = larger effects

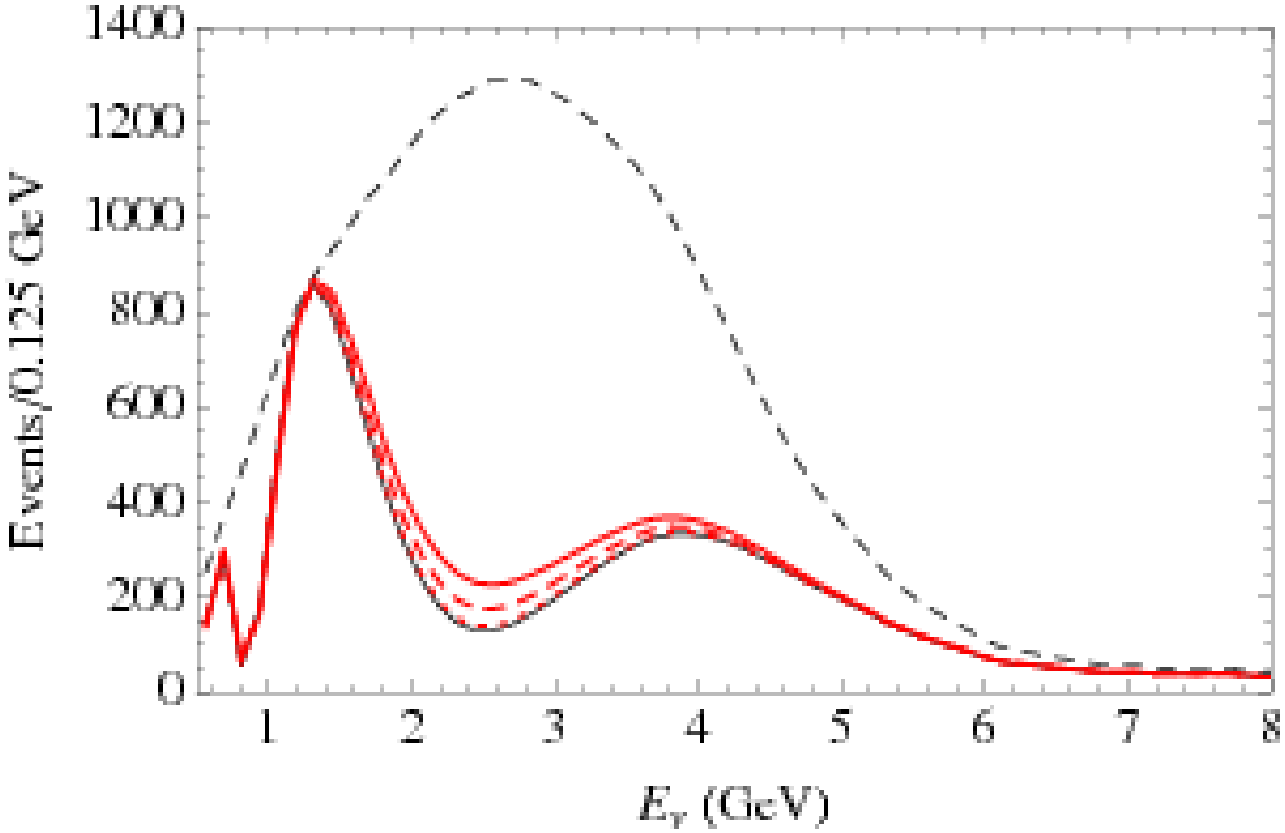
Expected Limits on Non-Standard Interactions in LBNE with 34kT LAr



Requires precision determination of 3-flavor oscillation parameters

Long Range Interactions

Phys.Rev. D84 (2011) 013009
Cases with $\alpha' = 1.0, 0.5, 0.1 \times 10^{-52}$ corresponding to thick solid, dashed, and dotted curves, respectively:



Requires long baselines and detailed spectral information

Summary and Conclusions

- *The Ash River site (or other NuMI off-axis sites) was optimized for θ_{13} appearance at small values, but the surface location, lack of spectral information and smaller event rates are not well matched to a broad physics program.*
- **Resolution of the mass hierarchy at 3σ for most δ_{cp} cannot be achieved by a single NuMI experiment. Combination with T2K and NOνA (16 yrs running) are needed. LBNE-Hmstk can resolve the mass hierarchy unambiguously for 90% of δ_{cp} values with $\approx$ 100 kt.yrs.**
- **Evidence of CP-violation (3σ) for 50% δ_{cp} values in a single experiment requires $\geq$ 200 kt.yrs of exposure of LBNE-Homestake with NO external constraints. NuMI options require $\geq$ 800 kt.yrs with a tight θ_{13} constraint and $\geq$ 400 kt.yrs with both MH and θ_{13} external constraints**
- **LBNE-Hmstk final stage with 34kt is the most competitive with T2HK for measurements of δ_{cp}, θ_{13}.**
- **LBNE-Homestake enables a broad long baseline physics program that extends beyond 3-flavor oscillation = unique capabilities compared to competition.**