Long Baseline Physics with LBNE-Homestake vs. NuMI Alternatives

LBL Physics Working Grp, 4/9/2012

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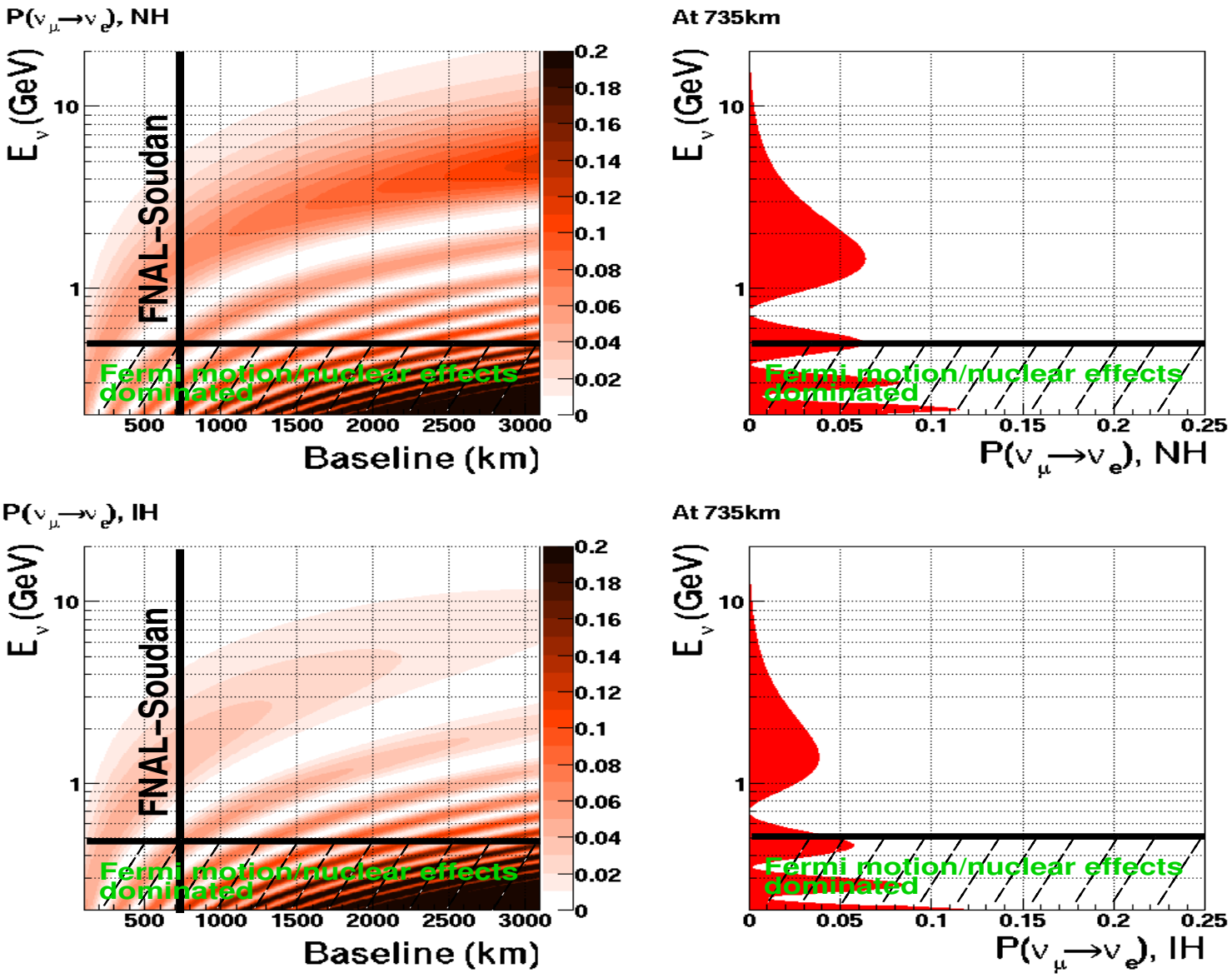
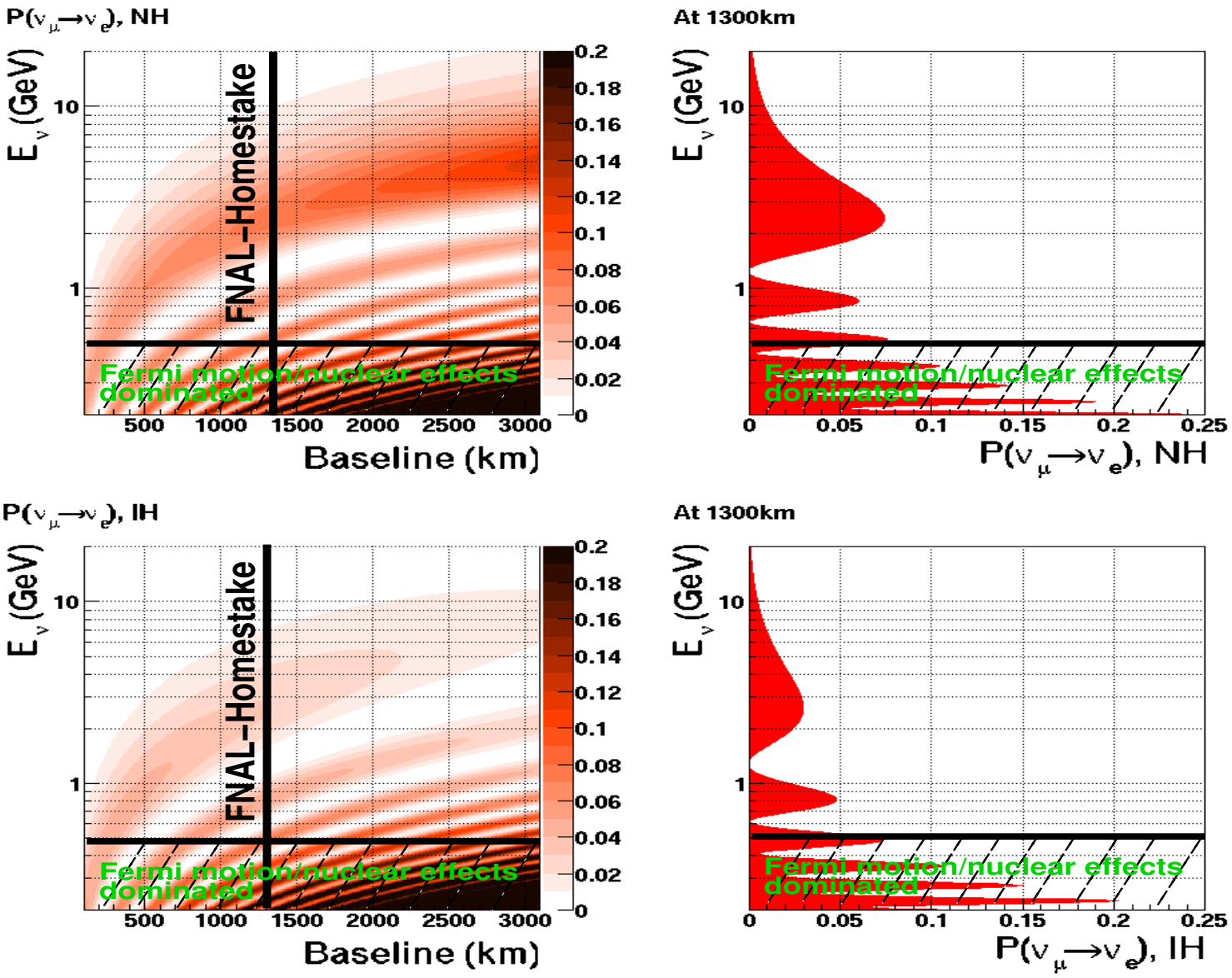
1 Oscillation Basics
2 Experimental Assumptions
3 Spectra and Event Rates
4 Sensitivities

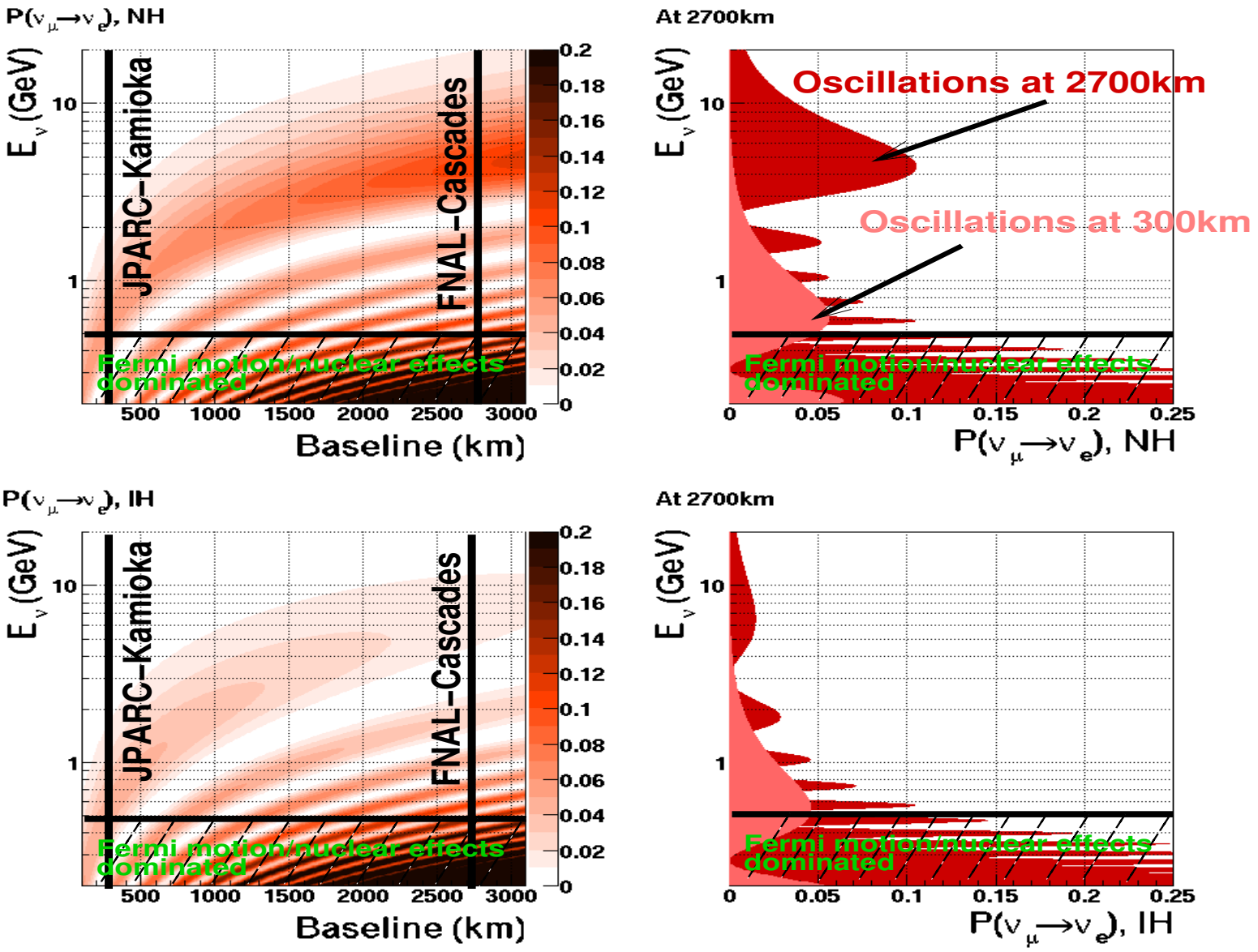
Oscillations at different baselines



Oscillations at different baselines



Oscillations at different baselines



Oscillations at different baselines

Longer baselines = more spectral information at higher energy. At 1300km, the first 2 nodes are $>$ 500 MeV.

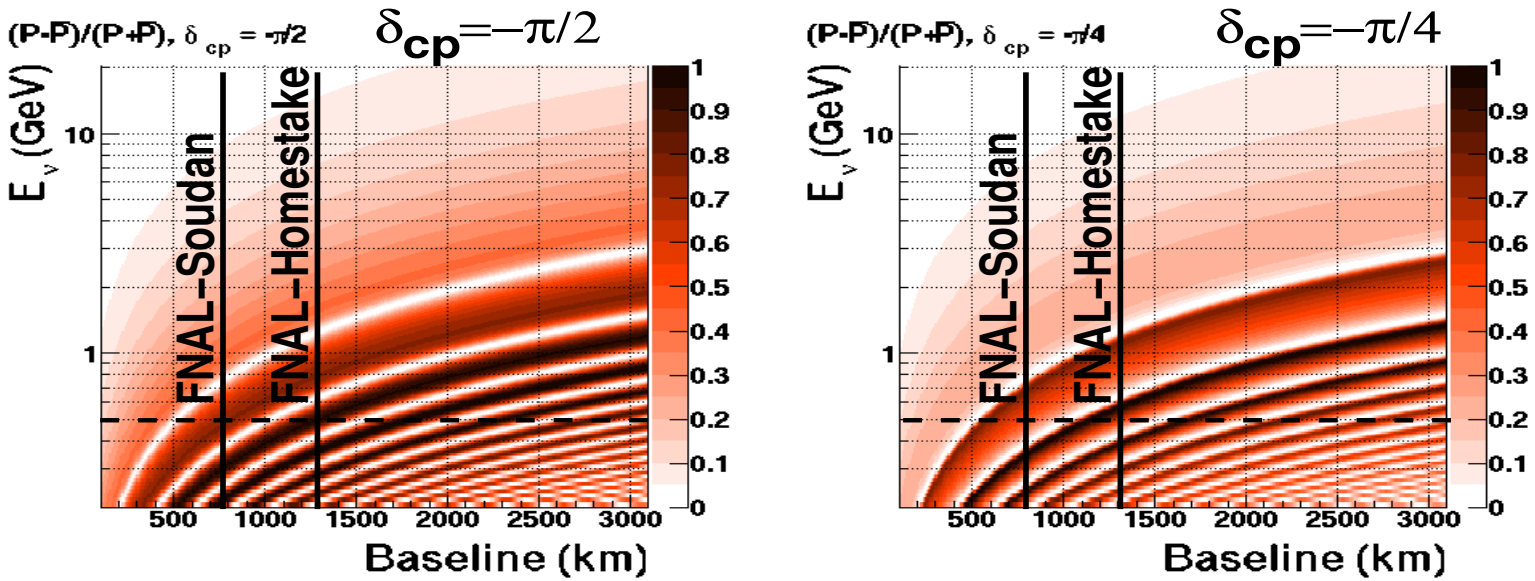
BUT, do we need to cover 2 nodes?

CP Asymmetries vs Baselines

The CP asymmetry is defined as

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

At $\sin^2 2\theta_{13} = 0.1$, CP asymmetries at 1st node are SMALL, almost negligible for values of $|\delta_{cp}| < \pi/4$:



The larger value of θ_{13} *increases* the importance of the 2nd node

Longer baselines are even MORE important now.

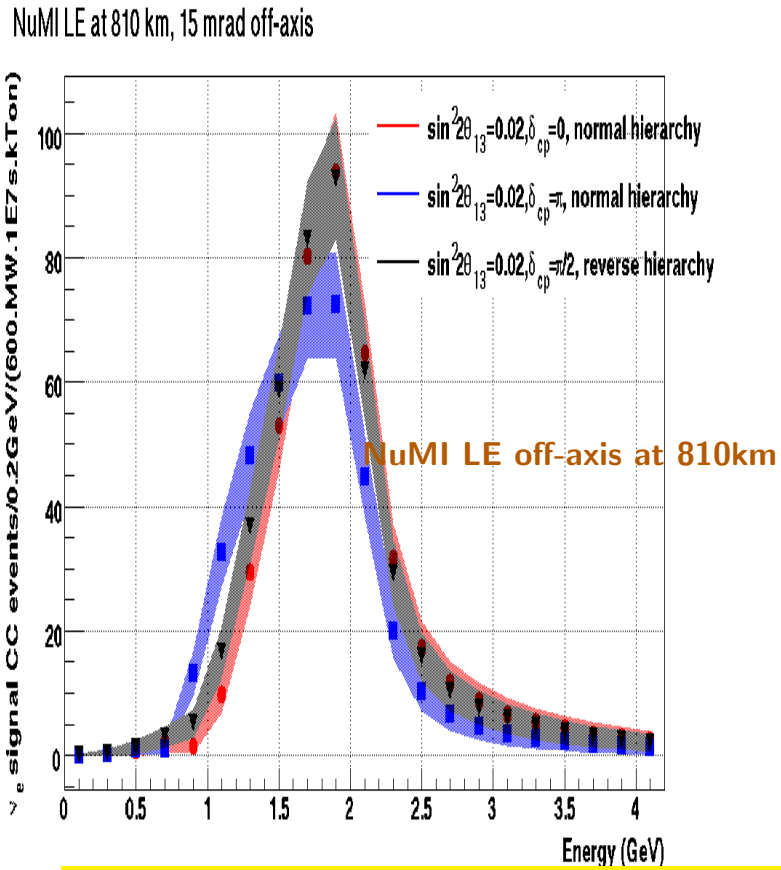
Wide-band vs narrow-band beams (OLD slide)

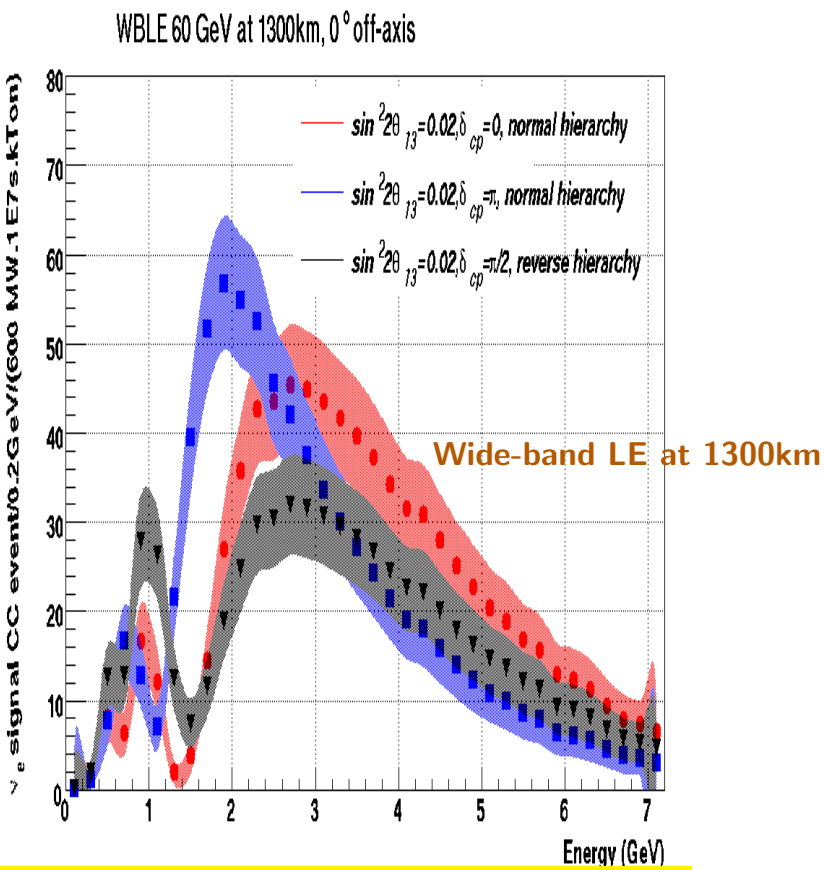
Assuming an exposure of 350 kT.MW.yr, with no detector effects:

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





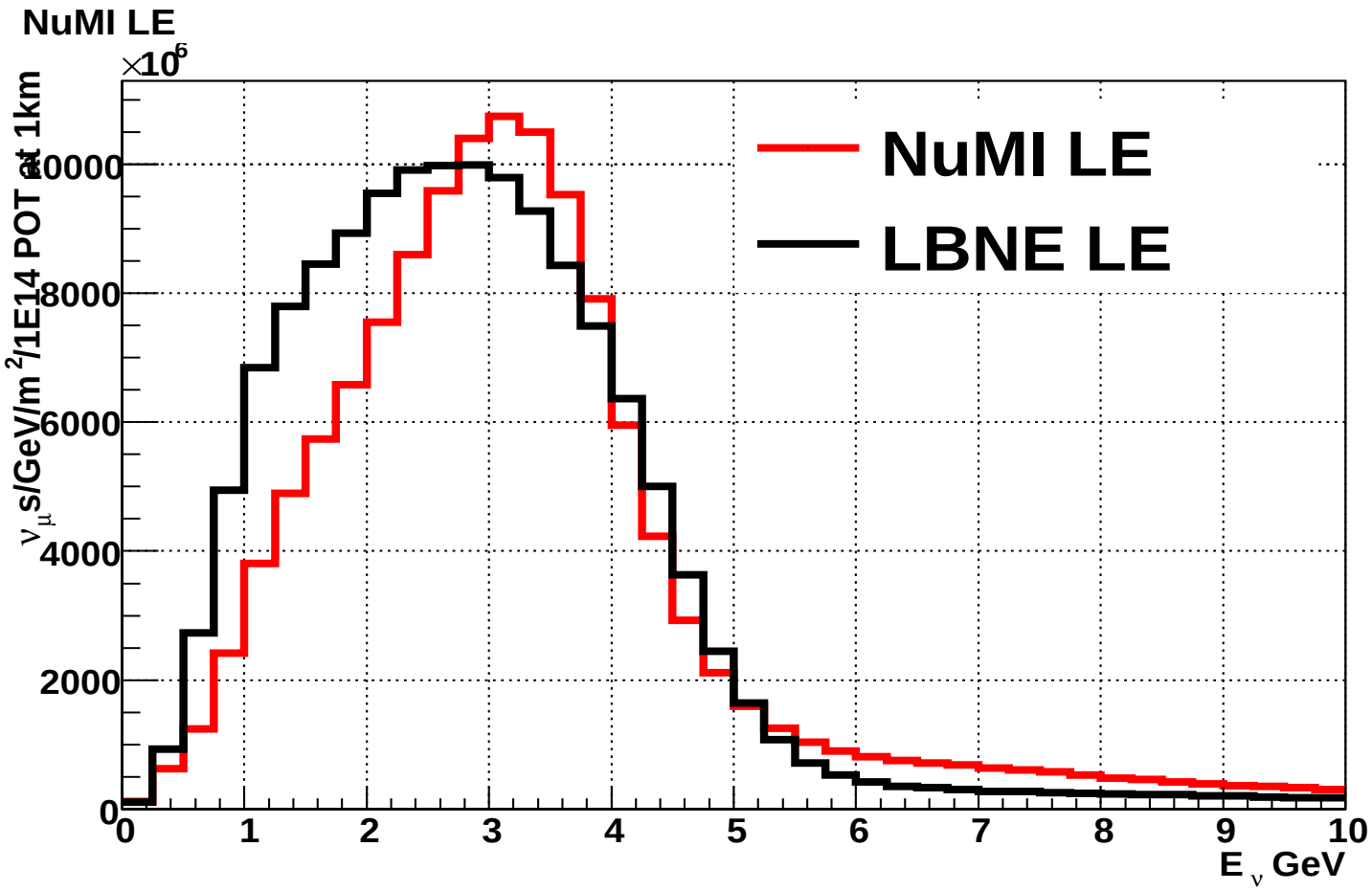
Wide-band beam spectral information = resolves degeneracies

LBNE/NuMI Neutrino Beam-line Simulation Parameters

Beam element	LBNE	NuMI
Primary beam	120 GeV p^+ $\sigma_x = \sigma_y = 0.15$cm	120 GeV p^+ $\sigma_x = \sigma_y = 0.1$cm
Target	Graphite, cylinder, $\rho = 2.1$ g/cm^3 d/l=1.2/80cm	Graphite, rectangloid $\rho = 1.784$ g/cm^3 w/h/l = 0.64/2.0/94cm
Horn 1	NuMI 250 kA	NuMI 185/200 kA (LE/ME)
Horn 2	NuMI 250 kA	NuMI 185/200 kA (LE/ME)
TGT-H1	-0.3m	-0.45/-1.35m (LE/ME)
H2-H1	6m	10/23m (LE/ME)
DP-H1	11.28m	45.28m
Decay channel	h=($^{+0.5}_{-0.8}$ m), w=$\pm$0.5m	h=($^{+0.36}_{-0.95}$ m), w=$\pm$0.58m
Decay pipe	d/l=4/280m evacuated *	d/l=2/677m evacuated/He

* The CDR LBNE design with 250m, He filled $\approx -5\%$ flux.

LBNE/NuMI Flux at 1km



LBNE: 1.8x more flux at 1 GeV, -30% less flux > 5 GeV

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%

NoVA Detector Performance Parameters

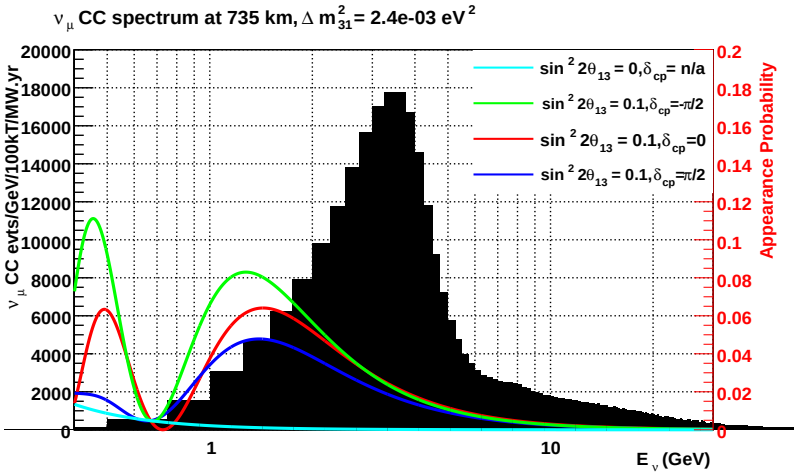
Oscillation Parameters used in Calculations

Parameter	Value
$\sin^2 2\theta_{12}$	0.87 ± 0.03
$\sin^2 2\theta_{23}$	> 0.91 (at 90% CL)
$\sin^2 2\theta_{13}$	0.1 ± 0.005
Δm^2_{21}	$(7.59 \pm 0.20) \times 10^{-5}$ eV^2
Δm^2_{32}	$(2.35^{+0.11}_{-0.08}) \times 10^{-3}$ eV^2
δ_{CP}	no measurement

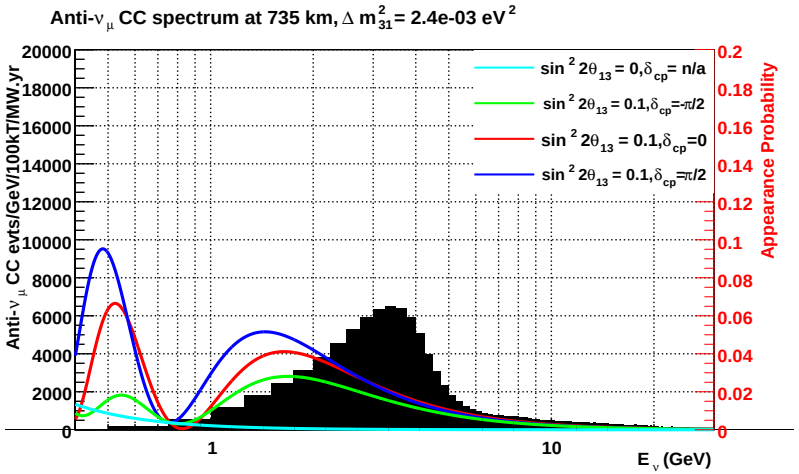
Beams vs Baselines

Baseline=735km, NuMI LE

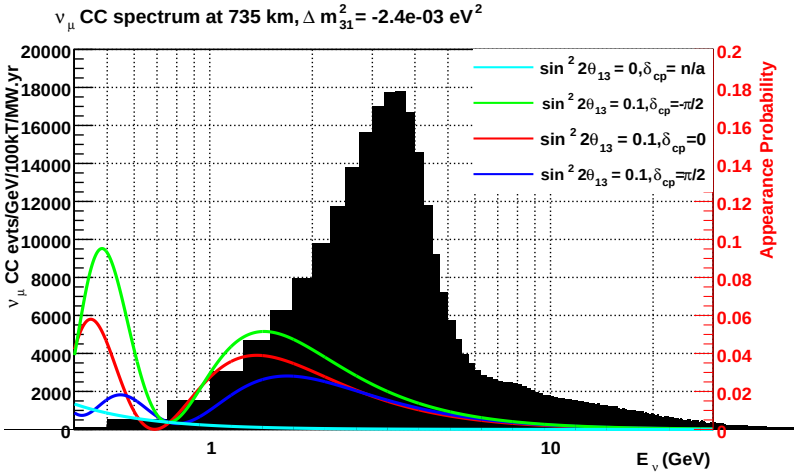
ν normal hierarchy



$\bar{\nu}$normal hierarchy



ν inverted hierarchy



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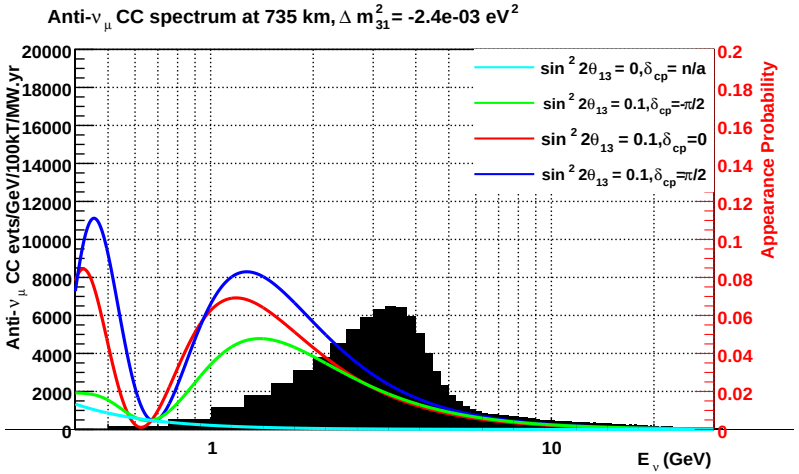
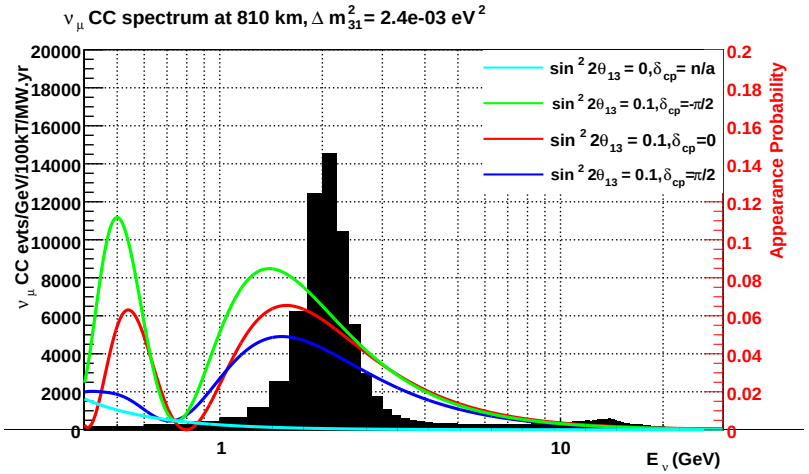


Beam is too high in energy - no coverage of 2nd node

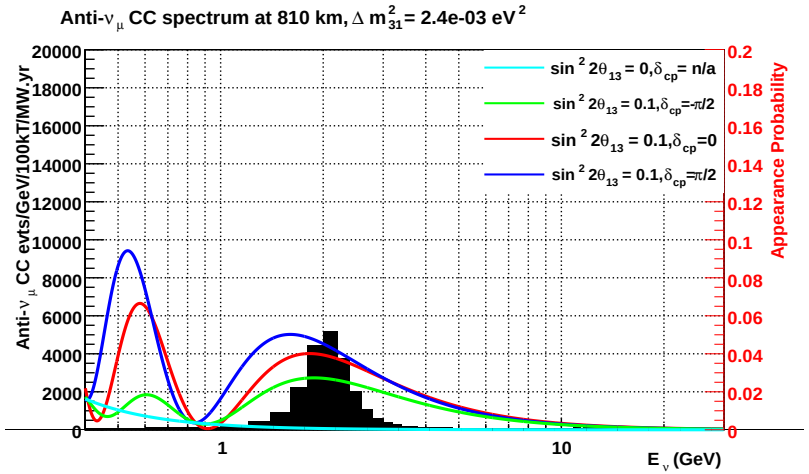
Beams vs Baselines

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

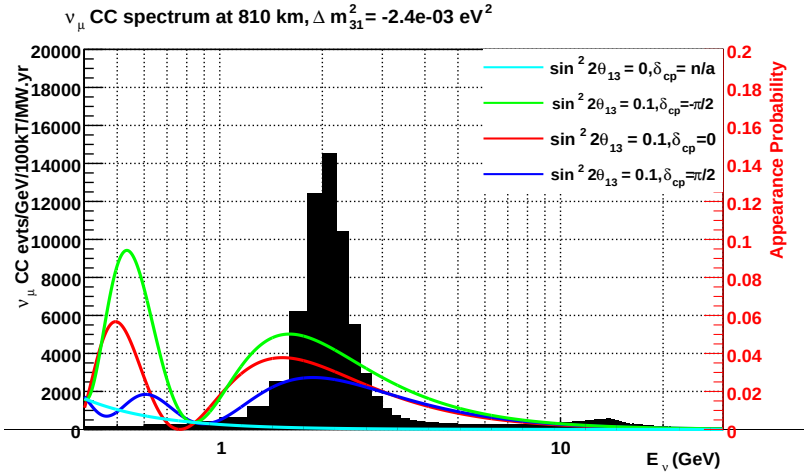
ν normal hierarchy



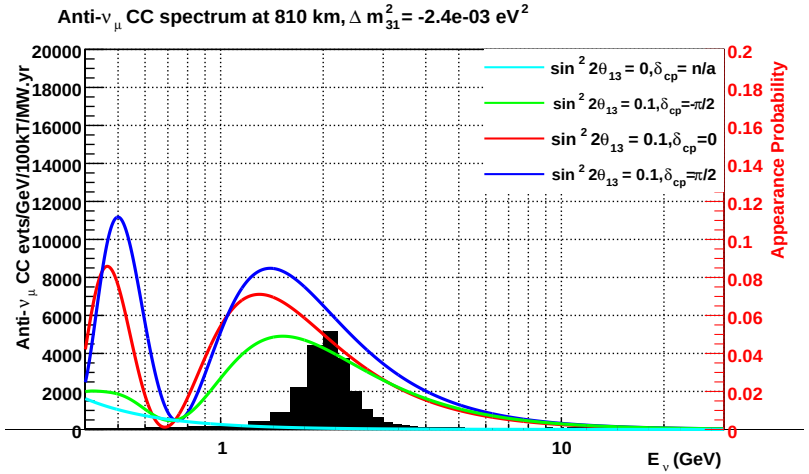
$\bar{\nu}$normal hierarchy



ν inverted hierarchy



$\bar{\nu}$ inverted hierarchy

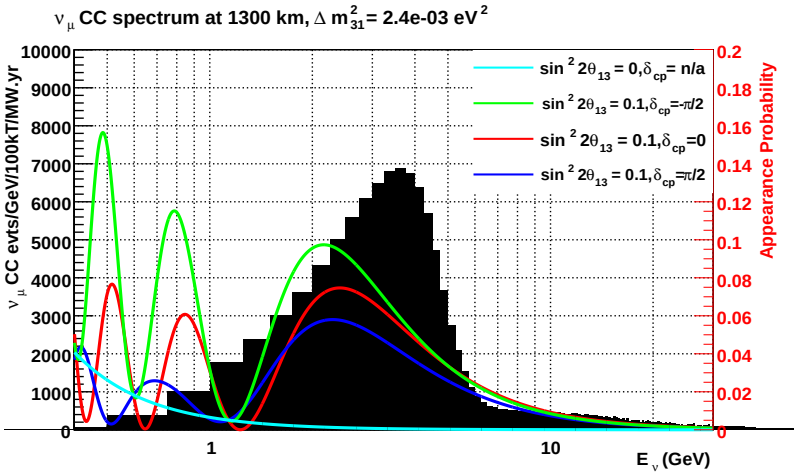


Only covers small portion of 1st node - CP/MH degeneracies

Beams vs Baselines

L=1300km, LBNE LE

ν normal hierarchy



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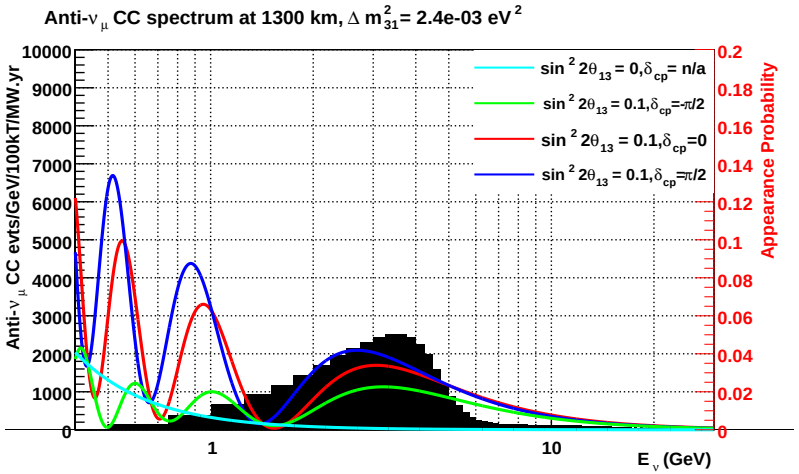
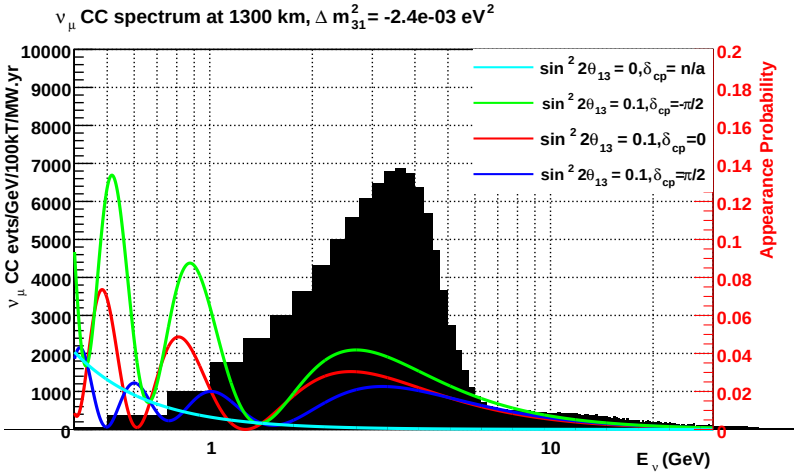
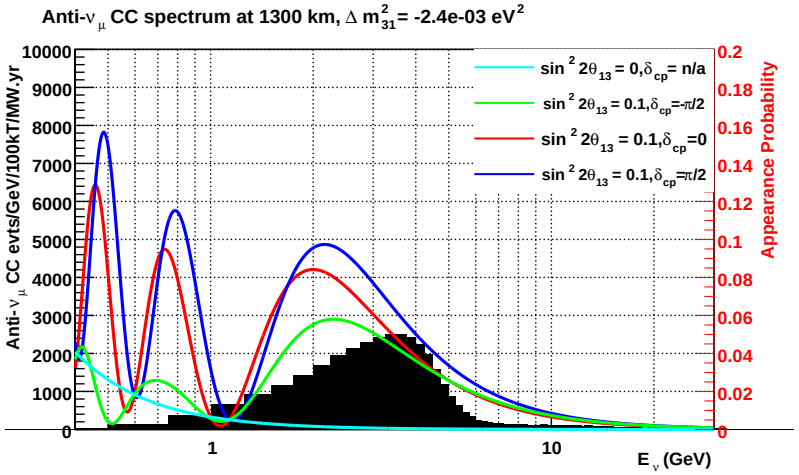


ν inverted hierarchy



$\bar{\nu}$ inverted hierarchy

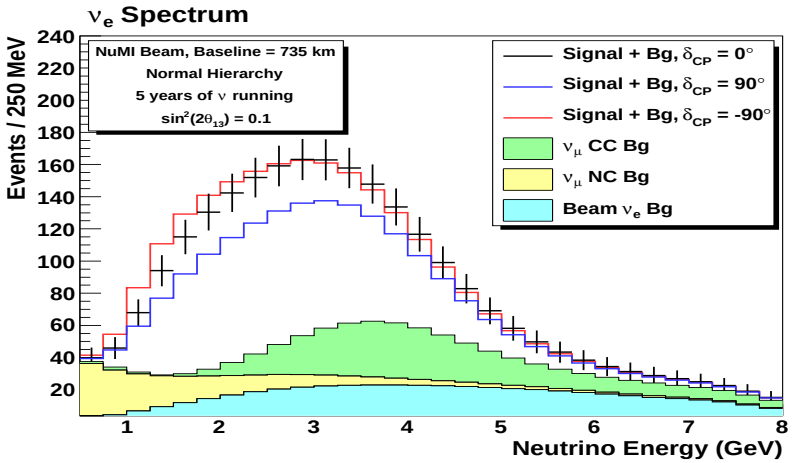


1st node covered, partial coverage of 2nd node

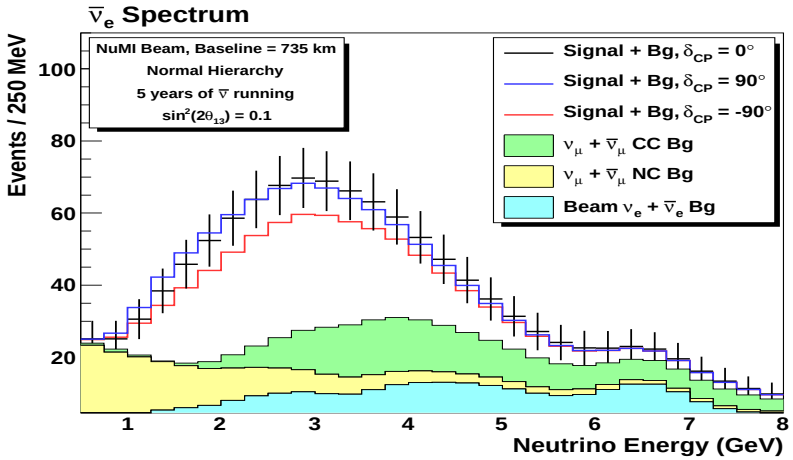
With a 34 kT LAr-TPC

L=735km, NuMI LE

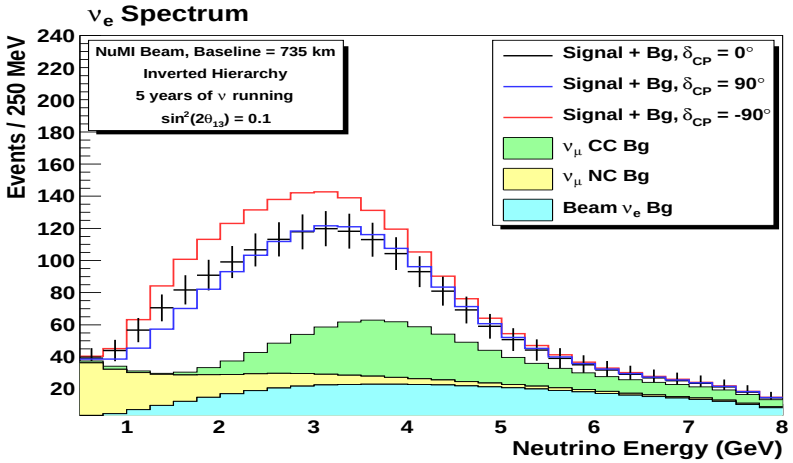
ν **normal hierarchy**



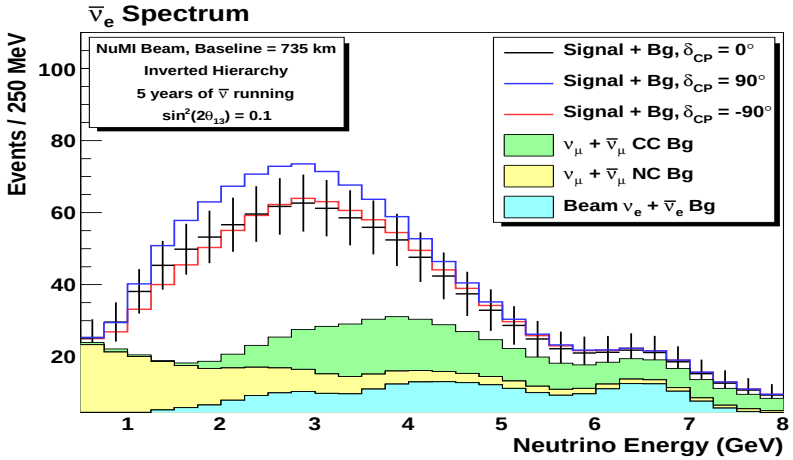
$\bar{\nu}$**normal hierarchy**



ν **inverted hierarchy**



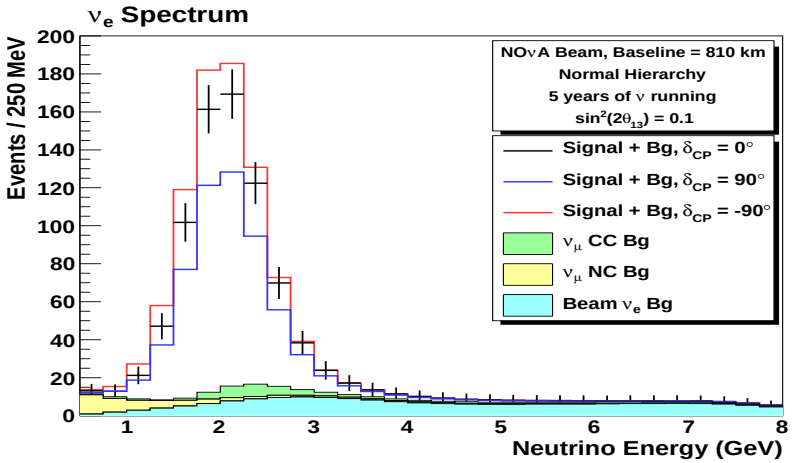
$\bar{\nu}$ **inverted hierarchy**



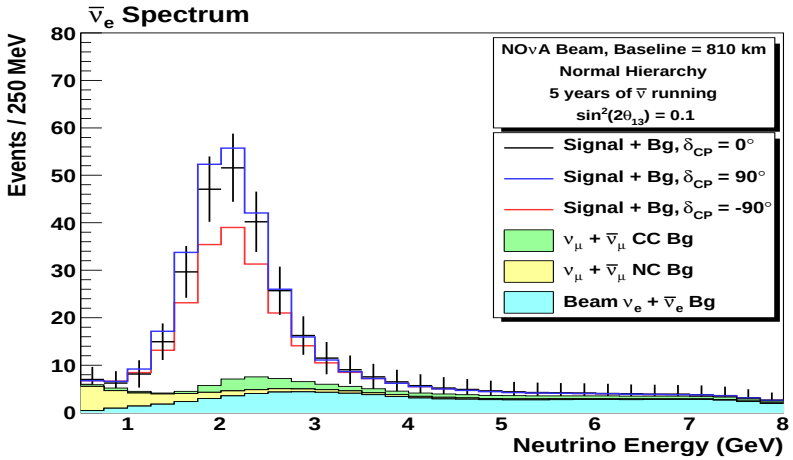
With a 34 kT LAr-TPC

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

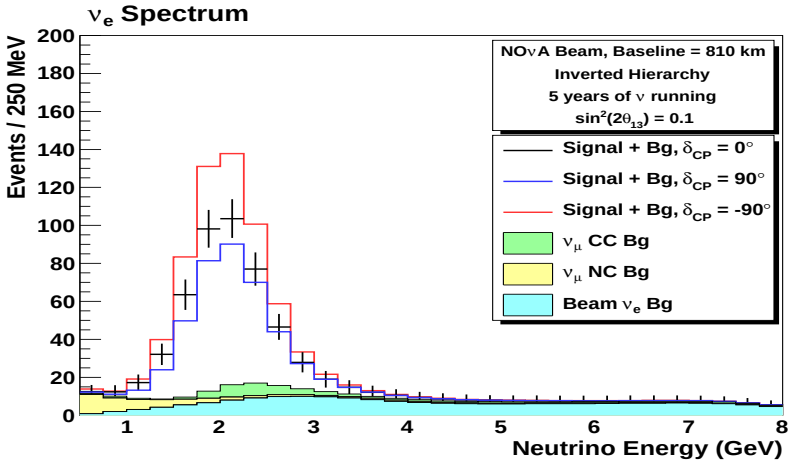
ν normal hierarchy



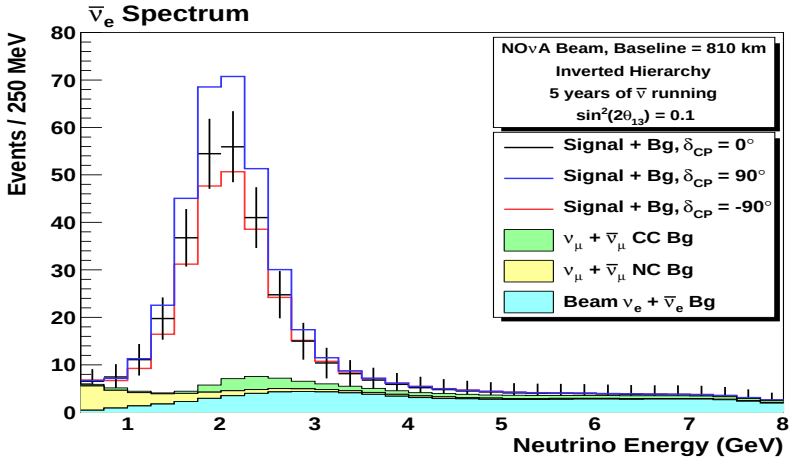
$\bar{\nu}$normal hierarchy



ν inverted hierarchy



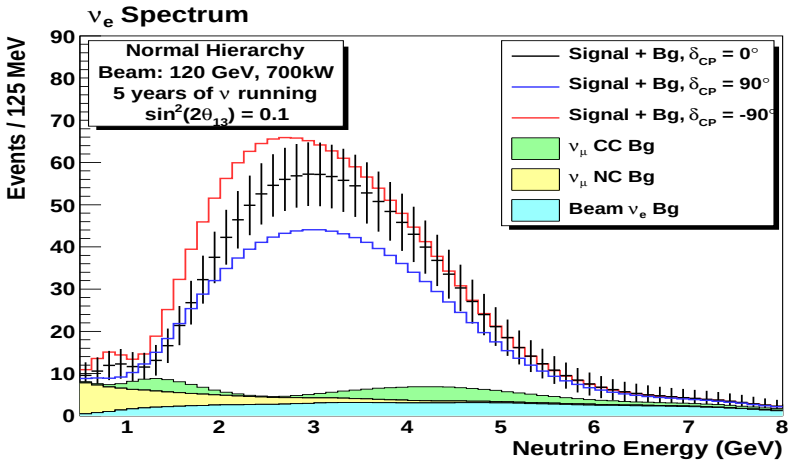
$\bar{\nu}$ inverted hierarchy



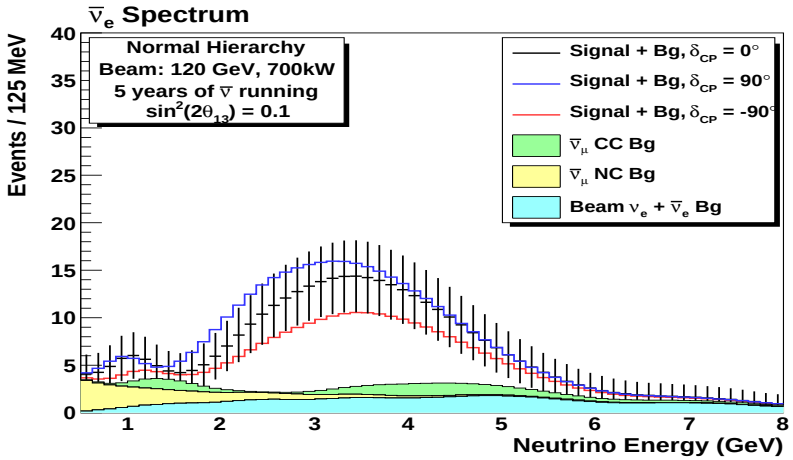
With a 34 kT LAr-TPC

L=1300km, LBNE LE

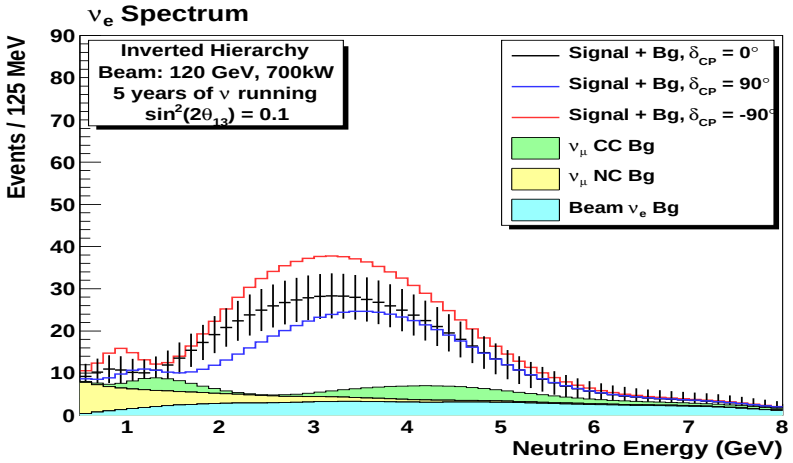
ν normal hierarchy



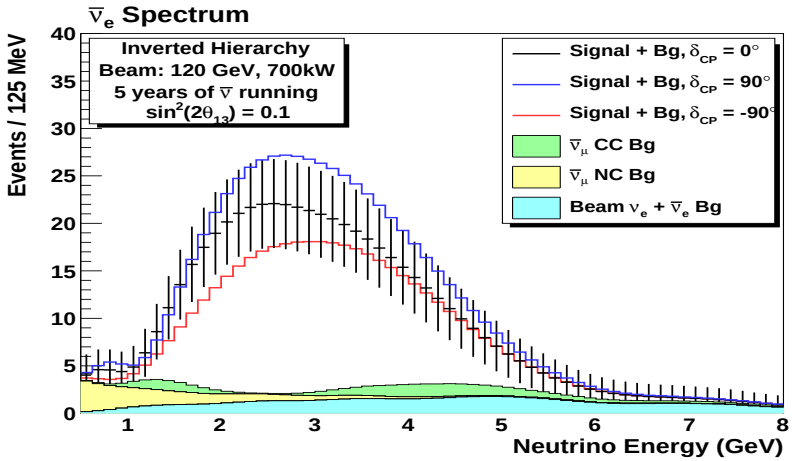
$\bar{\nu}$normal hierarchy



ν inverted hierarchy



$\bar{\nu}$ inverted hierarchy



Event rates - with 34 kT LAr-TPC

	Signal			CC BG	NC BG	Beam BG	Total BG
	δ_{CP}=-90°	δ_{CP}=0°	δ_{CP}=90°				
		L=735km, NuMI LE					
NuMI 735:							
Normal, Nu	1386	1338	1011	421	222	492	1135
Inverted, Nu	1085	796	762	424	222	497	1143
Normal, Anu	398	512	502	211	165	268	644
Inverted, Anu	454	454	579	212	165	267	644

Event rates - with 34 kT LAr-TPC

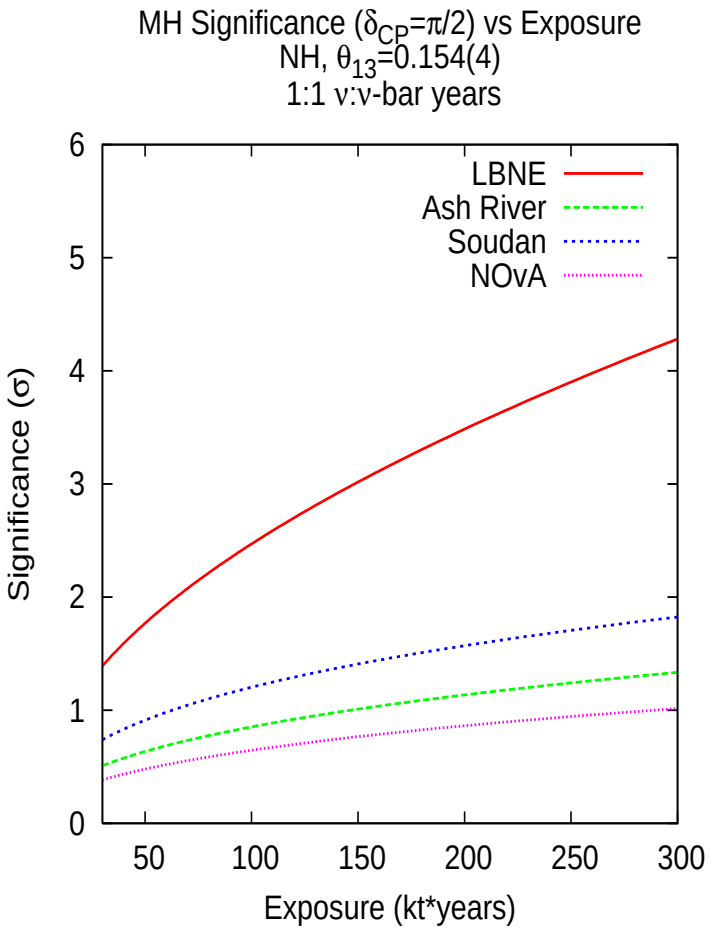
	Signal			CC BG	NC BG	Beam BG	Total BG
	δ_{CP}=-90°	δ_{CP}=0°	δ_{CP}=90°				
L=810km, NuMI ME 14mrad off-axis							
NuMI ME Off-axis:							
Normal, Nu	758	673	497	45	44	189	278
Inverted, Nu	536	388	321	46	44	192	282
Normal, Anu	161	213	228	26	25	85	136
Inverted, Anu	208	232	294	26	25	85	136

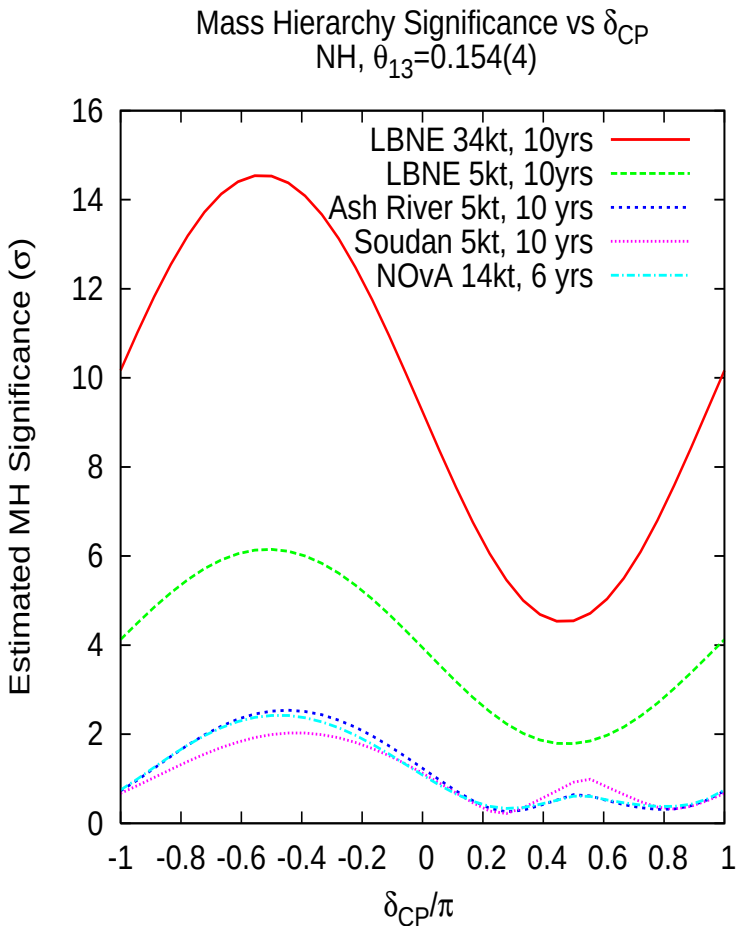
Event rates - with 34 kT LAr-TPC

	Signal			CC BG	NC BG	Beam BG	Total BG
	δ_{CP}=-90°	δ_{CP}=0°	δ_{CP}=90°				
L=1300km, LBNE LE							
LBNE:							
Normal, Nu	1366	1157	889	90	80	147	317
Inverted, Nu	733	518	406	90	80	153	323
Normal, Anu	250	327	353	48	55	73	176
Inverted, Anu	404	475	575	48	55	71	174

MH vs Exposure with $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ constraint (M. Bass)

Assumes 6.0×10^{20} p.o.t/yr:

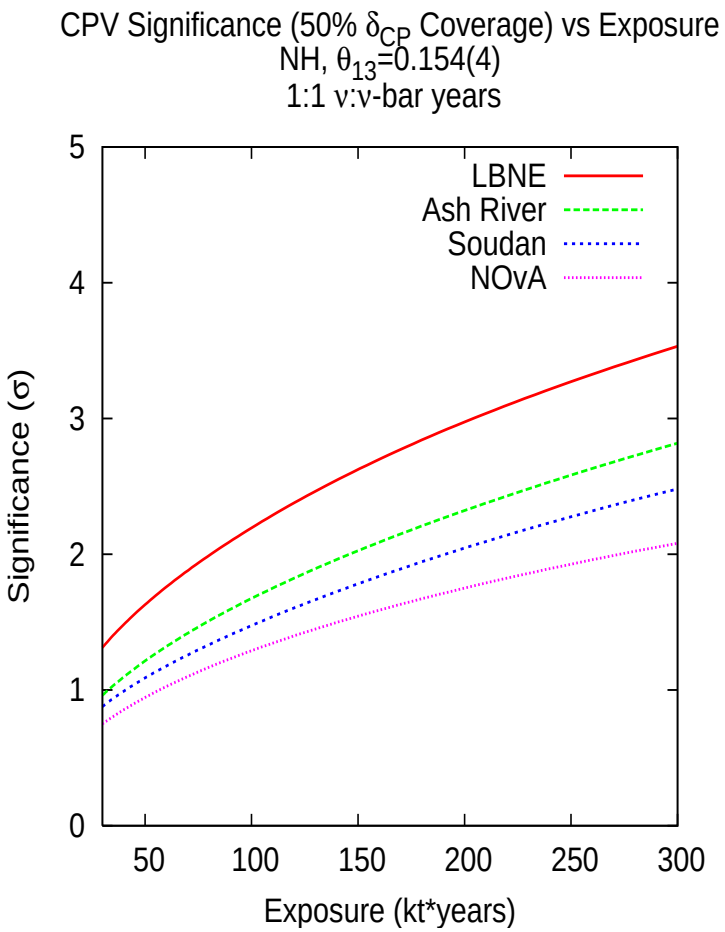


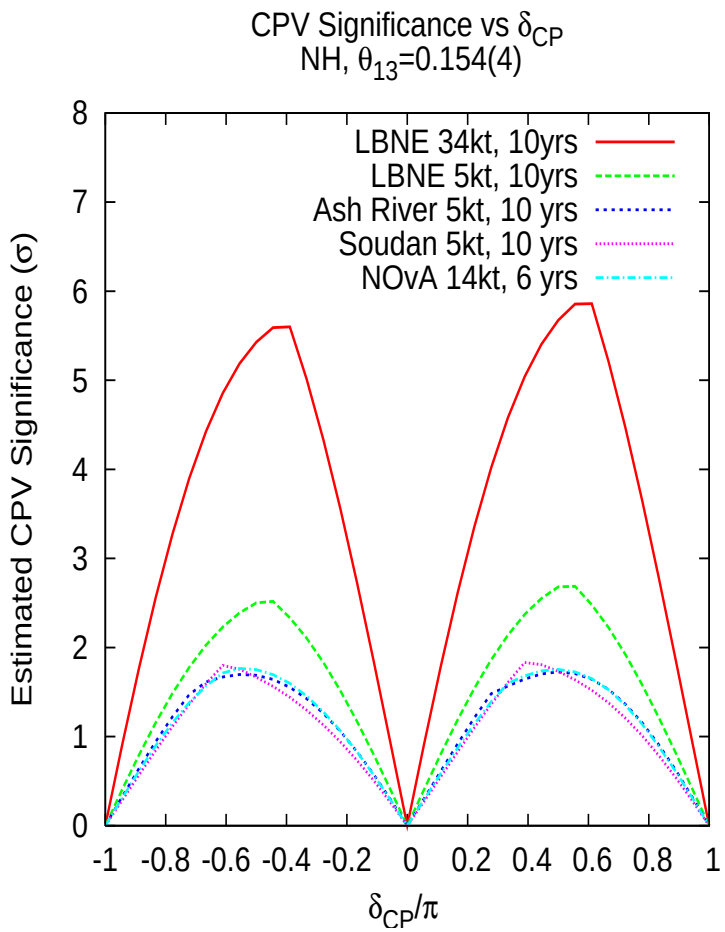


Ability to resolve MH for $\delta_{cp} > 0$ is very limited at NuMI sites

CPV vs Exposure with $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ constraint (M. Bass)

MH is known



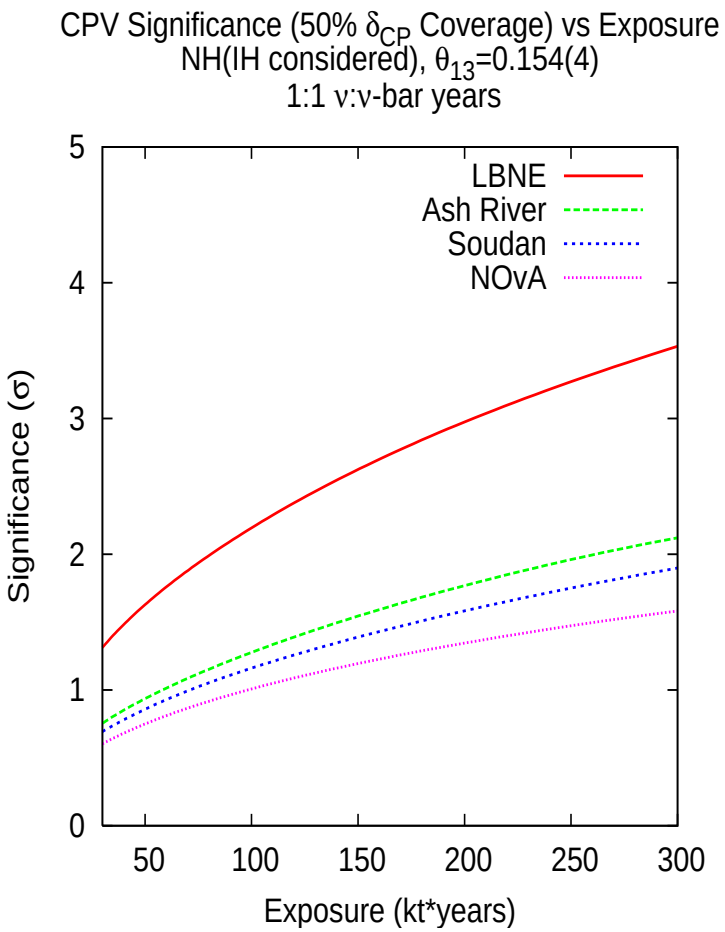


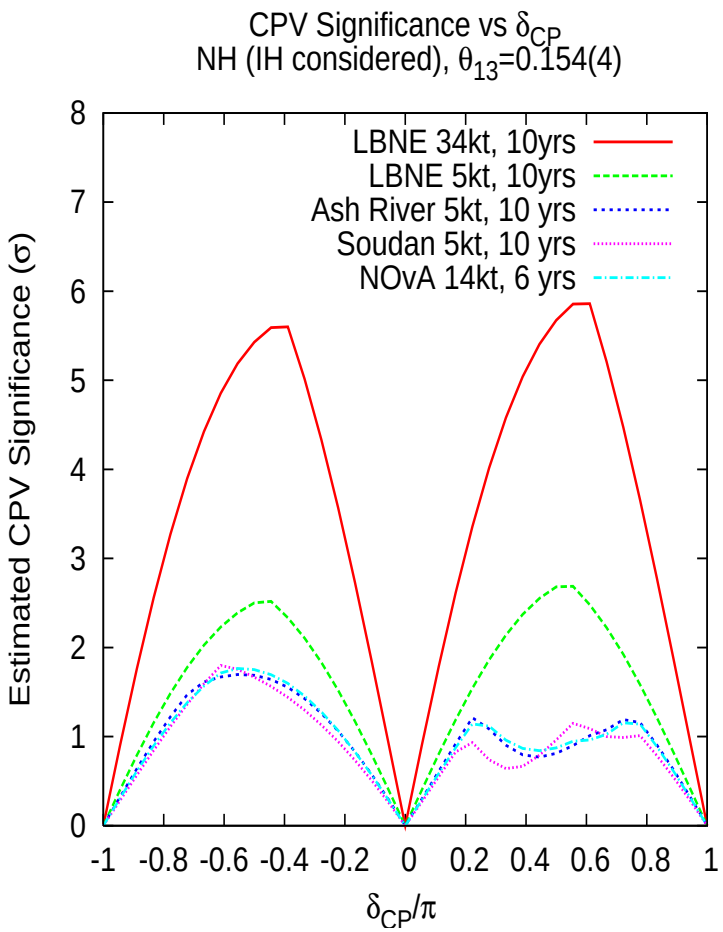
To resolve CPV at $\geq 2\sigma$ for 50% of δ_{cp}

LBNE: 80 kt.yrs. Soudan: 200 kt.yrs. Ash River: 150 kt.yrs

CPV vs Exposure with $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ constraint (M. Bass)

MH is unknown



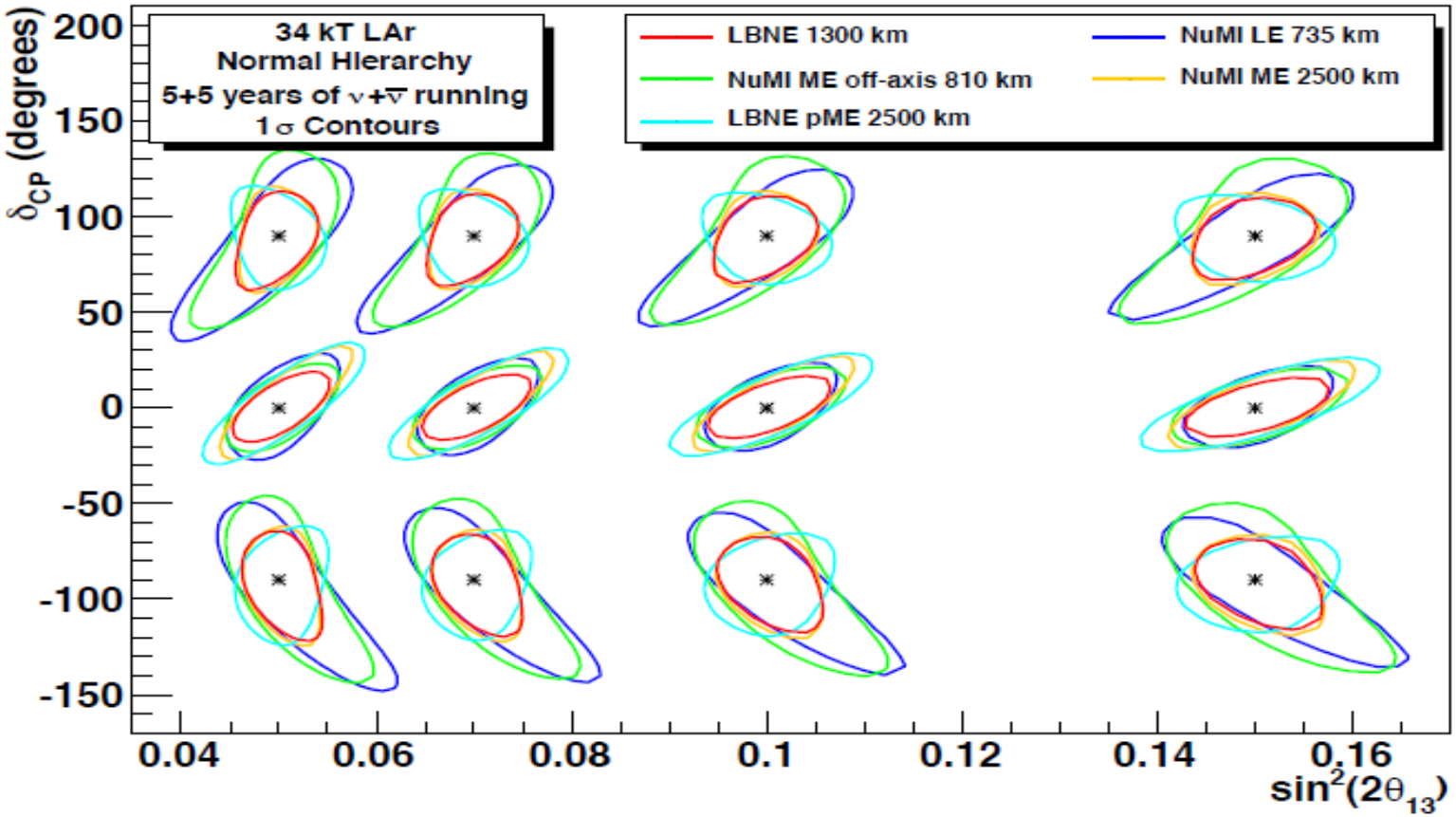


To resolve CPV at $\geq 2\sigma$ for 50% of δ_{cp}

LBNE: 80 kt.yrs. Soudan: $>$ 300 kt.yrs. Ash River: 250 kt.yrs

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

Assumes 7.3 e20 p.o.t/yr:

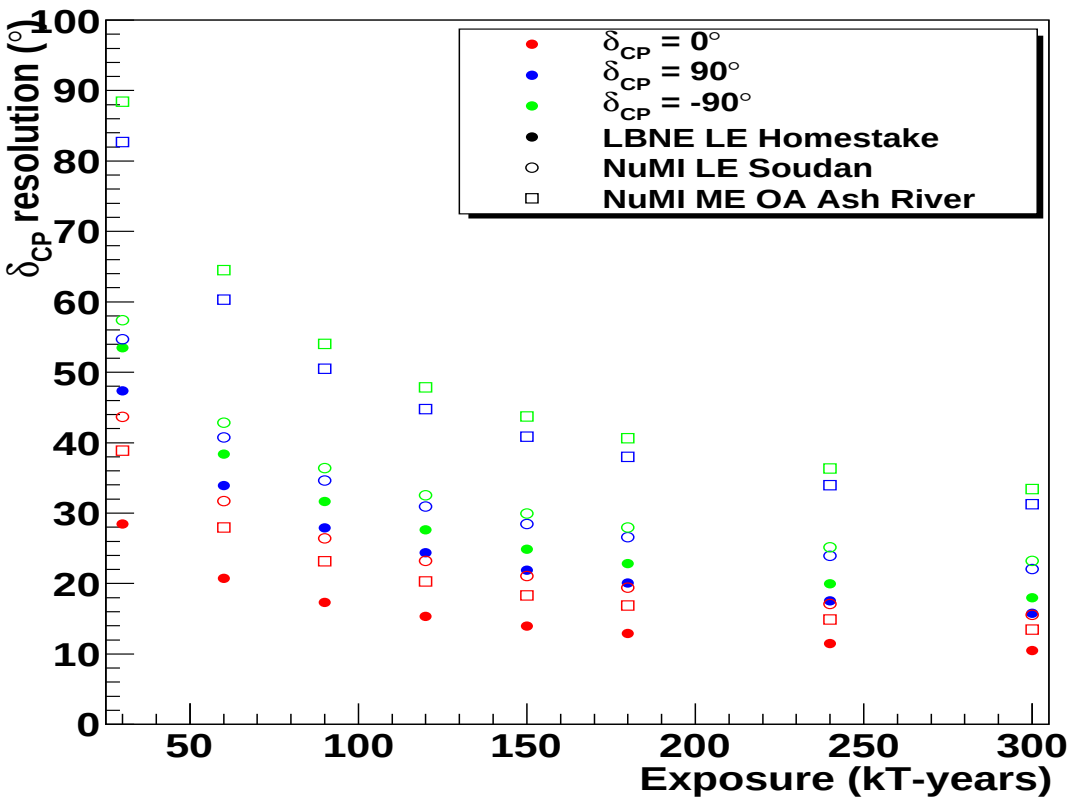


Independent measurement of θ_{13} with similar accuracy to Daya Bay

Requires baselines $\geq$ 1300 km

CP Resolution vs Exposure with $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ constraint (E. Worcester)

Assumes 7.3 e20 p.o.t/yr:

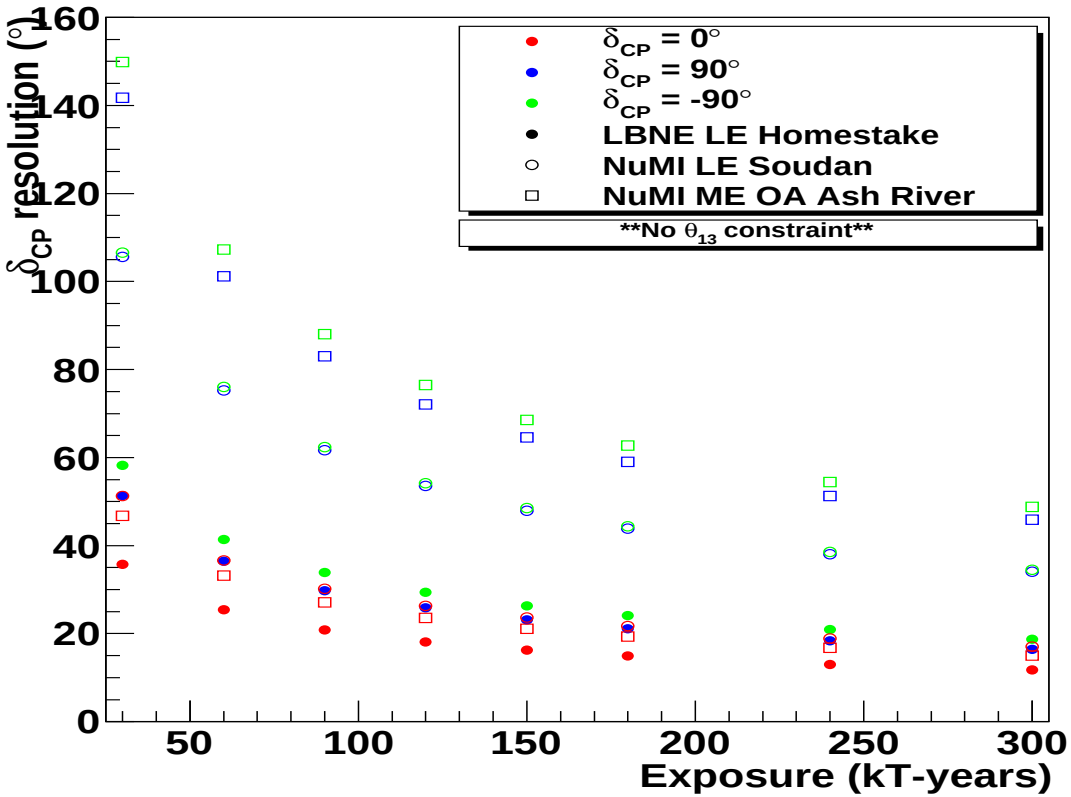


To reach 25° resolution for $\delta_{cp} = -\pi/2$ (worst case)

LBNE: 150 kt.yrs. Soudan: 240 kt.yrs. Ash River: >> 300 kt.yrs

CP Resolution vs Exposure - No constraint on θ_{13}

Assumes 7.3 e20 p.o.t/yr:

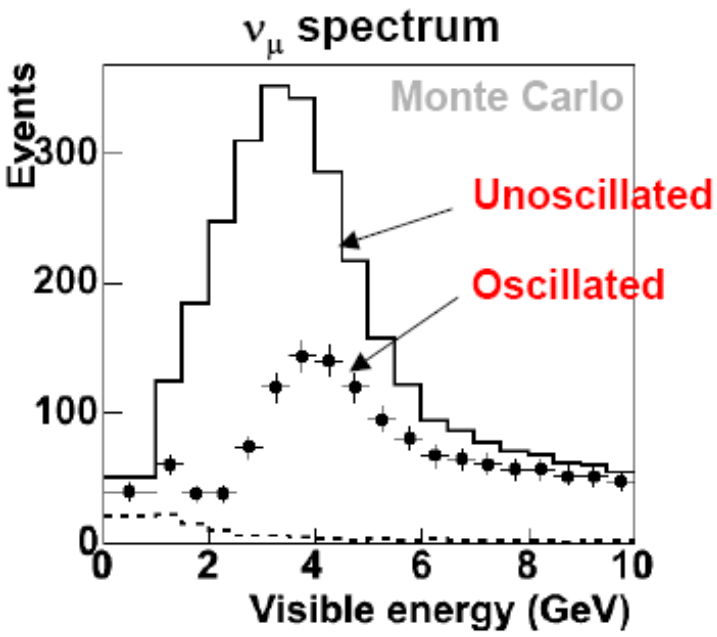


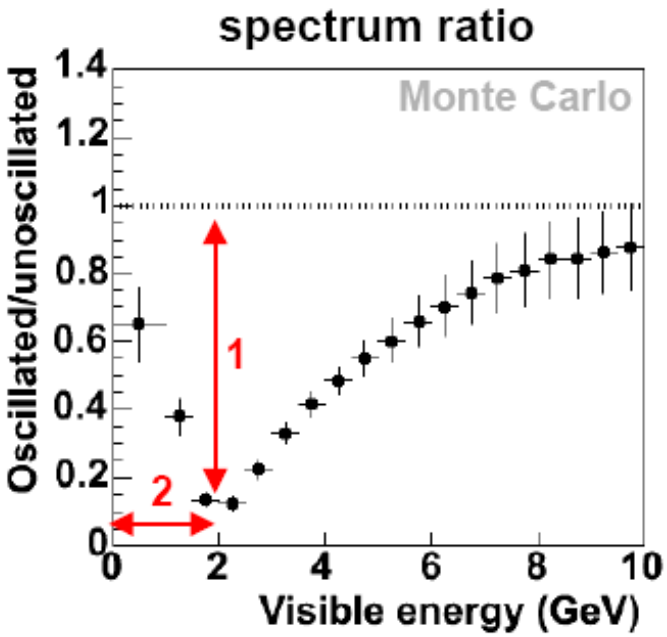
LBNE does NOT need external constraints for exposures $\geq$ 60 kt yrs.

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

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

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

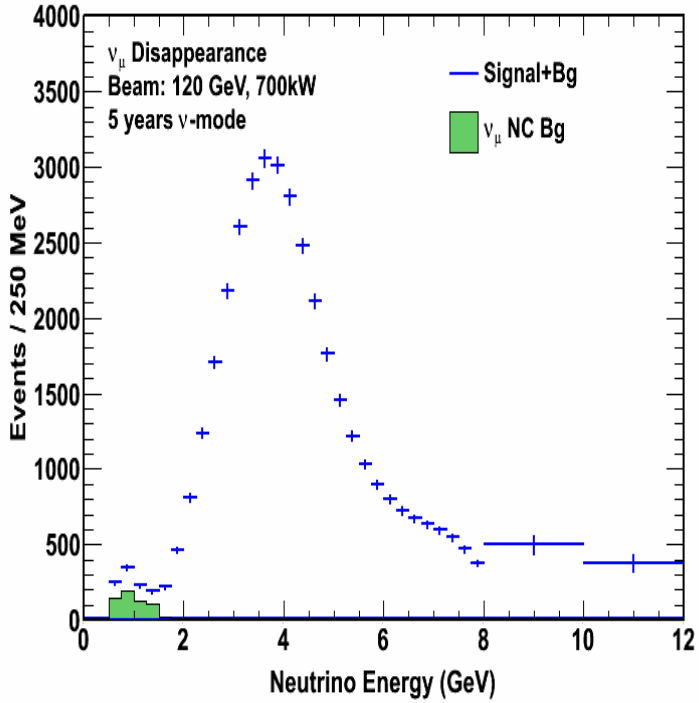


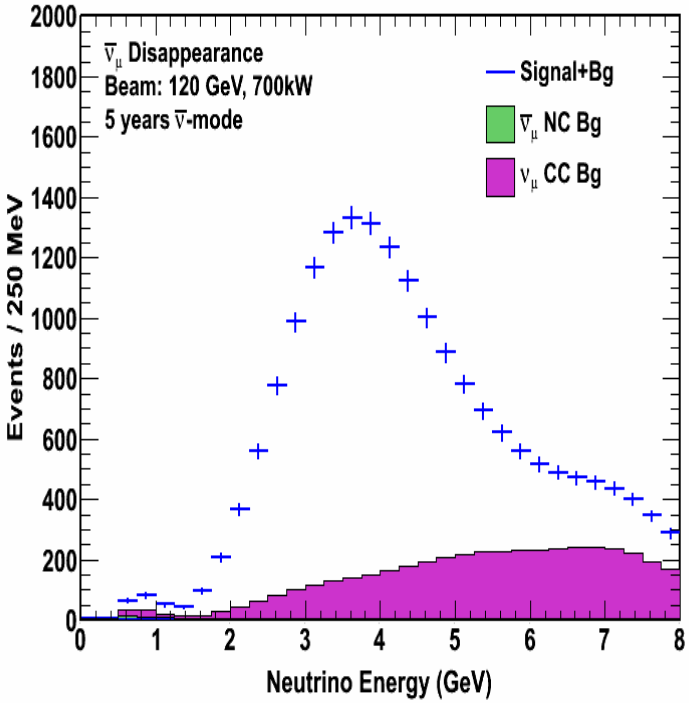


Disappearance Spectra (Z. Isvan)

L=735km, NuMI

ν, normal hierarchy **$\bar{\nu}$, normal hierarchy**



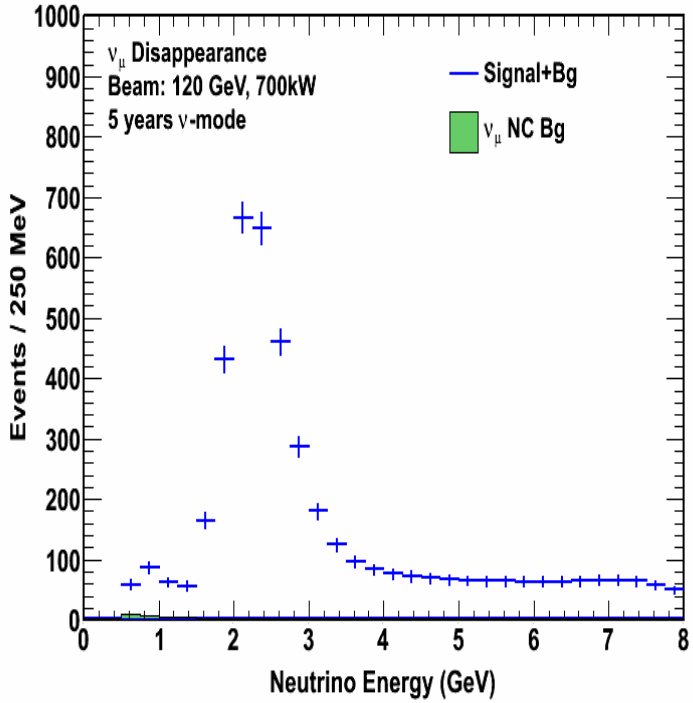


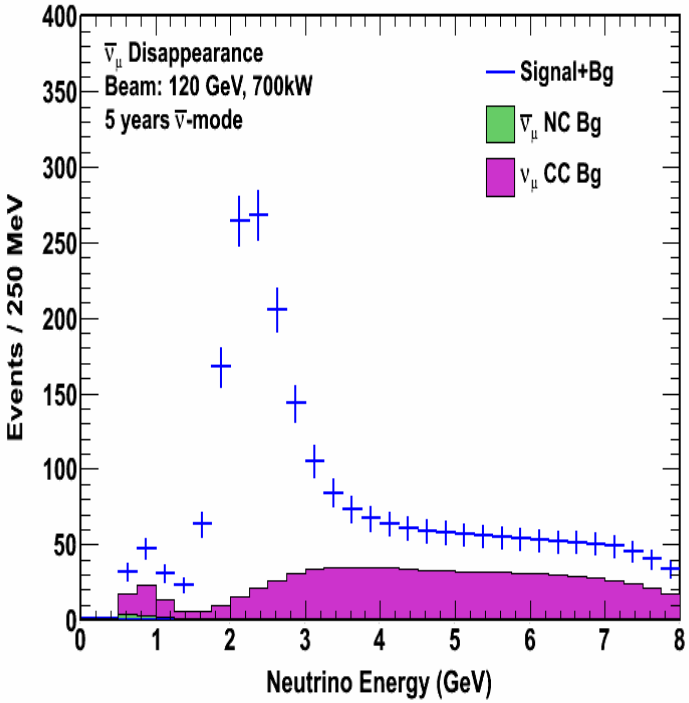
Larger backgrounds near dip in spectra.

Disappearance Spectra (Z. Isvan)

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

ν, normal hierarchy **$\bar{\nu}$, normal hierarchy**



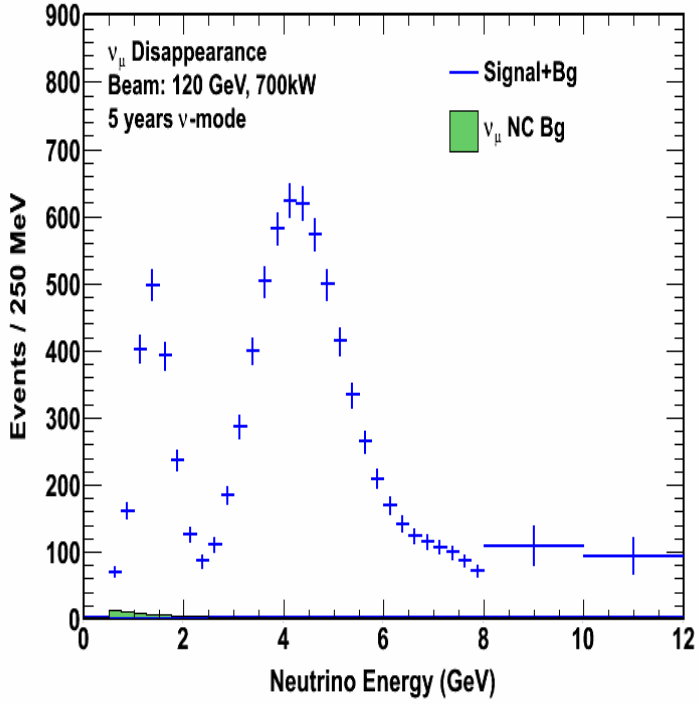


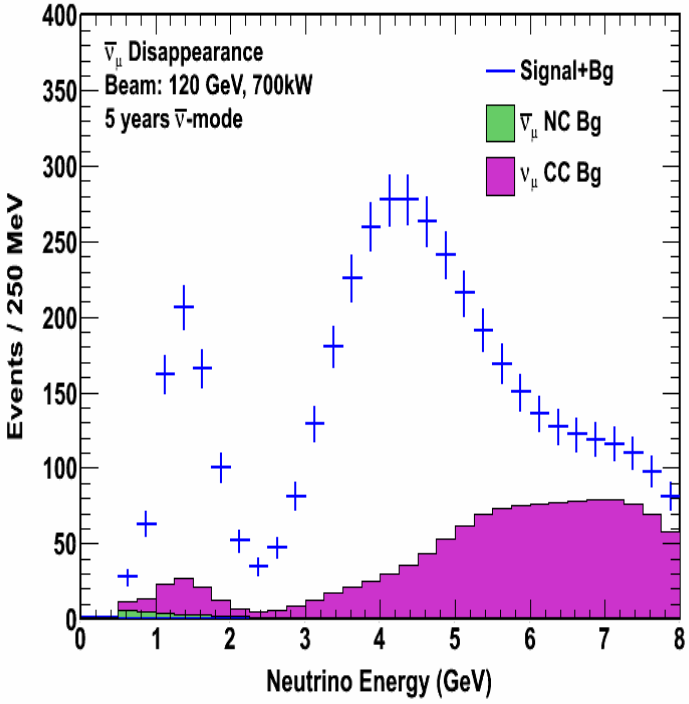
5 $\times$ lower statistics compared to NuMI LE on-axis.

Disappearance Spectra (Z. Isvan)

L=1300km, LBNE LE

ν, normal hierarchy **$\bar{\nu}$, normal hierarchy**





Observe detailed oscillation structure at 1300km.

LBNE measurement of atmospheric parameters (R. Guenette)

Assumes 7.3 e20 p.o.t/yr:

MINOS 2012

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

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

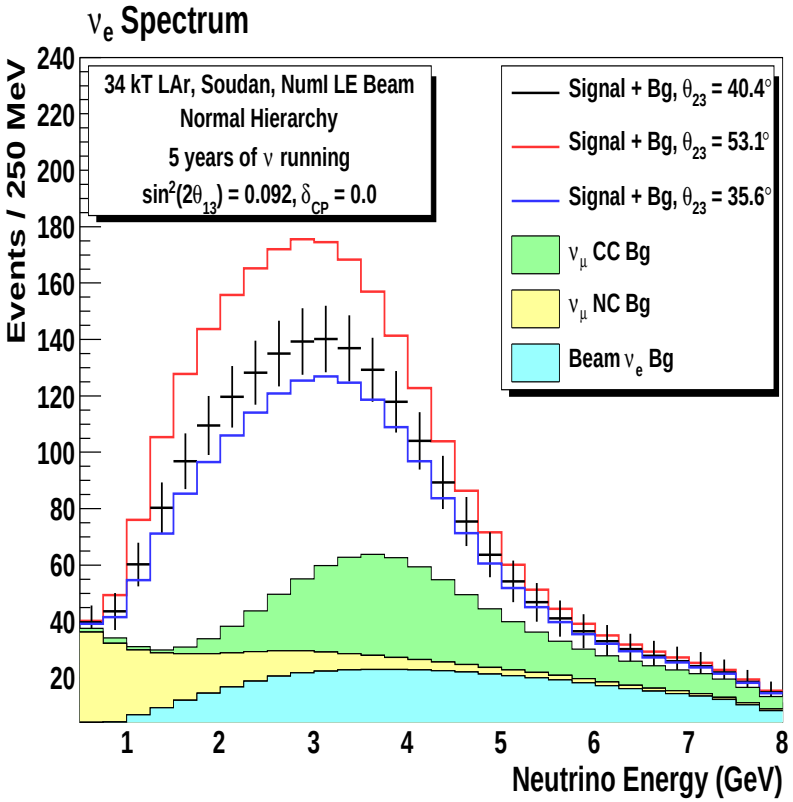
LBNE: $\sin^2 2\theta_{23} = 1.0, \Delta m^2_{32} = 2.41 \times 10^{-3}\ \mathrm{eV}^2$:

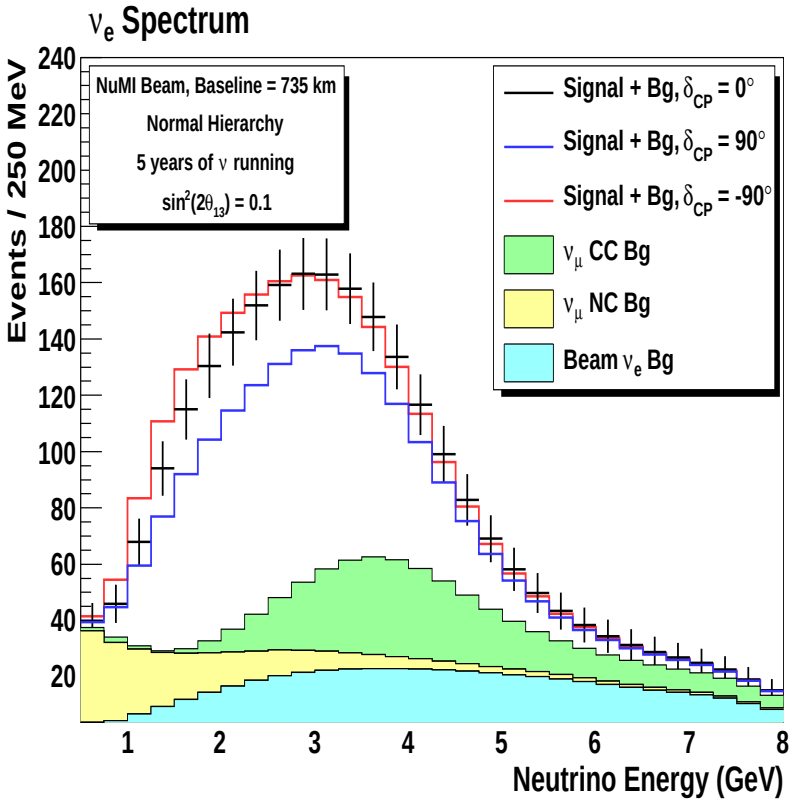
	ν		$\bar{\nu}$	
	$\delta(\sin^2 2\theta_{23})$	$\delta(\Delta m^2_{32}) \times 10^{-3}\ \mathrm{eV}^2$	$\delta(\sin^2 2\theta_{23})$	$\delta(\Delta m^2_{32}) \times 10^{-3}\ \mathrm{eV}^2$
30 kt-yrs LAr	0.012	0.034	0.018	0.054
50 kt-yrs LAr	0.010	0.028	0.015	0.045
75 kt-yrs LAr	0.008	0.023	0.012	0.035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

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

Vary θ_{23} octant **Vary δ_{cp}**

L=735km, NuMI LE





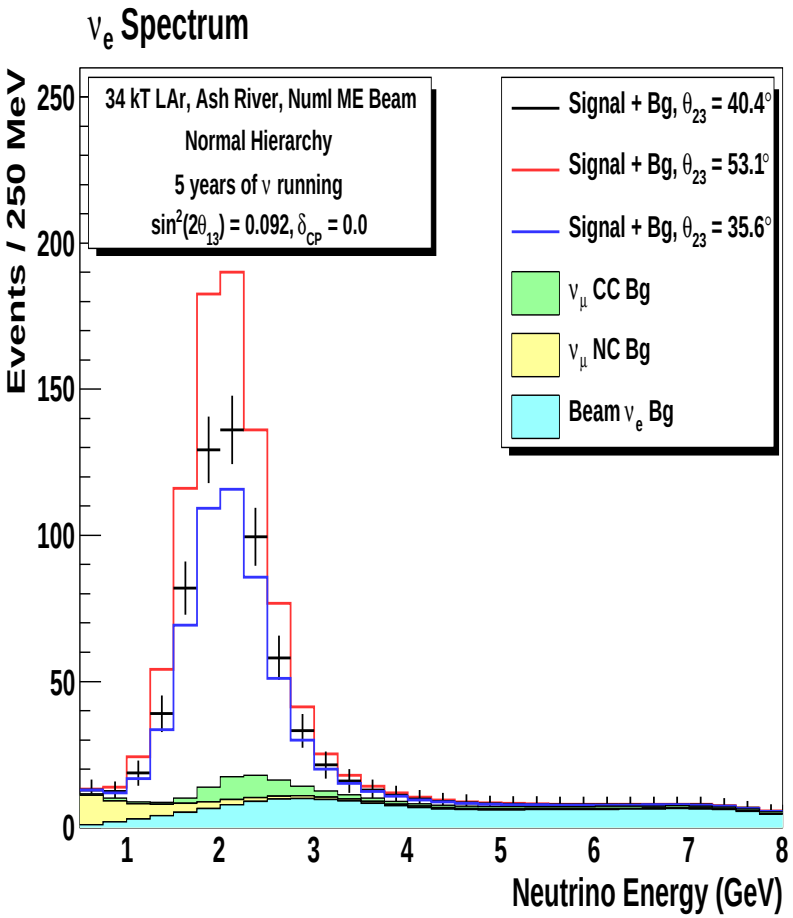
Spectral degeneracies with θ_{23} octant, δ_{cp}, mass hierarchy

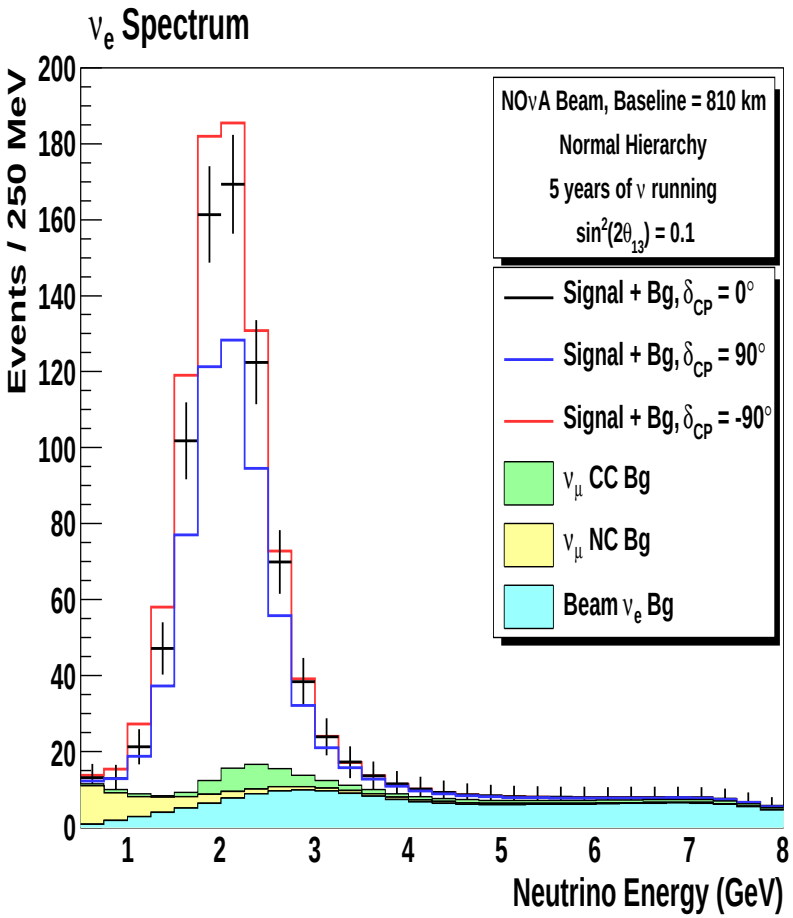
Need wide-band beams, anti-neutrino running .

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

Vary θ_{23} octant **Vary δ_{cp}**

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



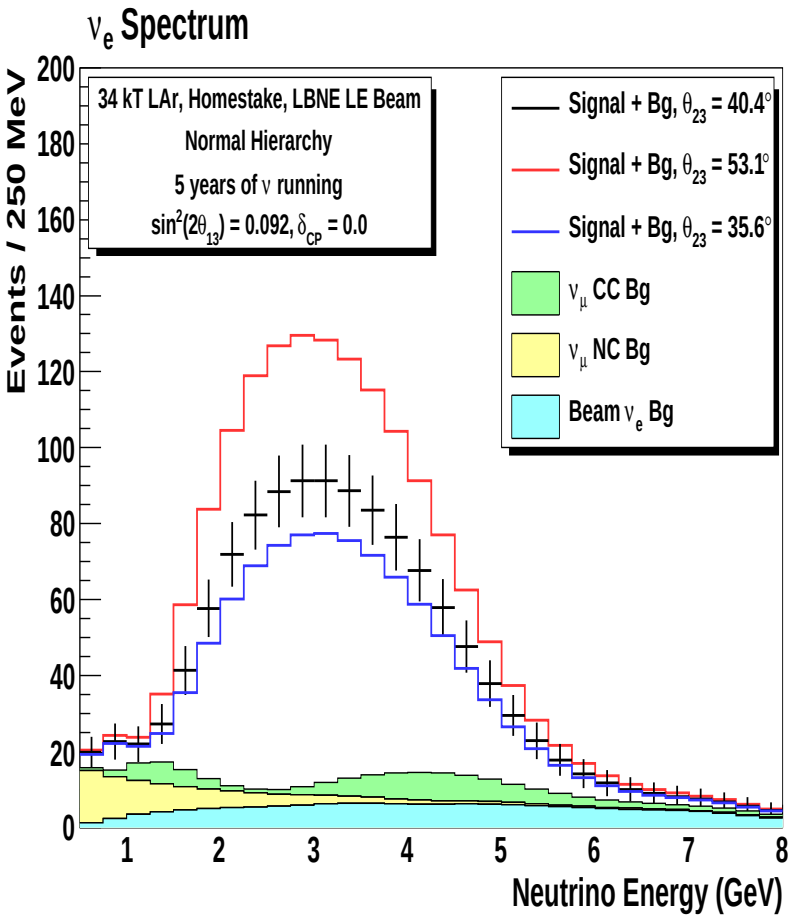


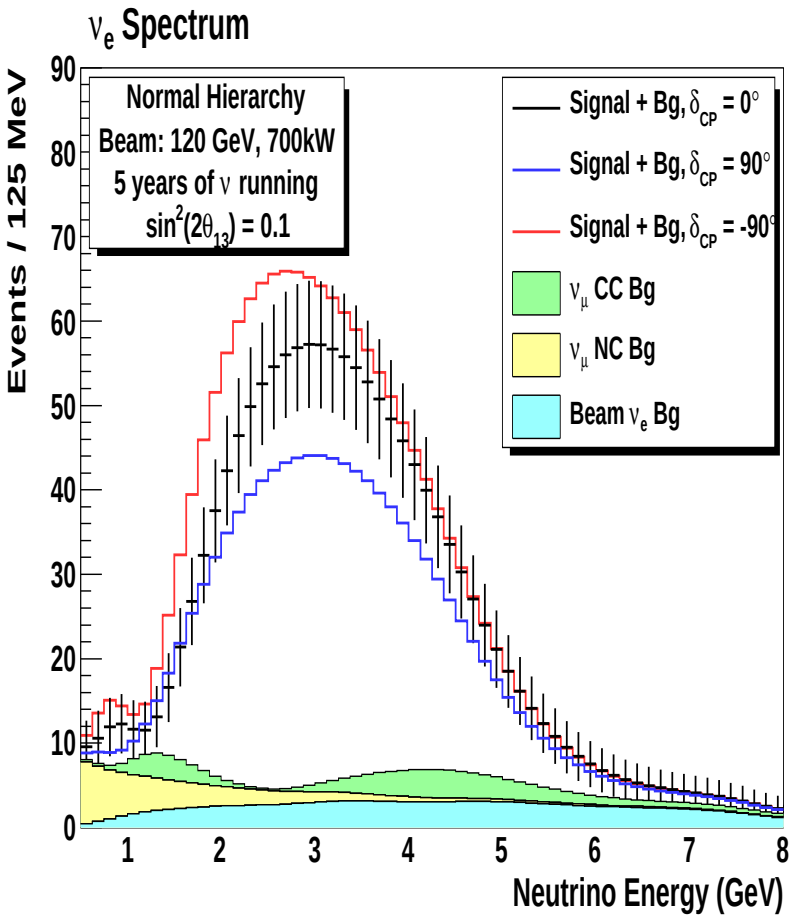
Narrow band beam = difficulty resolving degeneracies

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

Vary θ_{23} octant **Vary δ_{cp}**

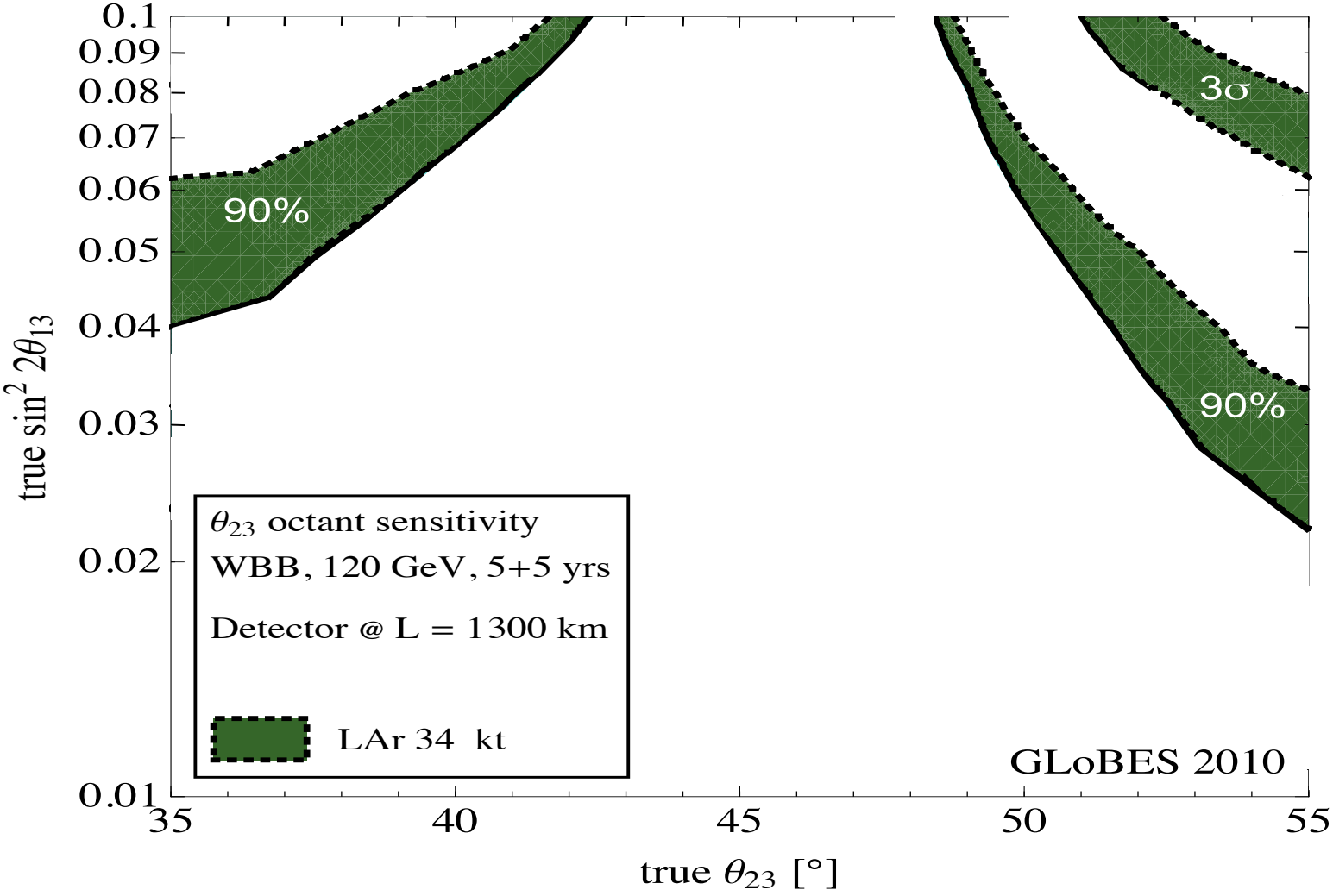
L=1300km, LBNE LE





Larger spectral differences at 1300km help break degeneracies

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



ν_τ CC Appearance Rates

Interaction rates per 100 kton.MW.yr (10^{21} protons-on-target) at the far detector site ($\sin^2 2\theta_{13} = 0.1$) with medium-energy beam tunes (0.5-20 GeV).

Beam/Baseline	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e CC beam	$\nu_\mu \rightarrow \nu_e$ CC	$\nu_\mu \rightarrow \nu_\tau$ C
LBNE 1300km	44K	28K	540	320	1100	640
NuMI 735km	233K	198k	2.7K	1730	2216	1141

The NuMI beamline is optimized for high energy running.

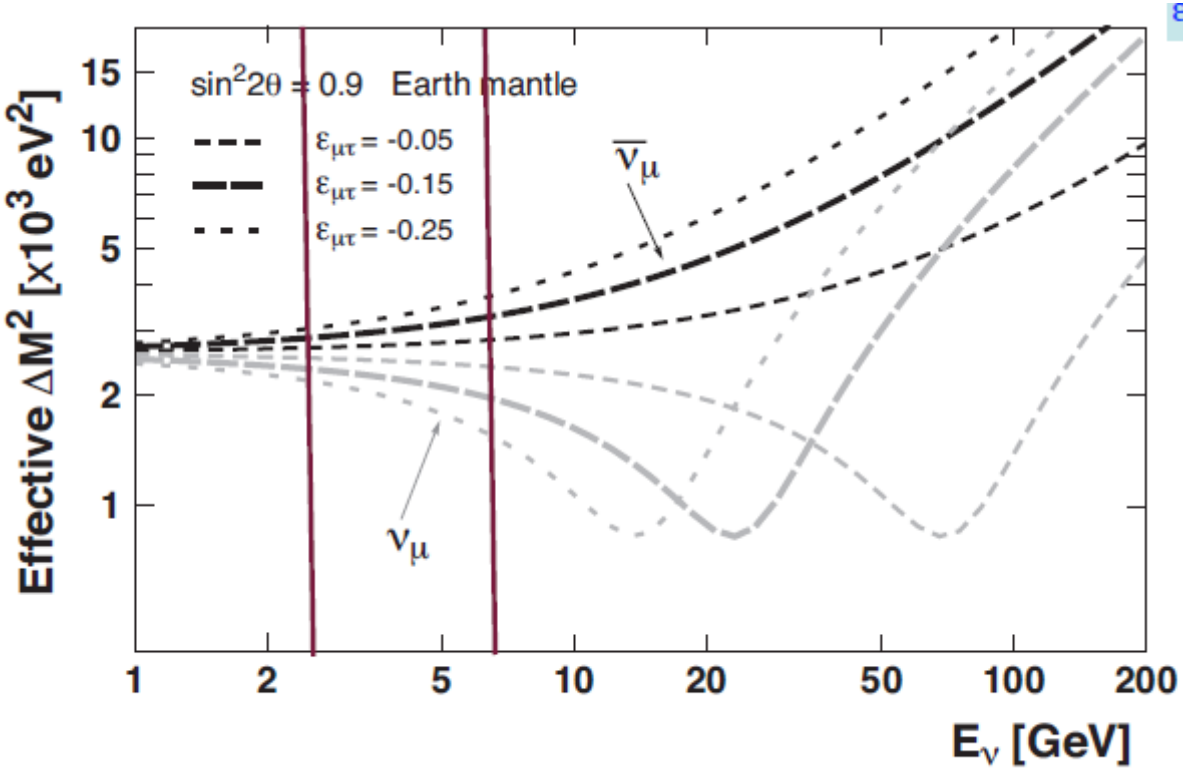
$\Rightarrow$ larger ν_τ appearance signal

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

Phys.Rev. D82 (2010) 113010:

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

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

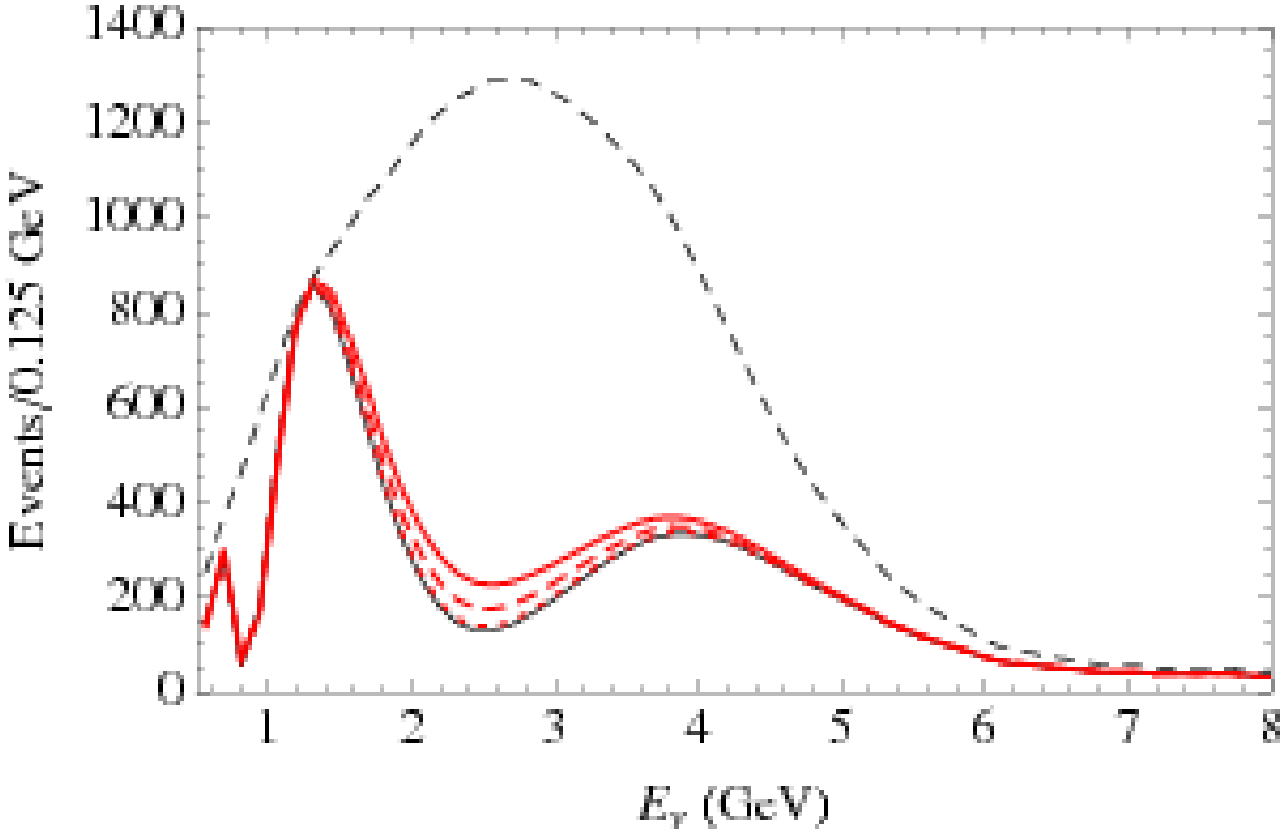


Mann A.W. et al., arxiv 1006.5720

Oscillations at larger E_ν (longer baselines) = larger effects

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 lack of spectral information and smaller event rate are not well matched to measurements of mass hierarchy and a broader program.*
- **LBNE-Homestake early stages outperform similar stages (=similar exposure) of the NuMI options. For the LBNE-Homestake option, no external constraints are needed for ν_e appearance measurements with exposures $\geq$ 60 kt.yrs.**
- **The ν_τ appearance measurements are better at NuMI-Soudan on-axis than in LBNE - but these measurements are already being done at CNGS with essentially the same baseline.**
- **The ultimate performance for CP-violation measurements with $\geq$ 300 kt.yrs of exposure of LBNE-Homestake is significantly better than the NuMI options.**
- **Longer baselines are better at ANY stage of the experiment.**