

Baselines and Oscillation Nodes

LBPWG, 08/08/2013

Mary Bishai

August 20, 2014

Outline

Baselines and
Oscillation
Nodes

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Nodes and
Asymmetries

Neutrino
Fluxes

Event Rates

Rate
Asymmetries

LBNE/LBNO
comparisons

1 Nodes and Asymmetries

2 Neutrino Fluxes

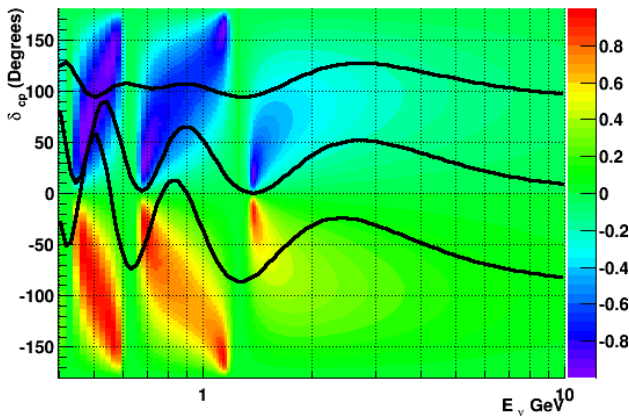
3 Event Rates

4 Rate Asymmetries

5 LBNE/LBNO comparisons

CP Asymmetry vs E_ν and δ_{cp}

Asymmetry at 1300km (Total), vacuum

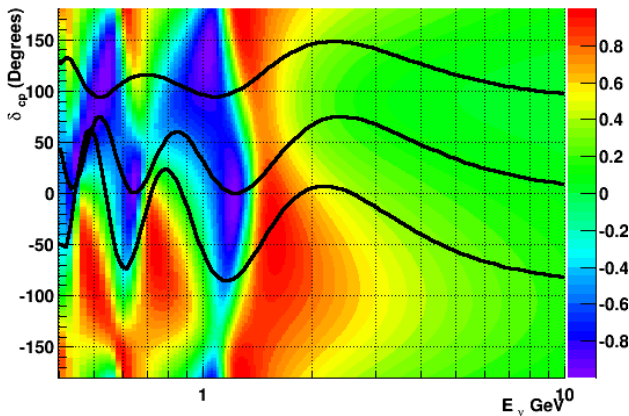


Asymmetries are larger near **minima**

BUT, events appear at the maxima!

CP Asymmetry vs E_ν and δ_{cp}

Asymmetry at 1300km (Total), NH

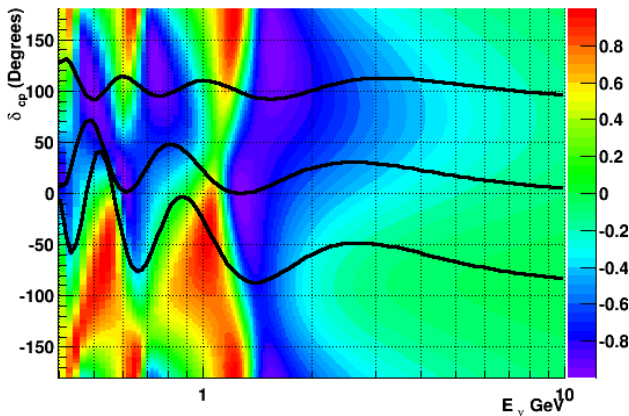


Asymmetries are larger near **minima**

BUT, events appear at the maxima!

CP Asymmetry vs E_ν and δ_{cp}

Asymmetry at 1300km (Total), IH



Asymmetries are larger near **minima**

BUT, events appear at the maxima!

Matter and CP Asymmetries at Maxima

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Oscillation
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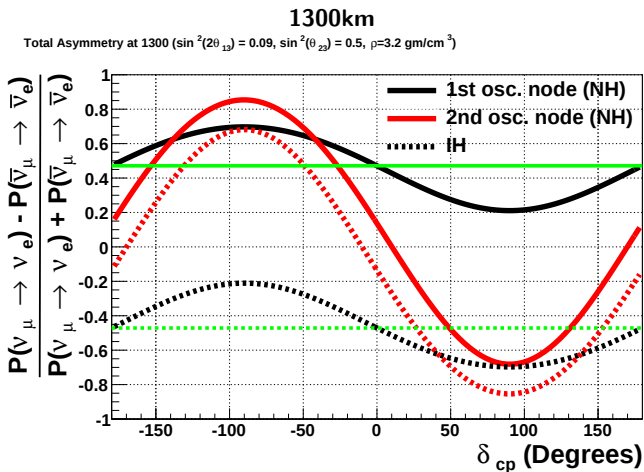
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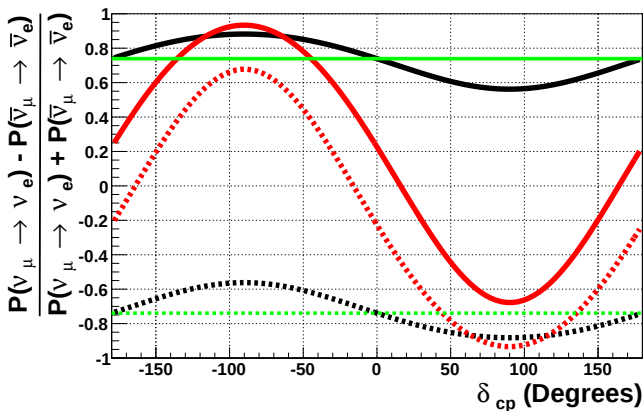
$$\mathcal{A}_{\text{matter}}^1 = 0.5, \mathcal{A}_{\text{CP}}^1 = 0.2$$

$$\mathcal{A}_{\text{matter}}^2 = 0.1, \mathcal{A}_{\text{CP}}^2 = 0.7$$

Matter and CP Asymmetries at Maxima

2300km

Total Asymmetry at 2300 ($\sin^2(2\theta_{13}) = 0.09$, $\sin^2(\theta_{23}) = 0.5$, $\rho = 3.2 \text{ gm/cm}^3$)



$$\mathcal{A}_{\text{matter}}^1 = 0.75, \mathcal{A}_{\text{CP}}^1 = 0.2$$

$$\mathcal{A}_{\text{matter}}^2 = 0.2, \mathcal{A}_{\text{CP}}^2 = 0.7$$

Osc. vs L/E

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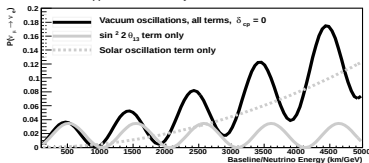
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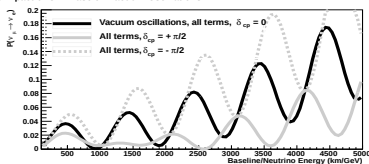
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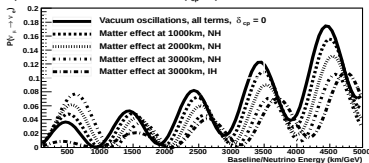
(a) Electron Neutrino Appearance Probability vs. L/E



(b) Impact of CP Phase on Vacuum Oscillations



(c) Impact of Matter Effects on Oscillations ($\delta_{CP} = 0$)



1st oscillation node is from
 $L/E \sim 100\text{km/GeV}$ to
 1000 km/GeV

2nd oscillation node is from
 $L/E \sim 1000\text{km/GeV}$ to
 2000 km/GeV

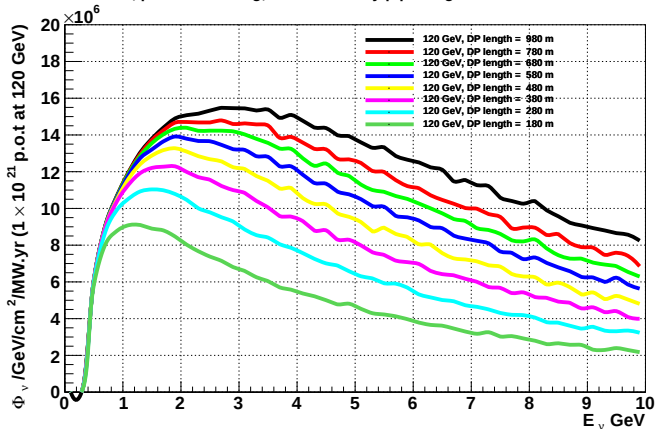
Assuming flat flux and
 $\sigma_\nu^2/\sigma_\nu^1 = 0.4$,
integrated event rates in
vacuum over 1st and 2nd
oscillation nodes are:

$$\begin{aligned} \frac{R^2}{R^1} &= \frac{(1/1000 - 1/2000)}{(1/100 - 1/1000)} \\ &\times \frac{0.05}{0.035} \\ &\times 0.4 \\ &= 3\% \end{aligned}$$

Neutrino fluxes with perfect focusing

120 GeV, decay channel lengths from 200m to 1km

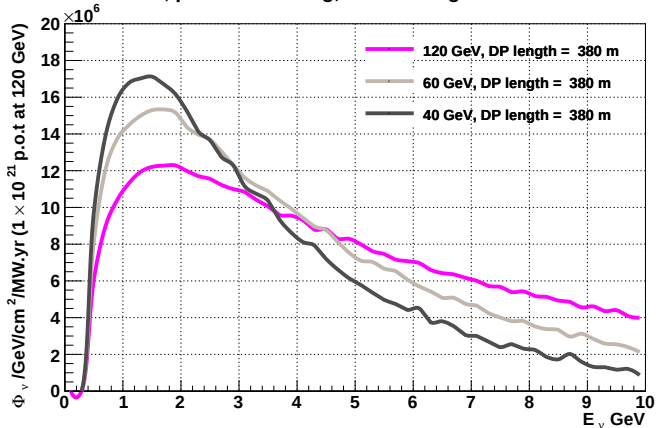
Flux at 1000km, perfect focusing, different decay pipe lengths



Neutrino fluxes with perfect focusing

40 to 120 GeV, decay channel length = 400m

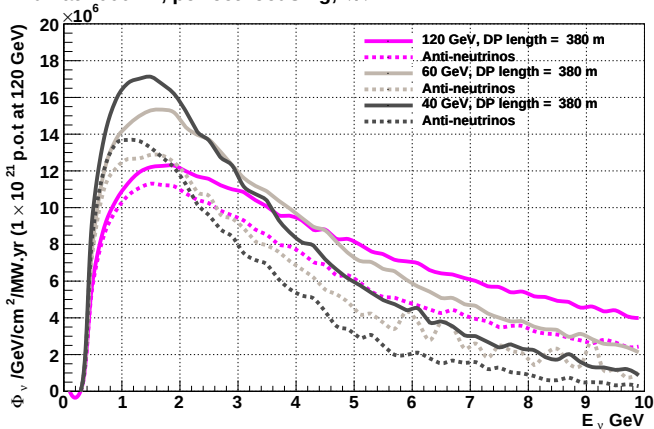
Flux at 1000km, perfect focusing, beam energies



Neutrino fluxes with perfect focusing

Neutrino vs anti-neutrino fluxes

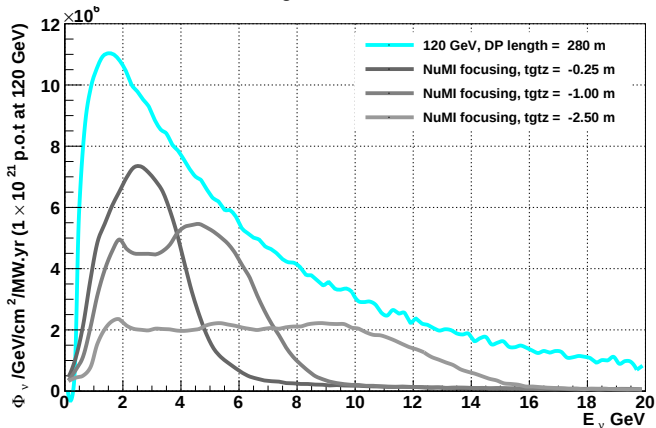
Flux at 1000km, perfect focusing, $\nu/\bar{\nu}$



Neutrino fluxes with perfect focusing

Variable NuMI Focusing

Flux at 1000km, NuMI focusing, 230kA, H1-H2 = 6.6m



Event Rates vs. Baseline

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Asymmetries

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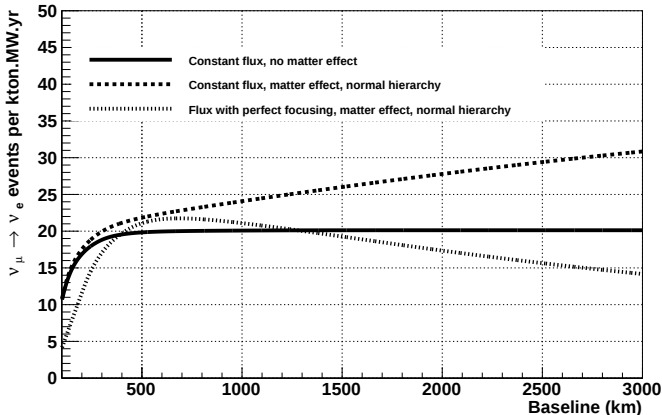
$$\mathcal{R} = \int \Phi_{\text{perfect}}^{\nu_{\mu}}(\mathbf{E}_{\nu}) \times \sigma(\mathbf{E}_{\nu}) \times P(\nu_{\mu} \rightarrow \nu_e) d\mathbf{E}_{\nu}$$

$$(\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.5, \delta_{\text{cp}} = 0, |\Delta m_{31}^2| = 2.4 \times 10^{-3})$$

Flux: 120 GeV, perfect focusing, $\sim 400\text{m}$ decay channel, on-axis

Normal Hierarchy

Appearance rates versus baseline



Event Rates vs. Baseline

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Fluxes

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Asymmetries

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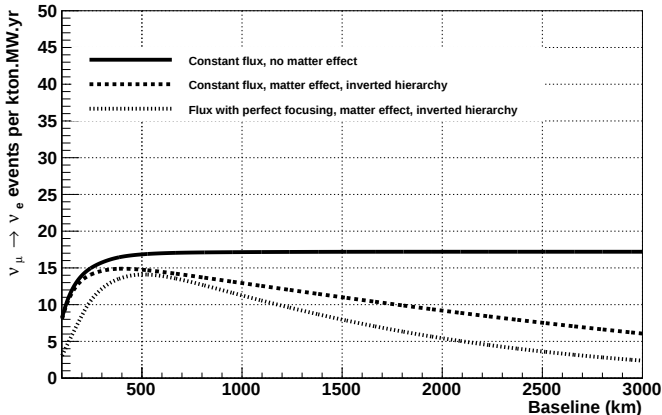
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Inverted Hierarchy

Appearance rates versus baseline



Event Rates vs. Baseline at 1st and 2nd Osc. Nodes

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Fluxes

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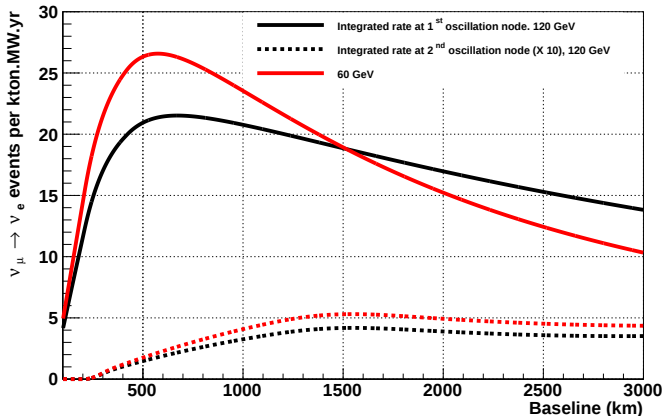
LBNE/LBNO
comparisons

1st osc. node from $E_1 = 1.267|\Delta m_{31}^2|L/\pi$ to $10 \times E_1$

2nd osc node from $E_2 = 1.267|\Delta m_{31}^2|L/(2\pi)$ to E_1

Normal Hierarchy

$\nu_\mu \rightarrow \nu_e$ appearance rates versus baseline



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Oscillation
Nodes

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Asymmetries

Neutrino
Fluxes

Event Rates

Rate
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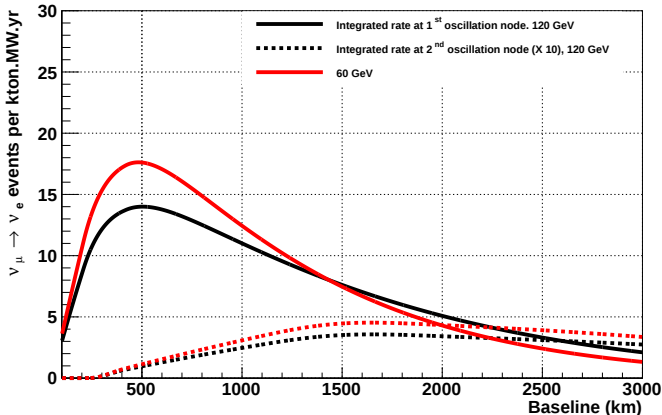
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Oscillation
Nodes

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Asymmetries

Neutrino
Fluxes

Event Rates

Rate
Asymmetries

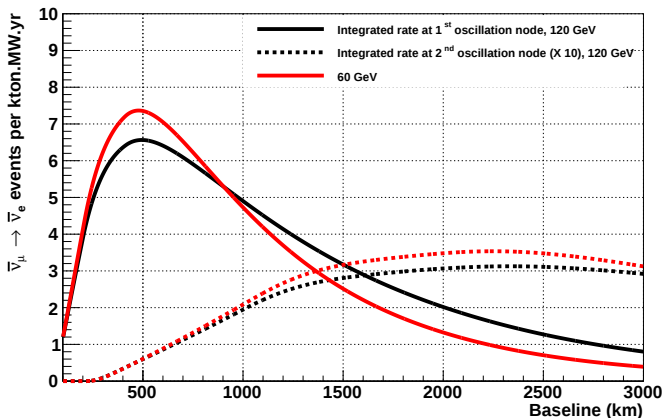
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Oscillation
Nodes

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Asymmetries

Neutrino
Fluxes

Event Rates

Rate
Asymmetries

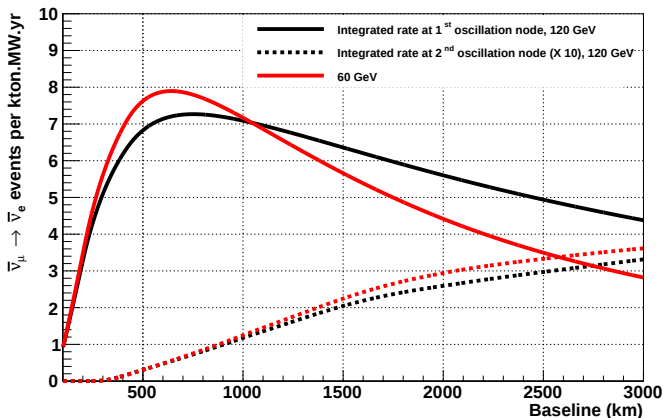
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Integrated Rate Asymmetries w/ Perfect Focusing

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Oscillation
Nodes

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Nodes and
Asymmetries

Neutrino
Fluxes

Event Rates

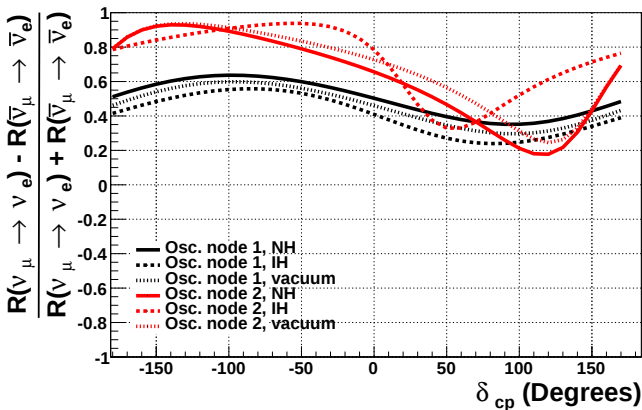
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$$(\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.5, \delta_{cp} = 0, |\Delta m_{31}^2| = 2.4 \times 10^{-3}, \rho = 2.4 \text{ gm/cm}^3)$$

300 km

Integrated Rate Asymmetry at 300 km ($\sin^2(2\theta_{13}) = 0.09, \sin^2(\theta_{23}) = 0.50, \rho = 2.8 \text{ gm/cm}^3$)



Integrated Rate Asymmetries w/ Perfect Focusing

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Oscillation
Nodes

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Nodes and
Asymmetries

Neutrino
Fluxes

Event Rates

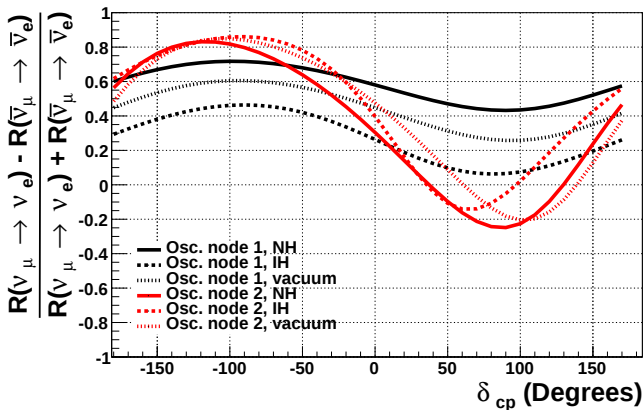
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810 km

Integrated Rate Asymmetry at 810 km ($\sin^2(2\theta_{13}) = 0.09, \sin^2(\theta_{23}) = 0.50, \rho = 2.8 \text{ gm/cm}^3$)



Integrated Rate Asymmetries w/ Perfect Focusing

Baselines and
Oscillation
Nodes

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Nodes and
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Neutrino
Fluxes

Event Rates

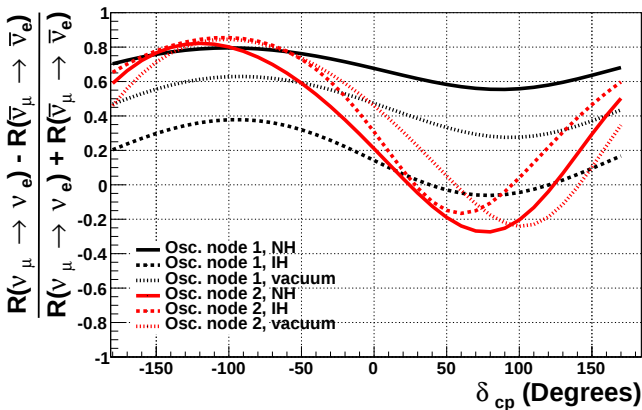
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1300 km

Integrated Rate Asymmetry at 1300 km ($\sin^2(2\theta_{13}) = 0.09, \sin^2(\theta_{23}) = 0.50, \rho = 2.8 \text{ gm/cm}^3$)

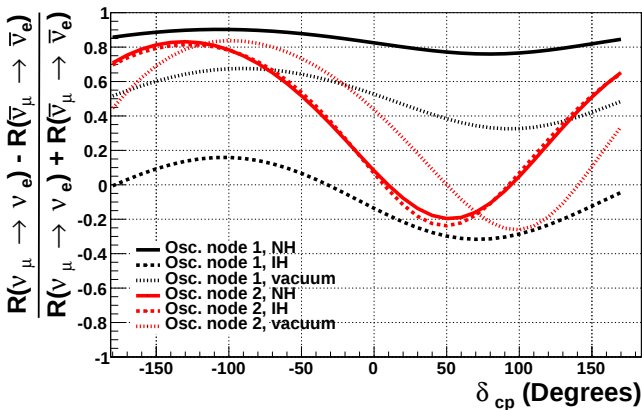


Integrated Rate Asymmetries w/ Perfect Focusing

$$(\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.5, \delta_{cp} = 0, |\Delta m_{31}^2| = 2.4 \times 10^{-3}, \rho = 2.4 \text{ gm/cm}^3)$$

2300 km

Integrated Rate Asymmetry at 2300 km ($\sin^2(2\theta_{13}) = 0.09, \sin^2(\theta_{23}) = 0.50, \rho = 2.8 \text{ gm/cm}^3$)



LBNO/LBNO fluxes

Baselines and
Oscillation
Nodes

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Asymmetries

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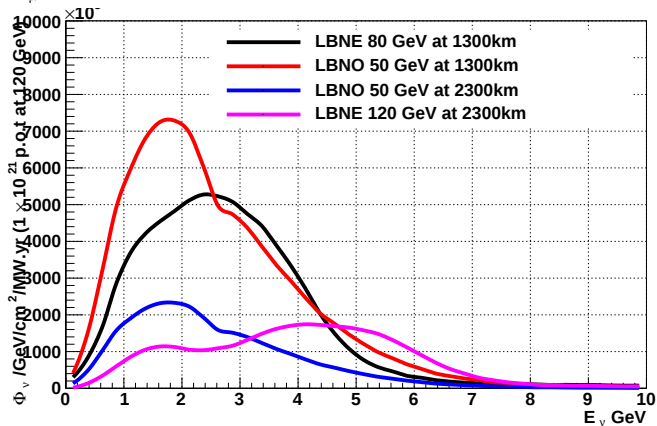
Event Rates

Rate
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LBNE/LBNO
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Forward horn current

ν_μ fluxes at 1300 and 2300km



LBNO/LBNO fluxes

Baselines and
Oscillation
Nodes

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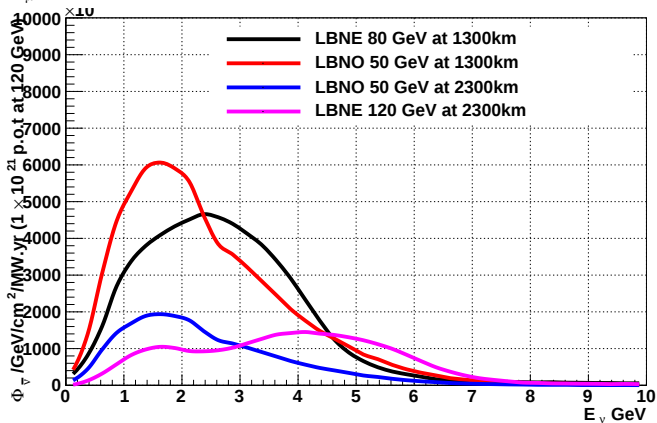
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Reverse horn current

$\bar{\nu}_\mu$ fluxes at 1300 and 2300km



Appearance Spectra (no detector effects) NH

$$\delta_{cp} = -\pi/2$$

$$\delta_{cp} = 0$$

$$\delta_{cp} = \pi/2$$

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Oscillation
Nodes

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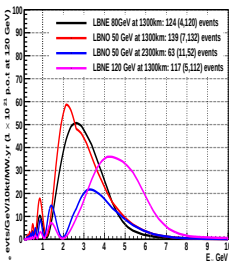
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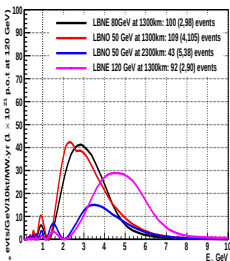
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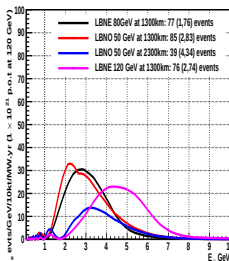
$\nu_\mu \rightarrow \nu_e$ rates at 1300 and 2300km



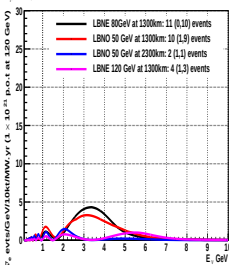
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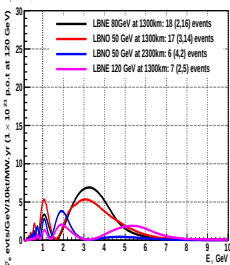
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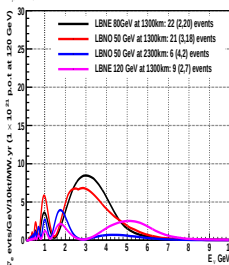
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Appearance Spectra (no detector effects) IH

$$\delta_{cp} = -\pi/2$$

$$\delta_{cp} = 0$$

$$\delta_{cp} = \pi/2$$

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Nodes

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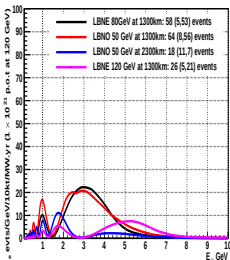
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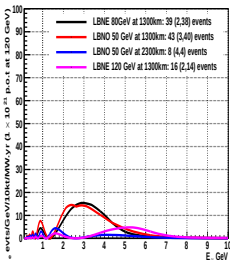
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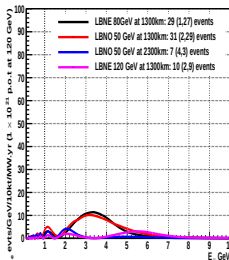
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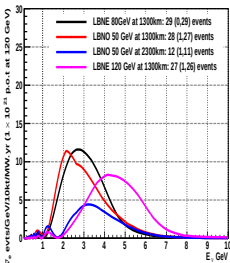
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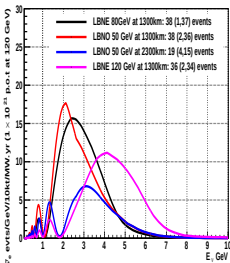
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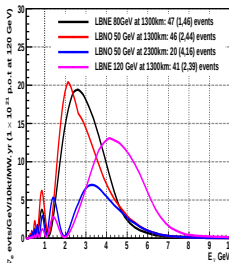
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$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ rates at 1300 and 2300km



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ rates at 1300 and 2300km



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$$\delta_{cp} = -\pi/2$$

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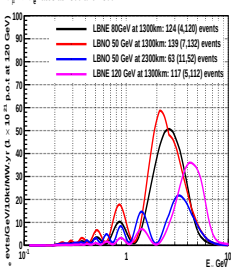
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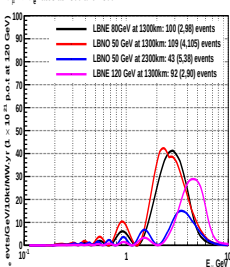
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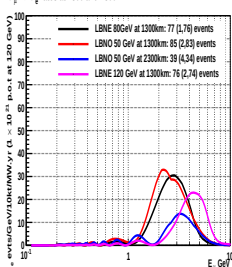
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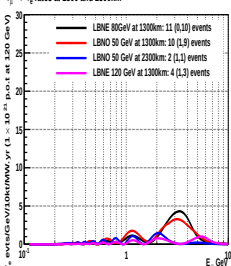
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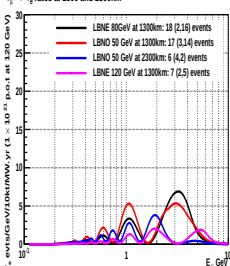
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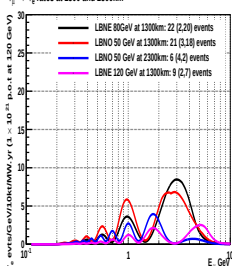
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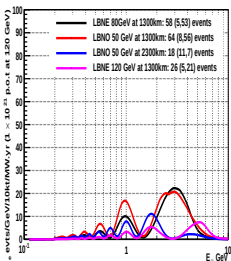
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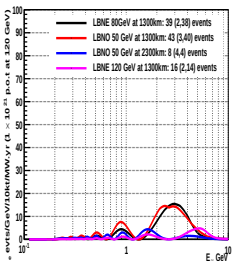
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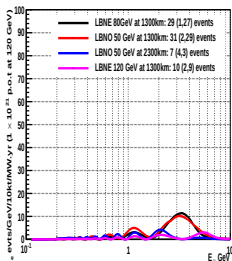
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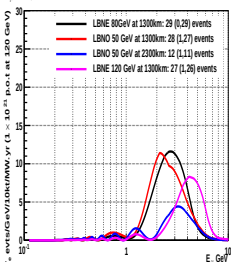
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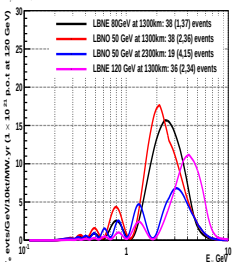
$\nu_\mu \rightarrow \nu_e$ rates at 1300 and 2300km



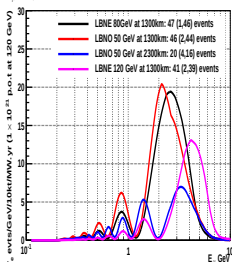
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ rates at 1300 and 2300km



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ rates at 1300 and 2300km



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ rates at 1300 and 2300km



Appearance Rates vs. δ_{cp} (no detector effects)

1st Osc. Node $\geq$ 2nd Osc. Node

Baselines and
Oscillation
Nodes

Mary Bishai

Nodes and
Asymmetries

Neutrino
Fluxes

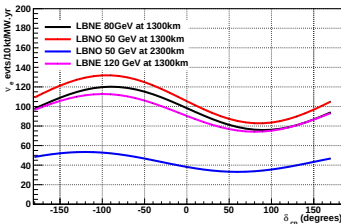
Event Rates

Rate
Asymmetries

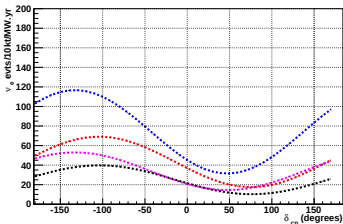
LBNE/LBNO
comparisons

$(\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.45, |\Delta m_{31}^2| = 2.5 \times 10^{-3}, \rho = 3.2 \text{ gm/cm}^3)$
Normal Hierarchy

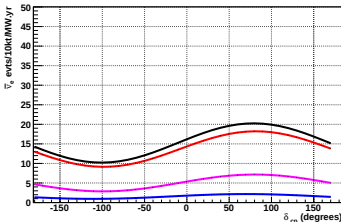
ν_e appearance rates 1st osc node, NH



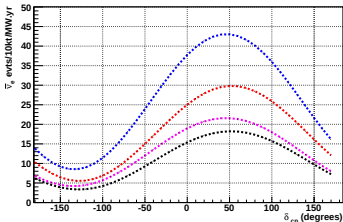
ν_e appearance rates at $\geq$ 2nd node (x10), NH



$\bar{\nu}_e$ appearance rates 1st osc node, NH



$\bar{\nu}_e$ appearance rates at $\geq$ 2nd node (x10), NH



Appearance Rates vs. δ_{cp} (no detector effects)

1st Osc. Node $\geq$ 2nd Osc. Node

Baselines and
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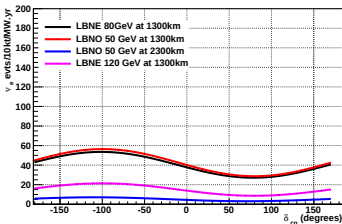
Rate
Asymmetries

LBNE/LBNO
comparisons

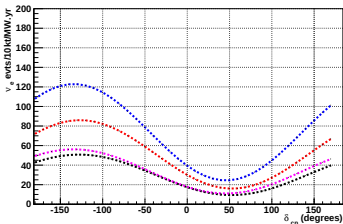
$$(\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.45, |\Delta m_{31}^2| = 2.5 \times 10^{-3}, \rho = 3.2 \text{ gm/cm}^3)$$

Inverted Hierarchy

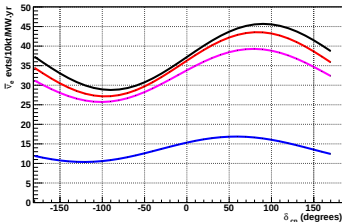
$\bar{\nu}_e$ appearance rates 1st osc node, IH



$\bar{\nu}_e$ appearance rates at $\geq$ 2nd node (x10), IH



$\bar{\nu}_e$ appearance rates 1st osc node, IH



$\bar{\nu}_e$ appearance rates at $\geq$ 2nd node (x10), IH

