Motivation

Oscillation Basics

ν Flux from DIF Beams

Event Rates

Spectral Information

ν Flux with Focusing

GLoBeS Studies

Summary

Baselines and Oscillations

Fermilab Neutrino Physics Discussion, 10/8/2014

Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian

October 8, 2014

Outline

1 Motivation

2 Oscillation Basics

3 ν Flux from DIF Beams

4 Event Rates

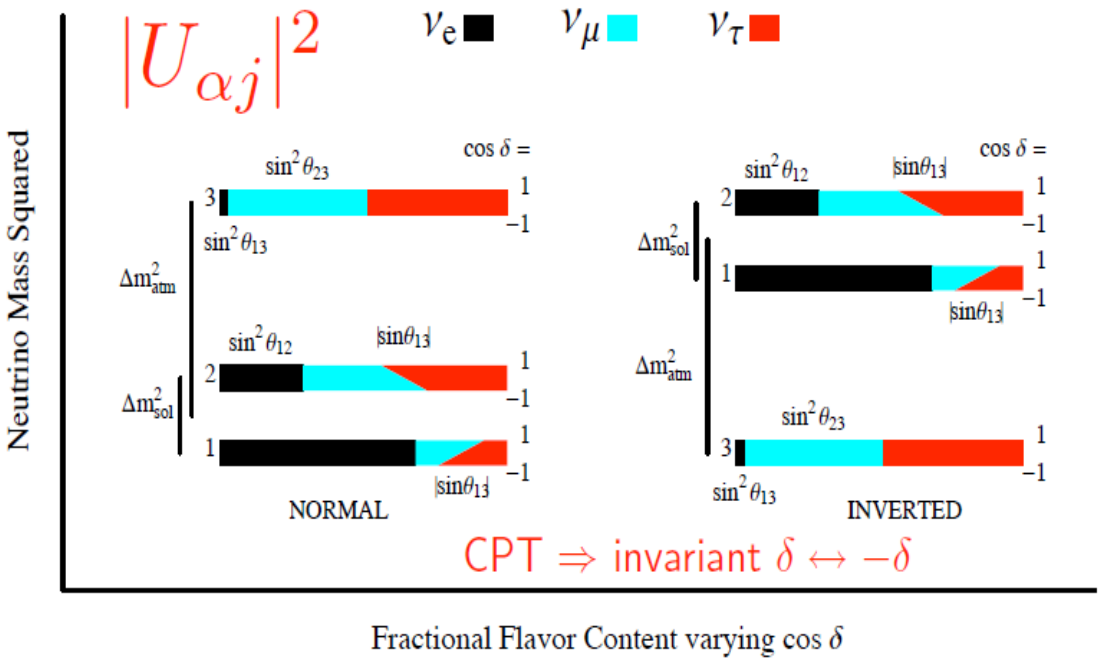
5 Spectral Information

6 ν Flux with Focusing

7 GLoBeS Studies

8 Summary

Neutrino Mixing



- What is the neutrino mass hierarchy? ($\delta m^2_{31} \equiv m^2_3 - m^2_1 > 0$)
- Is ν_3 mostly ν_μ or ν_τ ? ($\theta_{23} < \pi/4$ or $> \pi/4$)
- Is CP Violated in Neutrino Oscillations? ($\delta \neq 0, \pi$)

Neutrino CP Violation and Long Baseline Oscillations - Recap

In 2001, Bill Marciano (hep-ph/0108181) demonstrates that in the absence of matter effects the CP asymmetry is largely independent of baseline and θ_{13} for $400 < L < 2000$ km, $0.02 < sin^2 2\theta_{13} < 0.15$

Extra Long Baseline Neutrino Oscillations and CP Violation

William J. Marciano
Brookhaven National Laboratory, Upton, NY 11973

Abstract

The potential for studying CP violation in neutrino oscillations using conventional ν_μ and $\bar{\nu}_\mu$ beams is examined. For $\Delta m^2_{21} << \Delta m^2_{31}$ and fixed neutrino energy, E_ν, the CP violating asymmetry $A \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)/P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in vacuum is shown to be measurable with roughly equal maximal statistical precision at distances $L_n \simeq (2n+1)\left(\frac{2\pi E_\nu}{\Delta m^2_{21}}\right), n = 0, 1, 2 \ldots$ (up to some n in the leading Δm^2_{21} approximation). For extra long baselines, $n \geq 1$, the falloff in detected oscillation events, $N = N_{\nu_e} + N_{\bar{\nu}_e}$, by $\sim 1/(2n+1)^2$ is compensated by a factor $\sim (2n+1)$ increase in the asymmetry such that the statistical figure of merit F.O.M. $\equiv (\delta A/A)^{-2} = A^2 N/1 - A^2$ is approximately independent of n. However, for the larger $n \geq 1$ asymmetries,

n	$L_n(km)$	$N_{\nu_e} + N_{\bar{\nu}_e}$	A	F.O.M.
0	413	16000	0.134	293
1	1239	1952	0.366	302
2	2065	824	0.516	299
3	2891	512	0.586	268
4	3717	384	0.601	217
5	4543	315	0.585	164

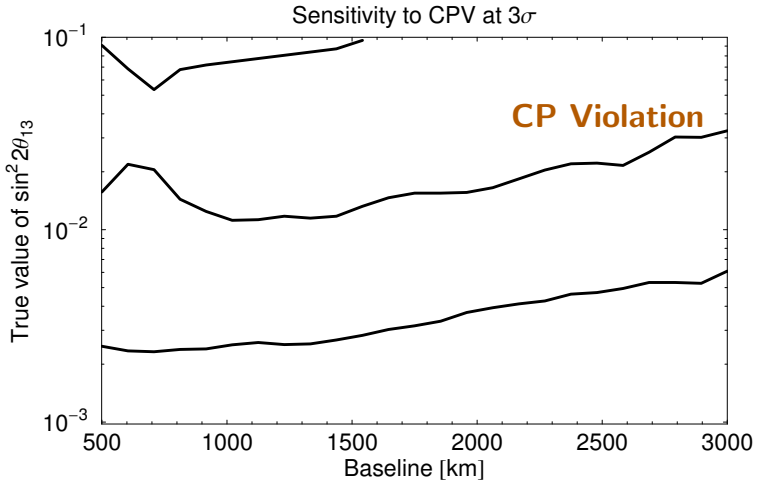
Table 1: Number of total oscillation events (after cuts) $N_{\nu_e} + N_{\bar{\nu}_e}$, the CP violating asymmetry A, and F.O.M. at different distances for the mixing parameters given above. $E_\nu \simeq 1$ GeV, $r = 1$ and the experimental conditions given in the text are assumed. A F.O.M = 293 corresponds to about a 17 sigma determination of the asymmetry A.

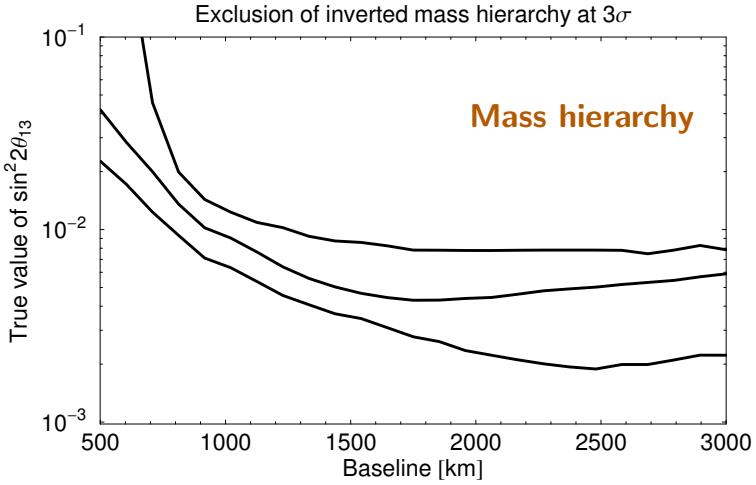
Neutrino CP Violation and Long Baseline Oscillations - Recap

In 2006, a study of long-baseline sensitivities (V. Barger *et al.*. Phys. Rev. D 74, 073004 (2006)) **as a function of baseline with:**

1. **A broad-band beam from the BNL 28 GeV AGS with peak interaction rate at $E_\nu = 2$ GeV, FWHM=3 GeV**
2. **A 300-kton water Cerenkov detector with realistic performance**
3. **An exposure of 5MW.yr (ν) + 10 MW.yr ($\bar{\nu}$)**

found CPV sensitivity best at baselines of 1000-1500km:





Minimum value of $\sin^2(2\theta_{13})$ for which the sensitivity is $> 3\sigma$

for (best,50%, worst) of δ_{cp} values

//

Updated Study on the Role of Baselines in ν Oscillations

With better knowledge of the oscillation parameters, and a more detailed understanding of pion decay-in-flight beams we can refine our understanding of the interplay between neutrino oscillations, beams, baselines and the CP and matter asymmetries.

This study is intended mostly as a pedagogical approach to understanding the role of the baseline in determining CP violation and the mass hierarchy in very long baseline experiments REGARDLESS of experimental design or site/beam design constraints. The only constraint is on the energy of the primary proton beam of 60-120 GeV (Main Injector).

Examples of particular experimental designs and comparisons between them will be shown at the end of the study.

CP Violation in PMNS and CKM

In 3-flavor mixing the degree of CP violation is determined by the Jarlskog invariant:

$$J_{CP}^{\mathrm{PMNS}} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \delta_{\mathrm{CP}}.$$

Given the current best-fit values of the ν mixing angles :

$$J_{CP}^{\mathrm{PMNS}} \approx 3 \times 10^{-2} \sin \delta_{\mathrm{CP}}.$$

For CKM:

$$J_{CP}^{\mathrm{CKM}} \approx 3 \times 10^{-5},$$

despite the large value of $\delta_{CP}^{\mathrm{CKM}} \approx 70^{\circ}$.

$\nu_\mu \to \nu_e$ Oscillation Basics

The oscillation probability of $\nu_{\mu,e} \to \nu_{e,\mu}$, keeping terms up to second order in $\alpha \equiv |\Delta m^2_{21}|/|\Delta m^2_{31}|$ and $\sin^2\theta_{13}$, is (M. Freund. Phys. Rev. D 64, 053003 (2001))**:**

$$P(\nu_\mu \to \nu_e) \cong P(\nu_e \to \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + P_{\cos\delta} + \underbrace{P_3}_{\text{solar oscillation}}$$

where for oscillations in vacuum:

$$P_0 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta),$$

$$P_3 = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta),$$

$$P_{\sin\delta} = \alpha\, 8J_{cp}\sin^3(\Delta),$$

$$P_{\cos\delta} = \alpha\, 8J_{cp}\cot\delta_{\rm CP}\cos\Delta\sin^2(\Delta),$$

and where $\Delta = \Delta m^2_{31}L/4E$

For $\bar\nu_\mu \to \bar\nu_e$, $P_{\sin\delta} \to -P_{\sin\delta}$

$\nu_\mu \to \nu_e$ Oscillation Basics

The oscillation probability of $\nu_{\mu,e} \to \nu_{e,\mu}$, keeping terms up to second order in $\alpha \equiv |\Delta m^2_{21}|/|\Delta m^2_{31}|$ and $\sin^2\theta_{13}$, is (M. Freund. Phys. Rev. D 64, 053003 (2001))**:**

$$P(\nu_\mu \to \nu_e) \cong P(\nu_e \to \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + P_{\cos\delta} + \underbrace{P_3}_{\text{solar oscillation}}$$

where for oscillations in matter with constant density:

$$P_0 = \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_3 = \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),$$

$$P_{\sin\delta} = \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_{\cos\delta} = \alpha\frac{8J_{cp}\cot\delta_{\rm CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

and where $\Delta = \Delta m^2_{31}L/4E$ and $A = \sqrt{3}G_F N_e 2E/\Delta m^2_{31}$.

For $\bar\nu_\mu \to \bar\nu_e$, $P_{\sin\delta} \to -P_{\sin\delta}$

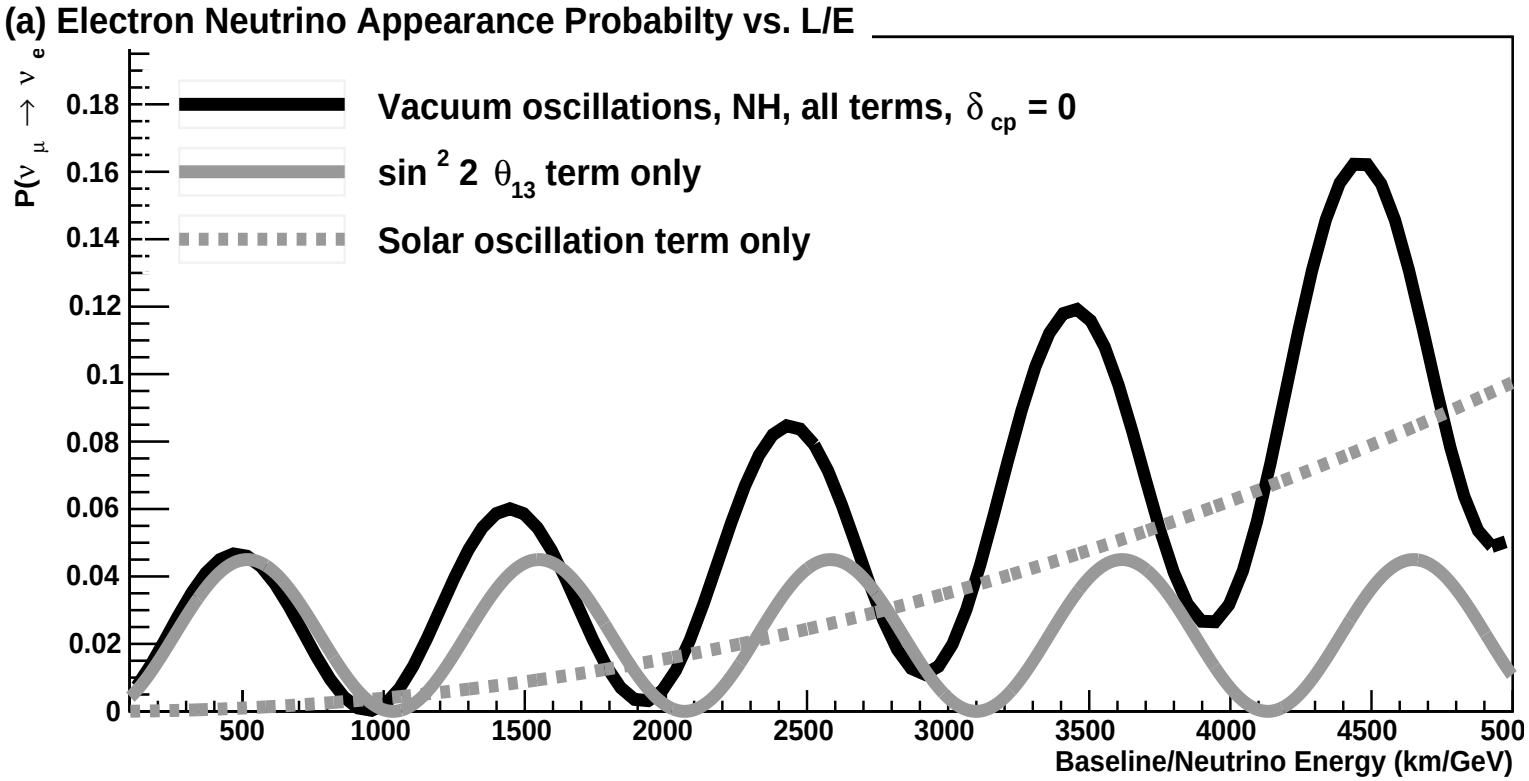
Osc. vs L/E

$\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3} \mathrm{eV}^2$

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right) \frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Oscillations in vacuum - different terms ($\delta_{\mathrm{CP}} = 0$)



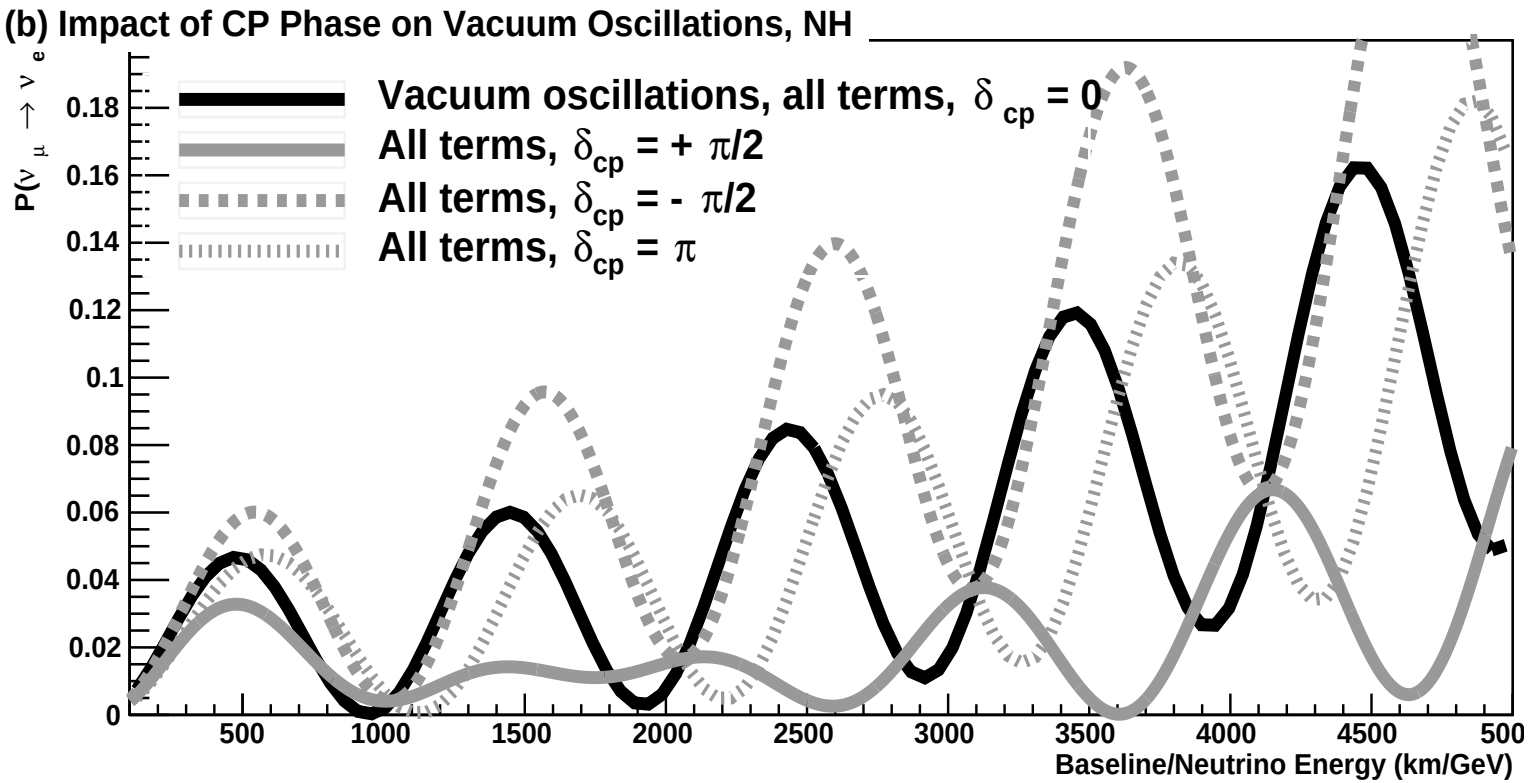
Osc. vs L/E

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Impact of δ_{CP} on oscillations in vacuum, NH



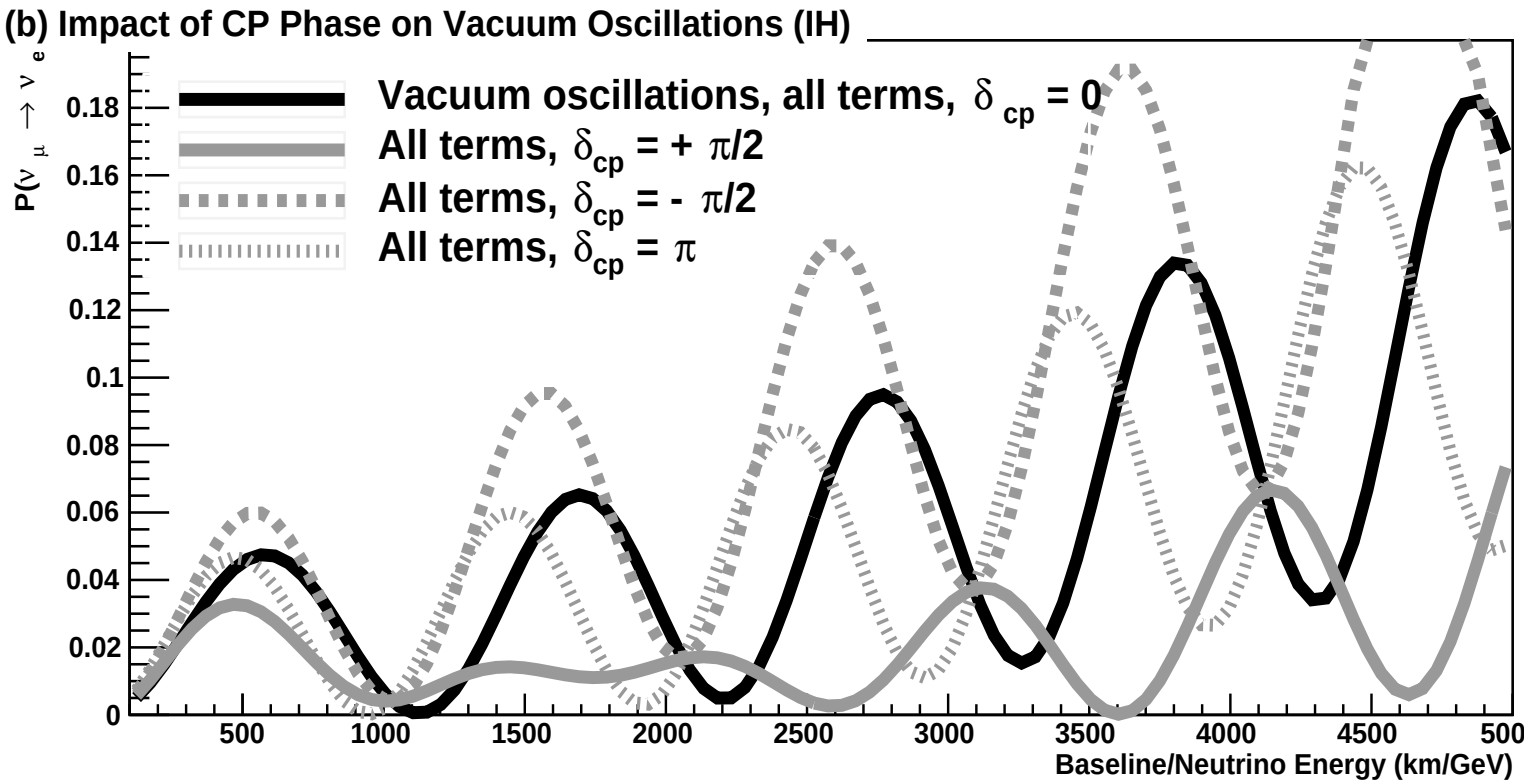
Osc. vs L/E

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Impact of δ_{CP} on oscillations in vacuum, IH



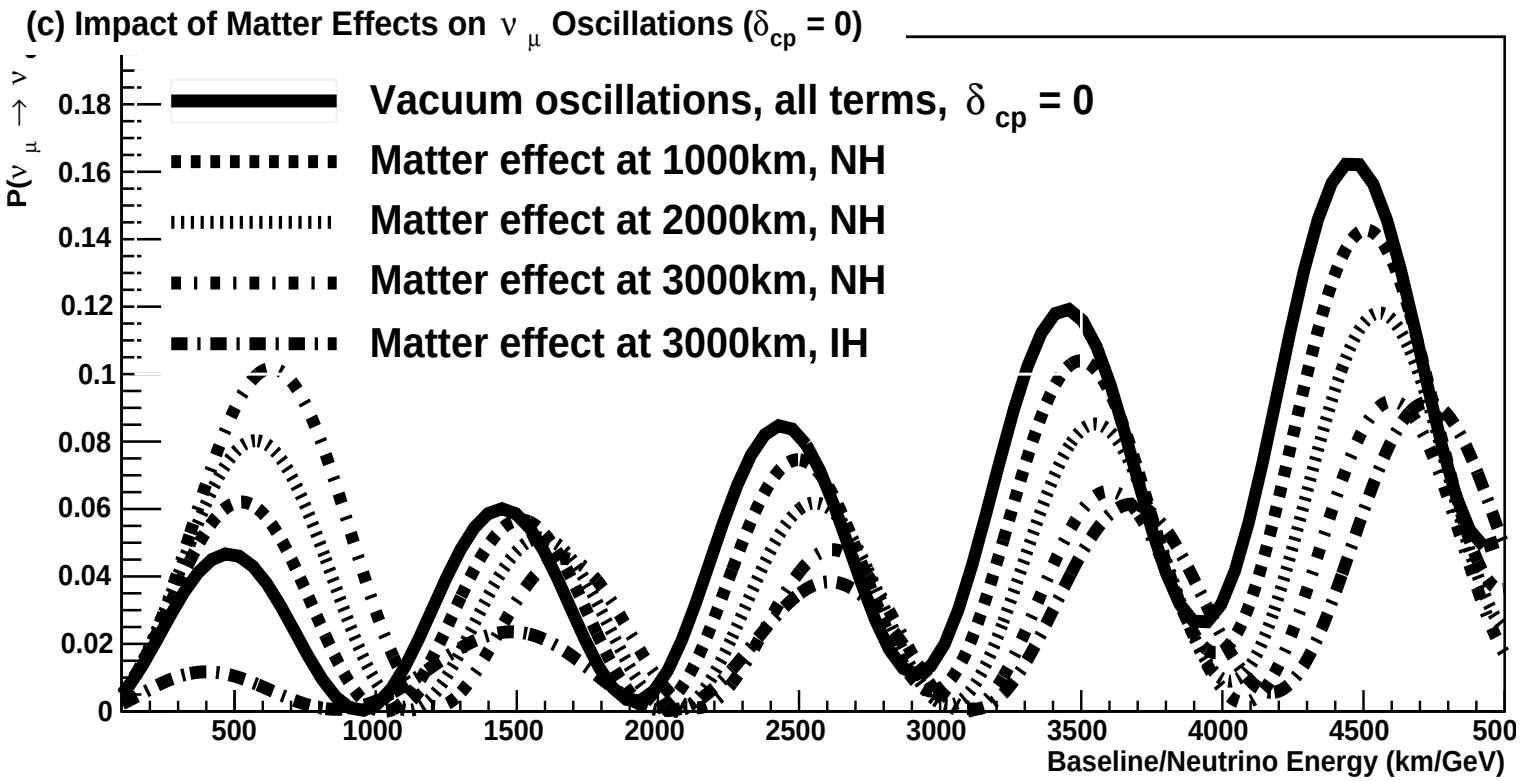
Osc. vs L/E

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Impact of matter effect on ν_μ oscillations ($\delta_{\mathrm{CP}} = 0$)



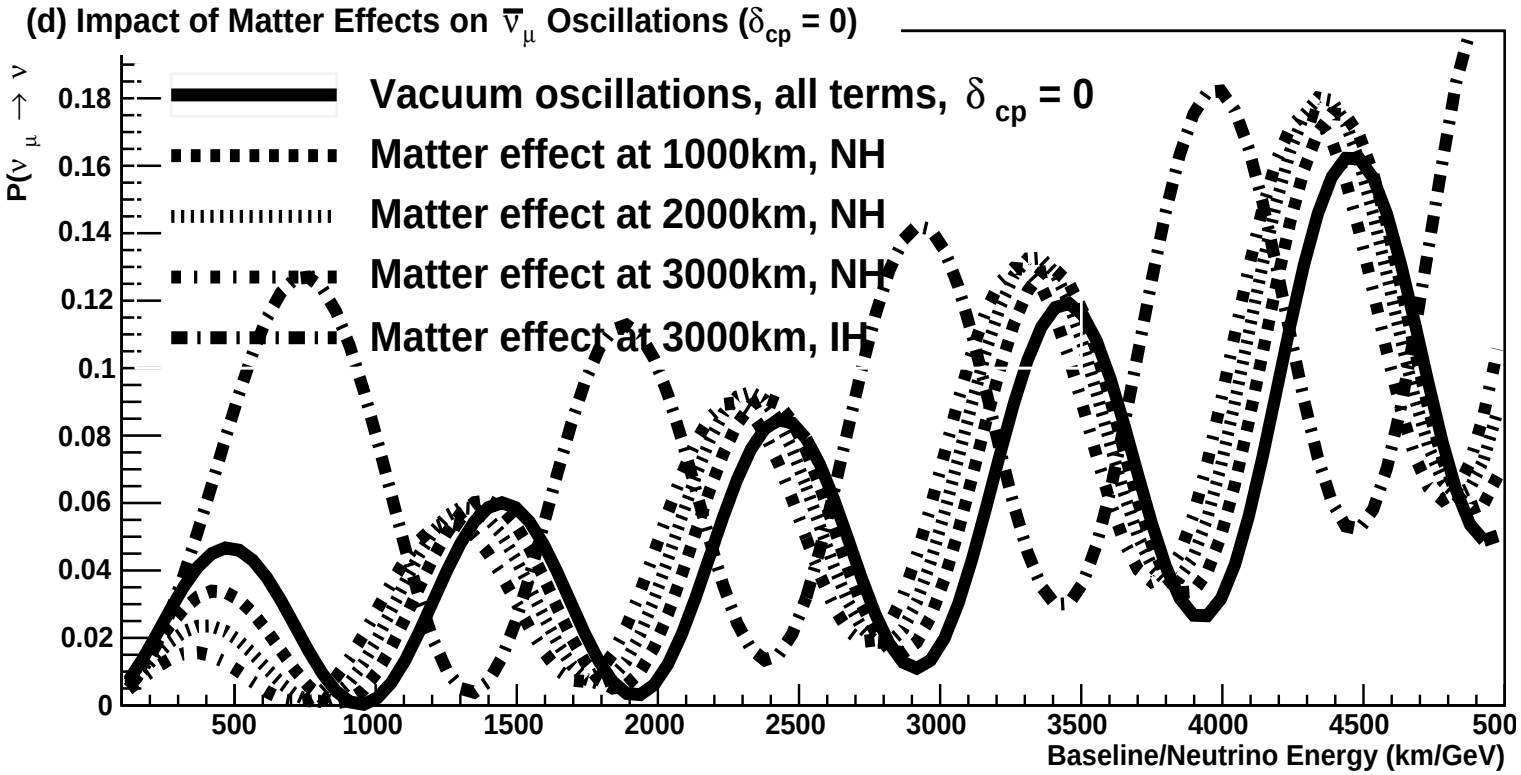
Osc. vs L/E

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Impact of matter effect on $\bar{\nu}_\mu$ oscillations ($\delta_{\mathrm{CP}} = 0$)



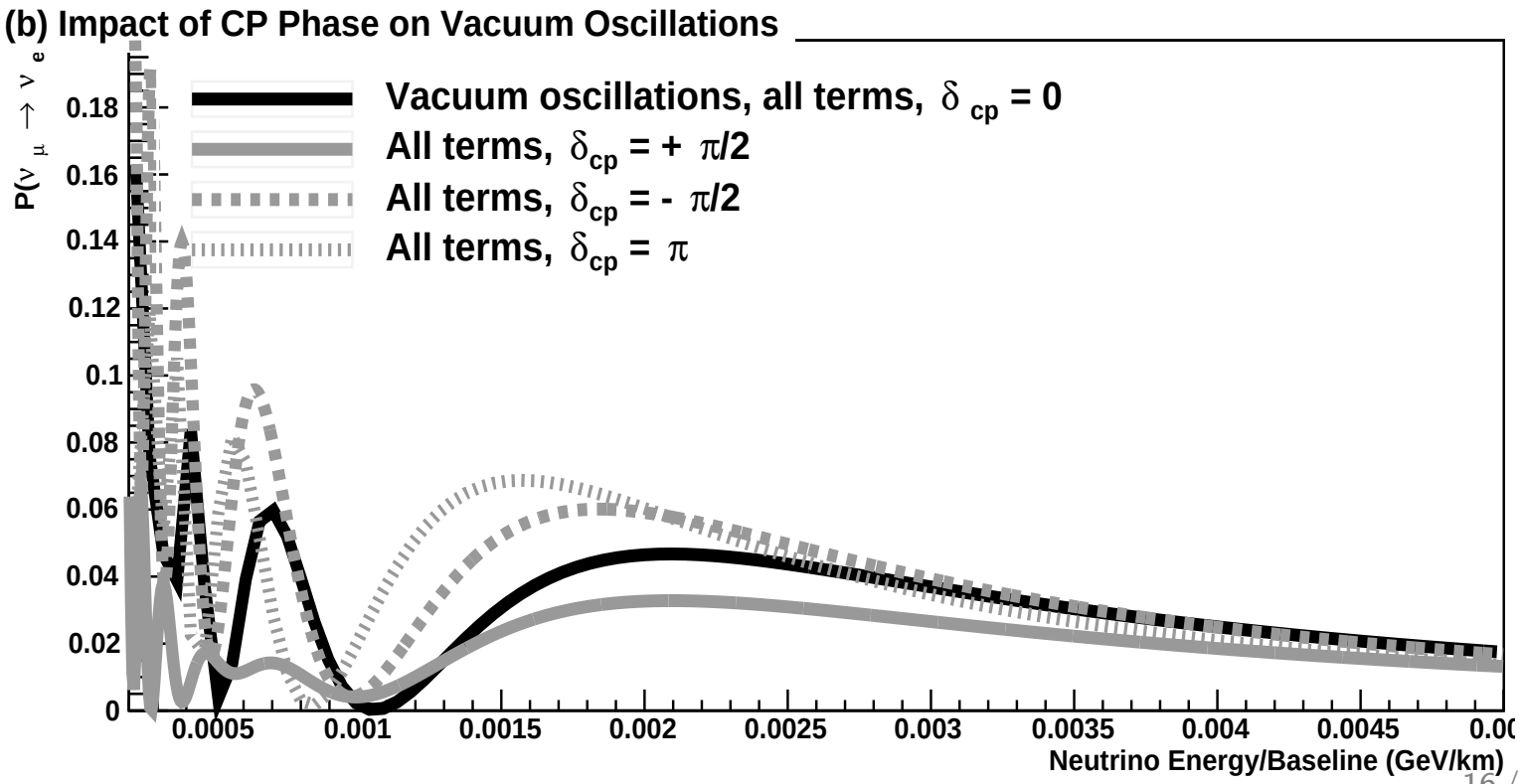
Osc. vs E/L

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$

For experiments at fixed baselines and variable energies, extracting information from the secondary maxima is challenging.

Assuming flat flux, the ratio of ν_e appearance event rates in vacuum integrated over the 1st and 2nd oscillation maximum at $\delta_{\mathrm{CP}} = 0$:

$$\frac{R_2}{R_1} = \frac{\Phi_2^\nu \sigma_2^\nu P_2 \Delta E}{\Phi_1^\nu \sigma_1^\nu P_1 \Delta E} = \frac{1}{3} \times \frac{0.06}{0.045} \times \frac{(1/1000 - 1/2000)}{(1/200 - 1/1000)} \sim 6\%$$



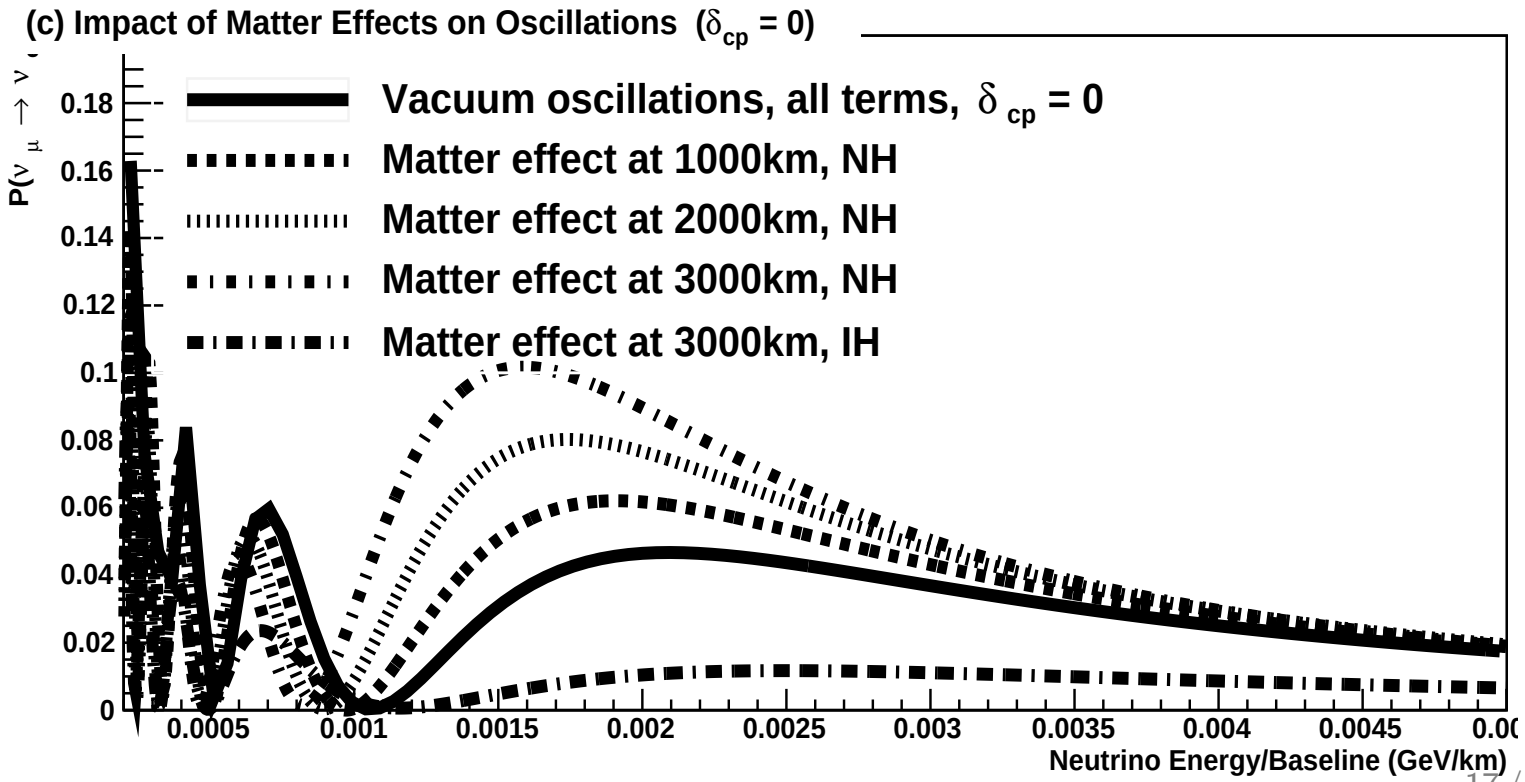
Osc. vs E/L

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$

For experiments at fixed baselines and variable energies, extracting information from the secondary maxima is challenging.

Assuming flat flux, the ratio of ν_e appearance event rates in vacuum integrated over the 1st and 2nd oscillation maximum at $\delta_{\mathrm{CP}} = 0$:

$$\frac{R_2}{R_1} = \frac{\Phi_2^\nu \sigma_2^\nu P_2 \Delta E}{\Phi_1^\nu \sigma_1^\nu P_1 \Delta E} = \frac{1}{3} \times \frac{0.06}{0.045} \times \frac{(1/1000 - 1/2000)}{(1/200 - 1/1000)} \sim 6\%$$

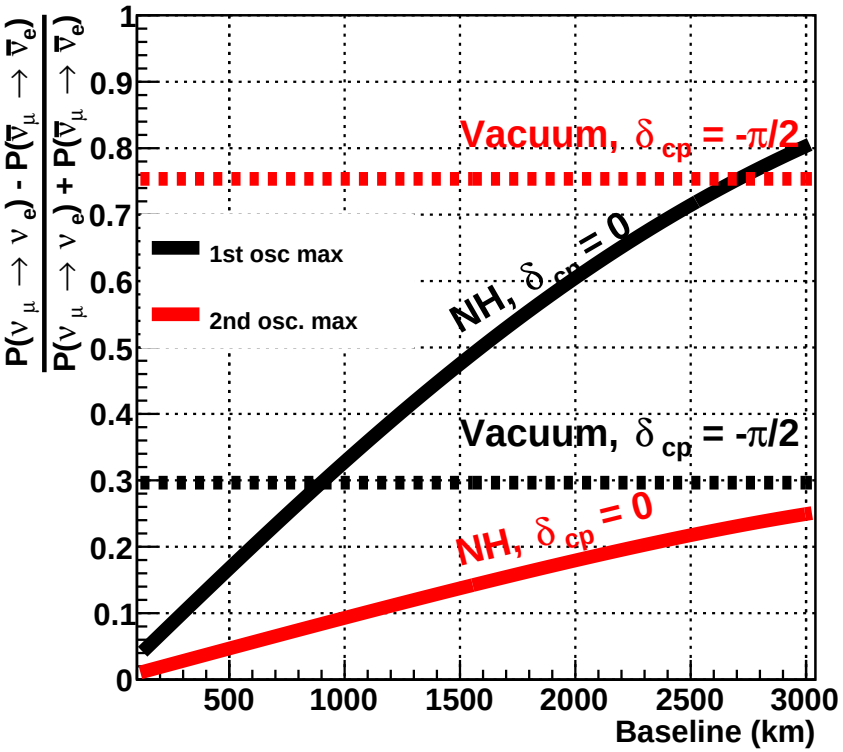


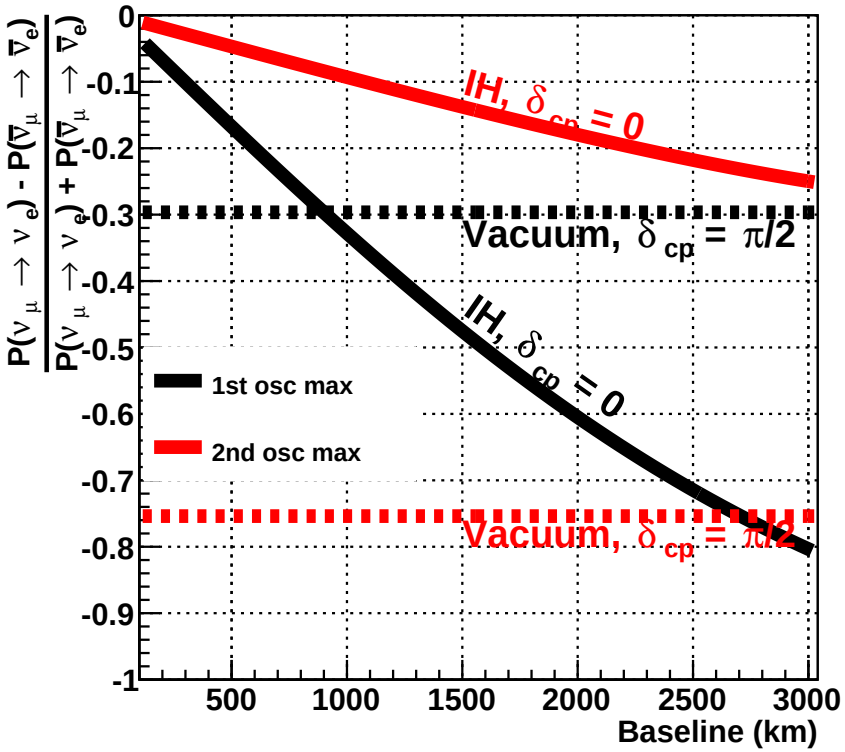
Matter and CP Asymmetries vs Baseline

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2, \rho = 2.8\mathrm{gm/cm}^3$

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

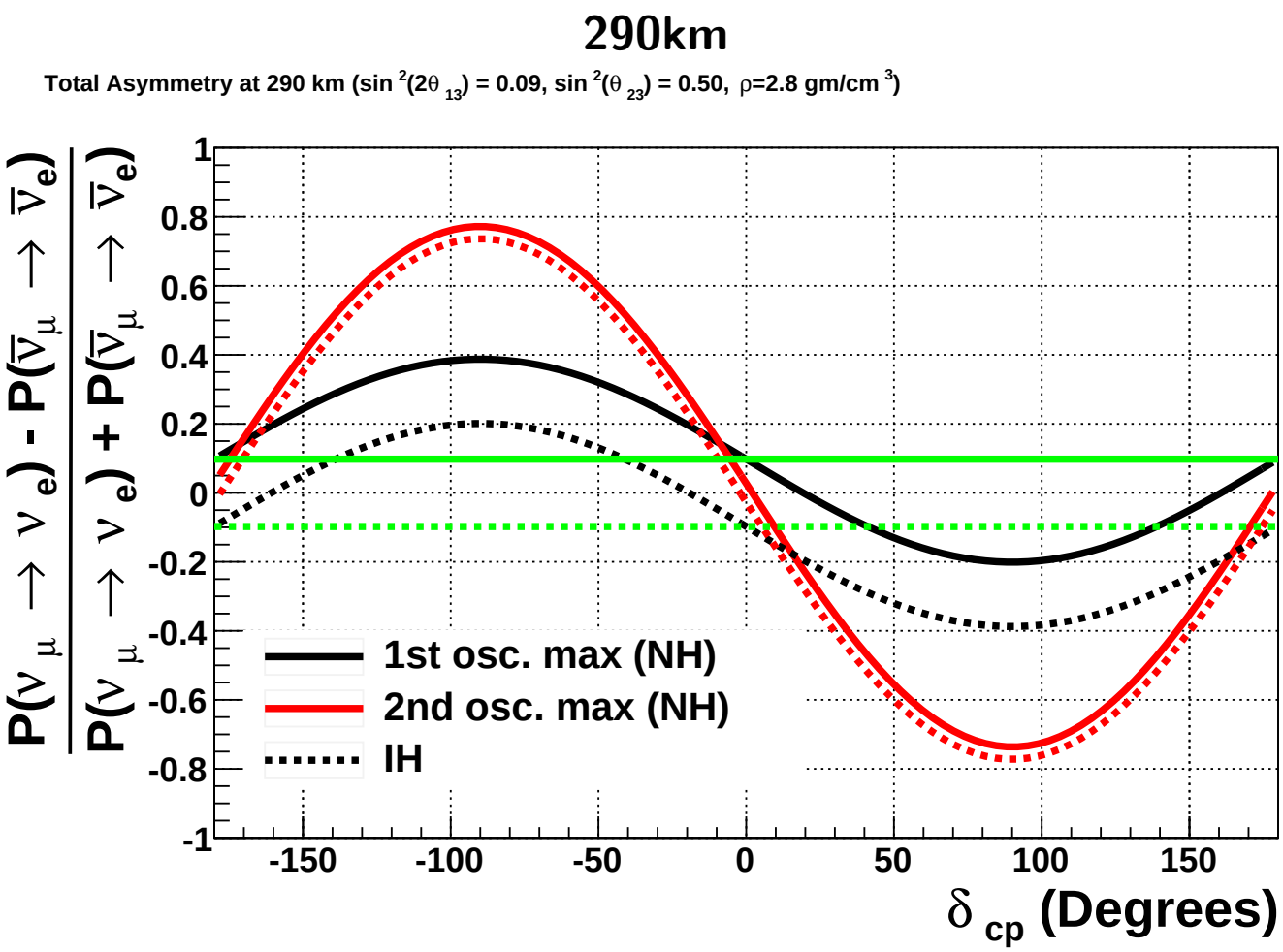
$$\sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{\mathrm{CP}}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$





Matter and CP Asymmetries at Maxima

$\sin^2 2\theta_{13} = 0.09$, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$, $\rho = 2.8\mathrm{gm/cm}^3$



$\mathcal{A}^1_{matter}(\delta_{\mathrm{CP}} = 0) = 0.10$, $\mathcal{A}^1_{CP_{max}}(\rho = 0) = 0.30$

$\mathcal{A}^2_{matter}(\delta_{\mathrm{CP}} = 0) = 0.03$, $\mathcal{A}^2_{CP_{max}}(\rho = 0) = 0.75$

Matter and CP Asymmetries at Maxima

$\sin^2 2\theta_{13} = 0.09$, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$, $\rho = 2.8\mathrm{gm/cm}^3$

Baselines and Oscillations

Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian

Motivation

Oscillation Basics

ν Flux from DIF Beams

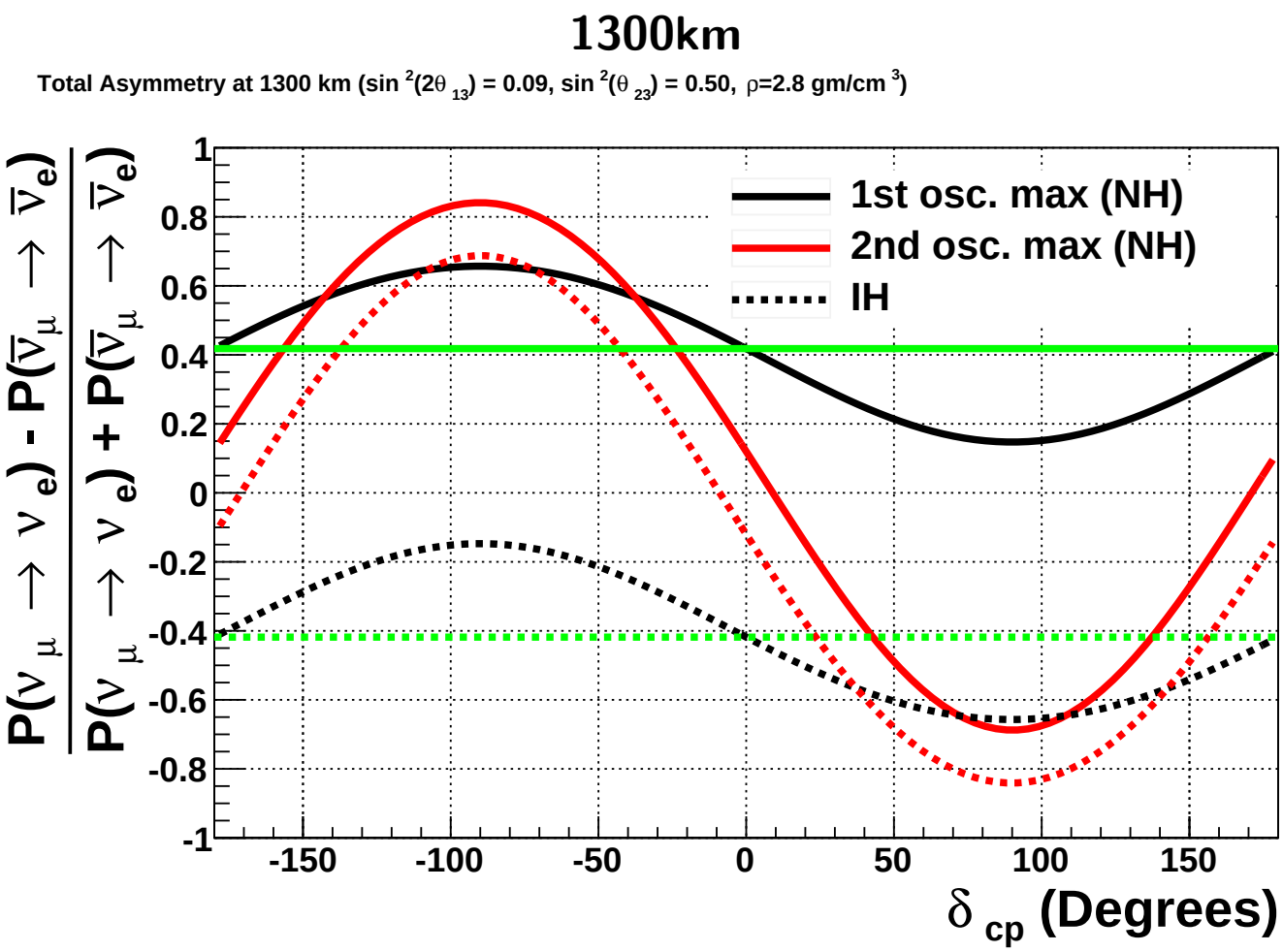
Event Rates

Spectral Information

ν Flux with Focusing

GLoBeS Studies

Summary



$\mathcal{A}^1_{matter}(\delta_{\mathrm{CP}} = 0) = 0.42$, $\mathcal{A}^1_{CP_{max}}(\rho = 0) = 0.30$

$\mathcal{A}^2_{matter}(\delta_{\mathrm{CP}} = 0) = 0.12$, $\mathcal{A}^2_{CP_{max}}(\rho = 0) = 0.75$

Matter and CP Asymmetries at Maxima

$\sin^2 2\theta_{13} = 0.09$, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$, $\rho = 2.8\mathrm{gm/cm}^3$

Baselines and Oscillations

Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian

Motivation

Oscillation Basics

ν Flux from DIF Beams

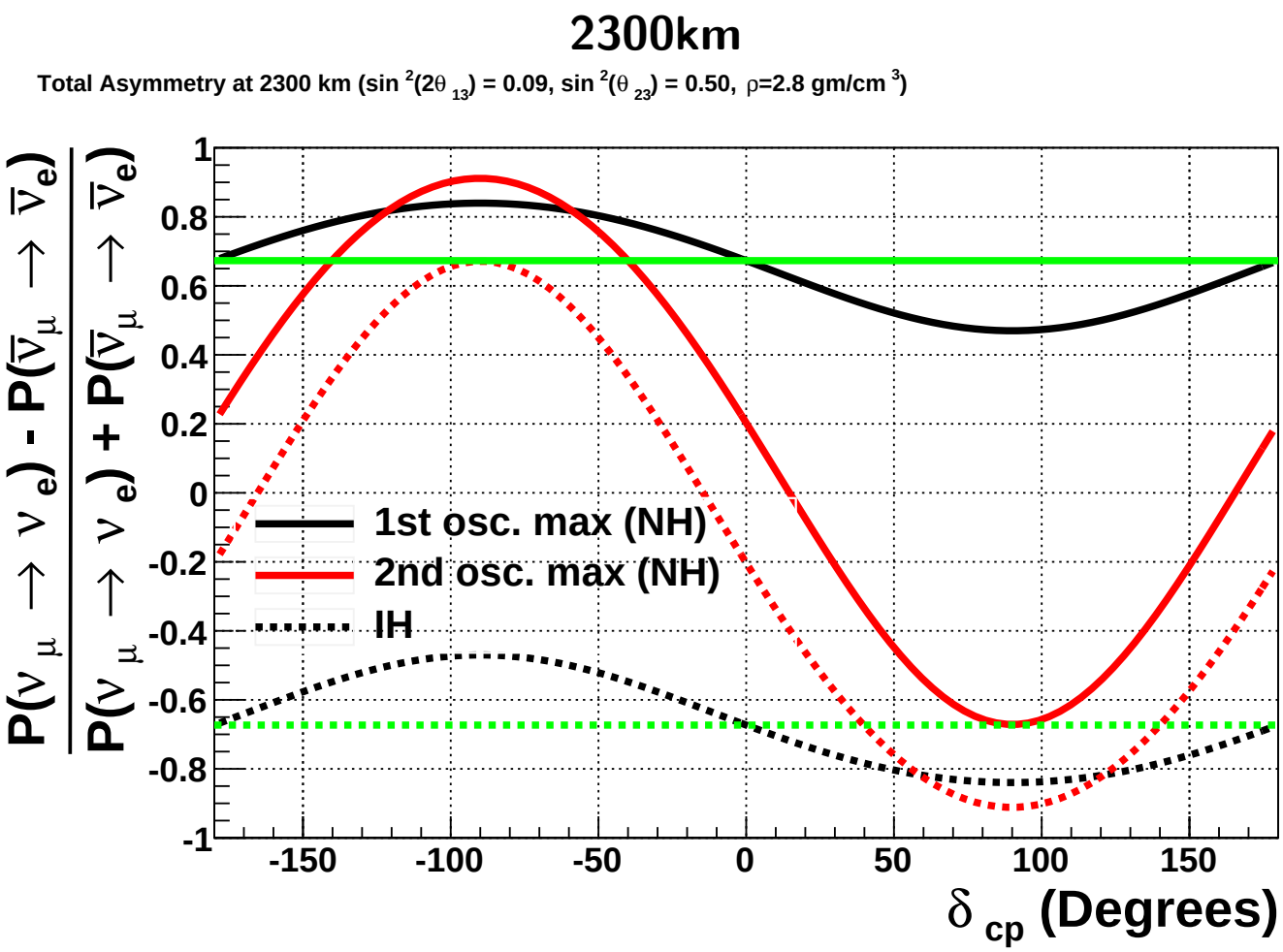
Event Rates

Spectral Information

ν Flux with Focusing

GLoBeS Studies

Summary

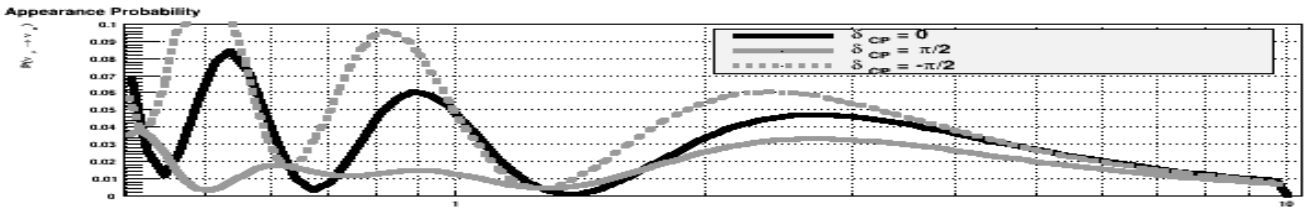


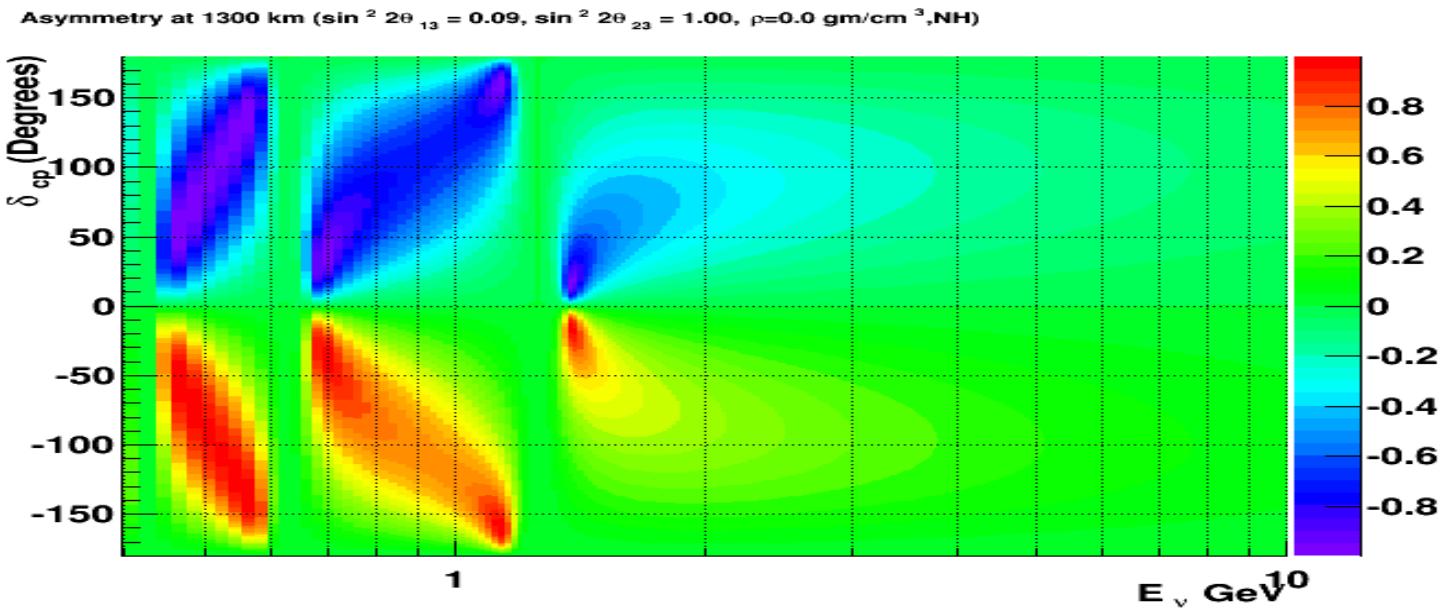
$\mathcal{A}^1_{matter}(\delta_{\mathrm{CP}} = 0) = 0.67$, $\mathcal{A}^1_{CP_{max}}(\rho = 0) = 0.30$

$\mathcal{A}^2_{matter}(\delta_{\mathrm{CP}} = 0) = 0.20$, $\mathcal{A}^2_{CP_{max}}(\rho = 0) = 0.75$

CP Asymmetry vs E_ν and δ_{cp}

Vacuum, NH



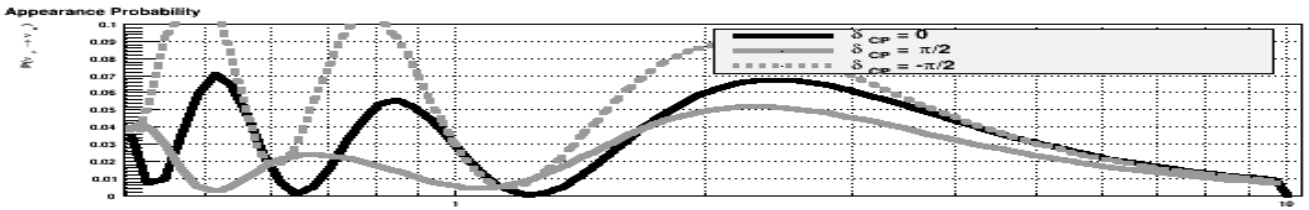


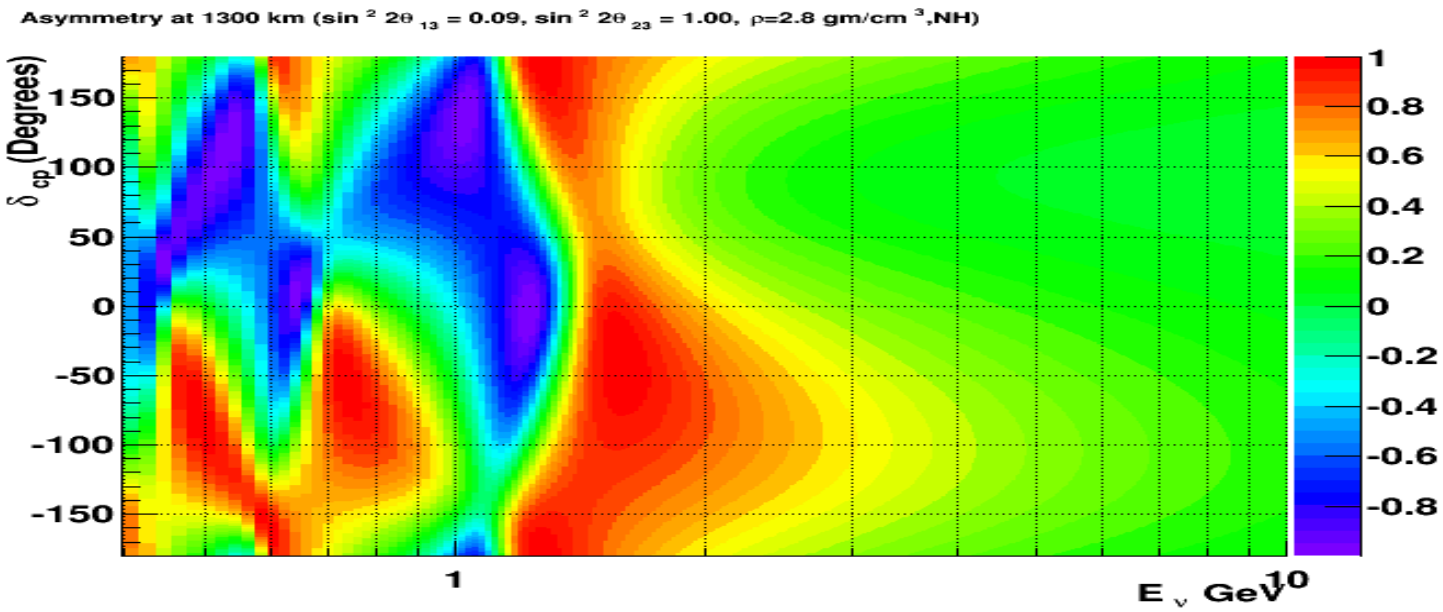
$\mathcal{A}$

Asymmetries are larger near minima. BUT, events appear at the maxima.

CP Asymmetry vs E_ν and δ_{cp}

At 1300km, NH



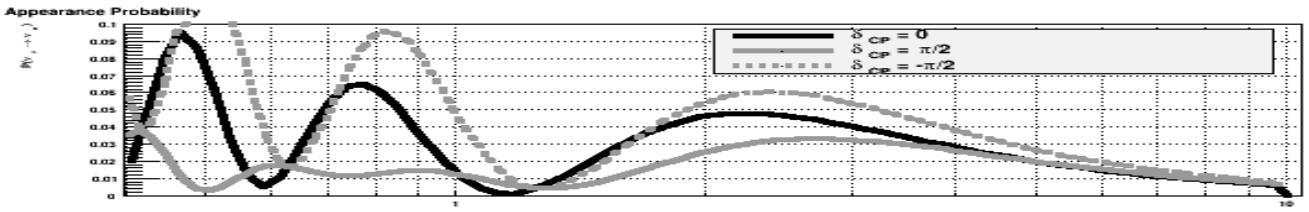


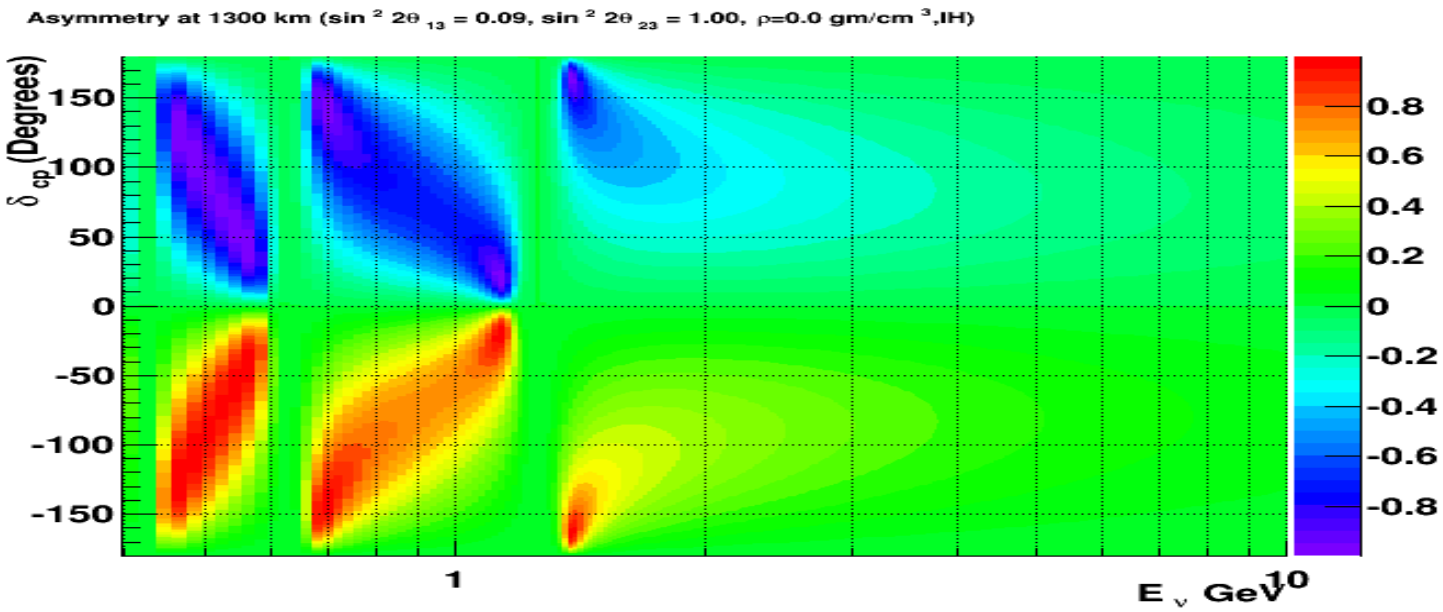
$\mathcal{A}$

Asymmetries are larger near minima. BUT, events appear at the maxima.

CP Asymmetry vs E_ν and δ_{cp}

Vacuum, IH



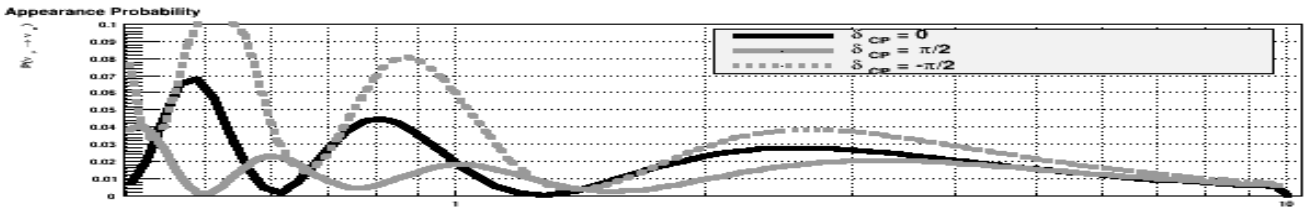


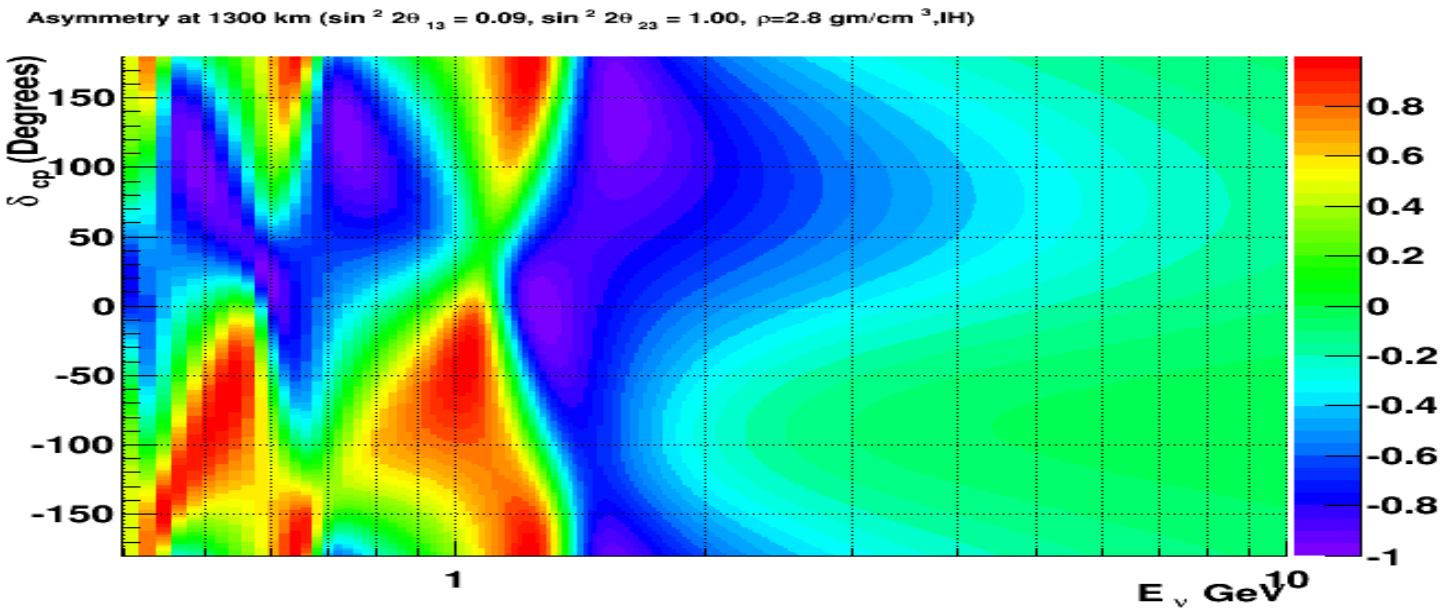
$\mathcal{A}$

Asymmetries are larger near minima. BUT, events appear at the maxima.

CP Asymmetry vs E_ν and δ_{cp}

At 1300km, IH





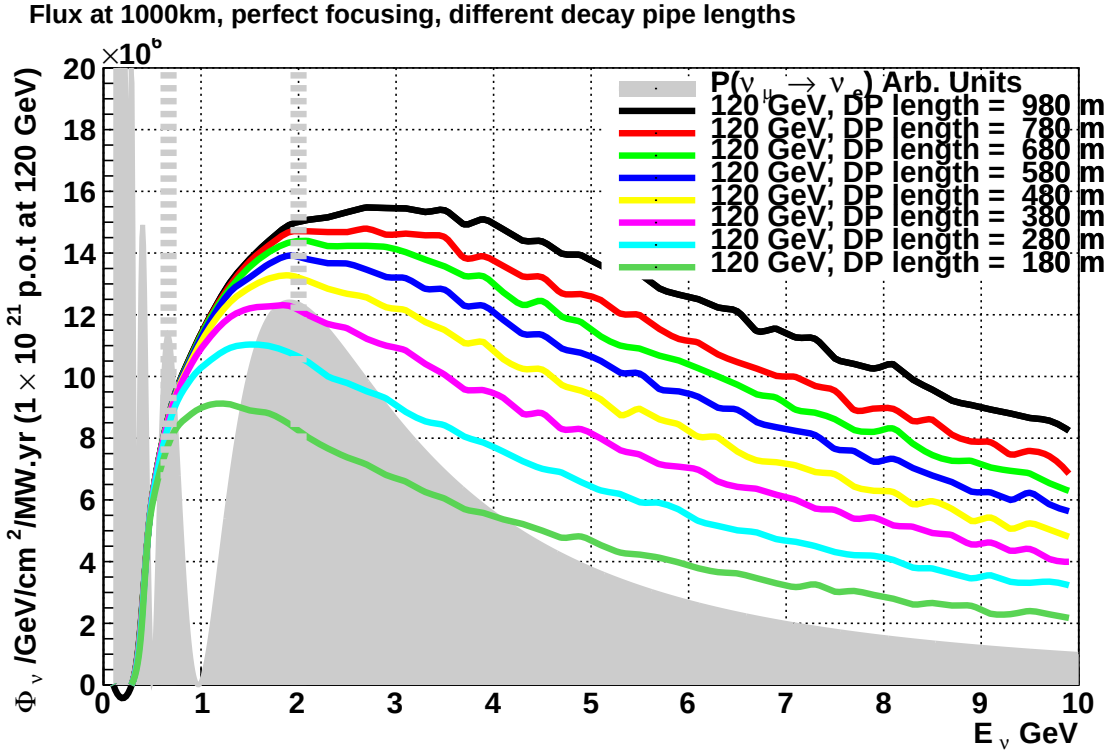
$\mathcal{A}$

Asymmetries are larger near minima. BUT, events appear at the maxima.

Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams, thin graphite target, and assuming perfect focusing and charge selection:

E_{proton} = 120 GeV, decay channel lengths from 200m to 1km

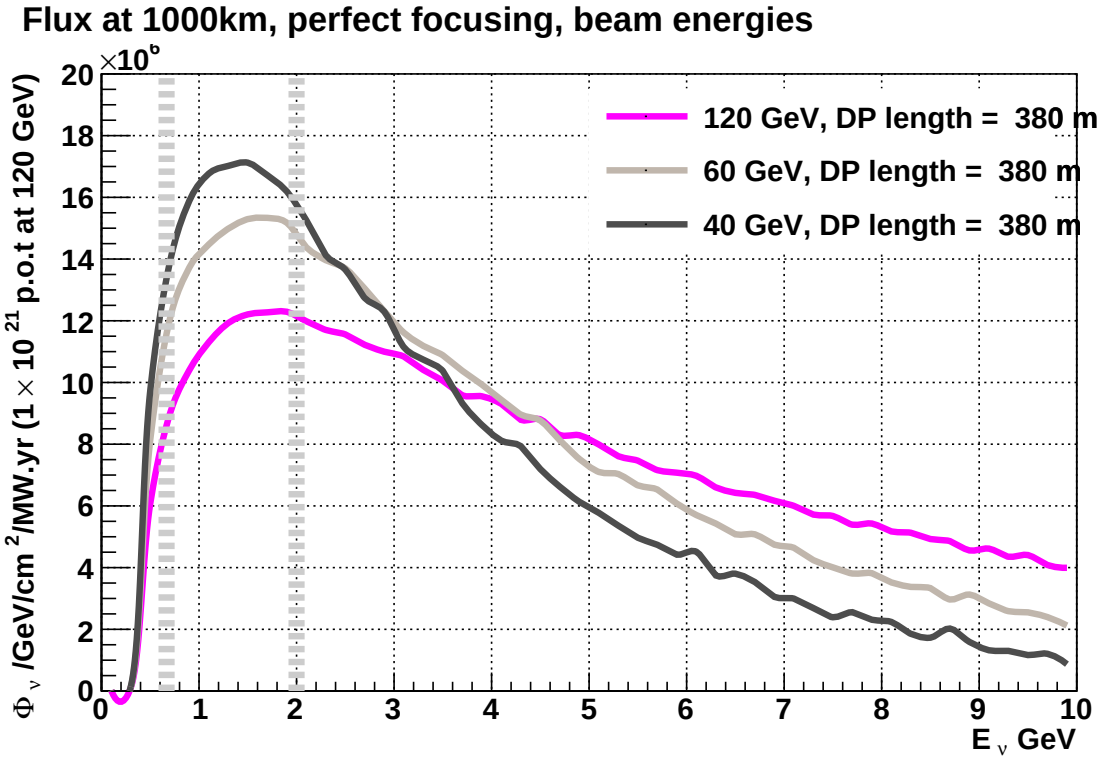


High energy pion decay in flight beams (on-axis) are well matched to baselines 700-3000 km

Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams, thin graphite target, and assuming perfect focusing and charge selection:

E_{proton} = 40 *to* 120 GeV, decay channel length $\sim$ 400m

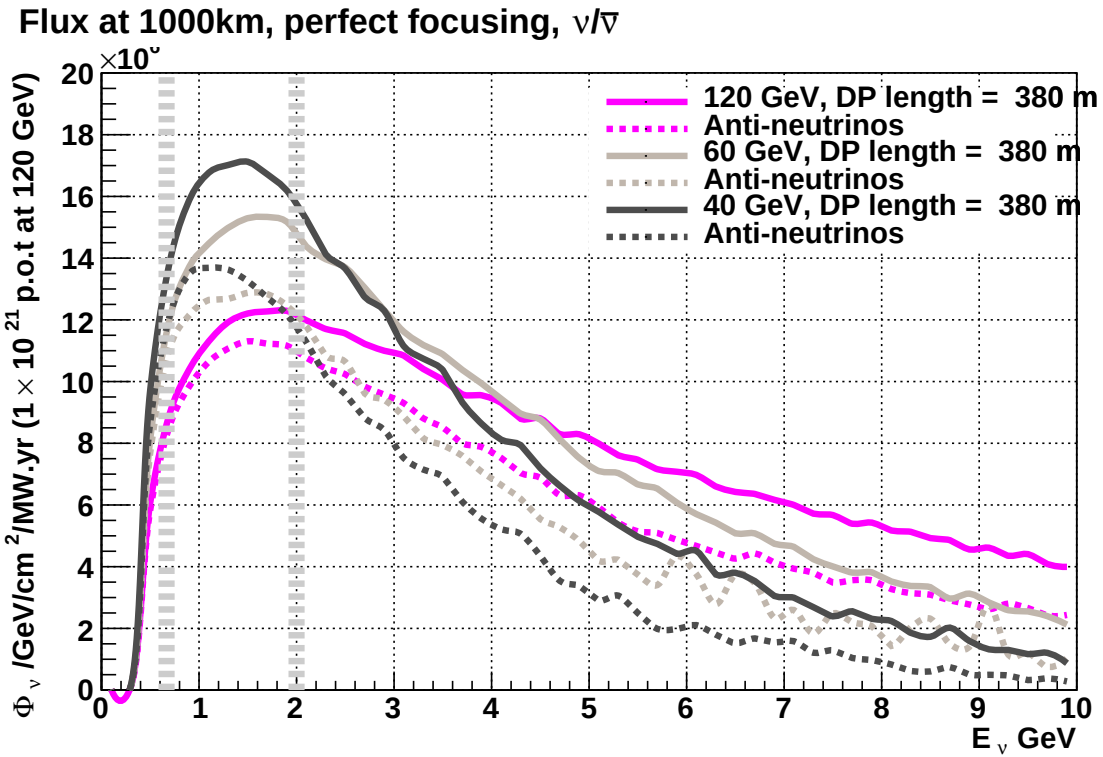


High energy pion decay in flight beams (on-axis) are well matched to baselines 700-3000 km

Neutrino fluxes with perfect focusing

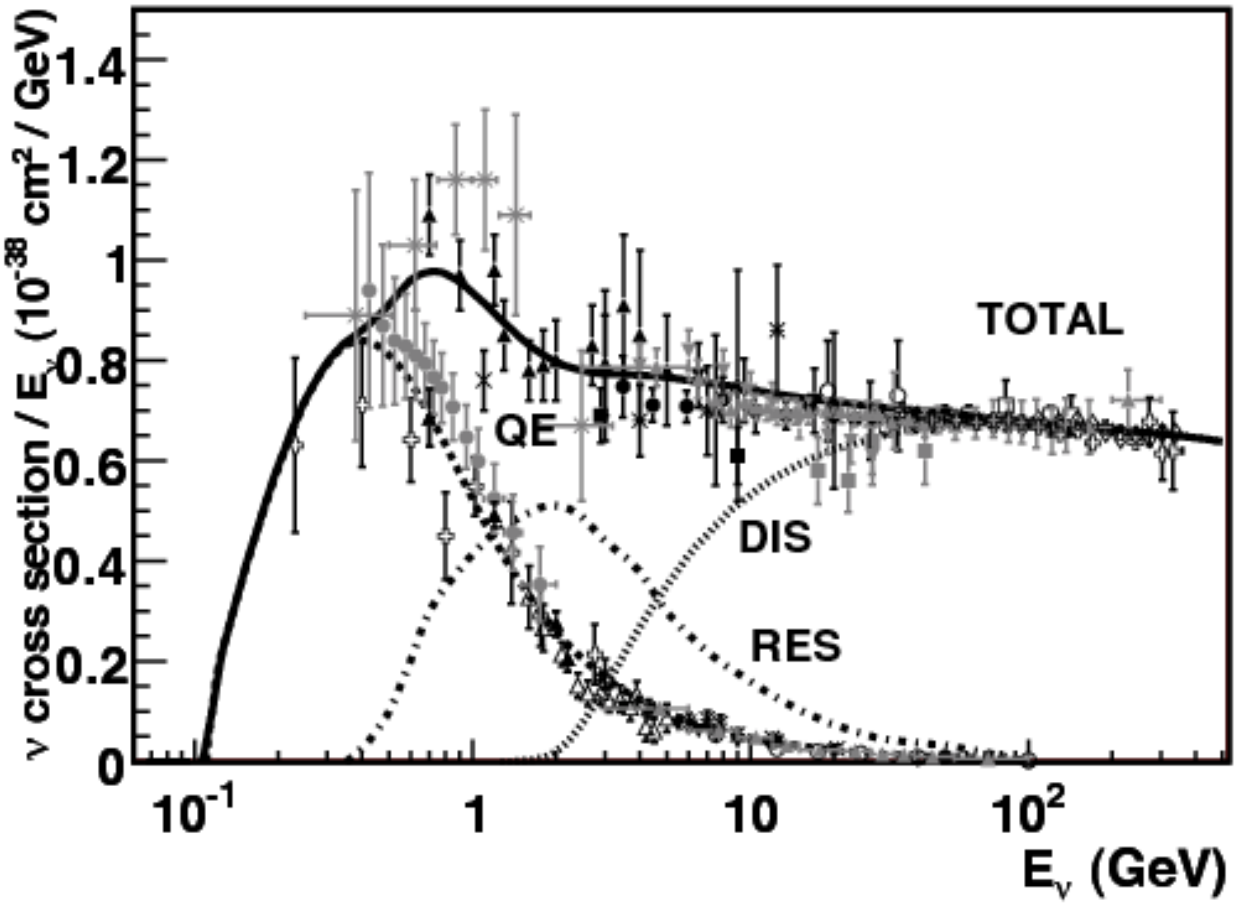
ν_μ fluxes from pion decay-in-flight (DIF) beams, thin graphite target, and assuming perfect focusing and charge selection:

Neutrino vs anti-neutrino fluxes



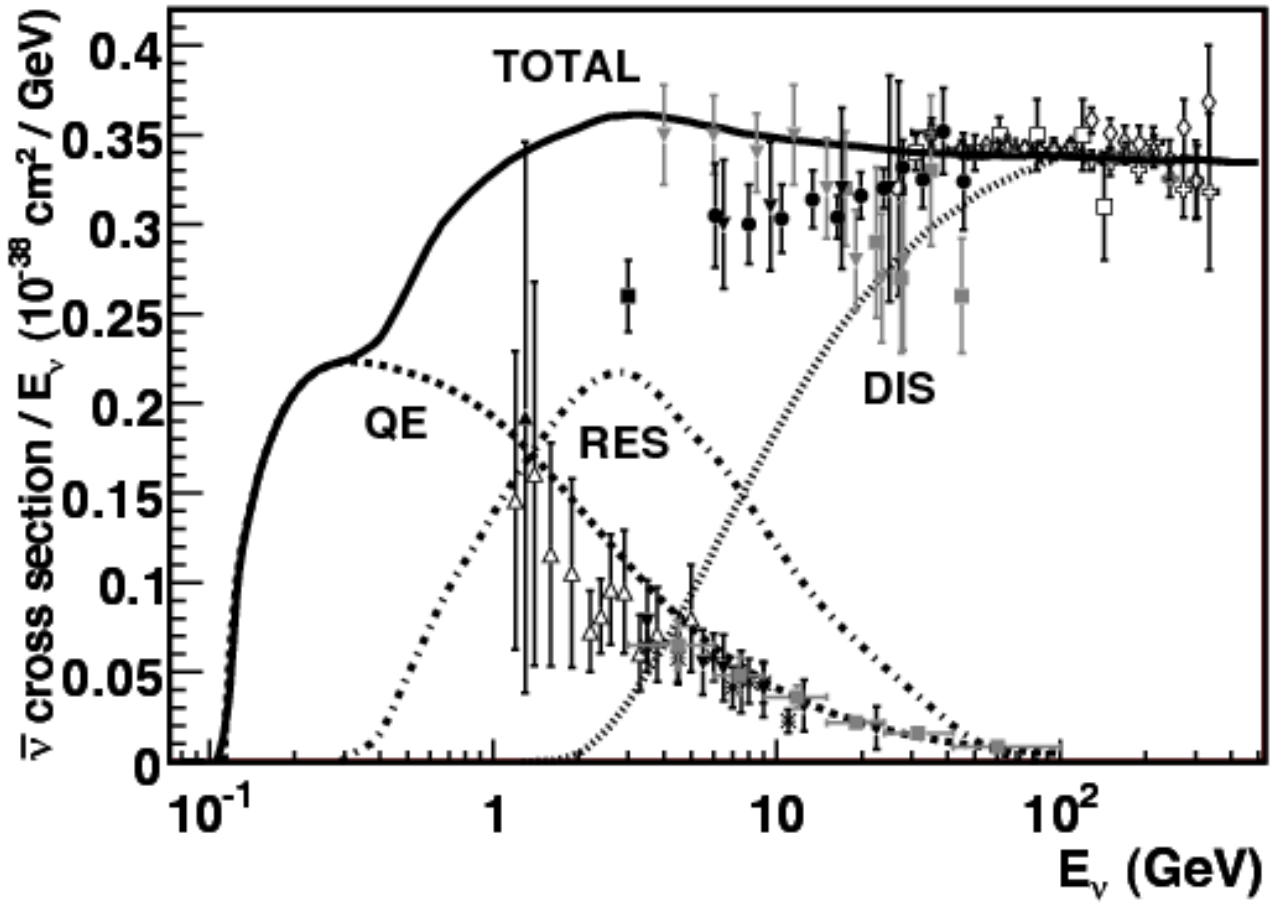
High energy pion decay in flight beams (on-axis) are well matched to baselines 700-3000 km

Neutrino Cross Sections



$$\sigma^{\nu}(E_{\nu}) \sim 0.75 \times 10^{-42}(\mathrm{m}^2/\mathrm{GeV}/N) \times E_{\nu}, \quad E_{\nu} > 1\ \mathrm{GeV}$$

Neutrino Cross Sections



$$\sigma^{\bar{\nu}}(E_\nu) \sim 0.34 \times 10^{-42}(\mathrm{m}^2/\mathrm{GeV}/N) \times E_\nu, \quad E_\nu > 1\ \mathrm{GeV}$$

Expected Appearance Signal Event Rates

The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N_{\nu_e}^{\text{appear}}(L) = N_{\text{target}} \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino beam source produces a wide coverage that is flat in energy in the oscillation region and approximate the probability with the dominant term (no matter effect)

$$\begin{aligned}
\Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV}//\text{MW/yr at 1 km} \\
P^{\nu_\mu \to \nu_e}(E_\nu, L) &\approx \underbrace{\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{31}^2 L/E_\nu)}_{P_0} \\
\sigma^{\nu_e}(E_\nu) &= 0.7 \times 10^{-42}(\text{m}^2/\text{GeV}/N) \times E_\nu, \quad E_\nu > 1 \text{ GeV} \\
N_{\text{target}} &= 6.022 \times 10^{32} N/\text{kt}
\end{aligned}$$

Assuming constant flux: $C \approx 1.2 \times 10^{17}\ \nu_\mu/\text{m}^2/\text{GeV}/(\text{MW/yr})$ at 1 km:

$$N_{\nu_e}^{\text{appear}}(L) \approx (2 \times 10^6 \text{events}/(\text{kt/MW/yr}))(\text{km/GeV})^2 \times \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \ a \equiv 1.27\Delta m_{31}^2.$$

For $x_0 = 100$ km/GeV and $x_1 = 2000$ km/GeV (1st and 2nd oscillation maxima)

$$N_{\nu_e}^{\text{appear}}(L) \sim \mathcal{O}(20) \text{ events}/(\text{kt/MW/yr})$$

independent of baseline !

Event Rates vs. Baseline

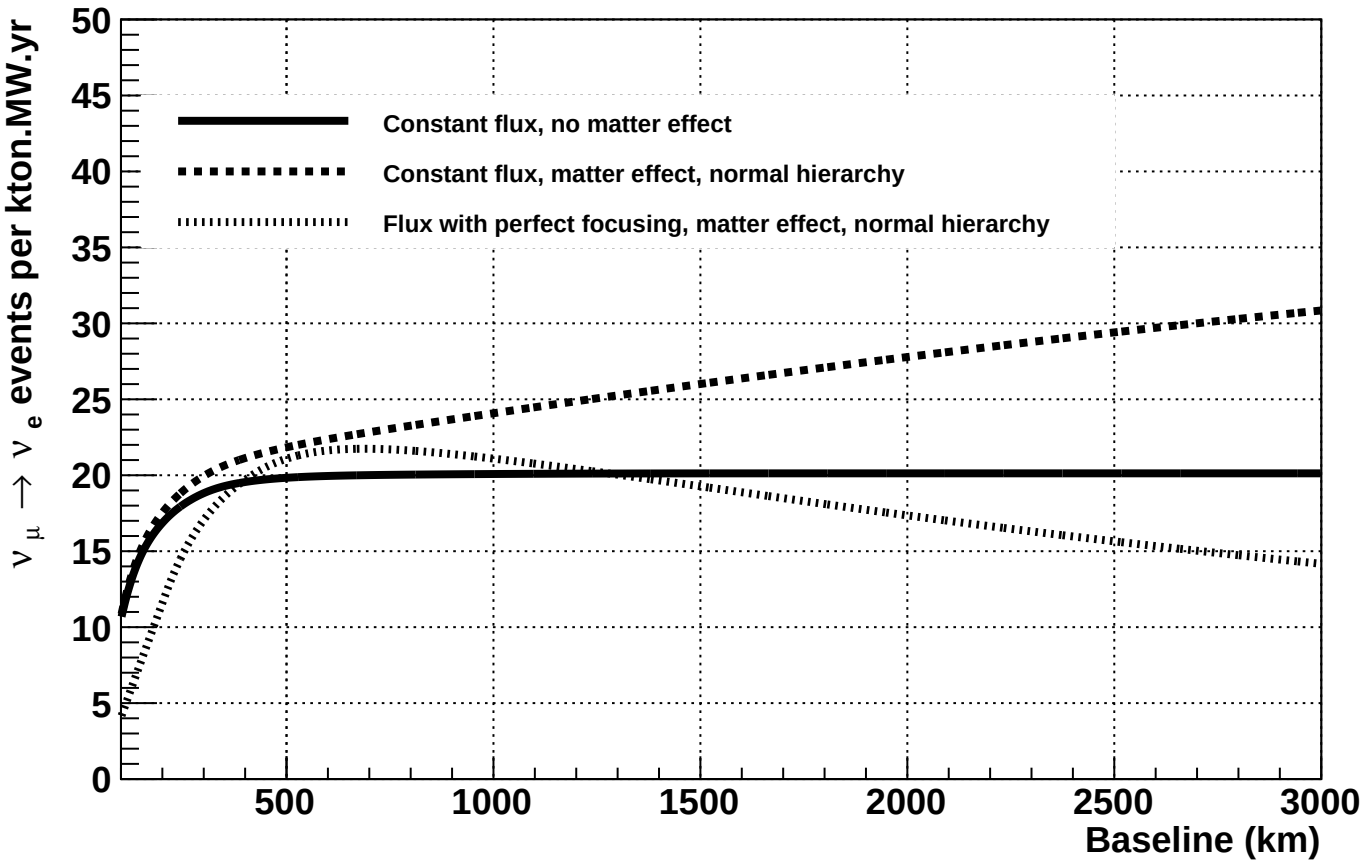
$$\mathcal{R} = \int \Phi^{\nu_\mu}_{\text{perfect}}(E_\nu) \times \sigma(E_\nu) \times P(\nu_\mu \to \nu_e)\, dE_\nu$$

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

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

Normal Hierarchy

Appearance rates versus baseline



Event Rates vs. Baseline

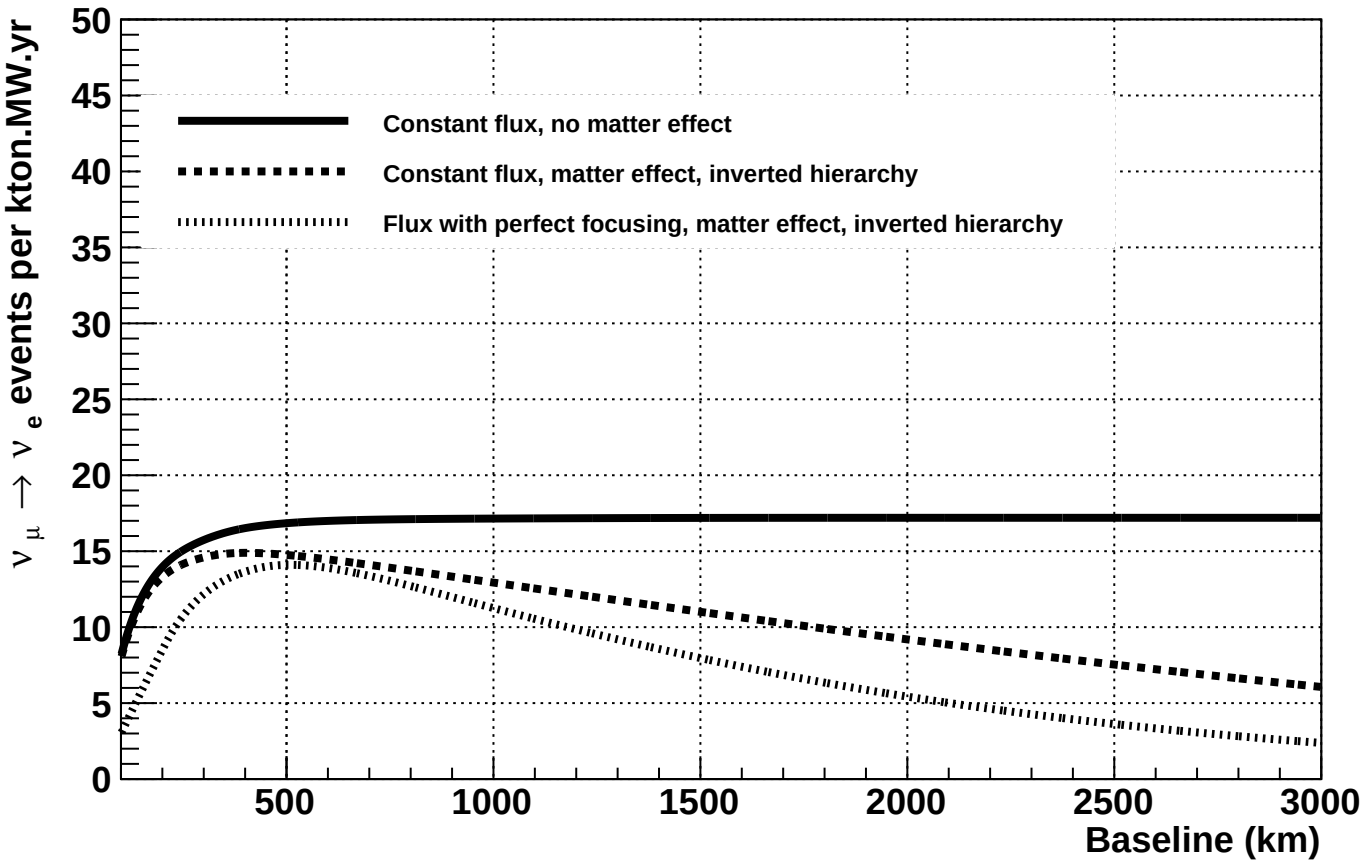
$$\mathcal{R} = \int \Phi^{\nu_\mu}_{\text{perfect}}(E_\nu) \times \sigma(E_\nu) \times P(\nu_\mu \to \nu_e)\, dE_\nu$$

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

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

Inverted Hierarchy

Appearance rates versus baseline

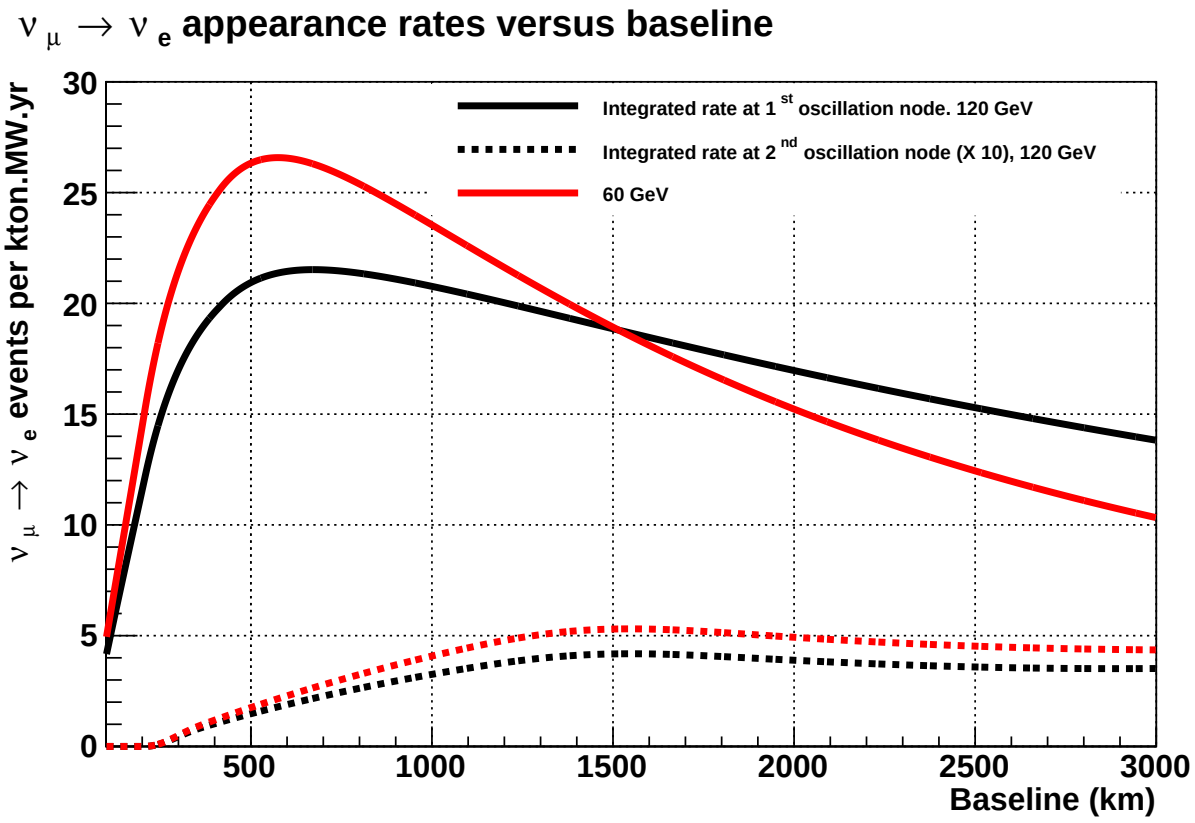


Event Rates vs. Baseline at 1st and 2nd Osc. Nodes with Perfect Focusing.

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

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

Normal Hierarchy



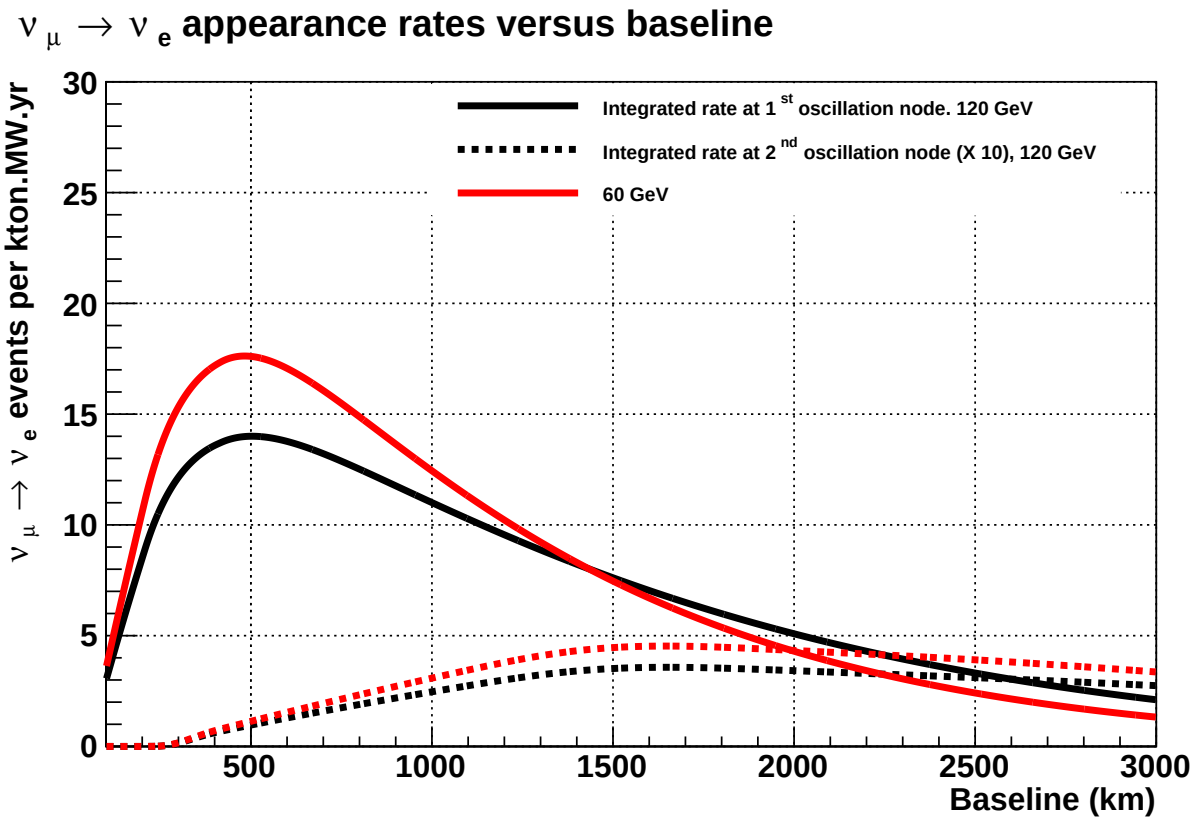
Event rates at 1st maximum drop for baselines $>$ 500 km. Approx. constant at the 2nd maximum at baselines $\geq$ 1500 km.

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

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

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

Inverted Hierarchy



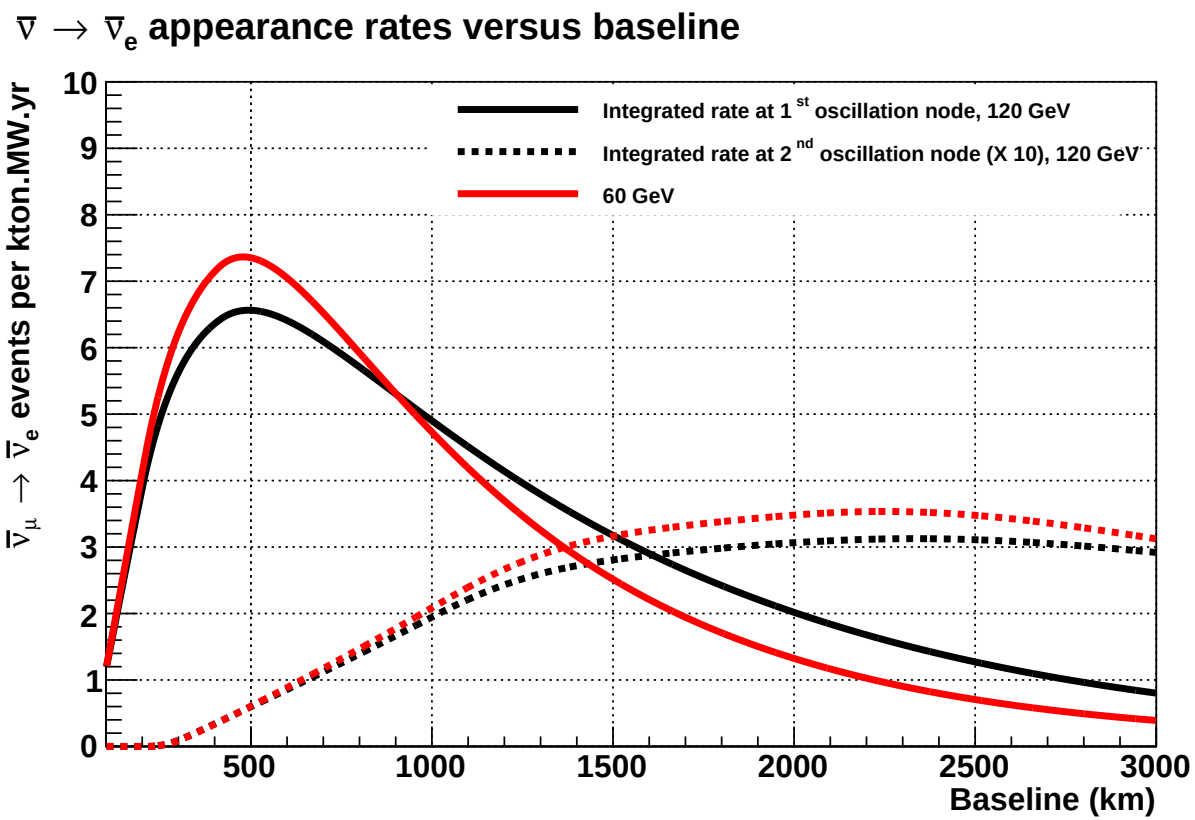
Event rates at 1st maximum drop for baselines $>$ 500 km. Approx. constant at the 2nd maximum at baselines $\geq$ 1500 km.

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

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

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

Normal Hierarchy



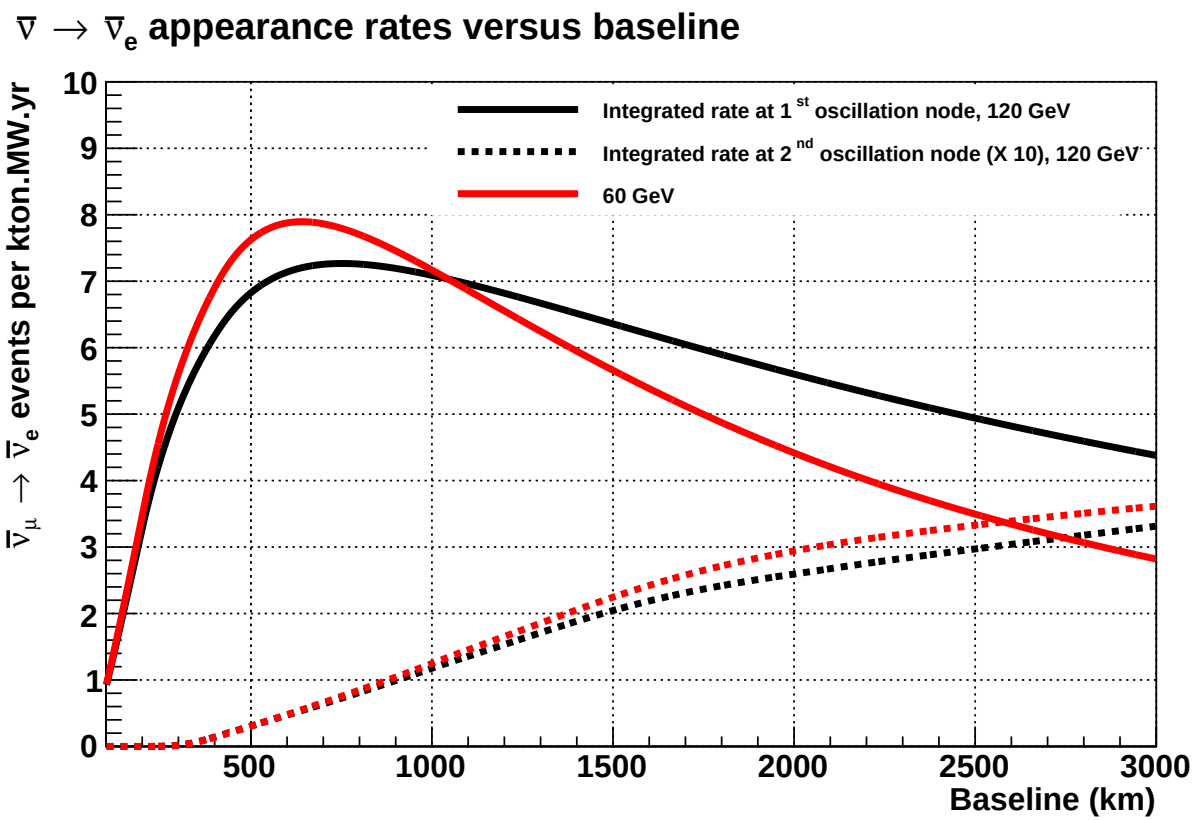
Event rates at 1st maximum drop for baselines $>$ 500 km. Approx. constant at the 2nd maximum at baselines $\geq$ 1500 km.

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

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

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

Inverted Hierarchy

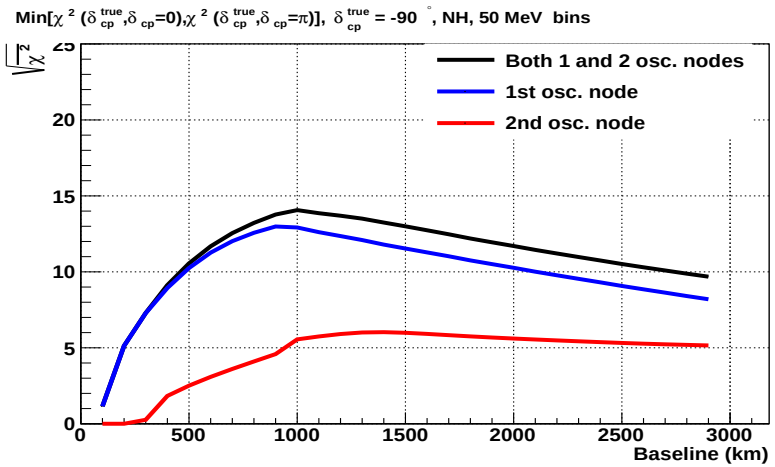


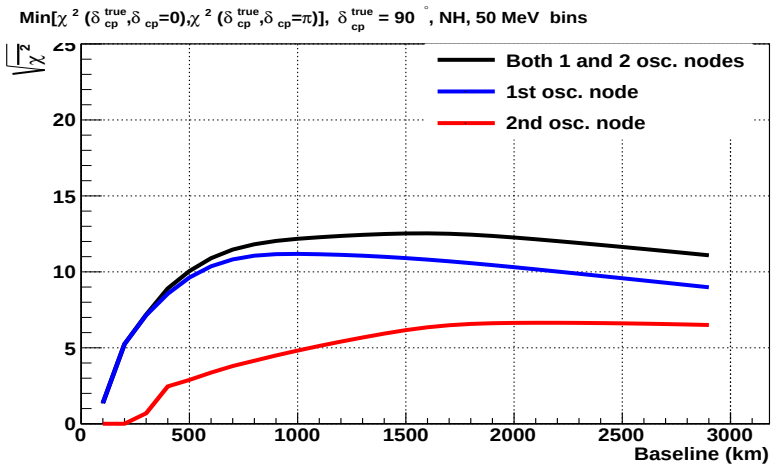
Event rates at 1st maximum drop for baselines $>$ 500 km. Approx. constant at the 2nd maximum at baselines $\geq$ 1500 km.

Spectral Differences (Poisson formula) Xin Qian 100 kT.MW.yr 50 MeV bins

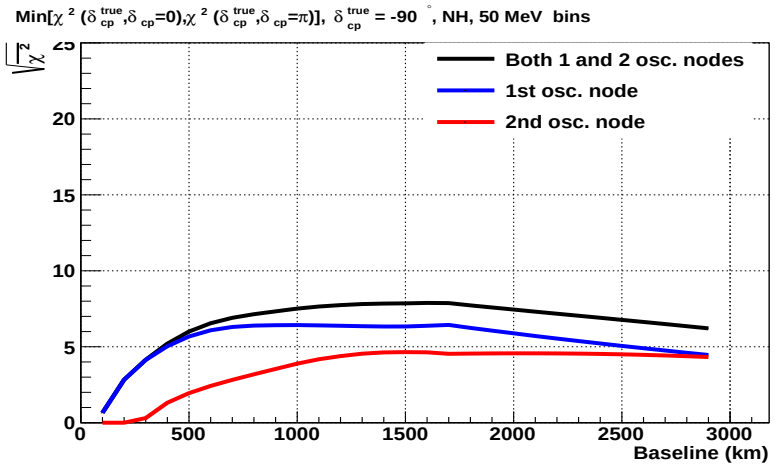
$$\chi^2 = \sum_i^{nbins} 2\left[R^i(\delta_{cp}=0,\pi) - R^i(\delta_{cp}^{true}) + R^i(\delta_{cp}^{true}) * \log\frac{R^i(\delta_{cp}^{true})}{R^i(\delta_{cp}=0,\pi)}\right]$$

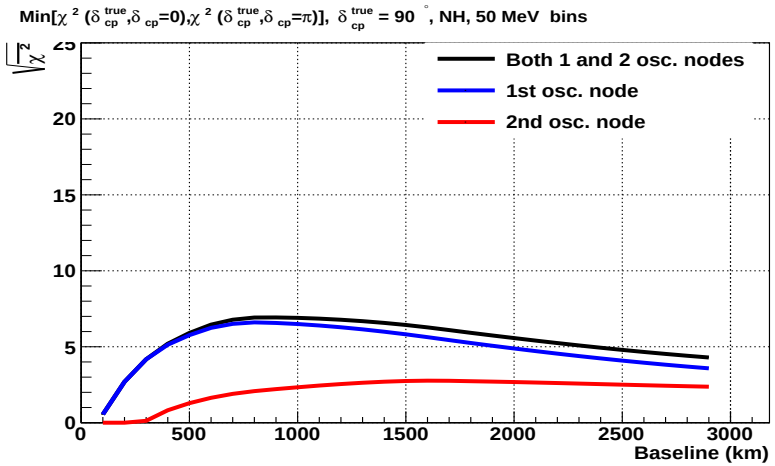
$\delta_{cp}^{true} = -\pi/2$ **Normal Hierarchy, $\nu_\mu \to \nu_e$** $\delta_{cp}^{true} = \pi/2$





Normal Hierarchy, $\bar{\nu}_\mu \to \bar{\nu}_e$

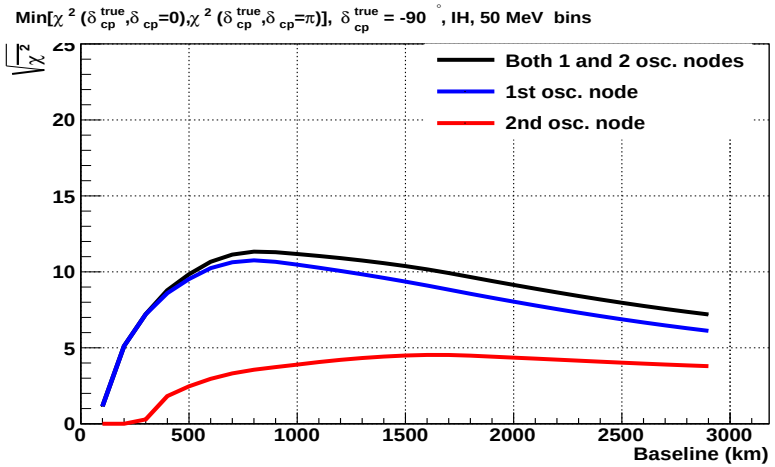


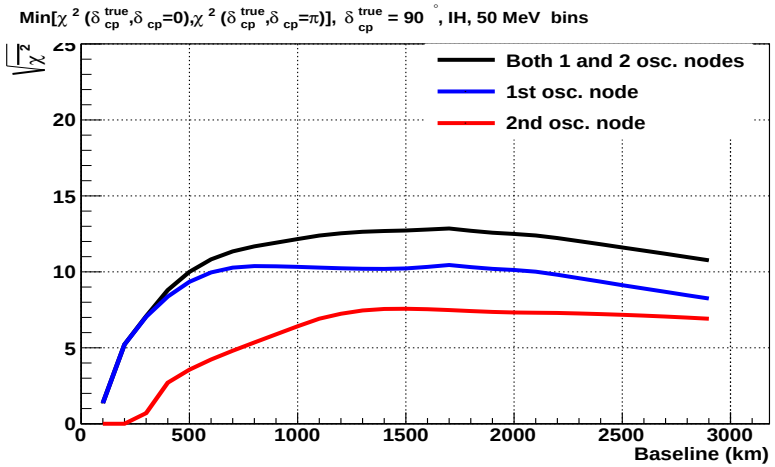


Spectral Differences (Poisson formula) Xin Qian 100 kT.MW.yr 50 MeV bins

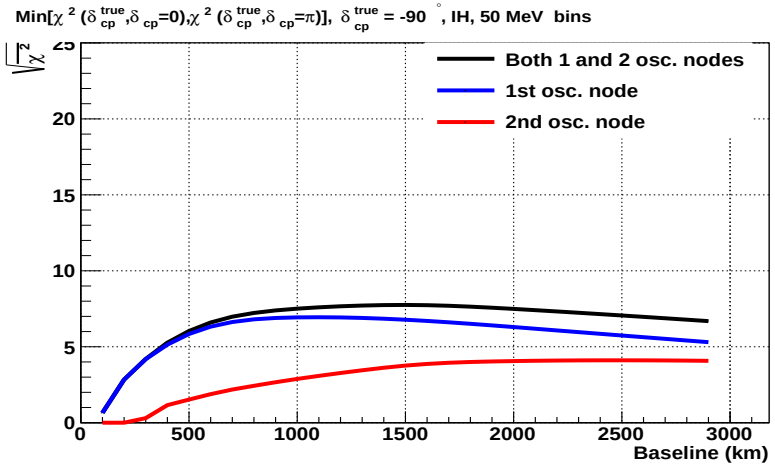
$$\chi^2 = \sum_i^{nbins} 2\left[R^i(\delta_{cp}=0,\pi) - R^i(\delta_{cp}^{true}) + R^i(\delta_{cp}^{true}) * \log\frac{R^i(\delta_{cp}^{true})}{R^i(\delta_{cp}=0,\pi)}\right]$$

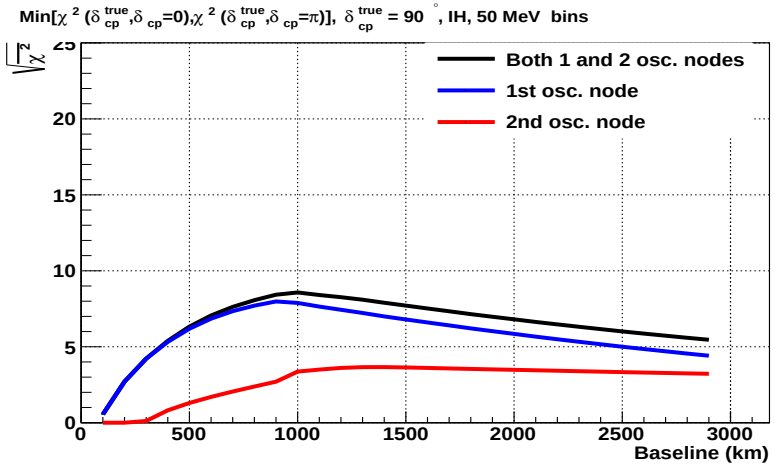
$\delta_{cp}^{true} = -\pi/2$ **Inverted Hierarchy, $\nu_\mu \to \nu_e$** $\delta_{cp}^{true} = \pi/2$



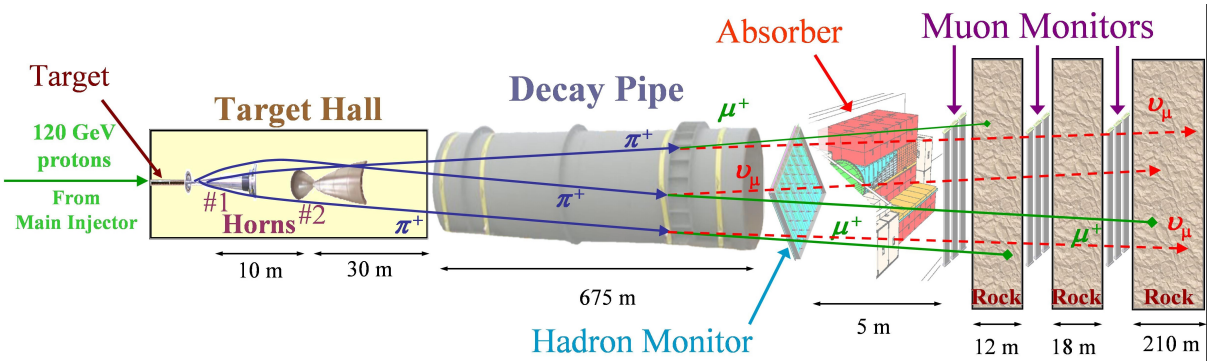


Inverted Hierarchy, $\bar{\nu}_\mu \to \bar{\nu}_e$

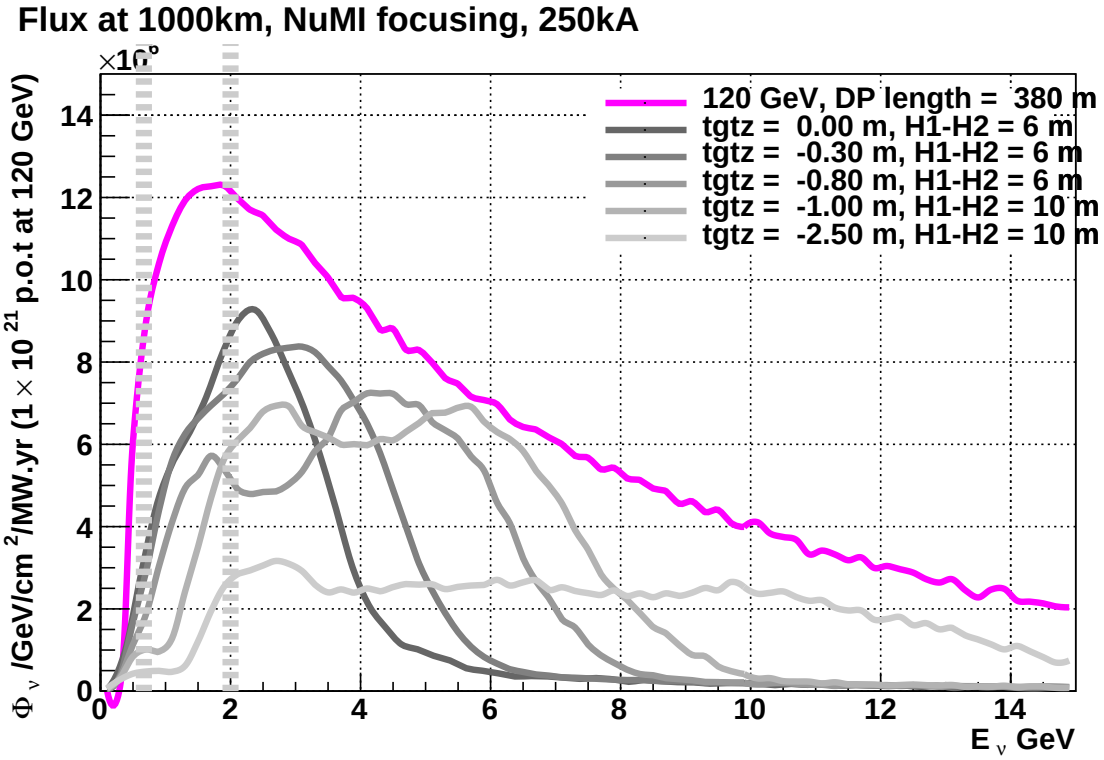




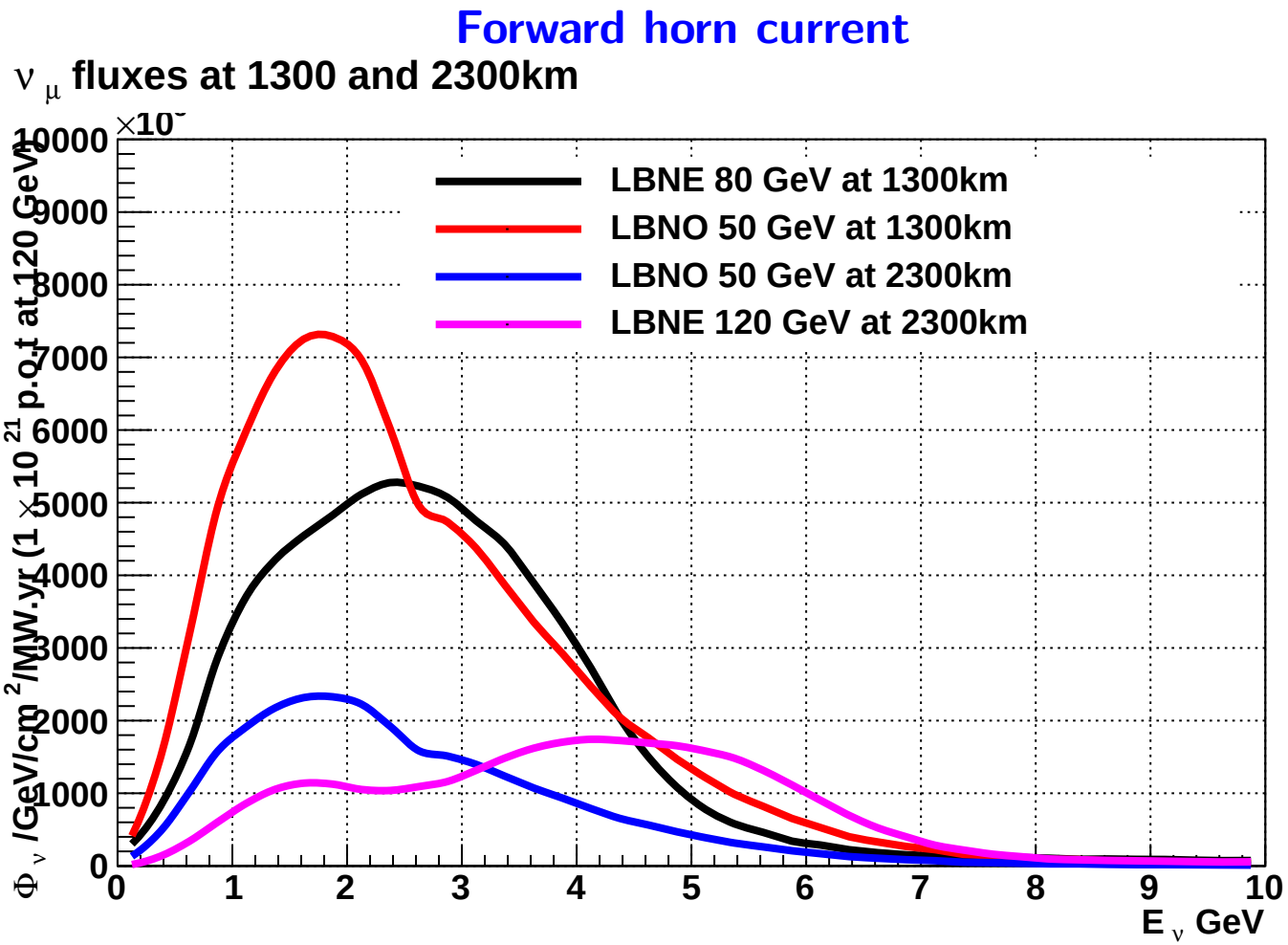
Variable NuMI Focusing



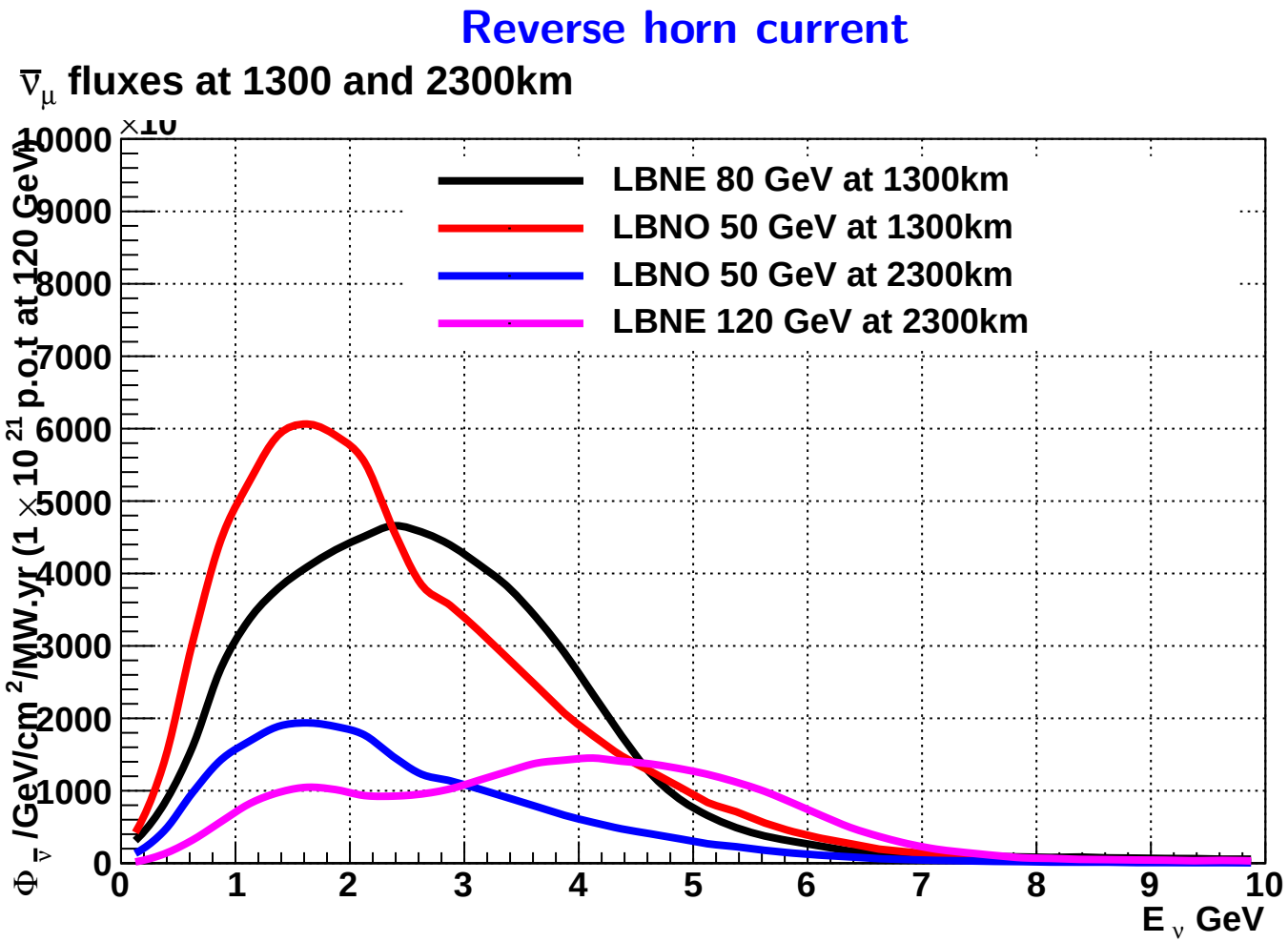
With a decay pipe 380m long, 4m in diamater:



LBNE/LBNO fluxes



LBNE/LBNO fluxes



$\nu_\mu/\bar{\nu}_\mu$ Survival Spectra Using GLoBeS

1300km 2500km

Baselines and Oscillations

Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian

Motivation

Oscillation Basics

ν Flux from DIF Beams

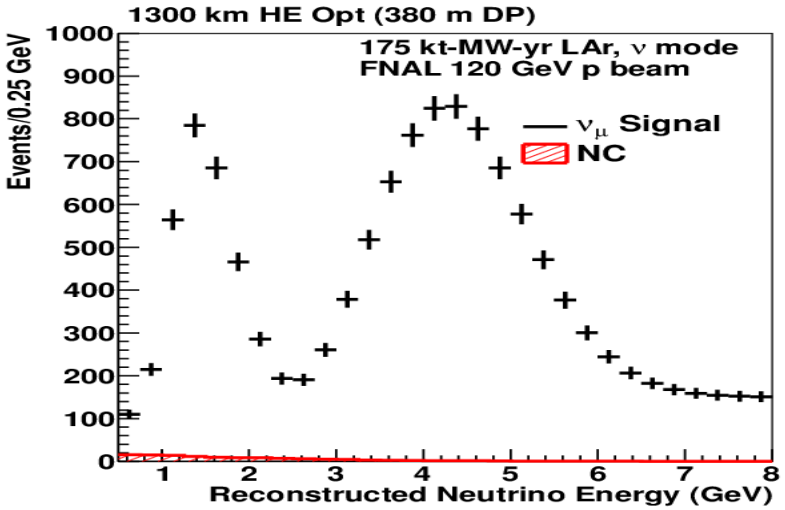
Event Rates

Spectral Information

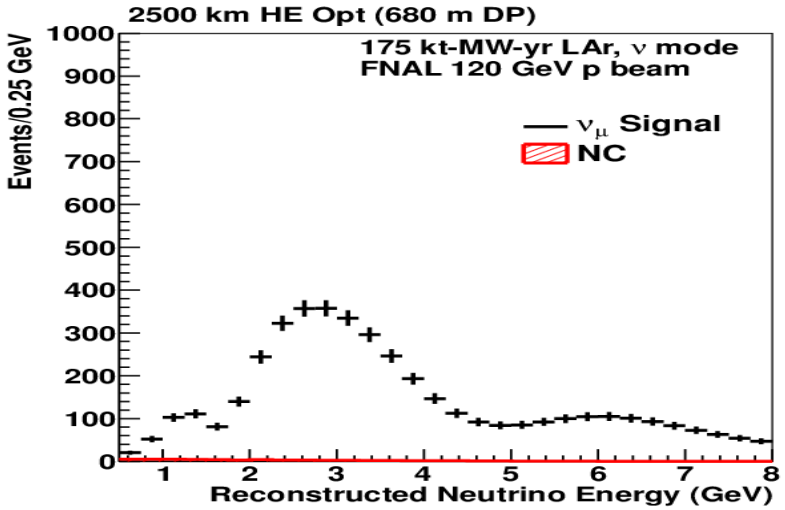
ν Flux with Focusing

GLoBeS Studies

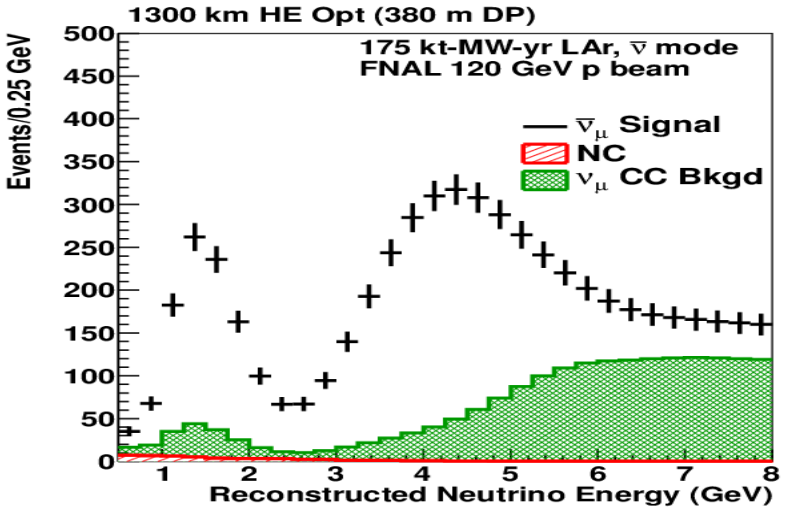
Summary



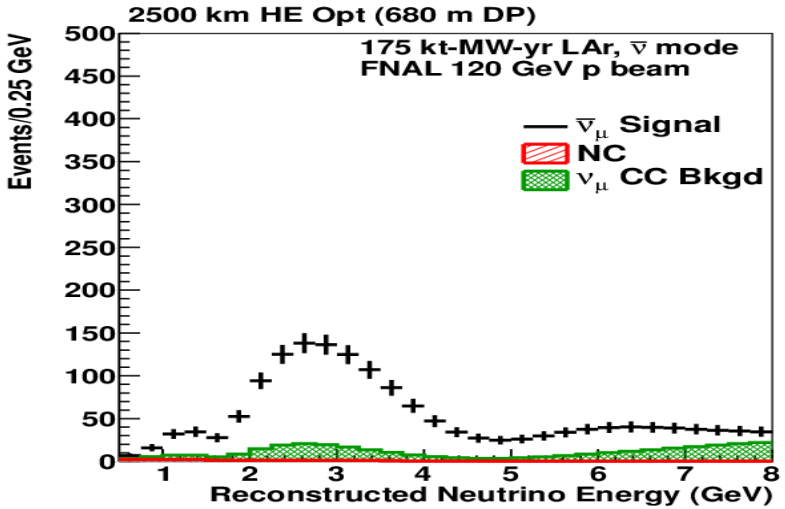
ν_μ Sig: 13268, Bkg: 127



Sig: 4504, Bkg: 60



$\bar{\nu}_\mu$ Sig: 3998, Bkg: 54+2720



Sig: 1346, Bkg: 14+508q

$\nu_e/\bar{\nu}_e$ Appearance Spectra Using GLoBeS (NH)

1300km 2500km

Baselines and Oscillations

Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian

Motivation

Oscillation Basics

ν Flux from DIF Beams

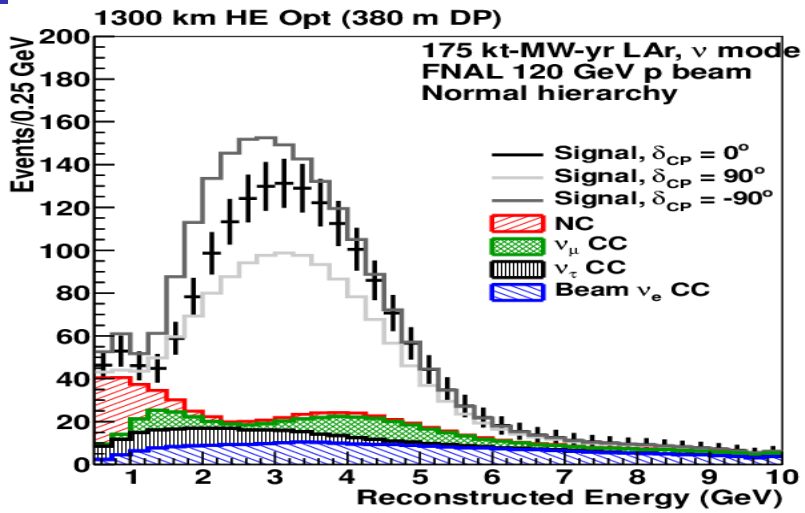
Event Rates

Spectral Information

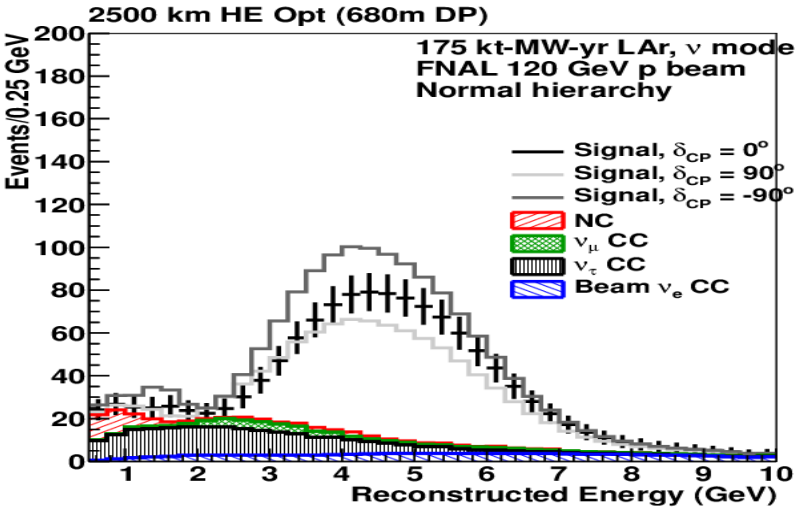
ν Flux with Focusing

GLoBeS Studies

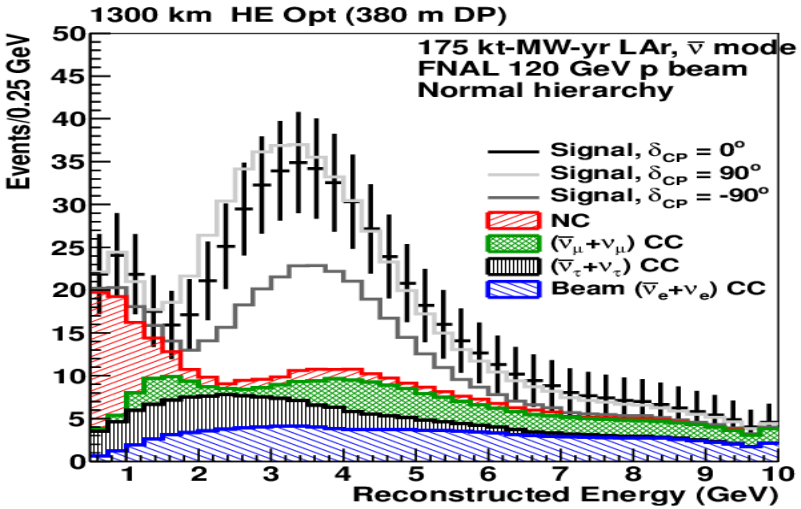
Summary



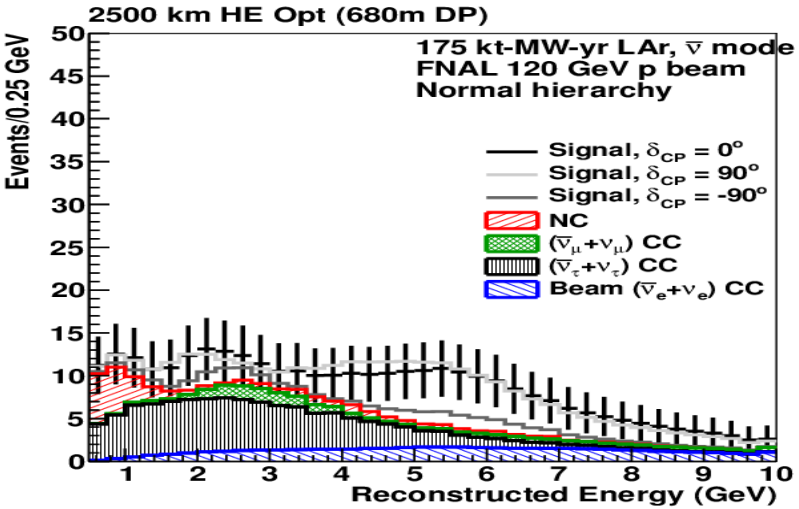
ν_e Sig: 1240 , Bkg: 116+156+110+269= 651



Sig: 877 , Bkg: 55+53+199+113= 420



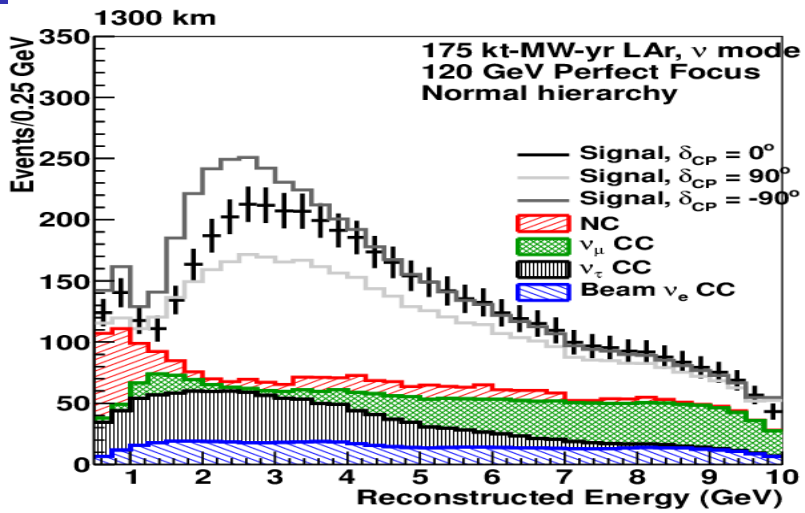
$\bar{\nu}_e$ Sig: 316 , Bkg: 65+79+64+115= 323



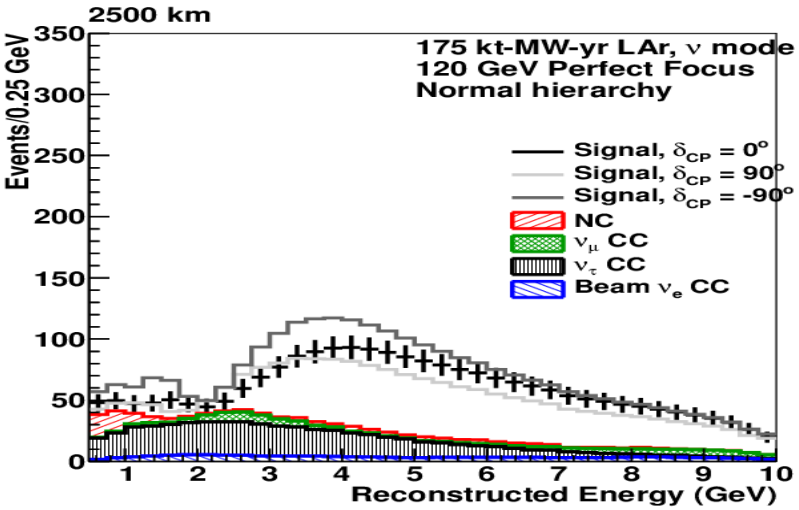
Sig: 128 , Bkg: 28+22+100+47= 197

$\nu_e/\bar{\nu}_e$ Appearance Spectra Using GLoBeS (NH)

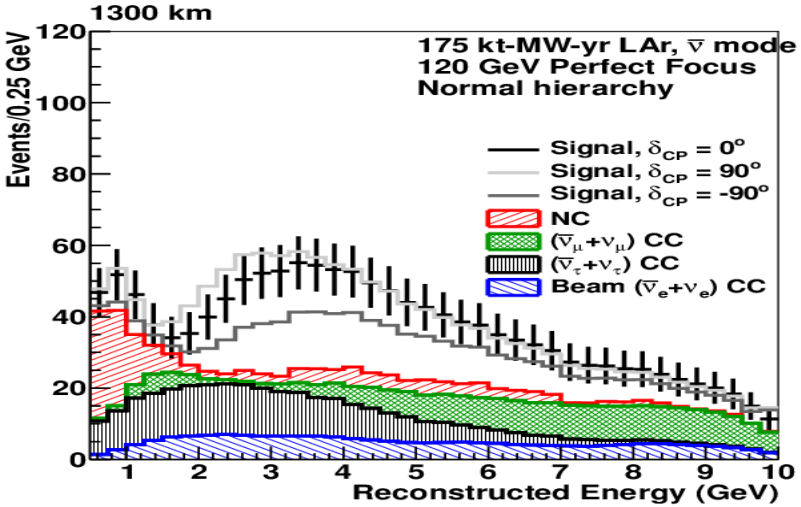
1300km 2500km



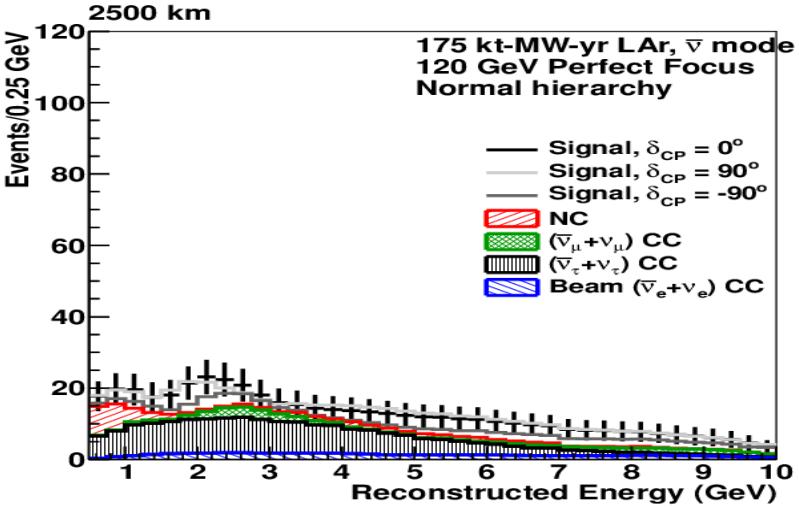
ν_e Sig: **2617**, Bkg: 404+780+735+551= **2470**



Sig: **1378**, Bkg: 109+131+501+140= **881**



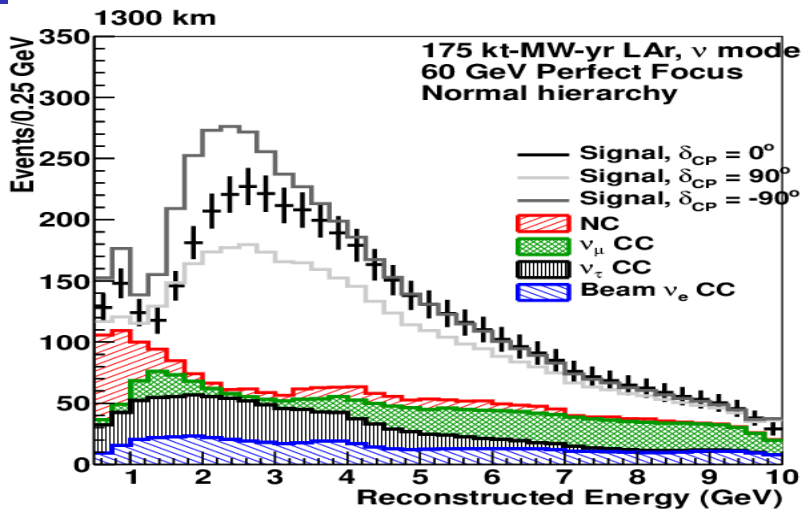
$\bar{\nu}_e$ Sig: **569**, Bkg: 162+237+253+181= **833**



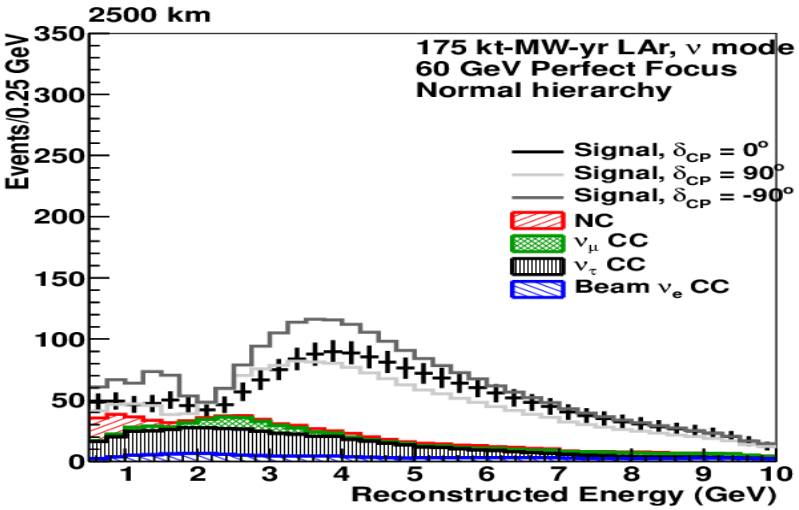
Sig: **164**, Bkg: 44+40+181+49= **314**

$\nu_e/\bar{\nu}_e$ Appearance Spectra Using GLoBeS (NH)

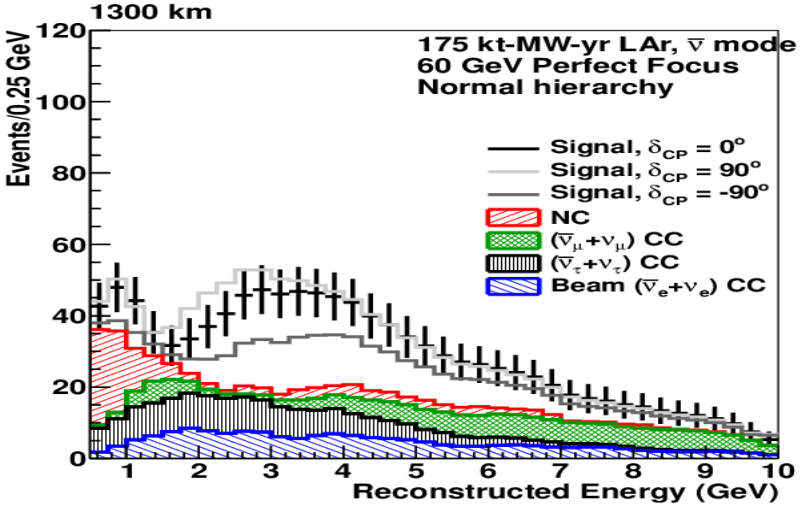
1300km 2500km



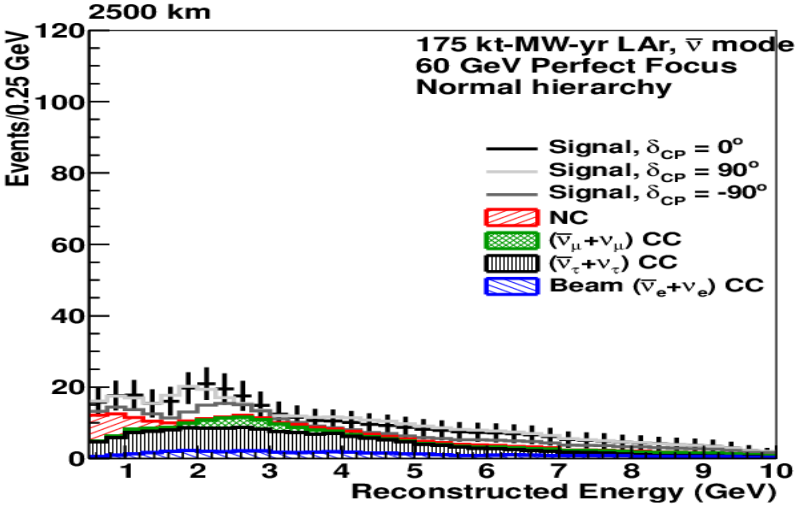
ν_e Sig: 2593 , Bkg: 347+637+569+546= 2099



Sig: 1233 , Bkg: 94+120+376+140= 730



$\bar{\nu}_e$ Sig: 569 , Bkg: 162+237+253+181= 833



Sig: 164 , Bkg: 44+40+181+49= 314

$\nu_e/\bar{\nu}_e$ Appearance Spectra Using GLoBeS (NH)

1300km 2500km

Baselines and Oscillations

Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian

Motivation

Oscillation Basics

ν Flux from DIF Beams

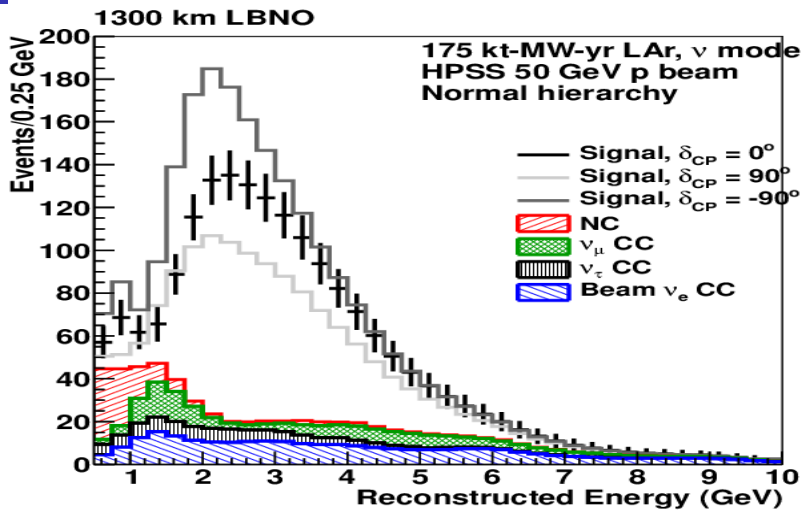
Event Rates

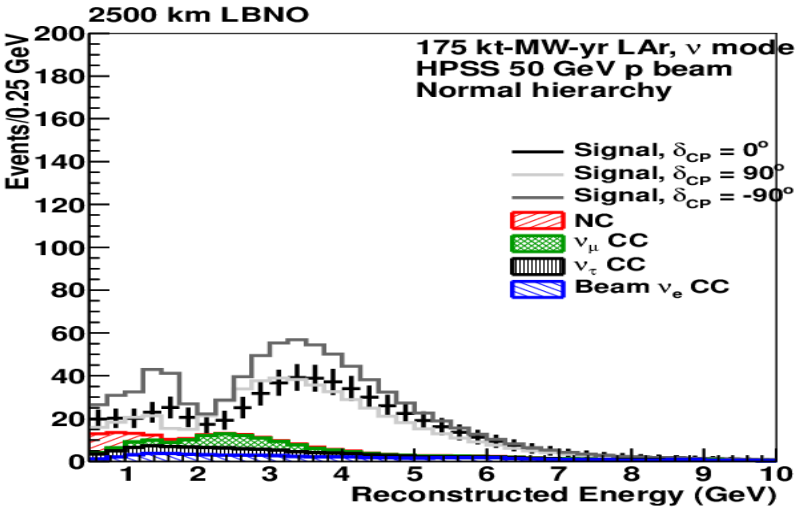
Spectral Information

ν Flux with Focusing

GLoBeS Studies

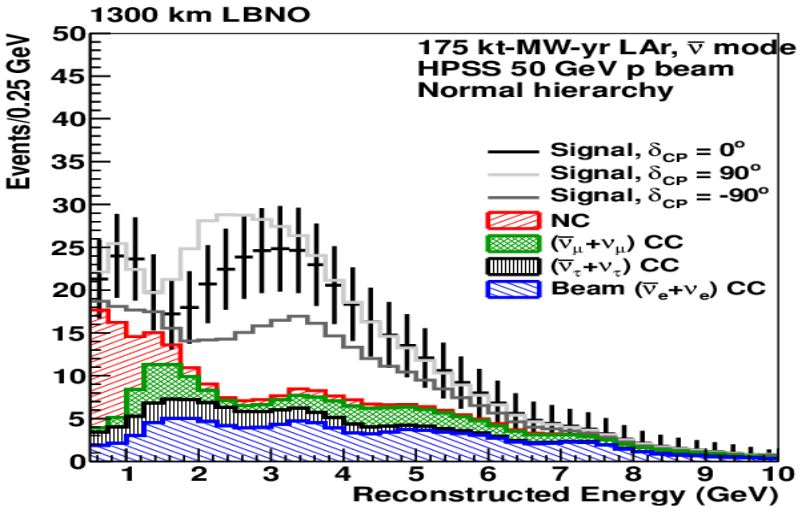
Summary

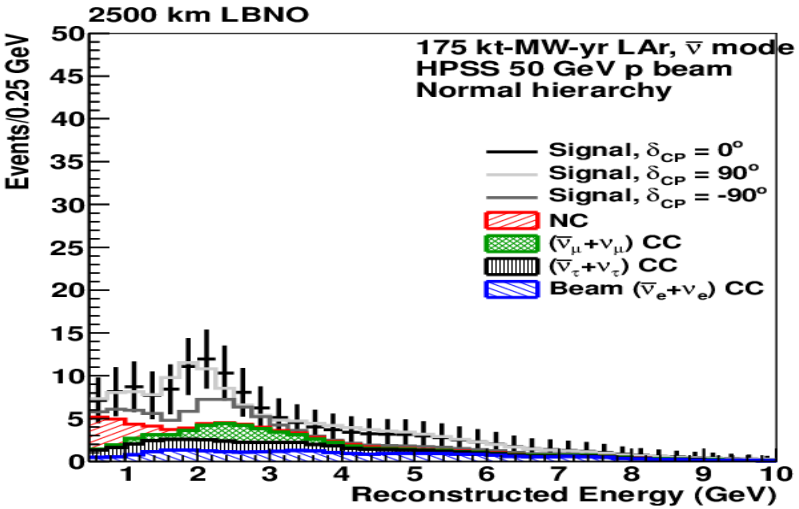




ν_e Sig: **1223**, Bkg: 110+161+89+261= **621**

Sig: **401**, Bkg: 30+52+49+67= **198**



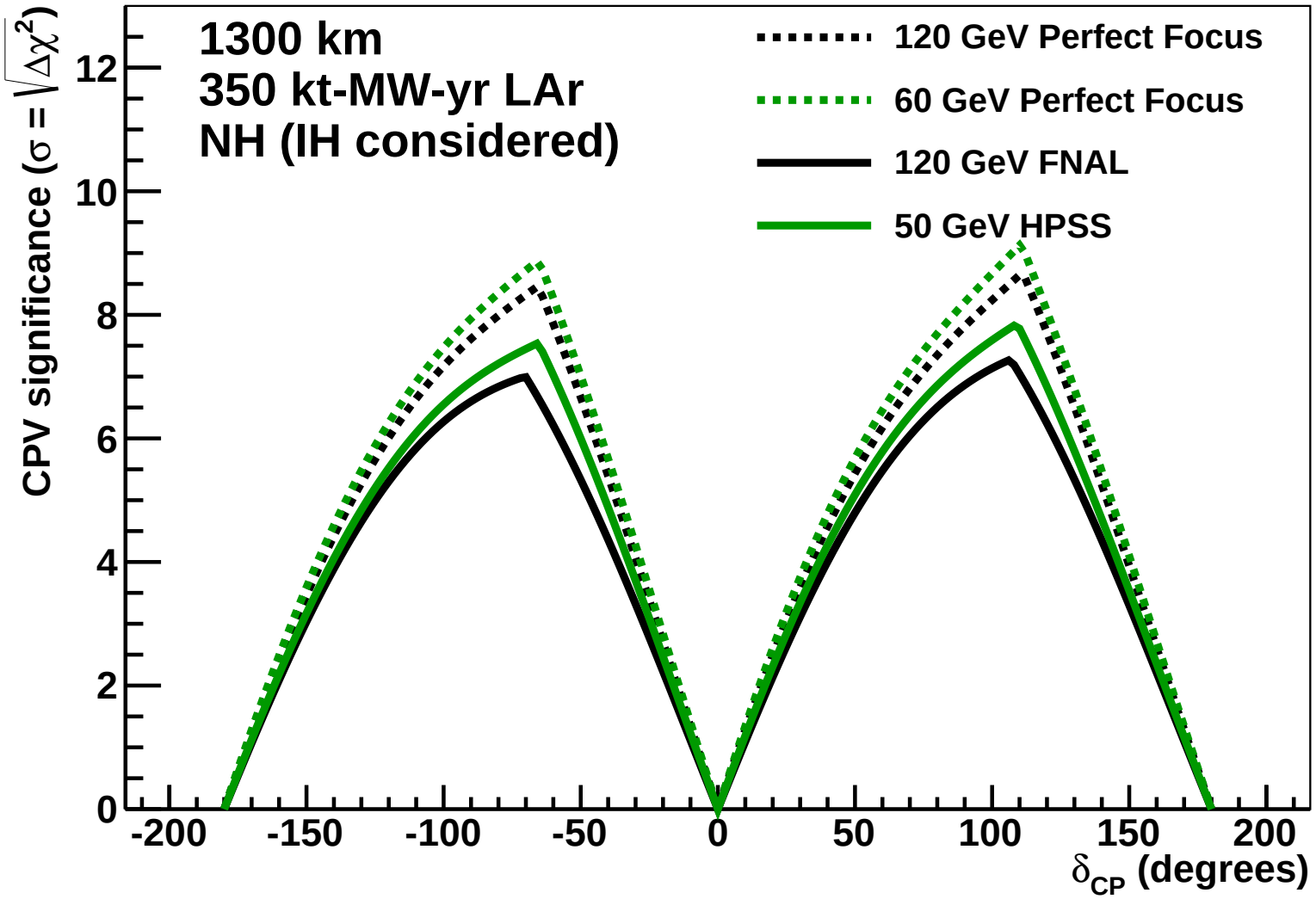


$\bar{\nu}_e$ Sig: **223**, Bkg: 47+51+32+105= **235**

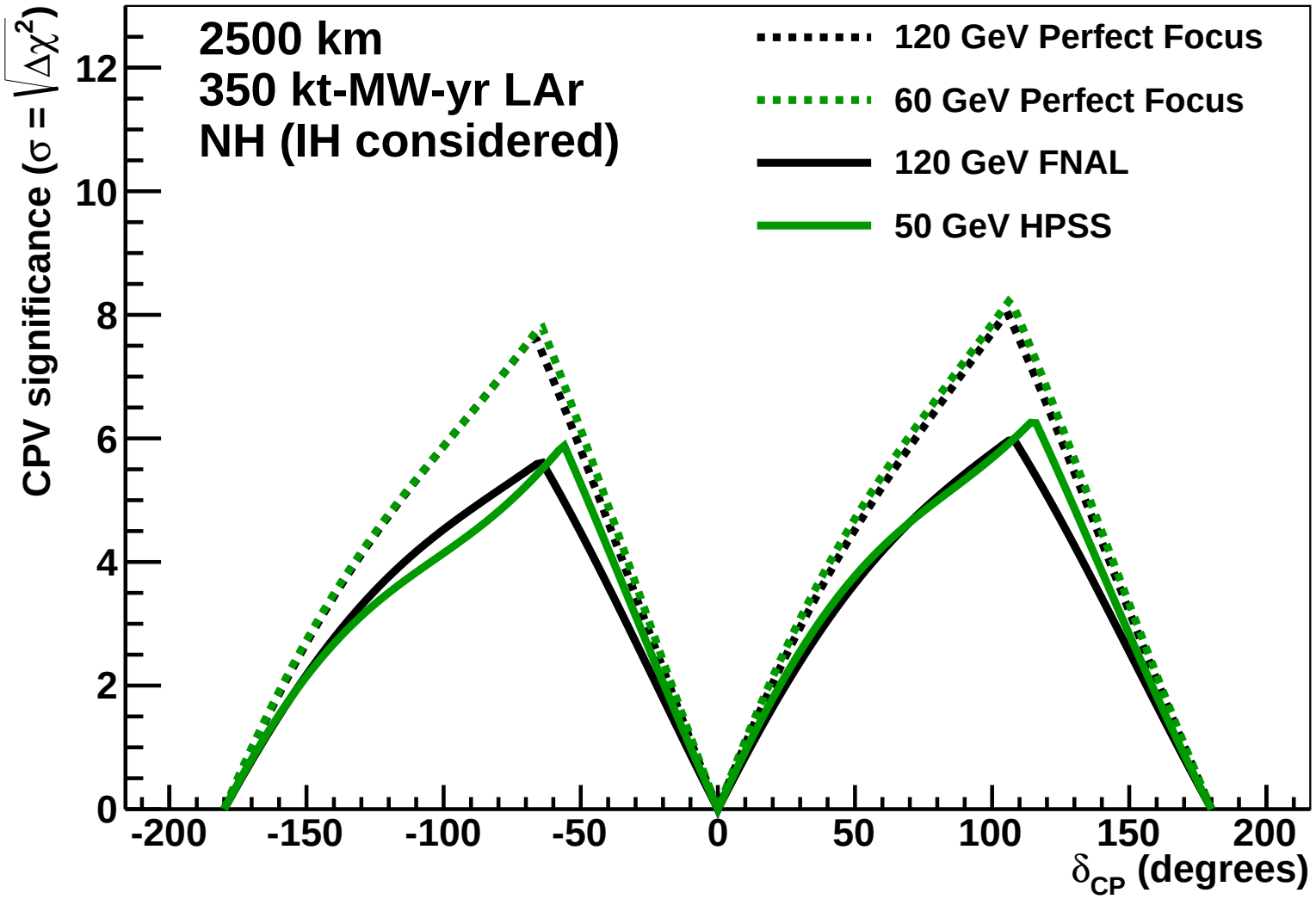
Sig: **68**, Bkg: 13+16+19+28= **76**

CP sensitivities

Baselines and Oscillations
Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian
Motivation
Oscillation Basics
ν Flux from DIF Beams
Event Rates
Spectral Information
ν Flux with Focusing
GLoBeS Studies
Summary

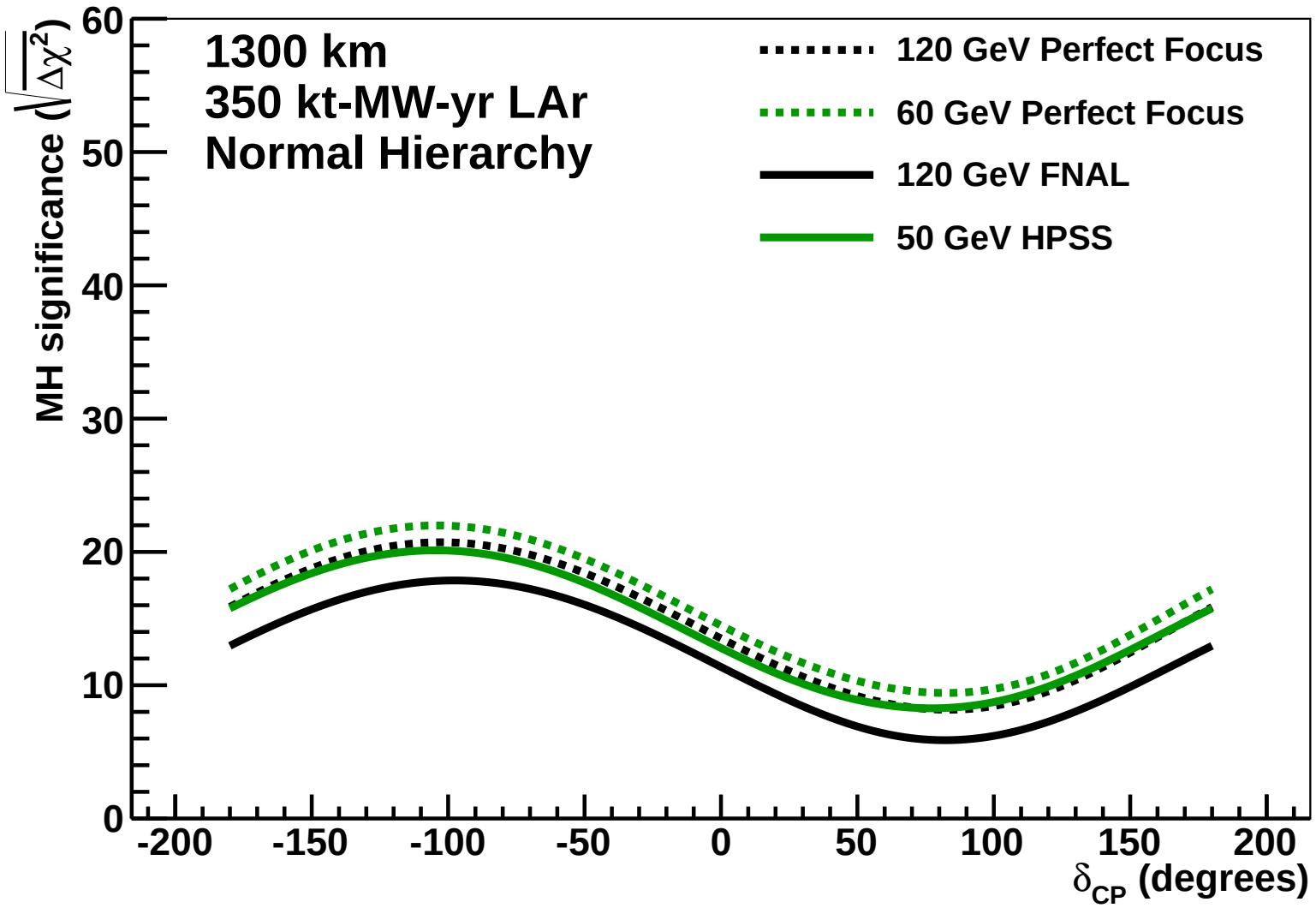


CP sensitivities

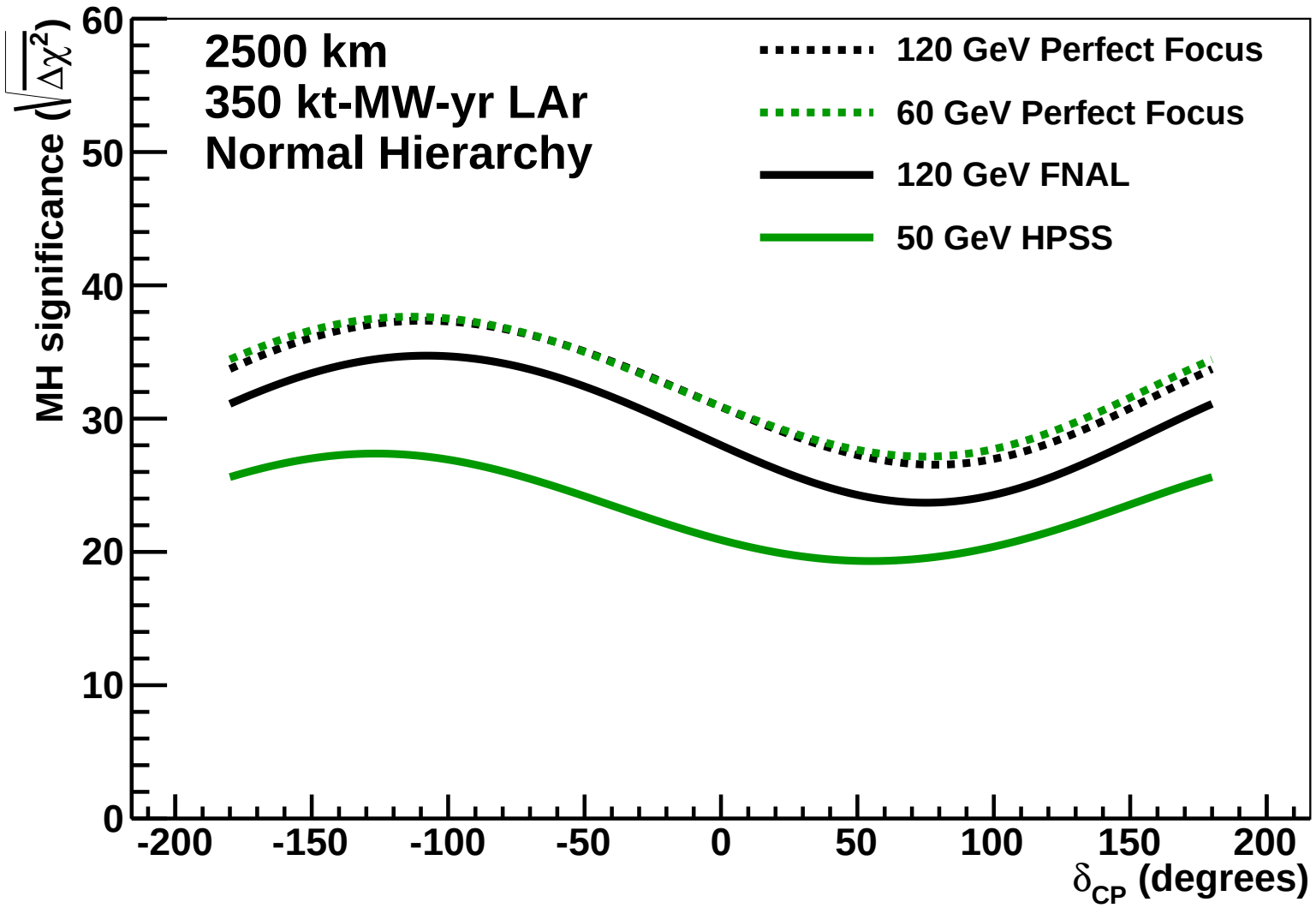


MH sensitivities

Baselines and Oscillations
Mary Bishai, M. Bass, D. Cherdack, L. Whitehead, E. Worcester, X. Qian
Motivation
Oscillation Basics
ν Flux from DIF Beams
Event Rates
Spectral Information
ν Flux with Focusing
GLoBeS Studies
Summary



MH sensitivities



Summary

- **Over the last 15 yrs, several studies with varying degrees of sophistication have demonstrated that the sensitivity to CP violation is roughly the same for baselines from $\sim$ 1000-2000km.**
- **Studies of the ν_e appearance spectra over the L/E region of the first two maxima are desirable to break degeneracies and reduce correlations.**
- **The ν_e appearance rate for baselines $>$ 500km decreases with baseline** *primarly due to hadron production spectrum from the target NOT the distance*.
- **The ν_e appearance rate at the 2nd maximum is of $\mathcal{O}(10)$ % of the rate at the 1st maximum and is very similar for baselines $\geq$ 1500km.**
- **The spectral information obtained from the wide first maximum dominates the CP sensitivity, but decreases with baseline. The spectral information from the 2nd maximum is roughly the same for baselines $\geq$ 1500km.**