Long Baseline Beams and Event Rates

Homestake Detector Meeting, FNAL, Oct 12, 2007

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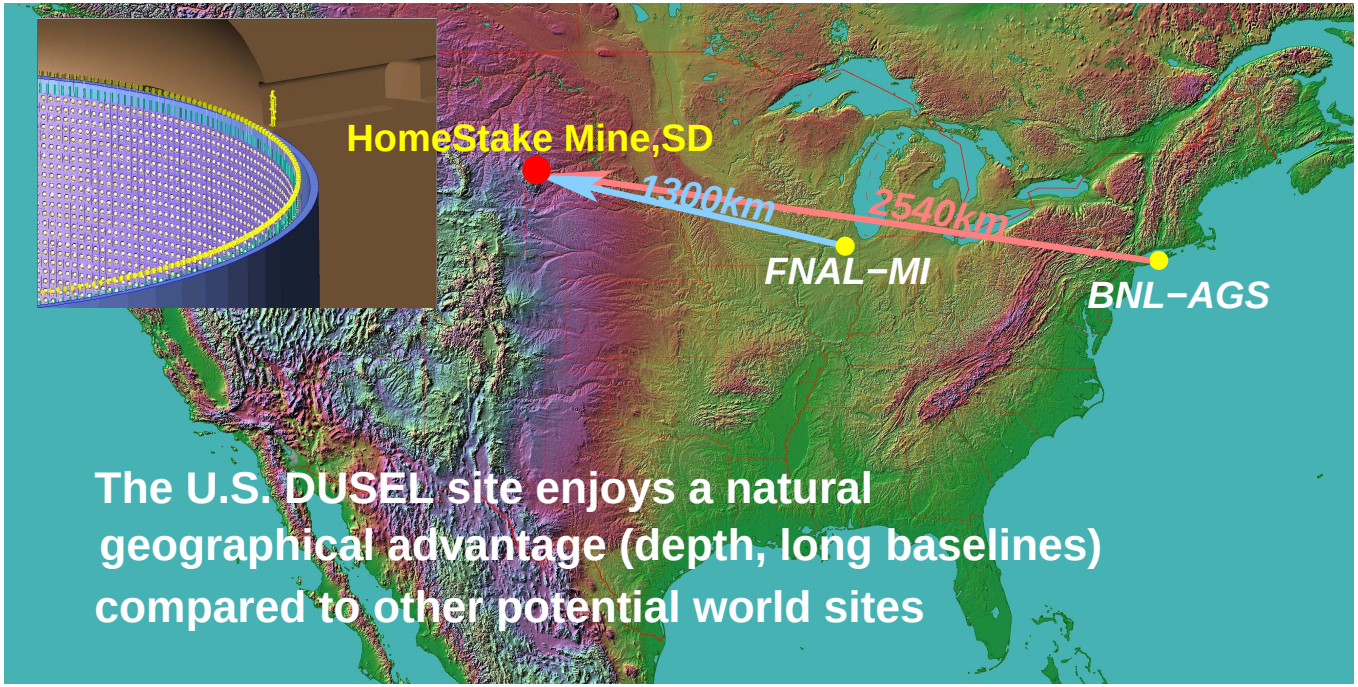
Future Long Baseline Expts.



The next generation of ν long baseline experiments require very large ($\sim$ 100's kT) detectors and mega-watt class conventional neutrino beams with very long baselines (1000-3000 km). The Homestake-FNAL baseline is well suited for these experiments.

Beam Design Requirements

The design specifications of conventional neutrino beams based at the Fermilab MI are driven by the physics of $\nu_\mu \rightarrow \nu_e$ oscillations:

Requirements:

-Maximal possible neutrino fluxes to encompass the 1st and 2nd oscillation nodes. For narrow-band beams $\Rightarrow$ 2 detectors at each maxima.

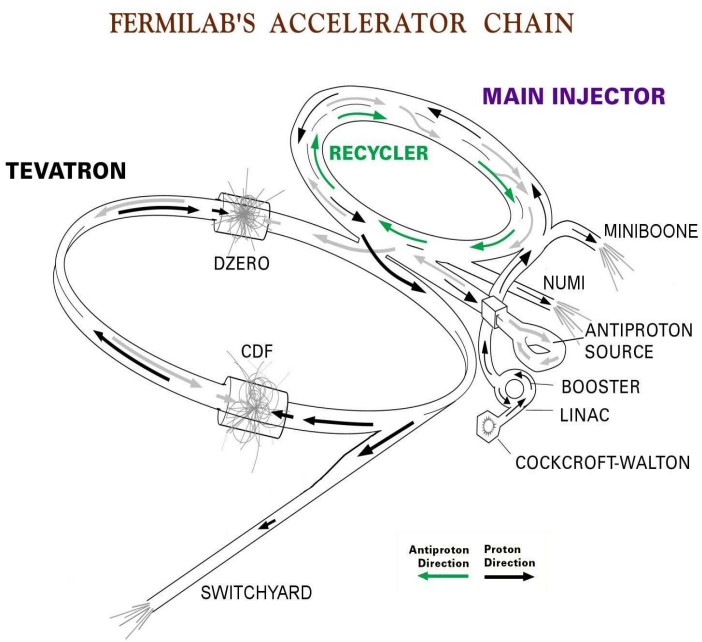
-For broad-band beams: Minimize the neutral-current feed-down contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 1st maxima where there is no sensitivity to the oscillation parameters is highly desirable.

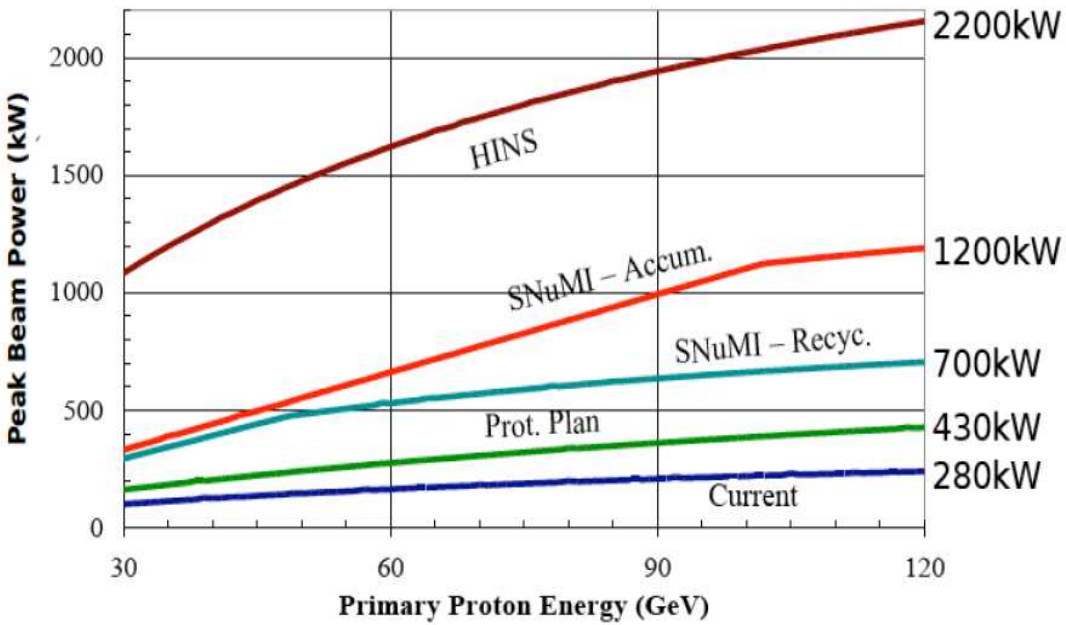
-High purity ν_μ beam with negligible ν_e

FNAL Beam Specs: E & Power

SNuMI: **Use the *existing* recycler and anti-proton accumulator to store protons from the 8 GeV 15 Hz Booster during the MI cycle then inject to MI $\longrightarrow$ increases MI intensity up to 6×10^{13} protons $\Rightarrow$ 1.2 MW at 120 GeV.**

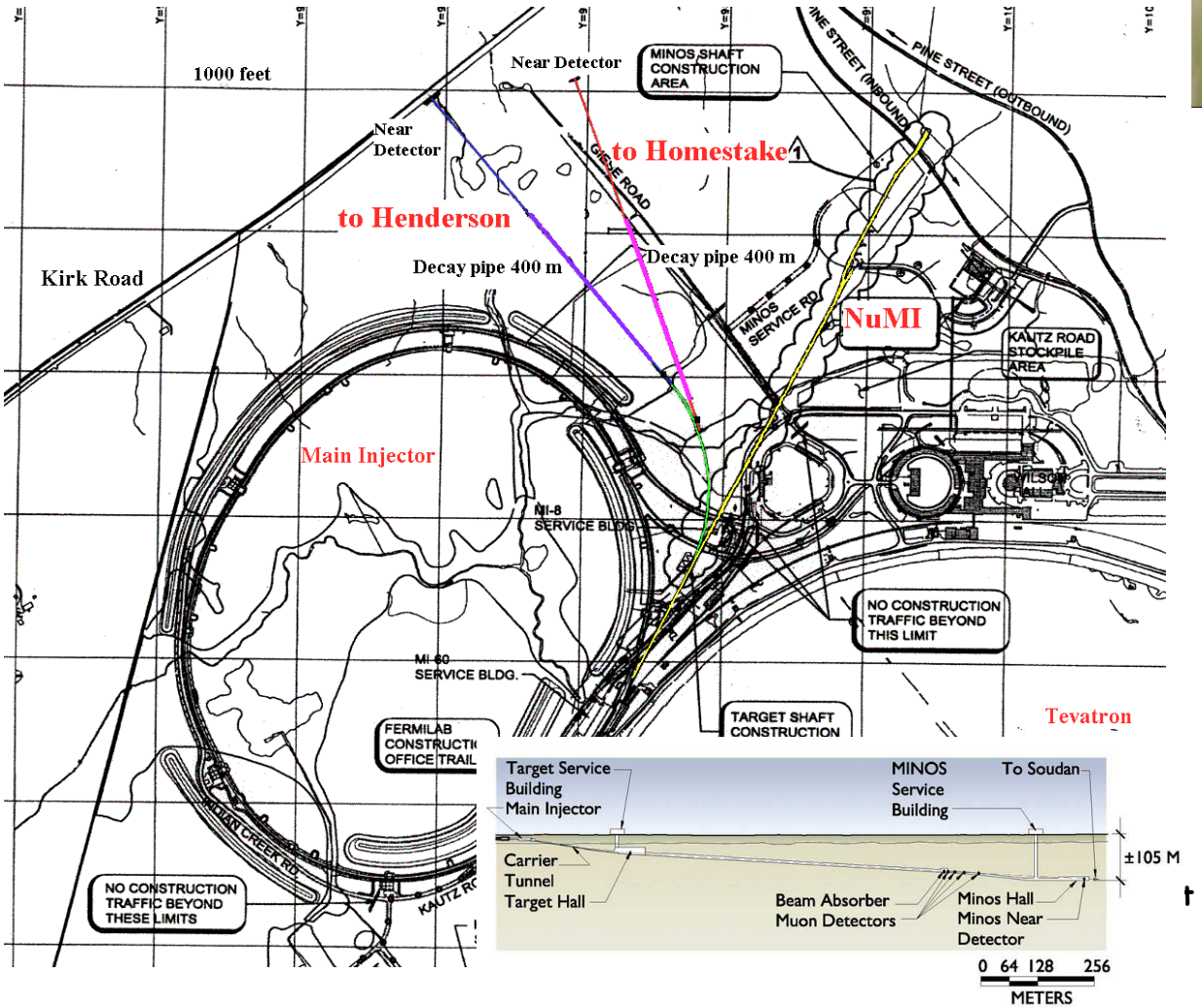
Project X: **S.C. Linac replaces 8 GeV Booster, MI upgrades $\Rightarrow$ 2.2MW at 120GeV**





DUSEL Beamline Siting at FNAL

See Dixon Bogert's talk



NuMI in MI

Angle down by 8.9°

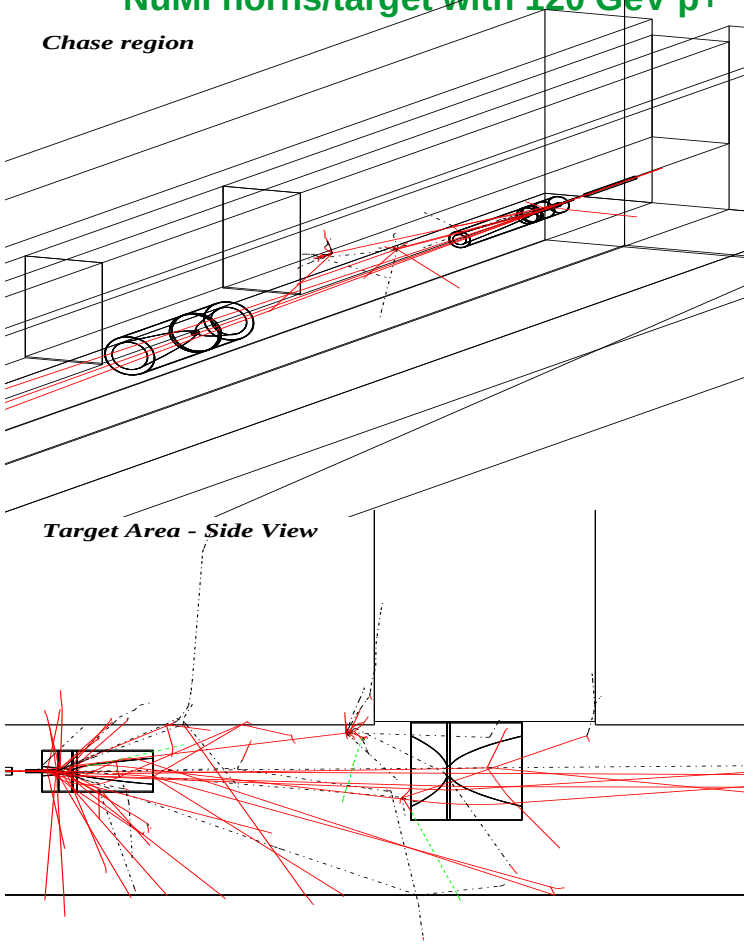
Carrier tunnel

Beamlines to DUSEL can accomodate a decay tunnel with $L \leq 400$m on-site

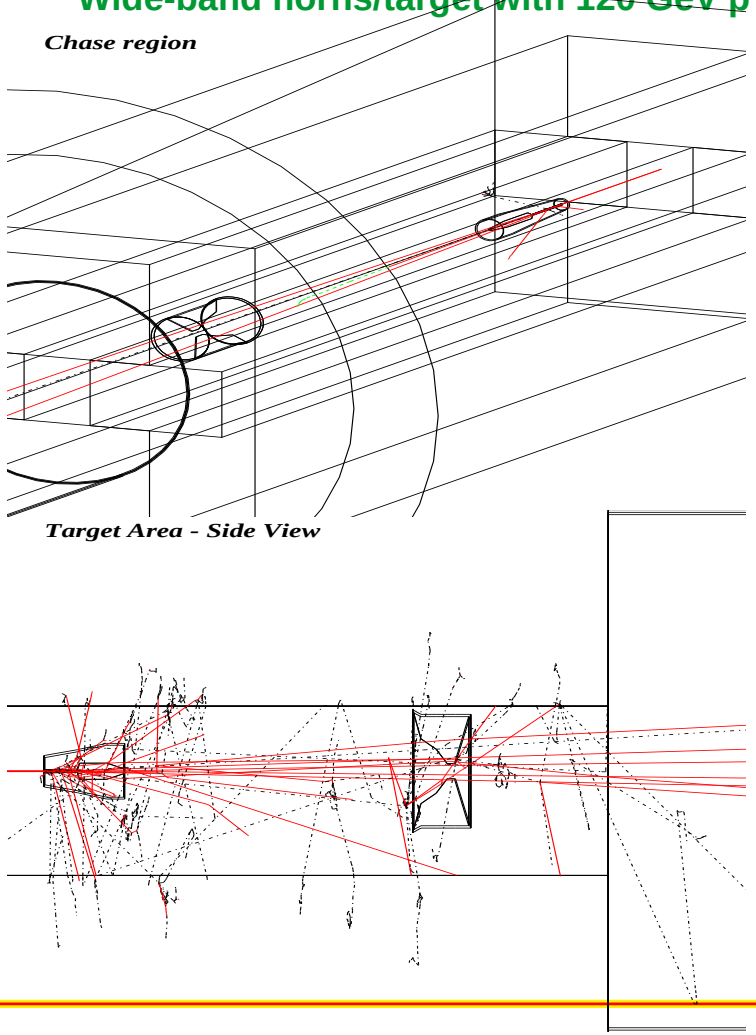
Targeting system design

Beam to DUSEL: carbon-composite target with a density of 2.1g/cm^3 for a MW class beam + 2 wide-band horns based on BNL-AGS E734/E889:

NuMI horns/target with 120 GeV p+



Wide-band horns/target with 120 GeV p+



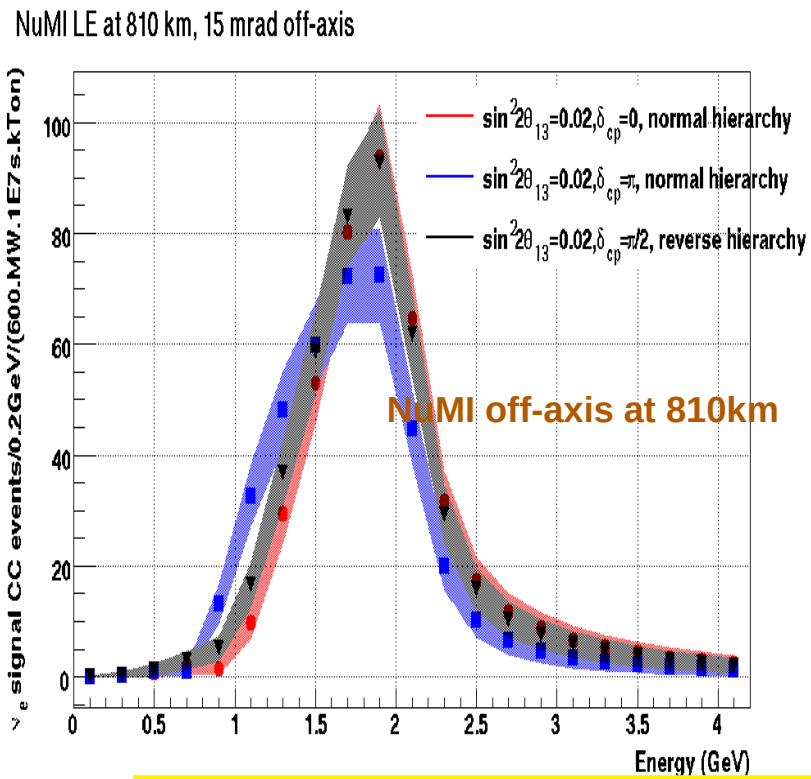
Advantages of a Wide-Band Beam

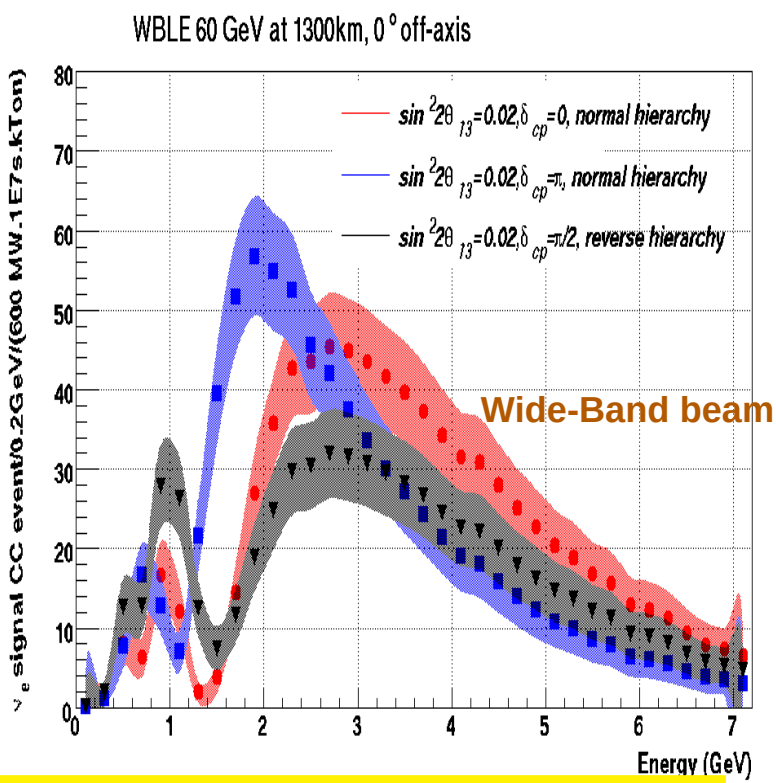
Observing $\nu_\mu \to \nu_e$ is sensitive to δ_{cp}, θ_{13} and the mass hierarchy:

Exposure of 350 kT.MW.yr, with no detector effects, $P(\nu_\mu \to \nu_e) \sim 1\%$:

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

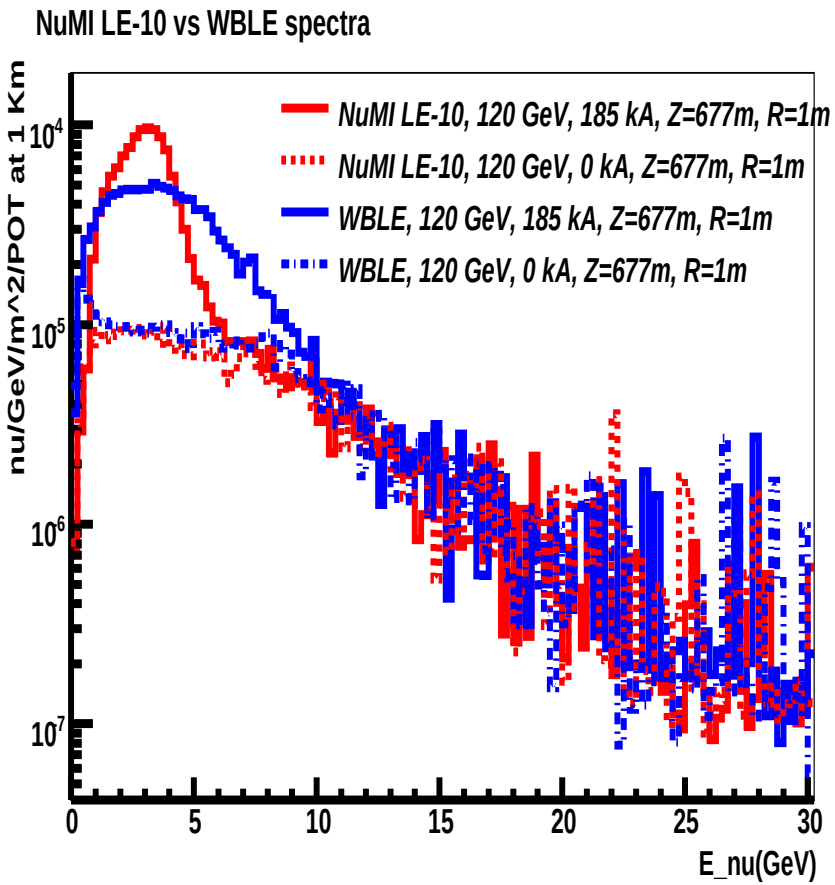


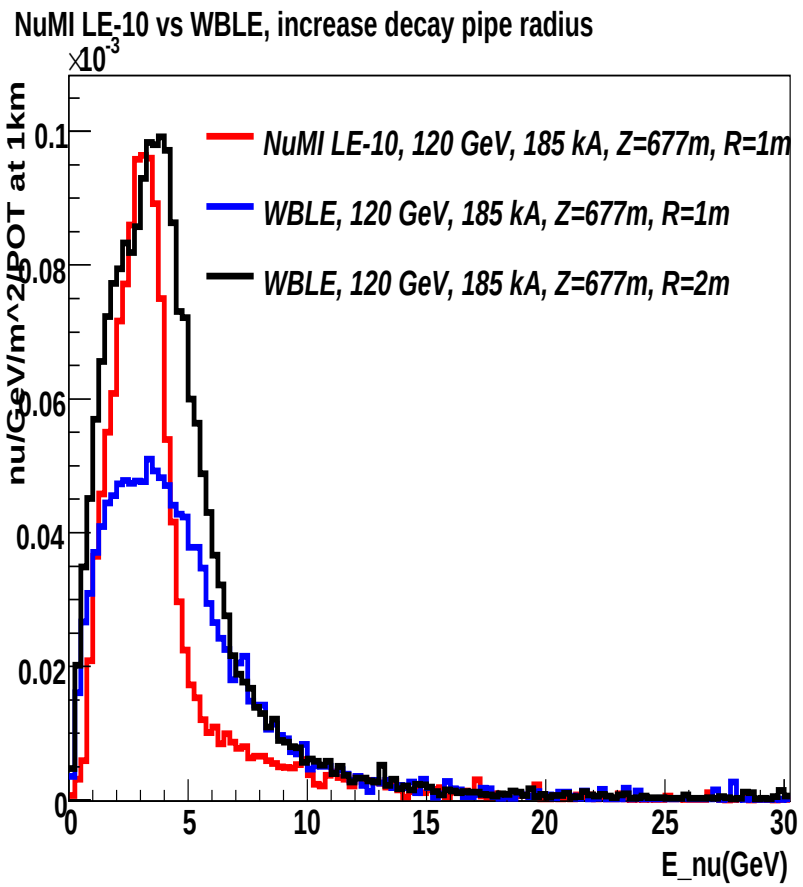


Wide-band beam spectral information = resolves degeneracies

NuMI LE vs WBLE

R and Z refer to the geometry of the decay volume which is cylindrical.





1m radius decay pipe

increase to 2m radius

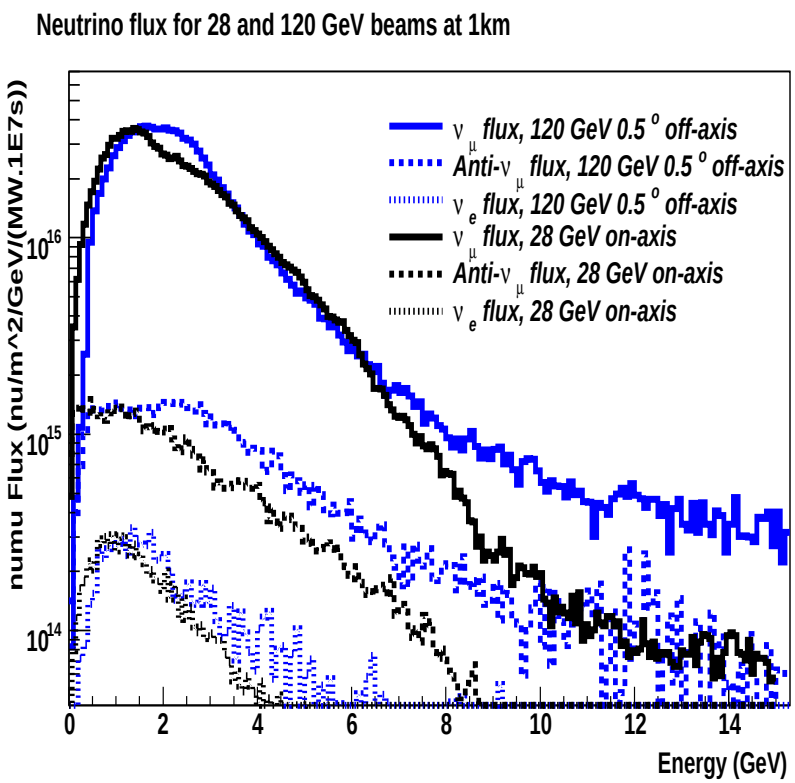
Larger diameter decay pipe = more flux at low E.

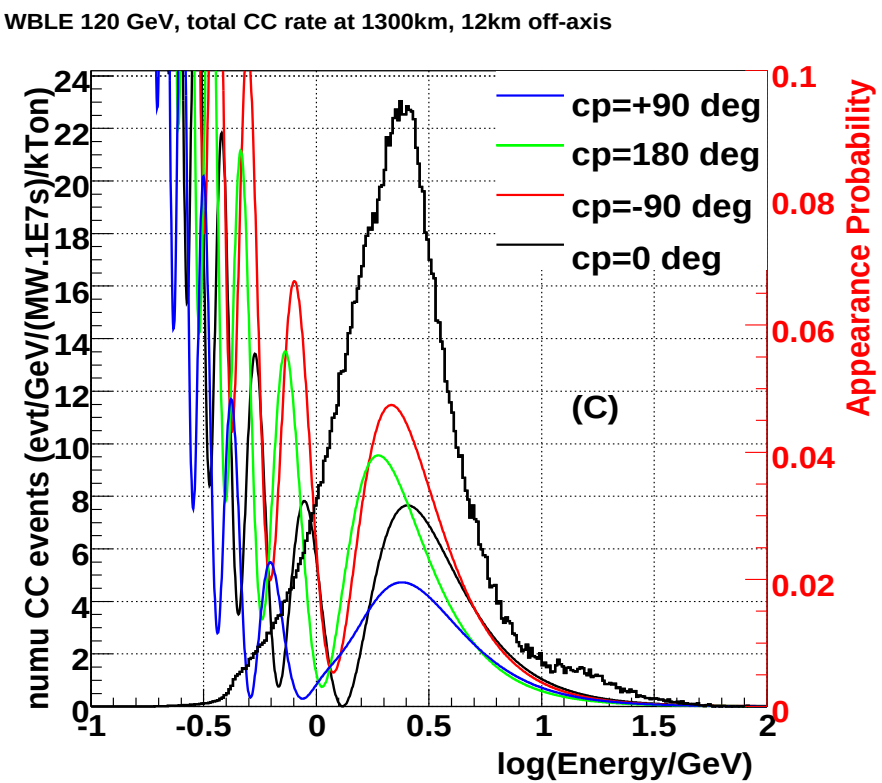
Wide-Band Low-Energy Spectra

Decay pipe radius chosen to be 2m = the maximum that can be accomodated in FNAL rock with concrete shielding for a MW class beam.

Siting restrictions at FNAL ⇒ decay pipe length is 380m

For higher p energy, small off-axis angle ⇒ can reduce long tails:





GEANT 3.21 simulation of wide-band horns+decay pipe, with FLUKA '05 for target hadro-production.

Based on NuMI simulation which matches observed MINOS event rate to 10% in 0 - 7 GeV range

$\nu_\mu \longrightarrow \nu_e$ Appearance Rates

Exposure: 100 kT $\times$ 1MW $\times$ 1 yr (1.7×10^7 seconds).

$\sin^2(2\theta_{13}) = 0.02, |\Delta m^2_{31}| = 2.5 \times 10^{-3}\mathrm{eV}^2$

Rate = $\sigma_{\mathrm{CC}} \times$ Flux $\times P_{\mu e}$, NO DETECTOR EFFECTS INCLUDED!

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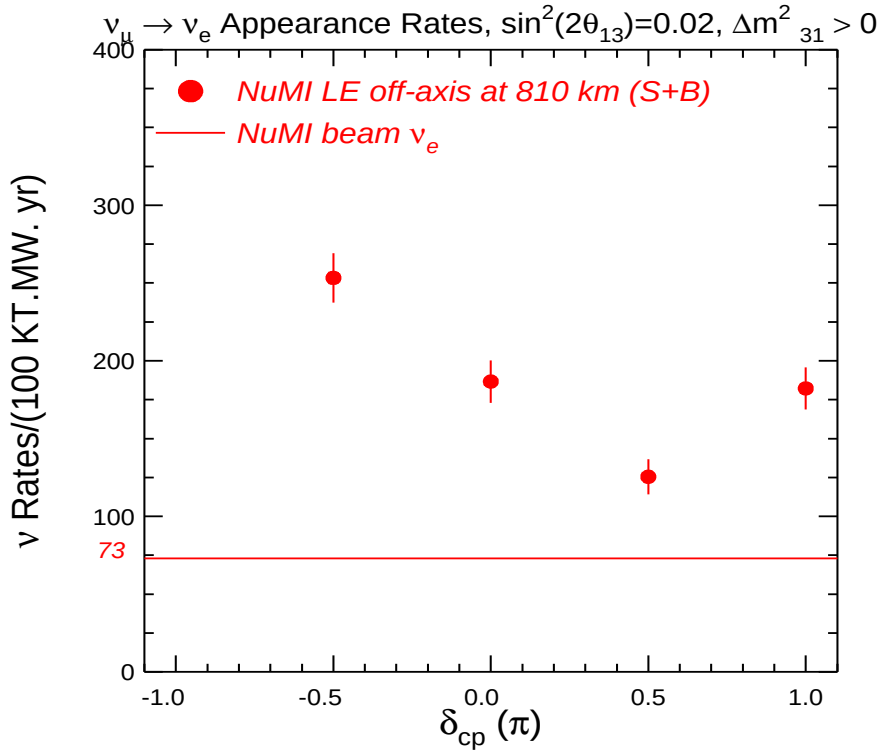
Normal Hierarchy



Even at 810km $\Rightarrow$ we need a LARGE detector

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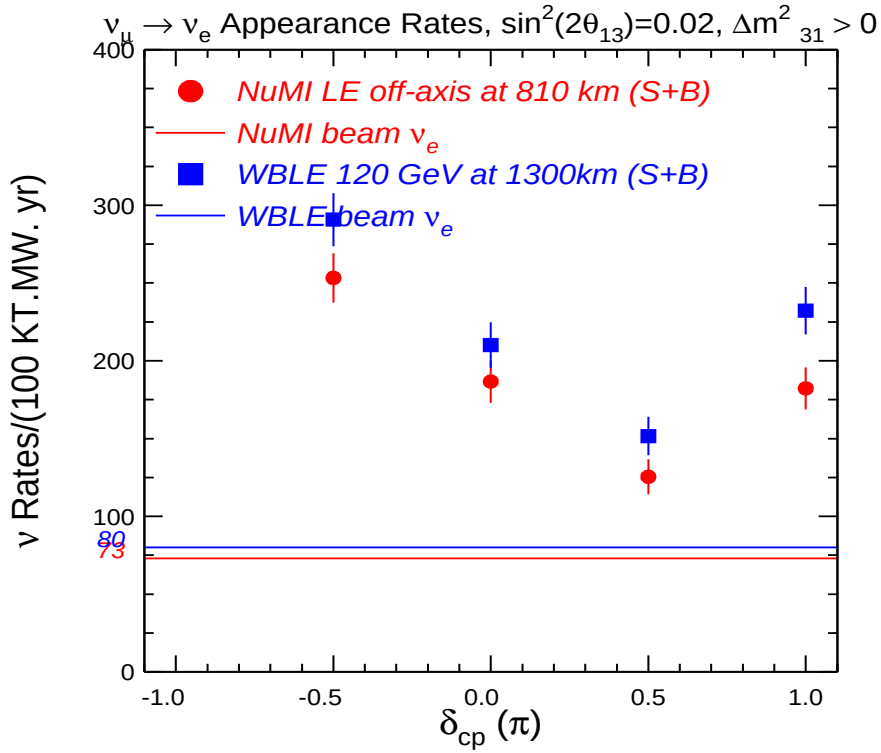

NuMI 0.8° o.a. rates at 810km $\sim$ WBLE 120GeV 0.5° o.a. at 1300km

$\nu_\mu \longrightarrow \nu_e$ Appearance Rates

Exposure: 100 kT $\times$ 1MW $\times$ 1 yr (1.7×10^7 seconds).

$$\sin^2(2\theta_{13}) = 0.02, |\Delta m^2_{31}| = 2.5 \times 10^{-3}\mathrm{eV}^2$$

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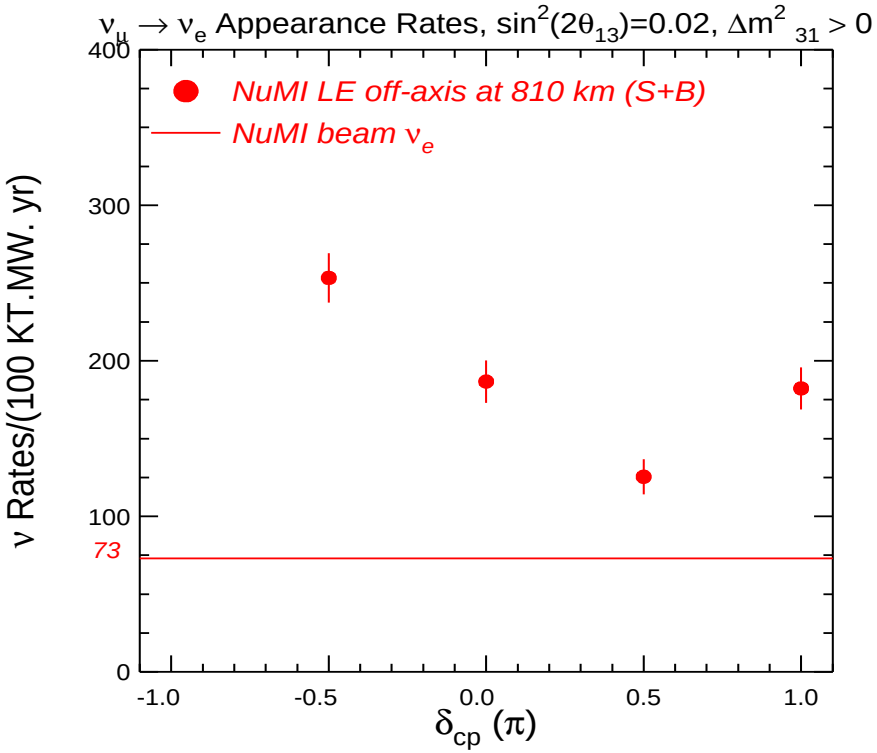
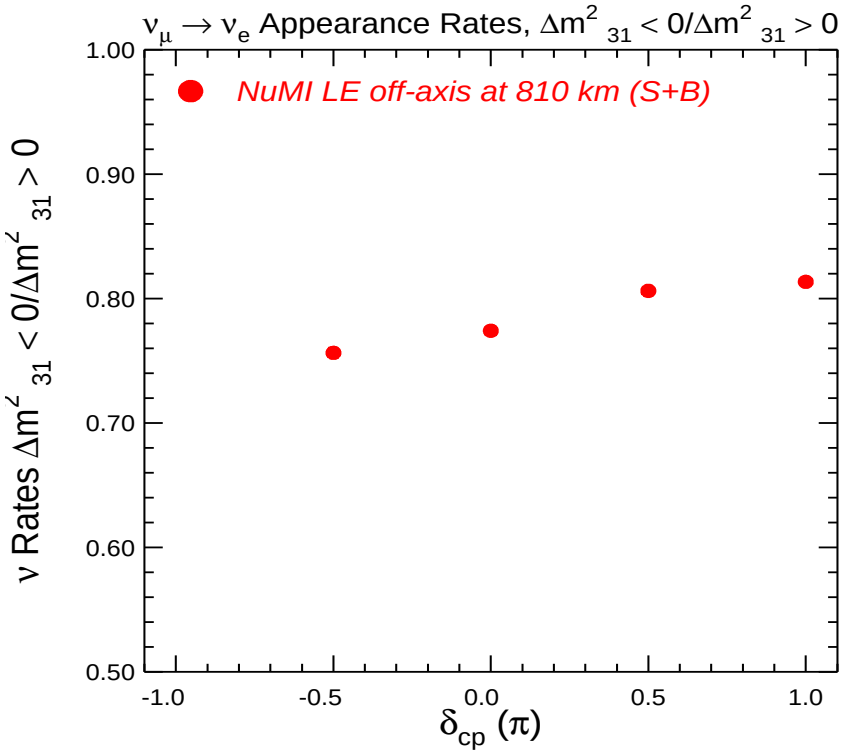


Reverse/Normal



Reverse hierarchy $\Rightarrow$ lower ν rates

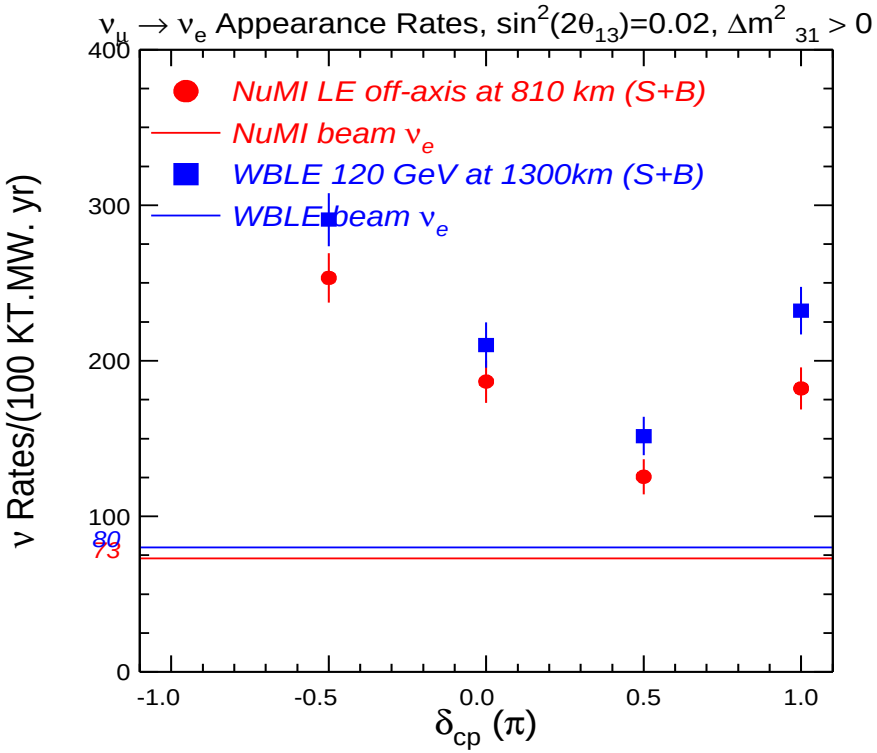
$\nu_\mu \longrightarrow \nu_e$ Appearance Rates

Exposure: 100 kT $\times$ 1MW $\times$ 1 yr (1.7×10^7 seconds).

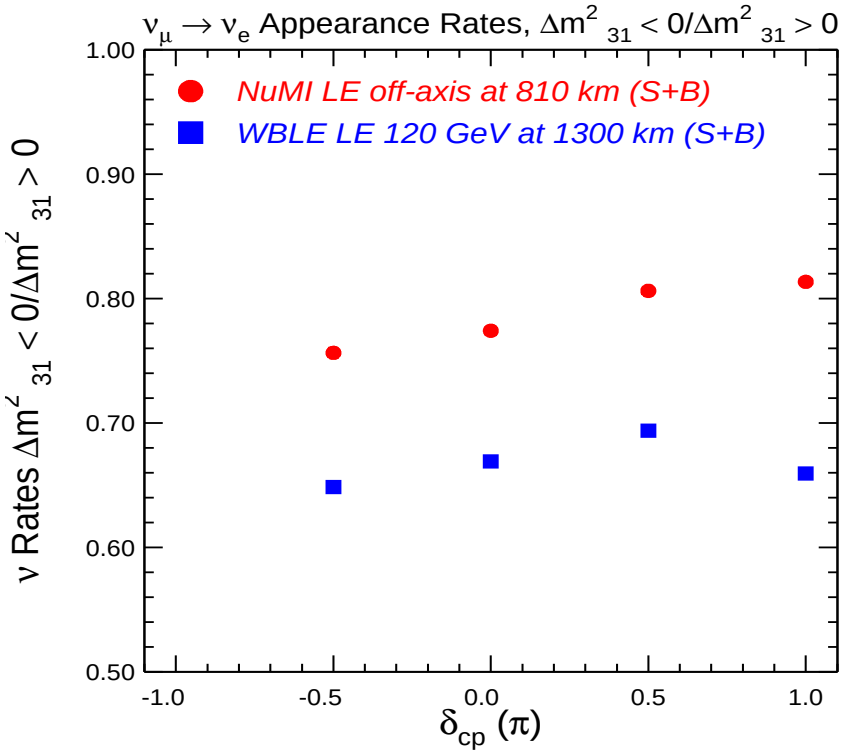
$$\sin^2(2\theta_{13}) = 0.02, |\Delta m^2_{31}| = 2.5 \times 10^{-3}\mathrm{eV}^2$$

Rate = $\sigma_{\mathrm{CC}} \times$ Flux $\times P_{\mu e}$, NO DETECTOR EFFECTS INCLUDED!

Normal Hierarchy



Reverse/Normal



Matter effects are larger at 1300km

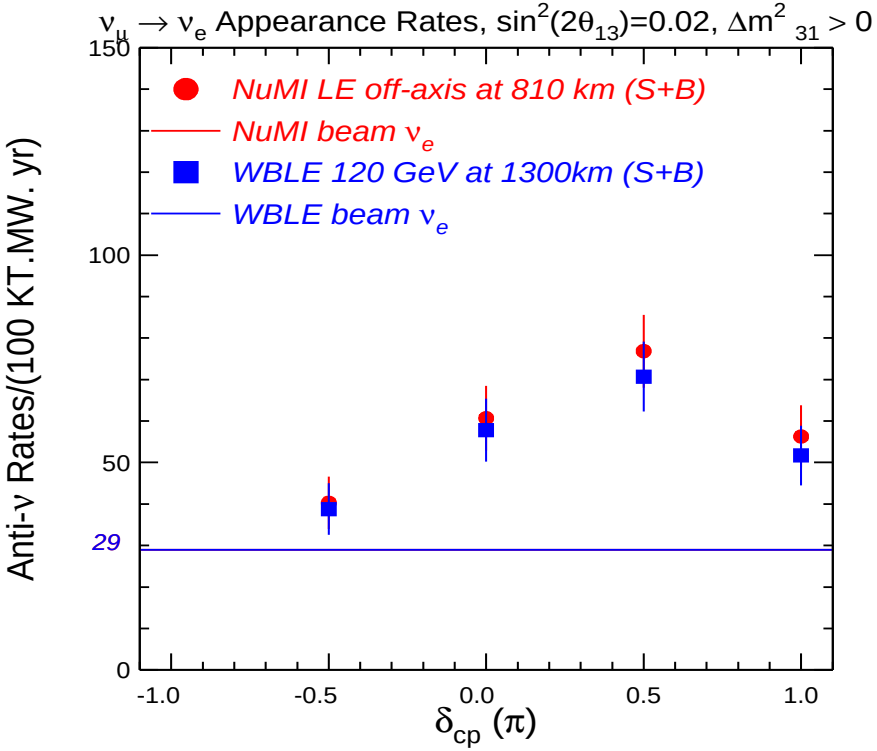
$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ Appearance Rates

Exposure: 100 kT $\times$ 1MW $\times$ 1 yr (1.7×10^7 seconds).

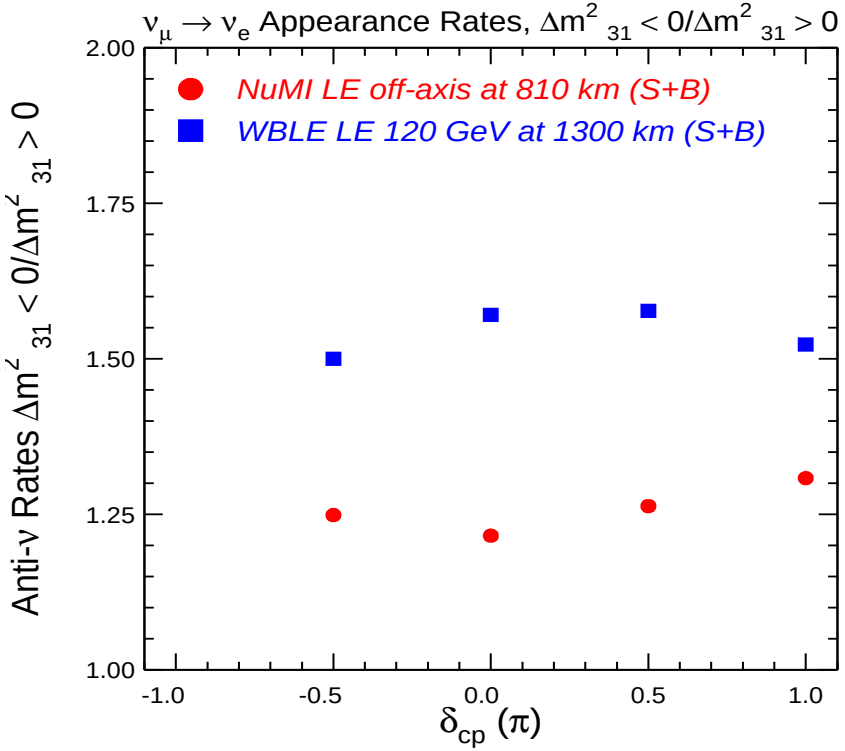
$$\sin^2(2\theta_{13}) = 0.02, |\Delta m^2_{31}| = 2.5 \times 10^{-3}\mathrm{eV}^2$$

Rate = $\sigma_{\mathrm{CC}} \times$ Flux $\times P_{\mu e}$, NO DETECTOR EFFECTS INCLUDED!

Normal Hierarchy



Reverse/Normal



Anti-ν $\Rightarrow$ lower rates, reverse matter effects

Rate Summary

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{12,23} = 0.86, 1.0$

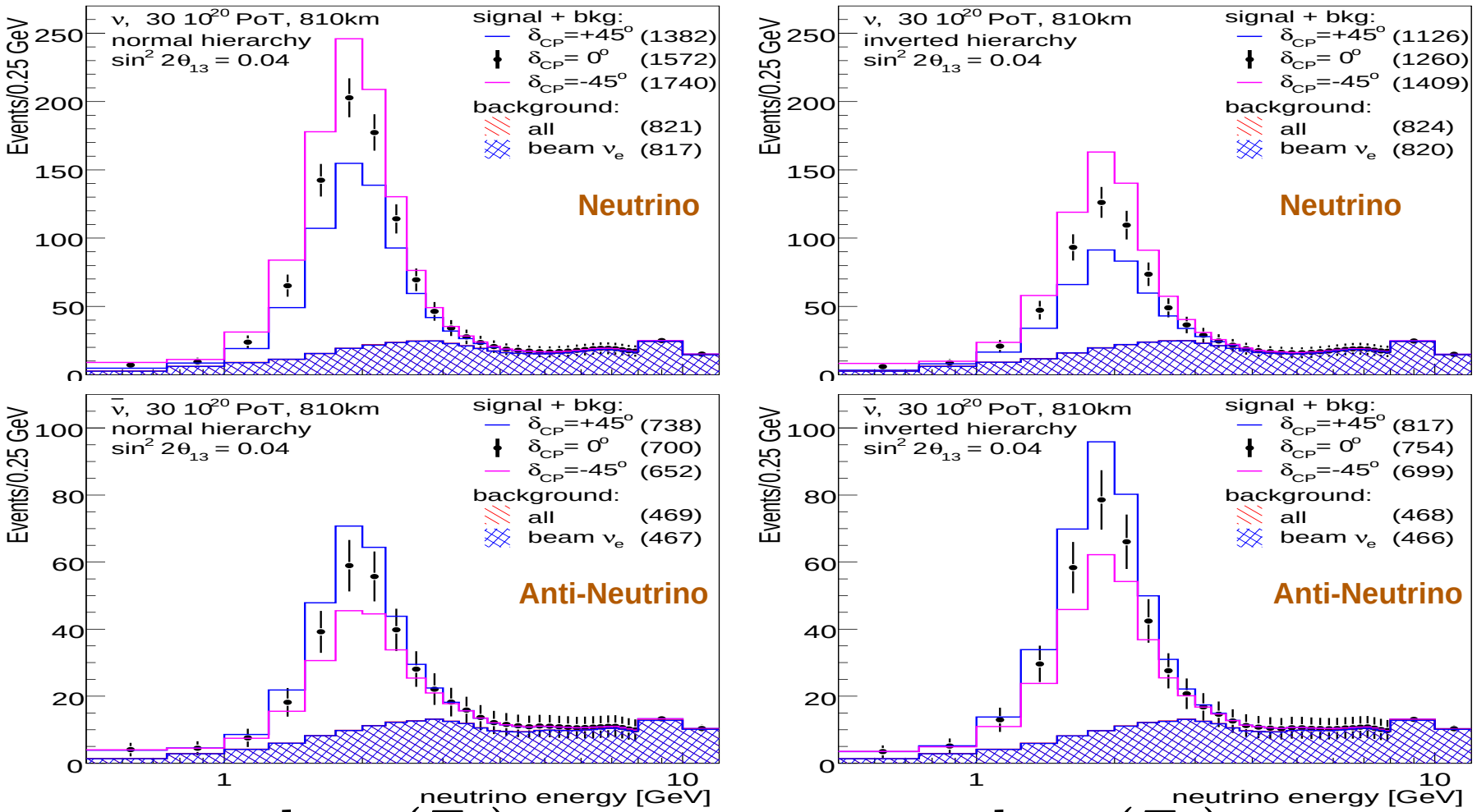
		$\nu_\mu \longrightarrow \nu_e$ rate				$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ rates			
(sign of Δm^2_{31})	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	-90°	180°	+90°	0°	-90°	180°	+90°
NuMI LE beam tune at 810km, per 100kT. MW. 10^7s									
15 mRad off-axis		Beam ν_e = 43*				Beam $\bar{\nu}_e$ = 17*			
(+)	0.02	76	108	69	36	20	7.7	17	30
(-)	0.02	46	77	52	21	28	14	28	42
WBLE beams at 1300km, per 100kT. MW. 10^7s									
120 GeV, 9 mRad off-axis		Beam ν_e = 47**				Beam $\bar{\nu}_e$ = 17**			
(+/-)	0.0	14	N/A	N/A	N/A	5.0	N/A	N/A	N/A
(+)	0.02	87	134	95	48	20	7.2	15	27
(-)	0.02	39	72	51	19	38	19	33	52
60 GeV, on-axis		Beam ν_e = 61**				Beam $\bar{\nu}_e$ = 22**			
(+)	0.02	138	189	125	74	30	12	19	37
(-)	0.02	57	108	86	34	46	27	48	67

* = 0-3 GeV ** = 0-5 GeV, 1 MW. 10^7s = 5.2×10^{20} POT at 120 GeV, 1yr $= 1.7 \times 10^7 s$

ν_e Appearance Spectra (1.2 MW, 3.4 yrs)

$\sin^2 2\theta_{13} = 0.04$, **100kT LAr.**, NuMI ME 0.8°, 810km, 30E20.

Normal hierarchy $(-\delta_{cp} = -45^\circ, -\delta_{cp} = +45^\circ)$ **Reversed hierarchy**



$\log_{10}(E_\nu)$ $\log_{10}(E_\nu)$

ν_e Appearance Spectra (1.2 MW, 3.4 yrs)

$\sin^2 2\theta_{13} = 0.04$, **100kT LAr.**, WBLE 120 GeV, 1300km, 30E20 POT.

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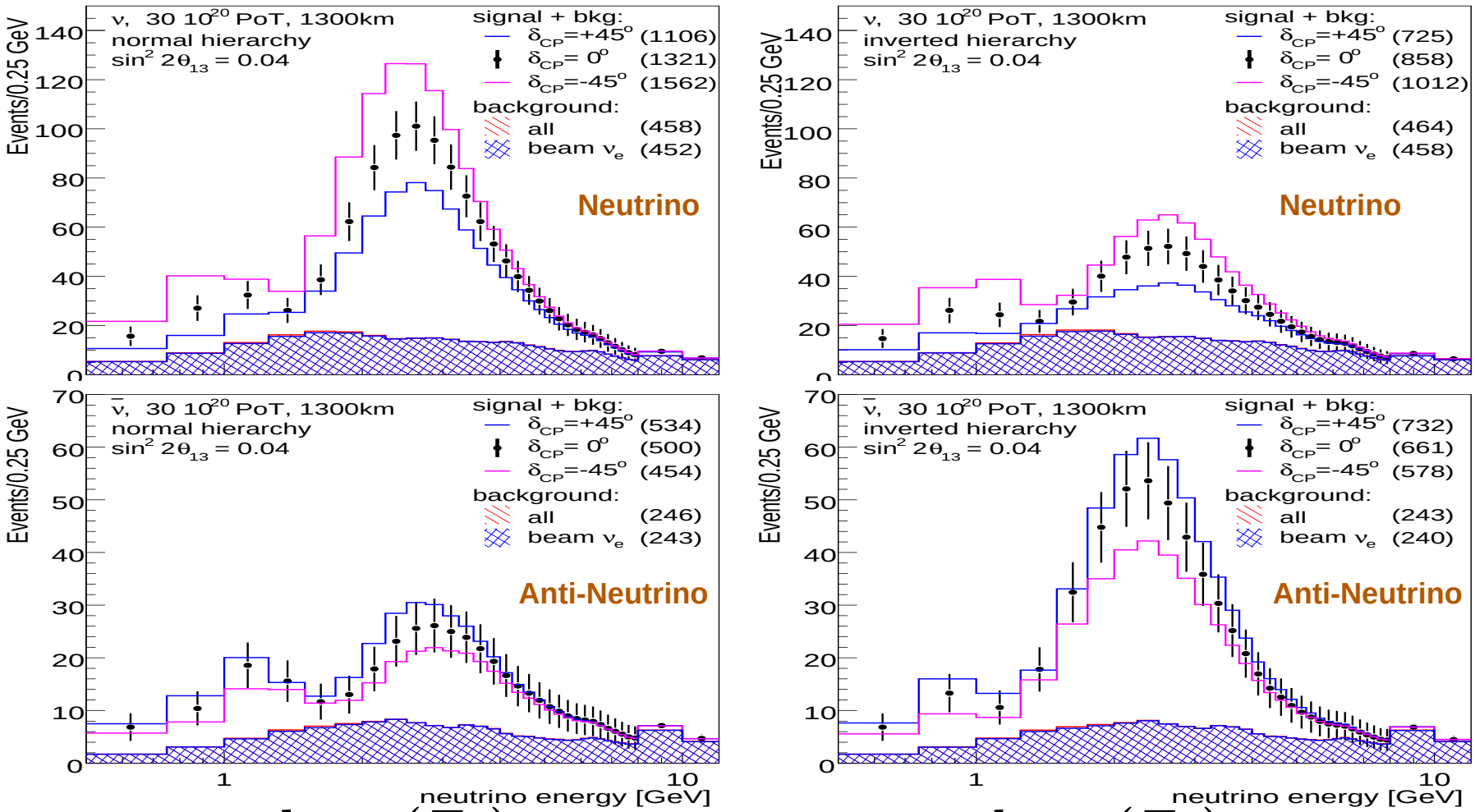
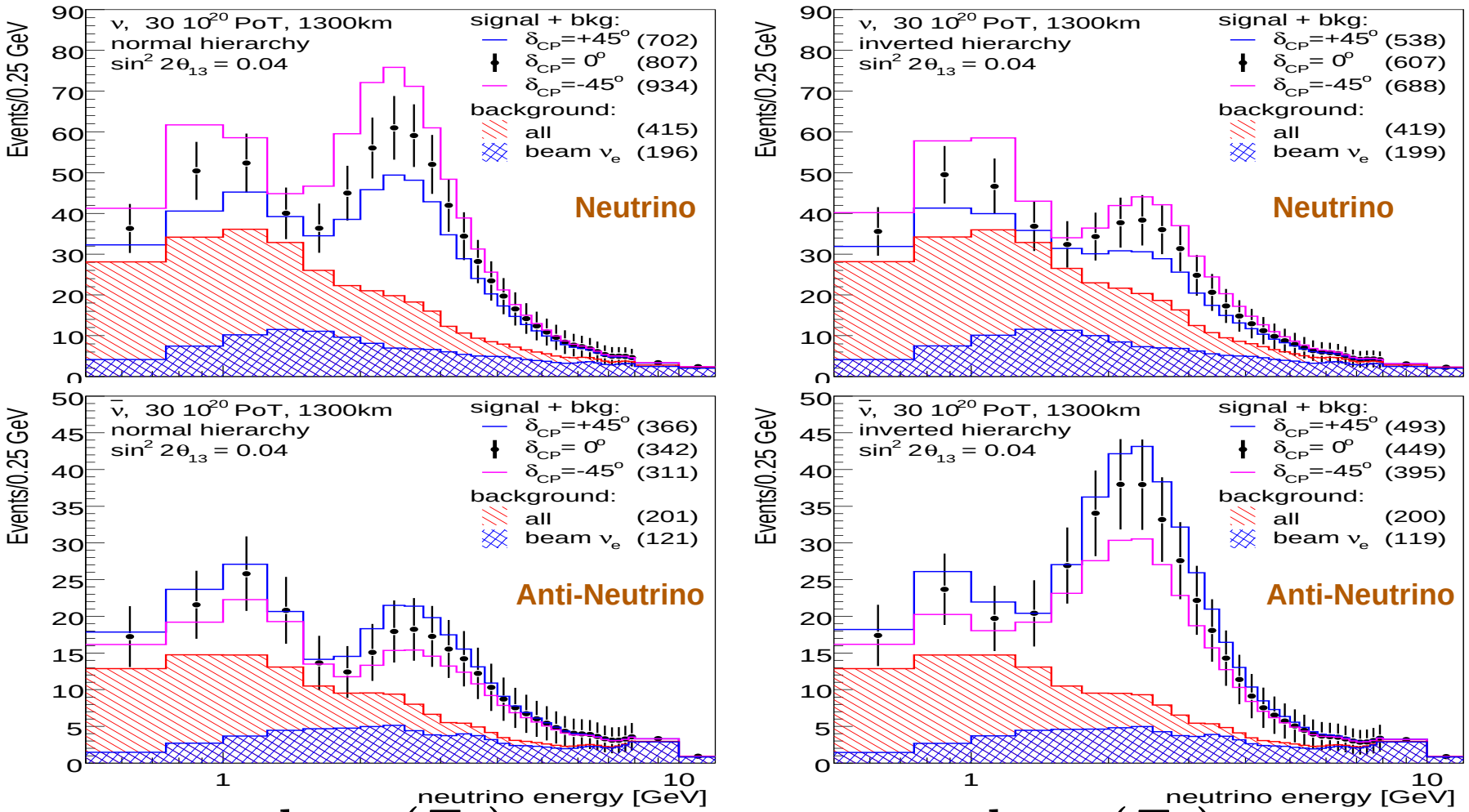


$\log_{10}(E_\nu)$ $\log_{10}(E_\nu)$

ν_e Appearance Spectra (1.2 MW, 3.4 yrs)

$\sin^2 2\theta_{13} = 0.04$, **300kT WCe.**, WBLE 120 GeV, 1300km, 30E20 POT.

Normal hierarchy $(-\delta_{cp} = -45°, -\delta_{cp} = +45°)$ **Reversed hierarchy**



$\log_{10}(E_\nu)$ $\log_{10}(E_\nu)$

Conclusions

- The FNAL-Homestake baseline (1300km) is well suited for the next generation of long baseline expts.
- A preliminary design has been produced of a Main Injector neutrino beamline to DUSEL w/ broad-band targeting system that well matches the physics requirements of Phase II long baseline experiments.
- Preliminary event rates have been estimated for many different wide-band beam energy scenarios.

We have selected a wide-band 120 GeV 0.5^0 off-axis beam for FNAL-Homestake.

- Event rates indicate the neutrino detectors will have to be massive (order of 100's kTs).

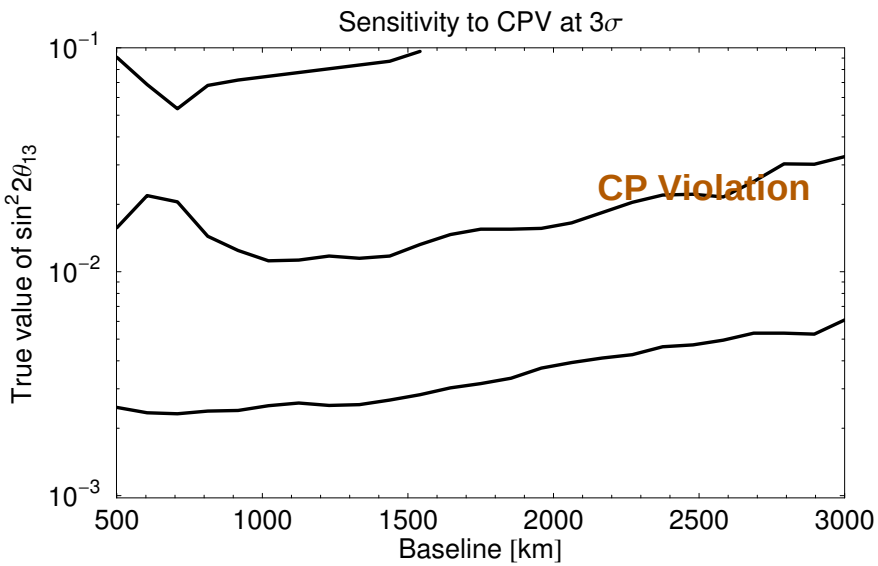
To Do

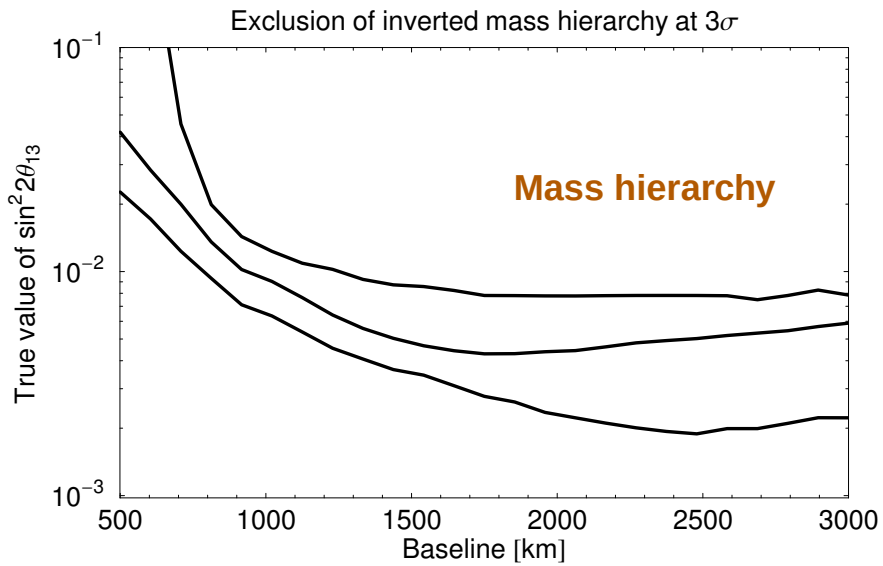
- **Beamline design:** Optimization of focusing system design for higher energy beams. Optimization of decay tunnel design (shielding, vacuum/He).
- **Targeting system R&D:** Further studies have shown carbon-composite is not rad hard. Lots of work needed to identify appropriate target materials and designs for MW class beams. More R&D needed on solenoid and plasma focusing systems.
- **Detector designs:** .....

BACKUP

Physics sensitivity vs baseline

Using a broad-band beam with a peak interaction rate at 2 GeV, FWHM=3 GeV, a parameterized water Cerenkov detector and exposure of 5MW.yr (ν) + 10 MW.yr ($\bar{\nu}$) (V. Barger *et al.*. Phys. Rev. D 74, 073004 2006):





Minimum value of $\sin^2(2\theta_{13})$ for which the sensitivity is $> 3\sigma$ for (best,50%, worst) of δ_{cp} values

Best sensitivity is for baselines 1200 - 2500km

Estimating Sensitivities

Details in Mark Dierckxsens presentation, WG1 Fri PM Aug 8th

Matrix parameters used & systematic uncertainties (FNAL-DUSEL):

-$\Delta m^2_{21,31} = 8.6 \times 10^{-5}(5\%), 2.7 \times 10^{-3}$ eV^2 (uncertainty determined from fit to disappearance mode) -$\sin^2 2\theta_{12,23} = 0.86(5\%), 1.0$(uncertainty determined from fit to disappearance mode) -Matter density (5%) -Background (10%) - Mass hierarchy fixed.

Systematic uncertainties (NuMI Off-axis):

-Negligible uncertainties on known matrix parameters and matter density - Background (5%) - Mass hierarchy is allowed to vary.

Determining θ_{13} sensitivity: Fit the appearance spectrum generated for a particular θ_{13}, δ_{cp} to the oscillation hypothesis with $\theta_{13} = 0$.

CP-violation sensitivity: Fit the appearance spectrum to the oscillation hypothesis with $\delta_{cp} = 0$ and π. Take the worst χ^2. θ_{13} floats in the fit.

sign(Δm^2_{31}): Fit the appearance spectrum to the oscillation hypothesis with the opposite mass hierarchy. BOTH θ_{13} and δ_{cp} float in the fit.

Sensitivity comparison

The sensitivity reach is given as

the *minimal* value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values have $\geq 3\sigma$ reach

for the choice of mass hierarchy with worst sensitivity.

Total exposure assumes equal amounts of ν and $\bar{\nu}$:

Beam	Baseline	Detector	Exposure (MW.yr*)	$\theta_{13} \neq 0$	CPV	$sign$ (Δm^2_{31})
NuMI ME, 0.9°	810 km	NOνA 20 kT	6.8	0.015	$>$ 0.2	0.15
NuMI ME, 0.8°	810 km	LAr 100 kT	6.8	0.002	0.03	0.05
NuMI LE, 0.8°, 3°,	810,700 km	LAr 2 $\times$ 50 kT	6.8	0.005	0.04	0.04
WBLE 120GeV, 0.5°	1300km	LAr 100 kT	6.8	0.0025	0.005	0.006
WBLE 120GeV, 0.5°	1300km	WCe 300 kT	6.8	0.006	0.03	0.011
WBLE 120GeV, 0.5°	1300km	WCe 300 kT	13.6	0.004	0.012	0.008

The best sensitivity is FNAL-DUSEL with a LAr-TPC

The 2$^{\rm nd}$ best is FNAL-DUSEL w/ 300 kT WCe. and NuMI off-axis w/ 100kT LAr