FNAL-Homestake Beam Design and Physics Flexibility

DUSEL Beamline Working Group Mtg, 1/5/09

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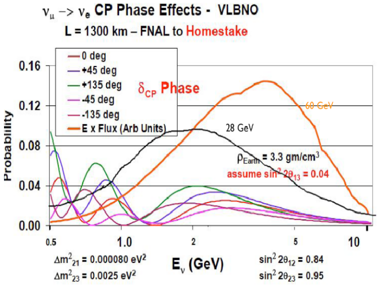
Outline

Requirements of the FNAL/Homestake Beam

The design specifications of a new WBLE beam based at the Fermilab MI are driven by the physics of $\nu_\mu \to \nu_e$ oscillations:



L = 1300 km

Requirements:

-Maximal possible neutrino fluxes to encompass the 1st and 2nd oscillation nodes, with maxima at 2.4 and 0.8 GeV.

-High purity ν_μ beam with negligible ν_e

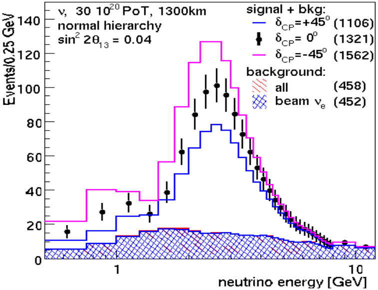
-Minimize the neutral-current feed-down contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is no sensitivity to the oscillation parameters is highly desirable.

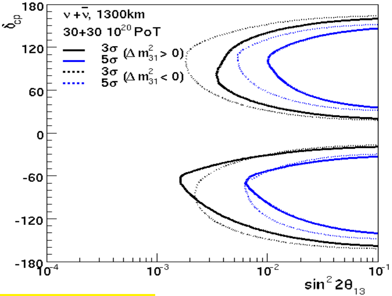
Maximizing sensitivity to CPV

CPV sensitivity with small Δm^2_{31}

Mark Dierckxsens

Latest measurement from MINOS: $\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3}\ \mathrm{eV}^2$





LAr detector - $\Delta m^2_{31} = 2.7$

CPV sensitivity with small Δm^2_{31}

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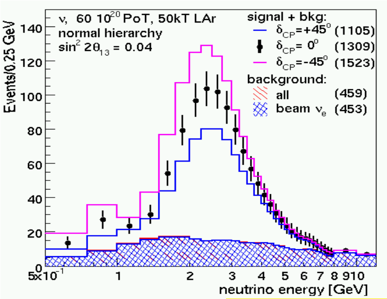
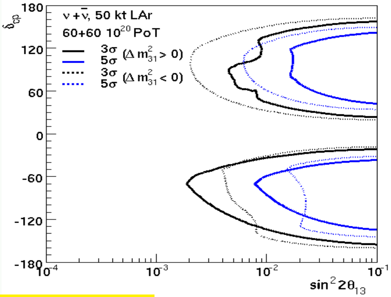
Latest measurement from MINOS: $\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3}$ eV^2





LAr detector - $\Delta m^2_{31} = 2.4$

CPV sensitivity with small Δm^2_{31}

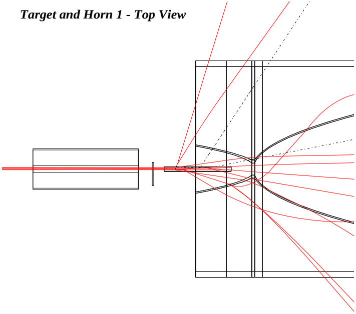
For water Cerenkov 2 possible beam design strategies to optimize CPV sensitivity

- **Strategy 1: Increase low energy flux and 2nd oscillation maximum through improved focusing. this talk.**
- **Strategy 2: Improve S:B at low energies by reducing high energy tail using beam plugs.**

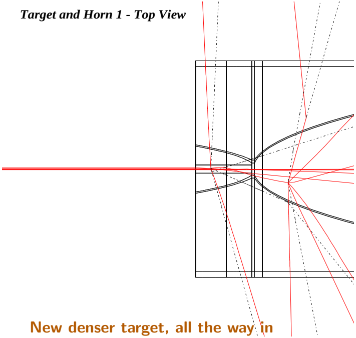
Optimization of target/focusing system design for CPV

Strategy 1: Optimize focusing to maximize ν_μ flux at 2nd oscillation maximum using NuMI-like horns

Insert CC target (r=6mm,L=80cm,$\rho = 2.1$ g/cm^3) into NuMI Horn1, increase current to 250kA:



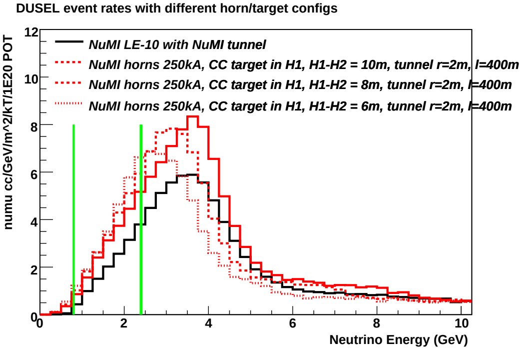
Default NuMI target/fin/baffle



New denser target, all the way in

Optimizing DUSEL spectra with NuMI horns

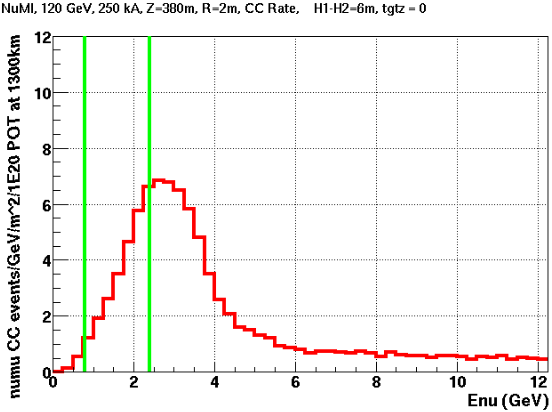
1-Decrease separation between Horn1 and Horn2 (fully embedded target)



Moving the horns closer increases the low energy flux

Are embedded targets necessary?

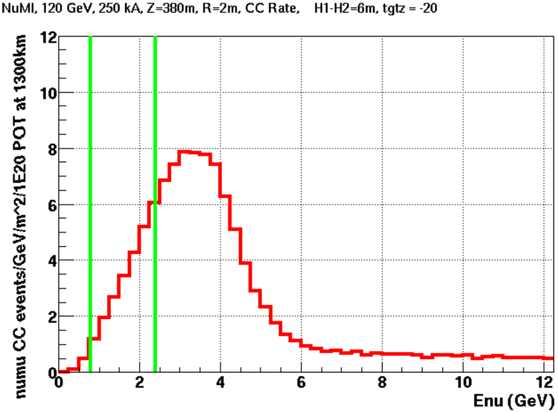
2- Target position in Horn 1. H1-H2 = 6m



Target fully embedded in horn

Are embedded targets necessary?

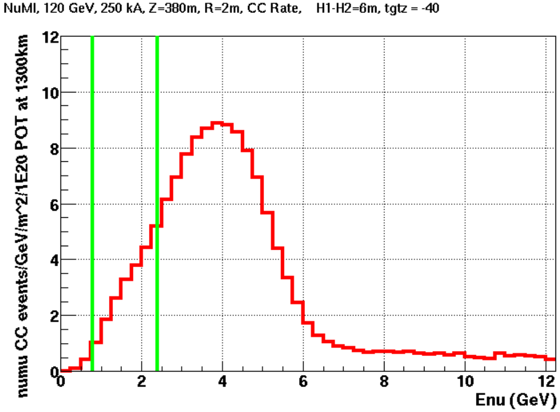
2- Target position in Horn 1. H1-H2 = 6m



Target pulled out 20cm from Horn 1 face

Are embedded targets necessary?

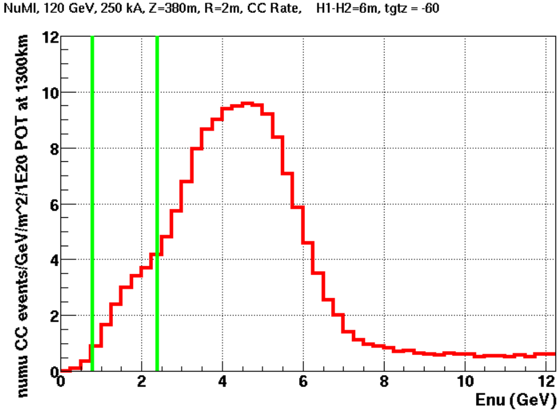
2- Target position in Horn 1. H1-H2 = 6m



Target pulled out 40cm from Horn 1 face

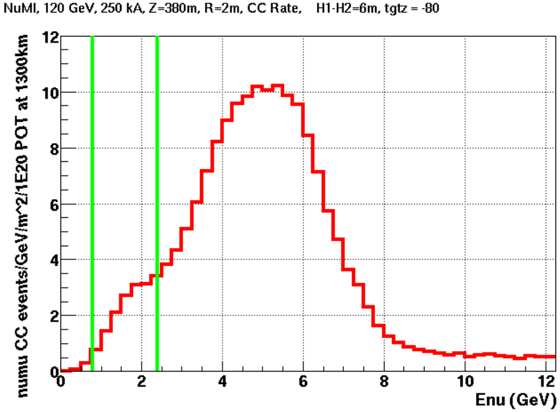
Are embedded targets necessary?

2- Target position in Horn 1. H1-H2 = 6m



Target pulled out 60cm from Horn 1 face

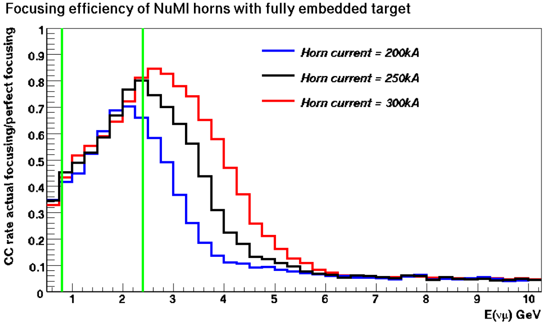
2- Target position in Horn 1. H1-H2 = 6m



Target pulled out 80cm from Horn 1 face

Current focusing efficiencies

Simulated "perfect" focusing by setting hadron $p_t = 0, p_z = p_{tot}$ at production point from target surface and using GEANT to propagate hadrons through the beamline.
With an 80cm target fully embedded in NuMI horn1, ν_μ rates at 1300km with realistic/perfect focusing are:



Can we improve the low energy focusing efficiency?

Strategy 2: Reducing the HE tails

Lessons learned from early NuMI design studies with various beam plugs placed between NuMI/MINOS horn 1 and horn 2. This study was conducted using the NuMI standard LE beam tune:

Plug configuration			Energy range (GeV)			
Material	Length	Location	0-3	3-6	6-10	10-50
Graphite	1.5m	4m	-7.6%	-2.5%	-26%	-70%
Graphite	2.5m	3.5m	-10%	-3.4%	-41%	-82%
Copper	1.5m	4.0m	-11%	-4.8%	-38%	-85%

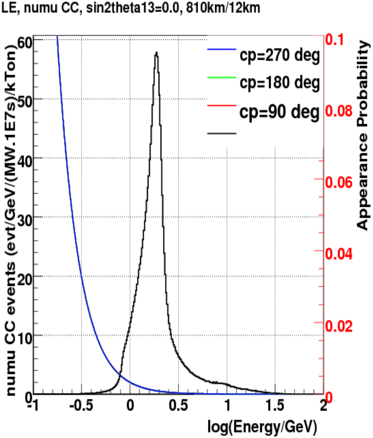
Effect on $\bar{\nu}$ rates??

Sensitivity to ν_e appearance for $\sin^2 2\theta_{13} < 0.005$

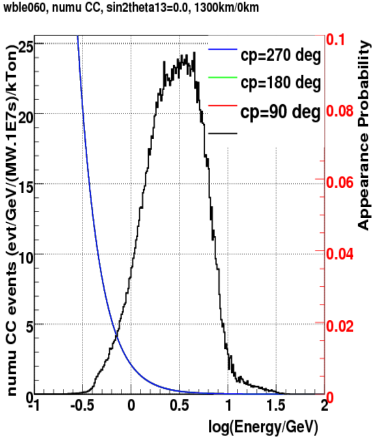
ν_e Appearance Probabilities

Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV^2,

NuMI off-axis at 810 km



WBLE 60 GeV at 1300km



$P(\nu_\mu \to \nu_e, \delta_{cp} = 0) = 0.9 \times 10^{-3}$

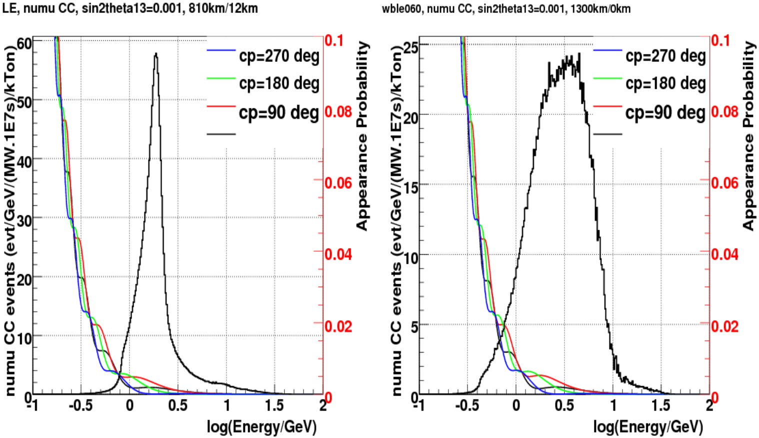
$P(\nu_\mu \to \nu_e, \delta_{cp} = 0) = 1.1 \times 10^{-3}$

$\sin^2(2\theta_{13}) = 0.000$

ν_e Appearance Probabilities

Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV^2,

NuMI off-axis at 810 km WBLE 60 GeV at 1300km



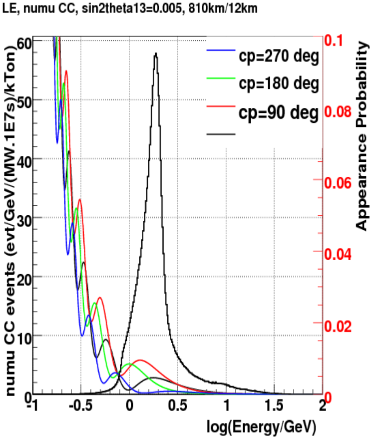
$P(\nu_\mu \to \nu_e, \delta_{cp} = 0) = 1.3 \times 10^{-3}$ $P(\nu_\mu \to \nu_e, \delta_{cp} = 0) = 1.6 \times 10^{-3}$

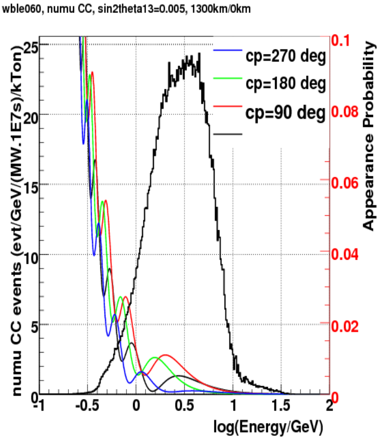
$\sin^2(2\theta_{13}) = 0.001$

ν_e Appearance Probabilities

Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV^2,

NuMI off-axis at 810 km | **WBLE 60 GeV at 1300km**





$P(\nu_\mu \to \nu_e, \delta_{cp} = 0) = 3.0 \times 10^{-3}$

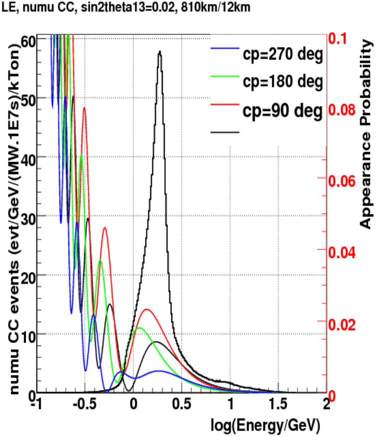
$P(\nu_\mu \to \nu_e, \delta_{cp} = 0) = 3.2 \times 10^{-3}$

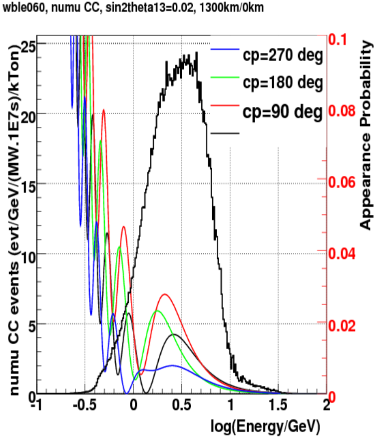
$\sin^2(2\theta_{13}) = 0.005$

ν_e Appearance Probabilities

Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV^2,

NuMI off-axis at 810 km | **WBLE 60 GeV at 1300km**





$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 8.9 \times 10^{-3}$

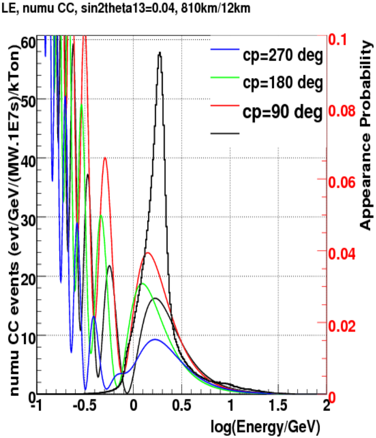
$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 9.1 \times 10^{-3}$

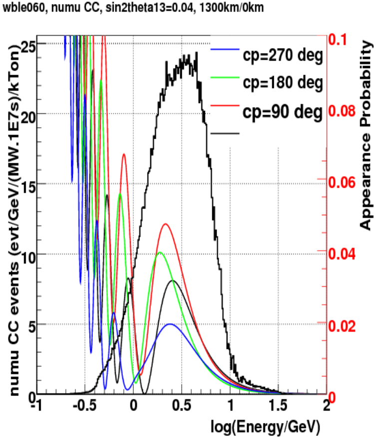
$\sin^2(2\theta_{13}) = 0.02$

ν_e Appearance Probabilities

Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV^2,

NuMI off-axis at 810 km — WBLE 60 GeV at 1300km





$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 1.7 \times 10^{-2}$

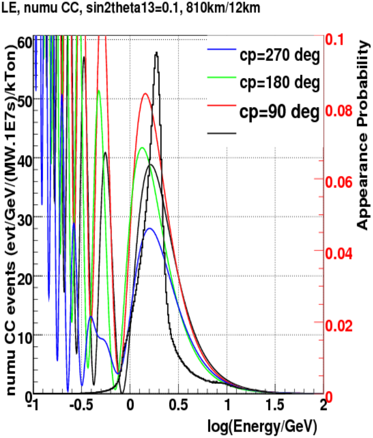
$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 1.7 \times 10^{-2}$

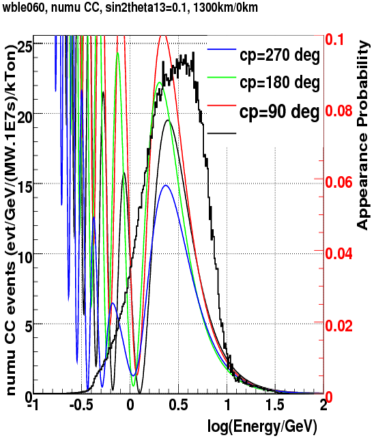
$\sin^2(2\theta_{13}) = 0.04$

ν_e Appearance Probabilities

Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV^2,

NuMI off-axis at 810 km | **WBLE 60 GeV at 1300km**



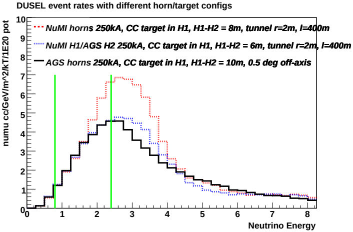


$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 4.0 \times 10^{-2}$

$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 3.9 \times 10^{-2}$

$\sin^2(2\theta_{13}) = 0.1$

Raw event rates



ν_μ rates at 1300km:

AGS horns (WBLE) 120 GeV 9mrad off-axis: 18,000 unoscillated ν_μ CC/100 kT/MW.yr (10^{21}) POT 7,600 oscillated ν_μ CC

Oscillated appearance rates at 1300km:

		$\nu_\mu \to \nu_e$ rate				$\bar{\nu}_\mu \to \bar{\nu}_e$ rates			
(sign of Δm^2_{31})	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	-90°	180°	$+90^\circ$	0°	-90°	180°	$+90^\circ$
WBLE beams at 1300km, per 100kT/MW. yr (10^{21}) POT									
wble 120 GeV, 9 mRad off-axis		Beam ν_e = 94**				Beam $\bar{\nu}_e$ = 34**			
(+/-)	0.0	28	N/A	N/A	N/A	10	N/A	N/A	N/A
(+)	0.005	62	110	70	24	18	6	14	26
(-)	0.005	38	70	50	18	28	8	22	42
(+)	0.02	174	268	190	96	40	14	30	54
(-)	0.02	78	144	102	38	76	38	66	104

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

1yr $= 2 \times 10^7$s $\Rightarrow$ 1 MW. yr $= 10^{21}$ POT at 120 GeV

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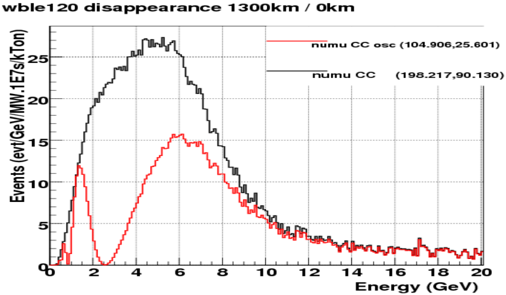
Physics with $\nu_\mu \longrightarrow \nu_{\mu,\tau}$

Precision measurements of ν_τ appearance

Using wide-band WBLE 120 GeV on-axis beam with a 4m diameter 400m length decay tunnel:



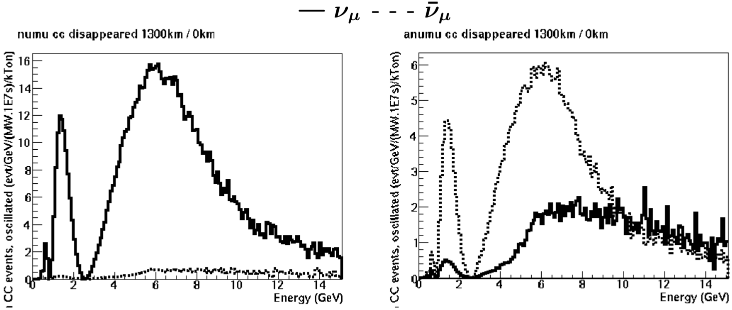
ν_μ rates: 4000 unosc CC/10kT/MW.yr (10^{21} POT), 2000 osc CC/10kT/MW.yr

Assuming lepton universality $\sigma^{CC}(\nu_\tau)/\sigma^{CC}(\nu_{\mu,e}) = 1.0$:

We expect 1280 ν_τ CC/10kT/MW.yr $\geq$ 3.2 GeV

- **For a smaller LAr detector we can see 100's of ν_τ appear (compared to 3-4 events in DONUT and $\sim$ 10? in OPERA)**
- **For water Cerenkov ν_τ QE interactions followed by $\tau \to \mu, e$ will**

Measuring Δm^2_{32} and $\Delta \bar{m}^2_{32}$



Neutrino running | Anti neutrino running

- **Separation of QE $\nu_\mu, \bar{\nu}_\mu$ interactions is possible in a non-magnetized detector - using μ lifetime and $\cos\theta_\mu$, angle of the outgoing muon w.r.t beam** (MiniBoone Nucl. Phys. Proc. Suppl. 159, 79(2006)).

DUSEL LB experiments = the best measurement of Δm^2_{32} and $\Delta \bar{m}^2_{32}$

$\nu_\mu, \bar{\nu}_\mu$ disappearance provide precision tests of CPT, sterile neutrino models, Lorentz violation...etc.

Summary and conclusions

Physics Sensitivities

Physics sensitivity with WCe, 3σ for all δ_{cp} (θ_{13}, hier)/50% δ_{cp} (CPV)

Beam	Det size (FIDUCIAL)	Exposure $\nu + \bar{\nu}$	bkgd uncert	$\sin^2 2\theta_{13}$	sign(Δm^2_{31})	CPV
NuMI/HStake	100kT	700kW 2.6+2.6yrs	5%	0.018	0.044	> 0.1
120 GeV	100kT	1MW 3+3yrs	5%	0.014	0.031	> 0.1
9mrad off-axis	300kT	1MW 3+3yrs	5%	0.008	0.017	0.025
	300kT	1MW 3+3yrs	10%	0.009	0.018	0.036
	300kT	2MW 3+3yrs	5%	0.005	0.012	0.012
	300kT	2MW 3+3yrs	10%	0.006	0.013	0.015

NB: Flux at 1st oscillation maximum has increased by 25% since these calculations

Summary

- **To improve CPV violation at lower Δm^2_{31} we need to increase flux at lower energies.**
- **Using an embedded target in the NuMI horns running with 250kA, we can achieve 80% focusing efficiency at the 1st oscillation maxima and 40% focusing efficiency at the 2nd oscillation maxima. We can still gain with a 120 GeV on-axis beam by improving low energy focusing efficiency.**
- **If we can measure the intrinsic ν_e background to $1-2\%$, then using a large detector with excellant S:B, we can observe ν_e appearance even if $\theta_{13} = 0$.**
- **High precision measurements of $\nu_\mu, \bar{\nu}_\mu$ disappearnce test universality, CPT, Lorentz violation, sterile neutrino models, light gauge boson models.**
- **Large appearance signal of ν_τ above the τ production threshold.**

Plans

- **Improving CPV sensitivity:**
  - **Explore some more horn design options to improve focusing efficiency at low energies - make horn bigger?.**
  - **Pursue Strategy 2 - improving S:B at the 2nd oscillation maxima - studies using beam plugs to cut high energy tails.**
  - **Adjustable off-axis targeting systems?**
- **Explore improving ν_τ physics sensitivity using an adjustable focusing system.**
- **Explore requirements for determining the θ_{23} quadrant.**