LBNE Physics
LBNE Physics with $\nu_\mu \to \nu_e$ at 1300km
Physics with $\nu_\mu \to \nu_\tau$
Recap of beam options considered
Sensitivities for various beam options
LBNE physics at low energies
Summary

LBNE Physics and Beam Designs

AHIPA Workshop, 10/10/09

Mary Bishai, Brookhaven National Lab

October 20, 2009

Outline

1 LBNE Physics
- LBNE
- Physics with $\nu_\mu \rightarrow \nu_e$ at 1300km
- Physics with $\nu_\mu \rightarrow \nu_\tau$

2 Recap of beam options considered

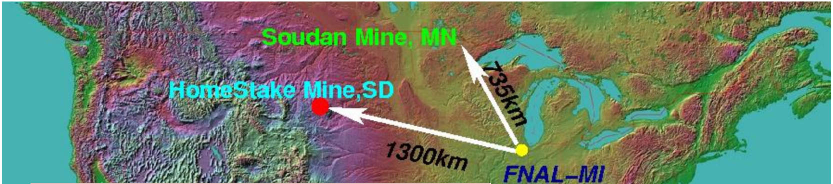
3 Sensitivities for various beam options

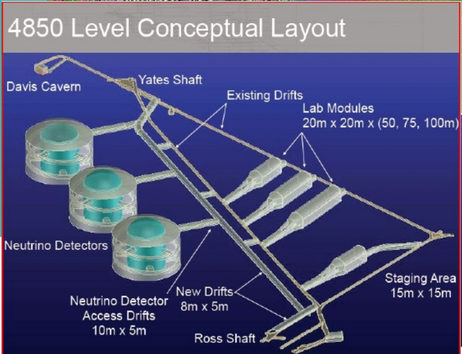
4 LBNE physics at low energies

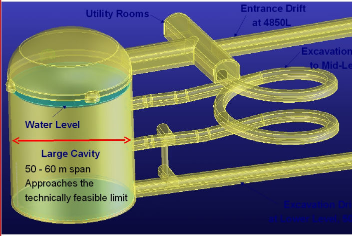
5 Summary

The Long Baseline Neutrino Experiment

A Long Baseline Neutrino Experiment (LBNE) from Fermilab to megaton scale detectors at Homestake is now being designed. CDR late 2010.

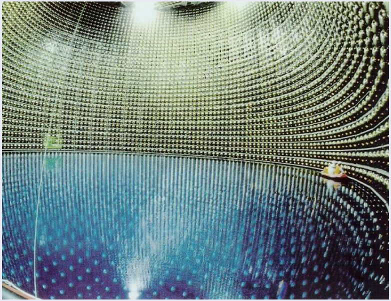






DUSEL Detectors

Water Cerenkov: 300kT

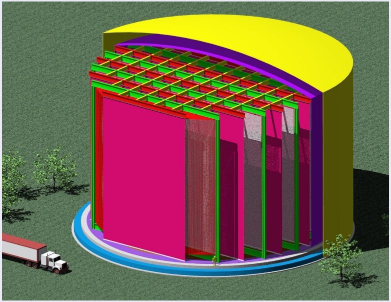


3 100kT models
$\approx$ 55m diameter, $\approx$ 60m height
60K 10" PMTs/module (25% coverage)

Known technology 2 – 3× SuperK

Higher backgrounds, low efficiency

Liquid Argon TPC: 50kT



Small prototype in the NuMI beam. Hand scanning and prelim automated MC studies (Tufts U., Yale).

High efficiency and purity

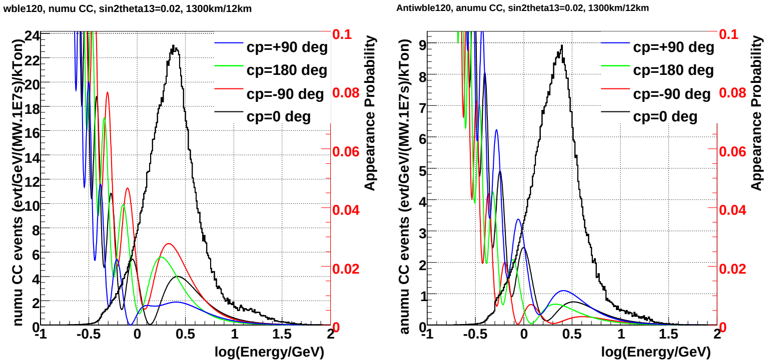
Requires 100× scale-up - unproven.

Physics with $\nu_\mu \rightarrow \nu_e$ at 1300km

Appearance probabilities of $\nu_\mu \rightarrow \nu_e$ at 1300km for different values of the CP phase:

Normal Hierarchy, $\sin^2 2\theta_{13} = 0.02$

ν $\bar{\nu}$

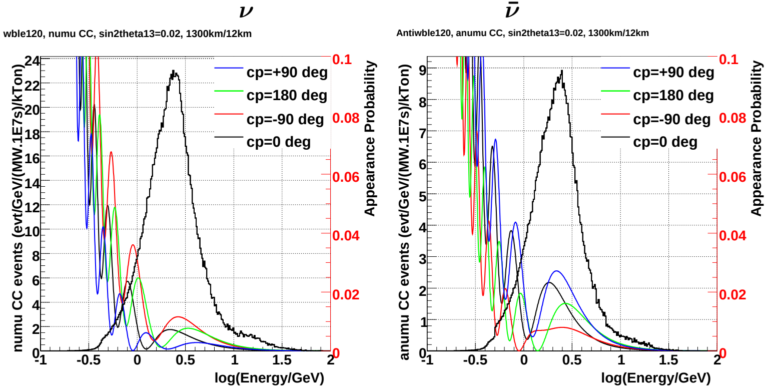


CP effects largest $E_\nu < 3$ GeV.

Physics with $\nu_\mu \rightarrow \nu_e$ at 1300km

Appearance probabilities of $\nu_\mu \rightarrow \nu_e$ at 1300km for different values of the CP phase:

Reversed Hierarchy, $\sin^2 2\theta_{13} = 0.02$



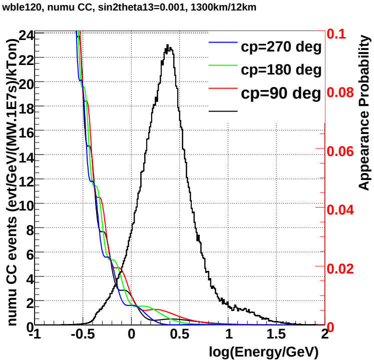
Matter effects large $E_\nu > 1.5$ GeV.

Physics with $\nu_\mu \longrightarrow \nu_e$ at 1300km

Appearance probabilities of $\nu_\mu \longrightarrow \nu_e$ at 1300km for different values of the CP phase:

Normal Hierarchy, $\sin^2 2\theta_{13} = 0.001$

ν $\bar{\nu}$



ν_e appears from solar term at $E_\nu < 1.0$ GeV $\Rightarrow$ measure $\sin^2(\theta_{23})$

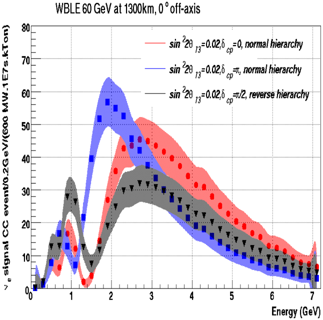
Sample Appearance Rates (no detector simulated)

Long baseline accelerator $\nu_\mu \to \nu_e$ appearance. 300 kT. MW. yr:

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



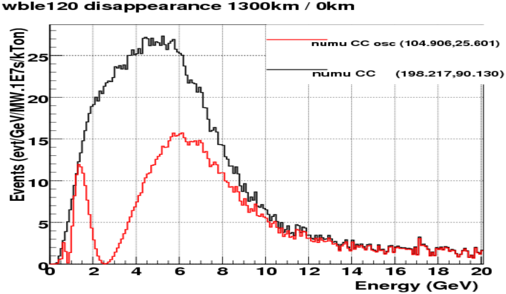
A wide-band beam at 1300km

V. Large detectors (100 kT+) + powerful beams (MW) $(\nu + \bar{\nu})$ needed!

Wide-band beam spectral information = resolves degeneracies

Precision measurements of ν_τ appearance

Using a wide-band beam HIGH ENERGY beam:



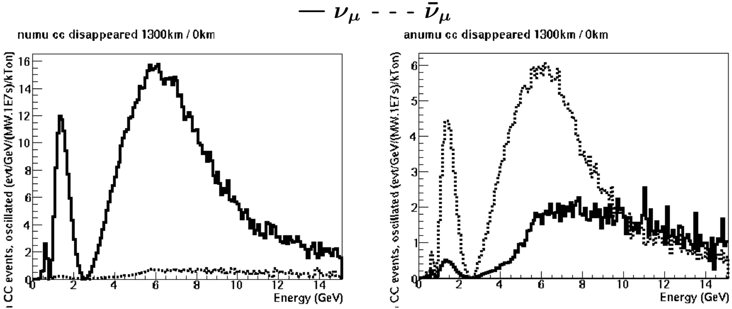
ν_μ rates: 4000 unosc CC/10kT/MW.yr (10^{21} POT), 2000 osc CC/10kT/MW.yr

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 produce an excess of single lepton events at multi GeV energies.**

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.

Beam Requirements for LBNE Physics at 1300km

We are designing a 20 YEAR program:

Physics topic	Beam characterisitcs
CPV	$E_\nu = 0.5 - 4$ GeV, significant flux at 1 GeV low ν_e contamination
Mass hierarchy	$E_\nu = 1 - 10$ GeV, more flux at higher energies
ν_τ appearance	$E_\nu = 3 - 10$ GeV peak E around 4-5 GeV
$\Delta m^2_{32}/\Delta\bar{m}^2_{32}$	$E_\nu = 1 - 10$ GeV completely cover two maxima
θ_{23} octant	$E_\nu = 0.2 - 1.5$GeV NO $\nu > 2$ GeV small low energy ν_e contamination
New physics searches	High energy νs (100's of GeV)?
Near detector physics	?

Not possible with a single wide-band beam! **We must design a tunable beam: primary proton energy 15-120 GeV, ability to put in different focusing systems (massive 100m superconducting solenoids?), change configuration of target/focusing system.**

FNAL beam power and energy

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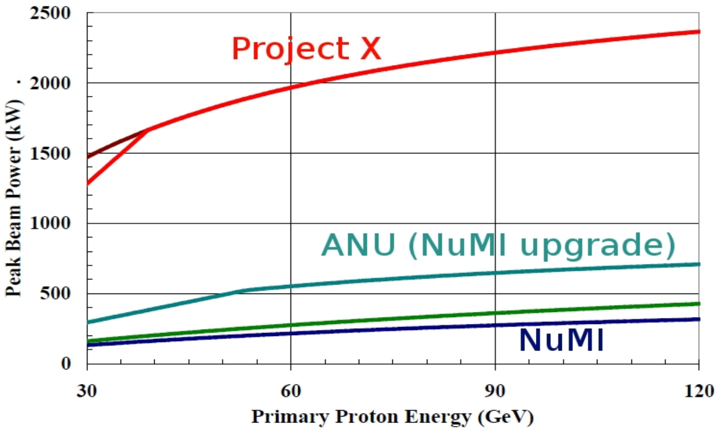


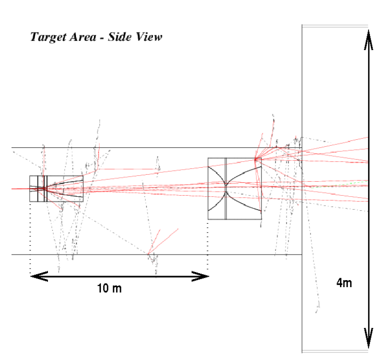
700 kW at 120 GeV is the CD1 baseline

BUT CURRENT beamline design is for 2 MW at 60-120 GeV

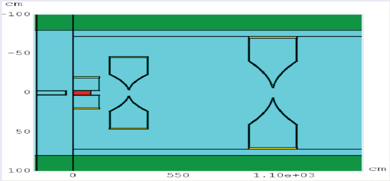
Focusing system alternatives

Two *INDEPENDANT* efforts on focusing system designs

M. Bishai Fluka05/GEANT3 (NuMI)



B. Lundberg MARS (T2K)

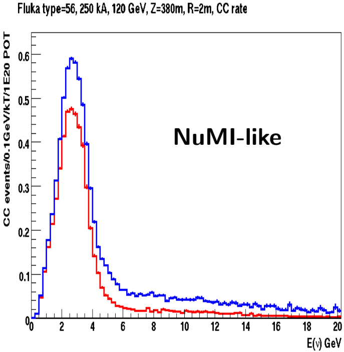


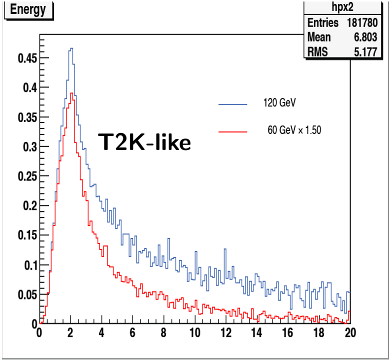
Both designs use fully embedded carbon targets and similar horn 2

In a 2 horn system, optimal separation = 6m (both designs)

Beam spectra from 2 alternatives

Using a decay pipe of 4m diameter and 250/280m (T2K/NuMI) decay length ON AXIS flux:



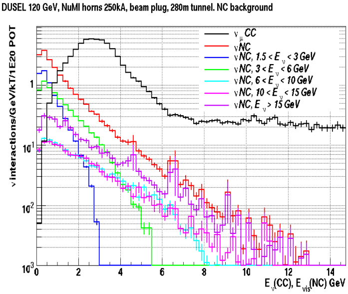


Simulation 120 GeV	0.8 GeV Rate	Peak Rate (E)	6 GeV Rate
	CC events/GeV/kT/1E20 pot at 1300km		
T2K-like	1.7	4.6 (2.0 GeV)	0.6
NuMI-like	1.2	6.2 (2.4 GeV)	1.3

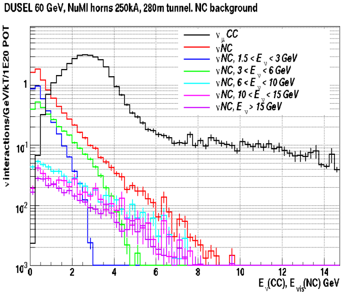
Assessing beam design options for $\nu_\mu \rightarrow \nu_e$

I estimate the NC spectrum for each beam option by using a simple exponential to parameterize the $E_\nu \rightarrow E_{vis}$ obtained from a NUANCE simulation. E_{vis} is based on the total visible energy of particles above Cerenkov threshold:

120 GeV



60 GeV



GOAL: maximize the total ν_e appearance signal rate

AND $S/\sqrt{B}$ at the 2nd oscillation peak

Optimization options considered

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Starting from a 2-horn NuMI-like focusing system, I considered the following optimization options:

- **Strategy 1: Increase low energy flux at the oscillation maximum through improved:**

  1a) target design: Size, material, position w.r.t horn 1
  1b) focusing: AGS horn design, NuMI horn design, horn material, horn separation, horn currents
  1c) beam energy: 60, 90, 120 GeV
  1d) decay pipe geometry: Diameter, length

- **Strategy 2: Improve S:B at low energies by reducing high energy tail using:**

  2a) beam energy
  2b) beam plugs
  2c) off-axis beams

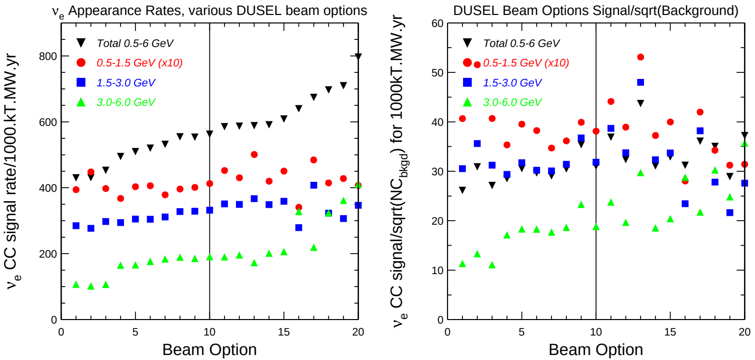
List of Simulated 2-Horn Beams

I considered over 20 variations on a 2 horn beam design using NuMI and AGS horn designs in order of the increasing total ν_e CC appearance rate at DUSEL (per MW). Option 10 is the default:

	E_{p+}	Target	horns	decay pipe	other
1	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 200kA	R=2.0m L=380m	
2	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	0.5° o.a.
3	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 200kA	R=2.0m L=380m	tgt z+20cm
4	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=1.5m L=380m	
5	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=280m	
6	120	C 2.1g/cm^3 R=1cm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	
7	120	C 1.8g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	
8	120	Be 1.9g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	
9	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	Beam plug
10	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	
11	90	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	
12	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Be dZ=6m, 250kA	R=2.0m L=380m	
13	60	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	
14	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=480m	
15	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.5m L=380m	
16	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=10m,250kA	R=2.0m L=380m	
17	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Li dZ=6m, 250kA	R=2.0m L=380m	
18	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 250kA	R=2.0m L=380m	tgt z-20cm
19	120	C 2.1g/cm^3 R=6mm L=80cm	A1N2 Al dZ=6m, 250kA	R=2.0m L=380m	
20	120	C 2.1g/cm^3 R=6mm L=80cm	NuMI Al dZ=6m, 350kA	R=2.0m L=380m	

2-Horn Beam Options Rates and Backgrounds

Using a simplified WCe detector response we can approximate the signal rates and NC backgrounds in various bins. Thus we can compare the different beam options:



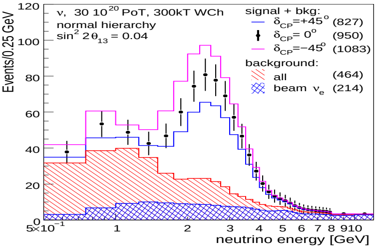
Option 20: highest horn current = highest appearance rate

Option 13: 60 GeV beam best $S/\sqrt{B}$

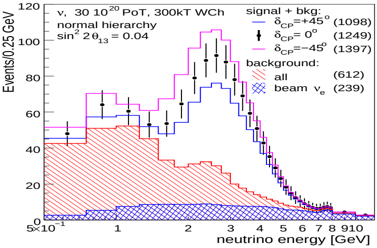
Water Cerenkov spectra for NuMI-like beams

with a 280m DP length

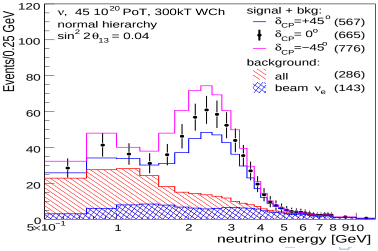
120 GeV, 250kA



120 GeV, 350kA



60 GeV, 250kA, 0.75× beam power

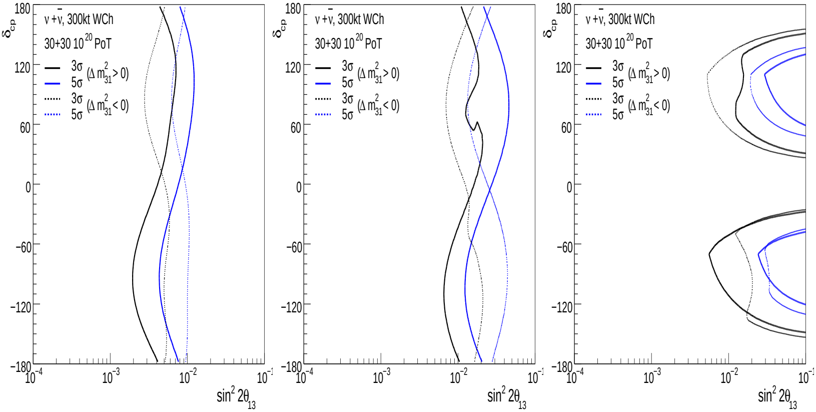


Sensitivities for various NuMI-like beam options

with a 280m DP length

Mark Dierckxsens

$\sin^2 2\theta_{13} \neq 0$ | mass hierarchy | $\delta_{cp} \neq 0, \pi$



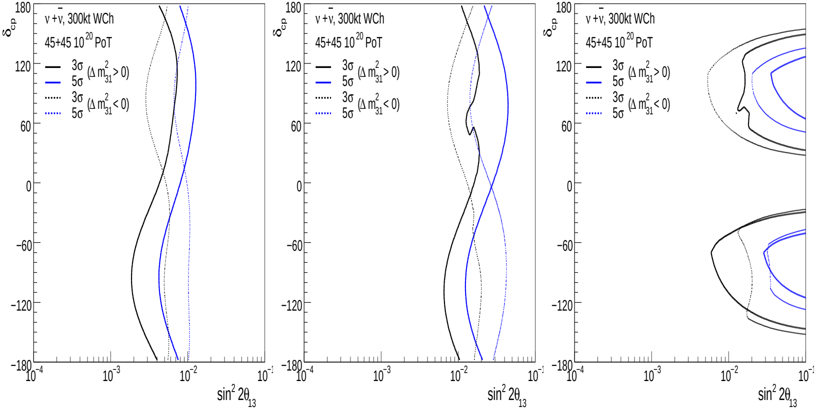
Default: 120 GeV, 250kA, no plug, 3+3 MW.yr

Sensitivities for various NuMI-like beam options

with a 280m DP length

Mark Dierckxsens

$\sin^2 2\theta_{13} \neq 0$ | mass hierarchy | $\delta_{cp} \neq 0, \pi$



Best $S/\sqrt{B}$ but 3/4 power: 60 GeV, 250kA, no plug, 2.25+2.25 MW.yr

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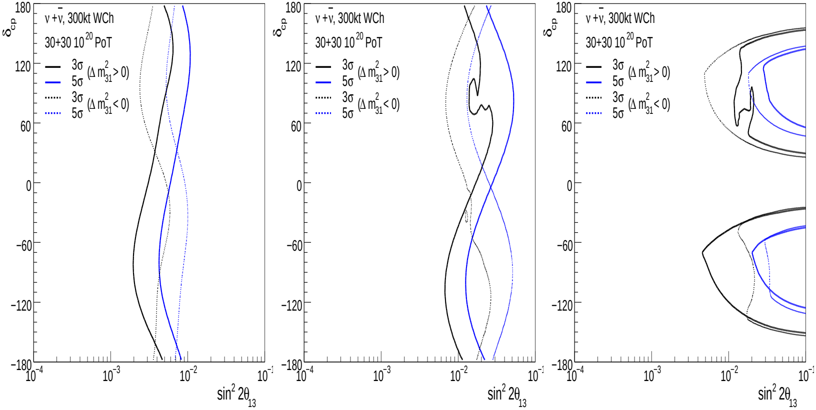
Sensitivities for various NuMI-like beam options

with a 280m DP length

Mark Dierckxsens

$\sin^2 2\theta_{13} \neq 0$ | **mass hierarchy** | **$\delta_{cp} \neq 0, \pi$**



Largest signal: 120 GeV, 350kA, no plug, 3+3 MW.yr

Sensitivity summary

Background systematic uncertainty = 5%

Minimum value of $\sin^2 2\theta_{13}$ at 3σ sensitivity:

Option	Exposure (MW.yr)	$\theta_{13} \neq 0$ all δ_{cp}	hierarchy all δ_{cp}	CPV $50\%\delta_{cp}$
	Project X			
60e250i002dr280dz*	7+7?	0.004?	0.011?	0.010?
120e250i002dr280dz	7+7	0.004	0.014	0.012
	700kW beam (at 120 GeV)			
120e350i002dr280dz**	3+3	0.006	0.025	0.017
60e250i002dr280dz*	3+3?	0.006?	0.017?	0.019?
120e250i002dr280dz_plg5	3+3	0.007	0.021	0.019
120e250i002dr280dz	3+3	0.007	0.021	0.021
60e250i002dr280dz	2.25+2.25	0.007	0.020	0.022

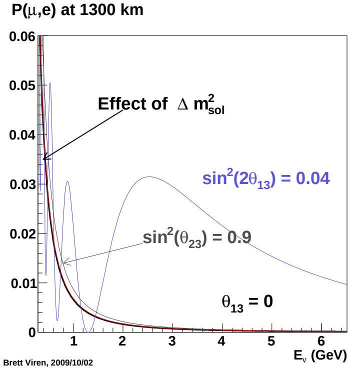
*Sensitivity was calculated for 0.75 beam power and scaled by $1/\sqrt{0.75}$

**There are islands developing in the mass hier/CPV sensitivity. I suspect its due to the worse $S/\sqrt{B}$ at the 2nd peak where you can no longer resolve δ_{cp} when there is a deficit in $P(\nu_\mu \rightarrow \nu_e)$.

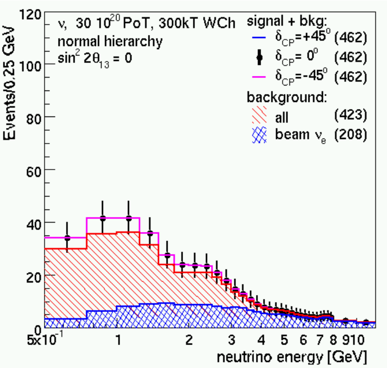
ν_e appearance at low energies

Current beam designs do not have enough flux at low energy to see ν_e *appearance due to the solar term and measure* $\sin^2\theta_{23}$ *- we can use this to determine whether* θ_{23} *is maximal:*

Appearance probability with Δm^2_{21}



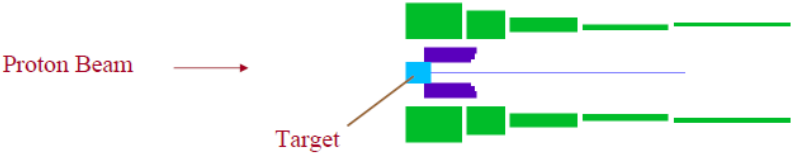
WCe appearance signal with $\theta_{13} = 0$

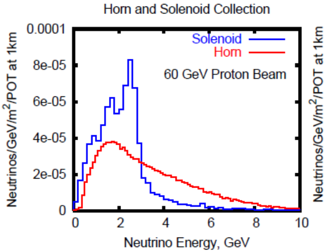


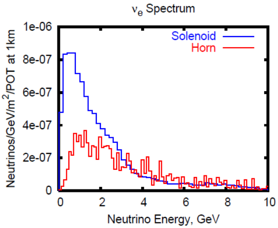
Solenoid Focusing

Harold Kirk, BNL

Novel focusing systems can enhance low energy flux:





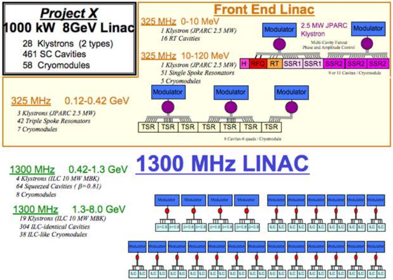


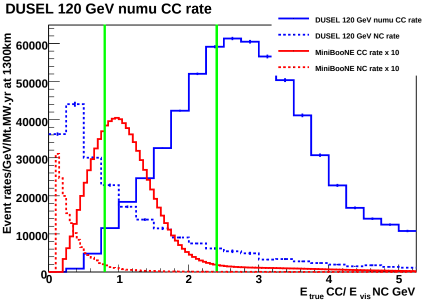
PROS: Tapered SC solenoids will produce MORE flux per POT

CONS: 30-100m long, focuses both $\nu_\mu/\bar{\nu}_\mu$

High power low energy beams?

Some Project X designs could produce 1MW at 8 GeV:





The MiniBoone flux/POT can be boosted by 2-3 (?) X by using more efficient focusing and the longer decay volume

Proposal: Combine running different beam energies from 8-120 GeV

We can improve S/$\sqrt{\mathrm{B}}$ at 2nd maxima AND access solar oscillation

WCe response

from Chiaki Yanagisawa

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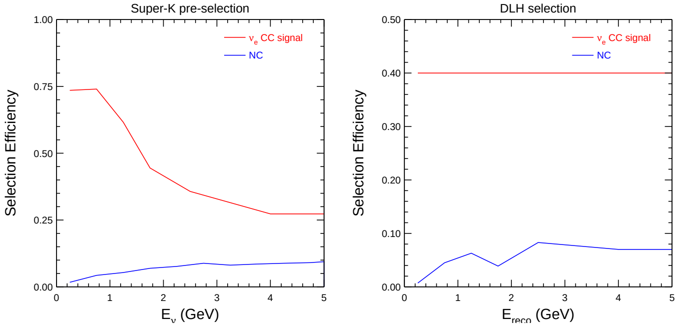
The current WCe simulation is based on SuperK MC with a single ring selection tuned to work with the high energy LBNE beam which produces large π^0 backgrounds from NC at low energies:

SuperK pre-selection eff. **Log-likelihood post-selection eff.**



A dedicated low energy beam lowers background

$\longrightarrow$ higher WCe detector efficiency

Summary and Conclusions

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- **Beam power mau be limited to 700 kW for CD1 BUT, we can increase the flux of neutrinos/POT using SMART, INNOVATIVE BEAM DESIGNS AND MATERIALS. We are NOT redesigning NuMI or T2K .**
- **We are designing a 20 YEAR PROGRAM.**
- **Increasing flux at 1st oscillation maxima improves $\sin^2 2\theta_{13}$ and mass hierarchy sensitivity, but compromises CPV. Combine runs with different beam energies (8-120GeV)?**
- **Maximizing LBNE physics flexibilty Requires different energy wide-band beam configurations. We have not yet considered the best combination needed in our beam designs.**
- **What kind of beams are needed to access new physics in neutrino interactions with matter? We may need to consider LBNE with $>$ 120 GeV.**