LBNE with Project X

Milind Diwan 11/9/2009
FNAL

Summary of calculations

- The proposal and calculations for a long baseline program with high intensity super beams and very massive detector were done by MD in 2001-2002.
- Detector and beam performance have been subject of intense scrutiny over last few years. (Mary Bishai, Mark Dierckxsens, Chiaki Yanagisawa, Ed Kearns, etc.)
- New calculations contain detailed beam simulations, and detector performance based on SuperK simulations; for Liquid argon assumption is a near perfect detector.
- There are many avenues for optimization beyond the initial calculations from nearly a decade ago. The initial calculations were most likely conservative.

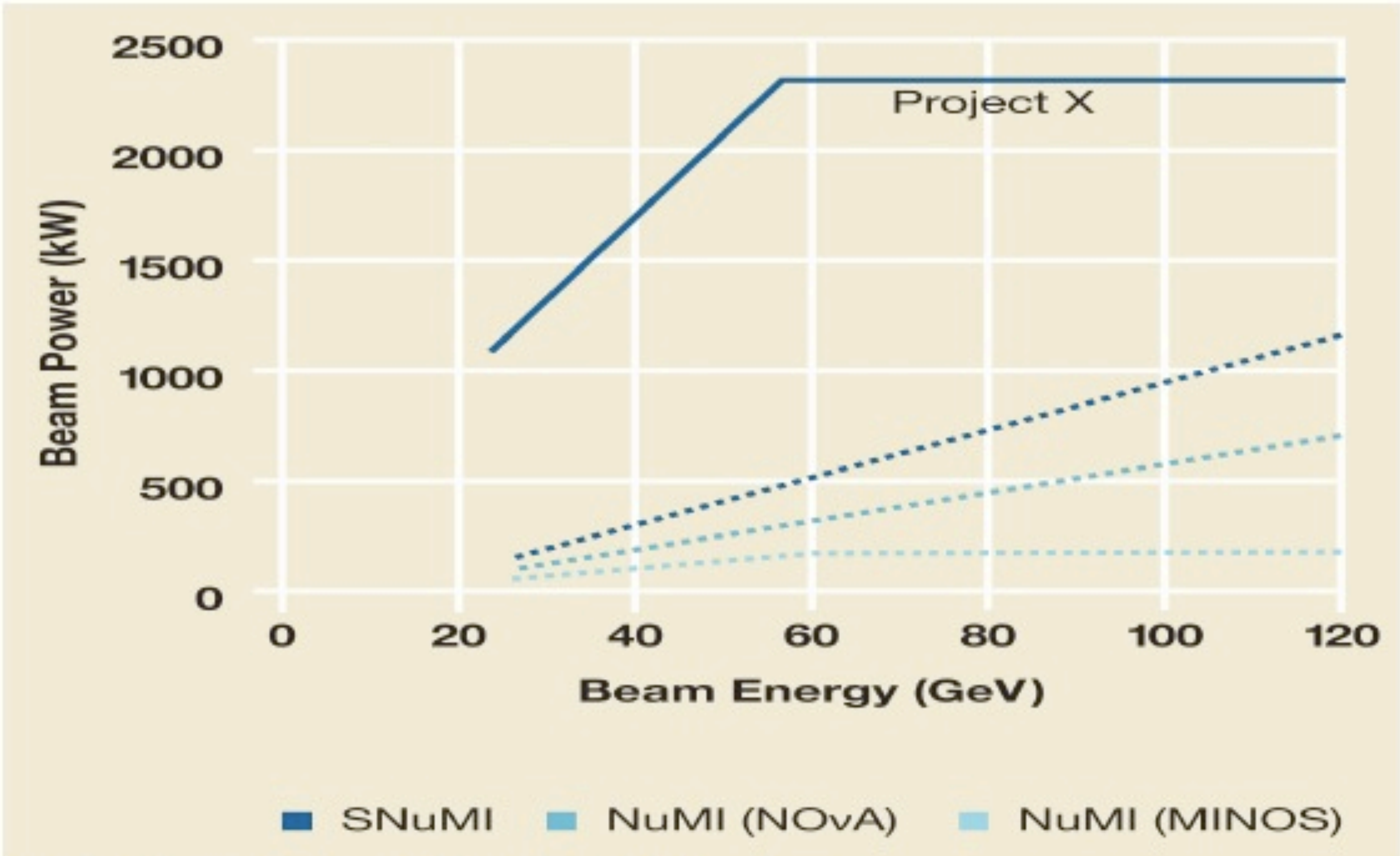
Beam Requirements for LBNE Physics at 1300km

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



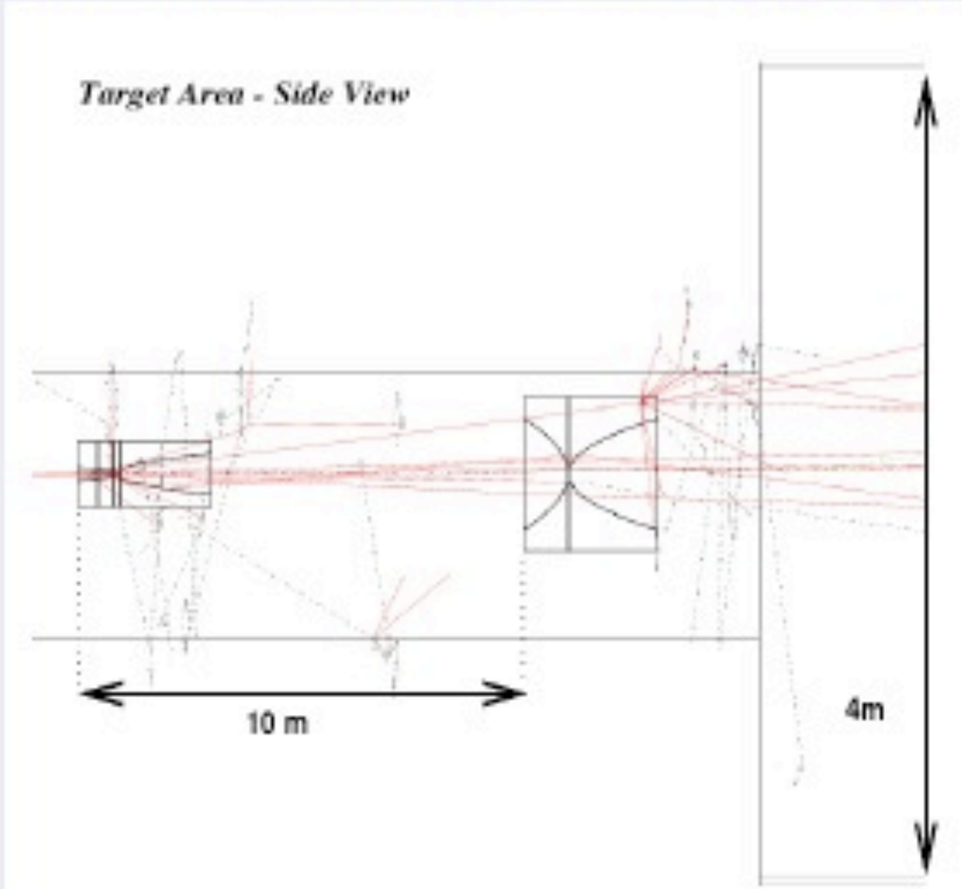
700 kW at 120 GeV is the CD1 baseline

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

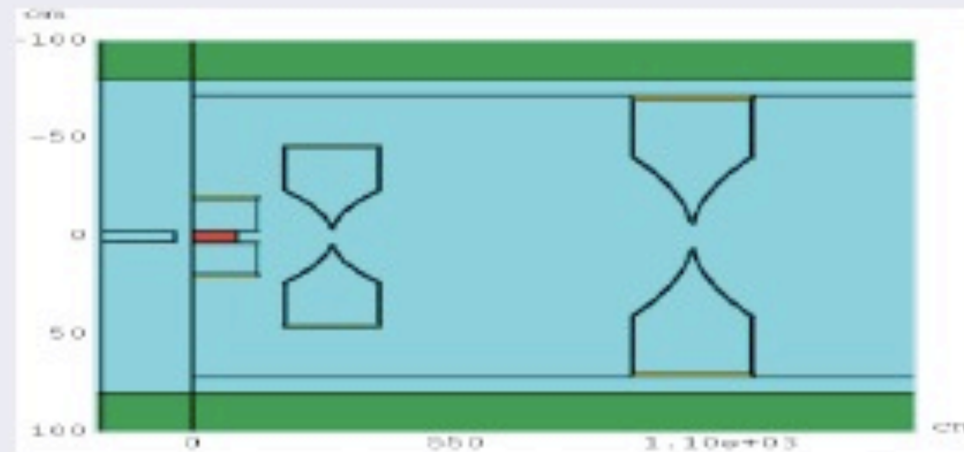
Focusing system alternatives

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)

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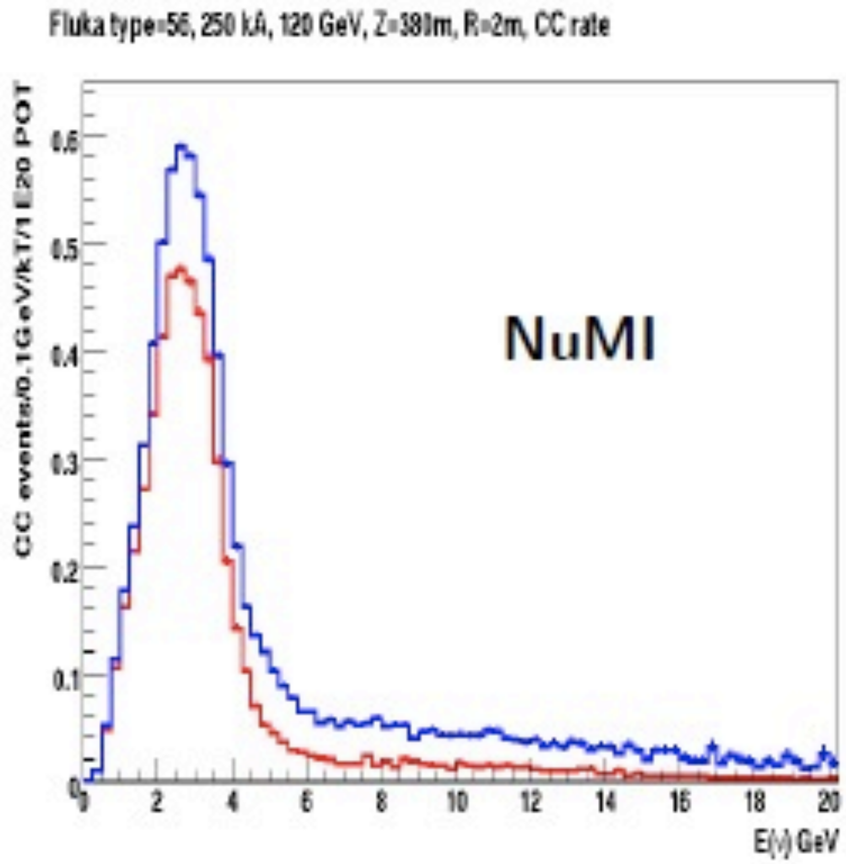
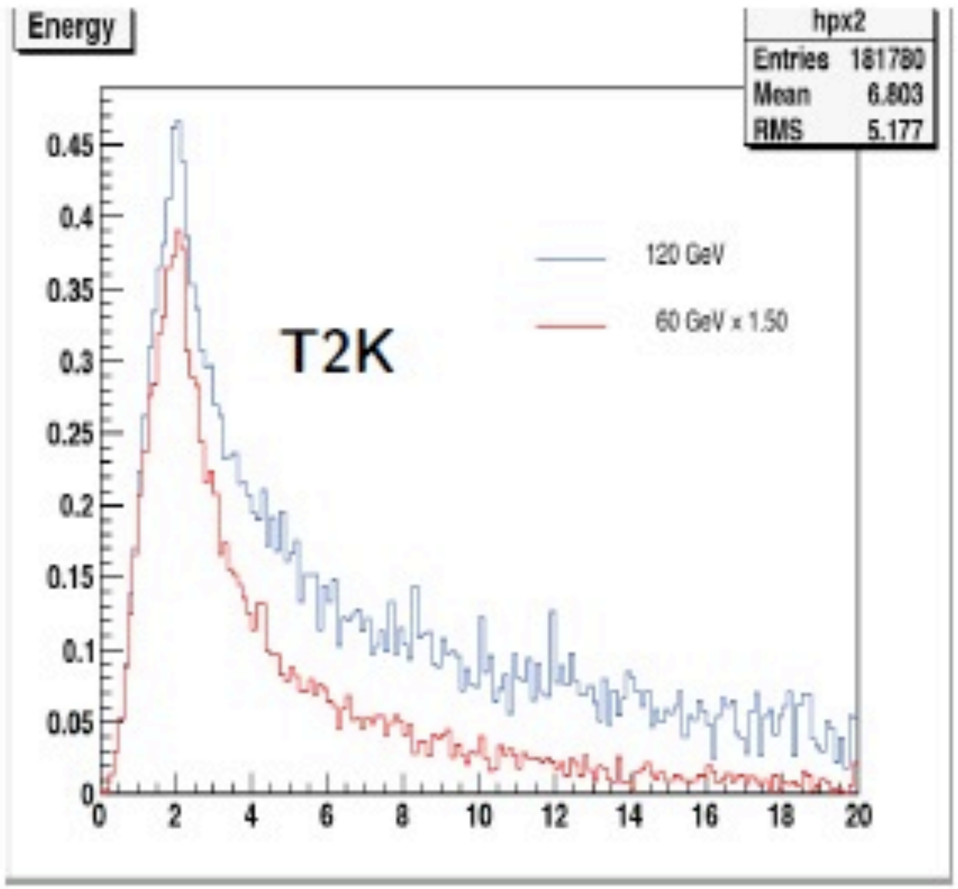
Beam spectra from 2 alternatives

LBNE Physics and Beam Designs

Mary Bishai, Brookhaven National Lab

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	1.7	4.6 (2.0 GeV)	0.6
NuMI	1.2	6.2 (2.4 GeV)	1.3

Optimization options considered

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

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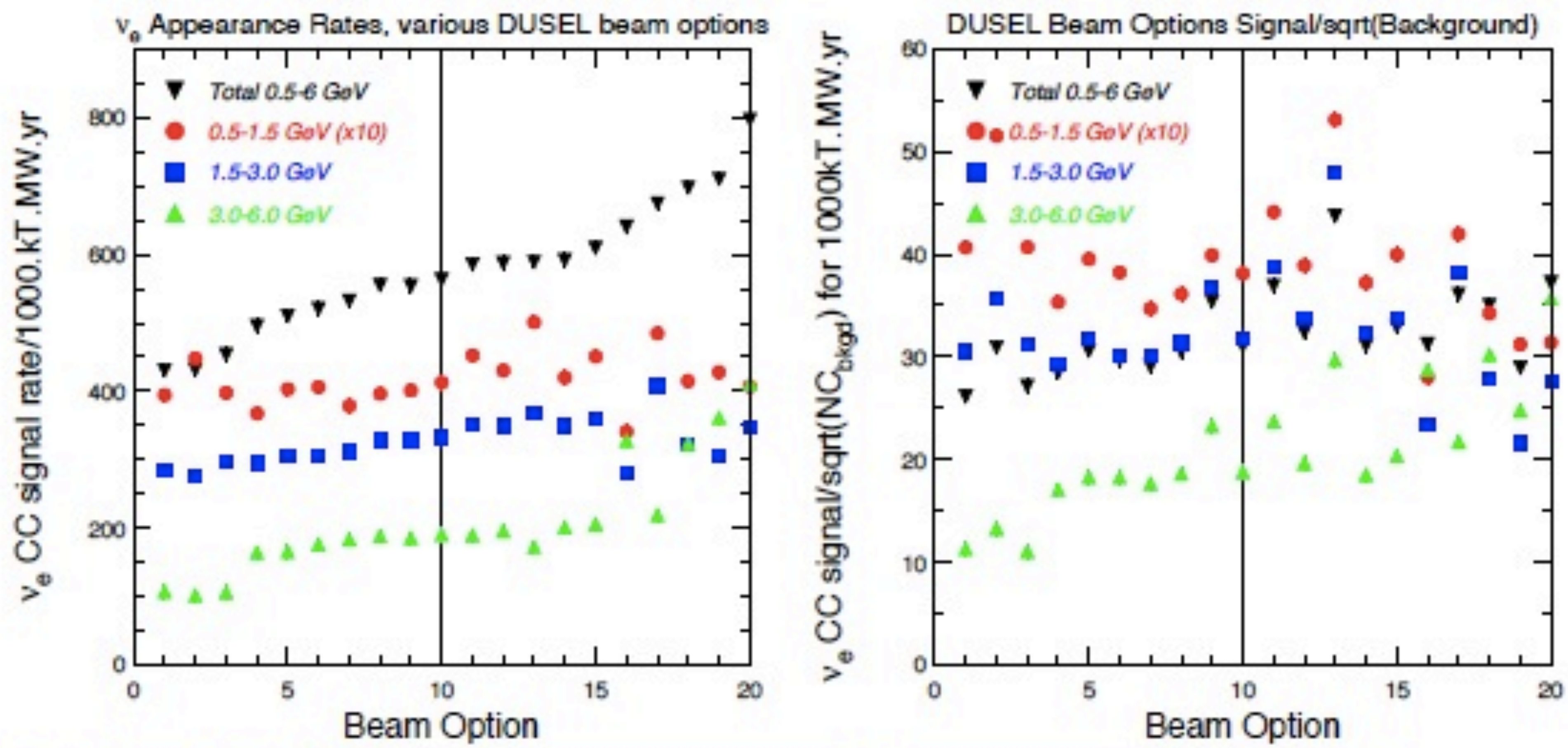
List of Simulated 2-Horn Beams

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:

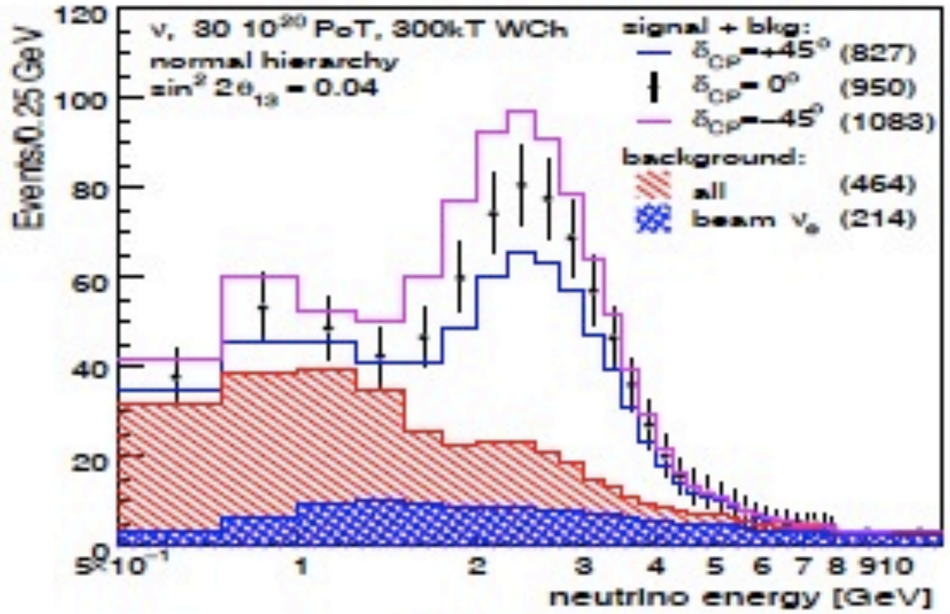


Option 20: highest horn current = highest appearance rate

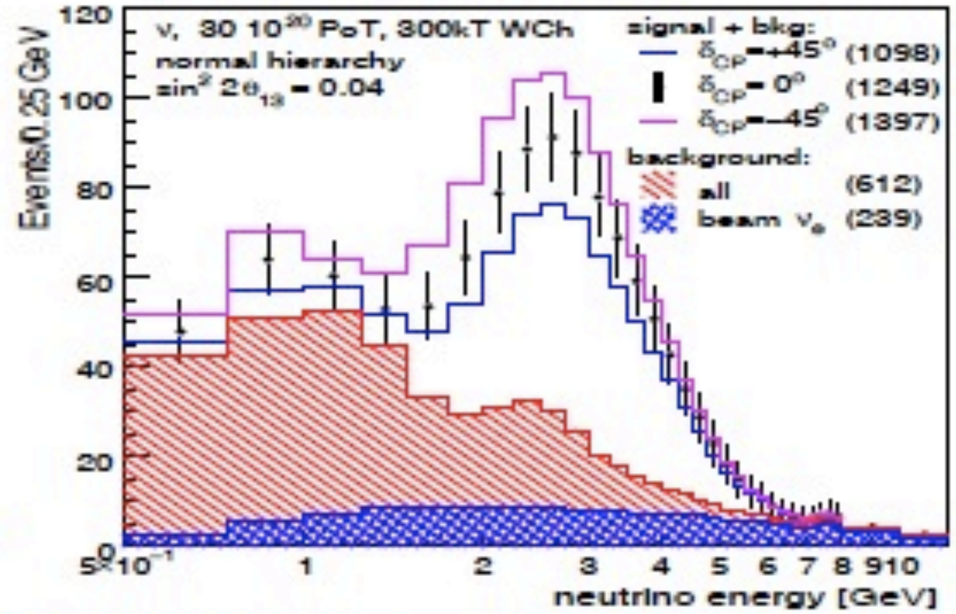
Option 13: 60 GeV beam best $S/\sqrt{B}$

Water Cerenkov spectra for NuMI-like beams
with a 280m DP length

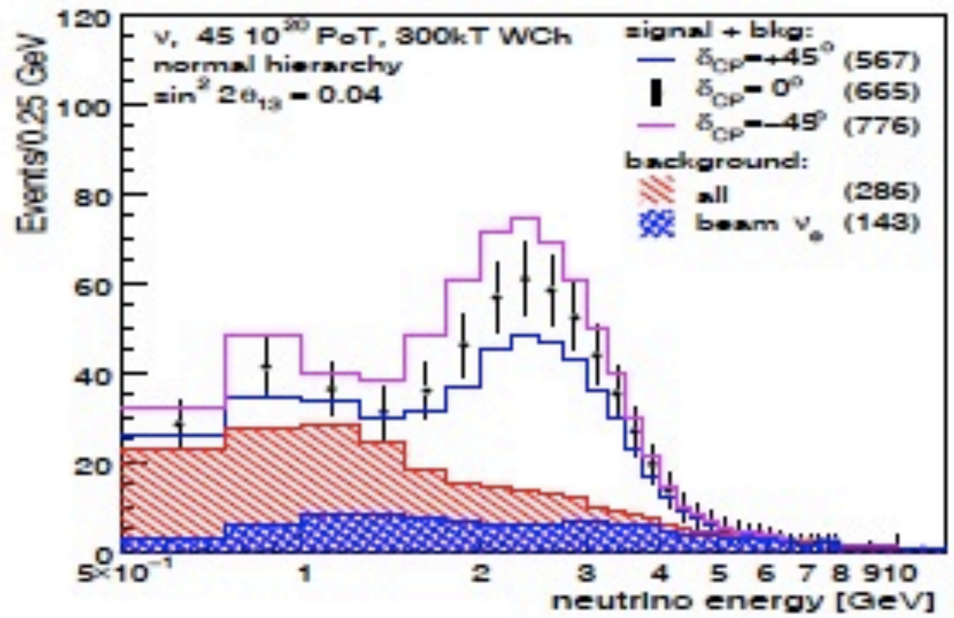
120 GeV, 250kA



120 GeV, 350kA

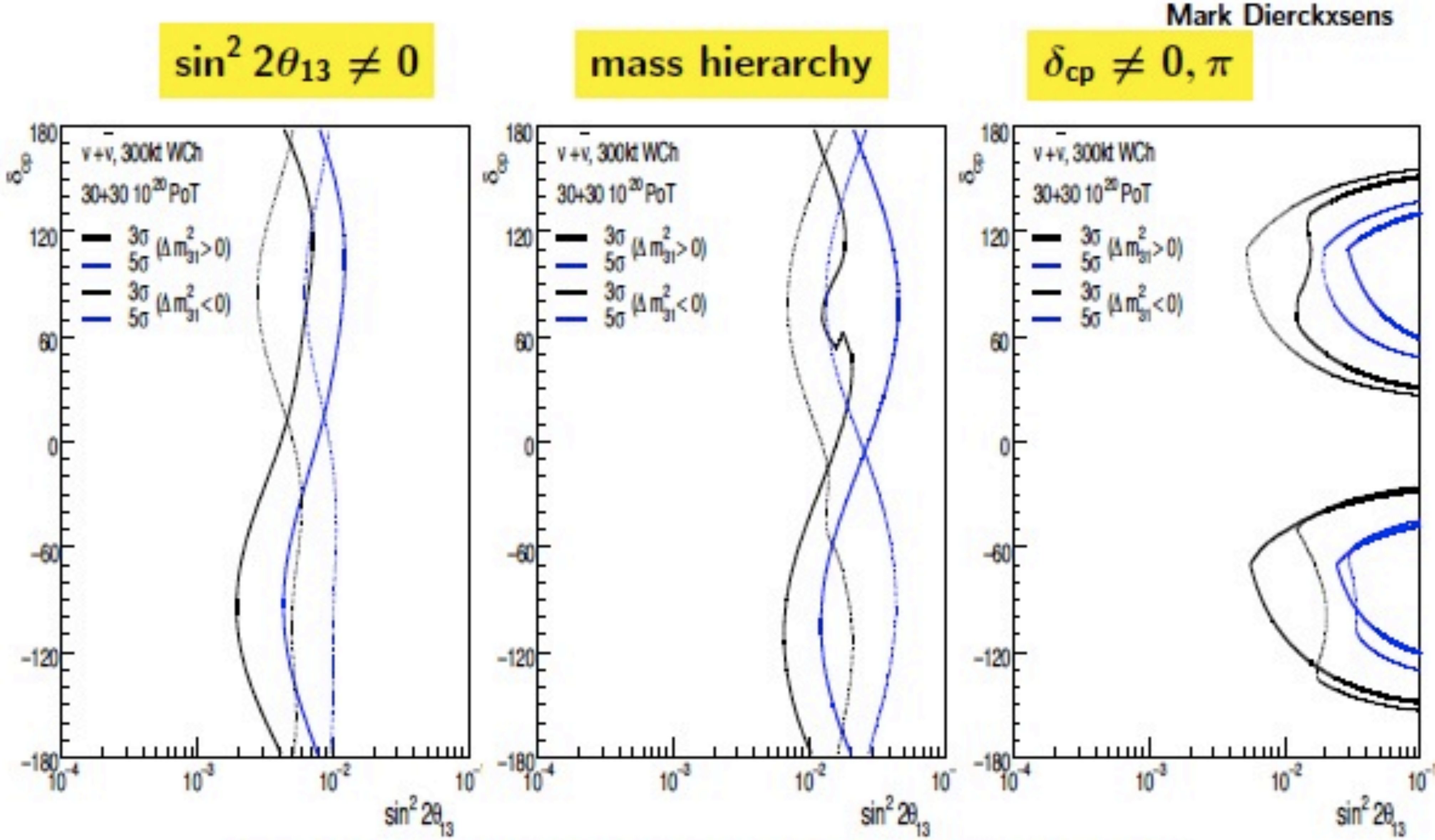


60 GeV, 250kA, 0.75× beam power



Sensitivities for various NuMI-like beam options
with a 280m DP length

Mark Dierckxsens

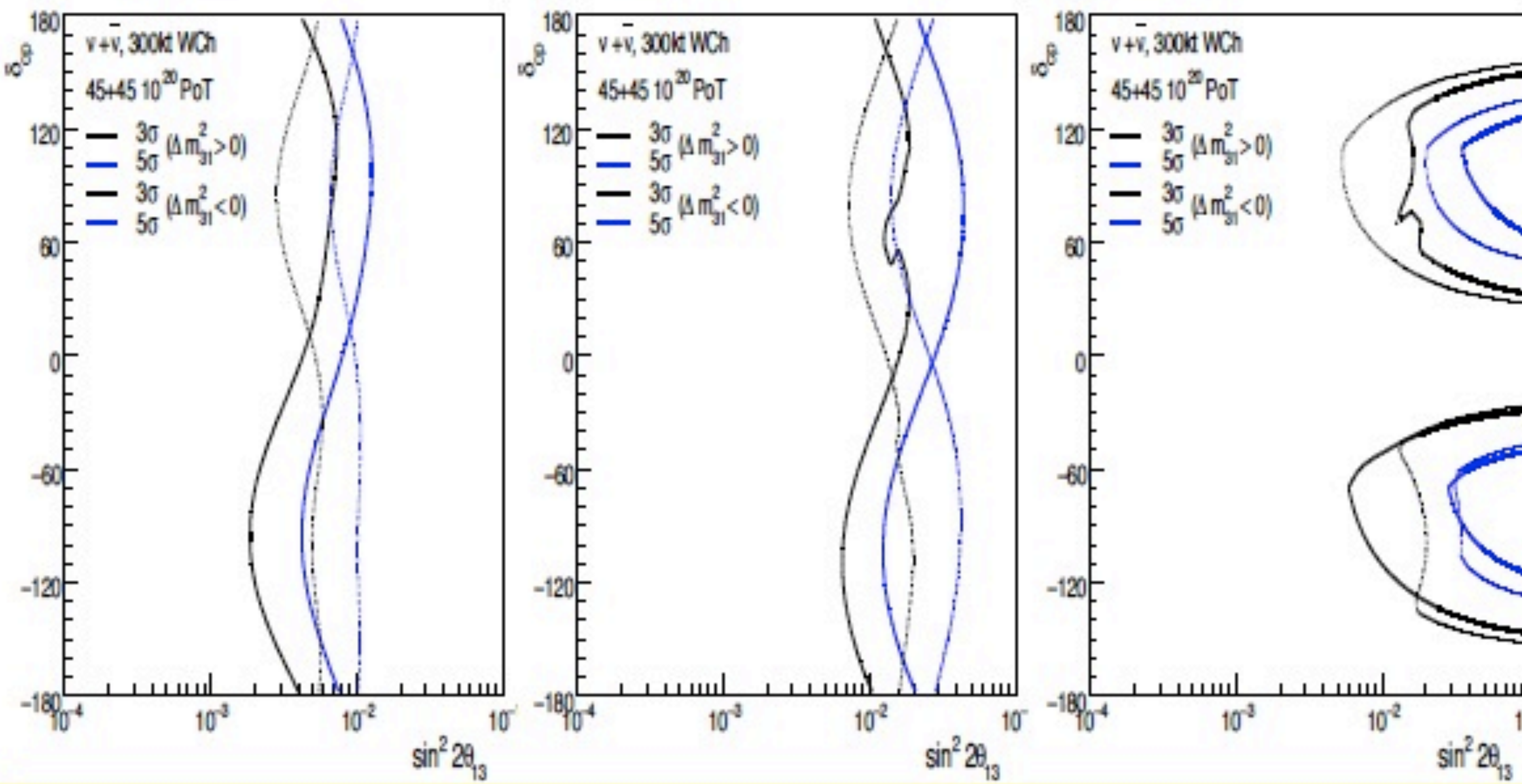


Default: 120 GeV, 250kA, no plug, 3+3 MW.yr

Sensitivities for various NuMI-like beam options
with a 280m DP length

Mark Dierckxsens

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

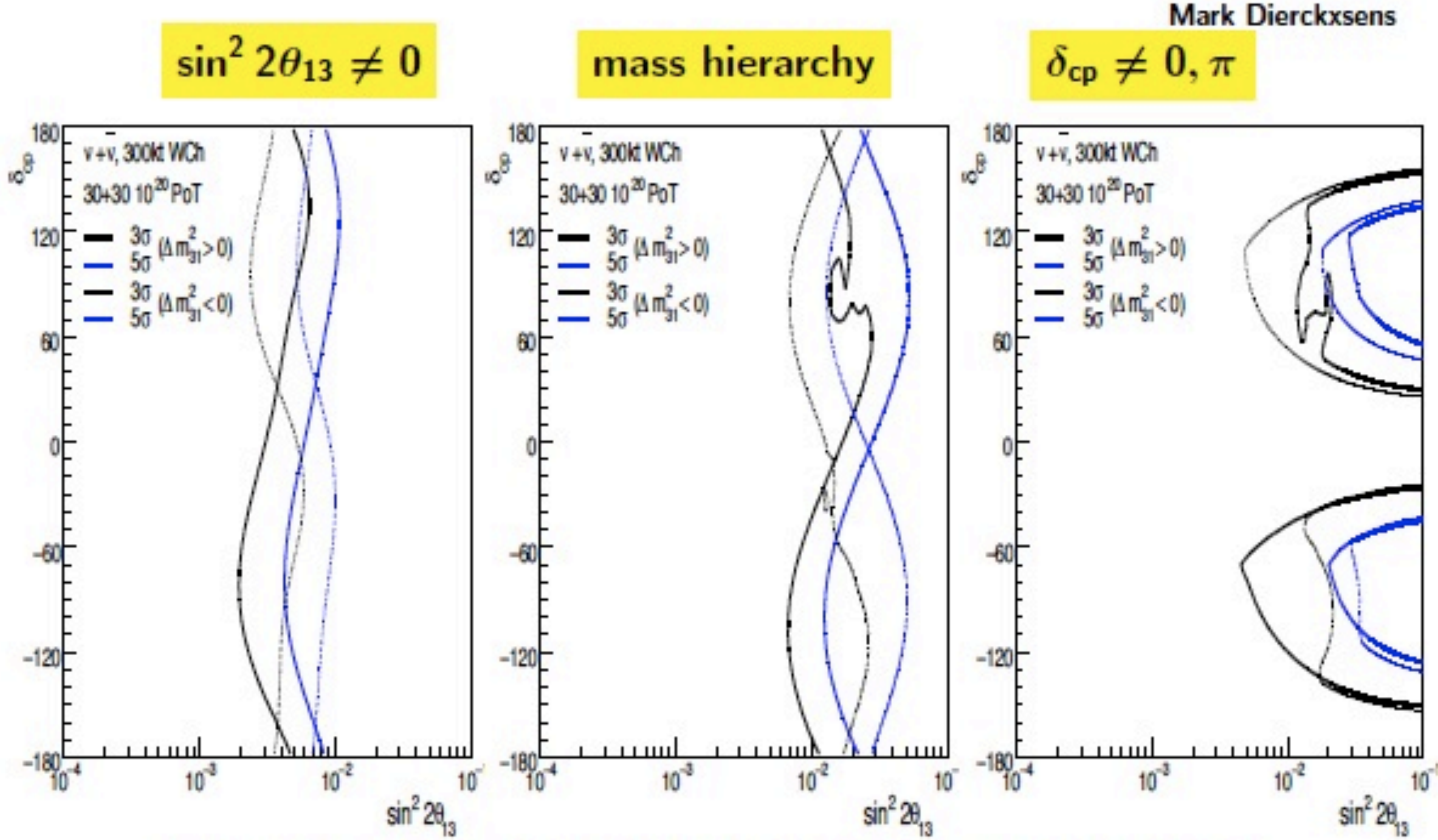


Best $S/\sqrt{B}$ but 3/4 power: 60 GeV, 250kA, no plug, 2.25+2.25 MW.yr

Sensitivities for various NuMI-like beam options

with a 280m DP length

Mark Dierckxsens



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 $P(\nu_\mu \to \nu_e)$.

Numbers produced last year with other beam conditions.

Beam	Det size (FIDUCIAL)	Exposure $\nu + \bar{\nu}$	syst. uncert on bkgd	$\sin^2 2\theta_{13}$	$\text{sign}(\Delta m^2_{31})$	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
NuMI/HStake	100kT	1MW 3+3yrs	5%	0.012	0.037	>0.1
60GeV on-axis	300kT	1MW 3+3yrs	10%	0.008	0.021	0.037
	300kT	2MW 3+3yrs	5%	0.005	0.013	0.015

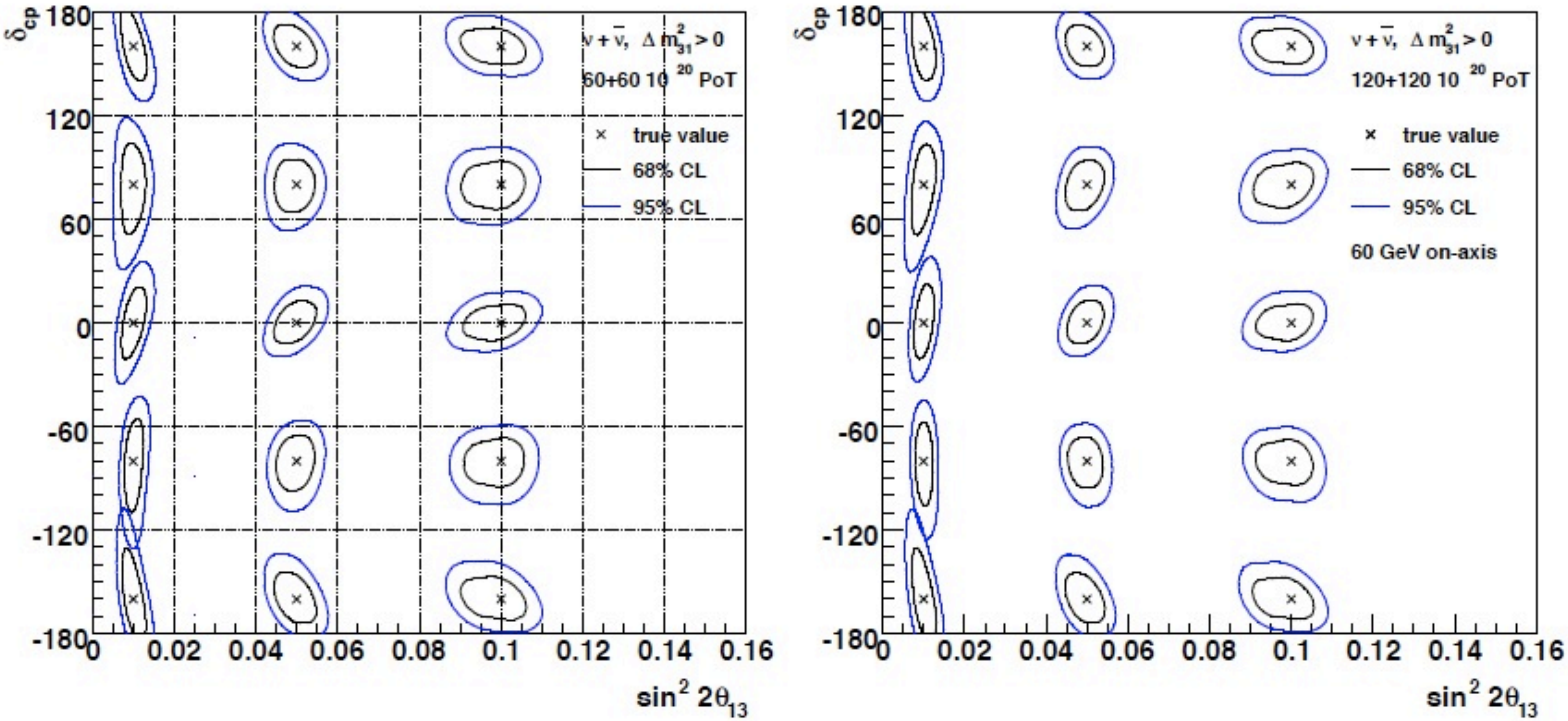
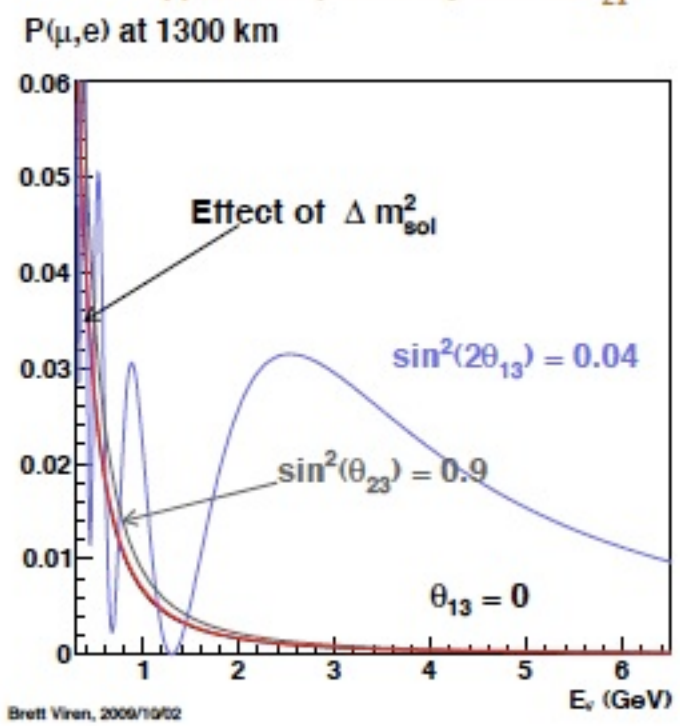


FIG. 8: Measurement of δ_{cp} and $\sin^2 2\theta_{13}$ with a 300kT fiducial detector with a 2MW beam 3+3 yrs. The left plot is for the 120 GeV 9mrad off-axis wide-band beam and the right plot is for a 60 GeV on-axis wide-band beam. Normal hierarchy and 5% bkgd systematic are assumed.

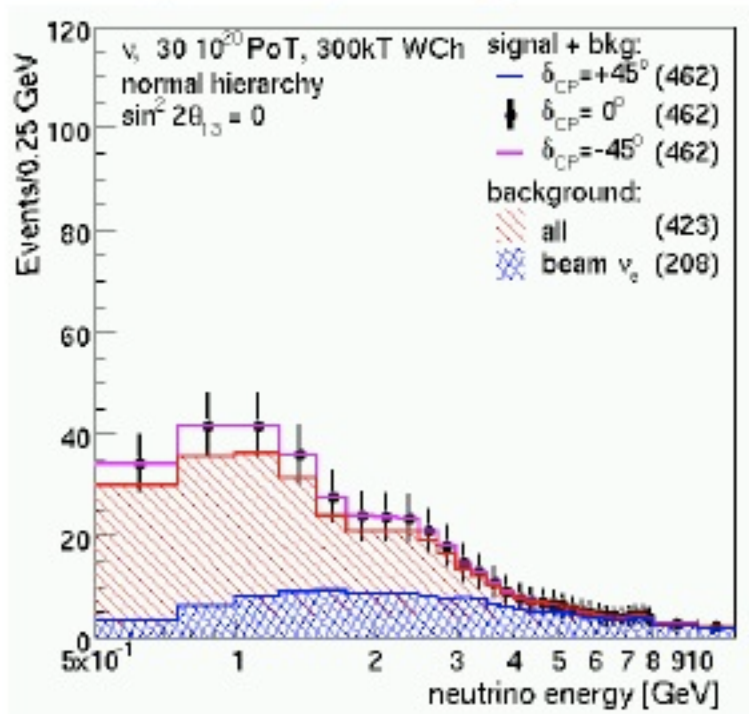
8 GeV running ?

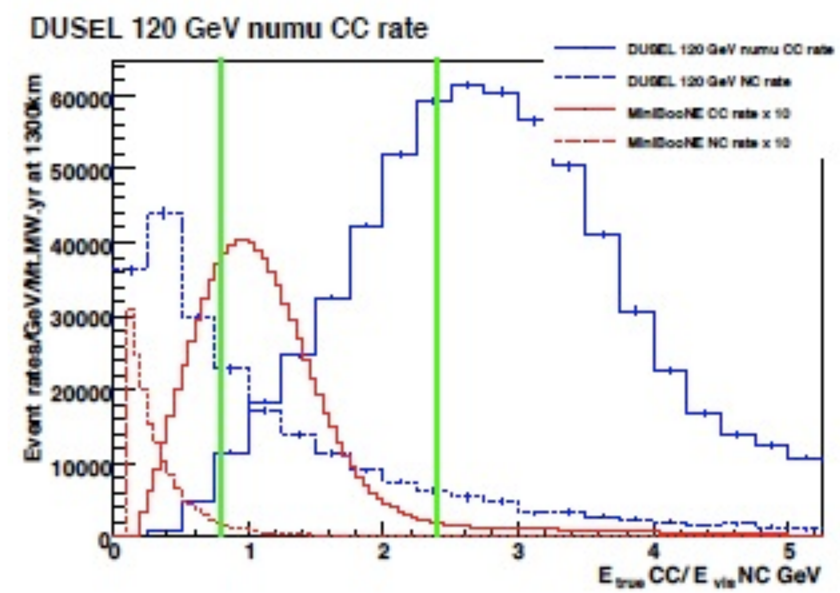
Current beam designs do not have enough flux at low energy to see ν_e appearance due to the solar term and measure $\sin^2\theta_{23}$ - we can use this to determine whether θ_{23} is maximal:

Appearance probability with Δm^2_{21}



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





- Need MW class 8 GeV beam. Could go after the solar term with a few hundred events.

Conclusions

- A lot of simulation work has been done since the initial proposal. The beam related work is now quite advanced. The detector optimization has started.
- Conclusion is that the sensitivity for CPV could be pushed down to $\sin^2 2\theta_{13} \sim 0.01$ where it gets limited by background.
- This requires a very large detector (300 kT for water and 50-100 kT for liquid argon) with a 1-2 MW class beam. The precision on the CP parameter is independent of $\sin^2 2\theta_{13}$