

Neutrino Oscillation Measurements with DUSEL Based Detectors Using Accelerator Beams

Mark Dierckxsens
University of Chicago

Underground Detectors Investigating Grand
Unification Workshop
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- Current status & near term future of neutrino oscillation measurements
- Long baseline + wideband beam concept
- Neutrino beams
- Water Cherenkov detector
- Liquid Argon detector
- Sensitivity calculations
- Sensitivities under various assumptions
- Conclusions

Neutrino Oscillations



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow$$

PMNS matrix:
3 mixing angles
1 CP phase
(2 CP Majorana phases)

solar

$$U = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{12} \approx 34^\circ$

atmospheric

$$\begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{i\delta} \\ \sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13} \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

???

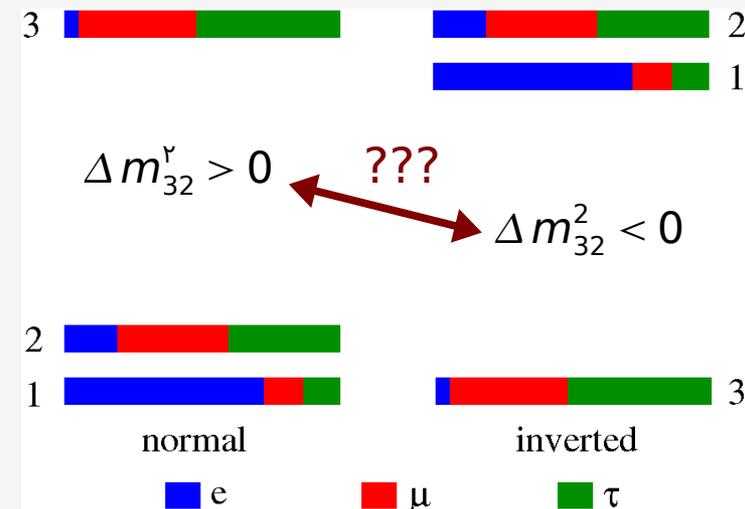
$\theta_{23} \approx 45^\circ$

neutrino masses must differ to observe ν oscillations:

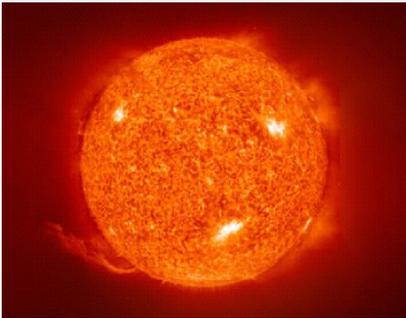
$$\Delta m_{21}^2 = m_2^2 - m_1^2 \approx +7.9 \cdot 10^{-5} \text{ eV}^2$$

$$|\Delta m_{31}^2| = |m_3^2 - m_1^2| \approx 2.4 \cdot 10^{-3} \text{ eV}^2$$

$$\Delta m_{31}^2 = \Delta m_{21}^2 + \Delta m_{32}^2$$



Current Status

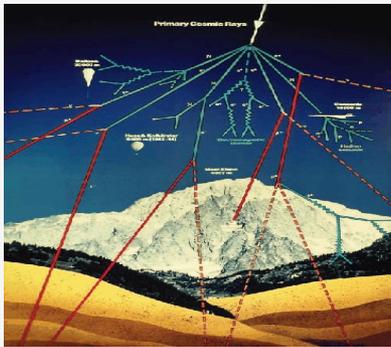


SNO, KamLAND, Super-K, ...

$$\Delta m_{21}^2 = 7.67_{-0.19}^{+0.16} \cdot 10^{-5} eV^2$$

$$\sin^2 \theta_{12} = 0.312_{-0.018}^{+0.019}$$

$$\theta_{12} \approx 34^\circ$$



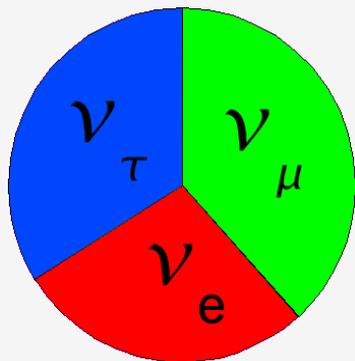
Super-K, MINOS, K2K, ...

$$|\Delta m_{31}^2| = 2.39_{-0.08}^{+0.11} \cdot 10^{-3} eV^2$$

sign?

$$\sin^2 2\theta_{23} > 0.95 \quad (90\% \text{ CL})$$

$$\theta_{23} \approx 45^\circ$$



Chooz, Solar, LB, Atm, ...

$$\sin^2 2\theta_{13} < 0.13 \quad (90\% \text{ CL})$$

$$< 0.18 @ 3\sigma$$

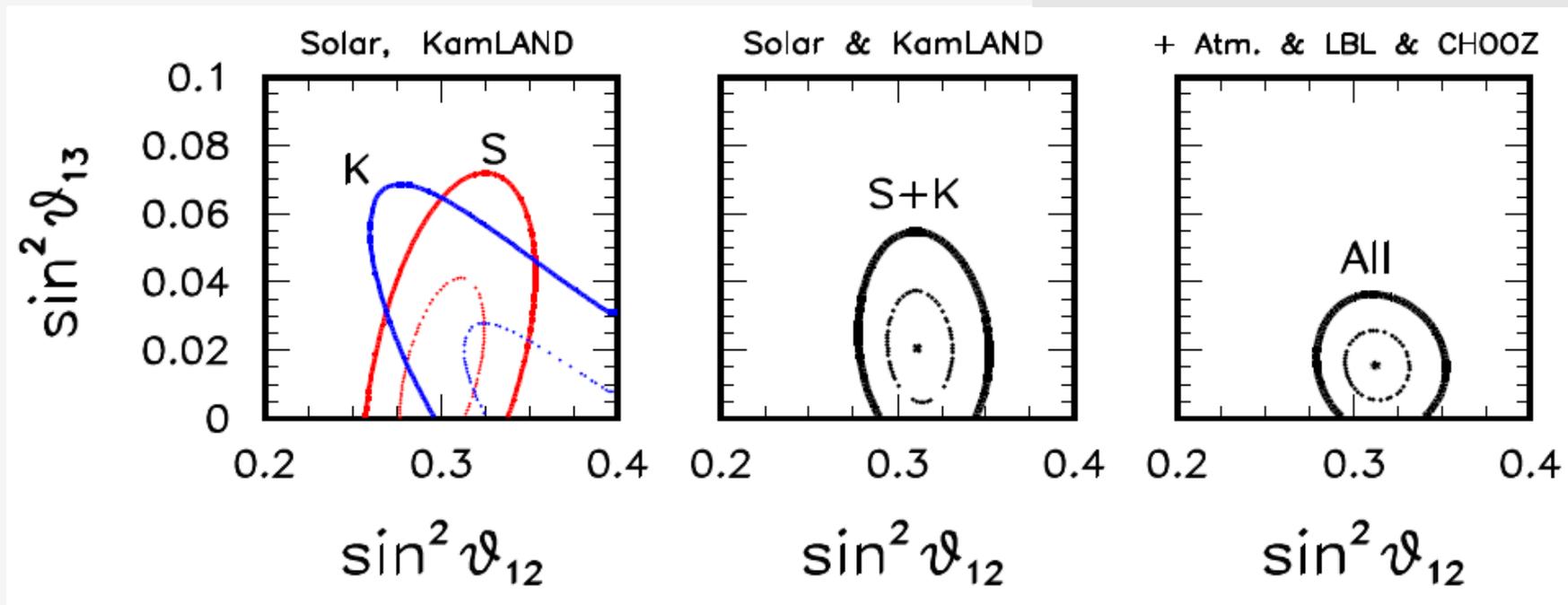
$$\delta_{CP} = ???$$

Fogli et al, arXiv:0805.2517



- Interesting results emerging from combination of global oscillation data: $\sin^2 2\theta_{13} = 0.063 \pm 0.039$

Fogli et al, arXiv:0809.2936



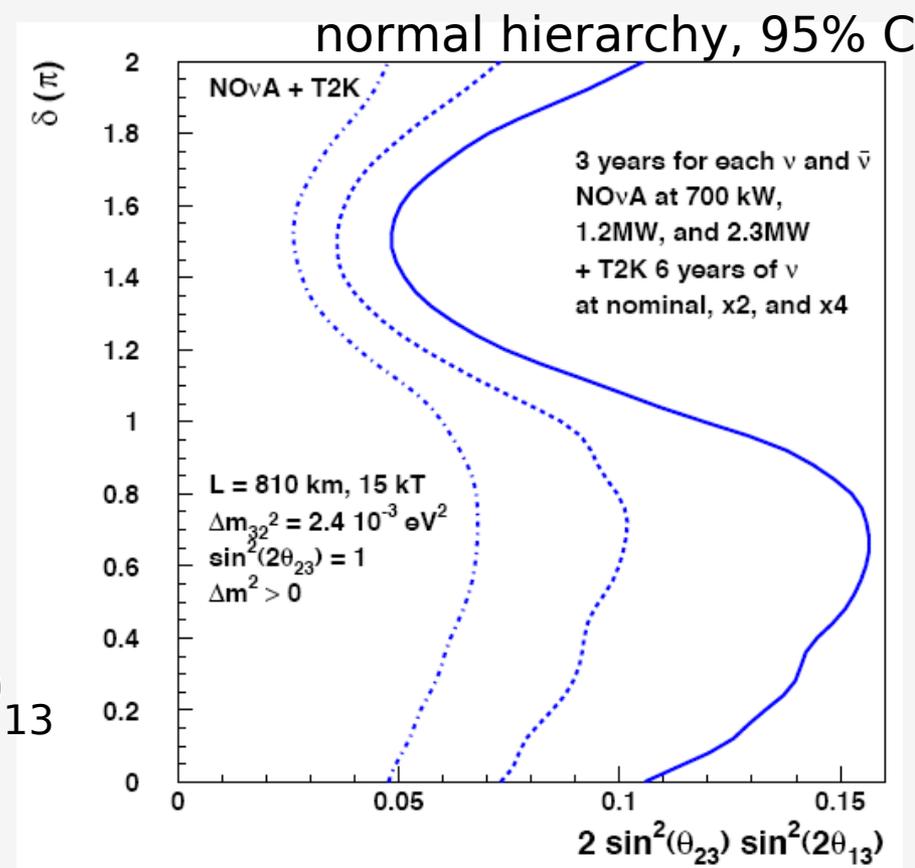
- Is θ_{13} really non-zero or “accidental”?
→ Will need experiments!

Near Future Experiments



- MINOS: just below current limits
- Next phase experiments will probe $\sin^2 2\theta_{13}$ around 0.01:

- Reactor neutrinos:
Double Chooz, RENO,
Daya Bay
- Off-axis beams: Nova, T2K
- Need next generation experiments to:
 - Extend search for/measure θ_{13}
 - Determine mass hierarchy
 - Explore CP violation



Wideband Beams – Long Baselines



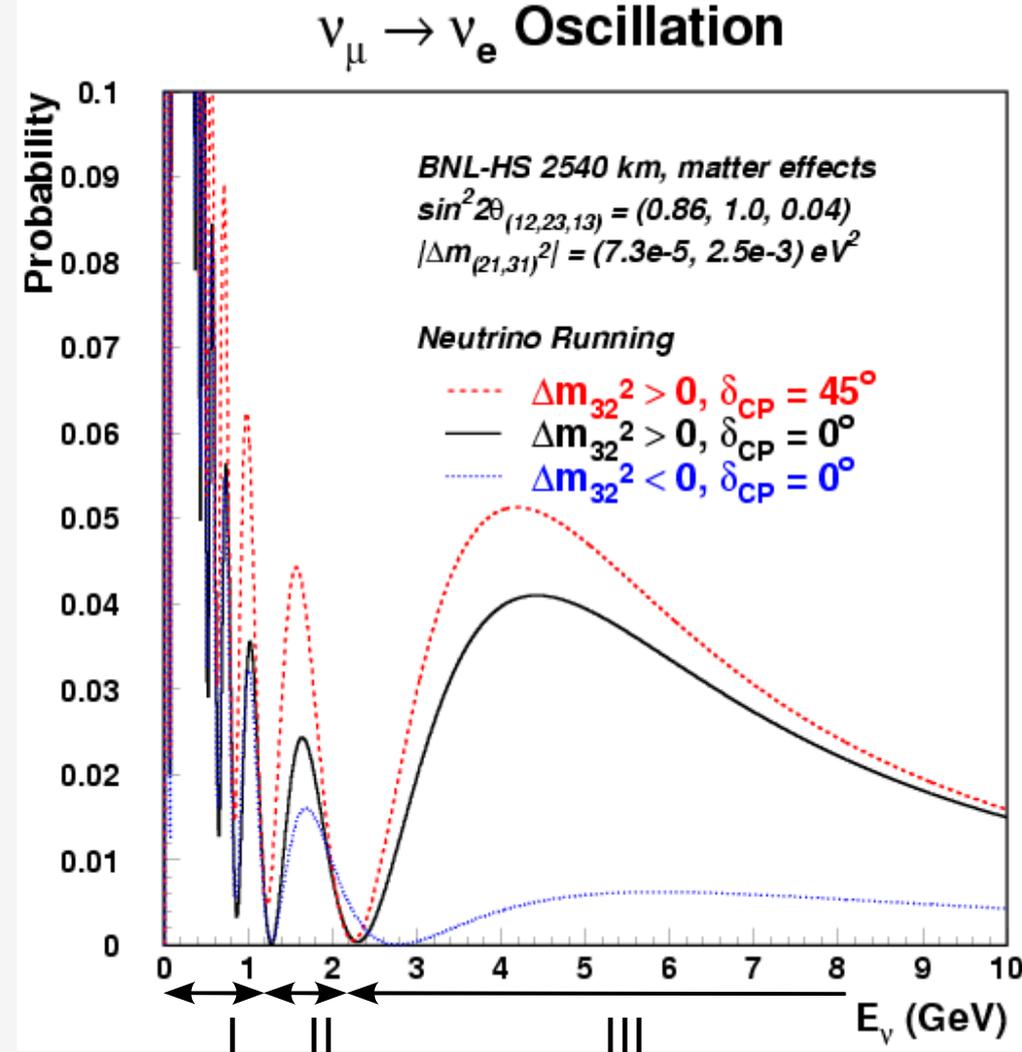
- Energy dependence:

	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
$\text{sign}(\Delta m_{32}^2)$	0	0	++
δ_{CP}	+	++	+
solar	++	+	0

- Longer baselines:

- Larger matter effects

- Oscillation nodes at higher energies: large xsections, away from NC background, above Fermi motion regime (>500MeV)





US Long Baseline Neutrino Experiment Study

✓ Charge:

- A broad-band proposal using either an upgraded beam of ~ 1 MW from the current Fermilab accelerator complex or future Proton Driver beam aimed at a DUSEL-based detector. Compare results with proposal for high intensity beam from BNL to DUSEL.
- Off-Axis next generation options using a 1-2 MW beam from Fermilab and a liquid Argon detector at either DUSEL or as second detector for NOVA.

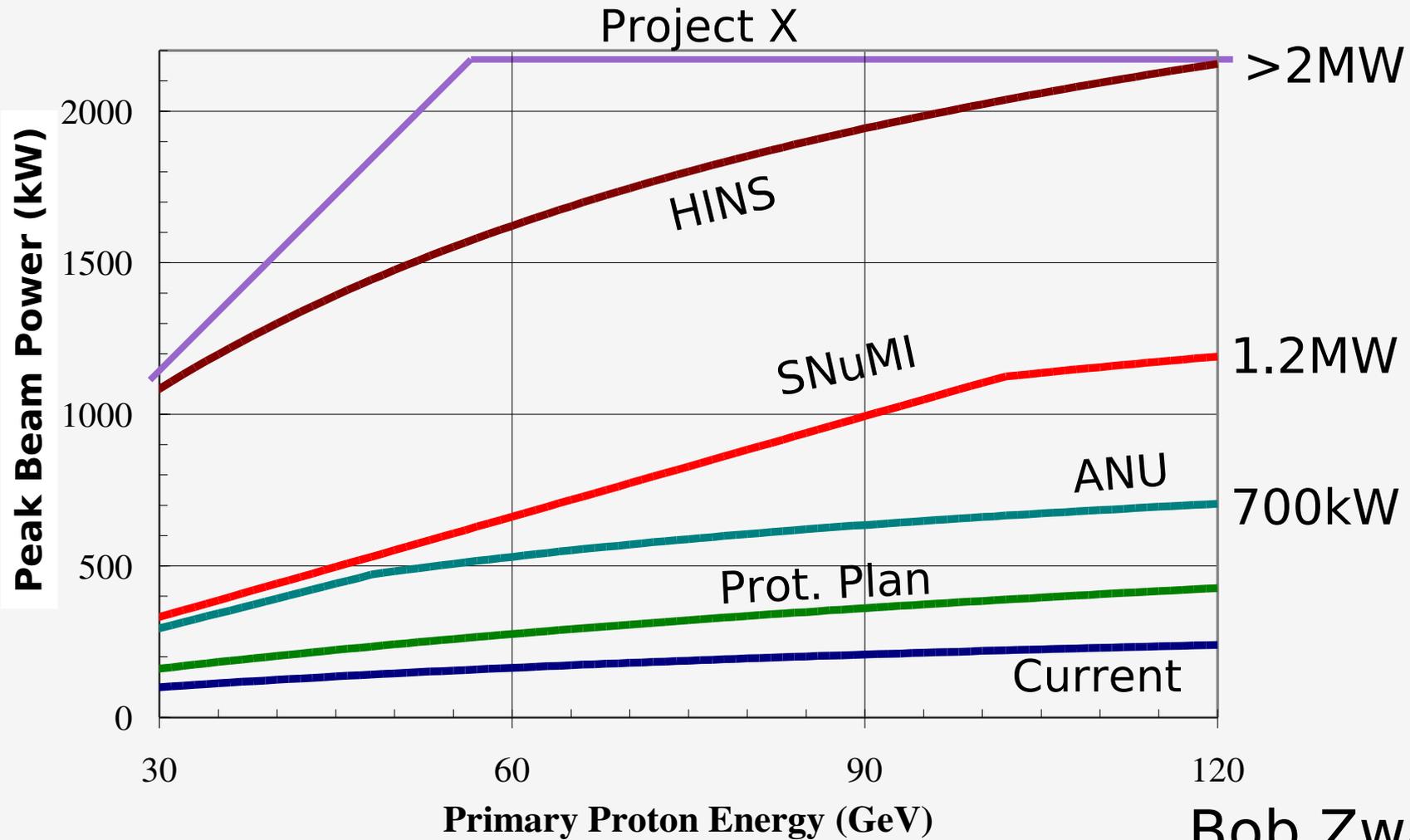
Report: [arXiv:0705.4396](https://arxiv.org/abs/0705.4396)

<http://nwg.phy.bnl.gov/fnal-bnl>

Proton Intensity

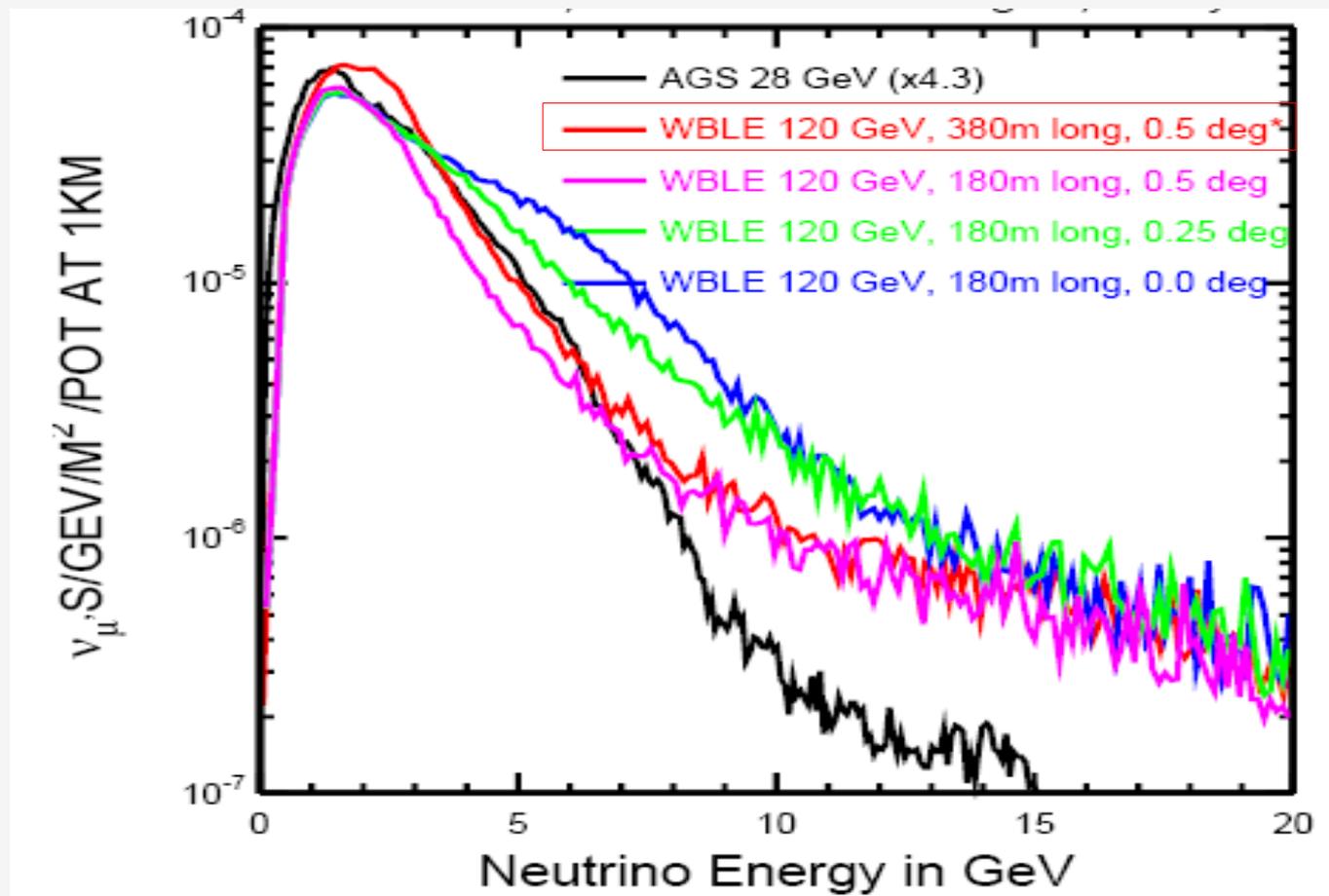


- Possible increases to proton intensity @ FNAL:





- Simulation using NuMI Monte Carlo, with modifications



- See talk M. Bishai

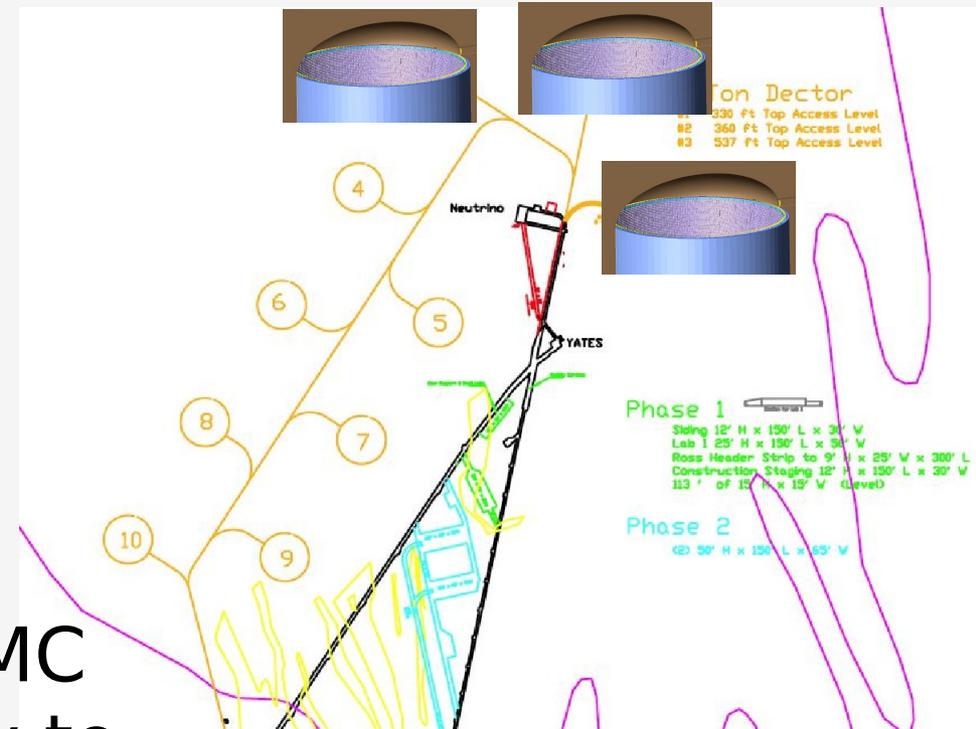


- Water Cherenkov:
 - Known technology
 - Scaling few times Super-K
 - Low efficiency & purity
- Liquid Argon:
 - High efficiency & purity
 - Not proven at the required size

Water Cherenkov Detector



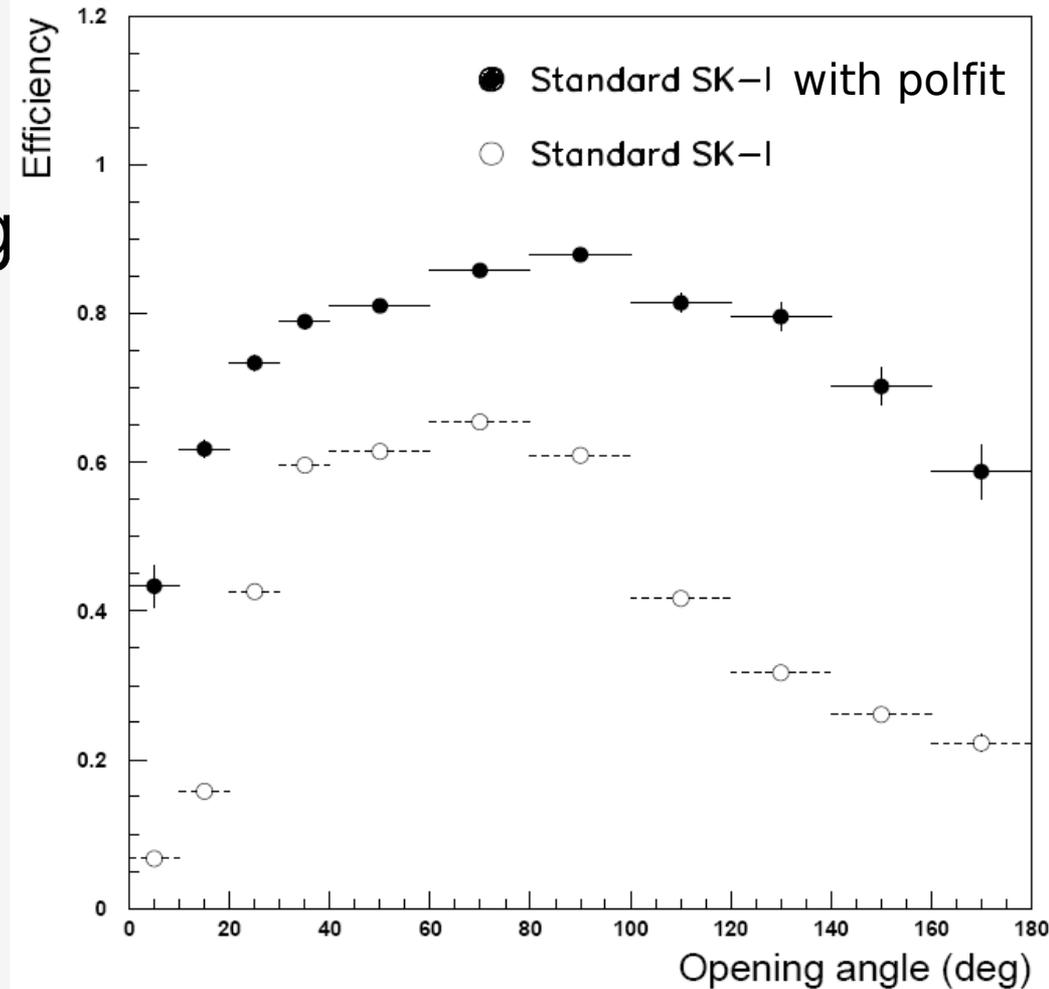
- 300kt fiducial mass
- Two independent studies to reduce NC background contamination in ν_e selection beyond SuperK:
 - C. Yanagisawa
 - F. Dufour & E. Kearns
- Use SuperK atmospheric MC and follow similar strategy to improve separation between electrons and π^0 decays
- Results from both studies are in agreement



Water Cherenkov Detector



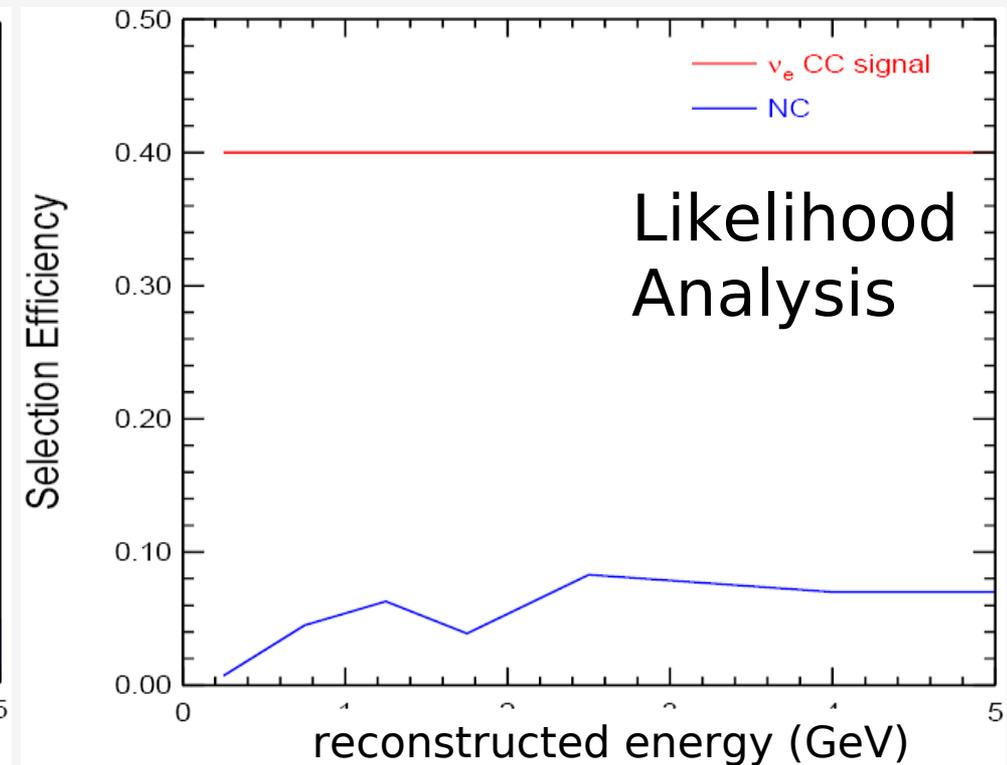
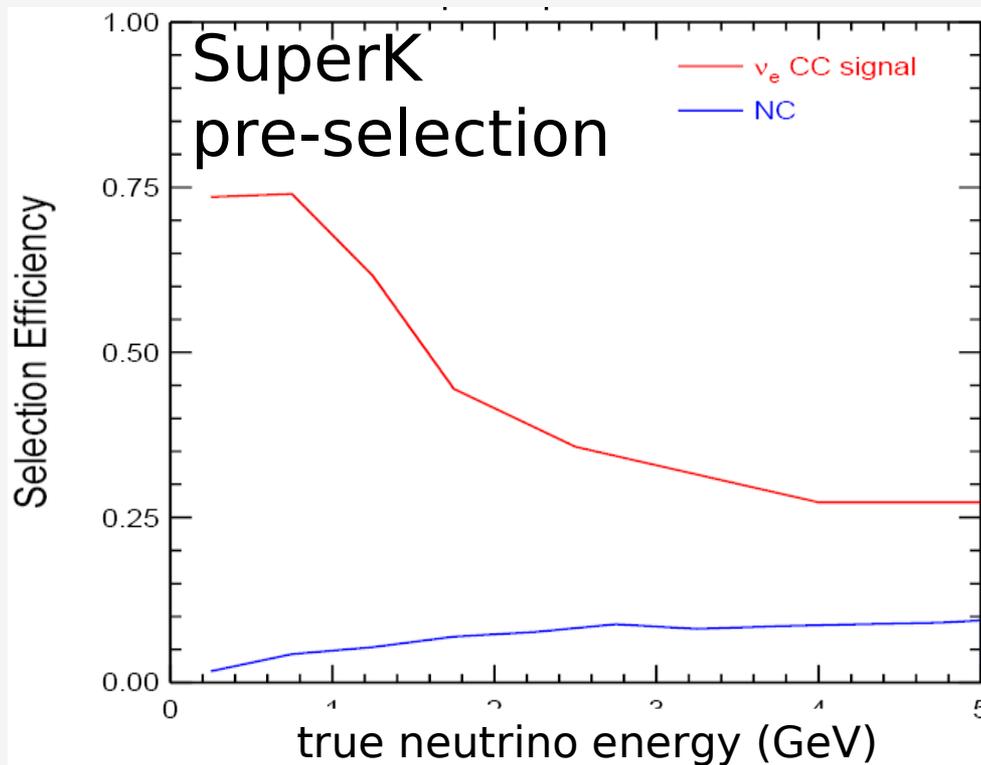
- Standard SuperK cuts used to select single ring e-like events
- An improved π^0 reco algorithm to find 2nd ring
increase efficiency by 20-30%
- 40% coverage with 20" PMTs: efficiency at low opening angles can be increased with finer granularity. Need dedicated MC studies



Water Cherenkov Detector



- Output of π^0 finder + several other variables (some related to the knowledge of neutrino direction) used as input for likelihood based selection

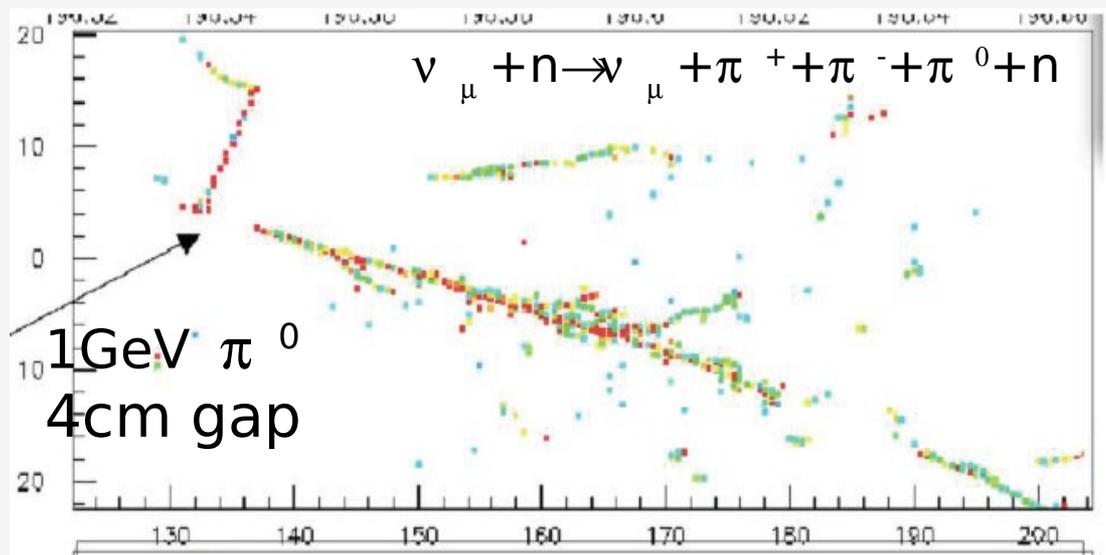
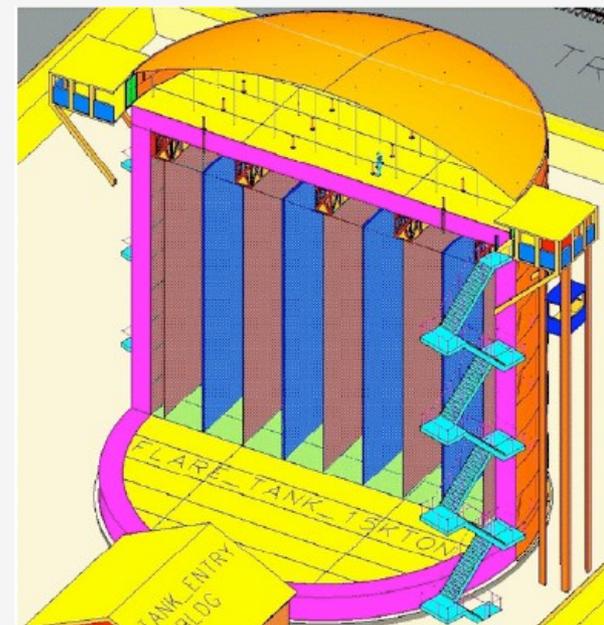


- Both efficiencies applied sequentially: overall ν_e efficiency 14%, NC rejection > 98%

Liquid Argon



- 50-100kt liquid Argon (Lar) TPC detector
- Signal & background efficiencies based on hand scanning:
(Tufts U. group)
 - ν_e CC selection efficiency: 80%
 - NC background rejection >99%



- Efficiency exceeded for QE using initial automated tools (A. Curioni)
- See talk K. McDonald



- **Sensitivity to non-zero θ_{13} :**
Fit spectrum generated for particular $(\theta_{13}, \delta_{cp})$ to hypothesis with $\theta_{13} = 0$.
- **Sensitivity to mass hierarchy:**
Fit spectrum for particular $(\theta_{13}, \delta_{cp})$ to hypothesis with opposite mass hierarchy.
Both θ_{13} and δ_{cp} are allowed to float.
- **Sensitivity to CP violation:**
Fit spectrum generated for particular $(\theta_{13}, \delta_{cp})$ to hypotheses $\delta_{cp} = 0$ and π . Take worst χ^2 .
 θ_{13} is allowed to float in fit.
- **$(\theta_{13}, \delta_{cp})$ measurement:**
Parameter measurement for a set of true values



- Two independent calculations with compatible results:
 - Fast MC implemented by N. Saoulidou (FNAL)
 - GloBES: M. Bishai, M. Diwan, M. Dierckxsens (BNL)
- Results shown here are from the latter
- Default assumption in background error is 5%
- Errors on oscillation parameters & matter density (5%) included
- Main change wrt FNAL-BNL study:
 - reduced Δm^2_{31} from $2.7 \cdot 10^{-3} \text{ eV}^2$ to $2.4 \cdot 10^{-3} \text{ eV}^2$

Sensitivity Calculations

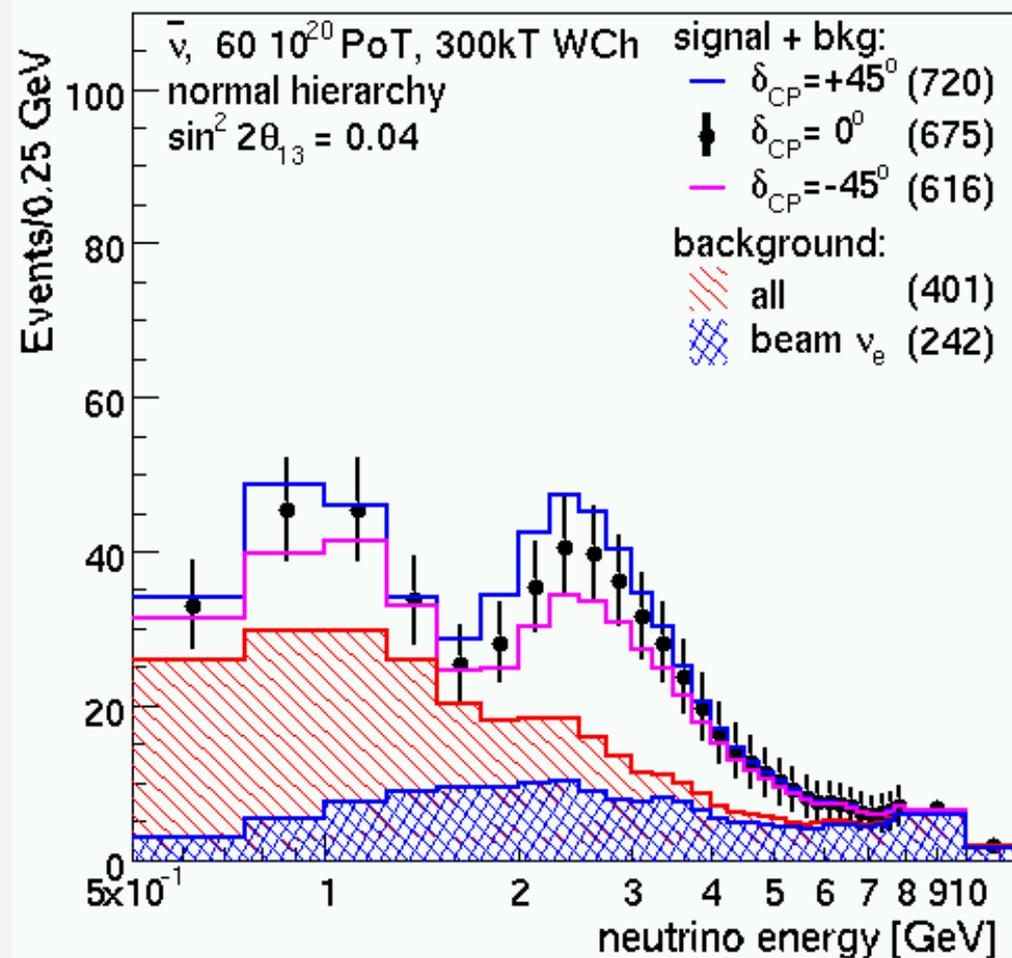
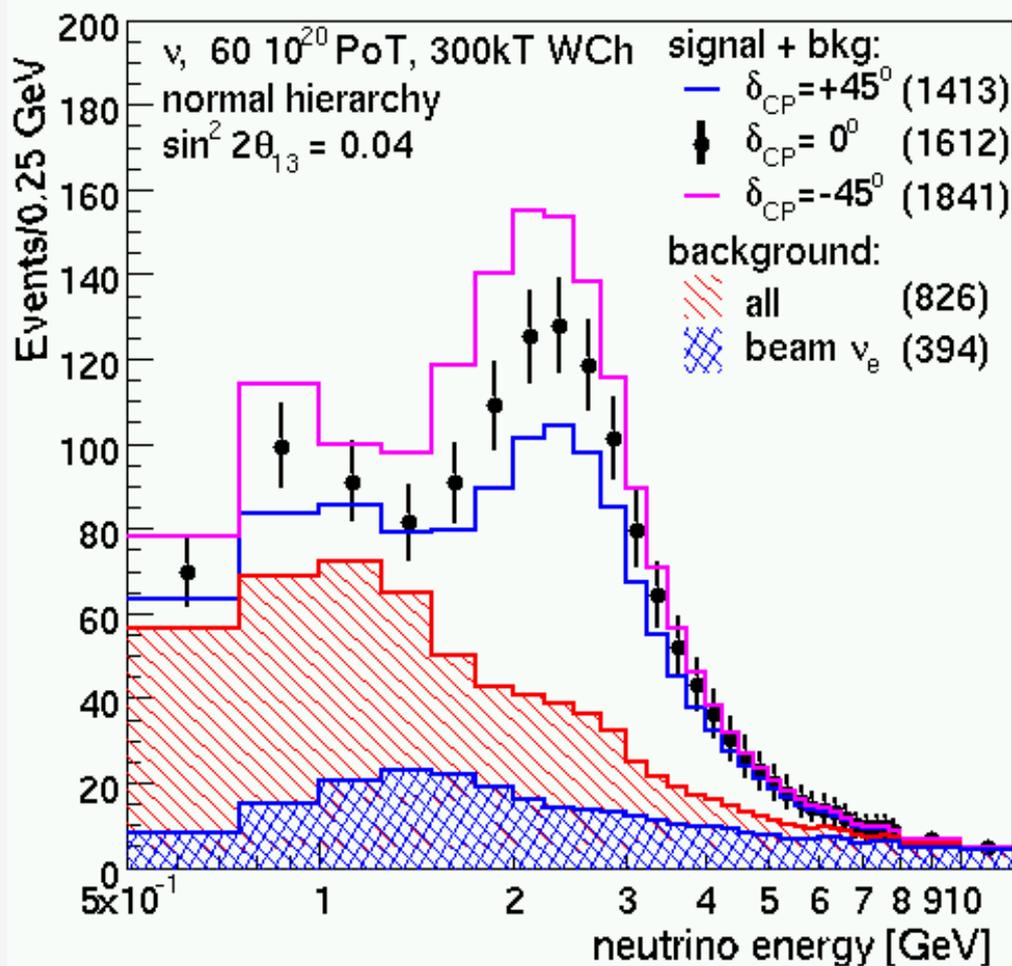


- Assumptions for GloBES implementation.
- Water Cherenkov:
 - Use efficiencies derived by C. Yanagisawa
 - Parametrized smearing functions:
 - ν_e CC: $\sigma(E) \sim 10\%$ at 1 GeV
 - ν_x NC: based on NUANCE
- Liquid Argon:
 - 80% efficiency ν_e CC
 - Complete rejection NC
 - $\sigma(E) = 5\%$ for QE, 20% for non-QE



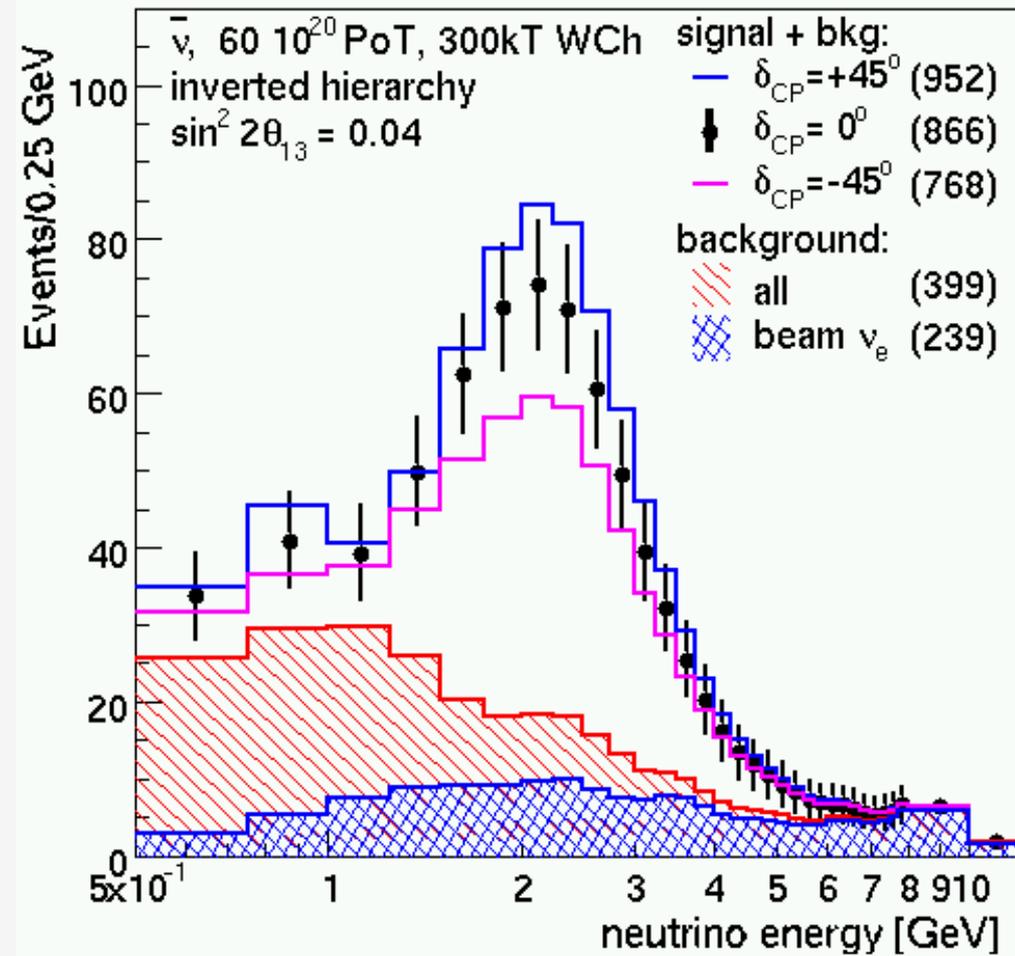
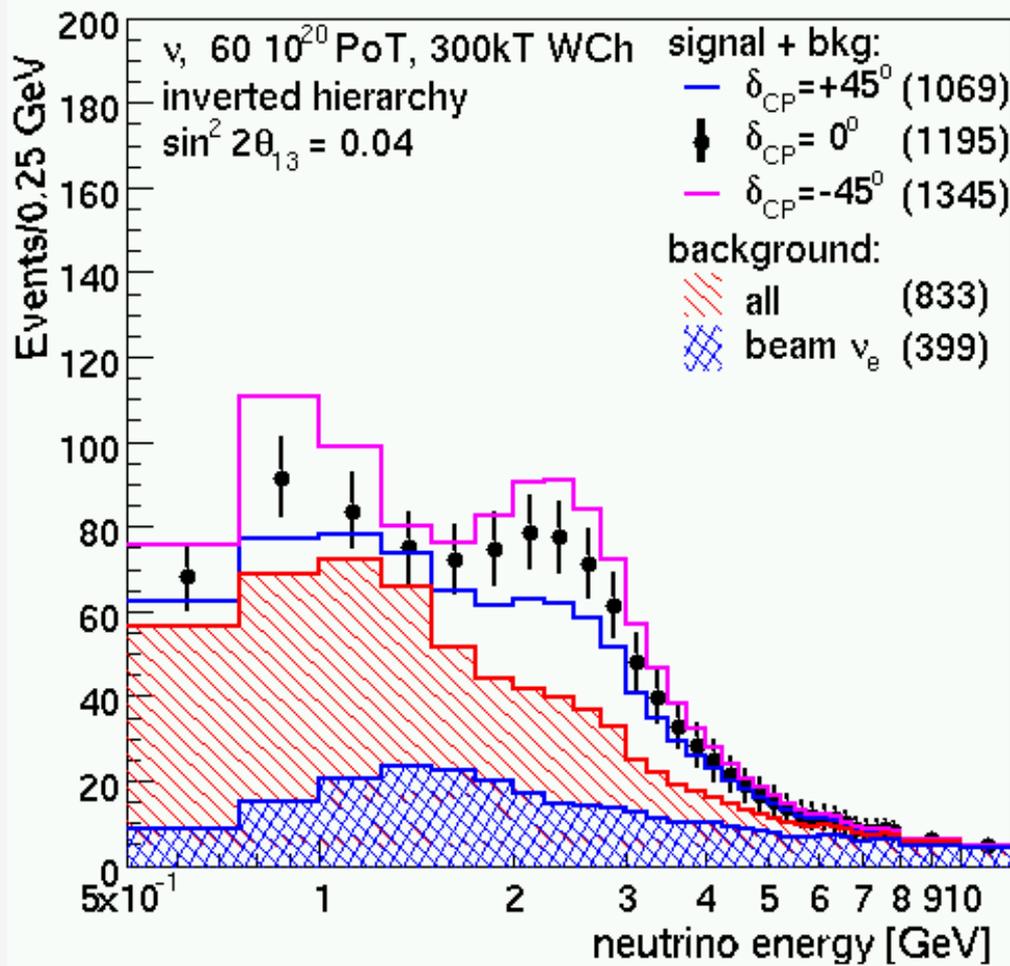
- Large detectors and powerful beams are needed to collect required statistics
- Use 120 GeV proton beam at 0.5° off-axis to reduce high energy tail
 - Other beam option where investigated during study, e.g. 60 GeV on axis at same power gives similar sensitivities
- Use beam powers of 1.2MW & 2.4MW
- Running time assumed is 3 yrs ν + 3 yrs anti- ν
- Detector mass:
 - WCh: 300 kt
 - LAr: $\epsilon_{\text{LAr}}/\epsilon_{\text{WCh}} \sim 6 \rightarrow 50\text{kt}$

Spectra – Water Cherenkov



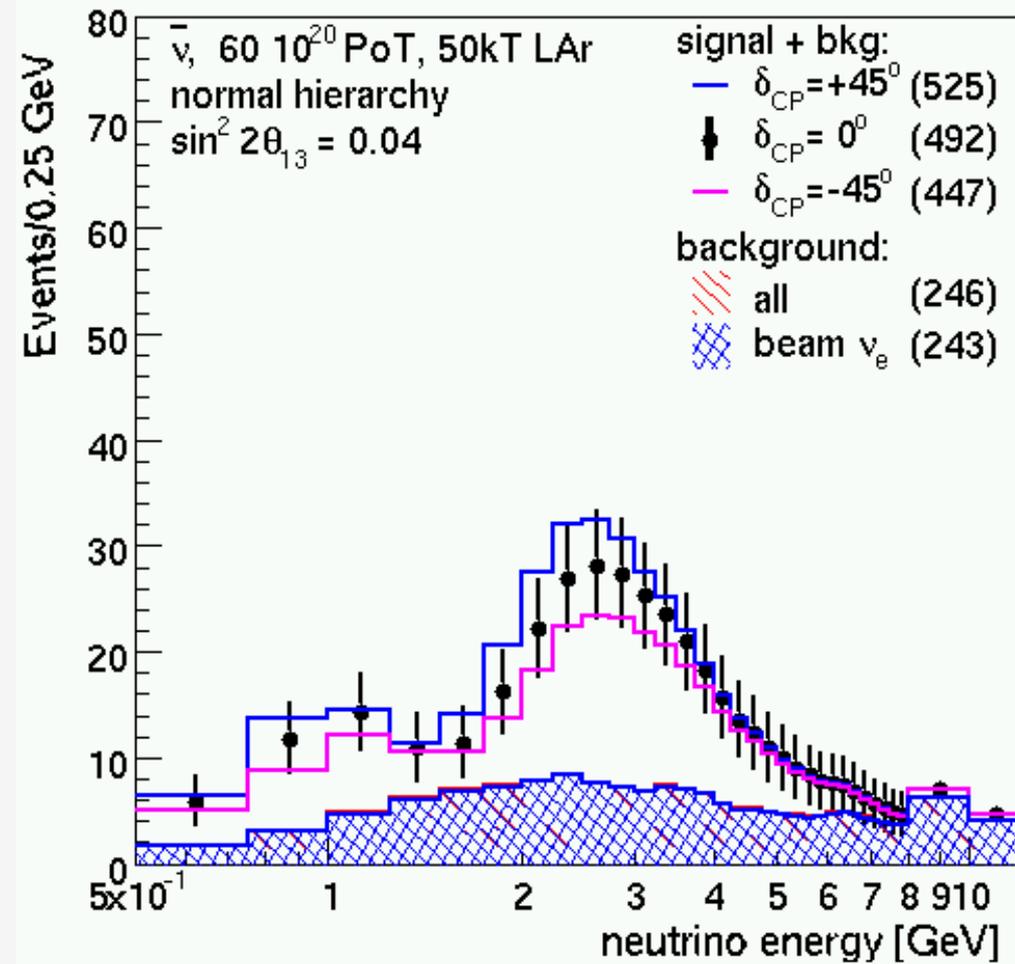
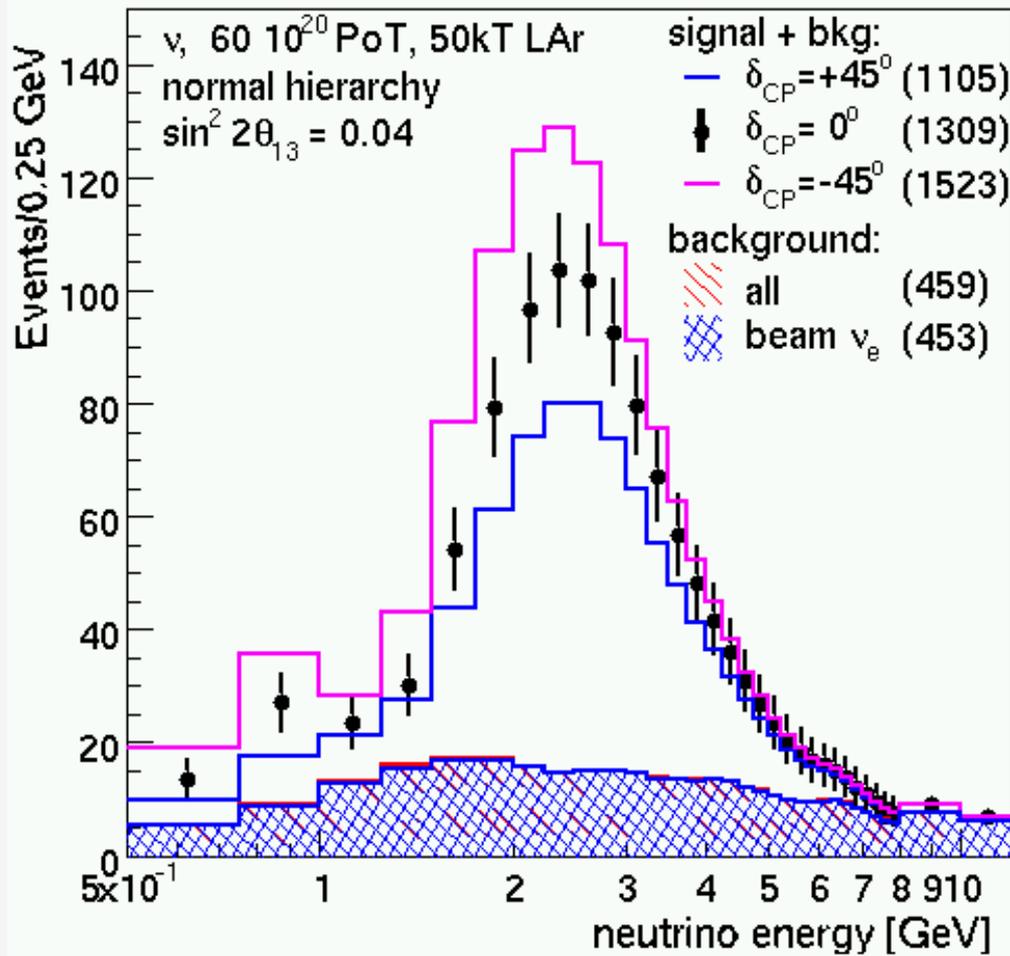
2.4MW beam, $\sin^2\theta_{13}=0.04$, normal hierarchy

Spectra – Water Cherenkov



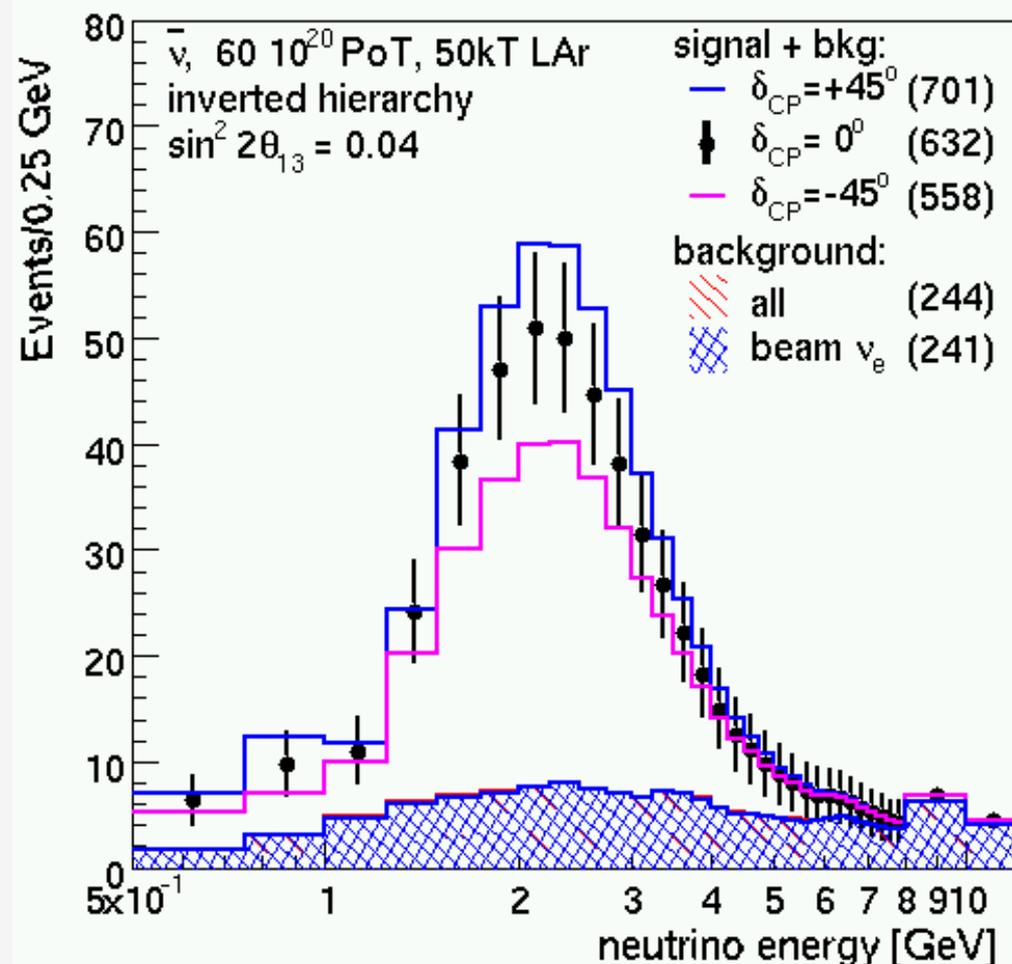
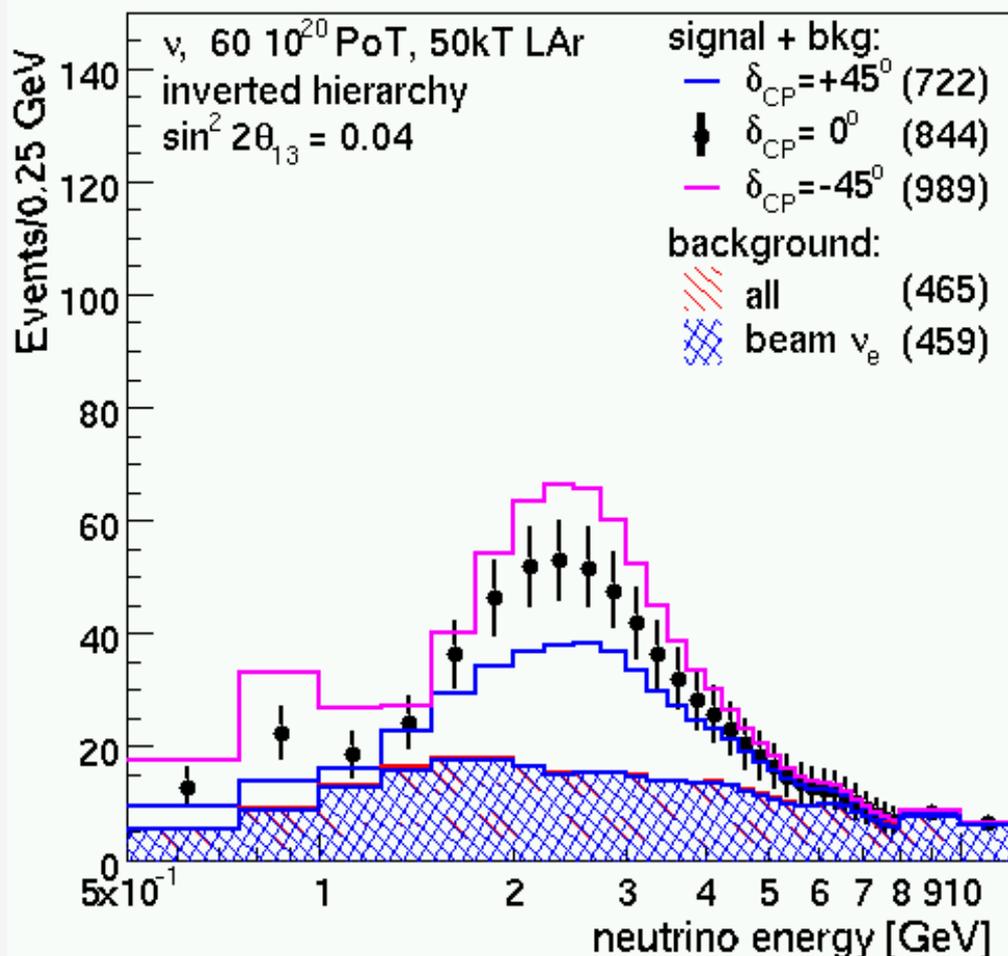
2.4MW beam, $\sin^2\theta_{13}=0.04$, inverted hierarchy

Spectra – Liquid Argon



2.4MW beam, $\sin^2\theta_{13}=0.04$, normal hierarchy

Spectra – Liquid Argon

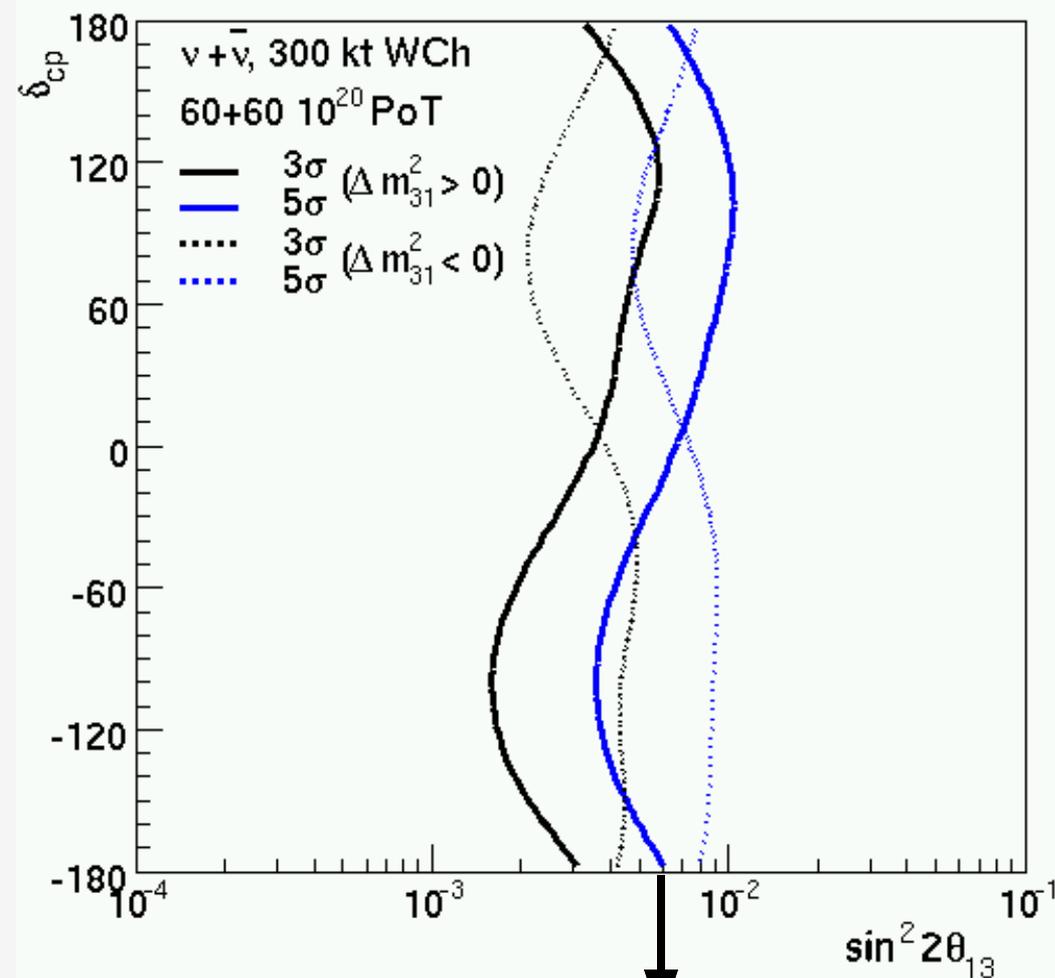


2.4MW beam, $\sin^2\theta_{13}=0.04$, inverted hierarchy

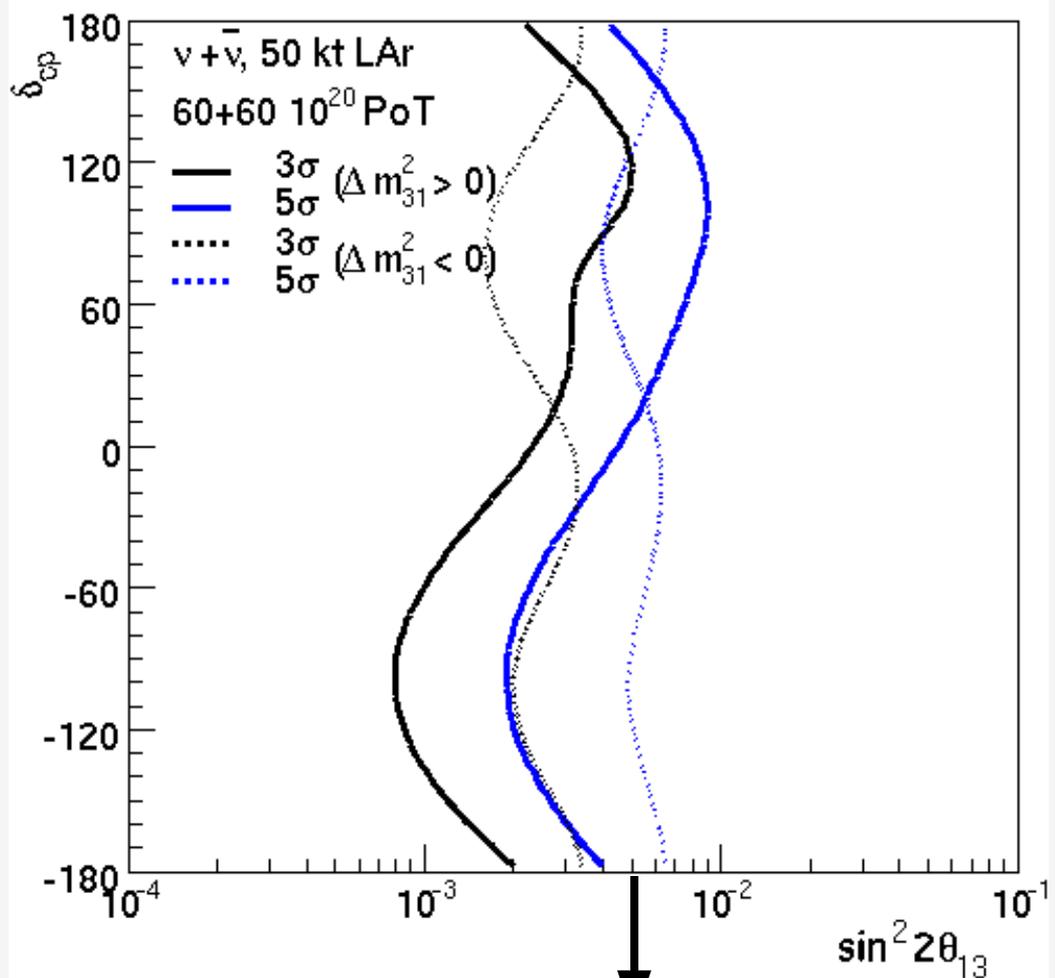
$$\sin^2 2\theta_{13} \neq 0$$



2.4MW beam



3σ , all δ_{cp} : 0.006

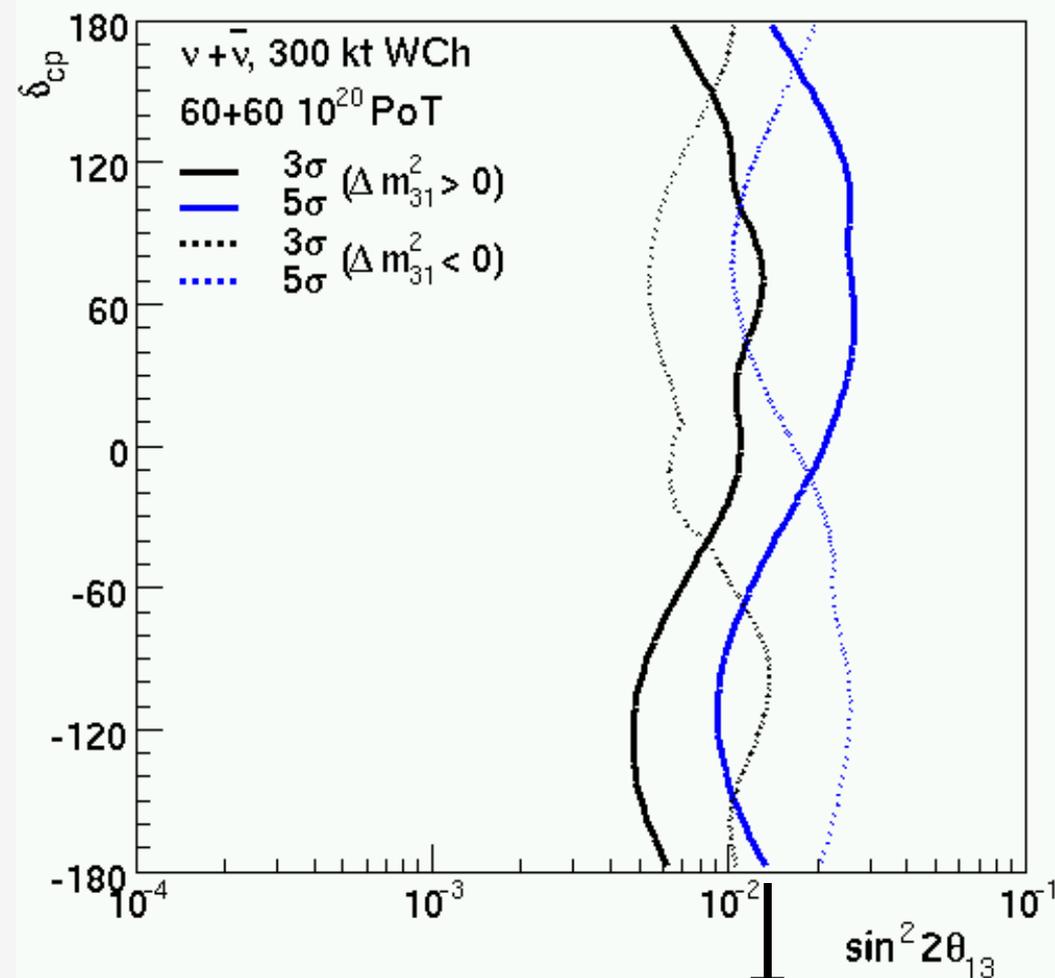


0.005

Mass hierarchy

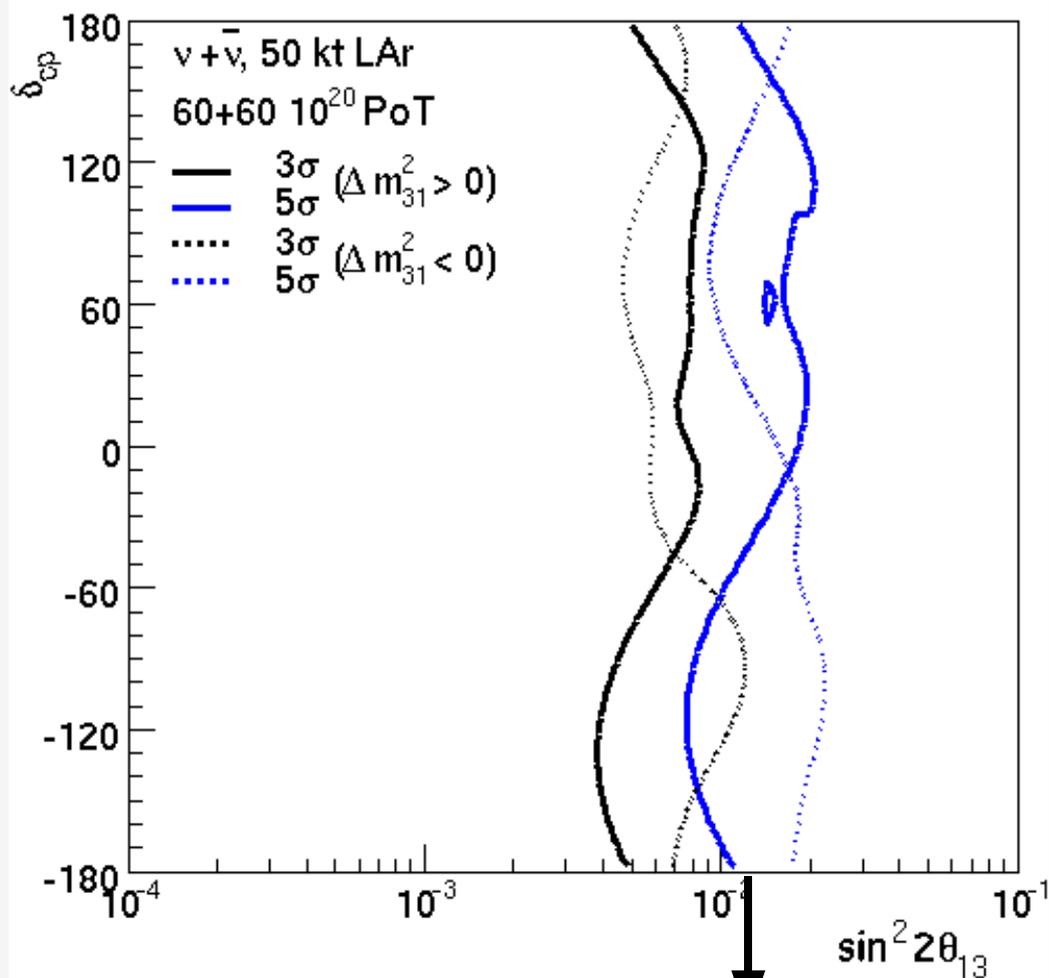


2.4MW beam



3σ , all δ_{cp} :

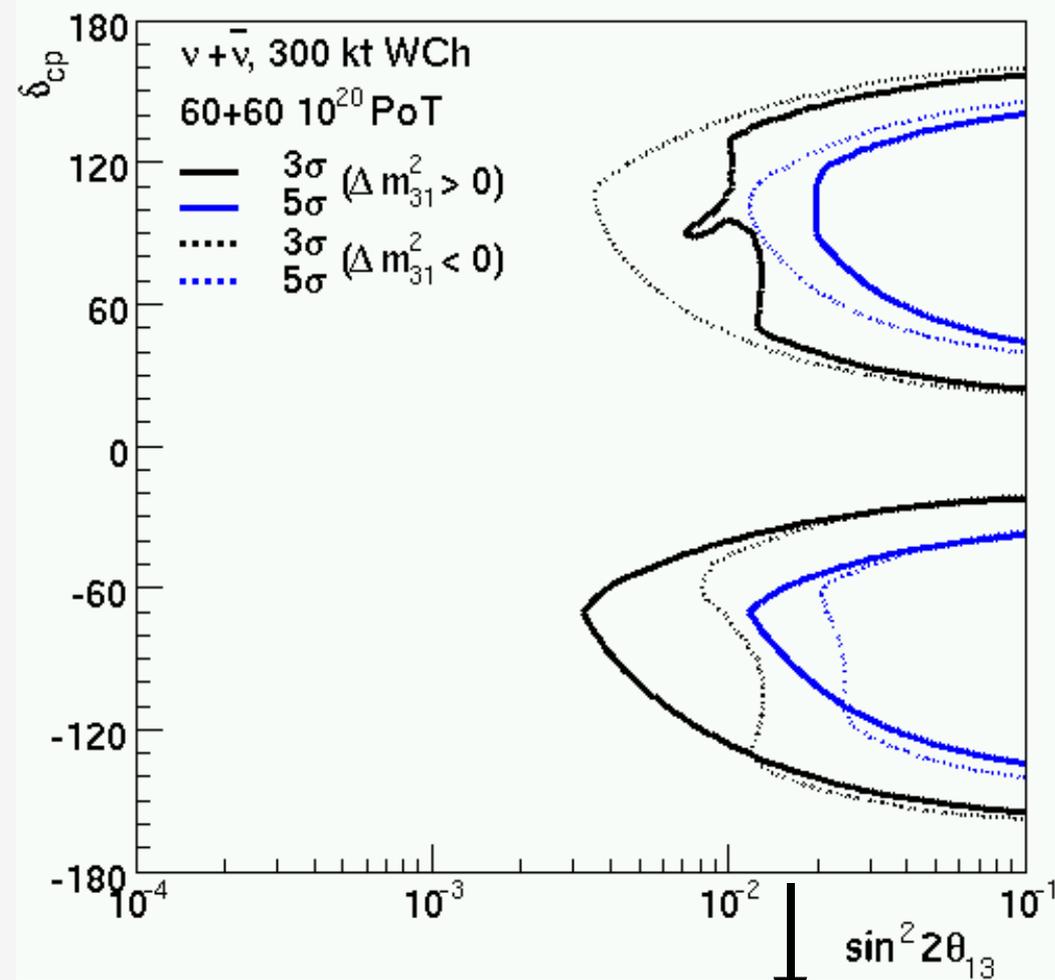
0.012



0.011

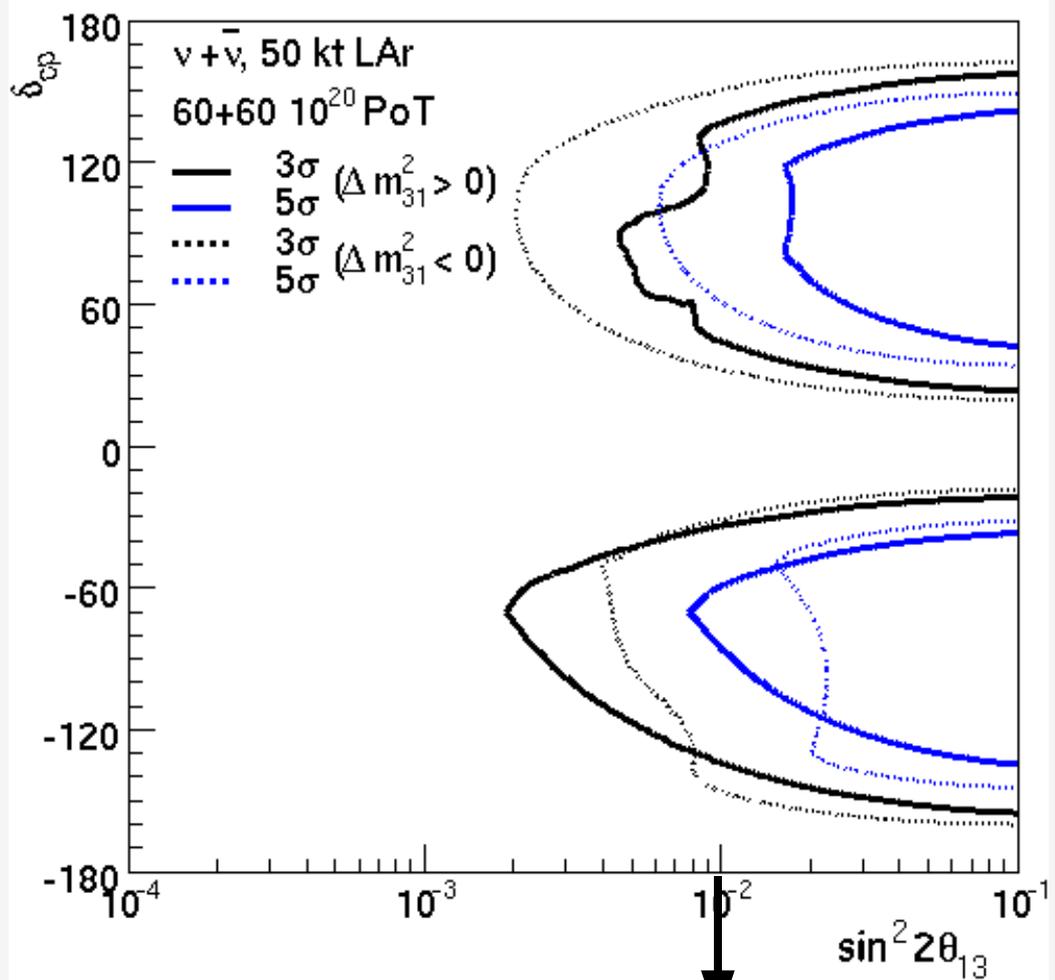


2.4MW beam



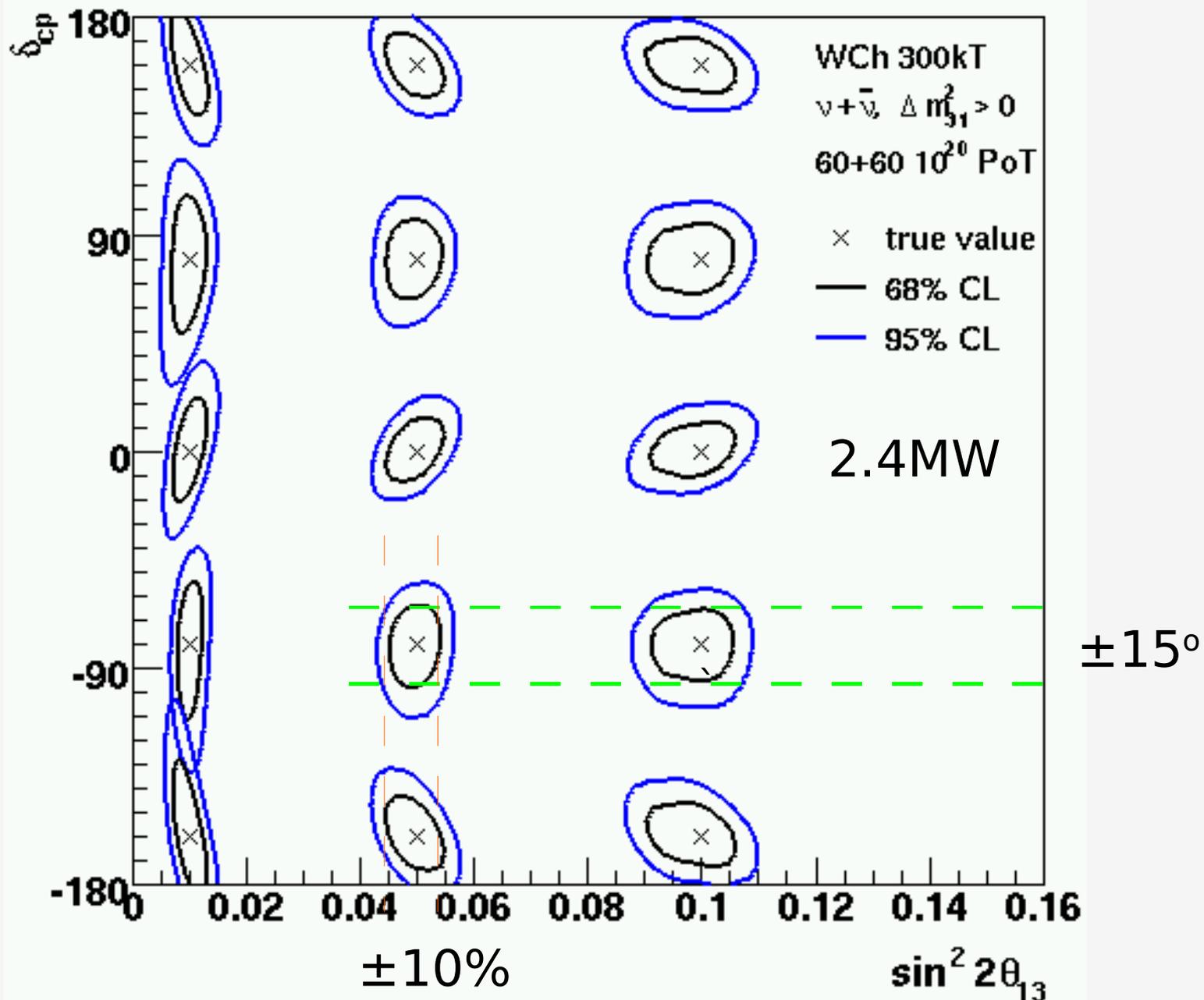
3σ , 50% δ_{cp} :

0.015



0.010

$(\theta_{13}, \delta_{cp})$ Measurement



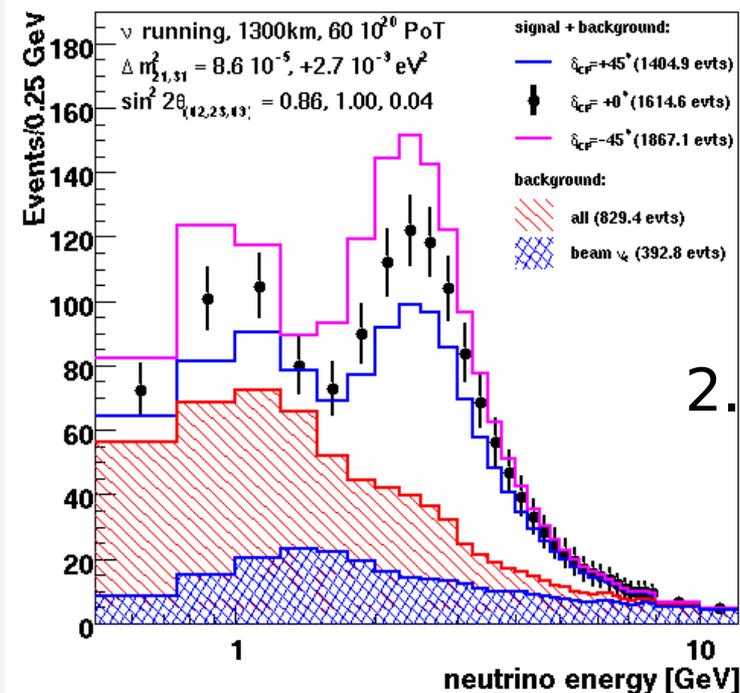
Different Exposures



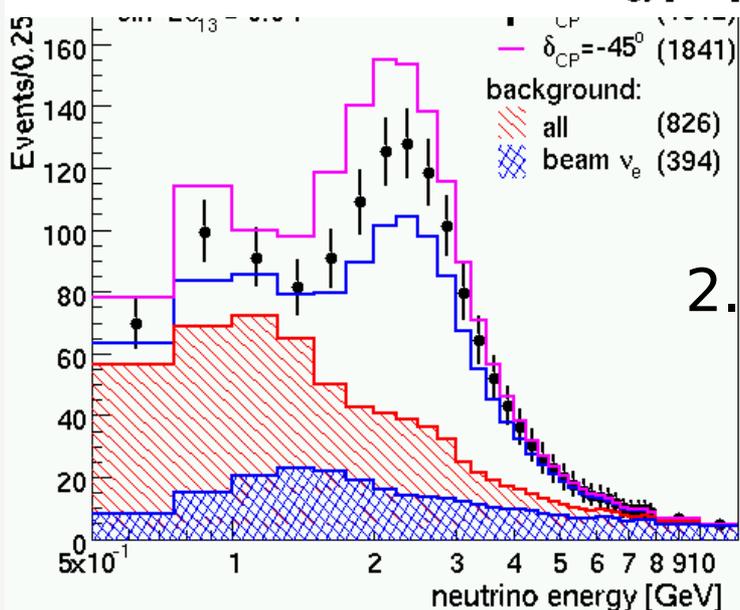
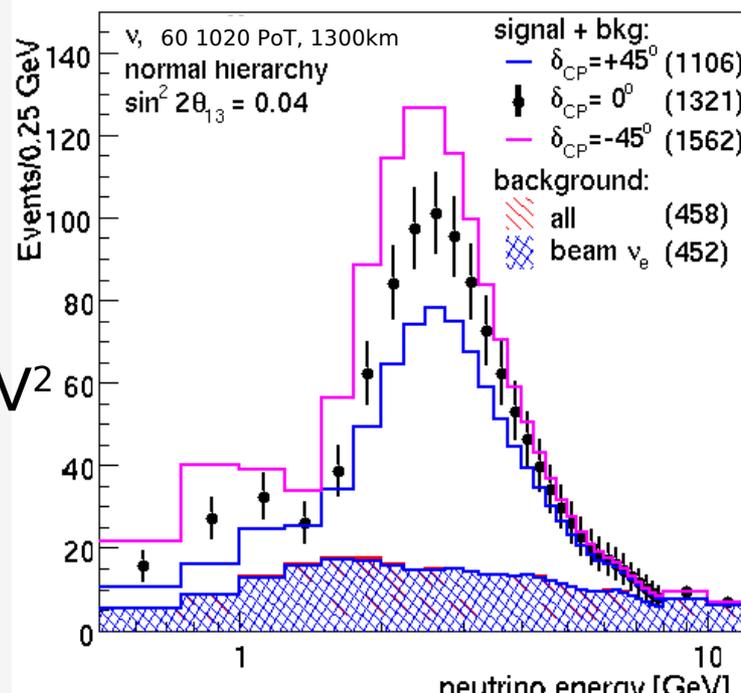
		$\sin^2 2\theta_{13} \neq 0$	$\text{sign}(\Delta m^2_{31})$	CPV
		3σ , all δ_{cp}	3σ , all δ_{cp}	3σ , 50% δ_{cp}
Water Cherenkov	300kt, 1.2MW	0.008	0.018	0.030
	300kt, 2.4MW	0.006	0.012	0.015
	600kt, 2.4MW	0.004	0.010	0.008
Liquid Argon	50kt, 1.2MW	0.007	0.014	0.018
	50kt, 2.4MW	0.005	0.011	0.010
	100kt, 2.4MW	0.003	0.008	0.003

Need ~6x smaller LAr to obtain similar sensitivities to WCh
Small NC bkg contamination will affect LAr, in particular CPV

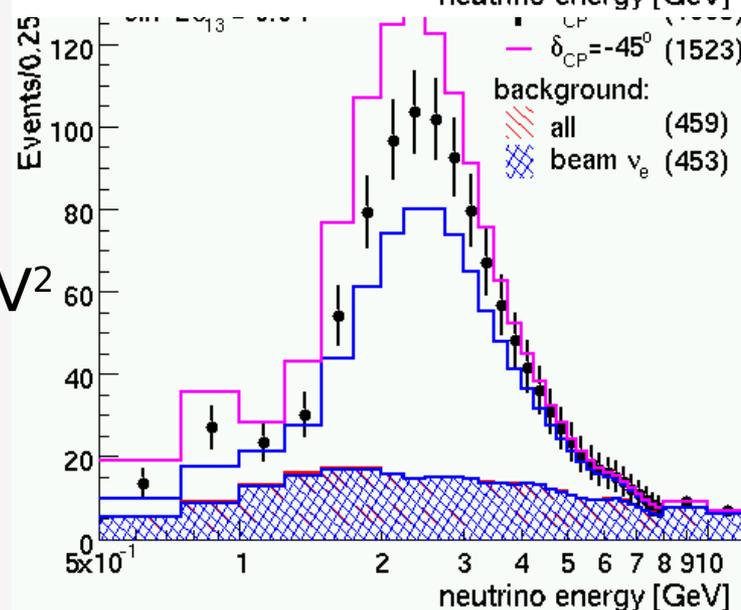
Effect of lower Δm^2_{31} on spectra



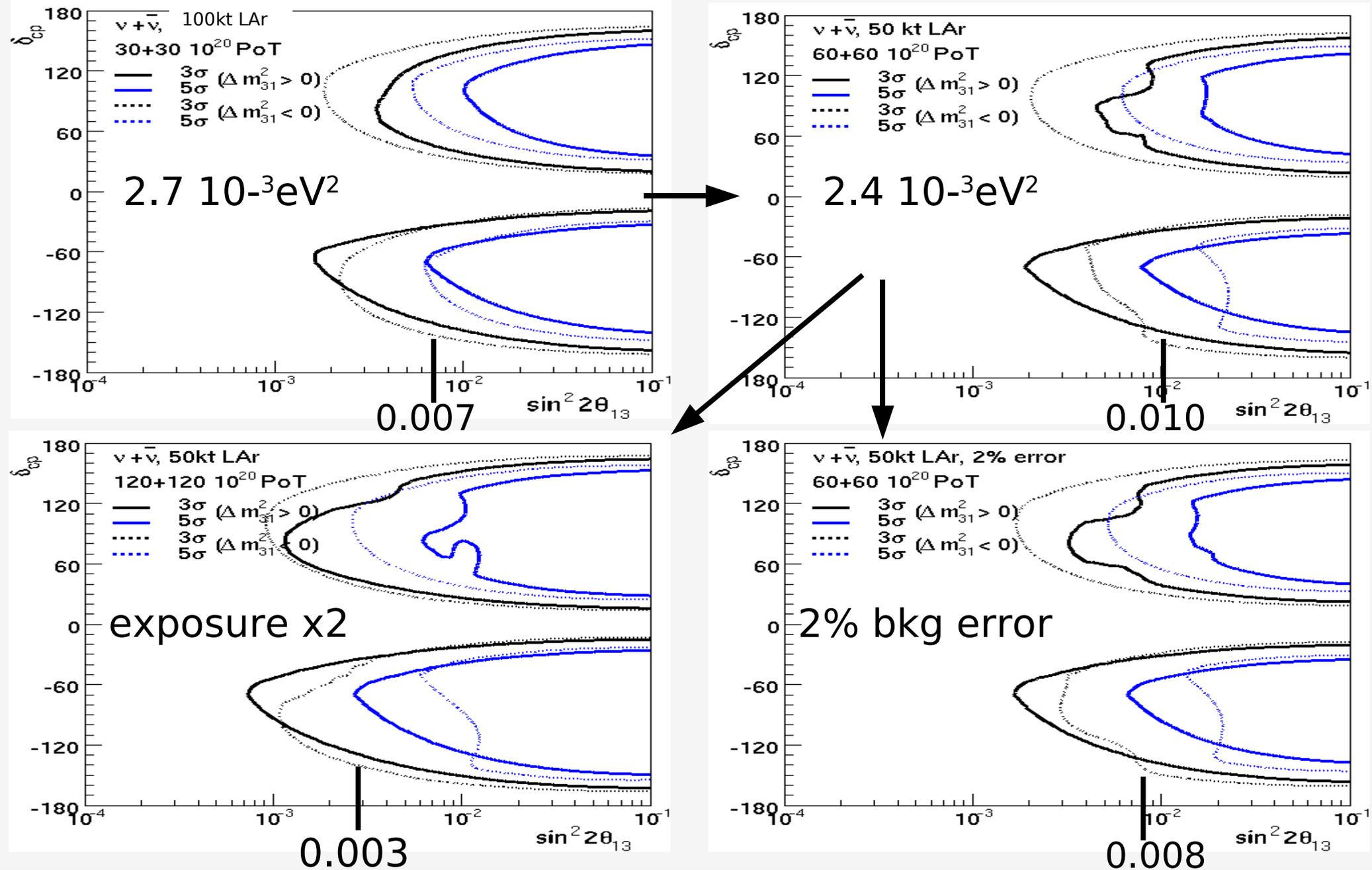
$2.7 \cdot 10^{-3} \text{ eV}^2$



$2.4 \cdot 10^{-3} \text{ eV}^2$



Effect of lower Δm^2_{31} on CPV



Background uncertainties



	background error	$\sin^2 2\theta_{13} \neq 0$ 3σ , all δ_{cp}	$\text{sign}(\Delta m_{31}^2)$ 3σ , all δ_{cp}	CPV 3σ , 50% δ_{cp}
Water Cherenkov 300kt	2%	0.005	0.012	0.013
	5%	0.006	0.012	0.015
	10%	0.006	0.013	0.016
Liquid Argon 50kt	2%	0.004	0.011	0.008
	5%	0.005	0.011	0.010
	10%	0.005	0.011	0.011

2.4MW beam, 6 years total



- With a 2.4MW beam, running 6 years total (ν +anti- ν) using either 300kt water Cherenkov or 50kt liquid Argon, the following measurements can be performed at 3σ level:

	$\sin^2 2\theta_{13} >$	
$\sin^2 2\theta_{13} \neq 0$	0.005 - 0.006	(all δ_{cp})
$\text{sign}(\Delta m^2_{31})$	0.011 - 0.012	(all δ_{cp})
CP violation	0.010 - 0.015	(50% δ_{cp})



- The 2nd oscillation node important for determining CPV. Focus at lower energies on:
 - Increasing neutrino flux
 - Understanding background rejection and uncertainties
 - (or go to longer baselines...)
- Need more detailed simulations for both detectors to:
 - Confirm and possibly improve assumed detector performance
 - Optimize detectors designs



Extras

Phased Approach

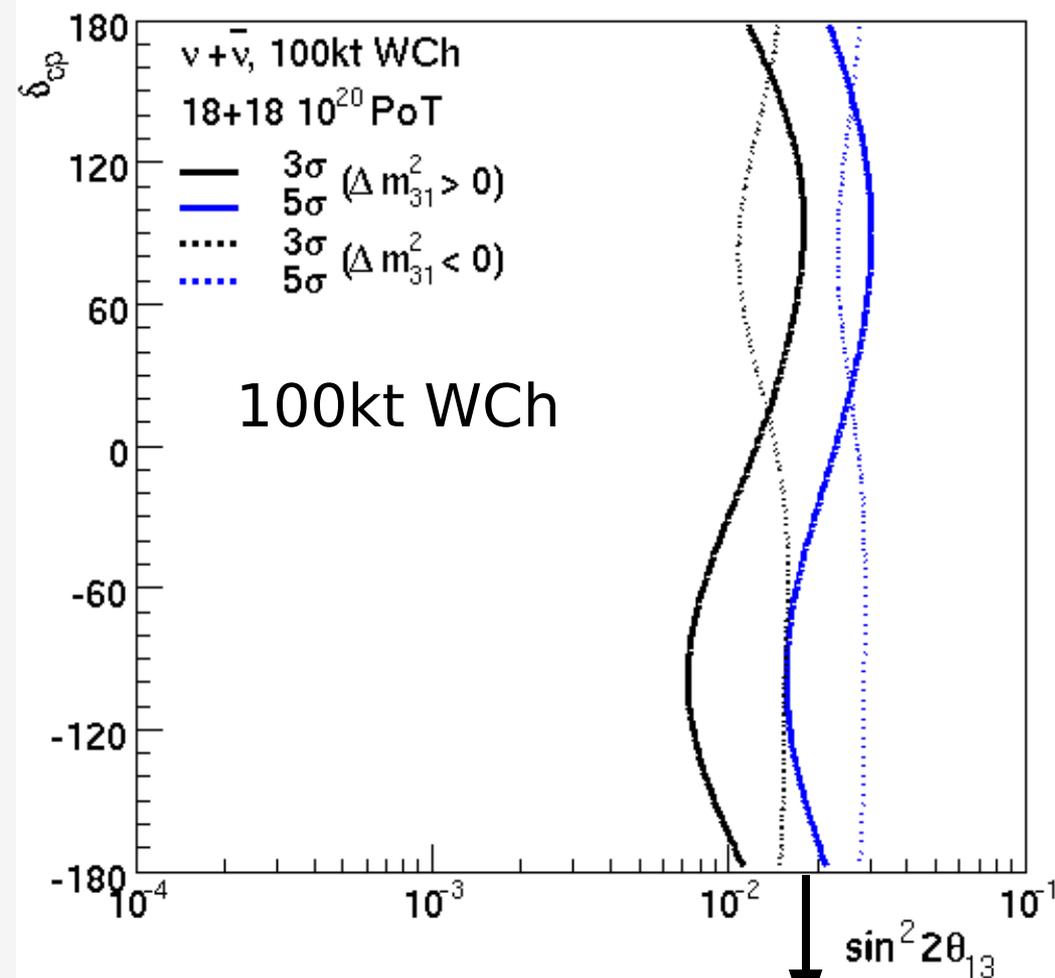


- Potential running plan: start with smaller detector ($\sim 1/3$ of full mass) and 700kW (or 1.2 MW) beam
- All other assumptions are the same
- Following pages show sensitivities for such a plan

$$\sin^2 2\theta_{13} \neq 0$$

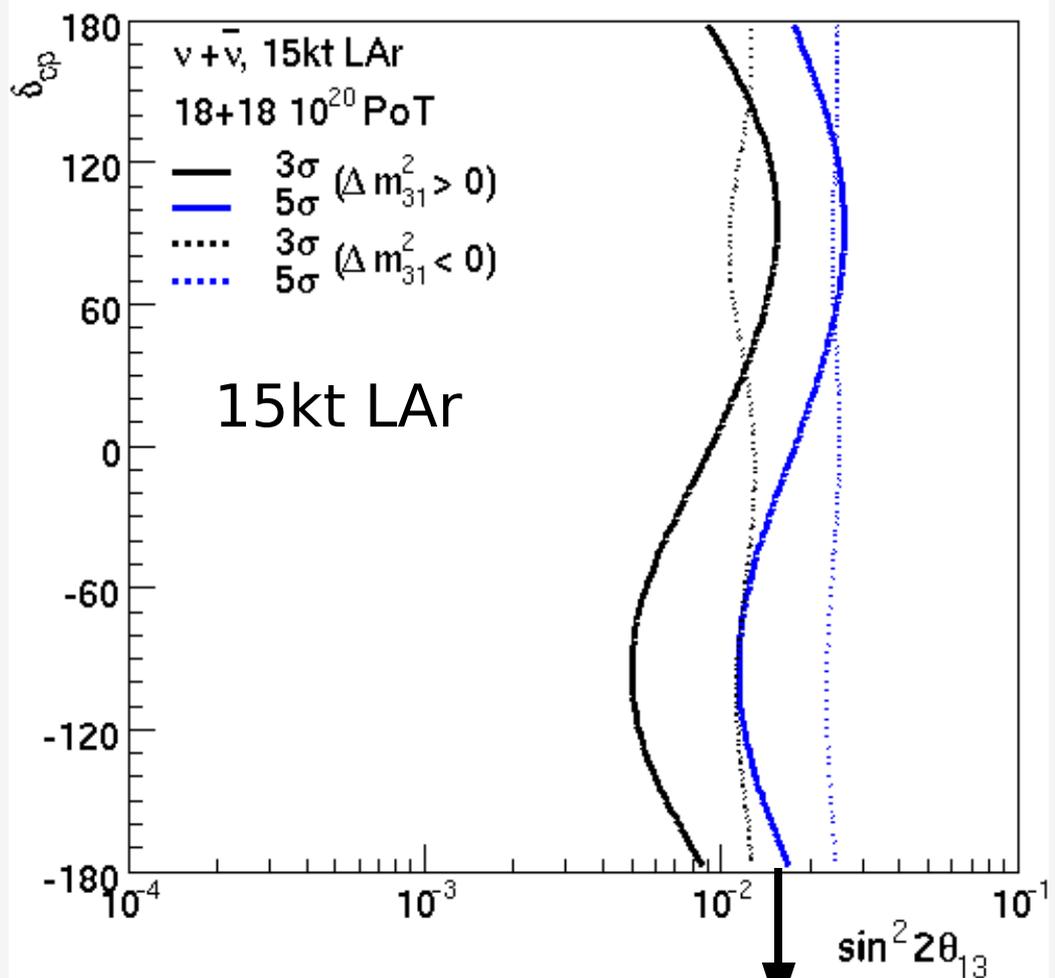


700kW beam



3σ , all δ_{cp} :

0.018

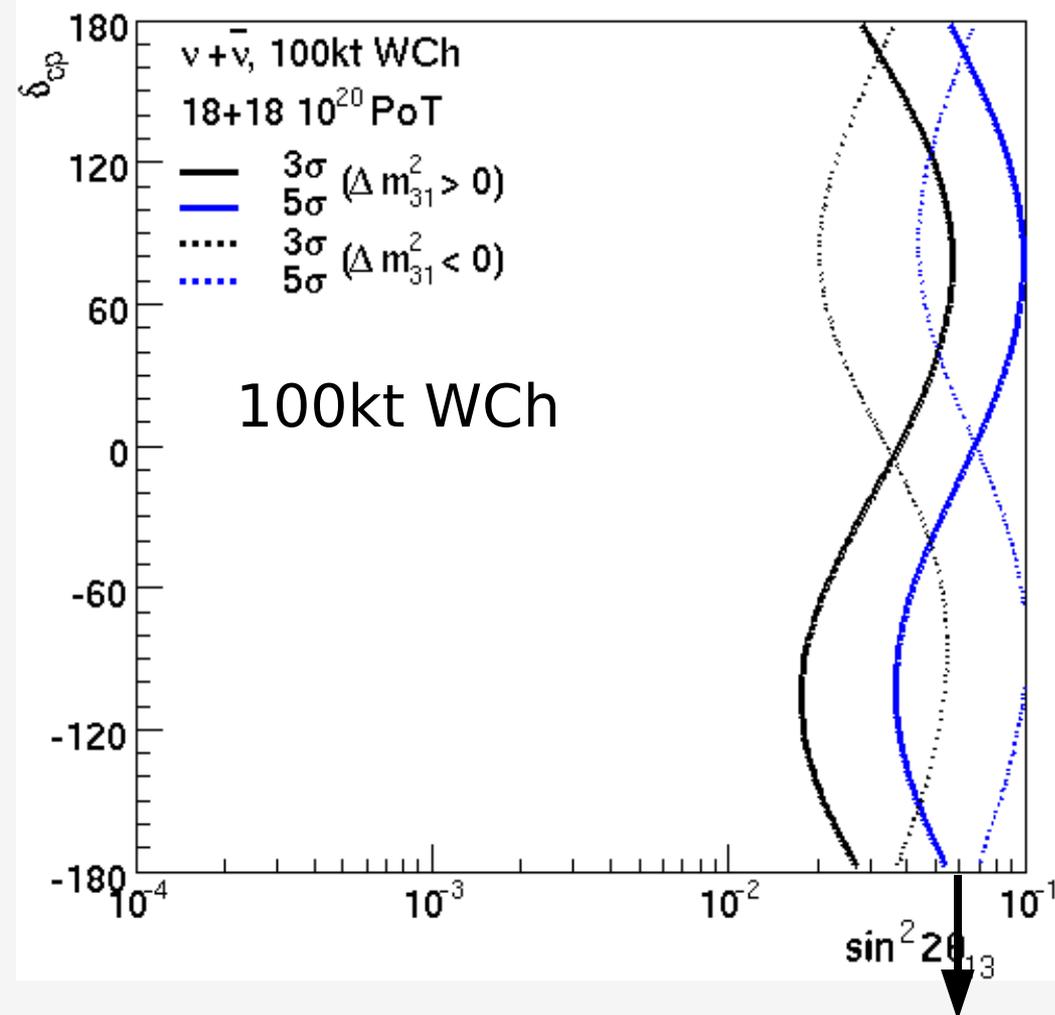


0.016

Mass hierarchy

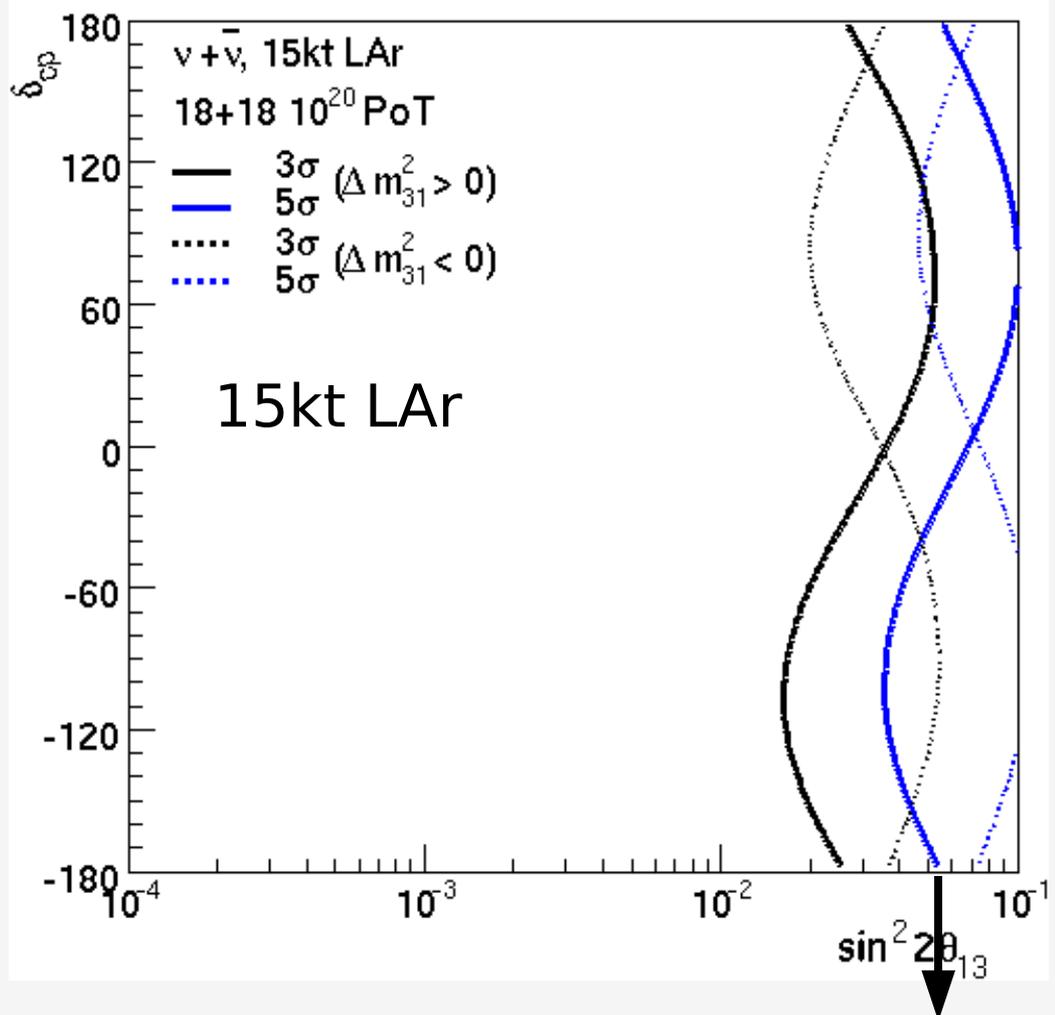


700kW beam



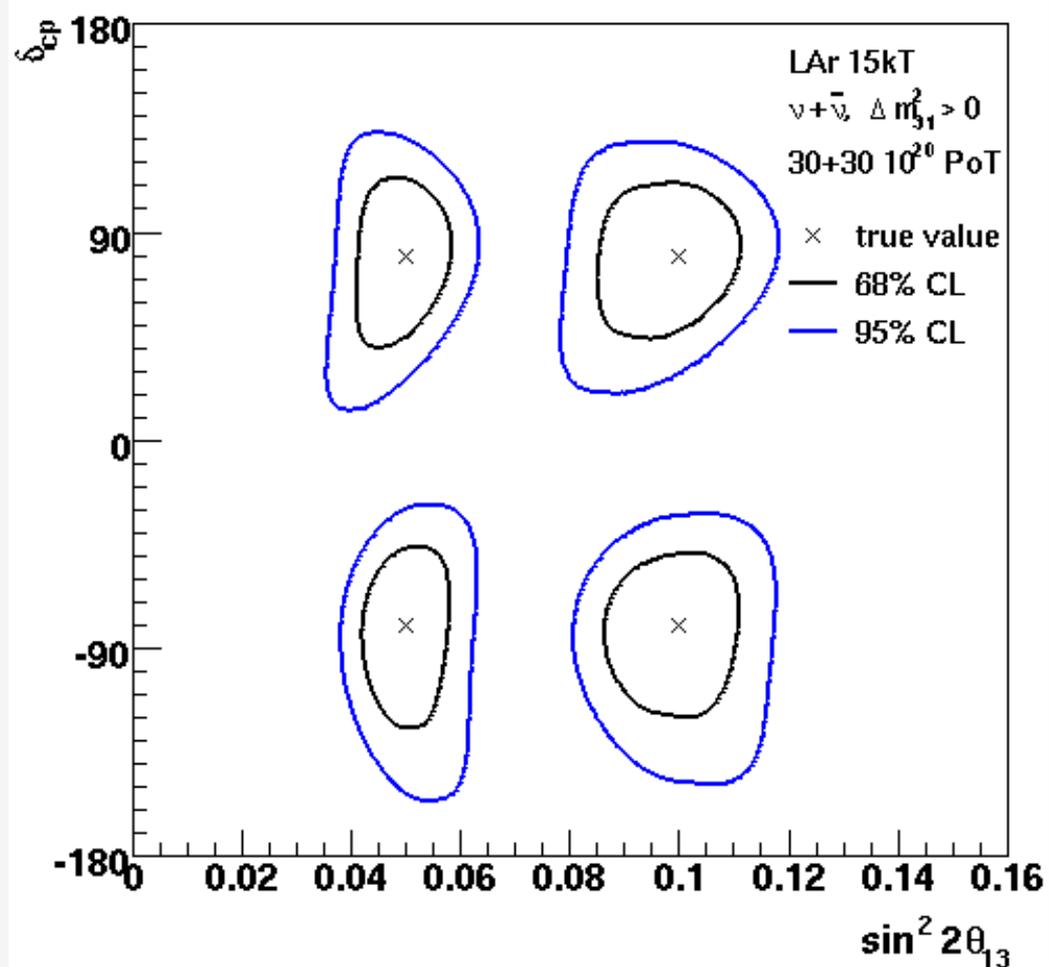
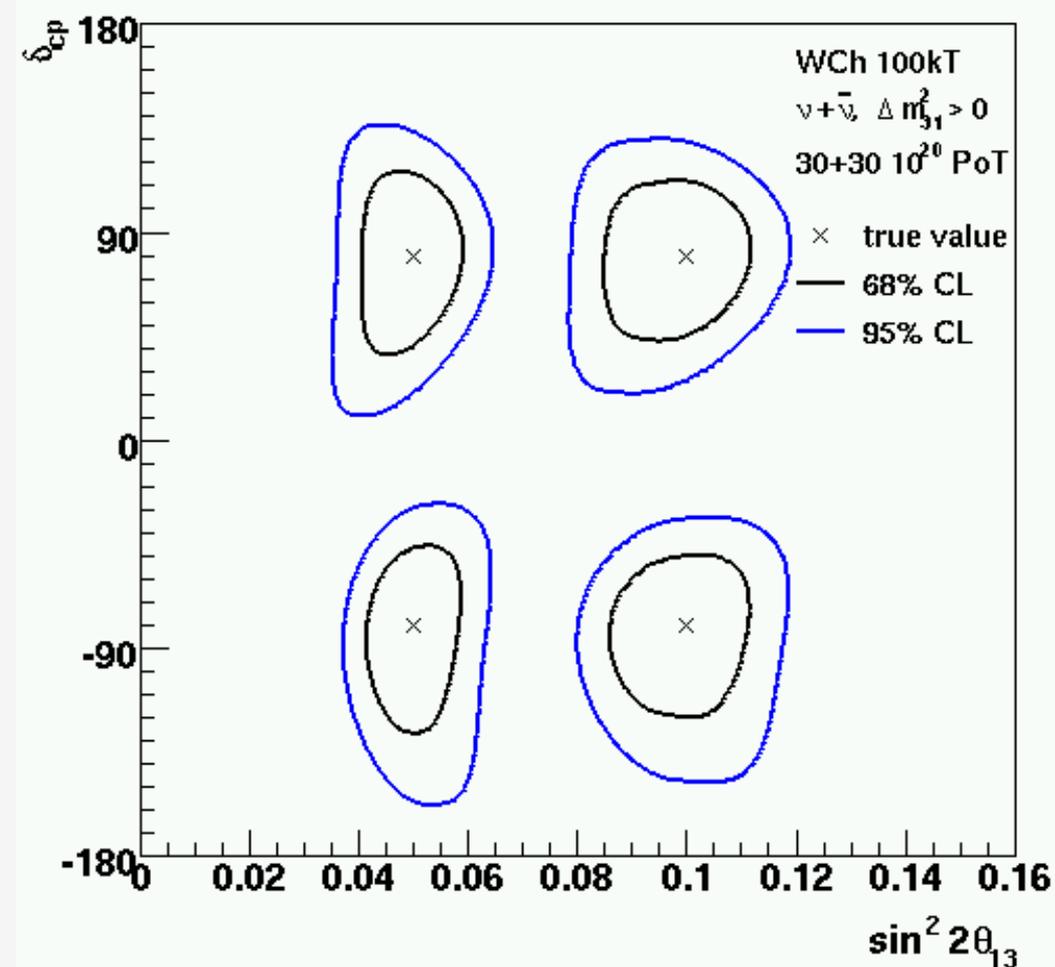
3σ , all δ_{cp} :

0.06



0.06

$(\theta_{13}, \delta_{cp})$ Measurement



Phased Approach Sensitivities



			$\sin^2 2\theta_{13} \neq 0$	$\text{sign}(\Delta m_{31}^2)$	CPV
Water Cherenkov 100kt	700kW	0.018	0.060	--	
	1.2MW	0.014	0.042	--	
Liquid Argon 15kt	700kW	0.016	0.057	--	
	1.2MW	0.012	0.037	--	