Physics Reach of a Very Long Baseline Neutrino Experiment using a Wide Band Beam

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Brookhaven National Laboratory

Particle Physics Seminar, BNL, April 12, 2007

Outline

- neutrino oscillations
- planned and proposed experiments
- VLBNO concept and recent progress
- sensitivities to oscillation parameters
- conclusions

Three neutrino oscillations

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$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow$$

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

solar | atmospheric

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$\theta_{12} \approx 34^{o}$ $\quad \sin^2 2\theta_{13} < 0.11$ (90%CL) $\quad \theta_{23} \approx 45^{o}$

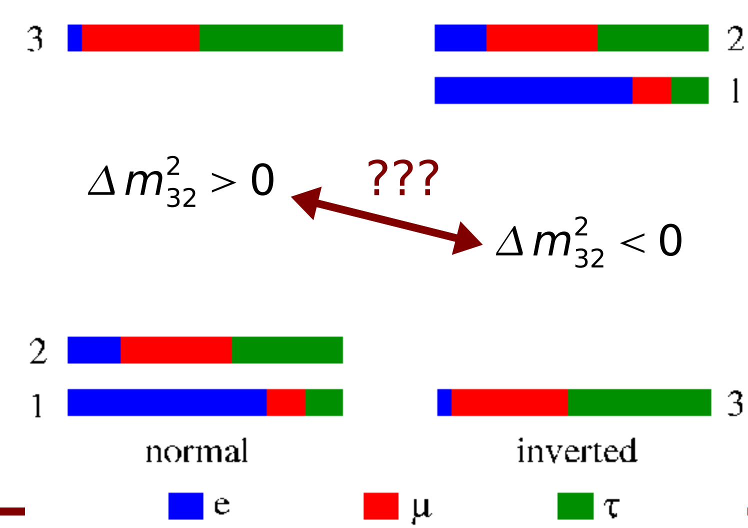
$\delta = ???$

neutrino masses must differ to observe ν oscillations:

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

$$|\Delta m_{32}^2| = |m_3^2 - m_2^2| \approx 2.6\ 10^{-3} eV^2$$

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



Neutrino Oscillations

LSND excess

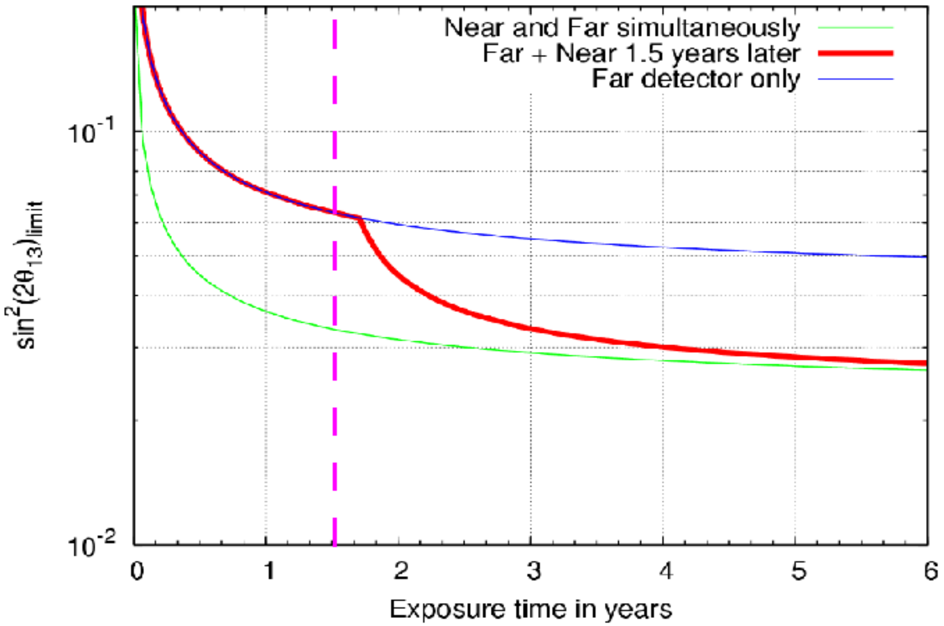
? MiniBooNE excess ?

Reactor Experiments

Reactor neutrino experiments: $\overline{\nu}_e$ disappearance

sensitive to θ_{13} only: clean measurement

Double Chooz

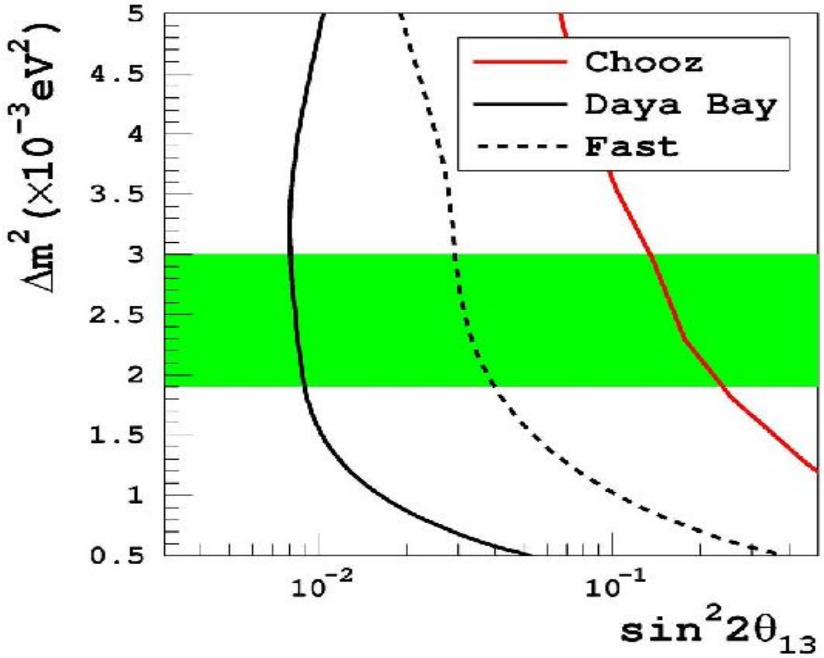


by 2012

90% CL: 0.03

3σ: 0.05

Daya Bay



by 2013

90% CL: 0.01

3σ: 0.02

Long Baseline Experiments

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- Measure ν_e appearance in ν_μ beam
- Approx. formula including matter effects (M. Freund) :

$$P_{\mu e} \approx \sin^2 2\theta_{13} \quad \sin^2\theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

$$+ \alpha \sin 2\theta_{13} \sin\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \alpha \sin 2\theta_{13} \cos\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha^2 \quad \cos^2\theta_{23} \sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

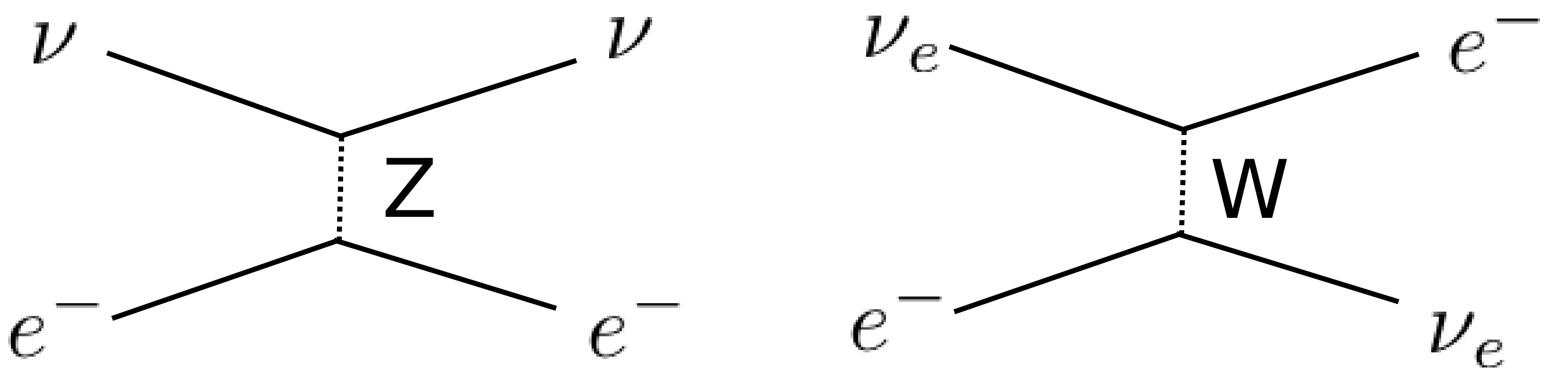
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \approx 0.03\,,\ \Delta = \Delta m^2_{31} L/4E$$

$$\hat{A} = 2\mathrm{VE}/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \ \text{(Earth's crust)}\,,\ V = \sqrt{2}\, G_F\, n_e$$

Depends on all oscillation parameters → ambiguities

Matter Effects

Oscillation probabilities modified in presence of matter



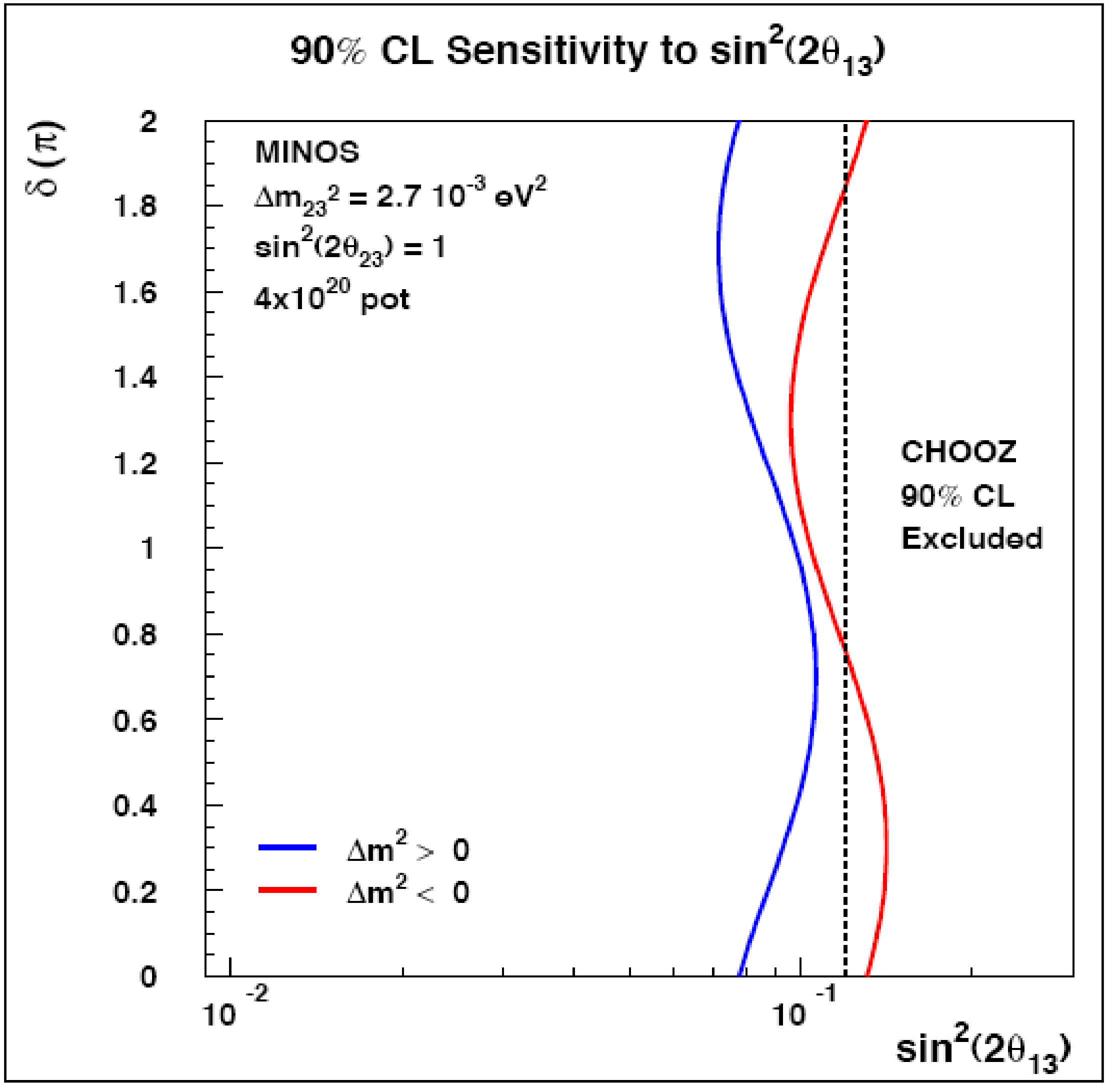
neutral current for all type of neutrinos

charged current for electron neutrinos only

extra potential for ν_e ($\bar{\nu}_e$): $V = \pm\sqrt{2}G_F N_e$

N_e: electron number density

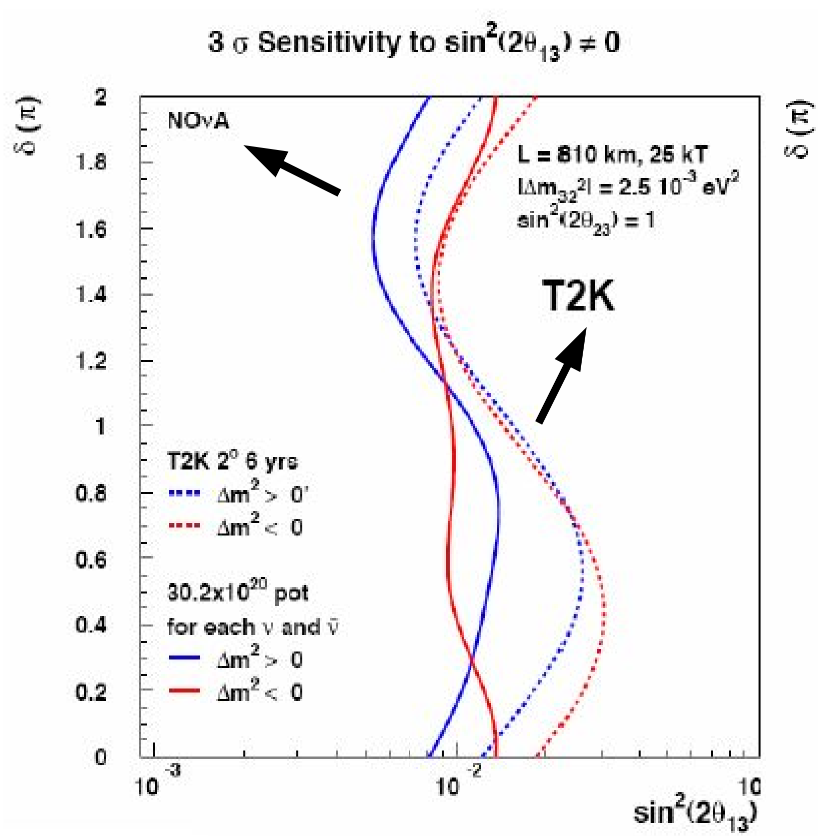
MINOS

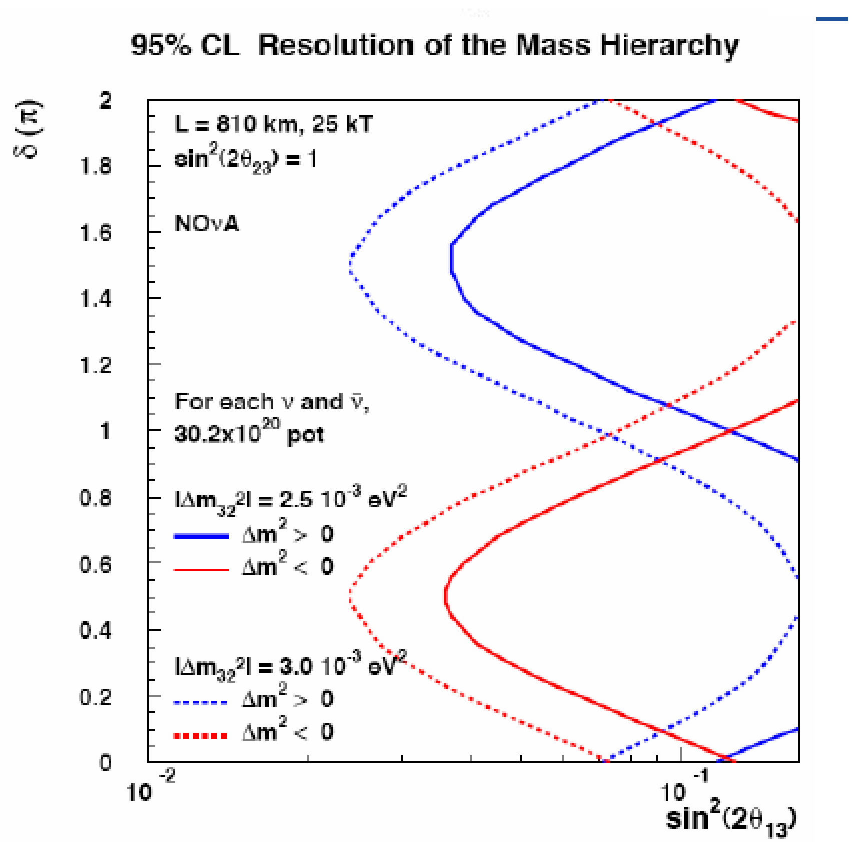


- ✔ 735km, on-axis
- ✔ 400kW designed ran at 300kW for 30 minutes
- ✔ collect 4 10^{20} pot by end of this year
- ✔ 10% systematics on background
- ✔ comparable with current CHOOZ limit

Off-axis: T2K/NOvA

- off-axis: narrow band beam, no high energy tail reduces NC background

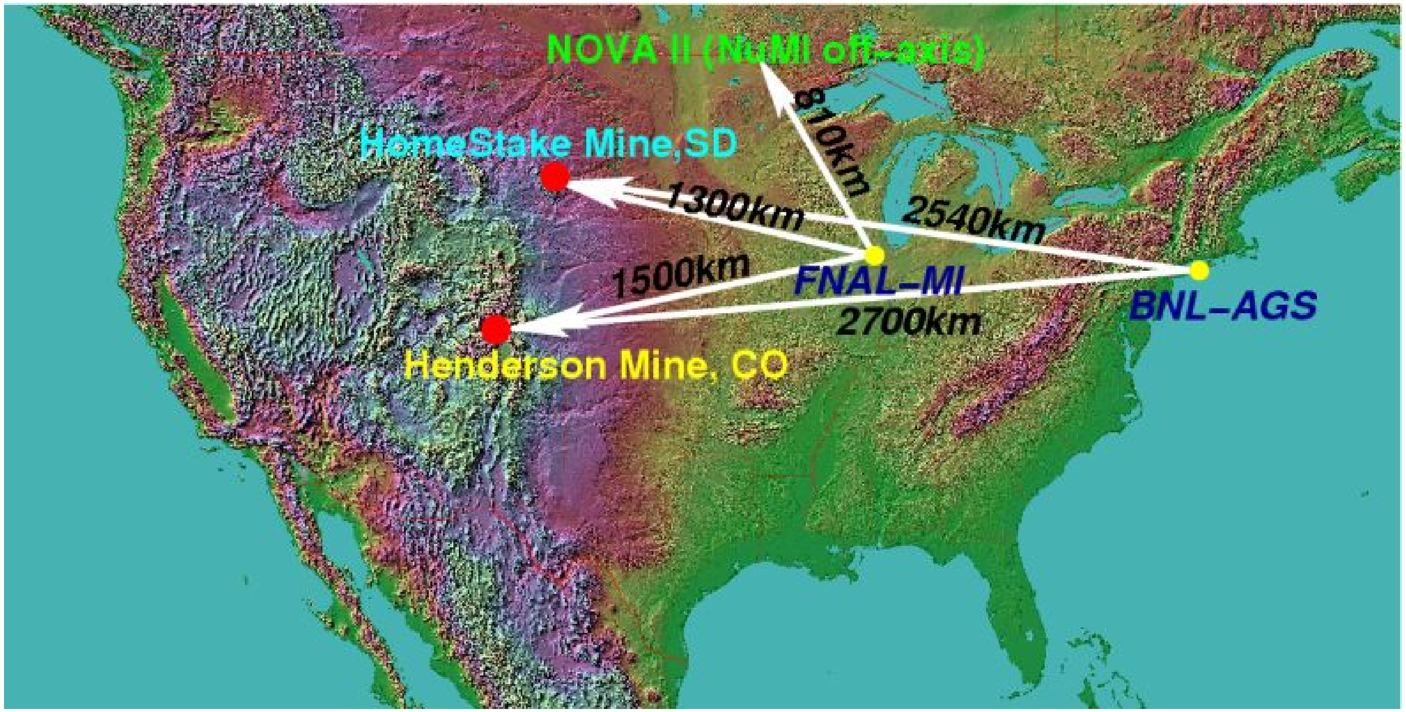




T2K: JPARC to SuperK
295km, 2.5° off axis
750kW, 50GeV protons

NOvA: upgrade NuMI
810km, 0.9° off-axis
700kW, 120 GeV protons

Possible Baselines in US



- ✔ Off axis beams using 120 GeV NuMI beamline at FNAL to sites at 810km.
- ✔ 28 GeV on-axis Wide-Band Beam (WBB) beam from BNL AGS to DUSEL sites at 2540 and 2700 km.
- ✔ Newly designed on-axis 120 GeV Wide Band Low Energy (WBLE) beam and beamline from FNAL MI to DUSEL sites at 1300km and 1500km.

  concentrate on beam options from FNAL for this talk

Joint FNAL-BNL Study

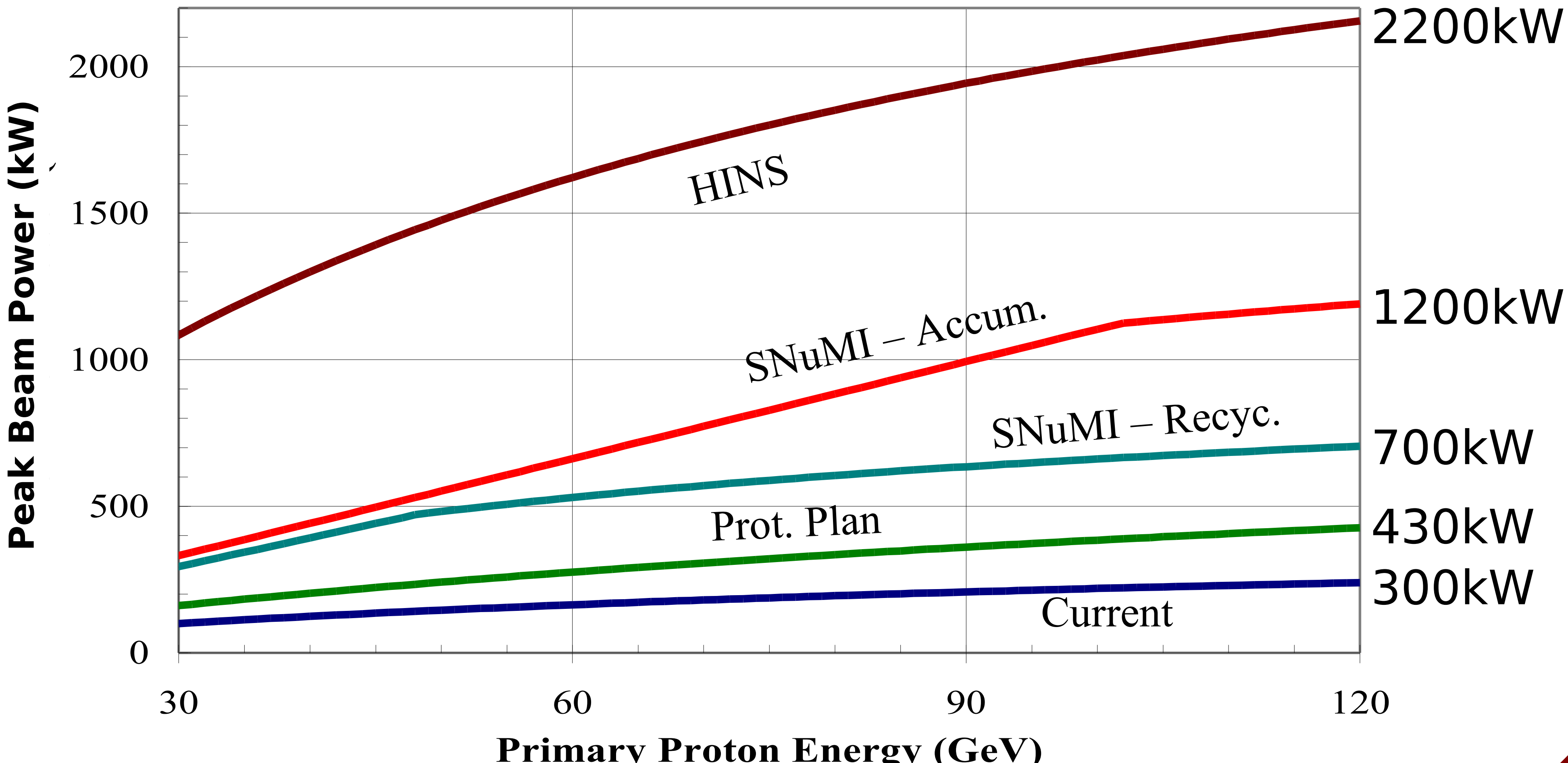
- Charge:
  - A broad-band proposal using either an upgraded beam of ~ 1 MW from current Fermilab accelerator complex or future Proton Driver ν beam aimed at a DUSEL-based detector. Compare results with proposal for high intensity beam from BNL to DUSEL.
  - Off-Axis next generation options using a 1-2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

- Several small workshops were held last year.
- Many reports on physics sensitivity,backgrounds, and beam alternatives.

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

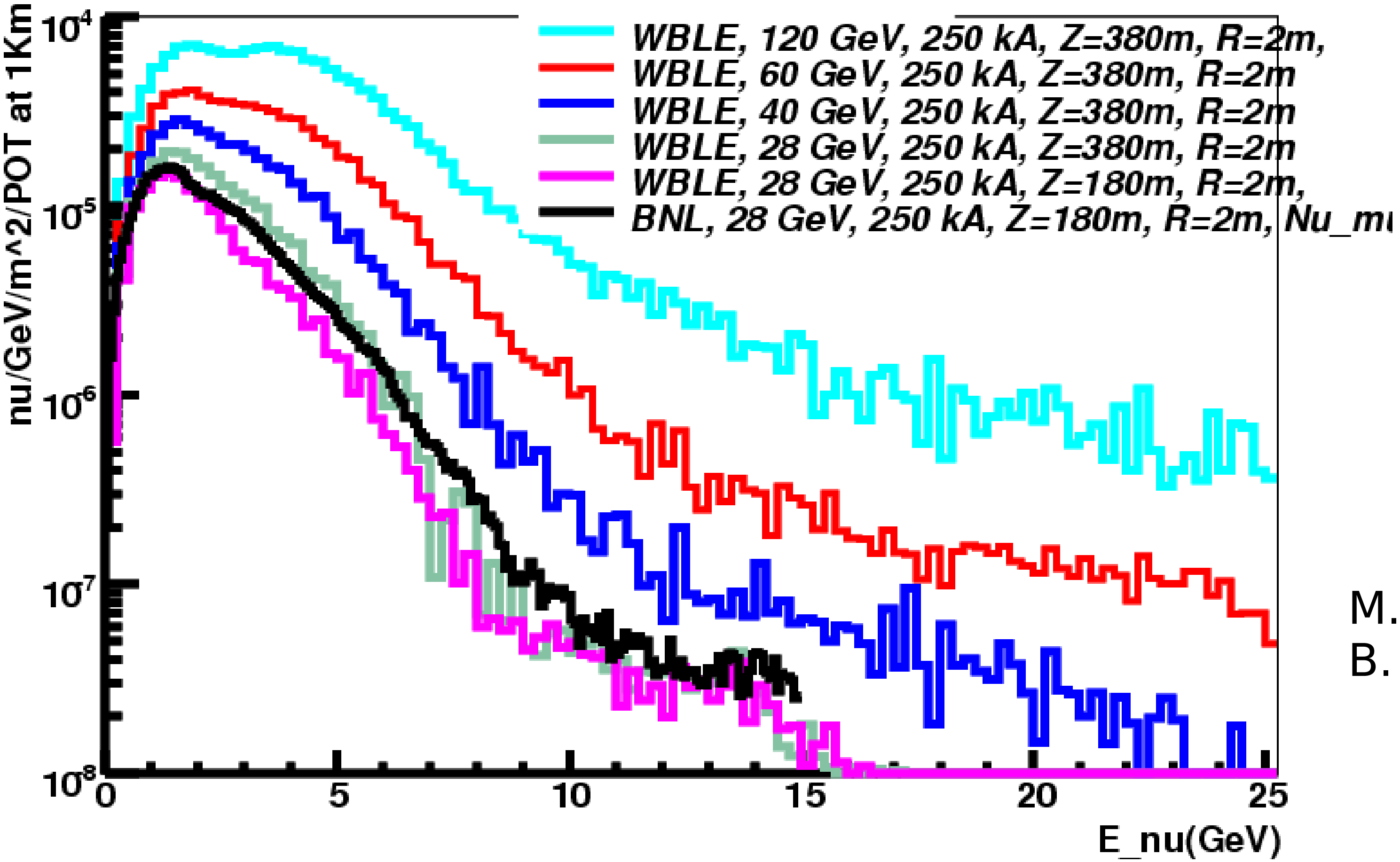
FNAL MI Upgrade

a) Proton plan: More protons in current MI
b) Super NuMI: Phase I: use Recycler as pre-injector
Phase II: also use Accumulator
c) High Intensity Neutrino Source (a.k.a. Proton driver):
Replace booster with 8GeV SC linac



Flux Calculations

- Beam Band Low Energy (WBLE) beam simulated based on NuMI MC (Geant3/Fluka05)



M. Bishai
B. Viren

- Good agreement BNL & WBLE calculations @ 28GeV
- Increase flux: longer decay pipe & higher proton energy

NOvA - II

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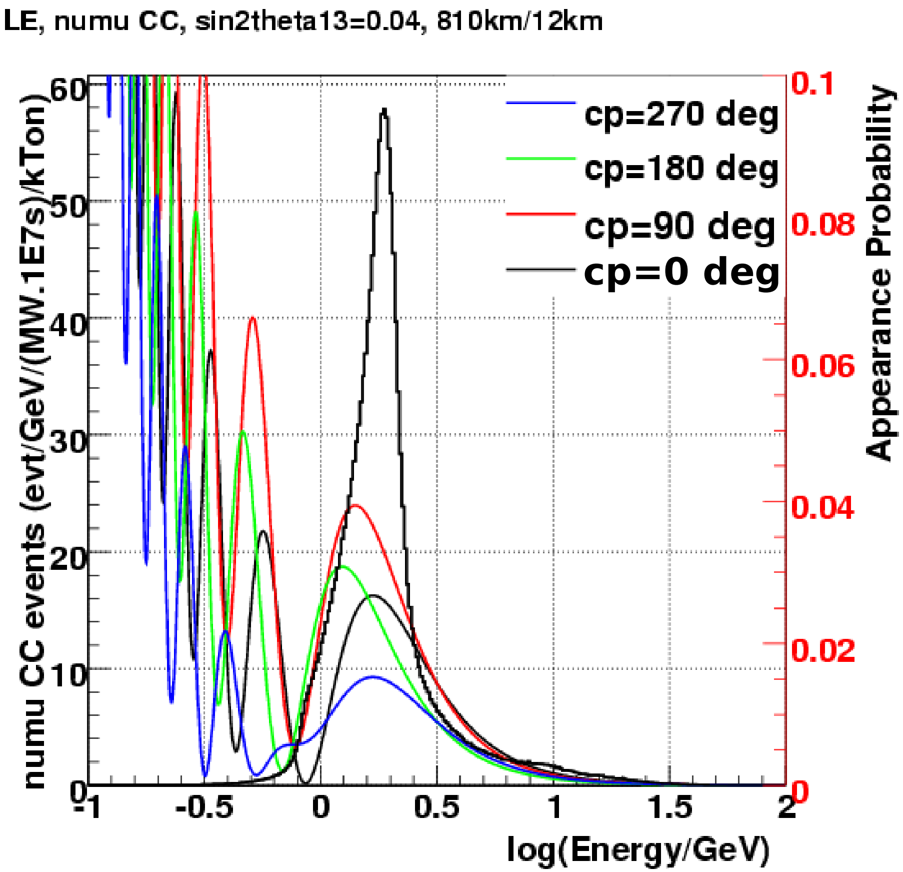
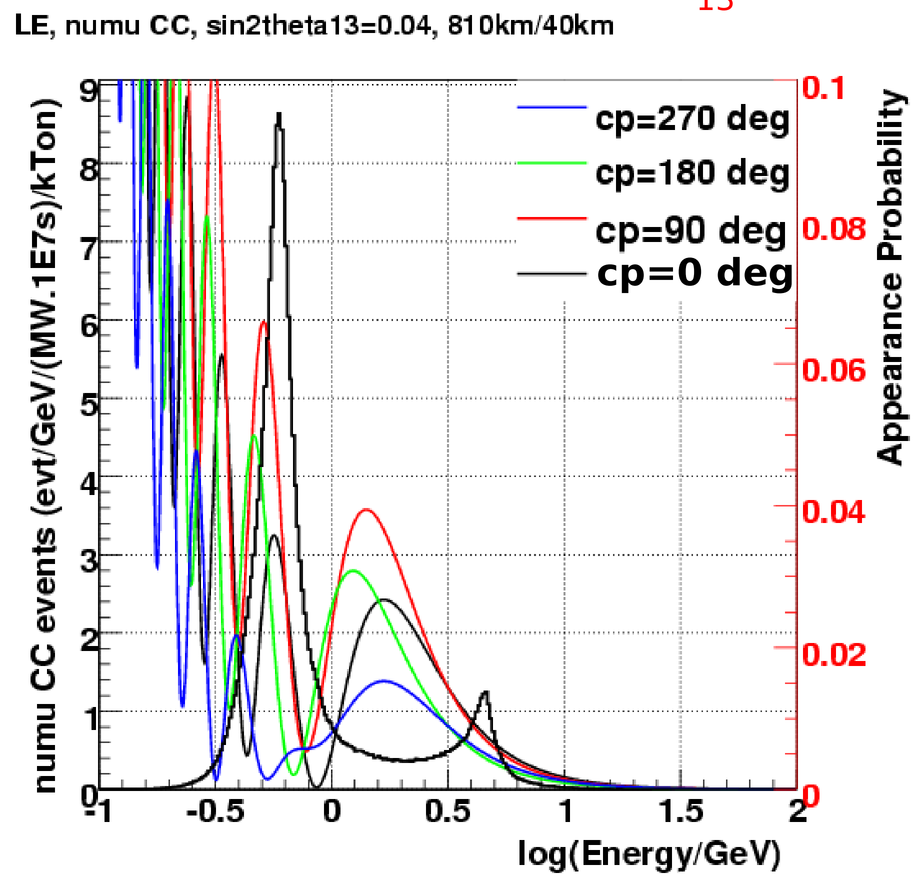
- ✔ Larger detector at 1st oscillation max, and/or 2nd det. at 2nd oscillation max

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





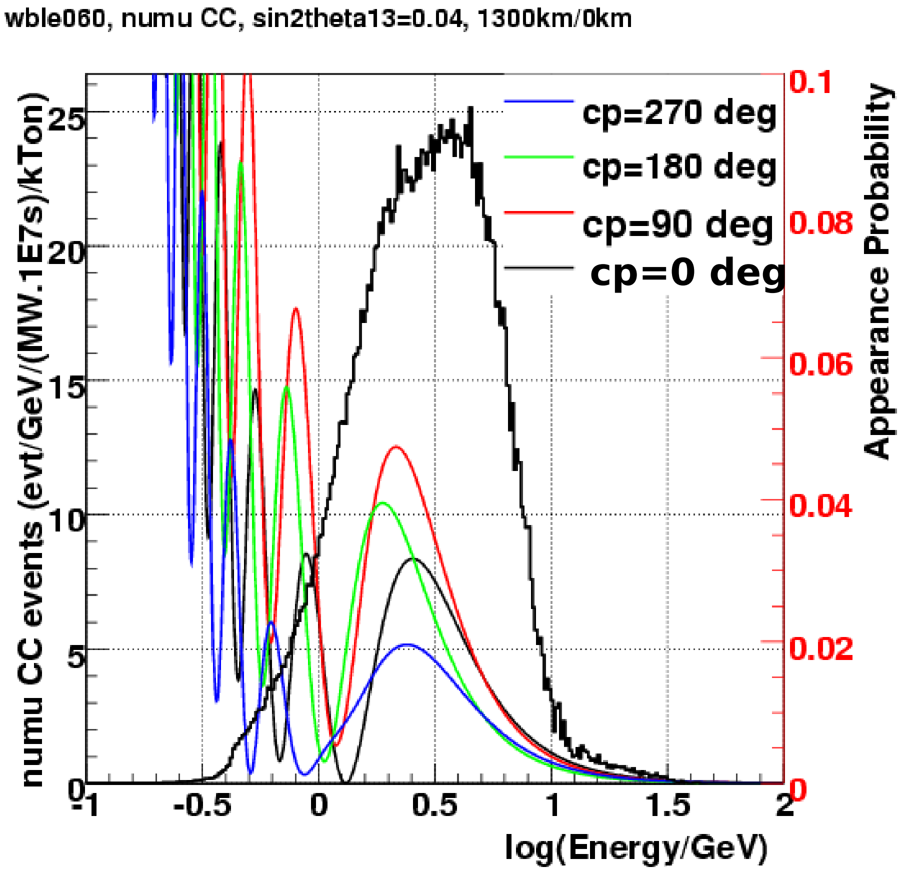
12km nova-I CC rate ~17.6 /(kT*10^{20} POT)

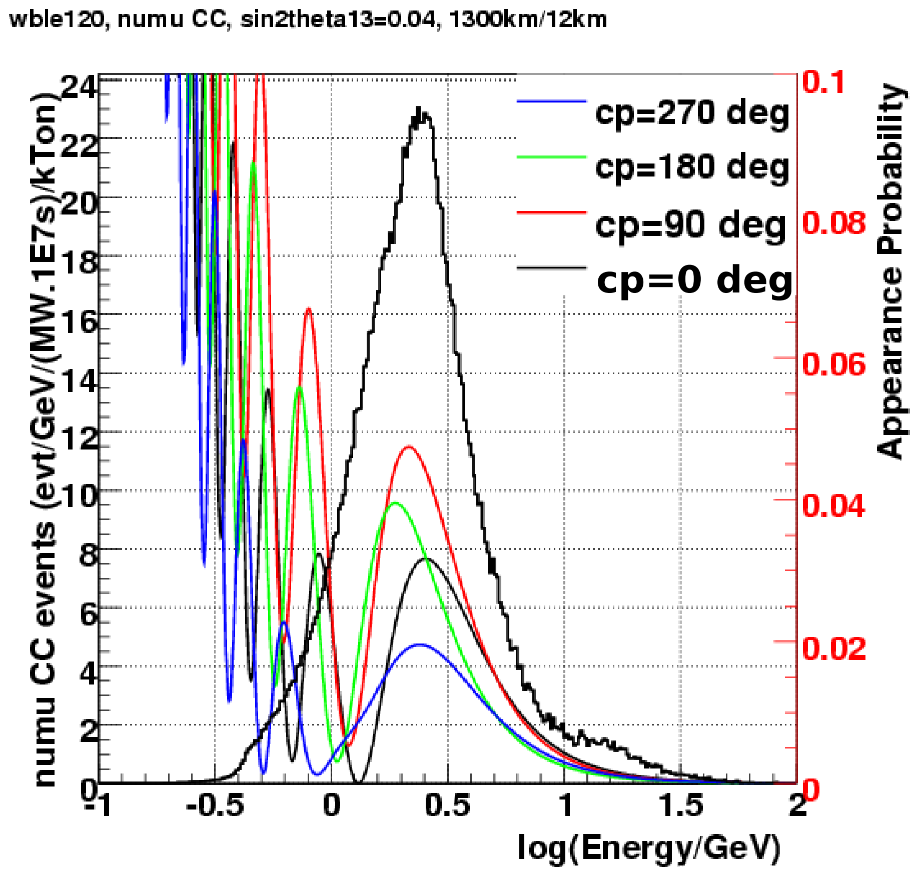
40km nova-II CC-rate ~1.1/(kT*10^{20} POT)

Wide band beam

- ✔ Exploit different energy dependency of parameters to resolve ambiguities

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

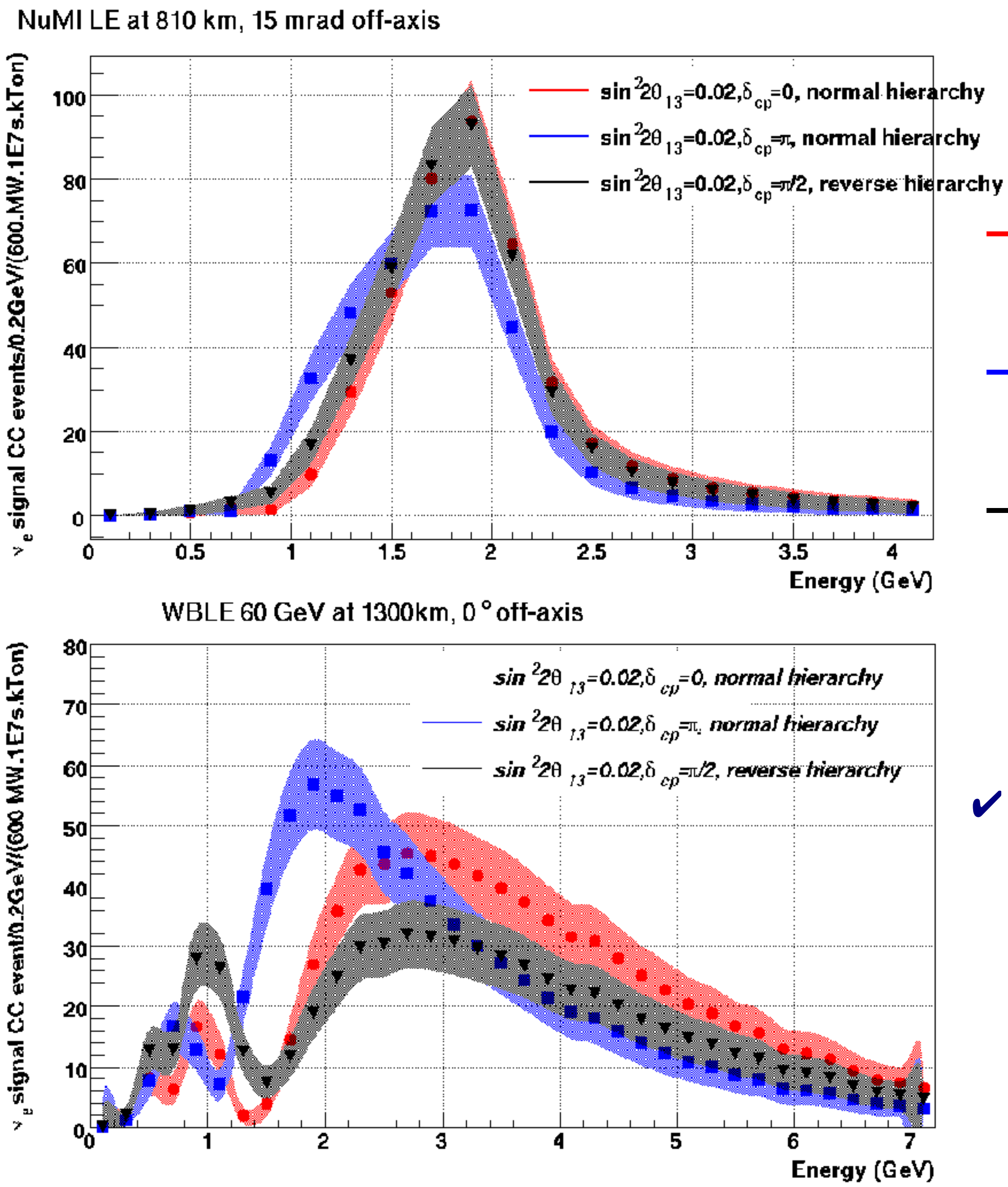




60GeV at 0°: ~16/(kT*10^{20}POT)

120GeV at 0.5°: ~20.5/(kT*10^{20}POT)

narrow vs wide band beam



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

✔ spectral information allows for resolving ambiguities with only one experiment

Detector techniques

Water Cherenkov detectors:

- known technology, wide dynamic range (5MeV-50GeV)
- can perform accel. ν, p-decay, astrophysical sources
- several 100kTs (depends on physics)
- scale few times Super-K 50kT (22.5kT fiducial)
- rejection neutral current interactions x10-20
- deep underground to reduce cosmics

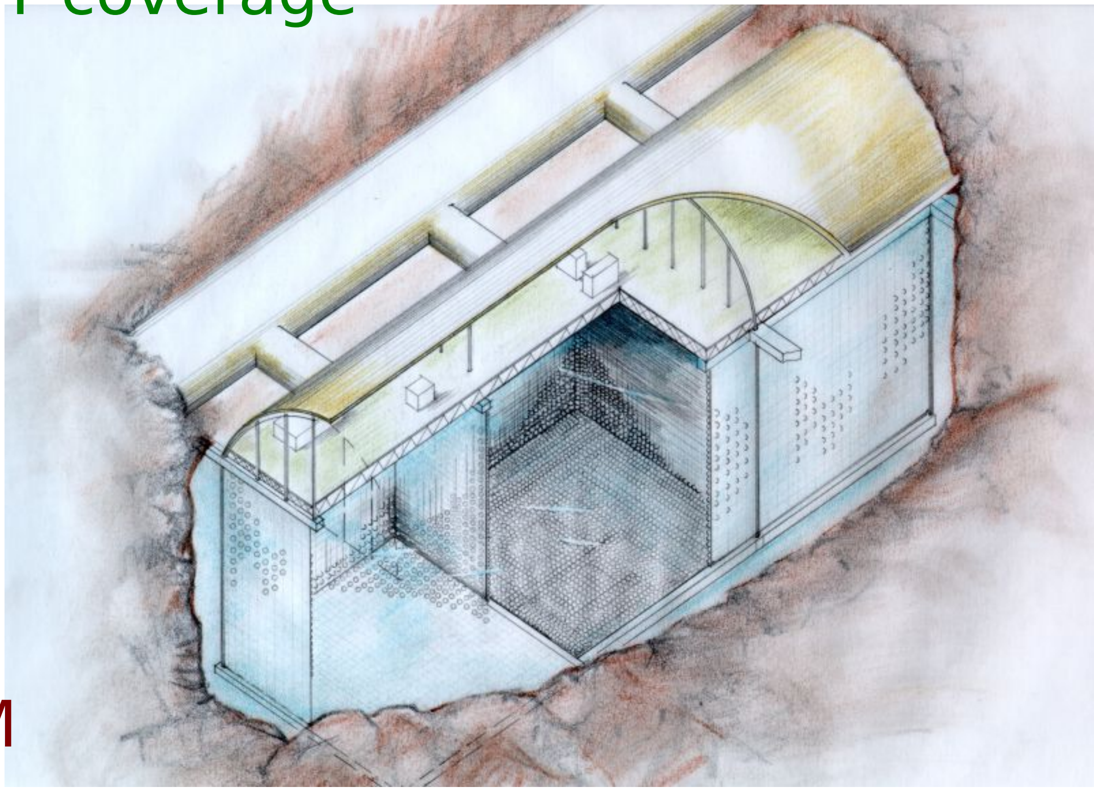
Liquid Argon detector:

- potential 3-4x better background reduction
- smaller detectors (~100kT)
- capability at this scale not proven yet (ICARUS=0.3kT)
- can it be underground? If not, can it deal with cosmic rate at surface?

Detector at Henderson

UNO detector:

- 1 large cavern
- 3 optically separated modules of 60x60x60 m^3
- total mass 440 kT fiducial
- central module 40% PMT coverage (low E physics)
- outer modules 10% PMT coverage
- optional finer granularity: 20 or 13 inch tubes
- optimal depth 5400mwe (2500 feet)
- construction time: 10 years
- coarse cost estimate scaling Super-K: $450M



Detector at Homestake

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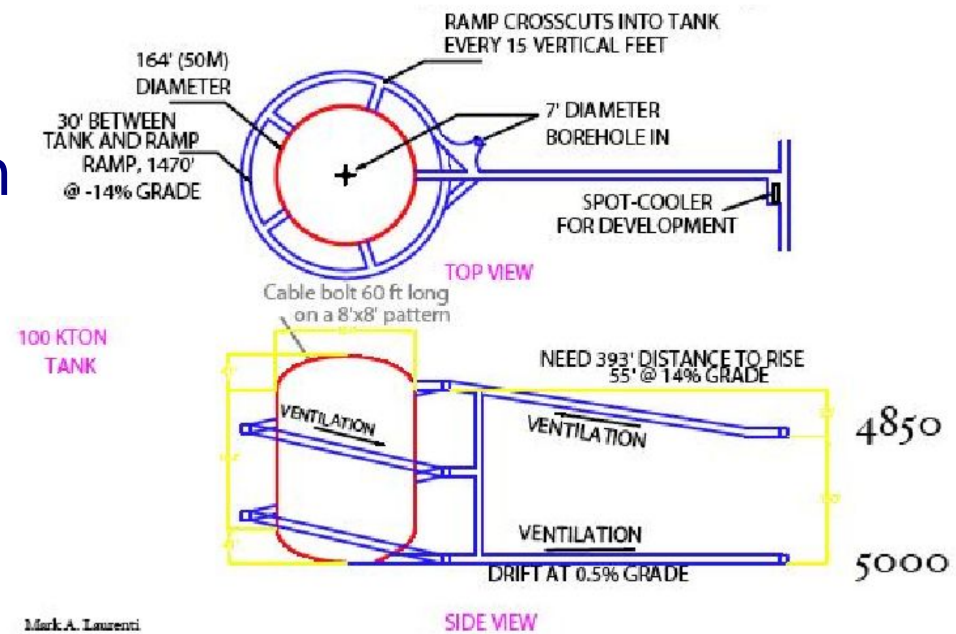
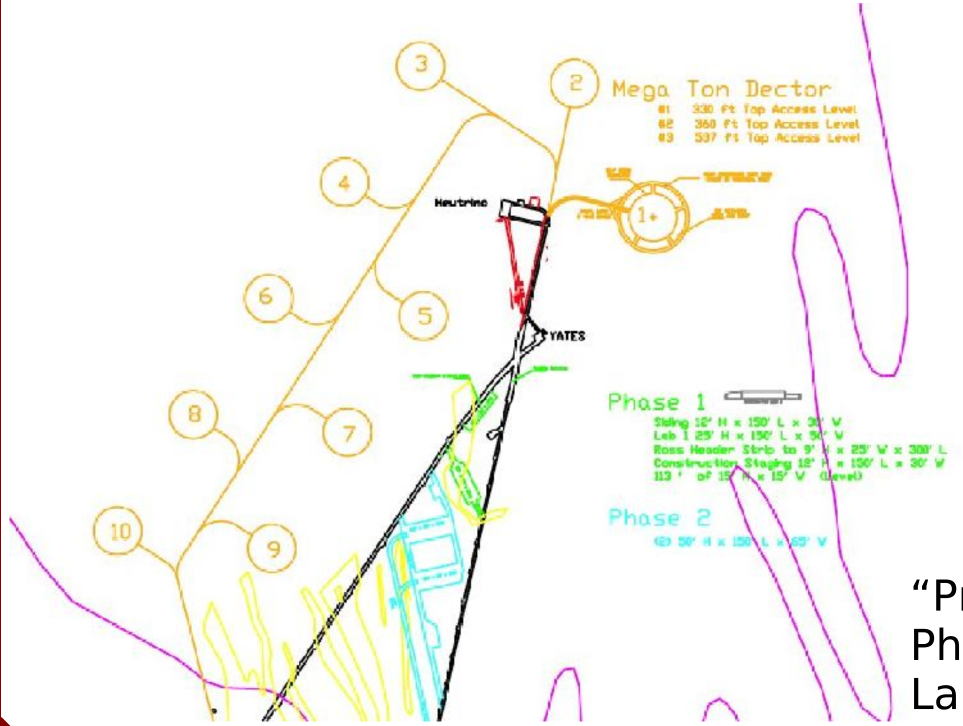
Modular detector:

- module: ~53m ∅, ~53m h
- 100kT fiducial
- depth 4850 mwe
- coverage 25%
- 12 inch PMT



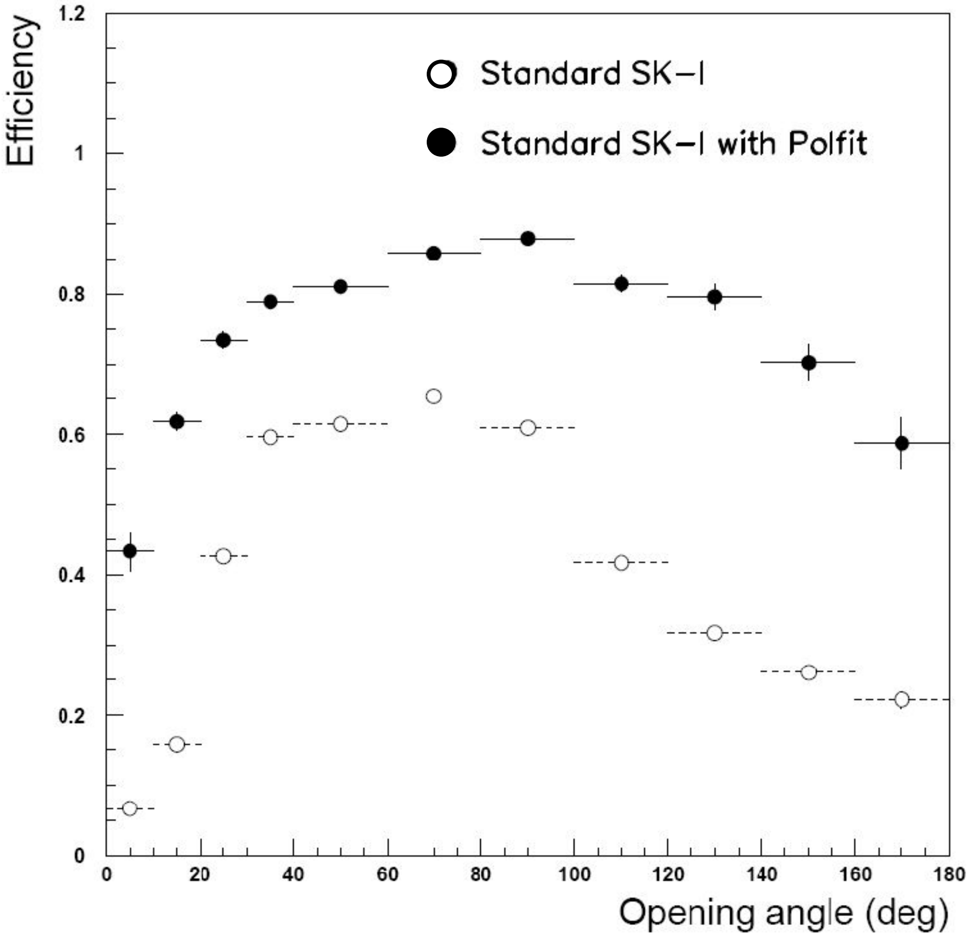


- initial detector 3 modules
- 6 yrs to complete 1st module, 8 yrs for all 3
- modules added if needed
- detailed cost estimate: $115M/module

“Proposal for an Experimental Program in Neutrino Physics and Proton Decay in the Homestake Laboratory", M. Diwan et al., hep-ex/0608023

Water Cherenkov Simulations

- Full GEANT simulation of Super-KamiokaNDE used
- 40% PMT coverage
- atmospheric neutrino MC reweighted to match expected flux 28GeV AGS beam



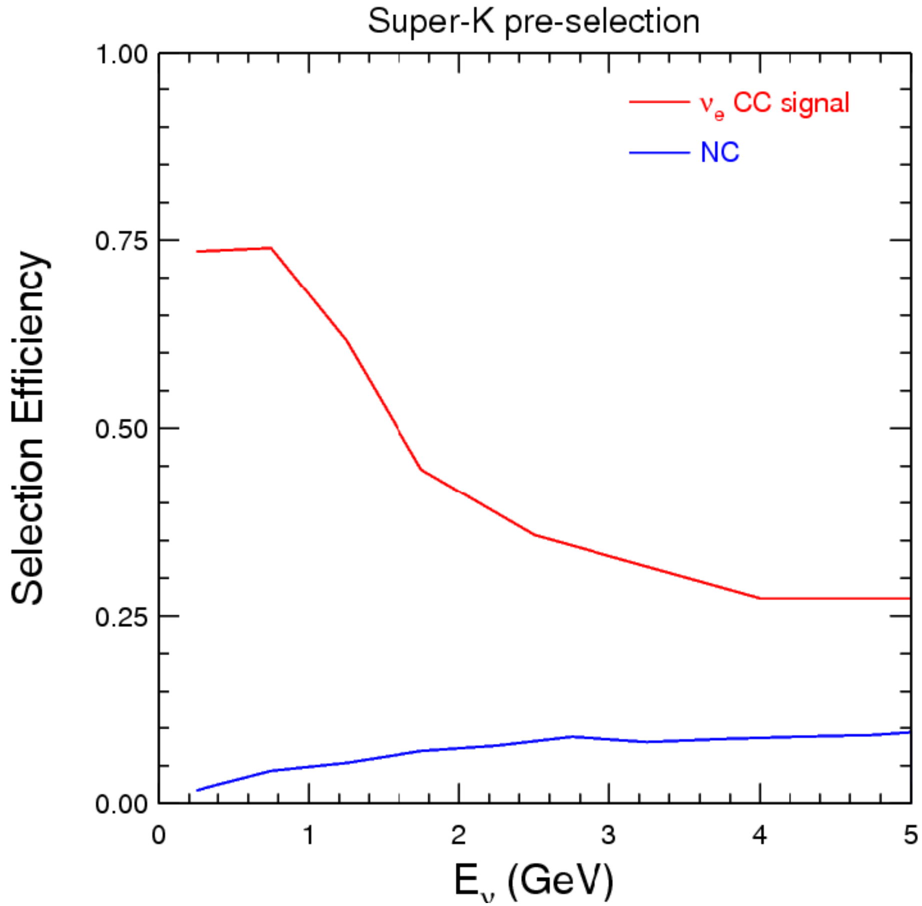
"Pattern of Light" fit improves standard Super-K π^0 finder

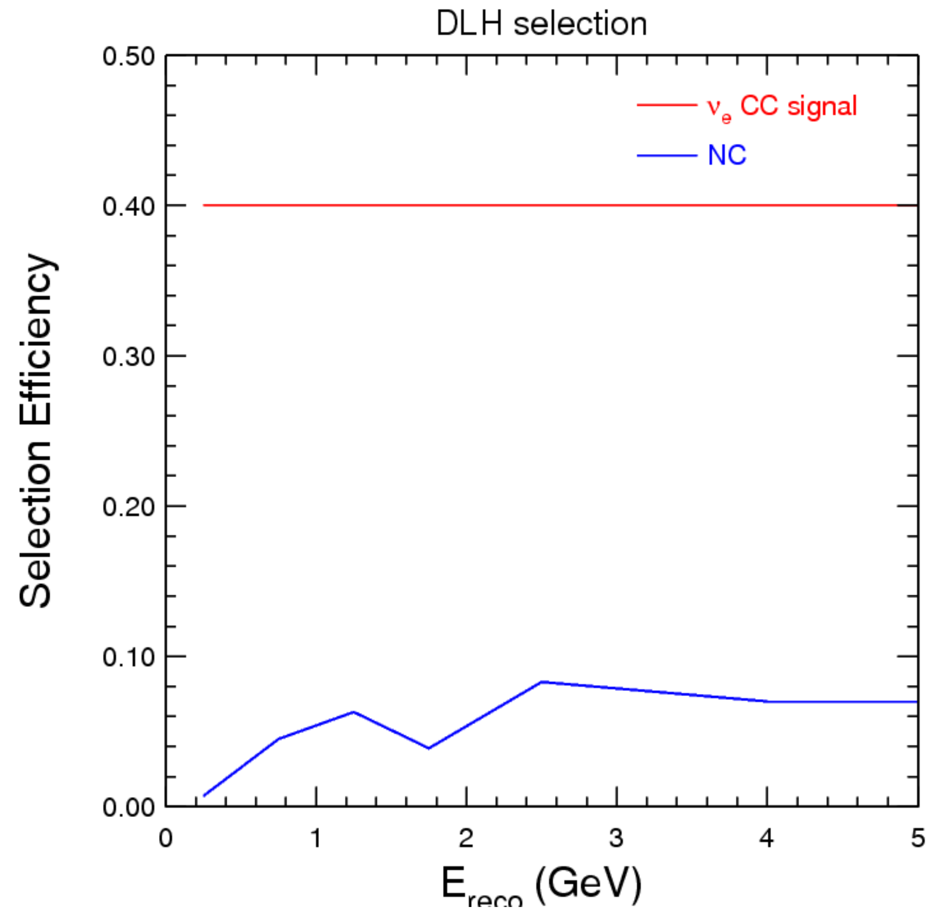
Improvements at lower opening angles with finer granularity expected

"Background Rejection Study in a water Cherenkov detector", C. Yanagisawa, C. K. Jung, P.T. Le, B. Viren, July 18, 2006

Water Cherenkov Simulations

- Select single ring events and electrons
- Likelihood analysis of single ring pattern





- Confirmed by indep. T2KK study, F. Dufour, Boston U.
- Not optimized for PMT coverage or granularity

Beam & WCh det assumptions

- All recent progress implemented in GLoBES
- Beam/baseline assumptions:
  - WBLE beam, 120 GeV, 0.5^0 off-axis
  - 1300km baseline
  - 30 10^{20} PoT for ν and $\bar{\nu}$ each
  - 1.2MW & 1.7 10^7 s $\Rightarrow$ 3+3 years
- Water Cherenkov (WCh) detector assumptions:
  - 300 kT fiducial mass
  - implemented new selection efficiencies
  - 10% energy resolution
  - 10% uncertainty on total background

WCh appearance spectra

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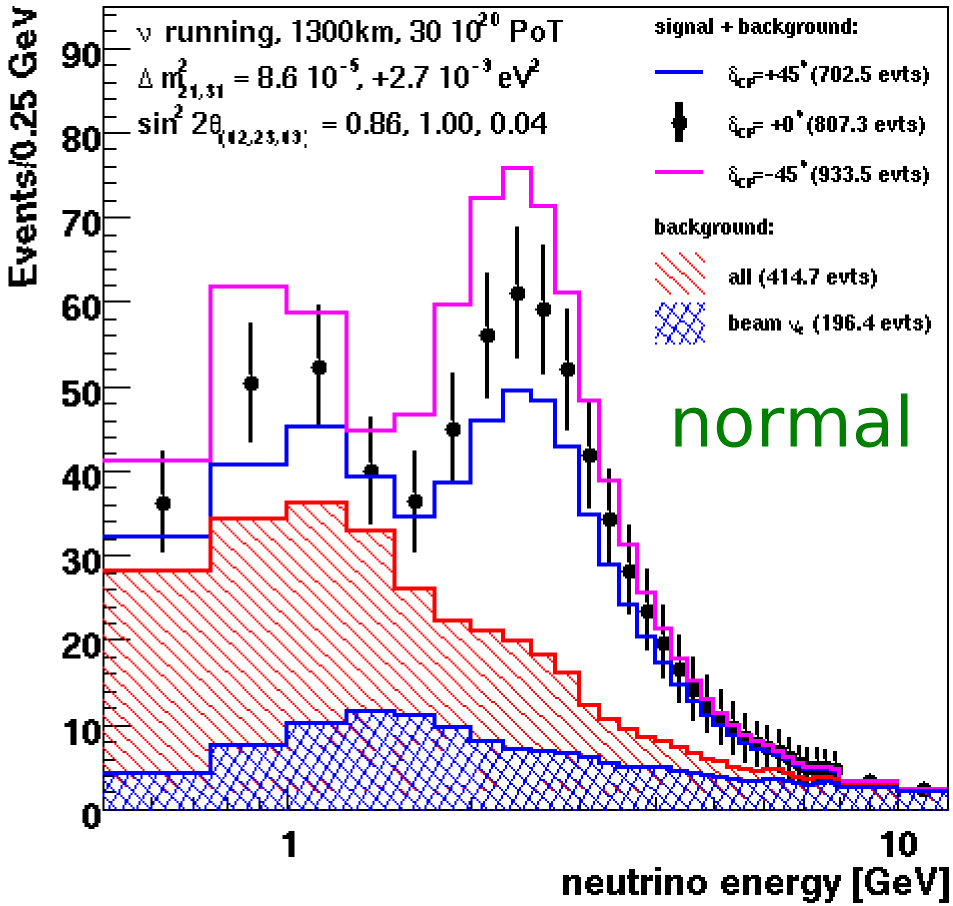
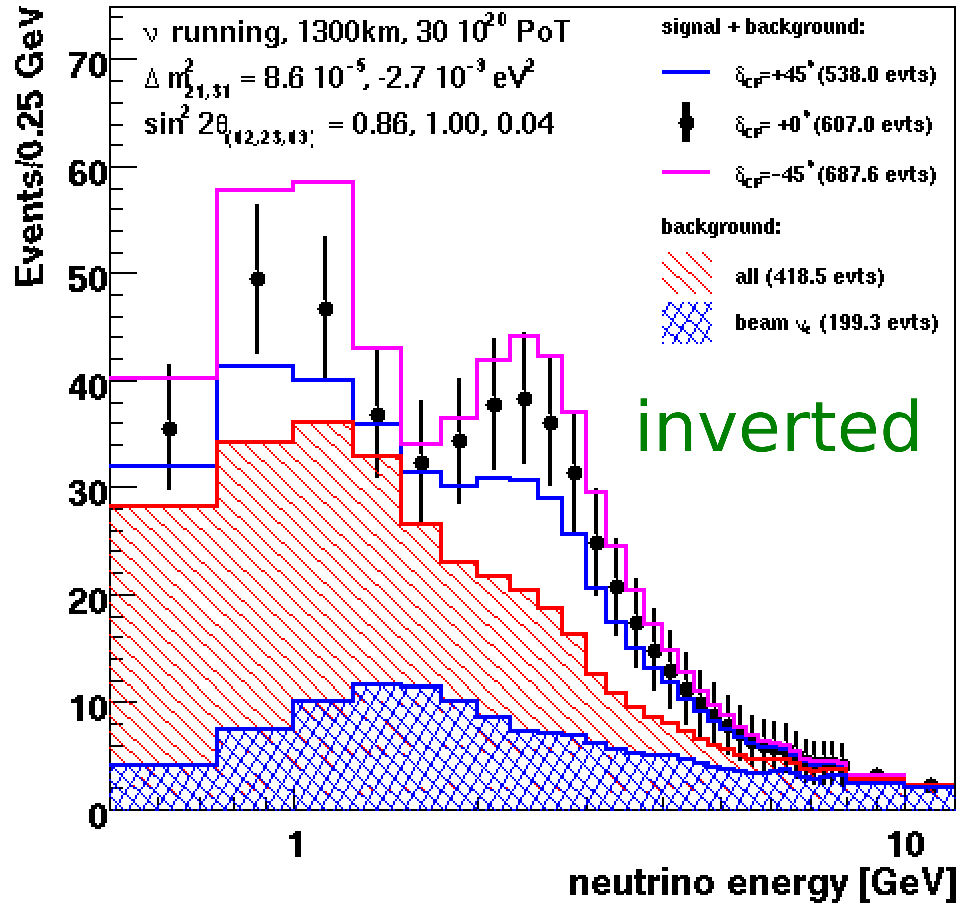
$\sin^2 2\theta_{13} = 0.04$ • $\delta_{CP} = 0^o$ — $\delta_{CP} = +45^o$ — $\delta_{CP} = -45^o$





s: 392.6
b: 414.7

s: 188.5
b: 418.5

WCh appearance spectra

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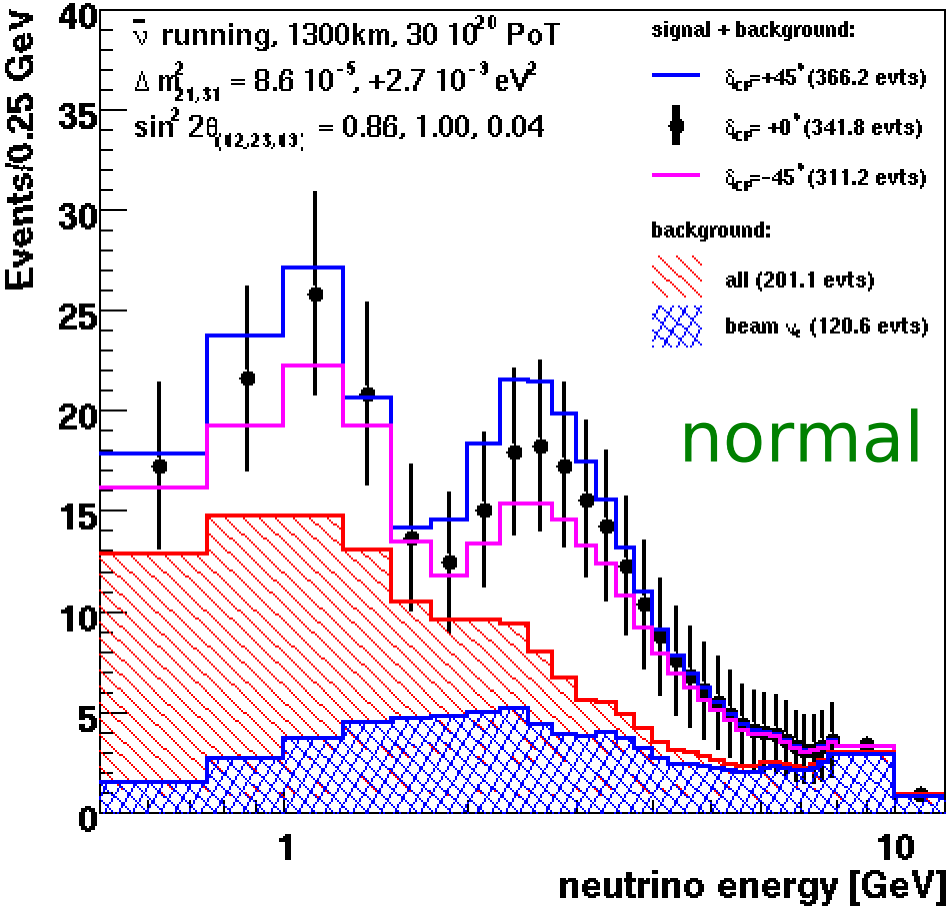
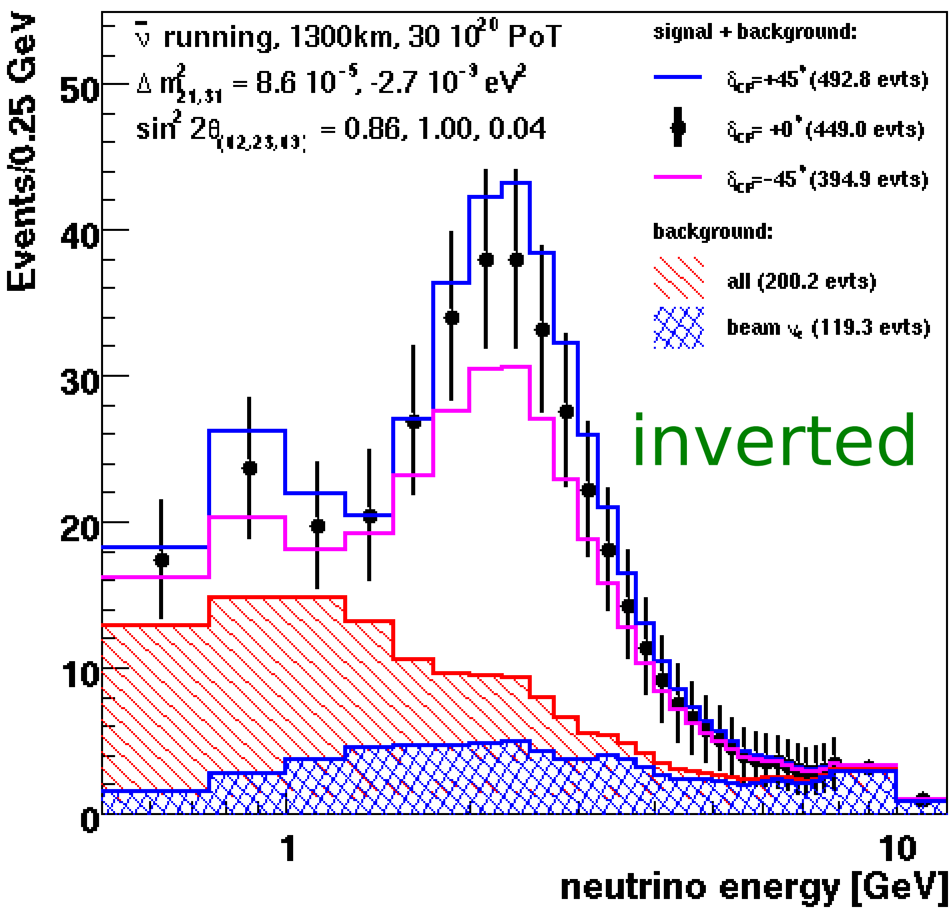




s: 140.7
b: 201.1

s: 248.8
b: 200.2

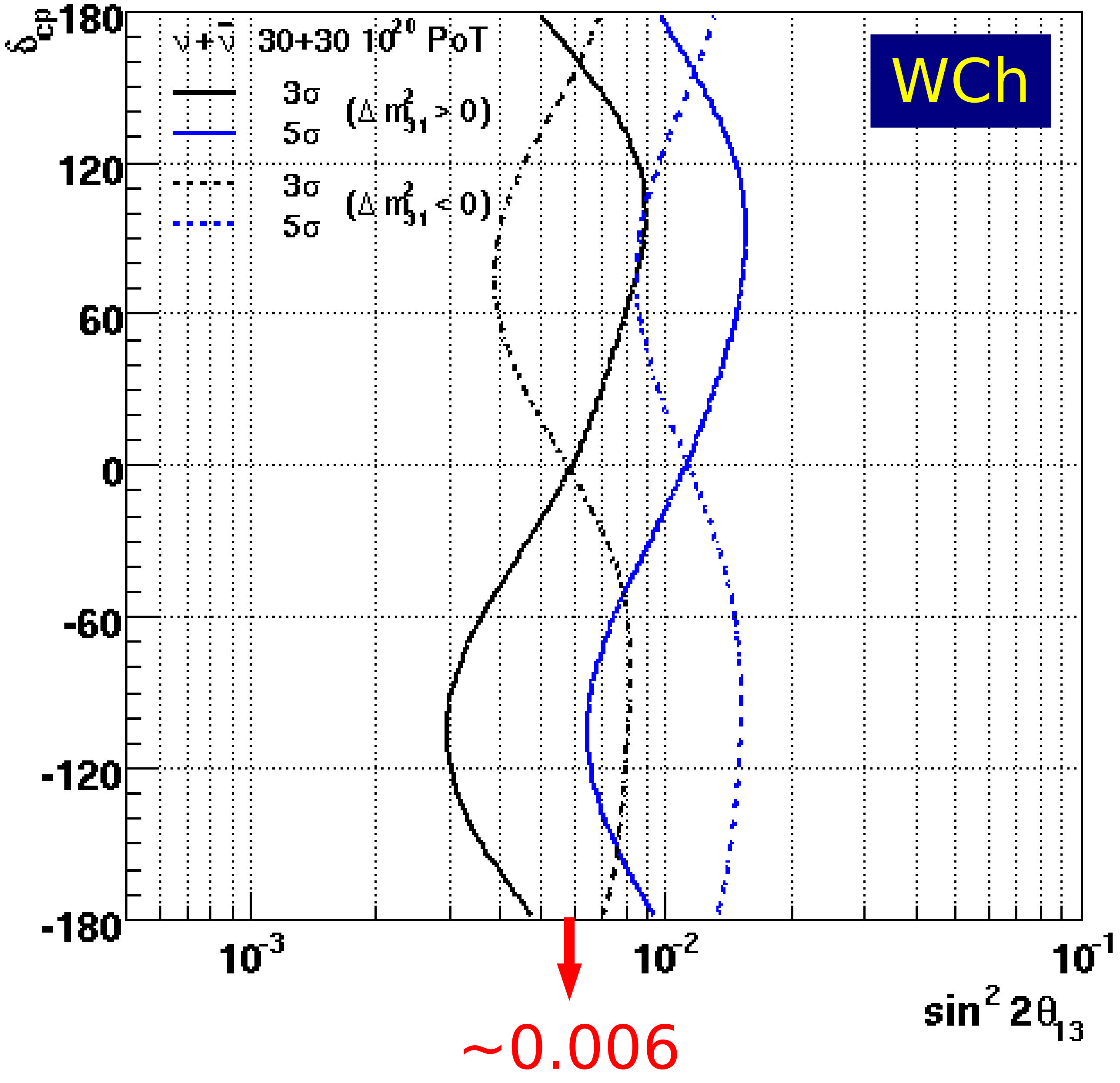
Sensitivity Calculations

- Test appearance spectra for true values of θ_{13} and δ_{CP} against several hypothesis.
- $\sin^2 2\theta_{13}$ discovery potential:
  - Fit to the hypothesis with $\theta_{13}=0$
  - Mass hierarchy is kept fixed
- CP-violation discovery potential:
  - Fit to oscillation hypotheses with $\delta_{CP}=0$ and π. Take worst χ^2
  - θ_{13} is allowed to float and mass hierarchy is fixed
- Resolving mass hierarchy:
  - Fit appearance spectra to oscillation hypothesis with opposite mass hierarchy.
  - Both θ_{13} and δ_{CP} are allowed to float

Input parameters

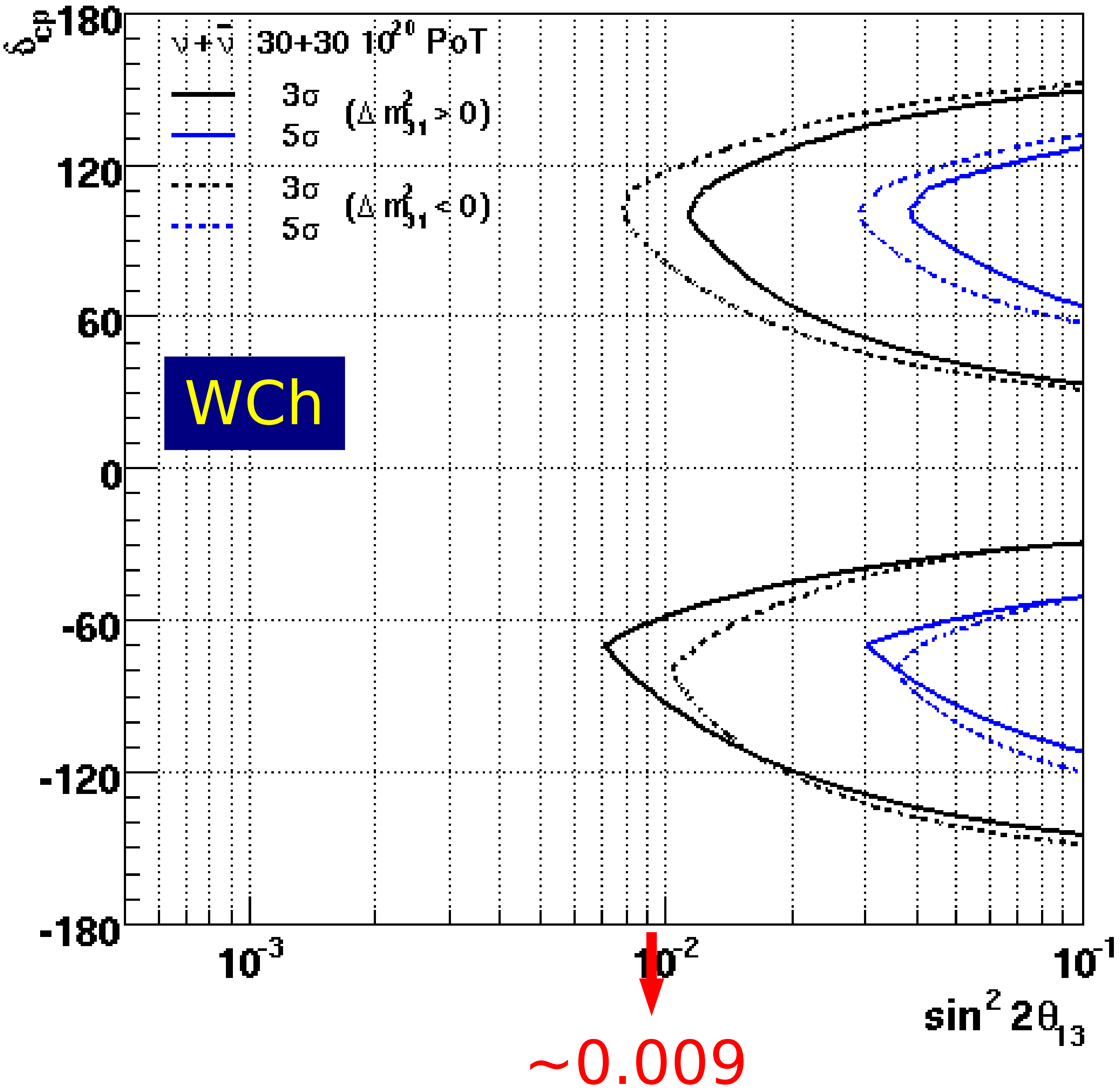
- input parameters:
  - $\theta_{12} = 0.55 \pm 5\%$, $\theta_{23} = \pi/4 \pm 22\%$
  - $\Delta m^2_{21} = 8.60 \pm 0.43\ 10^{-5}\ eV^2$
  - $|\Delta m^2_{31}| = 2.70 \pm 0.27\ 10^{-3}\ eV^2$
  - $\rho_{Earth} = 3.3\ g/cm^3 \pm 5\%$
- These parameters are allowed to float within these errors
- Experiment itself will measure θ_{23} and $|\Delta m^2_{32}|$ to O(1%) through disappearance channel and is included in fits

$\sin^2 2\theta_{13}$ sensitivity



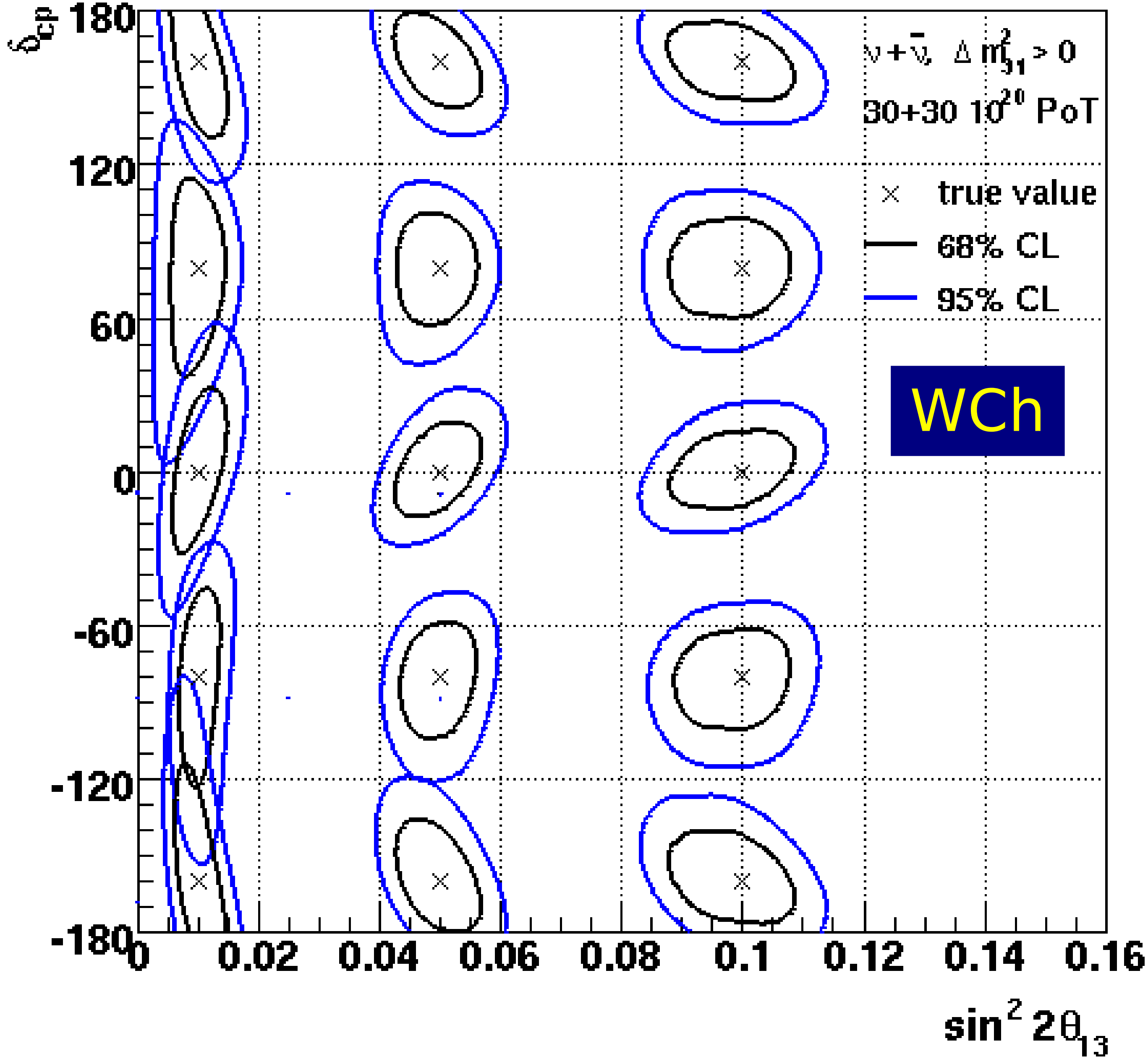
Values reported are for 50% of CP phases covered (CP fraction 0.5) and at 3σ C.L.

CP-exclusion

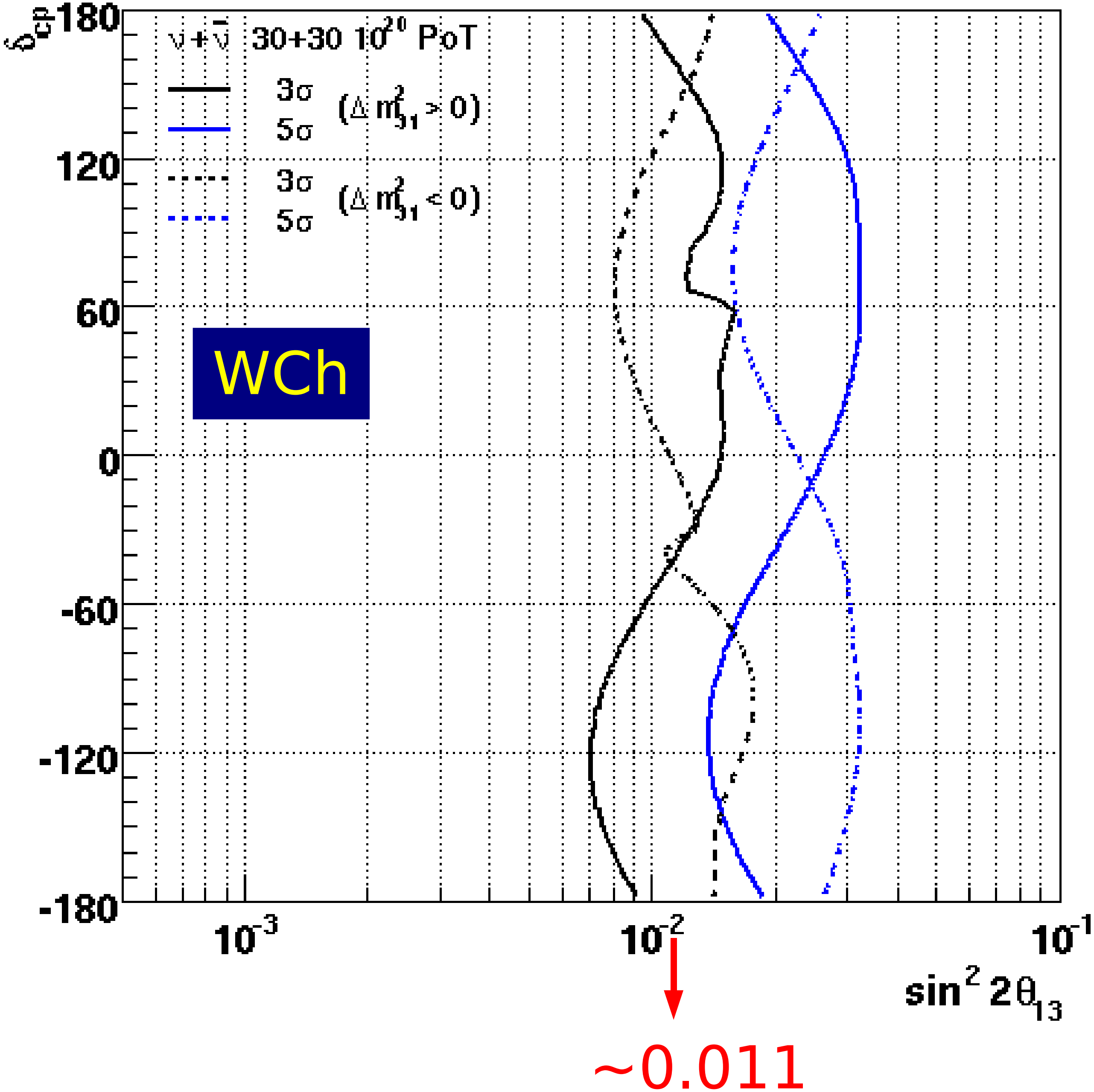


Values reported are averages for "lucky" values of pos and neg CP phases at 3σ C.L.

$(\sin^2 2\theta_{13}, \delta_{CP})$ measurement



Resolving mass hierarchy



Values reported are for 50% of CP phases covered (CP fraction 0.5) and at 3σ C.L.

WCh 60+60 10^{20} POT

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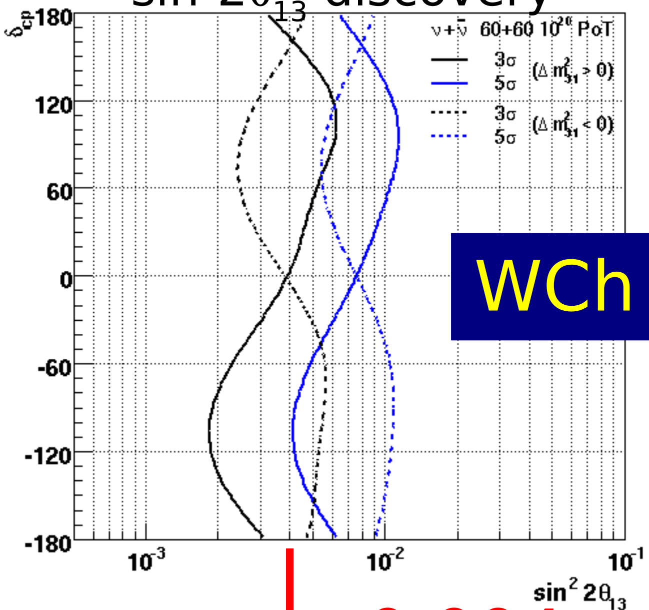
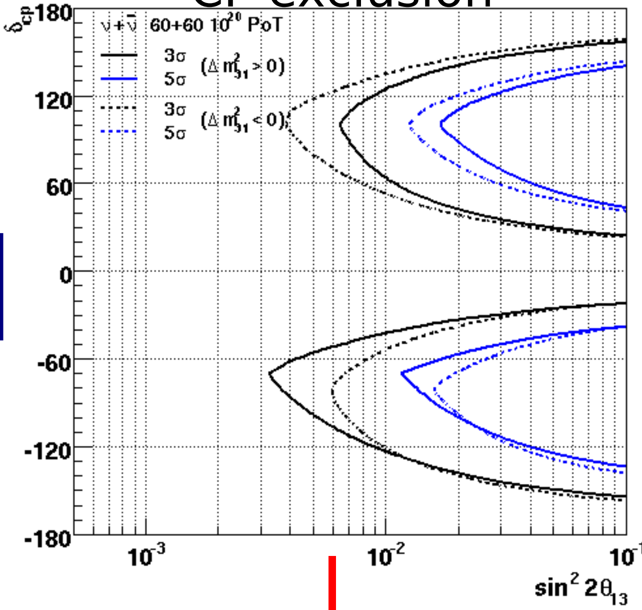
$\sin^2 2\theta_{13}$ discovery

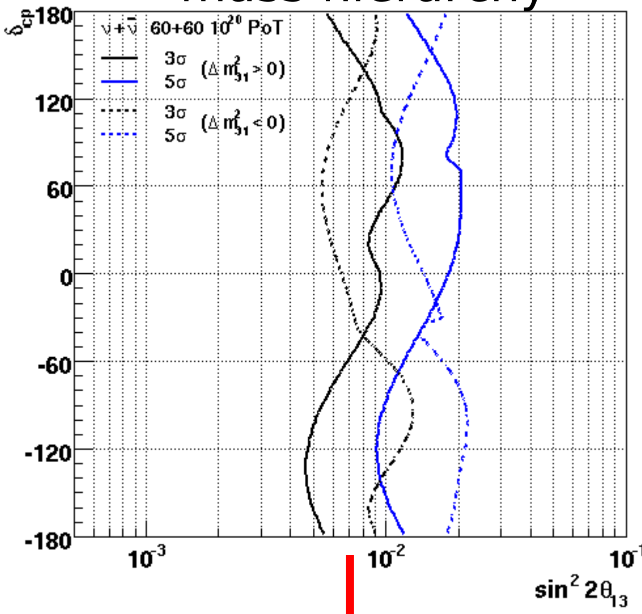


WCh

CP exclusion



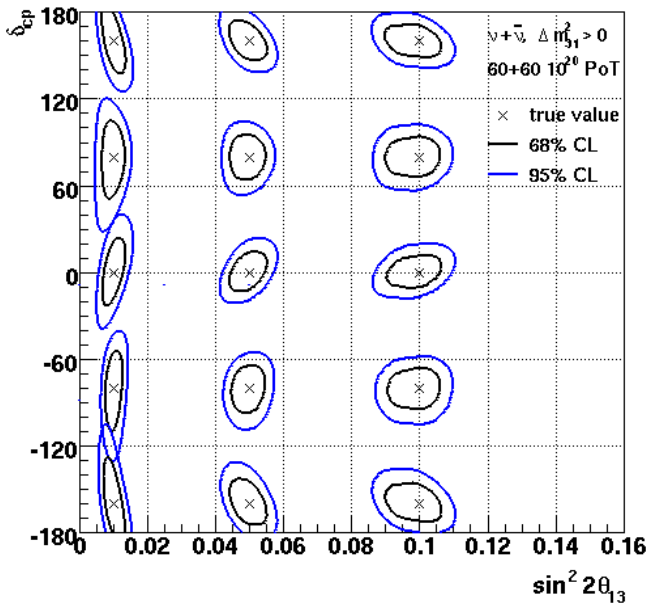
mass hierarchy



~0.004

~0.005

~0.008



- ✔ Values scale as expected from statistics: measurements are not systematics limited

LAr detector assumptions

- LAr assumptions:
  - 100kT fiducial mass
  - 80% efficiency for ν_e charged current events
  - $\sigma(E) = 5\%/\sqrt{E}$ for quasi-elastics
    $\sigma(E) = 20\%/\sqrt{E}$ for other CC events
  - no NC background
  - 10% uncertainty on total background (beam ν_e)

LAr Appearance Spectra

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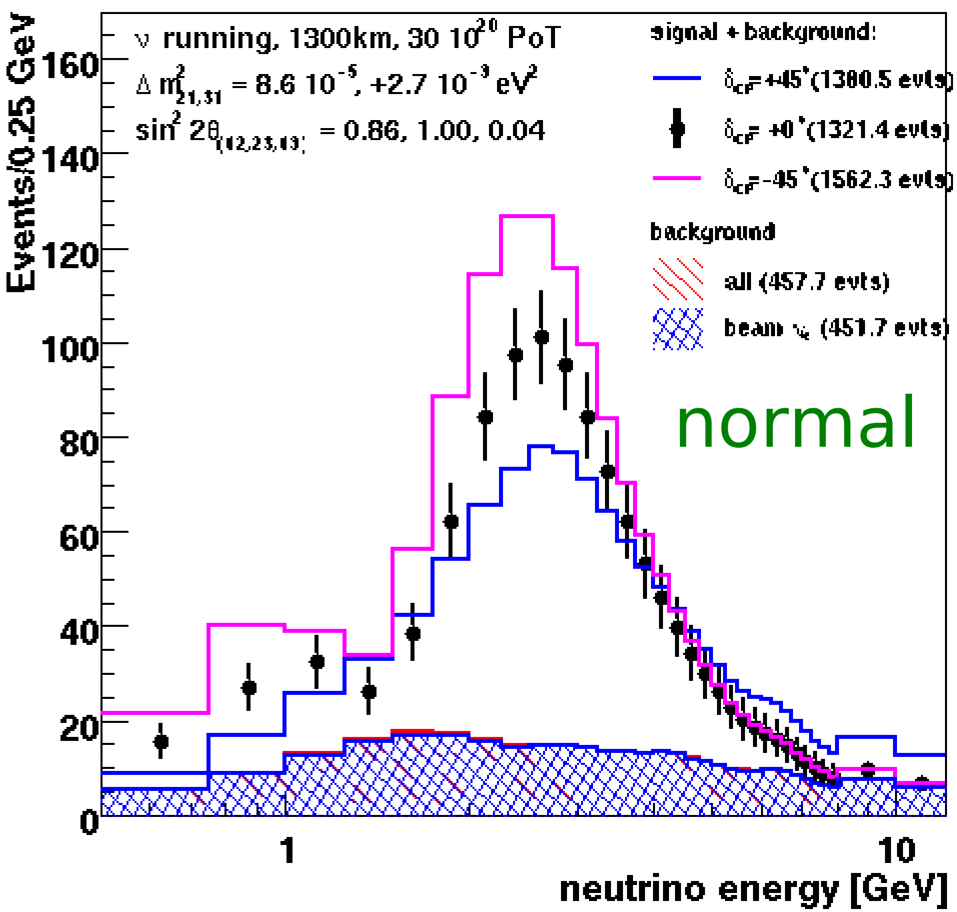
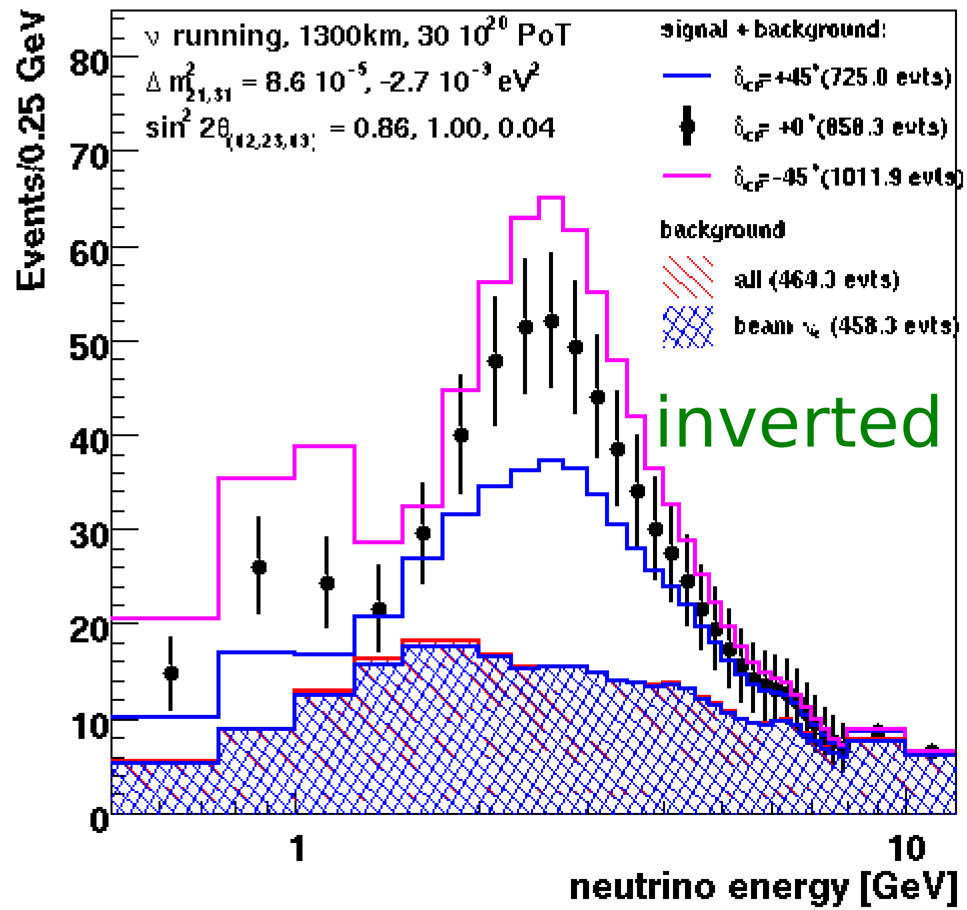
$\sin^2 2\theta_{13}=0.04$ • $\delta_{CP}=0^o$ — $\delta_{CP}=+45^o$ — $\delta_{CP}=-45^o$



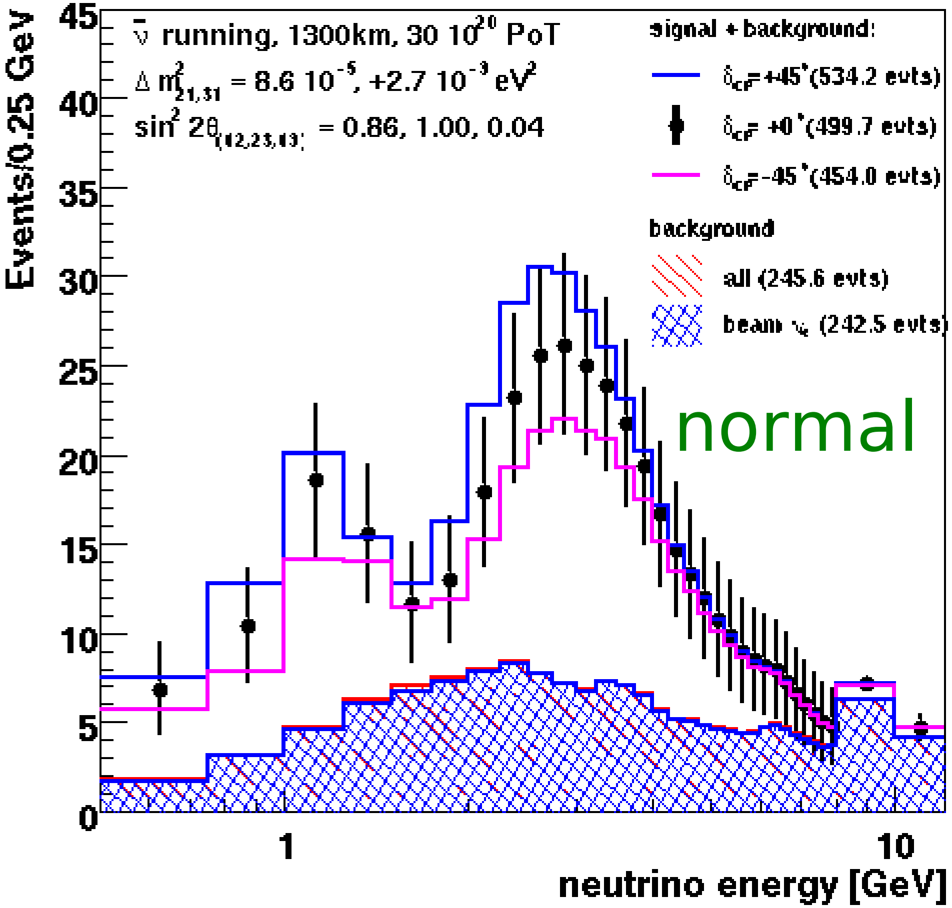


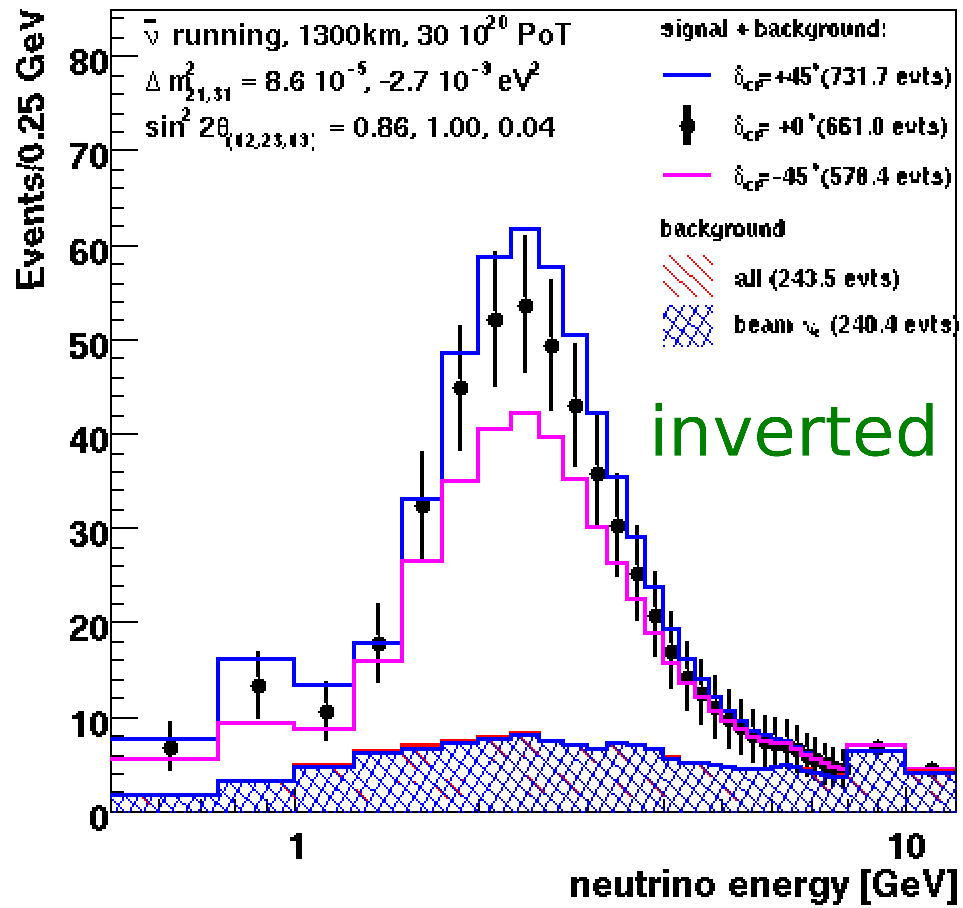
s: 863.7
b: 457.7

s: 394.0
b: 464.3

LAr appearance spectra

$\sin^2 2\theta_{13} = 0.04$ • $\delta_{CP} = 0^o$ — $\delta_{CP} = +45^o$ — $\delta_{CP} = -45^o$



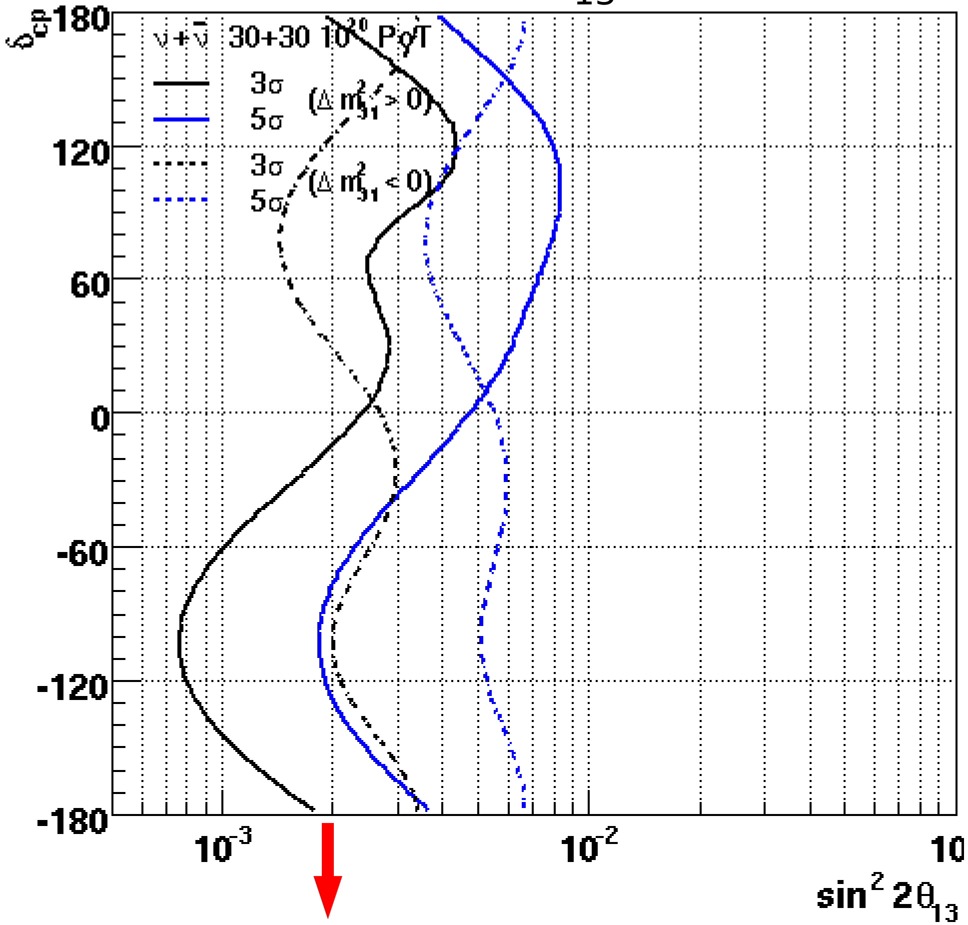


s: 254.1
b: 245.6

s: 417.5
b: 243.5

LAr sensitivities

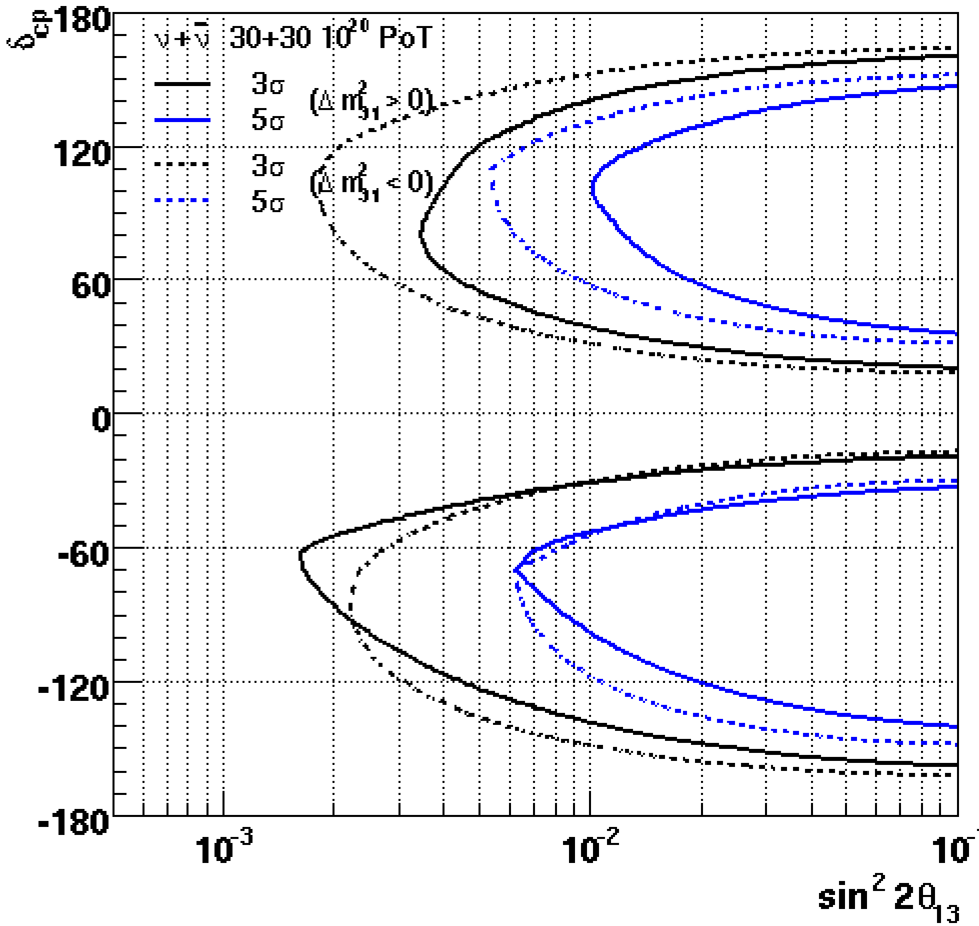
$\sin^2 2\theta_{13}$ discovery



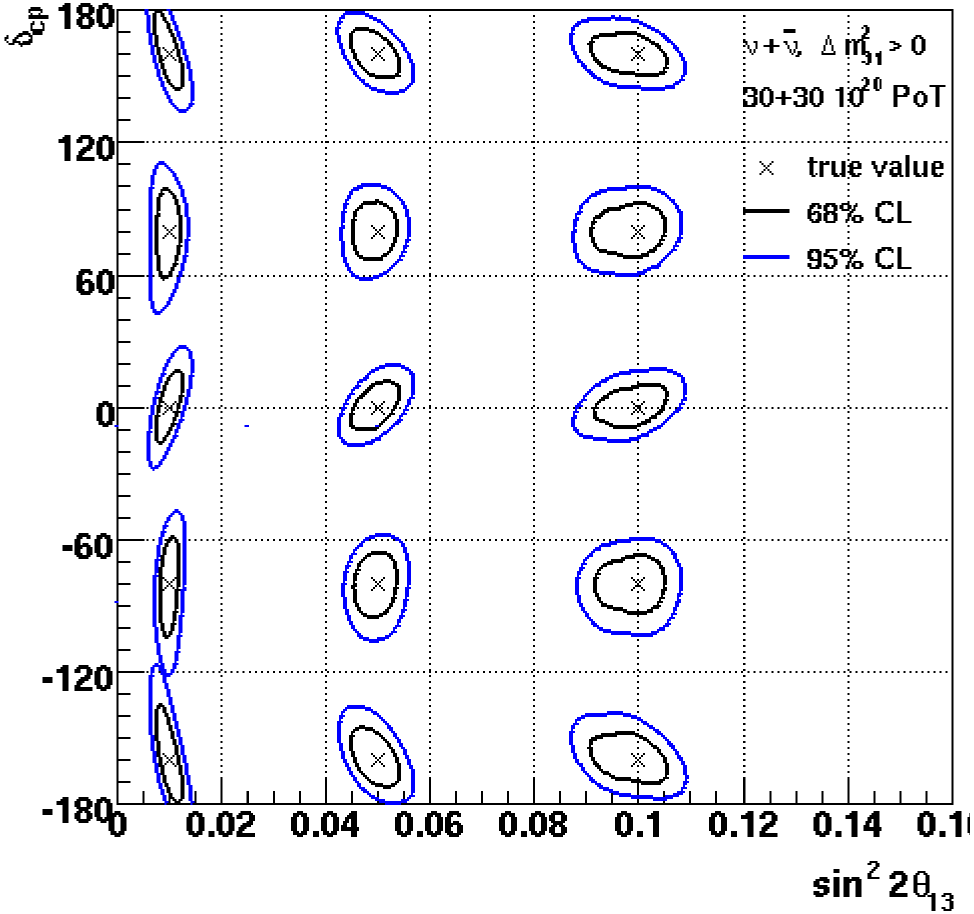
~0.002

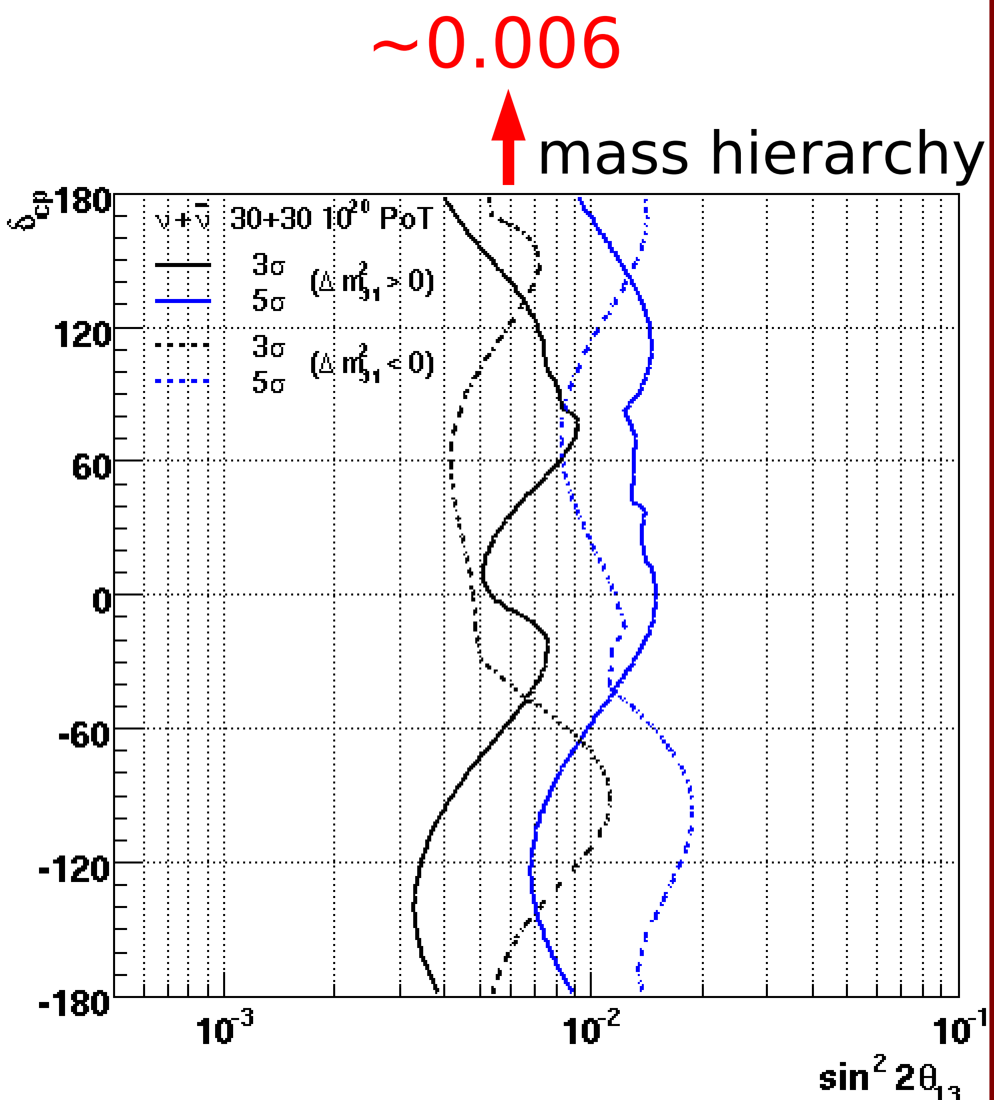
~0.025

CP exclusion



LAr sensitivities



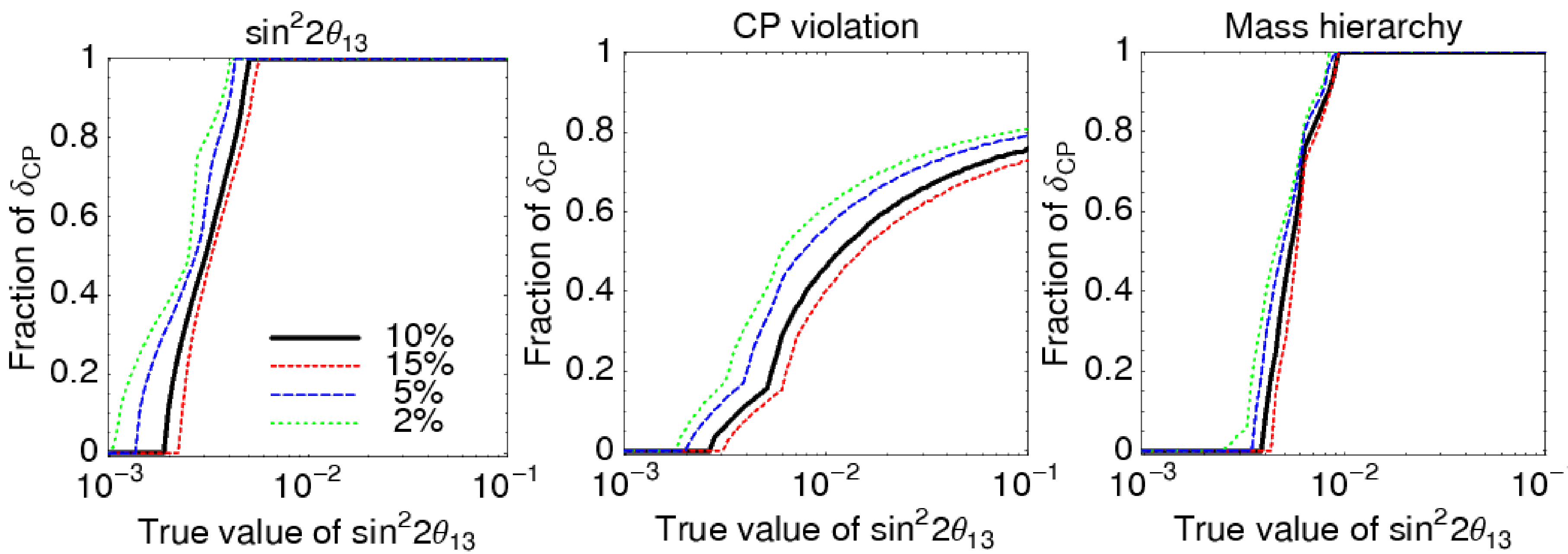


Previous results

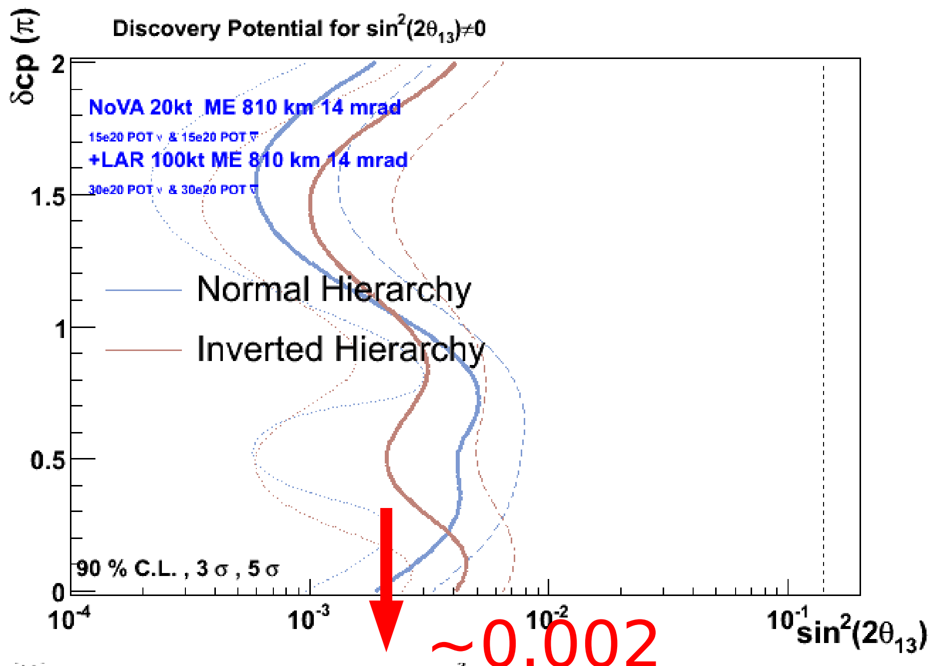
- ✔ Sensitivities using AGS beam simulation and previous detector efficiencies in publication:

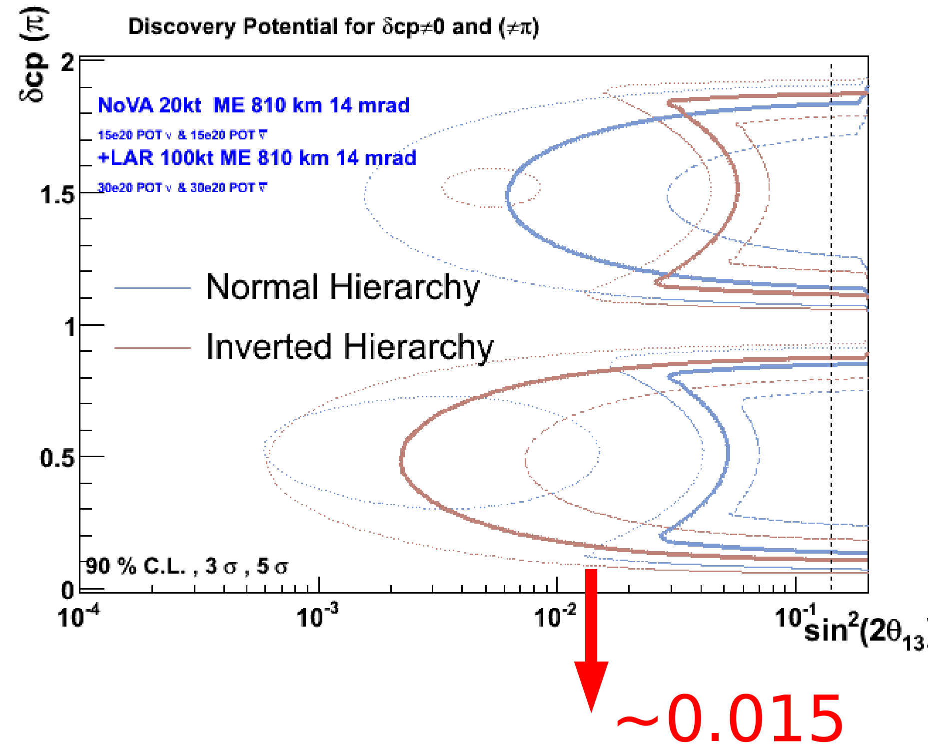
  Phys.Rev.D74:073004,2006 (V. Barger, M. Dierckxsens, M. Diwan, P. Huber, C. Lewis, D. Marfatia, B. Viren)

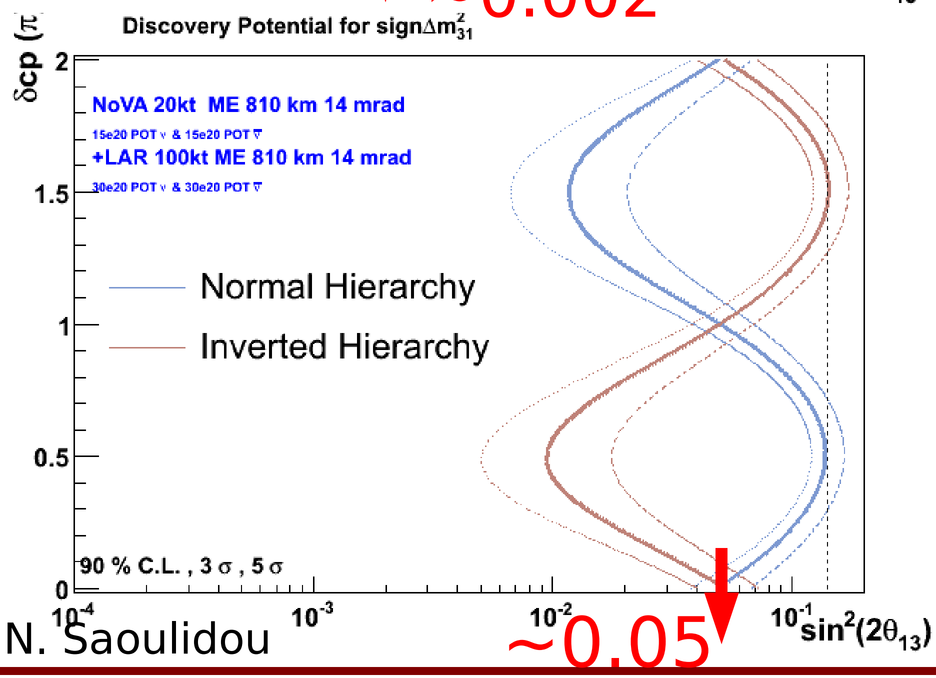
- ✔ Very similar sensitivities obtained
- ✔ Small differences understood
- ✔ Article also studied various bkg uncertainties



NOvA - II







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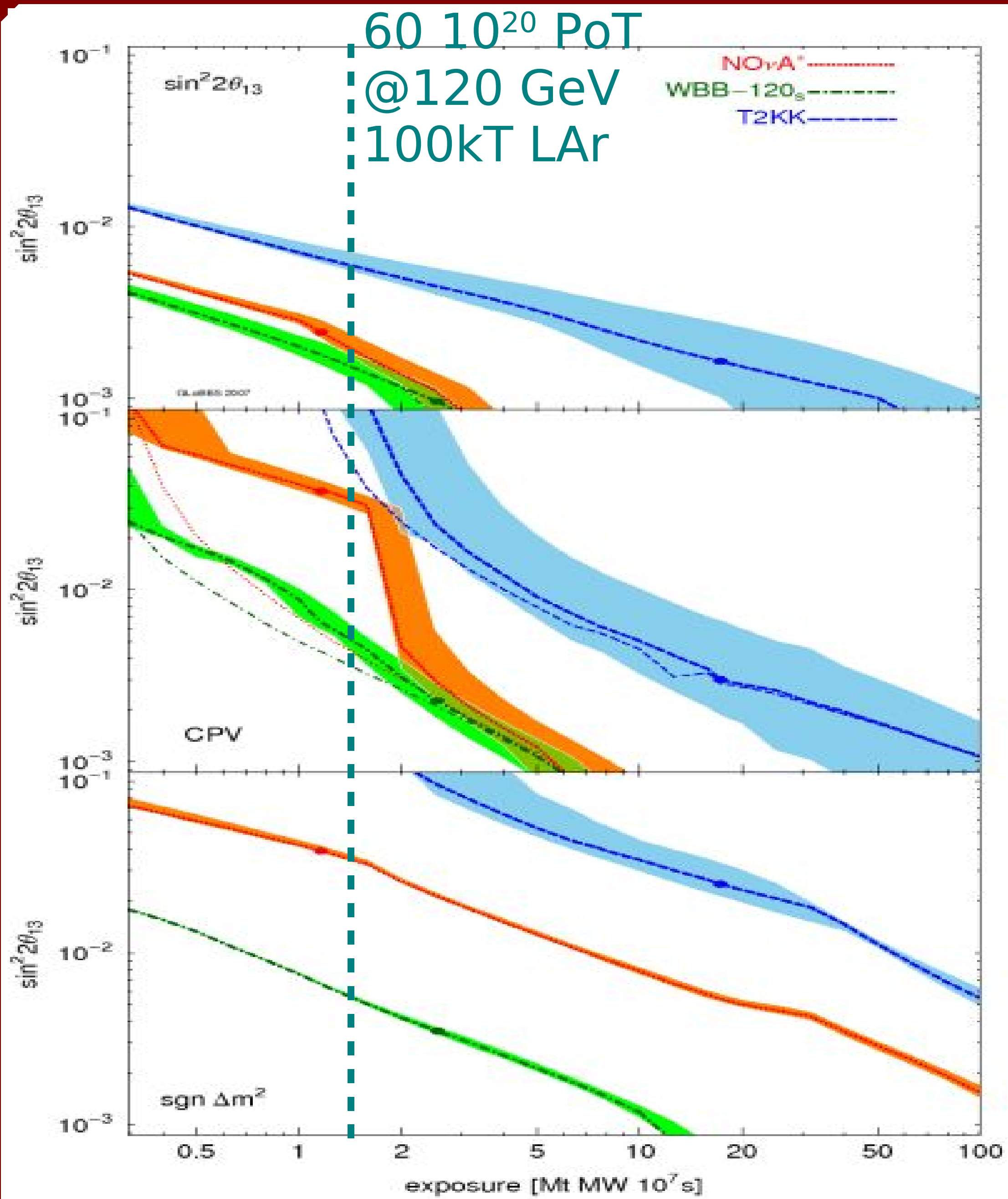
- ✔ Best option for off-axis experiment seems to be at NOvA-I location
- ✔ Sensitivities for 100kT LAr

Long Baseline Comparison



- Recent preprint:

  "Which long baseline neutrino experiment?"
  V. Barger, P. Huber,
  D. Marfatia, W. Winter,
  hep-ex/0703029

- Compares T2KK and LAr det. in the wide and narrow band beams
- Limits are at 3σ for CP fraction of 0.5
- Wide band approach clearly is the best option

Conclusions

- ✔ The physics potential of a very long baseline using a wide band neutrino was presented
- ✔ These calculations incorporated the progress made during the past year
- ✔ The conclusion remains the same: the program is doable using a beam from FNAL and know detector technologies (water Cherenkov)
- ✔ The sensitivities for a wide band beam are better than the narrow band approach
- ✔ LAr is the ultimate neutrino detector, but how (un)realistic are a 100kT detector and the assumptions made on the background reduction?