Long Baseline Neutrino Oscillations

CP Violation, θ_{13}, Matter Effects, "New Physics"…

A DUSEL Flagship Facility

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BROOKHAVEN NATIONAL LABORATORY

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- 54 inst. ~250 collaborators.
- Governance thru Inst. Board.
- Exec. Board for scientific and technical decisions.

OUTLINE

1. Introductory Remarks
2. Neutrino Masses and Mixing
3. Leptogenesis: Matter-Antimatter Asymmetry
4. *Leptonic CP Violation*

   i) *F.O.M. Insensitivity to θ_{13} & L (long distance)*

   ii) Requirements~200kton H_2O, 0.7-2MW protons,
   Neutrino Wide Band Beam (WBB) $E_\nu \approx 0.5$-5GeV

5. *"New Physics"* search via ν_μ Oscillations & Big Detector

   (Long & Short Distance New Physics!)

6. Outlook

   Anticipate Surprises - Unexpected Discoveries!

   (Design a robust experiment!)

1. Introduction

- **What is LBNE?**

Long Baseline Neutrino Oscillation Experiment: (*1300km*)

Intense Fermilab ν_μ **&** $\bar{\nu}_\mu$ **beams ➔ *DUSEL***

Requires a "very large" neutrino detector in Homestake

(200kton water and/or 34kton LArgon) Both!

Goal: (*Observe & Study*) $\nu_\mu \to \nu_e$ **&** $\bar{\nu}_\mu \to \bar{\nu}_e$ ***CP Violation!*****,**

θ_{13}, **Matter Effects,** Δm_{21}^2, θ_{23}, θ_{12} (better than 1%!)

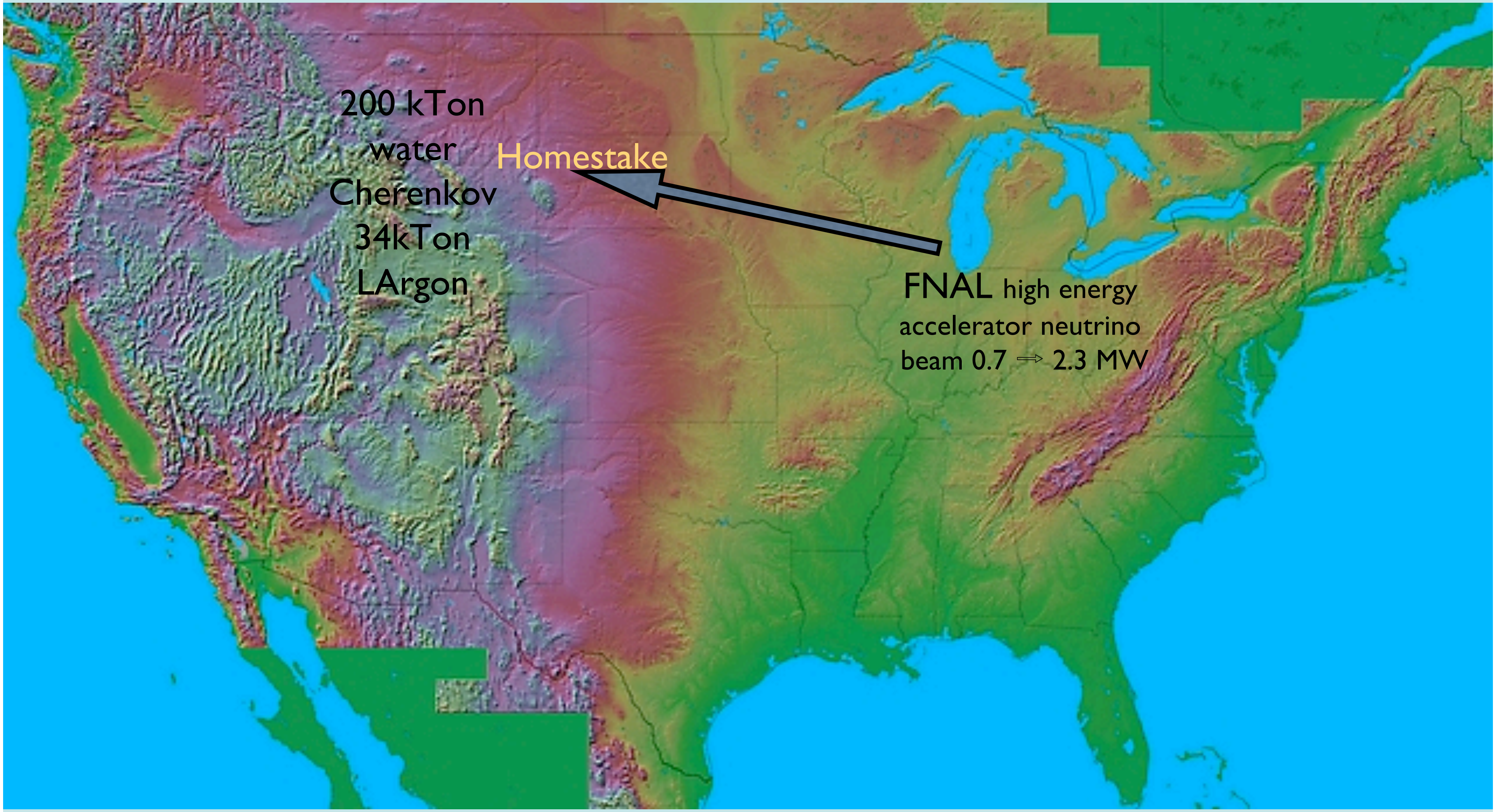
ALSO

$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E_\nu)$ disappearance

Very Large Statistics→High Precision: θ_{23}, Δm^2_{32},

Search for "New Physics" Effects

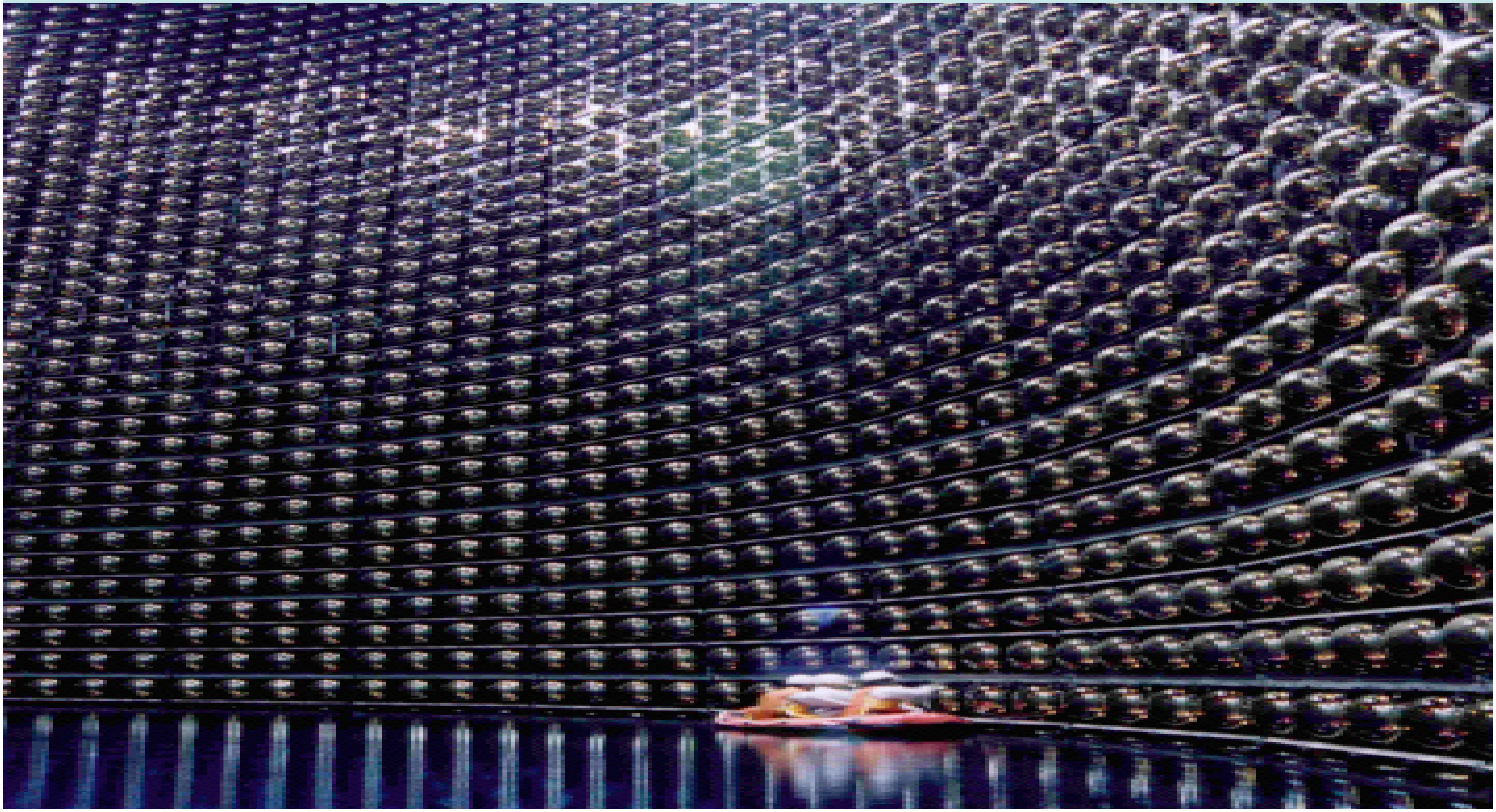
Long-Baseline Neutrino Experiment



Combination of a deep site, intense accelerator, and long baseline makes LBNE unique in the world

SUPER KAMIOKANDE = 22kton H_2O Fiducial

DUSEL = 100kton x 2 detectors=200kton Fiducial!



Physics Goals

- ***Measure Leptonic CP Violation (Why?)***

Leptogenesis: ***Our Origin in the Universe!***

Determine (Precisely) Neutrino Oscillation Parameters

Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12}, θ_{13}, δ

Search for "New Physics" (The Unexpected)

Sterile neutrinos, long and/or short range lepton flavor dependent interactions…Surprises!

Large Detector also probes: proton decay, n-$\bar{n}$ oscillations, *dark matter?*, supernova, atmospheric & solar neutrinos…

2. Neutrino Masses and Mixing

- 1969-90s Ray Davis Measured Solar ν_e Flux at Homestake Deep Underground (4850ft) Mine ~1/3 Expected!

  Gallex, Sage, SuperK, SNO, Kamland (Reactor)

  Interpretation: solar $\nu_e \rightarrow 1/3\ \nu_e + 1/3\nu_\mu + 1/3\nu_\tau$ (roughly)

  $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2) \times 10^{-5}\ \text{eV}^2$ (solar)

- 1980s IMB, Kamioka, measured atm. ν_μ flux, less than expected
- (Also observed supernova 1987a neutrinos!)

  SuperK (Koshiba); K2K, MINOS (Accelerators)

  Interpretation: atm. $\nu_\mu \rightarrow 1/2\nu_\mu + 1/2\nu_\tau$ (near maximal!)

  $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm\ 2.4(1) \times 10^{-3}\ \text{eV}^2$ (atmospheric)

Neutrino Oscillations Established →Neutrino Masses & Mixing Measured (Great Progress!)

(2002 Nobel Prize in Physics to Davis & Koshiba!)

3 Generation Mixing Formalism & Status

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = U \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix} \qquad (1)$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij}$$

$$J_{CP} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta. \qquad (2)$$

Current Neutrino Mass & Mixing Parameters

- $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm\, 2.4(1)\times 10^{-3}\ eV^2$ (atmospheric)
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2)\times 10^{-5}\ eV^2$ (solar)

(Very precise Minos & KamLAND Measurements)

$|\Delta m_{21}^2/\Delta m_{32}^2 \approx 1/30| \rightarrow$ CP Violation Exp Doable!

Hierarchy $m_3 > m_1 \& m_2$(normal) or $m_3 < m_1 \& m_2$(inverted)?

Large Mixing!

$\theta_{23} \sim 45°$ $\sin^2 2\theta_{23} \approx 1.0$ (θ_{23} or $90° - \theta_{23}$) (atm.)

$\theta_{12} \sim 34°$ $\sin^2 2\theta_{12} = 0.87(3)$ (solar)

$\theta_{13} \leq 10°$ $\sin^2 2\theta_{13} \leq 0.12$ (How Small? ***Best Fit ~ 0.04***)

$0 \leq \delta \leq 360°$?

$J_{CP} \cong 0.11 \sin 2\theta_{13} \sin\delta$ (potentially large!)

What do we still need to learn?

- 1. **Value of θ_{13}?** (Reactors: $\sin^2 2\theta_{13} \leq 0.12 \rightarrow 0.01$)
  (Accelerators $\nu_\mu \rightarrow \nu_e$ similar sensitivity)
  LBNE→ <0.003! If needed

- 2. **Sgn Δm_{32}^2?** *(Large Matter Effect at 1300km)*
  (Important for Neutrinoless $\beta\beta$ Decay)

- 3. **Value of** δ?, J_{CP}?, **CP Violation?** ***(Holy Grail of LBNE)***

- 4. **Precision** Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12} (statistical ±1% goal)

- 5. **"New Physics"** - Sterile ν, Long/Short Distance Physics
  (*Explore The Dark World - Very Weakly Coupled*)…

3. Leptogenesis: Matter-Antimatter Asymmetry

- **More baryons than antibaryons in our Universe**
- ***Baryogenesis via Leptogenesis***

1. Heavy Majorana Neutrinos Created and Decay

   $N \rightarrow H^- e^+$, $H^0 \bar{\nu}$ (***L & CP VIOLATION***)

   Leads to antilepton (excess)-lepton Asymmetry

2. ***Electroweak Phase Transition (250GeV)*** (Baryogenesis)

   't Hooft Mechanism B-L Conserved (B&L Violated)

   antilepton excess→baryon (quark) excess by 1 in 10^9

Is L Violated in Nature? ***(Neutrinoless ββ Decay)***

Is there Leptonic CP Violation? ***(ν oscillations)***

Indirect evidence for Leptogenesis (Best we can do.)

4. Leptonic CP Violation

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e)$$

$+$ matter $+$ smaller terms

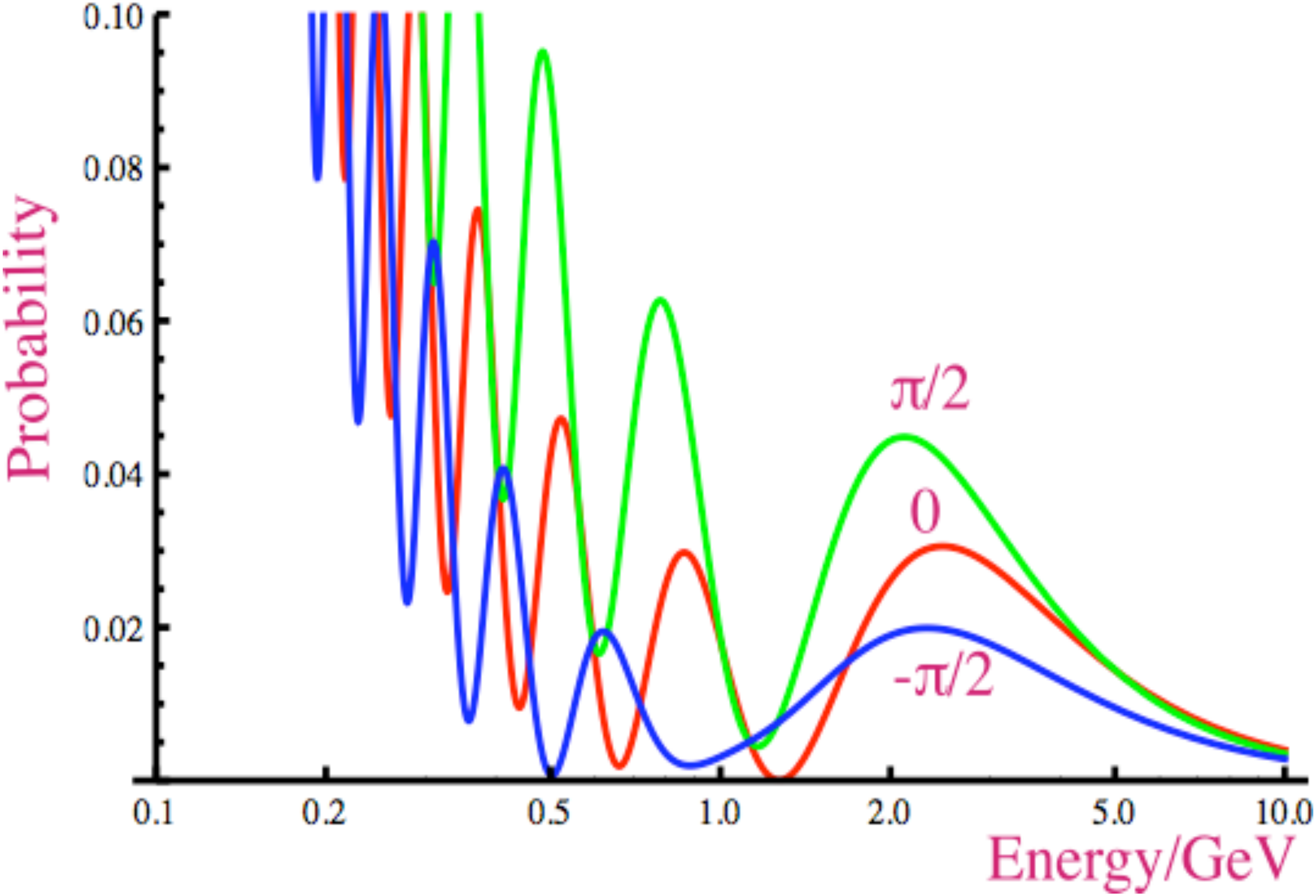
$$\mathbf{P}_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

$$\mathbf{P}_{II}(\nu_\mu \to \nu_e) = \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.$$
$$\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]$$

$$\mathbf{P}_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

For antineutrinos, $\delta \to -\delta$ and opposite matter effect.

$\nu_\mu \rightarrow \nu_e$ oscillation probabilities for various CP violating phases



CP Violation Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \qquad (3)$$

To leading order in Δm^2_{21} ($\sin^2 2\theta_{13}$ is not too small):

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects} \qquad (4)$$

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A^2_{CP} N}{1 - A^2_{CP}} \qquad (5)$$

N is the total number of $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ events.Since N falls (roughly) as $\sin^2\theta_{13}$ and $A^2_{CP} \sim 1/\sin^2\theta_{13}$, to a first approximation the F.O.M.is independent of $\sin\theta_{13}$. Similarly, given E_ν the neutrino flux and consequently N falls as $1/L^2$ but that is canceled by L^2 in A^2_{CP}.

i) CP Violation Insensitivities

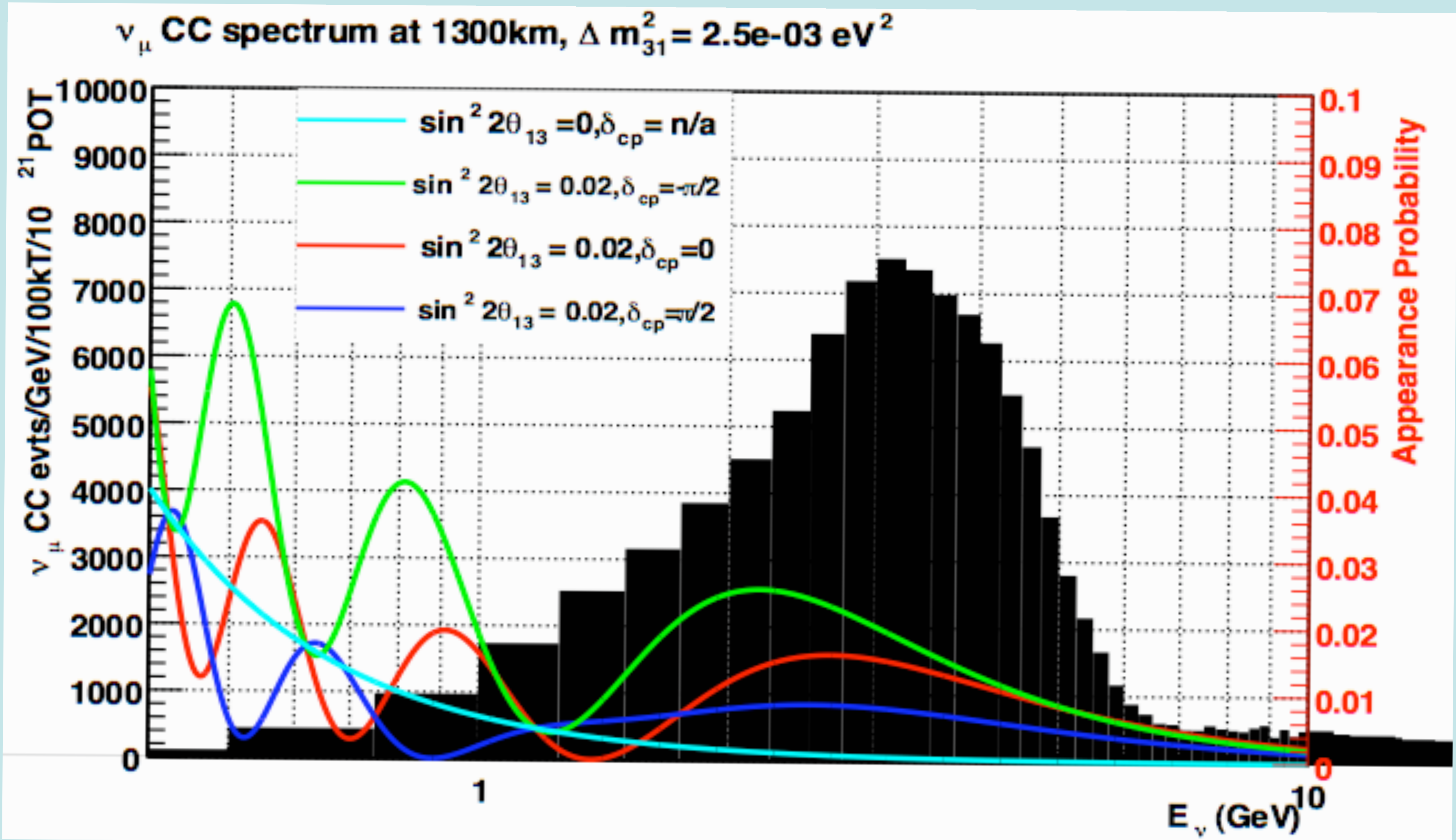
- To a very good approx., our statistical ability to determine δ or A_{cp} is **independent** of $\sin^2 2\theta_{13}$ (down to ~ 0.003) and the detector distance L (for long distance).

ii) CP Violation Requirements

- Pick any reasonable θ_{13} (eg $\sin^2 2\theta_{13}=0.04$)
  What does it take to measure δ to $\pm 15°$ in about
  10 years (1 Fermilab yr = $2\text{x}10^7$sec)?
  Answer (Approx.): 200kton Water Cerenkov Detector
  Roughly 20% Acceptance, or
  34 kton LArgon 90% Acceptance
  or Hybrid combination
  + Traditional Horn Focused ν WBB powered by
  0.7MW→2.3MW proton accelerator (Project X at FNAL?)

Project X would have a robust Intensity Frontier Program

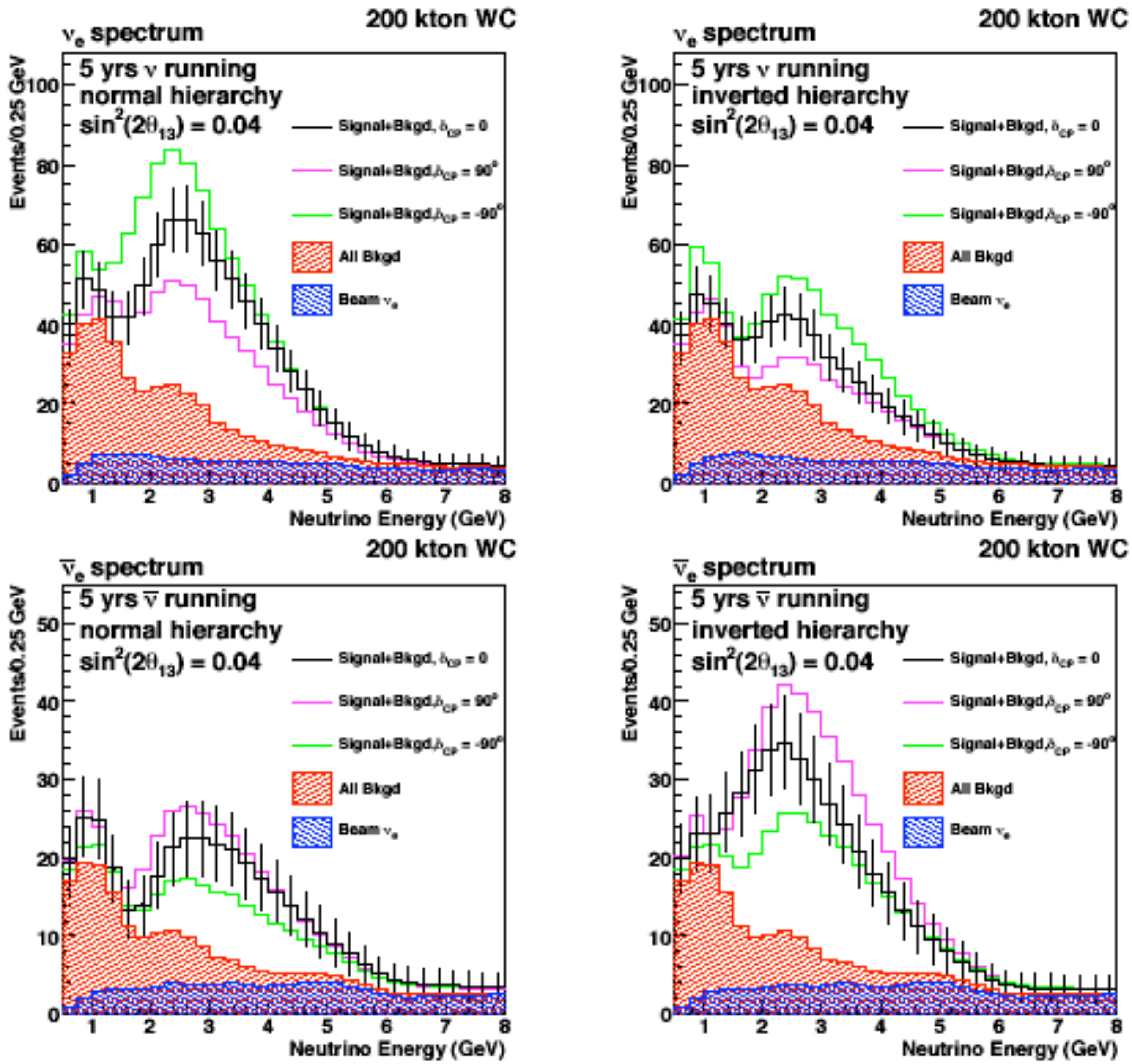
Wide Band Neutrino Spectrum
($\nu_\mu \rightarrow \nu_e$ oscillations)



Current FNAL beam design with osc probability normal inverted

nu

anti-nu



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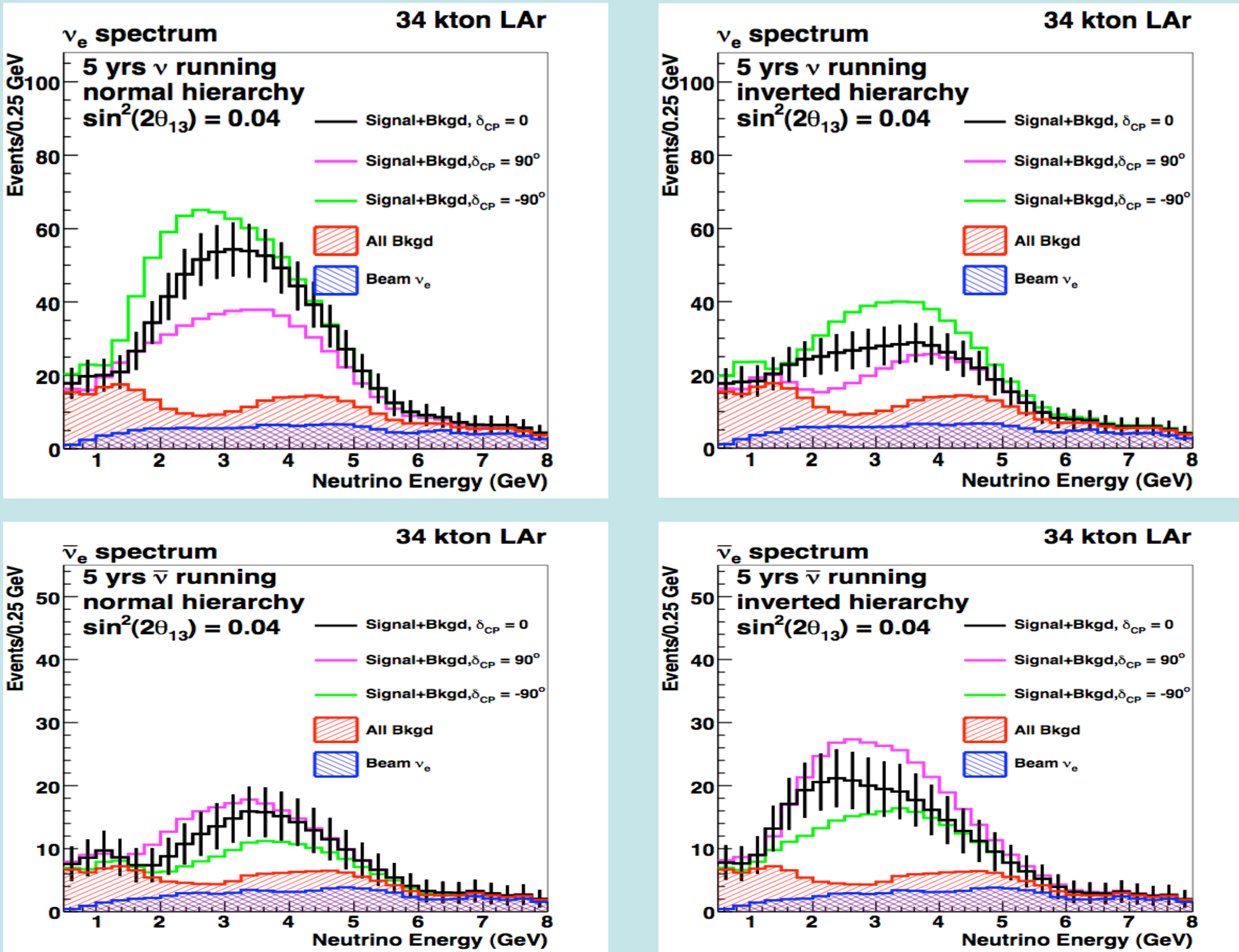
normal

inverted

nu

anti-nu



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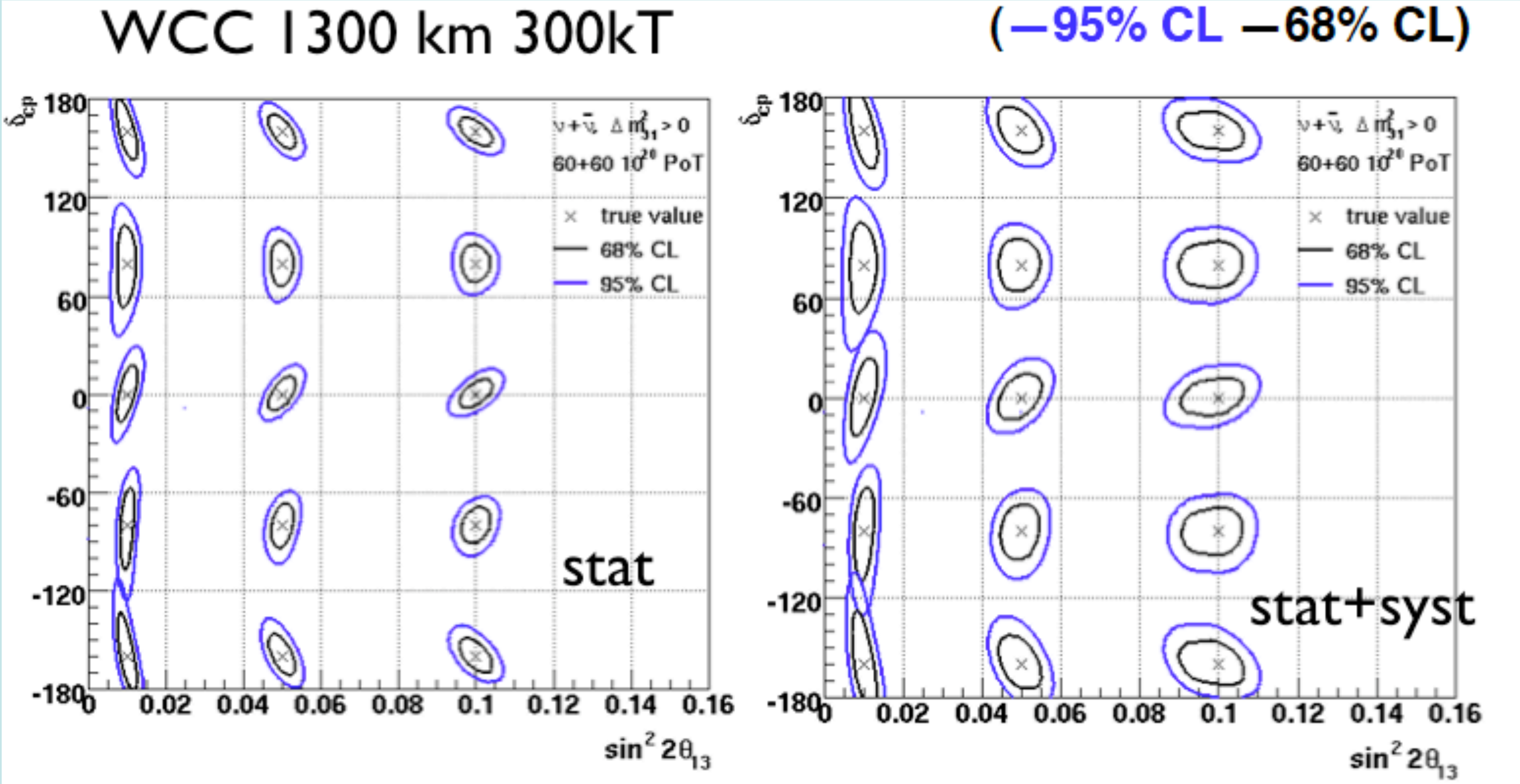
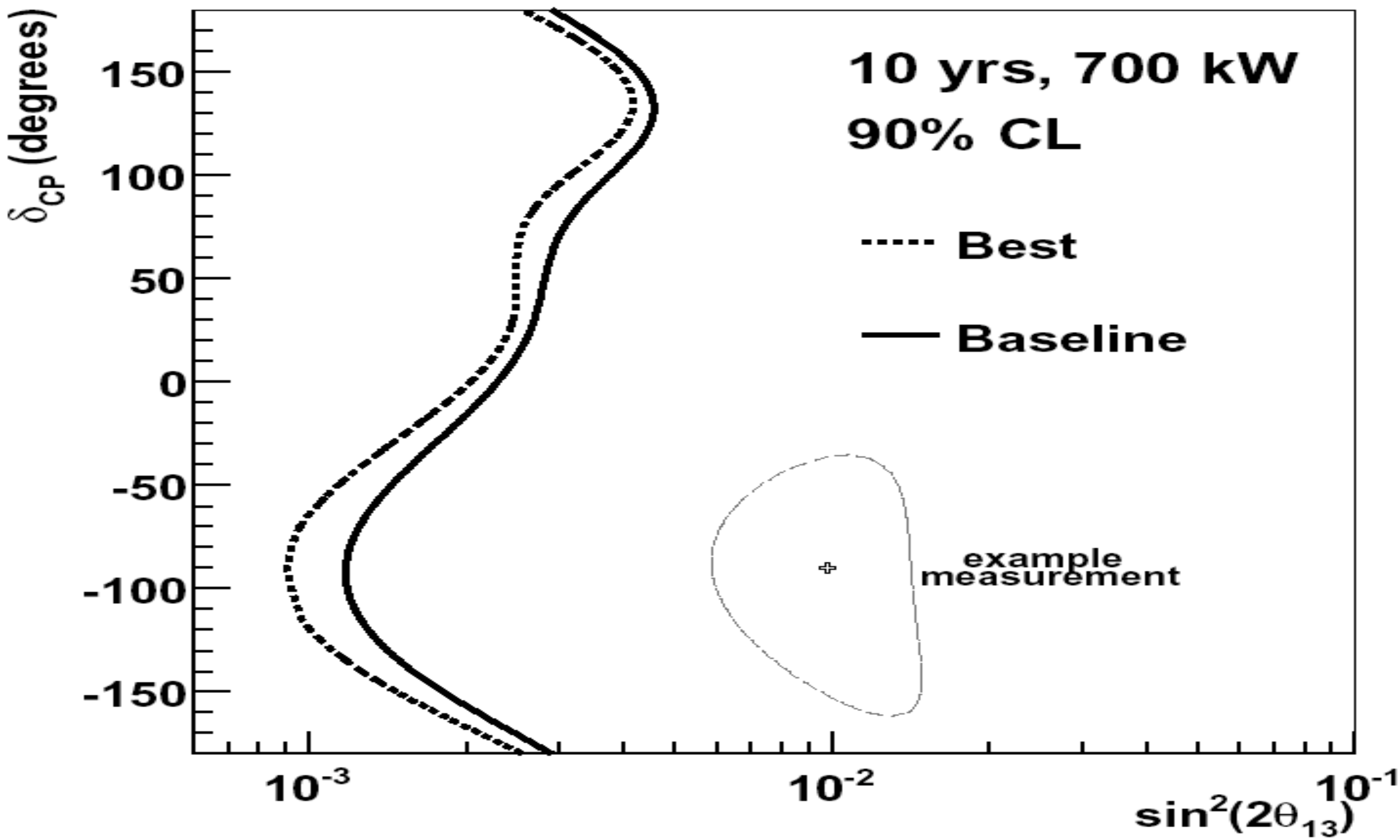
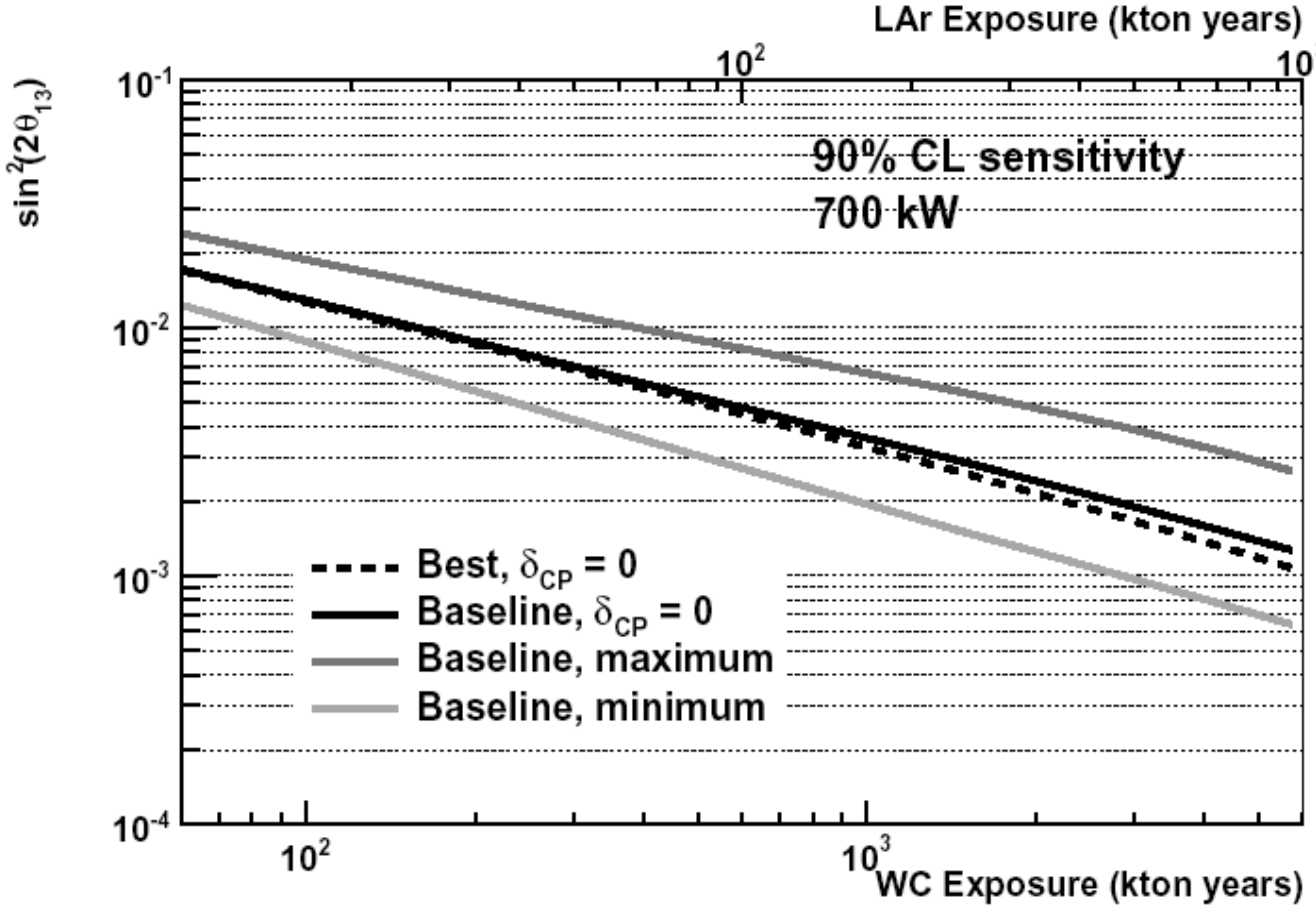
CP Phase Insensitivity to θ_{13} Value



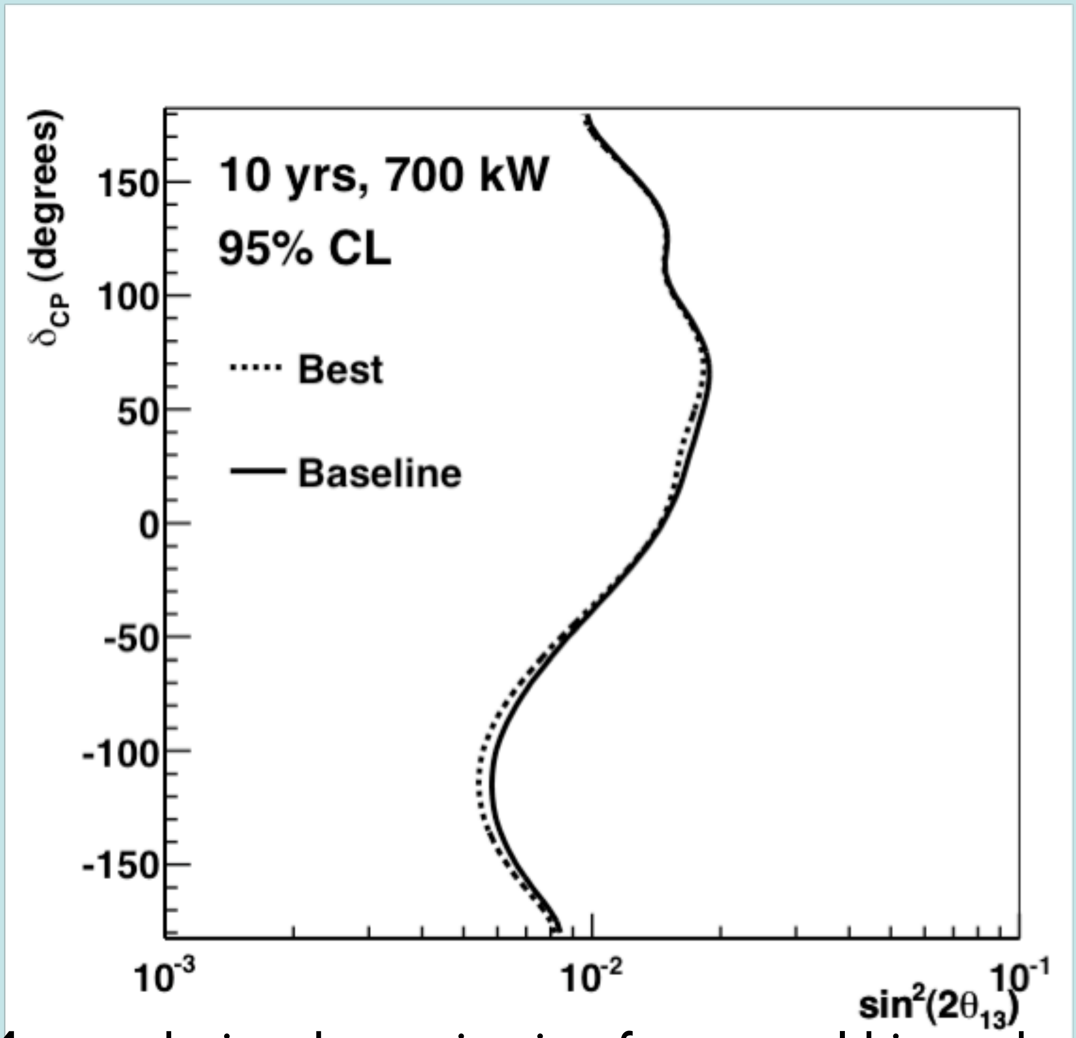
LBNE Sensitivity to $\sin^2 2\theta_{13}$



$\sin^2 2\theta_{13}$ Sensitivity vs Exposure=Detector Size x Time



Mass ordering reach



Mass ordering determination for normal hierarchy with
700 kW and 200
kTon water detector

5. "New Physics" search via ν_μ & $\bar{\nu}_\mu$ disappearance

Disappearance at MINOS $\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ show differences?

$$P(\nu_\mu \rightarrow \nu_\mu)=1-\sin^2 2\theta_{23}\sin^2(\Delta m^2_{32}L/4E_\nu)$$

$\nu_\mu \rightarrow \nu_\mu$: $\Delta m^2_{32}=2.35(11)\times10^{-3}eV^2$ $\sin^2 2\theta_{23}\sim1\ (>0.91)$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$: $\Delta m^2_{32}=3.36(45)\times10^{-3}eV^2$, $\sin^2 2\theta_{23}=0.86(11)$

2σ difference? 30%?

(Collaboration does not claim discrepancy!)

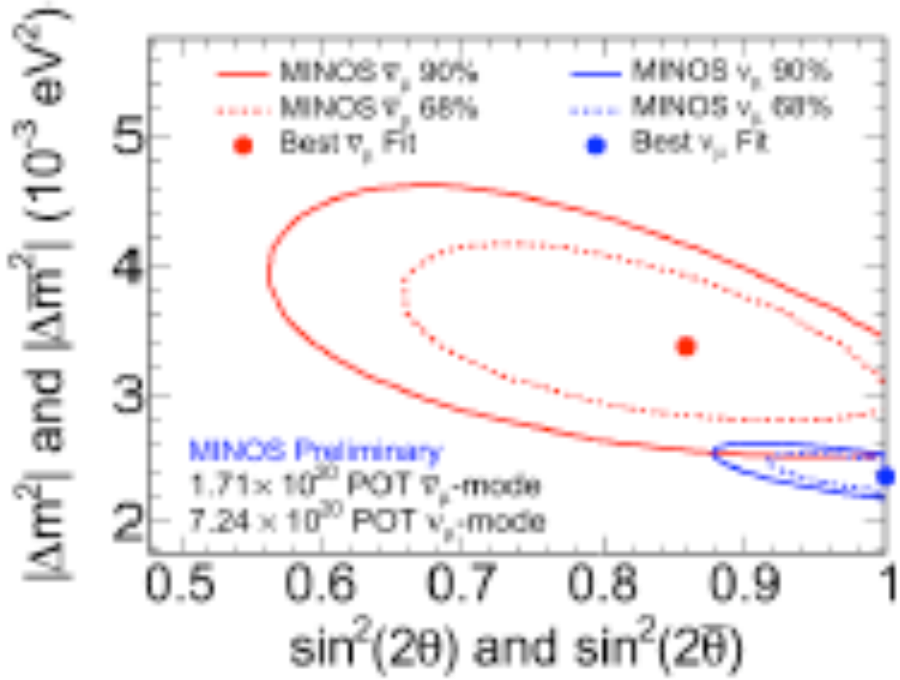
Hard too accommodate quantitatively

Potential Conflict with High Energy Atmospheric Neutrinos Osc.

But good motivation to examine "New Physics" effects in neutrino oscillation experiments, since at DUSEL one could expect better than 1% measurements!

Anticipate Surprises!

$\overline{\nu}_\mu$ oscillation parameters



- Contours include the effects of systematic uncertainties

ν_μ Disappearance

Very easy to get this effect
Does not need extensive pattern
recognition. Can enhance the seco
minimum by background subtracti

Neutrino Running

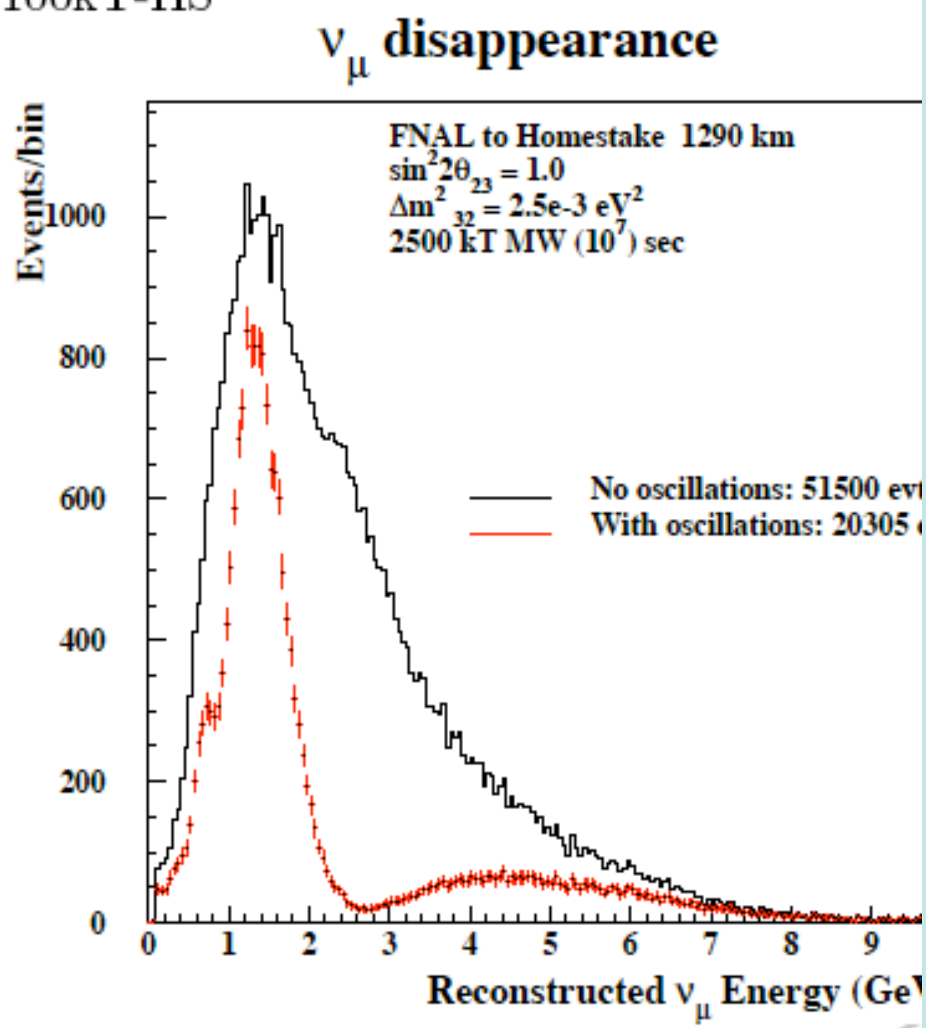
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

- 1% determination of Δm^2_{32}
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.



Δm^2_{32} and $\sin^2 2\theta_{23}$ can be measured in long baselines as functions of E_ν (*also obtained from atmospheric* ν).

$\nu_\mu \to \nu_\mu$ & $\bar{\nu}_\mu \to \bar{\nu}_\mu$ *Comparison*

Usually phrased as a test of CPT (true in vacuum)

Apparent CPT violation → "New Physics" in ν interactions

(in matter)

$\varepsilon\sqrt{2}G_F\bar{\nu}\gamma_\mu\nu'\bar{f}\gamma^\mu f$, $f=e, u, d$

Long or Short Distance Physics

Potential changes sign $\nu_\mu \to \bar{\nu}_\mu$

Sterile Neutrinos? Etc

$\Delta V \sim 10^{-12}$eV-10^{-13}eV explored!

"General bounds on non-standard neutrino interactions" by Biggio, Blennow and Fernandez-Martinez (2009)

Using solar/atm. oscillation & Scattering data in $\nu_e \nu_\mu \nu_\tau$ space

	ν_e	ν_μ	ν_τ	
	2.5	0.21	1.7	ν_e
$\lvert\varepsilon\rvert <$	0.21	0.046	0.21	ν_μ
	1.7	0.21	9.0	ν_τ

(Take with a grain of salt)

In Particular $\varepsilon_{\nu\tau\nu\tau} \leq O(1)$ likely from Atmospheric Neutrino Oscillations

ε represents the size of the "New Physics" potential relative to MSW potential (Weak Strength $\sqrt{2}G_F\bar{\nu}_e\gamma_\mu\nu_e\bar{e}\gamma^\mu e$)

Some Interesting Recent $\varepsilon \neq 0$ Examples

Engelhardt, Nelson and Walsh: sterile neutrinos & gauge B-L
new long distance weakly coupled physics

Mann et al.: New $\nu_\mu \rightarrow \nu_\tau$ Interaction $\varepsilon_{\mu\tau} \sim -0.1 \times \sqrt{2} G_F \bar{\nu}_\mu \gamma_\beta \nu_\tau \bar{e} \gamma^\beta e$

Joshipura &Mohanty (2004) Gauged L_e-L_μ or L_e-L_τ (lepton flavor)
$m_V < 10^{-18}$eV! ***very*** long range interaction (earth-sun),
Fifth Force: $\alpha' \leq 3\times10^{-53}$! Solar/Kamland Bound (***too weak for MINOS***)

Heeck and Rodejohann: gauge L_μ-L_τ, $m_V < 10^{-18}$eV, less constrained
Alternative:** gauge B-L+(L_μ-L_τ)=B-L_e-2L_τ (Davoudiasl, Lee & WJM***)

Either $O(\alpha/\Lambda^2)$ Λ large (short distance) or *α' and m small* (long distance)
Effective potential changes sign for $\nu_\mu \rightarrow \bar{\nu}_\mu$
All can lead to different ν_μ and $\bar{\nu}_\mu$ disappearance oscillation
"Apparent (but not real) CPT Violation"

$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance

- $$i\,d/dt \begin{vmatrix} \nu_\mu(t) \\ \nu_\tau(t) \end{vmatrix} = \begin{vmatrix} \Delta m^2_{32} s^2/2p_\nu & \Delta m^2_{32} sc/2p_\nu \\ \Delta m^2_{32} sc/2p_\nu & \Delta m^2_{32} c^2/2p_\nu - p_\nu(n_{\nu\tau} - n_{\nu\mu}) \end{vmatrix} \begin{vmatrix} \nu_\mu(t) \\ \nu_\tau(t) \end{vmatrix}$$

  $s = \sin\theta_V \quad c = \cos\theta_V$

  Could also be off diagonal matter effects, eg Mann et al

  $y = E_\nu \varepsilon / 10\text{GeV}$ (Big Effects For $y \sim O(1)$)

  $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_m \sin^2(\Delta m^2_{32}(\text{matter}) L/4E_\nu)$ disappearance

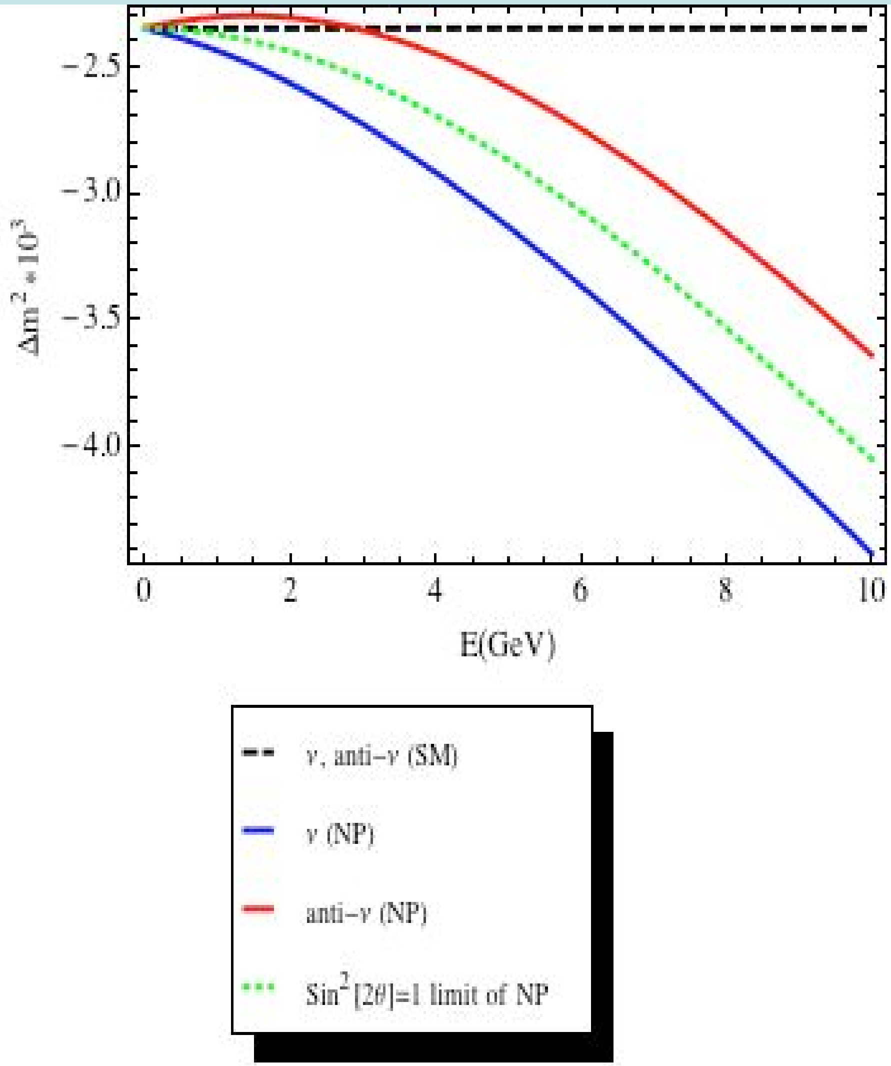
  (Suggests studies at high energies & long distances) with high precision

  $\sin^2 2\theta_m = \sin^2 2\theta_V / (1 \pm 2y\cos 2\theta_V + y^2)$

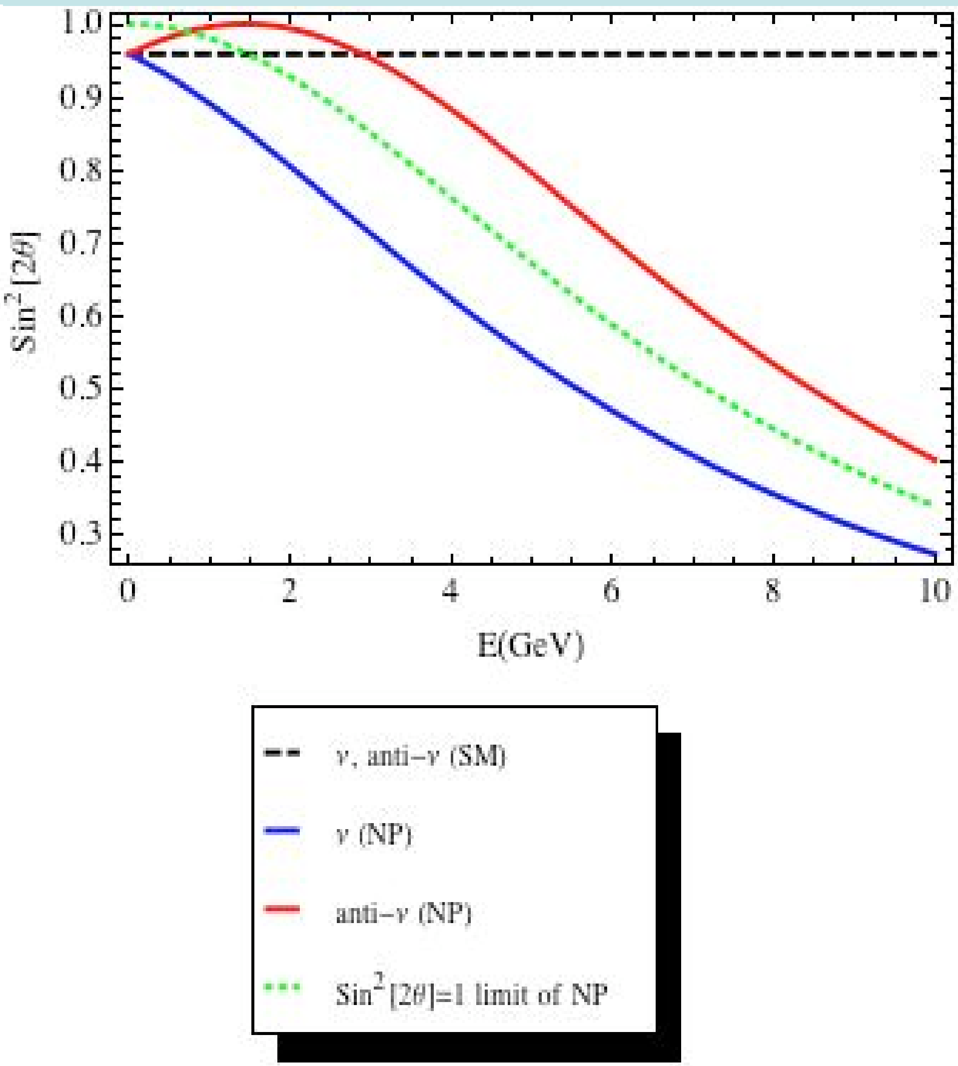
  $\Delta m^2_{32}(\text{matter}) = \Delta m^2_{32}(1 \pm 2y\cos 2\theta_V + y^2)^{1/2}$

Davoudiasl, Lee & WJM: Possible Long Range Solar Neutron Effect at DUSEL
(***Preliminary*** Gauged B-L_e-2L_τ, α'~few x10^{-52}, m_V<10^{-18}eV Example)

Effective Δm^2_{32}(matter) vs E_ν



Effective $\sin^2 2\theta_{23}$(matter) vs E_ν

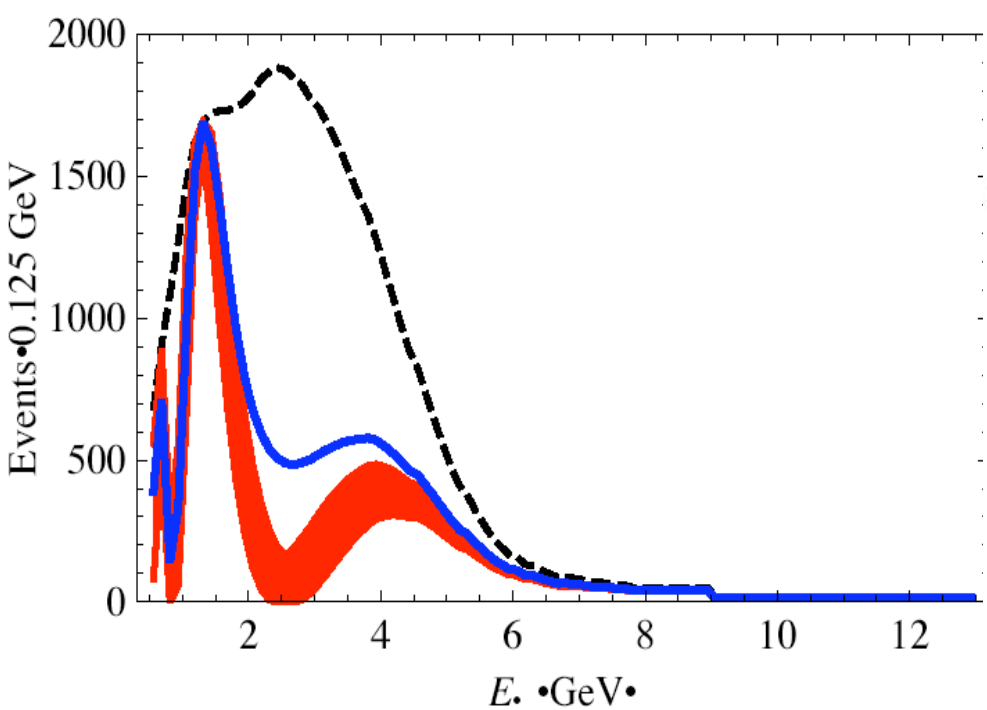


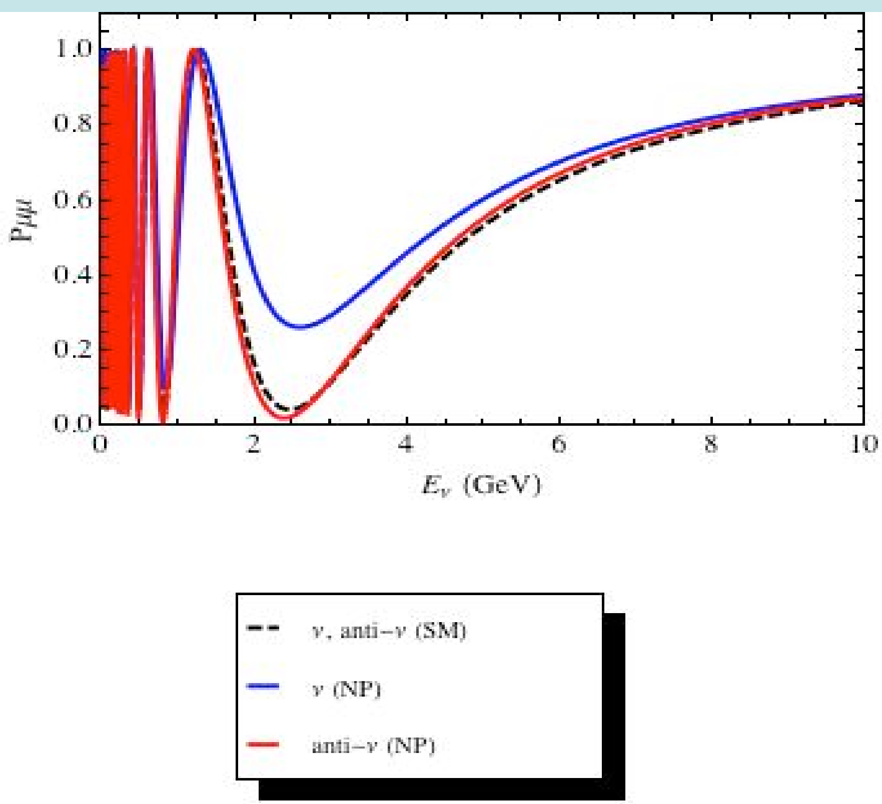
Davoudiasl, Lee & WJM: Possible Long range Solar Neutron effect at DUSEL
(Preliminary Generic Example)

Does not include possible constraint from Atmospheric E_ν>10GeV!

Blue Line =Gauged B-L_e-2L_τ, α'~few x 10^{-52}, m_V<10^{-18}eV example
Red Band = Standard $\nu_\mu \rightarrow \nu_\mu$ Survival Oscillations with current parameters

ν_μ disappearance probability





Anticipate *possible* differences in ν_μ and $\bar{\nu}_\mu$ & effective energy dependent mixing angles and Δm^2_{32}

(Eventually study energy dependence of Δm_{21}^2, θ_{13}, θ_{12}, δ)

Potentially 30x more sensitive!

Effects are rather generic! ***Energy Dependence***

Future experiments will measure those parameters with very high precision! Atmospheric as well as Long Baseline ν_μ and $\bar{\nu}_\mu$ disappearance will be unique probes of non standard (long and short distance) flavor dependent neutrino interactions!

***Moral**: Neutrino ν_μ and $\bar{\nu}_\mu$ Osc provides a potentially powerful Window to (weakly coupled) light and heavy "New Physics".*

6. Outlook

- LBNE will advance: θ_{13} ($\sin^2 2\theta_{13}$<0.003 sensitivity factor 40 below current bound!), Mass Hierarchy, ***ν CP Violation*** …

  Requires: Big Detector: 200kton H_2O or equivalent

  0.7-2.3MW Accelerator (Fermilab), Wide band neutrino beam
- ***"New Physics"***: sterile ν, extra dimensions, dark energy connection…
- ***Long/Short Distance Interactions via precision measurements!***

  (No other competitive approach! $\alpha' \leq O(10^{-52})$)!

  It will be the primary DUSEL facility - The Magnet Store

Also Does

- Atmospheric & Solar ν
- 100,000 supernova ν events (if in our galaxy)!
- Observe relic supernova ν (universe history)!
- ***Proton decay***, n-$\bar{n}$ osc., dark matter,…magnetic monopoles

  The potential for major discoveries & surprises is great!

  Complementary to the LHC (long & short distance frontiers)