Review of NuSAG for P5

P. Meyers – February 21, 2008

Goals of this talk

- Review physics issues for next phase of ν oscillation
- Snapshot at the time of NuSAG 3rd report (July ’07)
  - NuSAG charge/assumptions
  - Findings
  - Open issues
  - Recommendations
- Developments
- Issues going forward

From the original charge to NuSAG:

…we ask the NuSAG to make recommendations on the specific experiments that should form part of the broad U.S. neutrino science program.

- September 1, 2005: **Recommendations to the Department of Energy and the National Science Foundation on a United States Program in Neutrino-less Double Beta Decay**
- February 28, 2006: **Recommendations to the Department of Energy and the National Science Foundation on a U.S. Program of Reactor- and Accelerator-based Neutrino Oscillation Experiments**

You'll hear later about $0\nu\beta\beta$ and reactor ν-oscillation: both moving forward reasonably well.

From NuSAG’s second charge letter:

“Assuming a megawatt class proton accelerator as a neutrino source, please answer the following questions for accelerator-detector configurations including those needed for a multi-phase off-axis program and a very-long-baseline broad-band program.”

- July 13, 2007: **Recommendations to the Department of Energy and the National Science Foundation on a Future U.S. Program in Neutrino Oscillations**

Focus on this in my talk.

Neutrino Oscillation Basics

The mixing matrix is:

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

Where: $c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

Atmospheric ν_μ

Reactor $\overline{\nu}_e$

Accelerator ν_μ

Solar ν_e

Majorana

CP phases

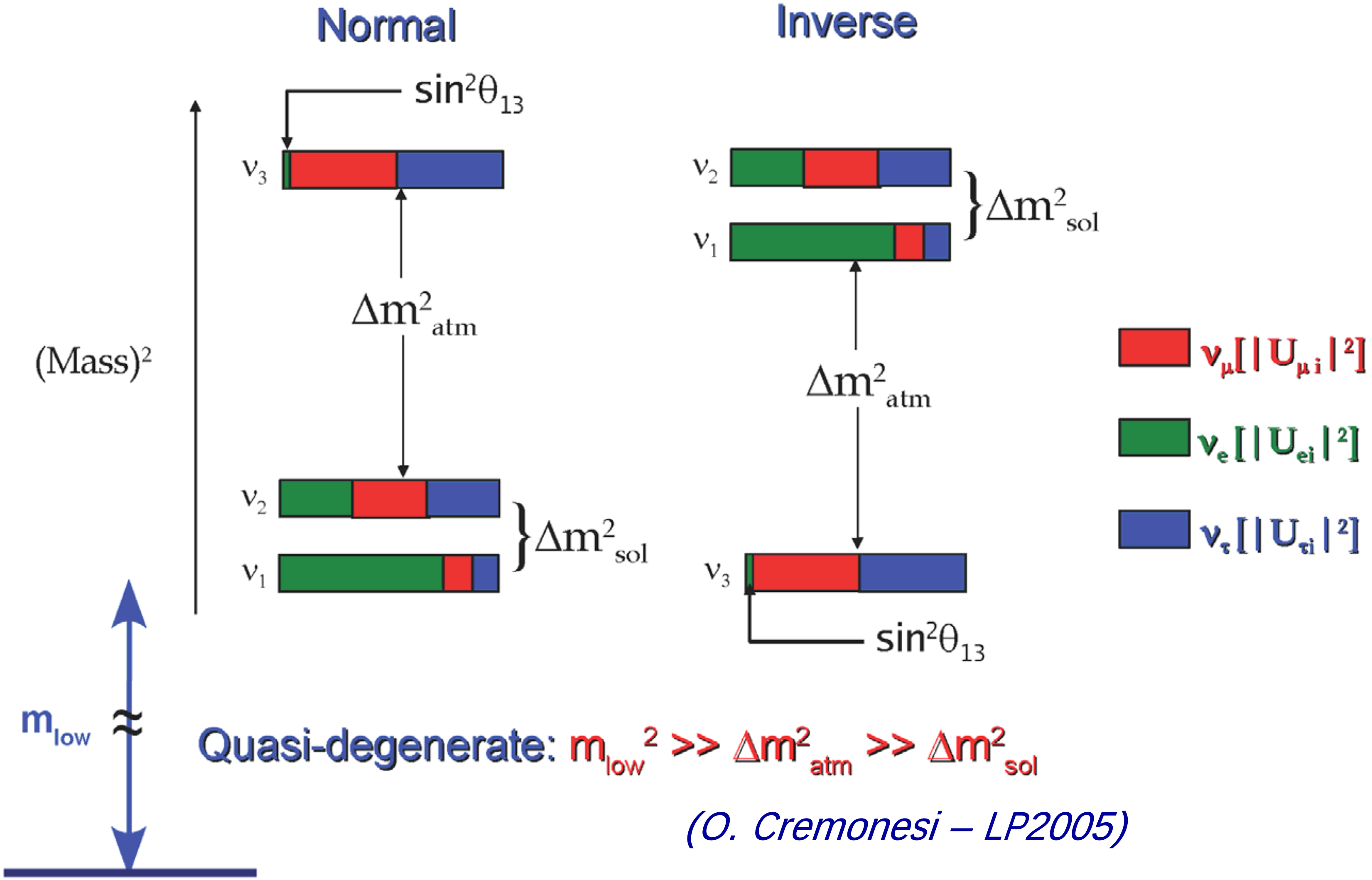
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\theta_{23} \approx \theta_{atm} \approx 45^\circ; \quad \theta_{12} \approx \theta_\odot \approx 34^\circ; \quad \theta_{13} \leq 12^\circ$$

δ *and* matter effects can lead to $P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$

Majorana CP phases are not accessible through oscillation experiments

The possible mass hierarchies



Quasi-degenerate: $m_{low}^2 \gg \Delta m^2_{atm} \gg \Delta m^2_{sol}$

(O. Cremonesi – LP2005)

Oscillations are sensitive only to Δm^2, not to the scale of m_ν

Measurement of CP violation and the mass hierarchy, even if technically within reach, is difficult, requiring huge detectors and high-power beams:

100-1000 kton detectors (Super-K: 22.5 kton)

≥1 MW beam (NuMI: 200 kW typical, 315 kW max)

Optimistic timescales run to 2030

Costs: n × \$100M, with $n >> 3$

To a good approximation, the probability P($\nu_\mu \rightarrow \nu_e$) for the neutrino oscillation is given by:

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 + \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

Where $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ is the small (~1/35) ratio between the solar and atmospheric (Mass)^2 splittings

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2}$$

Atmospheric

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

Interference:

CP violating

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP conserving

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

Solar

And: $\Delta = \Delta m^2_{31} L/4E_\nu$ **Kinematical oscillation phase**

$x = 2\sqrt{2} G_F N_e E_\nu / \Delta m^2_{31}$ **Matter effects: G_F = Fermi coupling**

N_e=electron density

Degeneracies: at fixed neutrino energy and baseline, $P(\nu_\mu \rightarrow \nu_e)$ depends on 3 (4) unknown parameters

- $\sin^2 2\theta_{13}$
- δ_{CP}
- $\mathrm{sgn}(\Delta m^2_{31})$
- $(\sin^2\theta_{23})$ – if $\theta_{23} \neq 45°$ ($\sin^2 2\theta_{23}$ is measured)

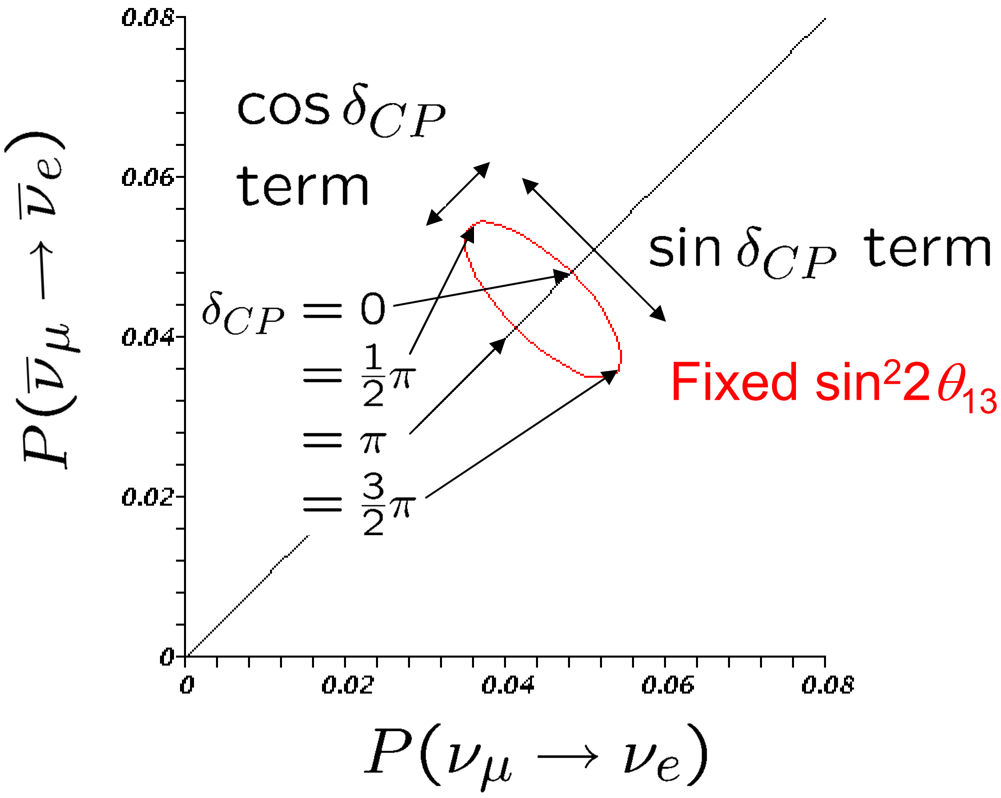
Strategies:

- More measurements
  - $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - multiple energies, multiple baselines
  - $\sin^2 2\theta_{13}$ from reactor experiments
- Longer baseline → higher E → larger matter effect
- Luck – there are outcomes that are non-degenerate

Bi-Probability Plot

E_ν=2.3 GeV, L=810 km - NOνA Parameters

CP violation – vacuum oscillations



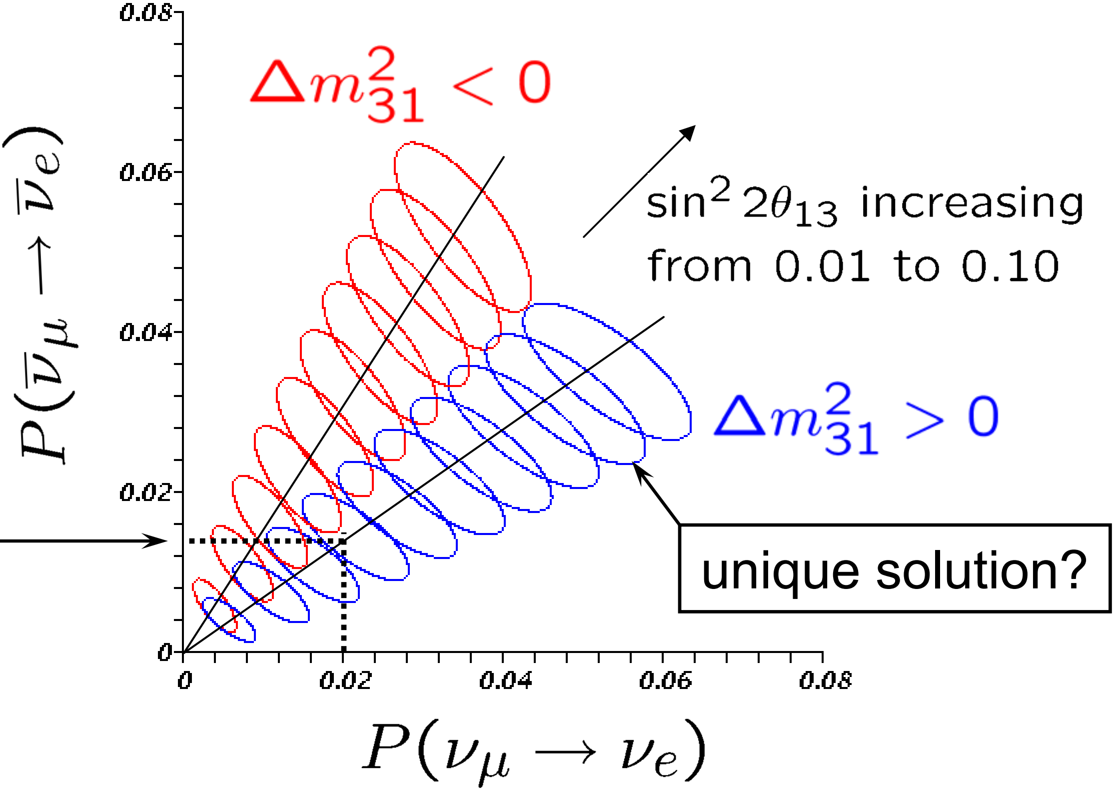
Fixed $\sin^2 2\theta_{13}$ = 0.10

Bi-Probability Plot

E_ν=2.3 GeV, L=810 km - NOνA Parameters

CP violation – matter oscillations

Δm^2_{31}>0 and
CP conserved
or
Δm^2_{31}<0 and
max CP violation



unique solution?

Still assuming perfect measurements of *P* and $\overline{P}$!

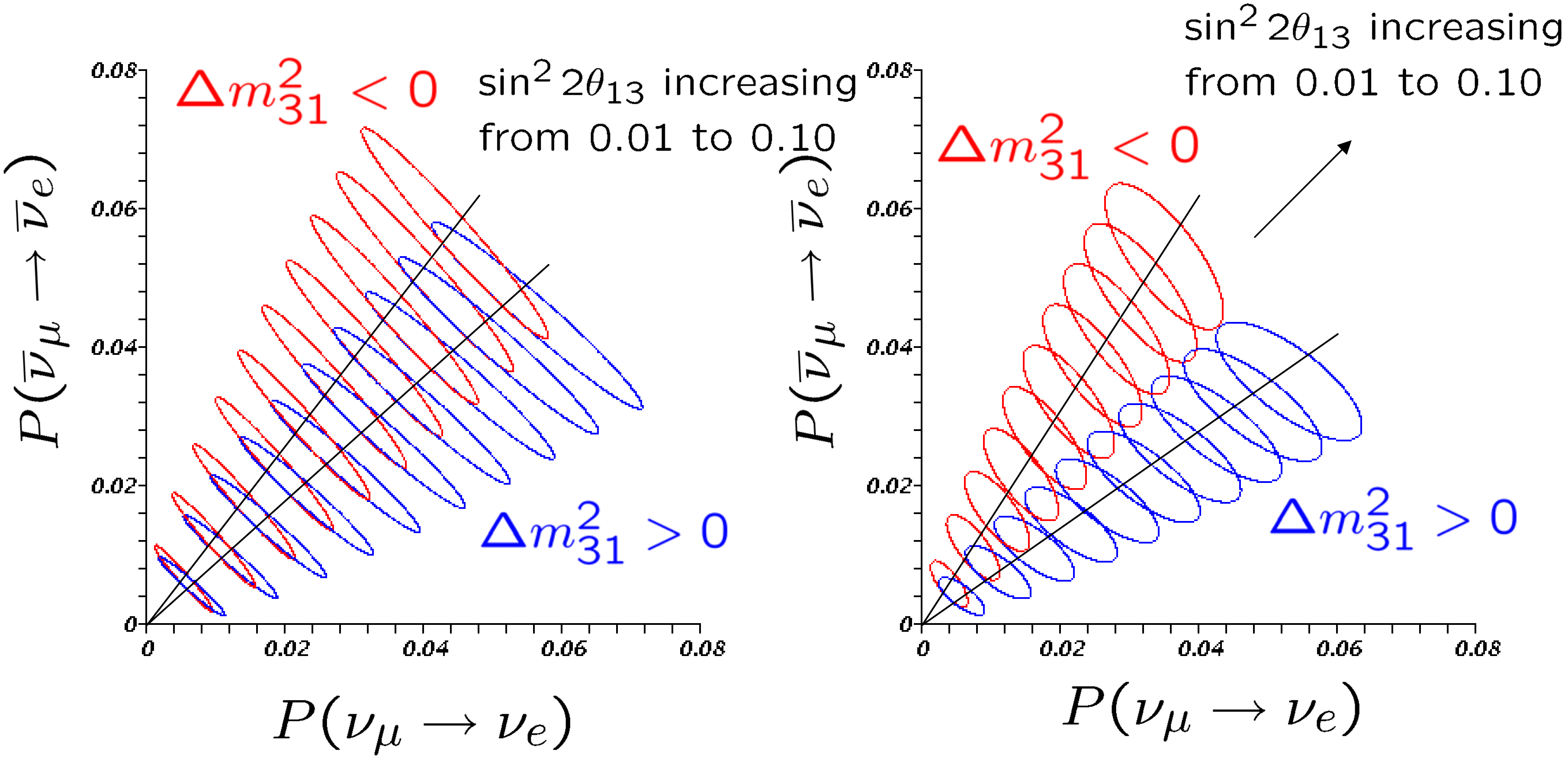
Bi-Probability Plot

E_ν=0.6 GeV, L=295 km

T2K Parameters

E_ν=2.3 GeV, L=810 km

NOνA Parameters



Still assuming perfect measurements of *P* and *P* !

NuSAG input environment, “current” ≡ 2006-7

“Phase 1”: currently approved or planned

Reactor experiments

- Double Chooz: 3σ sens $\sin^2 2\theta_{13} \sim 0.05$ by late 2012
- Daya Bay: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2013

Accelerator experiments (with currently planned beam power)

- T2K: 90%CL sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.01$ by late 2012
- NOvA: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2014; ~0.01 by late 2017
- NOvA+T2K: some sensitivity to mass hierarchy at the highest currently allowed θ_{13}'s

“Phase 2”: Next round of accelerator experiments to extend mass-hierarchy and CP violation sensitivity to $\sin^2 2\theta_{13} \sim 0.01$ – seems to be about the max reach with conventional beams

From NuSAG's second charge letter:

"Assuming a megawatt class proton accelerator as a neutrino source, please answer the following questions for accelerator-detector configurations including those needed for a multi-phase off-axis program and a very-long-baseline broad-band program."

Concurrently, BNL and FNAL convened a Study Group spanning both approaches – **NuSAG's major technical input.**

General consensus: **FNAL Main Injector would be the proton source** for either approach in the U.S.

Accelerator $\nu_\mu \rightarrow \nu_e$ appearance experiments

Signature:

- Electrons from ν_e Charged Current (CC) events
- Quasi-elastic (CCQE) cleanest and allow reconstruction of ν energy (smeared by Fermi motion) from *e* or μ

Backgrounds:

- “Intrinsics”: ν_e from μ and K decay, not oscillation
- “π^0”:
  - produced in higher-energy ν interactions
  - can resemble electrons if gammas merged or low energy gamma missed
  - Neutral Current (NC) π^0 most insidious of reducible bkg

Off-axis approach

- At a fixed angle from π beam direction, π's of **all** energies give ν's of about the **same** energy – a narrow-band beam
- Lose flux, but loss of HE flux decreases NC π^0 background at beam energy
- ν_e from K at different energy

Wide-band Beam approach

- Energy dependence lifts degeneracies
  (uses primarily spectrum across 1st max, as counting rate is low at 2nd)
- On-axis beam maximizes flux for long baselines
- Long baselines enhance matter effect

  but:
- High energy component brings π^0 background
- Use small off-axis angle to suppress

Detector technologies

Water Cherenkov

- Known, successful technology for ν osc and p decay
- Must be underground: DUSEL
- R&D on large caverns
- PMT’s drive cost and construction time→sensor R&D
- WBB application needs good π^0 rejection

  new algorithms appear to be good enough

  efficiency ~15-20%

Liquid Argon TPC

- Ability to reconstruct events in detail → excellent π^0 rejection and ~80% efficiency, ~4-5×Water Cherenkov
- If underground, good for $p \to K^+\nu$
- Existence proof: ICARUS T600 (2×300 ton total mass)
- Aggressive R&D needed to prove feasibility at 50-100 kton
- Must drastically reduce costs (<1/10 per-ton of T600)
- Plausible that it can work at surface – proof needed

Sensitivity calculations by BNL/FNAL Study Group

Options presented (many others looked at):

1. Off axis, 100 kton LAr at NOvA site
2. Off axis, 50 kton LAr at NOvA site + 50 kton LAr at 2nd max
3. Wide-band, 300 kton Water Cherenkov at Homestake
4. Wide-band, 100 kton LAr at Homestake

Note: rule of thumb was LAr ~ 3×WaterC, hence
300 kton WaterC ←→ 100 kton LAr
but under the assumptions developed for the calculations, the factor is more like ×4-5

Sensitivity calculations by BNL/FNAL Study Group

NuSAG's criteria:

- Establish $\theta_{13} \neq 0$: At what $\sin^2 2\theta_{13}$ is $\sin^2 2\theta_{13}=0$ rejected at 5σ for all values of δ_{CP}?
- Determine the mass hierarchy: At what $\sin^2 2\theta_{13}$ is the wrong mass hierarchy rejected at 5σ for all values of δ_{CP}?
- Find CP violation: At what $\sin^2 2\theta_{13}$ are $\delta_{CP}=0$ and π rejected at 5σ for 50% of the values of δ_{CP}?

The cost, effort, and time required demand that the program's discovery potential be held to high standards.

30×10^{20} p.o.t neutrino + 30×10^{20} p.o.t antineutrino
≈ 3-5 years neutrino + 3-5 years antineutrino @ 1 MW

Option	$\sin^2 2\theta_{13}$ 5σ, all δ_{CP}	CPV 5σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 5σ, all δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.008	0.08	0.18
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.011	>0.10	0.15
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.015	>0.10	0.032
4) WBB 0.5° 100 kt LAr, 1300 km	0.008	0.035	0.019

Entries are minimum $\sin^2 2\theta_{13}$ where null hypothesis is ruled out

Option	$\sin^2 2\theta_{13}$ 5σ, all δ_{CP}	CPV 5σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 5σ, all δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.008	0.08	0.18
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.011	>0.10	0.15
2A) 100/100 kt LAr	0.009	0.08	0.08
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.015	>0.10	0.032
3A) 60×10^{20} p.o.t. each	0.012	0.08	0.022
4) WBB 0.5° 100 kt LAr, 1300 km	0.008	0.035	0.019

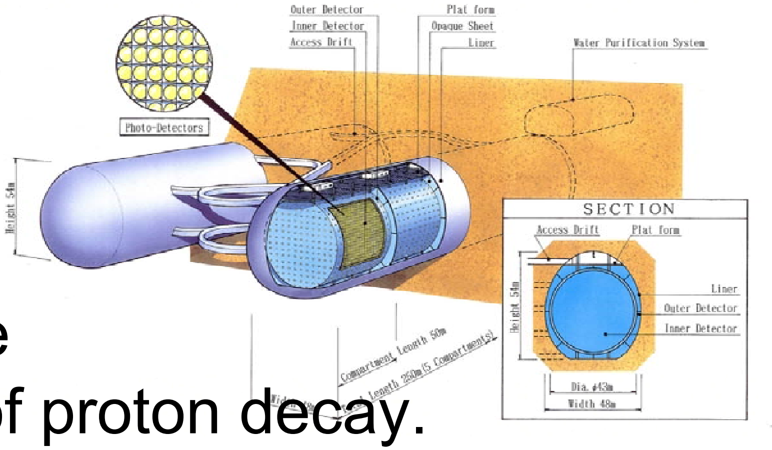
Entries are minimum $\sin^2 2\theta_{13}$ where null hypothesis is ruled out

30×10^{20} p.o.t neutrino + 30×10^{20} p.o.t antineutrino ≈ 3-5 years neutrino + 3-5 years antineutrino

Option	$\sin^2 2\theta_{13}$ 3σ,50% δ_{CP}	CPV 3σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 3σ,50% δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.002	0.02	0.05
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.004	0.05	0.04
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.006	0.02	0.01
4) WBB 0.5° 100 kt LAr, 1300 km	0.002	0.005	0.006

Entries are minimum $\sin^2 2\theta_{13}$ where null hypothesis is ruled out

International context for Phase 2



Japan:

Hyper-Kamiokande: 2×270 kton
T2K beam, upgraded power
Light sensor R&D underway
Plan: continue R&D until evidence that θ_{13} big enough for CPV or of proton decay.
Baseline too short for independent mass hierarchy.

Europe:

- Focus mostly on new neutrino source technology for $\sin^2 2\theta_{13}<0.02$: Beta beams, neutrino factory.
- Not usually considered competitive with Phase 2, but may have to be reconsidered.
- Also considering 500 kton WaterC, LArTPC.

Often assume: mass hierarchy will be known from U.S. experiments

Cost estimates/considerations: as of 2007
Physicist's estimates, not reviewed

- Water Cherenkov: 3×100, 440 kton
  - $335-$500M
  - PMTs are 40-60% of cost
- Liquid Argon TPC: 100 kton
  - No idea yet
  - LAr is ~$1M/kton
- Wide-band beam: FNAL to DUSEL
  - NuMI cost $109M, F2H is shorter, wider, steeper
  - Guess: $100-200M?
- Cost for 700 kW → ≥1 MW?

more on all this today

Timeline

A. Decision/approval

NuSAG advocates being prepared to proceed as soon as we know the size of $\sin^2 2\theta_{13}$ from Phase 1 experiments

- Double Chooz: 3σ sens $\sin^2 2\theta_{13} \sim 0.05$ by late 2012
- Daya Bay: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2013
- T2K: 90%CL sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.01$ by late 2012
- NOvA: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2014; ~0.01 by late 2017

NuSAG conclusion: 2012 at earliest

Project approval process: 3-4 years

Timeline – 2

B. Construction

Water Cherenkov: 7-10 years, limited by PMT production

– decrease by more suppliers? (cash flow issue)

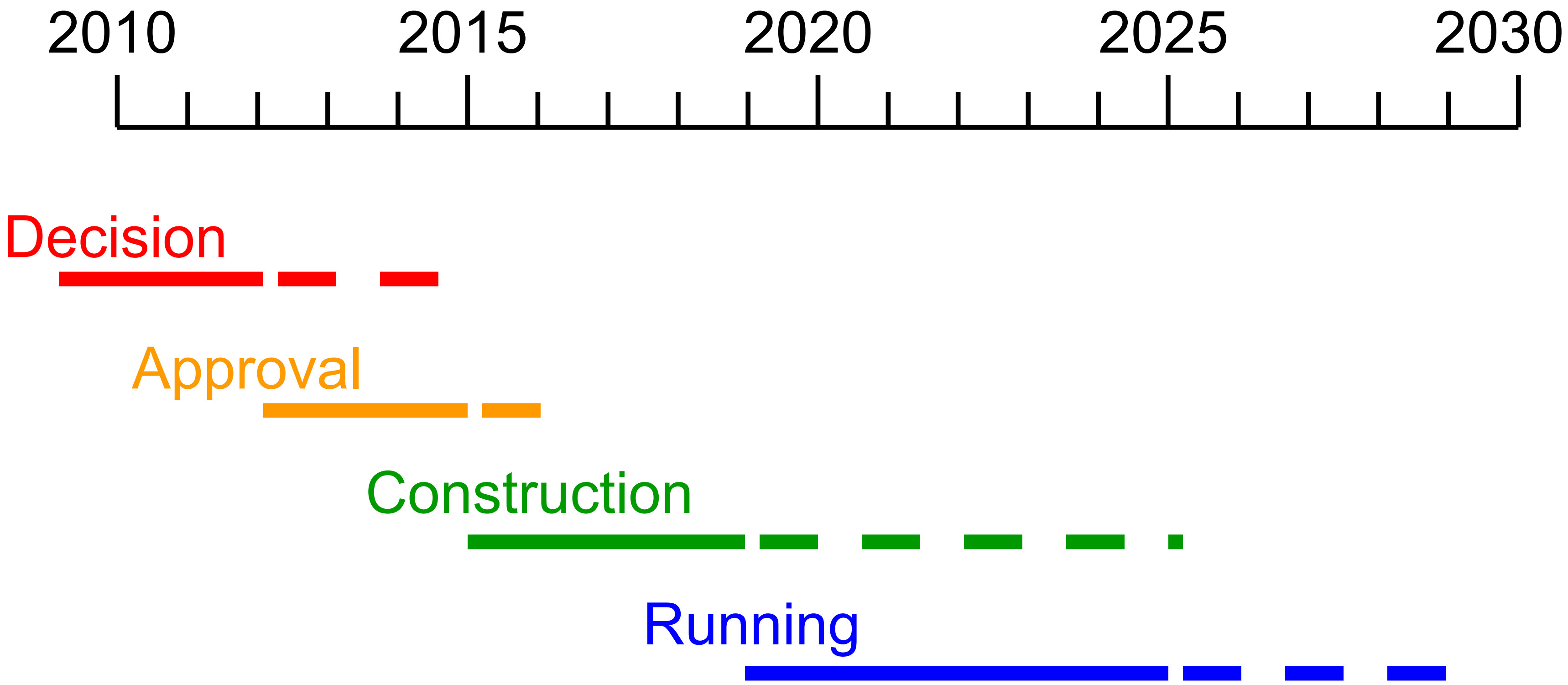
LArTPC: not known – guess 4-6 years??

If in DUSEL, ready for occupancy when?

C. Running

Sensitivity plots assumed 6-10 years @ 1 MW

Time for reaching this not included here


2010
2015
2020
2025
2030
Decision
Approval
Construction
Running

Recommendation 1. The US should prepare to proceed with a long baseline neutrino oscillation program to extend sensitivity to $\sin^2 2\theta_{13}$, to determine the mass ordering of the neutrino spectrum, and to search for CP violation in the neutrino sector. Planning and R&D should be ready for a technology decision and a decision to proceed when the next round of results on $\sin^2 2\theta_{13}$ becomes available, which could be as early as 2012. A review of the international program in neutrino oscillations and the opportunities for international collaboration should be included in the decision to proceed.

Recommendation 2. Research and development towards an intense, conventional neutrino beam suitable for these experiments should be supported. This may be in the form of intensity upgrades to the existing NuMI beam, as well as development of a new beam directed towards DUSEL, which would likely employ the wide-band beam approach.

Recommendation 3. Research and development required to build a large water Cherenkov detector should be supported, particularly addressing questions of minimum required photocathode coverage, cost, and timescale.

Recommendation 4. A phased R&D program with milestones and using a technology suitable for a 50-100 kton detector is recommended for the liquid argon detector option. Upon completion of the existing R&D project to achieve purity sufficient for long drift times, to design low noise electronics, and to qualify materials, construction of a test module that could be exposed to a neutrino beam is recommended.

Developments since the NuSAG report

- DUSEL site selection
- ILC schedule realism
- FNAL Steering Group/Project X
- FY08 budget: hits to NOvA, ILC R&D

Issues

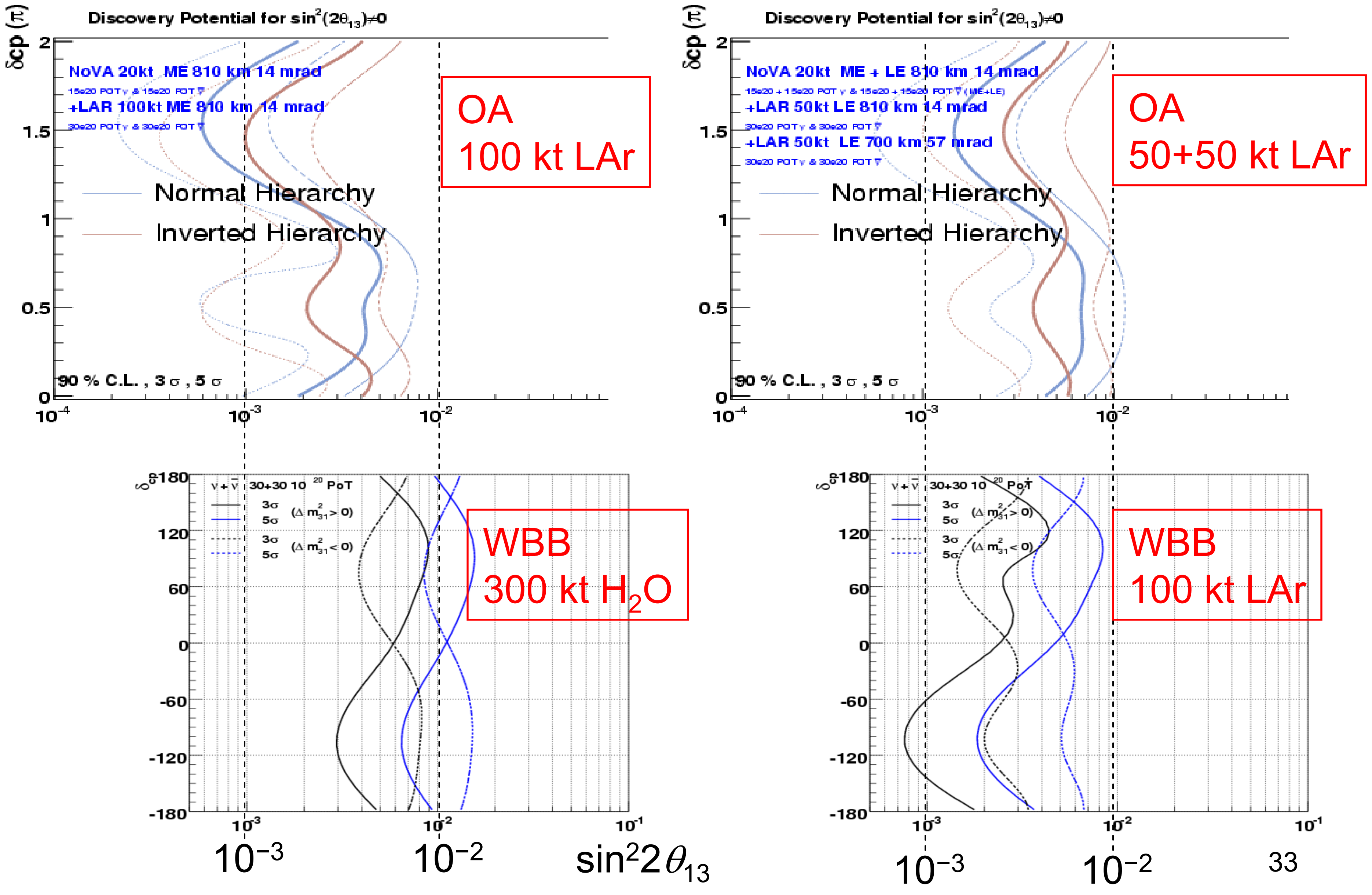
- LAr technical status, cost estimate
- NOvA schedule
- DUSEL schedule
- FNAL-Homestake beam cost
- Realistic strategies for large $\sin^2 2\theta_{13}$
- FNAL medium-term program

Members of NuSAG

Eugene Beier (University of Pennsylvania and Co-Chair)
Peter Meyers (Princeton University and Co-Chair)
Leslie Camilleri (CERN)
Boris Kayser (Fermi National Accelerator Laboratory)
Ed Kearns (Boston University)
Bill Louis (LANL)
Naomi Makins (University of Illinois)
Tsuyoshi Nakaya (Kyoto University)
Guy Savard (Argonne National Laboratory)
Heidi Schellman (Northwestern University)
Gregory Sullivan (University of Maryland)
Petr Vogel (California Institute of Technology)
Bruce Vogelaar (Virginia Tech)
Glenn Young (Oak Ridge National Laboratory)
Melvin Shochet (University of Chicago) *ex officio*
Robert Tribble (Texas A&M) *ex officio*

HEP/nuclear, expt/theory, US/not, ν physics/not

Sensitivity to $\sin^2 2\theta_{13}>0$



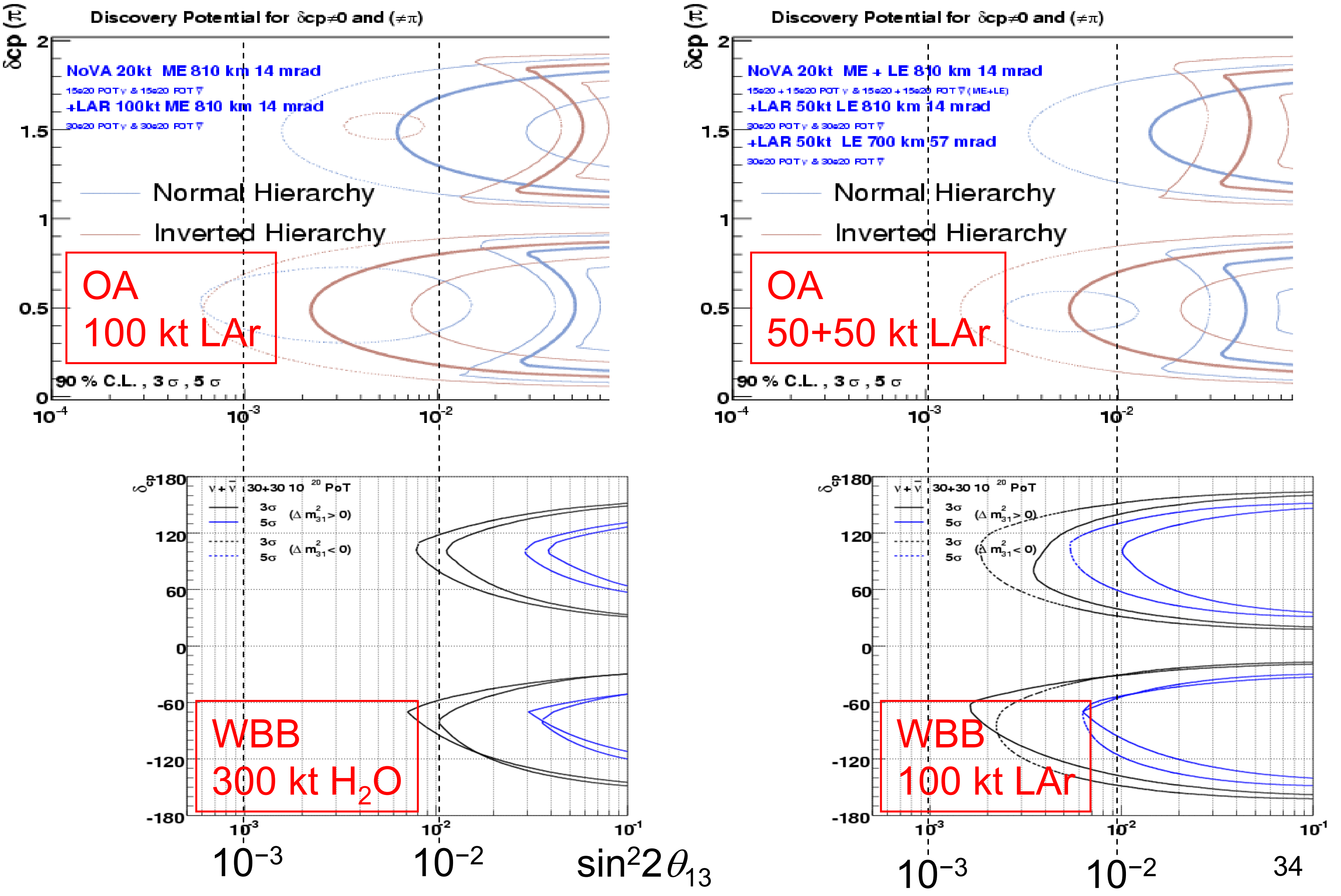
OA
100 kt LAr

OA
50+50 kt LAr

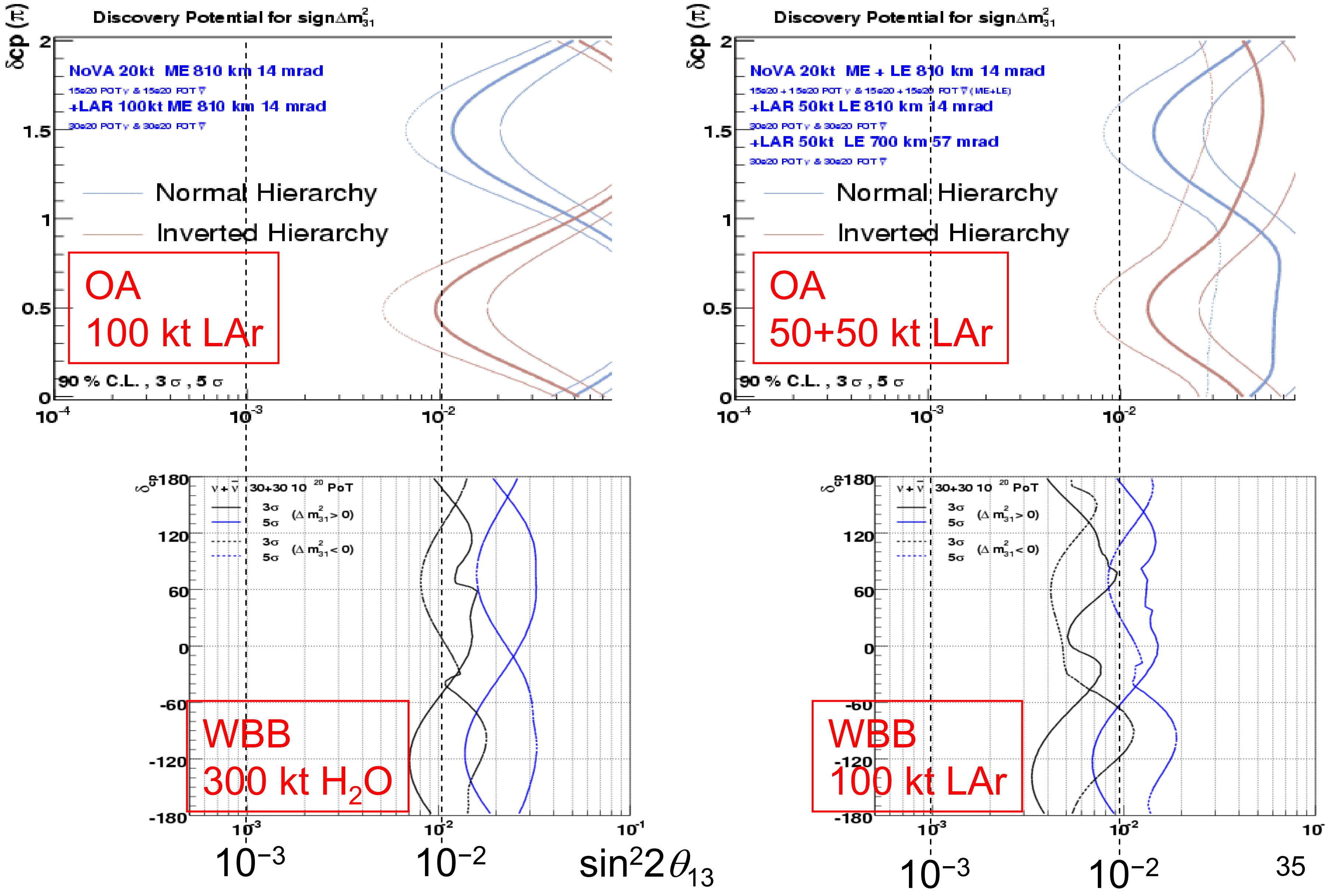
WBB
300 kt H_2O

WBB
100 kt LAr

Sensitivity to CP violation



Sensitivity to mass hierarchy



OA
100 kt LAr

OA
50+50 kt LAr

WBB
300 kt H_2O

WBB
100 kt LAr

Other Physics

Nucleon decay

- Water Cherenkov detector 15 times Super-K fiducial volume
  excellent general purpose detector
- Liquid argon TPC – excellent for SUSY preferred decay $p \rightarrow K^+ \nu_\tau$ due to good tracking
- Could become high priority if Super-K sees candidates

Low energy neutrino astrophysics

- Neutrino burst from galactic supernova
- Diffuse supernova neutrino background
- Some solar neutrino physics

Other physics may increase costs (e.g. more PMT's for Low E)