DOE/NSF-HEPAP/NSAC
Neutrino Scientific Assessment Group
“NuSAG”

Report to HEPAP

G. Beier, P. Meyers – February 23, 2007

- Goals of the next phases of neutrino oscillations
- The charge to NuSAG
- Off-axis and Wide Band Beam approaches
- Experimental realizations of these approaches
- Outstanding issues
- NuSAG schedule

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**

Members of NuSAG

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

The paradigm: 3-ν mixing

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

With $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$:

Atmospheric ν_μ — Reactor $\overline{\nu}_e$, Accelerator ν_μ — Solar ν_e — Majorana CP phases

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

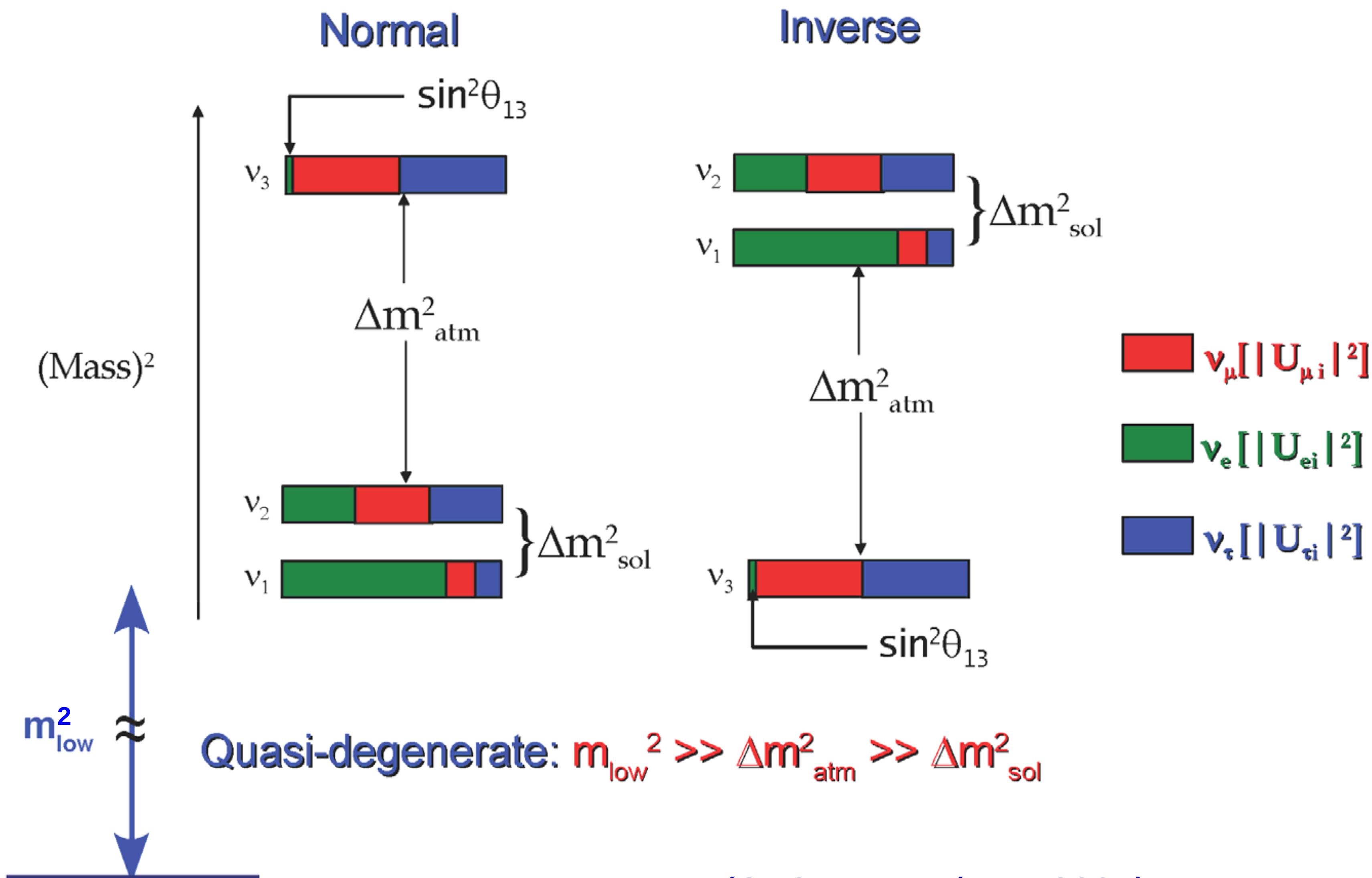
$\theta_{23} \approx \theta_{atm} \approx 45°$; $\theta_{12} \approx \theta_{sol} \approx 34°$; $\theta_{13} \leq 10°$

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

(LSND not consistent with this picture –

here is where you generally ask me about MiniBooNE)

The mass hierarchies



(O. Cremonesi – LP2005)

Goals of the next phases of the worldwide experimental program in neutrino oscillations

Fill out our understanding of 3-neutrino mixing and oscillations:

- What are the orderings and splittings of the neutrino mass states?
- What are the mixing angles?
- Is there CP violation in neutrino mixing?

A world-wide effort has laid out an ambitious program that can do ***all*** of this – subject to the values of the unknown parameters, a risk inherent to this ***experiment-driven*** field.

(Thanks to Boris Kayser)

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

unknowns

$$P[\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e] \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$
$$+ \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}$$
$$\sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta)$$
$$+ \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}$$

ν

$\bar{\nu}$

(solar)

$$(\Delta_{ij} \equiv 1.27 \Delta m_{ij}^2 (eV^2) L(km) / E(GeV))$$

Sensitivity to mass hierarchy via "matter effects":
Passage through matter:

Normal: increases $\nu_\mu \rightarrow \nu_e$, decreases $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Inverted: decreases $\nu_\mu \rightarrow \nu_e$, increases $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Note: $\sin 2\theta_{13}$ a factor in all the physics we are after!

Reactor $\overline{\nu}_e$ disappearance

$$P[\overline{\nu_e} \to \text{Not}\,\overline{\nu_e}] \cong \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

small at max of first term

Accelerator-based oscillation experiments

- θ_{13}>0
- mass *ordering* if θ_{13} large enough
- CP violation if θ_{13} large enough
- parameter extraction limited by degeneracies
  combine energies or reactor

Reactor-based oscillation experiments

- measure only θ_{13} but without ambiguity
- combine with accelerator to break degeneracies
  in some regions, if sufficient precision

"Phase 1": currently approved or planned

Reactor experiments

• Double Chooz: 3σ sens $\sin^2 2\theta_{13} \sim 0.05$ by 2012

• Daya Bay: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2013

Accelerator experiments (with currently planned beam power)

• T2K: 3σ sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.01$ by 2014

• NOvA: 3σ sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.005$ by 2015

• NOvA+T2K: some sensitivity to mass hierarchy at the highest currently allowed θ_{13}'s

"Phase 2": NuSAG's current charge

• Next round of accelerator experiments to extend mass-hierarchy and CP violation sensitivity to $\sin^2 2\theta_{13} \sim 0.01$

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."

The questions:

- Scientific potential
- Associated detector options, including rough cost
- Optimal timeline, including international context
- What other scientific inputs are needed?
- What additional physics can be addressed?

Historical context (c.2005-6) and the BNL/FNAL Study Group

• T2K and NOvA use "off-axis" neutrinos to create narrow-band beams, and both lay out potential programs including upgraded accelerator power, beams, and detectors.
• Meanwhile, an alternate approach using a "wide-band beam" proposed (originally by Brookhaven groups).

These are the approaches NuSAG is charged to evaluate.

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

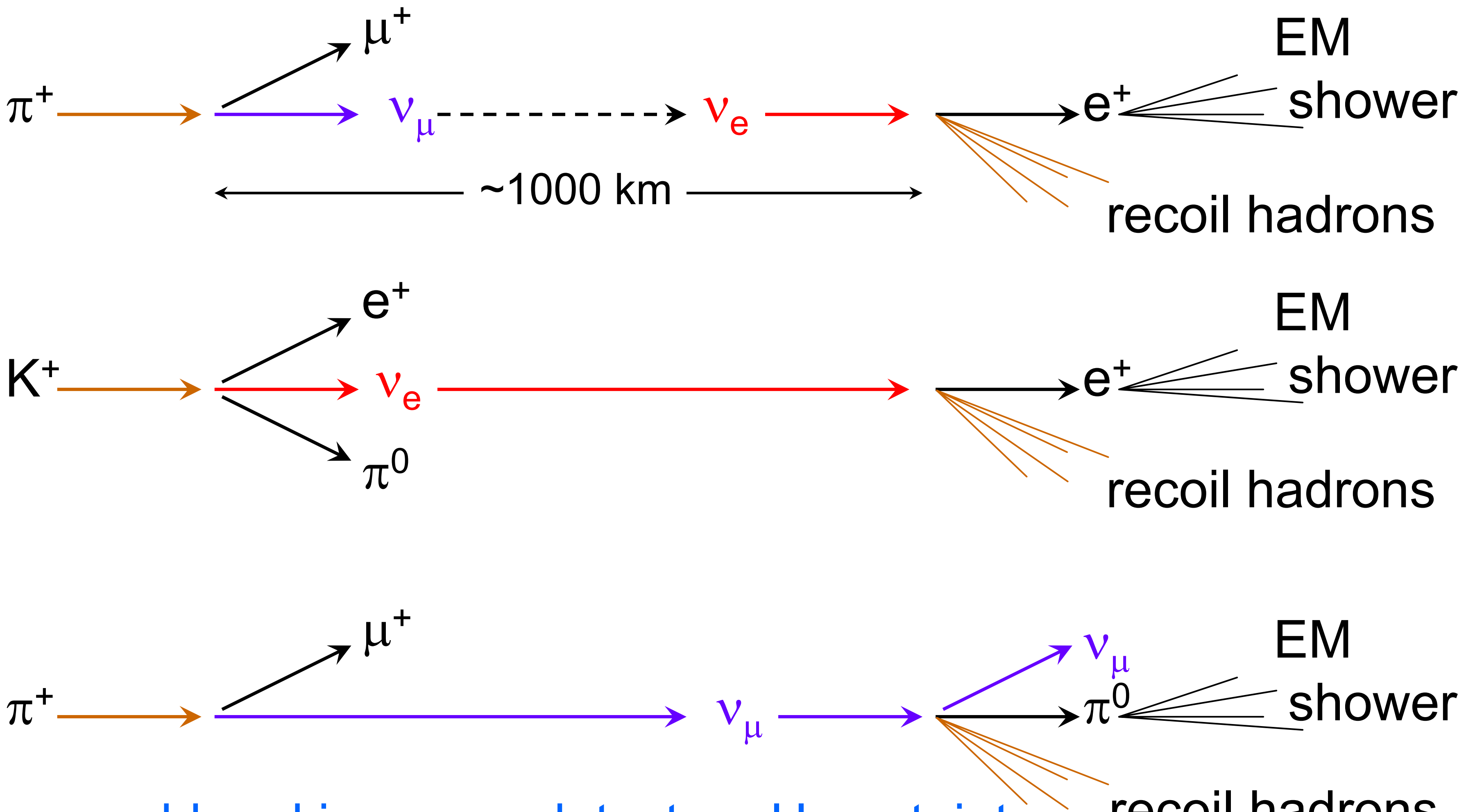
General consensus: FNAL Main Injector would be the proton source for either approach in the U.S.

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)

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

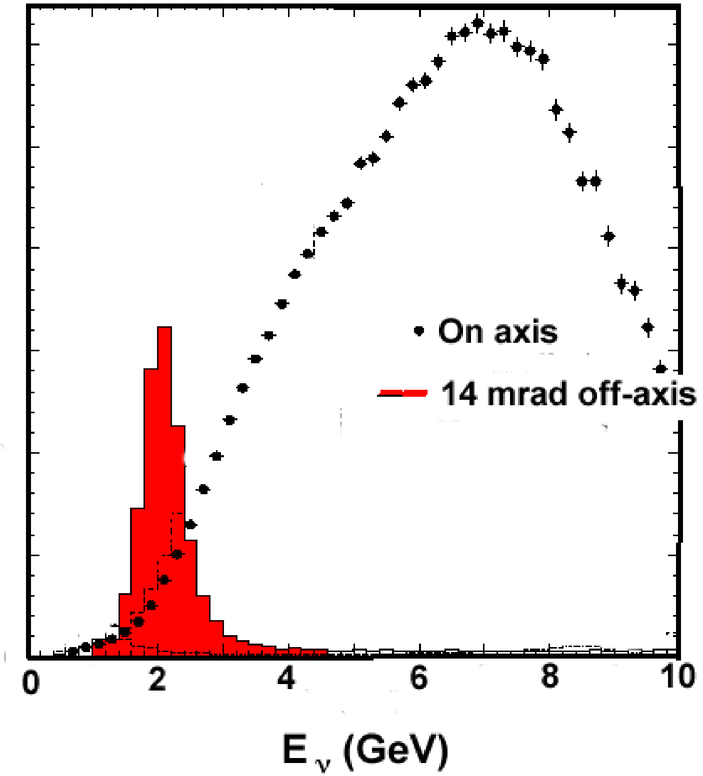
Accelerator $\nu_\mu \rightarrow \nu_e$ appearance experiments



Measure bkgnd in a near detector. Uncertainty in these measurements become systematic uncertainty in result

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



Ambiguities/degeneracies: examples

At a single energy and baseline (NOvA's used here),
a **perfect** measurement of $P(\nu_\mu \rightarrow \nu_e) = 0.02$

- Establishes $\theta_{13} > 0$

  but

- Is consistent with
  - $0.025 < \sin^2 2\theta_{13} < 0.075$
  - either mass hierarchy
  - any CP phase δ (including zero)

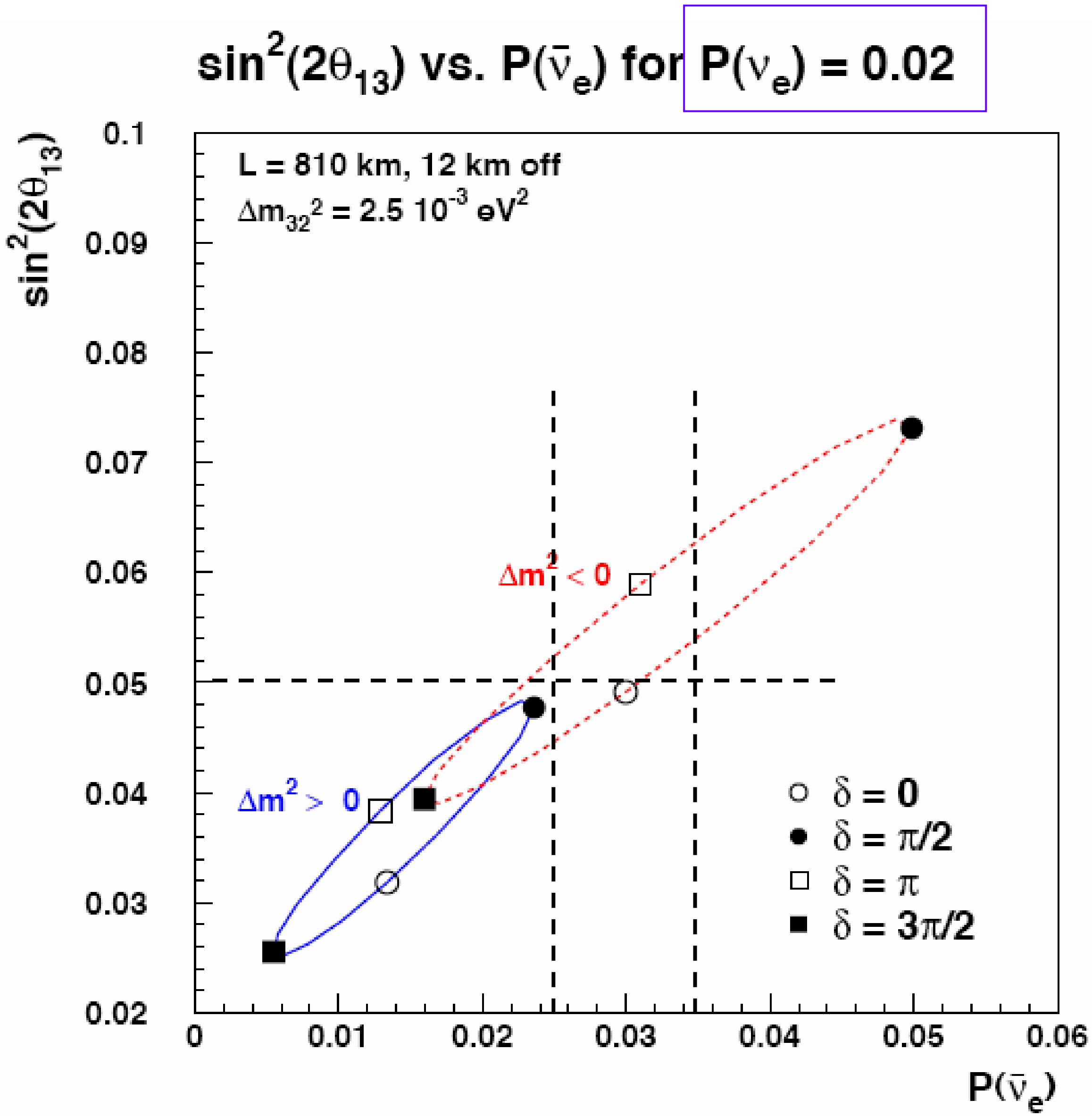
- Need more measurements: anti-ν, other E, reactor,…

Examples:
With $P(\nu_\mu \rightarrow \nu_e) = 0.02$:

- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) > 0.025$ determines mass hierarchy, > 0.035 establishes CP violation

or:

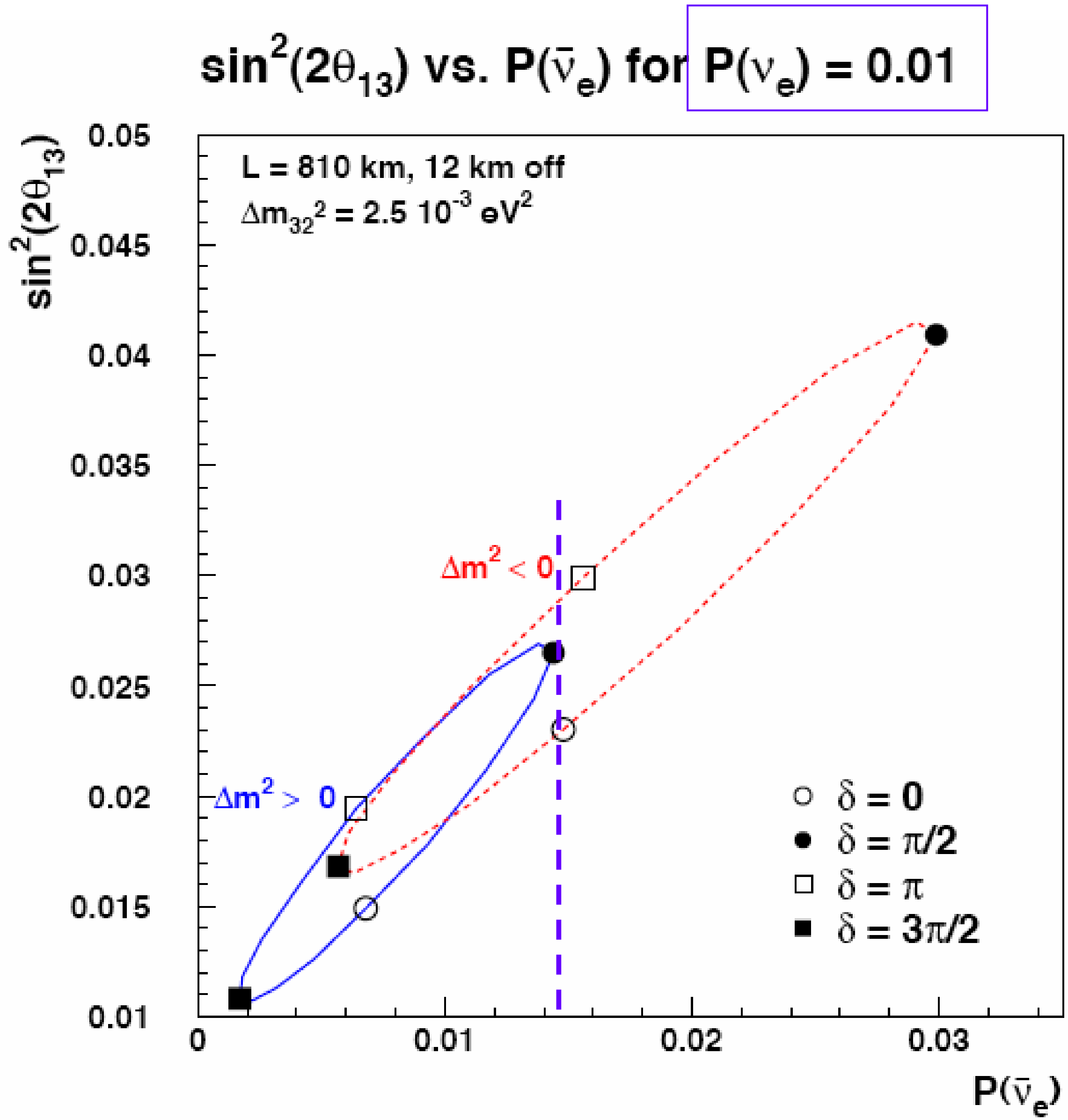
- Reactor measures $\sin^2 2\theta_{13} > 0.05$: mass hierarchy determined



(thanks to Gary Feldman)

A harder case:
With $P(\nu_\mu \rightarrow \nu_e) = 0.01$:

- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.015$ leaves mass hierarchy and CP violation unknown
- Reactor unlikely to settle things in this region



More measurements: other energies

- Another off-axis detector: 2^{nd} oscillation max?
- Some variation over width of narrow-band beam
- Use a Wide-band Beam (WBB)

Goal: mass hierarchy and CP violation sensitivity down to $\sin^2 2\theta_{13} \sim 0.01$, which seems to be about the max reach of conventional beams

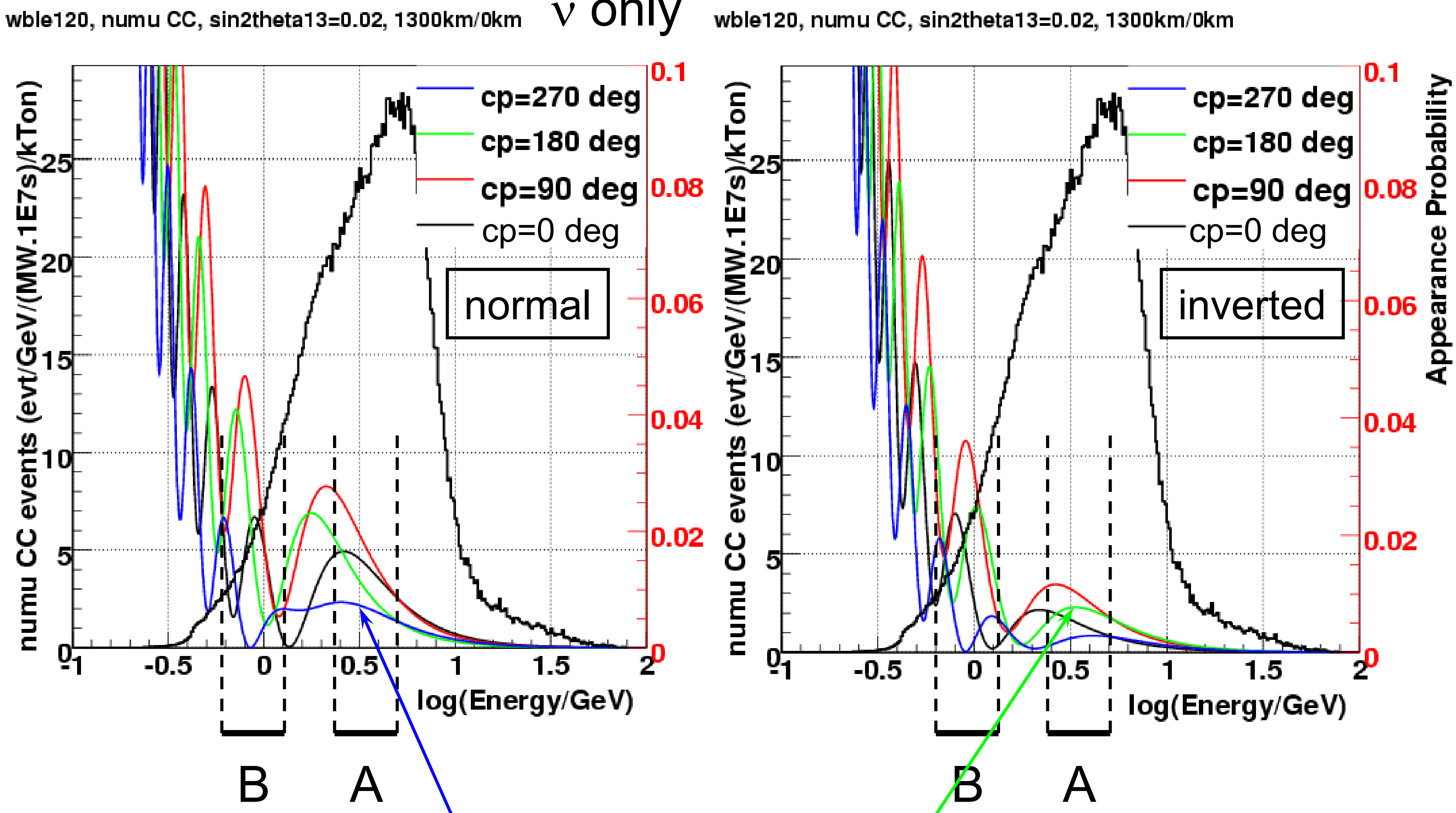
Wide-band Beam approach

- Energy dependence lifts degeneracies
- On-axis beam maximizes flux for long baselines
- Long baselines enhance matter effect

but:

- High energy component brings π^0 background

ν only



In band A: max CPV/normal ~ no CPV/inverted

In band B: node ≠ peak

U.S. experimental scenarios using these approaches

All start with Fermilab Main Injector

- Max achieved beam power: 315 kW @ 120 GeV
- Initial upgrade plan to 700 kW
- Longer-term upgrade plan to 1.2 MW
- Less beam power at lower energies

Off-axis

- ~100 kt of Liquid Argon TPC
- Use existing/upgraded NuMI beam
- Deploy all at NOvA site, or split with "2^{nd} max", or other

Wide-band beam, very long baseline

- ~300-500 kt of water Cherenkov (or ~100 kt LArTPC)
- In DUSEL
- New neutrino beam

Other physics with 100-500 kt neutrino detectors

Proton decay
Neutrinos from galactic supernovae
Diffuse SN neutrino background
Solar neutrino physics

Note: must ask if these require additional instrumentation

Detector technologies

Water Cherenkov

- Known, successful technology for ν osc and p decay
- Must be (deep?) underground: DUSEL
- R&D on large caverns
- PMT's drive cost and construction time
- R&D for new light sensors

LArTPC

- Ability to reconstruct events in detail → excellent π^0 rejection and ~3×efficiency of Water-C
- Aggressive R&D needed to prove feasibility at 50-100 kt scale with drastically reduced costs
- Plausible that it can work at surface – proof needed
- $p \rightarrow K^+\nu$, a possibly favored proton decay mode

Off-axis

Pro:

- Reduced π^0 background
- Known ν energy: use all CC events?
- Use existing beam
- Near detector same as far
- Allows incremental program (but steps still $$!)

Con:

- Must deal with ambiguities of ~single energy
- 2^{nd}-max site has very low event rates, HE ν's from K's
- Detector must be on surface to use NuMI beam – cannot use Water-C
- LArTPC needs intensive R&D
- Near detector sees very different beam

Wide-band beam, very long baseline

Pro:

- Full energy spectrum for resolving ambiguities
- Proven technology
- DUSEL deployment gives broader physics program
- Recent progress in Water-C π^0 rejection

Con:

- Large, ~all-at-once cost
- DUSEL timeline consistent with other constraints?
- With PMT's the cost driver, cost sensitive to coverage needed for π^0 rejection, other physics
- Near detector can't be Water-C

Current status and NuSAG plans

• BNL/FNAL Study Group working on directly-comparable sensitivity calculations for the different scenarios
• These define detector mass needed (cost) and may rule out some scenarios
• NuSAG is getting educated on the issues, including current thinking in Japan and Europe
• Findings on technical issues mostly in place, strategy recommendations need sensitivity info
• One strategic issue seems clear: can't start construction on Phase 2 without an observation of non-zero θ_{13}
• R&D needed: LArTPC, PMT's, large caverns, high beam power
• NuSAG report will be available before next HEPAP meeting