Neutrino Scientific Assessment Group
Status Report to NSAC

Eugene Beier/Peter Meyers

March 8, 2007

- Introduction to NuSAG and Charge
- Neutrino Oscillation Tutorial
- Strategies for Experiments
- Detector Options
- NuSAG Status and Projections

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**

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.
• An alternate approach using a “wide-band beam” has been proposed by a Brookhaven group.

These are the approaches NuSAG is charged to evaluate.

Concurrently, BNL and FNAL 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.

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)

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

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

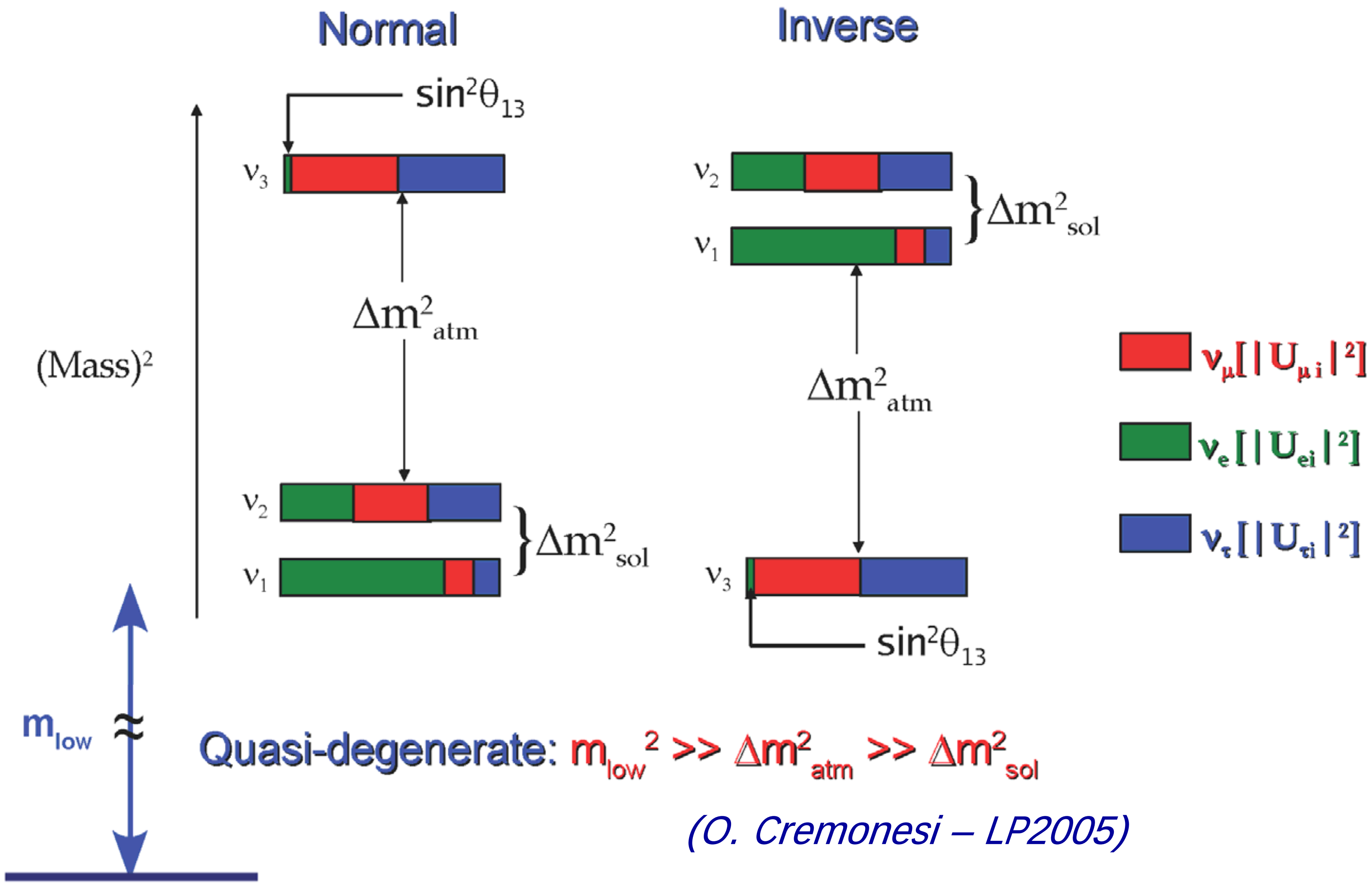
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}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

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

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



(O. Cremonesi – LP2005)

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

Goals of the next phases of the worldwide experimental program in neutrino oscillations beyond T2K, NOνA and reactors

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

- What are the mixing angles? Is θ_{13} large enough to search for CP violation?
- What are the orderings and splittings of the neutrino mass states?
- 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.

“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

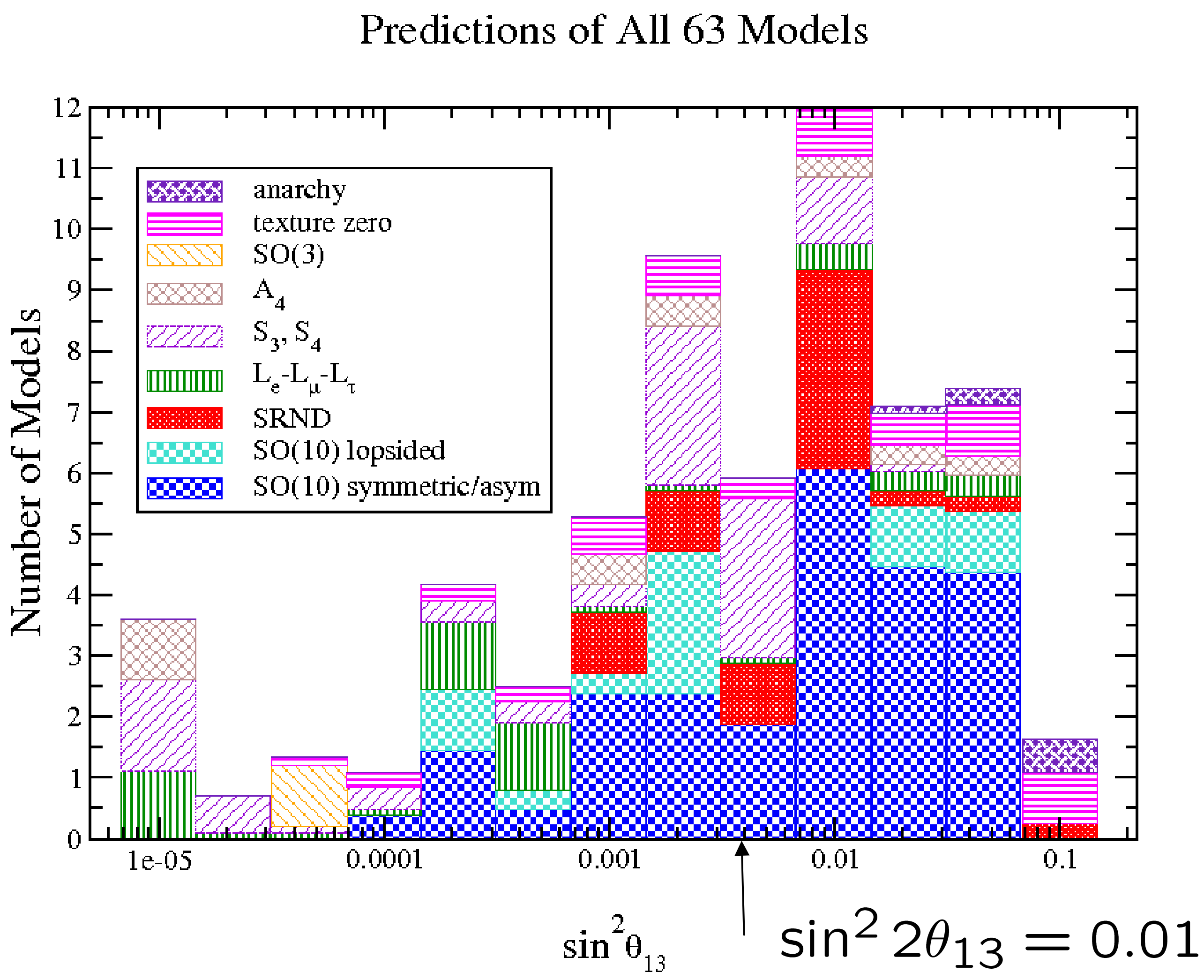
Accelerator experiments (with currently planned beam power)

- T2K: 3σ sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.01$ by 2014 (est.)
- NOvA: 3σ sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.005$ by 2016 (est.)
- 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 $\sin^2 2\theta_{13} \sim 0.01$

How large is θ_{13} ?



(C. Albright and M-C Chen, Phys. Rev. D74 (2006) 113006)

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

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

Where $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ is the small ($\sim$ 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

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

Solar

And:

$$\Delta = \Delta m^2_{31} L/4E_\nu$$

Kinematical oscillation phase

$$x = 2\sqrt{2} G_F N_e E_\nu / \Delta m^2_{31}$$

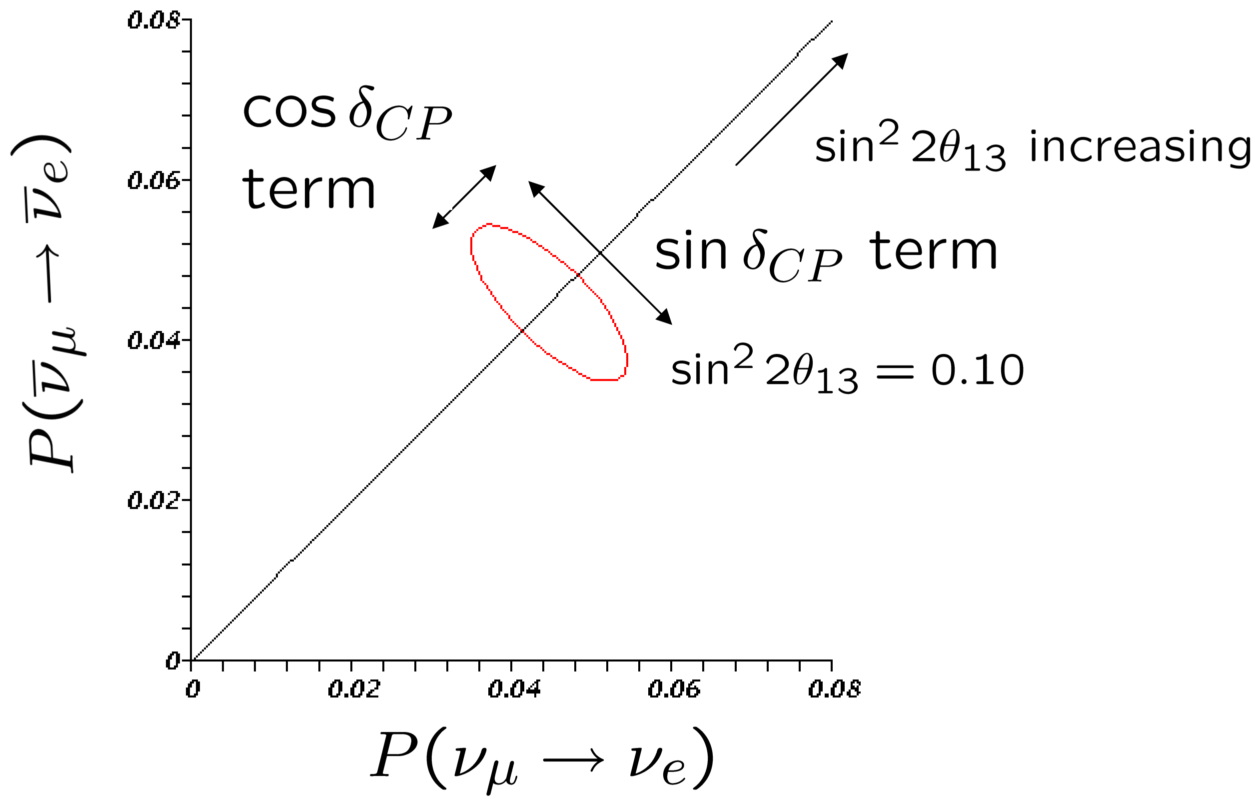
Matter effects: G_F = Fermi coupling

N_e=electron density

Bi-Probability Plot

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

CP violation – vacuum oscillations



Bi-Probability Plot

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

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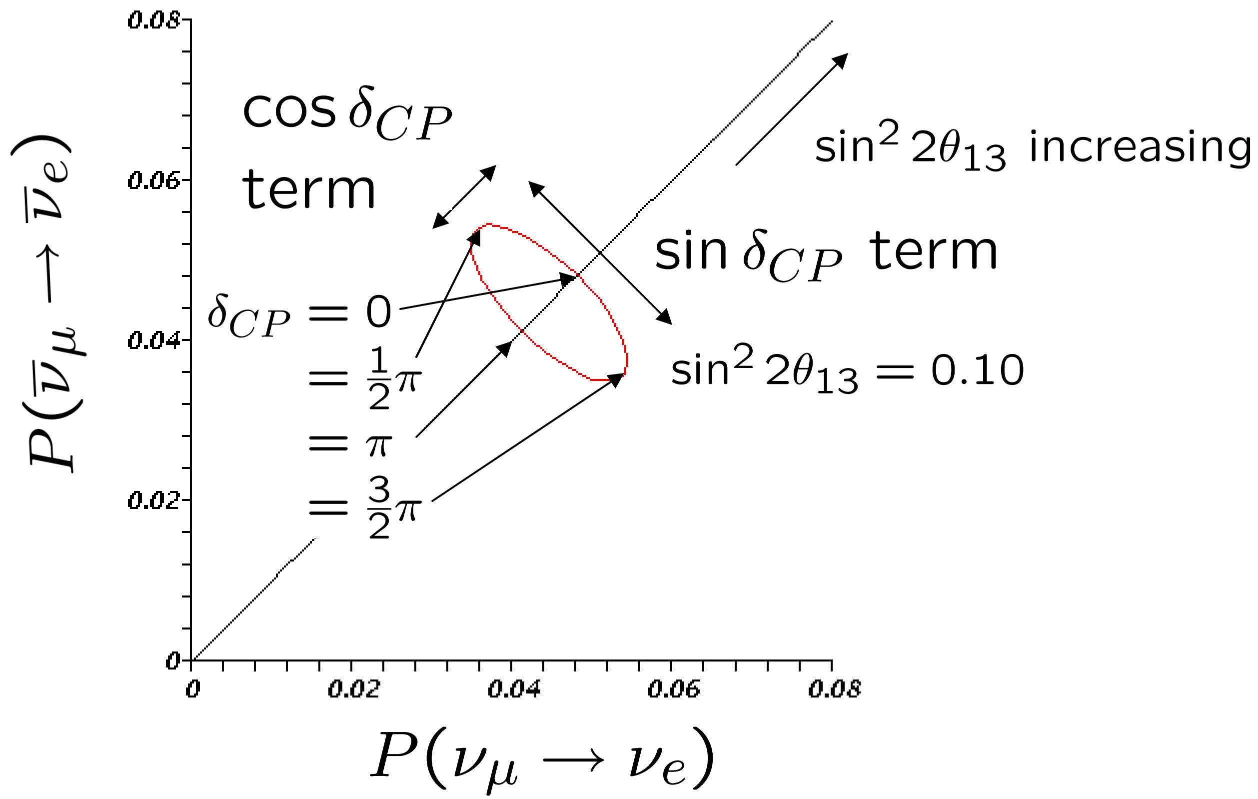

Bi-Probability Plot

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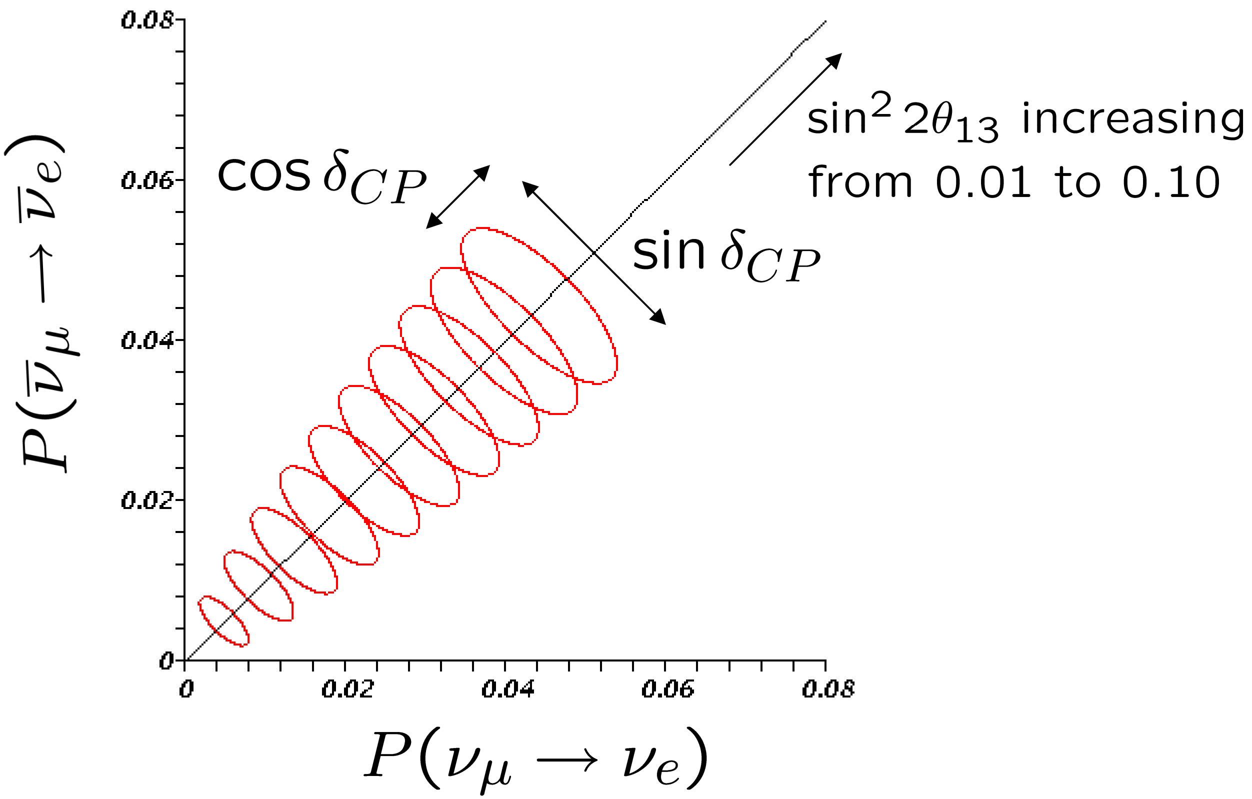
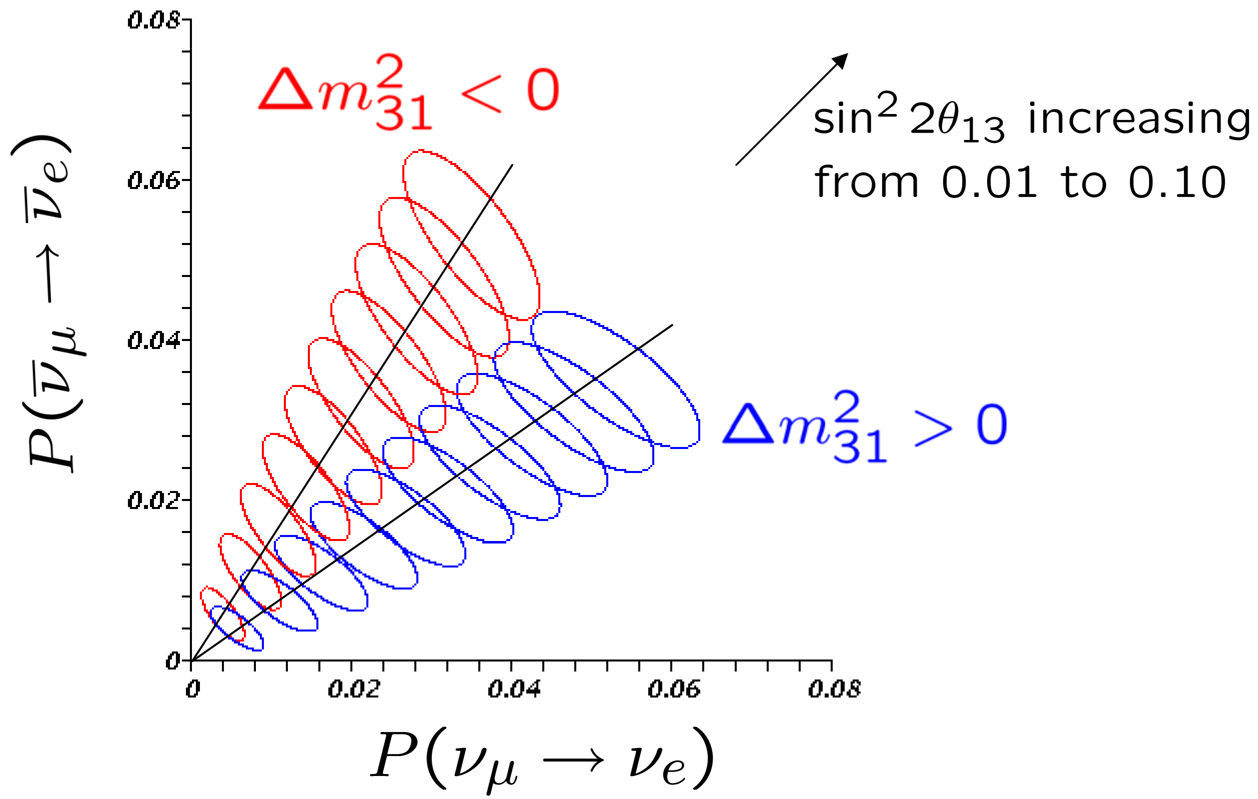


Bi-Probability Plot

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

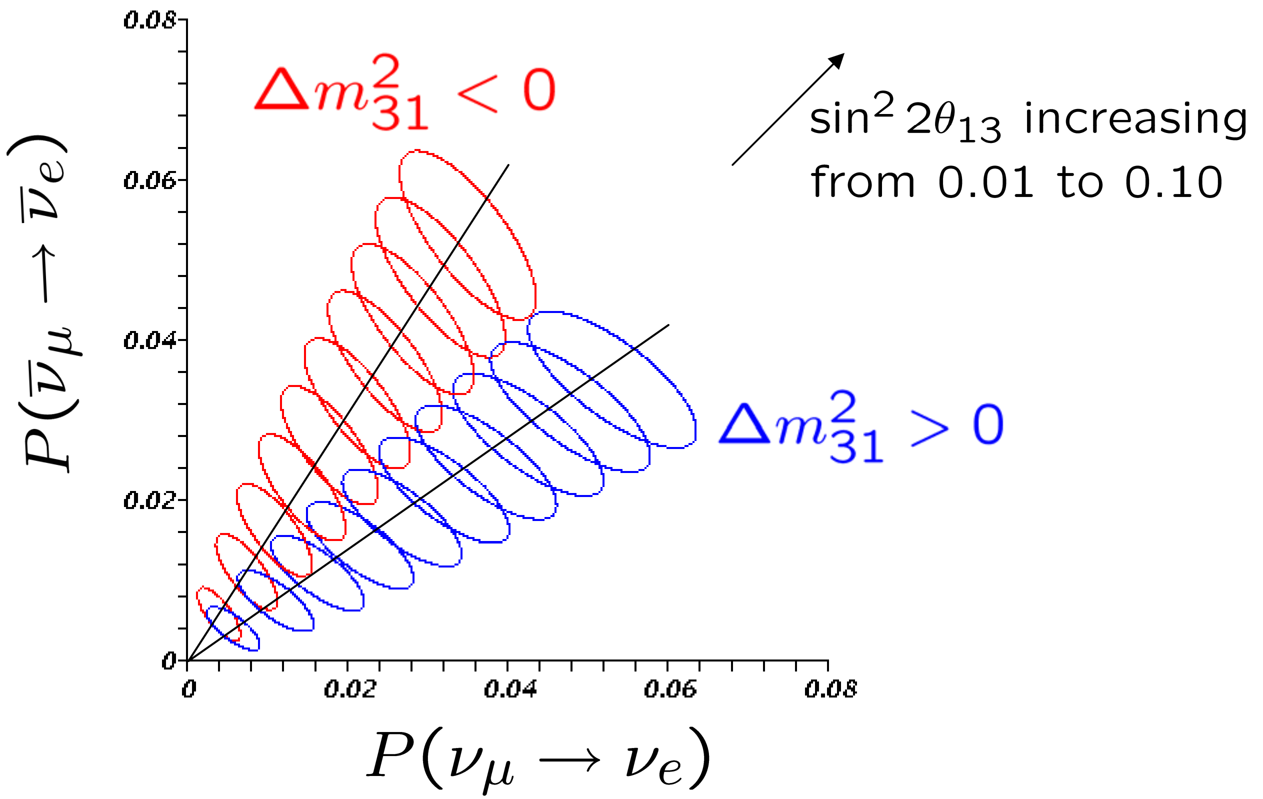
CP violation – matter oscillations



Bi-Probability Plot

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

CP violation – matter oscillations

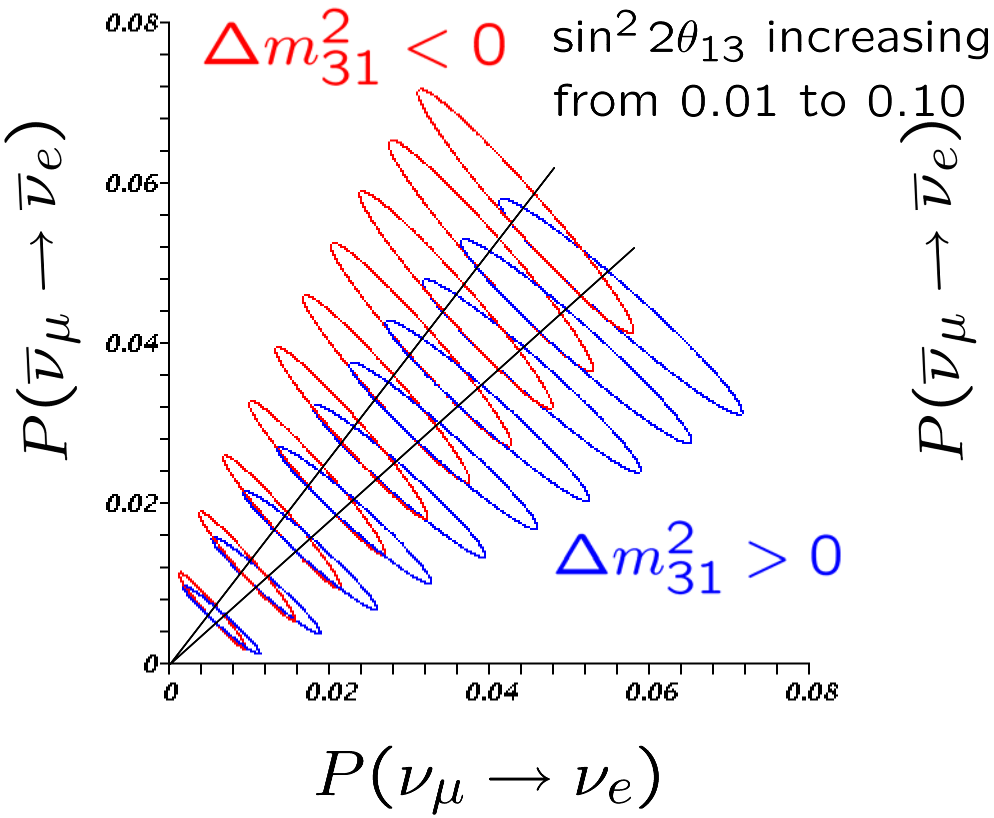


Get parameter degeneracies independent of measurement errors with mono-energetic beam model

Bi-Probability Plot

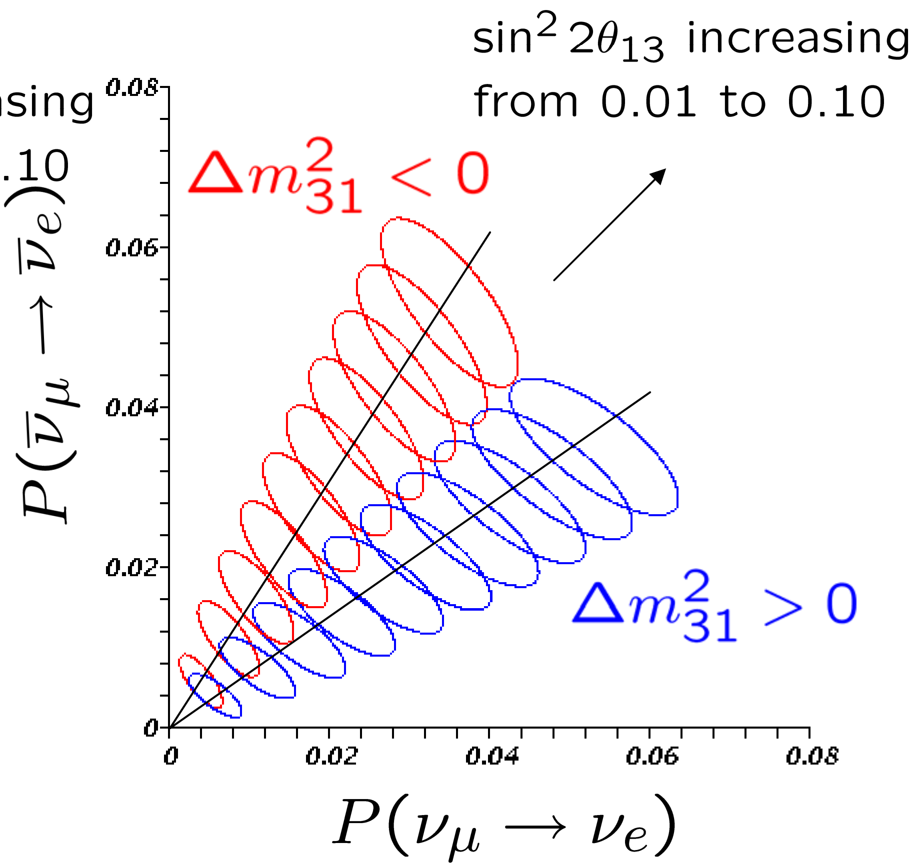
E_ν=0.6 GeV, L=295 km

T2K Parameters



E_ν=2.3 GeV, L=810 km

NOνA Parameters



For $\Delta m_{31}^2 < 0$ and δ_{CP} near $\pi/2$

Or $\Delta m_{31}^2 > 0$ and δ_{CP} near $3\pi/2$ - Solution may be unique

Breaking degeneracies

Reactor experiments measure the survival probability of $\overline{\nu}_e$

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \Delta - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_\odot$$

- Depends only mixing parameter
- No depedence on δ_{CP} or mass hierarchy

Solar term

Note for accelerator experiments:

Matter effects increase with larger energy

$$\sin^2 2\theta_{matter} \cong \sin^2 2\theta_{13} \left[1 \pm S \frac{E_\nu}{6\ GeV}\right]$$

± 1 for ν_μ, $(\overline{\nu}_\mu)$ beam

$S = \pm 1$ for $\Delta m^2_{31} > 0$ $(\Delta m^2_{31} < 0)$

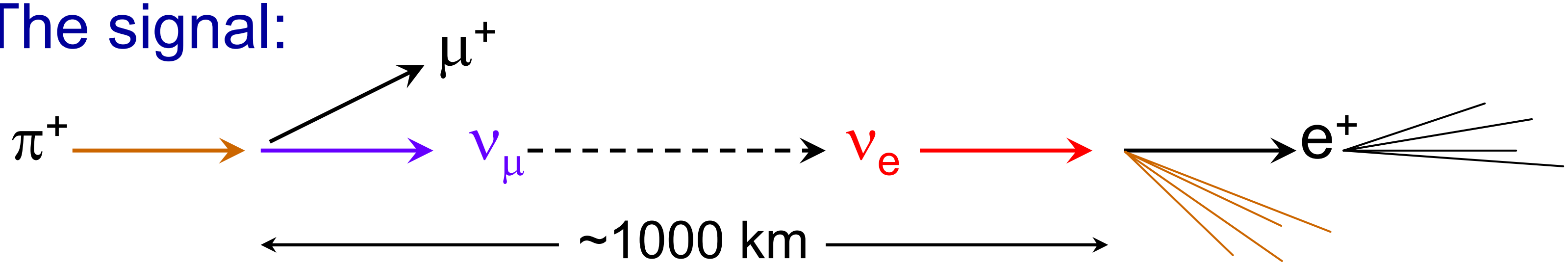
CP effects increase with smaller energy

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)} \cong \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta_{CP}$$

Using information from 2nd appearance maximum can help

Approaches to Appearance Experiments

The signal:



Acclerator beam produces mostly ν_μ with small contamination of ν_e

The signal is neutrino reactions producing electrons in a distant detector

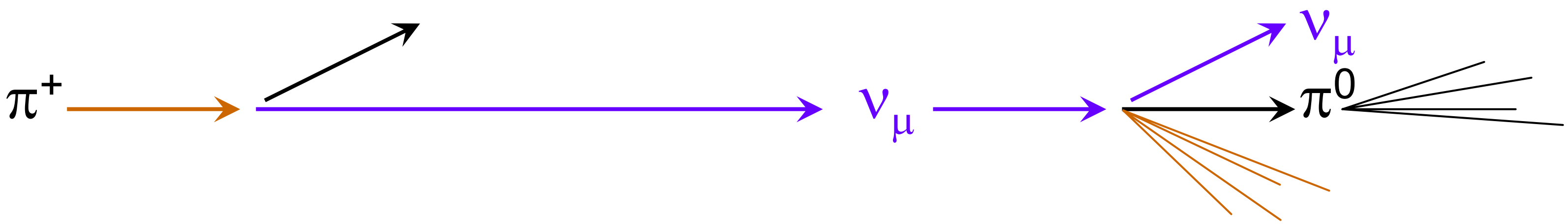
There are two principal backgrounds:

1. π^0 interactions from neutral current interactions of ν_μ where the two γ -rays are not distinguished from a single electron.

2. Intrinsic ν_e in the beam from the accelerator. This background is irreducible.

Backgrounds are measured in near detector to reduce systematic error.

Backgrounds



Background 1: Reject through electron detection mechanism

Water Cherenkov detectors (ala Super-Kamiokande) – select only quasi-elastic events, reconstruct neutrino energy and direction (within Fermi momentum uncertainty) from electron energy and direction.

Segmented liquid scintillator detectors (ala NOνA) – similar strategy, but scintillator permits detection of recoil nucleons and other sub-Cherenkov threshold particles. (No proponents)

Liquid argon time-projection chamber – excellent spatial resolution distinguishes π^0 from electron. Allows use of most ν_e charged current channels giving $\sim$3 times higher detection efficiency per unit mass.

Will return to suppressing π^0 production later.

Backgrounds

Background 2: Irreducible background from beam ν_e

K mesons (and muons) decay to ν_e at accelerator source. This background limits $\sin^2 2\theta_{13}$ to $\sim$ 0.005 for discovery and $\sim$ 0.01 for CP and mass hierarchy study.

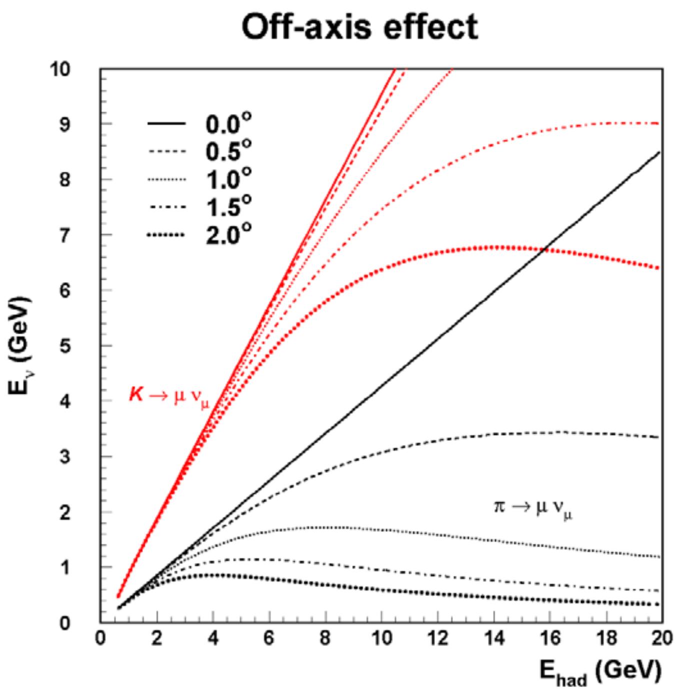
This background does not occur for the β – beam and neutrino factory beam technologies that are under development, especially in Europe.

Experimental Approaches

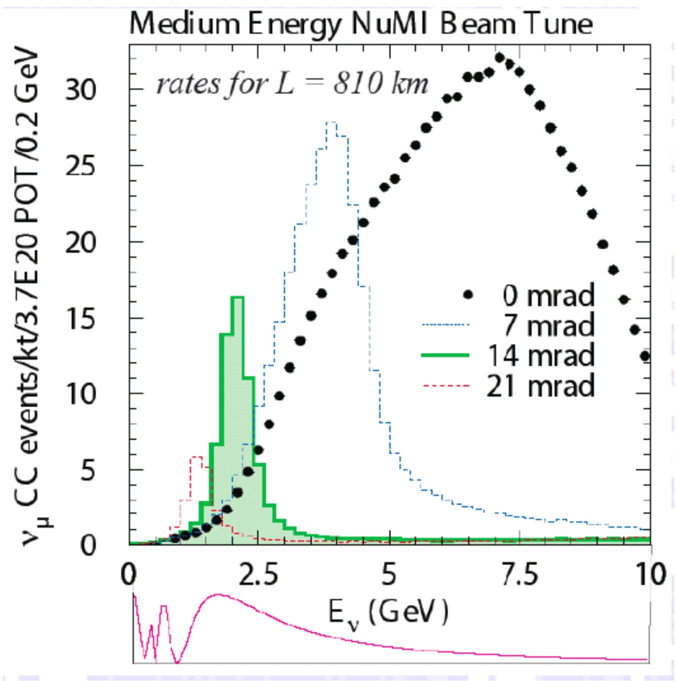
T2K and NOνA use an "off-axis" beam to obtain a narrow band of E_ν

Off-Axis: Match maximum flux to appearance maximum

WBB: Cover multiple nodes – use different L/E of nodes



(B. Viren)



(G. Feldman)

Experimental Approaches

The off-axis beam approach

- Is the experimental realization of the simple model of appearance experiments shown in bi-probability plots.
- Suppresses π^0s by reducing high energy neutrino flux
- Uses upgraded NUMI beam

The wide-band beam approach

- Uses a spectrum of energies to lift degeneracies
- Maximize flux for long baselines
- Uses longer baselines to enhance the matter effect

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 – on or near surface
- Use existing/upgraded NuMI beam
- Deploy all at NOvA site, or split with "2nd max", or other

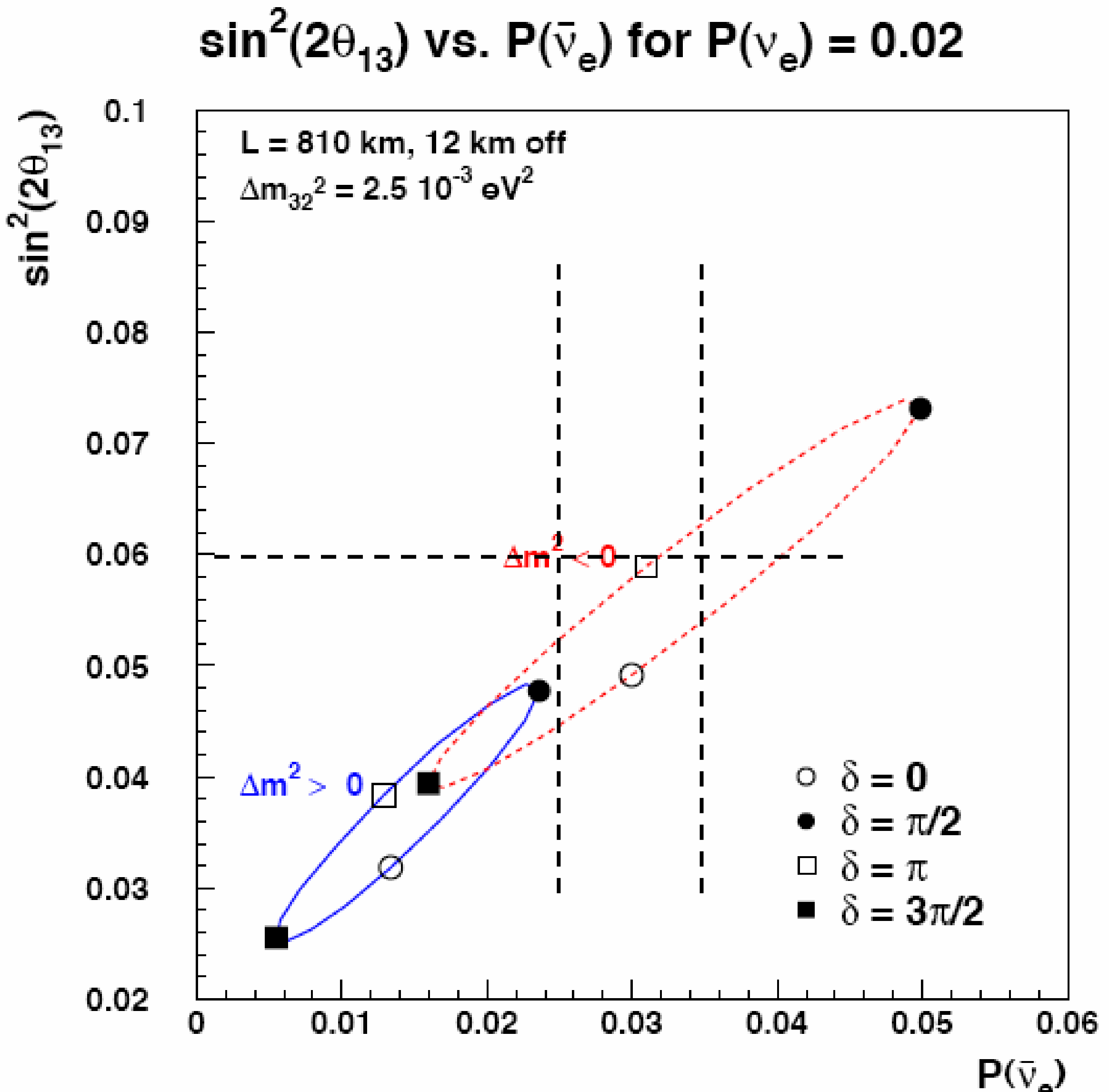
Wide-band beam, very long baseline
- ~300-500 kt of water Cherenkov (or ~100 kt LArTPC)
- In DUSEL
- New neutrino beam

Some Contourology – Off-Axis

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

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

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



(G.Feldman – NOνA)

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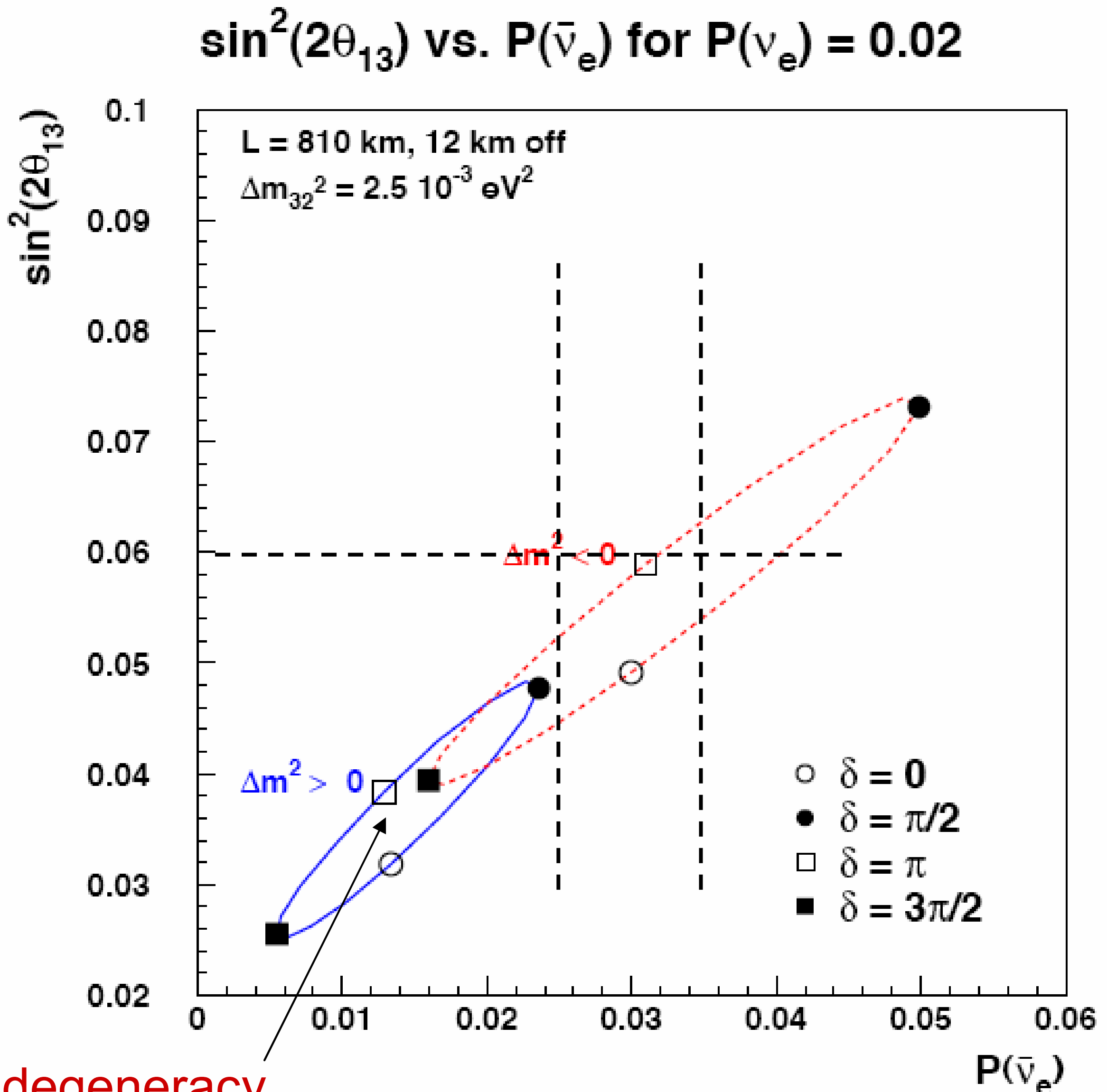


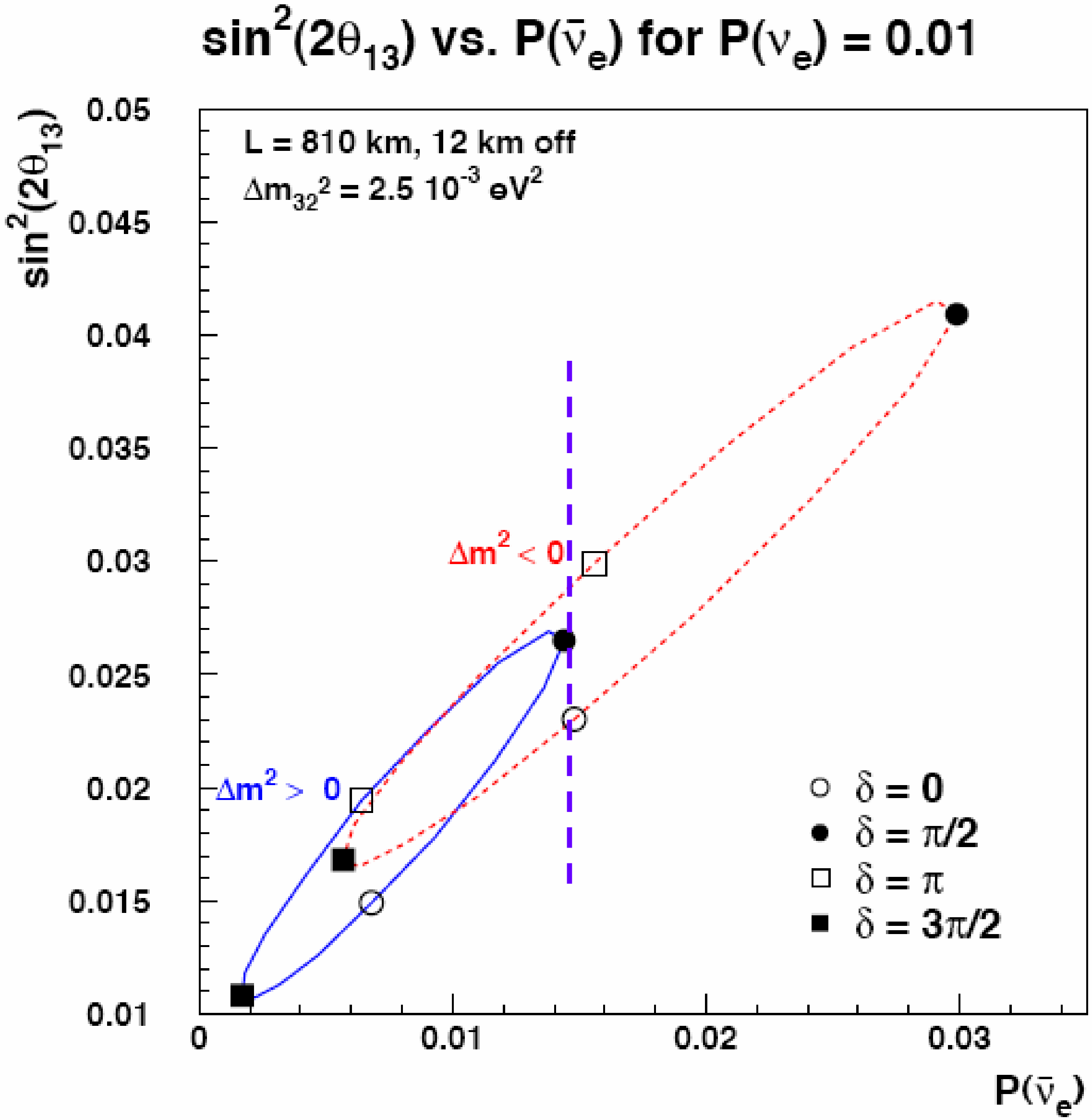
But – unbroken degeneracy

(G.Feldman – NOνA)

Some Contourology – Off Axis

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

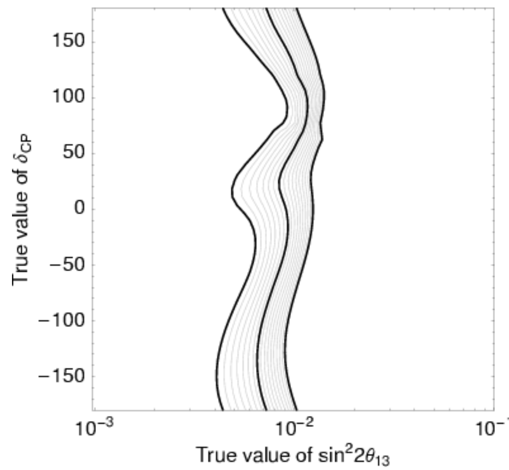


More contourology – Wide-band Beam

28 GeV protons, 5 yrs ν at 1 MW, 5 yrs $\overline{\nu}$ at 2 MW, 300 kton detector

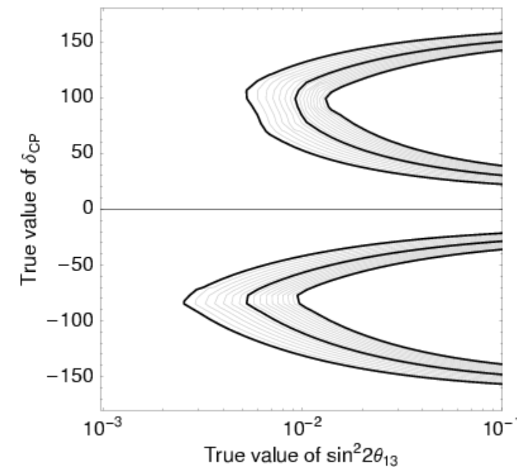
Discovery for normal mass Hierarchy 1300 km

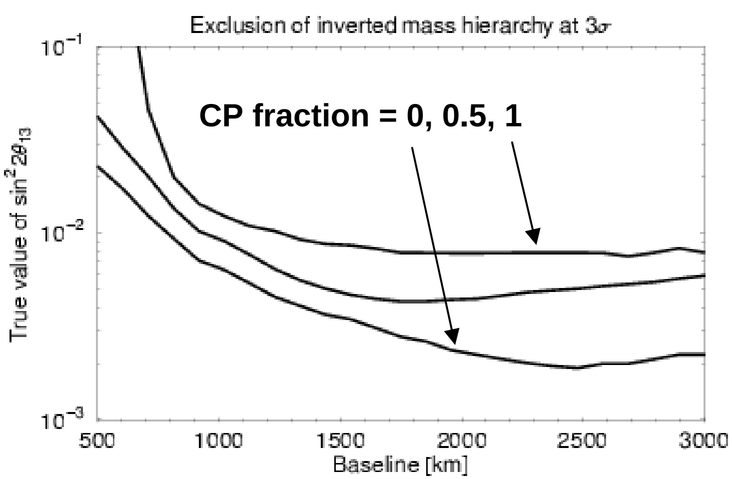
3, 4, 5 σ

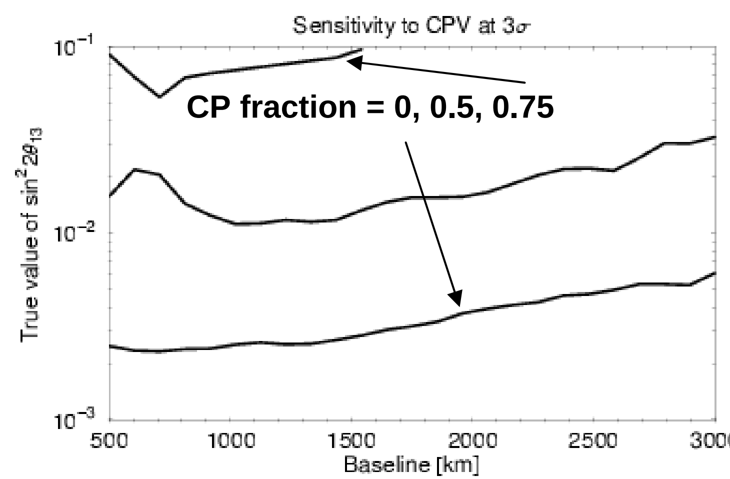


Discovery for CP Violation 1300 km

3, 4, 5 σ

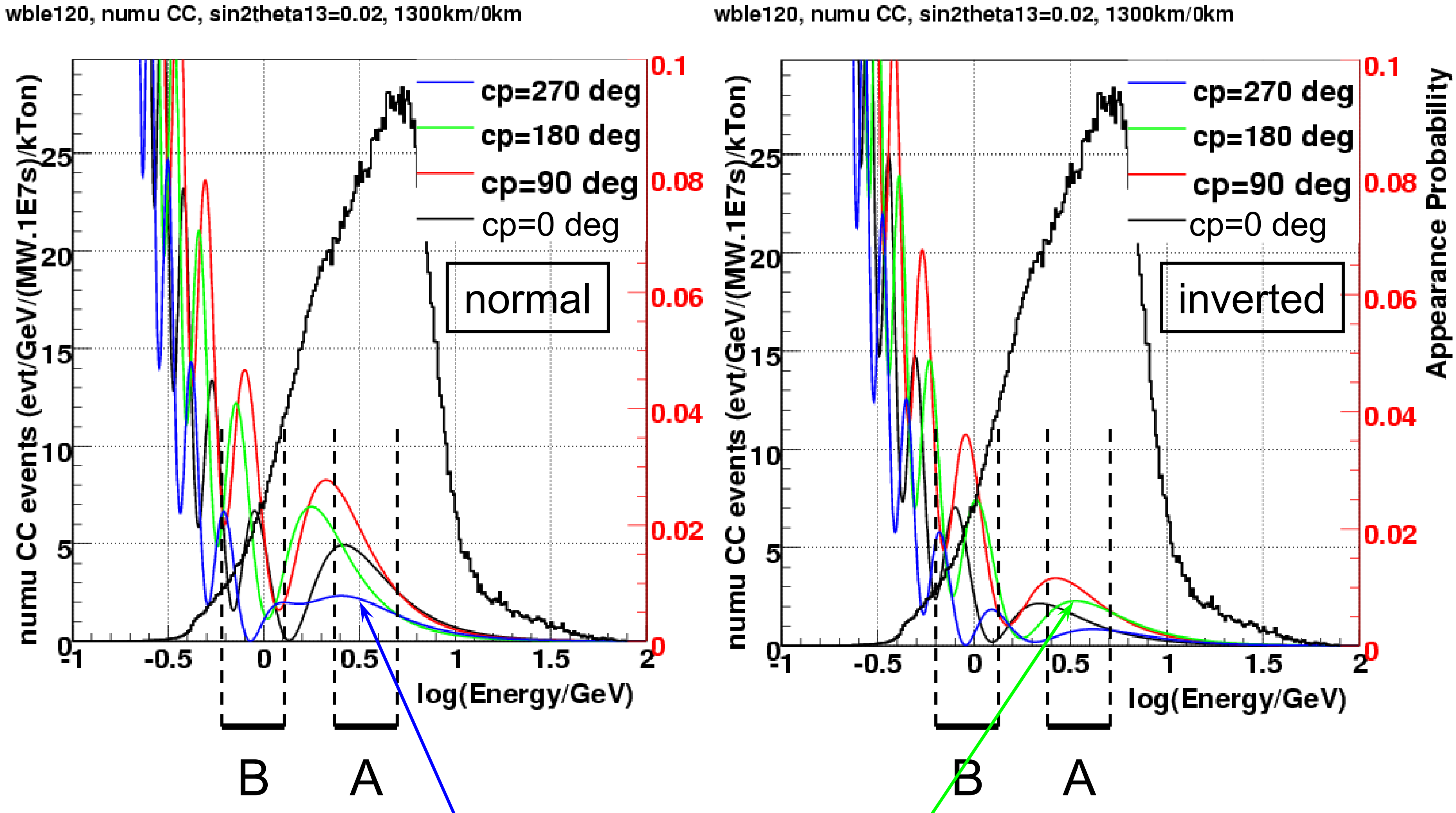






(V. Barger, et al.,PRD 74, 073004 (2006)

120 GeV Protons, ν only, WBB



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

In band B: node ≠ peak

Degeneracy broken

Summary for neutrino oscillation physics

Off-axis approach:

- Narrow band neutrino beam
- Suppression of high energy neutrinos reduces π^0 background
- Irreducible background from high energy K meson decay
- May require second off-axis detector at 2nd appearance maximum for resolution of parameter degeneracies

Wide-band beam approach

- The π^0 rejection looks OK at 60 GeV, waiting for 120 GeV
- Longer baseline gives larger matter effects

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 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)

Detector technologies

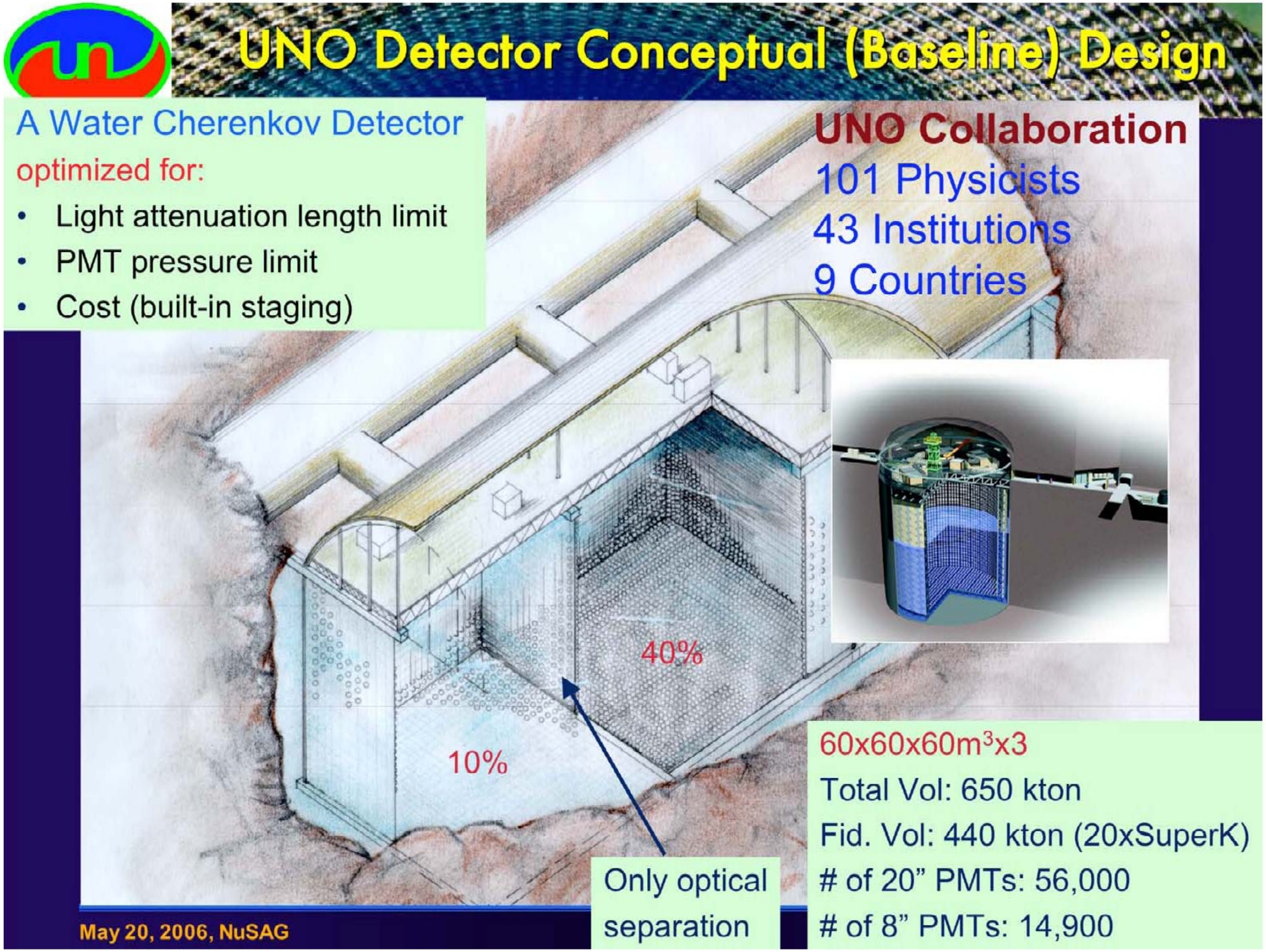
Water Cherenkov

- Known, successful technology for ν osc and p decay
- Large – 300 kton fiducial volume
- Must be underground to avoid cosmic rays: DUSEL
- PMT's drive cost and construction time
- R&D for new light sensors
- More PMTs needed for proton decay,

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
- Can it work at surface? – proof needed
- $p \rightarrow K^+\nu$, a possibly favored proton decay mode

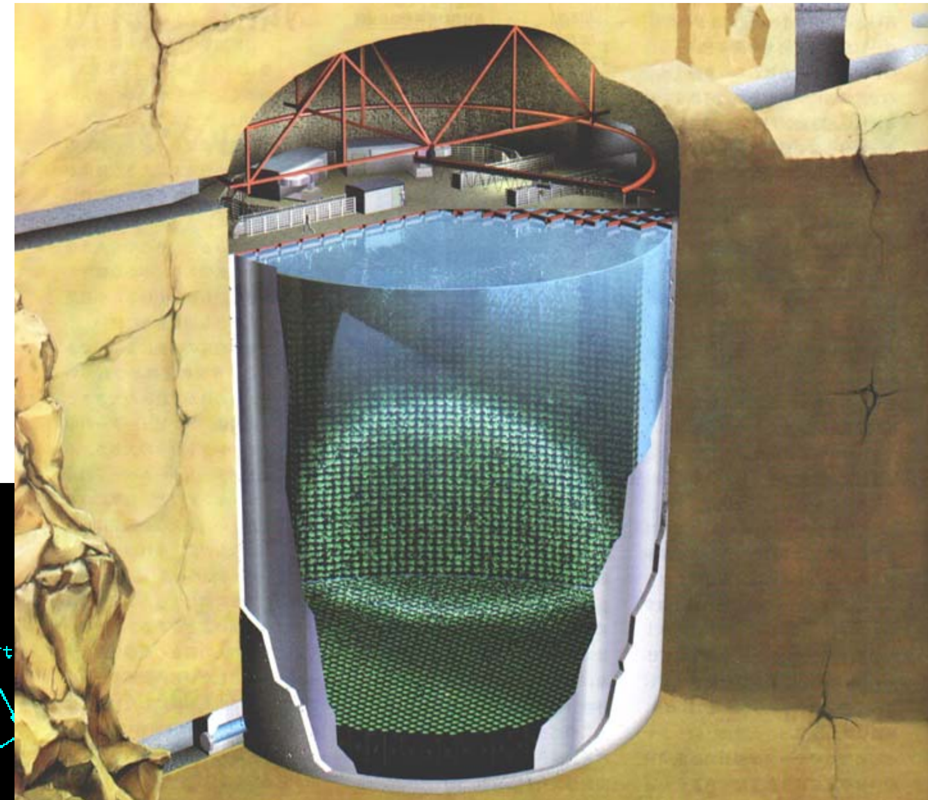
Monolithic Water Cherenkov Detector

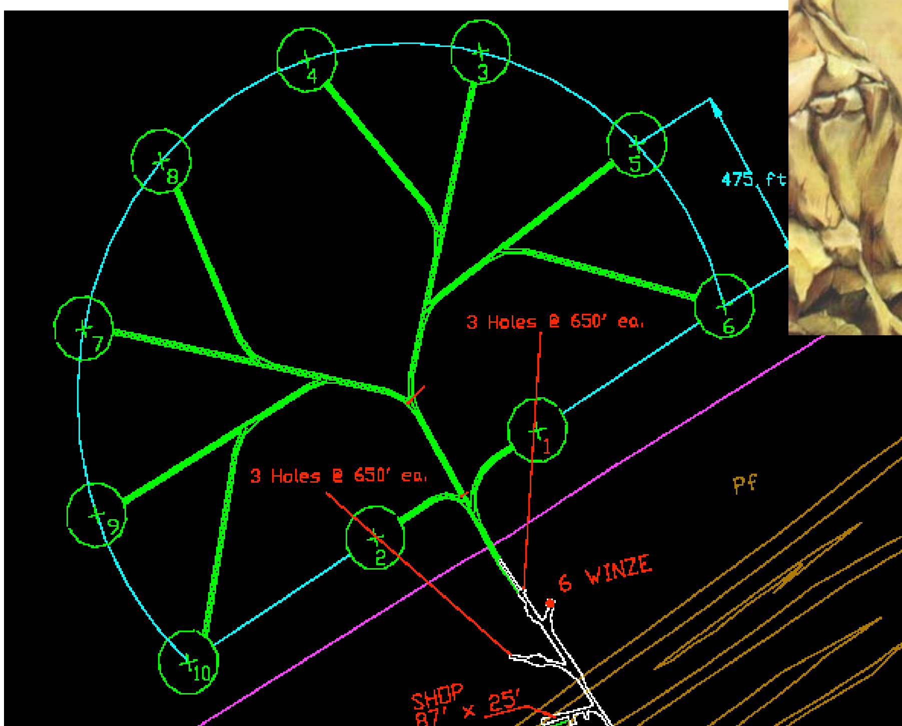


(C.-K. Jung)

Modular Water Cherenkov Detector

Build ten 100 kton detector modules – each looks like a scaled up Super-Kamiokande, probably with fewer PMTs.

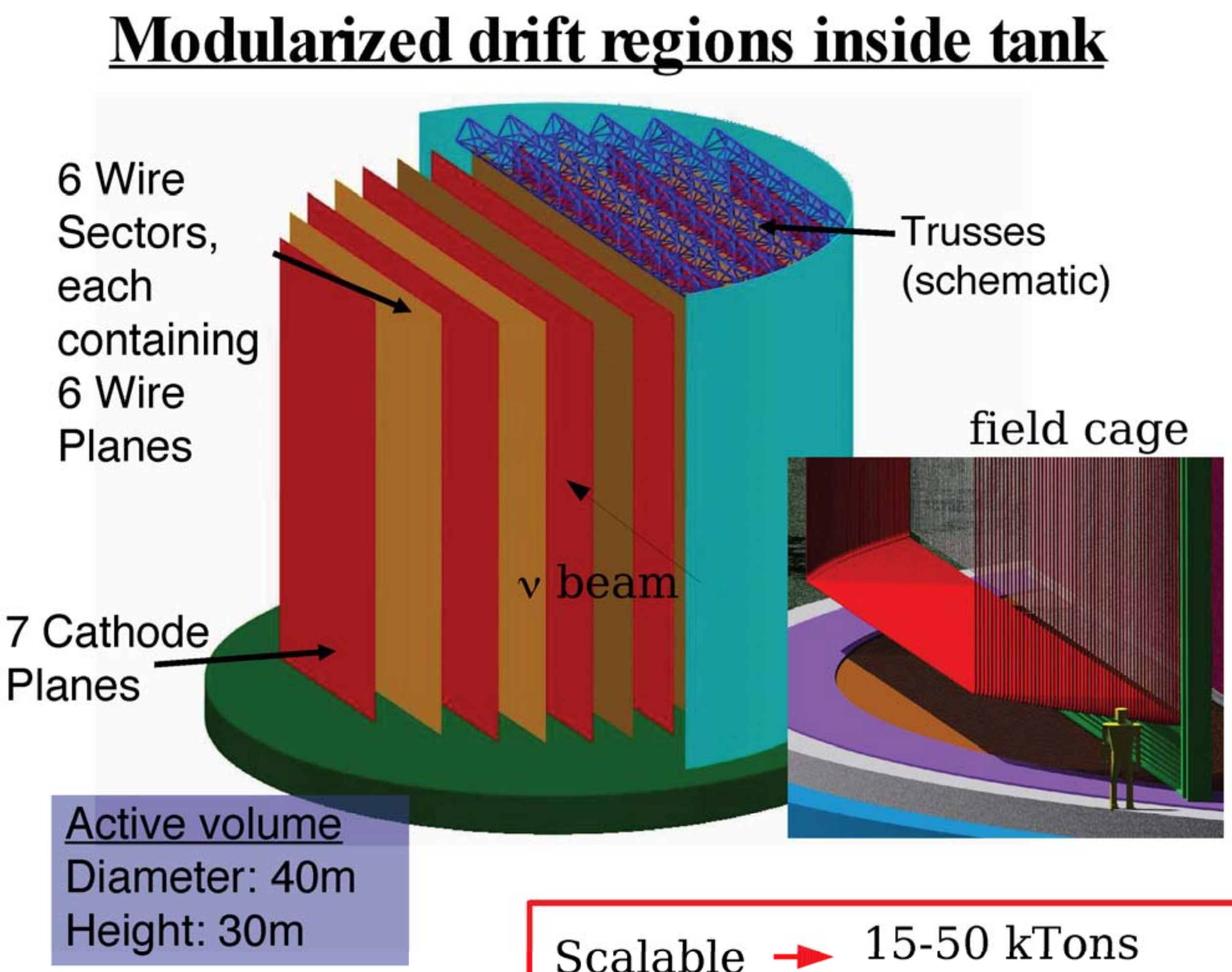




NuSAG presentation proposes starting with three modules.

Liquid Argon Detector

What is time scale for R&D, construction?



(B. Flemming)

Scalable → 15-50 kTons
4 - 6 wire planes

Off-axis

Pro:

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

Con:

- Must deal with ambiguities of ~single energy
- 2nd-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-Cherenkov

Current status and NuSAG plans

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