Report of the LBNE Reconfiguration Physics Working Group

Mel Shochet for

J. Appel, M. Bass, M. Bishai, S. Brice, E. Blucher, D. Cherdack, M. Diwan, B. Fleming, G. Gilchriese, Z. Isvan, B. Lundberg, W. Marciano, M. Messier, S. Parke, J. Reichanadter, G. Rameika, K. Scholberg, M. Shochet, J. Thomas, R. Wilson, E. Worcester, C. Young, G. Zeller

Outline

- **Physics issues**
- **Beams**
- **Detector**
- **Mass hierarchy and CP phase angle sensitivity**
- **Other beam-neutrino physics**
- **Proton decay, atmospheric neutrinos, supernova ν bursts**
- **Outstanding issues**
- **Summary**

Physics Case

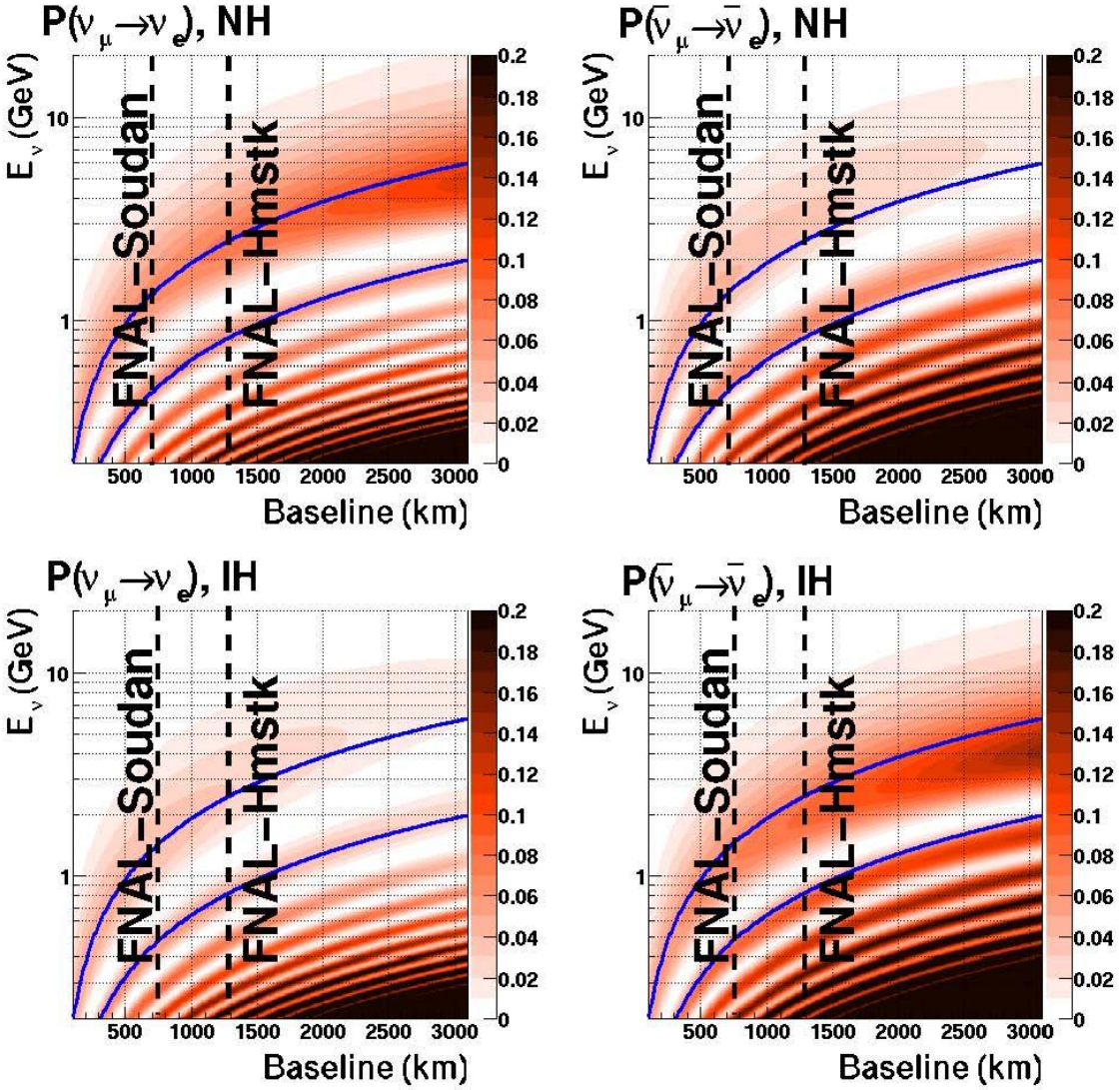
The P5 panel in 2008 had as a central pillar of the future US HEP program a long-baseline neutrino program driven by a high-intensity beam from Fermilab because it would address a number of important physics questions.

- **Is there CP violation in the neutrino sector?**
- **What is the ordering of the neutrino states?**
- **Is the proton stable?**
- **What physics & astrophysics can we learn from the neutrinos emitted in supernova explosions?**

Long-Baseline Neutrino Physics

- **Unitary 3-flavor neutrino mixing framework:**
  - **3 mixing angles: θ_{12}, θ_{23}, θ_{13}**
  - **CP-violating phase: δ (+ Majorana phases)**
  - **Mass eigenstate mass differences: Δm^2_{21} and Δm^2_{32}**
- **For CP violation to be manifest through the mixing matrix, all three mixing angles must be non-zero.**
  - **Until recently, it wasn't known whether θ_{13} is non-zero.**
  - **It is now measured to be 9° to better than ±1°.**
  - **This is large (c.f. 13°, 2°, and 0.2° for the quark matrix)**
  - **It opens the possibility to**
    - **determine the mass hierarchy (Δm^2_{32} positive or negative)**
    - **measure the CP-violating phase**
    - **test the 3-flavor framework**

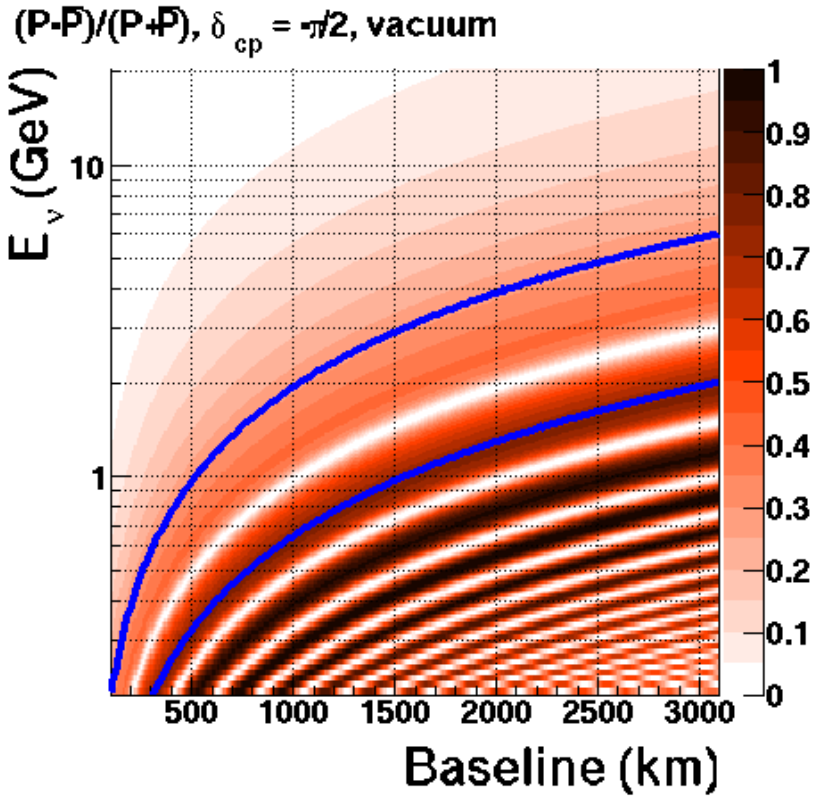
ν_e Appearance : Normal/Inverted Hierarchy, δ=0



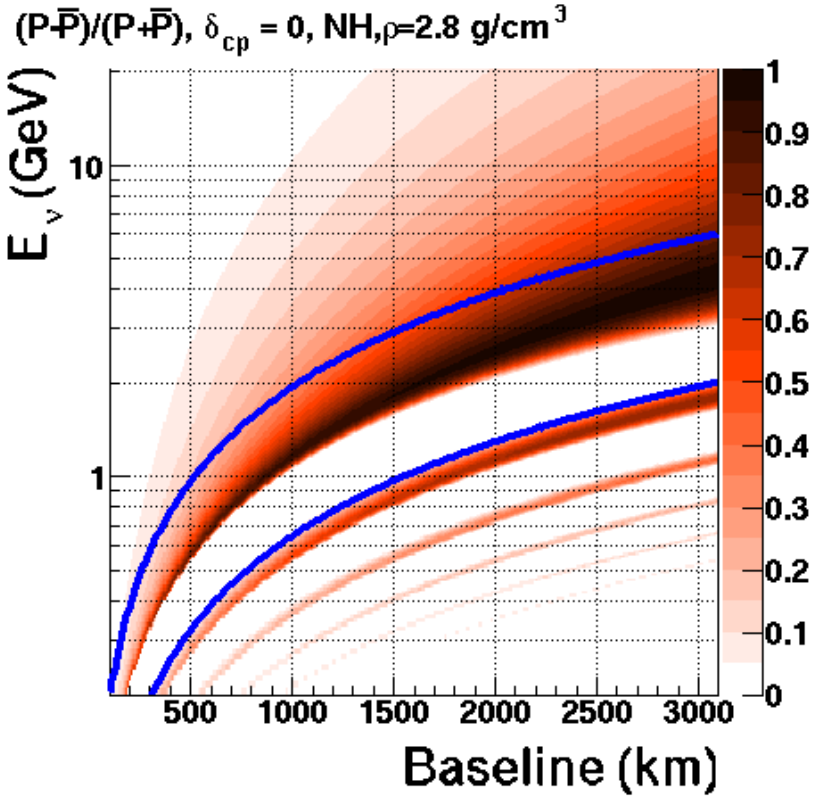
- **The blue lines: 1st & 2nd maxima in vacuum**

CP Asymmetry

$$A_{CP} = \frac{P\left(\nu_\mu \to \nu_e\right) - \bar{P}\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)}{P\left(\nu_\mu \to \nu_e\right) + \bar{P}\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)}$$



CP violation, no matter

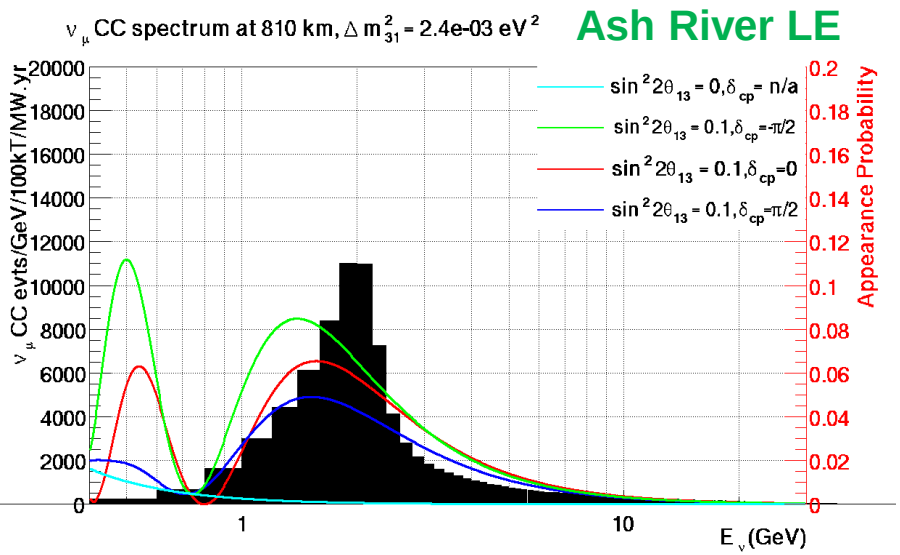


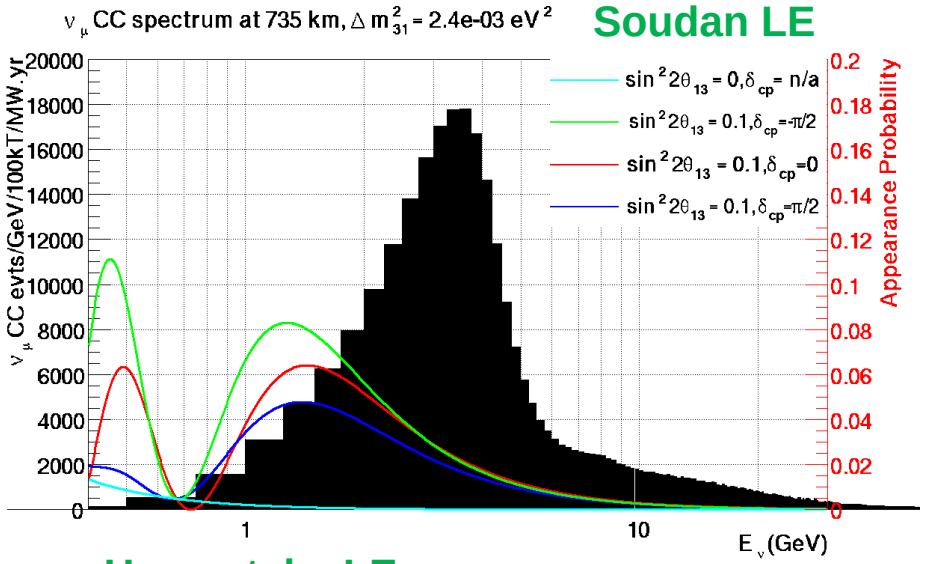
Matter, no CP violation

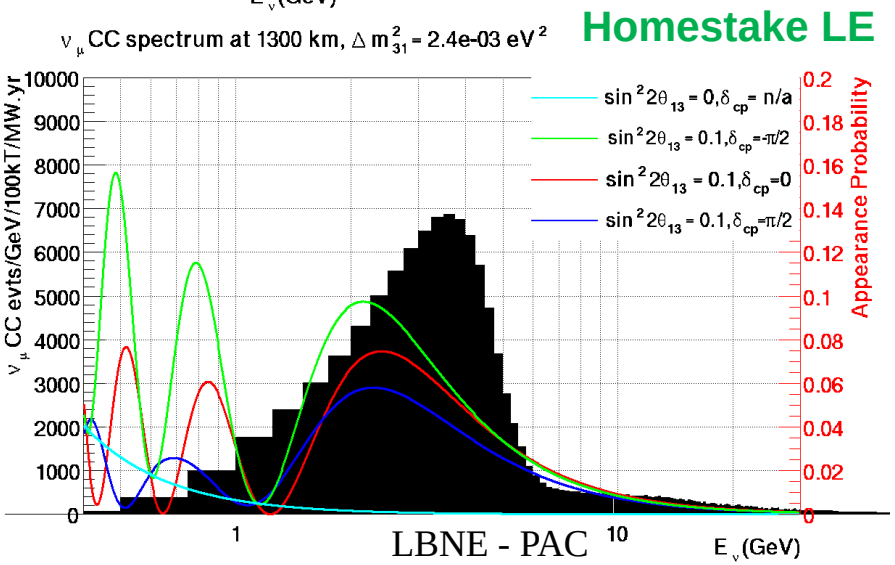
The Neutrino Beams

- **On-axis low energy (LE) beam to Homestake.**
- **On-axis low energy beam to Soudan.**
- **Off-axis low energy beam to Ash River.**
- **Off-axis medium energy (ME) beam to Ash River.**
- **In all cases:**
  - **120 GeV proton beam**
  - **700 kW**
  - **6×10^{20} protons on target per year**

- **Unoscillated ν_μ charged-current spectra with ν_e appearance probability curves.**





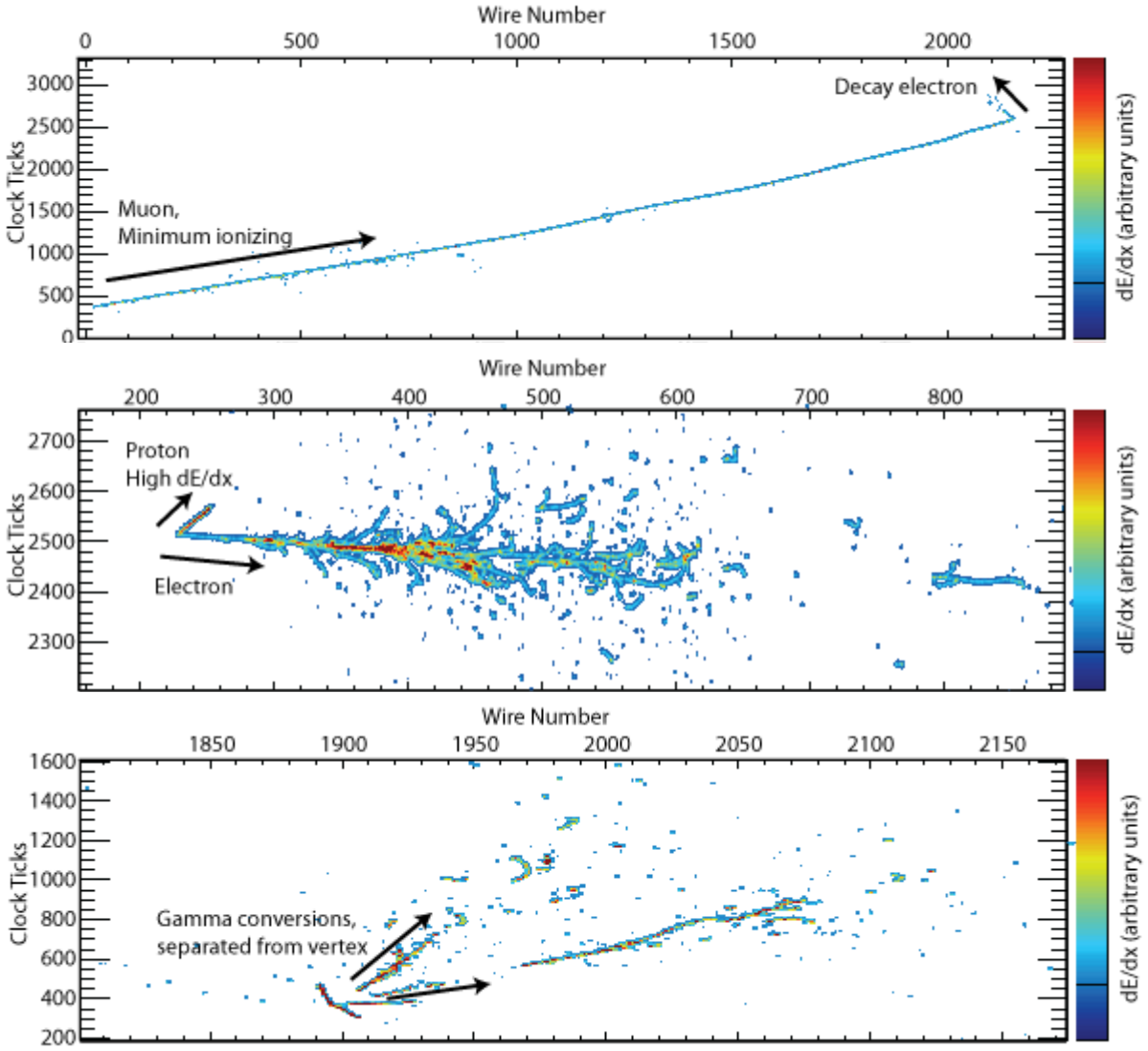


Liquid Argon TPC

ν_μ CC event w/ μ decay

ν_e QE event

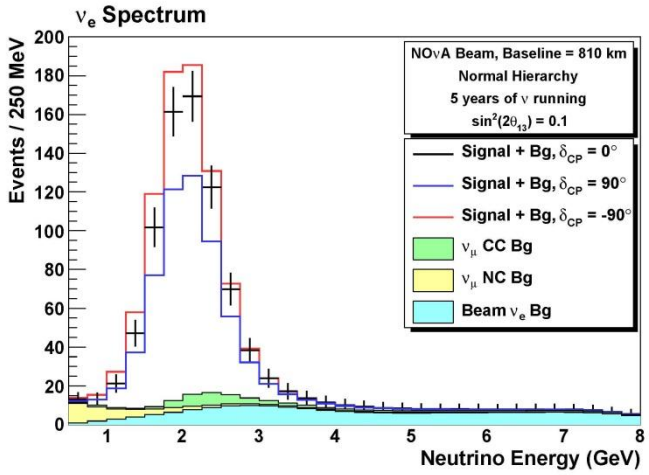
NC event w/ $\pi^0 \rightarrow \gamma\gamma$

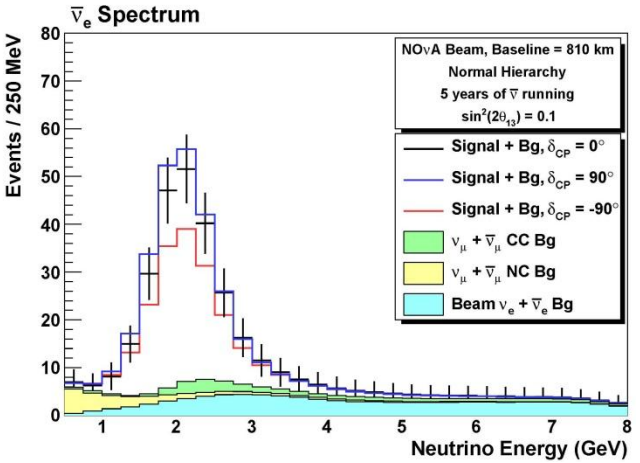


- **Exquisite event reconstruction! (3D reconstruction)**

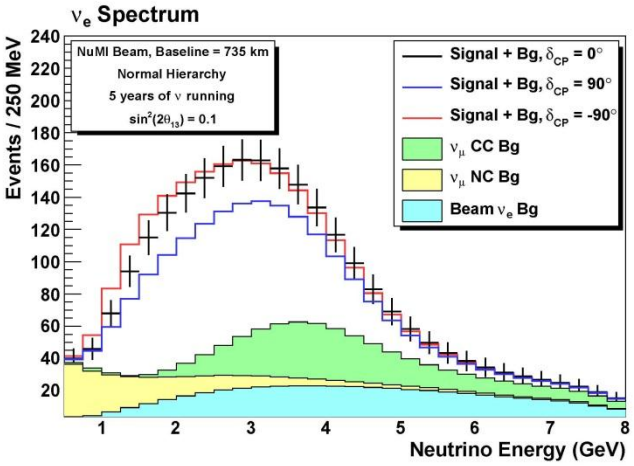
Expected ν_e appearance spectra

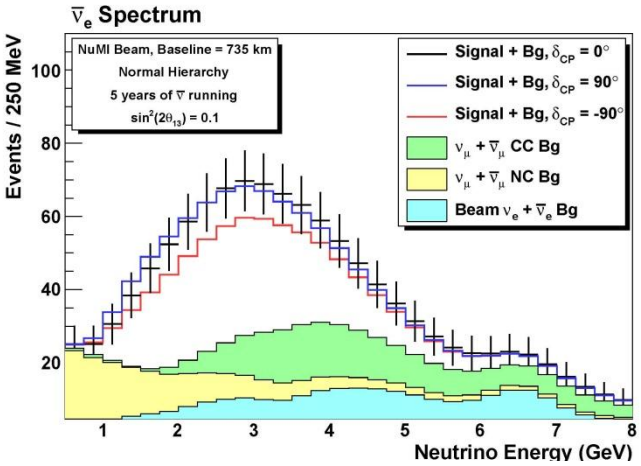
- **34 kT LAr detector**
- **Detection efficiencies and misidentification rates come from GEANT 4 simulation visual scans and ICARUS detector performance.**
- **5 years each of neutrino and antineutrino running**
- **normal mass ordering**



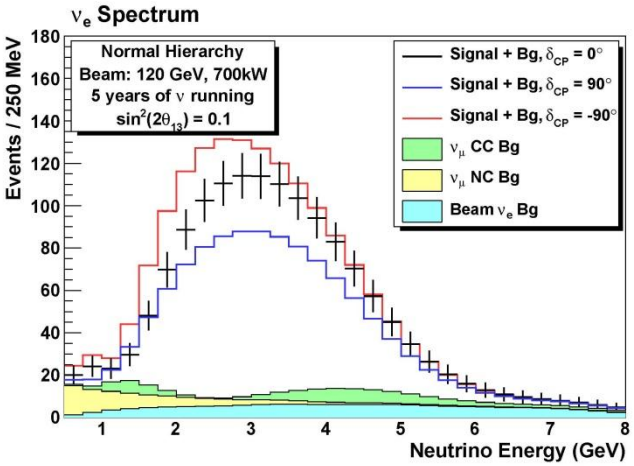


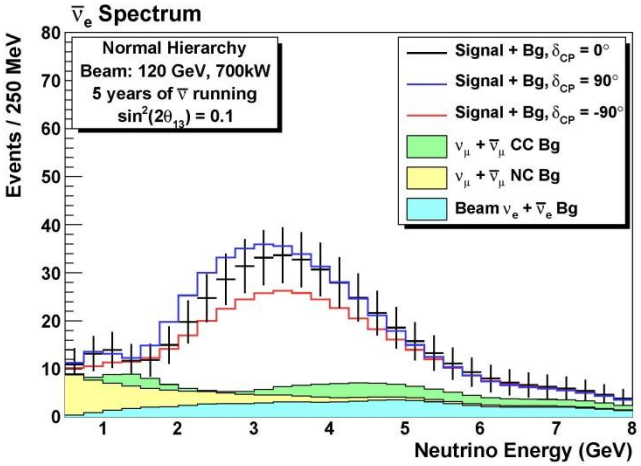
Ash River





Soudan

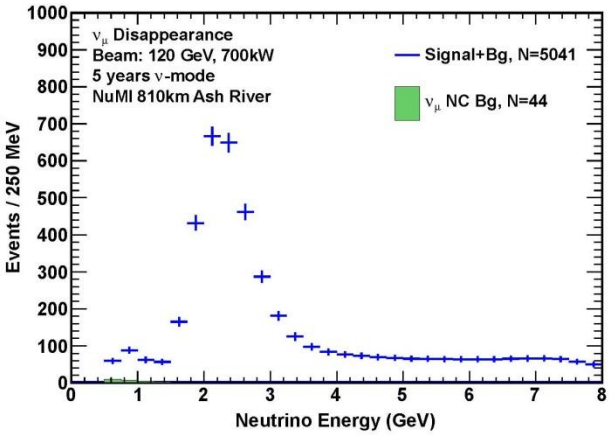




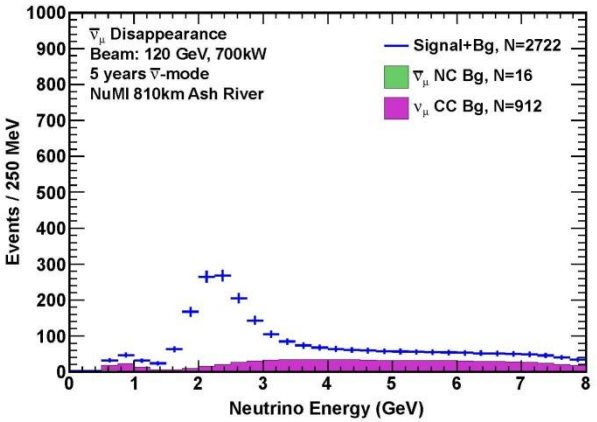
Homestake

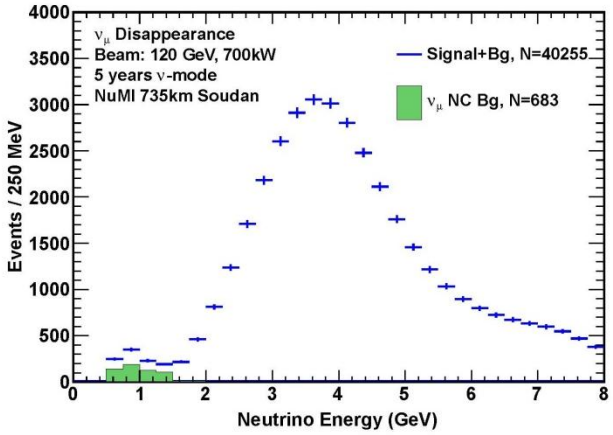
Expected ν_μ disappearance spectra

- **34 kT LAr detector**
- **5 years each of neutrino and antineutrino running**

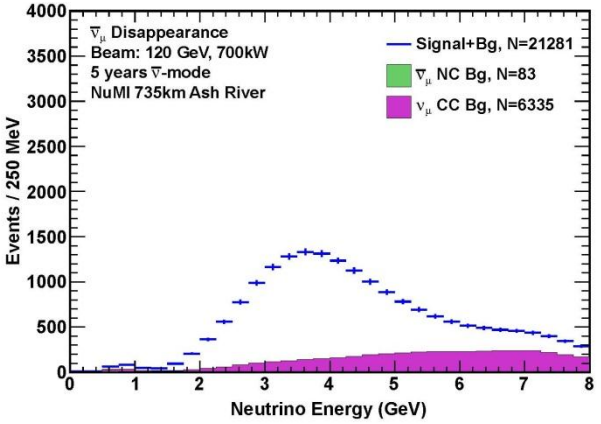


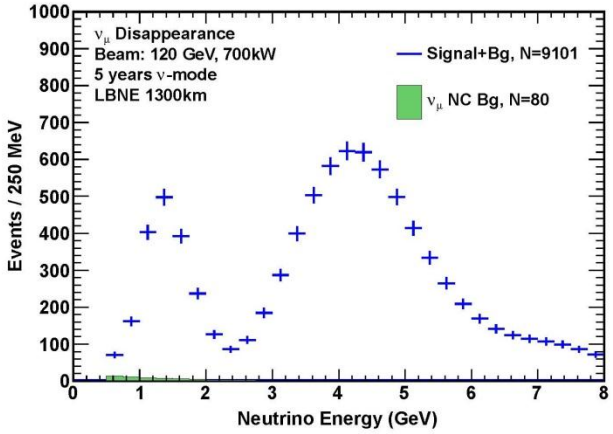
Ash River



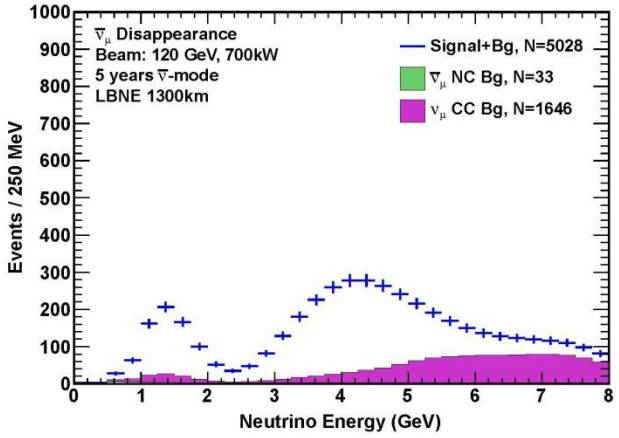


Soudan





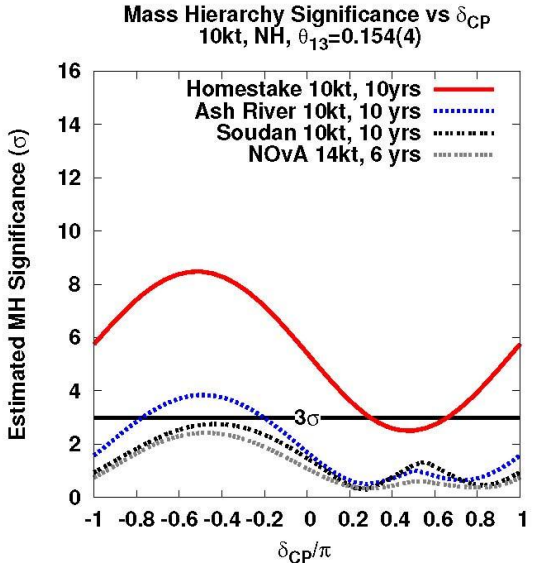
Homestake

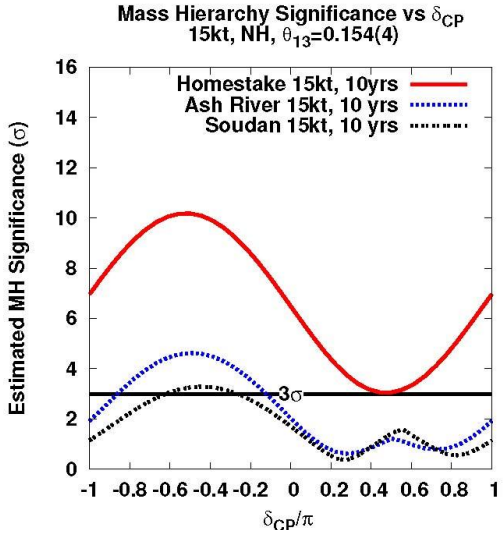


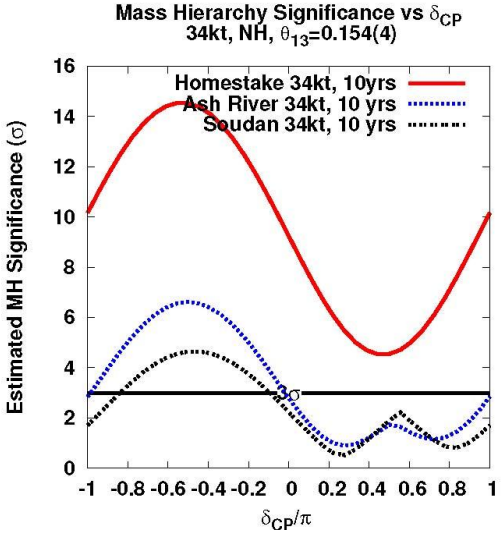
Mass Hierarchy and CP Violation Reach

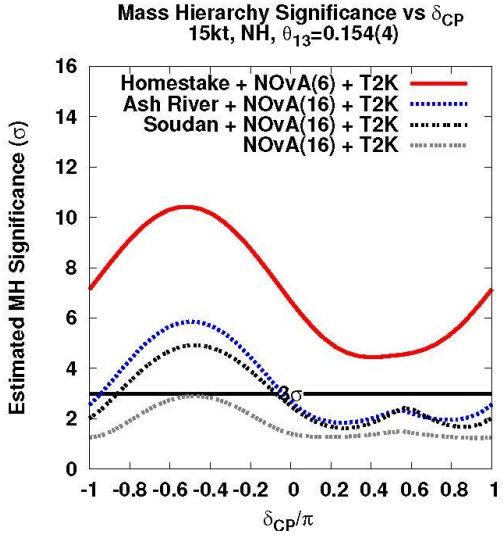
- **Estimate with GLoBES the significance to exclude the opposite mass hierarchy; the significance to exclude $\delta_{CP} = 0$ or π.**
  - **Generate an appearance spectrum for a given δ_{CP} & hierarchy.**
  - **Perform a χ^2 minimization to a given hypothesis. Take $\sigma = \sqrt{\chi^2}$.**
  - **Gaussian constraints to the other mixing parameters (including their correlations) are included.**
  - **The θ_{13} uncertainty at the end of LBNE data taking is taken to be current Daya Bay systematic uncertainty.**
  - **Include a disappearance spectrum to further constrain the mixing parameters.**
  - **Hierarchy reach: minimize over all values of δ_{CP}.**
  - **CP reach: include both hierarchies in the minimization.**

Mass Hierarchy Reach



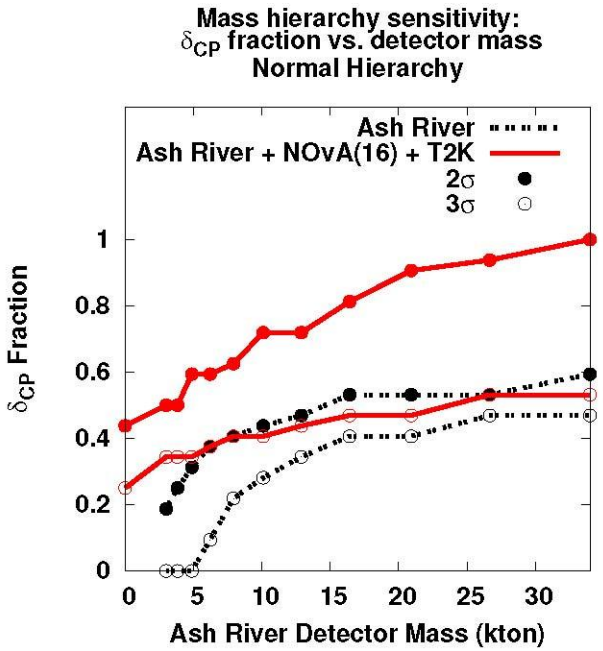


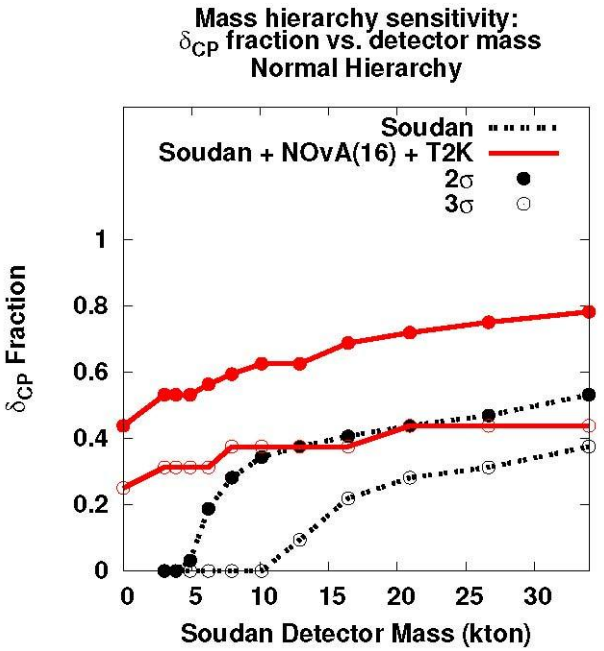


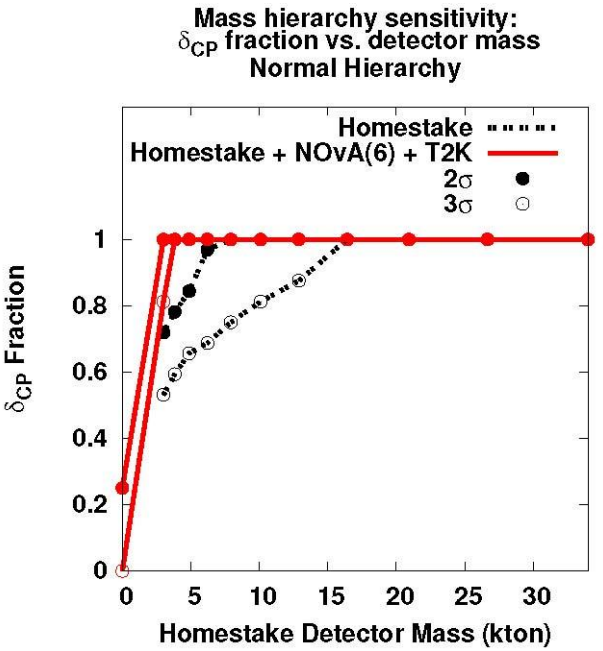


- **Adding NOvA & T2K data helps, especially at short baselines.**

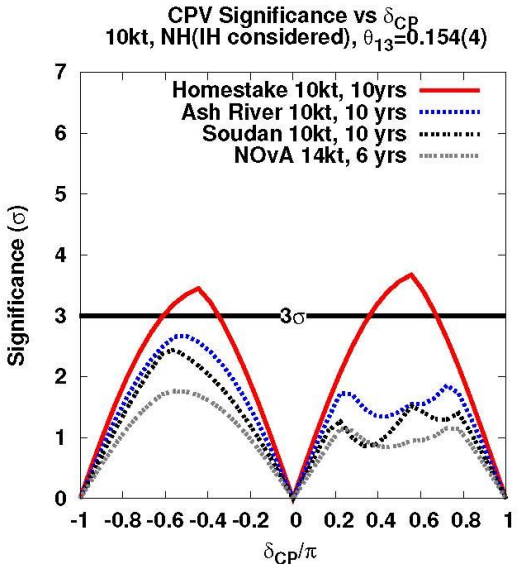
Fraction of δ_{CP} values for 2, 3 σ mass hierarchy sensitivity

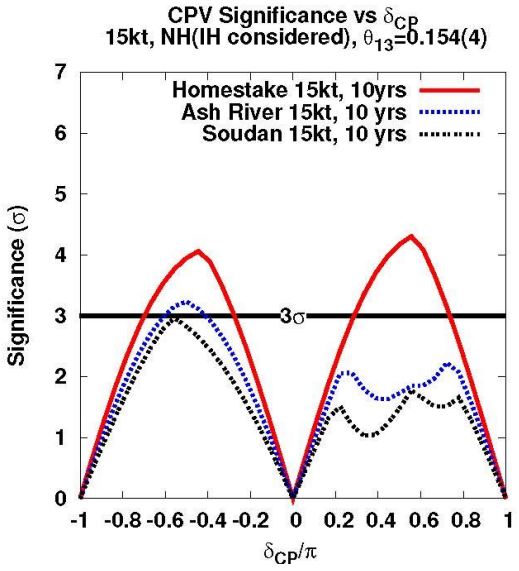


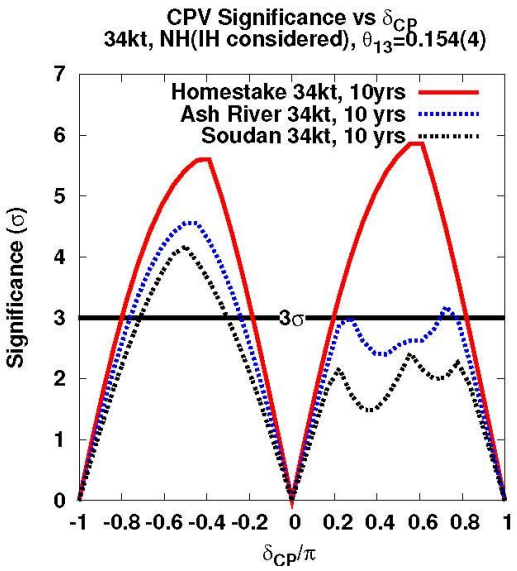




CP Violation Reach

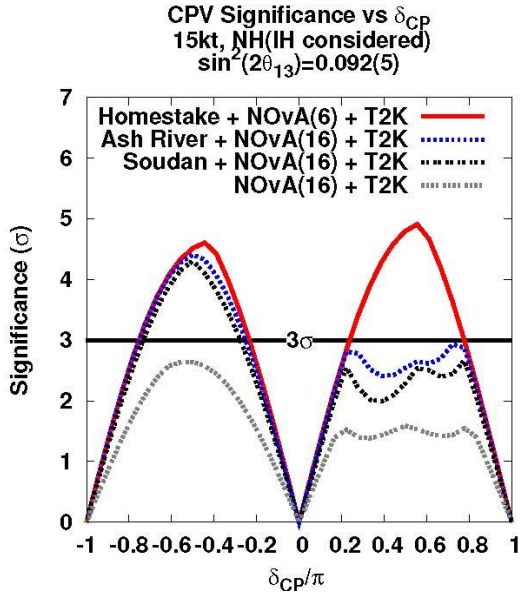




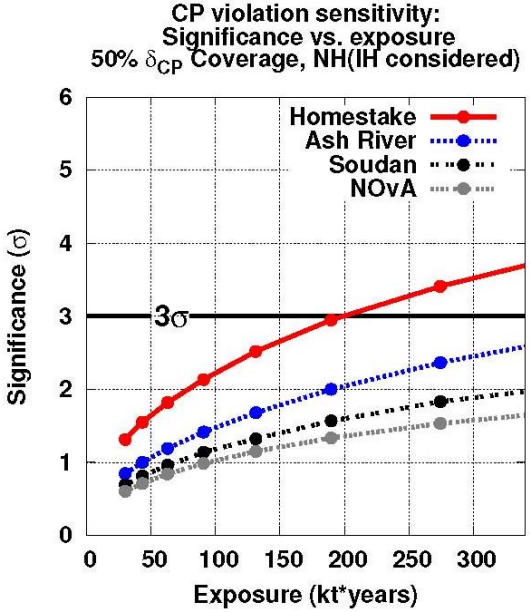


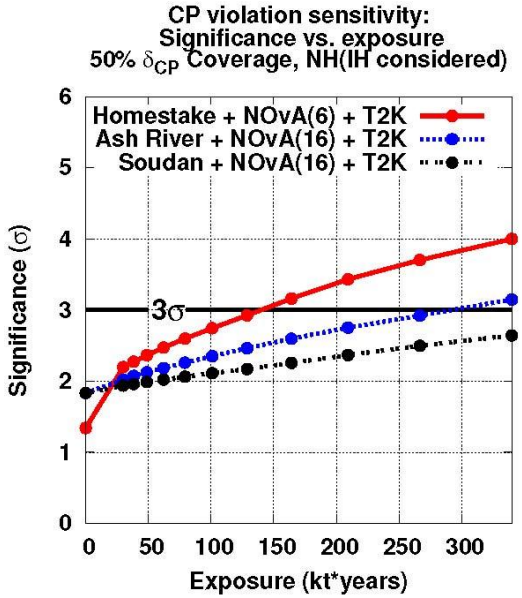
- **Hierarchy problem ⇒ δ_{CP}>0 problem (at short baselines)**

- **+ NOvA/T2K**

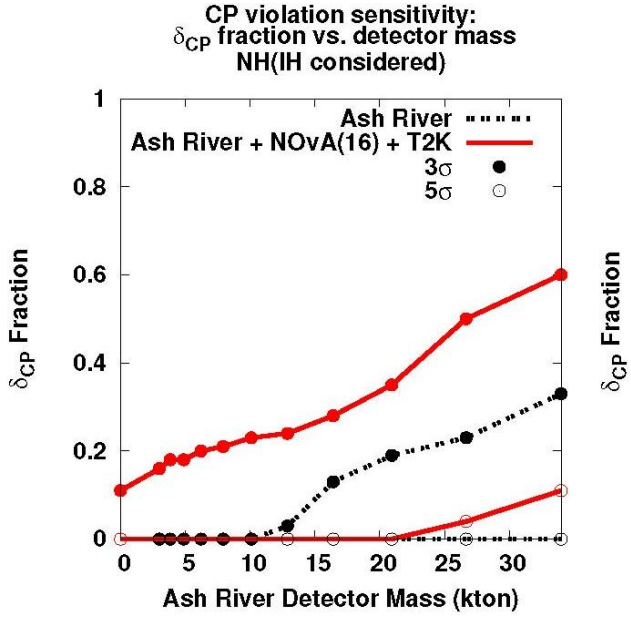


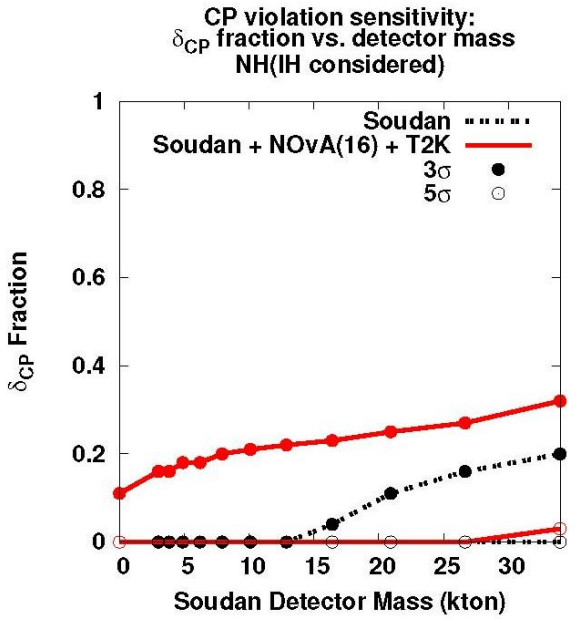
Exposure for 50% δ_{CP} coverage

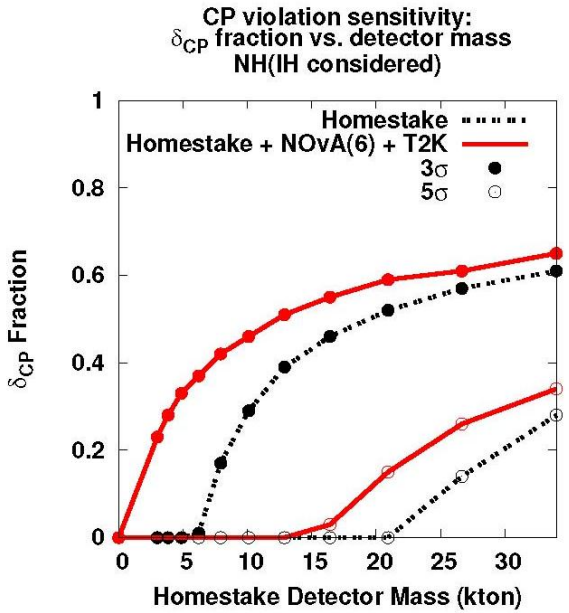




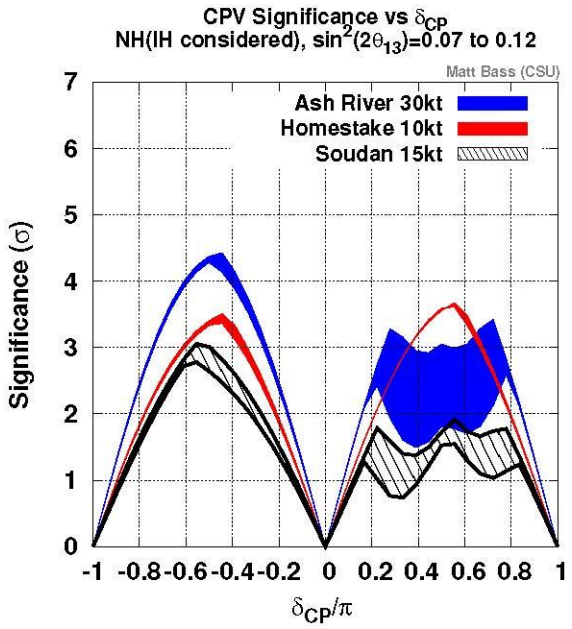
Fraction of δ_{CP} values for 3, 5σ δ_{CP} sensitivity

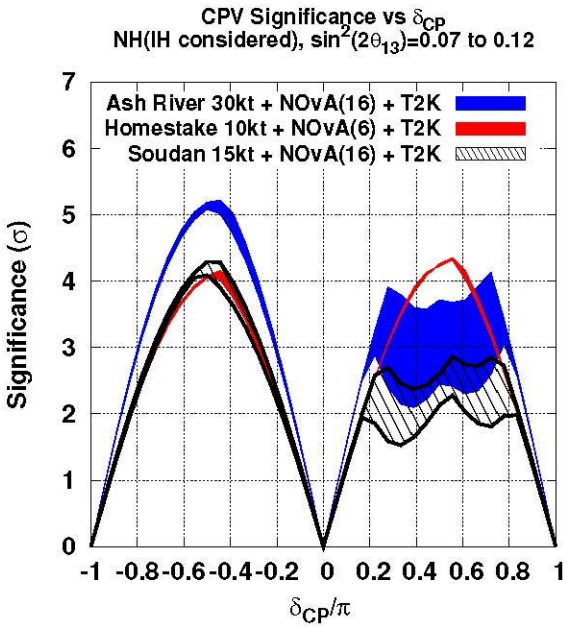




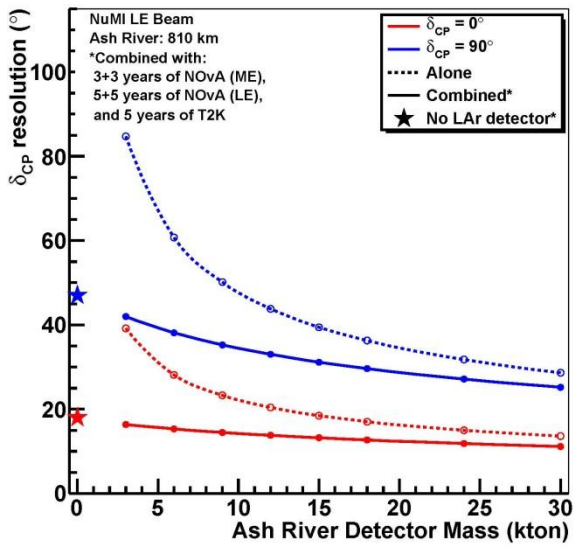


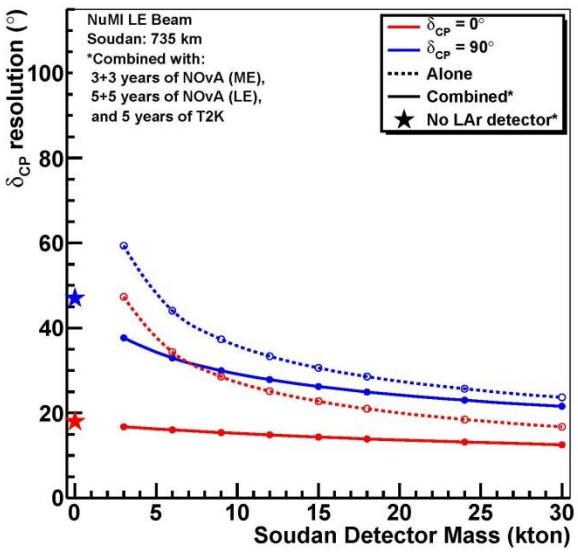
Impact of θ_{13} value on CP reach for the 3 options

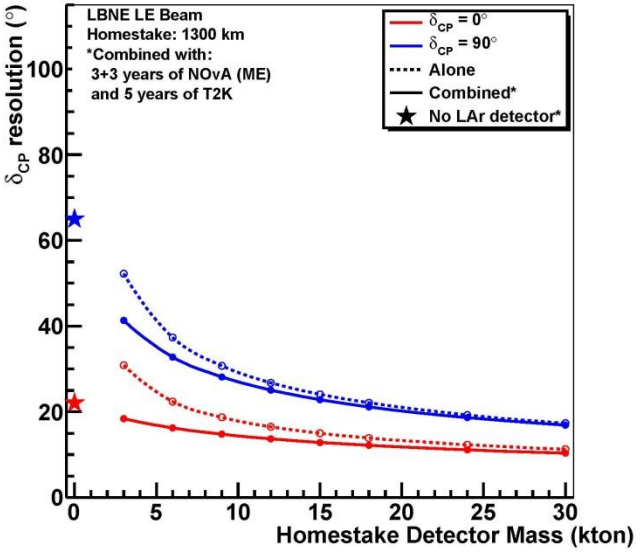




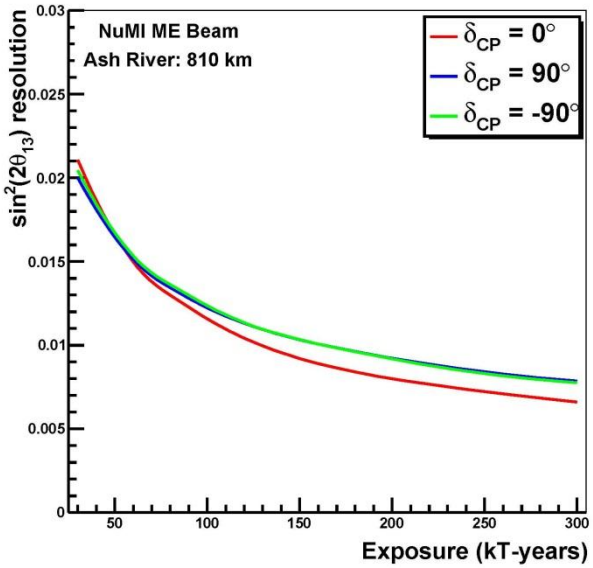
δ_{CP} resolution (hierarchy assumed known)

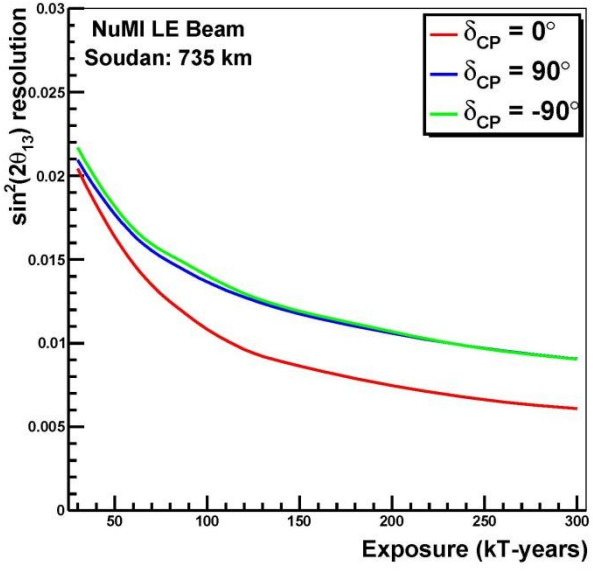


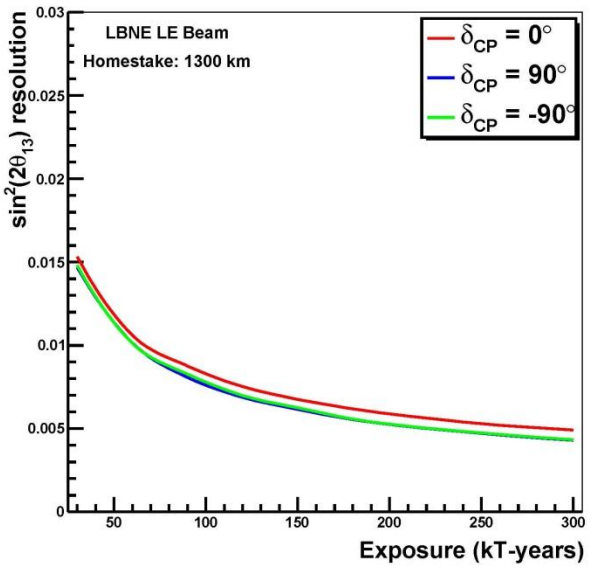


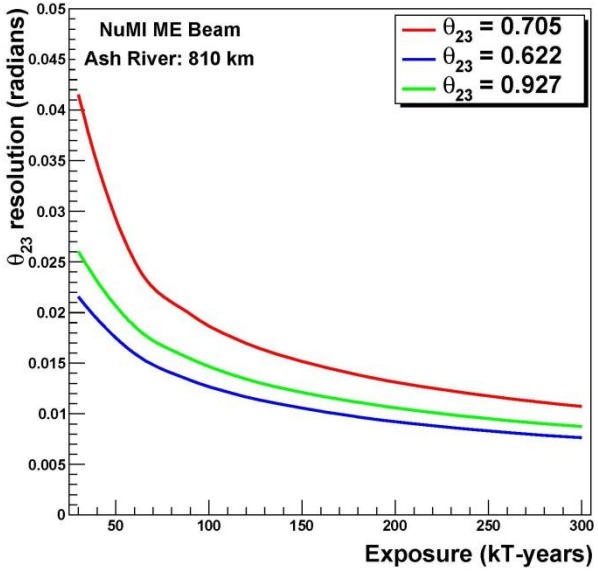


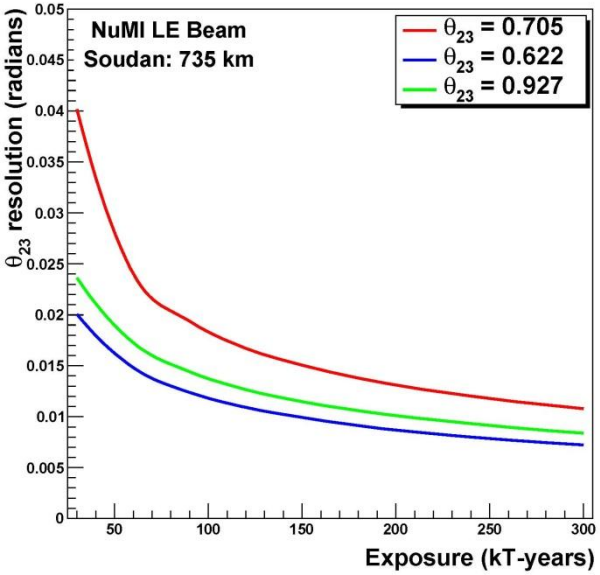
Other mixing parameters (if hierarchy known)

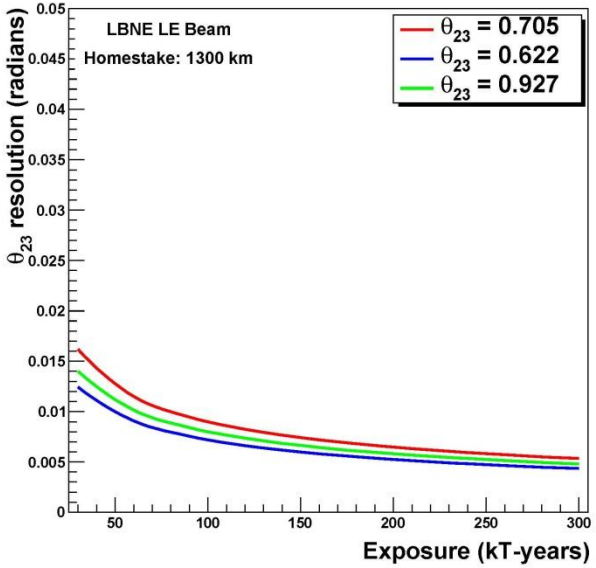










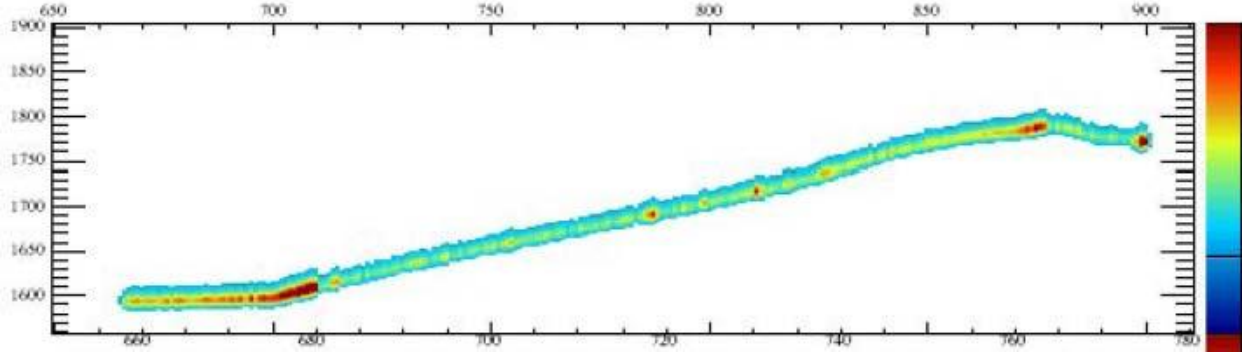


Searching for new physics

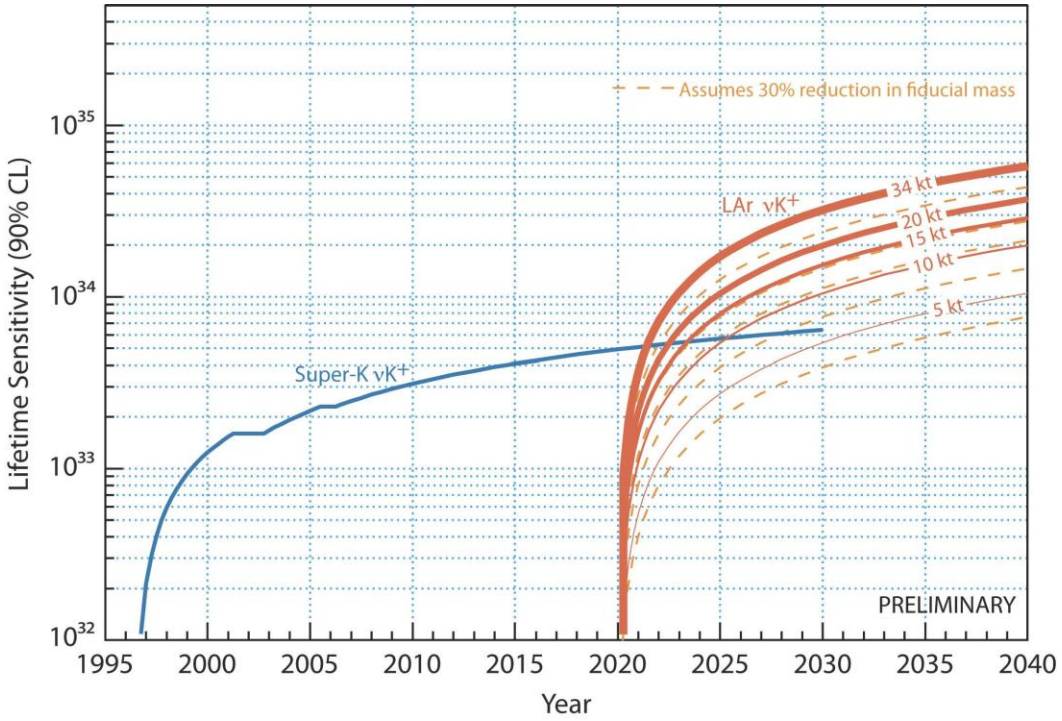
- **Using a wideband beam and long baseline to look for a failure of the 3 generation mixing model.**
  - **neutral current non-standard matter effects**
  - **long-range interactions between neutrinos and background sources**
  - **active-sterile neutrino mixing from the neutral current event rate**

Non-accelerator physics

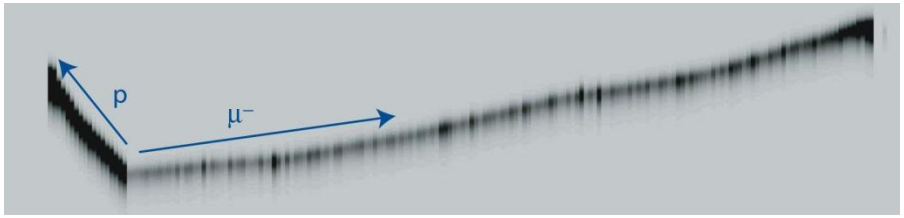
Proton Decay (p→Kν) – distinctive in LAr (K→μ→e)



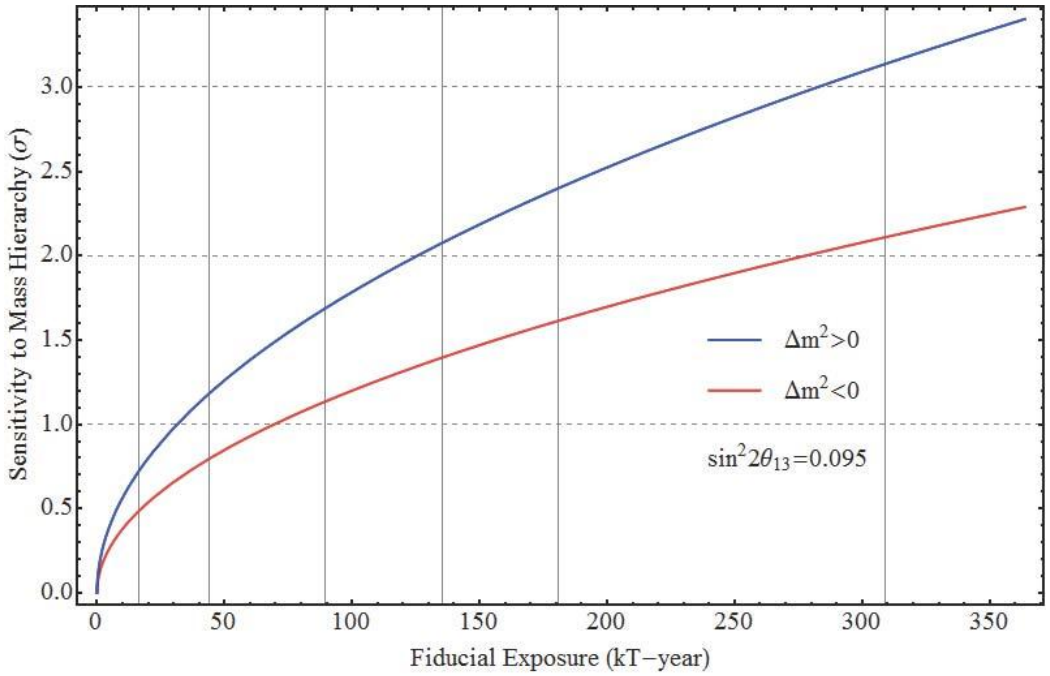
- **Must be underground and at least 10 kT to be competitive.**



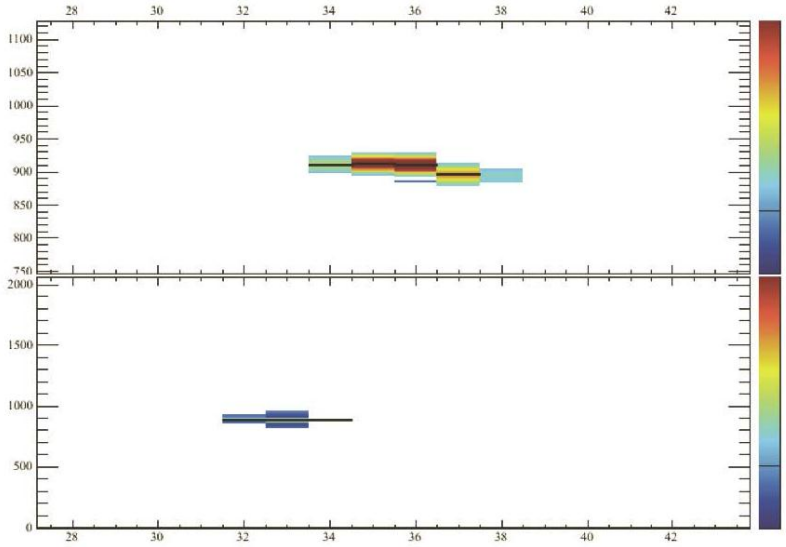
Atmospheric neutrinos (similar to accelerator-ν events)



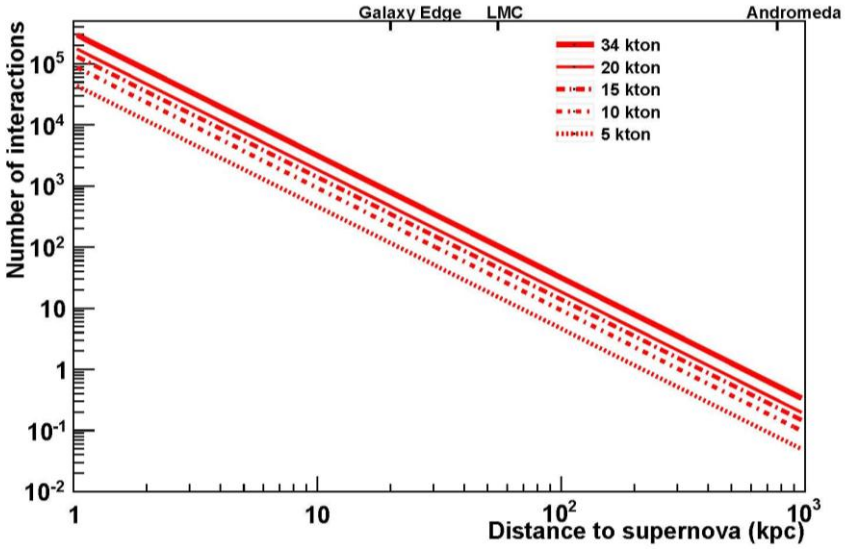
- **underground necessary (background)**
- **mass hierarchy sensitivity**



Supernova Core Collapse Neutrinos



- **A ratty signal!**
- **Must be underground**
- **A time-correlated burst over a well measured background rate.**



Outstanding Issues

- **Can a LAr detector successfully operate on the surface?**
  - **The LBNE collaboration has a group working on the answer.**
  - **There are 4 potential problems from cosmic muons:**
    1. **Saturating the DAQ**
    2. **Confusion in event reconstruction due to enough of the detector volume being obscured by muons**
    3. **Prohibitive offline computing**
    4. **Background, i.e. generating interactions in the argon that mimic neutrino events.**
  - **With the current design and the length of the DAQ window for each spill, items 1 and 3 should not be a serious problem.**
  - **Even with 200 muons per spill, the fine-grained LAr detector has $< 10^{-4}$ of the volume obscured. So 2 is not a problem.**

- **The background problem is the one that will take time to fully understand (muons producing neutrals that interact in the LAr).**
  - **Overburden (~4m of rock) for the soft component**
  - **Muon veto**
  - **Possible photon system**
  - **Identifying vertex activity (nuclear fragments)**
- **Detailed calculations are underway, but the final strategy will likely come from studying ICARUS and MicroBooNE data.**

- **The need for a near detector during Phase-1**
  - **For the Minnesota sites, there are the existing near detectors plus Minerva that could serve for Phase-1.**
  - **For Homestake, there could be (1) muon counters, (2) a mini detector to measure the electron neutrino flux, or (3) a full near detector. The impact of the choice is being studied by the LBNE collaboration.**
    - **The statistical uncertainties in a 10 kT detector will dominate, at least for the hierarchy and CP phase measurements.**
    - **Other experiments have achieved the needed uncertainty with no near detector.**
    - **Background determination will be better due to the LAr detector.**
    - **The LBNE beam will be very similar to NuMI, so the measurements there will be transferable.**
    - **Measurement of the neutrino and antineutrino cross sections on Argon will have been measured with MicroBOONE.**

- **However, if non-Standard-Model results are seen, the believability will be much greater if there is a near detector.**
  - **India wants to build a near detector; the issue is the cost of the civil construction.**

Summary

- **The neutrino hierarchy and the CP phase angle are accessible with the options being considered.**
- **For the shorter baselines, the results from T2K are needed.**
- **A longer baseline and a wide-band beam allow observation of multiple oscillation peaks and the valleys between them. This provides broader sensitivity to neutrino oscillation physics beyond that described by the standard 3×3 matrix.**
- **The search for proton decay and the study of atmospheric and supernova-burst neutrinos require the detector to be underground.**