Group #18
Long Baseline

Description of Experiment

Goal: Design a long baseline experiment to determine if CP is violated

Beam: 2 MW, 2E21 POT per year

Far detector baseline: 3000 km

Near detector baseline: ~ 1km

Peak neutrino energy: 6 GeV

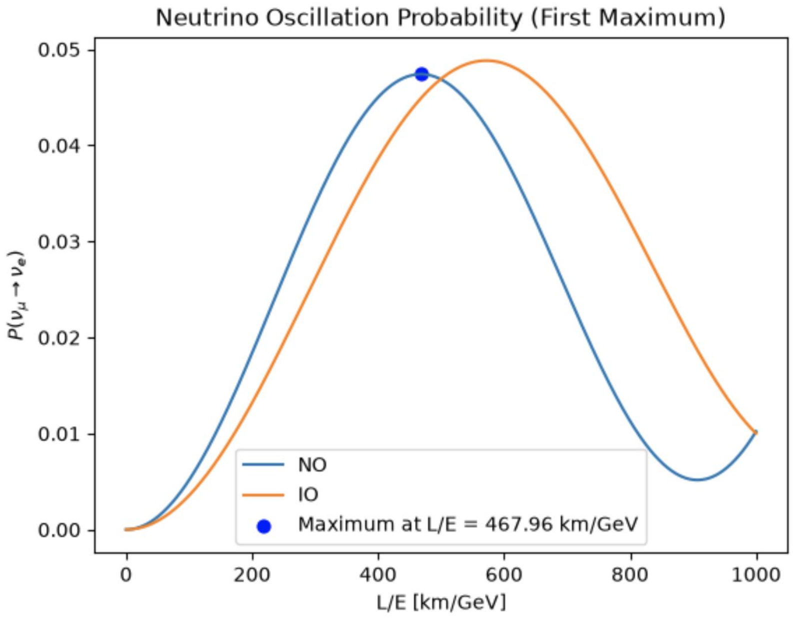
Off-axis angle: 4 mrad

Detector tech: Liquid Argon TPC

Detector size: 100 kt

Part 1: Choose Baseline

- δ_{CP} information is from the difference in the neutrino and antineutrino ν_μ to ν_e appearance probabilities
- Go to maximum of ν_e appearance prob
- Pmax is when L/E = ~500 km/GeV
- **L = 3000km, E = 6 GeV**
  - Chicago
  - Florence, Alabama
  - Raccoon Island, Tennessee



$$\begin{aligned}P(\nu_\alpha \to \nu_\beta) = &-4\Re[U_{\alpha1}U^*_{\beta1}U^*_{\alpha2}U_{\beta2}]\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)\\ &-4\Re[U_{\alpha1}U^*_{\beta1}U^*_{\alpha3}U_{\beta3}]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\\ &-4\Re[U_{\alpha2}U^*_{\beta2}U^*_{\alpha3}U_{\beta3}]\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\\ &+8\Im[U_{\alpha1}U^*_{\beta1}U^*_{\alpha2}U_{\beta2}]\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)\end{aligned}$$

The Beam: 2MW, 2E21 POT/yr

$$E_{\text{proton}} = 2 \cdot 10^6 \text{J/s} \times (2 \cdot 10^{21} \text{ protons/year})^{-1} \times 3.15 \cdot 10^7 \text{ seconds/year } \times 65\% \text{ uptime} \times 6.24 \cdot 10^9 \text{ GeV/J} \approx 127 \text{ GeV/proton}$$

$$E_\pi \approx 0.2 E_{\text{p}} = 25.4 \text{ GeV}$$

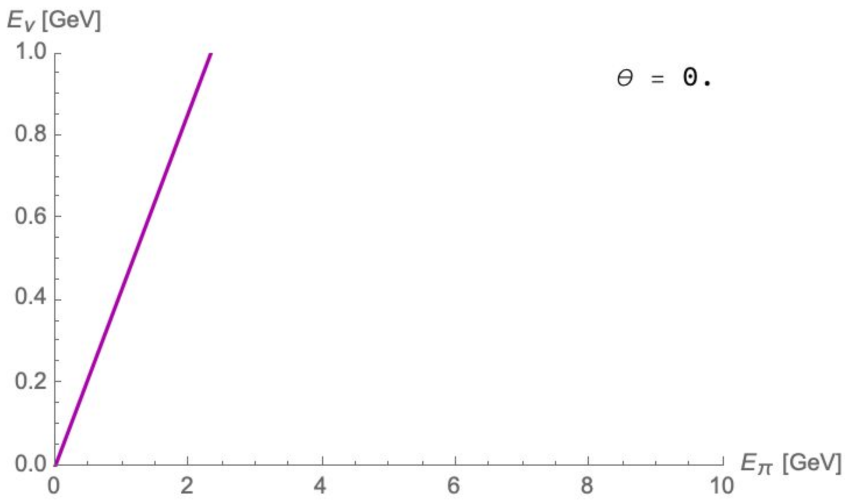
$$E_{\nu, \text{ on axis, peak}} = 0.43 E_\pi \approx 11 \text{ GeV}$$

The limit on the neutrino energy limits the baseline to less than about 5,500km for the first maximum. For a shorter baseline, we need to tune it using an off axis angle.

Part 2: Choose Angle

- As off-axis angle increases, neutrino energy becomes more sharply peaked
- Need $E_\nu = 6$ GeV
- Choose off-axis angle of 0.004 mrad = 0.23º
- Off-axis pros
    - More sharply peaked neutrino flux
- Off-axis cons
    - Lower flux

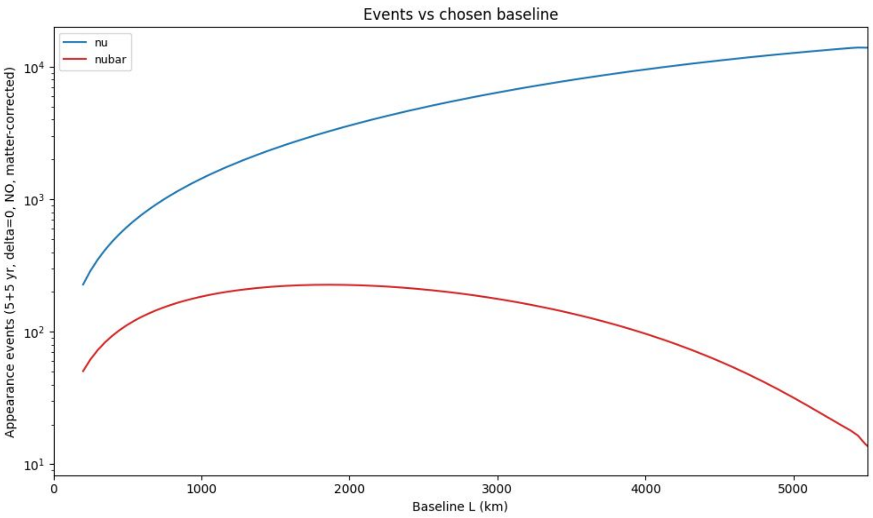
$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2} \qquad \gamma = E_\pi / m_\pi$$

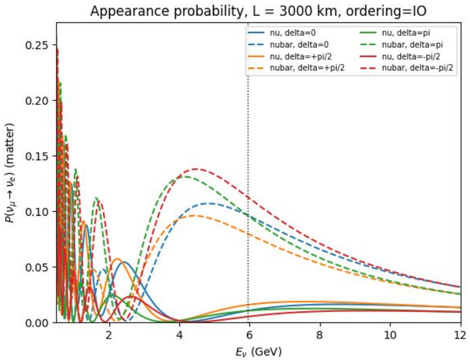


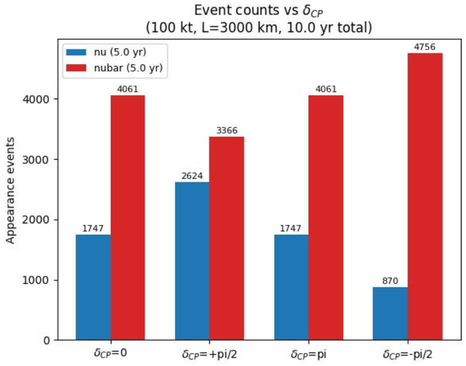
Part 3: Flux Estimates

$$N_{\text{events}} = (\dot{N}_{\text{POT}} \cdot t \cdot k_\nu) \times \frac{f(\gamma_\pi \theta)}{\pi L^2 / \gamma_\pi^2} \times \sigma_{CC} E_\nu \times N_{\text{nucleons}} \times P(\nu_\mu \to \nu_e)$$

beam | flux geometry | cross section | detector size | oscillations







Part 4: Matter Effect

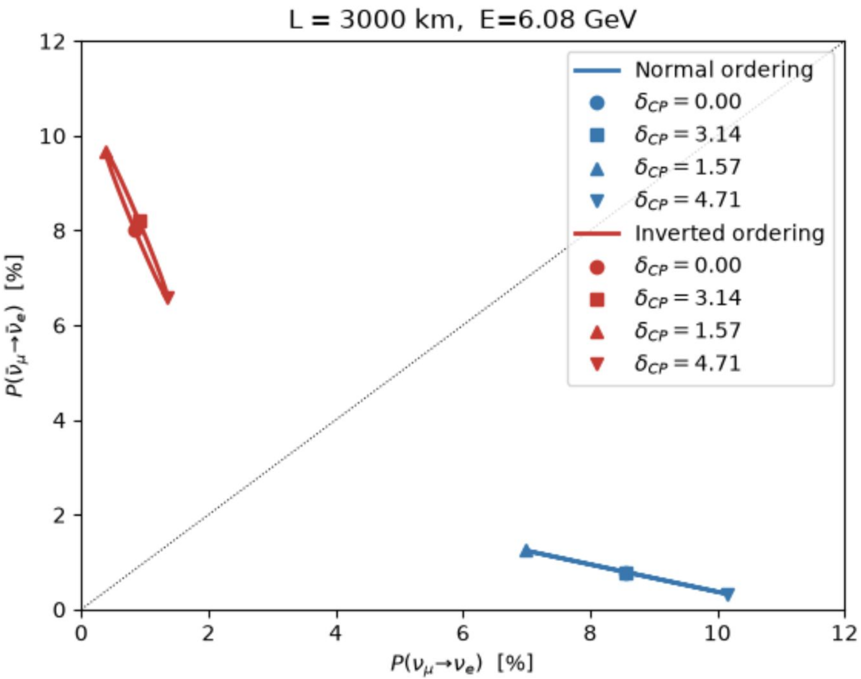
Mixing angles

Mass Ordering and $|\Delta m^2_{32}|$

CP Phase δ_{CP}

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31} \times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

From slide 42 of Zoya Vallari's presentation



- CP violation causes difference in neutrino vs antineutrino oscillation probability
- Matter effect causes a shift in the number of neutrino vs antineutrino events in opposite directions

Part 5: δ_{CP} Sensitivity

Can we exclude $\delta_{CP} = 0$ or π at 5 sigma?

- Pick a true δ_{CP} and mass ordering
- Find event counts for those values
- Find the best combination of mass ordering and $\delta_{CP} = 0$ or π to fake the event count given the true values. Significance comes from ability to differentiate between the two situations.
- Repeat for all true values to get sensitivity spectrum

Part 5: δ_{CP} Sensitivity

Sensitive to maximal CP violation at 5 sigma, and can see CP violation at most values to 3 sigma.

Obviously, a low true value of delta CP makes our significance for CP violation discovery very low.