Baseline Optimization in a Long-Baseline Neutrino Oscillation Experiment

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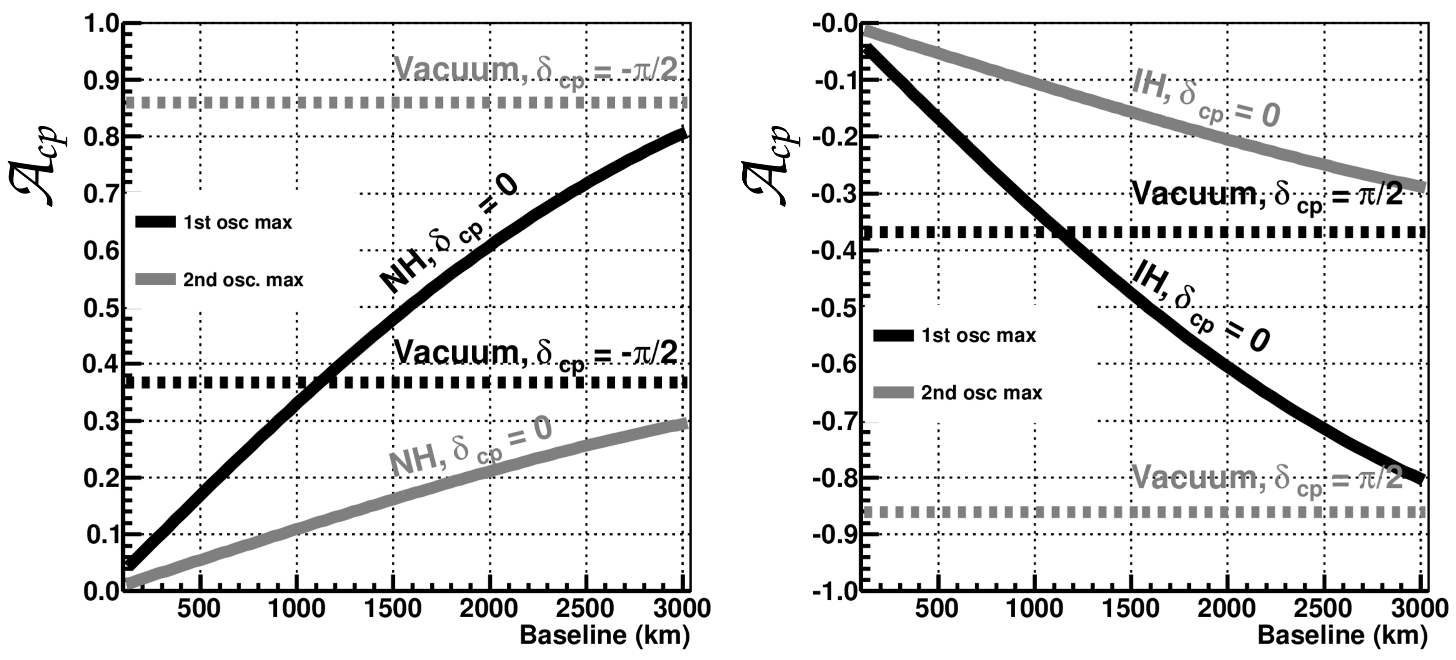
Long-Baseline Neutrino Physics

Next-generation long-baseline electron neutrino appearance experiments will seek to discover CP violation, determine the mass hierarchy, and resolve the θ_{23} octant. We consider the sensitivity of these measurements in a study to determine the optimal baseline from the Fermilab Main Injector, including practical considerations regarding beam and detector performance.

CP Asymmetry: $$\mathcal{A}_{cp}(E_\nu) = \left[\frac{\mathrm{P}(\nu_\mu \to \nu_e) - \bar{\mathrm{P}}(\bar{\nu}_\mu \to \bar{\nu}_e)}{\mathrm{P}(\nu_\mu \to \nu_e) + \bar{\mathrm{P}}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$



- The asymmetry due to nonzero δ_{CP} is constant as a function of baseline and larger than the matter asymmetry for baselines less than ~1000 km.
- Because the matter asymmetry grows as a function of baseline, the significance of a mass hierarchy measurement increases with baseline (assuming roughly equal statistics).
- At the 2nd oscillation node, the maximal CP asymmetry dominates the matter asymmetry at all baselines. A measurement at the 2nd node has good sensitivity to CP violation, independent of the mass hierarchy.
- At baselines <1000 km, the 2nd node is typically too low in energy to be observable; the sensitivity to CP violation suffers from the ambiguity between the matter asymmetry and the CP asymmetry in the 1st node.

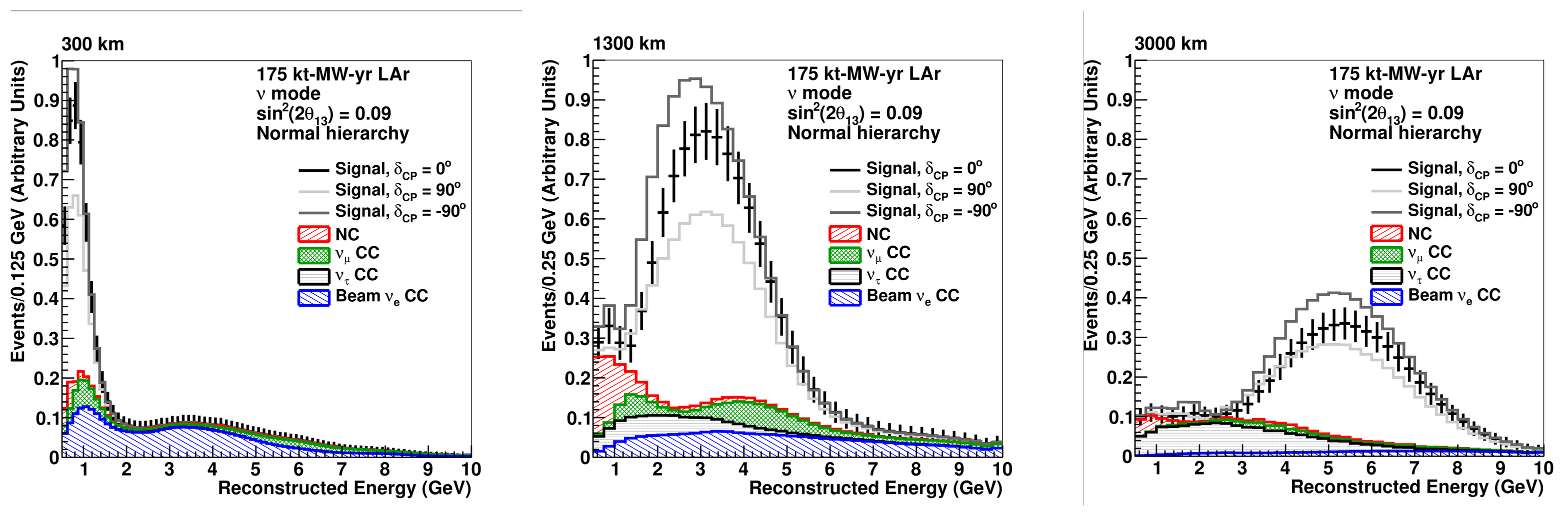
Conclusion: Baselines of 1000 km or more with a wide-band beam in which the 1st and 2nd oscillation nodes are both observable should lead to optimal sensitivity.

Experimental Assumptions and Analysis

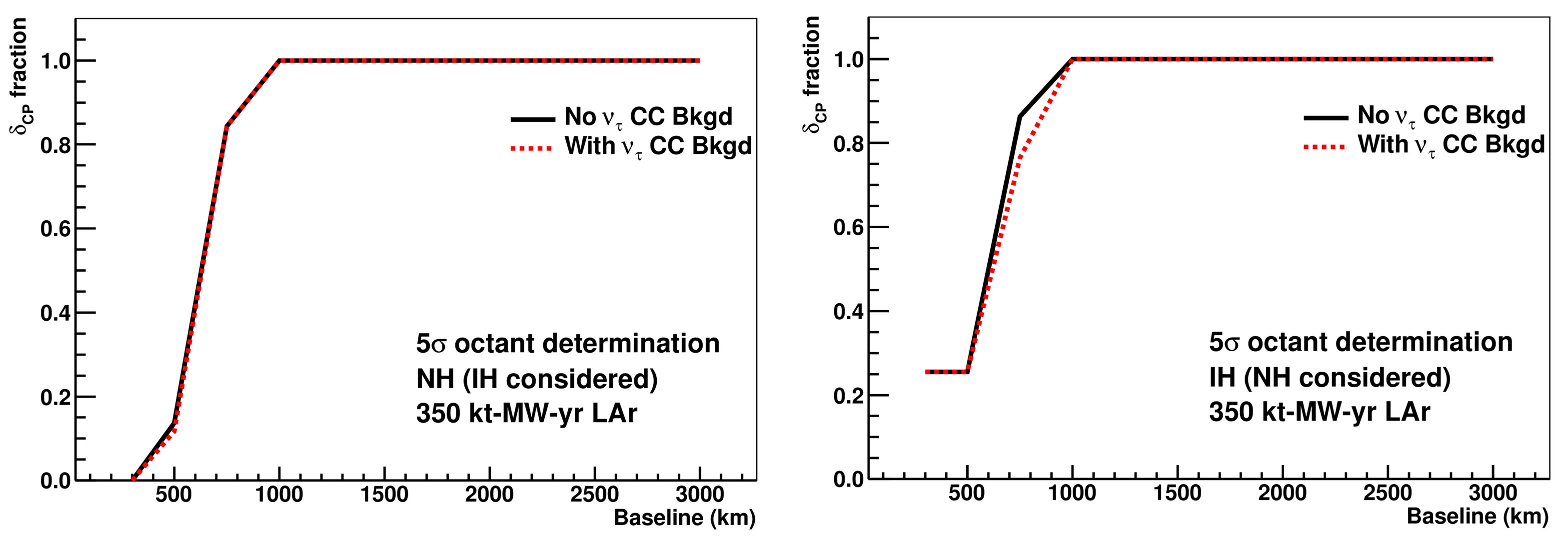
We assume a liquid argon TPC as the neutrino detector with a 350 kt-MW-year exposure; half of the exposure is with a neutrino beam and half with an antineutrino beam. Detector performance parameters are based on simulations and existing liquid argon TPC detector performance.

The GLoBES software package is used to calculate the predicted spectra and analyze the sensitivity at each baseline.

Example spectra (NH, neutrino beam)



θ_{23} Octant



The fraction of all possible δ_{CP} values for which we can determine the θ_{23} octant with a sensitivity of at least 5σ ($\Delta\chi^2$=25) as a function of baseline. The true mass hierarchy is assumed to be unknown. We take the true value of θ_{23} to be 38°.

Conclusion

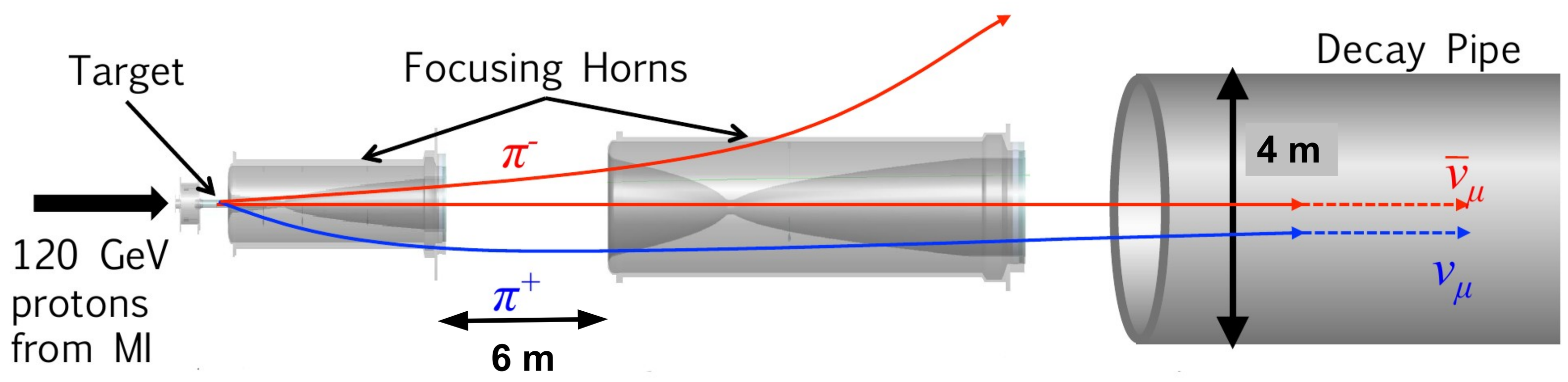
We have studied the sensitivity at various baselines to the key measurements for an electron neutrino appearance experiment using a wide-band muon neutrino beam. The fluxes are optimized for each baseline considered, assuming achievable beam power and energy from the Fermilab proton complex. We find that a detector at a baseline of at least 1000 km is optimal. In particular,

- Baselines of ~1000-1500 km are optimal to observe CP violation and measure δ_{CP}
- The mass hierarchy is resolved for all δ_{CP} with $\overline{\Delta\chi^2}$=25 for baselines ≥1300 km
- The octant is resolved at 5σ for all δ_{CP} for baselines ≥1000 km

Flux Optimization

To compare the sensitivity at each baseline, we produced neutrino and antineutrino fluxes derived from GEANT3 beamline simulations optimized to cover the energy region of the 1st oscillation node (and the 2nd if possible).

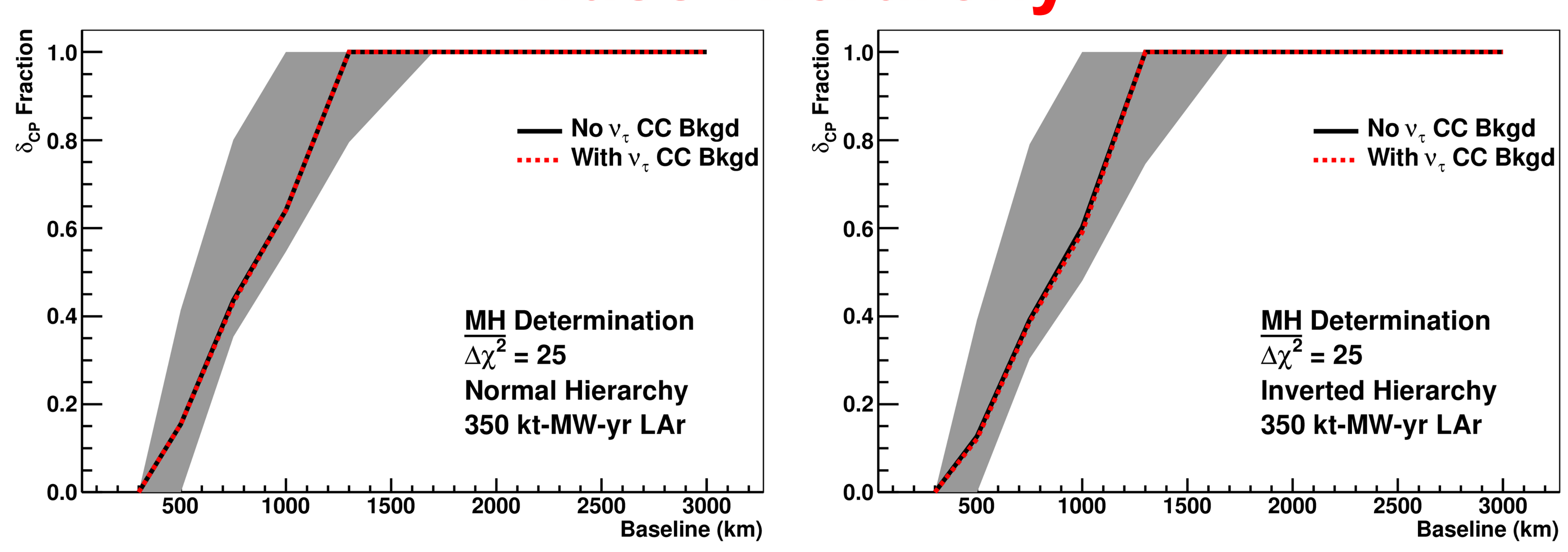
Beam simulation assumptions:
- 1.2 MW 120 GeV primary proton beam delivering 1×10^{21} protons-on-target/year
- Graphite target: diameter = 1.2 cm, length = two interaction lengths
- Double-parabolic NuMI focusing horn design; 6 m separation between horns
- Horn current of 250 kA
- Decay pipe with 4 m diameter
- Off-axis beam simulated for baselines <1000 km (because conventional neutrino beams are not currently efficient at focusing hadrons with energy <1GeV)



- Other parameters were varied for each baseline as shown in the table

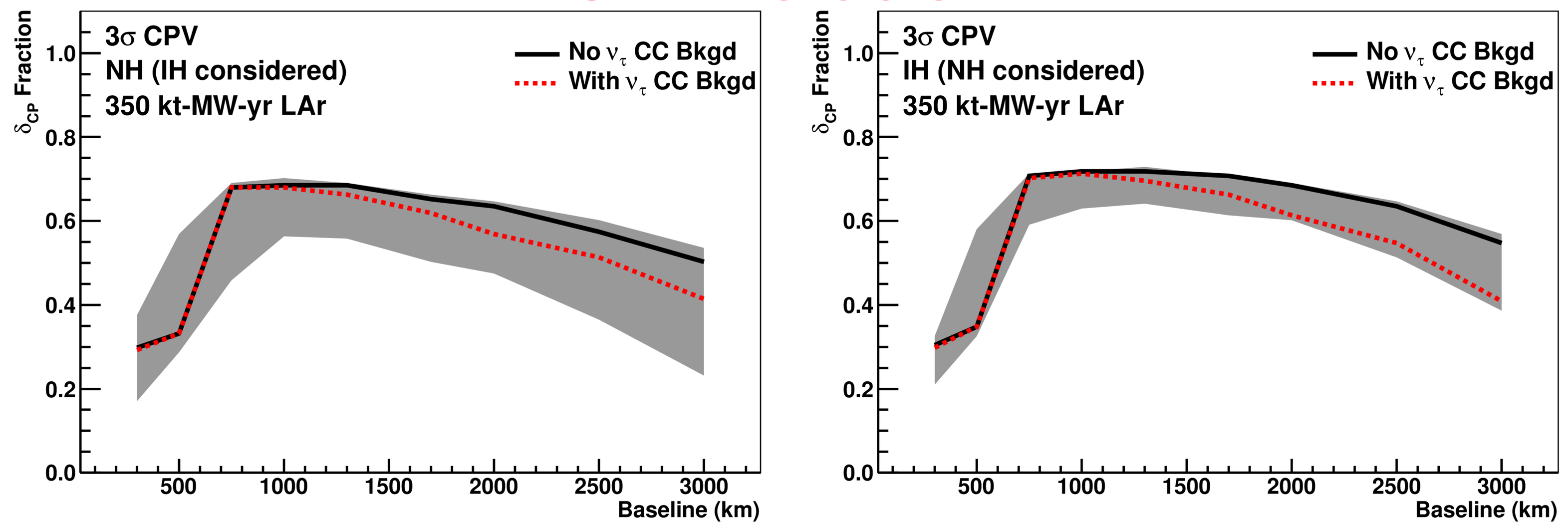
Baseline (km)	Target-Horn 1 distance	Decay pipe length	Off-axis angle
300	30cm	280m	2°
500	30cm	280m	1.5°
750	30cm	280m	1.0°
1000	0cm	280m	0°
1300	30cm	380m	0°
1700	30cm	480m	0°
2000	70cm	580m	0°
2500	70cm	680m	0°
3000	100cm	780m	0°

Mass Hierarchy

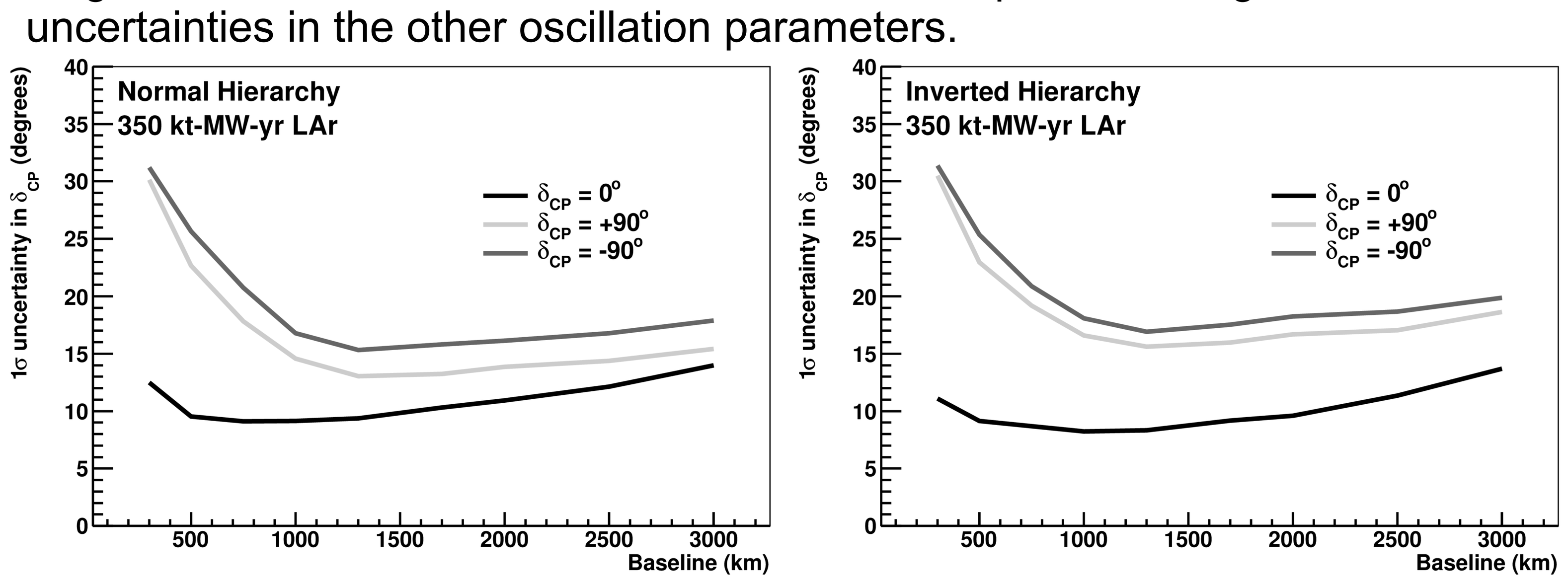


The fraction of all possible δ_{CP} values for which we can determine normal (left) or inverted (right) mass hierarchy with a minimum value of $\overline{\Delta\chi^2}$=25 as a function of baseline. (An expected average value of $\overline{\Delta\chi^2}$=25 corresponds to a 99.38% probability of determining the correct mass hierarchy according to the analysis in Phys. Rev. D86 113011). The shaded band indicates the possible range due to uncertainties in the other oscillation parameters.

CP Violation



The fraction of all possible δ_{CP} values for which we can observe CP violation with a sensitivity of at least 3σ ($\Delta\chi^2$=9) as a function of baseline. The true mass hierarchy is assumed to be unknown. If the true mass hierarchy is known, the sensitivity at shorter baselines improves to a level comparable to that of the longer baselines. The shaded band indicates the possible range due to uncertainties in the other oscillation parameters.



The 1σ uncertainty in the measured value of δ_{CP} as a function of baseline assuming different true values of δ_{CP}. The true mass hierarchy is assumed to be known.