1 The Importance of Systematic Errors in the Search/Study of CP-Violation in the Neutrino Sector

With the possibility of larger values of θ_{13}, it has been shown that the importance of systematic errors in establishing CP violations in the neutrino sector is increased significantly since the value of the expected measured asymmetry

$$A_{CP} = \frac{P(\nu_\mu \leftrightarrow \nu_e) - P(\overline{\nu_\mu} \leftrightarrow \overline{\nu_e})}{P(\nu_\mu \leftrightarrow \nu_e) + P(\overline{\nu_\mu} \leftrightarrow \overline{\nu_e})} \tag{1}$$

becomes smaller as θ_{13} increases. This implies that the measured sub-dominant oscillation probabilities of neutrino and anti-neutrino become more equal and any difference, an indication of CP-violation, can easily be hidden by measurement errors.

A careful determination of the systematic errors for a given experiment is always important and requires considerable effort. To better understand the challenge of determining systematic errors in oscillation experiments consider that the measured signal in our detectors is a convolution of energy-dependent ν flux $\otimes$ energy-dependent cross section $\otimes$ energy-dependent nuclear effects. Specifically for searching for indications of CP-violation, the energy dependence of flux, cross section and nuclear effects are different for ν and $\overline{\nu}$. In addition, since the energy spectrum of the flux entering the far detector is different than the near detector, these convoluted effects do NOT automatically cancel between near and far detectors even if the near and far detectors are made from the same nucleus.

If we assume the systematic errors on the neutrino flux and any detector systematics such as acceptance are determined independently, then a common challenge to all experiments is to determine the systematic errors introduced on the oscillation probabilities by the combined effects of energy-dependent cross section $\otimes$ energy-dependent nuclear effects. The way to unfold these effects in determining, for example, the probability to produce a single π^0 within a given energy band in the final detected state is to choose one of several models for the cross sections for pion production (single and multiple pions and all charge states) on a nucleon and then model the nuclear effects that govern the process including:

- The initial off-shell target nucleon is moving within the nucleus with a given p_N and t_N that can be given, for example, by spectral functions, fermi-gas models or shell-model considerations. Each of these models predict a different probability distribution for p_N and t_N and a systematic uncertainty must be assigned to this step.

- The initial q $\overline{q}$ state can travel through the nucleus before it forms into a strong-interacting meson. This "hadron formation length" has been measured in e/μ - nucleus scattering as a function of the energy-transfer to the nucleus but has a large error that is a systematic error in our measurement.

- once the strong-interacting meson is formed, it is subject to final state interactions that include absorption, charge-exchange scattering, other inelastic scattering phenomena. This is modeled via pion-nucleus data and carries another systematic error.

The process for determining the systematic errors associated with the energy-dependent cross section $\otimes$ energy-dependent nuclear effects has been started in the MINOS experiment and is continuing in more detail with the MINERνA experiment. We are now begining to consider these systematics in more detail for both the IDS-Neutrino Factory and the LBNE experiment and we propose creating a cross-experiment "Systematics Group" to bring all the knowledge and experience of concerned experiments to address this very challenging issue.