Systematics in Neutrino Oscillation Experiments

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Statistical errors

Clearly, we are on the (slow) road towards 3% measurements of the event rates. Translating this into a 3% measurements of the oscillation probability is very difficult.

Note, T2HK would reach 1000 $\nu_e$ signal events very quickly.
The Idea

In order to measure CP violation we need to reconstruct one out of these

\[ P(\nu_\mu \rightarrow \nu_e) \text{ or } P(\nu_e \rightarrow \nu_\mu) \]

and one out of these

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \text{ or } P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) \]

and we’d like to do that at the percent level accuracy.
The Reality

We do not measure probabilities, but event rates!

\[ R_\beta^\alpha(E_{\text{vis}}) = N \int dE \, \Phi_\alpha(E) \, \sigma_\beta(E, E_{\text{vis}}) \, \epsilon_\beta(E) \, P(\nu_\alpha \rightarrow \nu_\beta, E) \]

In order to reconstruct \( P \), we have to know

- \( N \) – overall normalization (fiducial mass)
- \( \Phi_\alpha \) – flux of \( \nu_\alpha \)
- \( \sigma_\beta \) – x-section for \( \nu_\beta \)
- \( \epsilon_\beta \) – detection efficiency for \( \nu_\beta \)

Note: \( \sigma_\beta \epsilon_\beta \) always appears in that combination, hence we can define an effective cross section \( \tilde{\sigma}_\beta := \sigma_\beta \epsilon_\beta \)
The Problem

Even if we ignore all energy dependencies of efficiencies, x-sections *etc.*, we generally can not expect to know any $\phi$ or any $\tilde{\sigma}$. Also, we won’t know any kind of ratio

$$\frac{\Phi_\alpha}{\Phi_{\bar{\alpha}}} \quad \text{or} \quad \frac{\Phi_\alpha}{\Phi_\beta}$$

nor

$$\frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_{\bar{\alpha}}} \quad \text{or} \quad \frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_\beta}$$

Note: Even if we may be able to know $\sigma_e / \sigma_\mu$ from theory, we won’t know the corresponding ratio of efficiencies $\epsilon_e / \epsilon_\mu$
The Solution

Measure the un-oscillated event rate at a near location and everything is fine, since all uncertainties will cancel, (provided the detectors are identical and have the same acceptance)

\[ \frac{R^\alpha_{\text{far}} L^2}{R^\alpha_{\text{near}}} = \frac{N_{\text{far}} \Phi_\alpha \tilde{\sigma}_\alpha P(\nu_\alpha \rightarrow \nu_\alpha)}{N_{\text{near}} \Phi_\alpha \tilde{\sigma}_\alpha 1} \]

\[ \frac{R^\alpha_{\text{far}} L^2}{R^\alpha_{\text{near}}} = \frac{N_{\text{far}}}{N_{\text{near}}} P(\nu_\alpha \rightarrow \nu_\alpha) \]

And the error on \( \frac{N_{\text{far}}}{N_{\text{near}}} \) will cancel in the \( \nu \) to \( \bar{\nu} \) comparison.
But . . .

This all works only for disappearance measurements!

\[
\frac{R_\beta^\alpha (\text{far}) L^2}{R_\beta^\alpha (\text{near})} = \frac{N_{\text{far}} \Phi_\alpha \tilde{\sigma}_\beta P(\nu_\alpha \rightarrow \nu_\beta)}{N_{\text{near}} \Phi_\alpha \tilde{\sigma}_\alpha 1}
\]

\[
\frac{R_\beta^\alpha (\text{far}) L^2}{R_\beta^\alpha (\text{near})} = \frac{N_{\text{far}} \tilde{\sigma}_\beta P(\nu_\alpha \rightarrow \nu_\beta)}{N_{\text{near}} \tilde{\sigma}_\alpha 1}
\]

Since \(\tilde{\sigma}\) will be different for \(\nu\) and \(\bar{\nu}\), this is a serious problem. And we can not measure \(\tilde{\sigma}_\beta\) in a beam of \(\nu_\alpha\).
\( \nu_e / \nu_\mu \) total x-sections

Appearance experiments using a (nearly) flavor pure beam can not rely on a near detector to predict the signal at the far site!

Large \( \theta_{13} \) most difficult region.

PH, Mezzetto, Schwetz, 2007

Differences between \( \nu_e \) and \( \nu_\mu \) are significant below 1 GeV, see K. McFarland’s talk
Neutrino cross sections

Our detectors are made of nuclei and compared to a free nucleon, the following differences arise

- Initial state momentum distribution
- Nuclear excitations
- Reaction products have to leave the nucleus
- Higher order interactions appear

As a function of $Q^2$ these effects are flavor blind, but we do NOT measure $Q^2$.

These effects are NOT the same for neutrinos and antineutrinos.
Quasi-elastic scattering

QE events allow for a simple neutrino energy reconstruction based on the lepton momentum. Nuclear effects will make some non-QE events appear to be like QE events \( \Rightarrow \) the neutrino energy will not be correctly reconstructed.

Coloma et al. 2013
Impact on oscillation

$\nu_\mu \rightarrow \nu_\mu$ in a T2K-like setup with near detector.

Coloma et al. 2013

If the energy scale is permitted to shift, tension and bias are reduced, but effects very hard to spot from $\chi^2$
Missing energy

In elastic scattering a certain number of neutrons is made. Neutrons will be largely invisible even in a liquid argon TPC. ⇒ missing energy

Ankowski et al., 2015
We can correct for the missing energy IF we know the mean neutron number and energy made in the event...
Towards precise cross sections

This will require better neutrino sources, since a cross section measurement is about as precise as the accuracy at which the beam flux is known.

- Percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- $\nu_\mu$ and $\nu_e$

A (the only?) source which can deliver all that is a muon storage ring, aka nuSTORM.