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The impact of nuclear effect modelling on the cross-section ratio ν_e/ν_μ and its impact for future measurements of CP violation

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Long-baseline (LBL) neutrino oscillation experiments search for Charge-Parity (CP) violation in the leptonic sector by precisely measuring the $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance probabilities. One of the dominant systematic uncertainties on the measurements of CP violation, comes from our modeling of the $\nu_e/\overline{\nu}_e$ cross-section ratio, which is subject to a range of uncertainties related to poorly-constrained nuclear physics processes. Whilst tight constraints on the $\nu_\mu/\overline{\nu}_\mu$ cross-section can be achieved using LBL experiment's near detector data, the lepton mass differences make the extrapolation to the $\nu_e/\overline{\nu}_e$ is not trivial.
Currently running LBL experiments reach a sensitivity to exclude the CP conserving hypothesis of about three standard deviations for a relatively large range of δ_{CP} values, hence a more accurate evaluation of the $\nu_e/\overline{\nu}_e$ related uncertainties becomes increasingly crucial. Following up on work by Nikolakopoulos et al. [1], we present the analysis from [2], quantifying the potential for mis-modelling of the ν_μ/ν_e, $\overline{\nu}_\mu/\overline{\nu}_e$ and $\nu_e/\overline{\nu}_e$ cross sections due to nuclear effects as a model spread in the full kinematic phase space for CCQE interactions. This impact is then propagated to simulated experimental configurations based on the Hyper-K and ESSνSB experiments.
Significant differences between the theoretical models are found, which largely lie in regions of phase space that contribute to only a small portion of the flux integrated cross sections. Overall, a systematic uncertainty on the oscillated flux-averaged $\nu_e/\overline{\nu}_e$ cross section of $\sim 2\%$ and $\sim 4\%$ is found for the simulated Hyper-K and ESSνSB experiments respectively.

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1. Introduction

Long-baseline neutrino experiments study the Charge-Parity symmetry (CP) violation by comparing the $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation probabilities, employing both a near detector (ND), located a few hundred meters downstream of the neutrino production point, and a far detector (FD), positioned a few hundred kilometres downstream where the oscillation probability reaches its maximum. Determining the oscillation probabilities requires the estimation of the $\overset{(-)}{\nu}_e$-flux $\Phi(E_{\overset{(-)}{\nu}})$ at the FD, which is linked to the measured event rate $N(E_{\overset{(-)}{\nu}})$ by the electron (anti) neutrino cross-section $\sigma_{\overset{(-)}{e}}$

$$N(E_{\overset{(-)}{\nu}}) \propto \sigma_{\overset{(-)}{e}} \times \Phi(E_{\overset{(-)}{\nu}}).$$

As the CP violating phase δ_{CP} is directly related to the ratio of the oscillation probabilities and as such to the ratio of observed FD fluxes, any bias in the cross-section ratio between σ_e and $\sigma_{\overline{e}}$ directly influences the measured value of δ_{CP}.

At the ND, the neutrino beam consists primarily of $\overset{(-)}{\nu}_\mu$, with a contribution of less than 1% of $\overset{(-)}{\nu}_e$. This is due to the branching ratios in the kaon and pion decays, which are the processes used to generate the neutrinos within the beam. Consequently, the ND's capacity to constrain $\sigma_{\overset{(-)}{e}}$ using data is restricted by statistical limitations. Thus, a constraint is derived from the measured muon (anti) neutrino cross-section, $\sigma_{\overset{(-)}{\mu}}$, utilizing model projections for the cross-section ratio between the electron and muon neutrinos. Discrepancies between models in this cross-section ratio directly impacts the assumed electron (anti)-neutrino cross-sections and, consequently, the measurement of δ_{CP}

Several publications [1, 3, 4], have investigated deviations between various neutrino-nucleus cross-section models, especially regarding the impact of nuclear effects in specific parts of the phase space. Nuclear effects arise from ν interactions with composite nuclei, such as oxygen and carbon. These are nuclear processes, such as nucleon Fermi motion, Pauli blocking, or nucleon-nucleon correlations, which can significantly bias the neutrino energy reconstruction.

2. Analysis

In this study, the deviations of the $\nu_e/\overline{\nu}_e$ cross-section ratio prediction of several models listed in table 1 are determined. Only charged current quasielastic interactions (CCQE) are considered and the impact on future experiments, i.e. Hyper Kamiokande (HK) and ESSνSB, is estimated by modeling them as counting experiments. We follow the approach laid out in [1] and study the single differential cross-section

$$\frac{d\sigma_\ell}{d\cos\theta_\ell}(E_\nu, \cos\theta_\ell),$$

in the (E_ν, θ_ℓ) phase space, ℓ denoting the final state lepton and E_ν the neutrino energy. θ_ℓ denotes the angle of the outgoing lepton with respect to the incoming neutrino direction.

In a first step the cross-section ratio between the electron and muon (anti) neutrino is calculated as

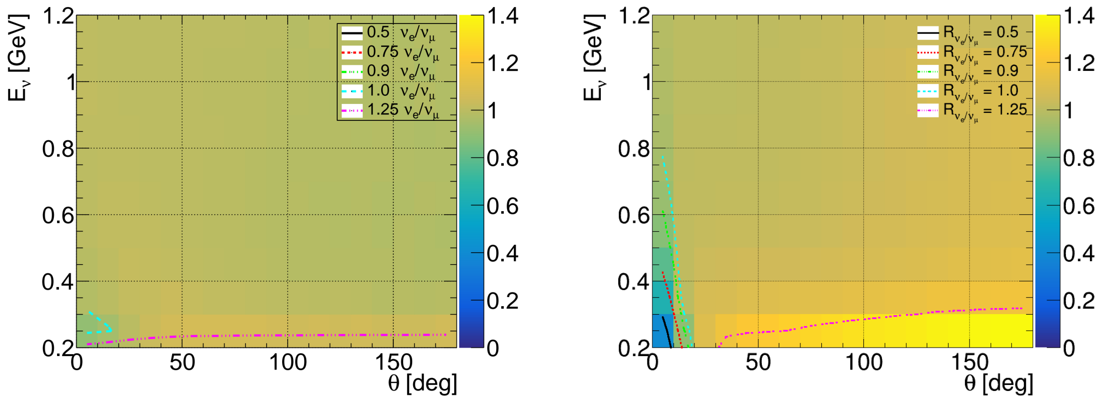
$$R_{\nu_e/\nu_\mu} = \tfrac{d\sigma_e}{d\cos\theta_e} / \tfrac{d\sigma_\mu}{d\cos\theta_\mu}.$$

The two models showing the largest spread are the Spectral Function (SF) and the Hartree-Fock mean field model with continuum random-phase approximation corrections (CRPA). Their neutrino

Model	Description
Hartree-Fock (HF)	Mean Field Model
HF-CRPA	HF with continuum random-phase approximation corrections [5]
HF-CRPA PW	HF-CRPA, plane-wave nucleons
HF-CRPA C	HF-CRPA, carbon target
SuSAv2	Mean Field Model [6]
Spectral Function (SF)	Nuclear Shell model [7]
SF w/o PB	SF with Pauli Blocking disabled
SF M_A^{QE}	SF the axial mass changed to given value
Local Fermi Gas (LFG)	Fermi Gas Model [8]

Table 1: The different model configurations considered in this study.

cross-section ratio is shown in fig. 1. Large deviations in the forward scattered region ($\theta < 10°$) where previously noted in [1], and are due to differences in the implementation of Pauli Blocking [3] between both models.



(a) Spectral Function prediction of R_{ν_e/ν_μ} for neutrinos

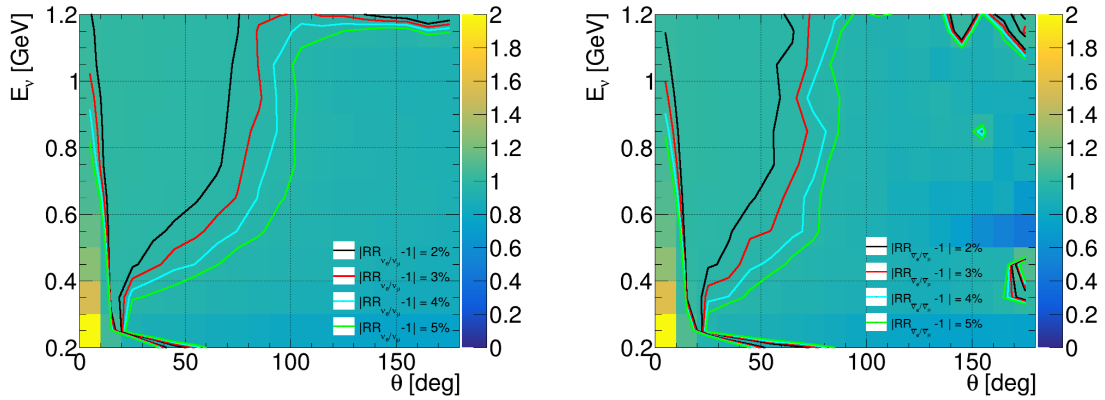
(b) HF-CRPA prediction of R_{ν_e/ν_μ} for neutrinos

Figure 1: The cross-section ratio R_{ν_e/ν_μ} for neutrinos as predicted for the SF and HF-CRPA models. Differences in the forward scattered region are discussed in [1].

A quantitative comparison between models can be achieved by determining the ratio of the cross-section ratios R_{ν_e/ν_μ}, between two models, as represented by the equation:

$$RR^{\text{Model A/Model B}}_{\nu_\alpha/\nu_\beta} = R^{\text{Model A}}_{\nu_\alpha/\nu_\beta}/R^{\text{Model B}}_{\nu_\alpha/\nu_\beta}.$$

In fig. 2 this comparison is shown for the SF and CRPA models, both for the neutrino and anti-neutrino cross-section ratio. Different levels of disagreement are indicated by contours at the 2,3,4 and 5% level. Deviations above 5% are seen beyond the previously discussed forward-scattered region, and include a significant portion of the backward-scattered phase space at angles above 100°. While a clear physical explanation cannot be provided, it should be noted that this region is less constrained by experimental data, primarily due to the forward-scattered nature of the neutrino interactions at these energies.

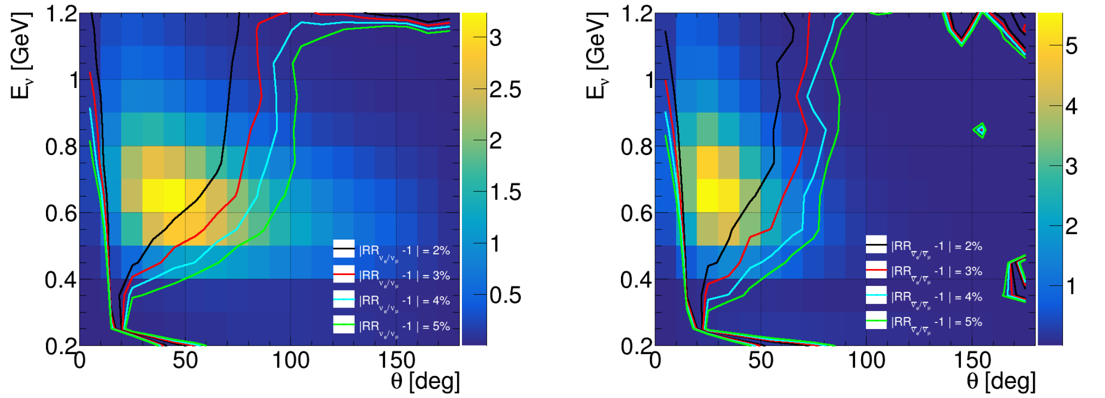


(a) $RR^{\text{SF/HF-CRPA}}_{\nu_e/\nu_\mu}$ for neutrinos **(b)** $RR^{\text{SF/HF-CRPA}}_{\nu_{\bar{e}}/\nu_{\bar{\mu}}}$ for anti-neutrinos

Figure 2: Comparison for the cross-section ratio between the SF and HF-CRPA models for neutrinos and anti-neutrinos. The superimposed lines indicate deviations away from unity at given levels.

3. Impact on long-baseline neutrino oscillation experiments

To understand the impact on neutrino oscillation experiments, the population of the experiments oscillated $\overset{(-)}{\nu}_e$ event rate in this phase-space needs to be considered. This is done by superimposing the contours indicating model deviations from fig. 2 on to the oscillated electron (anti)-neutrino event rate. For the HK experiment this is shown in fig. 4. The neutrino event rate shows a tail towards large angles, populating regions where deviations above 5% are observed. Due to their stronger forward scattered nature, the anti-neutrino plot shows a more concentrated event-rate, with less of its event-rate populating the region of large deviations.



(a) Oscillated HK event-rate for electron neutrinos **(b)** Oscillated HK event-rate for electron anti-neutrinos

Figure 3: HK oscillated event rates for electron (anti)-neutrinos, superimposed with lines indicating level of disagreement between SF and HF-CRPA models extracted from fig. 2.

To quantify the impact on the HK experiment, it is modeled as a simplified counting experiment. The deviations between models are averaged over the normalized event-rate. For the SF and CRPA models, this results in an uncertainty of 2.9% (1.3%) for the (anti-)neutrinos cross section ratio. These are then combined using error propagation to calculate the uncertainty on $\sigma_{e/\overline{e}}$, which was found to be 1.6% The same analysis was repeated for all models in table 1, with the results summarized in fig. 4. When comparing the same nuclear ground state model in different configurations, like using different axial masses M_A^{QE} or changing the target nucleus from carbon to oxygen, deviations below 0.3% are seen. However, when considering different ground state models, deviations are generally found to be larger and reach up to 2.2%

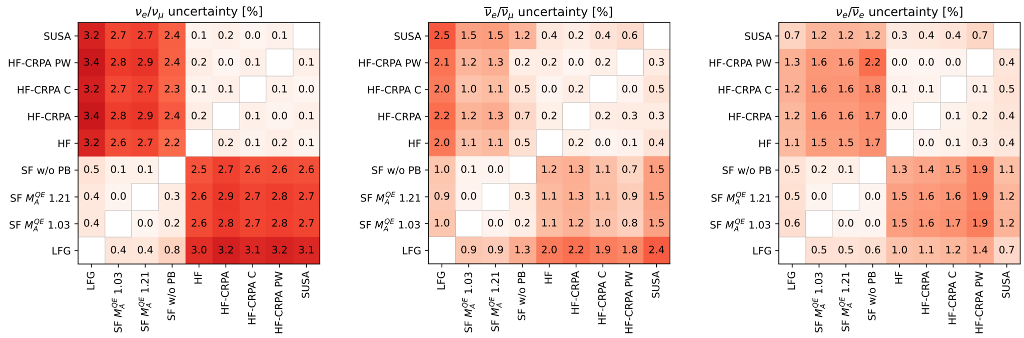


Figure 4: Estimated uncertainty for the HK experiment. The lower triangles are averaged over the event-rate predicted by the model on the x-axis, the upper triangle are the predictions when using the vent-rate predicted by the model on the y-axis. The $\nu_e/\overline{\nu}_e$ uncertainties are derived from the $\overset{(-)}{\nu}_e/\overset{(-)}{\nu}_\mu$ uncertainties by error propagation.

A similar study was performed for the ESSνSB experiment, which plans to use a mean beam energy of $\langle E_\nu \rangle = 0.2$ GeV, which is significantly lower compared to the HK experiments $\langle E_\nu \rangle = 0.6$ GeV. This makes the ESSνSB experiment more susceptible to the nuclear ground state and its modeling. This is reflected in a larger systematic uncertainty on the $\sigma_{e/\overline{e}}$ cross-section ratio, estimated to be 4%.

4. Summary

We have found that different nuclear ground state models for neutrino-nucleus interactions can alter the electron to muon neutrino cross-section ratio in a large part of the $(E_\nu, \cos\theta_\ell)$ phase space with angles above 100°. Treating the future HK and ESSνSB experiments as simplified counting experiments, this leads to uncertainties of approximately 2% and 4% respectively. As both experiments are expected to have systematic uncertainties of comparable size as statistical uncertainties or even smaller, it is important to take these uncertainties in to account. While we have only studied CCQE interactions, similar effects may play a role at different cross-section thresholds, i.e. the pion production threshold. A more detailed description of this study can be found in [2].

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