Impact of Nuclear Effects on the Extraction of Neutrino Oscillation Parameters

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study the possible impact of nuclear effects and final state interactions on the determination of the oscillation parameters due to the misreconstruction of nonquasielastic events as quasielastic events at low energies. We analyze a ν_μ disappearance experiment using a water Čerenkov detector. We find that, if completely ignored in the fit, nuclear effects can induce a significant bias in the determination of atmospheric oscillation parameters, particularly for the atmospheric mixing angle. Even after inclusion of a near detector, a bias in the determination of the atmospheric mixing angle comparable to the statistical error remains.

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Neutrino oscillation is firm evidence for physics beyond the standard model and, therefore, a rich program of neutrino oscillation experiments is ongoing and more ambitious projects are planned for the future. The eventual goal is to obtain sufficient precision as to be able to uncover the mechanism responsible for neutrino masses and mixing. Therefore, neutrino physics is evolving to become a precision science. In order to reach that goal, neutrino-nucleus interaction cross sections have to be known with sufficient accuracy. Thus far, only very few studies exist that establish a quantitative connection between uncertainties on neutrino cross sections and the resulting induced error in the determination of neutrino mixing parameters; see, e.g., Refs. [1–4].

Recent experimental results on neutrino cross sections, however, for instance, from the MiniBooNE Collaboration [5] or the MINERvA Collaboration [6], indicate that not only the total cross sections have large uncertainties but also the energy dependence and energy distribution of secondary particles is not well understood. The reason presumably lies in neglected nuclear effects and/or final state interactions—the fact that nucleons are bound inside the nucleus has multiple implications: (1) the initial and final state densities are modified, (2) many-particle correlations play an increased role, and (3) any reaction product has to make it out of the nucleus in order to be observed in the detector. For brevity we will refer to these phenomena collectively as nuclear effects. Obviously, a closed form description of this system is beyond our current abilities. Many approximate calculations exist, but only very few have been tested rigorously against data. A number of studies have addressed the impact of nuclear effects on oscillation analyses. In Refs. [7,8] the expected sensitivity of some oscillation experiments was presented for different assumptions of the nuclear model. No final state interactions were considered, though, and the nuclear model was assumed to be known by the time the data are analyzed. A different problem was considered in Refs. [9–11], where a *qualitative* description of the impact that final state interactions and multinucleon interactions may have on the event distribution was presented. In this work, we attempt to provide a *quantitative* estimate of the bias that the uncertainties on nuclear effects may induce in the determination of neutrino oscillation parameters, following a similar approach as in Refs. [9–11].

We focus the analysis on the so-called atmospheric oscillation parameters, θ_{23} and Δm^2_{31}, using quasielastic charged current (CC-QE) ν_μ events from a ν_μ beam, a so-called disappearance experiment. Generally speaking, in a neutrino oscillation experiment the amplitude of the oscillation provides a measurement of the mixing angle, while the energy dependence provides a measurement of the squared mass splitting. From this statement it is obvious that a correct identification of the neutrino energy is crucial to determine the mass splitting. However, a wrong identification of the neutrino energy can result in a pileup of the events at different neutrino energies, which would translate into a wrong determination of the mixing angle as well. For a CC-QE event, where the charged lepton produced in the final state is most readily observed, the neutrino energy is usually reconstructed using the kinematic variables of the charged lepton only. In the absence of nuclear effects, the number of events with neutrino energy E_i that are truly QE can be easily computed as

$$N_i^{\mathrm{QE}} = \sigma^{\mathrm{QE}}(E_i)\phi(E_i)P_{\mu\mu}(E_i), \qquad (1)$$

where $P_{\mu\mu}$ is the ν_μ disappearance oscillation probability, ϕ is the flux, and σ is the cross section for QE events, which is shown by the blue line in Fig. 1.

Let us consider now the case of a CC neutrino interaction that is not QE. Usually these interactions are discarded from the event sample if another charged particle (for example, a pion) is observed in the final state. However, there is a certain probability that the produced pion is absorbed by the nucleus and is therefore not detected. In this case, the only observable particle in the final state will be the charged lepton, and consequently this event will be added to the QE sample. In addition, since the event was

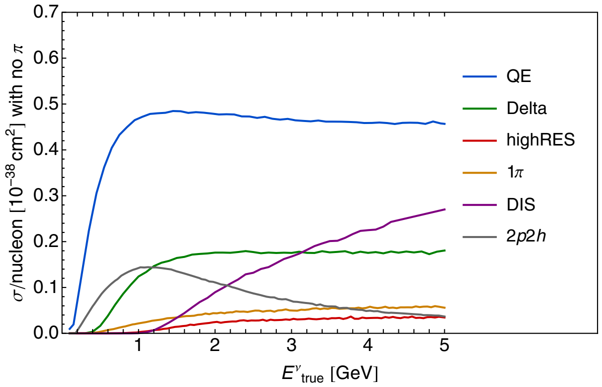

FIG. 1 (color online). Neutrino interaction cross section per nucleon for several processes in ^{16}O with no pions in the final state, as a function of the true neutrino energy. The labels in the legend indicate quasielastic (QE) Δ production (Delta), one pion production (1π), production of higher resonances (highRES), deep inelastic scattering (DIS), and two-particle-two-hole interactions ($2p2h$).

not purely QE and a particle in the final state was missed, this will most likely lead to a reconstructed energy smaller than the true incident neutrino energy. As a consequence, each bin in reconstructed neutrino energy will receive contributions from events that took place at different true neutrino energies:

$$N_i^{\text{QE-like}} = \sum_j M_{ij}^{\text{QE}} N_j^{\text{QE}} + \sum_{\text{non-QE}} \sum_j M_{ij}^{\text{non-QE}} N_j^{\text{non-QE}}$$
$$= \sum_j M_{ij}^{\text{QE}} \sigma^{\text{QE}}(E_j)\phi(E_j)P_{\mu\mu}(E_j)$$
$$+ \sum_{\text{non-QE}} \sum_j M_{ij}^{\text{non-QE}} \sigma_{0\pi}^{\text{non-QE}}(E_j)\phi(E_j)P_{\mu\mu}(E_j). \quad (2)$$

Here, the matrices M_{ij} account for the probability that an event with a true neutrino energy in the bin j ends up being reconstructed in the energy bin i. The matrix M_{ij}^{QE} is mostly diagonal and just adds a certain, quasi-Gaussian, smearing over Eq. (1). However, for non-QE this is not going to be the case. Different migration matrices are obtained depending on the particular interaction that has initially taken place. Therefore, a sum is performed over the different non-QE processes that take place in the detector with no second charged particle, i.e., pion, in the final state. The neutrino interaction cross sections on ^{16}O with no pions in the final state, $\sigma_{0\pi}$, are shown in Fig. 1 for all the processes under consideration in this work. Migration matrices for ^{16}O have been produced for each of these processes following Ref. [9]. The GIBUU [12] transport model has been used to generate both the migration matrices and the cross sections used in this work; see Ref. [12] for a useful review of transport models and details about GIBUU.

For the sake of simplicity we will use as input values for our analysis $\theta_{23} = 45°$ and $\Delta m_{31}^2 = 2.45 \times 10^{-3}$ eV^2 and choose the other oscillation parameters according to Ref. [13]. To illustrate the potential issues arising from nuclear effects, we choose as an example a low energy neutrino oscillation experiment, where a muon neutrino beam with a mean energy of 600 MeV is aimed at a water Čerenkov detector, mainly sensitive to QE events only. In particular, only events with one charged particle above the Čerenkov threshold are selected as signal, so-called single-ring events. The single-ring event criterion is very easy to implement in our calculation and the effect of non-QE events on the QE event sample therefore can be estimated without a detailed detector simulation. Many other experiments have detectors which are also sensitive to hadronic energy deposition in the detector and in some cases will even be able to reconstruct proton tracks (at least for a subset of events). For these detectors, a study of nuclear effects on energy reconstruction requires a detailed detector simulation, which is beyond the scope of this work. We consider only the $\nu_\mu \to \nu_\mu$ disappearance channel. The neutrino flux is the same as in Ref. [14]. For 5 yr of data taking assuming a beam power of 750 kW, our calculation yields an approximate number of ~850 true QE events and about ~1300 QE-like events. The event distributions as a function of the neutrino energy can be seen in Fig. 2 for both cases. The data are divided into 100 MeV bins between 0.2 and 2 GeV. Energy-dependent signal efficiencies for a water Čerenkov detector, following Ref. [15], have been included.

The uncertainties of the other oscillation parameters are negligible for the purpose of this work, and therefore we keep them fixed in the fit. Systematic uncertainties, on the other hand, are relevant and two types of systematic errors are included in the analysis: a 20% normalization error, bin to bin *correlated*, and a 20% shape error, bin to bin *uncorrelated*. A binned Poissonian $\chi^2_{i,D}$ is computed taking the signal rates per energy bin i and detector D as $S_{i,D}(\theta, \xi) = (1 + \xi_n + \xi_{\phi,i})N_{i,D}(\theta)$, where θ indicates the dependence on the oscillation parameters and $\xi_{\phi,i}$ and ξ_n stand for the nuisance parameters associated with flux and normalization uncertainties, respectively. The final χ^2 reads

$$\chi^2 = \min_{\xi}\left\{\sum_{D,i}\chi^2_{i,D}(\theta;\xi) + \left(\frac{\xi_{\phi,i}}{\sigma_\phi}\right)^2 + \left(\frac{\xi_n}{\sigma_n}\right)^2\right\},$$

where the first term corresponds to the binned Poissonian χ^2 and σ_k indicate the prior systematic uncertainties assumed (20% in all cases). More details on the χ^2 implementation can be found in Ref. [2]. We simulate an ideal near detector placed sufficiently far away from the source so that the observed spectrum is the same as in the far detector; i.e., we assume an energy-independent near/far ratio. Identical signal and background efficiencies are used as well. It should be stressed that, in real world cases, these conditions are likely not satisfied and the usefulness of the near detector is expected to be reduced. A Poissonian χ^2, where systematic errors are fully correlated between near and far detectors, is considered. We use a modified version of the

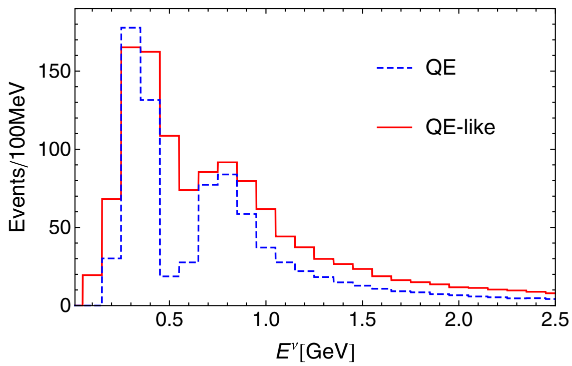

FIG. 2 (color online). Distribution of QE-like and truly QE events as a function of reconstructed neutrino energy. Signal efficiencies have already been accounted for. Background events are not included.

GLOBES software [16,17]; see Ref. [2] for details. In the fit, the *true* distribution of events is always computed according to Eq. (2). Two possible extreme situations arise: (1) nuclear effects are *completely ignored*, and we try to fit the true rates with the expected event rates computed from Eq. (1), or (2) nuclear effects are *perfectly known*, and the fit is done computing the expected event rates using Eq. (2). This is shown in the left-hand panel of Fig. 3. As can be seen from the fit, the very different distributions in the number of events in Fig. 2 lead to a significant shift in the best fit for the oscillation parameters, shown by the black triangle.

In reality, one is likely to be in between these two extremes of no versus perfect knowledge of nuclear effects. It is very difficult to quantify the "error" on models of nuclear effects, since they are generally not the result of a well-controlled expansion in some small parameter. One possible way to address this question from a phenomenological point of view is to introduce a parametrization which allows us to connect the two extremes in a continuous fashion:

$$N_i^{\text{test}}(\alpha) = \alpha \times N_i^{\text{QE}} + (1 - \alpha) \times N_i^{\text{QE-like}}, \qquad (3)$$

where α parametrizes the fraction of migration that is neglected in the fit: $\alpha = 0$ corresponds to Eq. (2) while $\alpha = 1$ corresponds to Eq. (1). The inclusion of this parameter may be regarded as an additional systematic uncertainty. Similar uncertainties were included, for instance, in Ref. [18]. However, it should be noted that in our fit it is not treated as a systematic uncertainty, since no marginalization over α is performed. Another possibility would be to compute migration matrices according to Eq. (2) using different nuclear models and take the spread of results as the measure of the error. For the following discussion α serves as a proxy for the error of the nuclear model. The result of varying α from 0 to 1 is shown in Fig. 3. The position of the best fit for different values of α is shown in the left-hand panel by the empty triangles. As can be seen from the figure, the deviation of the best fit from the true input value is progressively increased with the value of α. In the right-hand panel of Fig. 3 the increase of the minimum χ^2 as a function of α is shown: clearly, an error in the nuclear model would make the minimum χ^2 get worse. A sufficiently large value of the minimum of the χ^2 (with respect to the effective number of degrees of freedom) could eventually force rejection of the fit. Note that rejecting the fit at the end of

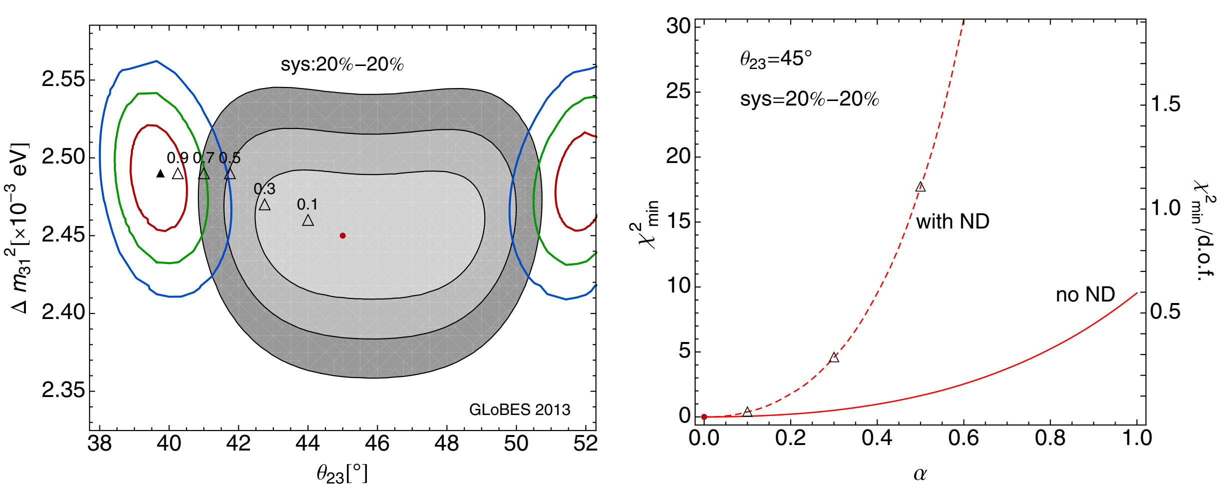

FIG. 3 (color online). Left: Confidence region in the $\theta - \Delta m^2$ plane for 2 degrees of freedom (d.o.f.) for different scenarios. Gray shaded areas show the results assuming the nuclear model is perfectly known. The lines depict the 1σ, 2σ, and 3σ regions for a fit taking $\alpha = 1$, where α represents the amount of migration due to nuclear effects that is being neglected in the fit; see text for details. A near detector is included in both cases. The triangles indicate where the best fit lies for the region enclosed by the colored lines as α is increased from 0 (red dot, corresponding to the true input value) to 1 (filled black triangle). Right: Minimum χ^2 as a function of α. For each line, the minimum value of the χ^2 is computed as the value of α is progressively increased from 0 to 1. The dashed and solid lines shows the result with and without a near detector (ND), respectively. For illustration purposes, some of the triangles in the left-hand panel (which correspond to the results including a near detector) are explicitly shown in this panel as well.

the experiment would still indicate its failure. The right-hand panel also indicates the effect of a near detector: the solid line shows the result without a near detector, whereas the dashed line shows the one with a near detector. Generally, the near detector adds more tension to the fit if the nuclear model is wrong and thus serves as an indicator that something is wrong. However, even for relatively large values of $\alpha \sim 0.3$–0.4 the minimum value of χ^2 would still be low enough so that the fit may be accepted, even if a near detector is included in the analysis. A value $\alpha = 0.3$ still corresponds, according to the left-hand panel, to a 1σ bias in the determination of the mixing angle. Therefore, it stands to reason that adding a near detector may not be sufficient to completely cure the problem: a successful experiment requires an accurate nuclear model, where the accuracy of the model has been independently verified.

Our results indicate that, for an experiment observing only QE-like events, a 1σ bias in the determination of θ_{23} could result from errors on the nuclear model even when taking full advantage of the near detector. This is a first study on the quantitative impact of nuclear effects on the determination of oscillation parameters. This type of study should be extended to experiments which can observe hadronic activity in the detector, as well as to appearance experiments, in particular, in the context of leptonic *CP* violation measurements.

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