Entanglement of Quasielastic Scattering and Pion Production

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Abstract. The extraction of neutrino oscillation parameters requires the determination of the neutrino energy from observations of the hadronic final state. Here we discuss the difficulties connected with this energy reconstruction for the ongoing experiments MiniBooNE and T2K. We point out that a lower limit to the uncertainty in the reconstructed energy from Fermi motion alone amounts to about 15%. The entanglement of very different elementary processes, in this case quasielastic scattering and pion production, in the actual observables leads to considerably larger errors. We discuss the sensitivity of the energy reconstruction to detection techniques and experimental acceptances. We also calculate the misidentification cross section for electron appearance in the T2K experiment due to neutral pion production.

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INTRODUCTION

Long-baseline experiments with neutrino beams use – due to the neutrino production mechanism – necessarily broad-band beams. This means that the neutrino (and antineutrino) energy is not sharp, but instead distributed over a fairly wide energy range. For example, the MiniBooNE experiment at Fermilab has an average neutrino energy of about 700 MeV, but the energy distribution extends all the way up to 2 GeV and beyond. This poses a challenge for all experiments that try to determine neutrino oscillation parameters from such experiments since the neutrino beam energy enters as a crucial parameter into all oscillation formulas. The only way out is then to try to reconstruct the neutrino energy from the hadronic and leptonic final state by assuming one special reaction type and using quasifree kinematics for this reaction on a target nucleon at rest. However, since all presently running experiments use nuclear targets the target nucleons all have momenta up to the Fermi momentum ($\approx 250$ MeV) so that there is a natural smearing of reconstructed energies even if the incoming energy distribution were sharp. In addition, the initial, primary final state is not observable. The same holds for the actual reaction mechanism of the first interaction of the incoming neutrino with a target nucleon. What is observable are knock-out nucleons and mesons that are created either in the first interaction (with a priori unknown reaction mechanism) or in some final state interaction (fsi). Various reaction mechanisms, such as quasielastic scattering (QE) or pion production dominate in different regimes of the energy transfer so that any broad-band experiment necessarily contains contributions from different reaction mechanisms. To isolate quasielastic scattering, for example, for use in the neutrino energy reconstruction then requires the use of event generators which are reliable not only for one particular
reaction type, but are well tested and reliable for a broad class of relevant reactions. In particular, the errors connected with the use of these generators have to be well under control [1, 2, 3].

**GIBUU TRANSPORT METHOD**

To account for all the different reaction types we use the GiBUU transport model [4], where the neutrino first interacts with one bound nucleon at a time (impulse approximation (IA)). The use of the IA requires a good description of both the elementary vertex and the in-medium-modifications. The final state of this initial reaction undergoes complex hadronic final-state interactions.

The GiBUU model is based on well-founded theoretical ingredients and has been tested in various very different nuclear reactions; in particular, against electron- and photon-scattering data [4, 5, 6]. The GiBUU model has been shown to work very well for QE scattering of electrons if the momentum-transfer is larger than about 300 MeV; comparison with photoproduction experiments for \( \pi^0 \) on nuclear targets shows that the cross section again is described very well up to the \( \Delta \) resonance peak, but comes out too low on the high-energy side of the \( \Delta \) by up to 20% for light nuclei [6]. These shortcomings may be due to a breakdown of the impulse approximation [7]. For more details on GiBUU we refer the reader to Ref. [4].

**QE-PION ENTANGLEMENT AND ENERGY RECONSTRUCTION**

In this section we now investigate how clean the experimental QE-like events actually are, to what degree they depend on the event reconstruction through some generator and how big the inaccuracies in the energy reconstruction actually are. We follow here closely the presentation in [8].

Fig. 1 shows the cross sections for scattering on \(^{12}\text{C}\) as a function of neutrino energy both for the Cherenkov (\(\mu, 0\pi\)) and the tracking detector (\(\mu, 1p, 0\pi\)) identification methods [8] for QE-like events. The solid curve in both cases shows the true CCQE cross section whereas the dashed line gives the QE-like cross section. It is seen that the Cherenkov detector identification method leads to a cross section that is about 20% higher than the true value; the surplus is due to primary resonance or pion production and subsequent fsi leading to pionless final states. For determination of the axial mass or for the reconstruction of the incoming neutrino energy this artificial surplus has to be removed with the help of an event generator. The opposite is the case for the tracking detector. Here the QE-like cross section is about 20% lower than the true value; this is because the secondary neutrons are not detectable. However, the QE-like sample is very ‘clean’ in that it contains nearly only original QE events.

A further complication arises because detectors are not perfect but have acceptance thresholds. In Fig. 2 we show the ratio of QE-like to true QE events as a function of proton kinetic energy threshold \(T\). It is seen that for a Cherenkov detector this ratio of \(\approx 1.2\) is rather independent of the proton detection threshold. On the contrary, for the tracking detector this ratio is a steeply falling function of \(T\) while the ratio depends much
less on the pion detection threshold (right part of Fig. 2). For the thresholds of about 175 MeV for the SciFi detector and about 75 MeV for the T2K tracking detector the ratios are about 50% or 70%, respectively. This means that a large part of the cross section is missing and has to be reconstructed by means of a generator, making the physics result depend to a large part on the quality of this generator. A similar result holds for pion production cross sections (for a detailed discussion see [8]).

We now discuss the quality of the energy reconstruction which is based on applying quasifree kinematics of true QE-scattering to QE-like events and neglecting Fermi motion [9]. Fig. 3 shows the distribution of reconstructed energies, obtained in a GiBUU simulation, for a fixed incoming neutrino energy of 1 GeV. The distribution is clearly affected by the two effects discussed above: Fermi motion leads to a broadening of the neutrino energy around the incoming energy; this accounts for the major peak at
The dashed curve gives the distribution of true QE events. Its width of about 16% is determined by Fermi motion alone and is thus always present; this defines the lower limit for any energy reconstruction via QE scattering. In addition the reconstructed energy distribution exhibits a clear bump at lower energies; this is caused by an initial pion production. The bump does depend on the pion detection threshold and amounts to about 15% of the true QE peak height at a realistic detection threshold of about 100 MeV pion kinetic energy. Taking this lower-energy bump into account raises the rms energy-width to about 22% (for a more detailed discussion see [8]). A qualitatively similar result has also been obtained by Tanaka (see Fig. 3 in [2]) using the GENIE event generator; there the lower-energy bump is even more pronounced.

The distribution of reconstructed neutrino energies for pion production events leads again to a rms energy-width of about 20% [8] (see Fig. 4). Since this uncertainty is unrelated to that inherent in the energy reconstruction for QE events, the overall uncertainty for the often-plotted ratio $1 \pi/CCQE$ as a function of neutrino energy also has an inherent inaccuracy of about $20\% \times \sqrt{2} = 30\%$ in its energy axis. Taking this properly into account can tilt the ratio as a function of neutrino energy quite significantly. We have just seen that the reconstructed energies carry an inherent error of at least about 16%, both for QE and for pion production.

These estimates rely on the impulse approximation. It has, however, recently been shown that the impulse approximation (IA) does not describe the full total neutrino cross section in the quasielastic region and that the identification method of the MiniBooNE experiment allows for a significant amount of non-QE $2p - 2h$ excitations in the QE-like cross section [10, 11, 12] that had not been removed by an event generator. These effects are not incorporated in the results above. Since for the $2p - 2h$ excitations the quasifree kinematics formulas used by experiment for the energy reconstruction do not apply, the actual energy uncertainty may even be larger. This point has not yet been studied in any detail.

**FIGURE 3.** (Color online) Distribution of the reconstructed neutrino energy using quasifree kinematics on a nucleon at rest for $E_{\nu}^{\text{real}} = 1$ GeV. Using only true CCQE events for the reconstruction leads to the dashed line. Including CCQE-like events (Cherenkov definition) with various charged pion detection thresholds, one obtains the solid line (no pion threshold), the dash-dotted line (100 MeV), and the dotted line (300 MeV) (from [8]).
The T2K experiment has recently reported the first experimental observation of electron neutrino appearance from a muon neutrino beam [9]. At the flux maximum the energy of is $\approx 600$ MeV. At this energy the error in the reconstructed energy, according to Table I in [8], amounts to about 21% for the Cherenkov detector. Fig. 1 shows that at 600 MeV the QE events are fairly clean, but that the admixture of pion production events rises significantly, already up to 1 GeV, reflecting the pion production threshold.

A crucial problem in any such experiment with Cherenkov counters is that the decay photons of neutral pions can be misidentified as electrons. We therefore, investigate in Fig. 5 the probability that a misidentified $\pi^0$ is counted as a $\nu_e$ appearance event. The probability that a $\pi^0$ cannot be distinguished from $e^\pm$ is given by the dashed line (taken from Fig. 2 of Ref. [14]). The solid line shows the weighted cross section averaged over...
the T2K flux and calculated using the elementary ANL data as input. The total cross section for misidentified events is now $0.09 \cdot 10^{-38}$ cm$^2$ and thus 26% of the true pion events. Again, this number does not include any $2p - 2h$ excitations.

**SUMMARY**

Broad-band long-baseline experiments with neutrino beams necessarily average over many different reaction types. This places particular requirements on any reliable event generator. Using GiBUU we have discussed the intimate entanglement of quasielastic scattering on target nucleons and of resonance excitations, which have to be disentangled for a determination of the neutrino energy. We have discussed the achievable accuracies for the latter. Fermi-motion alone already gives a minimum energy width of about 16% (at 1 GeV), independent of any special generator used. Misidentification of events raises this number up to 20 - 25%, larger than previously discussed values. Furthermore, in tracking detectors the sensitivity of QE identification to experimental detection thresholds is found to be large. The contribution of NC $\pi^0$ production to misidentification of electrons in T2K is found to amount to 26% of the total pion events. All of these numbers do not take into account any $2p - 2h$ effects and are thus lower limits.

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