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Systematic effects in MINOS- nuclear effects and hadronic energy scale uncertainty

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This paper gives some details of the analysis of an important component of the systematic error for the MINOS ν_μ disappearance measurement. The hadronic shower energy scale has a leading role in the Δm^2 measurement.

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1. Introduction

The MINOS experiment has been taking data since 2005 using the NUMI beam line at Fermilab. The parameters of ν_μ disappearance have been measured with increasing accuracy as the protons on target (POT) increase. The 2008 charged current (CC) analysis is based on $3.36x10^{20}$ POT and 848 events in the far detector [1]. The result is $\Delta m^2 = (2.43 \pm 0.13)x10^{-3} eV^2$ (68% CL) and $sin^2(2\theta) > 0.90$ (90% CL). Systematic errors are still smaller than the statistical errors, but gaining in importance as the data set increases. The largest components of the Δm^2 measurement and their dominant effect are the neutral current background (θ), near-far absolute normalization (Δm^2) and hadronic shower energy scale (Δm^2). Here we concentrate on the last item in this list. More details and a complete set of figures and references can be found in Ref. [3].

2. The NEUGEN3 Neutrino Event Generator

NEUGEN3 is a widely-used neutrino event generator that produces complete final states for neutrino-nucleus interactions for energies from 100 MeV to 100 GeV. It incorporates a Fermi Gas Model as the basic nuclear model with modifications for nucleon-nucleon correlations. The cross section model includes quasi-elastic interactions, resonance production, coherent neutrino-nucleus scattering, and non-resonant inelastic scattering. The model for non-resonant inelastic scattering is a modified DIS model which can describe electron scattering structure function data down to very low Q^2 and was designed for neutrino experiments in the few-GeV energy range. The most important model aspects for the hadronic shower scale uncertainty are the hadronization model, which determines the set of particles produced from a particular DIS event, the formation zone, and the intranuclear rescattering model, which determines how this set of hadrons is altered as altered by final-state interactions (fsi) as they exit the target nucleus. The model used for this study is version `v3.5.5` of `NEUGEN3` [4], the event generator version used for the production of the 2008 round of Monte Carlo simulations by the MINOS experiment.

3. Method

Details of the MINOS analysis can be found elsewhere [2]. The MINOS near detector measures the total hadronic energy (E_{had}) with a sampling calorimeter. A careful calibration process together with Monte Carlo modeling establishes the true value of E_{had}. The neutrino energy for each event is then the sum of this value and the muon energy. Modeling the missing energy is a key part of the analysis.

NEUGEN uses the AGKY hadronization model [5] to set the number and distribution of particles produced in a DIS interaction. It uses a mixture of models, each matched to neutrino-nucleus data. The concept of a formation zone for particles produced in the nuclear environment (it propagates a short distance with no interactions) is well-established in data. NEUGEN uses a constant time ($\tau_0 = 0.342 fm/c$) for this free step.

Like all neutrino event generator packages, the MINOS model for intranuclear rescattering of produced hadrons uses a semiclassical Intranuclear Cascade (INC) model. Here, we use the `INTRANUKE` model. Pions and nucleons propagating through the nucleus have a significant probability of final state interactions. The model uses a mean free path based on pion-nucleon cross sections and the nuclear matter density to choose where an interaction occurs. It then uses pion-iron and proton-iron cross section data and model results as a means to choose an interaction type. Extension to other nuclei is done assuming an $A^{2/3}$ dependence.

All these effects have significant influence on the spectrum of hadrons reaching the calorimeter and its response as modeled by GEANT. The estimated systematic error is based on results of E_{had} calculated with the proper neutrino spectrum as input to NEUGEN and a parameterized detector response. In a previous version, we used a reweighting technique [6]. Here, we make runs with parameters at new values and compare the corrected value of E_{had} to what was determined with the standard parameters. The main output is then the shift in the average value of E_{had} between the 2 parameterizations.

The parameters are divided into 2 classes, those based on external data and those based on model assumptions. Contributions from the 3 dominant physical effects will be presented.

4. Uncertainty due to final state interactions

For this part of the study we have evaluated the effect of the ten sources of uncertainty due to external data, each consistent with the estimated errors given in their publication. For this study we shifted each of these inputs by $+1\sigma$. In the case of specific reaction cross sections, the other cross sections are scaled down in their original proportions so that the total scattering cross section is unchanged. In each case the stated uncertainty refers to the magnitude of the relevant branching ratio or cross-section. The underlying cross-sections and branching ratios are energy dependent as are their uncertainties. The values adopted here correspond to the maximum value of the energy dependent uncertainties and are therefore overestimates.

Results are presented as the percentage change in the shower energy for a given model change as a function of the true value of ν, the energy transferred to the hadronic system. As in the previous study, pion absorption is the largest effect. Other contributions are less than 1%. Fig. 1(left) shows the contributions from all `INTRANUKE` external data sources added in quadrature.

Model uncertainties must be carefully evaluated. We found that to reproduce both hadron-nucleus total cross section data and neutrino pion production data [7], the mean free path had to be decreased with a larger effect at low energy hadron energy. We chose to model this as an increase in the nuclear size due to the Compton wavelength of the hadron. For the systematic error study, this value was changed to match the neutrino data estimated errors (a conservative choice). The other change was to double the number of nucleons emitted in pion absorption, also a very conservative choice. The results are shown in Fig. 2. For each, the change is about 5% at low ν energy, decreasing to less than 2% at about 5 GeV. The total error due to final state interaction sources is seen in Fig. 3 (right).

5. Uncertainties due to Formation zone and Hadronization

The treatment of the hadron formation zone used in `NEUGEN3` is a model presented by the SKAT collaboration to describe their data [8]. One source of uncertainty is a variation in the formation time, τ_0, by 50%. More recent data has shown a more complicated description is required. This new information has been incorportated into a new model. A preliminary version is available

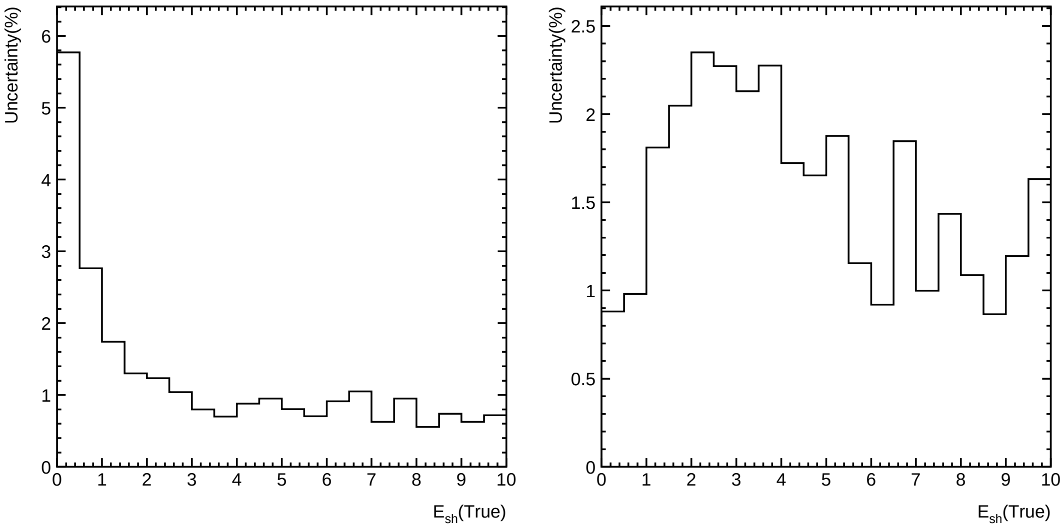

Figure 1: (left) Total uncertainty from all `INTRANUKE` external data sources. (right) Total uncertainty from all formation zone sources.

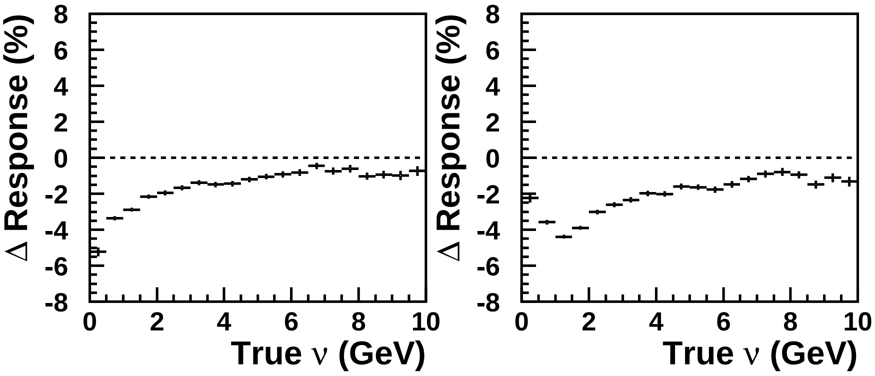

Figure 2: The results of model changes in the nuclear size (left) and the treatment of pion/nucleon absorption (right).

but not used in analysis yet. The differences between the present model and the preliminary model provides the second source. The quadrature sum of the two contributions to the formation zone uncertainty is shown in Fig. 3(right).

For hadronization model uncertainty, there are too many parameters to consider each one. Therefore, we compare the results of the present model (AGKY) vs. what was obtained with the previous model. Since the previous model was unable to describe data that the present model matches, this is also a conservative choice. The uncertainty in the shower energy response coming from the hadronization model is shown in Fig. 3 (right).

6. Conclusion

The quadrature sum of the contributions to the shower energy scale uncertainty from fifteen independent sources is summarized in Fig. 3 (right). Also shown are the contributions from each

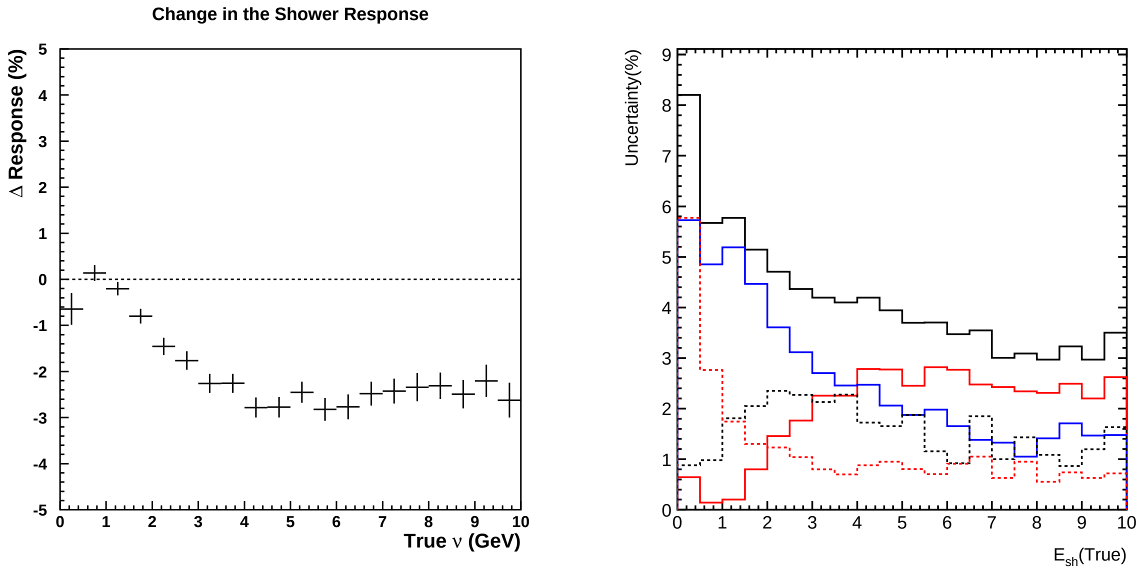

Figure 3: (left) Changes to the hadronization model. (right) Total uncertainty from all sources (solid black). Contributions from intranuke assumptions (blue), `INTRANUKE` input (dashed red), hadronization model (solid red), and formation zone (dashed black).

of the categories described in this paper. The largest excursion in a single bin is 8.2% and occurs in the lowest energy bin.

There is a strong energy dependence to the uncertainty. The main reason is that the first two energy bins largely populated by quasi-elastic events which are strongly affected by intranuclear rescattering. This is because the hadron energies are low; as a result the rescattering cross sections are large and these events are not subjected to the formation zone. At high energies the uncertainty is reduced because the formation zone carries most of the hadrons out of the nucleus before they have a chance to interact. For many MINOS analyses the hadronic energy scale uncertainty is characterized by a single number. When that is done, a conservative approach is chosen where the 8.2% value corresponding to the largest excursion a single energy bin will be used.

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