EVENT GENERATOR VALIDATION AND SYSTEMATIC ERROR EVALUATION FOR OSCILLATION EXPERIMENTS*

Hugh Gallagher

Tufts University, Medford, MA 02155, USA

(Received June 26, 2009)

In this document I will describe the validation and tuning of the physics models in the GENIE neutrino event generator and briefly discuss how oscillation experiments make use of this information in the evaluation of model-related systematic errors.

PACS numbers: 07.05.Tp, 13.15.+g

1. Introduction

One of the main difficulties in producing an event generator for the few-GeV energy regime of interest to long-baseline oscillation experiments is that this energy range straddles several different pictures of the fundamental scattering mechanisms. Nuclear physics plays a large role, and one has to piece together models which might overlap in their kinematic coverage, or require extrapolation beyond their stated range of validity, in order to generate events over the full phase space. A standard combination used in several generators [1–4] include quasi-elastic scattering using the Llwelleyn-Smith expressions [5], the Rein–Sehgal model for resonance production [6], and the Bodek–Yang modified LO model for non-resonant inelastic production [7]. Despite the use of 'identical' models, these generators can still produce large variations in predictions resulting from different form factors, different values of parameters like axial masses, different choices about how to implement models (such as whether to fully include interference terms in the Rein–Sehgal model), and choices about how to combine these various pieces into an overall cross-section model in ways that avoid discontinuities and double counting.

* Presented at the 45th Winter School in Theoretical Physics "Neutrino Interactions: from Theory to Monte Carlo Simulations", Lądek-Zdrój, Poland, February 2–11, 2009.

2. Event generator physics and tuning

One of the challenges recognized in the design phase of the GENIE package was the necessity to have transparent and easy-to-use validation packages. These procedures are used in a variety of situations: for the tuning of model parameters, for overall validation of the total model, for regression testing, to evaluate the effectiveness of new models, to decide which models to use as the default, and to guide systematic error evaluation for experimental users. A design decision was made for the GENIE package to try to make all of the information required to carry out these tasks a part of the GENIE package itself. This includes external data (distributed in XML format and stored in mySQL databases to facilitate complicated queries and data selection), software tools to facilitate validation [8], and separate packages to carry out canonical validation studies. Much of the data in the package was obtained from the Durham database [9] as well as private data collections which others have generously shared [10, 11].

2.1. Cross-section models

The cross-section model used in GENIE contains many separate processes [4]. A number of these processes, such as neutrino–electron elastic scattering, coherent production, and other rare processes are large decoupled in the determination of the overall cross-section model, and can be validated independently. For example, the GENIE coherent cross-section model is validated by comparing the total cross-section prediction for NC and CC channels with data from previous bubble chamber and counter experiments.

Combining quasi-elastic, resonance production, and non-resonant inelastic contributions to the total cross-section has been a subject of considerable debate. For this task we consider a variety of data, some of which is used for model tuning, and others are used strictly for validation of the total model.

In tuning the cross-section model we proceed in several stages: We start by examining the agreement between the Bodek–Yang model and charged lepton structure function data F_2 and neutrino data for F_2 and xF_3 [12]. Neutrino quasi-elastic scattering and Δ production data are used (particularly kinematic distributions), to determine the values for the axial masses. Given a scheme for combining these three ingredients into an overall model, we start with reasonable guesses for the parameters and compare the electron scattering predictions to inclusive electron scattering data at comparable kinematics, and then tune remaining parameters to neutrino total cross-section and single pion data. The specific algorithm for combining DIS, resonance and QEL channels is described elsewhere [13], but for the purposes of this discussion it is sufficient to point out that the approach involves 9 parameters, 2 for each combination of (CC/NC and neutrino/target), and one for an overall DIS cross-section scale factor. The assumption of isospin invariance and equating charged current and neutral current parameters reduces the number of parameters to three. These three parameters are then determined from fits to the charged current single pion and inclusive cross-section data. Comparison between the model and neutrino xF_3 data is shown in Fig. 1. In order to see the effect of combining models and to verify that the implementation is correct, the structure functions are extracted from the predicted doubly-differential cross-section [13].

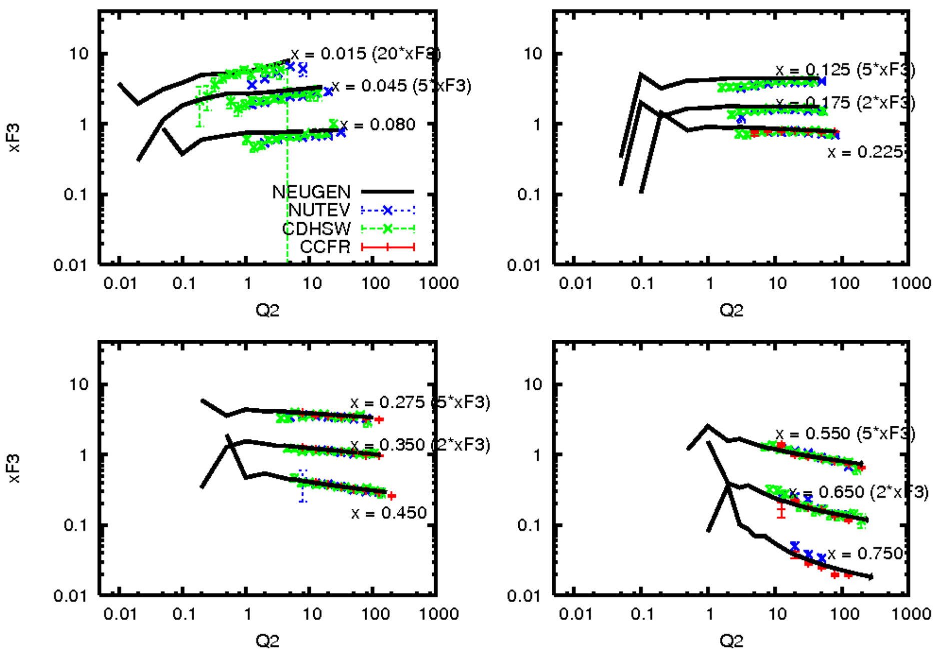

Fig. 1. Neutrino data on xF_3 compared with the predictions from the NEUGEN3/GENIE event generator.

2.2. Hadronization model

The characteristics of neutrino–produced hadronic systems have been extensively studied by the Big European Bubble Chamber (BEBC) at CERN, the 15-foot bubble chamber at Fermilab, and the SKAT bubble chamber in Russia. Measurements include averaged charged and neutral particle (π^0) multiplicities, forward and backward hemisphere average multiplicities and correlations, strange particle multiplicities, topological cross-sections of charged particles, neutral-charged pion multiplicity correlations, fragmentation functions (z distributions), $x_{\rm F}$ distributions, $p_{\rm T}^2$ (transverse momentum squared) distributions, and $x_{\rm F} - \langle p_{\rm T}^2 \rangle$ correlations ("seagull" plots). This data was extensively used to validate the AGKY hadronization model used in GENIE [14]. Over the range of invariant mass important to few-GeV experiments, several different hadronization models are used including resonance models at lowest invariant masses, a KNO-based empirical model at intermediate masses, transitioning up to JETSET [15] at 3.0 GeV/c^2. Being able to compare to a wide variety of data was invaluable for the tuning of this model, and data comparisons were done by generating large samples of simulated data and attempting to replicate the experimental cuts. An example of one such comparison, to the average charged-hadron multiplicity, is shown in Fig. 2.

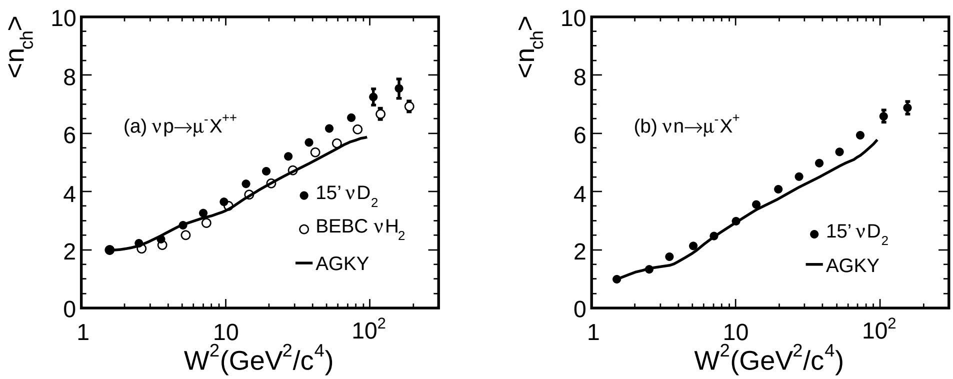

Fig. 2. Average charged-hadron multiplicity $\langle n_{\rm ch} \rangle$ as a function of W^2. (a) νp events. (b) νn events. Data points are taken from [16, 17].

2.3. Intranuclear rescattering

The intranuclear rescattering model has been tested and tuned based on comparisons to hadron–nucleus data, and validated against a limited sample of neutrino–neon data. Hadron–nucleus cross-sections are calculated by 'MC experiments' where a nucleus is being illuminated by a uniform hadron beam with transverse radius larger than the nucleus size. Figure 3 shows the comparison between INTRANUKE and data for π^+–Fe total and reaction cross-sections. The estimated probability of pion absorption for neutrino–neon events in a bubble chamber experiment weighted to an atmospheric neutrino flux was measured to be 22±5% [18], the comparable probability from a GENIE simulation of the experiment is 18.3±0.4%.

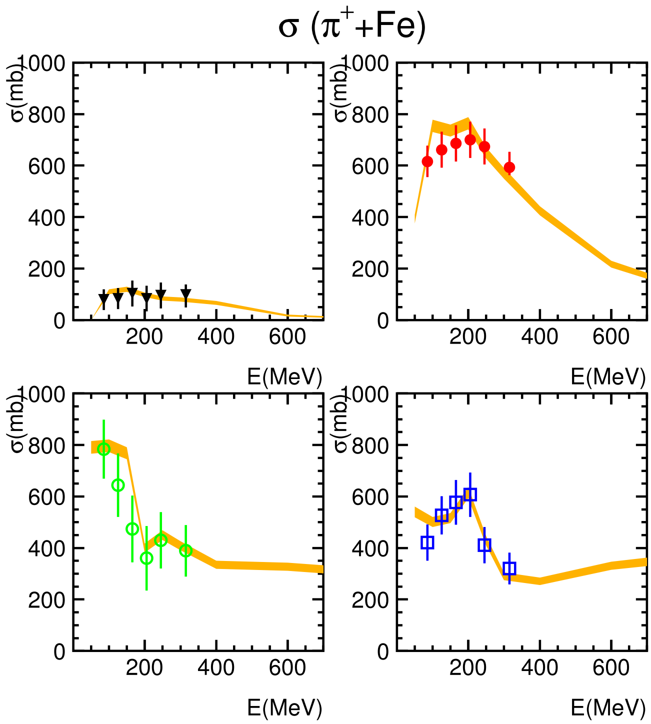

Fig. 3. Cross-sections for specific π^+–Fe reaction mechanisms. Points with error bars are data and colored bands are the INTRANUKE prediction. The width of the bands come from MC statistics. Top left: charge exchange. Top right: elastic scattering. Bottom left: inelastic scattering. Bottom right: pion absorption.

3. Systematic error evaluation

Experiments have devised a number of different methods for determining the systematic errors associated with model uncertainties. Assuming that the uncertainty in a particular model aspect has been estimated one can proceed in a number of ways:

(1) Generating entirely new Monte Carlo samples with the model shifted by some amount; data is reanalyzed with the new Monte Carlo to determine the change in the result.

(2) If the effect of the model change is in a parametrization in one of the models, and one can quickly calculate the probability for generating a particular event given a particular model, one can reweight the standard Monte Carlo sample to achieve the same result.

(3) Perform other estimates based on parametrizations of detector response fast Monte Carlos.

(4) Estimate systematic errors using data-based techniques from independent samples. In practice, most experiments end up using some combination of these various techniques.

For many of these approaches, it is important for experimenters to know what reasonable variation on the model parameters are. Providing the validation data together with software tools to compare GENIE predictions to this data gives an invaluable new tool in this regard.

4. Conclusion

To generate events over the full phase space for few-GeV interactions requires piecing together many different models. The tuning and validation of these models based on external data is a crucial procedure, and in this document we have briefly described the validation of the cross-section, hadronization, and intranuclear rescattering models used in GENIE. By design GENIE provides the external data, tuning, and validation procedures as part of the package so as to facilitate experimental tasks such as the evaluation of generator-related systematic errors. As the world's data set of neutrino interactions in the few-GeV energy range expands dramatically over the coming years, these tools will become increasingly important.

REFERENCES

[1] Y. Hayato, *Nucl. Phys. Proc. Suppl.* **112**, 171 (2002).
[2] D. Casper, *Nucl. Phys. Proc. Suppl.* **112**, 161 (2002) `[hep-ph/0208030]`.
[3] H. Gallagher, *Nucl. Phys. Proc. Suppl.* **112**, 188 (2002).
[4] C. Andreopoulos, *et al.*, `arXiv:0905.2517 [hep-ph]`.
[5] C.H. Llewellyn-Smith, *Phys. Rep.* **3**, 261 (1972).
[6] D. Rein, L.M. Sehgal, *Ann. Phys.* **133**, 79 (1981).
[7] A. Bodek, U.K. Yang, *J. Phys. G* **29**, 1899 (2003) `[hep-ex/0210024]`.
[8] C. Andreopoulos, H. Gallagher, *Nucl. Phys. Proc. Suppl.* **139**, 247 (2005).
[9] M.R. Whalley, *Nucl. Phys. Proc. Suppl.* **139**, 241 (2005) `[hep-ph/0410399]`.
[10] S.C. Wood, `http://hallcweb.jlab.org/resdata`
[11] S. Zeller, private communication.
[12] D. Bhattacharya, FERMILAB-THESIS-2009-11.
[13] H. Gallagher, *Nucl. Phys. Proc. Suppl.* **159**, 229 (2006).
[14] T. Yang *et al.*, `arXiv:0904.4043 [hep-ph]`.
[15] T. Sjostrand, *Comput. Phys. Commun.* **82**, 74 (1994).
[16] D. Zieminska *et al.*, *Phys. Rev.* **D27**, 47 (1983).
[17] P. Allen *et al.*, *Nucl. Phys.* **B181**, 385 (1981).
[18] R. Merenyi *et al.*, *Phys. Rev.* **D45**, 743 (1992).