Discussion: Confronting Theory and Experiment

Hugh Gallagher*, Yoshinari Hayato† and Jan Sobczyk**

*Tufts University, Department of Physics and Astronomy, Medford, USA
†University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan
**Wroclaw University, Faculty of Physics and Astronomy, Wroclaw, Poland

Abstract. This session focused on the current status of neutrino event generators, in practical terms the tool through which 'theory confronts experiment'. Comparisons of event generators, both in terms of input physics, and in terms of produced distributions, has been a staple of this conference series, and the activities in this area are summarized. In addition, we discuss the highest priorities for model development, discuss the changing needs of experimental users, and comment on challenges and needs for the road ahead.

Keywords: Neutrino-Nucleus Scattering, Monte Carlo Simulations
PACS: 13.15.+g,25.30.Pt

INTRODUCTION

Monte Carlo simulations play a crucial role in the analysis of data from neutrino experiments, and are indeed the arena where 'theory confronts experiment' (or vice versa). A glance back through the proceedings of NuINT conferences over the past 12 years demonstrates that the physics content of these simulations has been a ripe topic for conversation, and that broadly speaking, it has improved as a result of these discussions. This has happened both through the incorporation of new theoretical work into existing codes (NEUT [1], NUANCE [2] ,GENIE [3]), the development of entirely new simulation packages with modern treatments of crucial nuclear physics aspects (NuWro [4]), or through the expansion into neutrino-scattering by pre-existing nuclear interaction and scattering packages (GiBUU [5], FLUKA [6]).

Discussions of the accuracy of models for neutrino-nucleus simulations has been a focal point of this conference series from its inception, and the reason is clear: the increasing precision of neutrino oscillation experiments will require, over time, increasing precision in our ability to simulate neutrino-nucleus scattering processes. Several experiments are now in the position where systematic uncertainties in neutrino interactions are among the largest systematic uncertainties. While these may currently be smaller than the statistical uncertainties, it is clear that improvements are needed, in particular to aspects related to the nuclear physics, if we are to continue to improve our knowledge of the lepton sector. The recent discovery of large θ_{13} has reenergized our field and suggests that measurements of the mass hierarchy and δ_{CP} may be within the reach of the coming generation of experiments. This has accelerated the discussion of model accuracies, in particular as a large θ_{13}, while guaranteeing sizable signatures in future appearance experiments, will require much higher precision (less than 5%) in our modeling of backgrounds than currently exists. In addition, new proposals to measure the mass hierarchy depend on accurate predictions of the neutrino/anti-neutrino cross section ratio. As the experimental landscape shifts, so too does our focus on the areas of simulation that are most vital for the upcoming experimental campaigns.

MONTE CARLO COMPARISONS AND NEW DATA

Comparisons between the available event generators has been a recurring activity through the NuINT conference series [7, 8]. These comparisons have been valuable for a number of reasons. They have provided experimentalists with a sense of the model spread associated with particular observables; theorists have benefited from seeing how different models lead to differing predictions once all the other model components have also been included; and most importantly, perhaps, they provide a concrete means of starting conversations between generator developers, theorists, and experimental users about what is 'under the hood' in these complex packages.

Perhaps most surprising, given the large spread in predictions that these comparisons have produced, is that these generators are assembled largely from a set of common ingredients: descriptions of quasi-elastic/elastic scattering via nucleon form factors, models for single pion production via resonance production, modified parton-model based treatments of deep (and not-so-deep) inelastic scattering, impulse approximation treatments of nuclear dynamics, and intrancuclear cascade simulations. They differ most substantially in their content in the area of nuclear physics, nonetheless, many aspects of the free nucleon simulations lead to surprisingly large differences. Such elements include the tuning of parameter values (e.g. axial masses), how models are combined in regions of phase space where they overlap, and in the hadronization of hadronic systems with masses too low to be handled by JETSET.

One of the other conclusions from previous generator comparisons exercises is that choosing distributions for comparison can itself be a challenge. The wide variety of methods used by oscillation experiments make it impossible to select a small set of distributions that would be of interest to the entirety of the experimentalist audience. For this version, we opted for a different approach, and asked each of the running and near-future experiments to identify several distributions that they are particularly concerned about. These probe the crucial aspects of the simulation for that experiment, and it was hoped that the resulting comparisons and discussion would give these experiments a better sense of the model spread and theoretical uncertainty impacting their central measurements. The results of this exercise were presented in three talks at this conference [11, 12, 13].

As an example of one of the sets of distributions presented, see Figure 1. This request came from the LBNE collaboration, who asked to see proton multiplicity distributions for 2.5 GeV ν_μ CC interactions from Argon, with and without a 50 MeV KE cut. These distributions are dominated by the treatment of intranuclear rescattering, in particular pion absorption, which occurs with high probability at this energy. The large spread in the predictions is not surprising given the range of different microscopic models used in these simulations, and the lack of external data to constrain them. This comparison indicated that the prediction for the fraction of events that would have an identifiable proton (KE$>$ 50 MeV) ranges from approximately 8% to 27%.

Since liquid argon technologies are poised to be the centerpiece of the coming generation of large neutrino oscillation experiments, improving the modeling of detailed aspects of hadro-production will be important if these experiments are to achieve their full potential. In this vein, NuINT12 was a landmark conference, as within a few days of seeing these generator-to-generator comparisons, we were seeing comparisons between simulations, and actual data from a high-resolution liquid argon device (ArgoNEUT) [14]. While these comparisons were preliminary, it was clear that these data offer a wealth of new opportunities for studying in an unprecedented way details of the event that had previously been unmeasurable. We expect that these kinds of high-resolution comparisons will come to occupy a larger role in the coming years and will offer excellent opportunities for improving the modeling of one of the most important and complicated aspects of these simulations.

Multinucleon Ejection Contribution

Over the past decade this field has unearthed some interesting questions, which remain unresolved. Data on quasi-elastic-like scattering from nuclear targets produced results which disagree with the expectation from the bubble chamber era and the straightforward nuclear models. The exploration of this phenomena by the most recent generation of neutrino experiments, and the accompanying theoretical interpretation, has been one of the dominant investigations of the past five years. Revisiting this subject from the aspect of electron scattering has led to the intriguing interpretations of these data in terms of multi-nucleon scattering processes. The search for clear experimental evidence for the existence of such processes requires not only models for these processes, but for these models to be available in the experiment's simulations as the effect that these scattering processes have on a particular experiment's analyses depend entirely on how they populate different event samples. An additional complication is that these processes are intertwined with FSI effects. Finding evidence for meson exchange current (MEC) contributions, and disentangling them from FSI effects, is a daunting experimental challenge.

In this session there was a talk by T. Katori summarizing the progress on incorporating models for multi-nucleon scattering mechanisms into the various generators [15]. His talk highlighted some of the issues in having to actually generate events - which requires four-vectors for all outgoing particles - in particular in creating multi-nucleon hadronic systems. Here are a few of the questions that must be answered in producing full simulations of these events, and the approaches taken by the existing sets of programs (courtesy T. Katori [15]):

1. **What kind of Leptonic Model?** While GENIE uses a homegrown model [15], NuWRO makes available three different MEC models for CC reactions and one for NC [9]. GiBUU uses the transverse projector for the hadronic

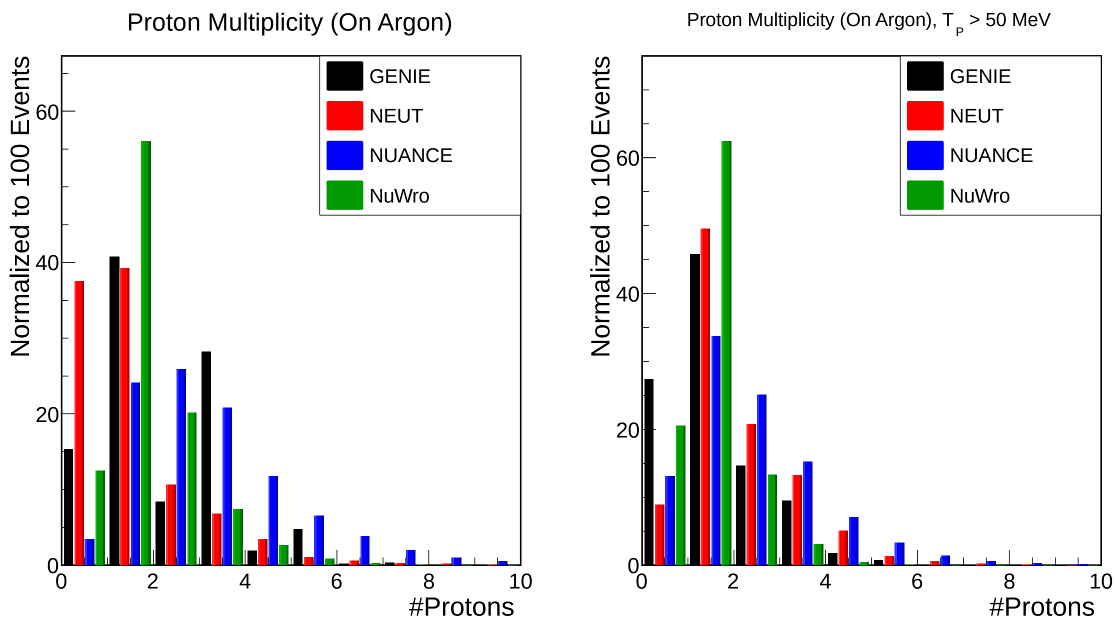

FIGURE 1. Proton Multiplicity for 2.5 ν_μ CC scattering from Argon. All protons (left), protons with KE>50 MeV (right) [13].

tensor [10].

2. **How To Choose the 2 Nucleon Momenta?** All simulations select them from the Fermi sea, independently. For GENIE and NuWRO their locations are random and there are no correlations, while in GiBUU they are at the same location and the cross section is weighted by the phase space density.
3. **What kinds of pairs are produced?** In GENIE the n-p and n-n pairs are selected in the ratio of 1:4, while in NuWRO they are in the ratio of 9:1, and in GiBUU they are selected in the ratio of 3:1.
4. **How to share energy-momentum transfer between the two nucleons?** In GENIE and NuWRO the 'nucleon cluster model' [9] is used.

It is clear that these modeling questions will have a significant impact on the search for MEC and the interpretation of data from experiments over the next few years. Having the opportunity to continue the detailed comparison between models, and between models and new data, will be vital as our community attempts to make headway on this challenging topic.

MORE GENERAL ISSUES

There were several themes that emerged from the discussion at this meeting. It was clear that the tension between prioritization of 'having the right physics' versus 'describing the data' is still with us, in particular as more data is becoming available. While a putative theorist or experimentalist might claim a strong preference for one side of this argument, the reality is that generator developers strive to achieve both aims.

The view was expressed that while generator comparisons are interesting, since there are so many things that could contribute to differences in distributions, a different approach might be desirable in the future. This would involve starting with comparisons to the more basic data used for tuning, for instance bubble chamber data on hydrogen and deuterium, and working one's way up through the variety of data that is used for tuning and validation purposes. This would certainly be a worthwhile undertaking and might help to improve our collective understanding of the perceived tensions that exist between various data sets at present, and it is clear that in many areas our simulations cannot be more accurate than our current knowledge of neutrino cross sections, which in many cases is on the order of 20%.

The question emerged of prioritization of model improvements. Of all the areas where the physics content of these simulations could be improved - which are the pressing priorities? From the talks and discussions at this conference it seemed clear that the leading candidate was in the area of multi-nucleon scattering processes. There were several interesting talks at this conference on work in this area, and we expect that this is a topic that will be heavily discussed at the next NuINT as well.

A perennial question, and one that we do not, as a community, seem to have made a great deal of practical progress on, is in defining mechanisms through which sophisticated theoretical models can be incorporated into existing simulations. This question touches on many practical questions, such as the phase space coverage of specific models and computational requirements, which often need to be hashed out on a case-by-case basis, nonetheless, this is probably an area where as a community we would move toward clarifying some of the useful steps. Some examples include the question of which format for model predictions is most suitable both for theorists and MC authors? Could nuclear response functions, or structure functions, serve this end? Can we as a community define a generic event generator output format, which would allow experiments to use the predictions of a variety of generators in a seamless way? It will be important to continue the discussion around these concrete topics, so that we can ensure that the new ideas that are being produced can be used by the widest community possible.

ACKNOWLEDGMENTS

The authors would like to thank the organizers of the NuINT 2012 Conference for the opportunity to discuss these important topics in such a collegial and spectacular environment. H.G. would like to acknowledge the support of DOE-HEP grant DE-FG02-12ER41791. J.S. would like to acknowledge the support of grant 4574/PB/IFT/12 (UMO-2011/01/M/ST2/02578).

REFERENCES

1. Y. Hayato, *Nucl. Phys. Proc. Suppl.* **112**, 171–176 (2002).
2. D. Casper, *Nucl. Phys. Proc. Suppl.* **112**, 161–170 (2002), hep-ph/0208030.
3. C. Andreopoulos, A. Bell, D. Bhattacharya, F. Cavanna, J. Dobson, et al., *Nucl.Instrum.Meth.* **A614**, 87–104 (2010), 0905.2517.
4. C. Juszczak, J. A. Nowak, and J. T. Sobczyk, *Nucl.Phys.Proc.Suppl.* **159**, 211–216 (2006), hep-ph/0512365.
5. T. Leitner, L. Alvarez-Ruso, and U. Mosel, *Phys.Rev.* **C73**, 065502 (2006), nucl-th/0601103.
6. G. Battistoni, A. Ferrari, M. Lantz, P. Sala, and G. Smirnov, *AIP Conf.Proc.* **1189**, 343–346 (2009).
7. H. Gallagher, D. Casper, Y. Hayato, and P. Sala, *Nucl. Phys. Proc. Suppl.* **139**, 278–285 (2005).
8. S. Boyd, S. Dytman, E. Hernandez, J. Sobczyk, and R. Tacik, *AIP Conf.Proc.* **1189**, 60–73 (2009).
9. T. Golan, C. Juszczak, and J. T. Sobczyk, *Phys.Rev.* **C86**, 015505 (2012), 1202.4197.
10. O. Lalakulich, K. Gallmeister, and U. Mosel, *Phys.Rev.* **C86**, 014614 (2012), 1203.2935.
11. S. Dytman, these Proceedings.
12. T. Golan, these Proceedings.
13. N. Mayer, these Proceedings.
14. K. Partyka, these Proceedings.
15. T. Katori, these Proceedings.