ECT* Workshop
Modelling v Interactions

NuFact 2019

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ECT* - European Centre for Theoretical Studies

Located in beautiful Trento, Italy

ECT* Support research in:
Nuclear Structure and Nuclear Reactions, and related topics

Hosting workshops
Modelling $\nu$ interactions Workshop

Goals:

To improve the neutrino-nucleus events generators by:

- Learning from the nuclear physics community
- Share models, tunes and methods inside the generators community
Modelling v interactions Workshop

Organisers:
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Participants:
Generator representative, Theory groups, Electron scattering experimentalists

Structure:
4 main working group with assigned homework in advance
Review task list for the meeting
Ending presentation on progress and plans

Website: https://indico.ectstar.eu/event/53/
This workshop followed a theory oriented one: https://indico.ectstar.eu/event/48/
Bridging between $\nu$ and N communities

The neutrino community needs:

- Valid predictions for different interaction channels
- Heavy nuclei studies

The electron scattering experiments measures and theorist predicts:

- Inclusive rates vs. energy transfer
- Only lower $A$ nuclei till now
WG2 Cross Section Focus
WG2 Cross Section Focus

- Models
- THEORY
- EXPERIMENTS
- GENERATORS

Empirical Models
WG2 Cross Section Focus

Testing models
The background & efficiencies are model dependent

\[ \sigma = \frac{N_{on} - N_{off} - B_n}{\eta_n \cdot \Phi\, \cdot \, N_{\text{targets}} \cdot \Delta^\mu_n} \]
Generators goals

Comparison between models

Implementing specific models

Unified models for neutrino and electrons scattering
Generators goals

1. Structure for exclusive models
2. Design an interface for theorists to provide models.
3. Better ability to compare multiple models and generators
4. Improved reweighting functionality and documentation of reweighting
5. More information about, and ability to interact with and modify, the tuning of the parameters in interactions
Factorisation

\[ \frac{d^2\sigma}{dq_0 q_3} = \sigma_0 \eta_{ij}(q_0, q_3) W_{ij}(q_0, q_3) \]

Contraction of leptonic and hadronic tensors.

Expanding in general way one get 10 response functions most of them cancel when integrating over the hadronic kinematics.

The leptonic part is easily calculated

The hadron tensor elements are sorted in tables per target in \( q_0, q_3 \) space

Adapted from: https://indico.ectstar.eu/event/19/contributions/221
Factorisation

Generators like GENIE predict hadron kinematics:

1. Start with inclusive prediction
2. Pick random initial state nucleon momentum (irrespective to $q_0$ and $q_3$)
3. Get removal energy from RMF (re-throw if nucleon is pauli blocked)
4. Transfer all $q_0$ $q_3$ to nucleon (none to remnant)
5. conserve energy / momentum at the vertex to predict hadron kinematics (under impulse approximation)
6. add FSI cascade

In reality the components are not separable
e.g hadron tensors in primary interaction should encapsulate the nuclear model.
Factorisation

This method is useful for speeding up new models implementation limitations:
- Lepton kinematics only
- No ability to tune or reweight parameters used to make the tables

Possible to add hadron kinematics by including more tabulated responses.

Testing the factorisation approach:
compute exclusive results using theory, compare to same theory implemented in generator

Note, the spectral function formalism in does not have this problem
Nuclear ground state should be same for all channels
FSI should be consistent across processes
initial state effects should be consistent

& get this by design
Comparing Generatros and models
## Final State Interaction

<table>
<thead>
<tr>
<th>Generator</th>
<th>for π</th>
<th>for nucleons</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEUT</td>
<td>Based on Oset et al with later fit to pion-nucleus data</td>
<td>Bertini model</td>
<td></td>
</tr>
<tr>
<td>Genie</td>
<td>Oset et al</td>
<td>Pandharipande-Pieper with in medium modifications</td>
<td>Also available: hA data driven model</td>
</tr>
<tr>
<td>WNUW</td>
<td>Oset et al</td>
<td>Pandharipande-Pieper and nucleon-nucleon correlation effects [arXiv:1902.05618 [hep-ex]]</td>
<td></td>
</tr>
</tbody>
</table>
π production

π+ C - σ reac

π+ C - σ abs

π+ Ar - σ reac

π+ Ar - σ abs
Transparency

Calculated as the ratio of counted protons before and after FSI

Proton transmission on Carbon

Proton transmission on Iron

Reasonable agreement at high kinetic energy
Implementing specific models
Relativistic Mean field models

1. Write a nucleon-nucleon interaction Hamiltonian

   For the relativistic case, extension of $\sigma$-$\omega$ Walecka model Ann. Phys. 83, 491 (1974)

2. Solve the equations of motion in the mean-field

   All nucleons feel the same average interaction
   Solve equations self-consistently until the solutions converge.

3. Obtain bound-states, binding energy and potentials

4. Solve the final state wave function in the same potential

   \[
   \frac{d^5\sigma}{dE_f d\Omega_f d\Omega_N} = \mathcal{F} p_N E_N k_f \epsilon_f \frac{l_{\mu\nu} h^{\mu\nu}_{QE}}{(2\pi)^5 f_{rec}}
   \]

   \[
   h^{\mu\nu} = \sum_{s_N, m_j} \langle \Psi_f | \mathcal{O} | \Psi_i \rangle \dagger \langle \Psi_f | \mathcal{O} | \Psi_i \rangle
   \]

   See Alexis Talk from yesterday
Relativistic Mean field models

- Relativistic mean field model describes well the $\nu A$ interaction
- Features consistency and orthogonality.
- Can be used as an input to the MC generators without double counting the FSI.
- To implement the RMF fully one needs to sample the fivefold cross section and not decouple the momentum distribution.

See Alexis Talk from yesterday
Spectral functions

Spectral Function is the probability distribution of removing a nucleon with momentum $p$ and leaving the residual nucleus with the excitation energy $E$.

\[
S(E_m, p_m) = \sum_n |\langle \psi_{n}^{A^{-1}} | a_{p_m} | \psi_{0}^{A} \rangle |^2 \delta(E_m + E_0 - E_n)
\]
Spectral functions

Available for: Carbon, Oxygen, Calcium, Argon, and Iron

1. Choose $k_{\nu}$
2. Choose $p_n$
3. Boost to the CMS frame
4. Choose scattering angles
5. Boost back to the LAB frame
6. \[
\frac{d^6\sigma}{d\omega d|q|dE_m dp_m}
\]

Calculate the cross section
Spectral functions

Available for: Carbon, Oxygen, Calcium, Argon, and Iron

Exclusive results

Neutral current scattering of $\nu_e$ on protons, arXiv:1902.05618
Spectral functions

The default models are using RFG

Currently working on first implementation of SF using Self Consistent Green’s Function Model
SuSAv2

Describes well inclusive data

$^{12}\text{C}(e,e')$

G. D. Megias PRD 94, 013012 (2016)
SuSAv2

Super Scaling 1p1h and 2p2h models were recently implemented in GENIE

Based on the Valencia model implementation using Hadronic Tensors

Successfully reproducing inclusive predictions

S. Dolan Based on: arXiv:1905.08556
Unified models for ν and e scattering
Learning from electron scattering data

Comparing neutrino generators to electron scattering data can help benchmark the models and constrain their vector part

$^{12}\text{C} \oplus E = 0.56 \text{ GeV} & \theta = 145^\circ$
Learning from electron scattering data

The e4V project deals with the following challenges:

1. The detector acceptance
2. Removing irrelevant background
3. Radiative effects
4. How to probe relevant phase space

In addition the community has learnt about Short Range Correlation studies done with electron scattering.
Generators

We’ve created a database for all e and ν model implementation in all relevant generator.

See backup slides for more
Generators

Calculate the cross section for $\nu$ and $e$ in one chosen model.

In the past, had some separate models and codes for $\nu$ and $e$ (QE Rosenbluth for $e$ wrt to Llewellyn Smith for $\nu$)

Until recently calculates cross section for $\nu$ and scaling it to $e$.

Possible to read different hadronic tensors for $e$, not yet used.

Recent developments will allow reading the different hadronic tensors in a joint QE MEC environment.

Started at the workshop to implement the QE model
Generators

Single calculation

Allows various model sets (referred to as tunes)
Each model has it free parameters which can be tuned
The frameworks allows comparison and reweighting of one tune to the other
Unified models - methods

**Separate calculation / Scaling approach**

Zeroing out the axial-vector contribution to the cross section and modifying the coupling constants and if needed also the used form factors

Right now this is the method being used in GENIE and GiBUU

During the workshop:
- Suggest what can be done to ensure the consistency is kept in subsequent evolutions of the code
Unified models - method

**Hadronic tensors approach**

Currently each model supplies different tables for $\nu$ and $e$.

Challenges: hard to reweight, alter the model if need-be, estimate errors

Hadron tensors implicitly integrate over the momenta of outgoing particles, don’t have final state

During the workshop:

- Using the equivalent tables for both $e$ and $\nu$ modes.
- Using the same model for (same ground state) QE & 2p2h tensor.
Summary

Many of the topics have been actually opened during this week and will need time to produce results.

A survey among participants consulting their opinion about the workshop organisation.

Most participants considered the selected topics and discussions very useful and most of them consider this workshop the beginning of a series of similar events in the future.
Summary

Especially useful were:

1. Comparisons between the implementation of some models such as Spectral Functions and on the other hand FSI in different generators

2. Discussion about the importance for exclusive predictions and the way to obtain those.

3. Discussion about the need for common reweighing and tuning infrastructure for models.

4. The lively discussion about the optimal implementation of electron scattering models in the neutrino interaction generators.
Thank you & see you in Trento