Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

GENIE development updates

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9 March 2020

Neutrino Theory/Experiment WG Meeting

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Ghent CRPA for GENIE

- Initially, we plan to use the same table-based hadronic tensor ($W^{\mu\nu}$) interface as for the SuSAv2 model
  - Discussed at this meeting previously, see implementation note (**GENIE docDB #137**)
  - Computes inclusive differential cross section using precomputed tensor elements interpolated on a 2D grid

$$\frac{d\sigma}{d\omega\, d|\mathbf{q}|} \propto L_{\mu\nu} W^{\mu\nu}$$

  - Grid axes are the energy transfer (ω) and 3-momentum transfer ($|\mathbf{q}|$)
  - Machinery used to generate event kinematics based on implementation of Valencia MEC model

- Low barrier to get started, possibility to transition to implementation in code
  - Fortran wrapper
  - Direct C++ translation

- Calculation provides only an inclusive prediction: well-suited to this approach
  - However, a recipe to "make up" the hadronic final state is still needed

Ghent CRPA for GENIE

- Nuclear response calculation uses one-body operators only

- This fits into the GENIE "QE" category . . . mostly

  - CRPA includes treatment of low-energy nuclear excitations important at small ω

  - Tracking hit nucleon through classical intranuclear cascade may become inappropriate here

  - Compound nucleus models are an option
    - Implemented in codes like ABLA07, FLUKA, NON-SMOKER, MARLEY
    - How to treat the compound → direct transition rigorously in this context is currently unclear to me

  - Can start with something like the traditional GENIE approach, improve from there
    - Choose a nucleon from the active nuclear model
    - Transfer 4-momentum
    - Apply the usual FSI treatment (intranuclear cascade)

Spectral Function overview

- The spectral function approach uses a more realistic treatment of the initial nuclear state than the Fermi gas models traditionally used in GENIE
  - In particular, the nucleon removal energy E is variable and correlated with its initial 3-momentum $\mathbf{p}$
  - In contrast, the GENIE Fermi gas models treat the binding energy E_B (related to E) as a fixed parameter
- Noemi kindly provided me with the following inputs:
  - A table file for the ^{12}C spectral function $P(\mathbf{p}, E)$
  - Tabulated EM nuclear responses R_L and R_T
  - Fortran code that computes the differential cross section $d\sigma/d\omega d\Omega$ for electron-^{12}C scattering

Scope of recent GENIE work

- Current implementation work for spectral functions has focused on QE
  - Spectral function $P(\mathbf{p}, E)$ usable as nuclear model for other channels (e.g., RES)
  - However, not always consistent (e.g., existing MEC models make other assumptions)
- This has been a slow process, thanks for the patience!
  - Issues discovered early on in GENIE v3 removal energy treatment for QE
  - Resolution led to v3.0.4 bug-fix release (**GENIE docDB #113**)

Design considerations

- GENIE's QE treatment has historically used separate pieces of code for differential cross sections
  - EM: Rosenbluth
  - NC: Ahrens
  - CC: Llewellyn-Smith (and recently Nieves)
- This has been fine in the past, but there are limitations

- **Example #1:** neutrino/electron consistency

  - If you tune EM form factor parameters to electron scattering data, can you immediately use them for the vector part of CC/NC?
  - For NC, not unless you chose dipole vector form factors (hard-coded)
  - As discussed at ECT* workshop last June, unified code that treats EM / weak on an equal footing makes this sort of thing much simpler

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- **Example #2:** Extensions to non-standard processes

  - Discussed at FNAL Generator Tools workshop in January
  - Some BSM models use, e.g., a modified leptonic tensor $L_{\mu\nu}$ while keeping the rest of the cross section ingredients the same
  - Hard work to modify existing cross section code to allow for this sort of variation
  - And then there's the next theorist's modification to $L_{\mu\nu}$ . . .

UnifiedQELXSec

- I've tried to address some of these issues by writing a new C++ class, UnifiedQELXSec, that computes QE differential cross sections
  - EM + NC + CC, all in one piece of code
  - Couplings, form factors, etc. modified appropriately

- Helper classes for the lepton and nucleon tensors
  - LeptonTensor ($L^{\mu\nu}$)
  - FreeNucleonTensor ($A^{\mu\nu}$) → as opposed to one modified for, e.g., RPA effects
  - Compute elements of themselves
  - Multiplying these tensors together yields the contraction $L_{\mu\nu}A^{\mu\nu}$
  - BSM process? Write a function that computes the tensor elements → framework does the rest

- Expressions used in $A^{\mu\nu}$ include placeholders for second-class current (SCC) form factors $F_V^3(Q^2)$ and $F_A^3(Q^2)$
  - Zeroed out for now, but functions for these are all that is needed to include SCCs

- Compatible with GENIE v3 QELEventGenerator
  - Recent improvements to CCQE generation now can be applied to EM, NC

Validation: cross section ingredients

- Expression for $A^{\mu\nu}$ (including SCCs) taken from **arXiv:1506.02355**
  - They denote the same tensor by $J^{\mu\nu}$
  - Checked against full calculation (Dirac traces, etc.) using the **FeynCalc** package
  - Note factor of 2 discrepancy between eq. (9) and eq. (A1) → corrected in GENIE
    - Otherwise, FeynCalc exactly reproduces the expression from the paper

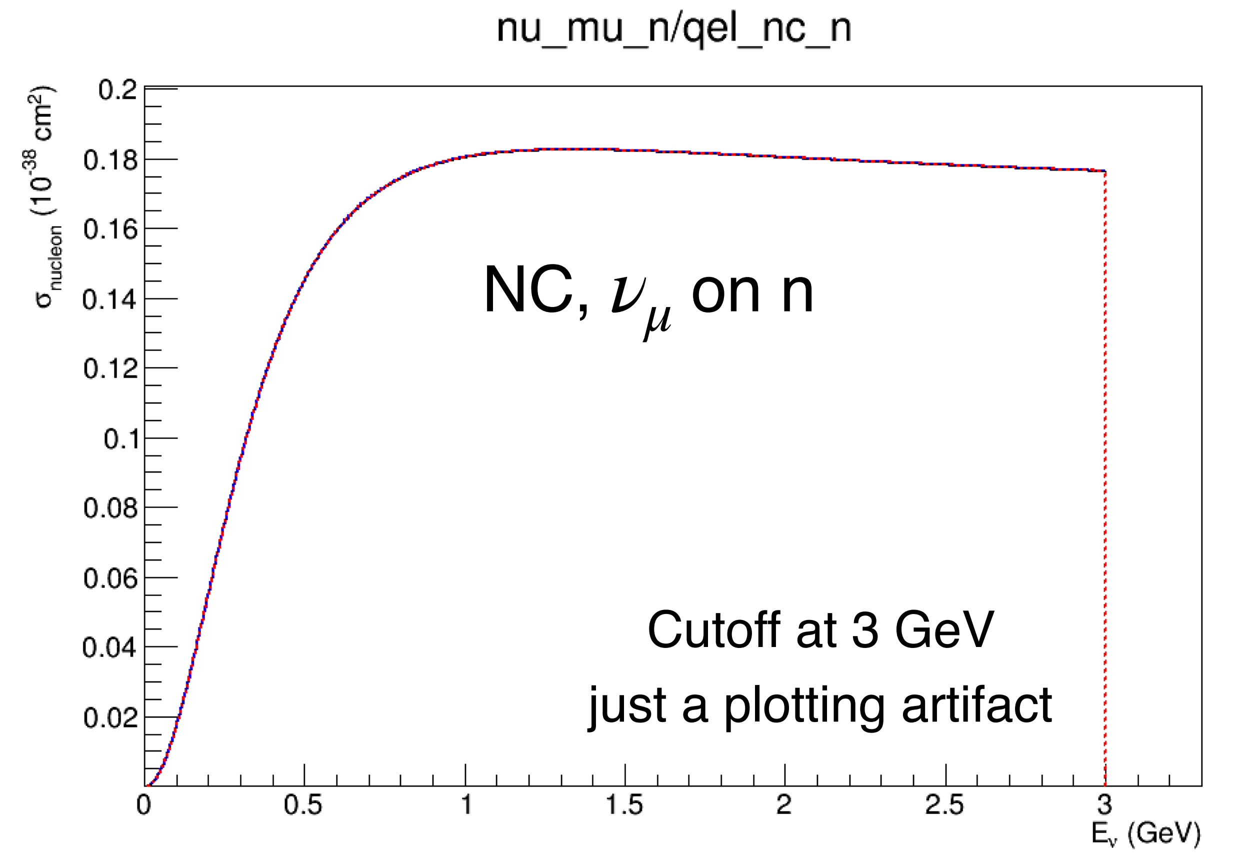
- GENIE numerical calculation of tensor elements checked against FeynCalc
  - Dummy 4-momenta, form factor values
  - Very close agreement

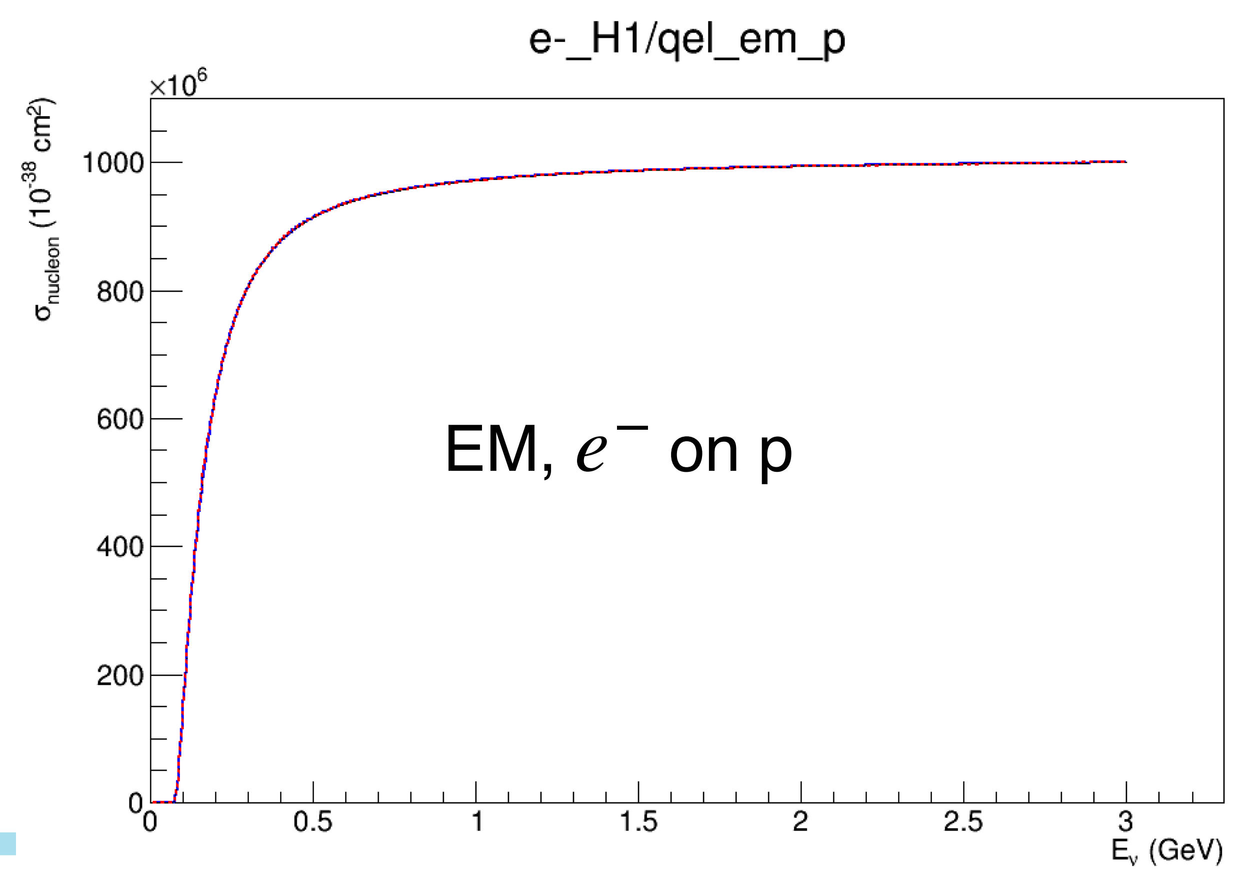
- Free nucleon total cross sections
  - No spectral function needed here
  - $\sigma(E_{e\text{ or }\nu})$ tests correctness of couplings, tensors, cross section integration, etc.
  - When configured to match choice of form factors, etc., UnifiedQELXSec reproduces free nucleon predictions for existing GENIE models (see next slide)

Validation: free nucleon cross sections

- Red is UnifiedQELXSec, blue is existing GENIE model appropriate for the reaction mode of interest

- Consistency achieved for p/n targets and e^- ($\nu + \bar{\nu}$) projectiles for EM (CC/NC)





Validation: event-based differential cross section calculation

- Differential cross section $d\sigma/d\omega d\Omega$ for electron-^{12}C scattering checked against output of Noemi's Fortran code

- Close agreement, differences from other GENIE nuclear models noticeable