GENIE Fortran Wrapper for Lepton-Nucleus QE Scattering

with Noemi Rocco, Minerba Betancourt, Steven Gardiner

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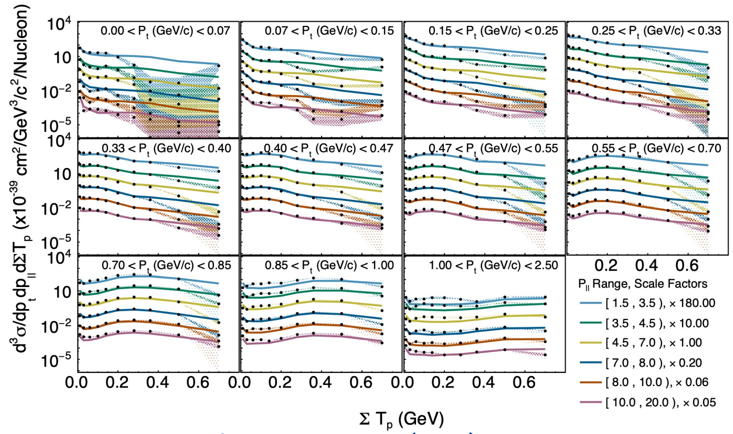
Workshop on Neutrino Event Generators
15 March 2023

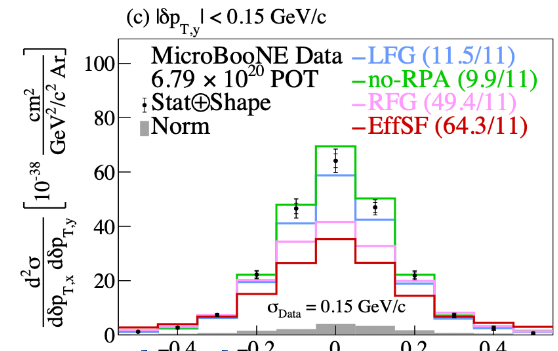
Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Challenges

- Neutrino community at an exciting moment where new data is challenging our models
  - Higher precision, More Differential
  - Exclusive channels
  - New targets, Electron scattering probes
- Need for theory driven models
  - Nuclear effects cannot be completely explained by older, simpler, sometimes empirically driven models in our event generators
  - Need state of the art theory, leveraging collaboration with nuclear, electron scattering, and neutrino scattering theorists.
  - How do we incorporate these new models into our event generators?
    - Focus on GENIE



MINERvA Phys.Rev.Lett. 129 (2022) 2, 021803



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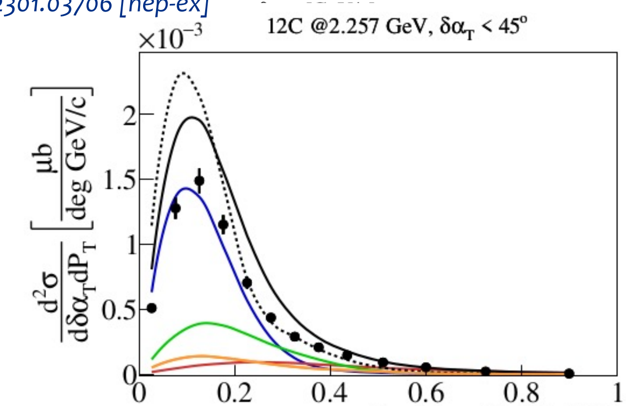

A.Papadopoulou, et al, In preparation

Incorporating new models into event generators

- Common issue is large time/person investment
  - Translating codes/phase space/form factors/constants/FSI models/etc..
- Create some kind of common interface so that theorists can plug their calculations into event generators
- In GENIE this is currently done with the HadronTensorTable Framework
  - At the inclusive level

$$\frac{d^2\,\sigma}{d\,\omega d\,\Omega} = \frac{\mathcal{C}}{\pi^2}\,\frac{|\mathbf{k}'|}{|\mathbf{k}|}\,L_{\mu\nu}\,W^{\mu\nu}$$

$$W^{\mu\nu} = \overline{\sum}_f \langle 0|J^{\mu\dagger}|f\rangle\langle f|J^{\mu}|0\rangle\delta^4(p_f - p_i - q)$$

  - Pre-computed tables of nuclear responses or tensor elements evaluated on grid of (ω,|**q**|) where hadron kinematics has been integrated over

Summary of Workshop on Common Neutrino Event Generator Tools

Josh Barrow[1], Minerba Betancourt[2], Linda Cremonesi[3], Steve Dytman[4], Laura Fields[2], Hugh Gallagher[5], Steven Gardiner[2], Walter Giele[2], Robert Hatcher[2], Joshua Isaacson[2], Teppei Katori[6], Pedro Machado[2], Kendall Mahn[7], Kevin McFarland[8], Vishvas Pandey[9], Afroditi Papadopoulou[10], Cheryl Patrick[11], Gil Paz[12], Luke Pickering[7], Noemi Rocco[2,13], Jan Sobczyk[14], Jeremy Wolcott[5], and Clarence Wret[8]

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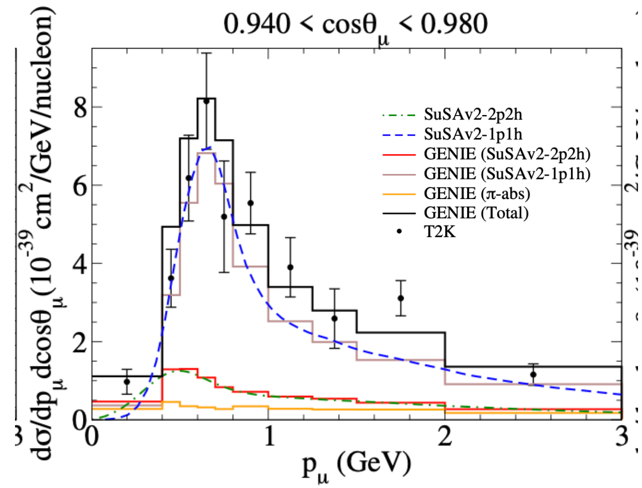
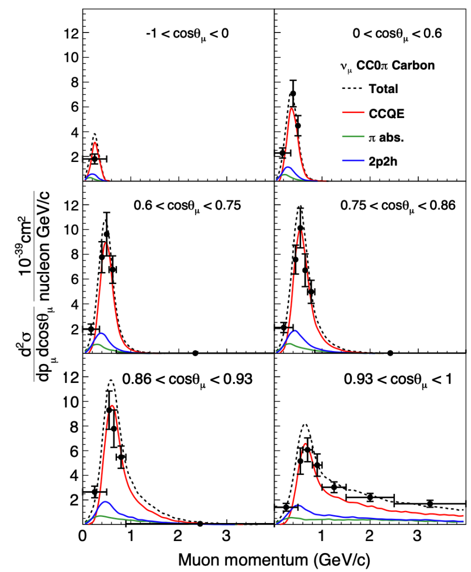
Incorporating new models into event generators

- HadronTensorTable framework has allowed for implementation of several new theory driven models
  - SuSAv2
  - Short time approximation
  - HF-CRPA

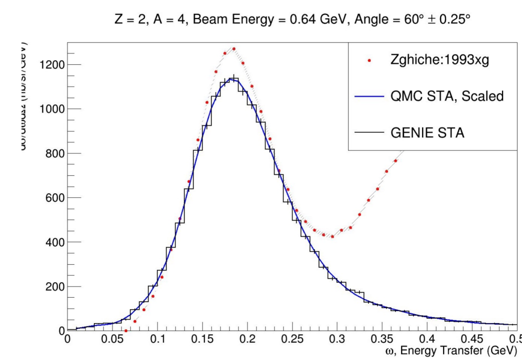
- Limitations!
  - Only inclusive as outgoing hadron system has been integrated out
  - Consistency between event generator and theory code used to produce table
  - Must regenerate any time new form factors are introduced
  - Different EM and neutrino tables



S. Dolan et al. Phys.Rev.D 101 (2020)



S. Dolan et al. 2110.14601 [hep-ex]



J. L. Barrow et al. Phys.Rev.D 103 (2021)

GENIE Fortran Interface

- Instead of a pre-computed hadron tensor, compute it on the fly!

- Use existing Fortran code to compute $A^{\mu\nu}$ (different than W!)
  - Fully exclusive

- Leverage as much existing infrastructure in GENIE as possible
  - Single nucleon form factors
  - Leptonic tensor
  - Phase space generators/Integrators
  - Fully configurable via GENIE xml files

- Pass hadronic tensor to GENIE for cross section calculation

GENIE Fortran Interface – Details

- Developed Unified cross section model for (e + ν)A scattering
  - Set up calculation based on probe (FF, constants, etc.)
    - Use same QELEventGenerator & Spline integrator as Nieves/LwylnSmith xsecs
    - Cross section computed in d^3pdEd^3k' phase space

$$d\sigma = \frac{\mathcal{NC}}{32\pi^2 E_{\mathbf{p}} E_{\mathbf{p}'} E_{\mathbf{k}'} E_{\mathbf{k}}} P(\mathbf{p}, E) L_{\mu\nu} \tilde{A}^{\mu\nu} \delta(E_{\mathbf{k}} + E_{N_i} - E_{\mathbf{k}'} - E_{\mathbf{p}'}) d^3\mathbf{p} dE d^3\mathbf{k}',$$

  - Off Shell initial nucleon to account for removal energy

$$E_{N_i} = p^0 = m_{\mathbf{p}} - E = M_i - E_f$$

  - GENIE computes Form Factors and leptonic tensor based on process of interest

$$L_{\mu\nu} \equiv \begin{cases} \mathrm{Tr}\left[\gamma_\mu(1-\gamma_5)\not{k}\gamma_\nu(1-\gamma_5)(\not{k}' + m_{\mathbf{k}'})\right] \\ \frac{1}{2}\,\mathrm{Tr}\left[\gamma_\mu(\not{k} + m_{\mathbf{k}})\gamma_\nu(\not{k}' + m_{\mathbf{k}})\right] \end{cases} = \begin{cases} 8(k_\mu k'_\nu + k'_\mu k_\nu - k\cdot k' g_{\mu\nu} \mp i\epsilon_{\mu\nu\rho\sigma} k^\rho k'^\sigma) & \text{CC, NC} \\ 2(k_\mu k'_\nu + k'_\mu k_\nu + [m_{\mathbf{k}}^2 - k\cdot k']\, g_{\mu\nu}) & \text{EM.} \end{cases}$$

GENIE Fortran Interface – Details

- Cross section model only needs *nucleon* level response tensor from Fortran
  - Implement subroutine that can be called from GENIE cross section model
  - Pass all hadron kinematics + Energy transfer, Single nucleon form factors, Dummy Tensor

```
extern"C"
{

void compute_hadron_tensor_(double *wt, double *xk_x, double *xk_y, double *xk_z, double
 *xp_x, double *xp_y, double *xp_z, double *f1v, double *f2v, double *ffa, double *ffp,
std::complex<double> resp[4][4]);

}
```

  - Fortran code constructs nucleon level response tensor however the theorist/model builder desires
  - Response tensor passed back to GENIE for contraction and cross section calculation

GENIE Fortran Interface – Proof of principle

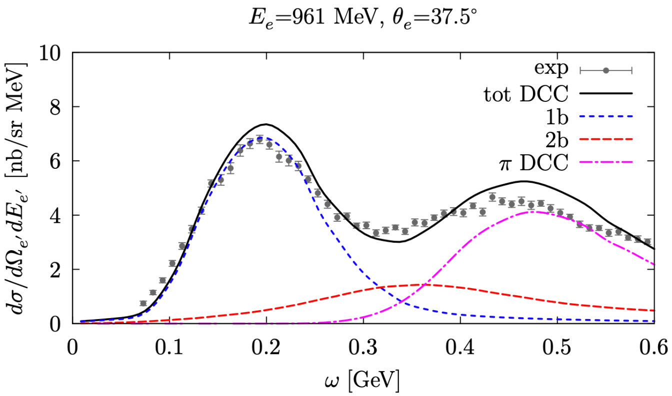
- First test of API:
  - Implemented Spectral Function + Extended factorization scheme for lepton nucleus QE scattering

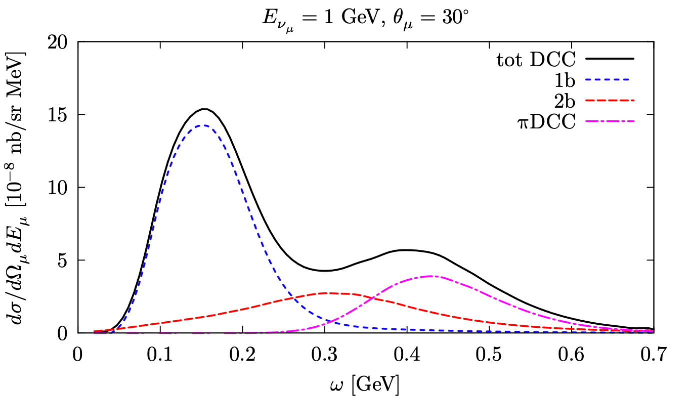
$$J_A^\mu \longrightarrow \sum_i j_i^\mu \ , \qquad |X\rangle \longrightarrow |x, \mathbf{p}_x\rangle \otimes |R, \mathbf{p}_R\rangle$$

$$d\sigma_A = \int dEd^3k \ d\sigma_N \ P(k, E)$$

  - Single nucleon cross section computed using relativistic currents and spinors

- Consistent scheme to incorporate QE + MEC + RES + …. in a single unified framework
  - As well as predict electron and neutrino scattering cross sections simultaneously
  - Test QE first

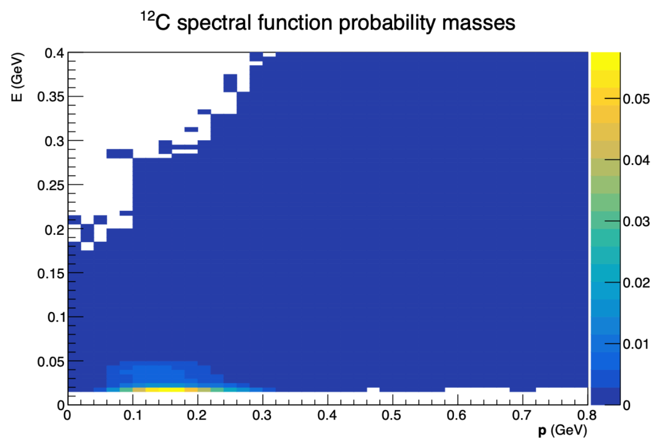




Noemi Rocco et al.
Phys.Rev.C 100 (2019) 4, 045503

GENIE Fortran Interface – SF Details

- Include SF (Benhar) as a nuclear model in GENIE



  – 2D in p,E_r : Can be utilized by any calculation (except table based models) via xml config files, switched for any new spectral function

  – Normalized to unity $$\int P(\mathbf{p}, E)\, d^3\mathbf{p}\, dE = 1.$$

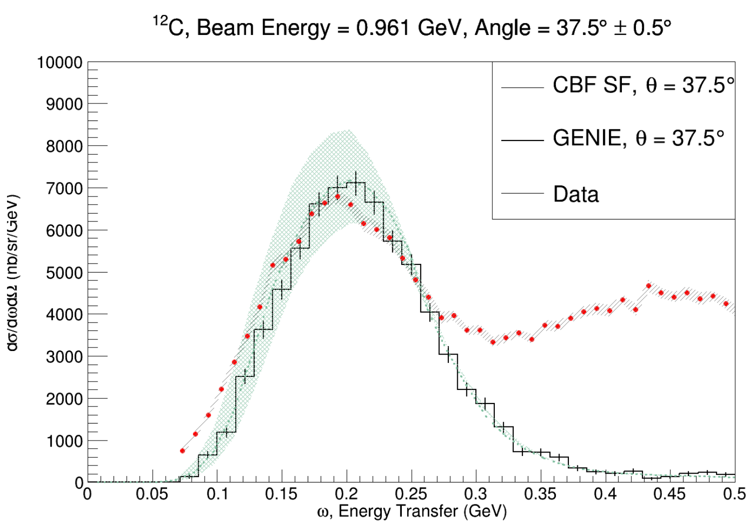
  – Nucleons sampled from 2d distribution $$P_{\text{bin } ij} = \frac{4\pi}{Z} \Delta|\mathbf{p}|\, \Delta E\, |\mathbf{p}|_i^2\, F(|\mathbf{p}|_i, E_j).$$

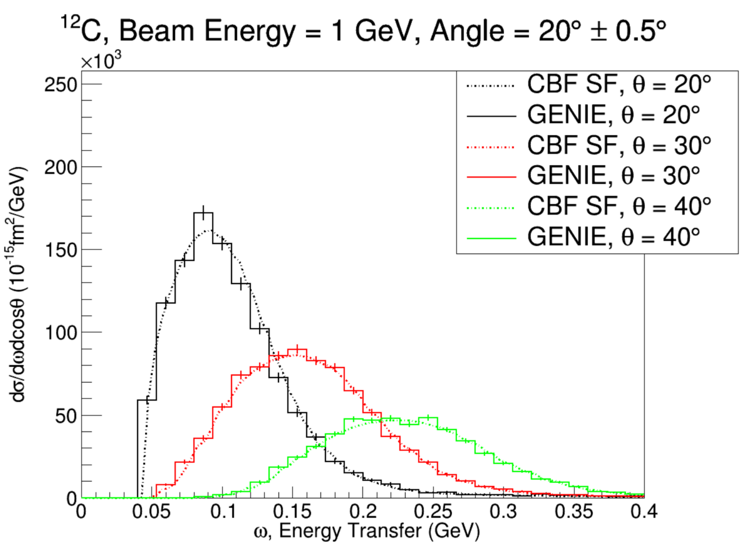
    - Treated as constant within each bin

GENIE Fortran Interface – Validation and Comparisons

- Unified framework for lepton-nucleus scattering
  - Any tunes from charged lepton scattering data can be immediately applied to neutrino scattering predictions within the same code
  - Utilize GENIE's fluxdriver, geometries, reweighting framework, etc.
- Validation
  - Inclusive charged lepton scattering

Inclusive neutrino CC Scattering



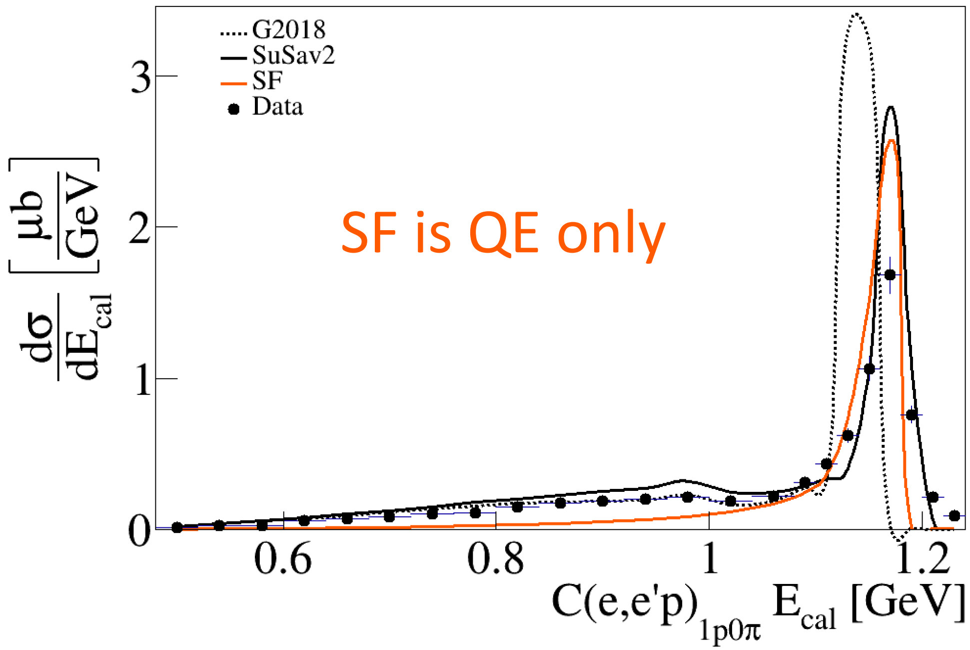


  - Confirmation of inclusive cross sections with standalone theory code

GENIE Fortran Interface – Beyond Inclusive

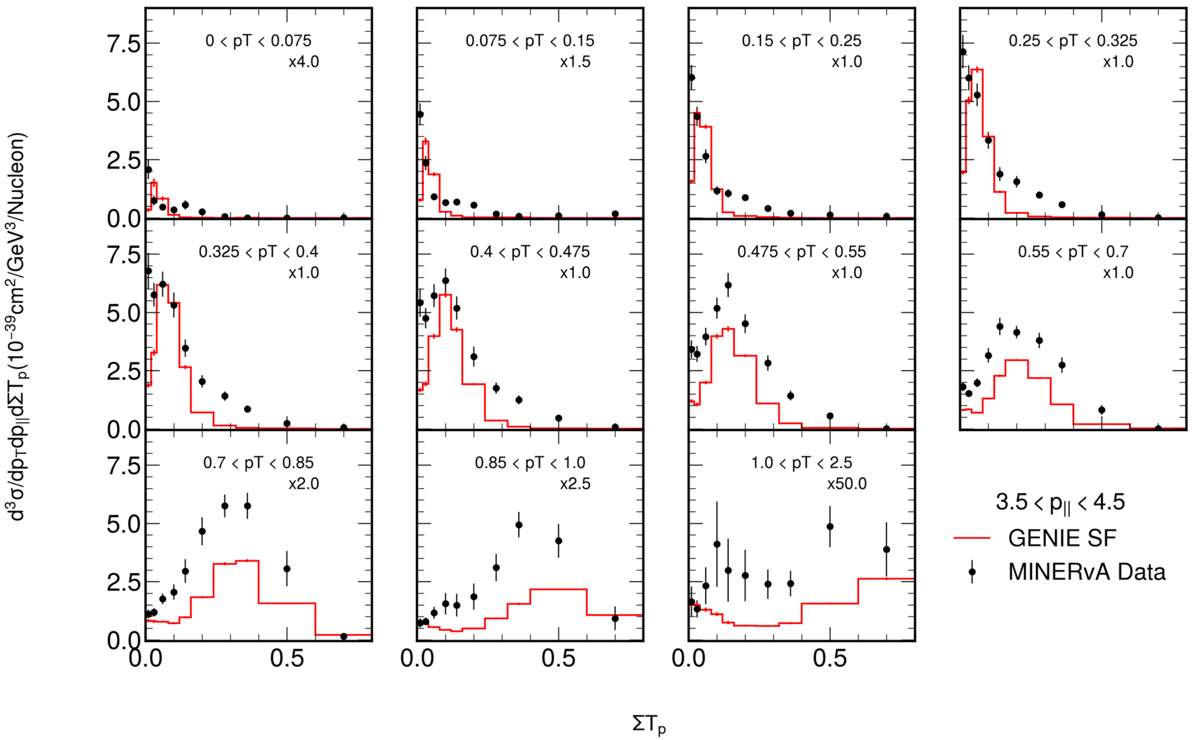
- As we know, inclusive observables are not enough to discriminate models with todays precision data
  - GENIE SF implementation provides fully exclusive observables
- E4v $(e,e'p)_{0\pi}$ Reconstructed Calorimetric Energy

$$E_{cal} = E_l + T_p + \epsilon$$



GENIE Fortran Interface – Beyond Inclusive

- As we know, inclusive observables are not enough to discriminate models with todays precision data
- GENIE SF implementation provides fully exclusive observables
  - MINERvA M.E. Triple Differential Cross Section in p_T, $p_{||}$, ΣT_p



SF is QE only

Fermilab

GENIE Fortran Interface

- To plug in your QE Fortran interface:
  - Need subroutine which accepts hadron information event information & form factors
  - Hadron tensor is std::complex<double> [4][4] array
  - Hadron tensor should not contain factors from phase space
    - $[W_{\mu\nu}] = GeV^2$
  - Currently have to adjust makefile to build and link your fortran code but this will be done via xml config file in the future
  - Can use any of GENIE's initial nuclear models and nucleon form factors
    - Dipole, Zexp, BBBA, etc
    - RFG, LFG, SF, etc.
    - Configurable via. Xml file

Conclusion

- Modern neutrino scattering data has shown the need for advanced theoretical models

- Putting those models into event generators is not straightforward
  - Tensor tables are one example but right now they are inclusive only

- Our GENIE Fortran Wrapper is one possible way in which new models can be implemented

- We have tested the API by implementing the SF + Extended factorization scheme for QE scattering via our wrapper
  - Realistic nuclear model
  - Exclusive predictions
  - Extendible to other reaction mechanisms like MEC and RES
  - Currently not in any official GENIE release but will be publishing results soon
- Thanks!