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Implementation of SF 1p1h model in GENIE

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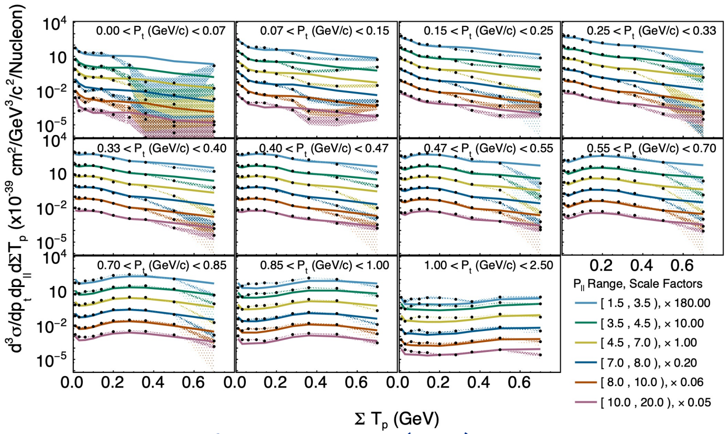
Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

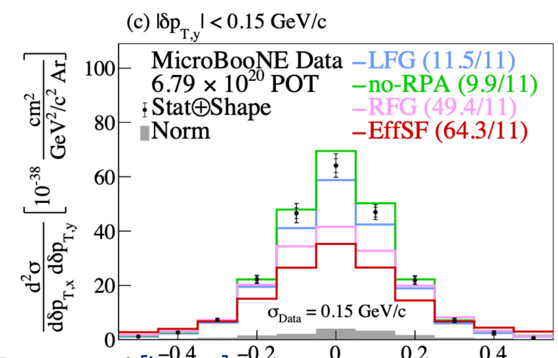
Challenges

- Neutrino community at an exciting moment where new data is challenging our models
  - Higher precision, More Differential
  - Exclusive channels
  - New targets, Electron scattering probes

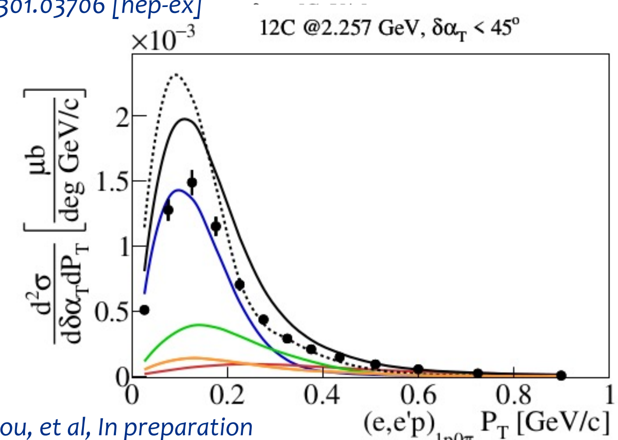
- Need for theory driven models
  - Include nuclear effects beyond empirical models
  - Provide fully (semi)exclusive predictions
  - Quantify theory systematic errors
  - Unify reaction mechanisms into one coherent model
  - Incorporate into event-generators



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



MicroBooNE 2301.03706 [hep-ex]



A.Papadopoulou, et al, In preparation

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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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GENIE Fortran Interface

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

- Use existing Fortran code to compute unintegrated $A^{\mu\nu}$ (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

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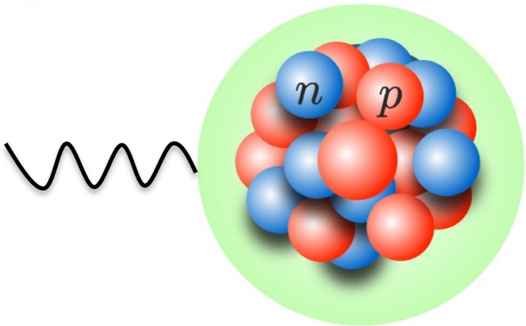
Many Body solution to Lepton-Nucleus Scattering

- Lepton-nucleus scattering described by leptonic and nuclear response tensors

$$\sigma \sim L_{\mu\nu} R^{\mu\nu}$$



- Nuclear response to probe (EW boson) contains all information on the structure of the nucleus

$$R^{\mu\nu} = \sum_f \langle 0 | J^{\mu\dagger} | f \rangle \langle f | J^{\nu} | 0 \rangle \delta(E_0 + \omega - E_f)$$

$$J^\mu = \sum_i j_i^\mu + \sum_{j>i} j_{ij}^\mu \longleftrightarrow H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

- Hamiltonian provided by AV18 and IL7 potentials
  - Other option: χPT Hamiltonian

- Provides an underlying microscopic model from which to derive consistent EW currents and use realistic nuclear ground states

Extended Factorization Scheme

- For sufficient $|\mathbf{q}|$, scattering factorizes

  - Single nucleon knockout (QE)

$$|f\rangle = |\mathbf{p}'\rangle \otimes |\Psi_f^{A-1}, \mathbf{p}_{A-1}\rangle$$

  - Multi nucleon knockout (MEC)

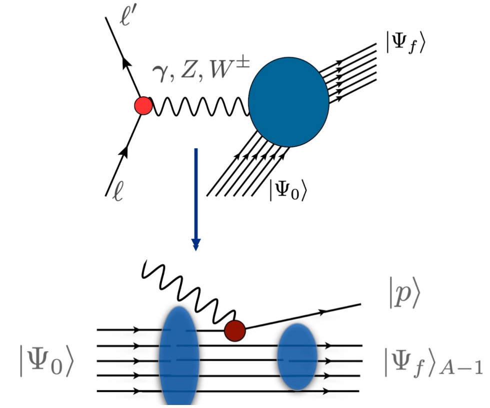
$$|f\rangle = |\mathbf{p}_1'\mathbf{p}_2'\rangle \otimes |\Psi_f^{A-2}, \mathbf{p}_{A-2}\rangle$$

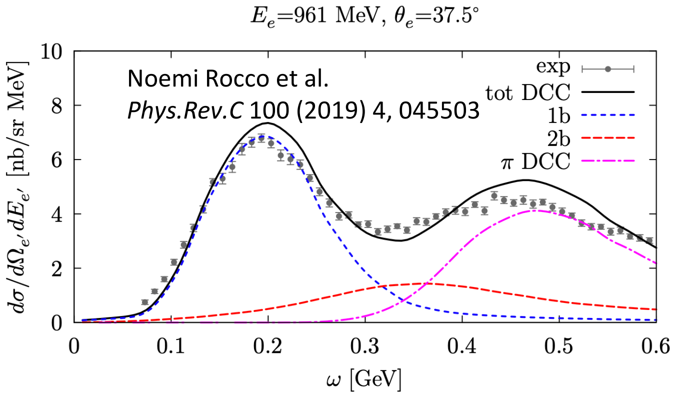
  - Single Pion Production

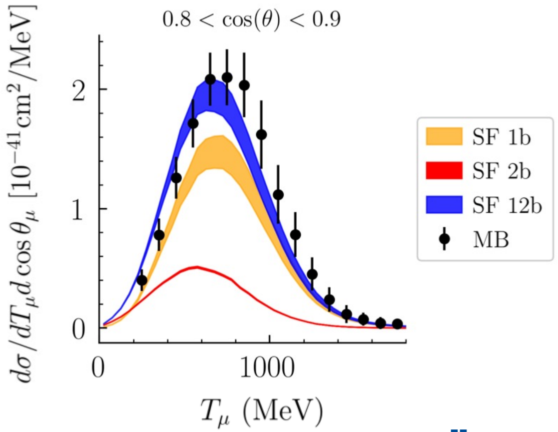
$$|f\rangle = |\mathbf{p}'\mathbf{p}_\pi\rangle \otimes |\Psi_f^{A-1}, \mathbf{p}_{A-1}\rangle$$

- Transition from nuclear ground state captured by the Spectral Function

$$P_h(\mathbf{k}, E) = \sum_f |\langle\psi_0^A|[|k\rangle \otimes |\psi_f^{A-1}\rangle]|^2$$
$$\times\, \delta(E + E_f^{A-1} - E_0^A)$$



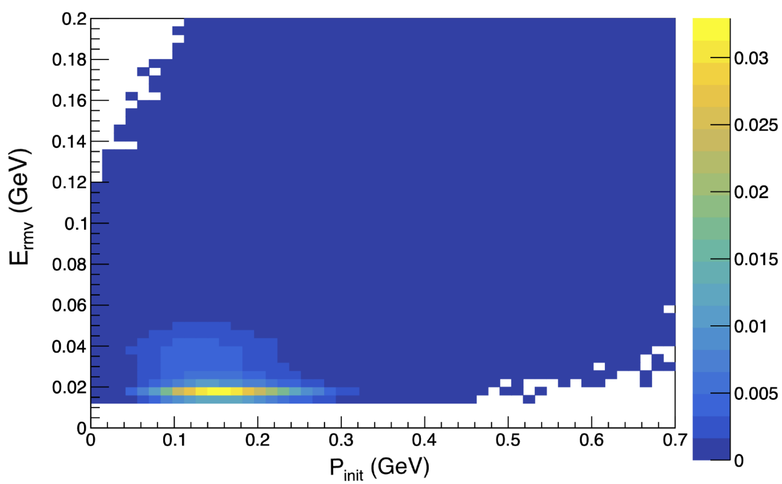


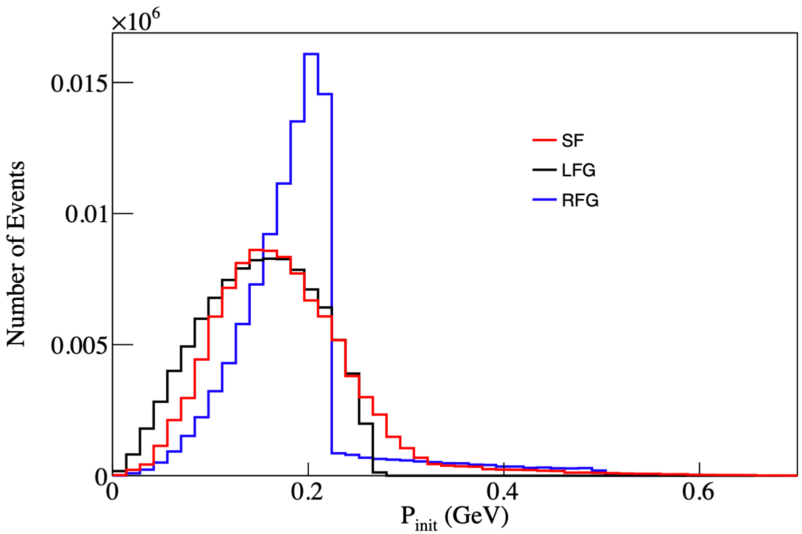


Incorporation of SF 1p1h model into GENIE

- CBF SF for ^{16}O and ^{12}C as a nuclear model in GENIE

$$P_\tau(\mathbf{k},E) = P_{\rm MF}(\mathbf{k},E) + P_{\rm corr}(\mathbf{k},E)$$





  – 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

Incorporation of SF 1p1h model into GENIE

- Developed Unified cross section model for (e + ν)A scattering
  - Set up calculation based on probe (FF, constants, etc.)
    - Cross section computed in d^3pdEd^3k' phase space

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

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

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

  - 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]);

}
```

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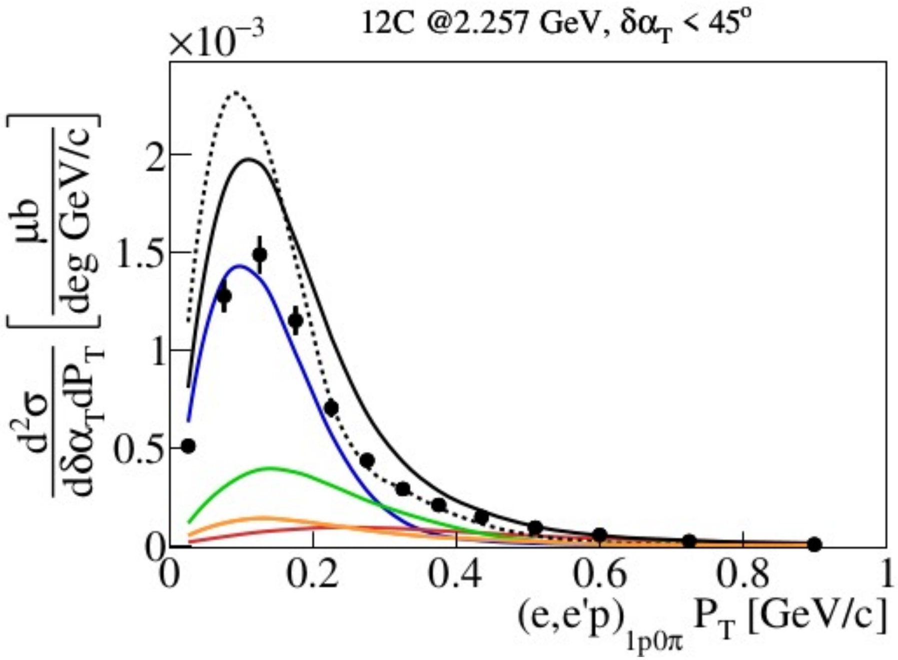
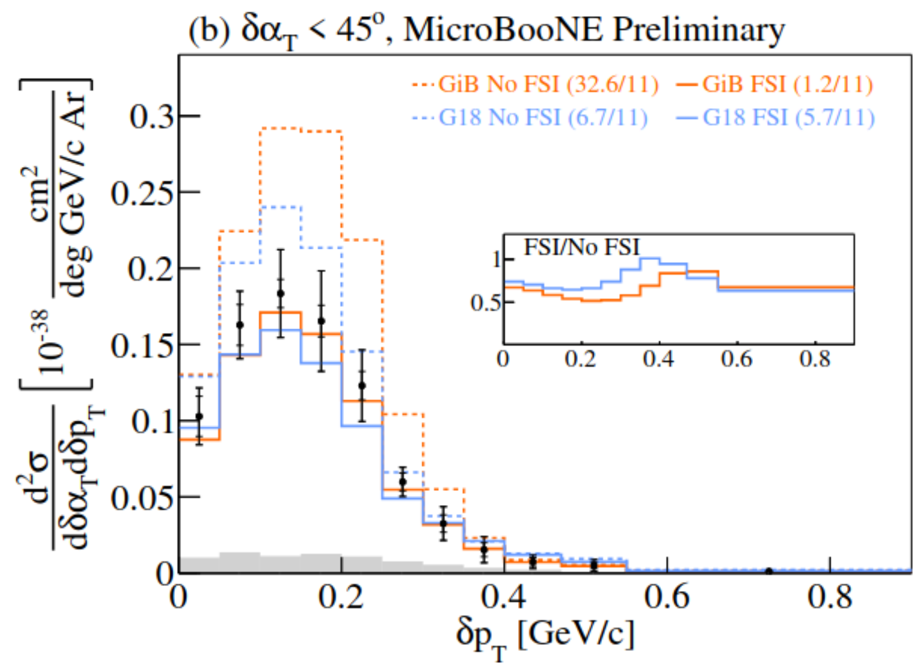
Charged lepton/neutrino complementarity

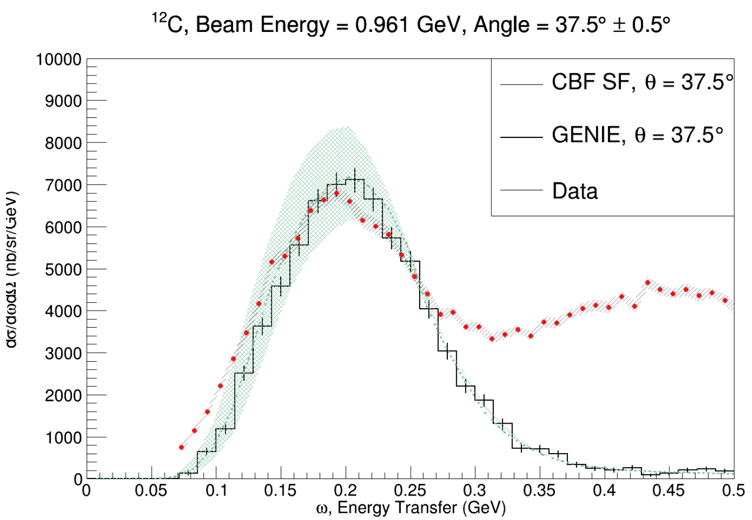


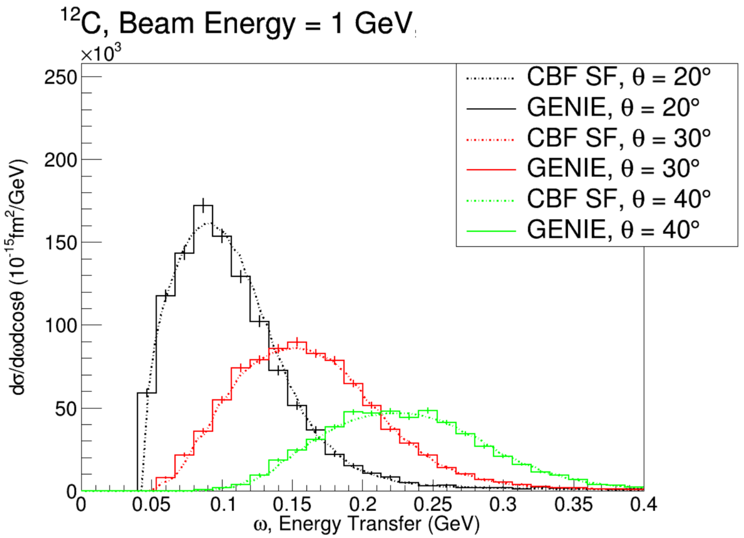


GENIE Fortran Interface – Validation and Comparisons

- 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
- Validation
  - Inclusive charged lepton scattering

Inclusive neutrino CC Scattering

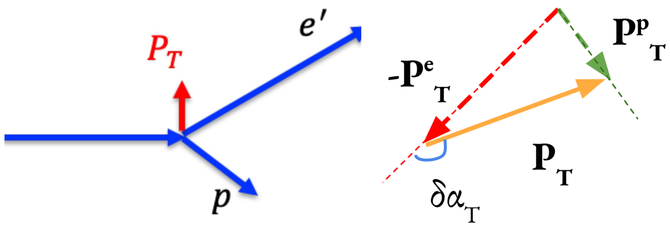




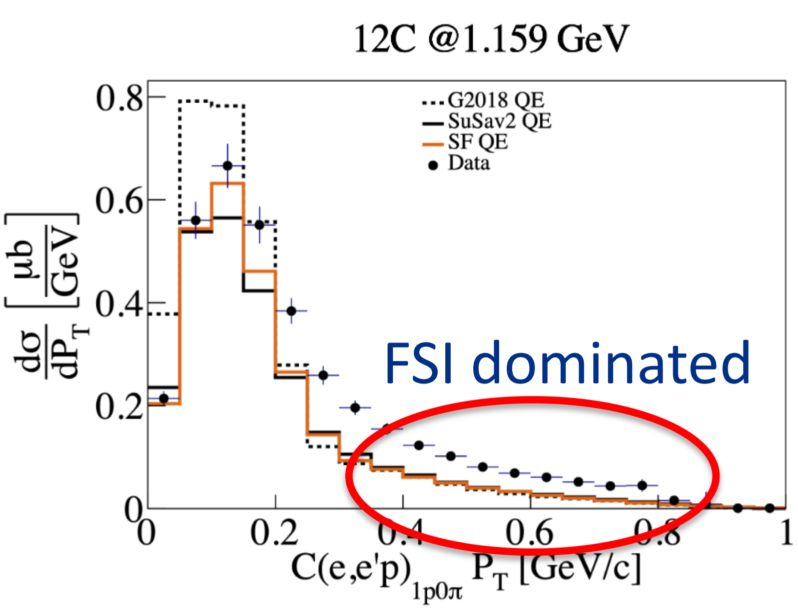
  - Confirmation of inclusive cross sections with standalone theory code

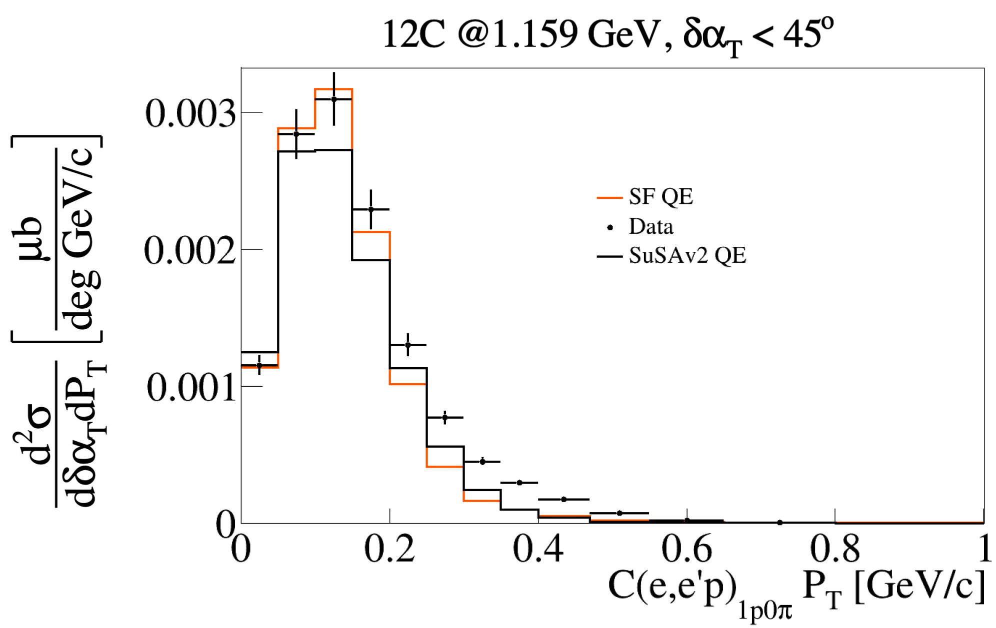
GENIE Fortran Interface – Beyond Inclusive

- As we know, inclusive observables are not enough to discriminate models with todays precision data
  - GENIE SF implementation provides fully exclusive observables
  - TKI variables probe nuclear effects independent of lepton energy



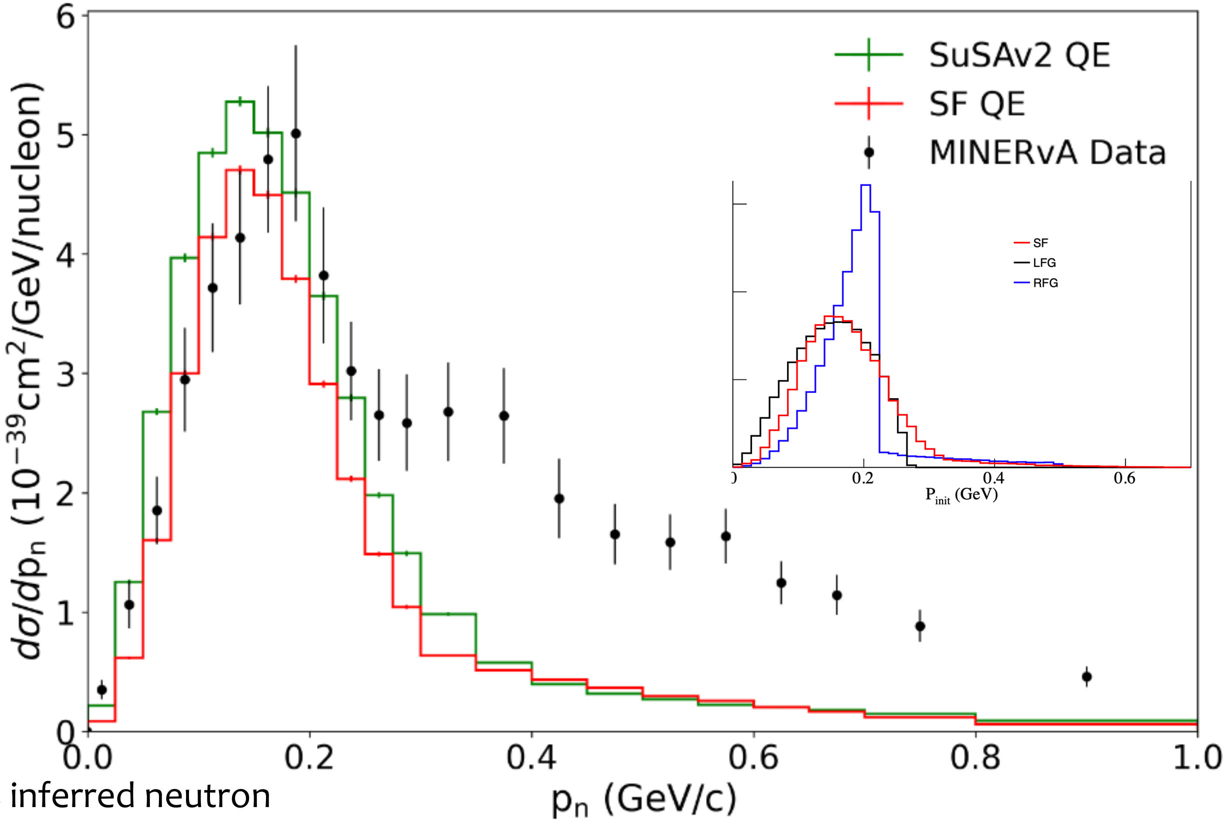
$$\mathbf{P}_\mathrm{T} = \mathbf{P}_\mathrm{T}^{\mathrm{e}'} + \mathbf{P}_\mathrm{T}^{\mathrm{p}}$$





GENIE Fortran Interface – Beyond Inclusive

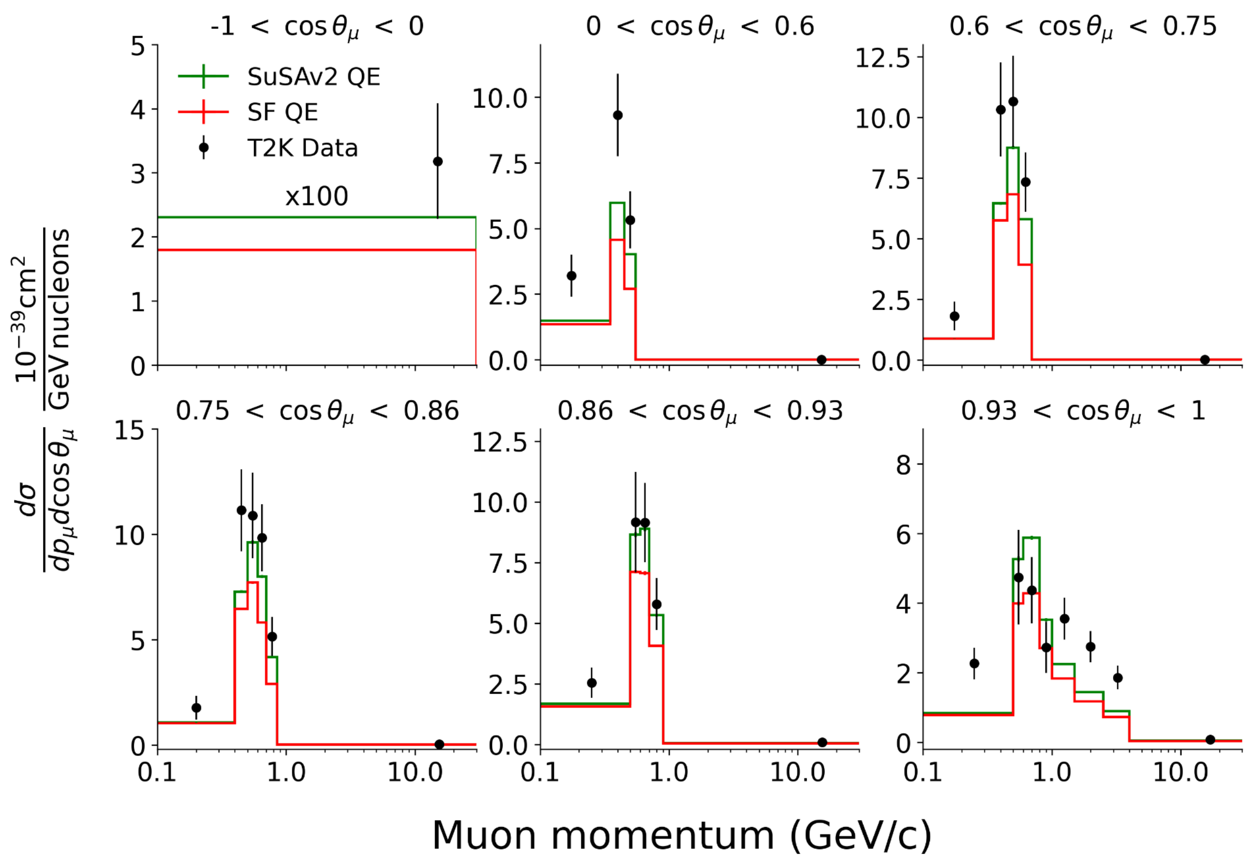
- MINERvA CCQE-like



- P_n represents inferred neutron momentum
- Compare with initial nucleon momentum

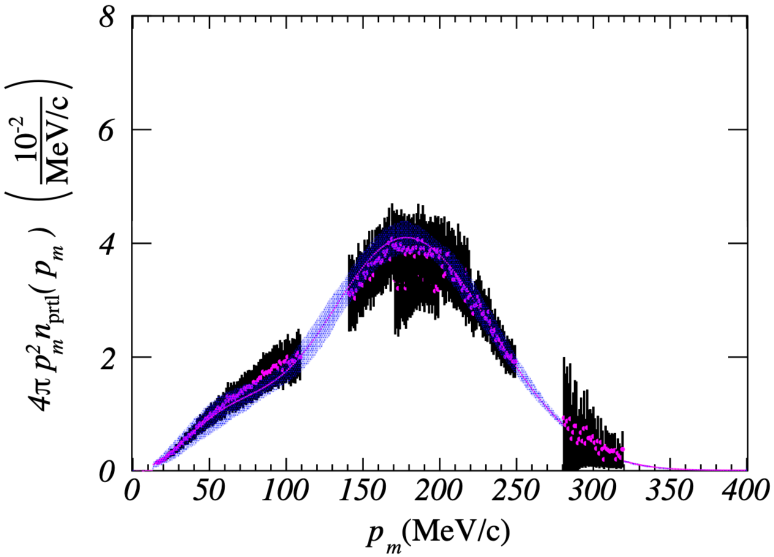
GENIE Fortran Interface – Beyond Inclusive

- Spectral functions for other nuclei like Oxygen, Iron are also included
- T2K CC0π sample on oxygen



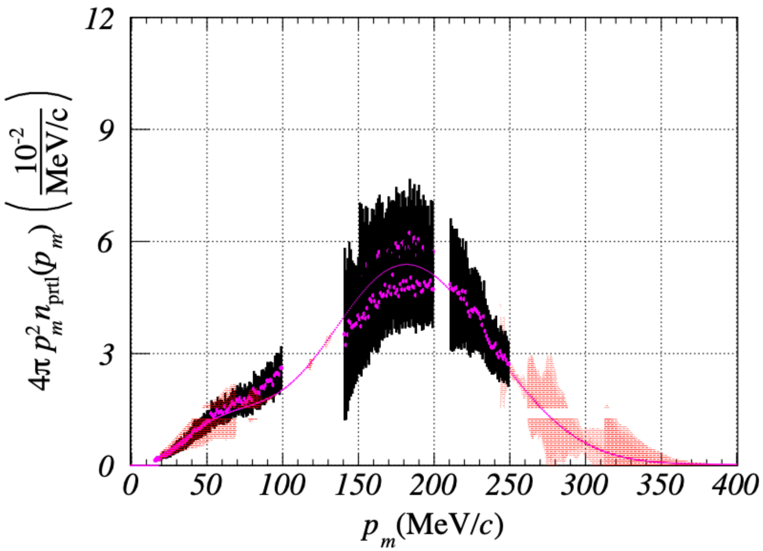
Prospects for future – Argonne

- Inclusion of Argon SF (+ Ti SF) will allow for more detailed study of nuclear effects in Argon



Argon (e,e'p)

Phys.Rev.D 105 (2022) 11, 112002 e-Print: 2203.01748 [nucl-ex]



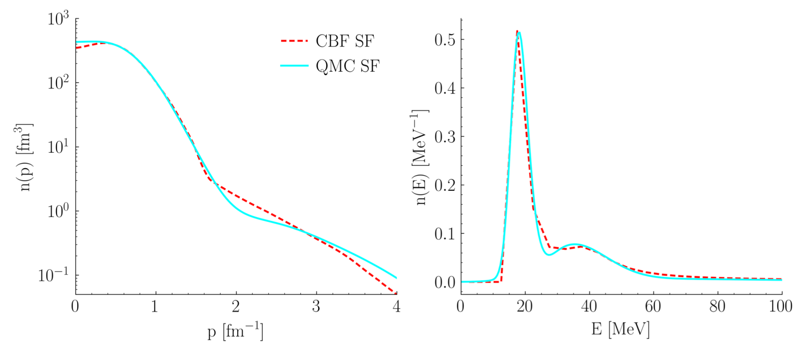
Titanium (e,e'p)

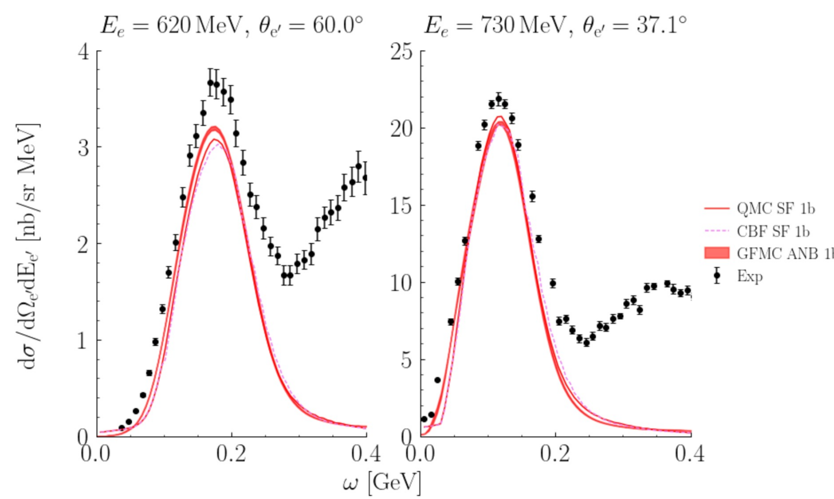
Phys.Rev.D 107 (2023) 1, 012005 e-Print: 2209.14108 [nucl-ex]

- Test use of Titanium proton SF for Argon neutron SF
- Compare with theoretical calculations of Argon SF
- Compare with MicroBooNE

Prospects for future - Systematics

- Systematic studies
  - Comparison of different spectral functions
  - QMC SF derived directly from underlying nuclear Hamiltonian
  - Comparison with GFMC (same underlying Hamiltonian but virtually exactly results) gives systematic on use of factorization scheme





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
  - Currently not in any official GENIE release

- Thanks!

Interfacing Electron and Neutrino Quasielastic Scattering Cross Sections with the Spectral Function in GENIE

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