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# Electron Scattering Developments in GENIE

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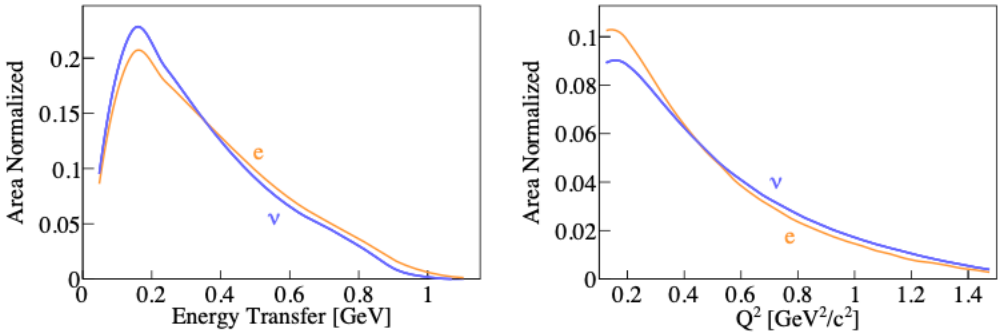
NuSTEC Workshop on Electron Scattering
28 March 2022

# Overview of Electron QE scattering in GENIE

- Neutrino and electron scattering community have combined forces
  - Remarkable similarity between electron-nucleus and neutrino-nucleus cross sections




A. Papadopoulou et al. Phys.Rev.D 103 (2021)

  - Electron scattering probes same vector current as neutrino scattering, sensitivity to nuclear ground state, and transport of final state hadrons
  - “Any model which fails to accurately describe eA (vector-vector) scattering data cannot be used with confidence to simulate vA (vector- vector + axial-axial + vector-axial) interactions"

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

# Overview of Electron QE scattering in GENIE

- Electron scattering has been incorporated into GENIE's mission statement
  - Leverage precision electron scattering measurements
  - Use GENIE to transfer insight from electron scattering to neutrino scattering within the same framework

- Major time investment in GENIE from collaborators and theorists to incorporate realistic models for electron scattering
- Along these lines, GENIE now includes a suit of diverse QE models to test against data in this effort
  - SuSAv2
  - STA
  - HF-CRPA
  - More to come

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**Electron Scattering and Neutrino Physics**

A NF06 Contributed White Paper

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

arXiv:2203.06853 [hep-ex]

# Framework – Inclusive QE Scattering

- For most models, lepton-nucleus inclusive cross sections (lepton kinematics only) can be put into a factorized form

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

- This piece is independent of model
  - Global (process dependent) pre-factor that depends on lepton kinematics and leptonic tensor

- Hadronic Tensor is the model dependent piece

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

  - Depends on details of microscopic calculation
  - Nuclear model used
  - Different combinations of tensor elements make it into final cross section

# Framework – Inclusive QE Scattering

- GENIE has adopted a hadron tensor table framework for theorists to incorporate their models

- Pre-computed tables of nuclear responses or tensor elements evaluated on grid of $(\omega,|\mathbf{q}|)$
  - Nearest neighbors bilinear interpolation scheme used to evaluate tensor elements between grid points
  - Method originated from work to implement Valencia MEC model into GENIE and was then generalized

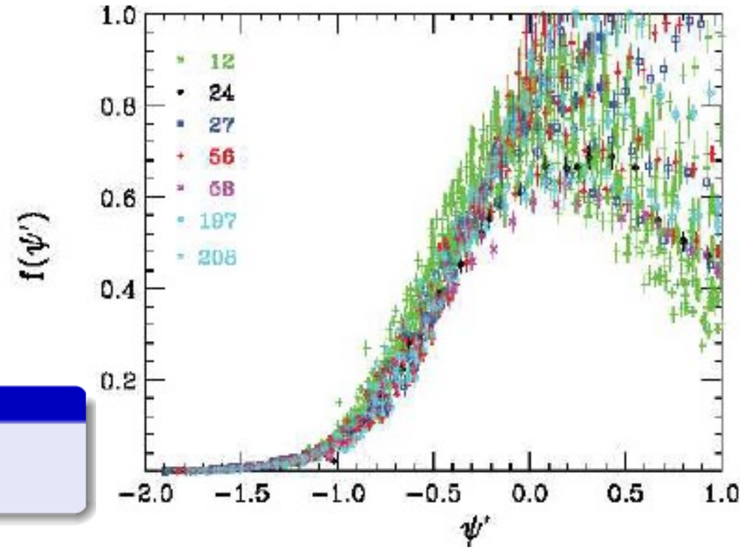
# SuSAv2

- SuSAv2 approach uses SuperScaling
  - Write inclusive cross section in terms of universal function

**In inclusive QE scattering we can observe:**

- ☆ Scaling of 1$^{st}$ kind (independence on $q$)
- ☆ Scaling of 2$^{nd}$ kind (independence on $Z$)

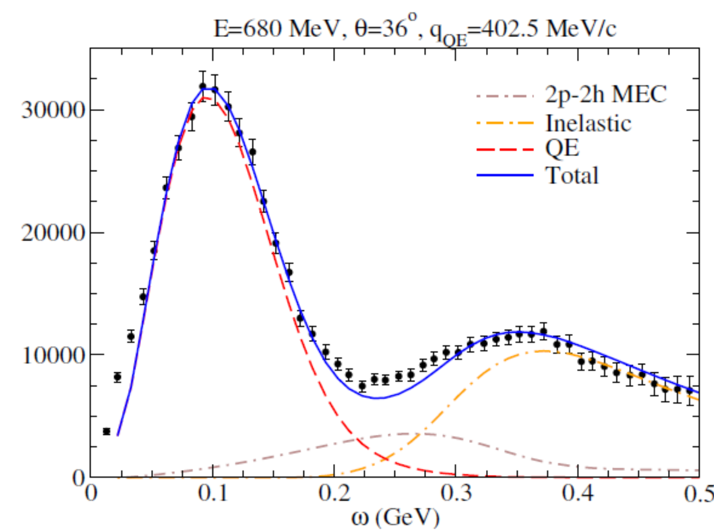
$\Longrightarrow$ SuperScaling




  - For EM scattering scaling function is

$$f(\psi') = k_F \frac{\frac{d^2\sigma}{d\Omega_e d\nu}}{\sigma_{Mott}(v_L G_L^{ee'} + V_T G_T^{ee'})}$$

  - Relativistic Mean Field model of nuclear ground state used in 1p1h SuSAv2 implementation
  - 2p2h MEC contributions within RFG-based calculation
    - Fully relativistic

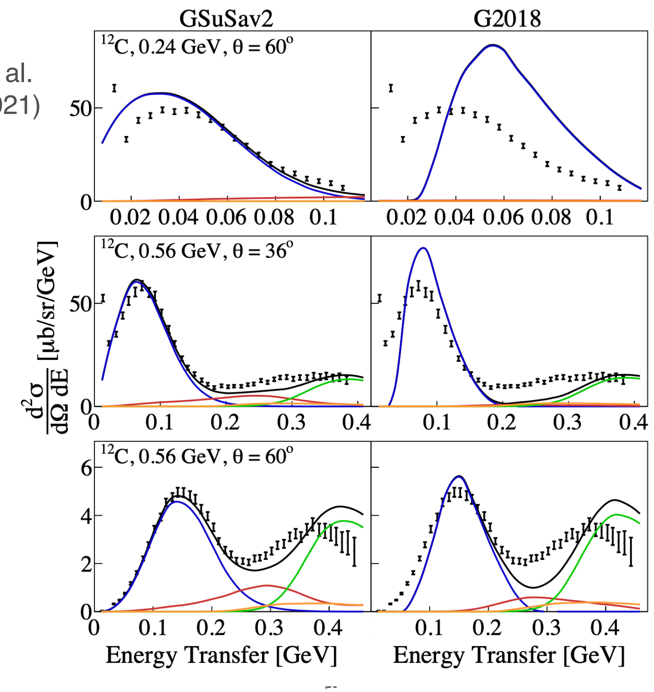


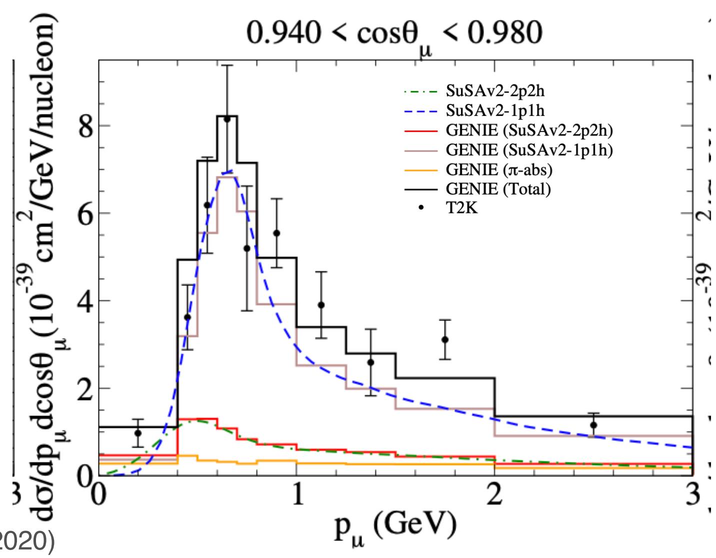

G. D. Megias et al. PhysRevD.94.013012

# SuSAv2

- Well validated on electron scattering
- Implemented in GENIE-v3 (Available as of early March 2022)
  - Hadronic tensor on finely spaced (5 MeV) grid in ($q_3$, $q_0$)
  - Excellent agreement for electron and neutrinos in the QE + MEC region
  - Implementation gives almost identical inclusive predictions
  - Tested against e4nu data and T2K data
  - Some work on semi-inclusive predictions
    - Cuts on final state hadron
    - Not guaranteed due to factorization
      - Outgoing hadronic system has been integrated over in tensor table

A. Papadopoulou et al.
Phys.Rev.D 103 (2021)




S. Dolan et al.
*Phys.Rev.D* 101 (2020)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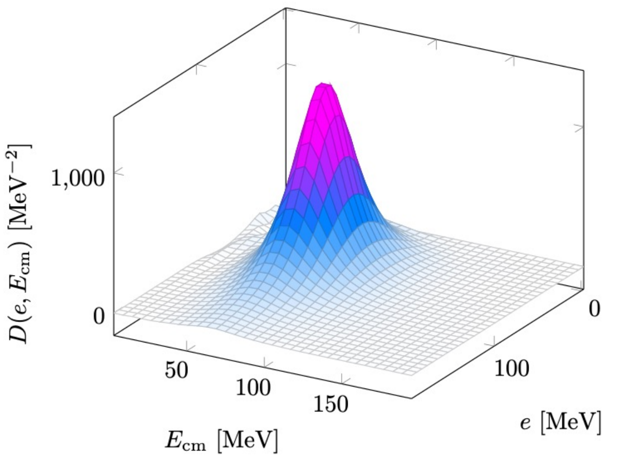
# Short Time Approximation (STA)

- STA is one of a number of Quantum Monte Carlo (QMC) techniques developed recently to study electron and neutrino scattering
  - Response functions ($R_L$ and $R_T$) written as:

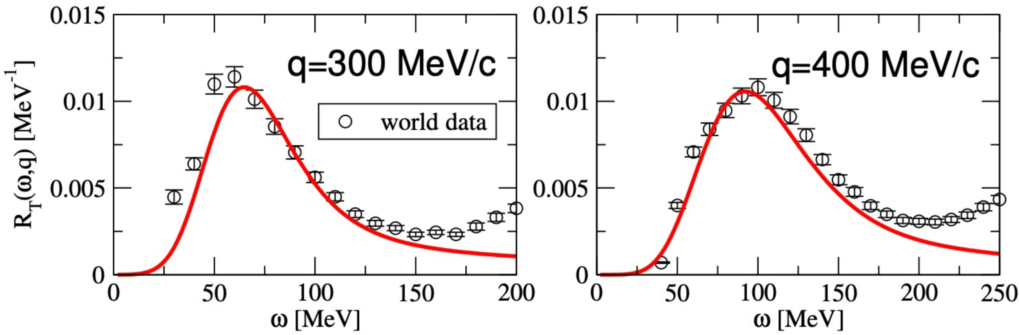
$$R_\alpha(\mathbf{q},\omega) = \int_{-\infty}^{\infty} \frac{dt}{2\pi}\, \mathrm{e}^{i(\omega+E_0)t} \times \langle \Psi_0 | J_\alpha^\dagger(\mathbf{q})\, \mathrm{e}^{-iHt}\, J_\alpha(\mathbf{q}) | \Psi_0 \rangle$$

  - In STA matrix element is evaluated for short times
    - Full QMC ground state and current operators + FSI at the two-nucleon level
    - Pairs of correlated nucleons interact with probe including consistently 1 and 2 body currents (includes interference)
    - Response functions obtained as integral of response density over relative and CM energy
    - Gives access to exclusive cross sections
      - See S. Pastore's talk tomorrow




L. Andreoli et al.
Phys.Rev.C 105 (2022)

S.Pastore et al.
*Phys.Rev.C* 101 (2020)





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# Short Time Approximation (STA)

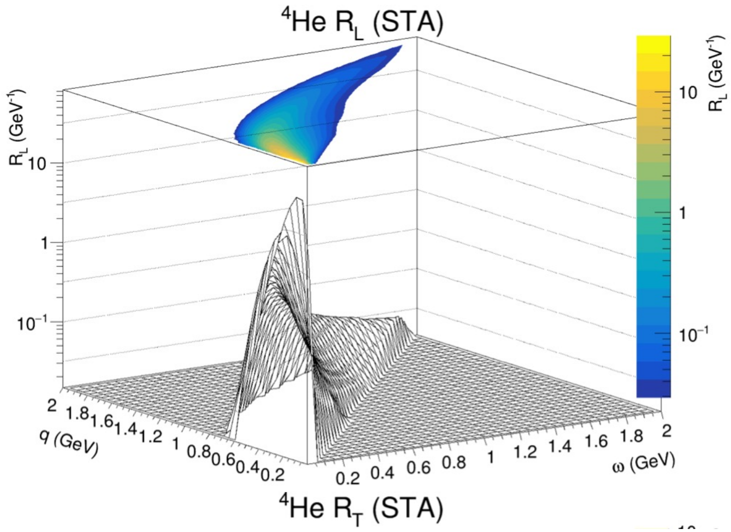
- STA is implemented in GENIE as with other models via a Hadron Tensor Table
  - Computational cost inhibits calculation of a finely spaced grid in |q| and ω
  - Use of (non relativistic) scaling allows for construction of more dense grid to be interpolated across
    - "Average" scaling function constructed from tabulated responses

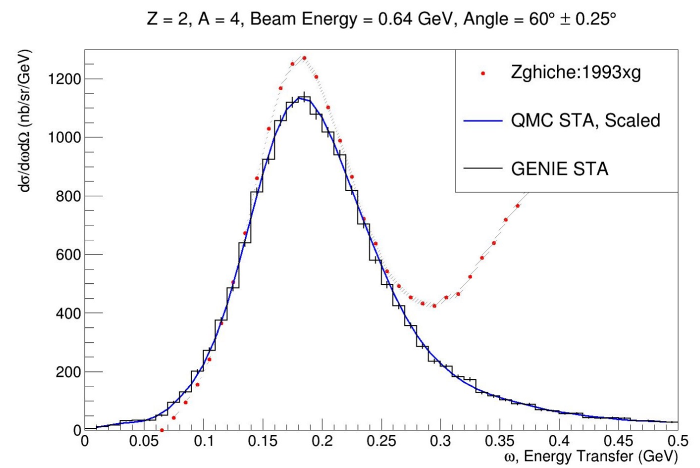
$$\overline{f_\alpha^{nr}}[\psi^{nr}(|\mathbf{q}|,\omega)] = \frac{1}{N}\sum_{i=1}^{N} f_{\alpha,i}[\psi^{nr}(|\mathbf{q}_i|,\omega \in \widetilde{Q})],$$

    - From which many new response functions can be computed

$$R_\alpha^{nr}(|\mathbf{q}|,\omega) = \frac{1}{k_F}\cdot G_\alpha(|\mathbf{q}|)\cdot \overline{f^{nr}}[\psi^{nr}(|\mathbf{q}|,\omega)].$$

    - Plans to include response densities in future to give access to both lepton and hadrons moving out from the interaction vertex




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

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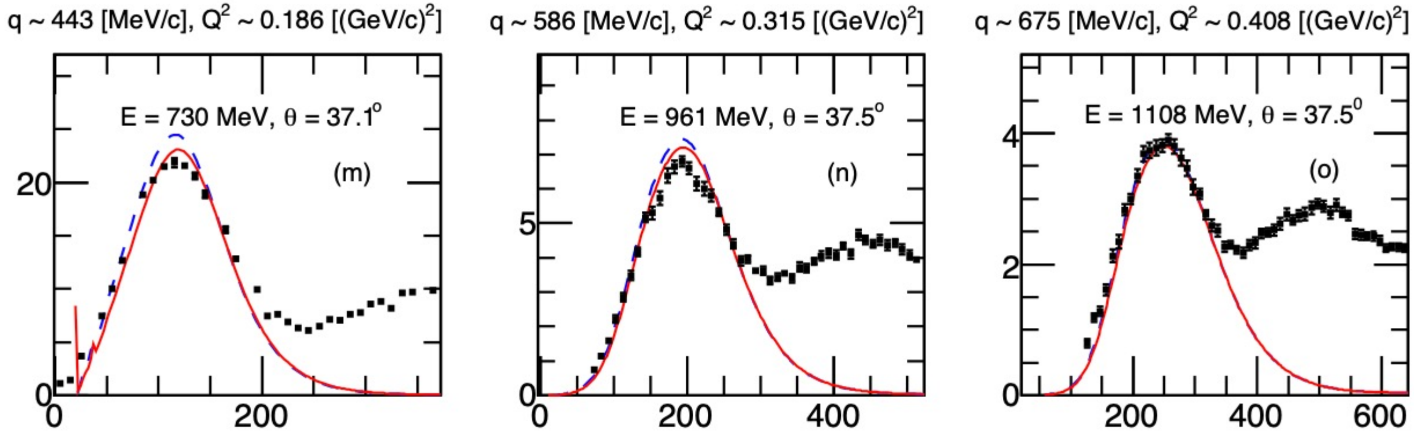
# HF-CRPA

- Hartree-Fock (HF) mean-field + Continuum random phase approximation (CRPA) V. Pandey et al. *Phys.Rev.C* 92 (2015)
- Model predicts significantly different cross sections at low energy transfer
  - MF potential obtained by solving Hartee-Fock equations
  - Wave function of outgoing nucleons automatically include effects from FSI
  - Long range correlations introduced by solving CRPA equations





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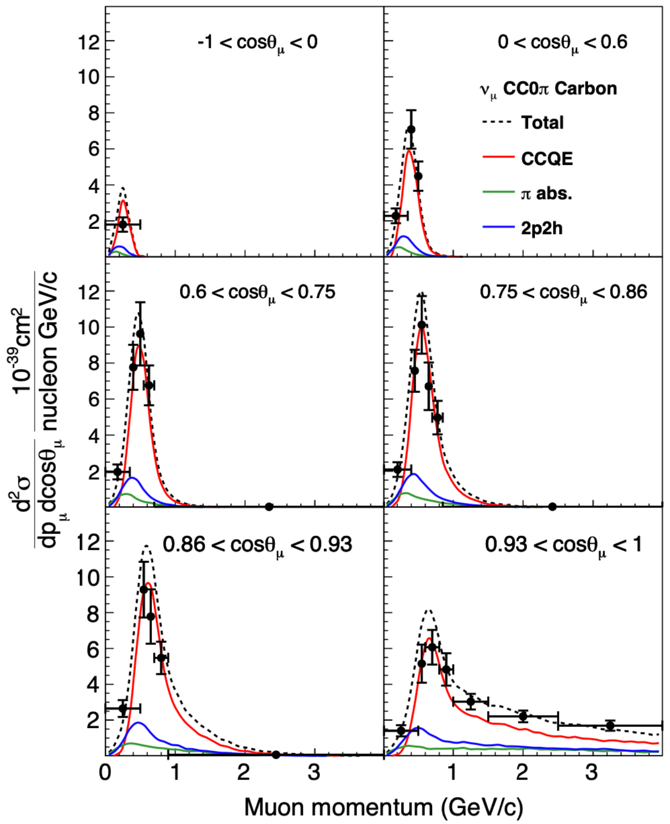
# HF-CRPA

- CRPA approach also not limited to inclusive observables
  - Cross section does not factorize due to RPA and FSI
  - In GENIE cross section is approximately factorized by integrating over outgoing nucleon momentum
  - Hadron Tensor table provided to GENIE
    - Carbon, Oxygen, Argon
    - Comparisons with and without RPA
    - Responses can be separated into V-V, V-A, A-A contributions
      - Same tables can be used for electron/neutrino interactions, and form factors can be modified by rescaling tables




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



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# Theory API's: Extended Factorization + SF

- Need for common interface to incorporate models into generators
  - Implemented via a Fortran wrapper around existing theory code
    - Theory code computes Hadronic Tensor which is then passed to GENIE
    - In contrast to tables, response functions can be computed on the fly on an event by event basis

- First test API by incorporating the extended factorization scheme + Spectral function

- For |**q**| > 500 MeV, factorize final state

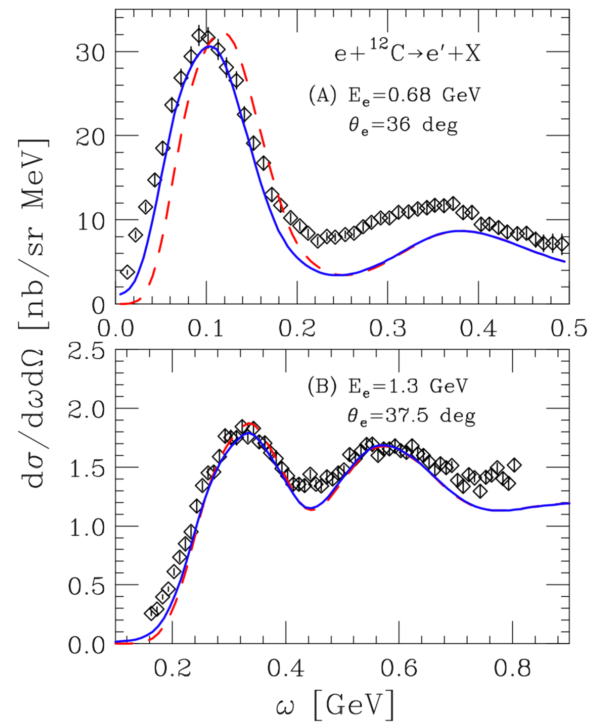
$$d\sigma_A = \int dEd^3k \; d\sigma_N \; P(k,E)$$

- Extended factorization scheme allows calculation beyond QE
  - 2p2h + Pion production
  - Opens door for consistent scheme to evaluate contributions from all interaction mechanisms

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]

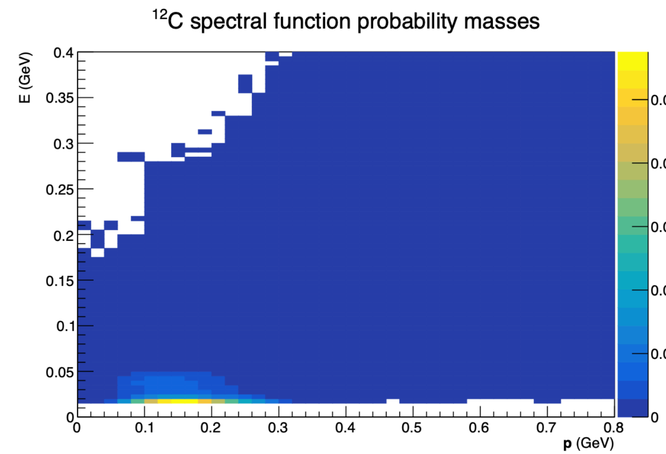
arXiv:2008.06566 [hep-ex]



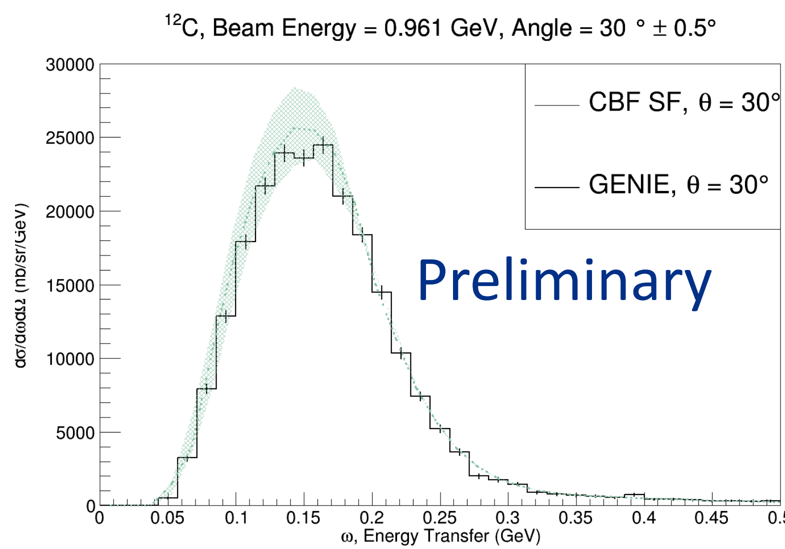

N. Rocco et al.
*Phys.Rev.Lett.* 116 (2016)

# Factorization scheme + Spectral Function (SF)

- CBF spectral function available as nuclear model in GENIE
  - Removal energy and momentum correlated
- Factorization scheme implemented for QE electron scattering (neutrinos soon)
- New event generator which samples 4-momentum of outgoing lepton **and** nucleon
  - Cross section computed as $d\sigma/d^4k d^4p$, a universal form
    - Methods for efficiently sampling this phase space available, see J. Isaacson's talk!
  - Exclusive observables




12C spectral function probability masses in GENIE, provided by S. Gardiner



# Conclusion

- Synergy between our understanding of electron scattering and neutrino scattering

- Plethora of realistic models have been added to GENIE which were originated from electron scattering
  - Can now be applied to neutrino scattering

- More models and novel comparisons to data to come

- Thank you