Spectral Function Implementation in Neutrino Event Generator and Its Impact on Neutrino Oscillation Parameters

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Outline

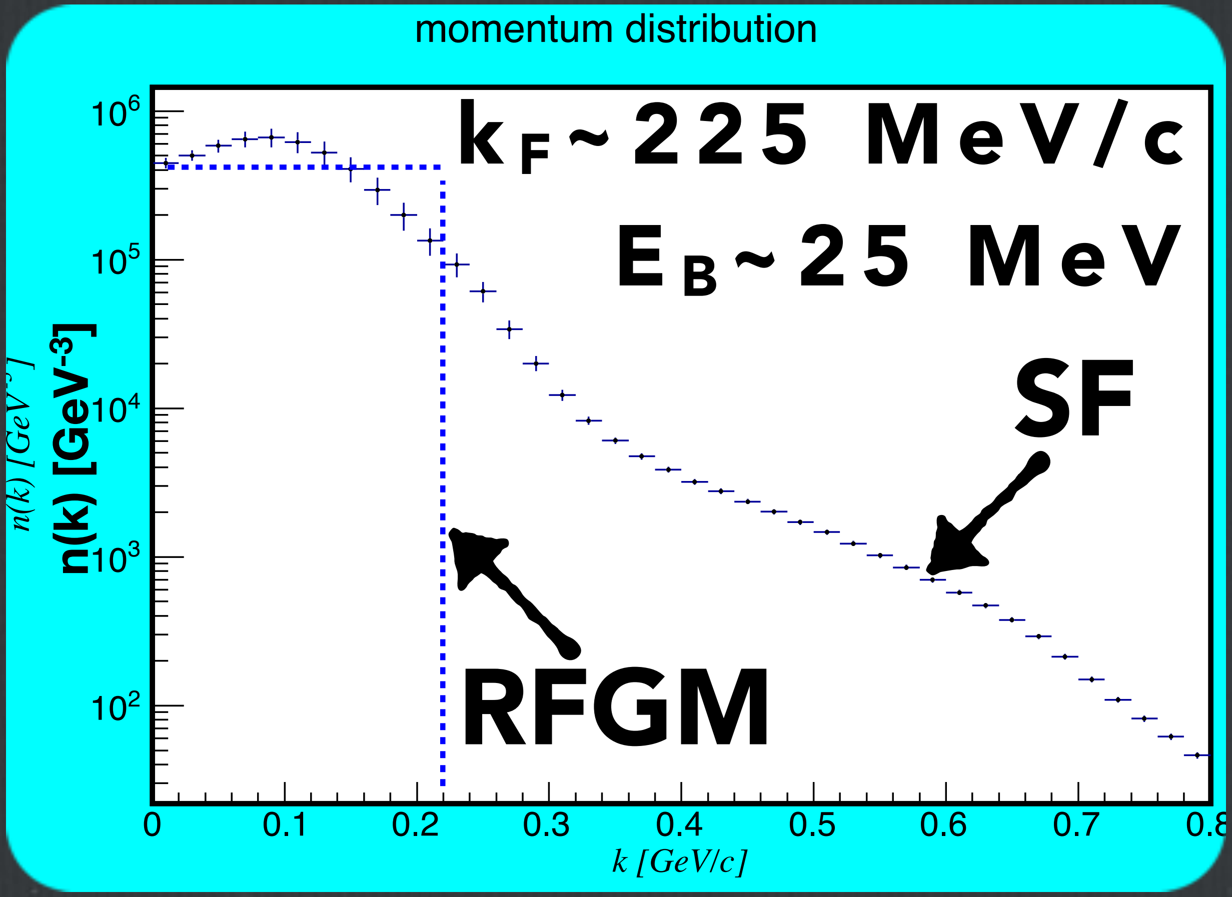
- Nuclear Models: Relativistic Fermi Gas vs. Spectral Function
- The Role of Nuclear Models in Cross Section Calculation
- Electron Validation
- Neutrino Cross-section
- Impact on Oscillation Parameters
- Conclusions

Qualitative Comparison

white - RFGM

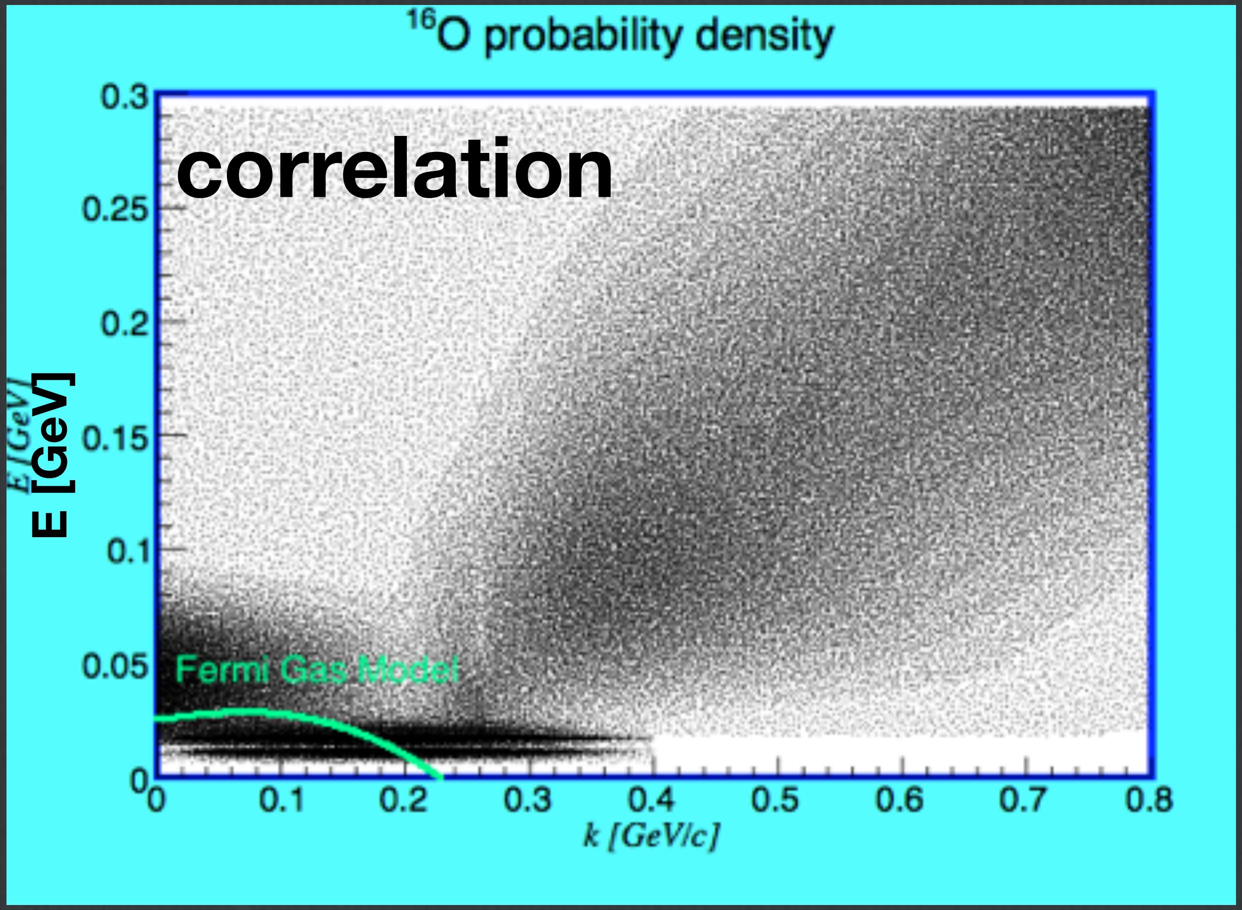
Green - Spectral Function

NUCLEAR MODEL
RFG VS. SF
ONE-BODY CURRENT - MODIFIED SHELL MODEL



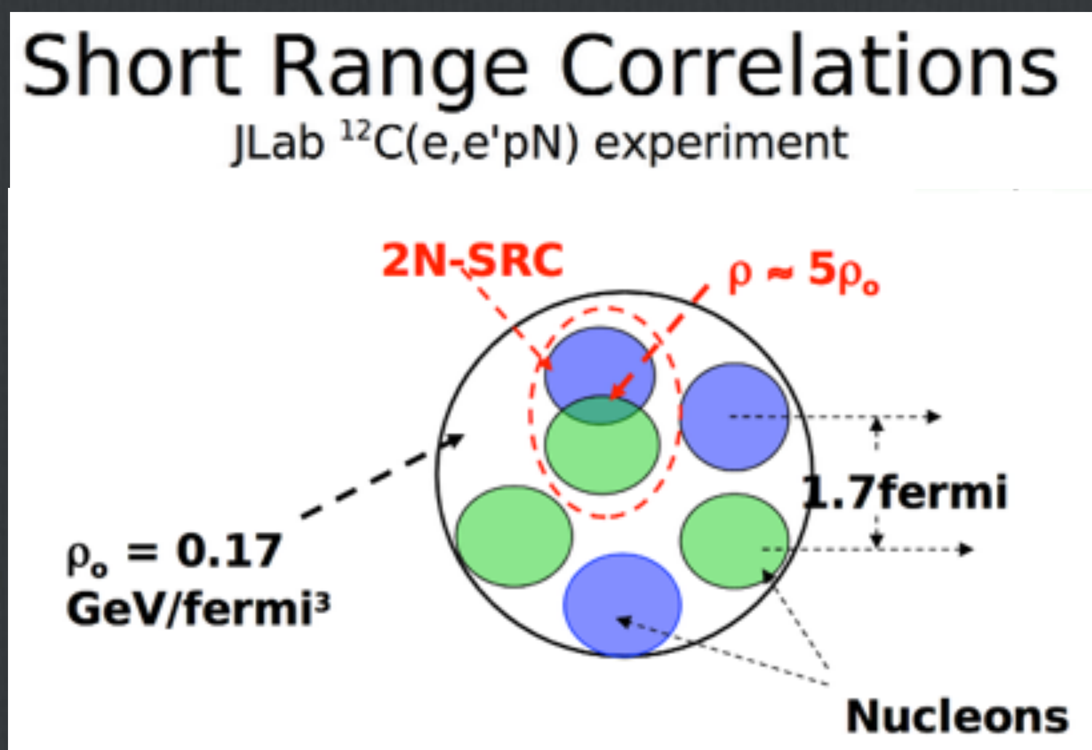
- initial-state nucleon's momentum distribution, k_n, is uniform in between 0 and k_F
- k_n is non-uniform in the spectral function theory, and yields a much better prediction to the measured electron cross-section than RFGM

NUCLEAR MODEL
RFG VS. SF
ONE-BODY CURRENT - MODIFIED SHELL MODEL



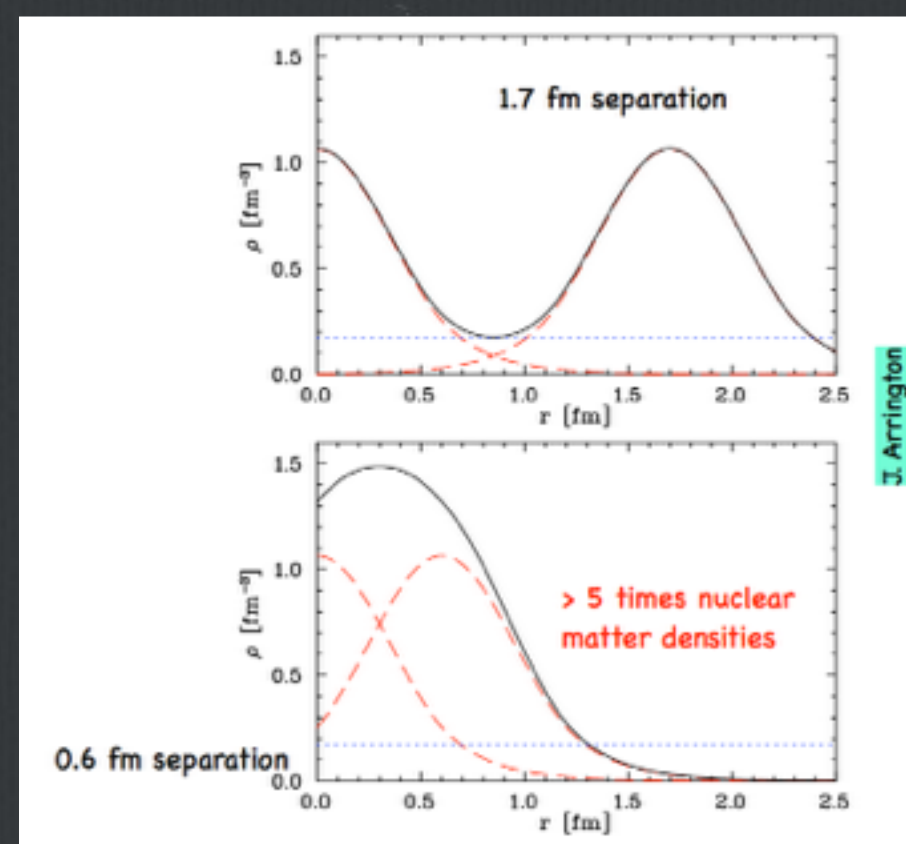
- the spectrum of each shell is assumed to be delta-function like
- removal energy is averaged to be one constant parameter for each struck nucleon
- in reality, the spectrum instead is a gaussian distribution
- the overlapping of gaussian tails in between two adjacent shells leads to the (position) correlation
- removal energy is correlated to k_n (momentum-dependent)

NUCLEAR MODEL
RFG VS. SF
ONE-BODY CURRENT - MODIFIED SHELL MODEL



courtesy of S. Wood, JLab @ NUINT'07 talk

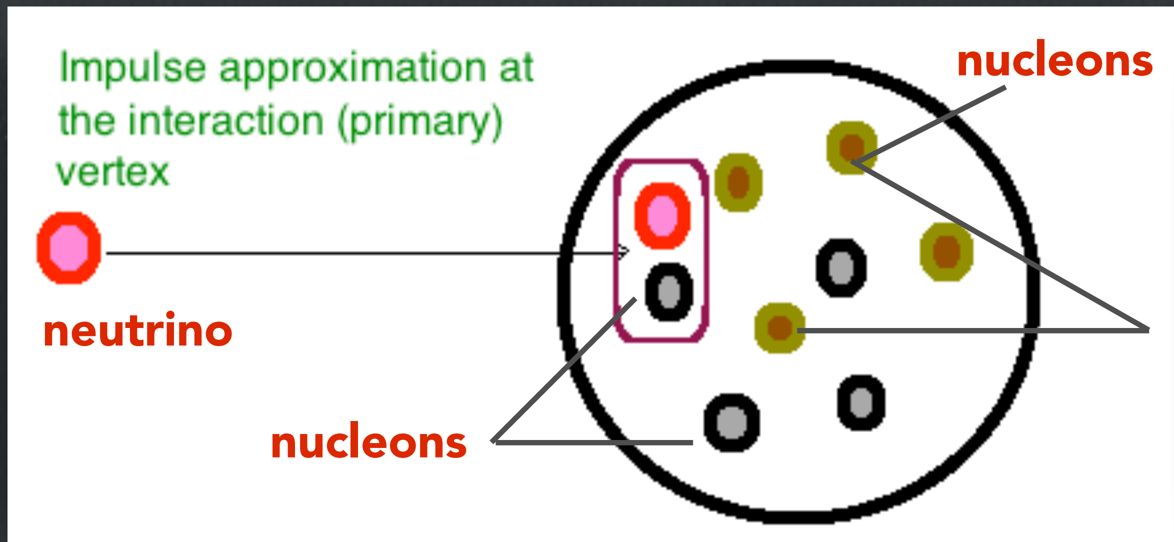
- no nucleon-nucleon (short-range) correlation effects considered
- N-N (2N) correlation is not negligible

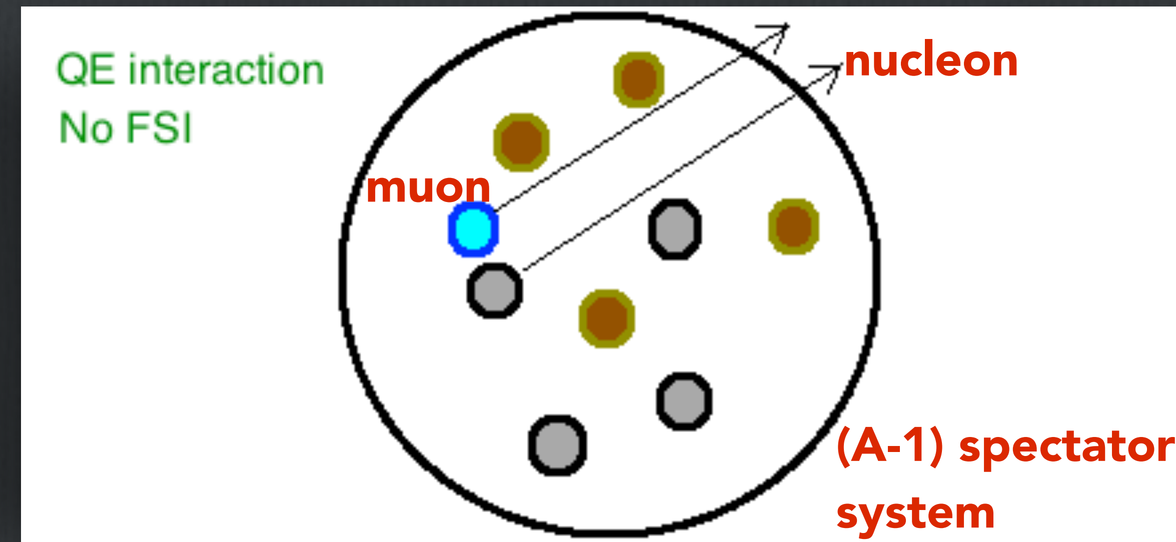


Quantitative Comparison

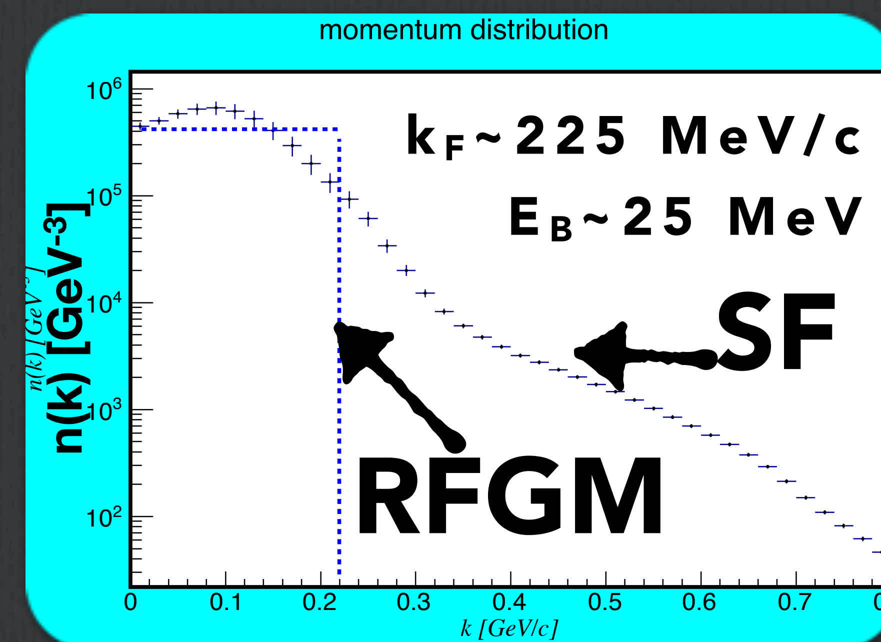
white - RFGM

Green - Spectral Function





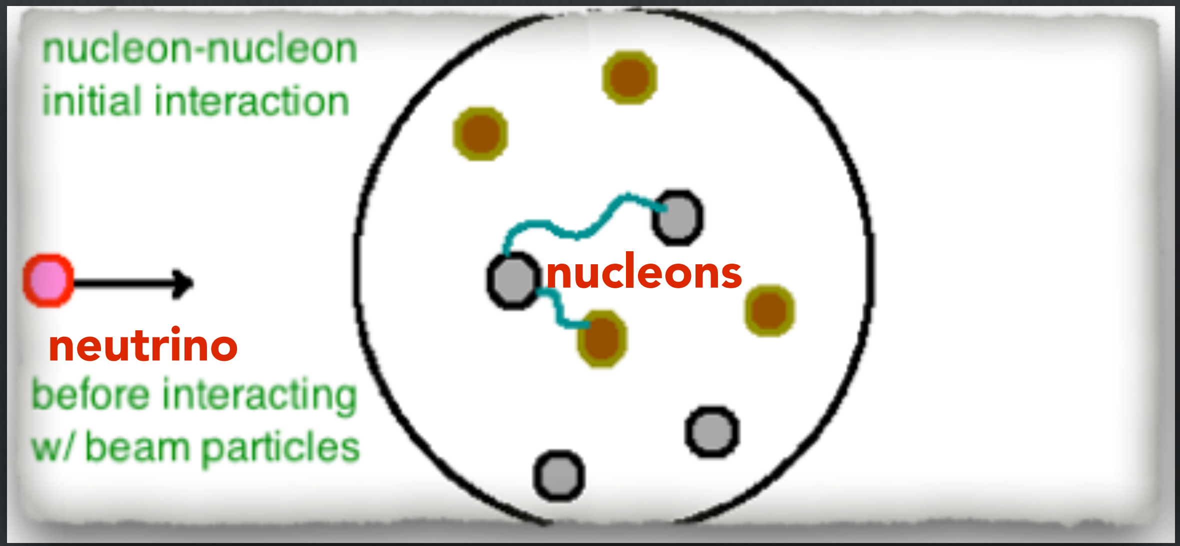
r (interaction length) ~ nucleon size ~ 1/|q|

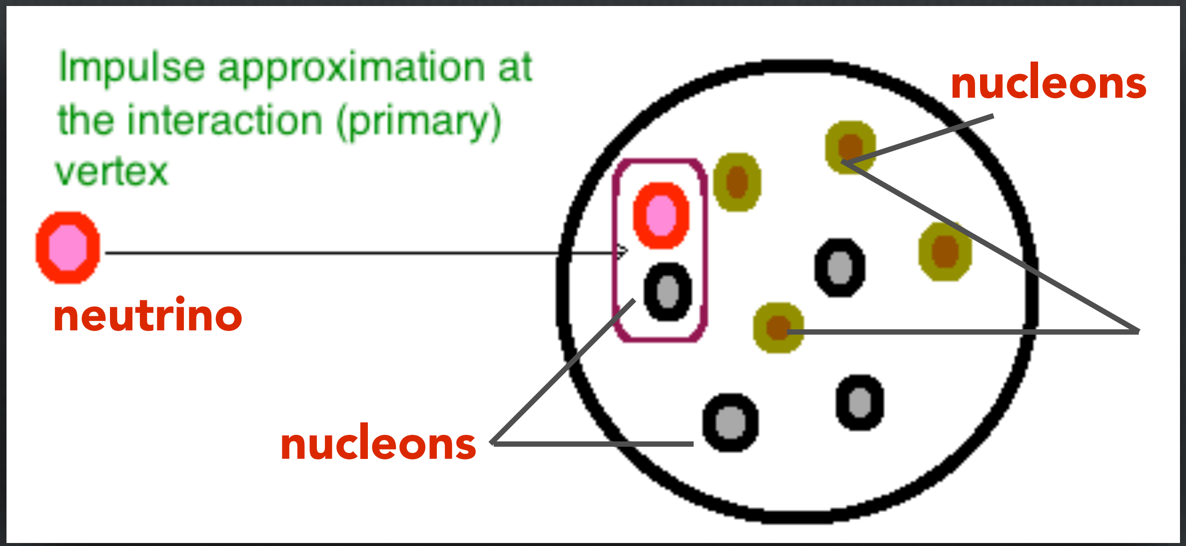


- RFG model

$$P(|\vec{\mathbf{p}}|, E) = \frac{3}{4\pi k_F^3}\theta(k_F - |\vec{\mathbf{p}}|)\delta(\sqrt{m^2 + |\vec{\mathbf{p}}|^2} - m - E_B + E)$$

step function energy-momentum conservation





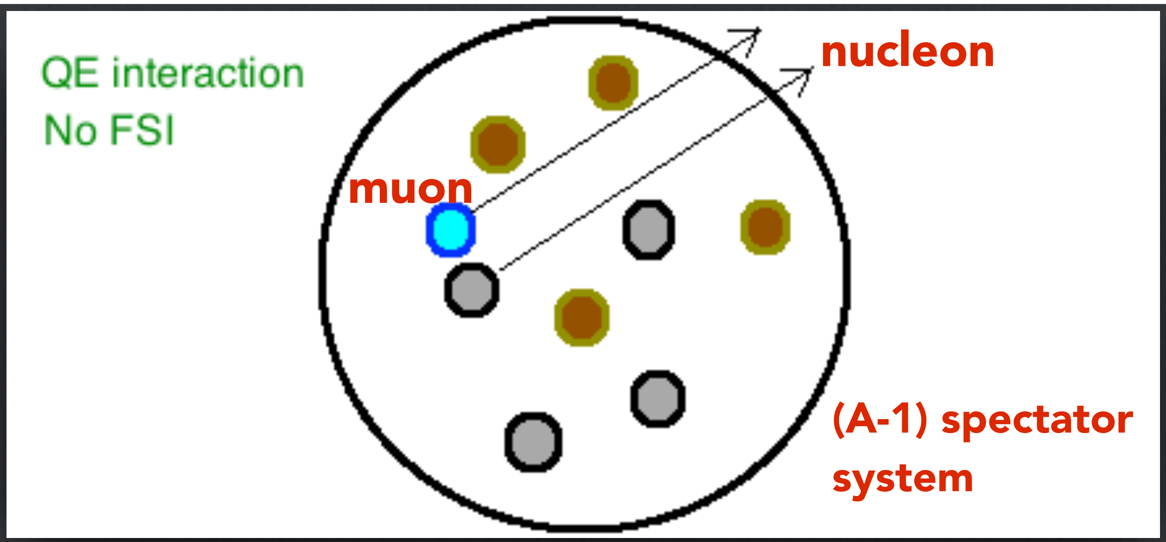
r (interaction length) ~ nucleon size ~ 1/|q|

- **SF model (1p-1h : the simplest situation)**

$$P(|\vec{\mathbf{p}}|, E) = |<^{40}Ar|^{39}Ar, p>|^2 \delta(E_{^{40}Ar} - E_{^{39}Ar} - m_n + E)$$

probability amplitude of knocking out one nucleon — energy-momentum conservation

- the spectral function theory represents different joint probabilities to find different nucleons sitting on different shells (with different missing momentum (q) and missing energy (w))
- the delta function guarantees the energy conservation.



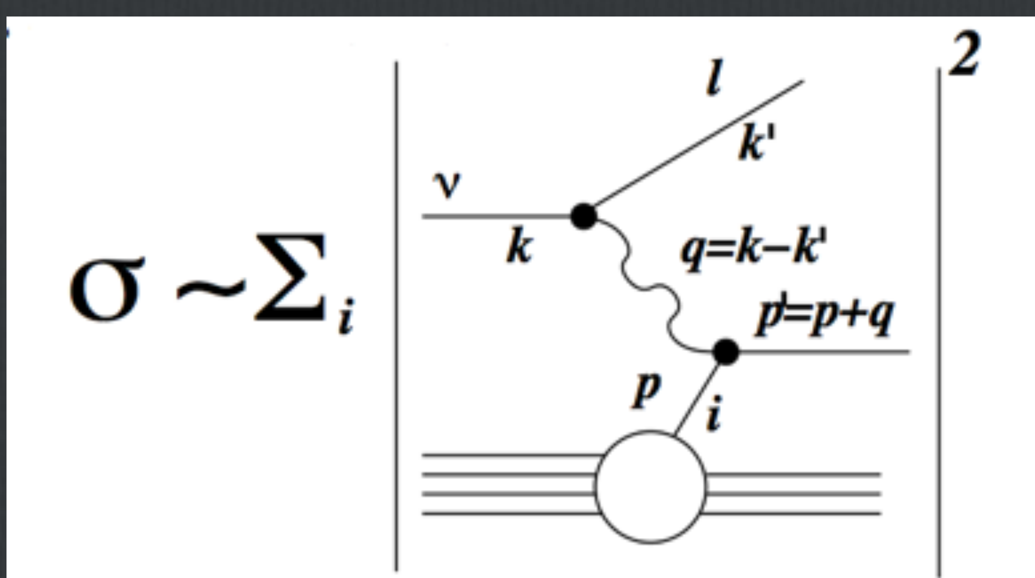
CROSS-SECTION
ONE-BODY CURRENT

elementary process of each isolated nucleon

$$\left(\frac{d^2\sigma}{d\omega\, d\Omega_{k'}}\right)_N \propto L_{\mu\nu}(k,k')\,W^{\mu\nu}(\widetilde{p},\widetilde{p}+\widetilde{q})$$

beam particles + outgoing leptons

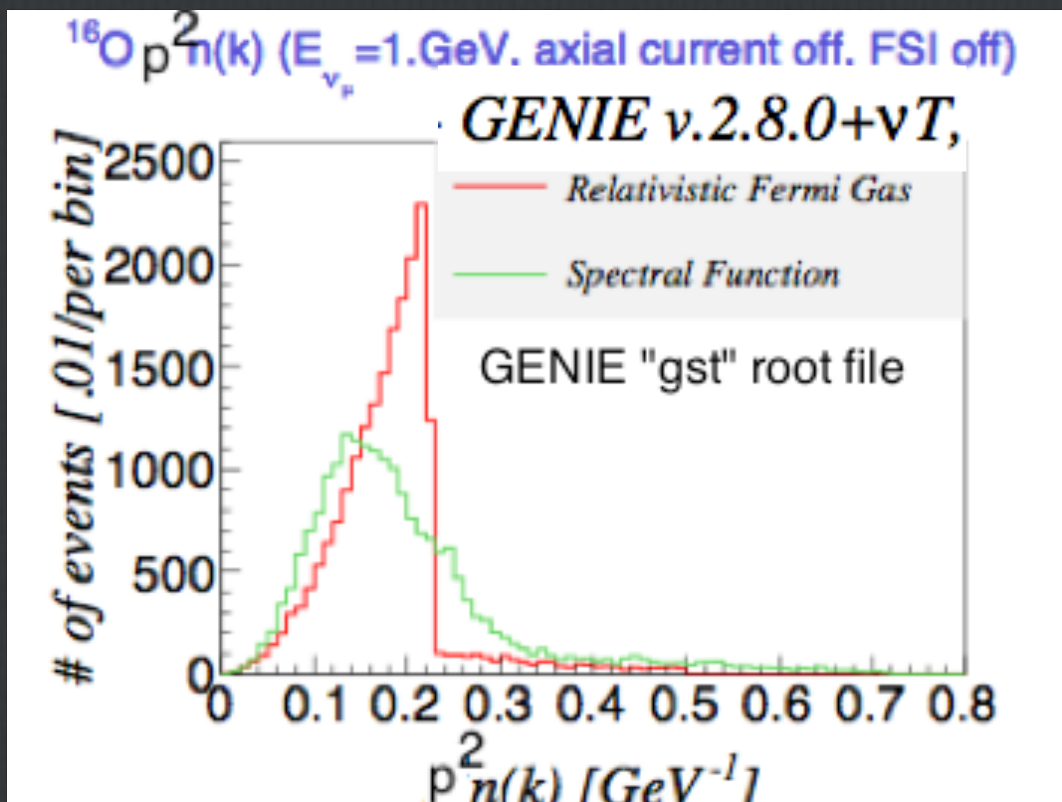
struck nucleon + residual nuclear system



- the differential cross-section is composed of two separate parts: the lepton tensor and the target structure tensor (nucleon form factors) and is a function of (q, w)
- the total cross-section is the incoherent sum of differential cross-sections for different elementary scattering processes

NUCLEAR MODEL IN CROSS-SECTION

ONE-BODY CURRENT



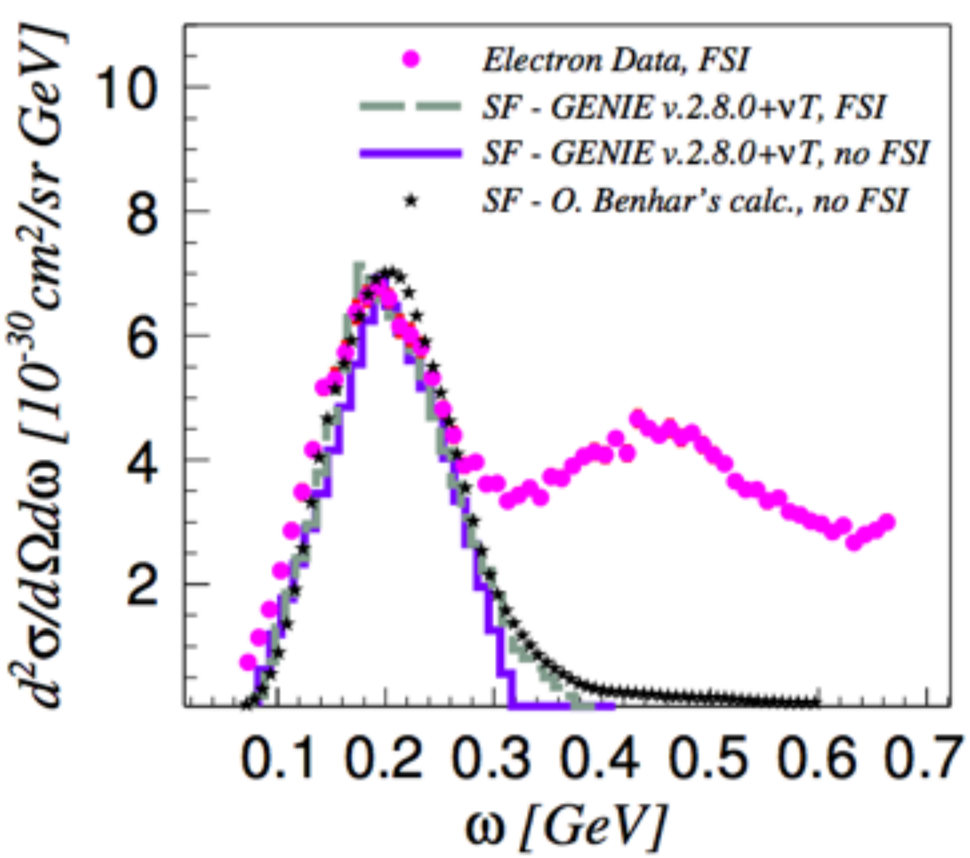
- **in RFGM, nucleons sitting around Fermi sea are most likely to interact with beam particles**
- **according to the spectral function theory, the probability of interacting of each nucleon with beam particles, however, is different from the one of RFGM**
- **"the interaction probability" plays an important role in determining the contribution to every elementary cross-section for each struck nucleon**

$$\left(\frac{d^2\sigma}{d\omega d\Omega_{k'}}\right)_A = \int d^3p\, dE \left(\frac{d^2\sigma}{d\omega d\Omega_{k'}}\right)_N P(|\mathbf{p}|, E)$$

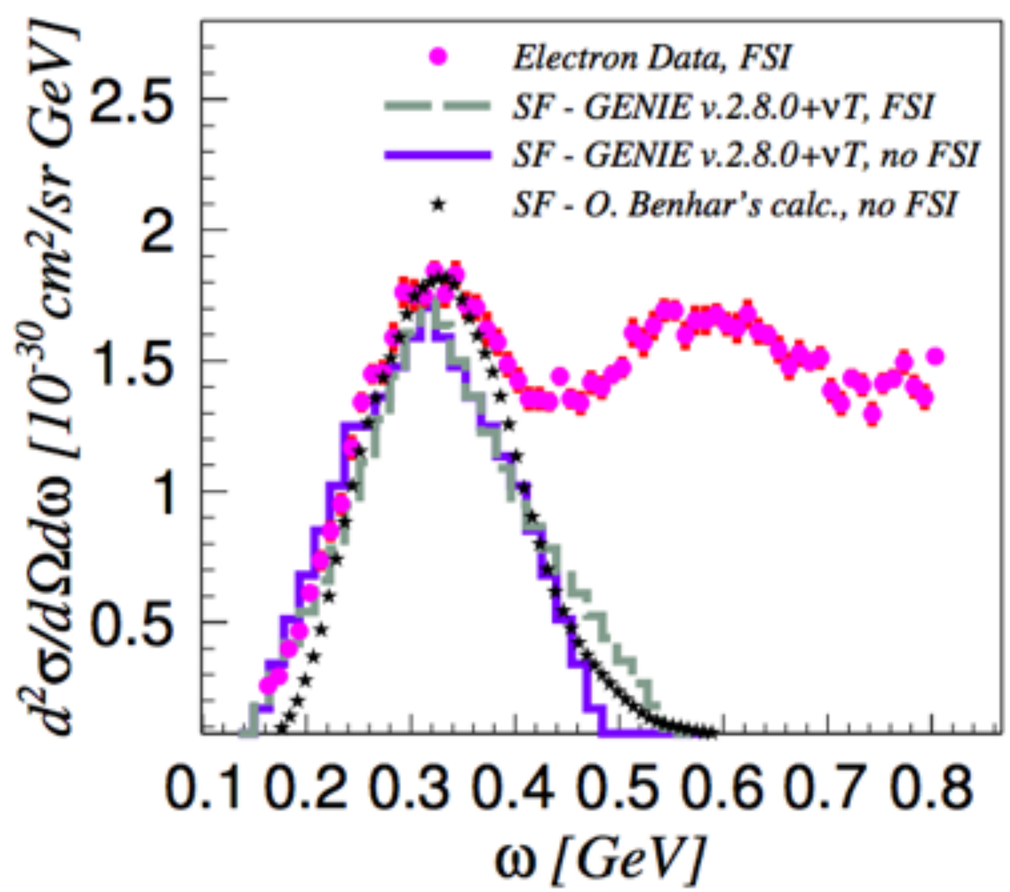
p^2dp

$$\times\ \delta(\omega + M_A - \sqrt{|\mathbf{p}+\mathbf{q}|^2 + m^2} - E_{A-1})\ .$$

Electron Validation

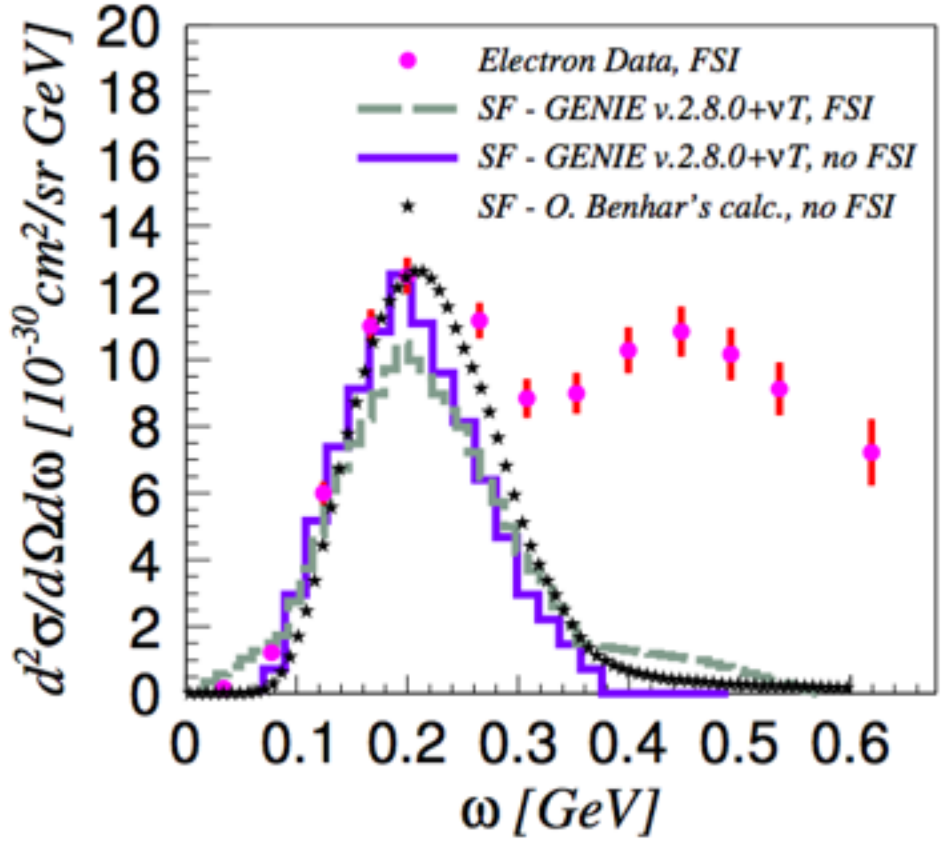


(a) $e + \mathrm{C} \rightarrow e' + X$, E_e=0.961 GeV, θ_e=37.5 deg

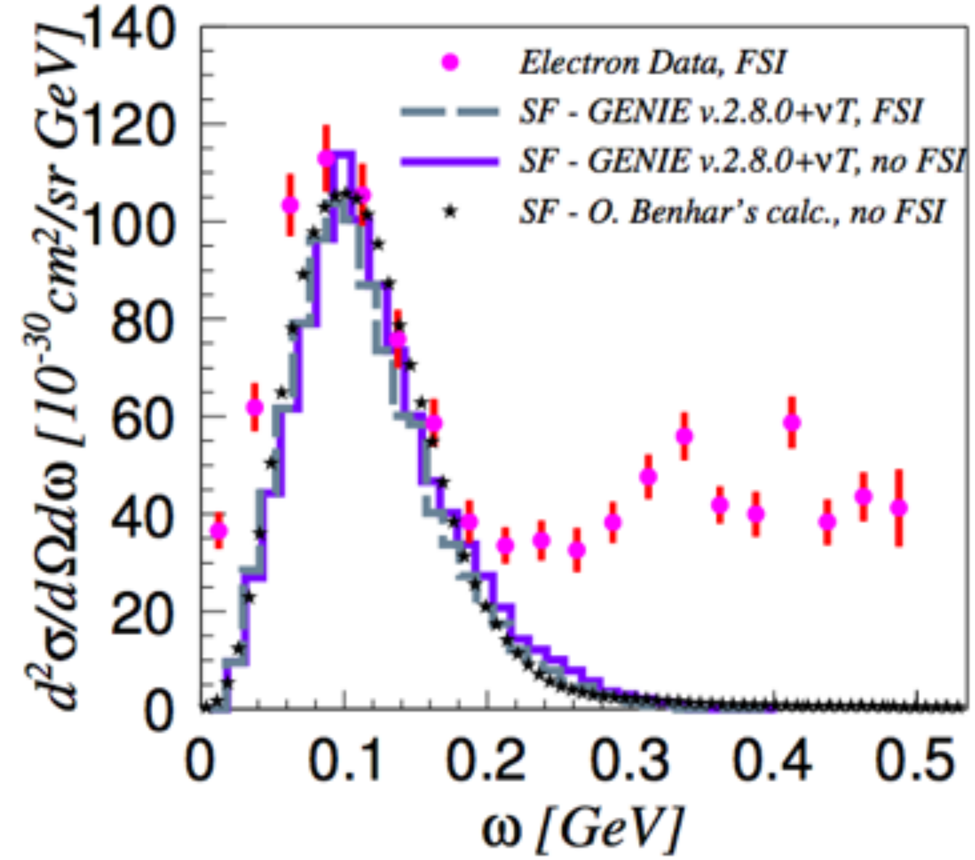


(b) $e + \mathrm{C} \rightarrow e' + X$, E_e=1.299 GeV, θ_e=37.5 deg

Electron Validation



(c) $e + \mathrm{Ca} \rightarrow e' + X$, E_e=0.841 GeV, θ_e=45.5 deg

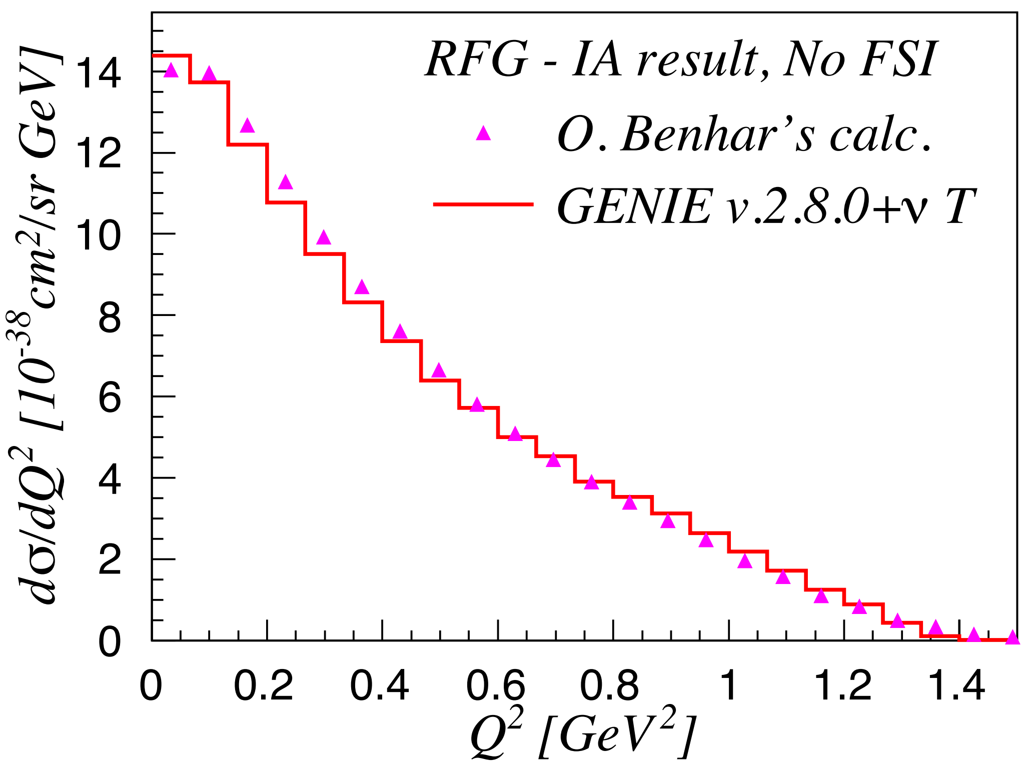


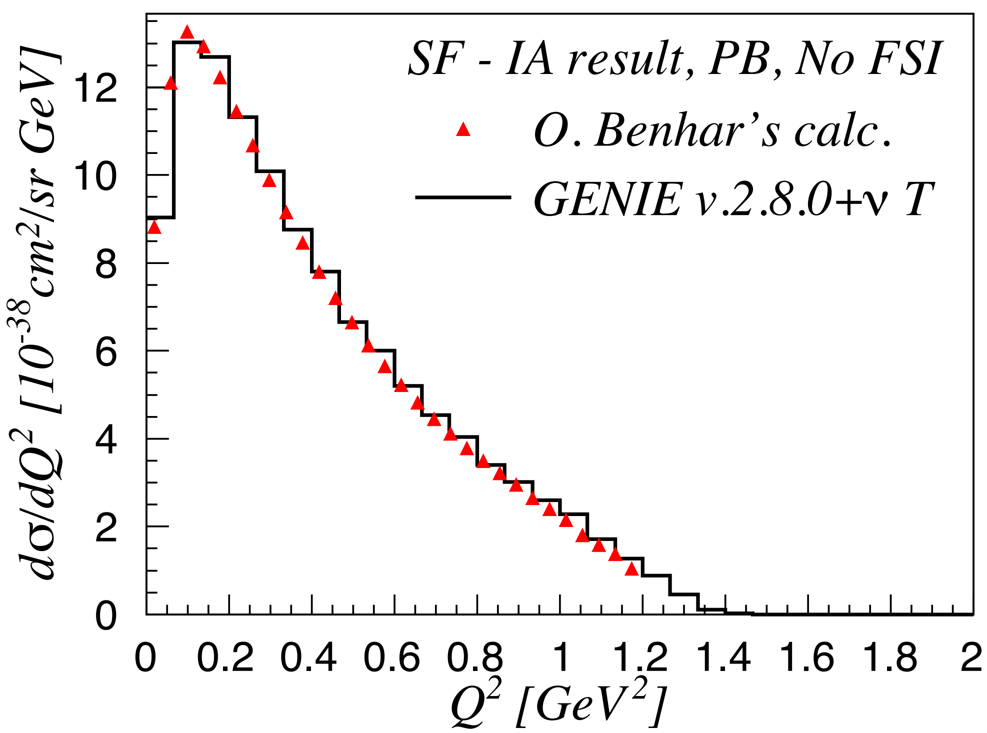
(d) $e + \mathrm{Ar} \rightarrow e' + X$, E_e=0.7 GeV, θ_e=32 deg

Owing to the lack of electron scattering data, the energy and momentum dependence of the model, spectral functions of calcium and argon, is not strongly constrained

Neutrino Cross-Section

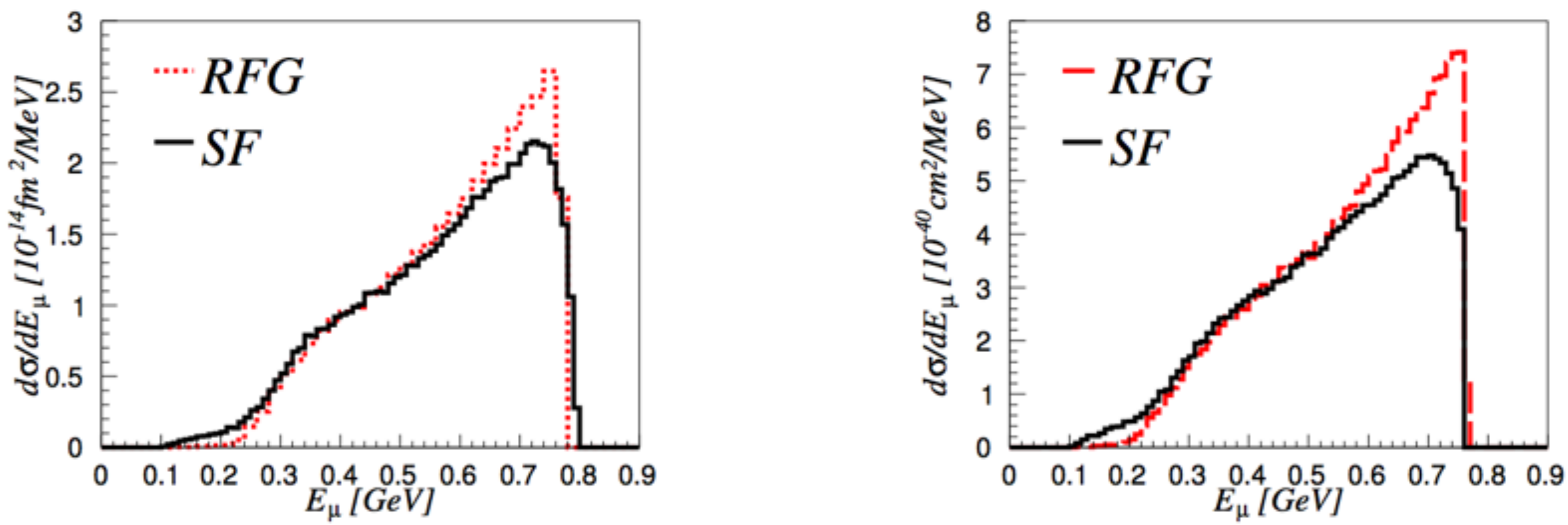
courtesy of O. Benhar, N. Farina, H. Nakamura, M. Sakuda, R. Seki PRD 72, 053005 (2005)





Neutrino Cross-Section

courtesy of A. M. Ankowski nucl-th/0608014v1 4 Aug 2006
courtesy of A. M. Ankowski, Jan T. Sobczyk PRC 77, 044311 (2008)



(a) $\nu + \mathrm{O} \rightarrow \mu + X$, GENIE 2.8.0 + νT, no Pauli Blocking, no FSI (b) $\nu + \mathrm{Ar} \rightarrow \mu + X$, GENIE 2.8.0 + νT, Pauli Blocking and FSI included

FIG. 7. (Color online). Comparison of the differential CCQE cross sections $d\sigma/dE_\mu$ of oxygen (a) and argon (b) at neutrino energy $E_\nu = 800$ MeV, obtained using GENIE 2.8.0 + νT with RFGM and SF.

Experimental Setup - **Simulation**

- Ideal and perfect near detector (^{12}C or ^{16}O), 1 km, 1kton
- Far detector at 295 km, 22.5 kton
  - **Oxygen**
  - Carbon (RFG and SF)
- Use T2K flux, peak at 0.6 GeV, 750kW, 5 years running
- Use SK reconstruction efficiency as function of energy
- Use migration matrices produced by **GENIE 2.8.0+νT**

Migration Matrix is reconstructed energies as a function of true energies

- Muon neutrino disappearance only -> fit to atmospheric parameters

GLoBES Fit

hep-ph/1402.6651 Jen, Ankowski, Benhar, Furmanski, Kalousis and Mariani (submitted to PRD)

- Neglecting all FSI and multinucleon contributions, we can compute the number of events as:

$$N_i^{QE} = \sigma_{QE}(E_i)\phi(E_i)P_{\mu\mu}(E_i)$$

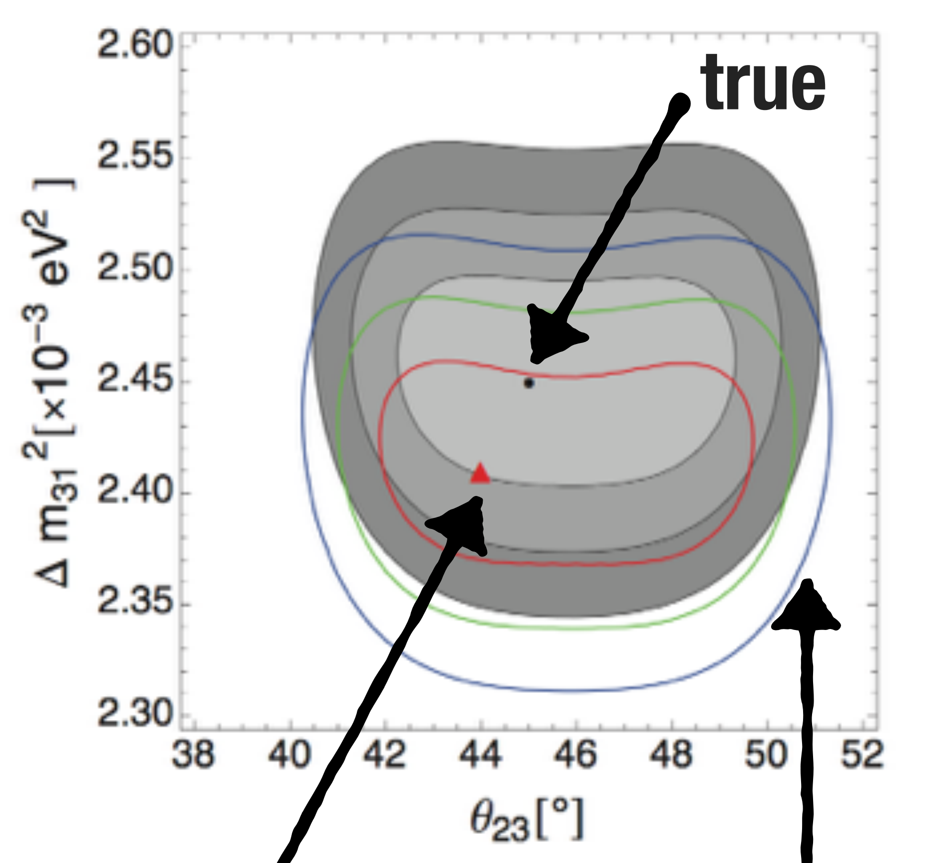
- However, in practice we will observe a different distribution at the detector, given by:

$$N_i^{QE-like} = \sum_j M_{ij}^{QE} N_j^{QE} + \sum_{non-QE} \sum_j M_{ij}^{non-QE} N_j^{non-QE}$$

- However, an intermediate situation would most likely take place:

$$N_i^{test}(\alpha) = \alpha N_i^{QE} + (1-\alpha) N_i^{QE-like}$$

Coloma and Huber, 1307.1243 [hep-ph]



true

hep-ph/1311.4506 Coloma, Huber, Jen, and Mariani (accepted by PRD)

- **the event distribution is a convolution of cross-section, flux, detector efficiency, oscillation probability and migration matrix**
- **different nuclear models consider different nuclear effects in treating nucleon's kinematics**
- **as a result, event distributions are different for different nuclear models**

SF - reconstructed from the true QE dynamics

1, 2 and 3σ allowed regions

Conclusions

- Argon spectral function already exists in GENIE (not yet released)
- Comparison to another neutrino event generator is already done; GENIE outputs are consistent to NuWro's
- However, due to the lack of knowledge in Argon nuclear structure, more electron data are needed.

Thanks for your attendance …

Numerical Implementation of lepton-nucleus interactions and its effect on neutrino oscillation analysis

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(Dated: April 4, 2014)

We discuss the implementation of the nuclear model based on realistic nuclear spectral functions in the GENIE neutrino interaction generator. Besides improving on the Fermi gas description of the nuclear ground state, our scheme involves a new prescription for Q^2 selection, meant to efficiently enforce energy momentum conservation. The results of our simulations, validated through comparison to electron scattering data, have been obtained for a variety of target nuclei, ranging from carbon to argon, and cover the kinematical region in which quasi elastic scattering is the dominant reaction mechanism. We also analyze the influence of the adopted nuclear model on the determination of neutrino oscillation parameters.

PACS numbers: 14.60.Pq, 14.60.Lm

Q & A

Acknowledgment: S. Dytman, H. Gallagher