SuSAv2-MEC model for electrons (WG1)

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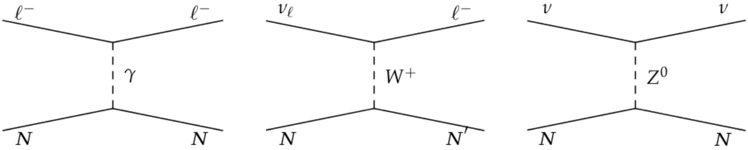
Testing and Improving Models of Neutrino Nucleus Interactions in Generators, Parallel sessions, ECT, 4 June 2019*

1. General Introduction
   - SuperScaling Approach: SuSAv2-MEC for electrons

Challenges and open questions for neutrino interaction models

1. Are current theoretical models (CRPA, Valencia LFG+2p2h, Benhar's SF, SuSAv2-MEC, RGF, etc.) good enough to analyze 1p1h and 2p2h channels in CC inclusive neutrino interactions?
2. Can we extend these models to semi-inclusive ν reactions?
3. What is the physics behind these models?
4. Can these models also reproduce inclusive (e, e') data and semi-inclusive $(e, e'p)$ processes?
5. Is it possible to introduce sophisticated microscopic models in generators in a fully consistent way?

Connection between ν-A and e-A reactions



(a) Electromagnetic scattering (b) Charged-current scattering (c) Neutral-current scattering

$l = e, \mu, \tau$

- Experimental conditions are different:
  ➠ (e, e'): E_e is well determined and different channels can be clearly identified by knowing the energy and momentum transfer
  ➠ CC(ν_l, l): E_ν is broadly distributed in the neutrino beam and different channels and nuclear effects can contribute to the same kinematics of the outgoing lepton
- From a theoretical framework, neutrino- and electron-nucleus scattering are obviously connected (CVC) to each other and a **reliable model** must be able to describe both processes.
- Neutrinos can probe both the vector and axial nuclear responses, unlike electrons which are only sensitive to the vector response.

$\Longrightarrow$ Although not sufficient to fully constrain neutrino cross sections, electron scattering constitutes a necessary test and a solid benchmark for nuclear models.

Theoretical description: ν-nucleus cross section

Double differential cross section

$\chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$

$$\left[\frac{d\sigma}{dk_\mu d\Omega_\mu}\right]_\chi = \frac{|\vec{k}_l|}{|\vec{k}_{\nu_l}|}\frac{G_F^2}{4\pi^2}\widetilde{\eta}_{\mu\nu}\widetilde{W}^{\mu\nu} = \sigma_0 \mathcal{F}_\chi^2 \quad ; \quad \sigma_0 = \frac{\left(G_F^2\cos\theta_c\right)^2}{2\pi^2}\left(k_\mu \cos\frac{\tilde{\theta}}{2}\right)^2$$

Nuclear structure information

$$\mathcal{F}_\chi^2 = V_L R_L + V_T R_T + \chi\,[2V_{T'}R_{T'}]$$

$$V_L R_L = V_{CC}R_{CC} + 2V_{CL}R_{CL} + V_{LL}R_{LL}$$

$$R_L = R_L^{VV} + R_L^{AA} \;;\; R_T = R_T^{VV} + R_T^{AA} \;;\; R_{T'} = R_{T'}^{VA}$$

Nuclear responses R_K can be calculated in terms of the single nucleon ones G_K and the nuclear dependence of the model $\Rightarrow R_K \approx F(nuclear)\cdot G_K$

$$R_{CC} = W^{00}$$
$$R_{CL} = -\frac{1}{2}\left(W^{03} + W^{30}\right)$$
$$R_{LL} = W^{33}$$
$$R_T = W^{11} + W^{22}$$
$$R_{T'} = -\frac{i}{2}\left(W^{12} - W^{21}\right)$$

Comparison with (e, e') reactions

$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right] = \sigma_{Mott}\left(v_L R_L^{VV} + v_T R_T^{VV}\right) \quad ; \quad \sigma_{Mott} = \frac{\alpha^2\cos^2\theta/2}{4E_i\sin^4\theta/2}$$

Double differential cross section $\chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$

$$\left[\frac{d\sigma}{dk_\mu d\Omega_\mu}\right]_\chi = \frac{|\vec{k}_l|}{|\vec{k}_{\nu_l}|}\frac{G_F^2}{4\pi^2}\widetilde{\eta}_{\mu\nu}\widetilde{W}^{\mu\nu} =$$

$$\sigma_0\left[V_{CC}(R_{CC}^{VV}+R_{CC}^{AA})+2V_{CL}(R_{CL}^{VV}+R_{CL}^{AA})+V_{LL}(R_{LL}^{VV}+R_{LL}^{AA})+v_T\left(R_T^{VV}+R_T^{AA}\right)+v_{T'}R_{T'}^{VA}\right]$$

$$=\sigma_0\left[v_L R_L^{VV}+V_{CC}R_{CC}^{AA}+2V_{CL}R_{CL}^{AA}+V_{LL}R_{LL}^{AA}+v_T\left(R_T^{VV}+R_T^{AA}\right)+v_{T'}R_{T'}^{VA}\right]$$

Comparison with (e,e') reactions

$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right] = \sigma_{Mott}\left(v_L R_L^{VV}+v_T R_T^{VV}\right) \quad ; \quad \sigma_{Mott} = \frac{\alpha^2\cos^2\theta/2}{4E_i\sin^4\theta/2}$$

☆ Going from the Hadron Tensors for ν to the (e,e') case is possible if the VV and AA nuclear responses are implemented separately.

☆ Reweighting parameters in the SuSAv2-MEC implementation such as Fermi momentum, binding energy (E_{shift}), M_A, axial and vector form factors, etc, is possible if the full SuSAv2 code is implemented in generators instead of just tables of precomputed hadron tensor elements. This is feasible, the SuSAv2 code is very straightforward and easy to manage. This full implementation will allows also to scale from one nuclei of reference to several nuclear targets.

Contents

SuperScaling Approach (SuSA)

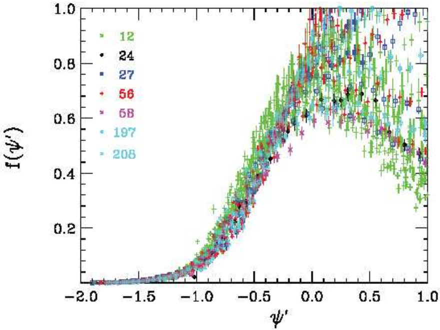
(see G.D. Megias' Thesis for details)

➠ The analysis of the large amount of existing (e, e') data at different kinematics is a solid benchmark to test the validity of theoretical models for neutrino reactions as well as to study the nuclear dynamics. The **SuperScaling Approach** exploits universal features of lepton-nucleus scattering to connect the two processes.

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**

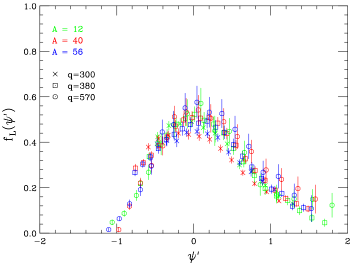


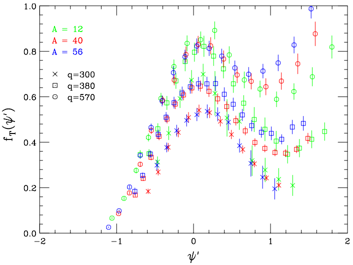
$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}\left(\substack{\text{nuclear}\\ \text{effects}}\right)}{\sigma_{\text{single nucleon}}\left(\substack{\text{no nuclear}\\ \text{effects}}\right)}$$

$$f(\psi') = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)_{exp}}{\sigma_{Mott}\left(v_L G_L^{ee'} + v_T G_T^{ee'}\right)}$$

Good superscaling behavior at $\psi' < 0$ (below QE peak). At higher kinematics (ψ'), other contributions beyond QE and IA (2p2h, Δ, etc.) can play an important role and scaling is broken.

Separate L/T scaling functions





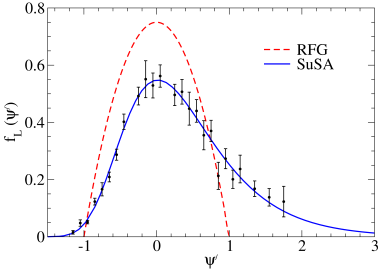
$$f_L = k_F R_L / G_L$$
$$f_T = k_F R_T / G_T$$

Scaling violations in the T channel ⇒ 2p-2h MEC, correlations, Δ-resonance ⇒ Mainly transverse

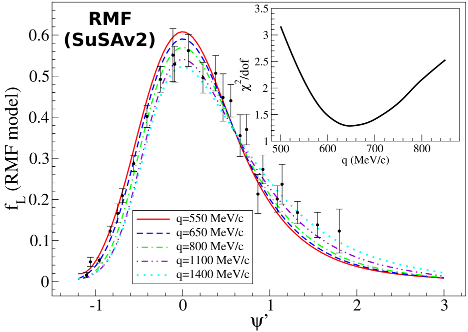
SuSA model: a semiphenomenological approach

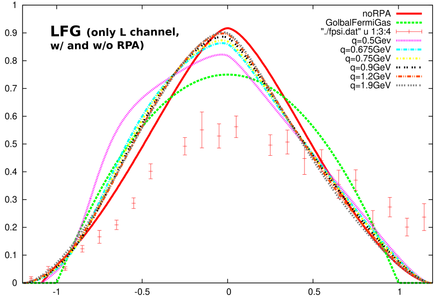
- Extracted from the (e, e') longitudinal scaling data
- Assumption $f_L(\psi) = f_T(\psi)$ (as in most IA models)

- It is experimentally observed $f^{ee'}_{T,\mathrm{exp}} > f^{ee'}_{L,\mathrm{exp}}$ (15-20%)



Testing SuperScaling for $^{12}C(e, e')$ in different nuclear models





The SuSAv2 model — *PRC90, 035501 (2014)* — *PRD94, 013012 (2016)*

✪ **SuSAv2 model:** lepton-nucleus reactions adressed in the SuperScaling Approach and based on Relativistic Mean Field (RMF) theoretical scaling functions (FSI) to reproduce nuclear dynamics.

✪ RMF: Good description of the QE (e, e') data and superscaling properties $(f^{ee'}_{L,exp})$.
RMF predicts $f_T > f_L$ ($\sim$ 20%) as a pure relativistic effect (FSI with the residual nucleus).
Strong RMF potentials at high q_3 are corrected by RPWIA and q-dependent blending function.

➠ RFG as a natural starting point to examinate the scaling concept

$$\frac{d^2\sigma}{d\Omega_l d\omega} = \sigma_0 \mathcal{F}_\chi^2 = \sigma_0 \left(V_L R_L^{VV} + V_{CC} R_{CC}^{AA} + 2V_{CL} R_{CL}^{AA} + V_{LL} R_{LL}^{AA} + V_T R_T + \chi V_{T'} R_{T'} \right)$$

$$\frac{d^2\sigma}{d\Omega_e d\omega} = \sigma_{Mott} (v_L R_L^{ee'} + v_T R_T^{ee'})$$

$$R_K^{QE} \Rightarrow W^{\mu\nu} = \frac{3\mathcal{N} M_N^2}{4\pi k_F^3} \int \frac{d^3p}{E(\mathbf{p})E(\mathbf{p}+\mathbf{q})} \times \theta(k_F - |\mathbf{p}|)\theta(|\mathbf{p}+\mathbf{q}| - k_F) \times\delta(\omega - [E(\mathbf{p}+\mathbf{q}) - E(\mathbf{p})]) \times \widetilde{W}^{\mu\nu}_{s.n.}(P_i + Q, P_i)$$

$$R_K^{QE} = \frac{1}{k_F} f_{RFG}(\psi') \frac{\mathcal{N}}{2\kappa\mathcal{D}} R_K^{s.n.} \equiv \frac{1}{k_F} f_{RFG}(\psi') G_K, \quad K = CC, CL, LL, T, T'$$

$$f_{RFG}(\psi') = \frac{3}{4}(1 - \psi'^2)\theta(1 - \psi'^2)$$

$$\psi' \equiv \frac{1}{\sqrt{\xi_F}} \frac{\lambda' - \tau'}{\sqrt{(1+\lambda')\tau' + \kappa\sqrt{\tau'(\tau'+1)}}}$$

$$\lambda' = \omega'/(2M_N), \quad \kappa = q/(2M_N)$$
$$\omega' = \omega - E_{shift}, \quad \tau' = \kappa^2 - \lambda'^2$$

Scaling functions can be extracted from experimental data or different nuclear models.

$$R_K^{QE} = \frac{1}{k_F} f_{model}(\psi') \frac{\mathcal{N}}{2\kappa\mathcal{D}} R_K^{s.n.} \equiv \frac{1}{k_F} f_{model}(\psi') G_K, \quad K = CC, CL, LL, T, T'$$

- Scaling functions obtained from the cross section:

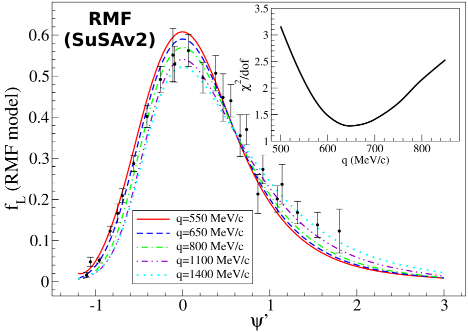
$$f^{QE(e,e')} = k_F \frac{\frac{d^2\sigma}{d\Omega_e d\omega}}{\sigma_{Mott}(v_L G_L^{ee'} + v_T G_T^{ee'})}$$

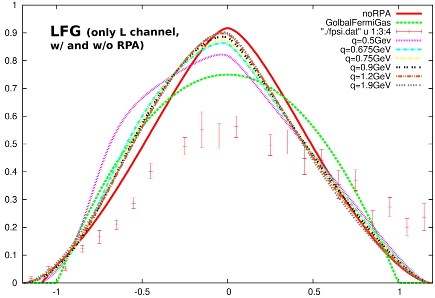
$$f^{QE(\nu)} = k_F \frac{\frac{d^2\sigma}{d\Omega_l d\omega}}{\sigma_0(V_L G_L^{VV} + V_{CC} G_{CC}^{AA} + 2V_{CL} G_{CL}^{AA} + V_{LL} G_{LL}^{AA} + v_T G_T + \chi v_{T'} G_{T'})}$$

- Specific scaling functions for the individual channels:

$$f_K = k_F \frac{R_K}{G_K}$$

Testing SuperScaling for $^{12}C(e, e')$ in different nuclear models





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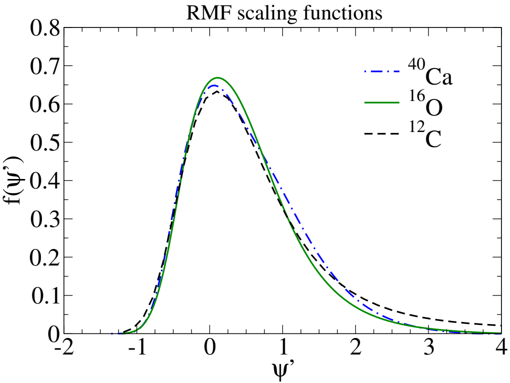
RMF predicts $f_T > f_L$ ($\sim$ 20%) as a pure relativistic effect (FSI with the residual nucleus).
Strong RMF potentials at high q_3 are corrected by RPWIA and q-dependent blending function.

Extension of the SuSAv2-MEC model to other nuclei

SuSAv2 scaling functions for different nuclei

- 2-nd kind scaling within the RMF and RPWIA models.
- k_F and E_{shift} are the only different parameters.



Fermi momentum and binding energy parameters in RFG ('and SuSAv2-MEC' but $E_{shift}(q)$, see PRC90, 035501 (2014))

Table 1: Adjusted Parameters

Nucleus	k_F (MeV/c)	E_{shift} (MeV)
Lithium	165	15
Carbon	228	20
Magnesium	230	25
Aluminum	236	18
Calcium	241	28
Iron	241	23
Nickel	245	30
Tin	245	28
Gold	245	25
Lead	248	31

Phys. Rev. C 65, 025502 (2002)

Density dependence of the 2p-2h MEC responses

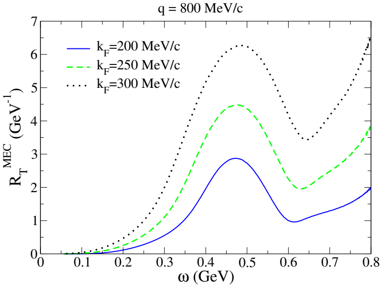
☆ Extension of the 2p-2h MEC analysis to other nuclei.

☆ A-scaling: independence on the nuclear species ⇒ Scaling of 2nd kind

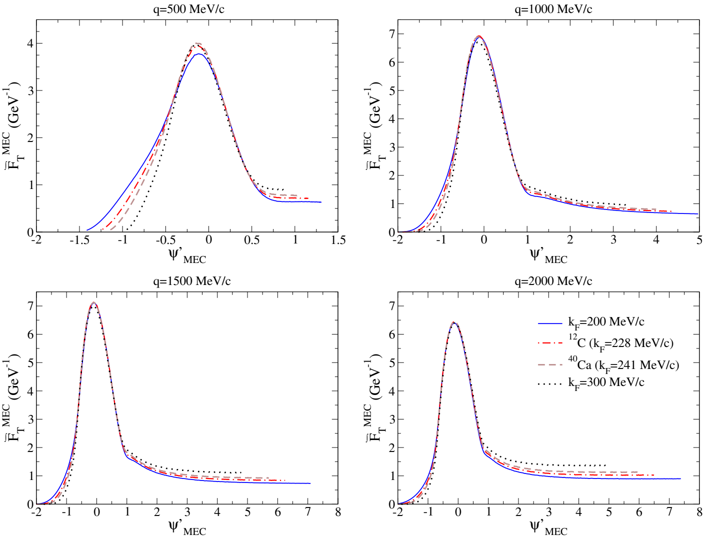
☆ $\eta_F = k_F/m_N$; k_F(Li)= 165 MeV/c; k_F(C)= 228 MeV/c; k_F(Ca)= 241 MeV/c; k_F(Pb)= 248 MeV/c

☆ A parametrization of this behavior in terms of k_F would imply to extend our calculation to other nuclei without further theoretical calculations, reducing significantly the computational time.

$$\widetilde{F}_T^{MEC}(q,\omega) \equiv \frac{1}{\eta_F^2}\frac{R_T^{MEC}(q,\omega)}{G_T^{ee'}(\tau)} \quad \text{(per nucleon)} \Rightarrow \text{ scales as } \quad A \cdot k_F^2$$

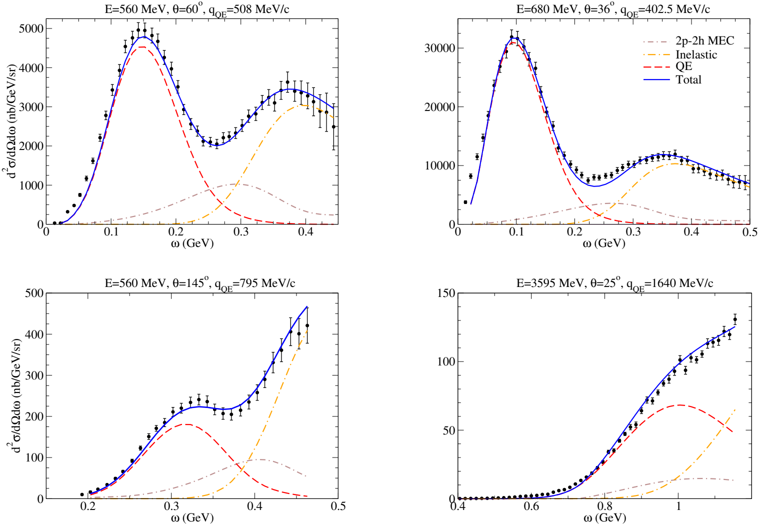


Density dependence of the 2p-2h MEC responses



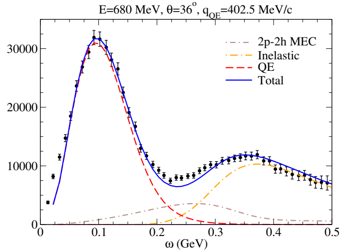
$\psi'_{MEC}(q, \omega, k_F)$

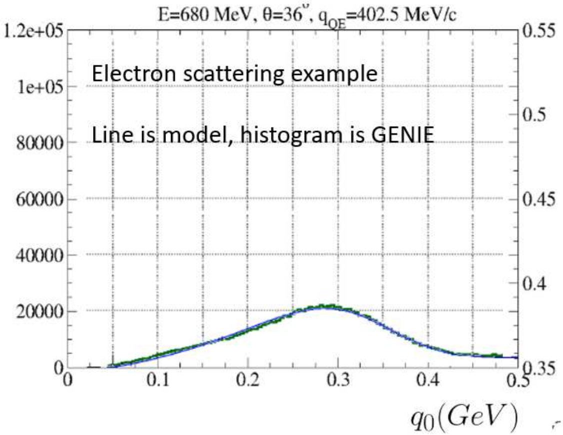
Inclusive $^{12}C(e, e')$ cross sections *PRD 94, 013012 (2016)*



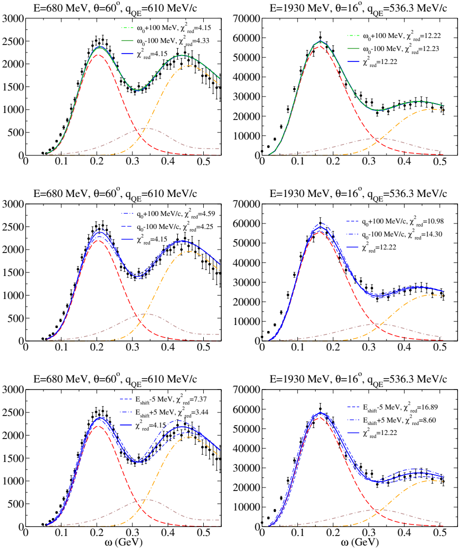
SuSAv2-MEC implementation in GENIE (2p2h for electrons)

$d^2\sigma/d\Omega/d\omega$ vs. ω for $(e,e')^{12}C$



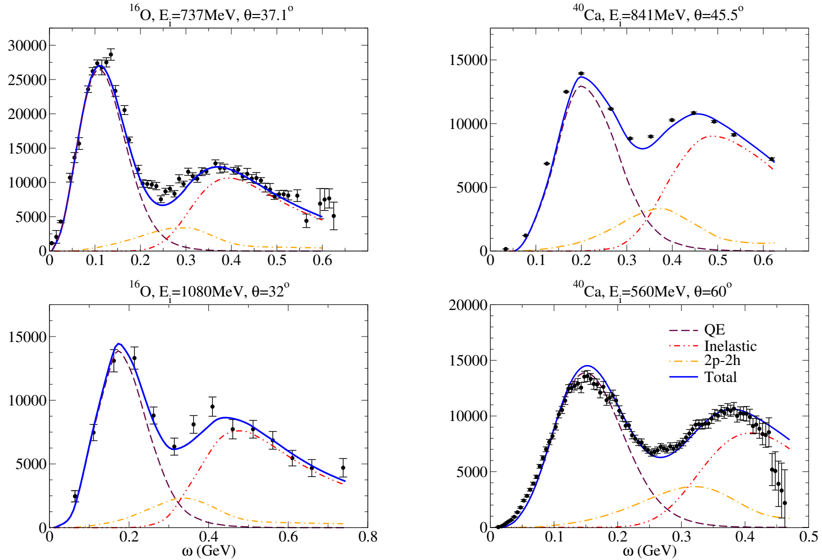


Sensitivity of the SuSAv2-MEC model on $(e,e')^{12}$C

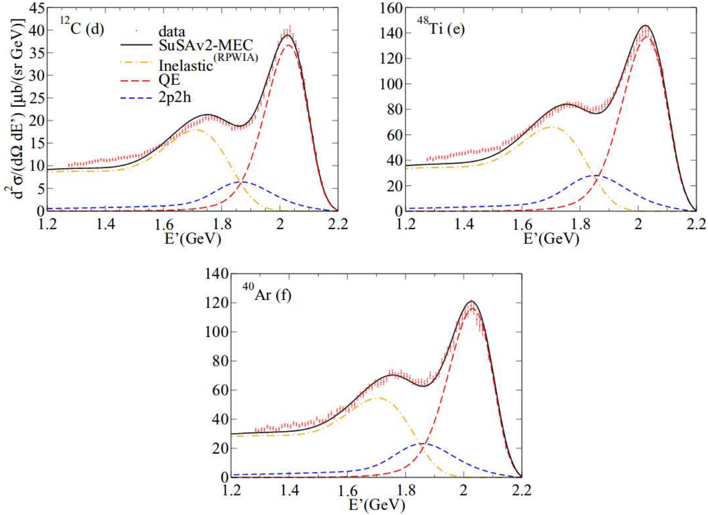


SuSAv2 parameters (p_F, E_{shift}), scaling functions, form factors (vector and axial), M_A^{QE}, etc. can be reweighted in the generators once the full SuSAv2 code is implemented rather than hadron tensor tables.

Inclusive $^{16}O(e, e')$ and $^{40}Ca(e, e')$ cross sections



(e, e') JLab data vs. SuSAv2-MEC *PRC99, 042501(R), 2019*



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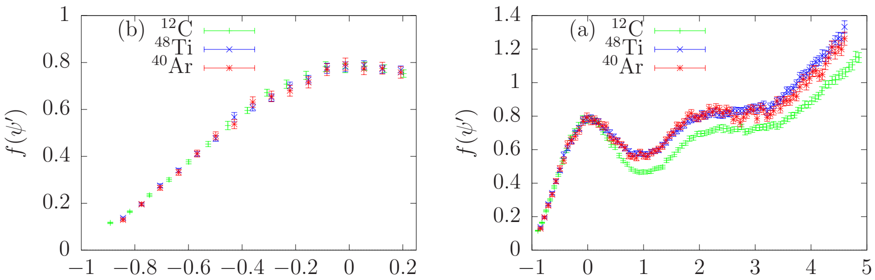
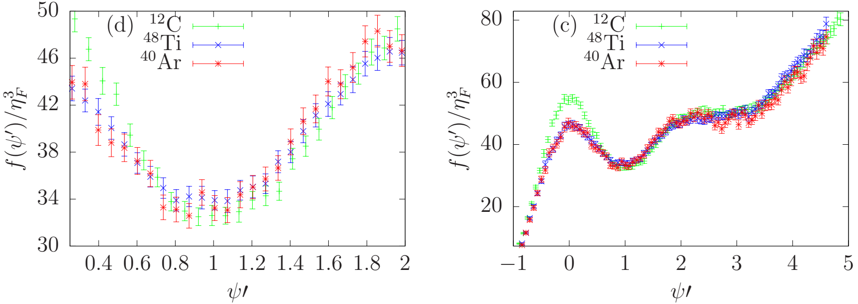
PRC99, 042501(R), 2019



Scaling behavior of the QE region: A/p_F

(e,e') JLab data vs. SuSAv2-MEC

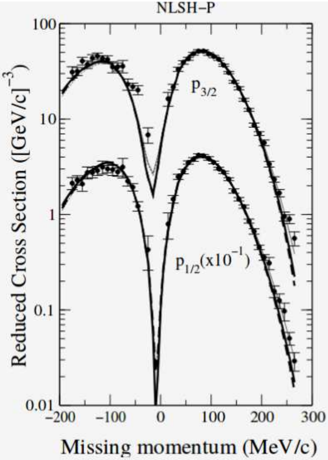
PRC99, 042501(R), 2019



Scaling behavior of the 2p2h region: $A \cdot p_F^2$

Semi-inclusive RMF predictions for $^{16}O(e, e'p)^{15}N$ data at $|Q^2| \leq 0.4$ (GeV/c)^2

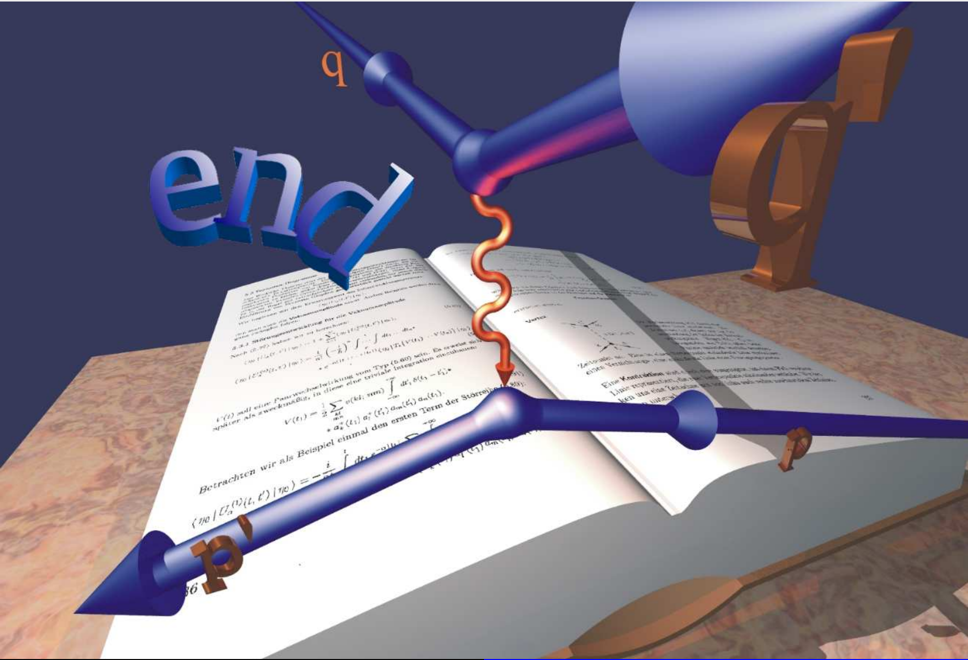
[Phys. Rev. C 64, 024614 (2001)]



Reduced cross-sections for proton knockout from $1p_{1/2}$ and $1p_{3/2}$ orbits in ^{16}O versus missing momentum p_m

Collaborators

- Stephen Dolan (LLR and CEA-Irfu, University of Paris-Saclay, France)
- Margherita Buizza-Avanzini (LLR, University of Paris-Saclay, France)
- Sara Bolognesi (CEA-Irfu, University of Paris-Saclay, France)
- T. William Donnelly (MIT, USA)
- Juan A. Caballero (University of Seville, Spain)
- Maria B. Barbaro (INFN and University of Turin, Italy)
- Raúl González-Jiménez (University Complutense of Madrid, Spain)
- J. M. Udías (University Complutense of Madrid, Spain)
- Jose E. Amaro (University of Granada, Spain)
- I. Ruiz-Simó (University of Granada, Spain)
- Martin Ivanov (Bulgarian Academy of Sciences, Bulgaria)
- Anton Antonov (Bulgarian Academy of Sciences, Bulgaria)
- W. Van Orden (Old Dominion University, JLab, USA)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Inelastic Nuclear Responses within the SuSAv2 Approach

➲ Extension of the SuSAv2 formalism to the complete inelastic spectrum ⇒ resonant (Δ), nonresonant and deep inelastic scattering (DIS).

$$R_{QE}^{L,T} = \frac{\mathcal{N}\xi_F}{\eta_F^3 \kappa m_N} R_{s.n.}^{L,T} f_{SuSAv2}^{L,T}(q_0^{QE}, \psi')$$

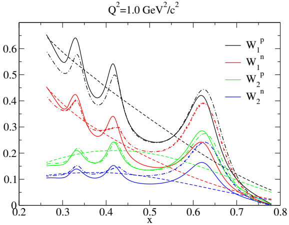
$$R_{inel}^{L,T} = \frac{\mathcal{N}\xi_F}{\eta_F^3 \kappa} \int d\mu_X \mu_X R_{inel(s.n.)}^{L,T} f_{SuSAv2}^{L,T}(q_0^{inel}, \psi'_X)$$

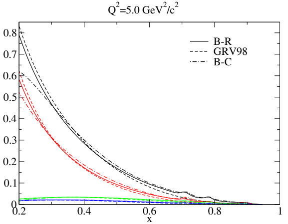
where $\mu_X = \frac{W_X}{m_N}$ is the dimensionless invariant mass, ψ'_X is the inelastic scaling variable and $U_{inel}^{L,T}$ depends on the single-nucleon inelastic structure functions W_1, W_2, W_3, obtained by using:

- Fits of the inelastic structure functions (Bodek-Ritchie, **Bosted-Christy**, ...)
- *PDFs* (GRV98 model, ...)

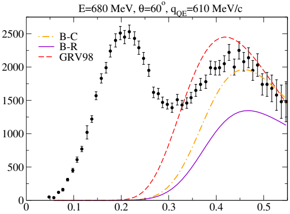
Inelastic Nuclear Responses & SuSAv2-inelastic model

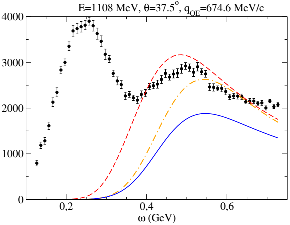
Inelastic structure functions





Inclusive ^{12}C(e, e') double differential cross section





<u>Bodek-Ritchie</u>: poor description of the resonance region.

<u>Bosted-Christy</u>: Good description of the resonant structures observed in (e,e') reactions.

<u>GRV98</u>: No resonant structures (average) and poor description at $Q^2 \lesssim 1$ GeV^2.