Introduction to the US group: SuSAv2-MEC and RMF models

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Neutrino group at University of Seville:

- **Juan A. Caballero**, Full Professor
- **Guillermo D. Megias**, Postdoctoral researcher (*now at ICRR, Univ. Tokyo*)
- **Juan M. Franco-Patiño**, PhD student
- **Jesus Gonzalez-Rosa**, PhD student

Research field: Analysis and development of $1p1h$ and $2p2h$ $e-A$ and $\nu-A$ interaction models (**SuSAv2-MEC, RMF**). *1π and DIS models in progress.*

Funded projects with Japan and T2K: EU H2020 MSCA Grant No. 839481; FY2020 & FY2021 ICRR Inter-University Research Program.

T2K and HK defined as research line of strategic interest by the University of Seville. Special allocation approved to cover Common Funds. 3-year R&D Project submitted to the Spanish Ministry of Science to cover expenses for the next years.

Previous and ongoing projects with T2K Collaborators:

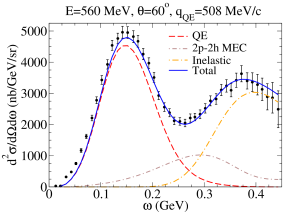
- Implementation of SuSAv2 and RMF models in NEUT and GENIE:

$\Rightarrow$ *reweighting parameters for oscillation analysis, study of nuclear-medium effects (FSI, E_b, shell model vs. SF), comparison between nuclear optical potentials and cascade models, etc.*

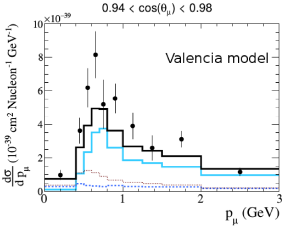
- Analysis of low-energy nuclear effects at T2K, Ninja and SK kinematics.
- C/O differences on ν_μ vs. ν_e and ν_l vs. $\bar{\nu}_l$.
- (Future) Collaboration with the IFAE group and ND280 Upgrade.
- Implementation of SuSAv2-MEC in NuWro.

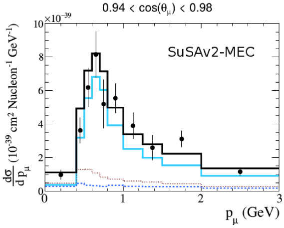
- T2K NIWG and XSEC WGs - Y. Hayato (ICRR) - S. Bolognesi (CEA) - F. Sanchez (UGeneva) - S. Dolan (CERN) - T. Lux (IFAE) - M. Buizza-Avanzini (LLR) - K. Niewczas, J. Sobczyk (NuWro)

SuSAv2-MEC model vs. $(e, e')^{12}C$



SuSAv2-MEC vs. T2K CC0π (^{12}C)





Valencia model vs. T2K CC0π (^{12}C)

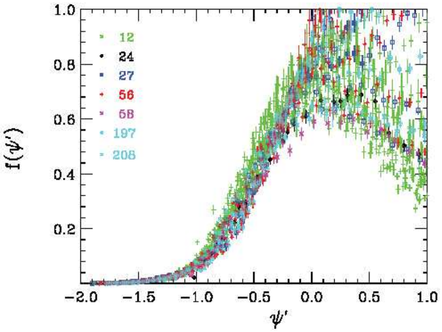
SuperScaling Approach (SuSA) (see G.D. Megias' Thesis for details)

➠ 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 1st kind (independence on q)
- ☆ Scaling of 2nd 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.

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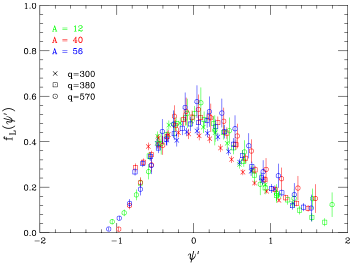
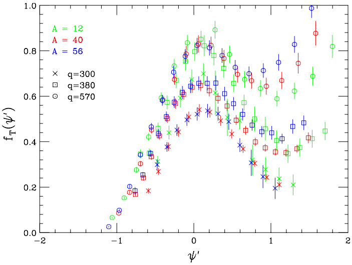
- ☆ Scaling of 2^{nd} kind (independence on Z)

$\Longrightarrow$ **SuperScaling**

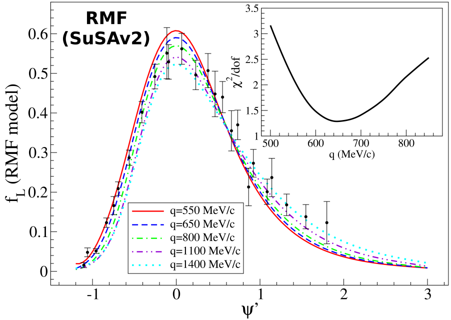


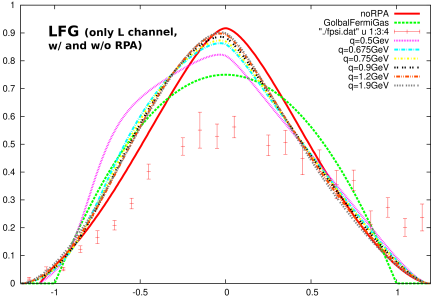


$$f_L = k_F R_L / G_L$$
$$f_T = k_F R_T / G_T$$

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

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





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

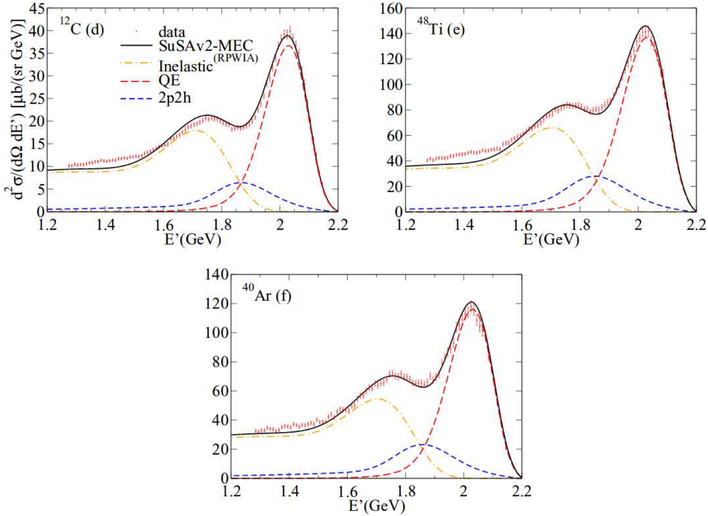
✪ **SuSAv2 model:** lepton-nucleus reactions adressed in the SuperScaling Approach and based on Relativistic Mean Field (RMF) theoretical scaling functions (FSI) to reproduce nuclear dynamics.

✪ 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.

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \quad ; \quad f(\psi') = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)_{exp}}{\sigma_{Mott}(v_L G^{ee'}_L + v_T G^{ee'}_T)}$$

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

PRC99, 042501(R), 2019

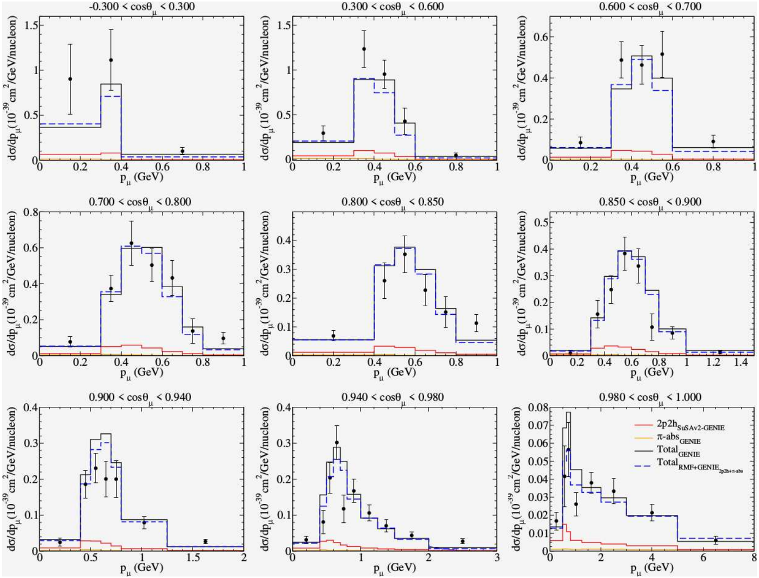


SuSAv2-MEC in GENIE: Validation plots (T2K CC0πNp, 0p > 500 MeV)

T2K CC0π $\nu_\mu - {}^{12}$C data (0p>500 MeV)

$\chi^2_{\text{SuSAv2-MEC GENIE}}$ = 168.92 (60 bins)

$\chi^2_{\text{RMF+GENIE(SusAv2-2p2h+pi-abs)}}$ = 171.87

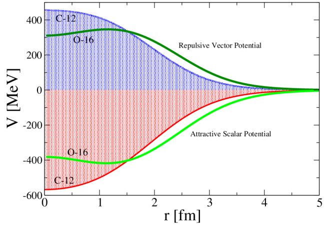


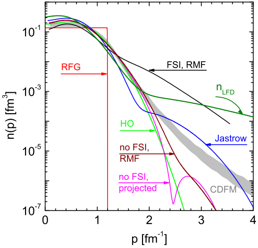
➠ **Relativistic Mean Field (RMF)**: Fully relativistic shell model with accurate description of nuclear dynamics and FSI. Bound nucleons: self-consistent Dirac-Hartree solutions, derived within a RMF Lagrangian with local energy-independent potentials (S+V) fitted to saturation properties of nuclear matter, radii and nuclear masses $\Rightarrow$ good description of (e,e') and CC0π data at low and intermediate kinematics, fulfiling the scaling behavior observed in (e,e') data, while other models fails. El RMF potentials are too strong to describe FSI at high kinematics. **RPWIA** ("RMF w/o FSI, final-state plane waves") does a better job.

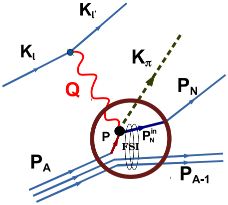
➠ **SuSAv2** builds a trade-off between RMF and RPWIA models (linear combination of RMF and RPWIA scaling functions via q-dependent transition function), but low-energy nuclear effects and scaling violations are not properly included at very low kinematics ($< 50 - 100$ MeV).

➠ **ED-RMF**: Energy-Dependent S+V RMF potentials, via $f(T_N)$ weighted by the SuSAv2 results at intermediate-high kinematics ($T_N > 100 MeV$), producing similar data comparison as SuSAv2 but solving low-kinematics issues.

RMF models could reveal C/O differences due to different binding energy and shell effects, mass of the residual nucleus, FSI and Coulomb distortions, etc.







Neutrino-Nucleus Interaction Models in the market (RFG,LFG,SF,RPA,RMF,SuSAv2,etc.)

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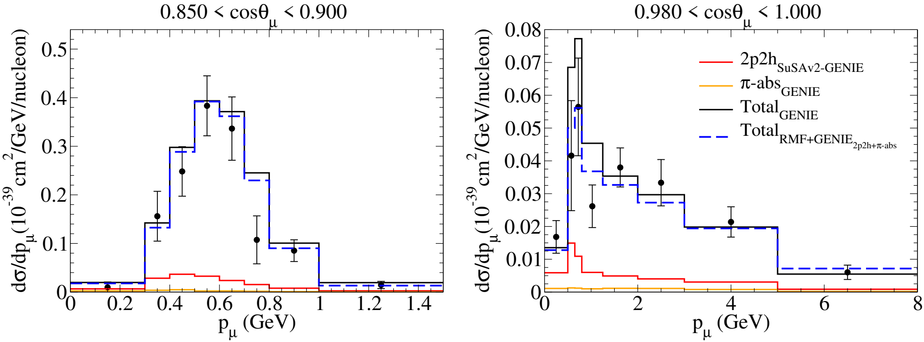
RMF and ED-RMF are available for 1p1h and SPP, easily extendable to all nuclei. See also PRC100, 045501 (2019), PRC101, 015503 (2020), and A. Nikolakopoulos' talk.

Model	Low kin.	Intermediate kin.	High kin.	(e,e')	CC0pi	CC1pi	Inelastic
RMF	✓	✓	X	✓	✓	✓	X
RPWIA	X	~	✓	✓	✓	✓	X
SuSAv2	~	✓	✓	✓	✓	*	*
ED-RMF	✓	✓	✓	✓	✓	✓	X

*Under some approaches

SuSAv2-MEC 2p2h model is based on RFG microscopic calculations as most 2p2h models (Valencia, Martini, etc.)

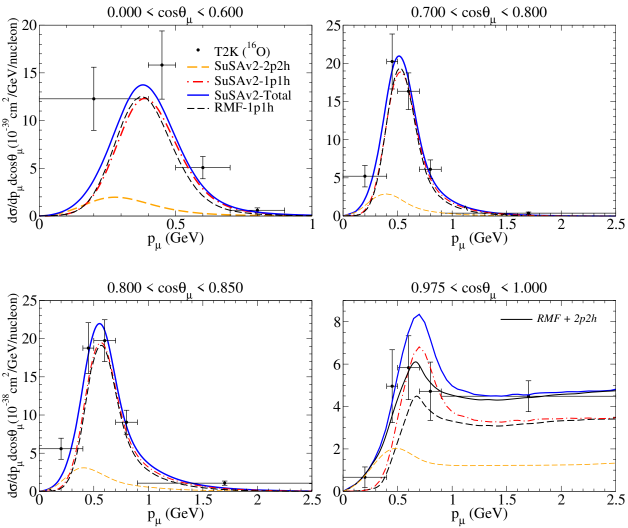
Low-energy effects and scaling violations are only appreciable at very forward angles (low q_3, q_0 values). RMF is more accurate than SuSAv2 at these kinematics.



Low-energy nuclear effects and its proper description can have an important effect in the C to O extrapolation, which is essential for T2K and HK.

T2K CC0π ν_μ–H_2O cross sections

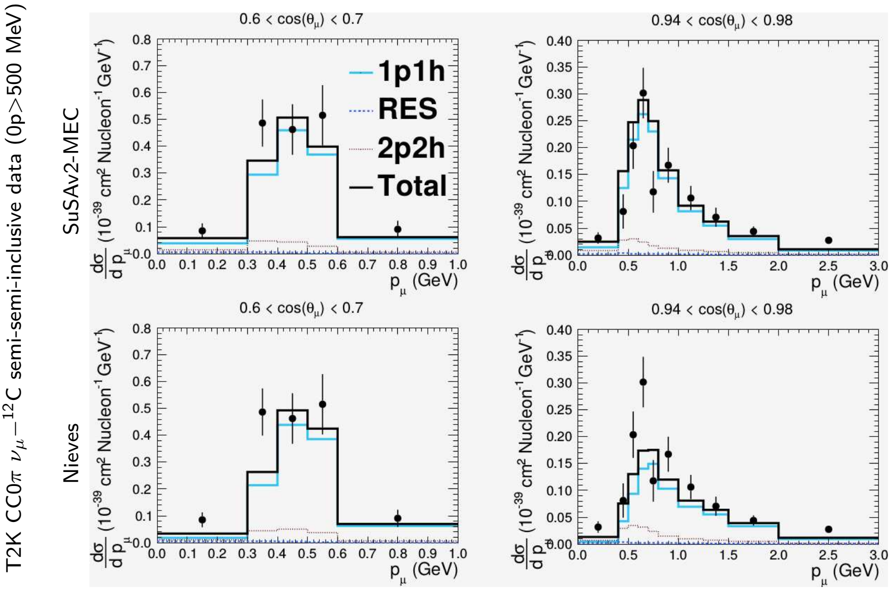
arXiv:1711.00771 [nucl-th] (2017)



Good comparison with T2K-^{16}O data but some overstimations appear at very forward angles within the SuSAv2-MEC model ⇒ Possible RMF scaling violations at low q_0, q_3 not completely included in the SuSAv2 formalism makes the model questionable at these kinematics.

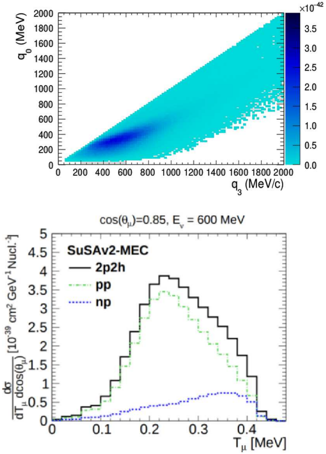
Although RMF scaling functions are almost identical for $q_3 \gtrsim 400$ MeV/c, at very low q_3 they can differ (*scaling is broken*) ⇒ Solution: ED-RMF

Comparison between 1p1h+2p2h models in generators *arXiv:1905.08556*

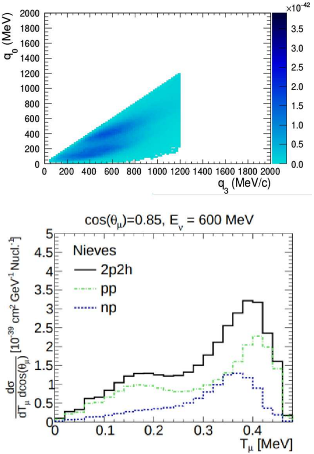


Comparison of SuSAv2-MEC^{Genie} with Nieves^{Genie} 2p2h

New SuSAv2 implementation



Nieves implementation



Differences in np/pp separation are mostly related to the treatment of 2p2h direct/exchange interference terms (absent in Nieves model) $\rightarrow$ strongly affects np/pp ratio by a factor $\sim$ 2 (PRC94:054610,2016) $\Rightarrow$ Implications in nucleon multiplicity and hadron E_{reco}

Recent publications regarding T2K and the SuSAv2-MEC and RMF models

- *Implementation of the SuSAv2-MEC in GENIE and analysis of nuclear effects in T2K*. **S. Dolan, G. D. Megias, S. Bolognesi**. PRD 101, 033003 (2020).

- *New evaluation of axial nucleon form factor from e- and ν-scattering data and impact on $\nu - A$ cross-section*. **G. D. Megias, S. Bolognesi, M. B. Barbaro, E. Tomasi-Gustafsson**. PRC 101, 025501 (2020).

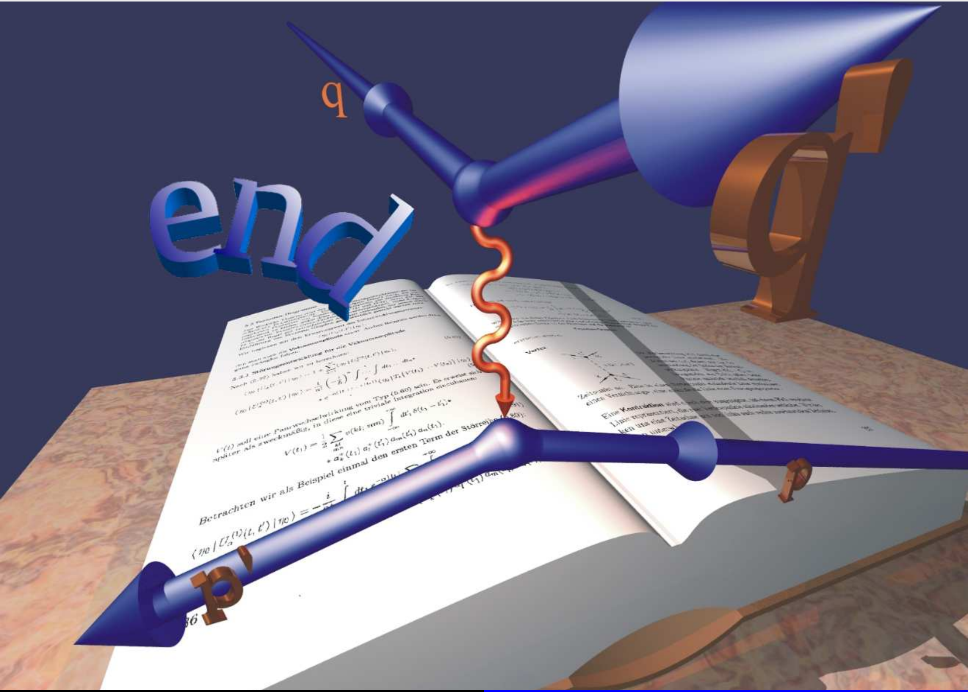
- *Simultaneous measurement of the ν_μ CC cross section on O and C without pions in the final state at T2K* **(T2K Collaboration)** PRD101, 112004 (2020).

- *Electron- versus neutrino-nucleus scattering*. **J.E. Amaro, M.B. Barbaro, J.A. Caballero, R. González-Jiménez, G.D. Megias, I. Ruiz Simo**. JPG 47, 124001 (2020).

- *Semi-inclusive charged-current neutrino-nucleus cross sections in the relativistic plane wave impulse approximation*. **J.M. Franco-Patino, J. Gonzalez-Rosa, J.A. Caballero, M.B. Barbaro**. PRC 102, 064626 (2020).

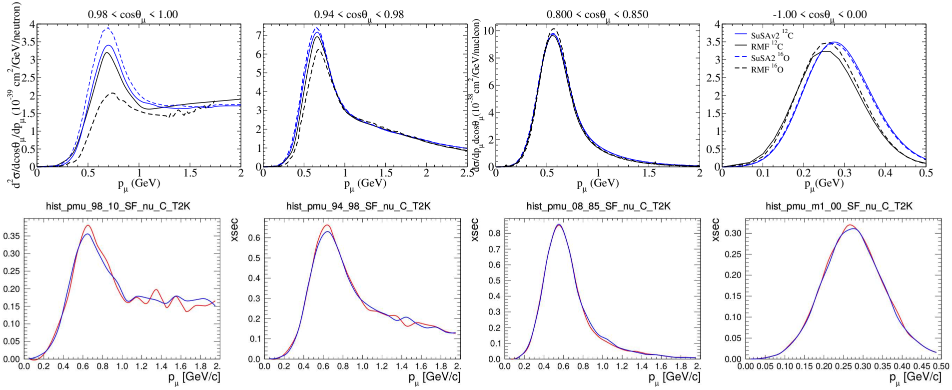
- *Neutrino energy reconstruction from semi-inclusive samples*. **R. González-Jiménez** *et al.* **(J. A. Caballero, G. D. Megias)**. arXiv:2104.01701 [nucl-th] (2021).

- *Theoretical description of semi-inclusive T2K, MinervA and MicroBooNE neutrino-nucleus data in the relativistic plane wave impulse approximation*. **J. M. Franco-Patino, M. B. Barbaro, J. A. Caballero, G. D. Megias**. arXiv:2106.02311 [nucl-th] (2021).


end
q
q'
p
p'

BACKUP SLIDES

$d^2\sigma/dp_\mu/d\cos\theta_\mu$ vs. p_μ: SuSAv2 and RMF (top) vs NEUT SF (bottom)



Large differences between 12C and 16O emerges at very forward angles (low-energy region) within the **RMF model** due to different nuclear effects (binding energies of the different shells and different S+V nuclear potentials).

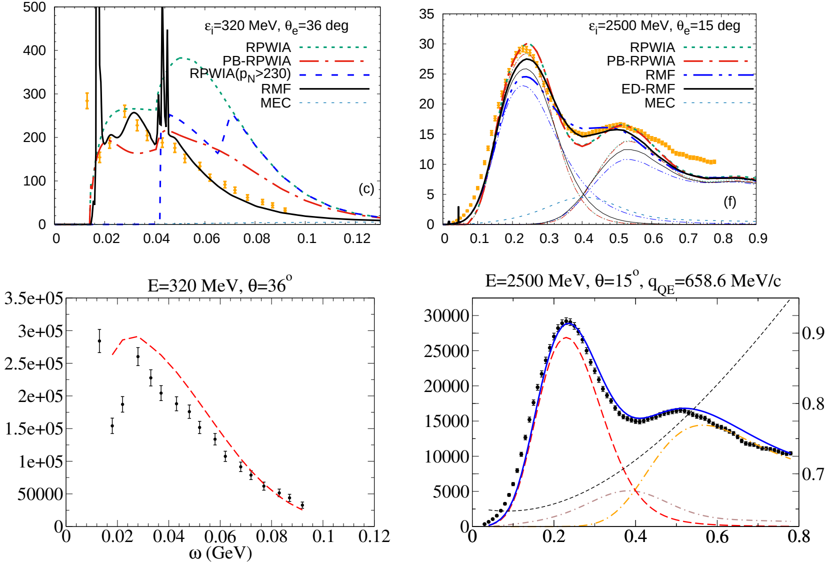
SF (12C) $\sim$ RMF (12C) SF (16O) $>$ RMF (16O) at low-kinematics

SF curves: Red (12C), Blue (16O)

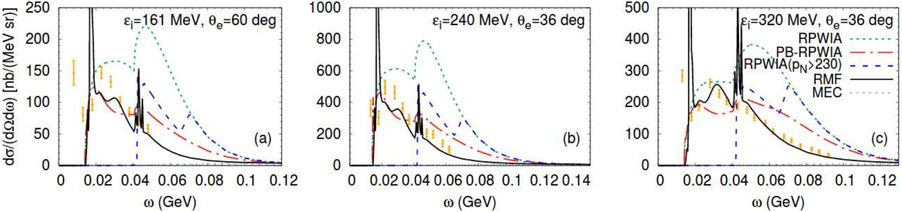
ED-RMF, RMF, SuSAv2 for $(e, e')^{12}C$ $\quad d^2\sigma/d\Omega/d\omega$ vs. ω

RMF, ED-RMF, others

SuSAv2

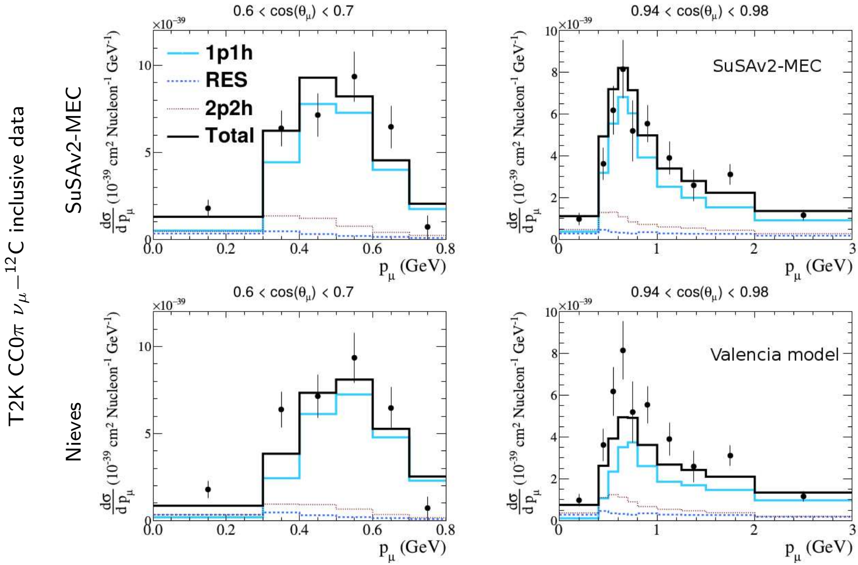


Low-energy nuclear effects within the RMF and SuSAv2 models



✪ E_b (RMF): nucleon binding energies in the different shells.
✪ E_b (SuSAv2): included in the E_{shift} parameter which is derived from RMF results to reproduce the position of the QEP in inclusive electron scattering. $E_{shift}(q)$ to address the effect of strong RMF potentials at high kinematics.

Comparison between 1p1h+2p2h models in generators *arXiv:1905.08556*

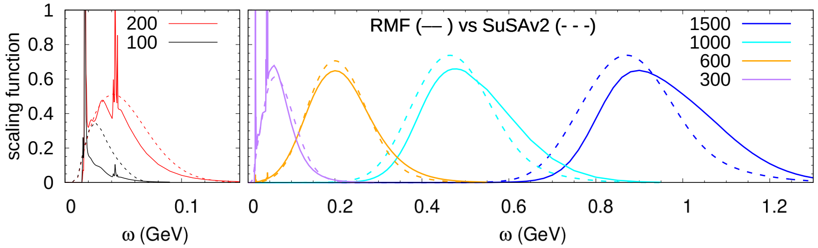


✪ Scaling violations and low-energy effects present in RMF are not fully included in the SuSAv2-MEC model. **Solution: Parametrize and introduce low-q RMF effects in SuSAv2**

✪ Strong q-dependence of RMF vector and scalar potentials at high kinematics is addressed in SuSAv2 with a blending function to introduce RPWIA (no FSI). *To have a more consistent model and preserve orthogonality, unitarity and dispersion relations* ⇒ **Solution: ED-RMF (both inclusive and semi-inclusive for ^{12}C, ^{16}O, ^{40}Ar, etc.)**

✪ The **ED-RMF** model introduces an Energy-Dependent potential (based on SuSAv2) to the RMF that keeps the strength for slow nucleons but makes the RMF potential softer for increasing nucleon momenta. **See PRC 100, 045501 (2019),PRC 101, 015503 (2020) for details**

✪ SuSAv2 is a pure inclusive model. **Solution: ED-RMF (both inclusive and semi-inclusive for ^{12}C, ^{16}O, ^{40}Ar, etc.)**



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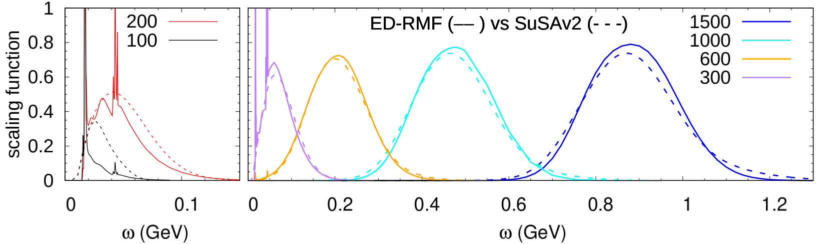
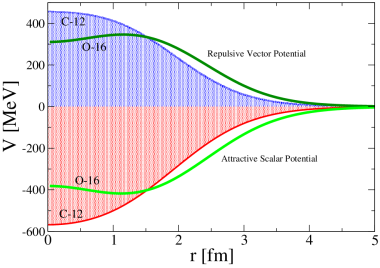
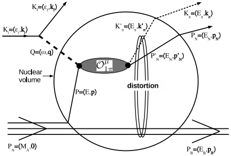
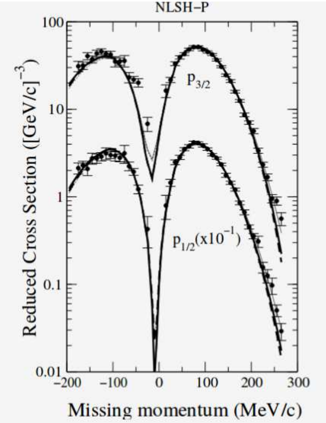


✪ **RMF FSI effects:** S+V real potentials ⇒ kinematical distortion of the outgoing nucleon (incl and semi-incl). Imaginary part of potential also needed for semi-incl to produce absorption, i.e., flux lost into the unobserved channels.

✪ **1p1h semi-inc** $(\nu_\mu, \mu^- p)$ focuses on elastic channel $N(A, A')N'$, i.e. elastic N scattering, no more hadrons emitted ⇒ imaginary potential is needed (or cascade effects) to subtract other processes: $(\nu_\mu, \mu^- NN)$, $(\nu_\mu, \mu^- N\pi)$, etc.







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

Semi-inclusive RMF predictions for ^{16}O$(e, e'p)^{15}$N data at $|Q^2| \leq 0.4$ (GeV/c)^2 [PRC 64, 024614 (2001)]

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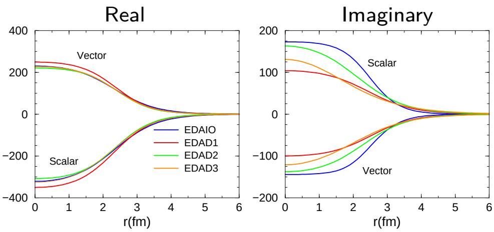
Imaginary part: phenomenological ED complex OP fitted to elastic $p - A$ scattering data.
Real part: microscopic RMF real potentials $\equiv$ phenom. real OP



Cascade models in generators: N emmited is moved step by step (mean free paths) until interacting with other nucleon or escaping from the nucleus. If N interacts $\Rightarrow$ intranuclear effects (absorption, (in)elastic, charge exchange, other particle productions) are simulated.

RMF model can be implemented with/without the imaginary OP so can be compared with cascade effects
$\Rightarrow$ *No double-counting.*