The relevance of neutrino-nucleus interaction models in T2K and SuperKamiokande

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1. General introduction
   - State of the art: Challenges and Open Questions
   - Connection between $e - A$ and $\nu - A$ reactions
   - SuperScaling Approach: SuSAv2 and RMF models
2. SuSAv2-MEC implementation in MC event generators
   - Implementation of SuSAv2-MEC in MC event generators
   - Validation of the implementation and Data comparison
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   - ED-RMF vs. SuSAv2
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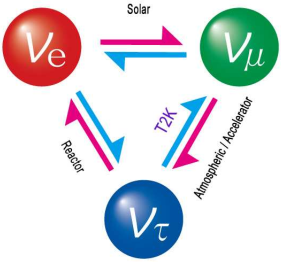
Why ν-A interaction models are essential for oscillation experiments?

- Discovery of neutrino oscillation $\rightarrow$ evidence for neutrino mass (mass hierarchy, matter-antimatter asymmetry and CP violation processes)
- Weak interaction $\rightarrow$ ν: probe to study hadronic and nuclear dynamics (axial structure or strangeness content of the nucleons)
- Astrophysical implications (supernovae, dark matter, sterile neutrinos)



Neutrino oscillation between three generations

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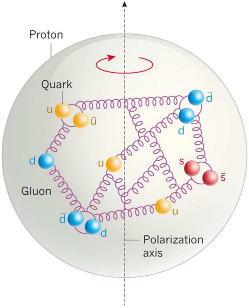

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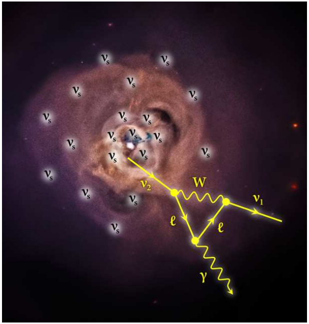
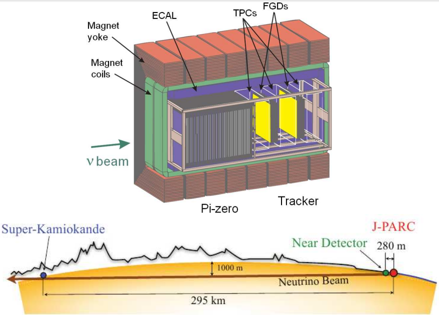


Why ν-A interaction models are essential for oscillation experiments?

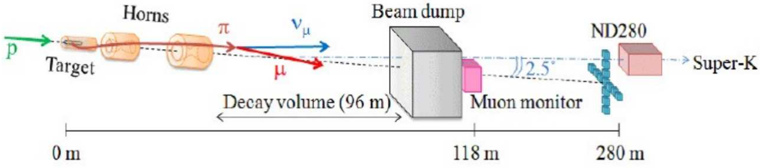
Ample experimental program to characterize and determine ν oscillations

Long-Baseline accelerators: T2K, SK, HK (J-PARC), MINERνA, NOvA, DUNE (FermiLab). Detection of neutrino oscillations in facilities at hundreds of kms from the neutrino source. Main aims: direct measurement of oscillation parameters (mixing angles, CPV, NMH) or data production to reduce systematics (mostly ν-A scattering and nuclear medium effects).



Long-baseline accelerator neutrino oscillation experiments

Neutrinos produced as secondary decay products of hadrons (π, K) generated in primary reactions of p with nuclei $\Rightarrow$ broad energy beam.



Experimental difficulties:

➠ The neutrino flux: broad energy distribution around a maximum $\rightarrow$ True energy for a detected event is unknown. Inaccuracy in the meson flux also affects the ν-flux prediction.

➠ To reduce flux uncertainties, two identical detectors are employed. *Near Detector* placed near the neutrino production region and *Far Detector* where a maximum/minimum oscillation is expected. MonteCarlo simulations are also employed to reconstruct the neutrino energy for each individual event detected.

➠ The reliability of ν-oscillation experiments depends on a precise determination of the ν-nucleus cross section measurements and on the ν flux at ND.

T2K systematics today and needs for HyperK and DUNE

- Precise knowledge of ν properties require accurate ν-A interaction models.
- Global experimental **systematics in T2K** are around a **4%** (**7%**) for ν_μ (ν_e) reactions and are dominated by flux and cross section uncertainties (**3%**) $\Rightarrow$ It is essential to improve description of neutrino interaction physics.
- Oscillation measurements in future experiments (HyperK, DUNE) aim to $\sim 1-3\%$ systematic uncertainty and determine mass hierarchy and δ_{CP} violation phase.

	1-Ring μ		1-Ring e	
Error source	FHC	RHC	FHC	RHC
SK Detector	1.86	1.51	3.03	4.22
SK FSI+SI+PN	2.20	1.98	3.01	2.31
Flux + Xsec constrained	3.22	2.72	3.22	2.88
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46
NC1γ	0.00	0.00	1.08	2.59
NC Other	0.25	0.25	0.14	0.33
Osc	0.04	0.03	3.86	3.60
All Systematics	4.40	3.76	6.10	6.51
All with osc	4.40	3.76	7.27	7.44

- A reduction of 2% would improve CPV sensitivity from 5σ to 6σ while reducing by two experimental exposure.
- Need for development and **implementation** of sophisticated neutrino interaction models in **event generators**.
- This can help to understand $\nu/\bar{\nu}$ asymmetry, to improve hadron detection efficiency, the characterization of FS particles or the extrapolation from the usual ^{12}C target analysis to other nuclei (^{16}O [T2K ND280 upgrade], ^{40}Ar, etc.)

T2K systematics today and needs for HyperK and DUNE

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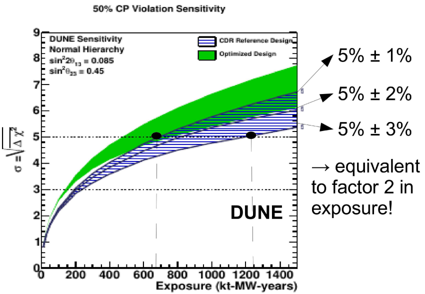

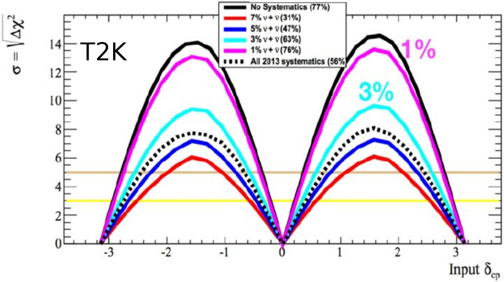

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Challenges for nuclear models

Significant improvements of nuclear models by theorists are essential and should include:

1. The development of a unified model of nuclear structure giving the initial kinematics and dynamics of nucleons bound in the nucleus.
2. Providing total kinematics of leptons and outgoing particles for all possible FS.
3. Improving our understanding of the relevance of FSI (rescattering of produced hadrons in the nucleus) and initial nucleon-nucleon correlations.
4. Expressing these improvements of the nuclear model in terms that can be successfully incorporated in the simulation of neutrino events by neutrino event generators.

Inclusive vs. Semi-inclusive reactions

Example of CC neutrino reactions on ^{12}C

$$
\begin{aligned}
\nu_\ell + {}^{12}\mathrm{C} \;&\rightarrow\; \ell^- + {}^{12}\mathrm{N} \\
&\rightarrow\; \ell^- + p + {}^{11}\mathrm{C} \\
&\rightarrow\; \ell^- + n + {}^{11}\mathrm{N} \\
&\rightarrow\; \ell^- + p + p + {}^{10}\mathrm{B} \\
&\rightarrow\; \ell^- + p + n + {}^{10}\mathrm{C} \\
&\qquad \vdots \\
&\rightarrow\; \ell^- + \pi^{\pm} + \mathrm{X} \\
&\qquad \vdots \\
&\rightarrow\; \ell^- + (\mathrm{d}, {}^{3}\mathrm{H}, {}^{3}\mathrm{He}, {}^{4}\mathrm{He}, \cdots) + \mathrm{X} \\
&\rightarrow\; \ell^- + \gamma + \mathrm{X} \\
&\qquad \vdots
\end{aligned}
$$

$\sum$ All open channels

$= \sigma$ inclusive

... assuming only that the muon is detected

**Adapted from Bill Donnelly's talk at ECT* 2018 workshop "Modeling neutrino-nucleus interactions"*

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&\rightarrow \ell^- + \gamma + \mathrm{X} \\
&\quad \vdots
\end{aligned}
$$

Σ All open channels + only 1 other particle $= \sigma$ semi-inclusive

... together with detection of the muon

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inclusive
exclusive-1 = semi-inclusive
exclusive-2
exclusive-3
...

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Inclusive vs. Semi-inclusive reactions

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&\quad\vdots
\end{aligned}
$$

1p1h

2p2h

inclusive
exclusive-1 = semi-inclusive
exclusive-2
exclusive-3
...

I will focus on 1p1h and 2p2h inclusive and semi-inclusive CC neutrino reactions

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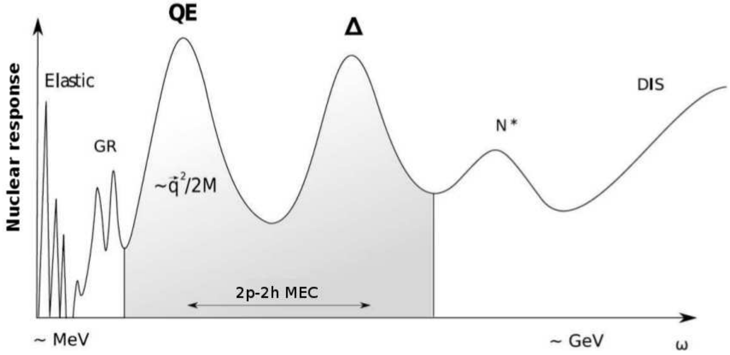
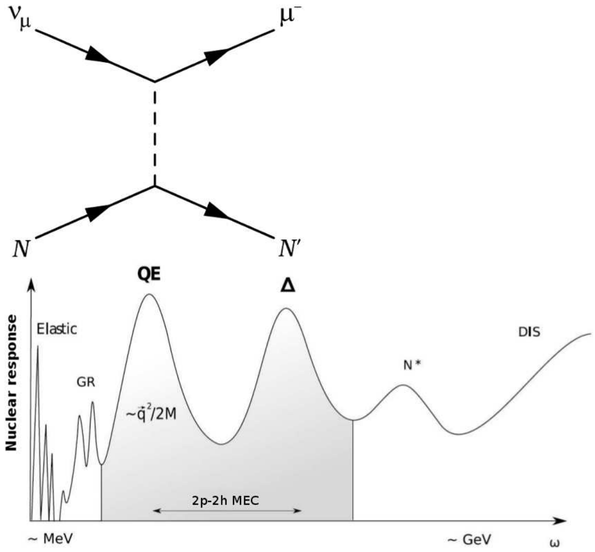
Nuclear effects in neutrino-nucleus reactions

Neutrino-nucleus interactions over the whole experimental range (of the order of 100s of MeV up to 10s of GeV) implies a large variety of nuclear effects: quasielastic (QE), multinucleon excitations (2p-2h MEC), meson production via nucleon resonances (Δ) and deep inelastic processes. At these kinematics, charged-current quasielastic (CCQE) ν-A scattering is the dominant interaction in oscillation experiments ($\gtrsim$ 40%).



Nuclear response in terms of the energy transfer



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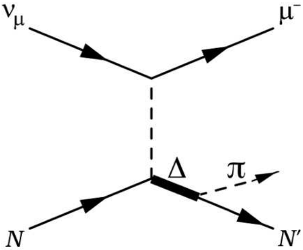
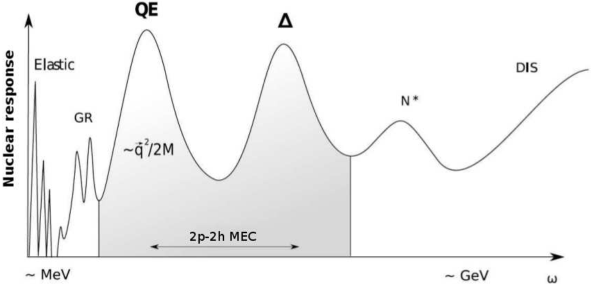


$$\nu_\mu p \rightarrow \mu^- \Delta^{++}$$
$$\nu_\mu n \rightarrow \mu^- \Delta^{+}$$
$$\bar{\nu}_\mu p \rightarrow \mu^+ \Delta^{0}$$
$$\bar{\nu}_\mu n \rightarrow \mu^+ \Delta^{-}$$



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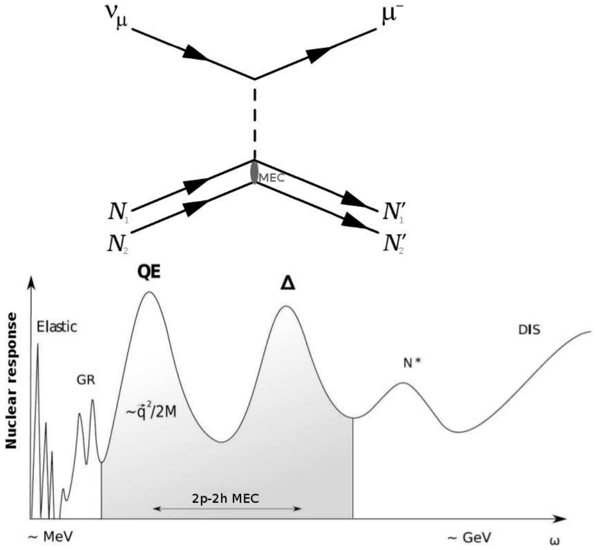

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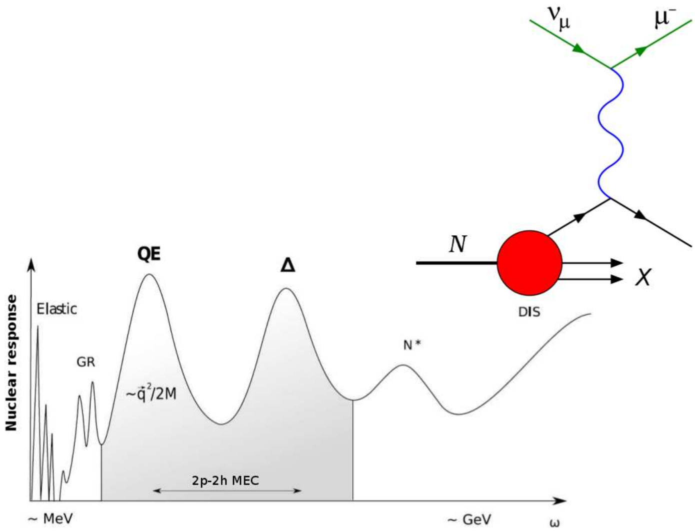
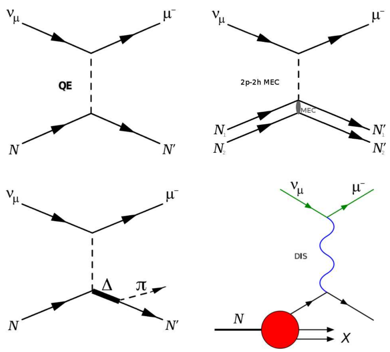
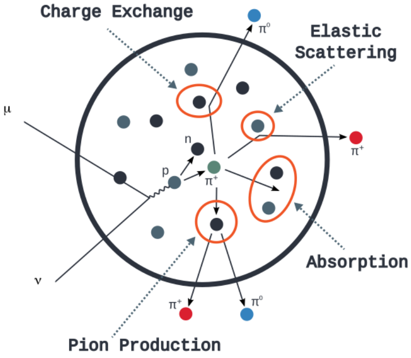


Nuclear effects and disentangling of final state events

CCQE, CCQE-like, CC0π events and FSI effects

CC0π = CCQE-like without subtraction of π absorption background





CCQE process

$$\nu_\mu + n \rightarrow \mu^- + p$$

primary background : CC pion production

$$\nu_\mu + p(n) \rightarrow \mu^- + p(n) + \pi^+$$

Neutrino-Nucleus Interaction Models in the market

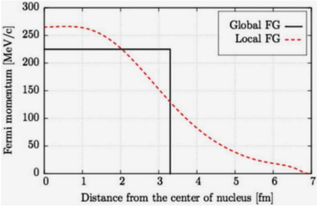
➠ **Relativistic Fermi Gas (RFG)**: nucleus as a system of non-interacting on-shell nucleons. Bound nucleons below p_F. Too simple. Used for most 2p2h models. Easily extendable to all nuclei.

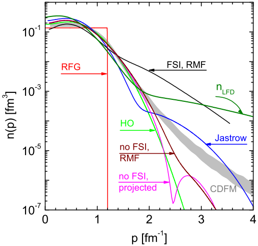
➠ **Local Fermi Gas (LFG)**: RFG extension with local density approx ($n(p)$ depends on nucleon position, nuclear finite size effects). Used in NEUT and GENIE. Bad agreement with (e,e') data.

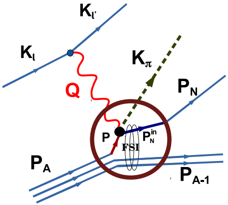
➠ **Spectral Function (SF)**: based on the factorization ansatz ($\sigma_{\nu-N} \cdot S(p, E_b)$) where S represents the probability of finding a nucleon (p, E_b) within the nucleus. Semiphenomenological based on (e,e'p) data, mean-field calculations and LFG. Shell model. Non relativistic. Implemented in NEUT.

➠ **Random Phase Approximation (RPA)**: can be added to the top of LFG/SF/HF/MF to incorporate NN correlations. Very good description at low q_0, Q^2 but not relativistic.

➠ **Relativistic Mean Field (RMF, ED-RMF, SuSAv2)**: Fully relativistic shell model with accurate description of nuclear dynamics and FSI effects. Bound nucleons: self-consistent Dirac-Hartree solutions, derived within a RMF Lagrangian with local relativistic potentials (S+V) fitted to saturation properties of nuclear matter, radii and nuclear masses. Valid for 1p1h and SPP (π), easily extendable to all nuclei.







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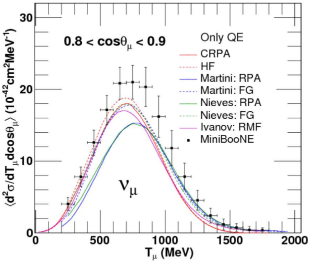
➠ Most models give $\sim \nu$-A inclusive predictions (lepton kin.). Main differences for hadron kin. due to nuclear effects. **Semi-inclusive processes:** Next step in theoretical ν interaction community.



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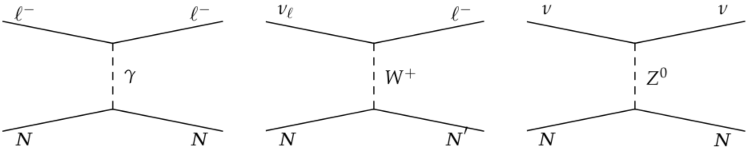
Connection between ν-A and e-A reactions



(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
  ➠ $CC(\nu_l, l)$: 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-A inclusive cross section

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

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

Nuclear structure information

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

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

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

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

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

Comparison with (e, e') reactions

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

Contents

SuperScaling Approach (SuSA)

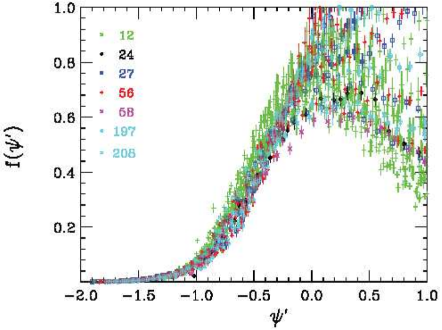
(see G.D. Megias' Thesis for details)

➟ 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**



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

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

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

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

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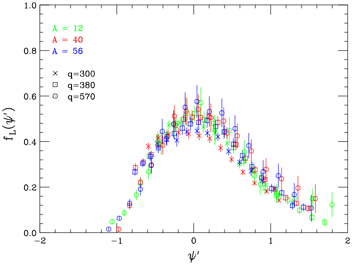
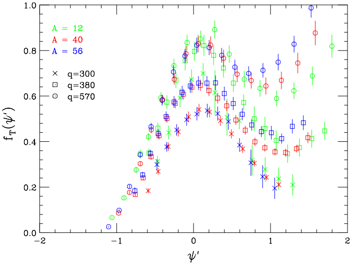




$$f_L = k_F R_L / G_L$$
$$f_T = k_F R_T / G_T$$

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

➠ RFG as a natural starting point to examine 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.

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

- Scaling functions obtained from the cross section:

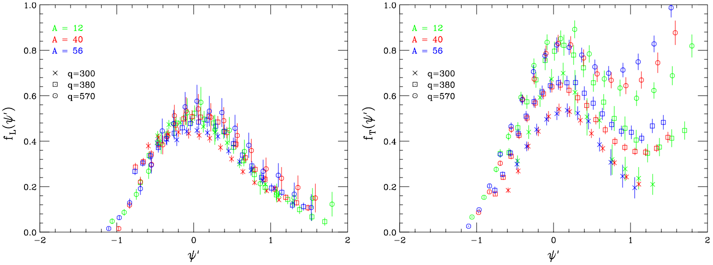
$$f^{QE(e,e')} = k_F \frac{\frac{d^2\sigma}{d\Omega_e d\omega}}{\sigma_{Mott}(v_L G_L^{ee'} + v_T G_T^{ee'})}$$

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

- Specific scaling functions for the individual channels:

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

Separate L/T scaling functions



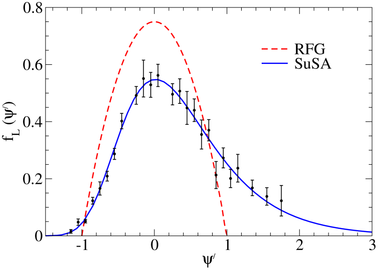
$$f_L = k_F R_L / G_L$$
$$f_T = k_F R_T / G_T$$

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

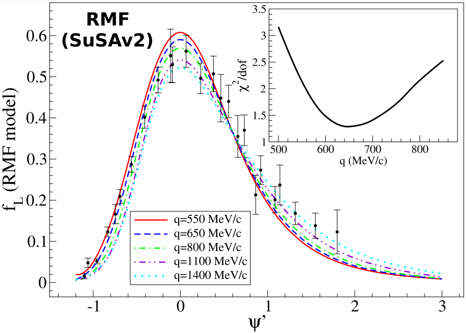
SuSA model: a semiphenomenological approach

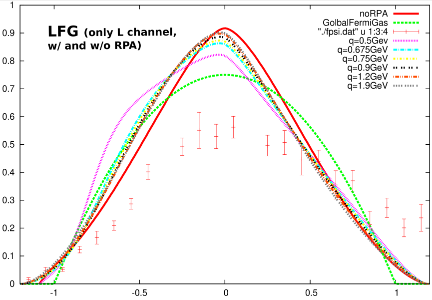
- Extracted from the (e,e') longitudinal scaling data
- Assumption $f_L(\psi) = f_T(\psi)$ (as in most IA models)

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



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



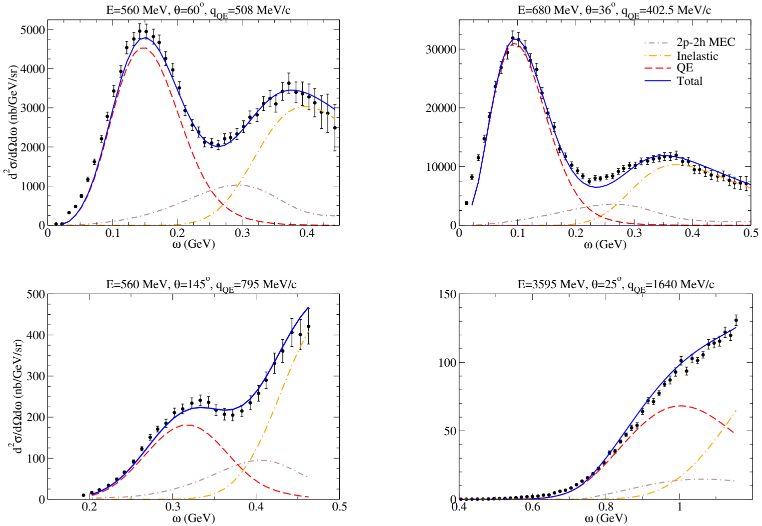


The SuSAv2 model *PRC90, 035501 (2014)* *PRD94, 013012 (2016)*

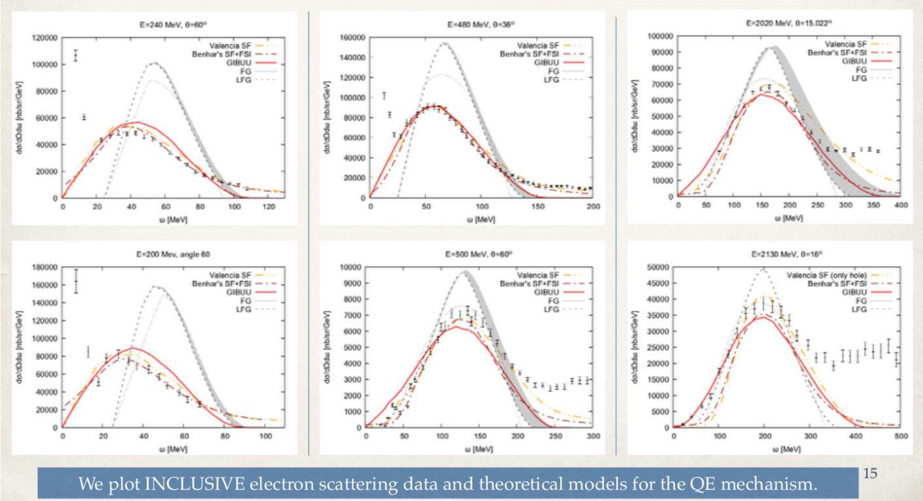
✪ **SuSAv2 model:** lepton-nucleus reactions adressed in the SuperScaling Approach and based on Relativistic Mean Field (RMF) theoretical scaling functions (FSI) to reproduce nuclear dynamics.

✪ 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.

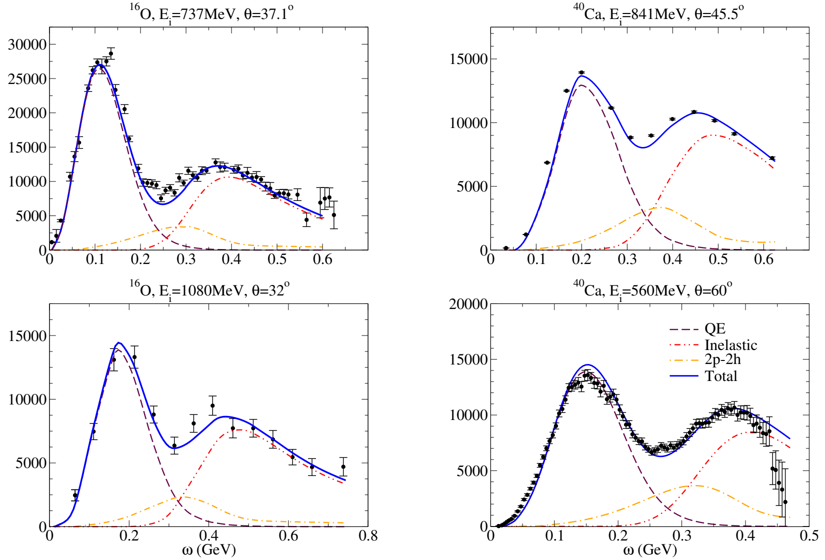
Inclusive $^{12}C(e,e')$ cross sections *PRD 94, 013012 (2016)*



Inclusive $^{12}C(e,e')$ cross sections with different models (J.Sobczyk's talk at NUINT18)

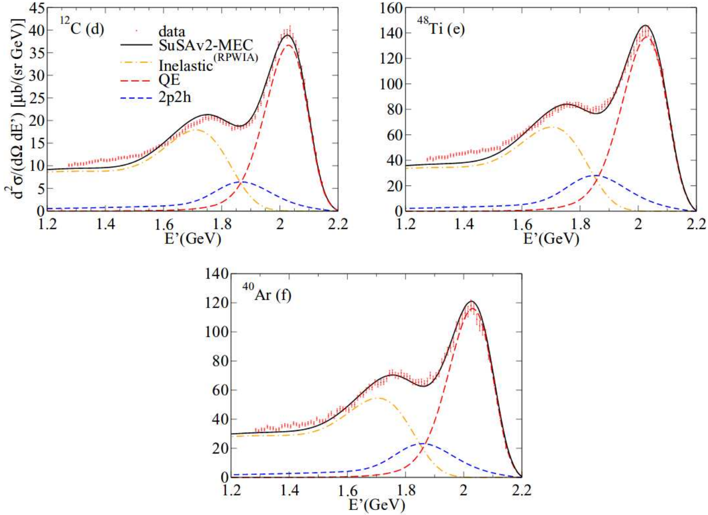


Inclusive $^{16}O(e, e')$ and $^{40}Ca(e, e')$ cross sections



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

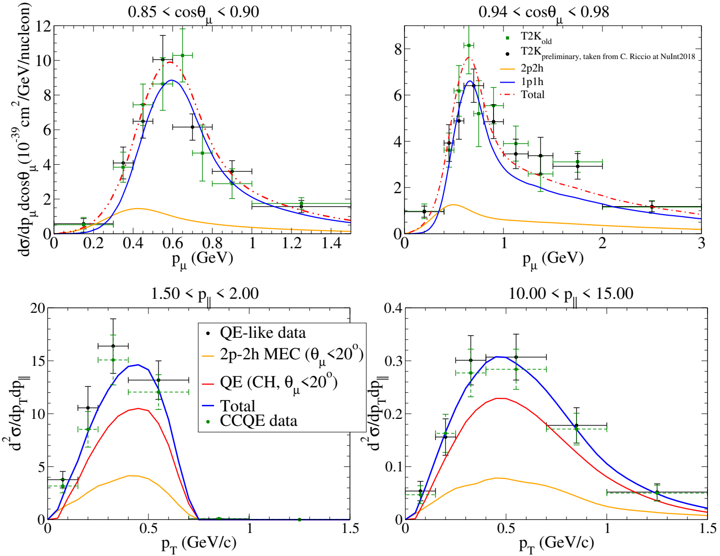
PRC99, 042501(R), 2019



Comparison with CC0π ν_μ-nucleus data

T2K CC0π $\nu_\mu - C_8H_8$

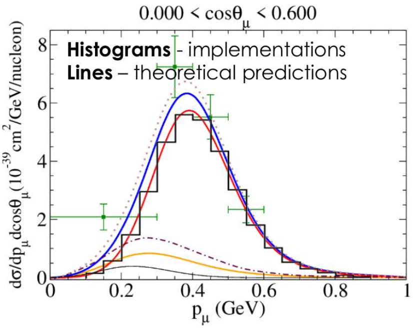
MINERνA $\bar{\nu}_\mu$-CH

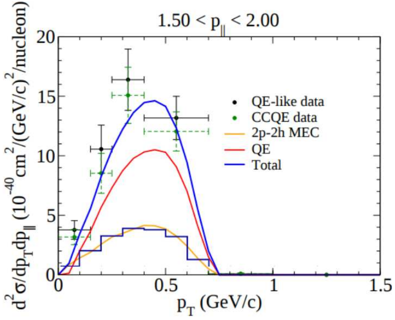


Contents

SuSAv2-MEC implementation in MC event generators *arXiv:1905.08556*

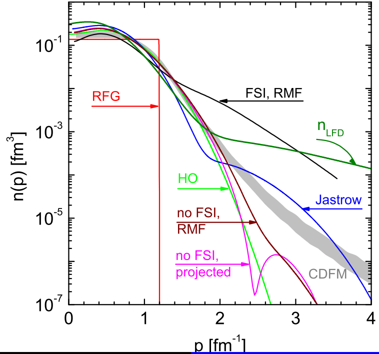
- **Implemented the SuSAv2 1p1h and 2p2h models in GENIEv3** for both (e, e') and CC ν_μ scattering. **Next step: Implementation in NEUT.**
- **New 1p1h and 2p2h model calculated using pre-computed hadron tensors for (e, e') and CC ν reactions**. The hadron tensor elements are stored in tables in terms of q_0 and q_3 in bins of 5 MeV between 0 and 2 GeV (no limits). Implementation of the hadron tensor components using the SuSA formalism (Rosenbluth-like decomposition: L and T components, V and A channels).
- Global factor / lepton tensor are easily calculated - shared by other models
- Use a GENIE's bilinear interpolation function to evaluate specific q_0, q_3 values
- Hadron tensors are initially provided for **a few targets** (C and O so far, may add others). Can easily scale to other nuclei.





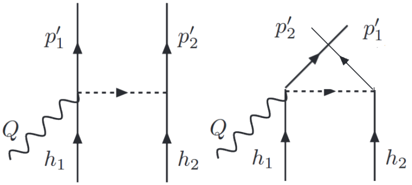
1p1h implementation: RMF and SuSAv2

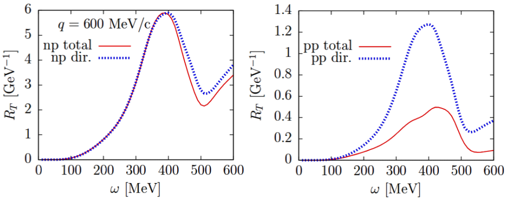
- **1st step:** Implementing SuSAv2 hadron tensor $W^{\mu\nu}(q,\omega)$ + LFG on the top and comparison with original SuSAv2 model
- **2nd step:** Adding SuSAv2 formulas, parameters and parametrization of scaling functions into generators to speed up simulations and to allow reweighting (M_A^{QE}, p_F, E_b, etc.)
- **3rd step:** Introducing RMF nucleon momentum distribution in generators to fully test factorization approach.
- **4th step:** Implement full RMF semi-inclusive model in generators



2p-2h MEC for (e, e') and CC ν reactions *PRD91, 073004 (2015)*

- The numerical evaluation of the hadronic tensor $W^{\mu\nu}_{2p2h}(R^{2p2h}_K)$ is performed in the RFG model in a fully relativistic way without any approximation. It can be easily extended to all nuclei.
- Separation into *pp*, *nn* and *np* pairs in the FS $\Rightarrow$ also valid for $N \neq Z$ (^{40}Ar, ^{56}Fe, ^{208}Pb)
- It is computationally non-trivial and involves 7D integrals of thousands of terms (+1 for ν-flux) $\Rightarrow$ High increase of the computing time of R^{2p2h}_K $\Rightarrow$ **Parametrization/Implementation**
- **Accurate implementation of np/pp pairs for the 2p2h channel using separate hadron tensors for *np* and *pp* pairs.**

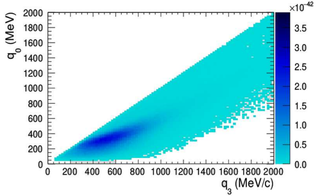


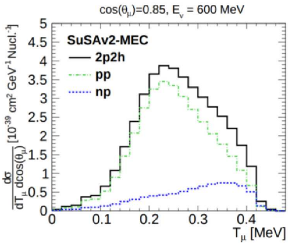


Other 2p2h models neglect direct/exchange interference terms $\Rightarrow$ **strongly affects np/pp ratio by a factor** ~ 2 (PRC94:054610,2016) $\Rightarrow$ Implications in **nucleon multiplicity** and hadron E_{reco}

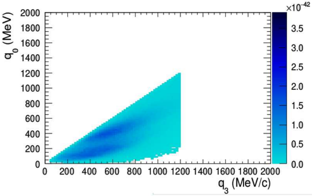
Comparison of SuSAv2-MEC^{Genie} with Nieves^{Genie} 2p2h *arXiv:1905.08556*

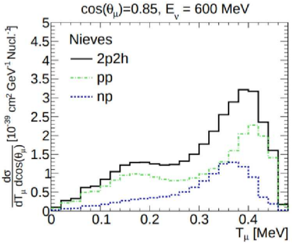
New SuSAv2 implementation





Nieves implementation





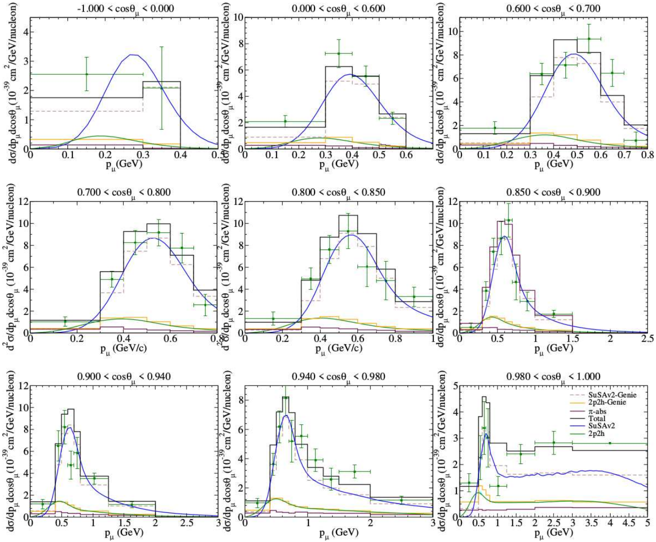
Differences in np/pp separation are mostly related to the treatment of 2p2h direct/exchange interference terms (absent in Nieves model) $\rightarrow$ strongly affects np/pp ratio by a factor $\sim$ 2 (PRC94:054610,2016) $\Rightarrow$ Implications in nucleon multiplicity and hadron E_{reco}

Contents

SuSAv2-MEC implementation in GENIE: Validation plots (T2K CC0π)

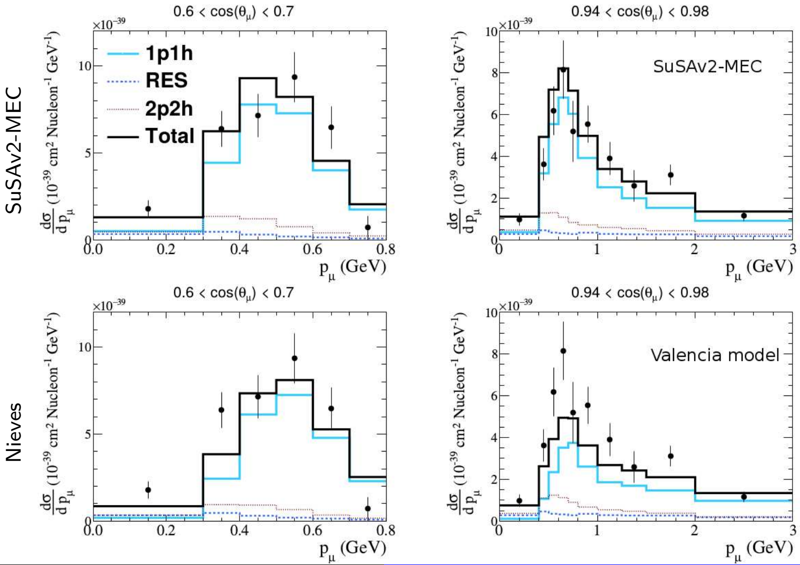
T2K CC0π $\nu_\mu-{}^{12}$C data vs. SuSAv2-MEC$_{GENIE}$

$\chi^2 = 255.8$ (67 bins)



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

T2K CC0π $\nu_\mu$$-^{12}$C inclusive data

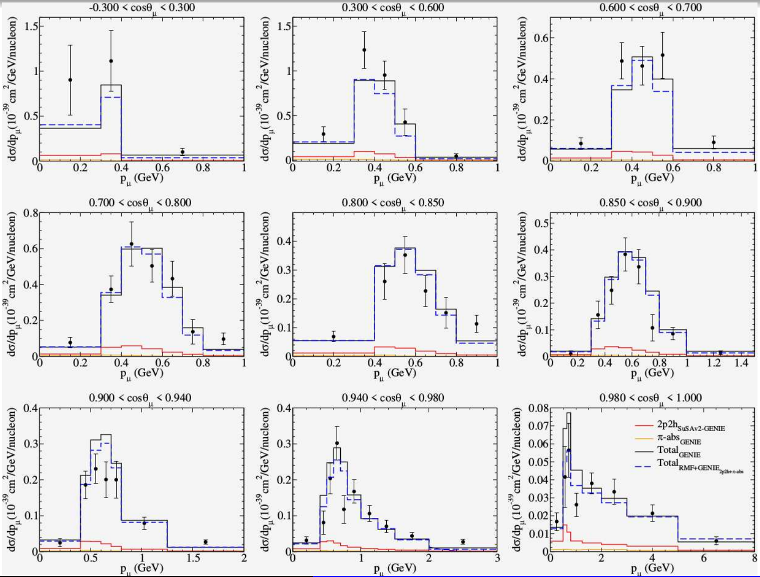


SuSAv2-MEC in GENIE: Validation plots (T2K CC0πNp, 0p > 500 MeV)

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

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

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

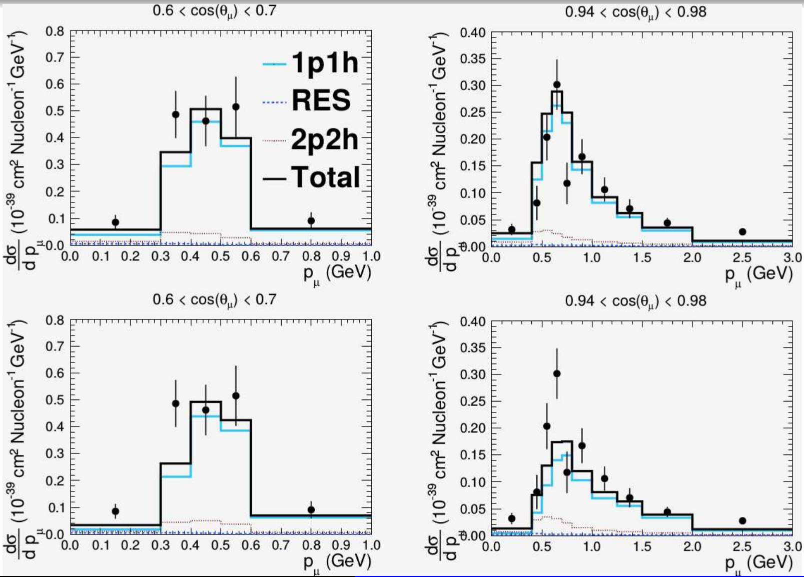


Comparison between 1p1h+2p2h models in generators *arXiv:1905.08556*

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

SuSAv2-MEC

Nieves

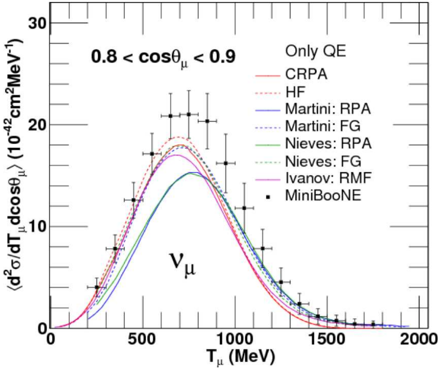


Contents

CCQE ν inclusive cross sections with different models

Different models can give similar inclusive CS but different semi-inclusive ones (more sensitive to nuclear-medium effects) $\Rightarrow$ **very different ν oscillation analyses (which relies on semi-inclusive predictions)**

THE FUTURE IS SEMI-INCLUSIVE $\Rightarrow$ Best way to produce consistent theory-vs-data comparison. Less dependency on simulations and deeper analysis of model nuclear effects.



PROBLEM: Current lack of full semi-inclusive models and proper implementation in generators.

Semi-inclusive $\Rightarrow$ **Inclusive (but not viceversa)** $\Rightarrow$ **Factorization approach is questionable**.

Different models can give similar inclusive CS but different semi-inclusive ones (more sensitive to nuclear-medium effects) $\Rightarrow$ **very different ν oscillation analyses (which relies on semi-inclusive predictions)**

PROBLEM: Current lack of full semi-inclusive models and proper implementation in generators.

Semi-inclusive $\Rightarrow$ Inclusive (but not viceversa) $\Rightarrow$ Factorization approach is questionable.

- QE and 2p2h inclusive: We only need $W^{\mu\nu}(q,\omega)$ or, equivalently, $W^{\mu\nu}(p_\mu, \cos\theta_\mu)$
- QE semi-inclusive : 5D diff. CS $(\theta_\mu,\, p_\mu,\, p_N,\, \theta_N,\, \phi_N)$ - 2p2h semi-inclusive: 9D diff. CS.

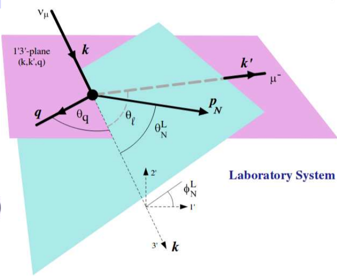
Double differential inclusive cross section $\chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$

$$\left[\frac{d\sigma}{dk_\mu\, d\Omega_\mu}\right]_\chi = \sigma_0 \left(V_{CC}R_{CC} + 2V_{CL}R_{CL} + V_{LL}R_{LL} + V_T R_T + \chi\left[2V_{T'}R_{T'}\right]\right)$$

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

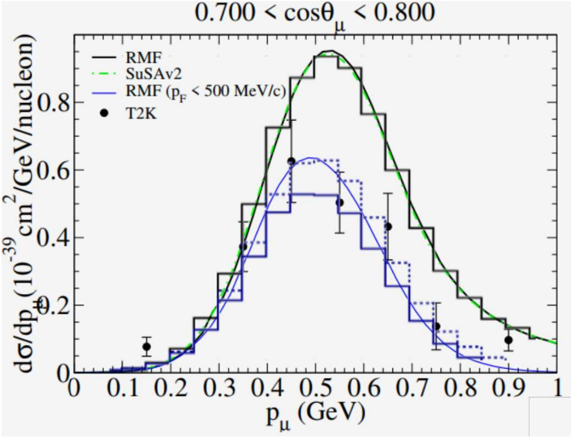
$$\frac{d\sigma}{dk' d\Omega_{k'} dp_N^2 d\Omega_N^L} = \frac{G^2\cos^2\theta_c m_N k'^2 \varepsilon\, p_N^2 W_{A-1} v_0}{2(2\pi)^5 k\varepsilon' E_N \sqrt{X_B^2 + m^2 a_B}} \mathcal{F}_\chi^2 \delta(k - k_0)\,,$$

$$\begin{aligned}
\mathcal{F}_\chi^2 =& \hat{V}_{CC}(w_{CC}^{VV(I)} + w_{CC}^{AA(I)}) + 2\hat{V}_{CL}(w_{CL}^{VV(I)} + w_{CL}^{AA(I)}) + \hat{V}_{LL}(w_{LL}^{VV(I)} + w_{LL}^{AA(I)}) \\
&+ \hat{V}_T(w_T^{VV(I)} + w_T^{AA(I)}) + \hat{V}_{TT}\left[(w_{TT}^{VV(I)} + w_{TT}^{AA(I)})\cos 2\phi_N + (w_{TT}^{VV(II)} + w_{TT}^{AA(II)})\sin 2\phi_N\right] \\
&+ \hat{V}_{TC}\left[(w_{TC}^{VV(I)} + w_{TC}^{AA(I)})\cos\phi_N + (w_{TC}^{VV(II)} + w_{TC}^{AA(II)})\sin\phi_N\right] \\
&+ \hat{V}_{TL}\left[(w_{TL}^{VV(I)} + w_{TL}^{AA(I)})\cos\phi_N + (w_{TL}^{VV(II)} + w_{TL}^{AA(II)})\sin\phi_N\right] \\
&+ \chi\left[\hat{V}_{T'}w_{T'}^{VA(I)} + \hat{V}_{TC'}(w_{TC'}^{VA(I)}\sin\phi_N + w_{TC'}^{VA(II)}\cos\phi_N) + \hat{V}_{TL'}(w_{TL'}^{VA(I)}\sin\phi_N + w_{TL'}^{VA(II)}\cos\phi_N)\right.
\end{aligned}$$



Testing the factorization approach on CC0πNp T2K data

Comparison of RMF "semi-semi-inclusive" prediction and GENIE SuSAv2 implementation to T2K data (μ kinematics with restriction of $p_{proton} < 500$ MeV/c).



Curves - theory

Histograms - GENIE

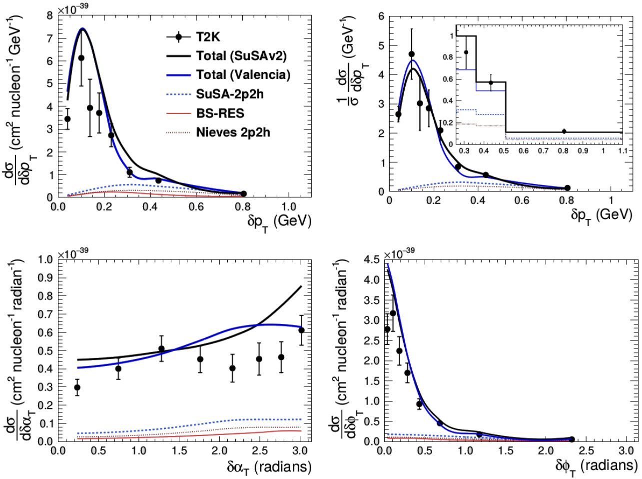
Blue: With cut in p_{proton}

Dotted line - no FSI in GENIE

Factorization approach does not seem a bad approximation for semi-semi-inclusive analysis (SuSAv2 + LFG on the top (Genie) vs. RMF code. To be done with RMF on the top).

What about more semi-inclusive measurements?

Comparison of semi-inclusive T2K STV data with SuSAv2-MEC^{Genie} + BS π abs and Valencia model + BS π abs (*arXiv:1905.08556*). Goodness of fit: For δp_T: $\chi^2_{SuSA} = 20.5$, $\chi^2_{Valencia} = 27.1$. For $\delta\alpha_T$: $\chi^2_{SuSA} = 45.3$, $\chi^2_{Valencia} = 31.4$. For $\delta\phi_T$: $\chi^2_{SuSA} = 40.1$, $\chi^2_{Valencia} = 36.8$.

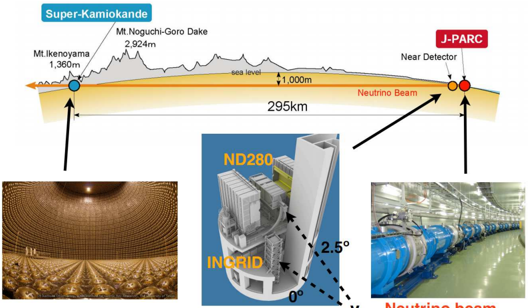


Work in progress to test the factorization approach in semi-inclusive measurements when RMF momentum distribution is implemented.

Contents

Why is the C to O extrapolation important?

➲ T2K ND280 is primarily based on C_8H_8 (also containing H_2O active target regions), whereas the FD is water-based.
➲ ND measurements on C_8H_8 are essential to constrain flux and CS uncertainties, but C/O differences are not well constrained (one of the dominant remaining systematic uncertainties).
➲ Proper analysis of CC ν interactions on water are essential for T2K ND and FD but also to future water-based atmospheric and LB experiments (HyperK) $\Rightarrow$ $\nu-{}^{12}$C / $\nu-{}^{16}$O differences will be carefully studied in this project for 1p1h and 2p2h.



Super-Kamiokande

INGRID (on-axis) and ND280 (off-axis)

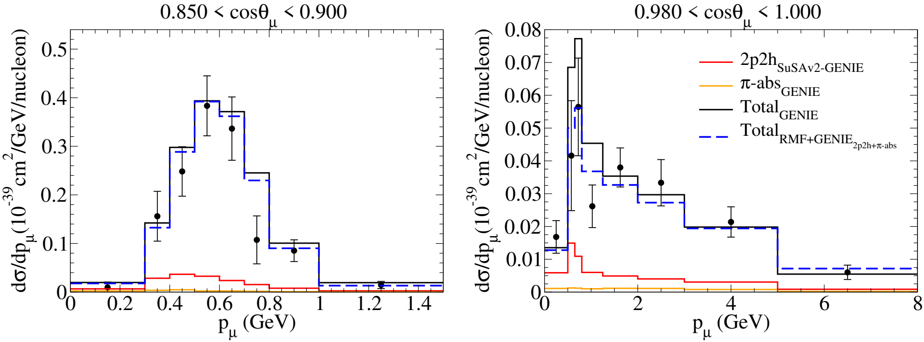
Neutrino beam created at J-PARC main ring

RMF (1p1h) could reveal C/O differences due to different binding energy and shell effects, mass of the residual nucleus, FSI and Coulomb distortions, etc.

The implementation of **2p2h** *np* **and** *pp* **pairs** can have an impact on this issue. 2p2h direct-exchange interference terms can imply a factor 2 in the *np*/*pp* ratio with regard to other models $\Rightarrow$ Relevant for T2K and HyperK projects where FS nucleon multiplicity is detected and for SK-Gd where Gd salts are added to the H_2O target to improve *n* detection and sensitivity to discover CPV via $\nu/\bar{\nu}$ differences, since the latter produce more neutrons.

Low-energy effects at T2K CC0π 0p >500 MeV/c *arXiv:1905.08556*

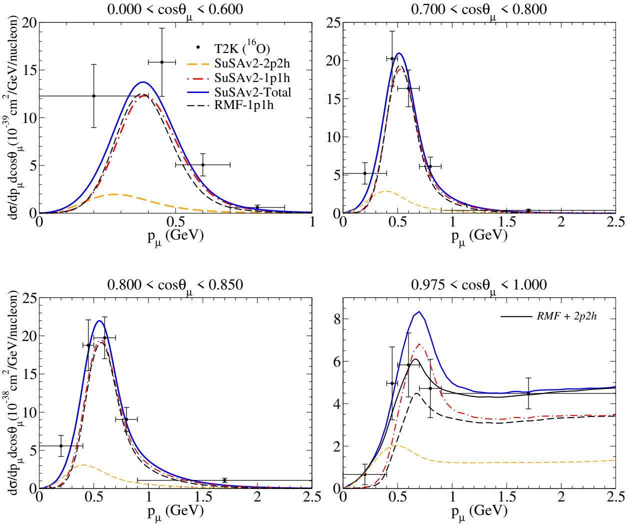
Low-energy effects and scaling violations are only appreciable at very forward angles (low q_3, q_0 values). RMF is more accurate than SuSAv2 at these kinematics.



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

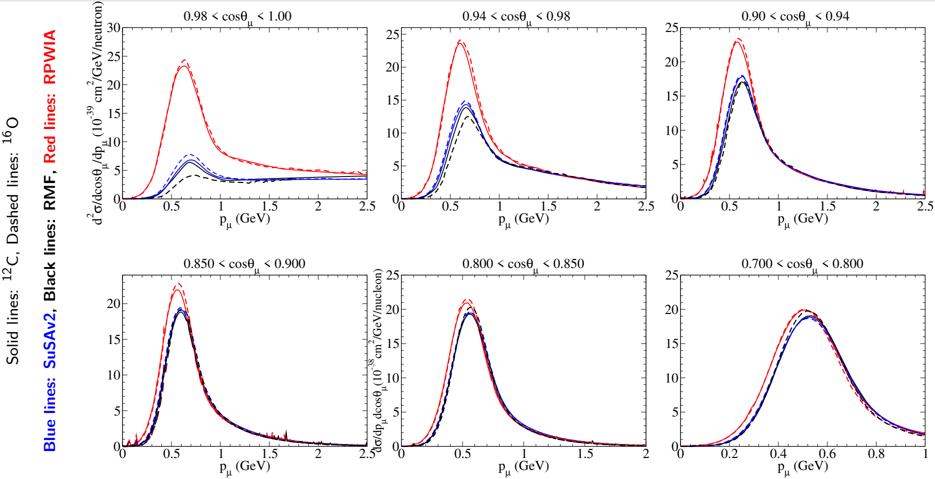
arXiv:1711.00771 [nucl-th] (2017)



Good comparison with T2K-^{16}O data but some overstimations appear at very forward angles within the SuSAv2-MEC model $\Rightarrow$ 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*) $\Rightarrow$ Solution: Determine and characterize low-q_3 RMF scaling functions to be added in the SuSAv2 formalism as well as in the implementation.

Improvement of the SuSAv2-1p1h model at very low kinematics



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Contents

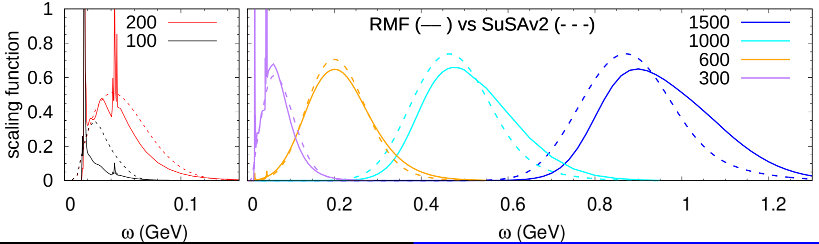
RMF, ED-RMF and SuSAv2 models arXiv:1904.10696

✪ 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.)**



RMF, ED-RMF and SuSAv2 models arXiv:1904.10696

- 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.)**
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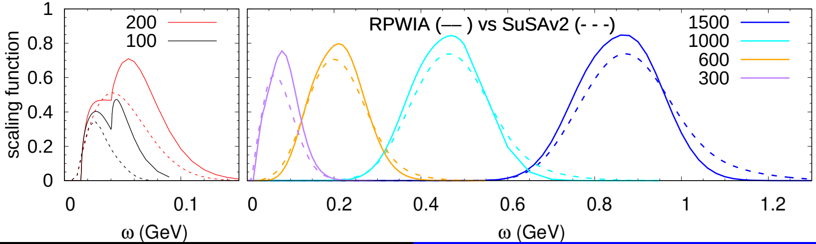

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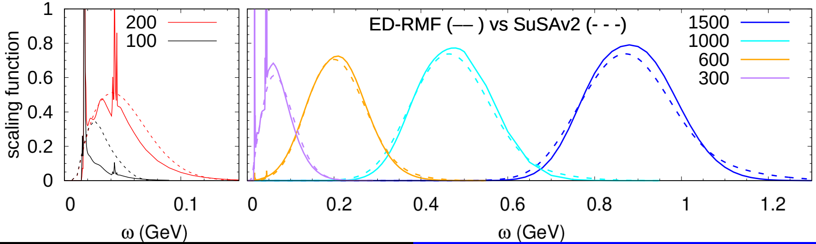
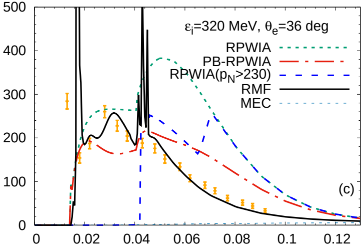
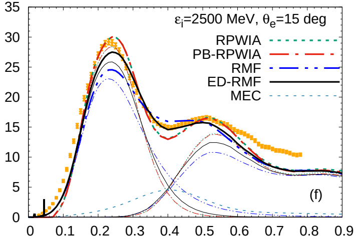


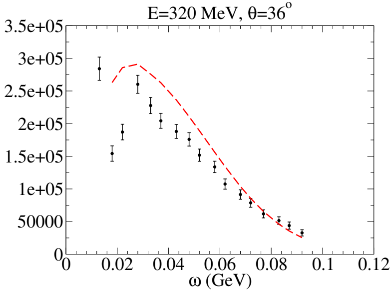
ED-RMF, RMF, SuSAv2 for $(e,e')^{12}C$ $\quad d^2\sigma/d\Omega/d\omega$ vs. ω

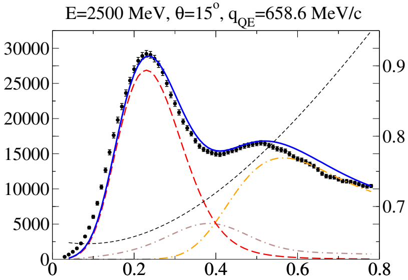
RMF, ED-RMF, others





SuSAv2



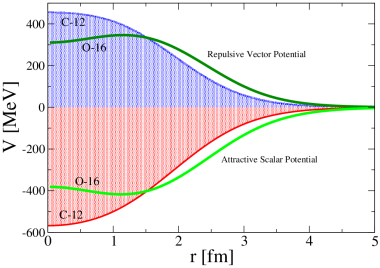


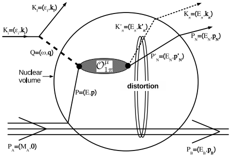
Contents

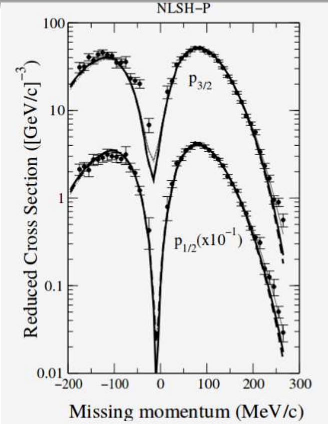
FSI effects for the ejected nucleon state: Cascade (generators) vs. Optical potentials (RMF)

✪ **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)]

FSI effects: Cascade (generators) vs. Optical potentials (RMF)

✪ **RMF FSI effects:** S+V real potentials $\Rightarrow$ 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.

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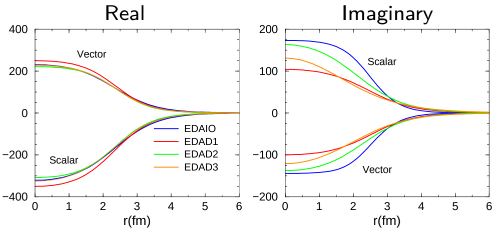
Imaginary part: phenomenological ED complex OP fitted to elastic $p - A$ scattering data.
Real part: microscopic RMF real potentials $\equiv$ phenom. real OP



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.*

Summary and Conclusions

➲ **Neutrino-nucleus interactions are essential for ν oscillation experiments (T2K, SK)**, being one of the major sources of current systematics.

➲ **The extrapolation to other nuclei (C, O, Ar)** will be essential for future experiments such as HyperK as well as to analyze nuclear-medium uncertainties and inconsistencies between experiments, such as NOvA or MINERvA.

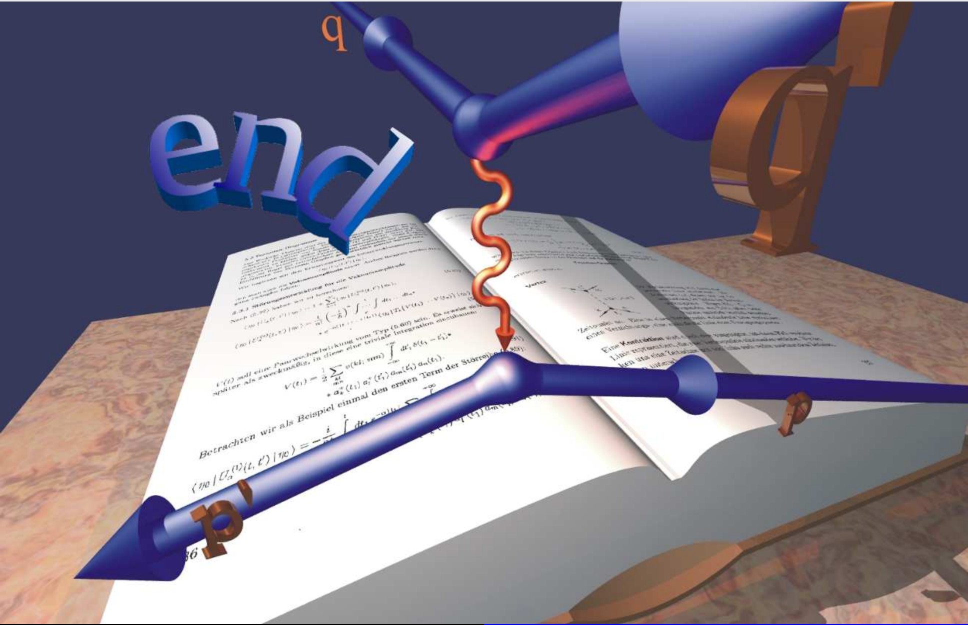
➲ **Forthcoming measurements in water (T2K WAGASCI and NINJA experiments)** will be very useful to validate nuclear models already present in generators.

➲ **Collaboration between experimentalists, generator developers and theorists is essential** to reduce systematics, improve models in MC event generators and gain sensitivity to determination of oscillation parameters, CPV, NMH.

➲ **Validation against (e, e') data is a solid benchmark for nuclear models in ν experiments.** Superscaling is a valuable tool to connect electron and neutrino scattering.

➲ Analysis of semi-inclusive reactions (more sensitive to nuclear model details) is essential for ν oscillation experiments and will help to analyze physics of theoretical models and provide more consistent theory-vs-data comparisons. Different models can give similar inclusive CS but probably different exclusive ones.

➲ Satisfactory comparison of SuSAv2-MEC with (e, e') and (ν, l) inclusive and semi-inclusive data for C, O and other nuclei makes them promising candidate for this purpose.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