SuSAv2-MEC model: main features, implementation in generators and further works

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Testing and Improving Models of Neutrino Nucleus Interactions in Generators,
Plenary sessions, ECT, 3 June 2019*

1. General Introduction
   - SuperScaling Approach: SuSAv2 and RMF models
   - Comparison with CC ν_μ-nucleus experimental data
2. SuSAv2-MEC implementation in GENIE
   - Implementation of SuSAv2-MEC in GENIE
   - Validation of the implementation and Data comparison
   - From inclusive to semi-inclusive models
3. Further works and Next Steps
   - Low-energy effects and scaling violations
   - ED-RMF vs. SuSAv2
   - Treatment of the Δ propagator in 2p2h and Δ decay width

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?

Contents

SuperScaling Approach (SuSA)

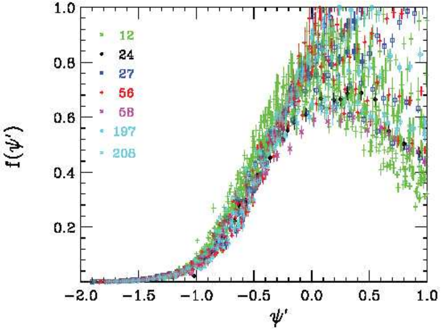
(see G.D. Megias' Thesis for details)

➠ 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**



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

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

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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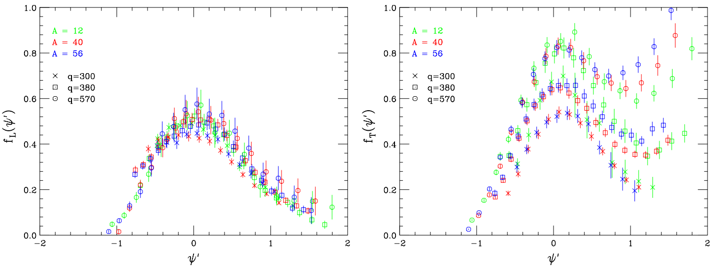
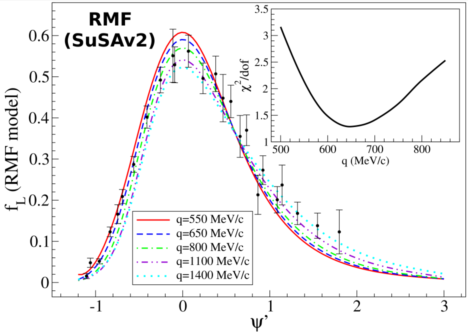
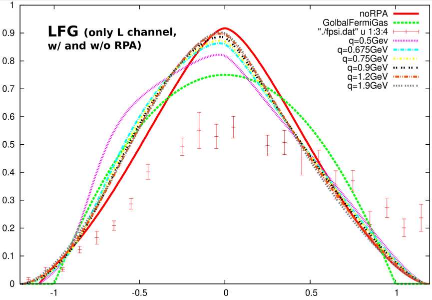


$$f_L = k_F R_L / G_L$$
$$f_T = k_F R_T / G_T$$

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

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



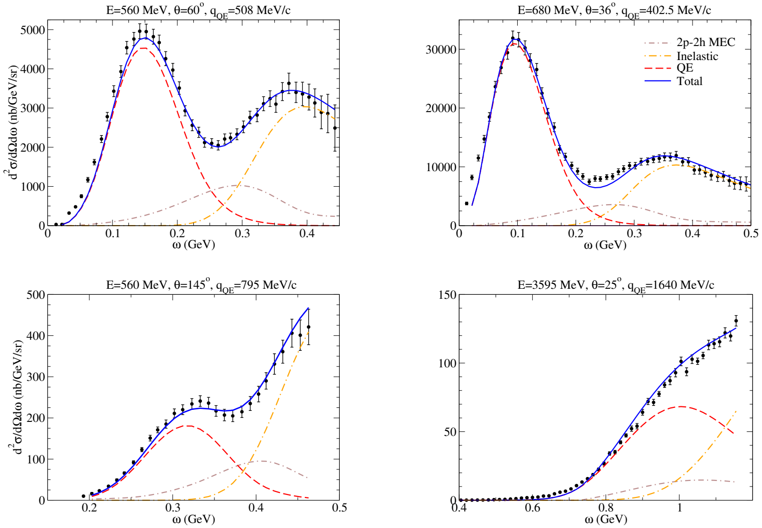


The SuSAv2 model *PRC90, 035501 (2014)* *PRD94, 013012 (2016)*

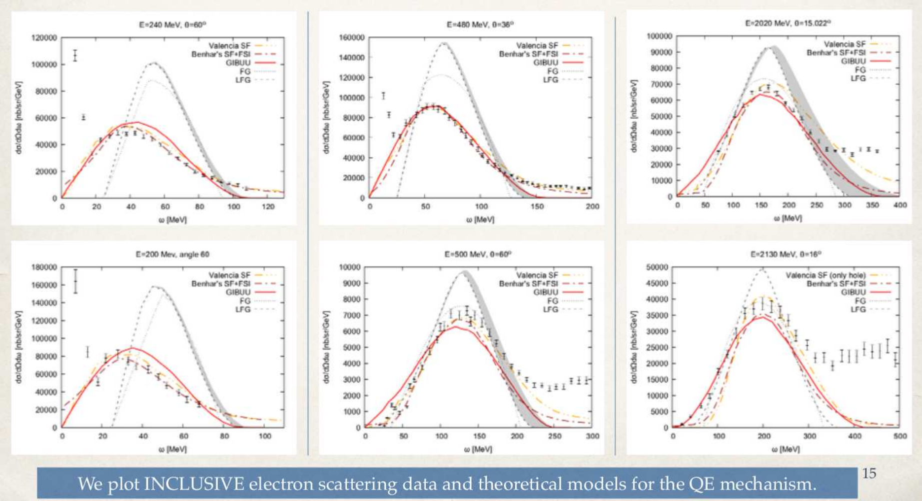
- **SuSAv2 model:** lepton-nucleus reactions adressed in the SuperScaling Approach and based on Relativistic Mean Field (RMF) theoretical scaling functions (FSI) to reproduce nuclear dynamics.

- 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)



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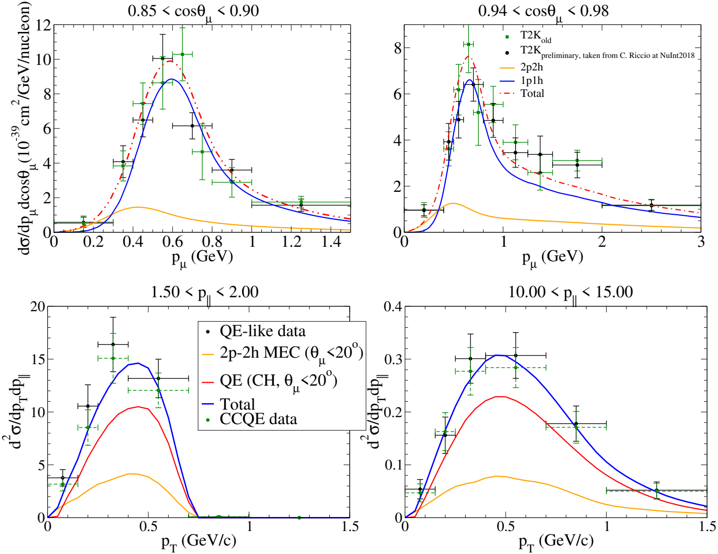
Comparison with CC0π data

T2K CC0π $\nu_\mu - C_8H_8$

MINERνA $\bar{\nu}_\mu$-CH



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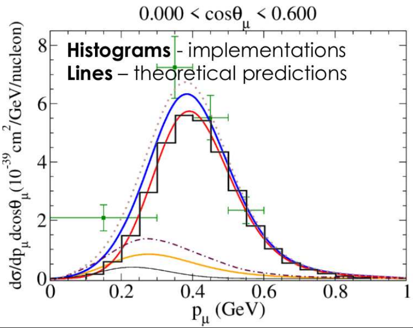
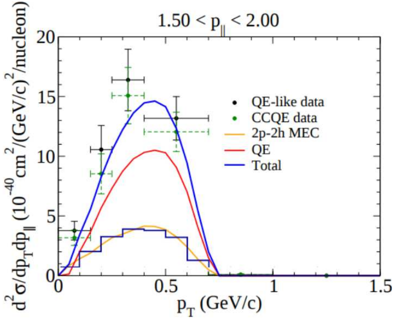
SuSAv2-MEC implementation in GENIE *arXiv:1905.08556*

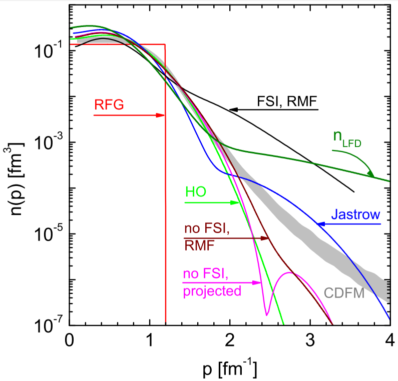
- **Implemented the SuSAv2 1p1h and 2p2h models in GENIEv3** for both (e, e') and CC ν_μ scattering. Now undergoing final validations and first physics studies before official release. **Next step: Implementation in NEUT.**
- **New 1p1h and 2p2h model calculated using pre-computed hadron tensors for (e, e') and CC ν reactions**. The hadron tensor elements are stored in tables which specify 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 will be initially provided for **a few targets** (C and O so far, may add others). Can easily scale to other nuclei.





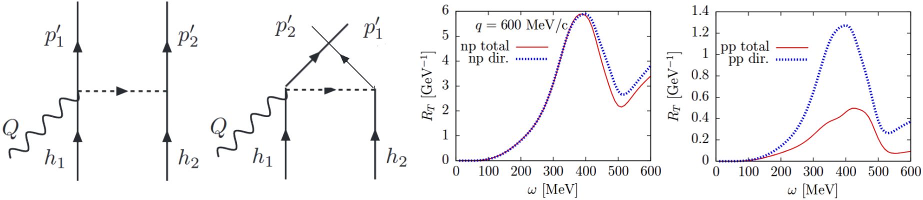
1p1h implementation: RMF and SuSAv2

- **1st step:** Implementing SuSAv2 hadron tensor $W^{\mu\nu}(q,\omega)$ + LFG on the top and comparison with original SuSAv2 model (short term, already done)
- **2nd step:** Adding SuSAv2 formulas, parameters and parametrization of scaling functions into GENIE to speed up simulations and to allow reweighting (mid term)
- **3rd step:** Introducing RMF nucleon momentum distribution in GENIE to fully test factorization approach (mid term)



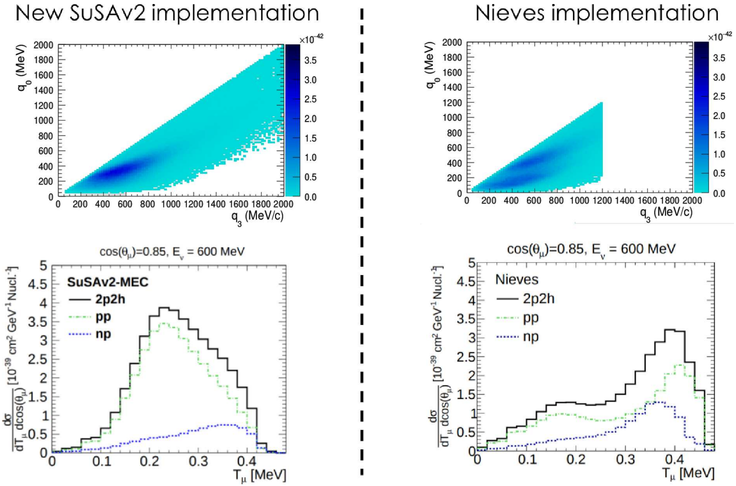
2p-2h MEC for (e, e') and CC ν reactions *PRD91, 073004 (2015)*

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}



- ✪ **Accurate implementation of np/pp pairs for the 2p2h channel using separate hadron tensors for *np* and *pp* pairs.**
- ✪ 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**

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



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

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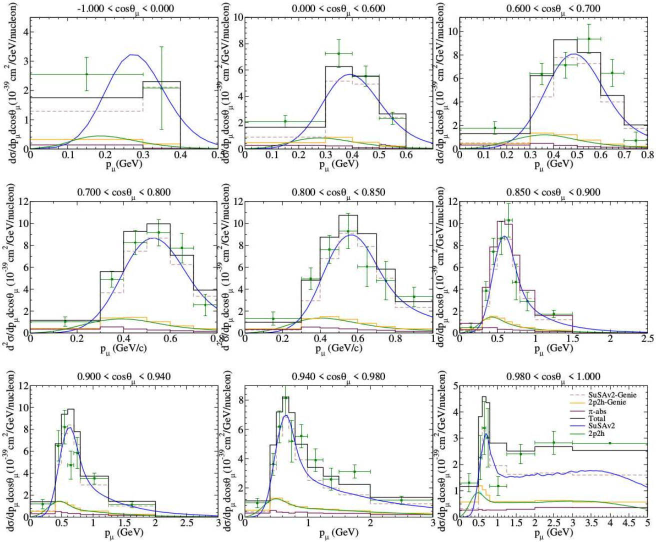
SuSAv2-MEC implementation in GENIE: Validation plots (T2K CC0π)

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

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

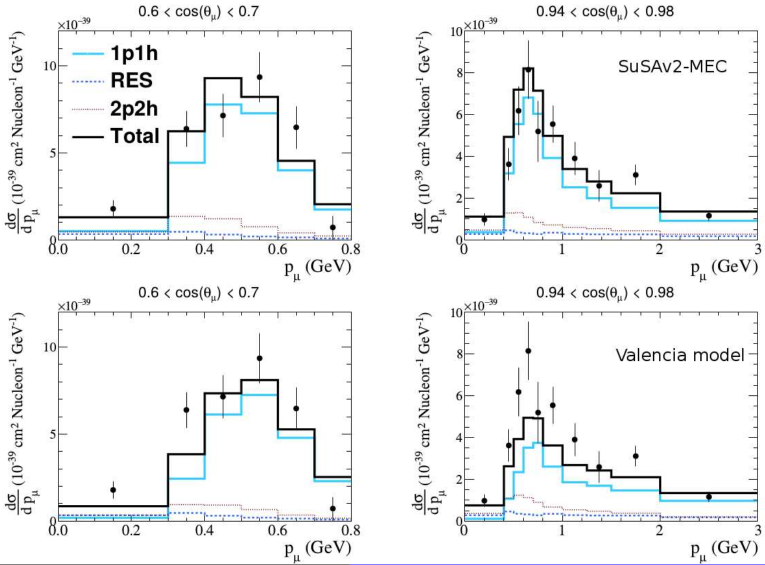


Comparison between 1p1h+2p2h models in generators *arXiv:1905.08556*

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

SuSAv2-MEC

Nieves

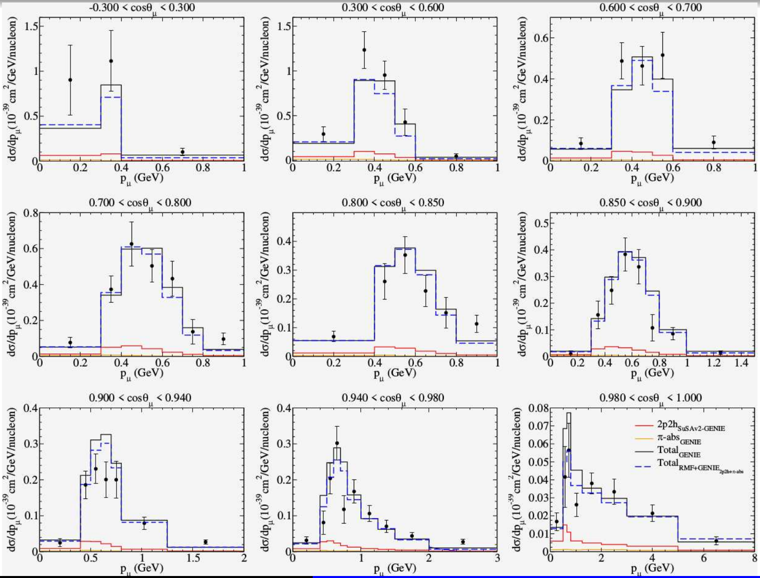


SuSAv2-MEC in GENIE: Validation plots (T2K CC0πNp, 0p > 500 MeV)

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

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

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



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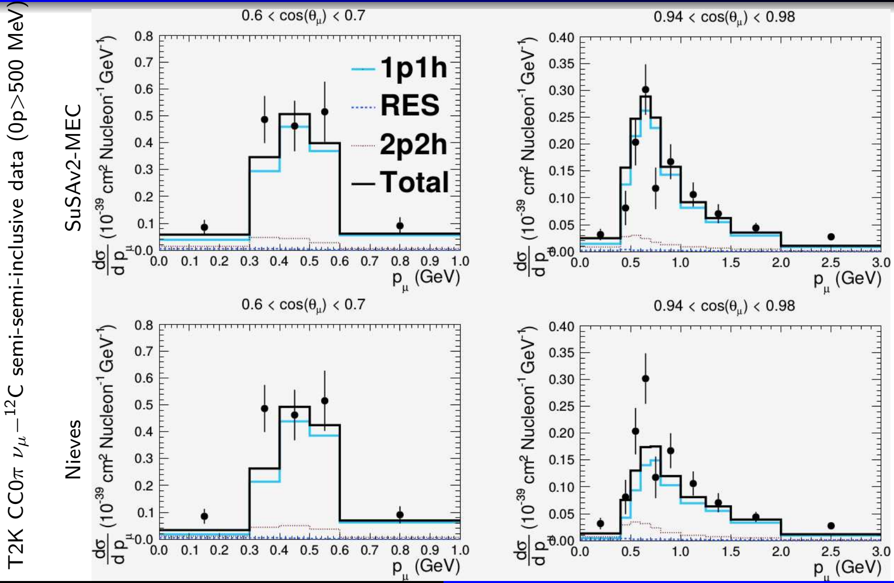

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Different models can give similar inclusive CS but different semi-inclusive ones (more sensitive to nuclear-medium effects) $\Rightarrow$ **very different ν oscillation analyses (which relies on semi-inclusive predictions)**

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.

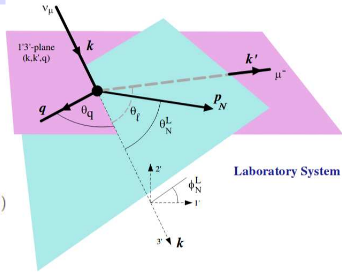
Double differential inclusive cross section $\chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$

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

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

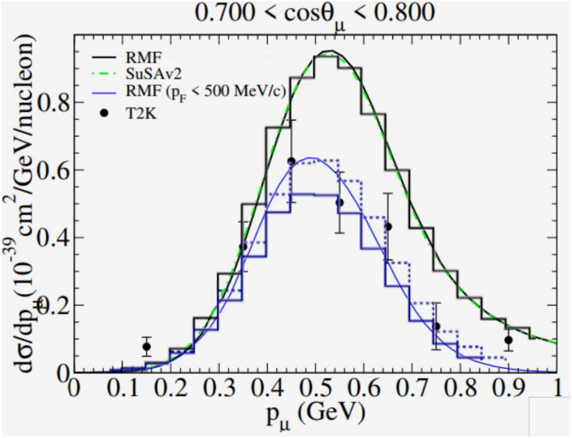
$$\frac{d\sigma}{dk' d\Omega_{k'} dp_N^2 d\Omega_N^L} = \frac{G^2\cos^2\theta_c m_N k'^2 \varepsilon\, p_N^2 W_{A-1} v_0}{2(2\pi)^5 k\varepsilon' E_N\sqrt{X_B^2 + m^2 a_B}} \mathcal{F}_\chi^2 \delta(k-k_0),$$

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



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

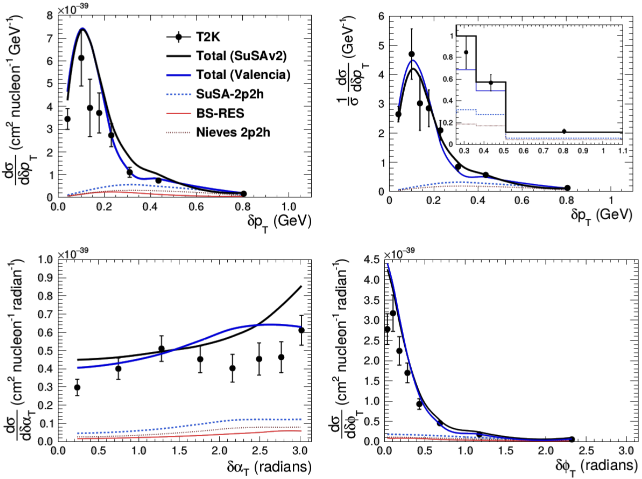
Blue: With cut in p_{proton}

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. **See S. Dolan's talk**

Summary and Conclusions

What we can do:

- ➲ Valid for all nuclear targets
- ➲ No kinematical restrictions
- ➲ Works for CC neutrino and electron scattering
- ➲ Minimal calculation on the fly - fast

What we can't yet do:

- ➲ Input model is inclusive (for the moment) ⇒ hadron kinematic predictions are ad-hoc (like all current GENIE models)
- ➲ Implementation of RMF momentum distribution soon. Long-term: 1^{st} implementation of a full semiinclusive formalism to produce all together lepton and hadron kinematic predictions. No factorization approach.
- ➲ Initial implementation does not allow to alter systematic parameters such as M_A^{QE}, k_F, binding energy effects, etc.

SuSAv2-MEC implementation is therefore useful as:

- ➠ Theory derived from microscopic model, predictions are significantly different from other models.
- ➠ A theory-driven mock-data studies for physics analyses.
- ➠ For model comparisons to neutrino scattering data.
- ➠ Phenomenological studies.

➲ Since current model is non-reweightable it cannot yet be used to calculate systematic uncertainties in physics analyses.

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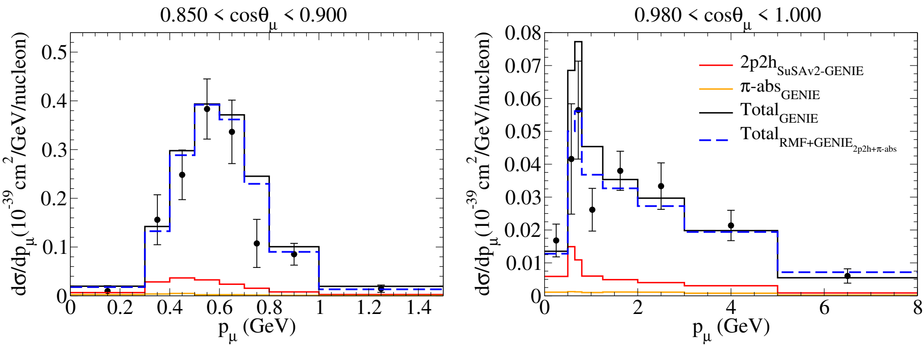
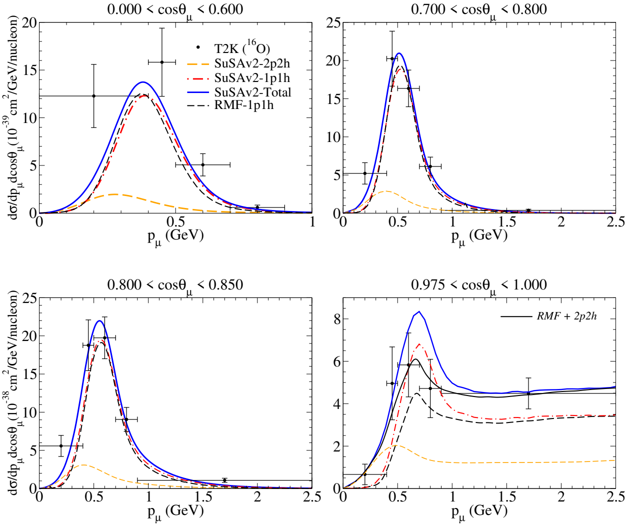
Low-energy effects at T2K CC0π 0p >500 MeV/c *arXiv:1905.08556*



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.

T2K CC0π $\nu_\mu - H_2O$ 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.

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RMF, ED-RMF and SuSAv2 models

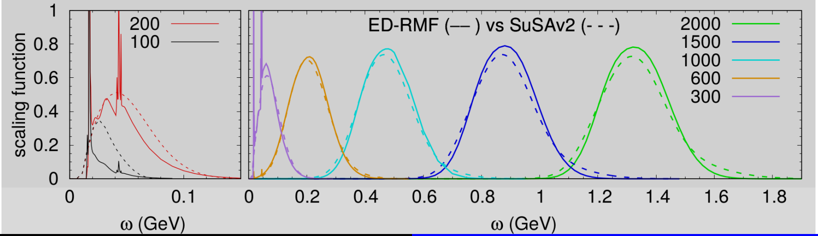
arXiv:1904.10696

✪ 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**

✪ The issue of the strong q-dependence of RMF vector and scalar potentials at high kinematics is addressed by using a blending function to introduce RPWIA effects (no FSI) in the SuSAv2-MEC model, yielding a good representation of (e, e') and CC0π data at intermediate and high kinematics. *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 the SuSAv2 approach) to the RMF that keeps the strength for slow nucleons but makes the RMF potential softer for increasing nucleon momenta. **See A. Nikolakopoulos and R. Gonzalez talks for details**

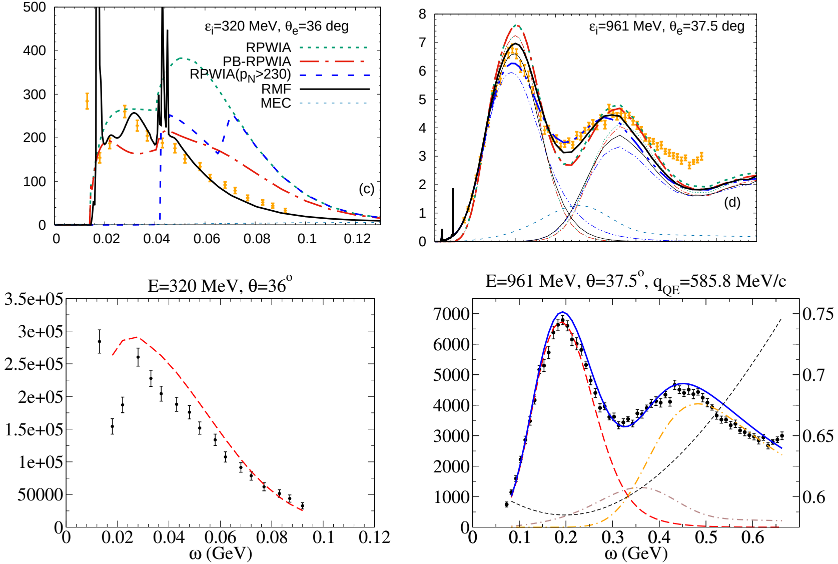
✪ SuSAv2 is a pure inclusive model. **Solution: ED-RMF (both inclusive and semi-inclusive for ^{12}C, ^{16}O, ^{40}Ar, etc.)**



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

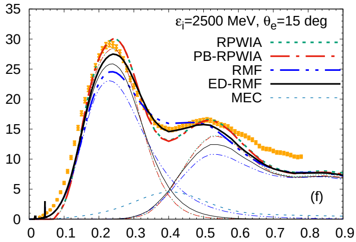
RMF, ED-RMF, others

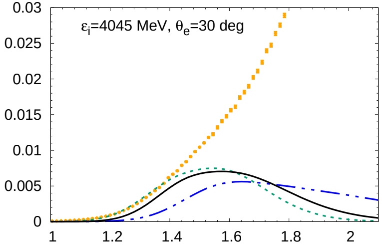
SuSAv2



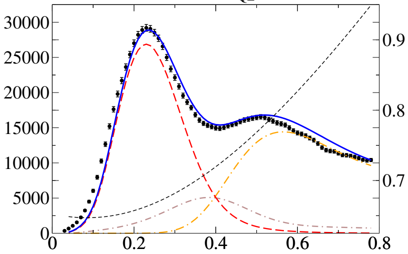
ED-RMF, RMF, SuSAv2 for $(e, e')^{12}C$ $d^2\sigma/d\Omega/d\omega$ vs. ω

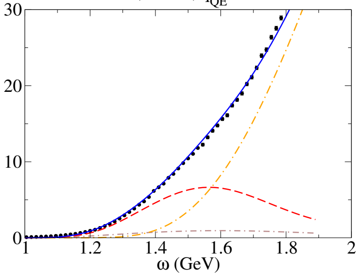
RMF, ED-RMF, others





SuSAv2





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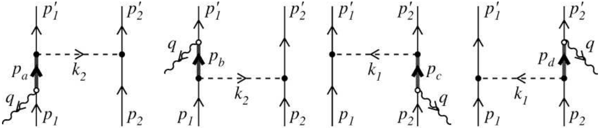
Δ propagator in 2p2h and Δ decay width (see also A. De Pace's talk)

➲ Our **2p2h-MEC model** can produce **semi-inclusive** (e, e') and CC0π results. Work in progress.

➲ An **open question** in 2p2h models (also in π production) is the **treatment of the Δ propagator** in 2-body currents and the Δ **decay width**. Taking only the real part of the propagator and assuming free Δ decay width is an approach taken by several 2p2h models and in our case it has resulted in a good empirical approach in very good agreement with (e, e') and CC0π data.

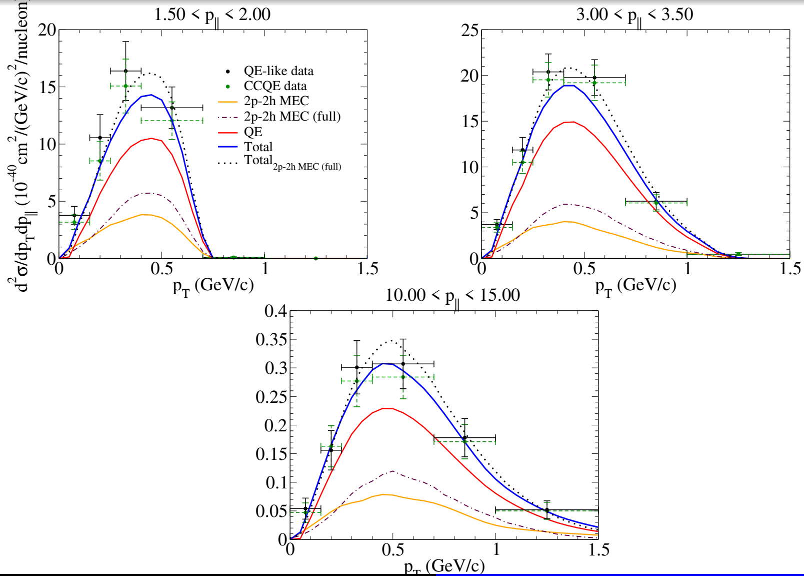
➲ **Next step (Solution?): Joint analysis of the 2p2h-MEC model (full propagator) and the ED-RMF (1p1h + π production)** in comparison with (e, e') data to infer a proper value of the Δ decay width with medium modifications.



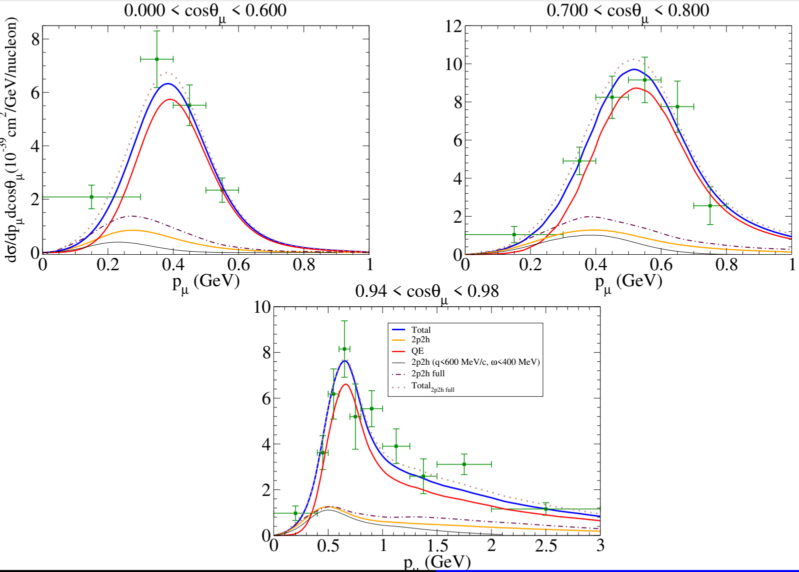
$$S_{\Delta,\alpha\beta} = \frac{-(\not{K}_\Delta + M_\Delta)}{K_\Delta^2 - M^2 + iM_\Delta \Gamma_{\text{width}}}\Big(\ldots\Big)_{\alpha\beta}$$

$$\Gamma_{\text{width}}^{\text{free}} \longrightarrow \Gamma_{\text{width}}^{\text{in-medium}} = \Gamma_{\text{Pauli}} - 2\Im(\Sigma_\Delta)$$
$$M_\Delta^{\text{free}} \longrightarrow M_\Delta^{\text{in-medium}} = M_\Delta^{\text{free}} + \Re(\Sigma_\Delta)\,.$$

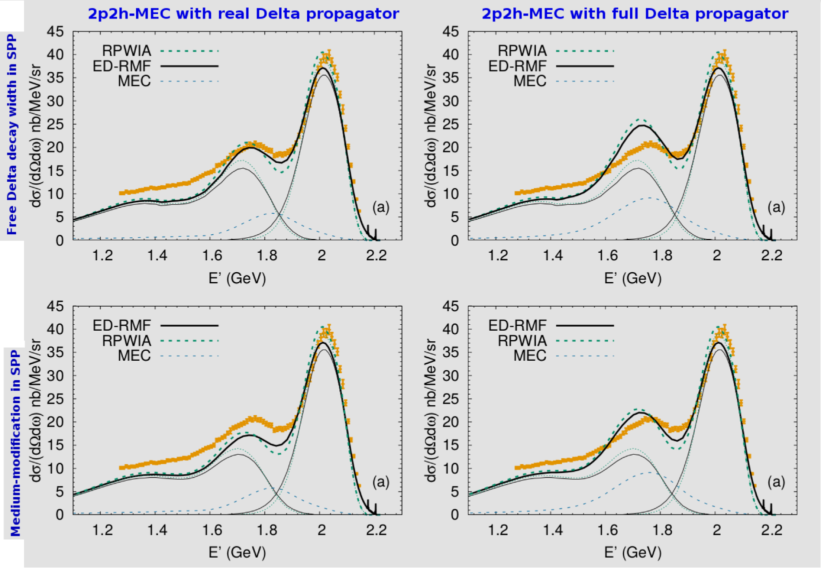
2p2h full/real Δ prop. vs MINERvA CC0π $\bar{\nu}$-CH data



2p2h full/real Δ prop. vs T2K CC0π ν-^{12}C data



2p2h full/real Δ prop. vs JLab $(e, e')^{12}$C data



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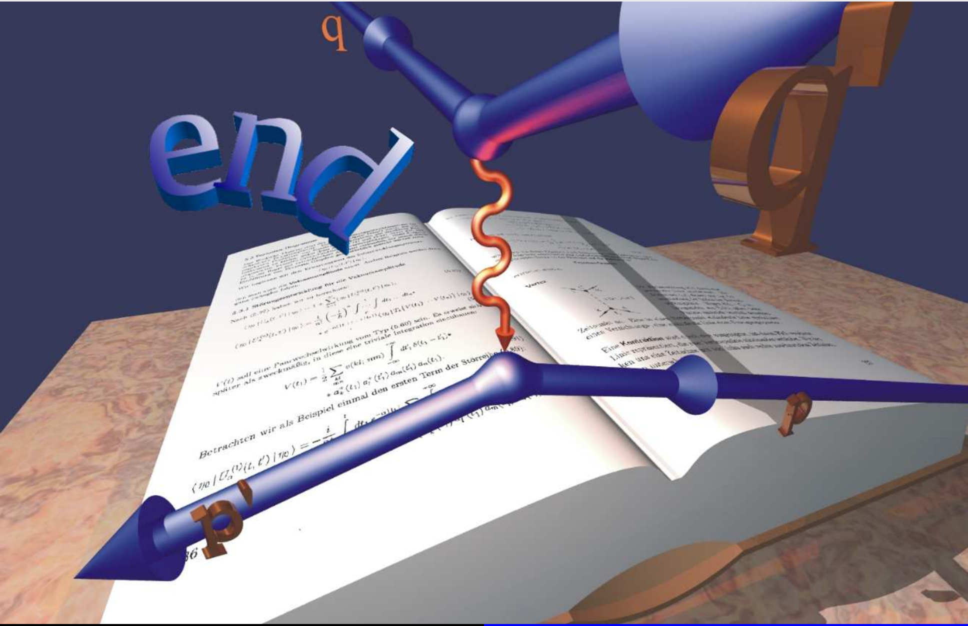
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