Relativistic modeling of 2p2h, implementation in GENIE and data comparison within the SuSAv2-MEC model

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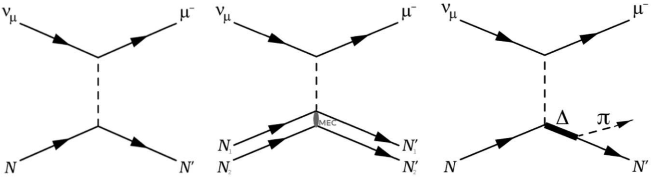
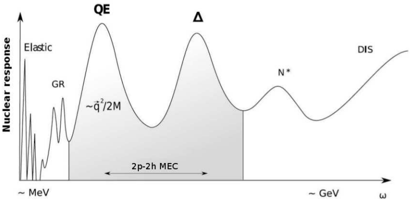
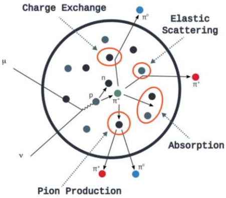
Neutrino-nucleus reactions for ν oscillation experiments

Challenges for theoretical nuclear models

- Modeling of nuclear structure giving the initial kinematics and dynamics of bound nucleons. Providing kinematics of final leptons and hadrons and accurate description of FSI.
- Expressing the nuclear model to be succesfully incorporated in neutrino event generators.







No clear ID of all FS particles

$\Rightarrow$ Relevance of 2p2h, FSI effects, rescattering processes and π-production background.

Event topology:
CCQE
CCQE-like = CCQE+CC2p2h
CC0π = CCQE-like with π absorption background
CC1π
CCDIS
...

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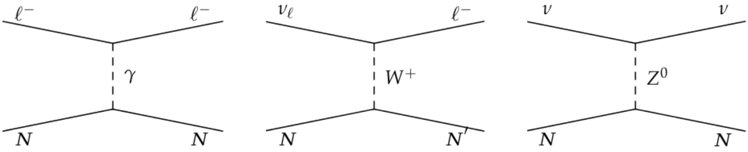
Connection between ν-A and e-A reactions



(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 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

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

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

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

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 J. A. Caballero's talk)

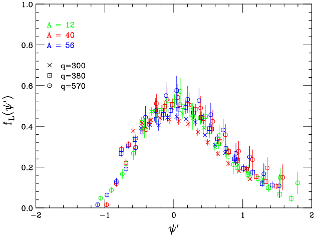
➠ The analysis of the large amount of existing (e, e') data at different kinematics is a solid benchmark to test the validity of theoretical models for neutrino reactions as well as to study the nuclear dynamics. The **SuperScaling Approach** exploits universal features of lepton-nucleus scattering to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

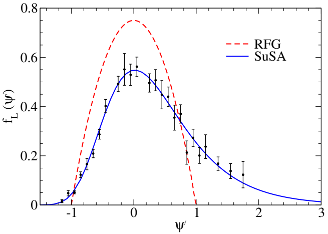
$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \; ; \quad f_L = k_F R_L/G_L \; ; \; f_T = k_F R_T/G_T$$

In inclusive QE scattering we can observe:

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

$\Longrightarrow$ **SuperScaling**



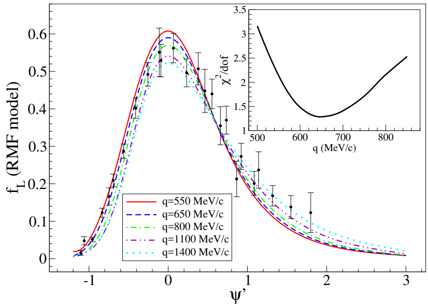


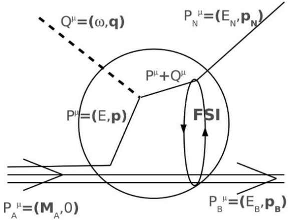
The scaling function $f(\psi)$ contains nuclear dynamics information and is related to the momentum distribution of the nucleons in the nucleus.

Theoretical description: RMF and SuSAv2 models

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

- **SuSAv2 model:** lepton-nucleus reactions adressed within the SuperScaling Approach and the sophisticated Relativistic Mean Field (RMF) theory (FSI) to determine theoretical scaling functions that reproduce nuclear dynamics. Complete set of scaling functions for all lepton-nucleus reaction channels (EM, weak, L/T, isovector/isoscalar, V/A).
- RMF: Good description of the QE (e, e') data and superscaling properties $(f^{ee'}_{L,exp})$

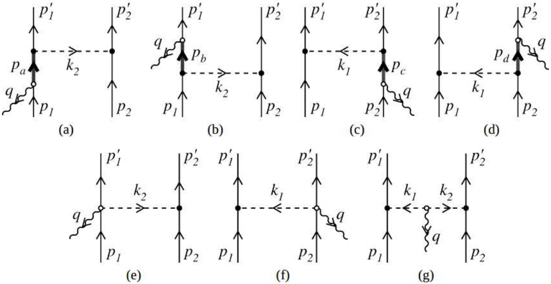




RMF-FSI: Scattered nucleon w.f. is solution of Dirac eq. in presence of the same potentials used to describe the bound nucleon w.f.

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

Over 100,000 terms are involved in the calculation, with seven-dimensional integrations



✪ The 2p-2h model is based on the calculation performed by De Pace et al., (2003) for (e, e') scattering and extended to the weak sector by Amaro, Ruiz Simo et al. [PRD 90, 033012 (2014); PRD 90, 053010 (2014); JPG 44, 065105 (2017); PLB 762, 124 (2016)].

✪ The numerical evaluation of the hadronic tensor $W^{\mu\nu}_{2p2h}$ is performed in the RFG model in a fully relativistic way without any approximation.

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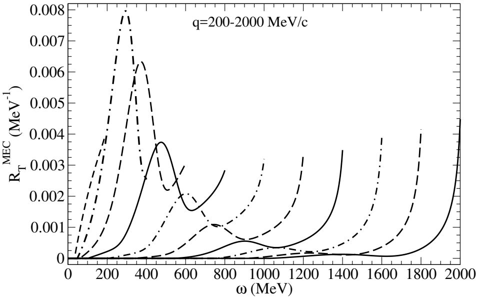

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✪ It is computationally non-trivial and involves 7D integrals of thousands of terms (+1 for ν-flux) $\Rightarrow$ High increase of the computing time of R_K^{2p2h} $\Rightarrow$ **Parametrization**

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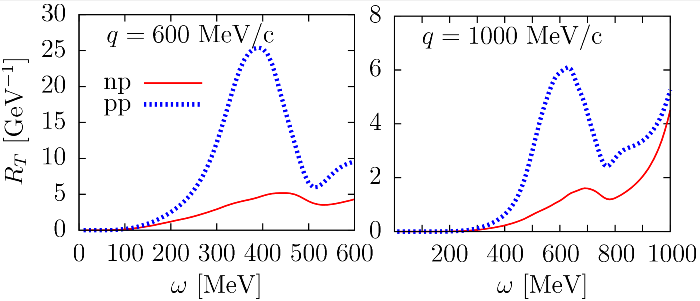

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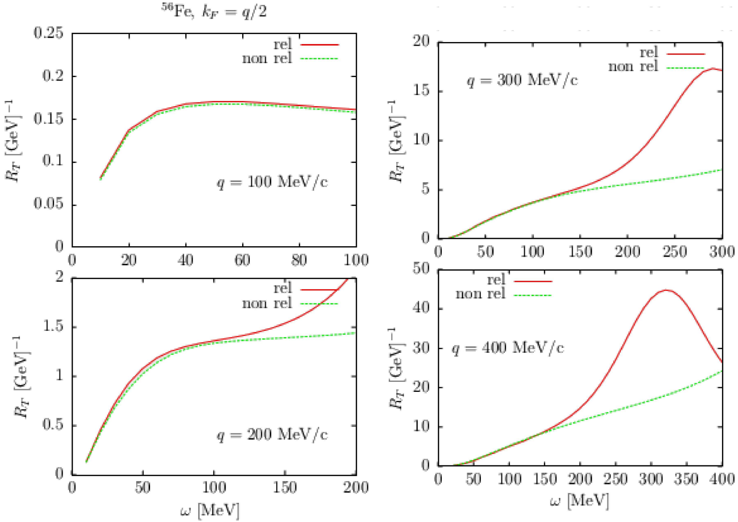
- It is computationally non-trivial and involves 7D integrals of thousands of terms (+1 for ν-flux) $\Rightarrow$ High increase of the computing time of R_K^{2p2h} $\Rightarrow$ **Parametrization**
- Separation into *pp*, *nn* and *np* pairs in the FS $\Rightarrow$ also valid for $N \neq Z$ (^{40}Ar, ^{56}Fe, ^{208}Pb)

Relativity is essential in 2p2h models

JPG 44, 065105 (2017)



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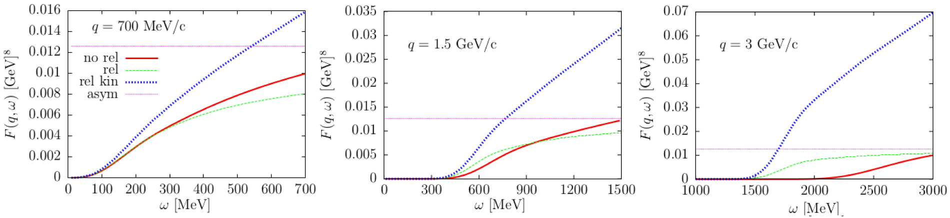


✪ Effect of implementing relativistic kinematics in a non-relativistic calculation of the phase-space function $F(q,\omega)$ can be delicate and misleading. Differences at high kinematics can be even larger than the ones related to a non-relativistic approach.

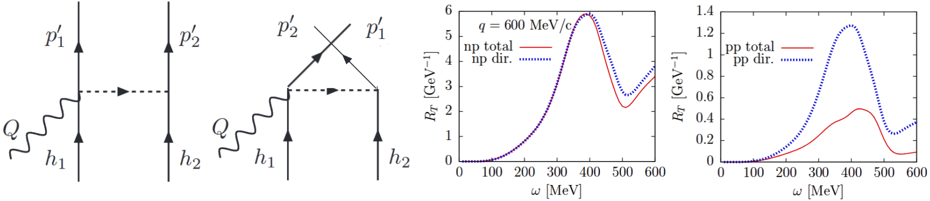
✪ All 2p-2h nuclear models should "agree" at the level of $F(q,\omega)$. Good starting point for model comparison.

2p-2h MEC hadronic tensor ($W^{\mu\nu}_{2p-2h}$) and elementary hadronic tensor ($r^{\mu\nu}_{2p-2h}$) in the RFG model

$$W^{\mu\nu}_{2p-2h} = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3h_1 d^3h_2 \frac{M^4}{E_1E_2E'_1E'_2}\Theta(p'_1,p'_2,h_1,h_2)r^{\mu\nu}(\mathbf{p}'_1,\mathbf{p}'_2,\mathbf{h}_1,\mathbf{h}_2)\delta(E'_1+E'_2-E_1-E_2-\omega)$$

$$F(q,\omega) = \int d^3p'_1 d^3h_1 d^3h_2 \frac{M^4}{E_1E_2E'_1E'_2}\Theta(p'_1,p'_2,h_1,h_2)\delta(E'_1+E'_2-E_1-E_2-\omega)$$

Relevance of direct/exchange interference in np/pp ratio



- Effect of implementing relativistic kinematics in a non-relativistic calculation of the phase-space function $F(q, \omega)$ can be delicate and misleading. Differences at high kinematics can be even larger than the ones related to a non-relativistic approach.
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Other Fermi Gas based 2p2h models

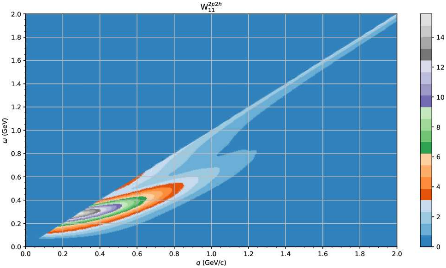
Martini model: Based on a non-relativistic treatment of MEC and correlations with relativistic corrections added and axial 2p2h estimated from vector one.

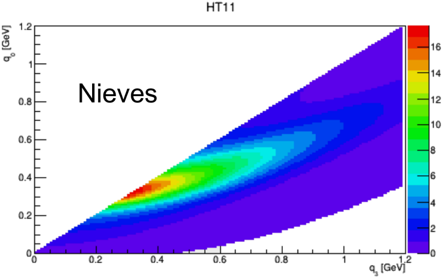
Nieves model: Relativistic with some approximations to compute the momentum-space integrals.

Both models neglect direct/exchange interference terms $\Rightarrow$ **strongly affects np/pp ratio by a factor** ~ 2 (see PRC94, 054610 (2016)).

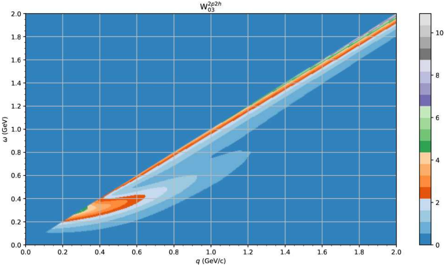
Comparison with other models implemented in GENIE

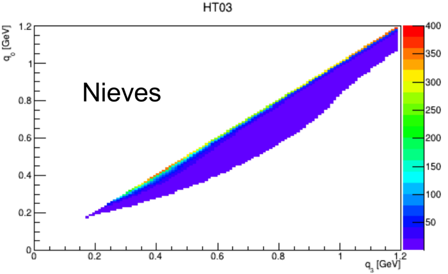
$W_{11}^{2p2h}(q,\omega) \sim R_T$



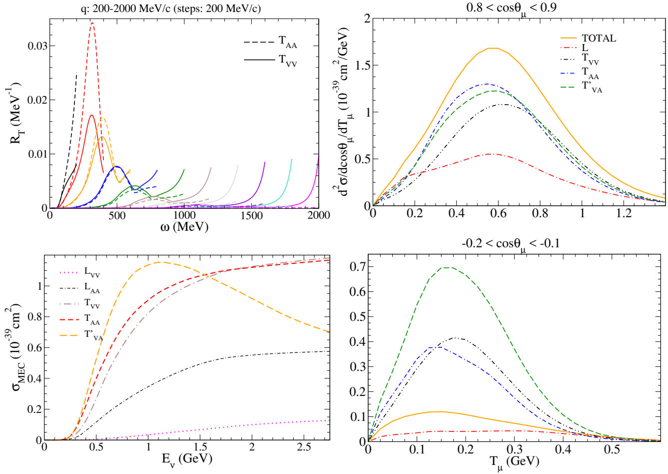


$W_{03}^{2p2h}(q,\omega) \sim R_{CL}$





2p2h for (e, e') processes $\not\Rightarrow$ 2p2h in CC (ν, l) reactions



$R_T^{AA} > R_T^{VV}$ at $q < 800$ MeV/c
$R_T^{AA} < R_T^{VV}$ at $q > 800$ MeV/c
$\Rightarrow \sigma(T_{AA}) \sim \sigma(T_{VV})$ but not for all lepton kinematics (see MiniBooNE $\bar{\nu}_\mu$ $d^2\sigma$, right panels).

$R_T^{VV}(e, e') \rightarrow R_T^{VV}(\nu, l)$
$R_T^{VV}(e, e') \nrightarrow R_T^{AA}, R_{T'}^{VA}(\nu, l)$

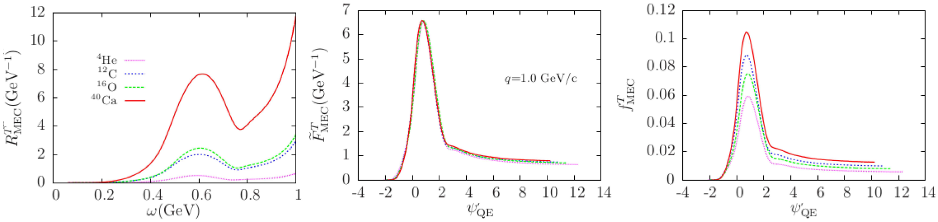
$R_L^{VV}(e, e')$ negligible but not $R_L(\nu, l)$ because of $R_L^{AA}(\nu, l)$. Highly relevant for antineutrino reactions ($\sigma_{T'}^{VA} < 0$).

Density dependence of 2p-2h MEC [PRC95, 065502 (2017)]

☆ Most existing calculations of 2p-2h MEC refer to ^{12}C, but other nuclei are interesing for oscillation experiments (^{16}O, ^{40}Ar) ⇒ Extension of the 2p-2h MEC analysis to other nuclei

☆ A-scaling (2^{nd} kind) on 2p-2h MEC responses? ⇒ A description of 2p-2h MEC responses in terms of k_F allow to extend easily 2p2h calculation to other nuclei reducing significantly the computational time.

$$\widetilde{F}_T^{MEC}(q,\omega) \equiv \frac{m_N^2}{k_F^2}\frac{R_T^{MEC}(q,\omega)}{G_T(\tau)} \quad ; \quad f_T^{MEC}(q,\omega) \equiv \frac{k_F}{m_N}\frac{R_T^{MEC}(q,\omega)}{G_T(\tau)}$$



⇒ **2p-2h responses scales as $A \cdot k_F^2$ whereas the QE one scales as A/k_F:**

$$R_T^{MEC} \sim k_F^2 \widetilde{F}_T^{MEC} G_T \qquad R_T^{QE} = \frac{1}{k_F} f_T^{QE} G_T$$

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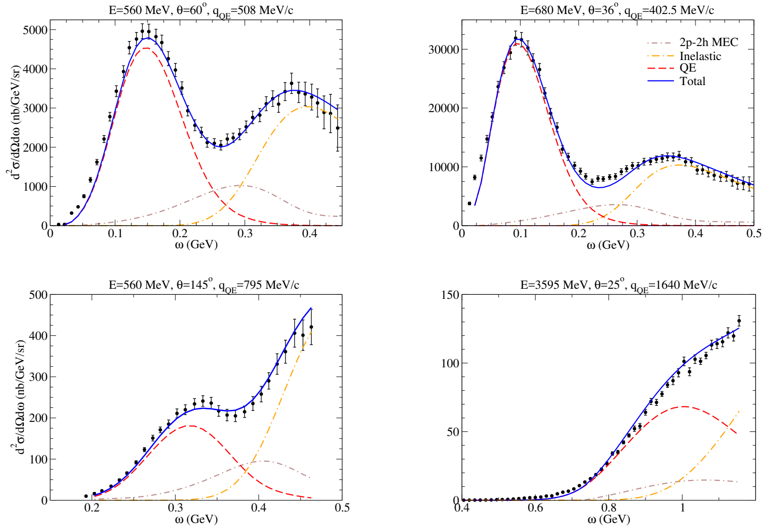
Inclusive $^{12}C(e, e')$ cross sections *PRD 94, 013012 (2016)*



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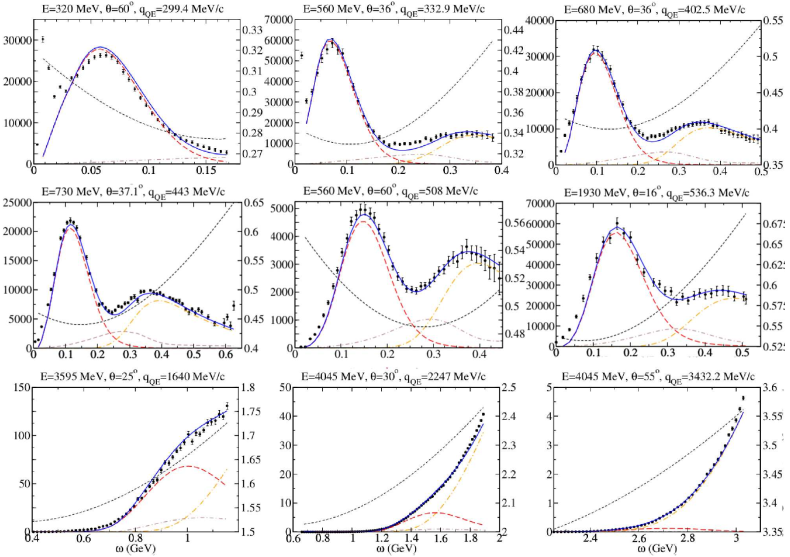
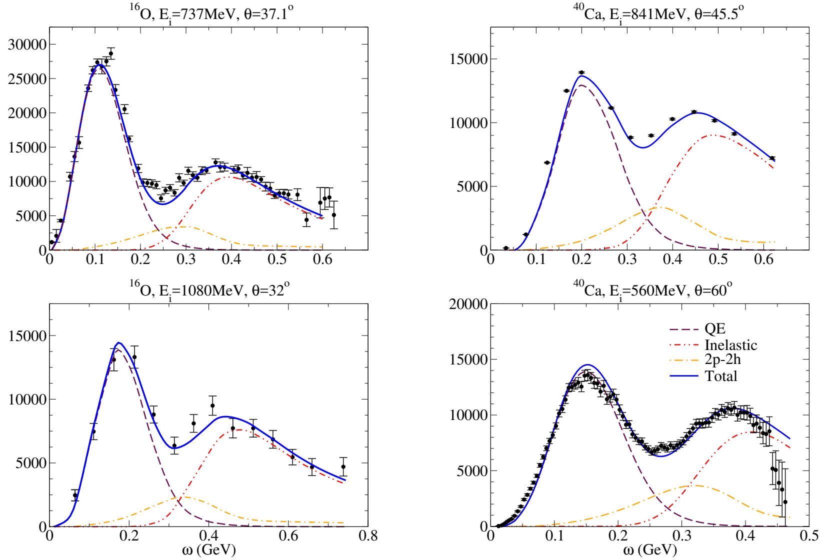


Inclusive $^{16}O(e, e')$ and $^{40}Ca(e, e')$ cross sections

arXiv:1711.00771 [nucl-th] (2018)



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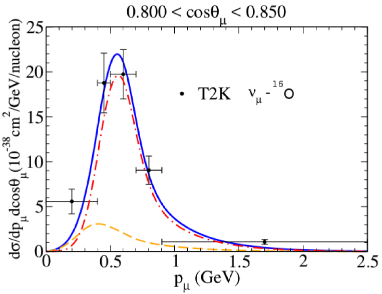
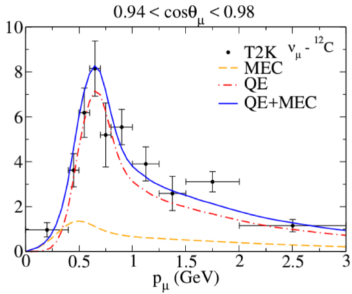
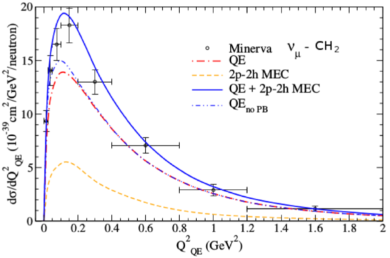
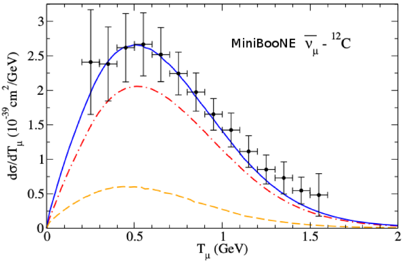






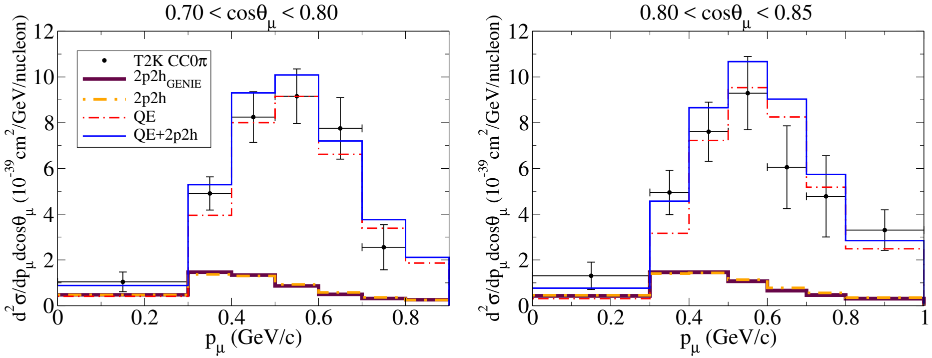


See PRD 94, 093004 (2016); arXiv:1711.00771 (2018) for more data comparison.

2p-2h implementation in MC event generators (PRELIMINARY)

Monte Carlo (MC) generators serve as a **bridge** between theoretical models and experimental measurements.

Sophisticated models in MC simulations ⇒ Accurate reconstruction of event topology (FS particles and kinematics ID) and inference of E_ν.



T2K CC0π data on ^{12}C

Characterization of nuclear effects at T2K ($E_\nu \sim 0.8$ GeV) 1802.05078 [hep-ex] (2018)

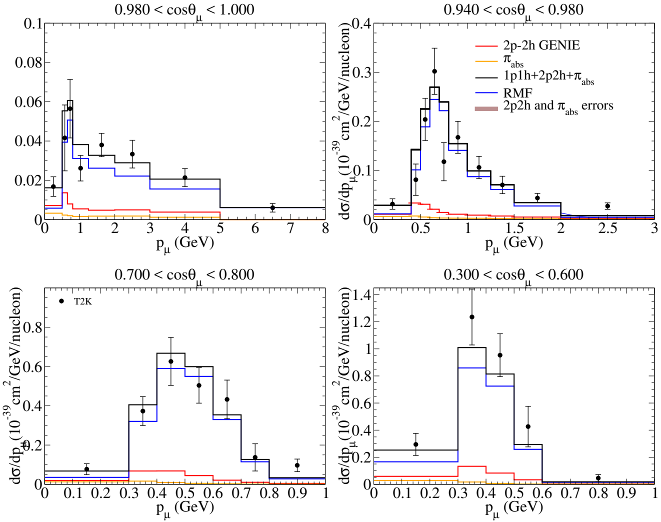
Neutrino oscillation measurements and E_ν^{rec} affected by large nuclear-medium uncertainties

⇒ Need for **robust model** prediction on the hadronic FS kinematics and nucleon multiplicity

⇒ **T2K CC0πNp data** ⇒ Exploration of p kinematics and of imbalances between p and μ kinematics ⇒ novel probe of nuclear-medium effects

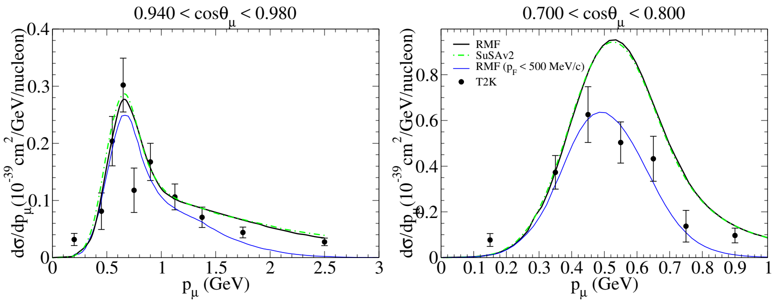
Analysis of **semi-inclusive reactions** (more sensitive to nuclear model details) should help to analyze physics of theoretical models.

Different models can give similar inclusive CS but different exclusive ones (see S. Dolan's talk).



"Semi-semi-inclusive" T2K CC0πNp data on ^{12}C with 0p above 500 MeV/c

Characterization of nuclear effects at T2K experiment 1802.05078 [hep-ex] (2018)



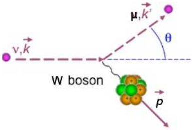
T2K CC0πNp data on ^{12}C with 0p above 500 MeV/c

➲ At this point, it is clear that we need to study correlations between p and μ in CC0πNp events $\Rightarrow$ Less dependent on simulations and enable deeper analysis of model nuclear effects.

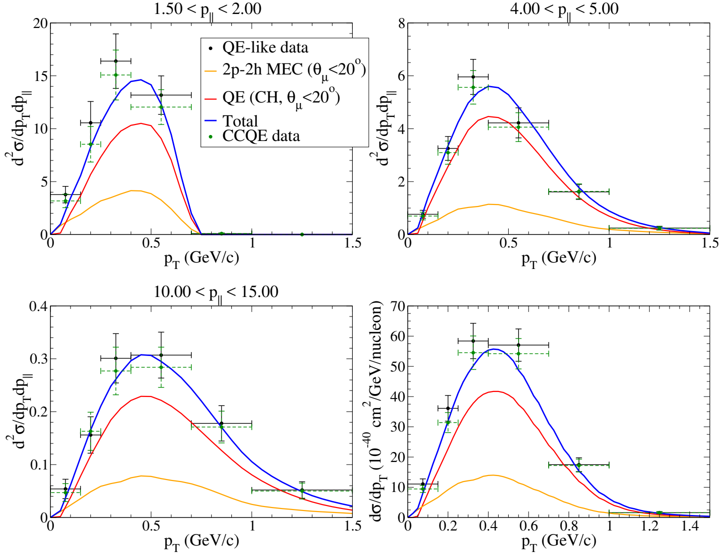
➲ Next step: Analysis of **transverse variables** (T2K, MINERνA) within the SuSAv2-MEC model.

➲ Transverse variables: more sensitive to different nuclear effects and useful to disentangle initial state (initial momentum distribution, in medium modifications) from final state (rescattering) effects (see S. Dolan's talk).

MINERνA $\bar{\nu}_\mu$-CH_2 reactions at $E_\nu \sim 3$ GeV



$p_{||} = p_\mu \cos\theta_\mu$
$p_T = p_\mu \sin\theta_\mu$



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➲ **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.

➲ Satisfactory comparison of the SuSAv2-MEC model with (e, e') and (ν, l) data for different nuclei (^{12}C, ^{16}O and ^{40}Ca) and also in preliminary analysis of hadron kinematics (RMF) in semi-inclusive reactions (more sensitive to nuclear model effects). Next step: Transverse variables

➲ The SuSAv2-MEC model can be easily described for different nuclei, translating sophisticated and computationally demanding microscopic calculations into a straightforward formalism, easing its implementation in MC event generators **(GENIE: 2p2h implemented, *1p1h in progress*)**.

➲ **Works in progress**: Inclusive neutrino scattering including all inelasticities (DIS).

➲ Extension to $Z \neq N$ nuclei (^{40}Ar, ^{56}Fe) $\Rightarrow$ RMF n and p scaling functions and separate 2p-2h pn, pp and nn channels. First steps: arXiv:1806.08594 (2018); PLB762, 124 (2016)

Conclusions and Further Work

➲ **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.

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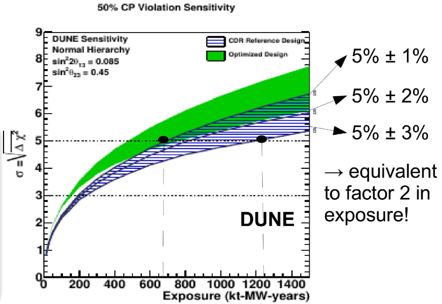
Systematic errors due to ν cross section and flux uncertainties are dominant ($\sim 3\%$) ...



➲ **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.

➲ Satisfactory comparison of the SuSAv2-MEC model with (e, e') and (ν, l) data for different nuclei (^{12}C, ^{16}O and ^{40}Ca) and also in preliminary analysis of hadron kinematics (RMF) in semi-inclusive reactions (more sensitive to nuclear model effects). Next step: Transverse variables

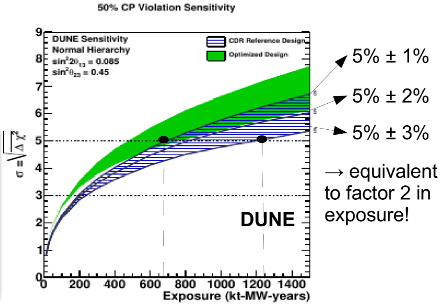
➲ The SuSAv2-MEC model can be easily described for different nuclei, translating sophisticated and computationally demanding microscopic calculations into a straightforward formalism, easing its implementation in MC event generators **(GENIE: 2p2h implemented, *1p1h in progress*)**.

➲ **Works in progress**: Inclusive neutrino scattering including all inelasticities (DIS).

➲ Extension to $Z \neq N$ nuclei (^{40}Ar, ^{56}Fe) $\Rightarrow$ RMF n and p scaling functions and separate 2p-2h pn, pp and nn channels. First steps: arXiv:1806.08594 (2018); PLB762, 124 (2016)

Systematic errors due to ν cross section and flux uncertainties are dominant ($\sim 3\%$) ...

It is faster and cheaper to pay a theoretician to reduce 2 % your systematics than building huge detectors!



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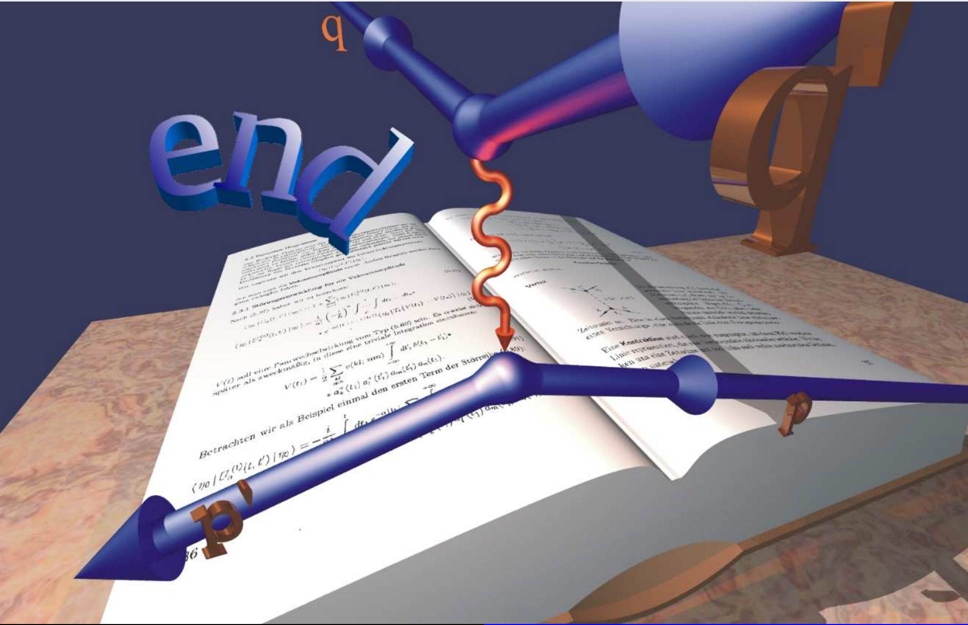
Thanks for your attention!

Conclusions and Further Work



BACKUP SLIDES

SuSAv2 model: Scaling phenomenon and RMF theory

SuSAv2: Neutrino-nucleus reactions adressed within the SuperScaling Approach and the RMF theory in order to reproduce nuclear dynamics.

SuperScaling Approach (SuSA) [Amaro et al., PRC71 (2005)]

➠ Many high-quality $e - A$ data exist, which must be used to test models as well as an input for predicting $\nu - A$ observables. The **SuperScaling Approach** exploits universal features of lepton-nucleus scattering to connect the two processes.

➠ In most IA models (RFG, RMF, RPWIA) the inclusive lepton-nucleus cross section factorizes into a single-nucleon cross section times a specific function of (q, ω) which embodies the nuclear dynamics.

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \quad ; \quad \psi\text{-scaling variable}$$

➠ In some situations this function **scales** $f(\omega, q)$, becoming dependent on a single **scaling variable** $\psi = \psi(\omega, q) \Rightarrow f(\psi)$. (ex: Bjorken scaling)

➠ This scaling function $f(\psi)$ can be related to the momentum distribution of the nucleons in the nucleus under some approaches.

In inclusive QE scattering we can observe two kinds of scaling [Donnelly and Sick, PRL82 & PRC60 (1999)]:

☆ Scaling of 1^{st} kind (independence on q)
☆ Scaling of 2^{nd} kind (independence on Z)

$\Longrightarrow$ **SuperScaling**

SuperScaling Approach (SuSA)

➠ The analysis of the large amount of existing (e, e') data at different kinematics is taken as a solid benchmark to test the validity of theoretical model for neutrino reactions as well as to study the nuclear dynamics and scaling properties.

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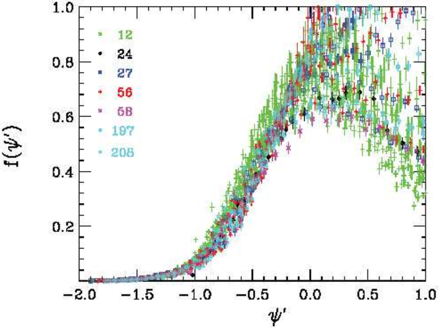
$\Longrightarrow$ **SuperScaling**



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

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

SuperScaling Approach (SuSA)

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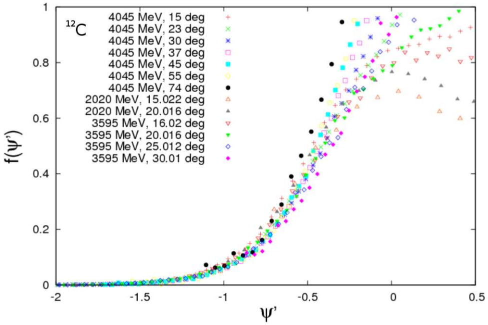

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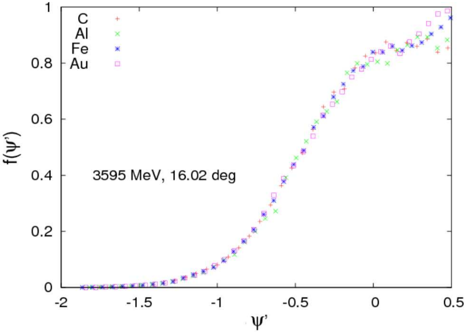

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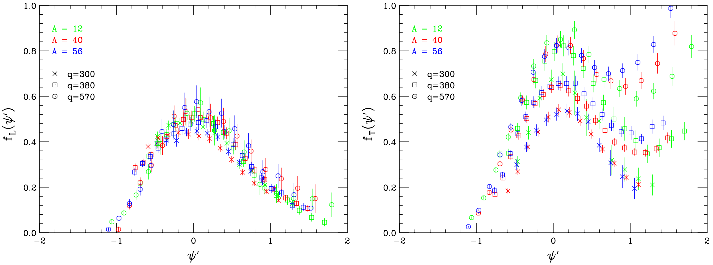
Separate L/T scaling functions



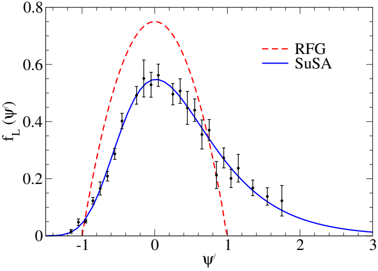
$$f_L = k_F R_L / G_L$$
$$f_T = k_F R_T / G_T$$

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)

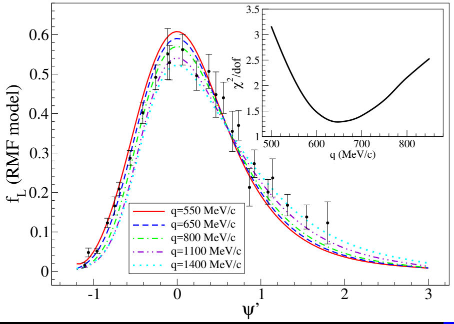
- It is experimentally observed $f^{ee'}_{T,\text{exp}} > f^{ee'}_{L,\text{exp}}$ (15-20%)



Theoretical description: RMF and SuSAv2 models

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

- In the SuSAv2, the scaling functions are calculated within the Relativistic Mean Field model (FSI), which predicts, for instance, different scaling functions in the L and T channels and for the different isospin channels (CCν reactions are purely isovector).
- RMF: Good description of the QE (e,e') data and superscaling properties ($f_{L,exp}^{ee'}$)
- RMF predicts $f_T > f_L$ ($\sim$ 20%) as a pure relativistic effect (distortion of the lower components of the outgoing Ψ_N by the FSI with the residual nucleus)



$$R_{L,T}^{ee'} = \frac{1}{k_F}\left[f_{L,T}^{T=1,ee'}(\psi')G_{L,T}^{T=1} + f_{L,T}^{T=0,ee'}(\psi')G_{L,T}^{T=0}\right]$$

$$R_L^{VV,\nu(\overline{\nu})} = \frac{1}{k_F} f_L^{VV,\nu(\overline{\nu})}(\psi')G_L^{VV}$$

$$R_{CC,CL,LL}^{AA,\nu(\overline{\nu})} = \frac{1}{k_F} f_{CC,CL,LL}^{AA,\nu(\overline{\nu})}(\psi')G_{CC,CL,LL}^{AA}$$

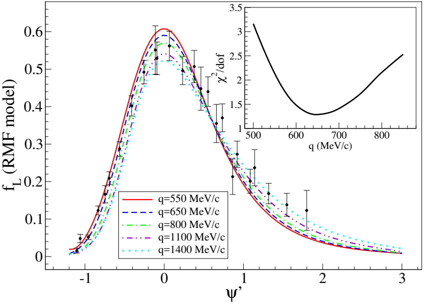
$$R_T^{VV(AA),\nu(\overline{\nu})} = \frac{1}{k_F} f_T^{VV(AA),\nu(\overline{\nu})}(\psi')G_T^{VV(AA)}$$

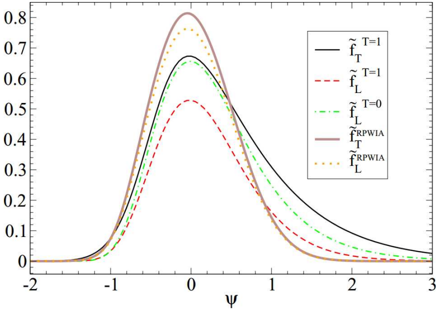
$$R_{T'}^{\nu(\overline{\nu})} = \frac{1}{k_F} f_{T'}^{VA,\nu(\overline{\nu})}(\psi')G_{T'}^{VA}.$$

Theoretical description: RMF and SuSAv2 models

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

- **SuSAv2 model:** lepton-nucleus reactions adressed within the SuperScaling Approach and the sophisticated Relativistic Mean Field (RMF) theory (FSI) to determine theoretical scaling functions that reproduce nuclear dynamics. Complete set of scaling functions for all lepton-nucleus reaction channels (EM, weak, L/T, isovector/isoscalar, V/A).
- RMF: Good description of the QE (e, e') data and superscaling properties $(f^{ee'}_{L,exp})$

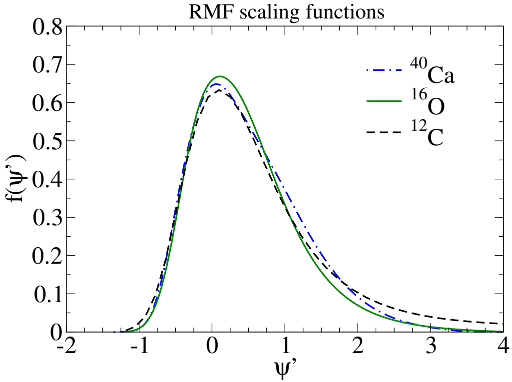




Extension of the SuSAv2-MEC model to other nuclei

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.



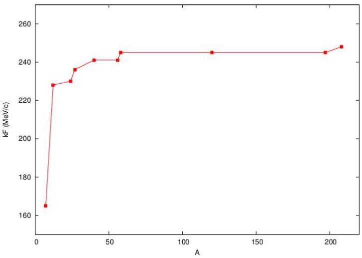
Density dependence of the 2p-2h MEC responses

☆ Most existing calculations of 2p-2h MEC refer to ^{12}C, but other nuclei are interesing for oscillation experiments (^{16}O, ^{40}Ar) ⇒ Extension of the 2p-2h MEC analysis to other nuclei
☆ In the RFG and in the SuSAv2-MEC model, each nucleus is characterized by two parameters: k_F and E_{shift}, fitted to reproduce the width and position of the QEP in inclusive electron scattering.

TABLE I. 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

Maieron, Donnelly, Sick, PRC65 (2002)



$k_F(A)$

☆ A-scaling (2nd kind) on 2p-2h MEC responses? ⇒ A description of 2p-2h MEC responses in terms of k_F allow to extend easily our calculation to other nuclei reducing significantly the computational time.

Density dependence of 2p-2h MEC [PRC95, 065502 (2017)]

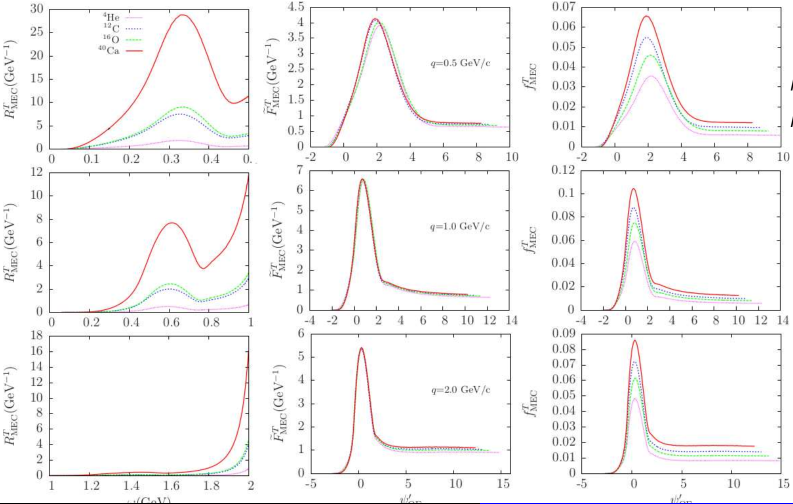
$$\widetilde{F}_T^{MEC}(q,\omega) \equiv \frac{m_N^2}{k_F^2}\frac{R_T^{MEC}(q,\omega)}{G_T(\tau)} \quad ; \quad f_T^{MEC}(q,\omega) \equiv \frac{k_F}{m_N}\frac{R_T^{MEC}(q,\omega)}{G_T(\tau)}$$

⇒ 2p-2h responses scales as $A \cdot k_F^2$ whereas the QE one scales as A/k_F

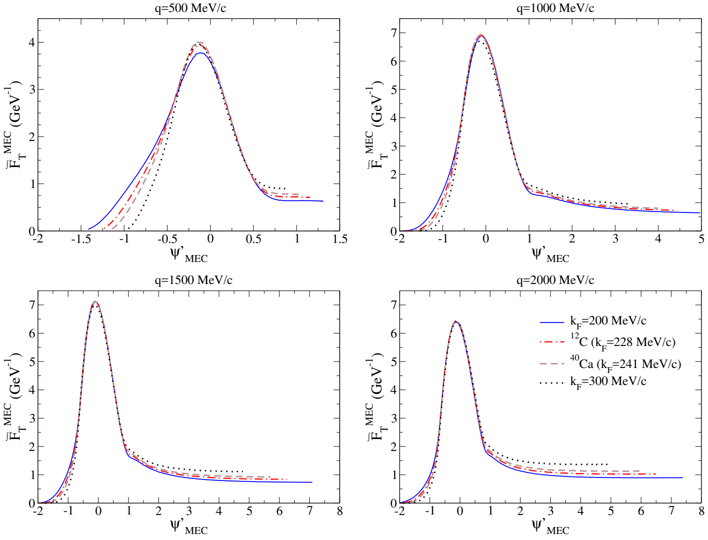
⇕

$$R_T^{MEC} \sim k_F^2 \widetilde{F}_T^{MEC} G_T$$

$$R_T^{QE} = \frac{1}{k_F} f_T^{QE} G_T$$



Density dependence of 2p-2h MEC [PRC95, 065502 (2017)]

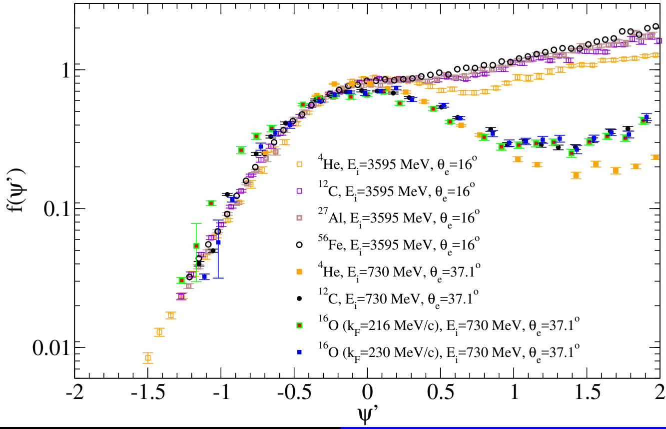


$\psi'_{MEC}(q, \omega, k_F)$

Extension of the SuSAv2-MEC model to other nuclei

Determination of k_F and E_{shift} for ^{16}O

➥ Analysis of experimental scaling (e, e') data.



Energy shift and Fermi momentum in RFG and SuSAv2 models

- E_{shift}: small energy shift included to have the QE peak at $\psi' = 0$ ($\omega = |Q^2|/2m_N$). It is a phenomenological way to introduce in ψ the separation energy, $E_s \sim$(binding energy), the difference between the sum of the nucleon plus ground-state daughter masses and the target ground state-mass. This E_s actually implies a small shift.

- k_F and E_{shift} for RFG and SuSA models are obtained from global fits to (e, e') data for different nuclei. In the SuSAv2 model, we introduce a soft q-dependence in E_{shift} due to the strong potentials at higher kinematics coming from RMF theory.

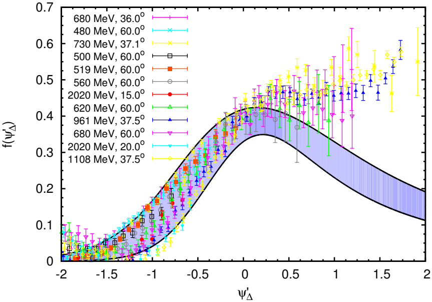
Inelastic regime within the SuSAv2 Approach

The SuSA approach can be extended to the inelastic spectrum in two ways:

➲ Extending the SuSAv2 formalism to the complete inelastic spectrum (from the Δ resonance to DIS) by using PDFs or phenomenological fits of the single-nucleon inelastic structure functions and assuming that scaling functions are equivalent in all energy regions: $(f^{L,T}_{SuSAv2,QE}(\psi') \rightarrow f^{L,T}_{SuSAv2,inel}(\psi'_X))$: PRD 94, 013012 (2016), PRC 69, 035502 (2004).

➲ Constructing a phenomenological scaling function for the Δ-resonance region by subtracting from the inclusive (e, e') data the QE and MEC contribution and dividing the results by the appropriate $N \rightarrow \Delta$ elementary function : PLB711, 178 (2012), J.Phys.G 43, 045101 (2016).

$$f^{\mathrm{non-QE}}(\psi_\Delta) = k_F \frac{\left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{non-QE}}}{\sigma_M(v_L G_L^\Delta + v_T G_T^\Delta)}$$



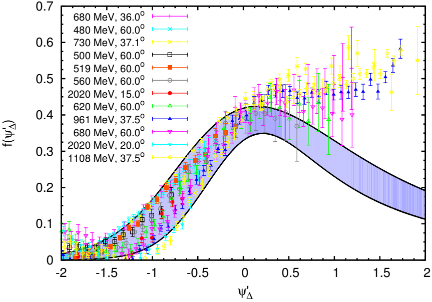
Inclusive total cross section ⇒ Δ-scaling model

Extension of the SuSA approach into the non-QE region, obtained by substracting the QE + 2p-2h MEC contributions from the total cross section ⇒ assuming that it is dominated by the Δ-resonance.

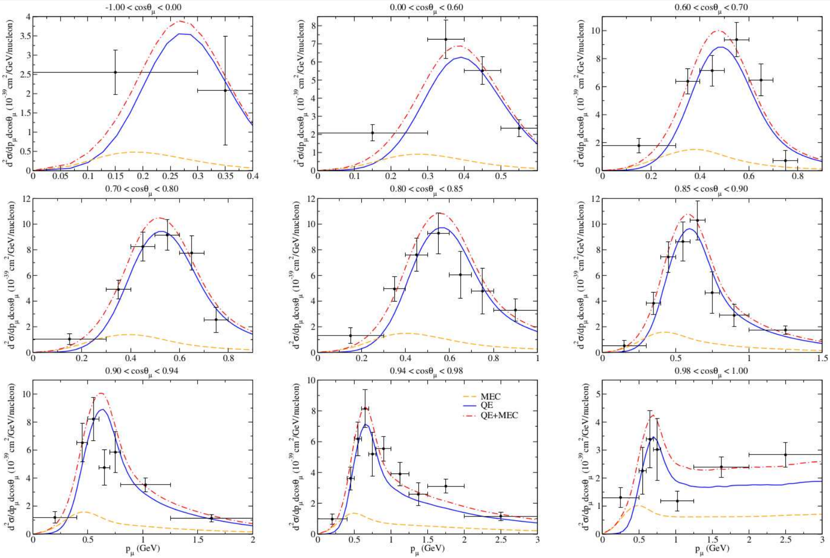
$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{non-QE}} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{exp}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{QE,SuSAv2}}_{\mathrm{1p1h}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{MEC}}_{\mathrm{2p2h}}$$

$$f^{\mathrm{non-QE}}(\psi_\Delta) = k_F \frac{\left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{non-QE}}}{\sigma_M(v_L G_L^\Delta + v_T G_T^\Delta)}$$

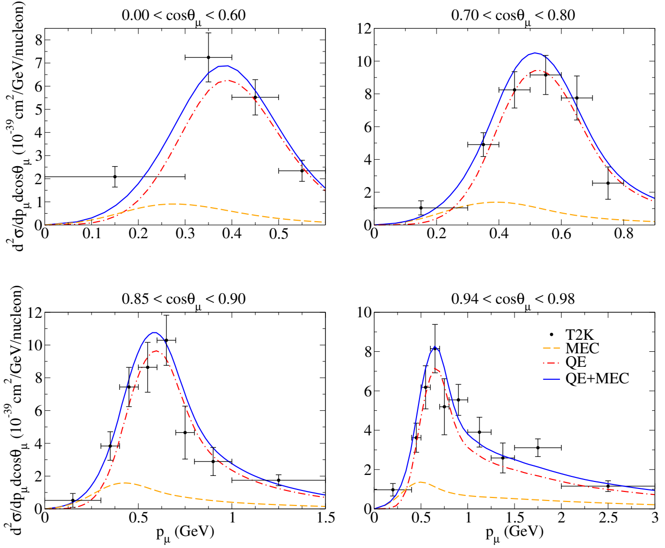
Scaling works well up to the center of the Δ peak, $\psi_\Delta = 0$, while it breaks at higher energies where other inelastic processes appear ⇒ Error band



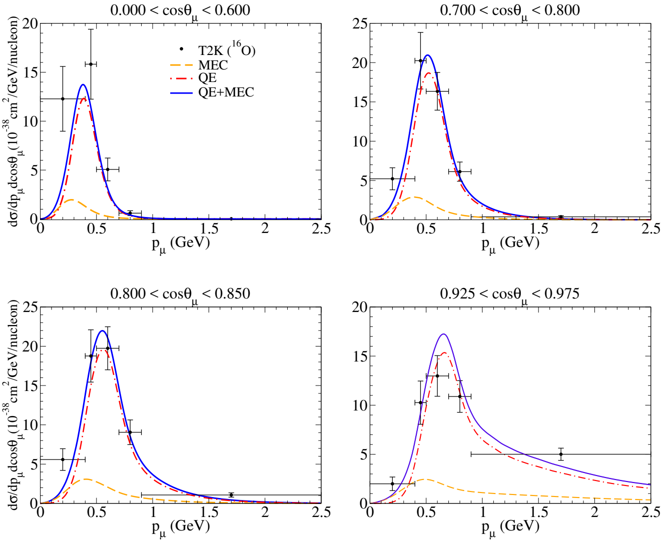
T2K $\nu_\mu - {}^{12}C$ cross sections



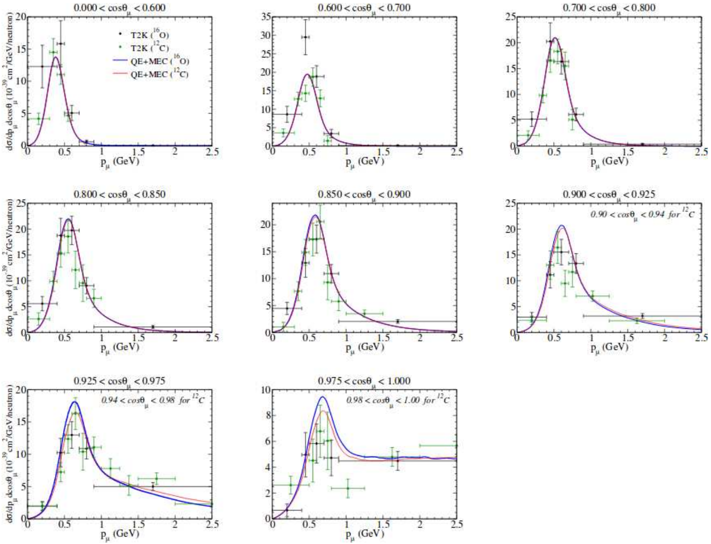
T2K $\nu_\mu - C_8H_8$ cross sections PRD 94, 093004 (2016)



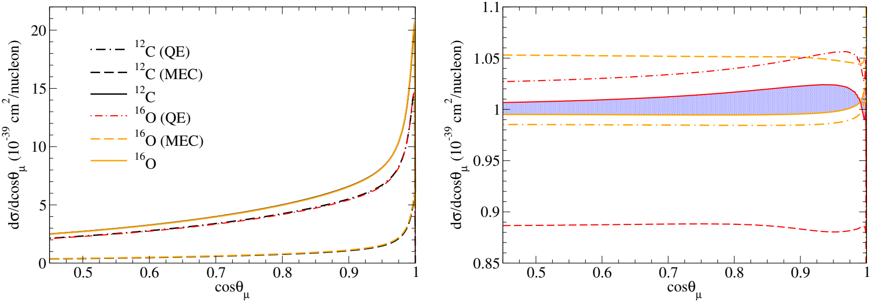
T2K $\nu_\mu - H_2O$ cross sections arXiv:1711.00771 [nucl-th] (2017)



T2K $\nu_\mu - C_8H_8$ versus $\nu_\mu - H_2O$ cross sections



T2K $\nu_\mu - C_8H_8$ versus $\nu_\mu - H_2O$ cross sections



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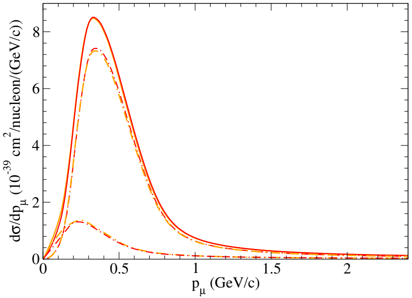

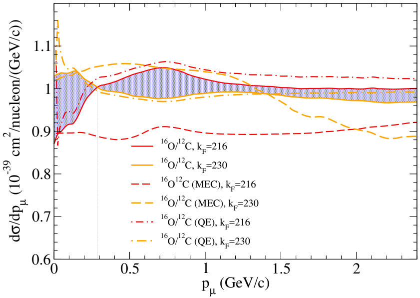

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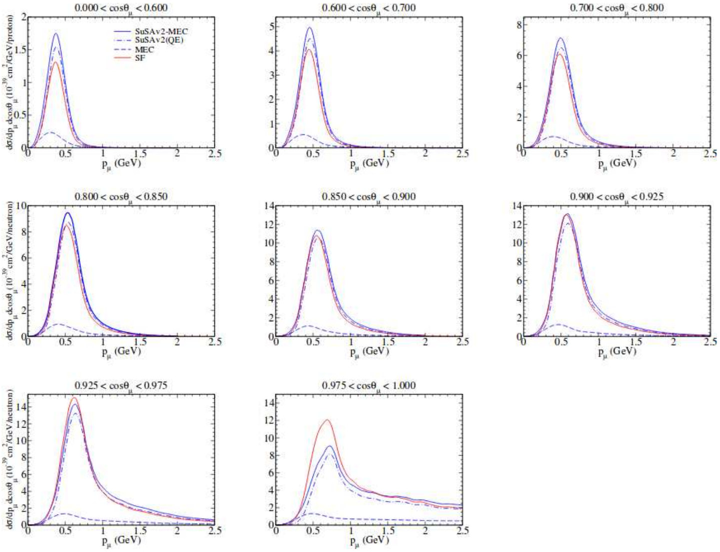
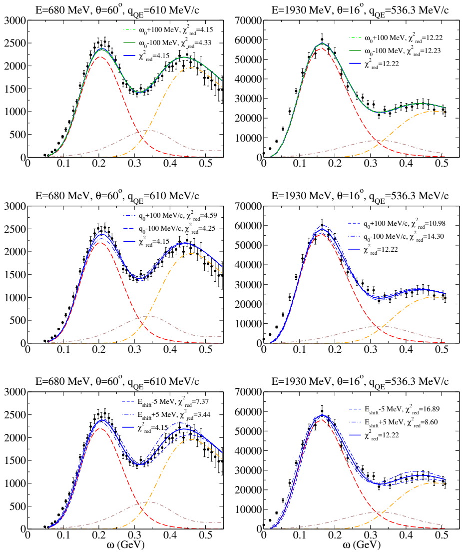
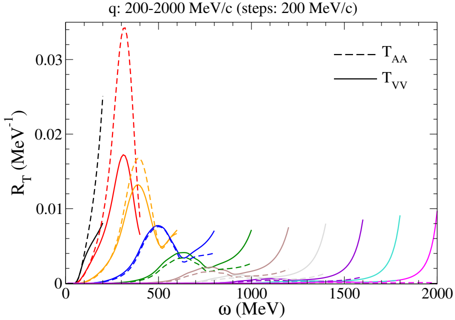
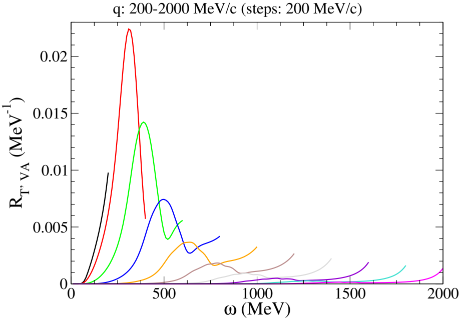


Sensitivity of the SuSAv2-MEC model



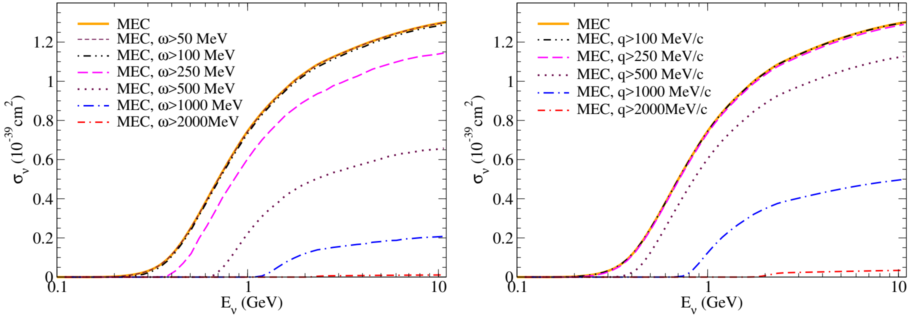
Analysis of 2p-2h MEC vector and axial responses





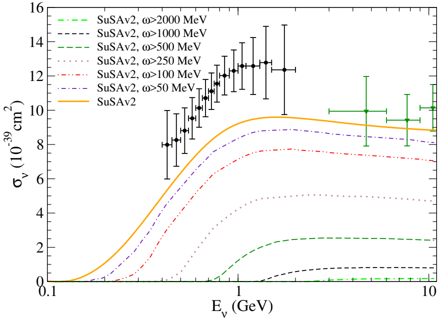
- T'_{VA} of the same order as T_{VV} and T_{AA}
- Although $T_{AA} > T_{VV}$ at $q < 600$ MeV/c $\Rightarrow \sigma(T_{AA}) \sim \sigma(T_{VV})$

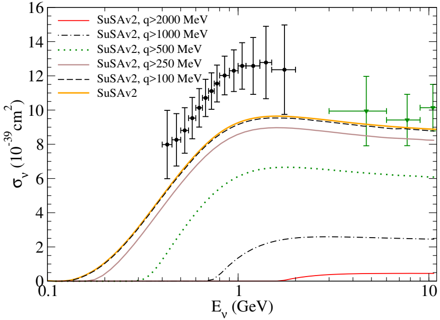
Relevant kinematic regions in the QE cross section



The main contribution to the total QE CS comes from $q < 1$ GeV/c and $\omega < 0.5$ GeV, even at high neutrino energies.

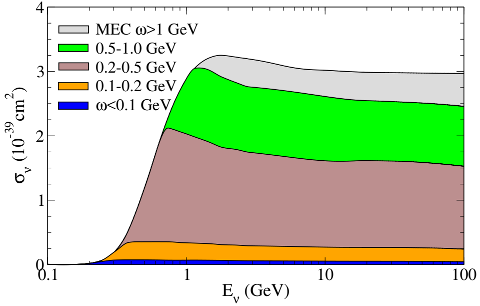
Relevant kinematic regions in the QE cross section

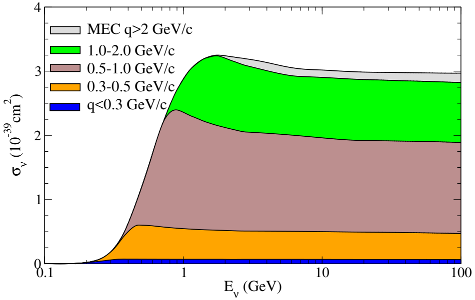




The main contribution to the total QE CS comes from $q < 1$ GeV/c and $\omega < 0.5$ GeV, even at high neutrino energies.

Relevant kinematic regions in the 2p-2h MEC cross section



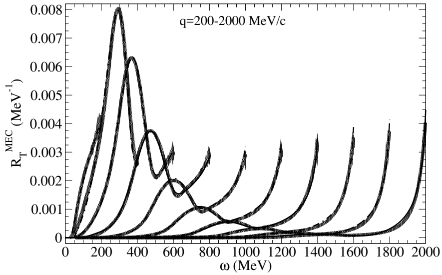


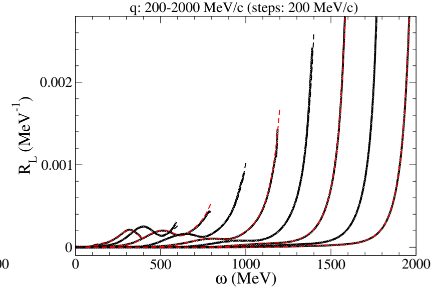
Although very similar to the QE case, the relevance of 2p-2h MEC contributions extends slightly to higher kinematics.

2p-2h MEC parametrization *PRD91, 073004 (2015) PRD94, 093004 (2016)*

$$R_X^{2p-2hMEC}(\psi', q) = \frac{2a_{3,X} e^{-\frac{(\psi' - a_{4,X})^2}{a_{5,X}}}}{1 + e^{-\frac{(\psi' - a_{1,X})^2}{a_{2,X}}}} + \sum_{k=0}^{2} b_{k,X} \cdot (\psi')^k$$

$X = CC, CL, LL, T(= T_{VV} + T_{AA}), T'_{VA}$ $\qquad a_{i,X}(q), b_{k,X}(q)$

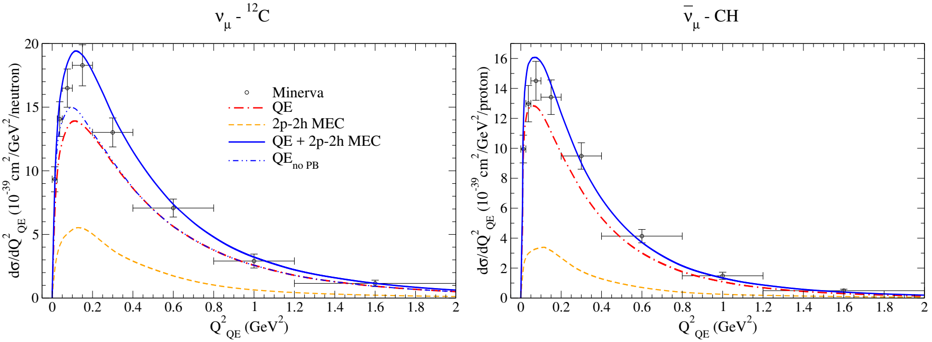




MINERνA $\nu_\mu(\bar{\nu}_\mu)$−CH cross sections PRD 94, 093004 (2016)

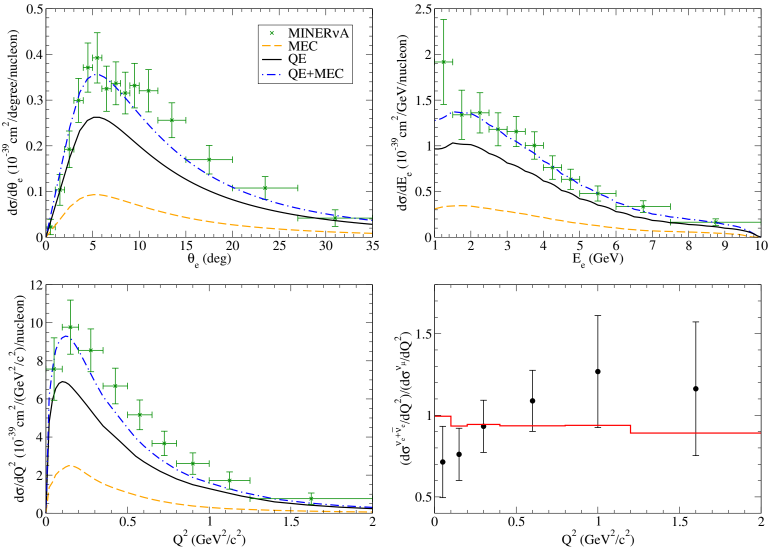
T2K, MiniBooNE: $< E_\nu >\sim 0.8$ GeV $\Longrightarrow$ MINERνA: $< E_\nu >\sim 3.0$ GeV

More prominent 2p-2h MEC effects

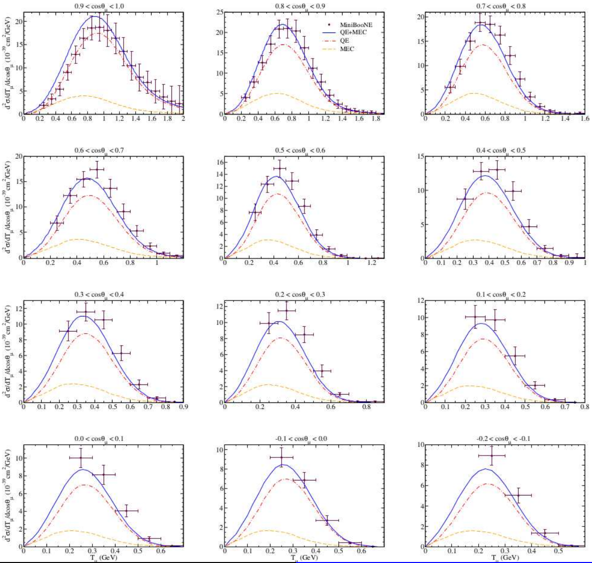


MINERνA ν_e—^{12}C cross sections

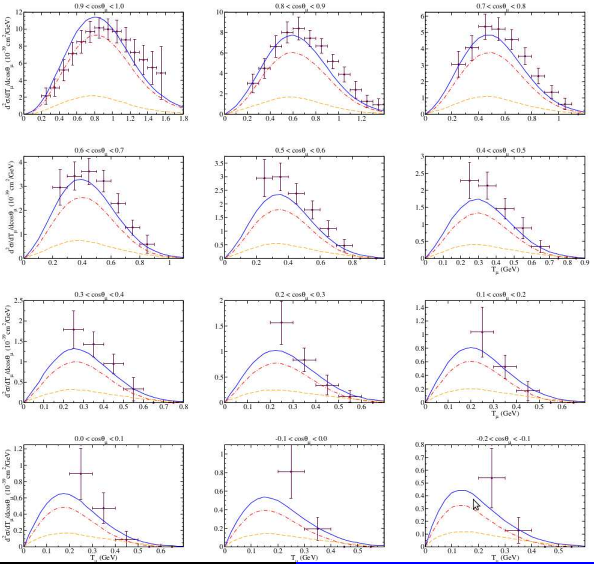
PRD 94, 093004 (2016)



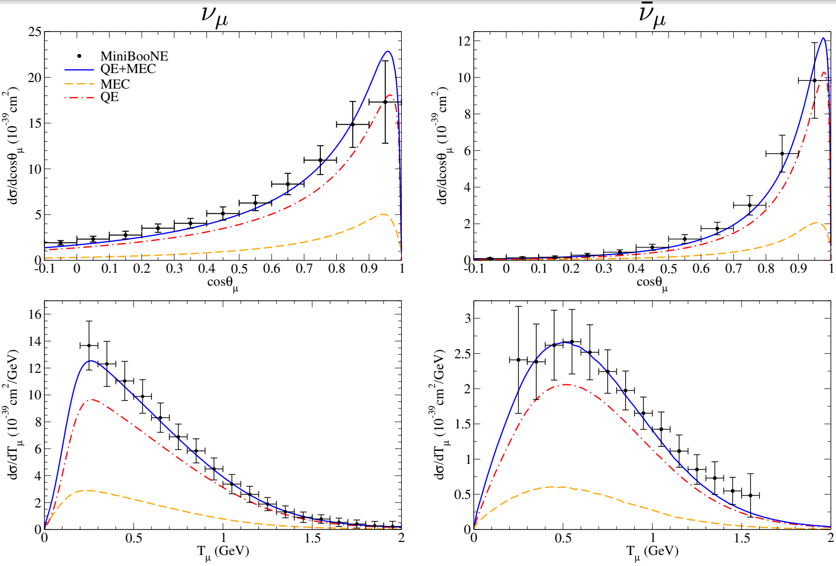
MiniBooNE $\nu_\mu-{}^{12}$C double differential cross sections



MiniBooNE $\bar{\nu}_\mu-{}^{12}$C double differential cross sections



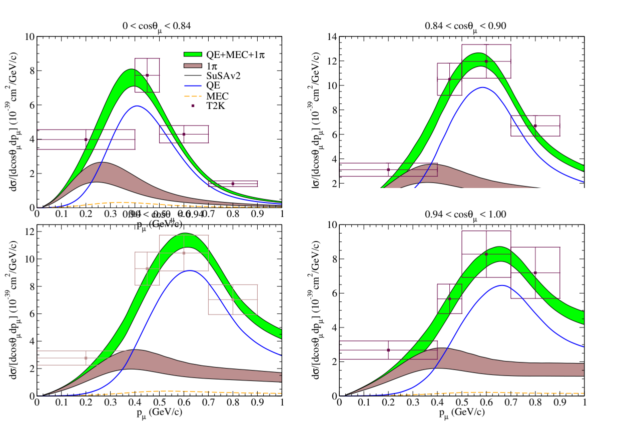
MiniBooNE $\nu_\mu - {}^{12}C$ single differential cross sections



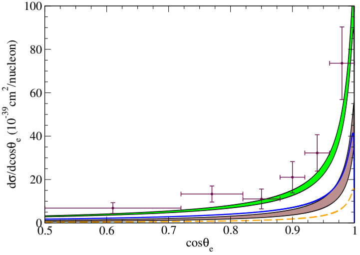
QE+MEC+Δ contributions in $\nu_\mu-{}^{12}$C scattering

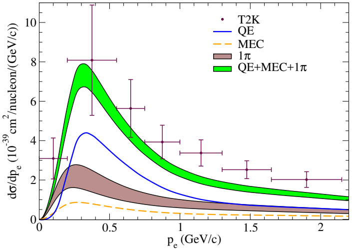
Analysis of T2K ν_μ data ($< E_{\nu_\mu} > \sim 0.8$ GeV)
J.Phys.G 43, 045101 (2016)

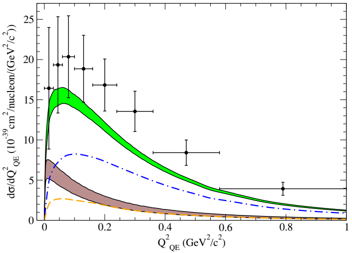
➥Deep Inelastic Scattering contributions are not relevant at T2K kinematics.
➥Work in p … data.



T2K $\nu_e - {}^{12}C$ cross sections





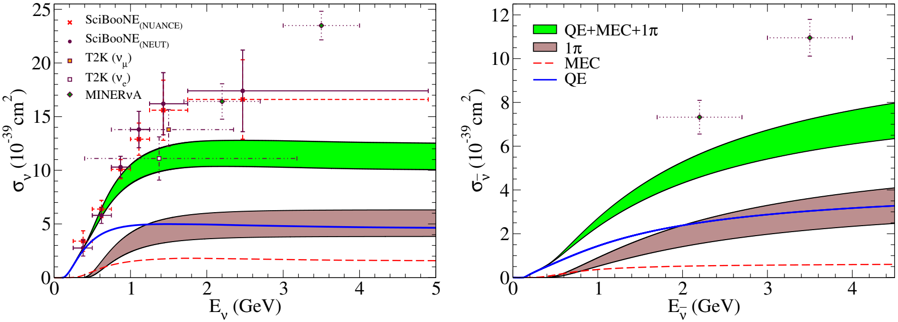


Analysis of T2K ν_e data ($< E_{\nu_e} > \sim 1.3$ GeV)
J.Phys.G 43, 045101 (2016)

➥Agreement with data is slightly worse as for $E_\nu \gtrsim 1$ GeV DIS starts to be relevant.

Inclusive total cross section ⇒ Δ-scaling model

Extension of the SuSA into the non-QE region assuming Δ-resonance dominance [*J.Phys.G 43, 045101 (2016)*]. Substraction of the QE + 2p-2h MEC contributions from the total CS.



QE+MEC+Δ contributions are not enough to describe inclusive cross section at $E_\nu \gtrsim 1$ GeV ⇒ Work in progress to include DIS in the ν interaction model.

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

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

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

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

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

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

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

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:

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

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

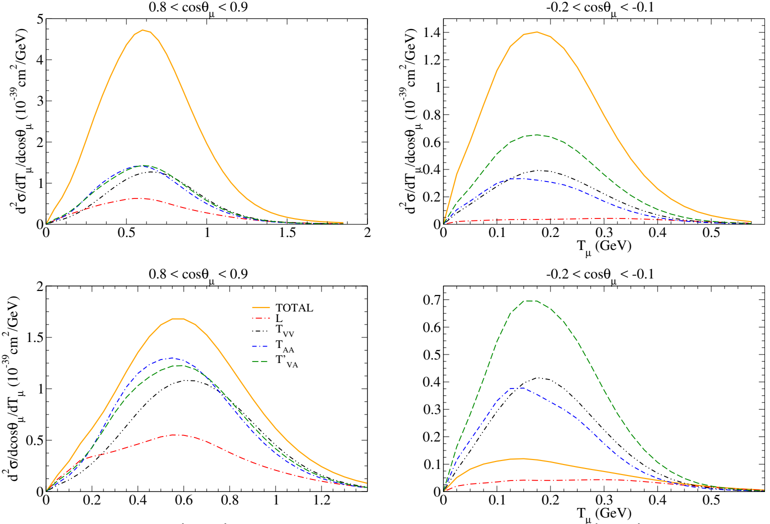
- Specific scaling functions for the individual channels:

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

2p-2h MEC channels at MiniBooNE kinematics

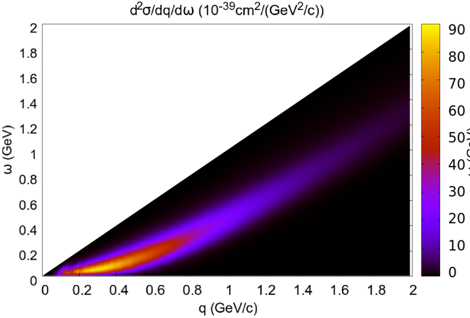
$\nu_\mu \Rightarrow$

$\bar{\nu}_\mu \Rightarrow$

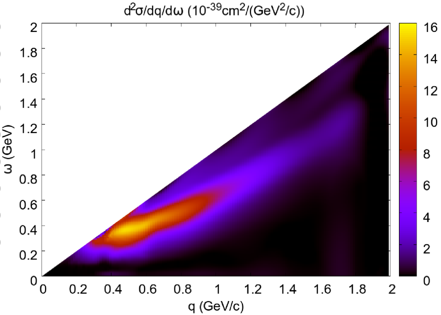


T_μ(GeV) T_μ(GeV)

Relevant kinematic regions at $E_\nu = 3$ GeV



QE



2p-2h MEC

Although very similar to the QE case, the relevance of 2p-2h MEC contributions extends slightly to higher kinematics.

Theoretical description: CCQE 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

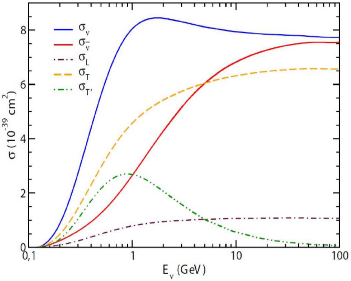
$$\mathcal{F}_\chi^2 = V_L R_L + V_T R_T + \chi\left[2V_{T'}R_{T'}\right]$$

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

$$L \to (\mu\nu) = (00, 03, 30, 33);$$

$$T \to (11, 22);\ T' \to (12, 21)$$

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



Nuclear responses

Composed of VV (vector-vector), AA (axial-axial) and VA (vector-axial) components arising from the V and A weak leptonic and hadronic currents: $j^\mu = j_V^\mu + j_A^\mu \quad ; \quad J^\mu = J_V^\mu + J_A^\mu$.

Theoretical description: CCQE ν-nucleus cross section

Double differential cross section

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

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

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$L \rightarrow (\mu\nu) = (00, 03, 30, 33)$;

$T \rightarrow (11, 22)$; $T' \rightarrow (12, 21)$

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

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

Elastic vs. QE responses

In general, each nuclear response R_K can be calculated in terms of the single nucleon contribution G_K times the nuclear dependence of the model $\Rightarrow R_K \approx F(nuclear) \cdot G_K$

Theoretical description: CCQE 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

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

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

$L \to (\mu\nu) = (00, 03, 30, 33)$;

$T \to (11, 22)$; $T' \to (12, 21)$

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

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

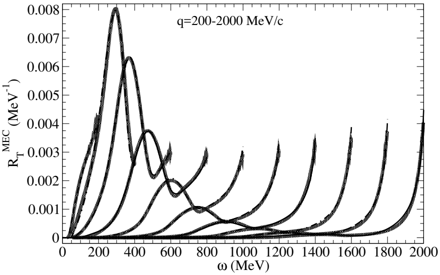
Comparison with (e, e') reactions

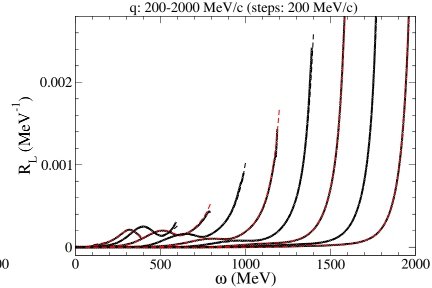
$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right] = \sigma_{Mott}\left(v_L R_L^{VV} + v_T R_T^{VV}\right) \quad ; \quad \sigma_{Mott} = \frac{\alpha^2 \cos^2\theta/2}{4E_i \sin^4\theta/2}$$

2p-2h MEC parametrization *PRD91, 073004 (2015) PRD94, 093004 (2016)*

$$R_X^{2p-2hMEC}(\psi', q) = \frac{2a_{3,X}\, e^{-\frac{(\psi' - a_{4,X})^2}{a_{5,X}}}}{1 + e^{-\frac{(\psi' - a_{1,X})^2}{a_{2,X}}}} + \sum_{k=0}^{2} b_{k,X} \cdot (\psi')^k$$

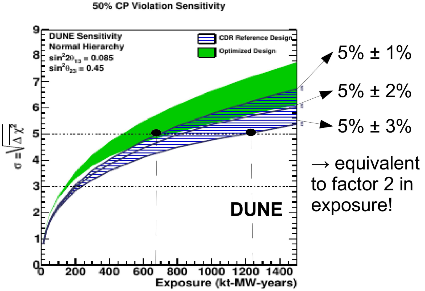
$X = CC, CL, LL, T(= T_{VV} + T_{AA}), T'_{VA}$ $\quad$ $a_{i,X}(q), b_{k,X}(q)$

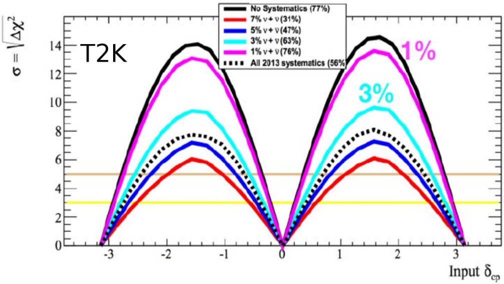




T2K systematics today and needs for HyperK and DUNE

- Global experimental systematics in T2K are around a 4% (7%) for ν_μ (ν_e) reactions and are dominated by 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.





It is faster and cheaper to pay a theoretician to reduce 2 % your systematics than building new huge detectors!

Conclusions and Further Work

➲ **The validation against electron scattering data is a solid benchmark to assess the validity of nuclear models for the analysis of neutrino experiments.** Superscaling is a valuable tool to connect electron and neutrino scattering.

➲ Satisfactory comparison of the SuSAv2-MEC model with (e, e') and (ν, l) data for different nuclei (^{12}C, ^{16}O and ^{40}Ca).

➲ The SuSAv2-MEC model can be easily described for different nuclei, translating sophisticated and computationally demanding microscopic calculations into a straightforward formalism and, hence, easing its implementation in MonteCarlo simulations used in ν oscillation experiments (GENIE, *in progress*). MC generators serve as a bridge between theoretical models and experimental measurements.

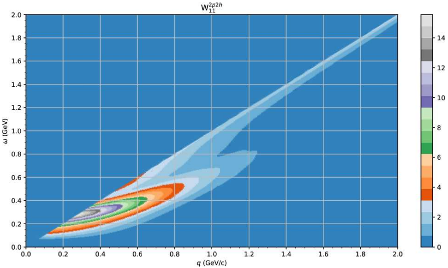
➲ **Works in progress**: Inclusive neutrino scattering including all inelasticities (DIS).

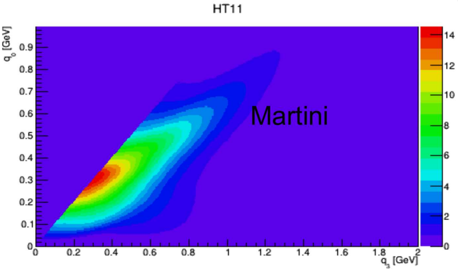
➲ Extension to **asymmetric nuclei** ($Z \neq N$), ^{40}Ar or ^{56}Fe, will be provided by supplying the separate RMF n and p scaling functions and the 2p-2h charge channel contributions, *pn*, *pp* and *nn* emission.

➲ SuSAv2 model integrates over the **FS hadronic kinematics** but they can be analyzed from the RMF theory ⇒ Analysis of semi-inclusive reactions (more sensitive to nuclear model details) should help to analyze physics of theoretical models. Different models can give similar inclusive CS but probably different exclusive ones. Work in progress on $(e, e'N)$ RMF $\rightarrow$ $(\nu, l^- N)$ RMF.

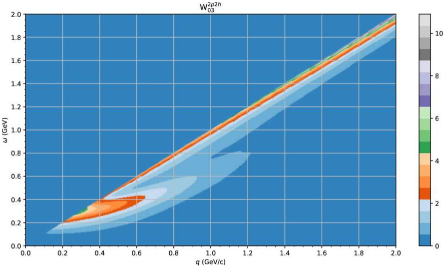
Comparison with other models implemented in GENIE

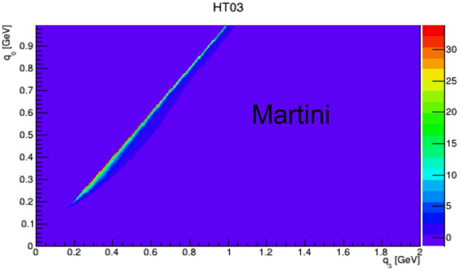
$W_{11}^{2p2h}(q,\omega) \sim R_T$



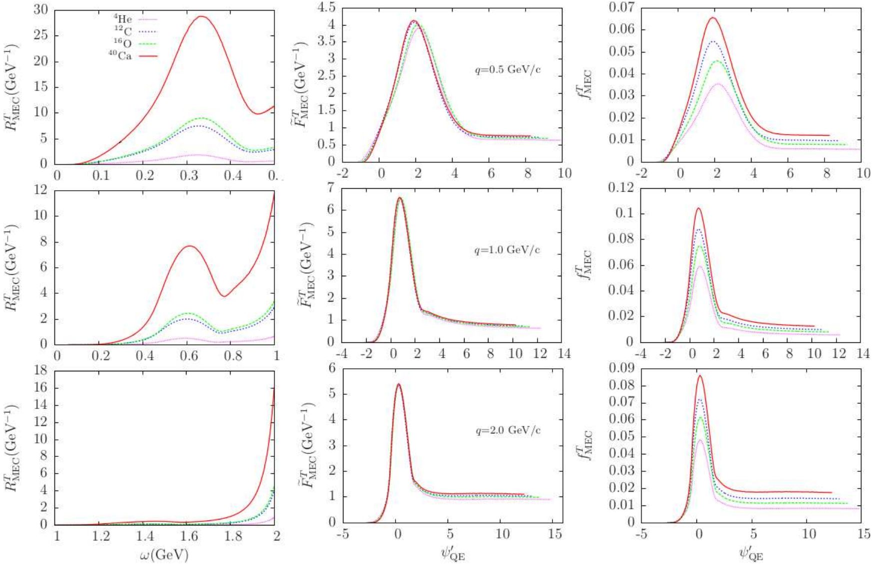


$W_{03}^{2p2h}(q,\omega) \sim R_{CL}$



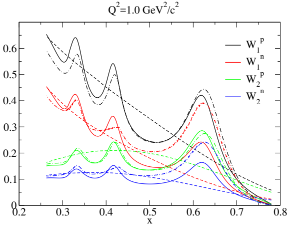


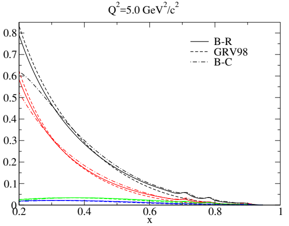
Density dependence of 2p-2h MEC [PRC95, 065502 (2017)]



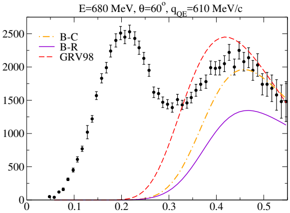
Inelastic Nuclear Responses & SuSAv2-inelastic model

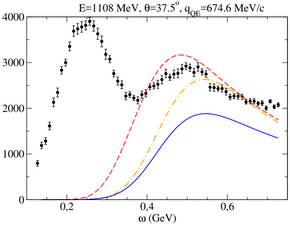
Inelastic structure functions





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





Bodek-Ritchie: poor description of the resonance region.

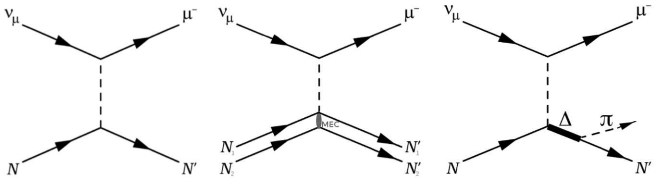
Bosted-Christy: Good description of the resonant structures observed in (e,e') reactions.

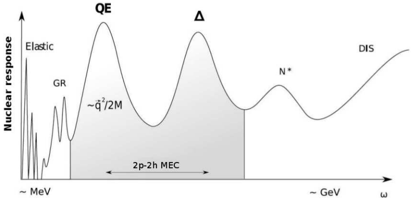
GRV98: No resonant structures (average) and poor description at $Q^2 \lesssim 1$ GeV^2.

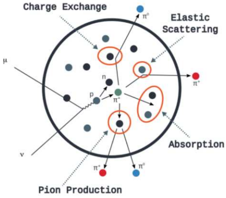
Neutrino-nucleus reactions for ν oscillation experiments

➠ Reliability of ν-oscillation experiments largely depends on ν-nucleus cross section. FS particles ID and E_ν reconstruction involve nuclear models and MC event generators.

➠ Range: $\sim$ 100's MeV - 10's GeV $\Rightarrow$ Large variety of nuclear effects: QE ($\gtrsim$ 50%), multinucleon emission (2p2h), $\Delta \to \pi$ production, DIS, ...







No clear ID of all FS particles

$\Rightarrow$ Relevance of 2p2h, FSI effects, rescattering processes and π-production background.

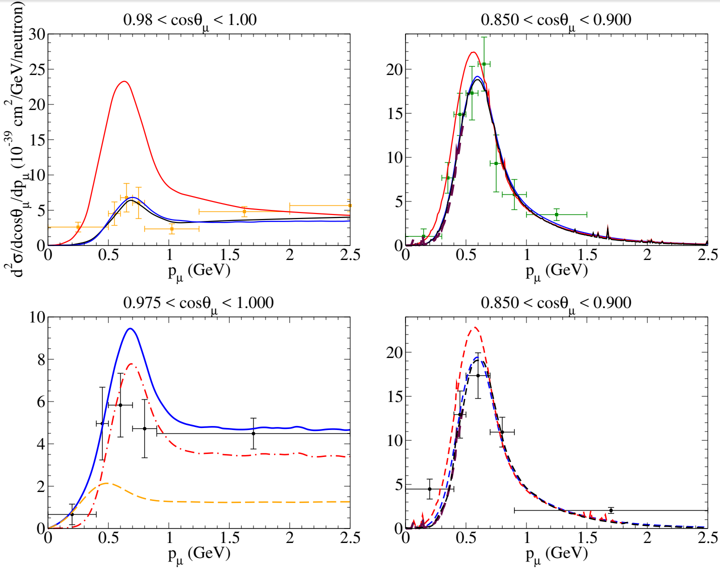
Event topology:
CCQE
CCQE-like = CCQE+CC2p2h
CC0π = CCQE-like with π absorption background
CC1π
CCDIS
...

SuSAvX... low $q - \omega$ improvements, DIS, etc

T2K CC0π ^{12}C

RMF: **black**
SuSAv2: **blue**
RPWIA: **red**

T2K CC0π ^{16}O



SuSAvX... low $q - \omega$ improvements, DIS, etc

T2K CC0π ^{12}C

RMF: **black**
SuSAv2: **blue**
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T2K CC0π ^{16}O