Analysis of electron scattering within the SuSAv2-MEC approach and extension to CC neutrino reactions

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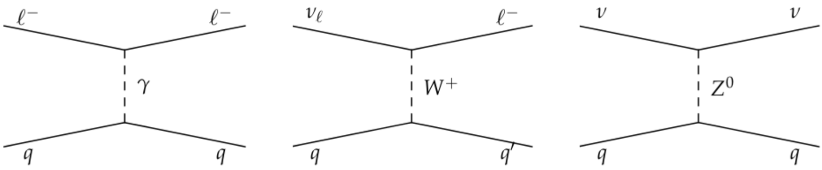
Electroweak Interactions with nucleons and nuclei



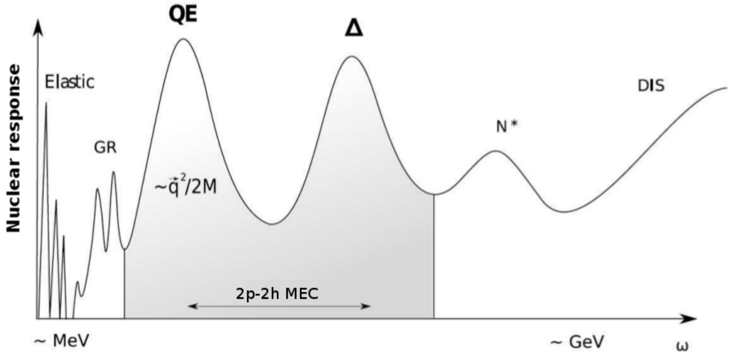
(a) Electromagnetic scattering (b) Charged-current scattering (c) Neutral-current scattering

$l = e, \mu, \tau$

Lepton-nucleus interactions

- Electron-nucleus interaction, mediated by γ (EM) and Z (weak)
- Neutrino-nucleus interaction, mediated by $W^\pm$ (Charged-Current) and Z (Neutral-Current)
- QED description

Nuclear response in terms of the energy transfered



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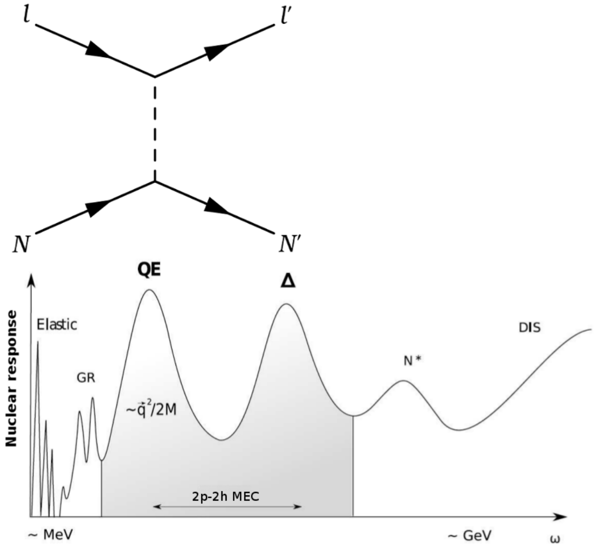

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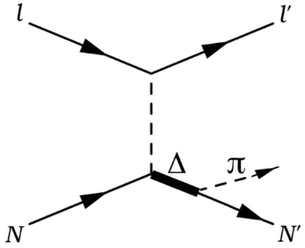

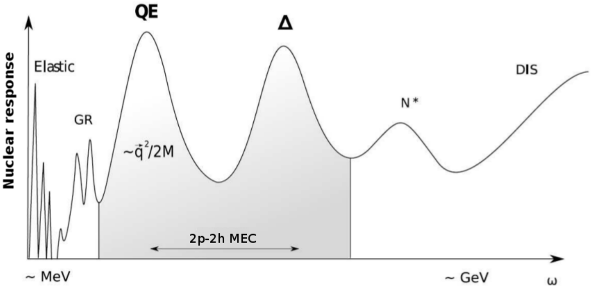

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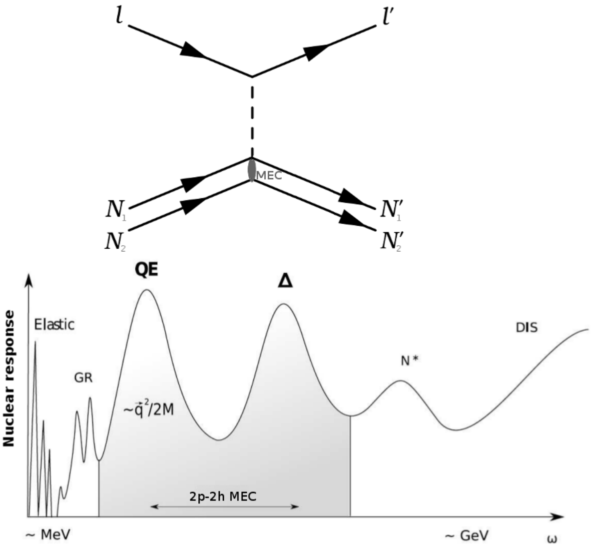

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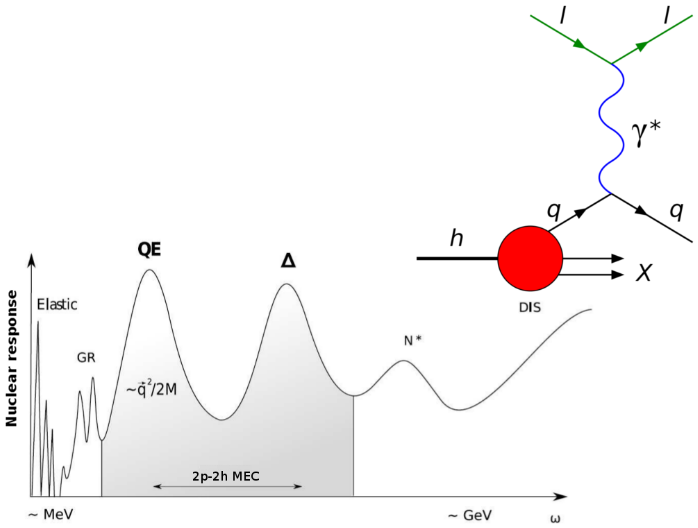


Quasielastic Regime

(e, e') QE scattering

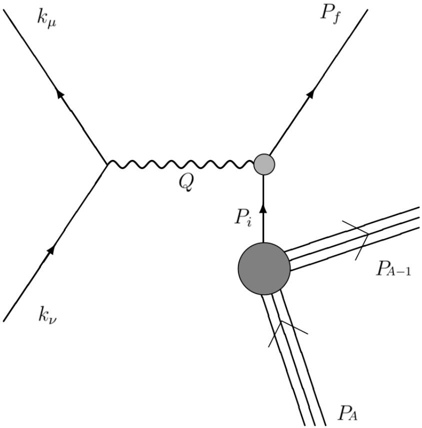
$$e + A \rightarrow e' + p + (A-1)$$

CCQE scattering

$$\nu_\mu(\bar{\nu}_\mu) + A \rightarrow \mu^-(\mu^+) + p(n) + (A-1)$$

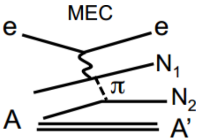
Impulse Approximation (IA)

The lepton only interacts with a single bound nucleon.

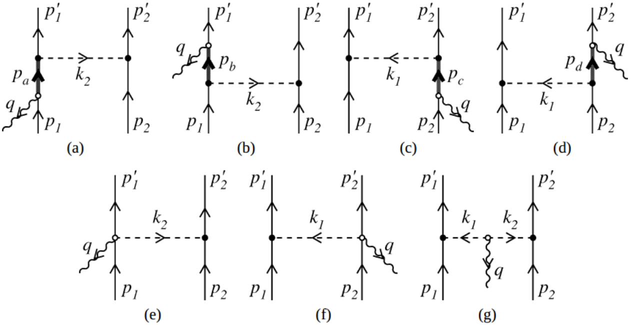


2p-2h MEC contributions

➠ A weak boson from the leptonic current is exchanged by a pair of nucleons (2-body current) ⇒ 2-nucleon emission from the primary vertex.
➠ 2p-2h effect dominated by the meson exchange current (MEC).



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



Experimental status

2p-2h effects on the experimental side

- Recent ν-CCQE measurements (MiniBooNE) have reported a large M_A value $\not\Rightarrow$ standard estimations $\Rightarrow$ Explanation: events interpreted as CCQE-like events are also due to 2p-2h MEC, correlations, etc.
- 2p-2h effect is essential to understand current and future neutrino oscillation experiments.
- The importance of MEC is well known from electron scattering data $\Rightarrow$ 'dip' region between the QE and the Δ peak.

Contents

Theoretical description: QE (e, e') cross section

Double differential cross section

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

Theoretical description: CCQE ν-nucleus cross section

Double differential cross section

$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right]_\chi = \sigma_0 \mathcal{F}_\chi^2 \quad ; \quad \sigma_0 = \frac{\left(G_F^2 \cos\theta_c\right)^2}{2\pi^2}\left(k_\mu \cos\frac{\tilde{\theta}}{2}\right)^2 \quad ; \quad \chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$$

Nuclear structure information

$$\mathcal{F}_\chi^2 = \hat{V}_L R_L + \hat{V}_T R_T + \chi\left[2\hat{V}_{T'} R_{T'}\right]$$

$$\hat{V}_L R_L = V_{CC} R_{CC} + V_{CL} R_{CL} + V_{LL} R_{LL}$$

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

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

Rosenbluth-like decomposition

$$R_L = R_L^{VV} + R_L^{AA}$$

$$R_T = R_T^{VV} + R_T^{AA}$$

$$R_{T'} = R_{T'}^{VA}$$

Leptonic (j^μ) & hadronic currents (J^μ)

$$j^\mu = j_V^\mu + j_A^\mu \quad ; \quad J^\mu = J_V^\mu + J_A^\mu$$

Weak nuclear current

$$J_V^\mu = \bar{u}(P')\left[F_1^V \gamma^\mu + \frac{i}{2m_N} F_2^V \sigma^{\mu\nu} Q_\nu\right] u(P)$$

$$J_A^\mu = \bar{u}(P')\left[G_A \gamma^\mu + \frac{1}{2m_N} G_P Q^\mu\right] u(P)$$

Nuclear responses

Composed of VV (vector-vector), AA (axial-axial) and VA (vector-axial) components arising from the V and A weak nuclear currents.

Theoretical description: Nuclear model dependence

➠ For this purpose we need to employ a nuclear model which can be applied up to very high energies.

➠ Two basic requirements: it has to be relativistic and it must describe QE electron scattering data from intermediate up to high energies.

First approach: Relativistic Fermi Gas (RFG)

- Relativistic description of the nucleus as a system of non-interacting on-shell nucleons.
- Explanation of the nucleon dynamics in the ground state (Fermi movement) and consistency with the description of a many-body system.
- The RFG is too simple to take into account all the physics involved in an accurate way. It should be taken as a guide for more sophisticated models.

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SuperScaling Approach (SuSA)

- Based on the superscaling function extracted from QE electron scattering data.
- **Scaling**: The response of a many-body system ***scales*** when it can be described in terms of a particular combination of two variables, called ***scaling variable*** $\psi(\omega, q)$.
- In lepton-nucleus scattering, nuclear effects can be analyzed through a **Scaling Function** $f(\psi)$ constructed from the ratio between the QE cross section and the proper single-nucleon one.

Theoretical description: Scaling phenomenon

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

In inclusive QE scattering we can observe:

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

$\Longrightarrow$ **SuperScaling**

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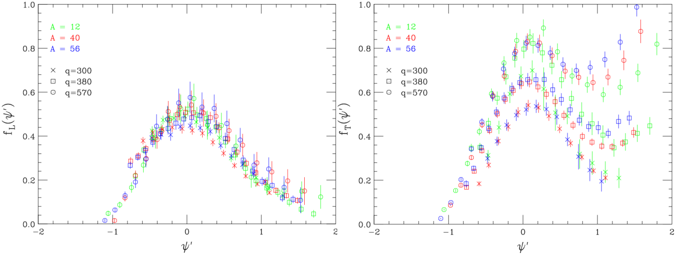


Scaling violations in the T channel ⇒ 2p-2h MEC, correlations

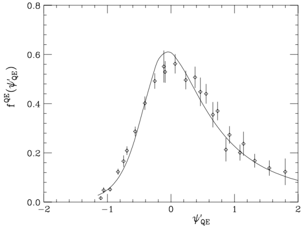
Theoretical description: Scaling phenomenon

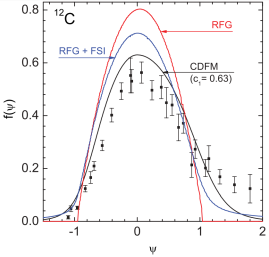
Original SuSA model:

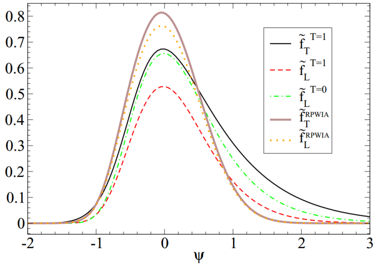
- Fit of the (e,e') longitudinal scaling data
- Assumption $f_L(\psi) = f_T(\psi)$

SuSAv2 *PRC90, 035501, 2014*

- An improved SuperScaling model based on RMF calculations (FSI).
- Decomposition into isoscalar and isovector components which is of interest for CC neutrino reactions.
- RMF & RPWIA models are employed to get a set of scaling functions valid for all lepton-nucleus scattering processes







Theoretical description: Scaling phenomenon

RMF/RPWIA transition: *PRD 94, 013012 (2016)*

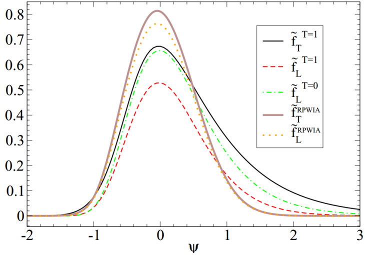
- RMF ⇒ FSI between the outgoing nucleon and the residual nucleus ⇒ low-intermediate q
- RPWIA ⇒ outgoing nucleon as a relativistic plane wave ⇒ higher q values

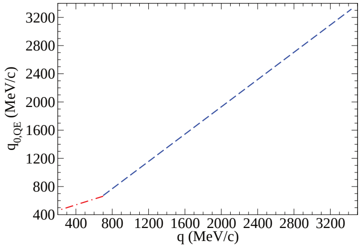
➥ SuperScaling Approach as a combination of RMF and RPWIA scaling functions:

$$\mathcal{F}_L^{T=0,1} \equiv \cos^2\chi(q,q_0)\tilde{f}_L^{T=0,1} + \sin^2\chi(q,q_0)\tilde{f}_L^{RPWIA}$$

$$\mathcal{F}_T \equiv \cos^2\chi(q,q_0)\tilde{f}_T + \sin^2\chi(q,q_0)\tilde{f}_T^{RPWIA}$$

➢ $q_0(q)$: RMF/RPWIA transition parameter, determined by performing a χ^2 analysis of the (e,e') data in a wide kinematical region.





Inelastic Nuclear Responses within the SuSAv2 Approach

➲ Inelastic model that includes the complete inelastic spectrum ⇒ resonant (Δ), non-resonant, and deep inelastic scattering (DIS). Based on *PRC69, 035502, 2004* and extended to the SuSAv2 formalism with a $q_0^{inelastic}$ RMF/RRPWIA transition parameter [PRD 94, 013012 (2016)].

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

where $f_{SuSAv2}^{L} \neq f_{SuSAv2}^{T}$ and $U_{QE}^{L,T}$ are the single nucleon responses.

$$R_{inel}^{L,T} = \frac{\mathcal{N}\xi_F}{\eta_F^3 \kappa} \int d\mu_X \mu_X U_{inel}^{L,T} f_{model}^{L,T}(q_0^{inel}, \psi_X')$$

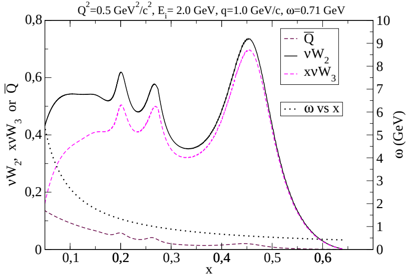
where $\mu_X = \frac{W_X}{m_N}$ is the dimensionless invariant mass, $U_{inel}^{L,T}$ depends on the inelastic structure functions W_1, W_2, obtained by using:

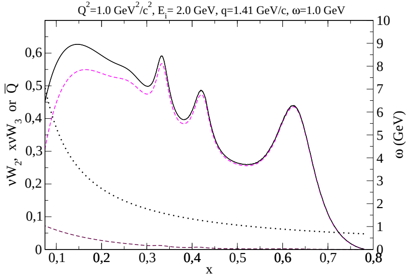
- **Fits of the inelastic structure functions (Bodek, Bosted-Christy, ...)**
- *PDFs*

➲ In computing the inelastic hadronic tensor, we employ phenomenological fits of the single-nucleon inelastic structure functions [Bosted-Christy parametrization PRC81,055213(2010), PRC77,065206,(2008)]

Inelastic Nuclear Responses

Following the prescription given in Bodek and Ritchie, PRD23, 1070 (1981) , $\nu W_2 = 2m_N x W1$, $x\nu W_3 = \nu W_2 - 2\bar{Q}$ where $\bar{Q}$ is the antiquark distribution.
Preliminary $\tilde{W}_1, \tilde{W}_2, \tilde{W}_3$ results.

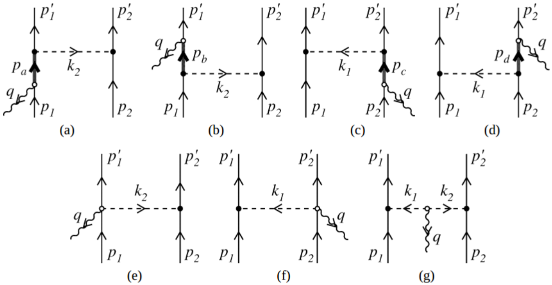




Inelastic structure functions for CC neutrino reactions
$\nu \tilde{W}_2^{weak} = \frac{18}{5} W_2^{EM}$
Next step: To develop the CC neutrino formalism for DIS and introduce $\tilde{W}_1, \tilde{W}_2, \tilde{W}_3$ into the SuSAv2 description.

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



✪ Dekker and De Pace: first attempts for a relativistic description of EM 2p-2h MEC ⇒ Extension to the weak sector [PRD 90, 033012 (2014); PRD 90, 053010 (2014)].

✪ The calculation is performed in the RFG model in which Lorentz covariance can be maintained.

✪ A fully relativistic calculation implies to integrate over the neutrino flux ⇒ High increase of the computing time of the nuclear response, involving 7D integrals of thousands of terms ⇒ **Parametrization**

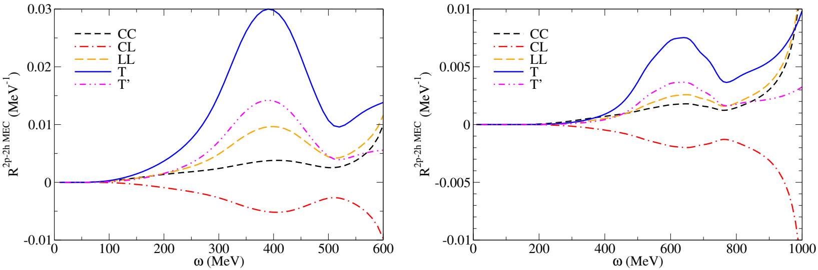
2p-2h MEC parametrization

PRD91, 073004, 2015

$$R_X^{2p-2hMEC}(\psi',q) = \frac{2a_3 e^{-\frac{(\psi'-a_4)^2}{a_5}}}{1+e^{-\frac{(\psi'-a_1)^2}{a_2}}} + \sum_{k=0}^{2} b_k(\psi')^k$$

$X = CC, CL, LL, T(= T_{VV}+T_{AA}), T'_{VA}$

$a_i(q), b_k(q)$



q=600 MeV/c

q=1000 MeV/c

2p-2h hadronic tensor in the RFG model

☆ Simplest approach that treats exactly relativity, gauge invariance and translational invariance. The nucleons are described by plane wave spinors.
☆ Parameter: Fermi momentum k_F. (also separation energy E_s)
☆ Final states: two particles $\mathbf{p}'_1$ and $\mathbf{p}'_2$ above the Fermi momentum, $p'_i > k_F$, and two holes $\mathbf{h}_1$ and $\mathbf{h}_2$ below the Fermi momentum, $h_i < k_F$.
Spin (isospin) indices: s'_i (t'_i) and s_i (t_i).

2p-2h hadronic tensor in the RFG model

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

where by momentum conservation, $\mathbf{p}'_2 = \mathbf{h}_1 + \mathbf{h}_2 + \mathbf{q} - \mathbf{p}'_1$.

E_i and E'_i are the on-shell energies of the holes and particles,
The volume of the system is $V = 3\pi^2 Z/k_F^3$, for symmetric matter, $Z = N = A/2$.
Pauli blocking step functions:

$$\Theta(p'_1, p'_2, h_1, h_2) = \theta(p'_2 - k_F)\theta(p'_1 - k_F)\theta(k_F - h_1)\theta(k_F - h_2).$$

2p-2h hadronic tensor in the RFG model

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$$r^{\mu\nu}(\mathbf{p}'_1,\mathbf{p}'_2,\mathbf{h}_1,\mathbf{h}_2)\delta(E'_1+E'_2-E_1-E_2-\omega)$$

Elementary 2p-2h hadronic tensor

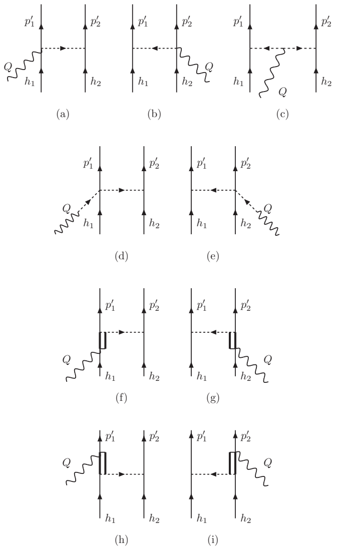
$$r^{\mu\nu}(\mathbf{p}'_1,\mathbf{p}'_2,\mathbf{h}_1,\mathbf{h}_2) = \frac{1}{4}\sum_{s_1s_2s'_1s'_2}\sum_{t_1t_2t'_1t'_2} j^{\mu}(1',2',1,2)^*_A j^{\nu}(1',2',1,2)_A.$$

- Two-body MEC antisymmetrized matrix element $j^{\mu}(1',2',1,2)_A$
- The sum over isospin combines all the possible charge channels in the final state, corresponding to emission of PP, NN, and PN pairs.
- In our formalism we separate the contributions of these charge states. This will allow us to apply the formalism to asymmetric nuclei $N \neq Z$. This will be of interest for neutrino experiments based on ^{40}Ar, ^{56}Fe or ^{208}Pb detectors.

Meson exchange currents

- The 2p-2h calculations implies 7D integrals. The numerical integration method is described in: I. Ruiz Simo, C. Albertus, J.E. Amaro, M.B. Barbaro, J.A. Caballero, T. W. Donnelly, PRD 90, 033012 (2014) (phase space in Lab system); PRD 90, 053010 (2014) (phase space in CM system)
- The MEC operator is written as the sum of four contributions, seagull (a,b), pion-in-flight (c), pion-pole (d,e), and Δ pole (f–i).

$$j^{\mu}_{\rm MEC} = j^{\mu}_{\rm sea} + j^{\mu}_{\pi} + j^{\mu}_{\rm pole} + j^{\mu}_{\Delta}$$



Isospin dependence of the MEC

CC neutrino scattering can induce two possible 2p-2h transitions: $NP \to PP$ and $NN \to NP$.

The total CC MEC for neutrino scattering can be written as

$$\begin{aligned} j^{\mu}_{\rm MEC} &= \tau_+(1)\, J^{\mu}_1(1'\,2';1\,2) + \tau_+(2)\, J^{\mu}_2(1'\,2';1\,2) \\ &+ (I_V)_+\, J^{\mu}_3(1'\,2';1\,2), \end{aligned} \tag{1}$$

where

$$J^{\mu}_1 = J^{\mu}_{\Delta 1} \tag{2}$$

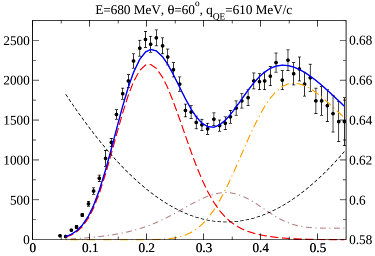
$$J^{\mu}_2 = J^{\mu}_{\Delta 2} \tag{3}$$

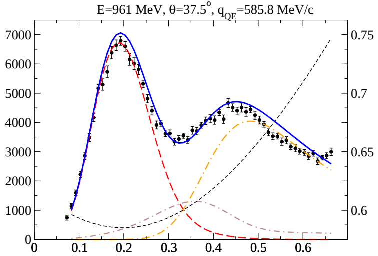
$$J^{\mu}_3 = J^{\mu}_{\rm sea} + J^{\mu}_{\pi} + J^{\mu}_{\rm pole} + J^{\mu}_{\Delta 3}. \tag{4}$$

- This expression can be applied to antineutrinos by taking the $(-)$ component of the isospin operators.
- For electron scattering, one should take the z component of the isospin operators and keep only the V part of the current.
- The resulting electromagnetic MEC is in agreement with previous expressions
- Expression (1) will be useful to obtain the response functions for the separate charge channels PP, PN, NN

Validation

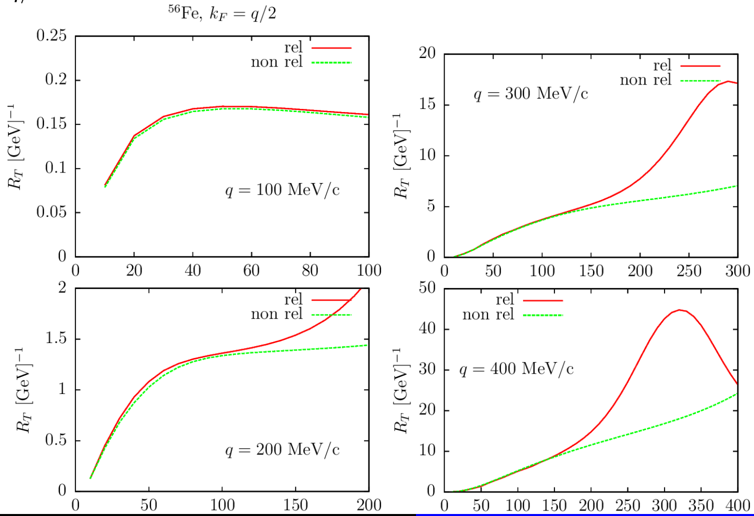
- The validation of the MEC contribution requires to compute the total (e, e') cross section including also both the quasi-elastic and inelastic
- Is possible to reproduce globally the experimental world-data for ^{12}C in the super-scaling approach using these 2p-2h MEC calculations?
- YES ⇒ G.D. Megias, J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly, Phys. Rev. D 94, 013012 (2016)



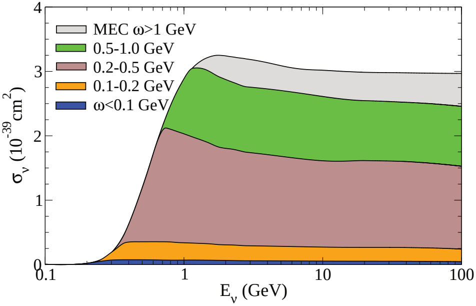


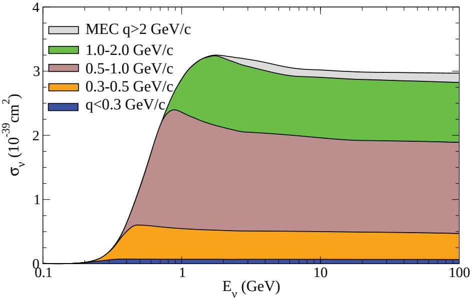
Non relativistic limit

Electromagnetic transverse response function for 2p-2h for low momentum q and $k_F = q/2$. We take $A = 56$.



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

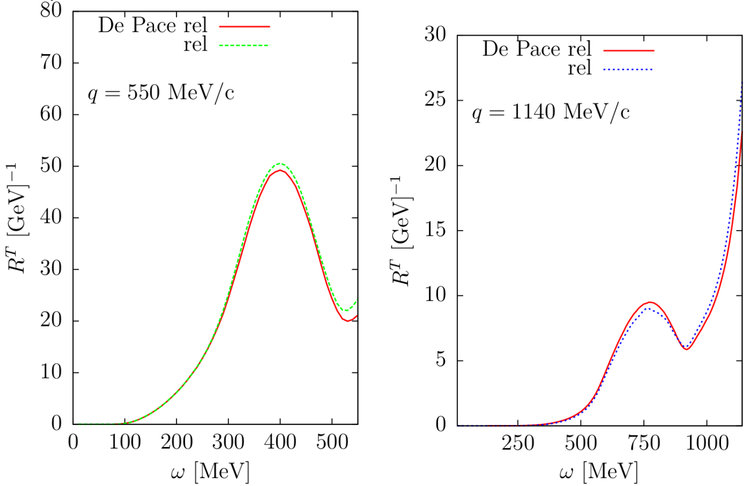




Although very similar to the QE case, the relevance of 2p-2h MEC contributions extends slightly to higher kinematics.

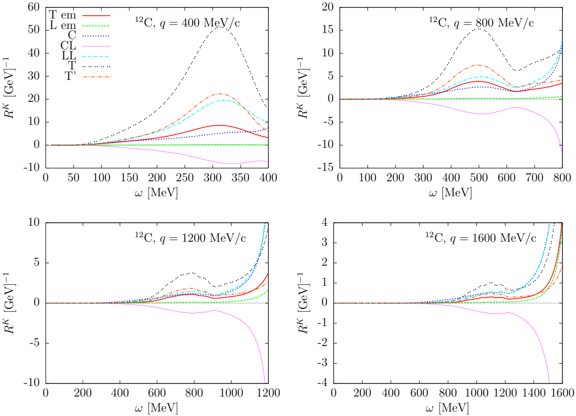
Comparison of models

Electromagnetic transverse response function for 2p-2h from ^{56}Fe for two values of q. Comparison with the model of ref. De Pace et al.



2p-2h response functions

Separate 2p-2h response functions of ^{12}C for four values of the momentum transfer. We show the L, T electromagnetic responses and the five weak responses for CC neutrino scattering.

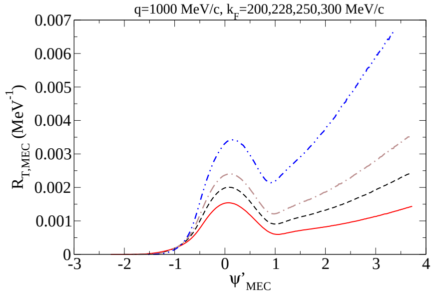


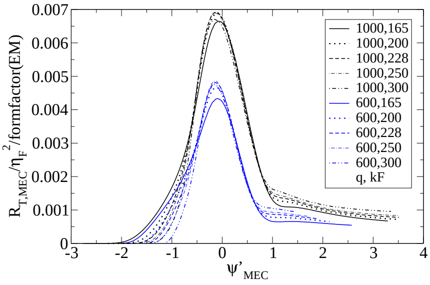
Summary

- We have extended the MEC model of De Pace to the weak sector by adding the axial MEC operators
- This model of MEC has been validated within the SuSA-v2 approach by fitting the (e, e') data
- Our model can be applied to compute neutrino cross sections
- We can compute the separate 2p-2h charge channels, asymmetric matter and angular distributions
- We are preparing and will publish a fortran library of routines (NuMEC) to compute the elementary 2p-2h response functions

k_F dependence of the 2p-2h MEC responses (See M. Barbaro's talk)

☆ Extension of the EM 2p-2h MEC analysis to other nuclei.
☆ A-scaling: independence on the nuclear species ⇒ Scaling of 2nd kind
☆ $\eta_F = k_F/m_N$; k_F(Li)= 165 MeV/c; k_F(C)= 228 MeV/c; k_F(Ca)= 241 MeV/c; k_F(Pb)= 248 MeV/c
☆ A parametrization of this behavior in terms of k_F (work in progress) could be valuable to extend our calculation to other nuclei without further theoretical calculations reducing significantly the computational time.



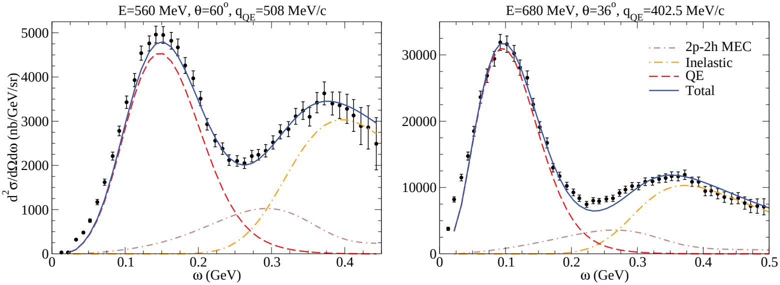


Contents

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

Theoretical description beyond the QE peak

- Good agreement of SuSAv2 model with (e,e') data
- Inelastic model that includes the complete inelastic spectrum ⇒ resonant (Δ), nonresonant, and deep inelastic scattering (DIS). Based on *PRC69, 035502, 2004*
- In computing the inelastic hadronic tensor, we employ phenomenological fits of the single-nucleon inelastic structure functions



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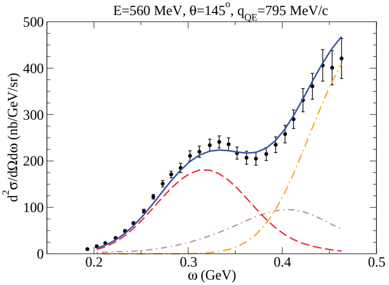
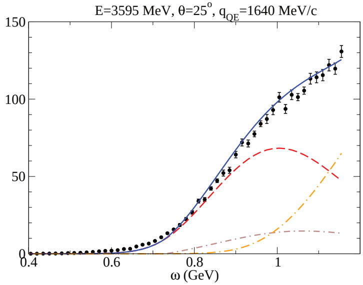
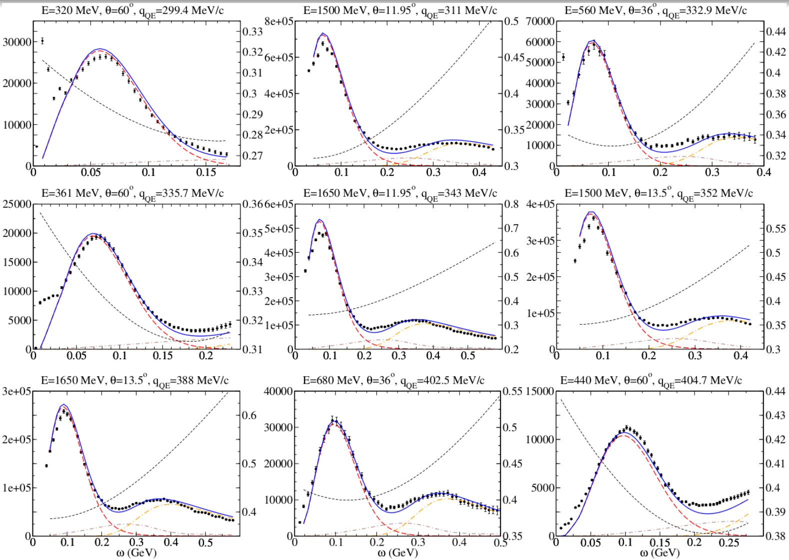
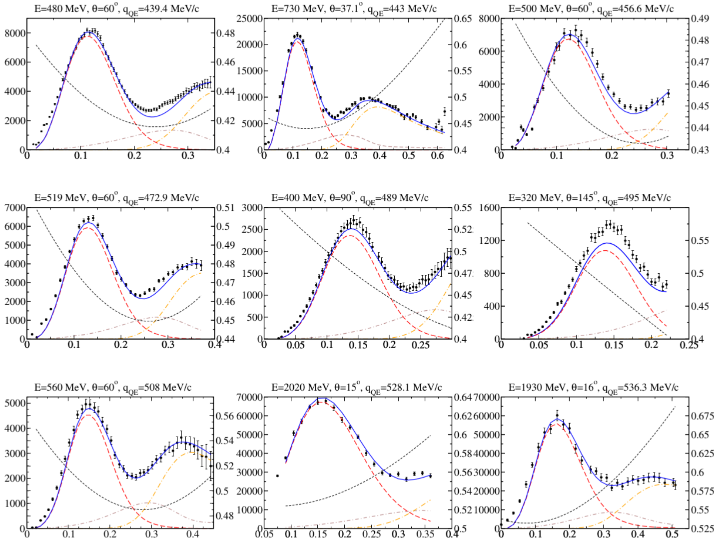




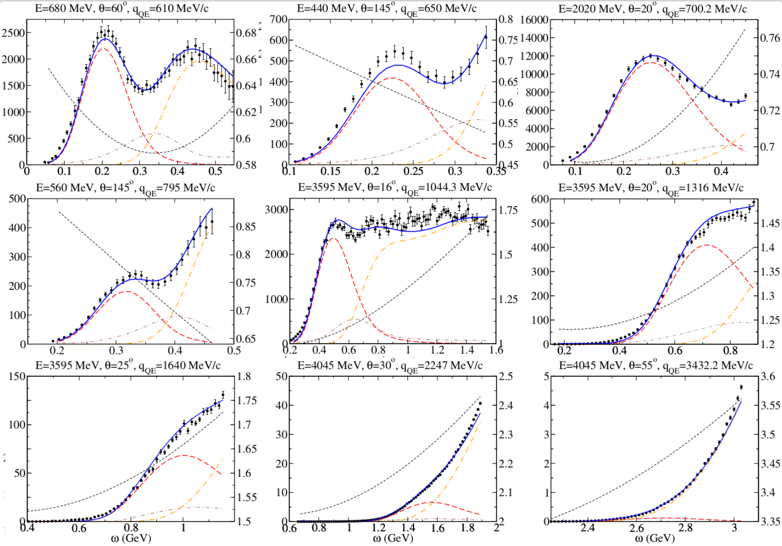
Inclusive $^{12}C(e, e')$ cross sections *PRD 94, 013012 (2016)*



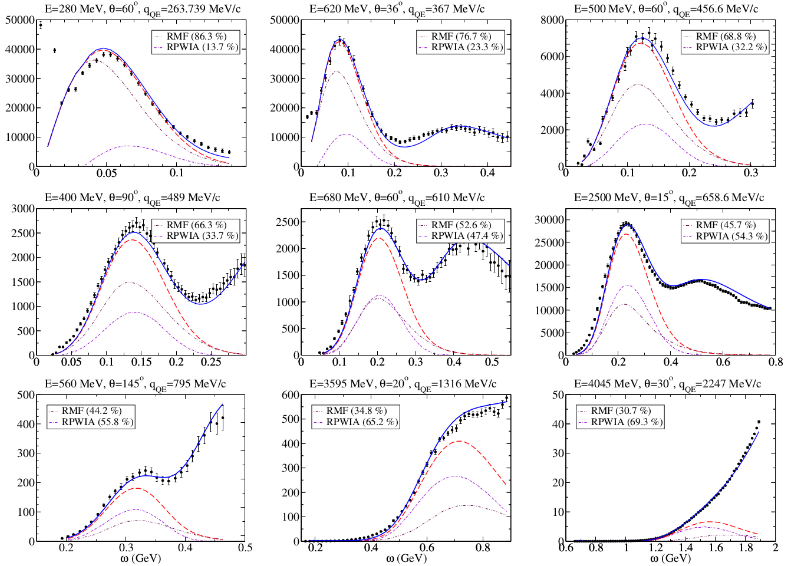
Inclusive $^{12}C(e, e')$ cross sections *PRD 94, 013012 (2016)*



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



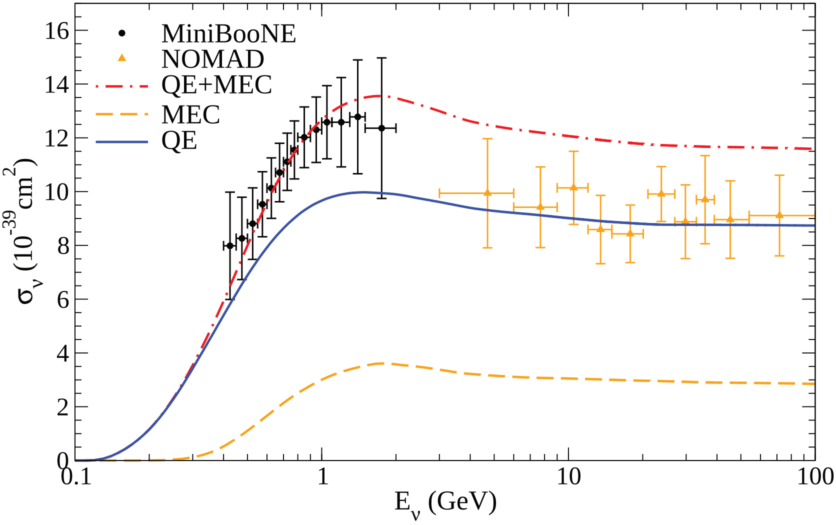
RMF vs. RPWIA contributions in the QE regime *PRD 94, 013012 (2016)*



Contents

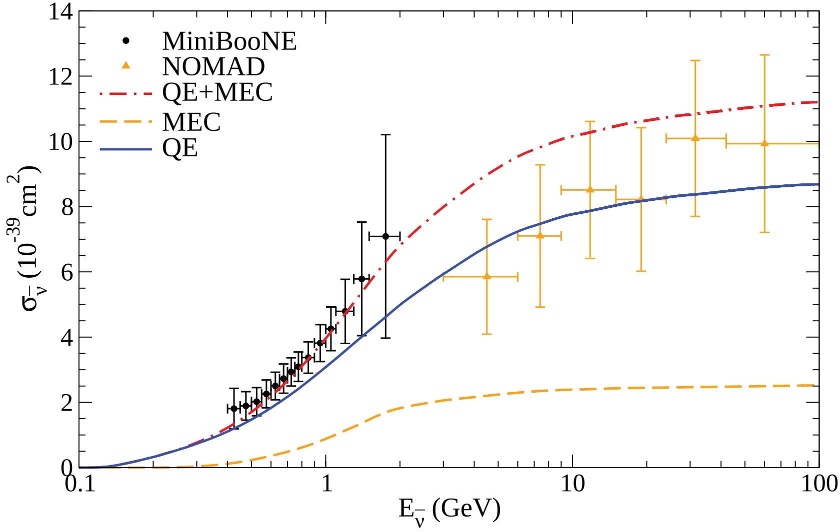
ν_μ-^{12}C CCQE scattering

PRD 94, 093004 (2016)



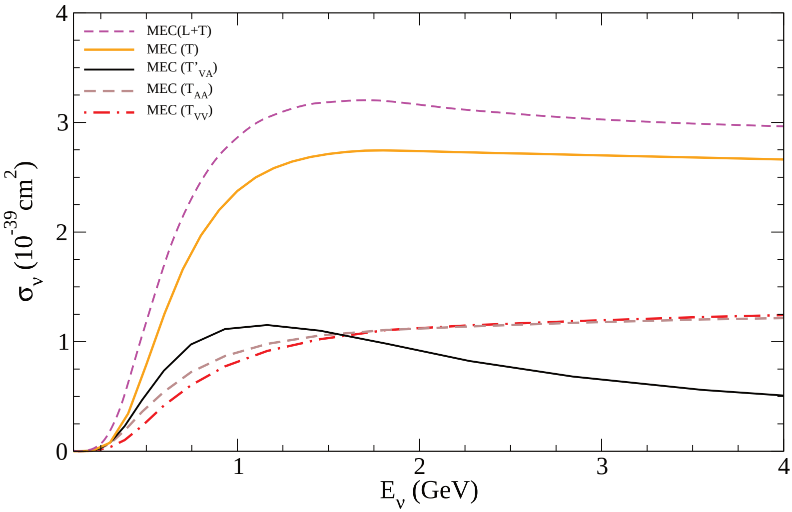
$\bar{\nu}_\mu$-^{12}C CCQE scattering

PRD 94, 093004 (2016)

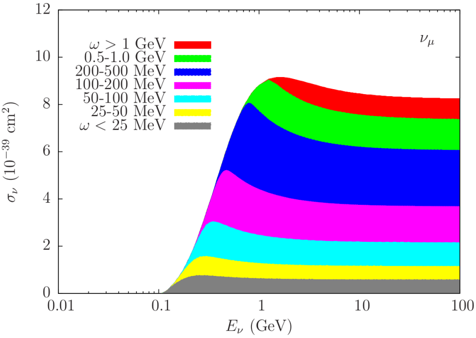


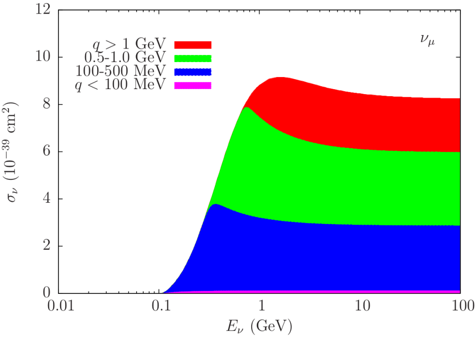
ν_μ-^{12}C CCQE scattering

PRD 94, 093004 (2016)



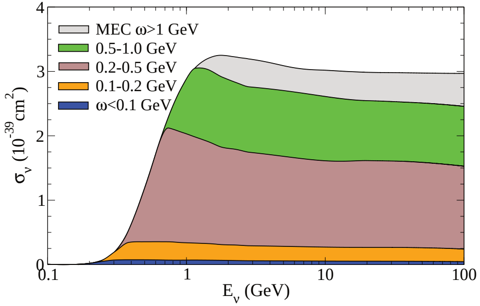
Relevant kinematic regions in the QE cross section

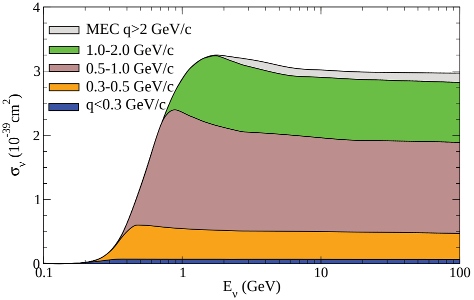




The main contribution to the total QE CS comes from $q < 1$ GeV/c and $\omega < 0.5$ GeV, even at high neutrino energies.

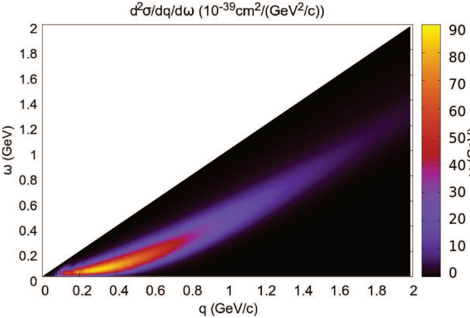
Relevant kinematic regions in the 2p-2h MEC cross section



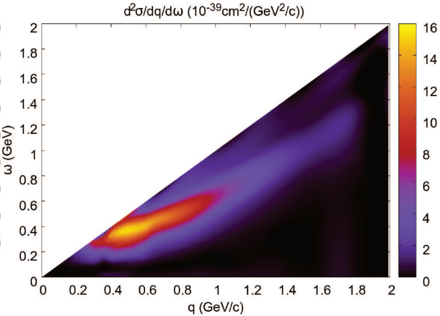


Although very similar to the QE case, the relevance of 2p-2h MEC contributions extends slightly to higher kinematics.

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



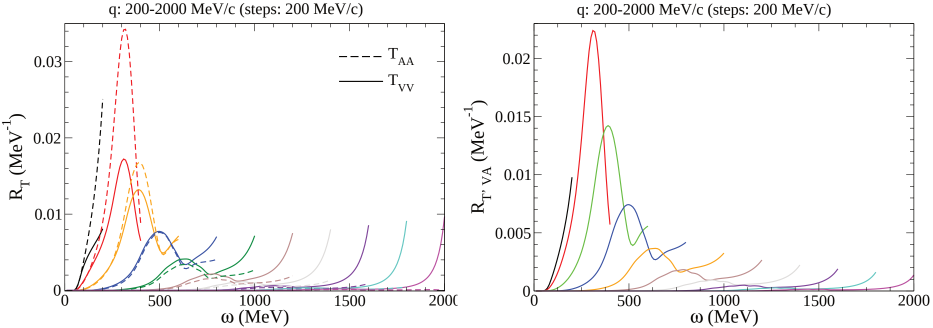
QE



2p-2h MEC

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

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

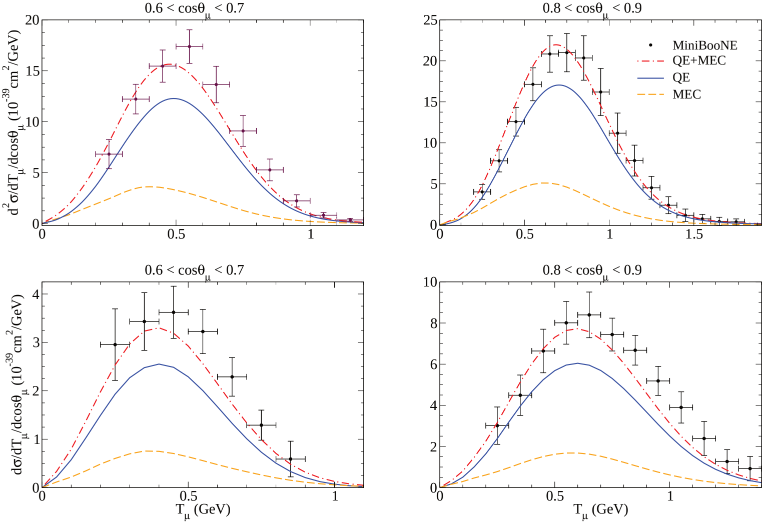


- T'_{VA} of the same order as T_{VV} and T_{AA}
- Although $T_{VV} > T_{AA}$ at $q > 600$ MeV/c $\Rightarrow \sigma(T_{AA}) \sim \sigma(T_{VV})$

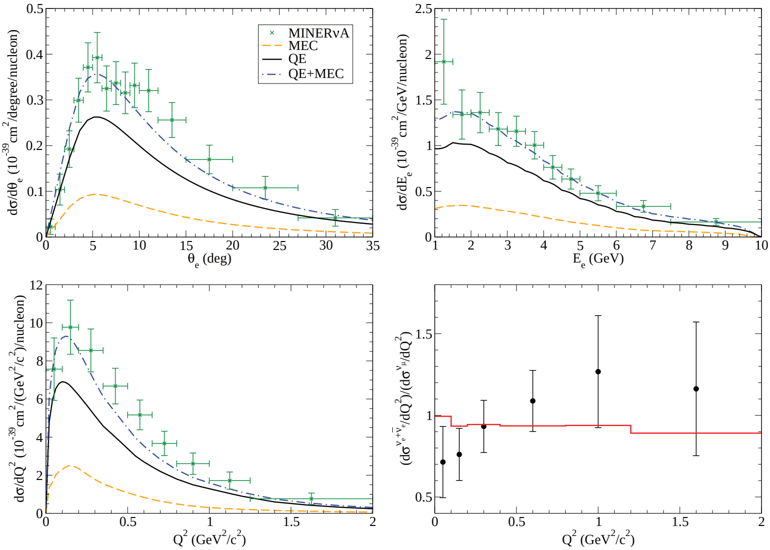
MiniBooNE $\nu_\mu-{}^{12}$C double differential cross sections

$\nu_\mu \Rightarrow$

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



MINERνA ν_e—^{12}C cross sections



Contents

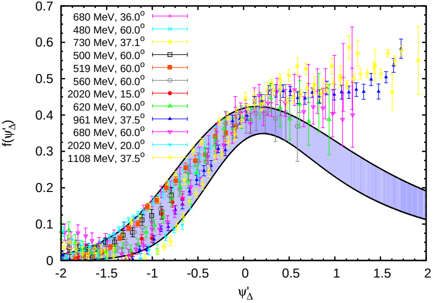
Inclusive total cross section ⇒ Δ-scaling model

Extension of the SuSA approach into the non-QE region (arXiv:1506.00801 [nucl-th]), obtained by substracting the QE + 2p-2h MEC contributions from the total cross section ⇒ assuming that it is dominated by the Δ-resonance.

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

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

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

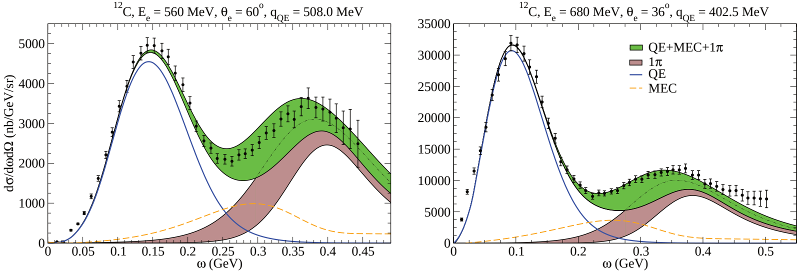


Inclusive total cross section ⇒ Δ-scaling model

This procedure yields a good representation of the electromagnetic response in both the QE and Δ regions.

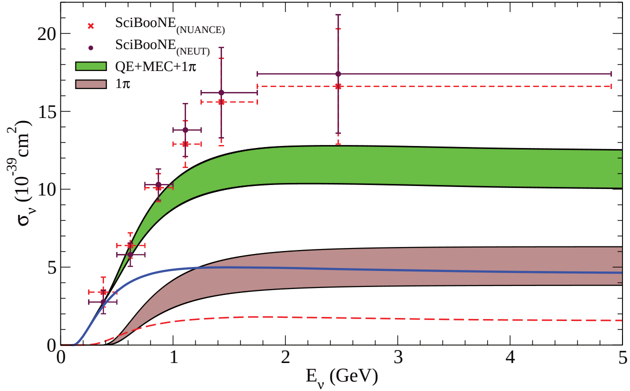
$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{non-QE}} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{exp}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{QE,SuSAv2}}_{\mathrm{1p1h}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{MEC}}_{\mathrm{2p2h}}$$

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



Inclusive total cross section ⇒ Δ-scaling model

Extension of the SuSA into the non-QE region assuming Δ-resonance dominance [*JPG43, 045101 (2016)*]. Substraction of the QE + 2p-2h MEC contributions from the total CS.

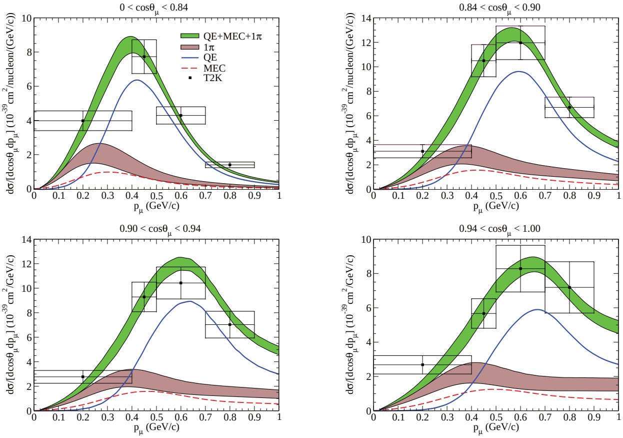


QE+MEC+Δ contributions are not enough to describe inclusive cross section at $E_\nu \gtrsim 1$ GeV ⇒ Work in progress to include DIS in the ν interaction model.

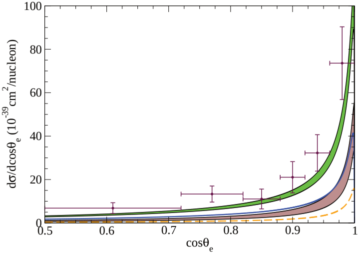
QE+MEC+Δ contributions in $\nu_\mu - ^{12}$C scattering

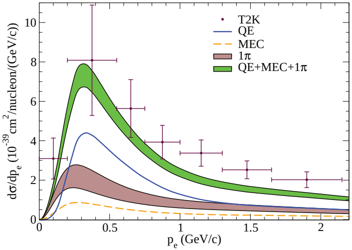
Analysis of T2K ν_μ data ($< E_{\nu_\mu} > \sim$ 0.8 GeV) *JPG43, 045101 (2016)*

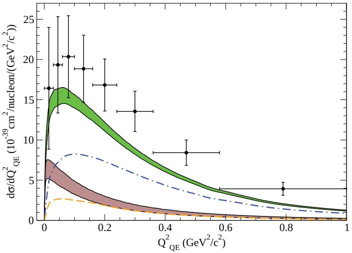
➡ Deep Inelastic Scattering contributions are not relevant at T2K kinematics.
➡ Work in progress to include the DIS description ⇒ analysis of higher-energy data.



T2K ν_e-^{12}C cross sections







Analysis of T2K ν_e data ($< E_{\nu_e} > \sim 1.3$ GeV)
JPG43, 045101 (2016)

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

Contents

Conclusions and Further Work

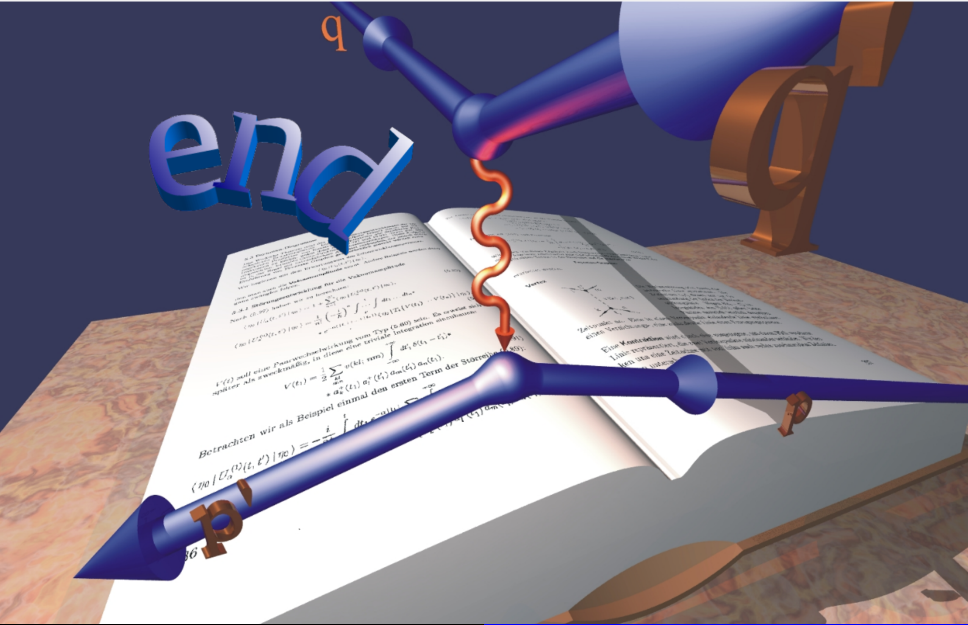
➲ The SuSAv2+MEC model has been widely tested against (e,e') data, showing a good agreement with ν-nucleus data from low to high-energy data.

➲ First 2p-2h MEC fully relativistic calculation including direct-exchange interferences in both axial and vector currents.

➲ Extension of the theoretical description of neutrino-nucleus scattering to include DIS contributions $\Rightarrow$ Complete analysis of all present and future experiments (T2K, MINERνA, ArgoNeuT, SciBooNE, etc.)

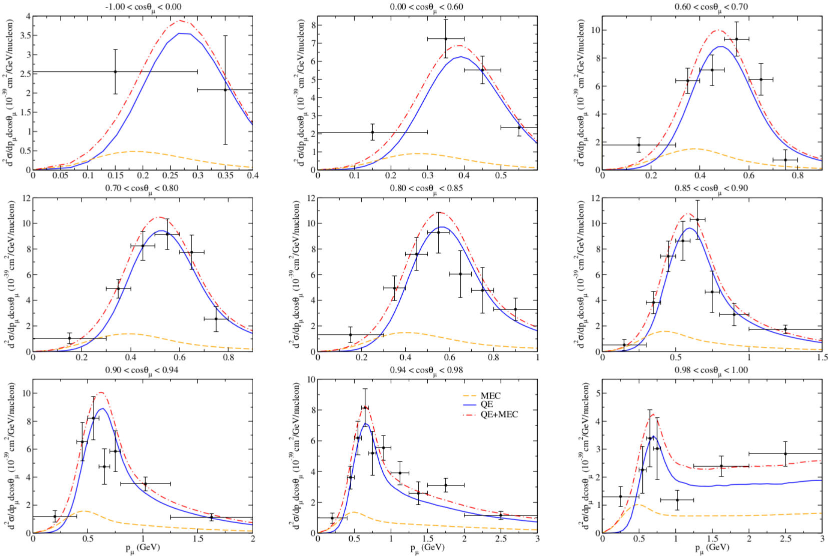
➲ Analysis of the nuclear dependence of the 2p-2h MEC in terms of the Fermi momentum (k_F). *Work in progress.*

➲ The possibility of describing the QE and the MEC contributions through a straightforward parametrization might be of interest to Monte Carlo neutrino event simulations used in the analysis of experiments.


q
end
p'
p

BACKUP SLIDES

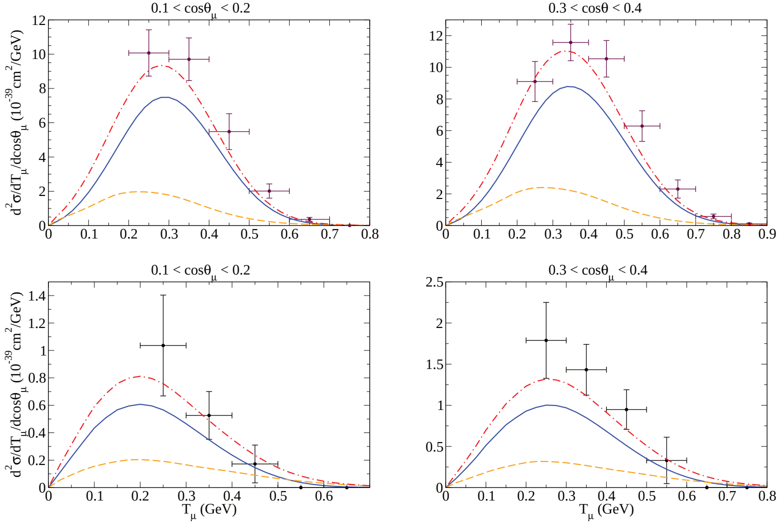
T2K $\nu_\mu - {}^{12}C$ cross sections



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

$\nu_\mu \Rightarrow$

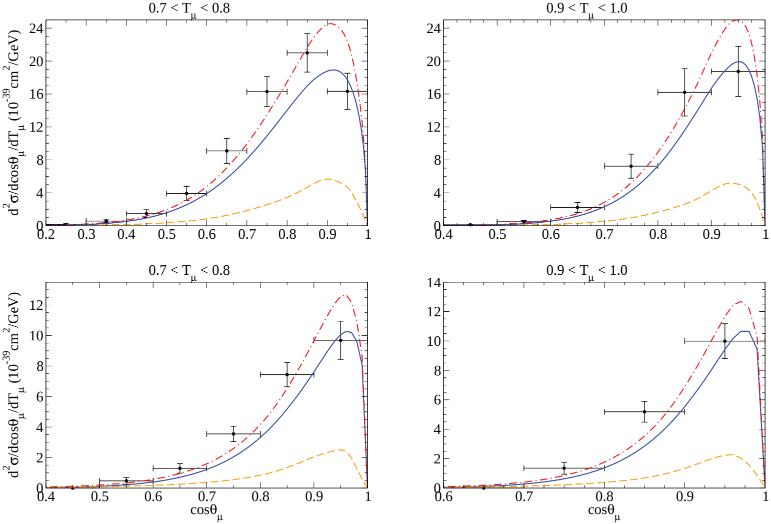
$\bar{\nu}_\mu \Rightarrow$



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

$\nu_\mu \Rightarrow$

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



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

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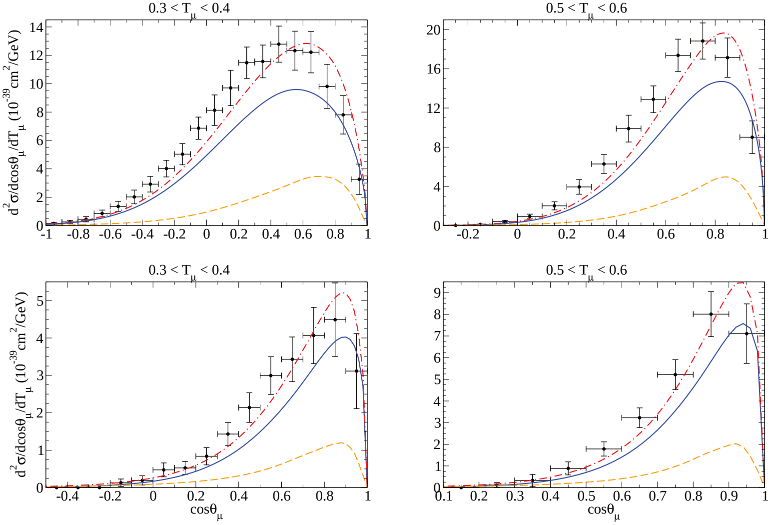
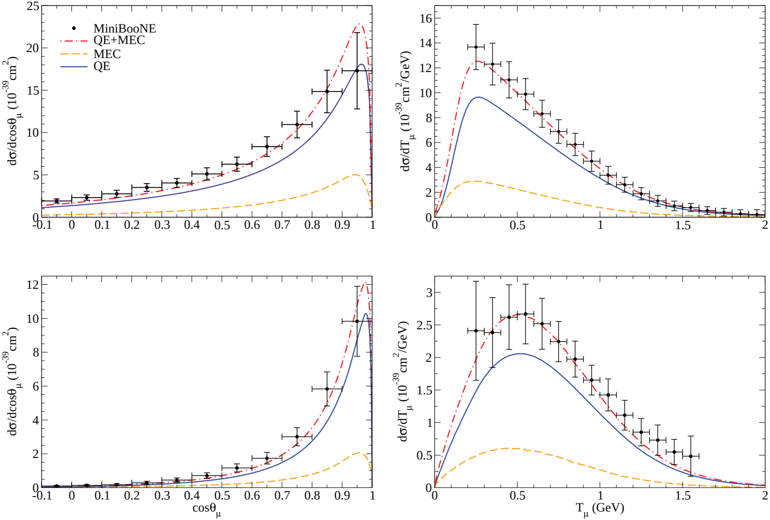


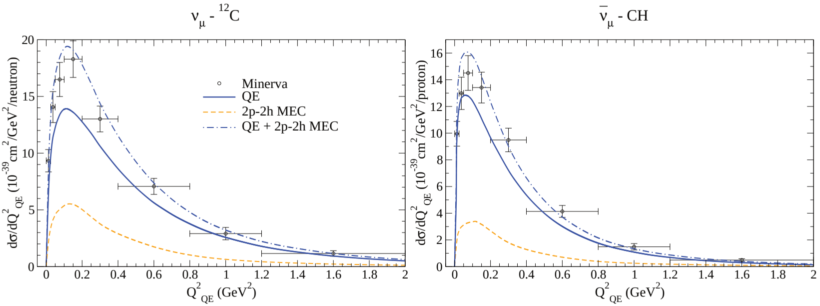
MiniBooNE $\nu_\mu - {}^{12}C$ single differential cross sections

$\nu_\mu \Rightarrow$

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

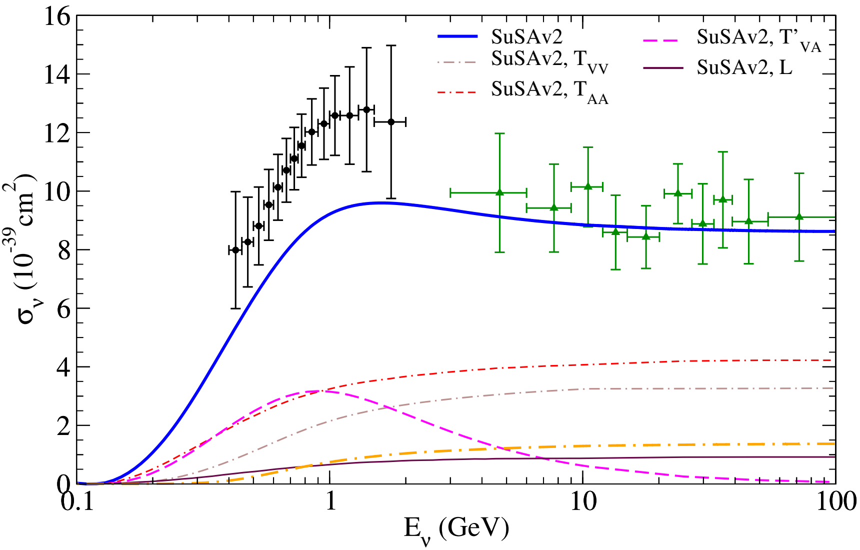


MINERνA $\nu_\mu-{}^{12}$C & $\bar{\nu}_\mu-$CH cross sections (NEW FLUX)

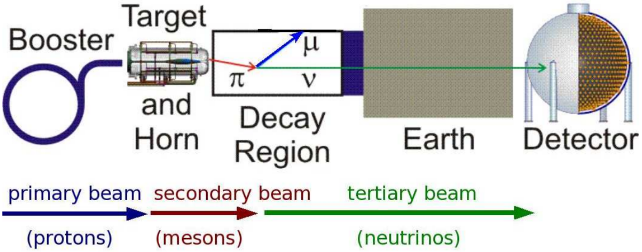


New MINERνA flux calculation. Data unpublished.

Separated Contributions in the SuSAv2 Model



Experimental status



Experimental difficulties:

- Determination of the incident neutrino flux, affected by uncertainties of the nuclear model as well as by background processes.
- Extremely reduced cross sections due to weak interactions ($\sim 10^{-6}$ EM) $\Rightarrow$ High experimental accuracy is essential.
- Most of experiments only detects the charged lepton in the final state, not the outgoing nucleon.

Theoretical description: CCQE ν-nucleus cross section

Differential cross section & Scattering matrix amplitude (S_{fi})

$$d\sigma = \frac{|S_{fi}|^2}{T \cdot \Phi_{inc}} dN_f \; ; \; S_{fi} = -i \int d^4X \cdot H_W(X) = -i \left[\frac{g}{2\sqrt{2}}\right]^2 \int j_\mu^{(l)}(X) D_W^{\mu\nu}(X\text{-}Y) J_\nu^{(N)}(Y)$$

Weak leptonic current: $j_\mu = j_\mu^V + \chi j_\mu^A$

$$j_\mu^V = \bar{u}(k')\gamma_\mu u(k)$$
$$j_\mu^A = \bar{u}(k')\gamma_\mu \gamma_5 u(k)$$

Weak hadronic current: $J^\mu = J_V^\mu + J_A^\mu$

$$J_V^\mu = \bar{u}(P')\left[F_1^V \gamma^\mu + \frac{i}{2m_N} F_2^V \sigma^{\mu\nu} Q_\nu\right] u(P)$$
$$J_A^\mu = \bar{u}(P')\left[G_A \gamma^\mu + \frac{1}{2m_N} G_P Q^\mu\right] u(P)$$

Double differential cross section

$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right]_\chi = \sigma_0 \mathcal{F}_\chi^2 \quad ; \quad \sigma_0 = \frac{\left(G_F^2 \cos\theta_c\right)^2}{2\pi^2}\left(k_\mu \cos\frac{\tilde{\theta}}{2}\right)^2 \quad ; \quad \chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$$

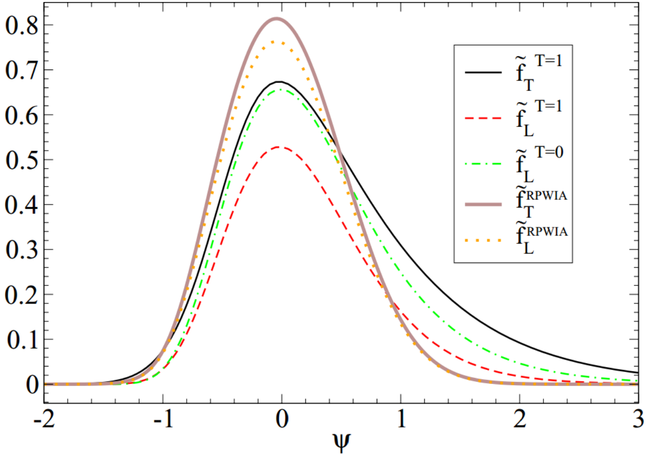
Nuclear structure information

$\mathcal{F}_\chi^2 = \hat{V}_L R_L + \hat{V}_T R_T + \chi\left[2\hat{V}_{T'} R_{T'}\right]$ $L \to (\mu\nu) = (00, 03, 30, 33)$; $T \to (11, 22)$; $T' \to (12, 21)$

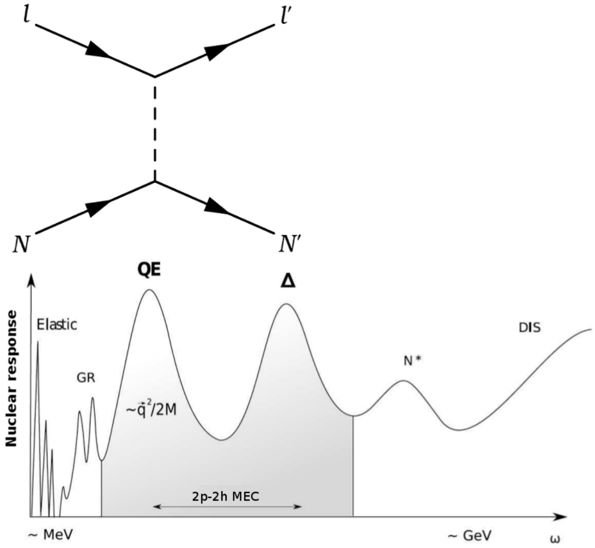
Rosenbluth-like decomposition: $R_L = R_L^{VV} + R_L^{AA}$; $R_{T'} = R_{T'}^{VA}$; $R_T = R_T^{VV} + R_T^{AA}$

Theoretical Description of the SuSAv2 model *PRC90, 035501, 2014*

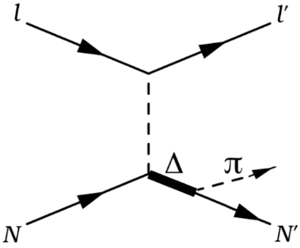
RMF+RPWIA; valid for all lepton-nucleus scattering processes

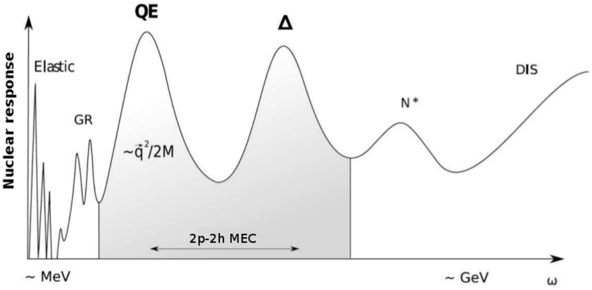


Nuclear response in terms of the energy transfered

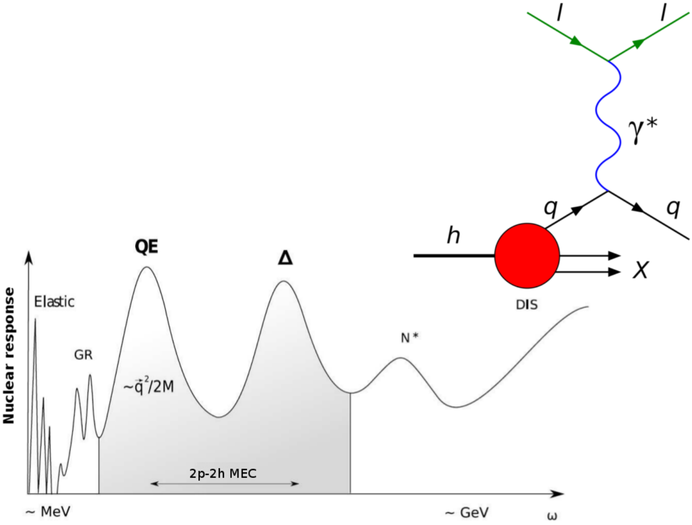


Nuclear response in terms of the energy transfered

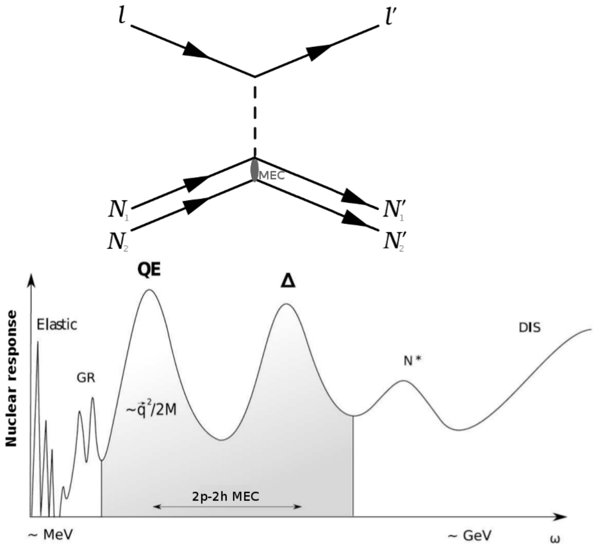




Nuclear response in terms of the energy transfered



Nuclear response in terms of the energy transfered



Theoretical Description of the SuSAv2 model *PRC90, 035501, 2014*

Present SuSA

Based on the superscaling function extracted from QE electron-nucleus scattering data.

. . .

SuSAv2

The Relativistic Mean Field model (RMF) is employed to improve the data analysis, where RMF accounts for FSI.

Longitudinal

Description of nuclear responses built only on the longitudinal scaling function. Assumption of $f_L(\psi) \approx f_T(\psi)$, scaling of 0^{th} kind.

. . .

Longitudinal + Transversal

Differences between transverse and longitudinal scaling functions are introduced in order to describe properly the nuclear responses.

Isoscalar + Isovector Structure

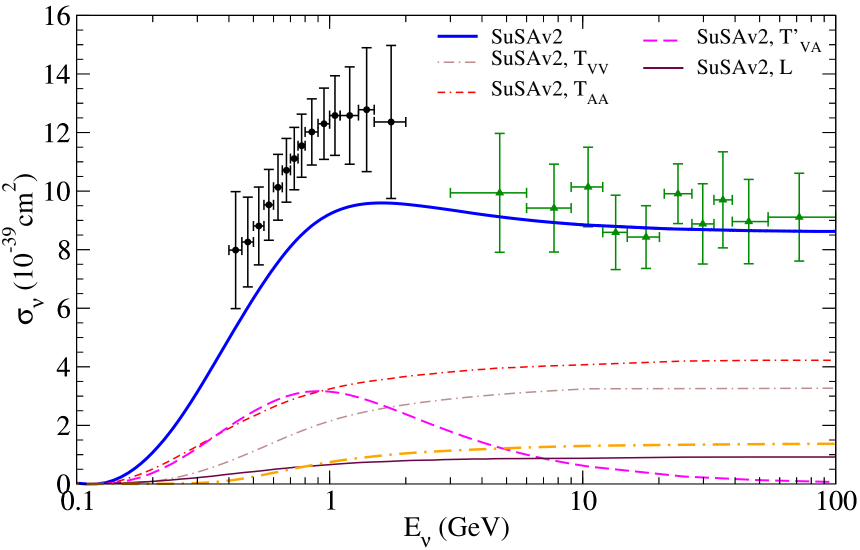
The scaling function based on QE electron scattering data takes into account isovector and isoscalar currents to describe the interaction between the electron and the nucleus.

. . .

Isovector structure

We separate the scaling function into isovector and isoscalar structure so as to employ a purely isovector scaling function for CCQE neutrino-nucleus processes where isospin changes.

Separated QE Contributions in the SuSAv2 Model



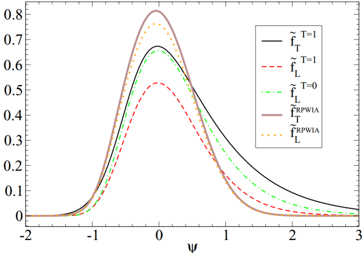
Theoretical description: Scaling phenomenon

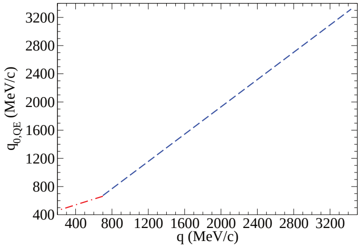
RMF/RPWIA transition: *arXiv:1603.08396 [nucl-th]*

- Whereas the RPWIA describes the outgoing nucleon as a relativistic plane wave, the RMF takes into account FSI between the outgoing nucleon and the residual nucleus using the same mean field as considered for the bound nucleon. the large kinetic energy of the outgoing nucleon at very high q should make the FSI effects negligible. new SuperScaling Approach as a combination of RMF and RPWIA scaling functions where the first dominates at low to intermediate q and the latter at high q

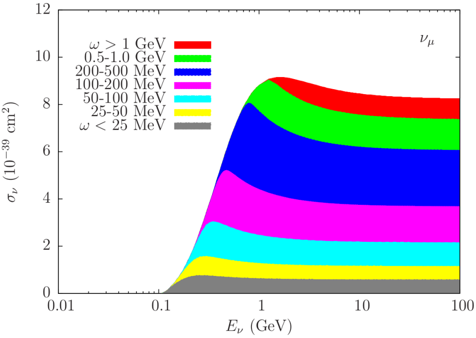
$$
\begin{aligned}
\mathcal{F}_L^{T=0,1} &\equiv \cos^2\chi(q,q_0)\tilde{f}_L^{T=0,1} + \sin^2\chi(q,q_0)\tilde{f}_L^{RPWIA} \\
\mathcal{F}_T &\equiv \cos^2\chi(q,q_0)\tilde{f}_T + \sin^2\chi(q,q_0)\tilde{f}_T^{RPWIA}
\end{aligned}
$$

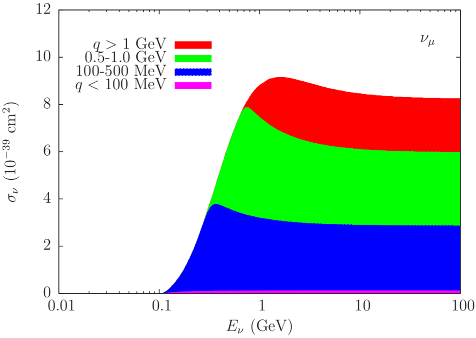
$q_0(q)$: RMF/RPWIA transition parameter, determined by performing a χ^2 analysis of the (e,e') data in a wide kinematical region





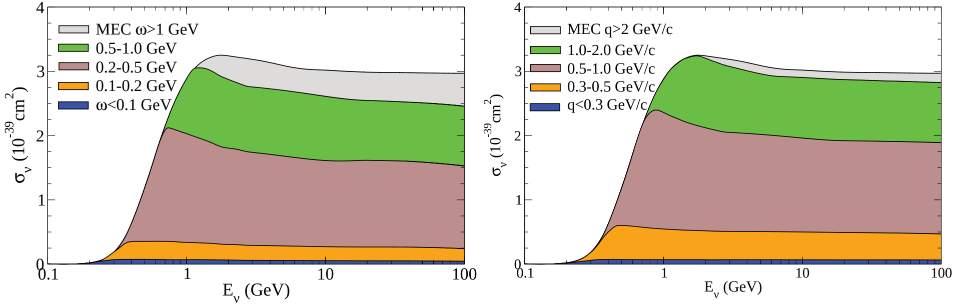
Relevant kinematic regions in the QE cross section





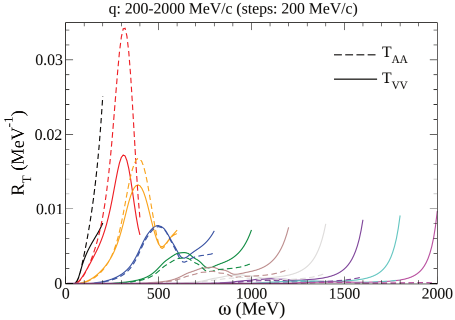
The main contribution to the total QE CS comes from $q < 1$ GeV/c and $\omega < 0.5$ GeV, even at high neutrino energies.

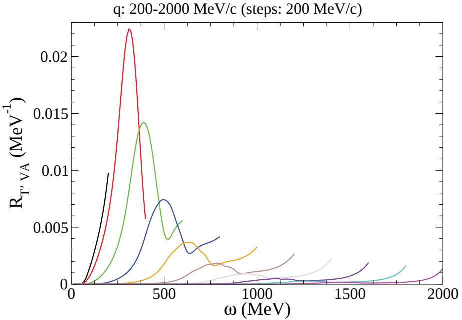
Relevant kinematic regions in the 2p-2h MEC cross section



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

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 $\Rightarrow \sigma(T_{AA}) \sim \sigma(T_{VV})$

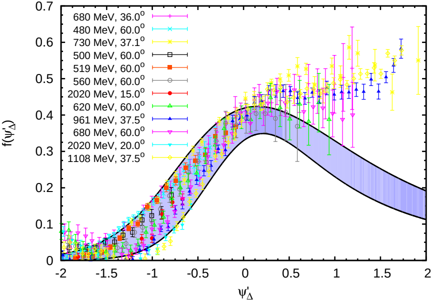
Inclusive total cross section ⇒ Δ-scaling model

Extension of the SuSA approach into the non-QE region [*JPG43, 045101 (2016)*], 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



Inclusive total cross section ⇒ Δ-scaling model

This procedure yields a good representation of the electromagnetic response in both the QE and Δ regions.

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

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