Meson-exchange currents and quasielastic predictions in the SuperScaling Approach

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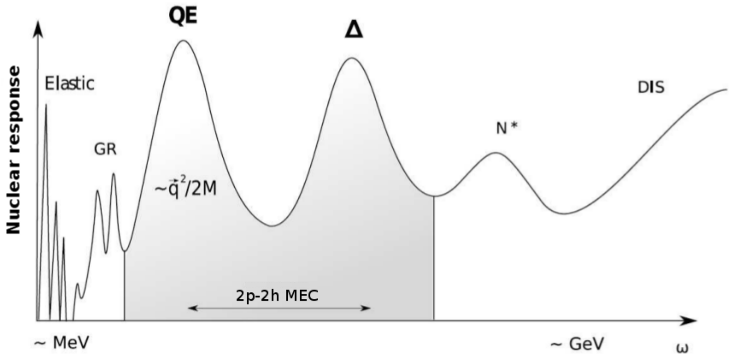
Nuclear response in terms of the energy transfered



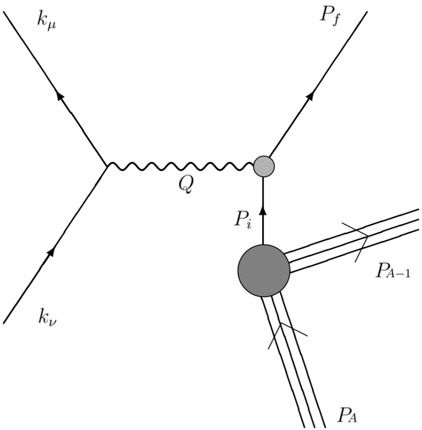
Quasielastic Regime

CCQE scattering

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

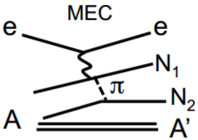
Impulse Approximation (IA)

The neutrino only interacts with a single bound nucleon.

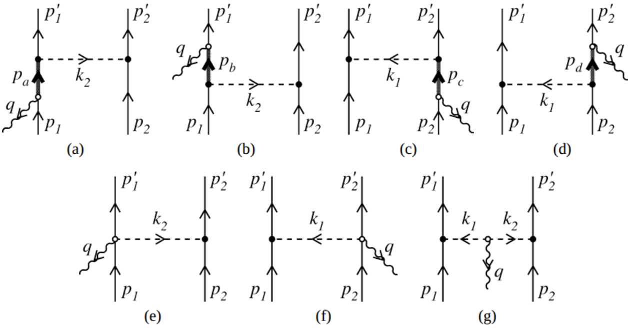


2p-2h MEC contributions

➠ 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 $\nRightarrow$ 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.

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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

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

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

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: 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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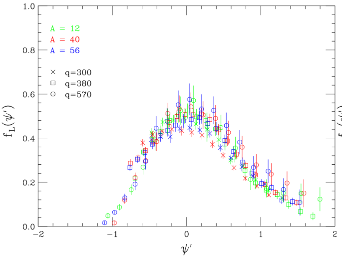
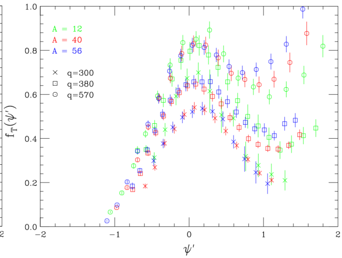




Scaling violations in the T channel $\Rightarrow$ 2p-2h MEC, correlations

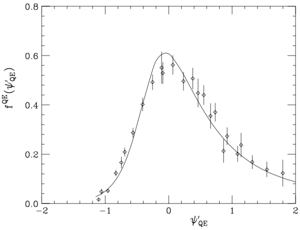
Theoretical description: Scaling phenomenon

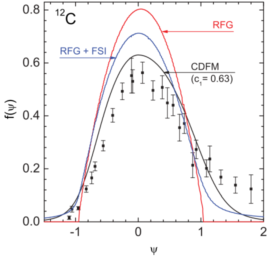
Original SuSA model:

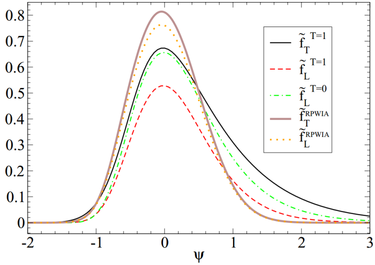
- Fit of the (e, e') longitudinal scaling data
- Assumption $f_L(\psi) = f_T(\psi)$

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

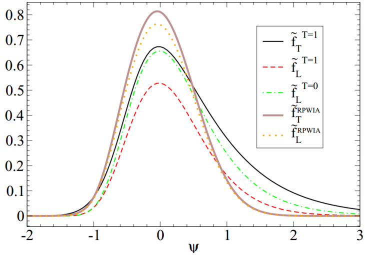
RMF/RPWIA transition: *arXiv:1603.08396 [nucl-th]*

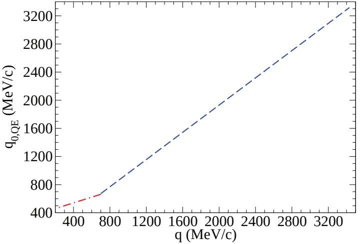
- RMF ⇒ FSI between the outgoing nucleon and the residual nucleus ⇒ low-intermediate q
- RPWIA ⇒ outgoing nucleon as a relativistic plane wave ⇒ higher q values

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

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

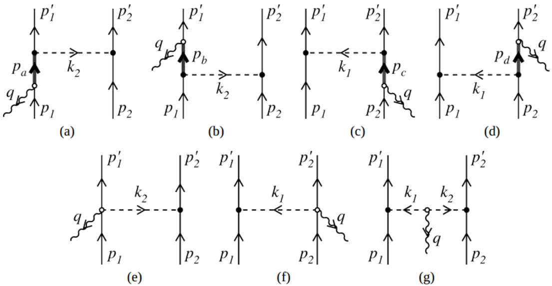
➢ $q_0(q)$: RMF/RPWIA transition parameter, determined by performing a χ^2 analysis of the (e,e') data in a wide kinematical region.





2p-2h MEC for CC neutrino 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)] (see Amaro's talk).

✪ 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**

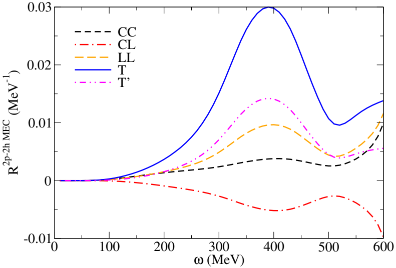
2p-2h MEC parametrization

PRD91, 073004, 2015

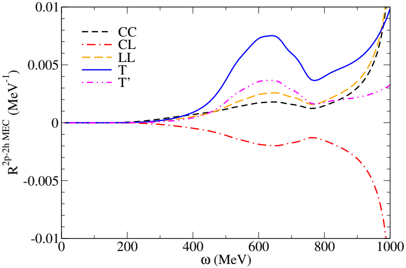
$$R_X^{2p-2hMEC}(\psi', q) = \frac{2a_3 e^{-\frac{(\psi'-a_4)^2}{a_5}}}{1+e^{-\frac{(\psi'-a_1)^2}{a_2}}} + \sum_{k=0}^{2} b_k(\psi')^k$$

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

$a_i(q), b_k(q)$



q=600 MeV/c



q=1000 MeV/c

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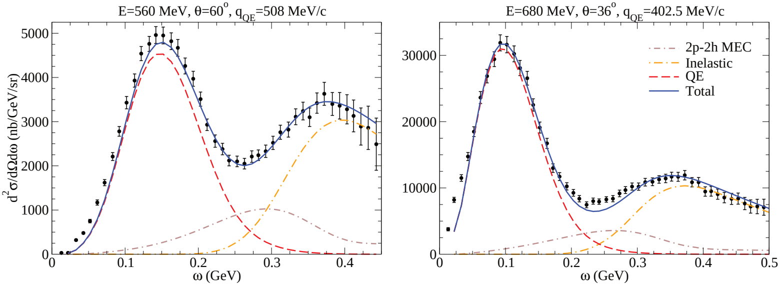
Inclusive $^{12}C(e,e')$ cross sections *arXiv:1603.08396 [nucl-th]*

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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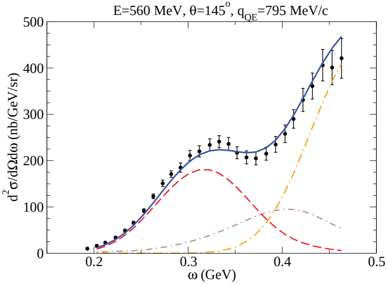

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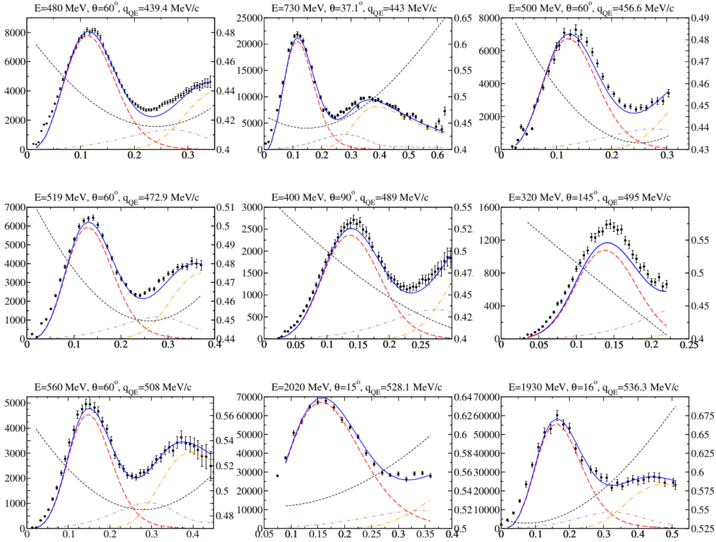

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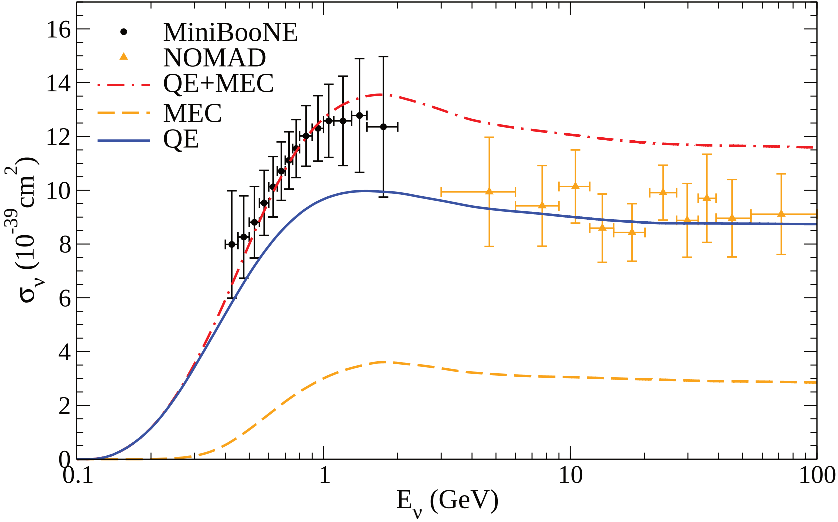
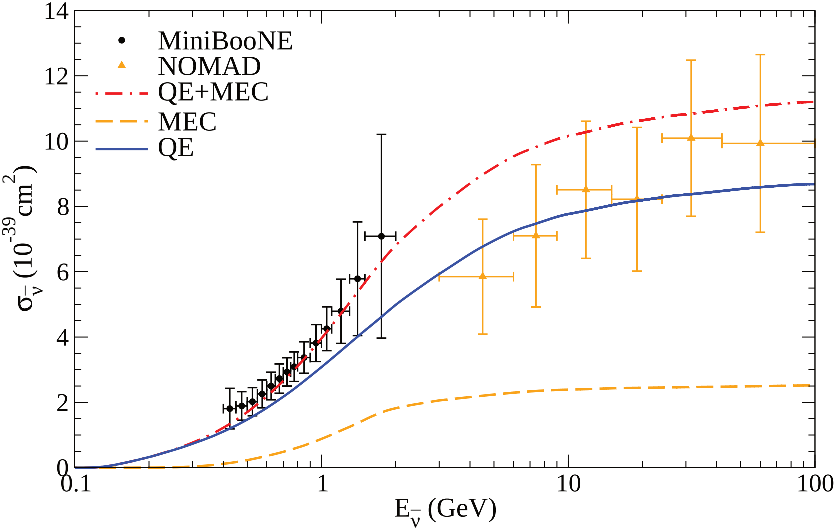
ν_μ-^{12}C CCQE scattering

PRELIMINARY RESULTS



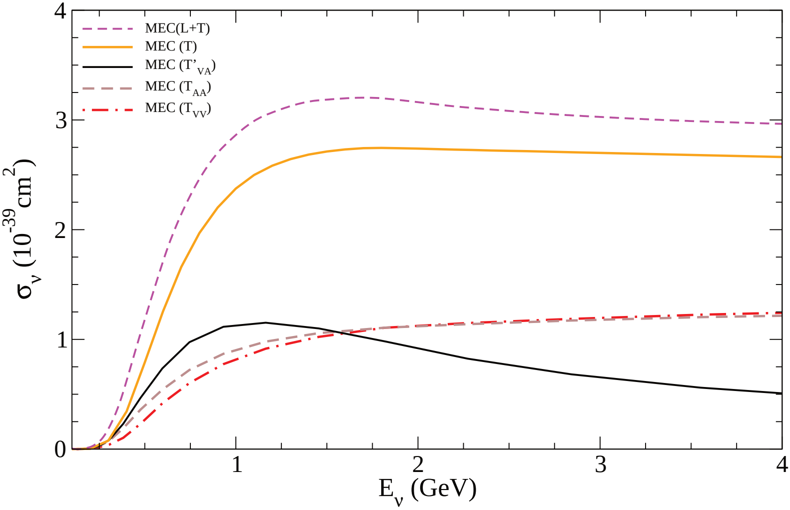
$\bar{\nu}_\mu$-^{12}C CCQE scattering

PRELIMINARY RESULTS



ν_μ-^{12}C CCQE scattering

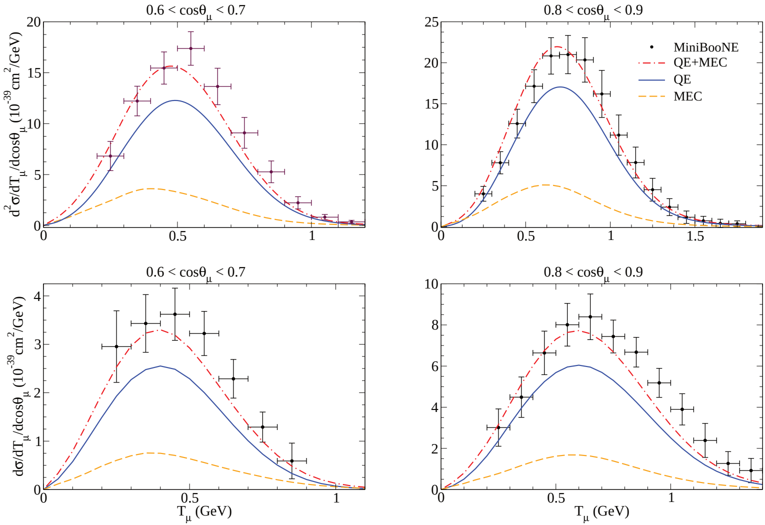
PRELIMINARY RESULTS



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

$\nu_\mu \Rightarrow$

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



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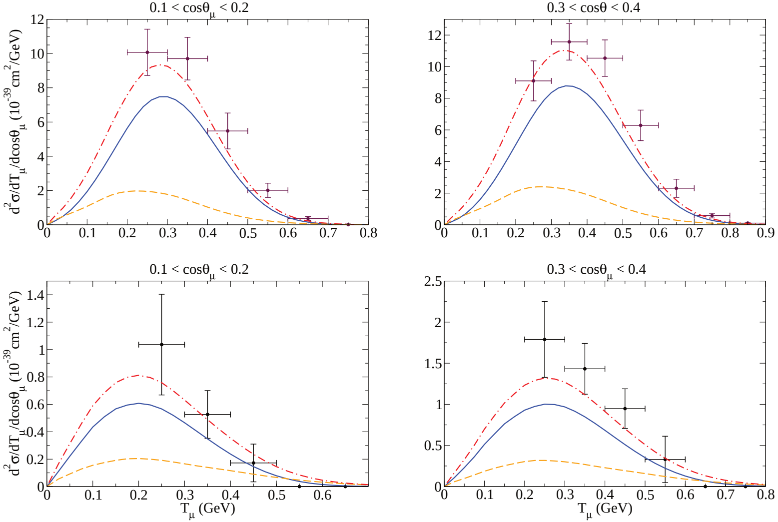

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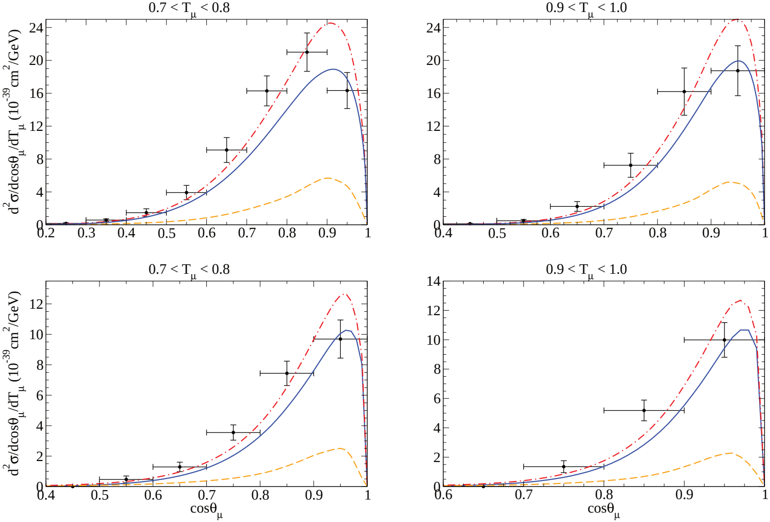

MiniBooNE $\nu_\mu - ^{12}$C double differential cross sections

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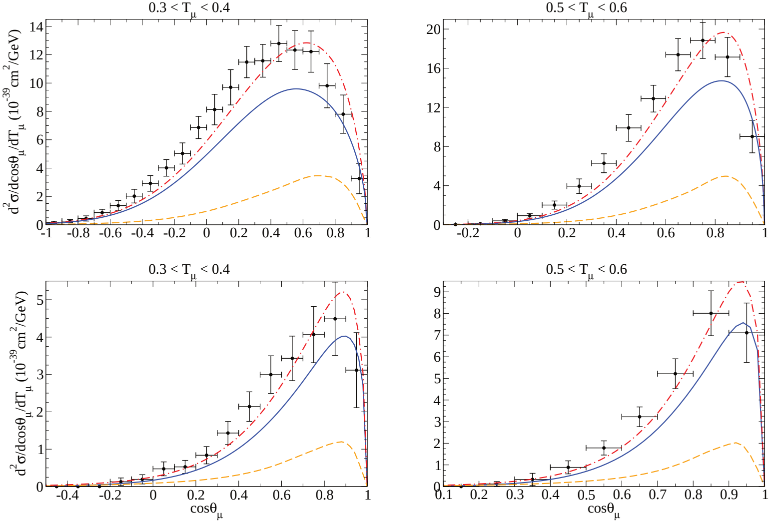

MiniBooNE ν_μ—^{12}C single differential cross sections

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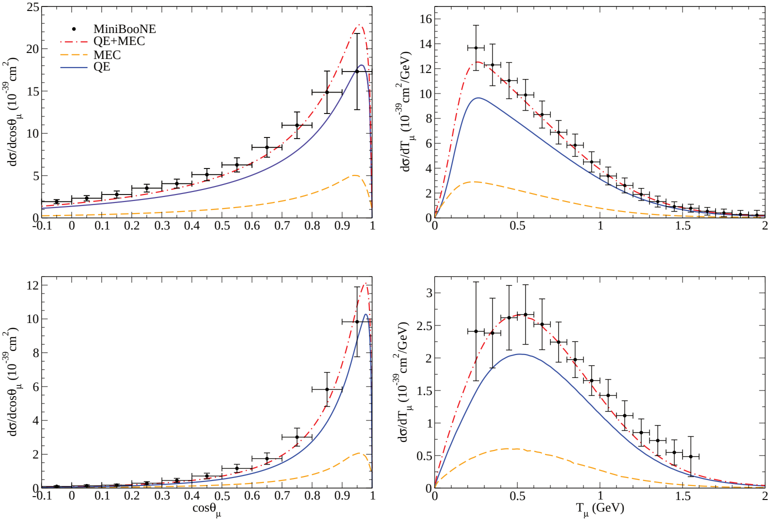
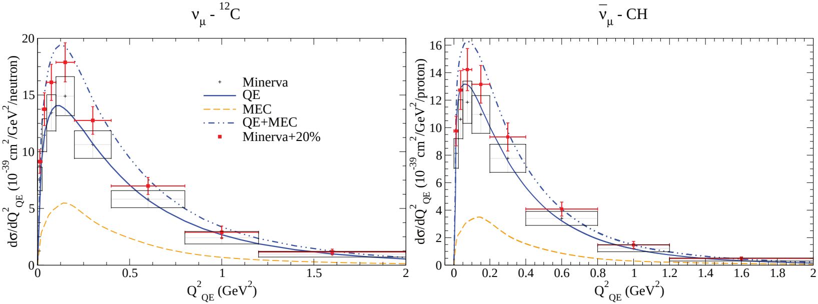


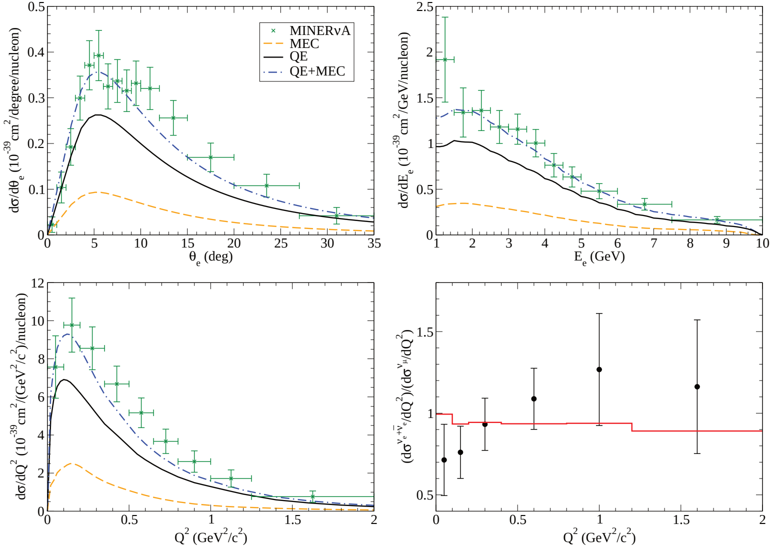
MINERνA $\nu_\mu-^{12}$C & $\bar{\nu}_\mu-$CH cross sections



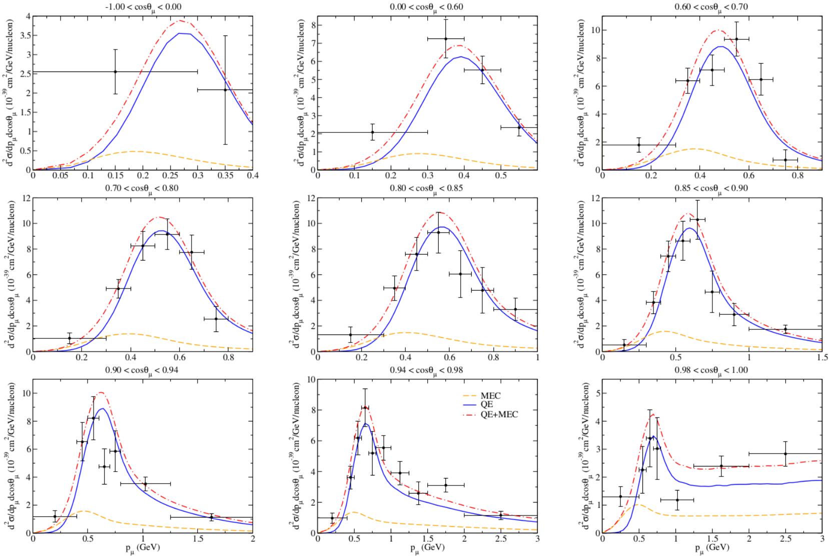
Our QE+MEC predictions overstimate experimental data.

The expected shift in cross-sections of $\sim$ 20% with the new MINERνA flux calculation (see Betancourt's talk in NuINT15) would result in a better agreement between our results and the experimental data.

MINERνA ν_e—^{12}C cross sections



T2K ν_μ—^{12}C cross sections



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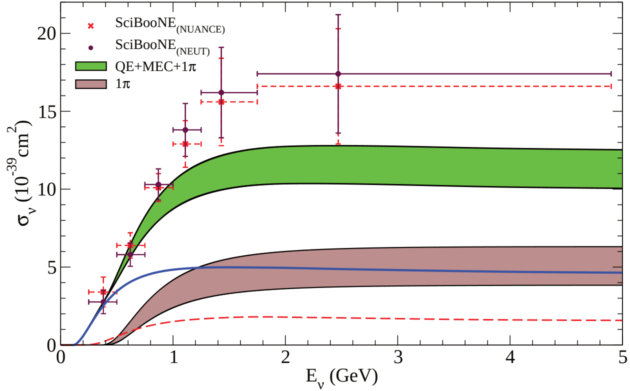
Inclusive total cross section ⇒ Δ-scaling model

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.

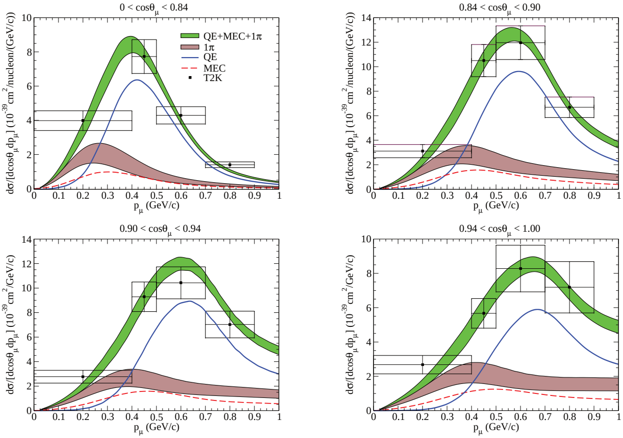


QE+MEC+Δ contributions are not enough to describe inclusive cross section at $E_\nu \gtrsim 1$ GeV ⇒ Work in progress to include DIS in the ν interaction model.

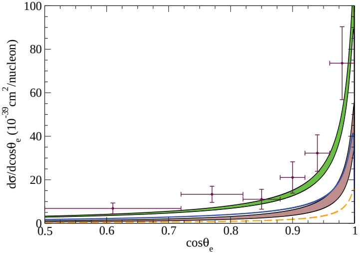
QE+MEC+Δ contributions in $\nu_\mu - ^{12}$C scattering

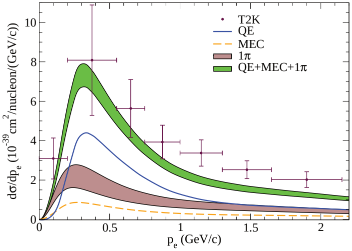
Analysis of T2K ν_μ data ($< E_{\nu_\mu} > \sim$ 0.8 GeV) *JPG43, 045101 (2016)*

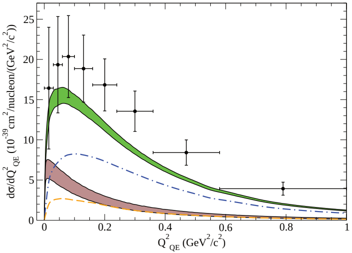
- Deep Inelastic Scattering contributions are not relevant at T2K kinematics.
- Work in progress to include the DIS description $\Rightarrow$ analysis of higher-energy data.



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 energies.

➲ 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 (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.*

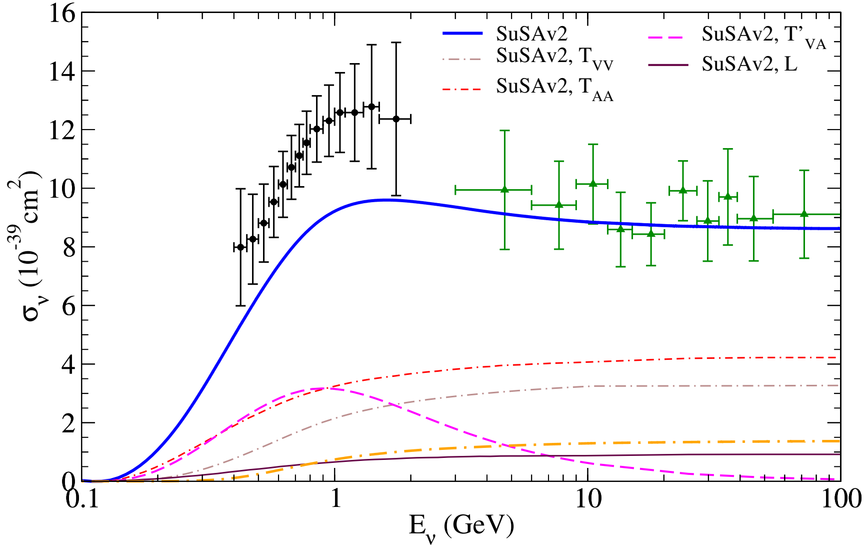
➲ The possibility of describing the QE and the MEC contributions through a straightforward parametrization might be of interest to Monte Carlo neutrino event simulations used in the analysis of experiments.

Conclusions and Further Work

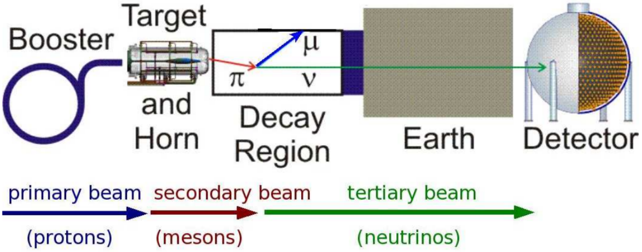
Backup Slides and References

- MiniBooNE: Phys. Rev. D 81, 092005 (2010); Phys. Rev. D 88, 032001 (2013)
- NOMAD: Eur. Phys. J. C63, 355 (2009)
- MINERνA: Phys. Rev. Lett. 111, 022501 (2013); Phys. Rev. Lett. 111, 022502 (2013); Phys. Rev. Lett. 116, 081802 (2016)
- T2K: Phys. Rev. D 87, 092003 (2013); Phys. Rev. Lett. 113, 241803 (2014); arXiv:1602.03652 [hep-ex]
- SciBooNE: Phys. Rev.D 83, 012005 (2011)

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

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

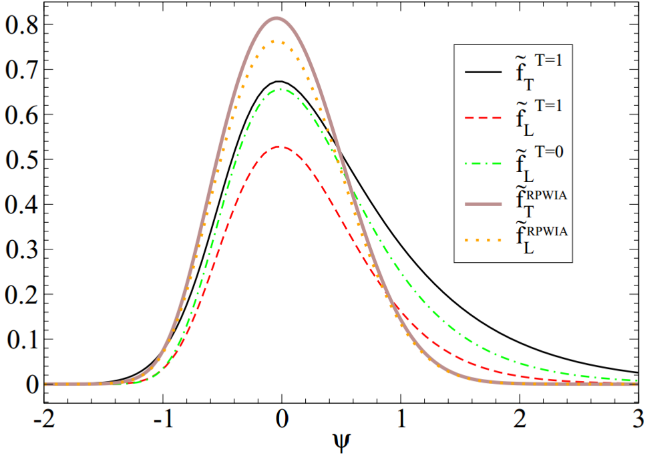
Nuclear structure information

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

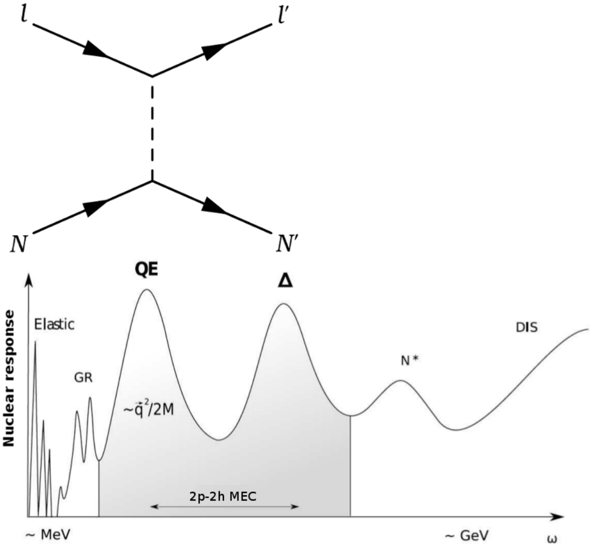
Rosenbluth-like decomposition: $R_L = R_L^{VV} + R_L^{AA}$; $R_{T'} = R_{T'}^{VA}$; $R_T = R_T^{VV} + R_T^{AA}$

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



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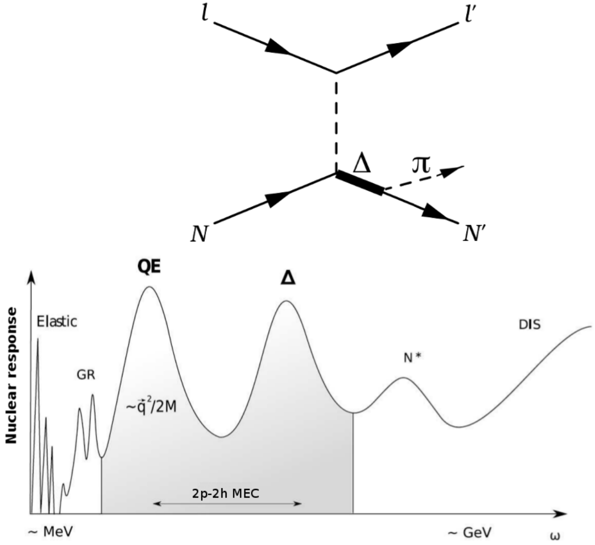
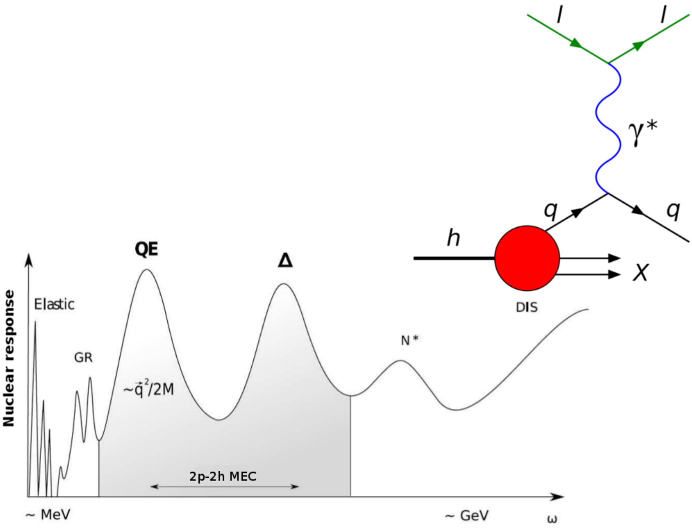


Nuclear response in terms of the energy transfered



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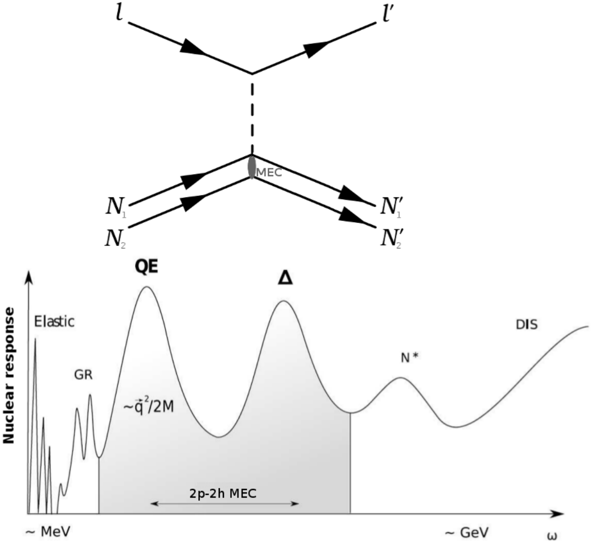


Theoretical Description of the SuSAv2 model *PRC90, 035501, 2014*

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

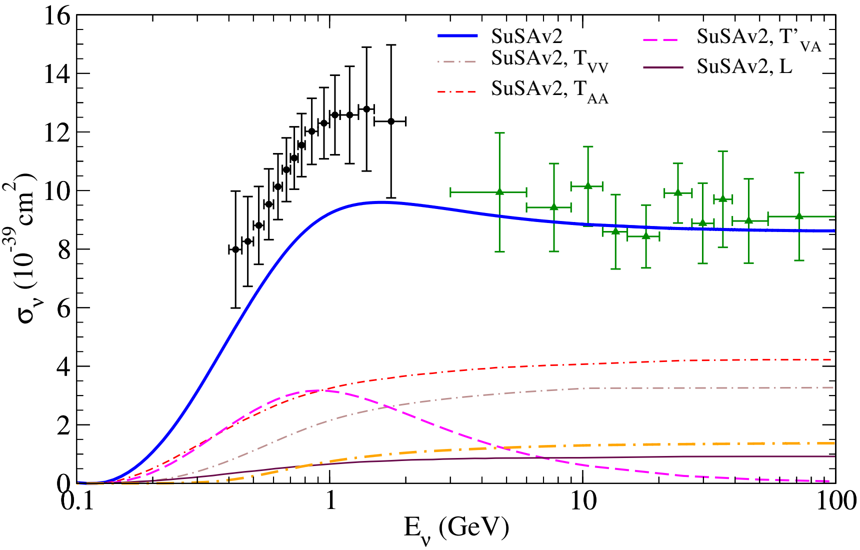
The scaling function based on QE electron scattering data takes into account isovector and isoscalar currents to describe the interaction between the electron and the nucleus.

...

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



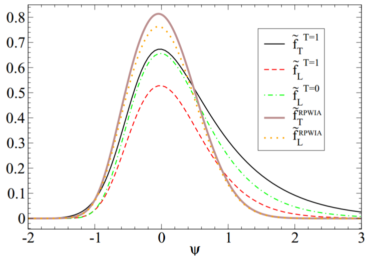
Theoretical description: Scaling phenomenon

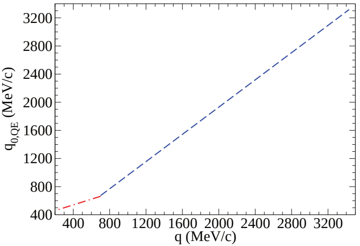
RMF/RPWIA transition: *arXiv:1603.08396 [nucl-th]*

- 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

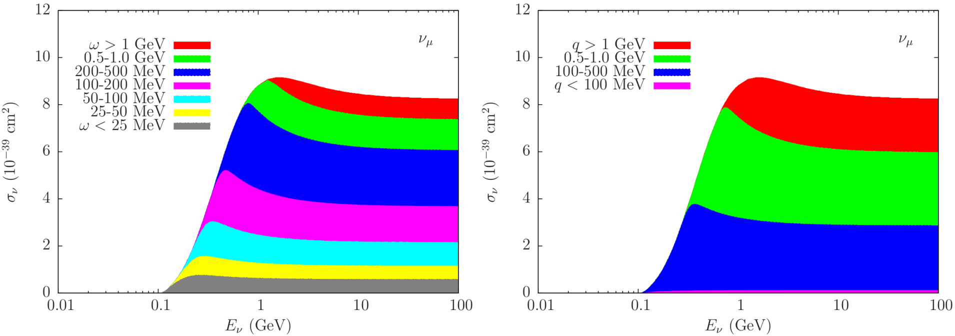
$$\mathcal{F}_L^{T=0,1} \equiv \cos^2\chi(q,q_0)\tilde{f}_L^{T=0,1} + \sin^2\chi(q,q_0)\tilde{f}_L^{RPWIA}$$
$$\mathcal{F}_T \equiv \cos^2\chi(q,q_0)\tilde{f}_T + \sin^2\chi(q,q_0)\tilde{f}_T^{RPWIA}$$

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



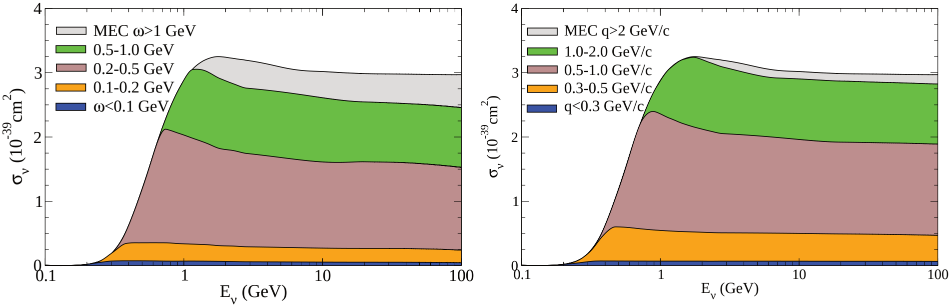


Relevant kinematic regions in the QE cross section



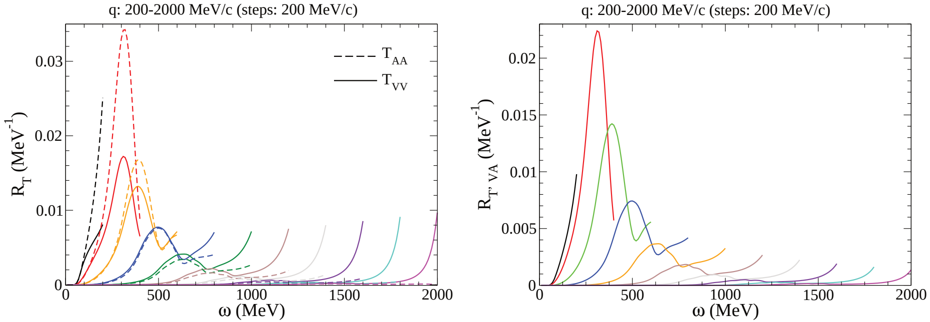
The main contribution to the total QE CS comes from $q < 1$ GeV/c and $\omega < 0.5$ GeV, even at high neutrino energies.

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

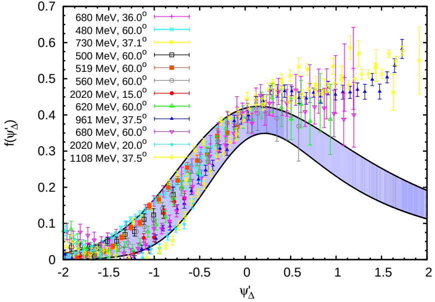
Inclusive total cross section ⇒ Δ-scaling model

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.

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

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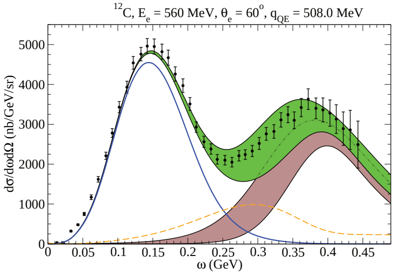

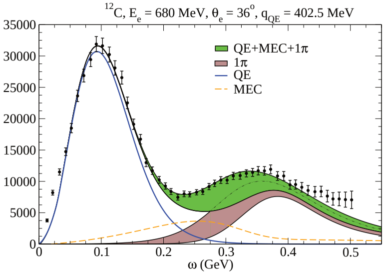

Theoretical description: Nuclear model dependence

➠ 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.

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.

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