Modeling neutrino-nucleus interactions in the GeV region

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WhatNext: Sezioni d'urto dei neutrini
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Motivation 1: neutrino physics

- Recent, ongoing and future accelerator experiments (MiniBooNE, SciBooNE, MINERνA, T2K, NOvA, MINOS, ArgoNeut, MicroBooNE, DUNE...) studying neutrino oscillations use complex nuclei (C, Ar, Fe, Pb, O) as targets

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- They cover a wide energy range $E_\nu \sim 1 - 10\ GeV$: nuclear effects in the different energy regions must be under control for the analysis and interpretation of data
- The neutrino energy is not well known experimentally (only the flux is known with some precision) and must be reconstructed from the scattering product on the basis of a model

$$P_{\alpha\to\beta} = |\langle\nu_\alpha|\nu_\beta(t)\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{im_i^2 L/2E_\nu}\right|^2$$

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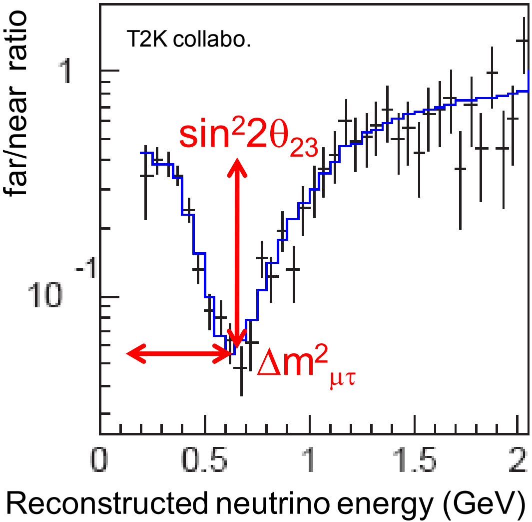

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- Neutrinos (weak probes) can give informations on the nuclear structure and dynamics complementary to electrons (e.m. probes)
- New insight on nucleonic physics can be gained by probing the nucleus with neutrinos:
  - CC events are sensitive to the nucleon axial mass M_A
  - NC events can probe the strangeness content of the nucleon

  Nuclear effects - final state interactions, NN correlations, two-body currents,... - must be well understood before drawing conclusions on the nucleonic physics

Goals

- Final goal: consistent treatment of nuclear effects in the energy range covered by accelerator experiments from low to intermediate and high values

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- Intermediate goal: quantitative assessment of the uncertainties associated with the theoretical description of the nuclear cross sections

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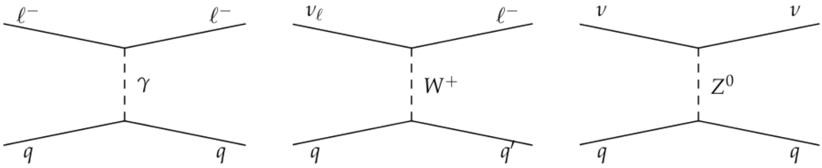

(a) Electromagnetic scattering (b) Charged-current scattering (c) Neutral-current scattering

$l = e, \mu, \tau$

Lepton-nucleus interactions

- Electron-nucleus interaction, mediated by γ (EM) and Z (weak)
- Neutrino-nucleus interaction, mediated by $W^\pm$ (CC) and Z (NC)

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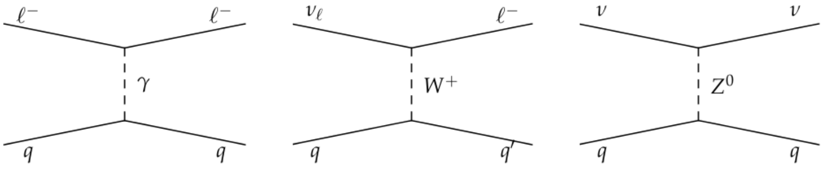

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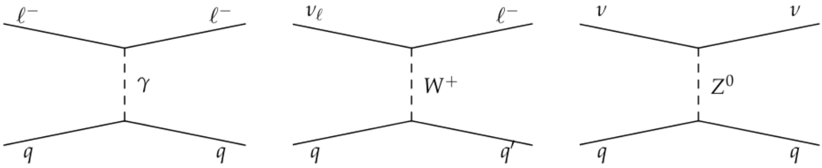

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- Neutrino-nucleus interaction, mediated by $W^{\pm}$ (CC) and Z (NC)
- **Many high quality $e - A$ data exist. For $\nu - A$ these**
  - **must be used as a test**
  - **can be used as an input**

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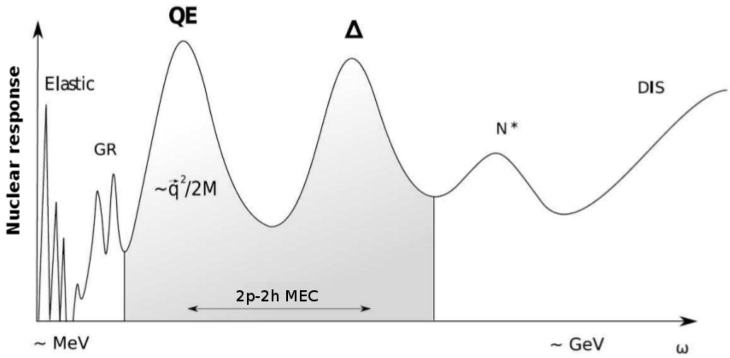
Nuclear response to an electroweak probe



G.D. Megias

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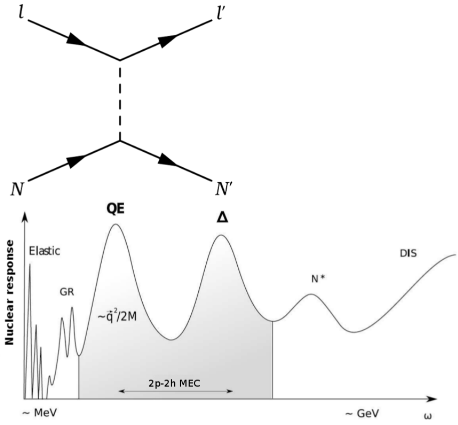

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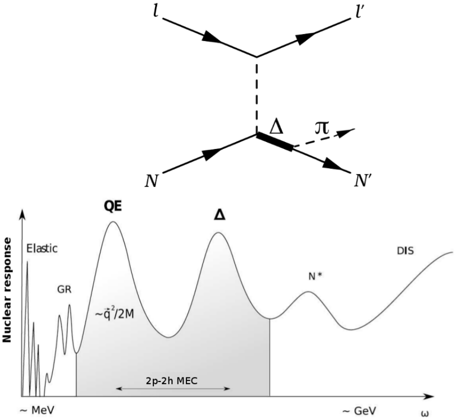

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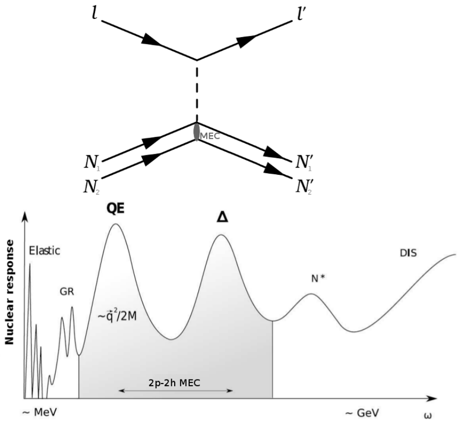

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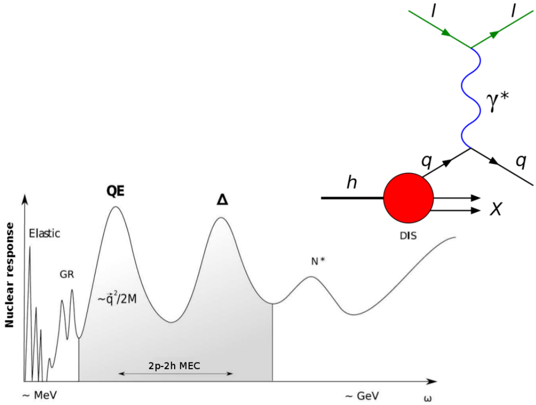

G.D. Megias

Reaction Mechanisms in the GeV region

- quasielastic scattering: 1p1h (one-particle-one-hole) excitation
- 2p2h excitations (Meson Exchange Currents)
- pion production, mainly through the excitation of a Δ resonance
- excitation of higher resonances and subsequent decay
- deep inelastic scattering

Major difference between ν and e experiments

- (e, e'): the electron energy is known and different mechanisms can be clearly identified by knowing the energy and momentum transfer (e.g., QE scattering corresponds to a well-defined peak in the ω spectrum);

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- CC (ν_l, l): E_ν is reconstructed from the detected lepton kinematics in a nuclear-model dependent way (e.g., QE is defined as "no pions in the final state").
- NC $(\nu_l, \nu_l')N$: the final neutrino cannot be detected, the ejected nucleon is observed (u-channel scattering). In this case the energy transfer is not fixed, even for monochromatic neutrino beams.

Nuclear models: requirements

A good model should

- contain relativistic ingredients (not only kinematics, but also nuclear dynamics and current operators), important in the GeV region;
- describe electron scattering data from intermediate up to high energies.

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The Relativistic Fermi Gas (RFG) model, employed in most neutrino generators, fulfills in part the first requirement, but not the second.

Our Model

Two approaches:

1. Phenomenological approach based on electron scattering: "Superscaling" (SuSA)
2. Microscopic model suited to describe lepton-nucleus scattering in the GeV region: Relativistic Mean Field (RMF)

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"SuSAv2"

- The combination of the three above ingredients defines the so-called SuSAv2 model

Other nuclear models

- RGF: Relativistic Green's Functions
  (Giusti, Pavia)
- SF: Spectral Function
  (Benhar, Roma)
- RPA: Random Phase Approximation
  (Nieves, Valencia; Martini, Saclay; Jachowicz, Gent)
- GFMC: Green Function Monte Carlo
  (Carlson, Schiavilla, Los Alamos, ODU)
- GIBUU: Giessen Boltzmann–Uehling–Uhlenbeck transport model
  (Mosel, Giessen)

Formalism: response functions

Double differential CC cross section

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

Nuclear structure information

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

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

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

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

Rosenbluth-like decomposition: 3 responses

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

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

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

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

$$j^\mu = j^\mu_V + j^\mu_A \quad ; \quad J^\mu = J^\mu_V + J^\mu_A$$

Weak nuclear current

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

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

Nuclear responses

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

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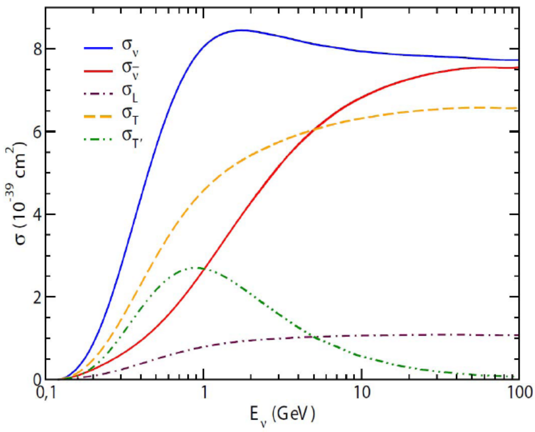
QE responses



The SuperScaling appraoch *PRC71, 015501, 2005*

The SuSA model is 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 one particular variable, called scaling variable.
- In lepton-nucleus scattering nuclear effects can be analyzed through a scaling function constructed from the ratio between the QE cross section and an appropriate function embodying the single-nucleon physics

The QE SuperScaling function

$$f(q,\omega) = k_F \frac{\frac{d^2\sigma_{QE}}{d\Omega d\omega}}{\sigma_{Mott}\left(v_L G_L + v_T G_T\right)} = \frac{\text{nuclear cross section}}{\text{elementary single nucleon function}}$$

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For high enough momentum transfer q (larger than about 400 MeV/c),

$$f(q,\omega) \to f(\psi) \tag{1}$$

where the scaling variable $\psi(\omega, q)$ represents *the minimum energy required to a moving nucleon inside the nucleus to participate in the reaction in the RFG model*.

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SuperScaling

Scaling of 1^{st} kind:
independence of the momentum transfer q
Scaling of 2^{nd} kind:
independence of the nuclear species A

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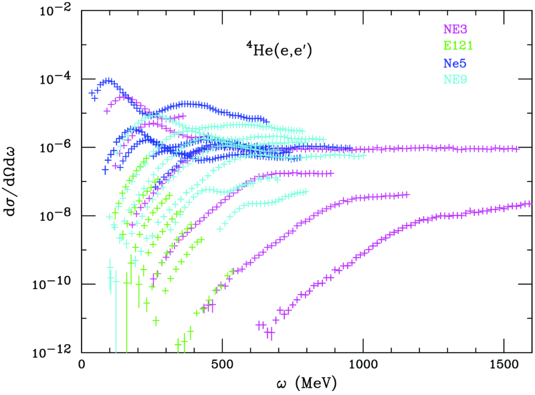
- Experimentally susperscaling is fullfilled with good accuracy for energy tansfers below the QEP (the so-called "scaling region")

Scaling of I kind

Donnelly and Sick, PRL82(1999)



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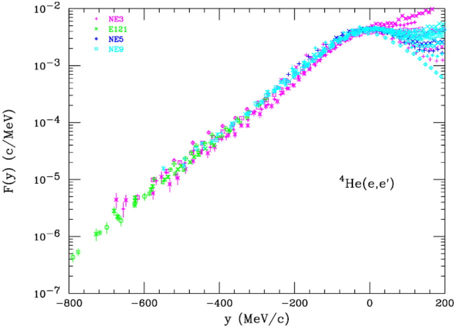
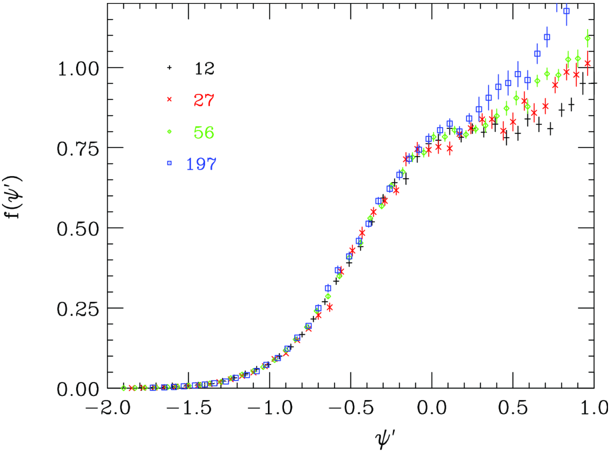


Scaling violations beyond the quasielastic peak due to non-QE processes

Scaling of II kind

Donnelly and Sick, PRL82(1999)



SuperScaling in the L and T channels

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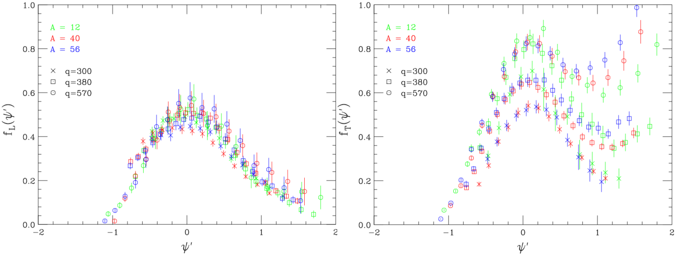
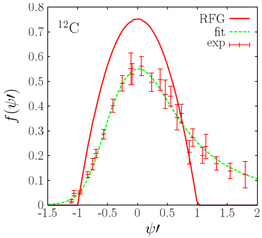


Scaling violations mainly reside in the T channel

SuperScaling and neutrino scattering

Amaro et al., PRC71, 015501, 2005



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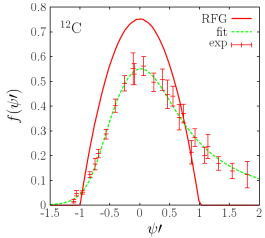

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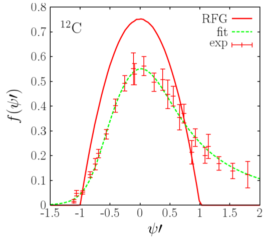

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- The approach is based on two assumption:
  1) $f_L(\psi) = f_T(\psi)$
  2) $f_{T=0}(\psi) = f_{T=1}(\psi)$

SuSAv2 *PRC90, 035501, 2014*

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- Ingredients of the RMF:
  - bound nucleon states are four-spinors, obtained from the self-consistent solution of the Dirac-Hartree equation, with underlying Walecka Lagrangian (σ, ω and ρ mesons);
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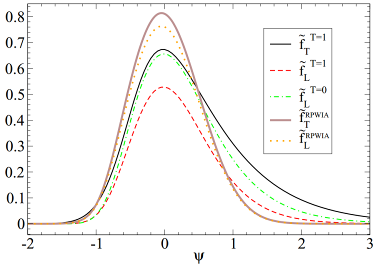
- Results:
  - good agreement with the phenomenological longitudinal scaling function;
  - the transverse scaling function exhibits an enhancement of $\sim$20% with respect to the longitudinal one, in agreement with the analysis of separated L/T data;
  - difference between the isoscalar and isovector components, of interest for CC neutrino reactions.

The SuSAv2 scaling functions *PRC90, 035501, 2014*



RPWIA = RMF with plane waves for the ejected nucleon (no FSI)

Asymmetric high-energy tail due to FSI

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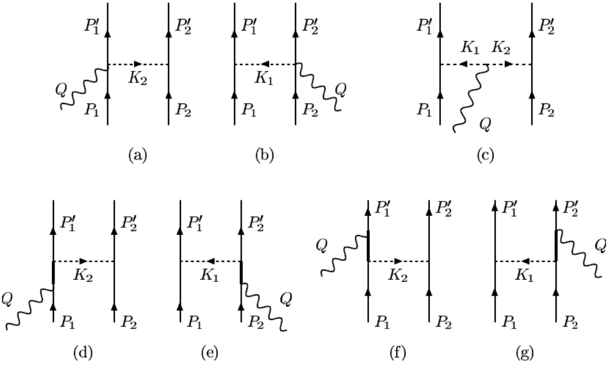
Two-body currents



The vector boson from the leptonic current is absorbed by a pair of nucleons (2-body current) ⇒ 2-nucleon emission from the primary vertex.

2p-2h MEC and CC neutrino reactions

- Our model for 2p2h contribution is based on the calculation De Pace et al., Nucl. Phys. A 726, 303 (2003) performed for electron scattering: first attempt for a relativistic description of electromagnetic 2p-2h Meson Exchange Currents

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- Recent extension to the weak sector [PRD 90, 033012 (2014); PRD 90, 053010 (2014)]

Comparison with other 2p-2h MEC models

- Discrepancy between the MiniBooNE data and traditional QE nuclear models ⇒ nuclear correlations, final-state interactions, and meson-exchange currents (MECs) play an important role.
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- 3 microscopic models based on RFG predicting multinucleon knockout effects QE $\nu-{}^{12}$C cross sections:

Model	Relativistic ingredients	Including
Martini	Based on a non-rel model relativistic kinematics added	MEC and pionic correlation diagrams direct-exchange interference neglected
Nieves	rel., with some kinematical approximations in the WNNπ vertex	momentum of the nucleon in the WNNπ vertex fixed direct-exchange interference neglected
SuSAv2	fully relativistic	2p-2h MEC but no correlations (in progress) including all interference terms

Martini et al. PRC81, 045502 (2010)
Nieves et al. PRC83, 045501 (2011)
Ruiz-Simo et al. PRD90, 033012 (2014); PRD91, 073004 (2015)

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The inelastic region

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

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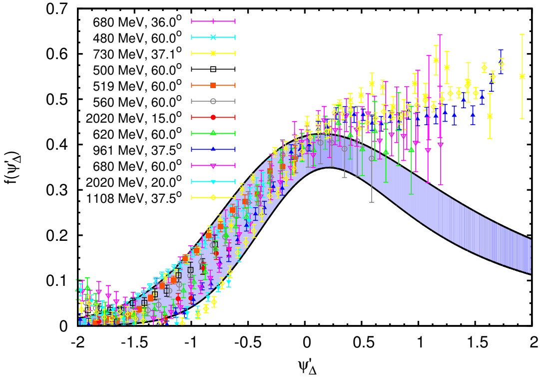
- employing phenomenological fits of the single-nucleon inelastic structure functions and assuming that the scaling function is the same in all energy regions $\longrightarrow$ full spectrum (from the Δ resonance to DIS) [PRC69, 035502, 2004]
- subtracting the QE + 2p-2h MEC contributions from the total cross section, assuming that it is dominated by the Δ-resonance [arXiv:1506.00801 [nucl-th]]

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

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

Scaling in the Δ region



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

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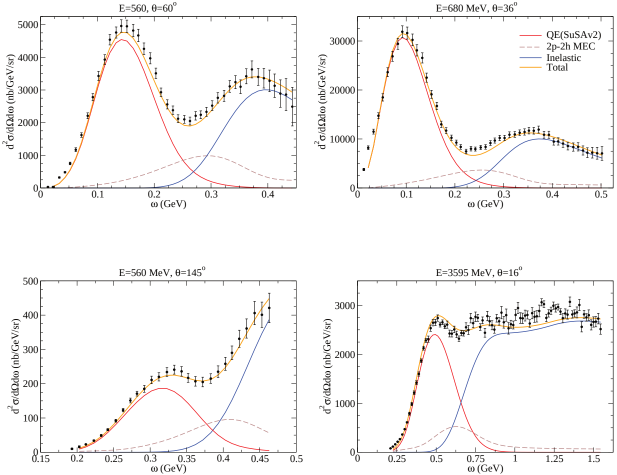
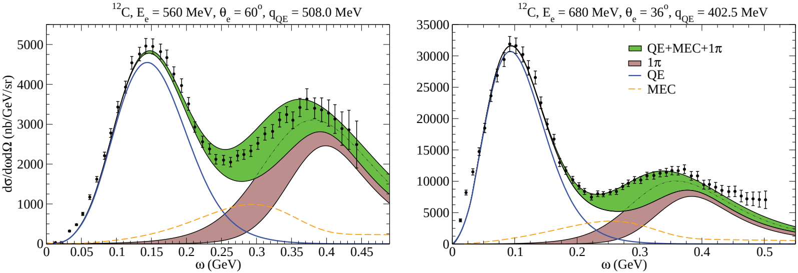
Inclusive $^{12}C(e, e')$ cross sections *(PRELIMINARY)*

QE SuSAv2 + 2p2h + full inelastic model:



Inclusive $^{12}C(e,e')$ cross sections *(PRELIMINARY)*

QE SuSAv2 + 2p2h + Δ superscaling:



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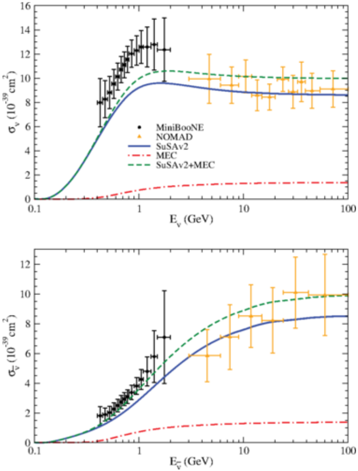
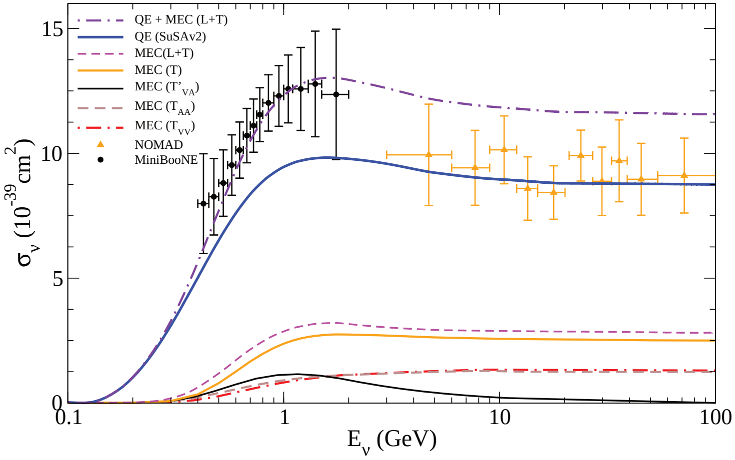
ν_μ-^{12}C CCQE, MiniBooNE and NOMAD only vector MEC

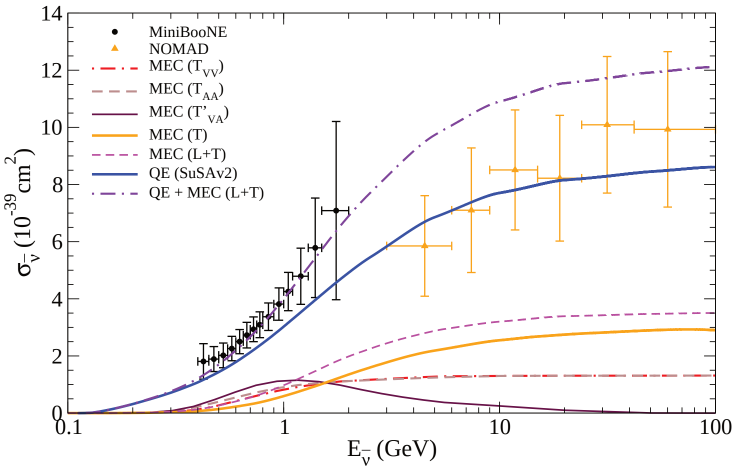


Megias et al., Phys.Rev. D91 (2015)

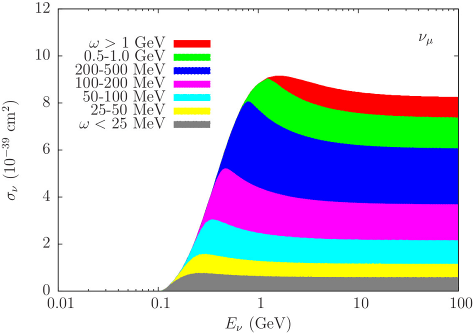
ν_μ-^{12}C CCQE, MiniBooNE and NOMAD full MEC *(PRELIMINARY)*

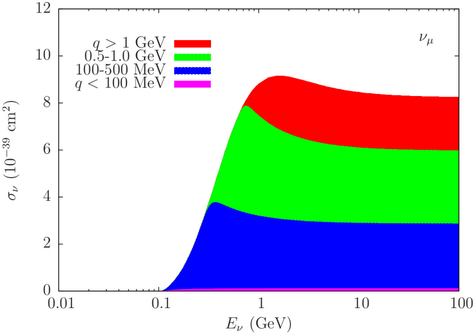


$\overline{\nu}_\mu$-^{12}C CCQE, MiniBooNE and NOMAD *(PRELIMINARY)*



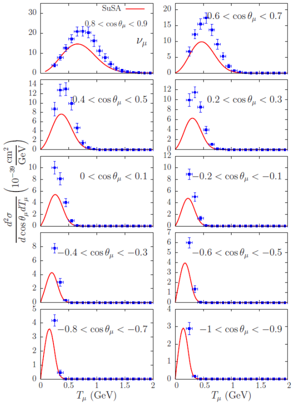
Relevant kinematic regions in the QE cross section



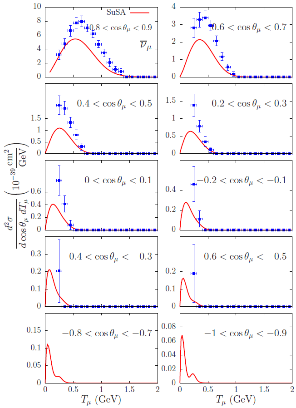


The main contribution to the total QE cross section comes from $q < 1$ GeV/c and $\omega < 0.5$ GeV, even at high neutrino energies.

MiniBooNE CCQE differential cross sections: SUSA (no MEC)



Neutrino, Amaro et al., PLB 696 (2011)

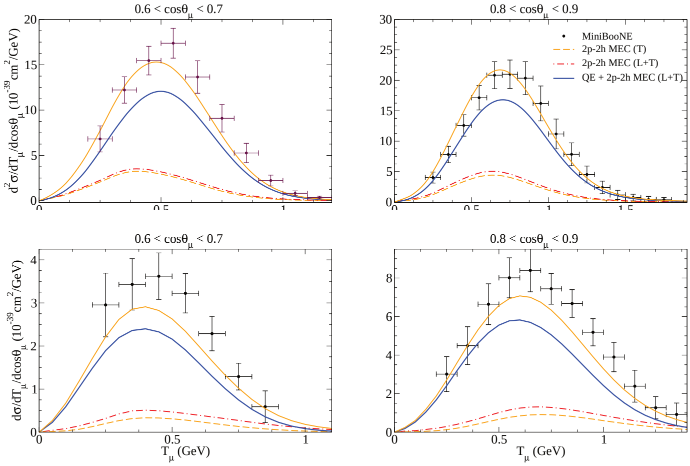


Antineutrino, Amaro et al., PRL 108 (2012)

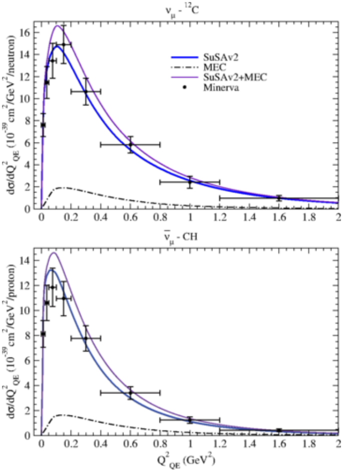
MiniBooNE CCQE differential cross sections: SUSAv2 full MEC (PRELIMINARY)

$\nu_\mu \Rightarrow$

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



MINERνA CCQE differential cross section



Megias et al., Phys.Rev. D91 (2015)

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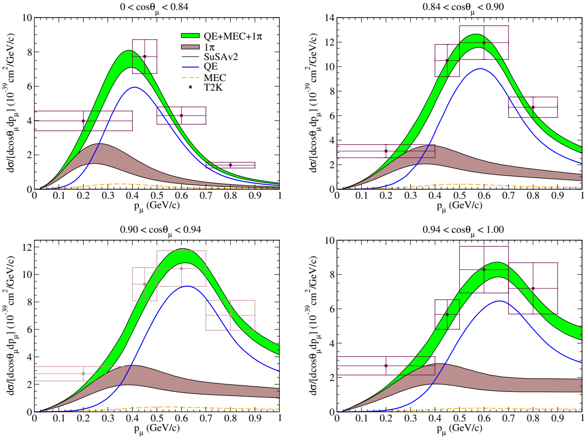
QE+MEC+1π contributions in $\nu_\mu-{}^{12}$C scattering: T2K

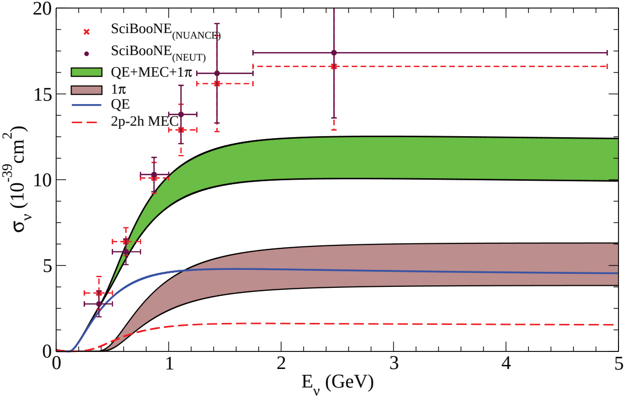
Comparison with T2K inclusive data ($< E_\nu >\sim 0.8$ GeV) [arXiv:1506.00801, nucl-th]



2p2h almost negligible at T2K kinematics; DIS contributions are not expected to be relevant.

Inclusive total cross section: SciBooNE

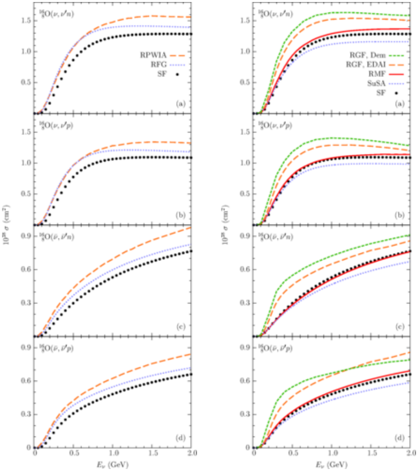
QE+MEC+1π contributions are not enough to describe inclusive cross section at $E_\nu \gtrsim 1$ GeV $\Rightarrow$ Work in progress to include DIS in the ν interaction model.



What Next?

- refine nuclear models and test their range of validity through comparison with electron scattering data;
- work on the possible implementation of models in MC codes;
- promote collaboration and comparison between thery groups to assess the uncertainty associated with the theoretical description of the nuclear cross sections, estimating it from the discrepancies between the predictions of different models.

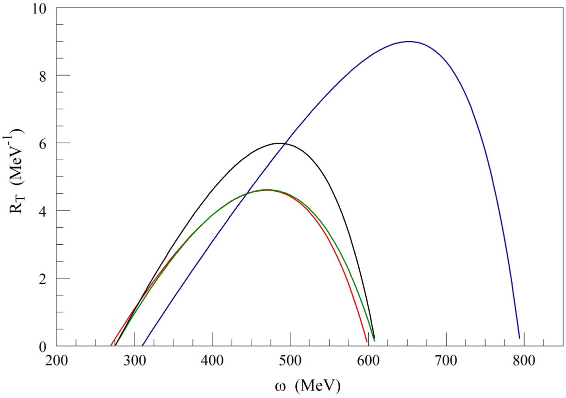
An example: Ankowski, MB, Benhar, Caballero, Giusti, Gonzalez, Megias, Meucci, PRC92 (2015)



Grazie

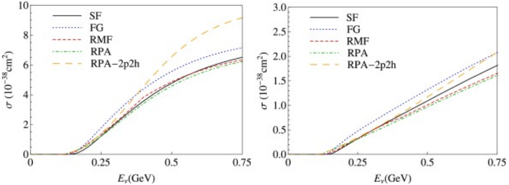
Backup slides

On the importance of relativistic effects

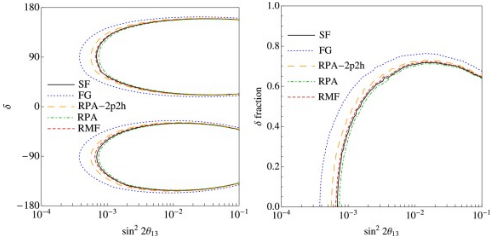


- Red: exact relativistic RFG
- Blue: exact non-relativistic NRFG
- Black: NRFG with relativistic kinematics only
- Green: NRFG with relativistic kinematics and current operators

Nuclear uncertainties and oscillation parameters



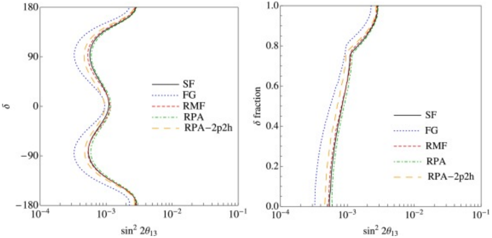
CP discovery potential



E. Fernandez-Martinez and D. Meloni, PLB697 (2011)

Nuclear uncertainties and oscillation parameters

θ_{13} discovery potential



90% CL contour plot for the input value $(\theta_{13}, \delta_{CP}) = (0.9^o, 30^o)$