Neutrino-nucleus scattering: recent progress in the superscaling approach

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TNPI2017 - XVI Conference on Theoretical Nuclear Physics in Italy

October 3-5, 2017, Cortona

Collaboration

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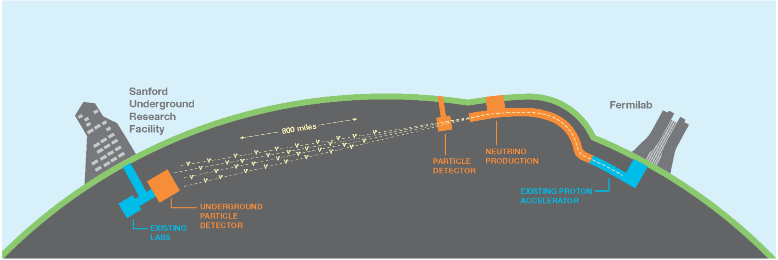
Outline

1. Motivation
2. Connection between ν-A and e-A scattering: SuperScaling
3. Meson-exchange currents: the role of 2p2h excitations
4. Results: comparison with electron and neutrino data
5. Summary and Conclusions

Motivation

- Long-baseline neutrino oscillation experiments aiming for:
  - measurement of CP-violation in the leptonic mixing matrix (δ_{CP})
  - improved accuracy for oscillation angles (θ_{23})
  - measurement of the neutrino mass ordering (NH vs IH)

  from appearence/disappearence of neutrinos of given flavour.
- Ex: DUNE - Deep Underground Neutrino Experiment ($\sim$ 2026)



- Accelerator neutrino experiments use nuclear detectors (typically C, O, Ar) and need reliable nuclear models for their analyses: percent-level control on systematic uncertainties, mainly coming from nuclear physics, is required.
- Oscillation probability (two-flavour case)

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

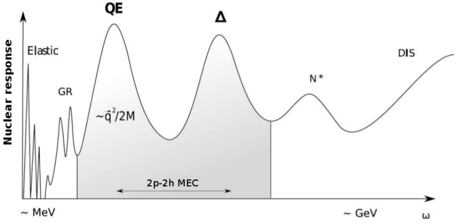
  depends on E_ν, which is unknown and must be reconstructed from the final state using a nuclear model.
- Nuclear physics motivation: neutrinos provide useful information on nuclear structure and dynamics complementary to what can be known from charged-lepton- or photon-nucleus scattering.

Accelerator-based neutrino experiments

- Neutrino beams are not monochromatic

Experiment	Baseline	Flux peak	Flux range (68% of total flux)	Target
Past:				
MiniBooNE	541 m	0.6 GeV	0.2-1.5 GeV	CH_2
Current:				
T2K	295 km	0.6 GeV	0.3-0.8 GeV	CH_2, H_2O
NOvA	810 km	2 GeV	1.5-2.7 GeV	CH_2
MINERvA		3.5 GeV	2-5 GeV	C, Fe, Pb, LHe, H_2O
Future:				
Hyper-K	295 km	0.6 GeV	0.3-0.8 GeV	H_2O
DUNE	1300 km	2 GeV	0.6-3.3 GeV	Ar

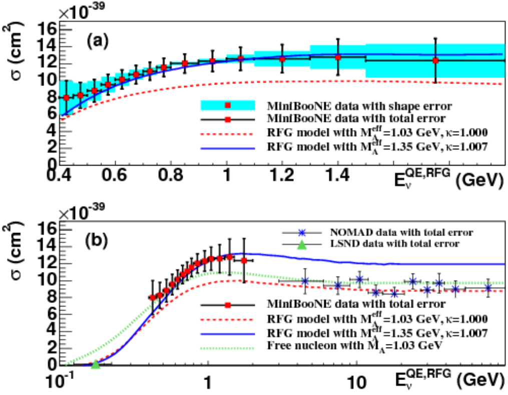
Since E_ν is not exactly know, CC neutrino-nucleus scattering is a multi-scale problem: different processes contribute to the measured cross section, depending on the energy region:



- Quasi-elastic scattering (CCQE): $\nu_l n \to l^- p, \qquad \bar{\nu}_l p \to l^+ n$
- Two-nucleon knockout: $\nu_l NN \to l^- NN, \qquad \bar{\nu}_l NN \to l^+ NN$
- Resonance production: $\nu_l p \to l^- \Delta^{++}, \quad \Delta^{++} \to p\pi^+$ and $\bar{\nu}_l n \to l^+ \Delta^-, \quad \Delta^- \to n\pi^-$,
- Deep inelastic scattering $\nu_l/\bar{\nu}_l(k) + N(p) \to \mu^\mp(k') + X(p')$
- Coherent meson production $\nu_l + A \to l^- + m^+ + A, \quad \bar{\nu}_l + A \to l^+ + m^- + A$ with $m^\pm = \pi^\pm, K^\pm, \rho^\pm, \ldots$

The "M_A-puzzle"

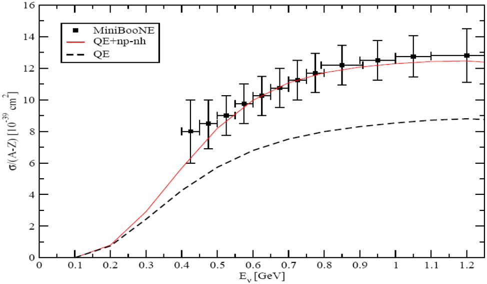
MiniBooNE coll., Phys.Rev. D81 (2010) 092005



- An "effective" nucleon axial mass $M_A = 1.35$ GeV is needed to reproduce the CCQE $\nu_\mu -^{12} C$ cross section with the Relativistic Fermi Gas model used in MC simulations
- First clear indication that the RFG is inadequate to describe the process: more realistic treatment of nuclear dynamics (NN correlations, FSI, 2-body currents...) must be taken into account.

2p2h excitations

An explanation of the puzzle: inclusion of multinucleon emission channels (2p2h, ... npnh)

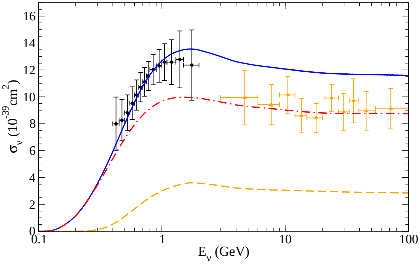


M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 80 065501 (2009)

- "CCQE-like" or "CC0π" = genuine CCQE + npnh
- Other calculations agree qualitatively on the enhancement of cross sections, but not quantitatively:
  - Amaro et al., PRD 84, 033004 (2011); PLB 696, 151 (2011)
  - Nieves et al., PRC 83, 045501 (2011)
  - Meucci et al., PRL 107, 172501 (2011): Relativistic Green's Function, no explicit 2p2h
  - New results from ab initio calculation $\longrightarrow$ A. Lovato's talk

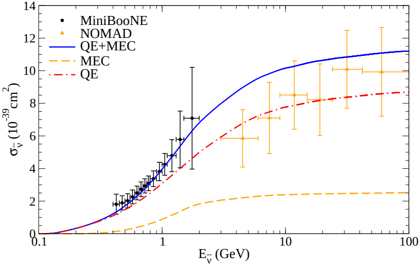
MiniBooNE and NOMAD CCQE [Megias *et al.*, PRD 94, 093004 (2016)]

$\nu_\mu - C$



Warning: E_ν is reconstructed in a model-dependent way. The real measured cross sections are double differential in p_μ and θ_μ

$\bar{\nu}_\mu - C$



NOMAD experiment is two track (outgoing muon and proton): in principle 2p2h are not contributing

Neutrino-nucleus scattering: formalism

- Double differential CC ν (+) and $\overline{\nu}$ (-) **inclusive** cross section (ν_l, l')

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

- Rosenbluth-like decomposition: **5** responses (components of the nuclear tensors)

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

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

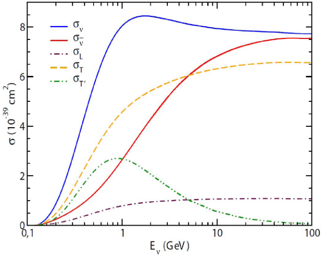
with

$R_L = R_L^{VV} + R_L^{AA}$ VV (vector-vector)

$R_T = R_T^{VV} + R_T^{AA}$ AA (axial-axial)

$R_{T'} = R_{T'}^{VA}$ VA (vector-axial)

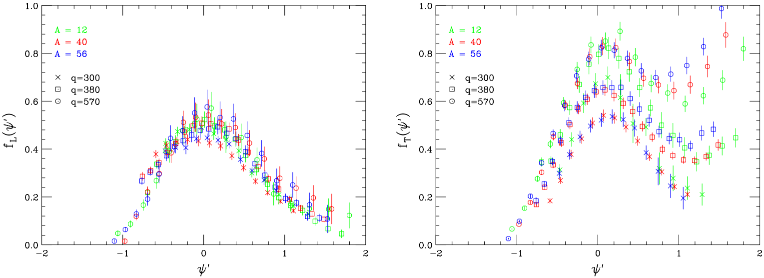
from the V and A components of the weak hadronic current $J^\mu = J^\mu_V + J^\mu_A$



- Note that for semi-inclusive reactions (ν_l, lN) the response functions are **10**
- In (e, e') only 2 vector responses, R_L and R_T

Superscaling

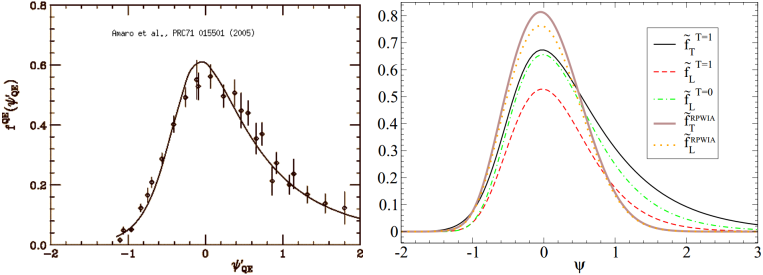
- High quality electron scattering data can be used not only as a test but also as an input for ν-A cross section
- Superscaling in the Longitudinal and Transverse channels: $f_{L,T} = k_F \times R_{L,T}/G_{L,T}$
  (Donnelly and Sick, PRL82 & PRC60, 1999)



- $\psi'(q,\omega) = \pm\sqrt{T_{min}/T_F}$ quasielastic scaling variable
- Asymmetric shape and long high energy tail of the L superscaling function
- Violations reside mainly in the transverse channel (2p2h MEC, Δ resonance excitation, ...)
- $f_T > f_L$: the transverse scaling function is higher than the longitudinal
- The RFG badly fails to reproduce the data: $f_L(\psi) = f_T(\psi) = \frac{3}{4}(1-\psi^2)\,\theta(1-\psi^2)$

Quasi-elastic response: the SuSAv2 model

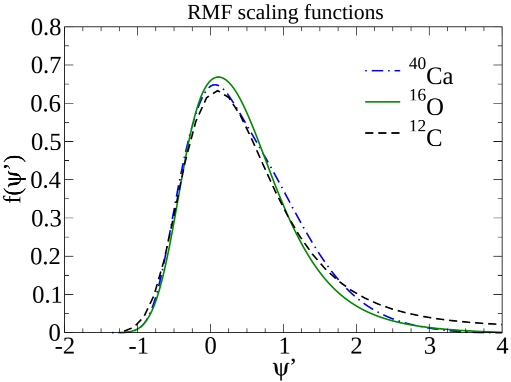
- The SuSA model is based on the quasielastic longitudinal superscaling function extracted from averaged separated (e,e') world data on ^{12}C, ^{40}Ca, ^{56}Fe and assumes $f_L = f_T$ [Amaro et al., PRC71 (2005)]
- In the SuSAv2 the scaling functions are calculated within the Relativistic Mean Field model, which predicts, for instance, different scaling functions in the L and T channels and in different isospin channels
  [Gonzalez et al., PRC90 (2014); Megias et al., PRD94 (2016)]
- The well-known shortcoming of RMF of being too strong at high energies is corrected for by introducing a q-dependent blending function which mixes RMF and RPWIA (two parameters)



SuSA (left) and SuSAv2 (right) scaling functions

The SuSAv2 model for different nuclei

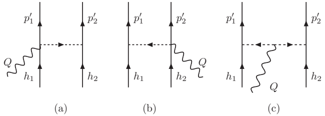
- 2-nd kind scaling within the RMF model: easy extension to different nuclei
- k_F and E_{shift} are the only different parameters



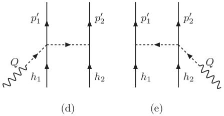
Meson-exchange currents: the 2p2h response

- In our model the MEC are carried by the pion and Δ degrees of freedom:

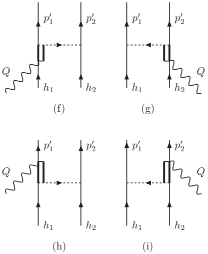
“Seagull” and
“Pion-in-flight”



“Pion-pole”



“Δ-MEC”

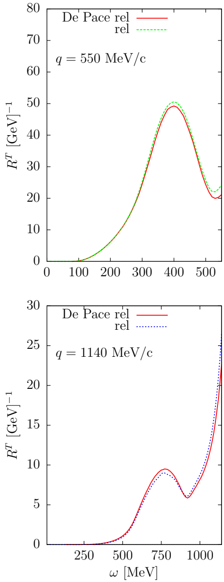


Meson-exchange currents: the 2p2h response

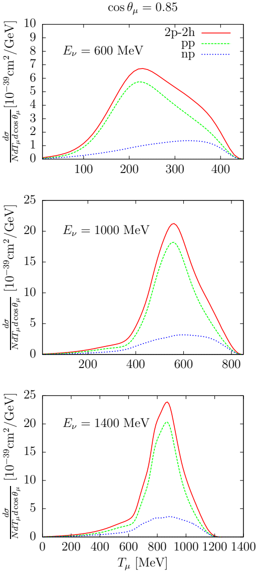
- The 2p2h model is based on the calculation performed by A. De Pace et al., (2003) for electron scattering, recently extended to the weak sector [I. Ruiz Simo et al., (2016)]
- All 2p-2h many-body diagrams containing two pionic lines are included (thousands of terms).
- The calculation is performed in the Relativistic Fermi Gas basis in which Lorentz covariance can be maintained. Relativistic effects are crucial in present and future neutrino oscillation experiments kinematics (in the GeV region).
- Although based on the simple RFG, it is computationally non-trivial and involves 7D integrals of many terms. Comparison with neutrino scattering data implies one additional integral over the neutrino flux.
- Two different techniques were used:
  - De Pace et al.: polarization propagator, many-body Goldstone diagrams, analytic manipulation of isospin traces and Dirac matrices spin traces using FORM, Monte Carlo integration.
  - Amaro et al.: numerical evaluation of the hadronic tensor $W^{\mu\nu}_{2p2h}$, including the spin traces.
  - Although the two methods are completely equivalent, the second has some practical advantages, like the possibility of separating the pp, nn, pn channels.

Comparison between Amaro and De Pace calculations

^{56}Fe



Separated charge channels in the 2p2h response

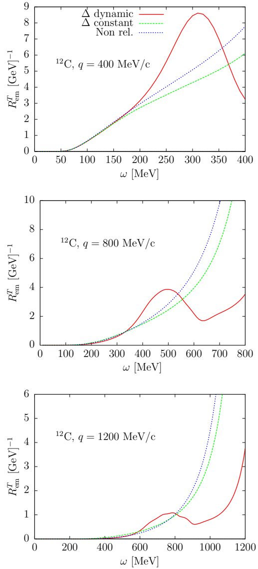


- pp final state largely dominate over np
- The ratio depends upon the kinematics
- The np cross section is shifted towards higher values of T_μ
- First step towards the treatment of $Z \neq N$ nuclei

[Ruiz Simo et al., PLB762 (2016)]

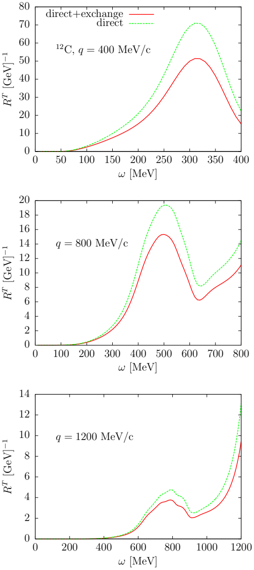
Different treatments of the Δ propagator in the 2p2h response

Relativistic effects are important even at intermediate energies



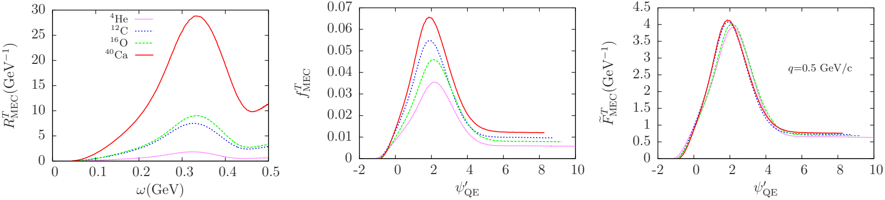
Direct and exchange 2p2h responses

Some approaches neglect the exchange terms: the error is not negligible



Density dependence of 2p2h meson-exchange currents [Amaro et al., PRC95 (2017), 065502]

- Most existing calculations of 2p2h MEC refer to ^{12}C, but other nuclei are interesting for oscillation experiments (mainly ^{16}O, ^{40}Ar)
- 2p2h MEC do not scale as the QE response



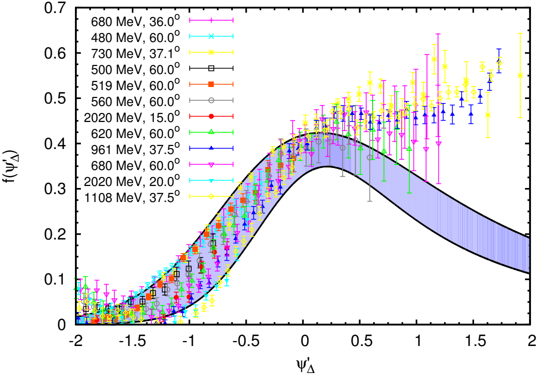
$$f^T_{\rm MEC} \equiv \frac{R^T_{\rm MEC}}{\widetilde{G}^2_M(\tau)} \frac{k_F}{m_N} \qquad \widetilde{F}^T_{\rm MEC} \equiv \frac{R^T_{\rm MEC}}{\widetilde{G}^2_M(\tau)} \frac{m_N^2}{k_F^2}$$

- The 2p2h response scales as k_F^2, while the QE response scales as $1/k_F \Longrightarrow$ 2p2h/QE $\sim k_F^3$

The inelastic region

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

- employing phenomenological fits of the single-nucleon inelastic structure functions and assuming that the scaling function is the same in all energy regions ⟶ full spectrum (from the Δ resonance to DIS) [MBB et al., PRC69 (2004); Megias et al., PRD94 (2016)]
- constructing a phenomenological scaling function to be used in the Δ-resonance region by subtracting from the inclusive (e,e') data the QE contribution and dividing the results by the appropriate $N \to \Delta$ elementary function [Ivanov et al., PLB711 (2012)]



Results

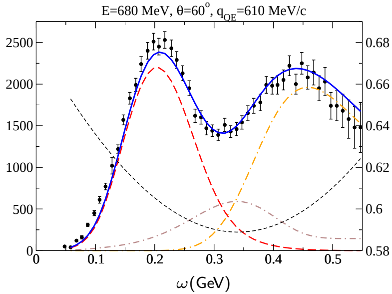
- Inclusive electron scattering on Carbon and Oxygen
- T2K CCQE-like ν_μ and $\bar{\nu}_\mu$ on Carbon and Oxygen
- T2K CC inclusive ν_μ and ν_e on Carbon
- MINERνA CCQE-like ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$ on Carbon
- MiniBooNE CCQE-like ν_μ and $\bar{\nu}_\mu$ on Carbon

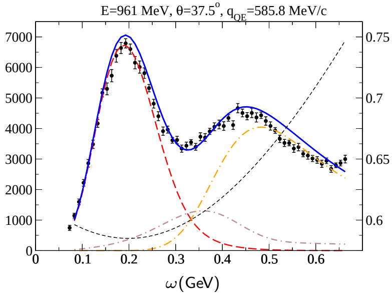
Inclusive electron scattering on Carbon and Oxygen

e-Carbon

Validation: electron scattering data on Carbon

Megias *et al.*, PRD 94, 013012 (2016)

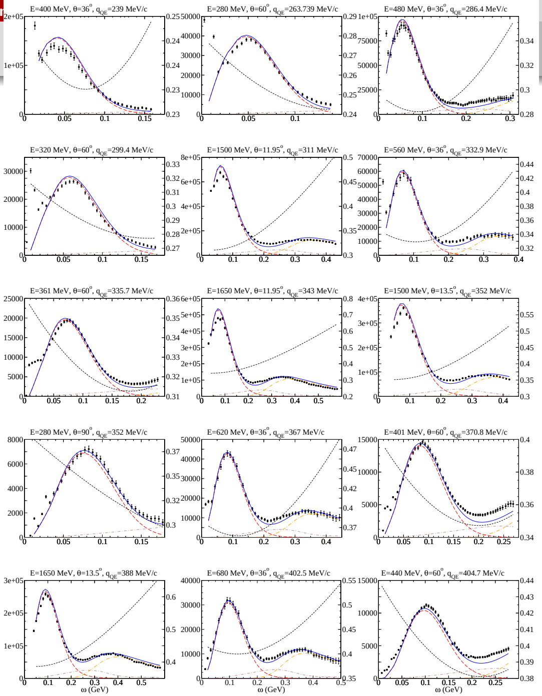




e-C data from Day *et al.*, http://faculty.virginia.edu/qes-archive/

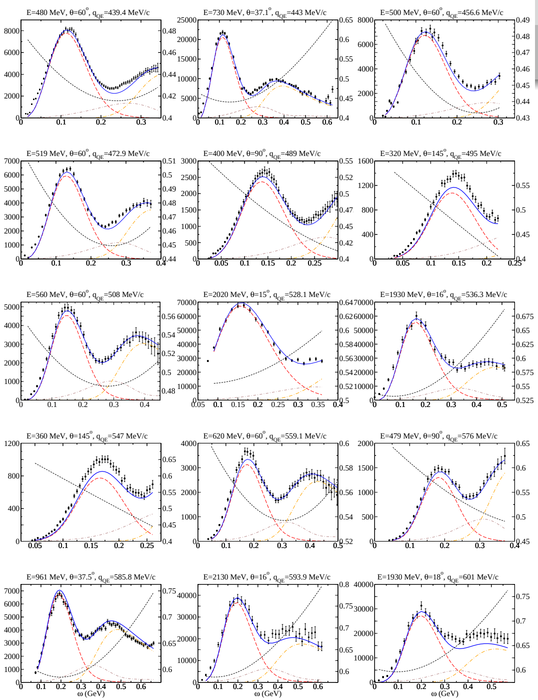
e-Carbon

q∼ 0.2-0.4 GeV/c



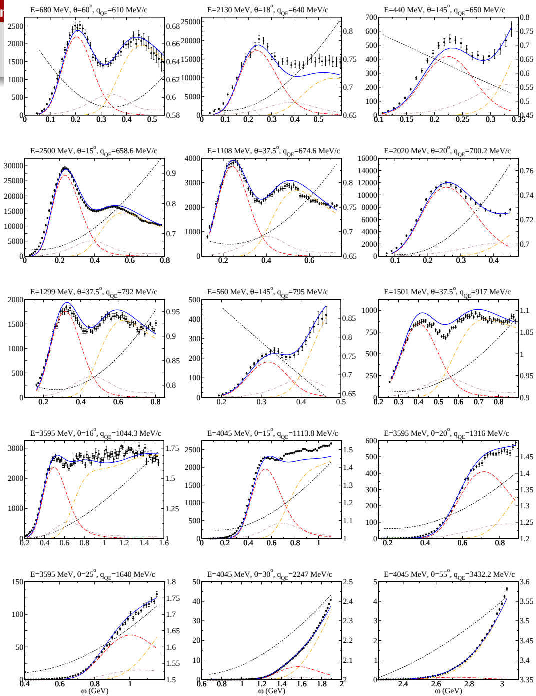
e-Carbon

q∼ 0.4-0.6 GeV/c



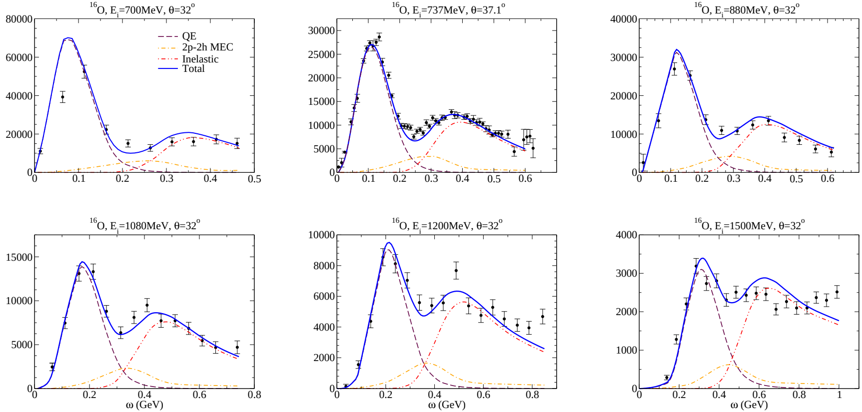
e-Carbon

q∼ 0.6-3.5 GeV/c



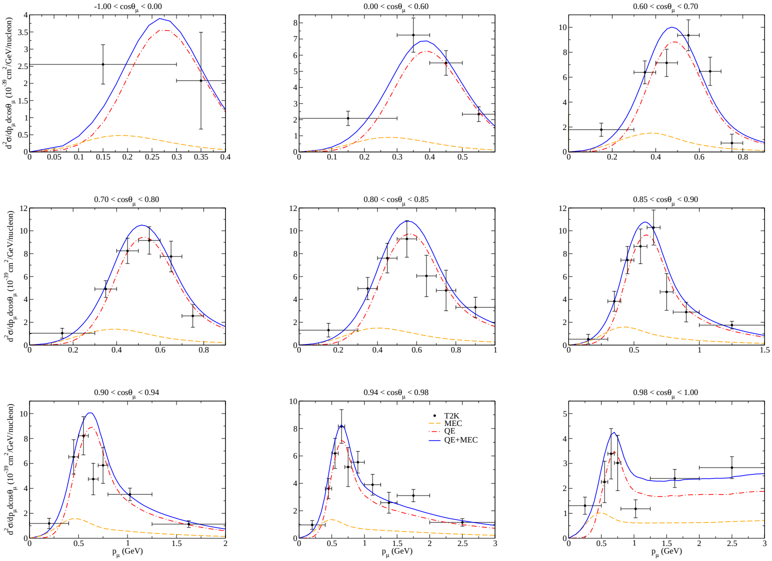
e-Oxygen

Validation: electron scattering data on Oxygen (few data)

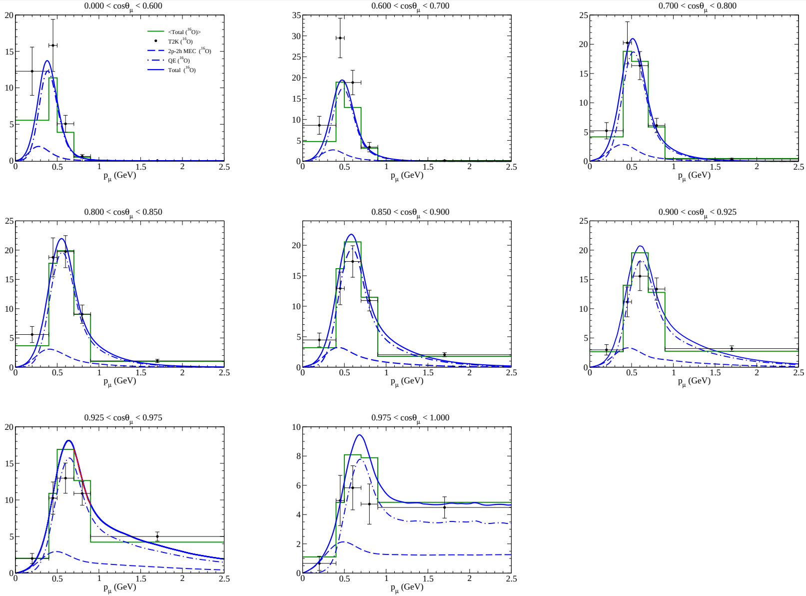


T2K

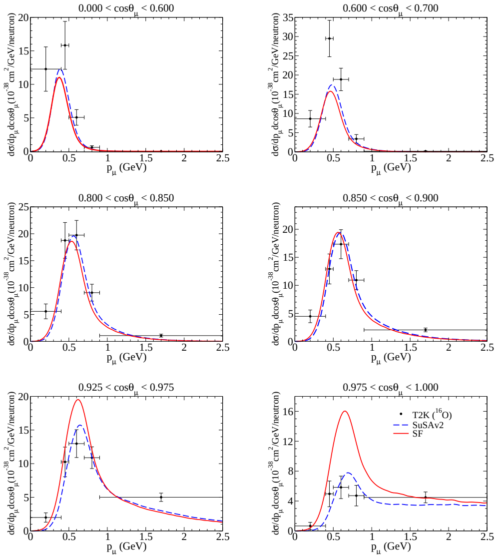
T2K CC0π ν_μ-C in the SuSAv2-MEC model



T2K CC0π ν_μ-O in the SuSAv2-MEC model



T2K CCQE ν_μ-O in the Spectral Function PWIA approximation

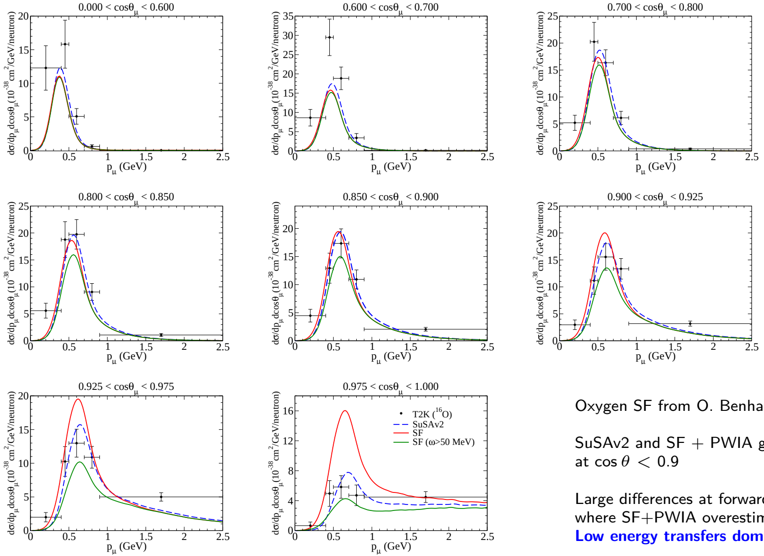


Oxygen SF from O. Benhar

SuSAv2 and SF + PWIA give similar results at $\cos\theta < 0.9$

Large differences at forward angles, where SF+PWIA overestimates the data

T2K CCQE ν_μ-O in the Spectral Function PWIA approximation

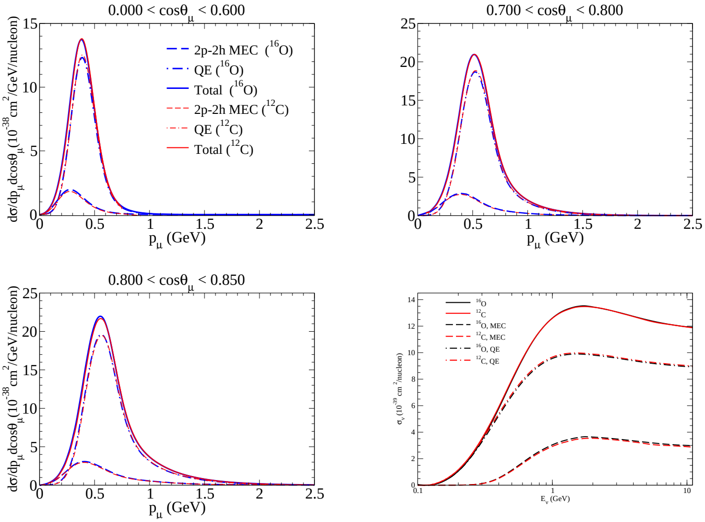


Oxygen SF from O. Benhar

SuSAv2 and SF + PWIA give similar results at $\cos\theta < 0.9$

Large differences at forward angles, where SF+PWIA overestimates the data
Low energy transfers dominate at small angles

Carbon vs Oxygen

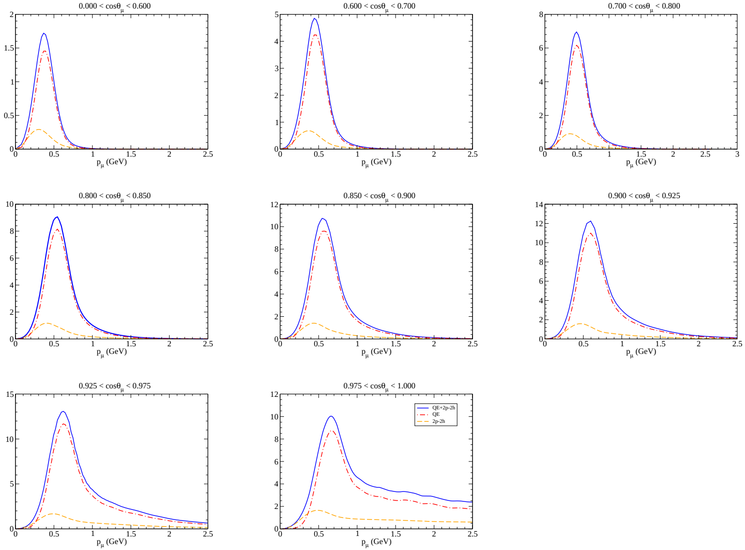


$0.000 < \cos\theta_\mu < 0.600$

$0.700 < \cos\theta_\mu < 0.800$

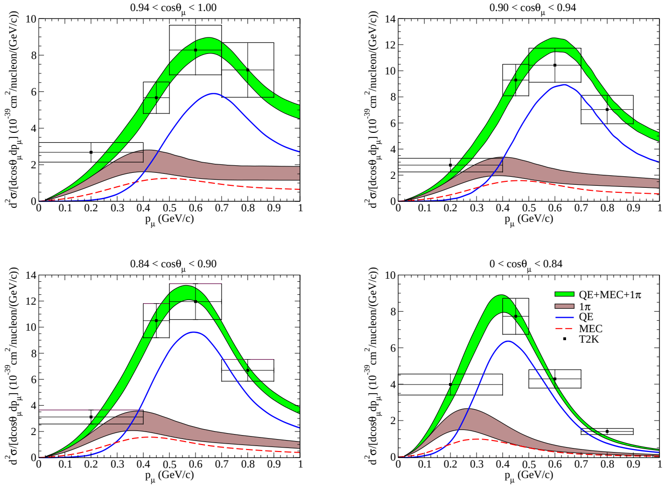
$0.800 < \cos\theta_\mu < 0.850$

T2K CC0π $\bar{\nu}_\mu$-O predictions in the SuSAv2-MEC model



T2K inclusive ν_μ-C $\quad < E_{\nu_\mu} > \sim 0.8$ GeV

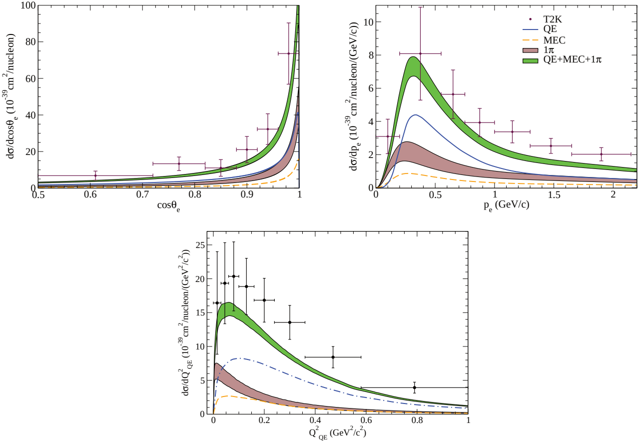
Megias *et al.*, PRD 94, 093004 (2016)



QE+MEC+1π model compatible with data

T2K inclusive ν_e-C $< E_{\nu_e} > \sim 1.3$ GeV

Megias *et al.*, PRD 94, 093004 (2016)

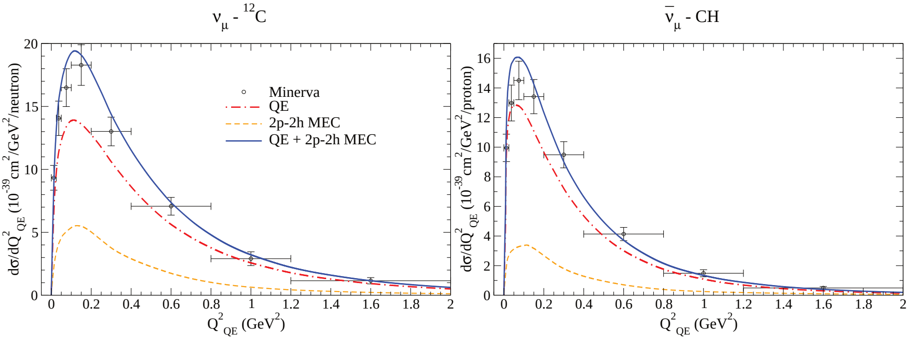


QE+MEC+1π model-data agreement is slightly worse, DIS starts being relevant

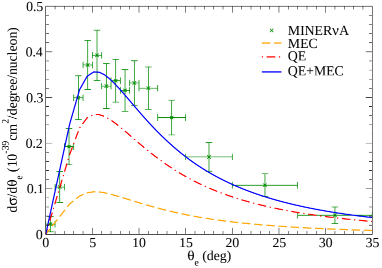
MINERνA

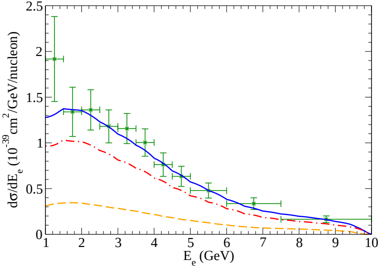
MINERνA CCQE-like ν_μ-C and $\bar{\nu}_\mu$-C

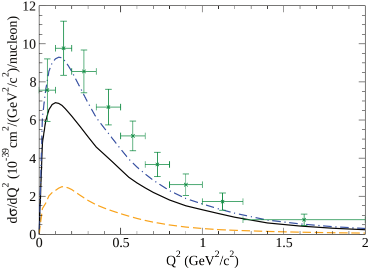
Megias *et al.*, PRD 94, 093004 (2016)



MINERνA CCQE-like ν_e-C







MiniBooNE

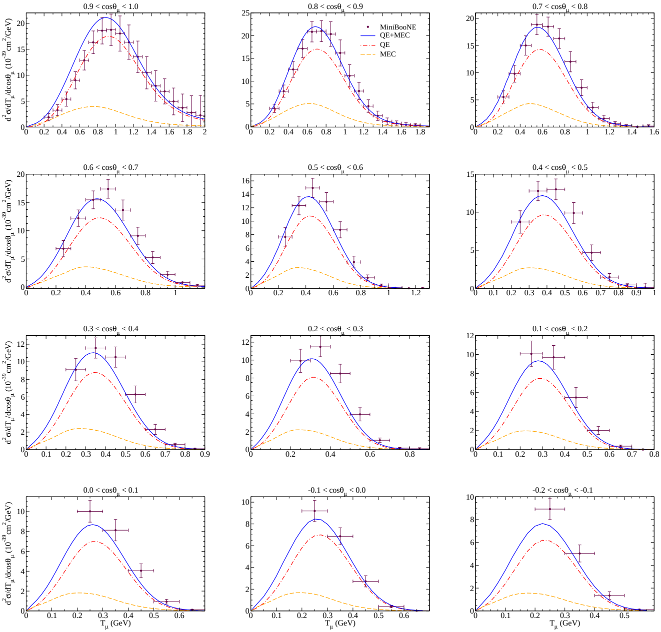
Results: comparison with electron and neutrino data

MiniBooNE

CCQE-like

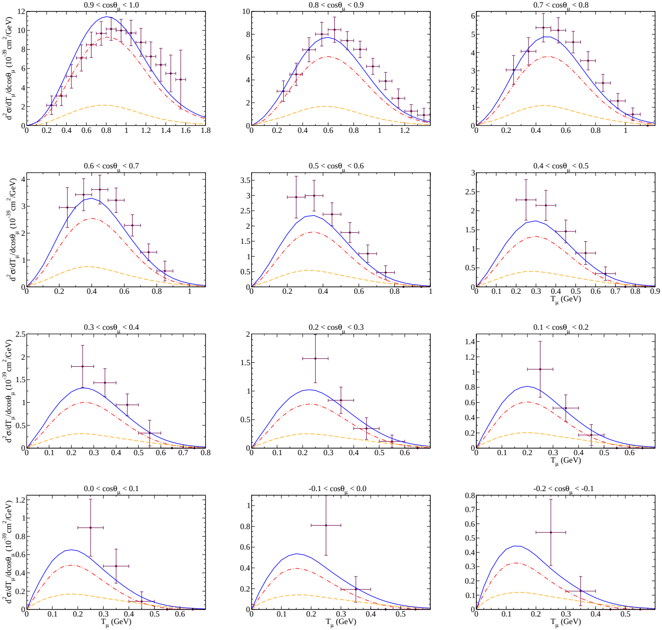
DDCS

$\nu_\mu - C$



Results: comparison with electron and neutrino data

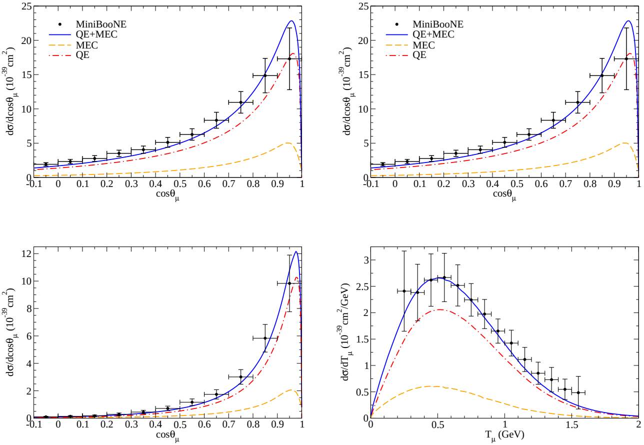
MiniBooNE
CCQE-like
DDCS
$\bar{\nu}_\mu - C$



MiniBooNE CCQE-like single-differential cross sections

ν_μ-C

$\bar{\nu}_\mu$-C



Summary and Conclusions

- **Validation against electron scattering** data is the best possible test of nuclear models used in neutrino experiment analyses
- **Superscaling** is a valuable tool to connect electron and neutrino scattering
- **MEC 2p2h excitations** give sizeable contributions to ν-A cross sections in the GeV region
- MEC 2p2h contributions violate scaling of both kinds: numerical studies show that **the ratio 2body/1body roughly scales as k_F^3**
- Comparison of the SuSAv2+MEC model with inclusive electron scattering data on ^{12}C and ^{16}O is very satisfactory in a wide range of kinematics
- Fair agreement of the SuSAv2+MEC predictions with CCQE-like neutrino scattering data on ^{12}C and ^{16}O
- **Inclusive data are reproduced equally well by very different models: testing models in more exclusive channels is necessary**
- **Work in progress**: extension to asymmetric nuclei, inclusive neutrino scattering including all inelasticities, semi-inclusive reactions, implementation in MC codes

Suggested reading:

NuSTEC[1] White Paper:
Status and Challenges of Neutrino-Nucleus Scattering
L. Alvarez-Ruso *et al.*, **arXiv:1706.03621 [hep-ph]**

Grazie

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[1] Neutrino Scattering Theory Experiment Collaboration