Nuclear effects in neutrino-nucleus cross sections

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NuSTEC talks, November 16, 2022

In collaboration with...

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Natalie Jachowicz (Ghent University)

Kajetan Niewczas (Ghent and Wroclaw Universities)

Stephen Dolan (CERN)

Federico Sánchez (University of Geneva)

Overview

1. The e4nu analysis.

2. Benchmarking intranuclear cascade models.

3. RDWIA approach: recent developments.

4. Some examples where quantum mechanics plays a relevant role.

5. Semi-inclusive neutrino-nucleus cross sections.

6. Summary and outlook.

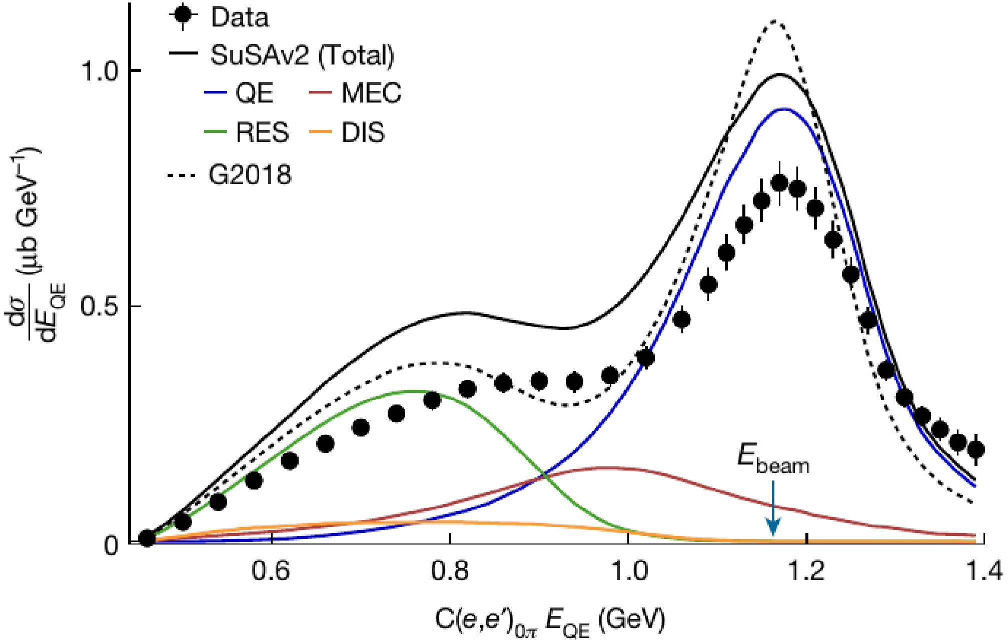
Article

Electron-beam energy reconstruction for neutrino oscillation measurements

https://doi.org/10.1038/s41586-021-04046-5

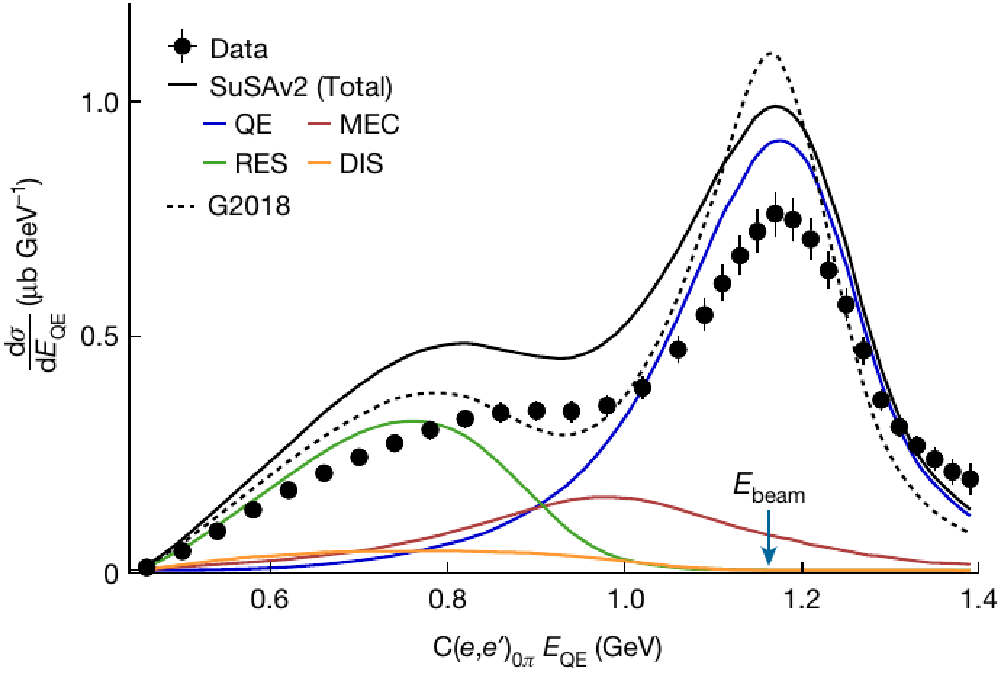
Received: 29 June 2020

M. Khachatryan[1,56], A. Papadopoulou[2,56], A. Ashkenazi[2✉], F. Hauenstein[1,2], L. B. Weinstein[1], O. Hen[2], E. Piasetzky[3], the CLAS Collaboration* & e4v Collaboration*



E(beam) = 1.159 GeV
scattering angle: 15° ≤ θe ≤ 45°

e4nu collaboration (June 2020)
https://doi.org/10.1038/s41586-021-04046-5



Ebeam = 1.159, and angles 15° ≤ θe ≤ 45°

(I'll focus on the QE peak.) So far, SuSAv2+MEC has proven to be able to reproduce quite well all inclusive (e,e') data. So, what's going on here? Some possibilities:

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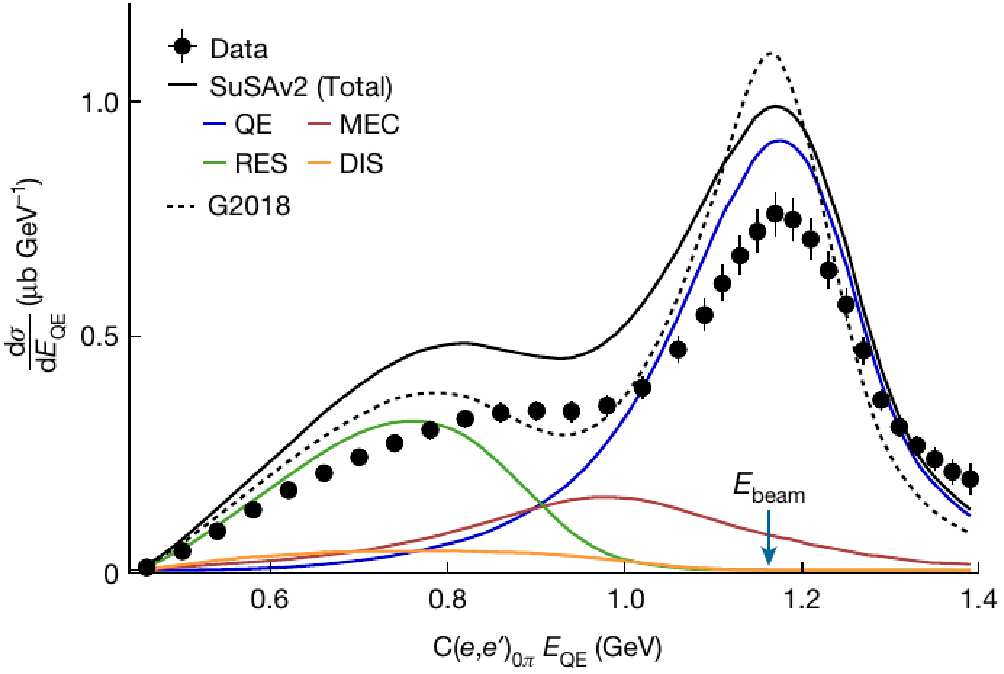

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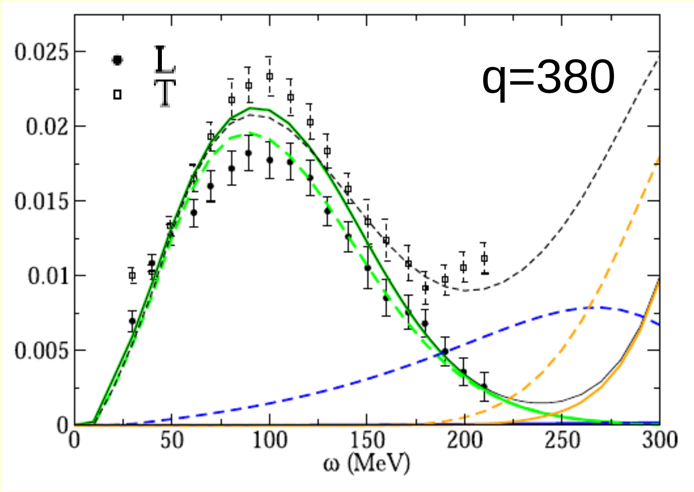
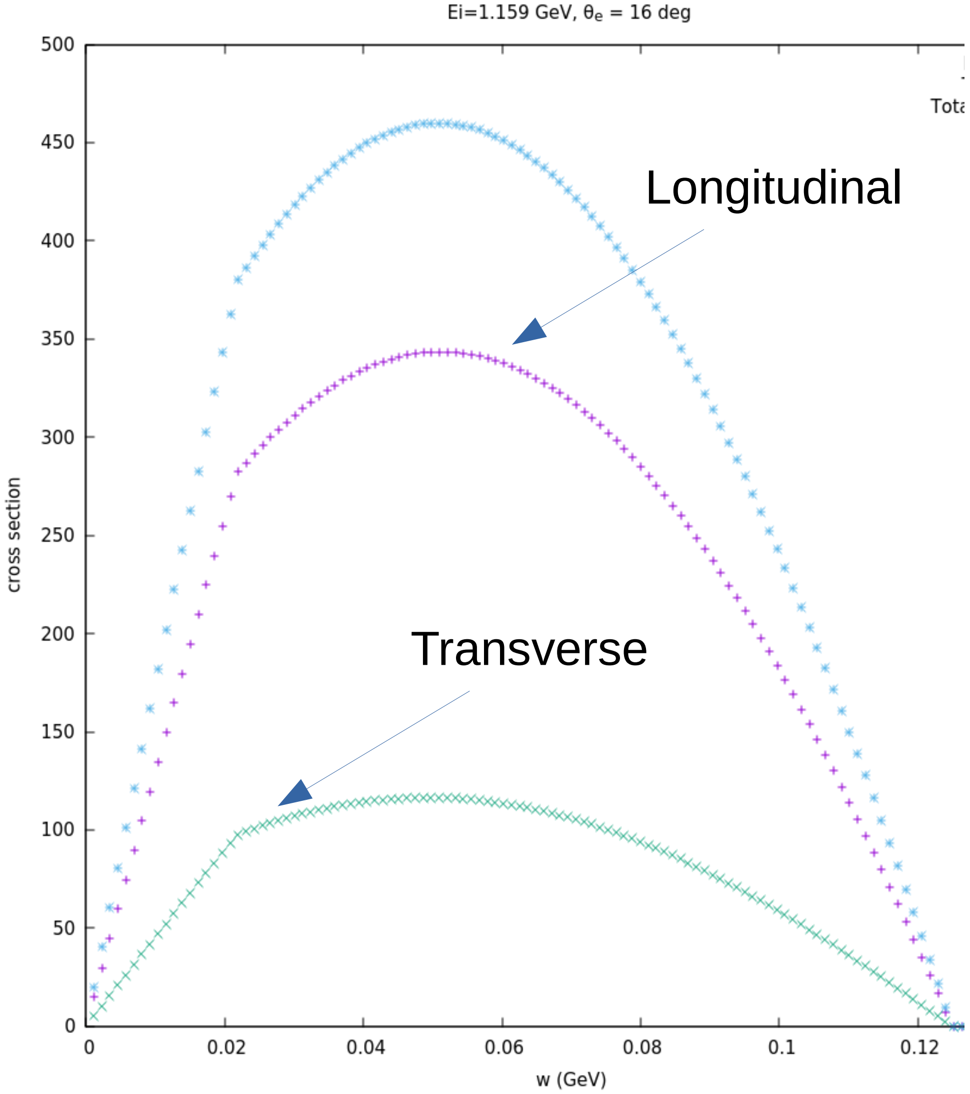
1. The cross section is dominated by forward scattering angles:

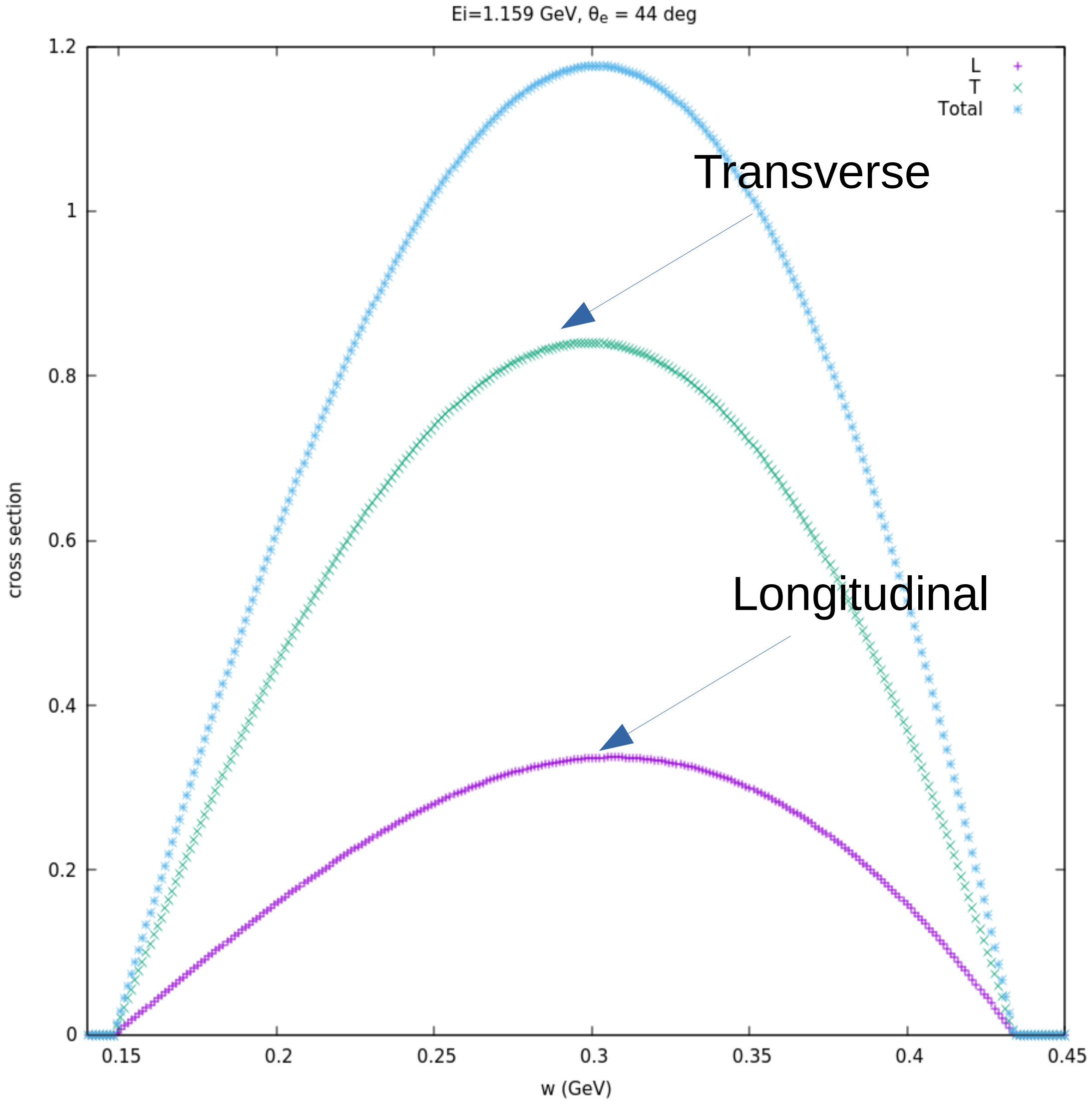
The **Longitudinal** response plays an important role. SuSAv2 overestimates the L response for carbon 12 (https://doi.org/10.1088/1361-6471/abb128).



Longitudinal: solid lines. Transverse: dashed lines.



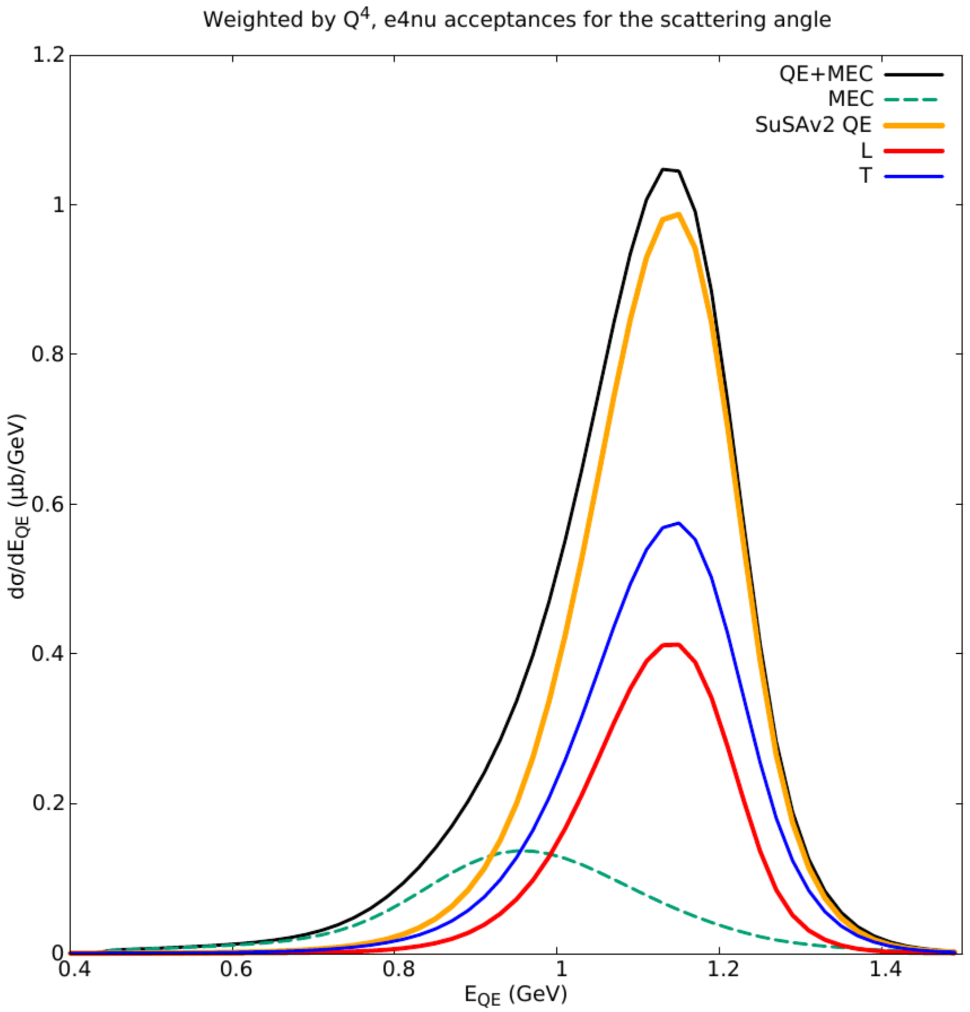
Ei=1.159 GeV, θe = 16 deg
cross section
w (GeV)
Tota
Longitudinal
Transverse



Ei=1.159 GeV, θe = 44 deg
cross section
w (GeV)
L
T
Total
Transverse
Longitudinal

The actual result is a bit different than expected due to the **Q^4 weighting factor** applied to the events.

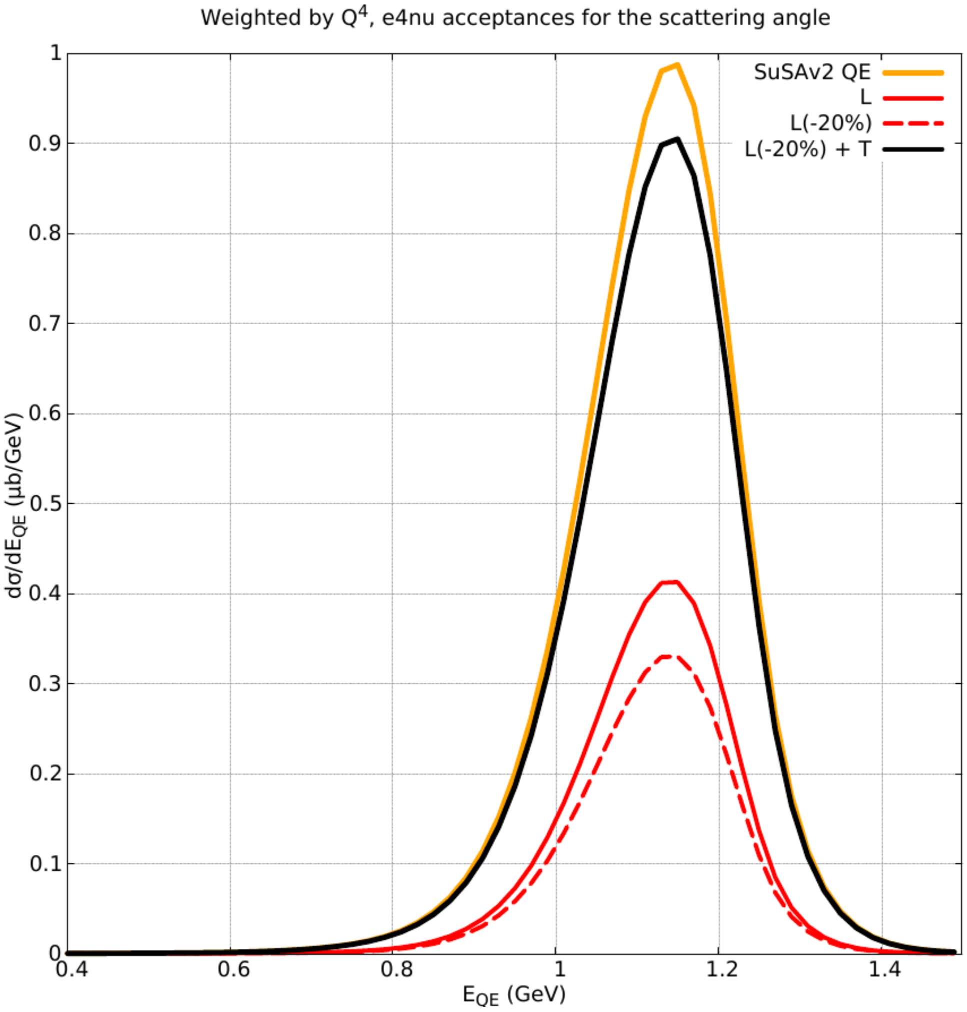
The L contribution is not dominant, but still, it plays an important role.



The actual result is a bit different than expected due to the **Q^4 weighting factor** applied to the events.

The L contribution is not dominant, but still, it plays an important role.

Experimental data tell us that the L response should be at least 20% lower than the model prediction.



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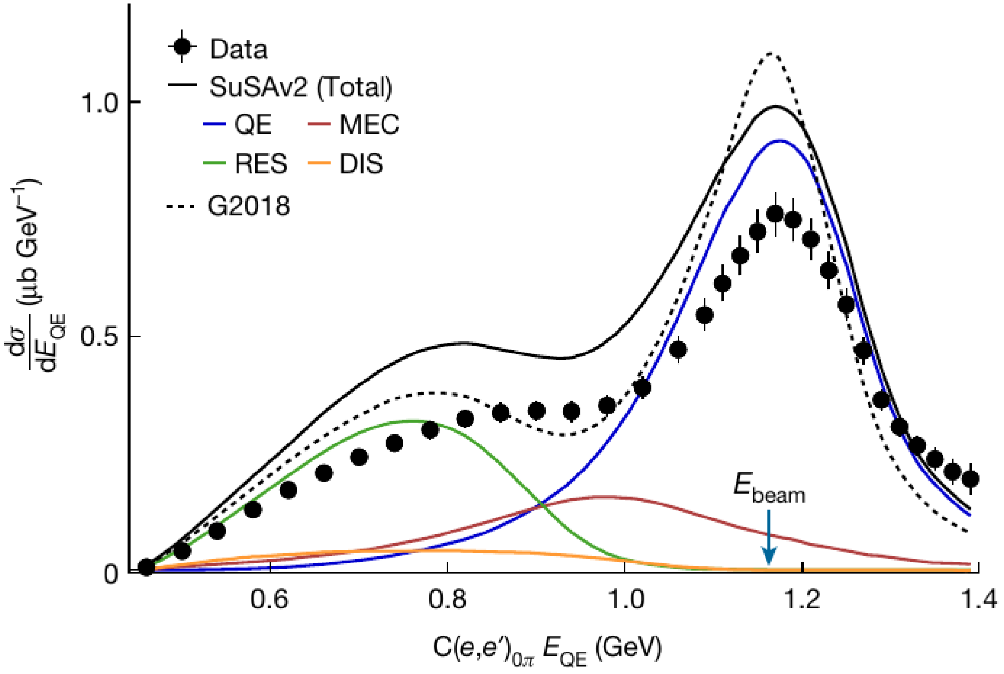

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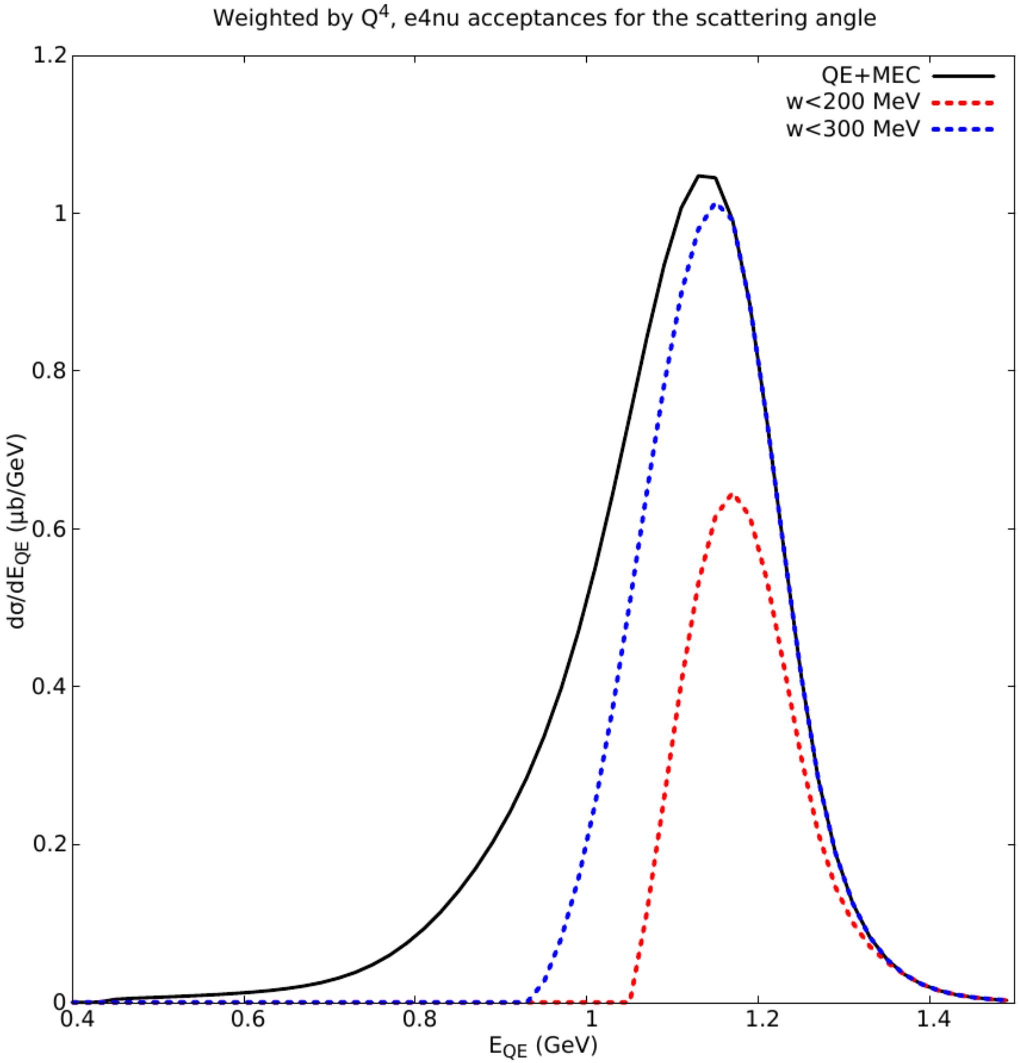
1. The cross section is dominated by forward scattering angles:
The **Longitudinal** response plays an important role. SuSAv2 overestimates the L response for carbon 12 (see https://doi.org/10.1088/1361-6471/abb128).

2. SuSAv2+MEC is an inclusive model, but this is not an inclusive dataset. However, there shouldn't be many pions below QE peak...

To create a real pion above the experimental threshold (T_π = 65 MeV) one needs at least this much energy transfer (w):

$w \approx T_\pi + m_\pi + E_{binding} \approx 220$ MeV

So, the dataset is nearly inclusive below the QE peak.



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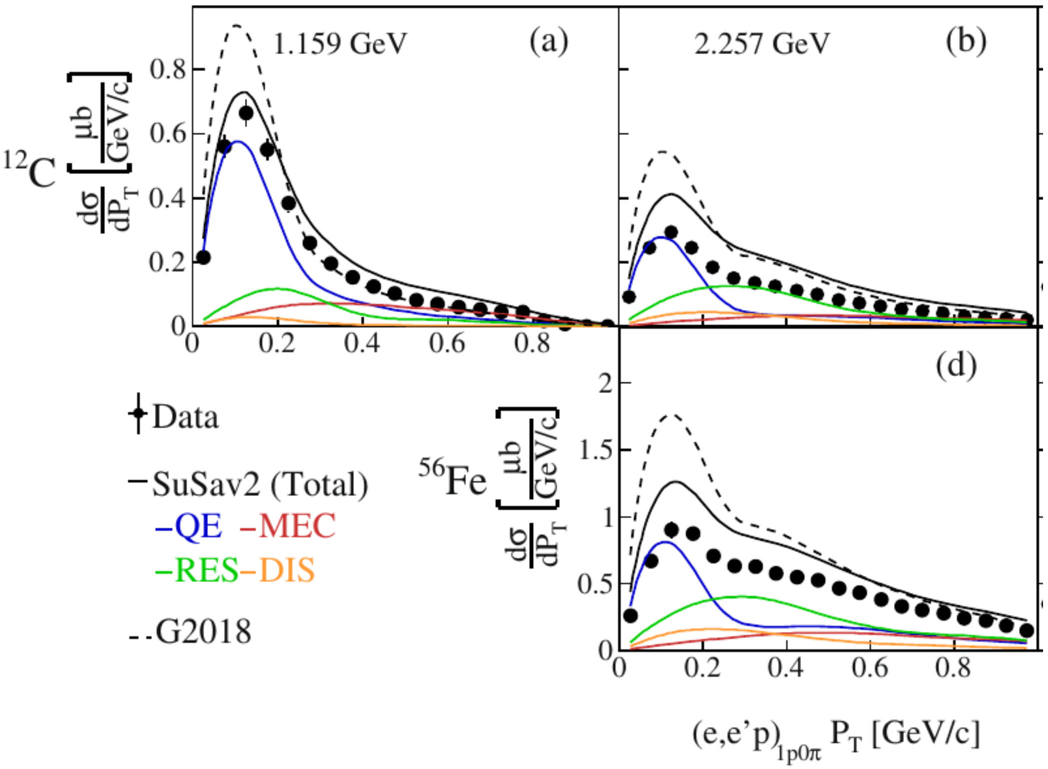


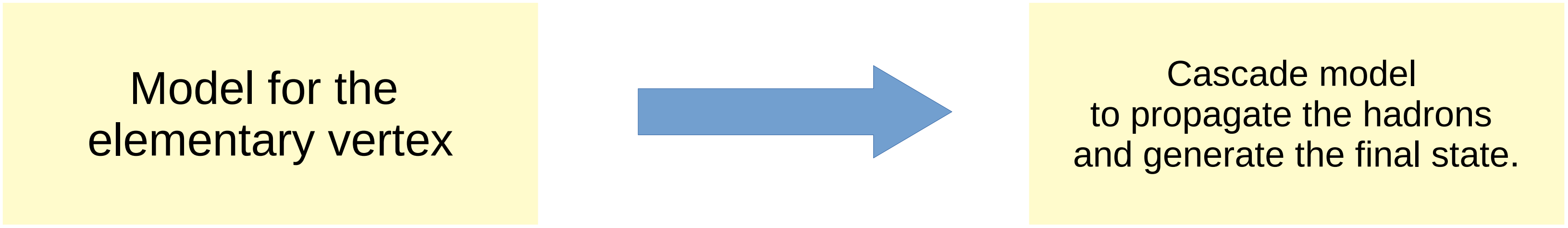
(e,e'p)$_{1p0\pi}$
This is not an inclusive dataset.

SuSAv2+MEC does not provide any information on the hadronic final state.

In this case, better to use (realistic) models that provide **information on the final hadron(s)** as well as a good inclusive cross section.

Summary of minimum requirements:

If we want to keep working in the framework:



+ The model must provide good inclusive cross sections (for all kinematics).

+ Better if the model provides information on the hadrons.

What **mean-field models** can offer

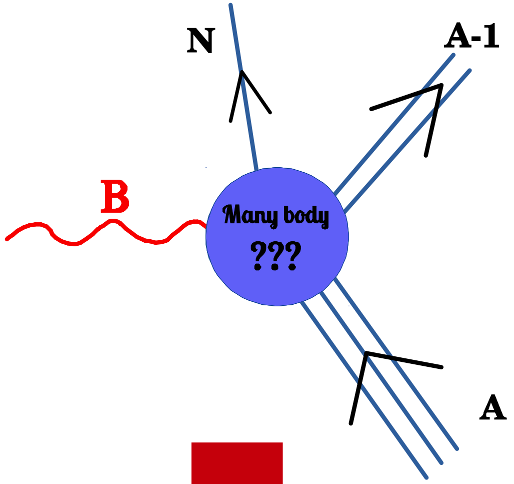
Overview of the nuclear model: Relativistic Distorted-Wave Impulse Approximation (RDWIA).

(Under some approximations) The cross section is proportional to the contraction of lepton and hadron tensors:

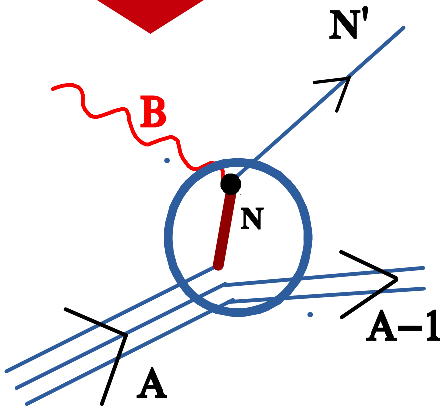
$$d\sigma \propto L_{\mu\nu} H^{\mu\nu}$$

(Under some approximations) The lepton tensor is easy. The hadron tensor is the complex quantity, it contains all the information on the boson-nucleus interaction, and all hadronic final-state interactions.

$$H^{\mu\nu} = J^{\mu}_{had} \left(J^{\nu}_{had}\right)^{*}$$



Impulse approximation



$$J^{\mu}_{had} = \langle N, A-1 | \hat{\mathcal{O}}^{\mu}_{many\text{-}body} | A \rangle$$

Impulse approximation

$$J^{\mu}_{had} = \int d\mathbf{p}\, \overline{\Psi}_F(\mathbf{p}+\mathbf{q}, \mathbf{p}_N)\ \mathcal{O}^{\mu}_{\text{one body}}\ \Psi_B(\mathbf{p})$$

Relativistic mean-field wave functions

Summary on the RDWIA approach:

Within the RDWIA framework, inclusive (e,e’) and exclusive* (e,e’p) cross sections are fairly reproduced.

+ For <u>exclusive cross sections</u>: Complex optical potential, i.e., it has **real and imaginary parts** (let’s call it ROP):

++ **Real part accounts for the distortion** (final-state interactions) in between the knocked out nucleon and the residual nucleus.

++ **Imaginary part removes** the **strength** that goes to inelastic channels.

+ <u>Inclusive cross sections:</u> Only the **real part** of the optical potential (let’s call it rROP).

(*) Missing energy below the two-nucleon emission threshold.
ROP: Relativistic Optical Potential.
rROP: real Relativistic Optical Potential.

PRC 105, 054603 (2022)

Benchmarking intranuclear cascade models for neutrino scattering with relativistic optical potentials

A. Nikolakopoulos,[1,2,*] R. González-Jiménez,[3] N. Jachowicz,[1] K. Niewczas,[1,4] F. Sánchez,[5] and J. M. Udías[3]

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INPUT (rROP model)
Events (1lepton+1proton) generated with a rROP model.

(Remember that the rROP model provides good agreement with inclusive data).

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NEUT cascade is fed with the rROP events

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We need to select the “only one proton” events.

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CASCADE

NEUT cascade is fed with the rROP events

Signal definition

We need to select the "only one proton" events.

BENCHMARK (ROP model)

The output from the cascade should match the ROP predictions.

(Remember that the ROP model provides good agreement with exclusive (e,e'p) data).

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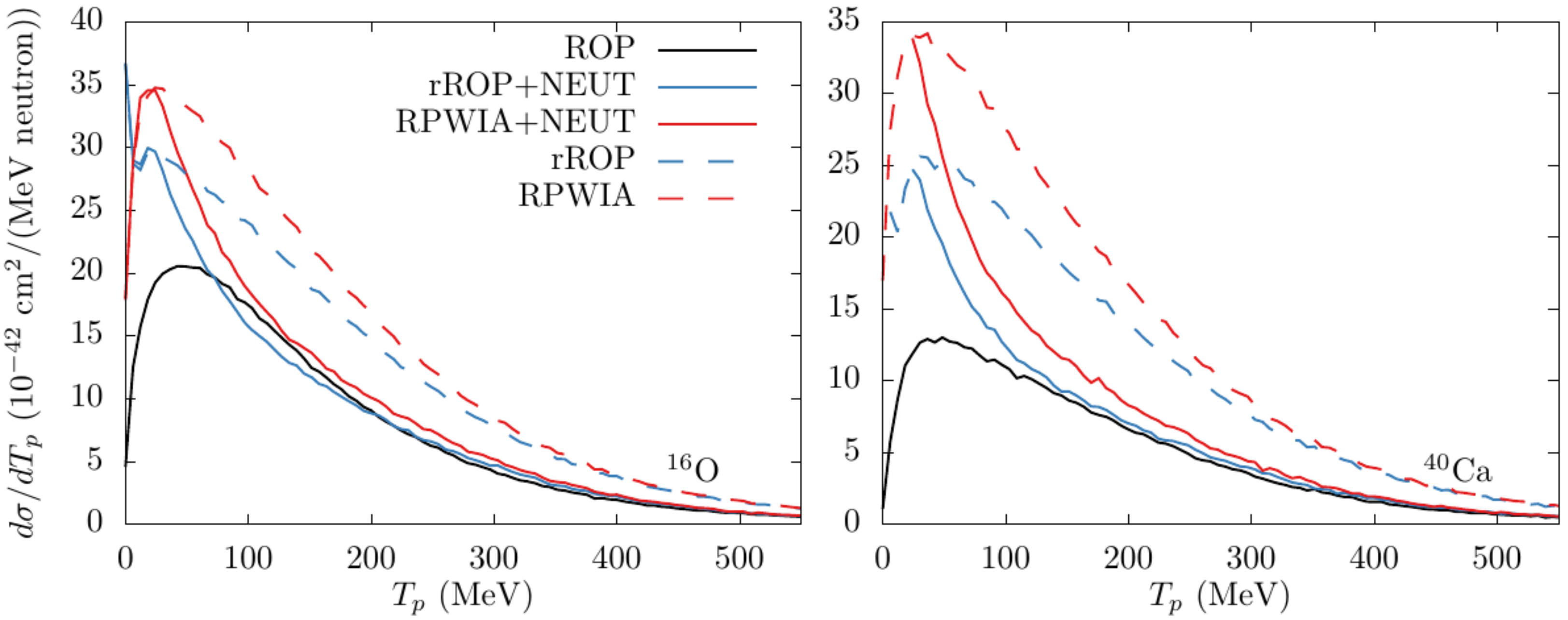

FIG. 7. Cross section in terms of the leading protons kinetic energy averaged over the T2K flux. All results include a cut in missing energy to isolate elastic events. ROP results are compared to the NEUT results when using rROP or RPWIA as input to the cascade. The results of the models before application of the cascade are shown by dashed lines.

PRC 105, 054603 (2022)

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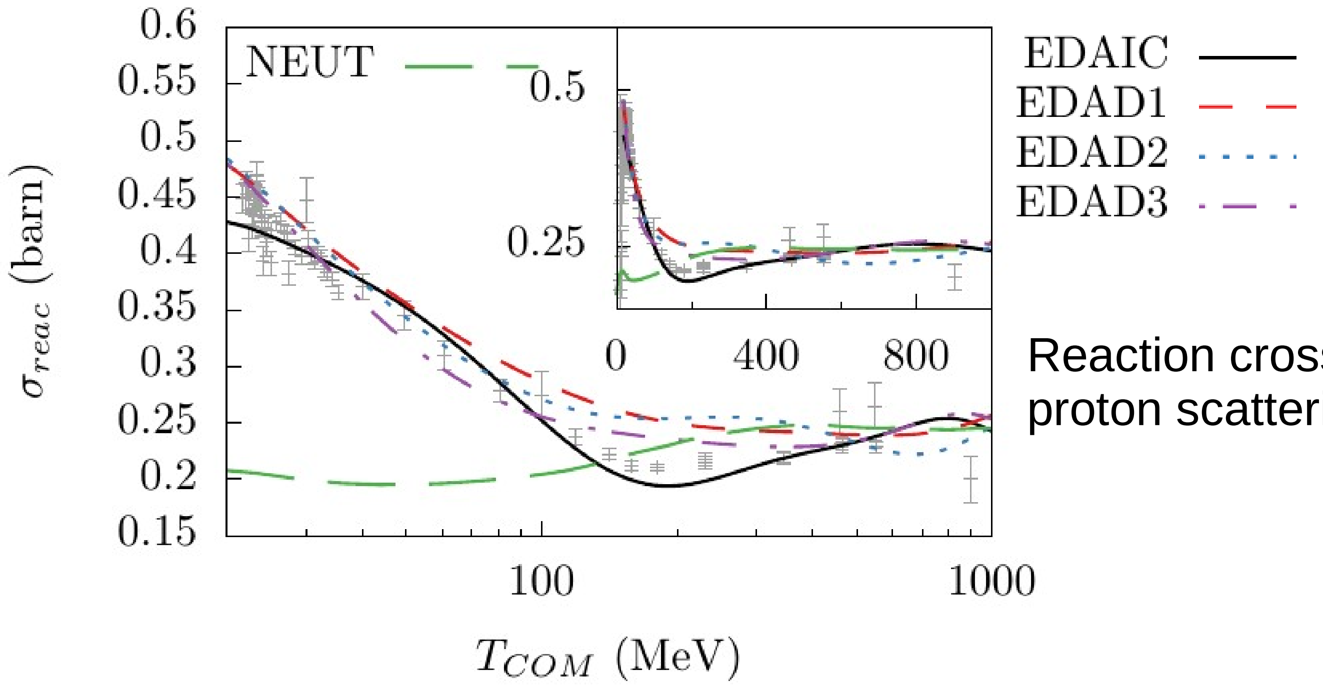

Reaction cross section for proton scattering off carbon.

Latest improvements in the model (on the 1 particle–1 hole sector):

+ More realistic energy profile for the shells.

+ Two-body current contribution.

We can now reproduce the **Longitudinal and Transverse EM responses** simultaneously.

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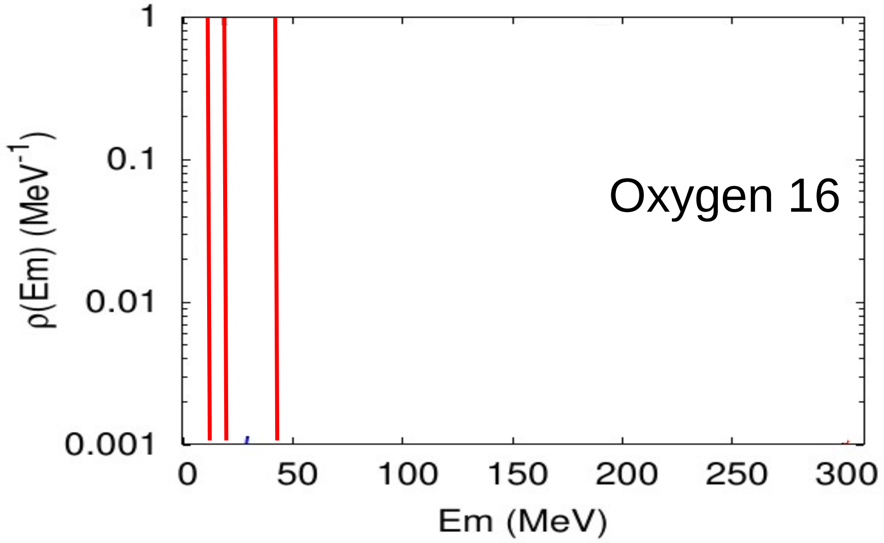
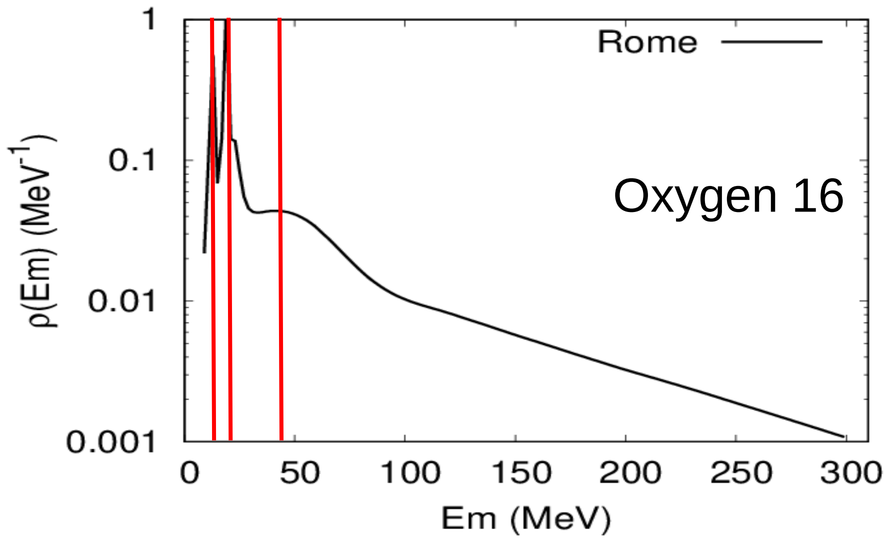
Missing energy distribution in a **pure shell model:**



$$\rho_\kappa(E_m) = \delta(E_m - E_m^\kappa)$$

Missing energy distribution from the Rome spectral function (O. Benhar et al. NPA 579, 493 (1994); PRD 72, 053005 (2005)):



$$\rho(E_m) = \int d^3\mathbf{p}_m S(E_m, p_m)$$

More details in PRC 105, 025502 (2022)

Latest improvements in the model (on the 1 particle–1 hole sector):

+ More realistic energy profile for the shells.

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We can now reproduce the **Longitudinal and Transverse responses simultaneously**

Effects of two-body currents in the one-particle one-hole electromagnetic responses within a relativistic mean-field model

T. Franco-Munoz,[1] R. González-Jiménez,[1] and J.M. Udías[1]

arXiv:2203.09996 [nucl-th]

$$J^{\mu}_{had} = \int d\mathbf{p}\, \overline{\Psi}_F(\mathbf{p}+\mathbf{q},\mathbf{p}_N) \left(\mathcal{O}^{\mu}_{\text{one body}} + \mathcal{O}^{\mu}_{\text{two body}}\right) \Psi_B(\mathbf{p})$$

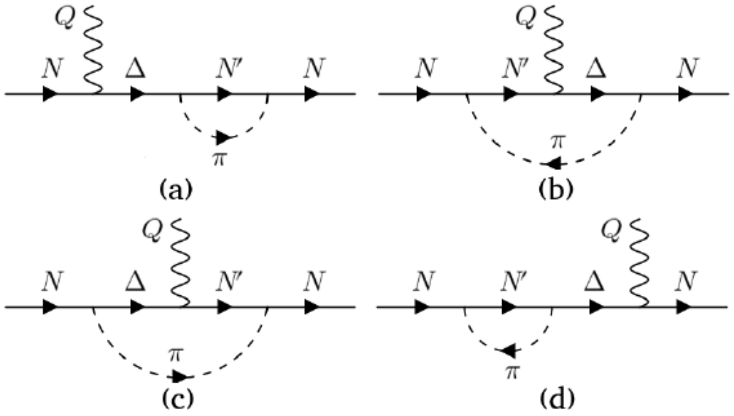


FIG. 1. Delta contributions.

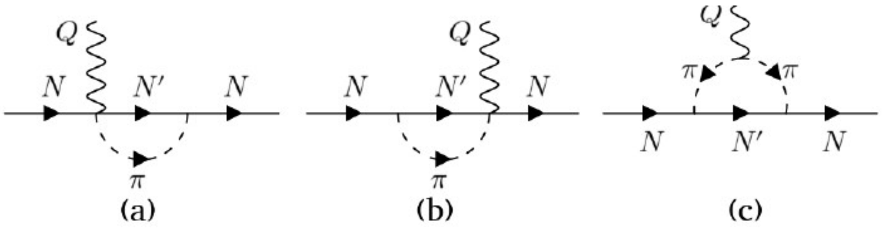
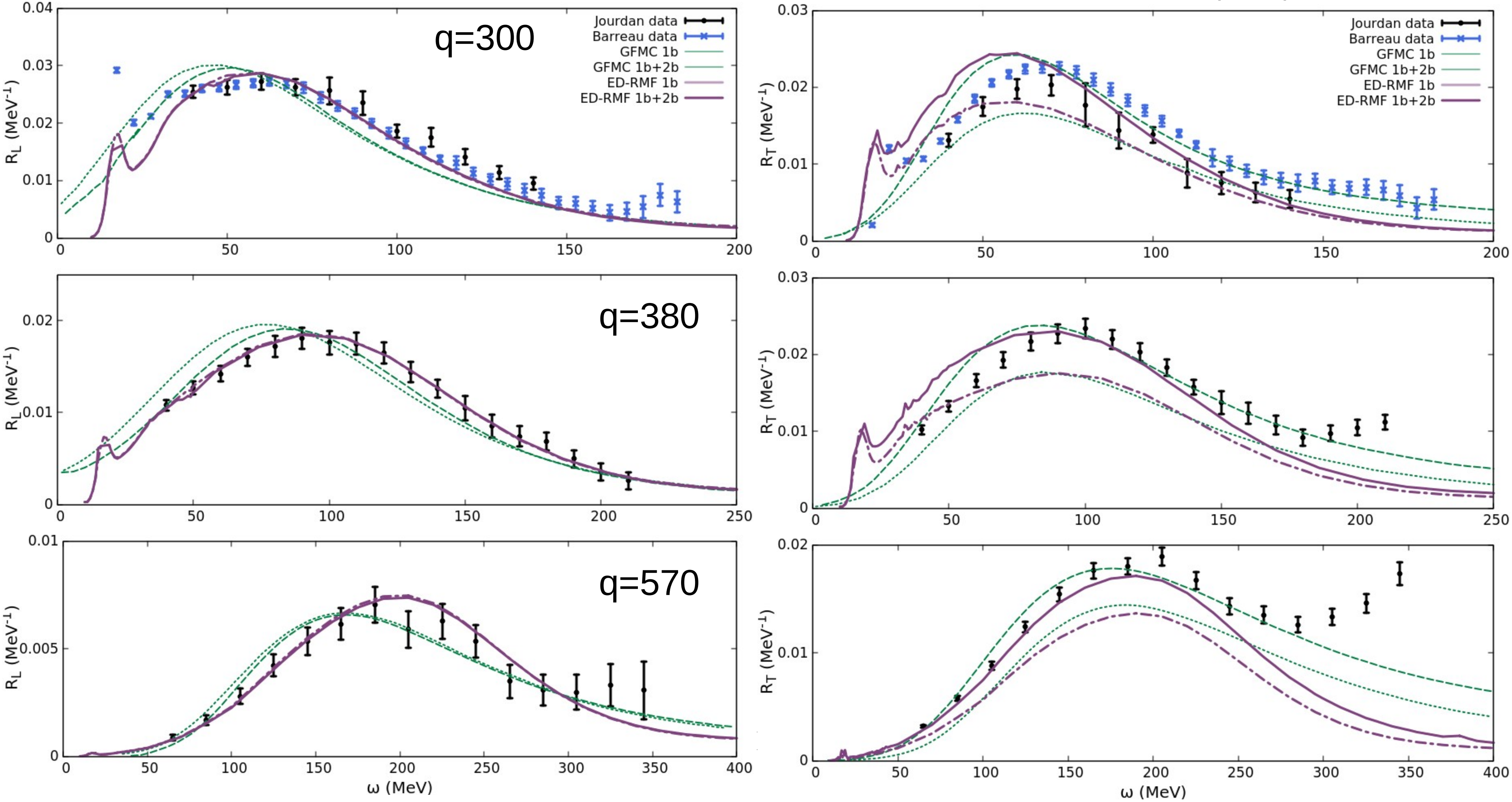


FIG. 2. Background contributions: seagull or contact [CT, (a) and (b)] and pion-in-flight [PF, (c)].

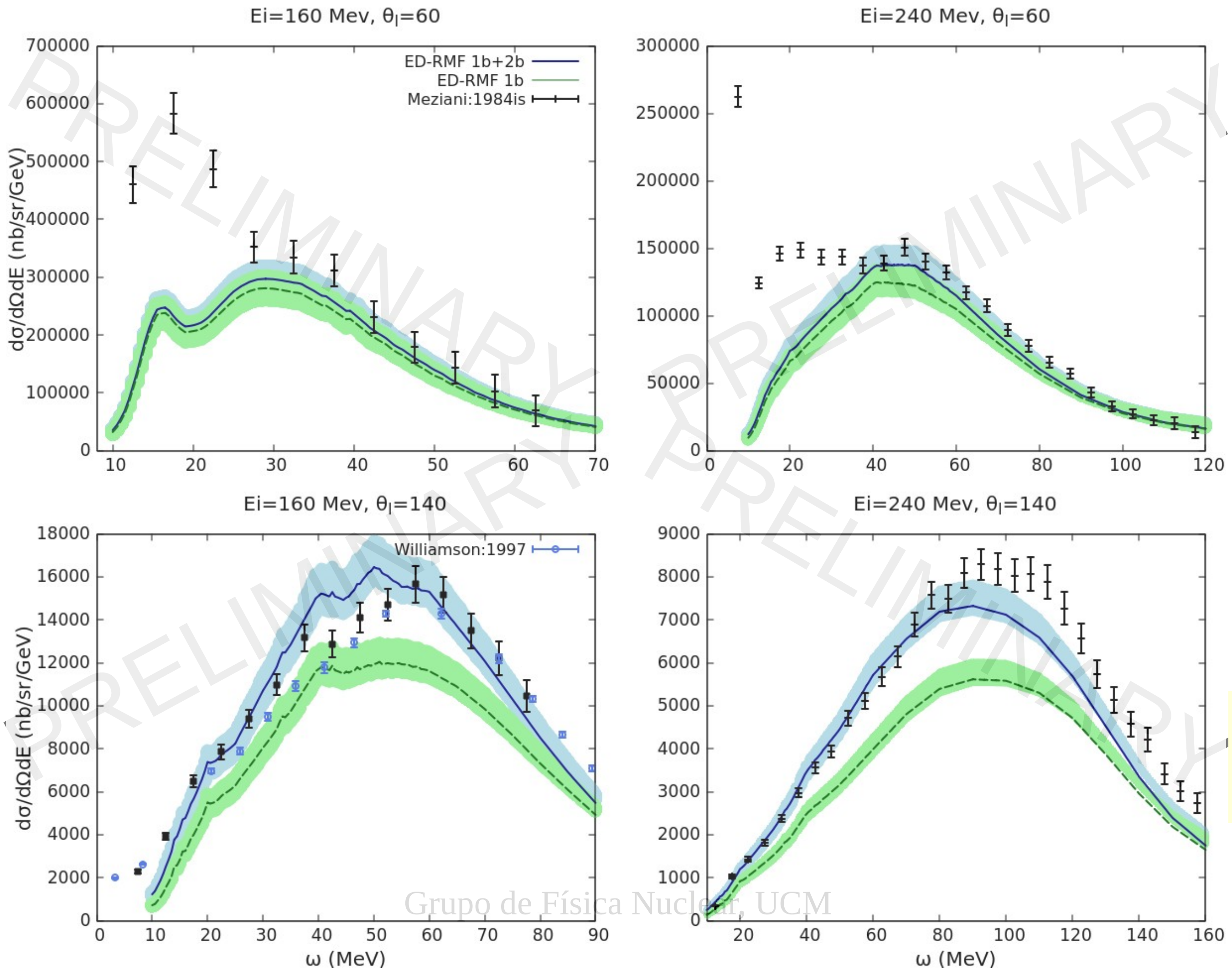
arXiv:2203.09996 [nucl-th]

Carbon 12 responses

green lines from Lovato et al.
PRL 117, 082501 (2016)



Calcium 40 cross sections



Work carried out by T. Franco-Munoz as part of her PhD.

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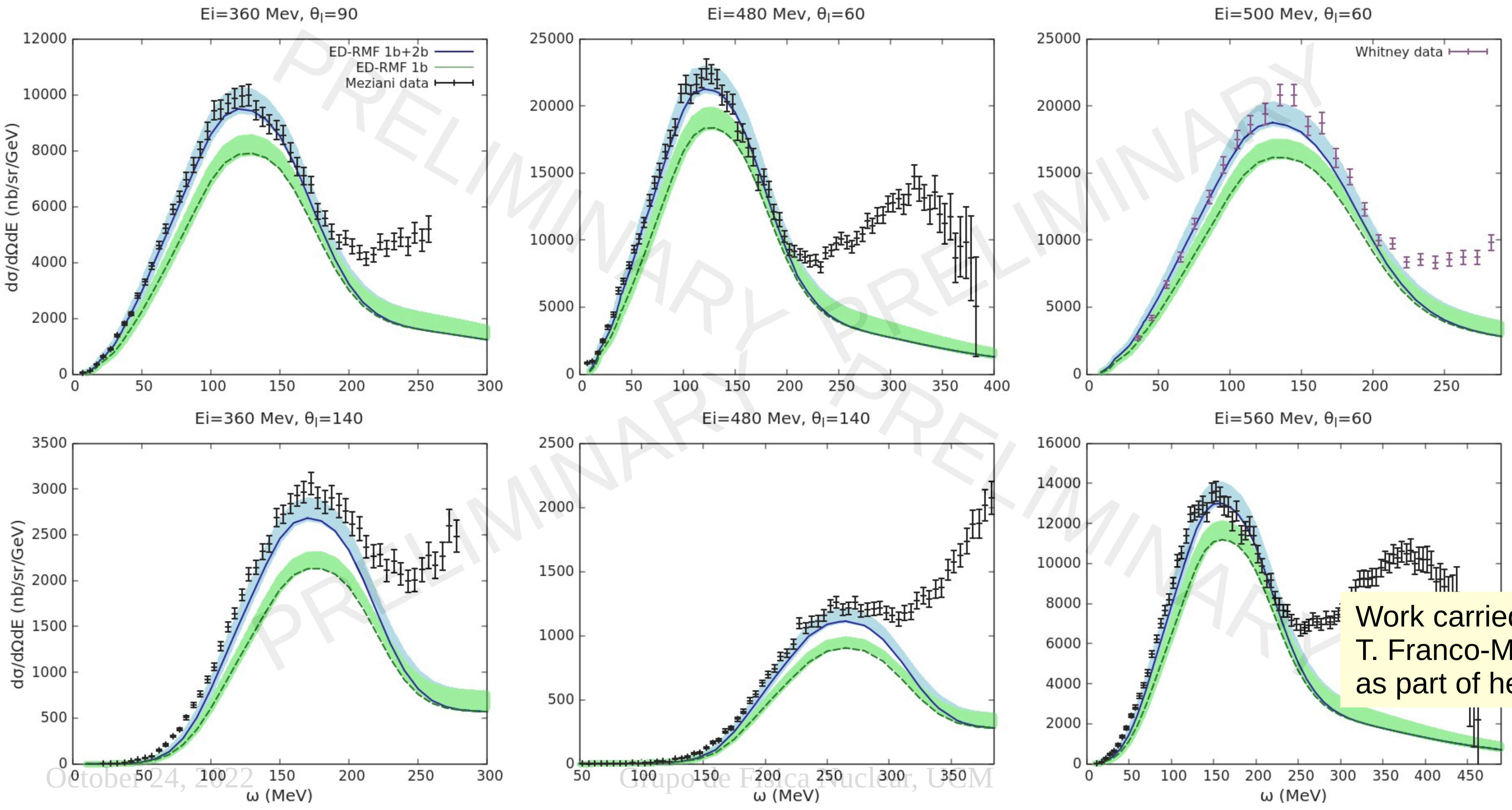

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Some interesting examples

where a proper quantum mechanical treatment of nuclear effects is relevant

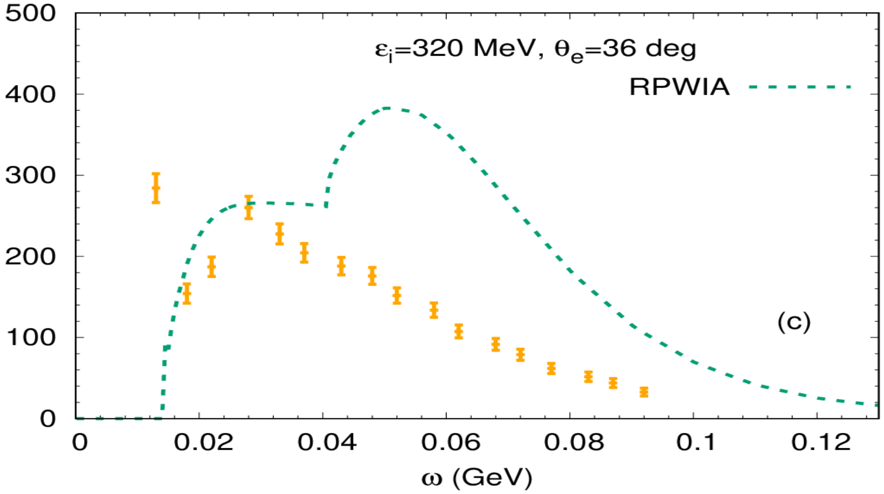
PHYSICAL REVIEW C **100**, 045501 (2019)

Nuclear effects in electron-nucleus and neutrino-nucleus scattering within a relativistic quantum mechanical framework

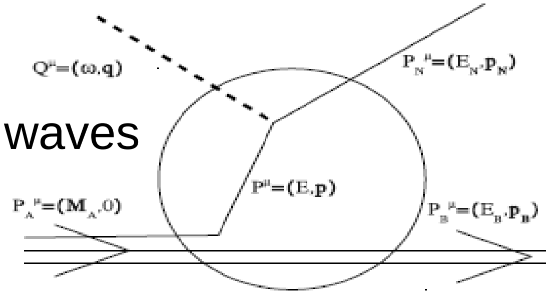
R. González-Jiménez,[1,*] A. Nikolakopoulos,[2,†] N. Jachowicz,[2,‡] and J. M. Udías[1,§]

Phys. Rev. C **100** 045501 (2019)

Inclusive electron scattering **at low q:**



Plane waves



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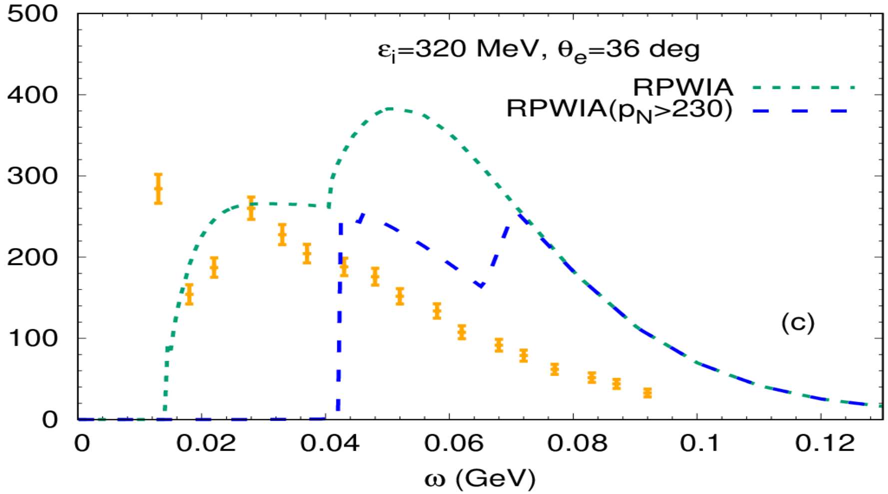

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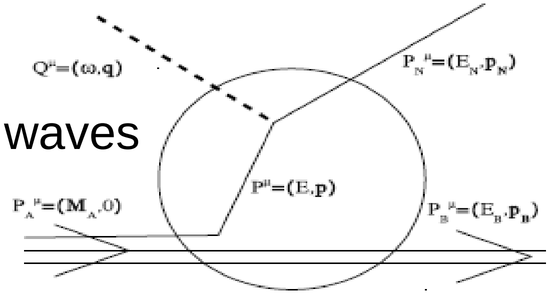

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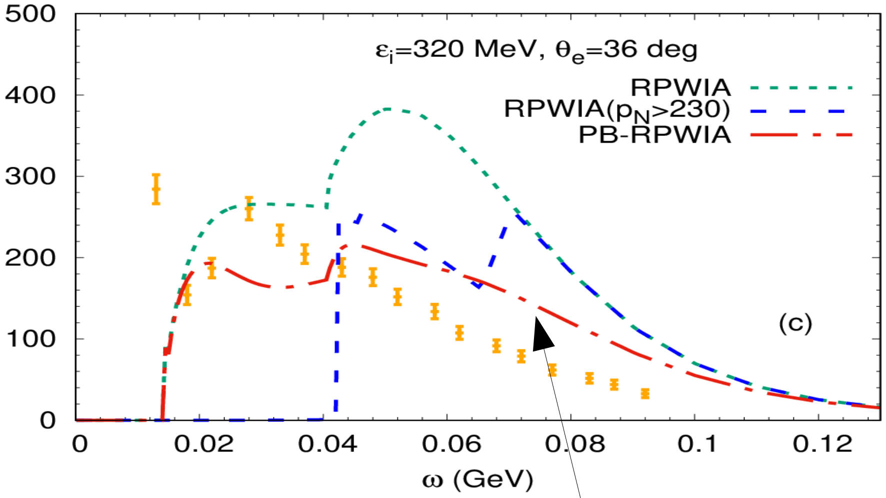

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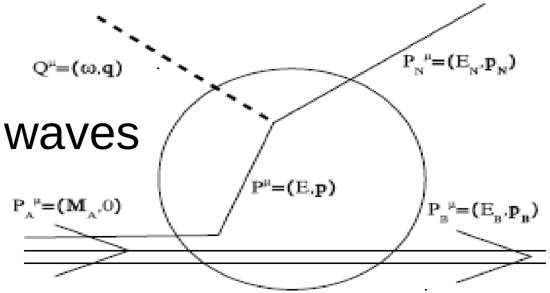

Orthogonalization

$$|\Psi^{s_N}(\mathbf{p}_N)\rangle = \left|\psi^{s_N}_{pw}(\mathbf{p}_N)\right\rangle - \sum_{\kappa,m_j}\left[C^{m_j,s_N}_{\kappa}(\mathbf{p}_N)\right]^\dagger \left|\psi^{m_j}_{\kappa}\right\rangle$$

Phys. Rev. C **100** 045501 (2019)

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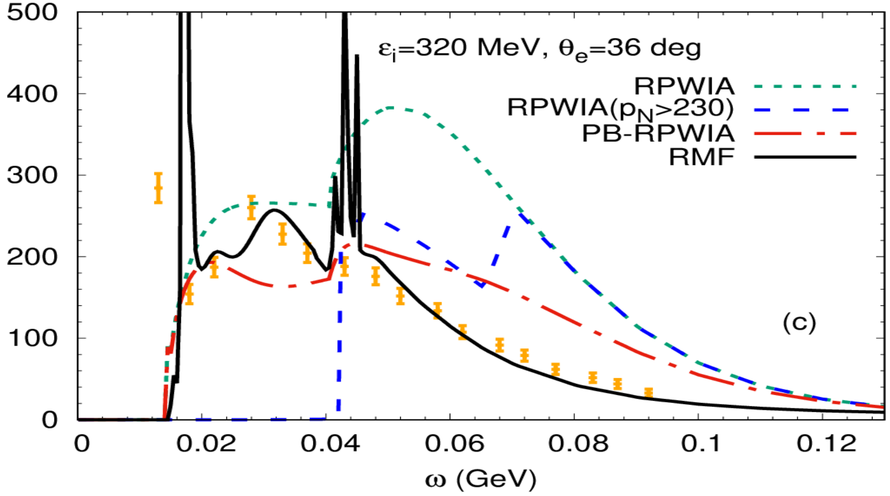

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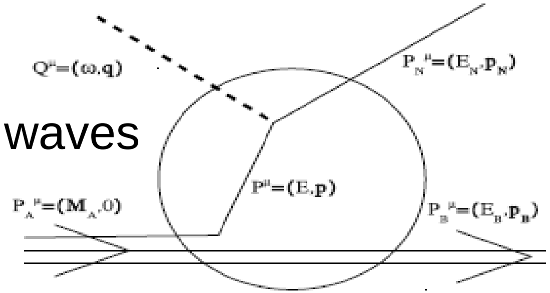
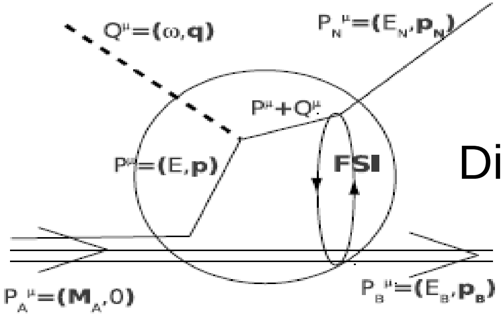
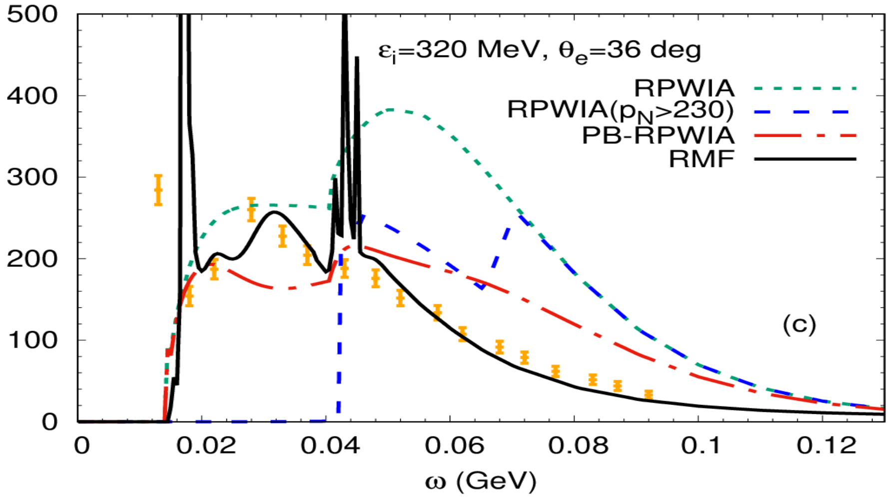




Distorted waves

Inclusive electron scattering **at low q:**



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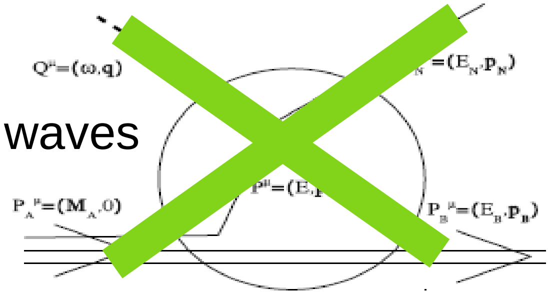
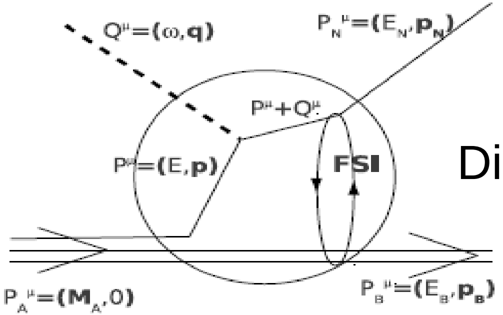
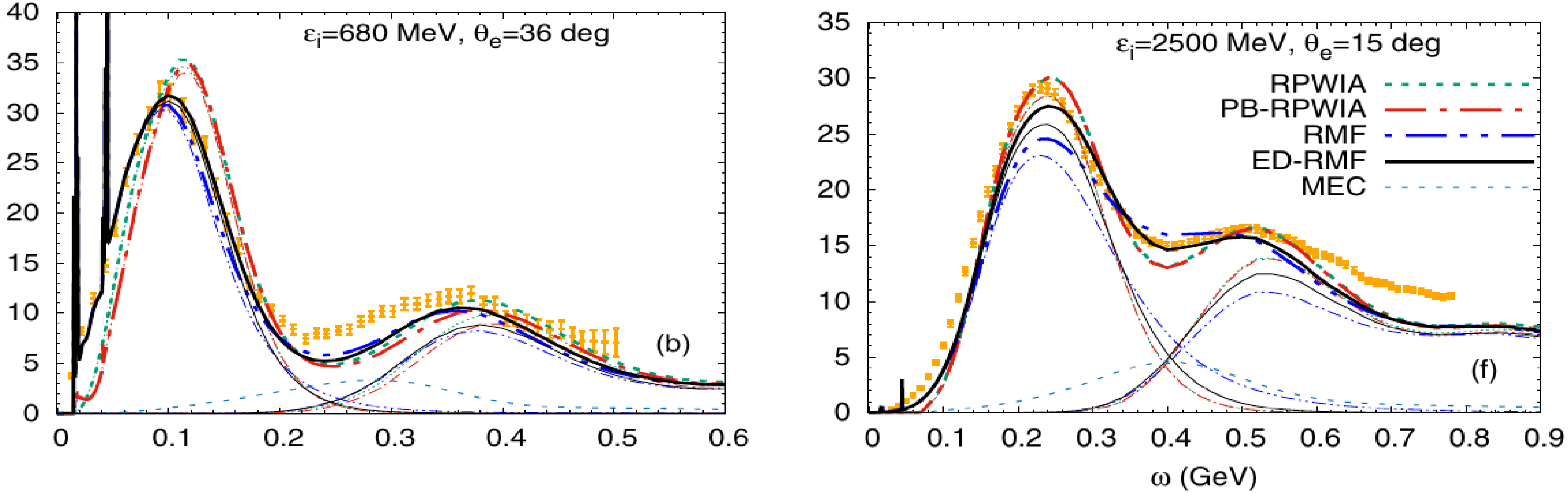




Distorted waves

Quantum Mechanics is important !!

Phys. Rev. C **100** 045501 (2019)



Distortion of the outgoing nucleon (= FSI in a Quantum Mechanical way) is important at intermediate energies too !!!

PHYSICAL REVIEW LETTERS **123,** 052501 (2019)

Electron versus Muon Neutrino Induced Cross Sections in Charged Current Quasielastic Processes

A. Nikolakopoulos,[1,*] N. Jachowicz,[1,†] N. Van Dessel,[1] K. Niewczas,[1,2] R. González-Jiménez,[3] J. M. Udías,[3] and V. Pandey[4]

For a given neutrino energy and scattering angle of the final lepton:

$$\frac{\nu_e \text{ QE cross section}}{\nu_\mu \text{ QE cross section}} = 1 \qquad ???$$

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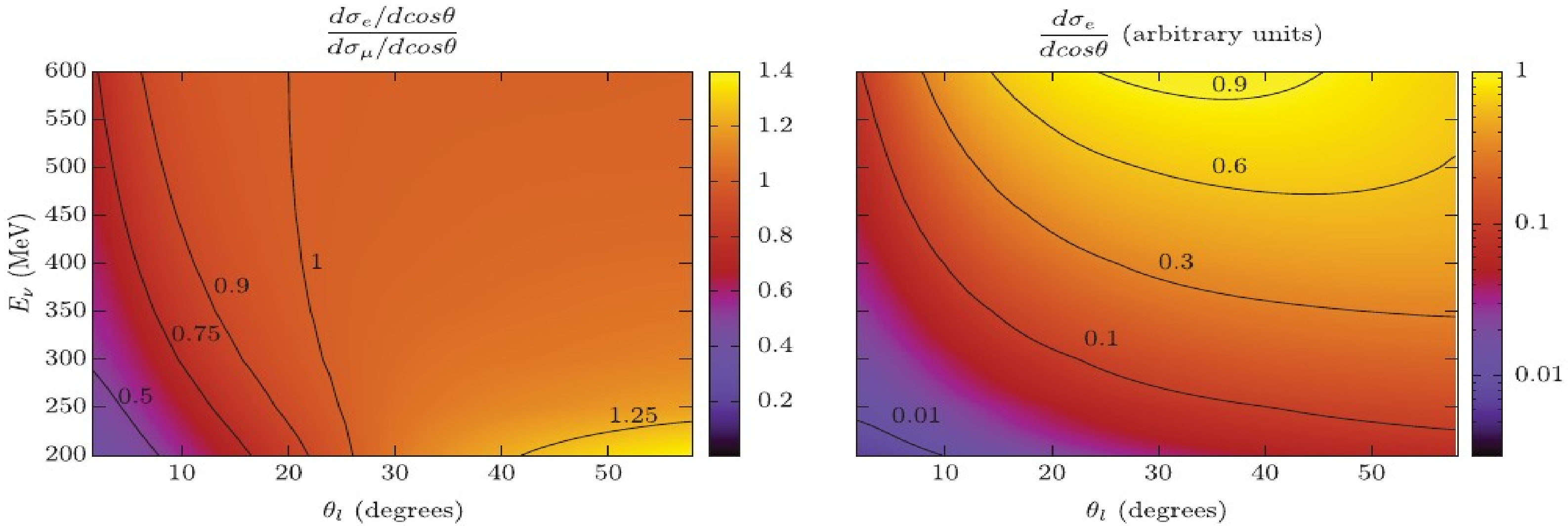

FIG. 4. Ratio of ^{12}C cross sections as a function of incoming energy and lepton scattering angle, combined with relative strength of the cross section at the same kinematics (normalized such that the maximum in this kinematic region is 1). Results shown here were obtained within the CRPA approach, RMF ratios are very similar [30].

Electron versus Muon Neutrino Induced Cross Sections in Charged Current Quasielastic Processes

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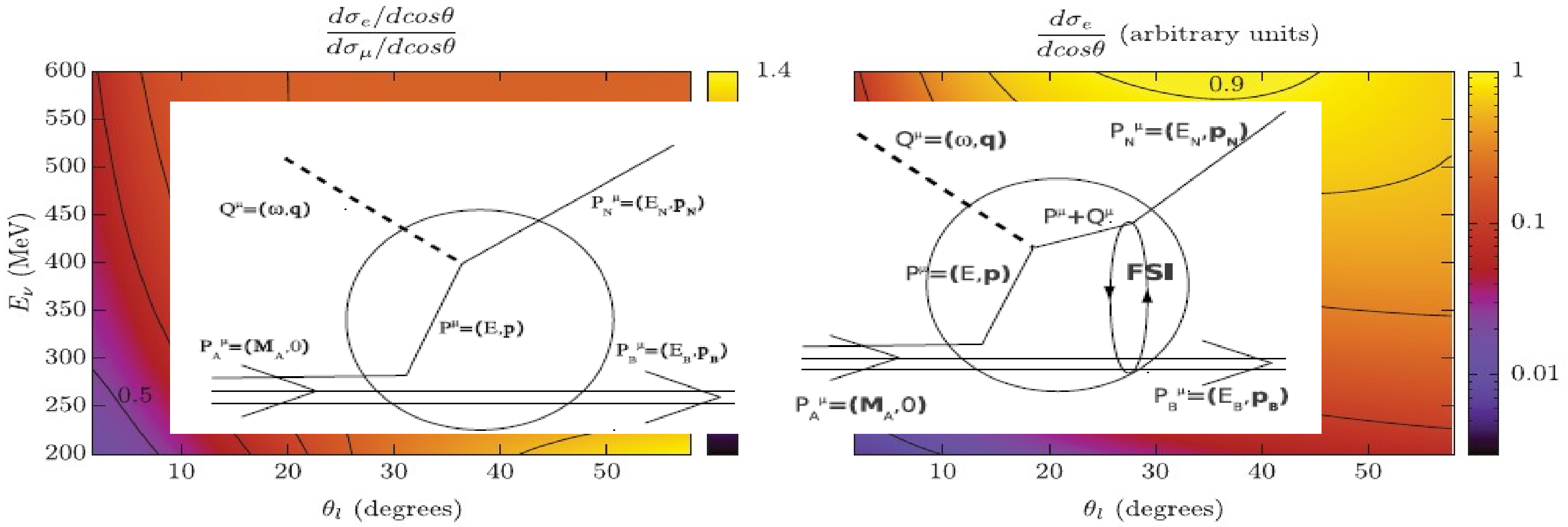

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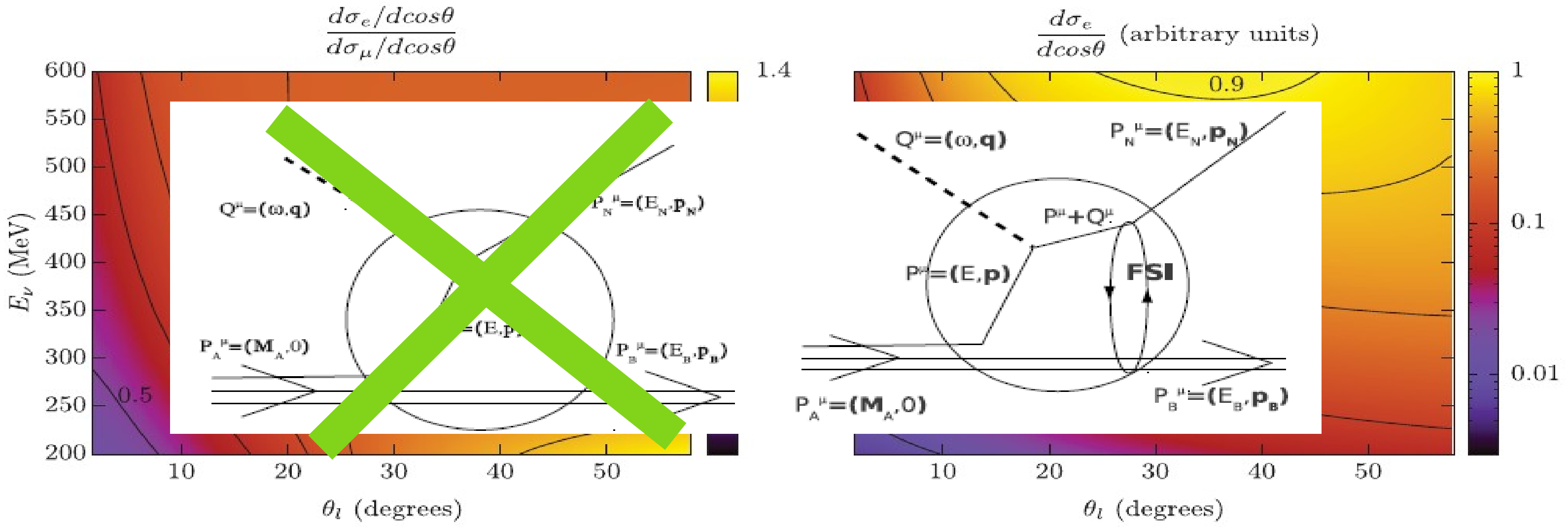

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Semi-inclusive cross sections

Final state interactions in semi-inclusive neutrino-nucleus scattering: Application to T2K and MINERνA experiments

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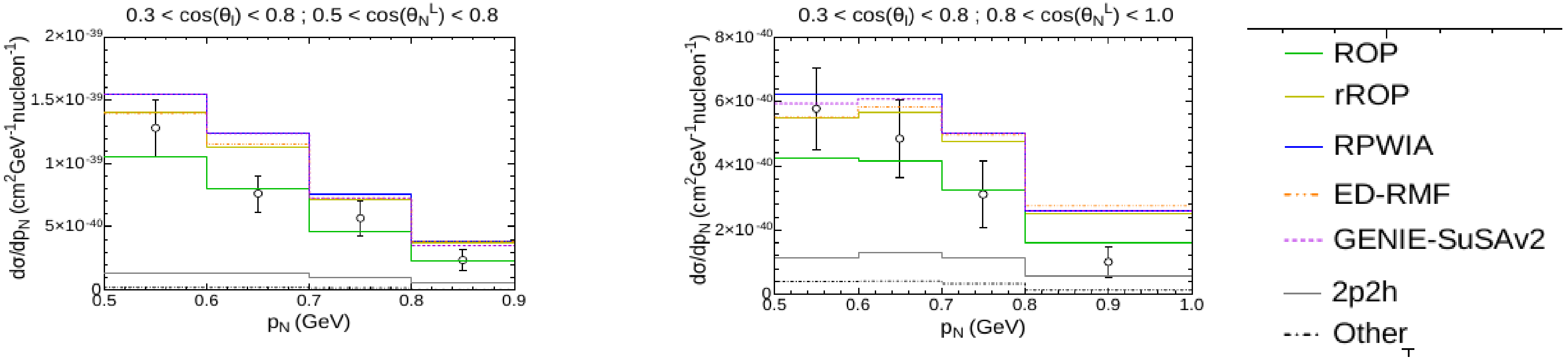
arXiv:2207.02086v1 [nucl-th]



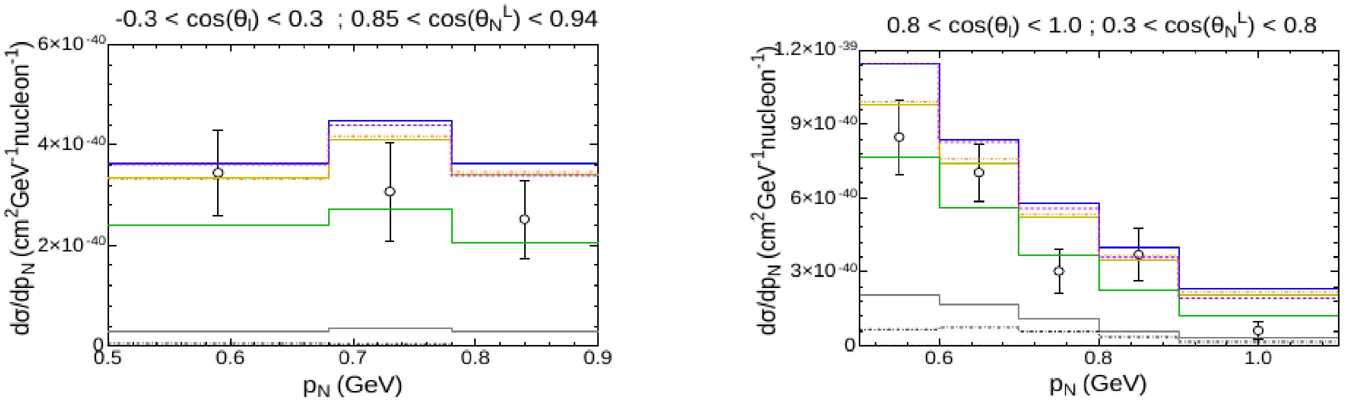


Figure 4: T2K CC0π semi-inclusive $\nu_\mu-{}^{12}C$ cross section with protons in the final state with momenta above 0.5 GeV as function of the final proton and muon kinematics. All curves include the 2p2h and pion absorption contribution (shown separately), evaluated using GENIE.

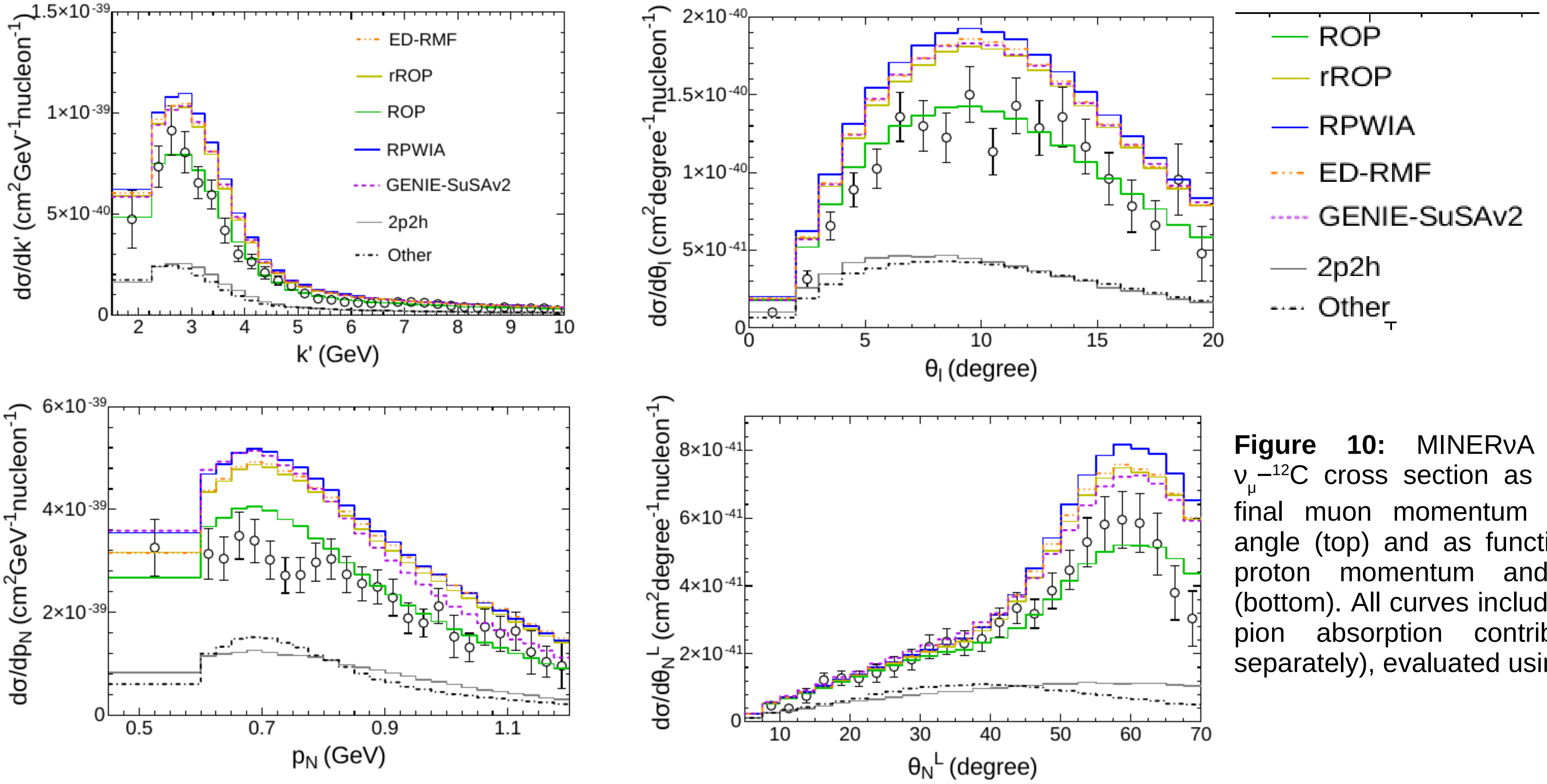


Figure 10: MINERνA semi-inclusive $\nu_\mu - {}^{12}C$ cross section as function of the final muon momentum and scattering angle (top) and as function of the final proton momentum and polar angle (bottom). All curves include the 2p2h and pion absorption contribution (shown separately), evaluated using GENIE.

Single-pion production

Assessing the theory-data tension in neutrino-induced charged pion production: the effect of final-state nucleon distortion

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https://arxiv.org/abs/2210.12144

Summary and Conclusions:

1. Possibilities to improve the reliability of MC event generators' predictions:

+ Use as input realistic models that provide good inclusive results and information on the hadrons.

+ Benchmark the cascade model by comparing the "only-1-proton-in-the-final-state signal" with the predictions from ROP models. Tune the cascade if necessary.

2. A two-body operator allows us to simultaneously reproduce the longitudinal and transverse EM responses.

3. A proper quantum mechanical approach is essential to reproduces features that appear at low-Q^2: Pauli blocking region, position of the QE peak and ν_e/ν_μ ratio.

4. Not discussed in this presentation but work is in progress on **single-pion production on the nucleus.**

Thanks for the attention