What mean-field models can offer to the neutrino interaction community

Raúl González Jiménez

**Grupo de Física Nuclear,
Universidad Complutense & IPARCOS,
Madrid, Spain**

NuInt 2022, Seoul (South Korea), October 24, 2022

In collaboration with...

Tania Franco Muñoz, Jose M. Udías (Complutense University of Madrid)

Alexis Nikolakopoulos, Vishvas Pandey (Fermilab)

Juan M. Franco Patiño, Guillermo D. Megías, Juan A. Caballero (Sevilla)

Maria B. Barbaro (Torino)

T. William Donnelly (MIT)

Natalie Jachowicz (Ghent University)

Kajetan Niewczas (Ghent and Wroclaw Universities)

Stephen Dolan (CERN)

Federico Sánchez (University of Geneva)

Overview

1. What do Monte Carlo event generators need? What we can actually model with an acceptable level of accuracy.

2. Benchmarking intranuclear cascade models.

3. RDWIA approach: recent developments.

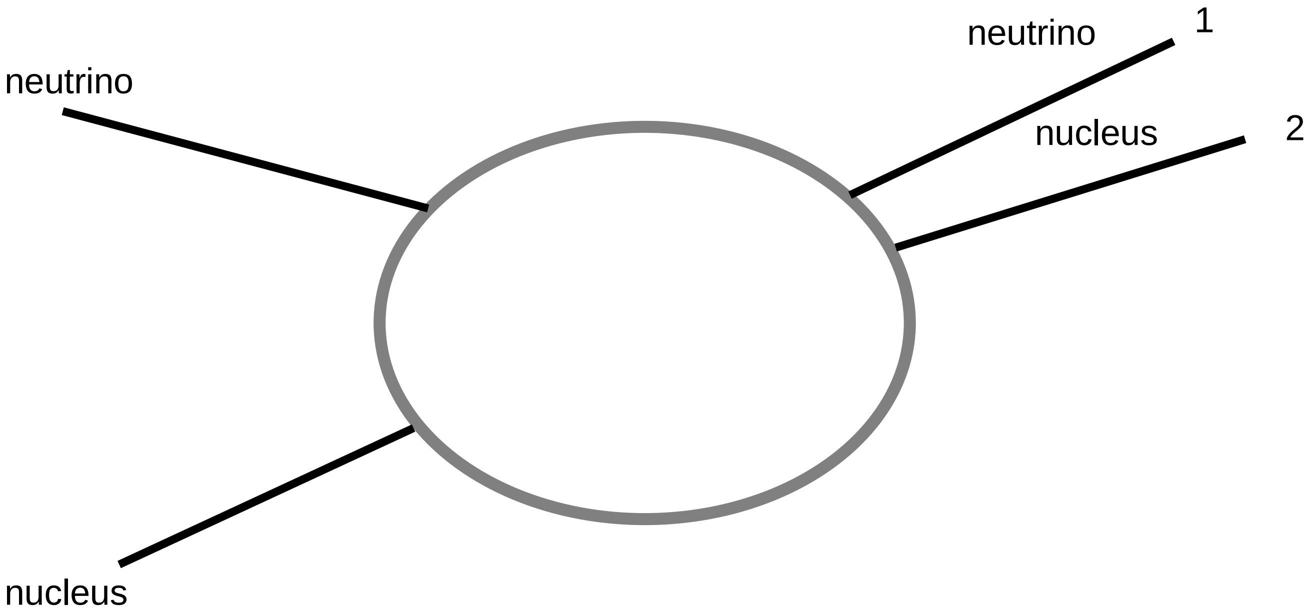
4. Some examples where quantum mechanics plays a relevant role.

5. Semi-inclusive neutrino-nucleus cross sections.

6. Summay and outlook.

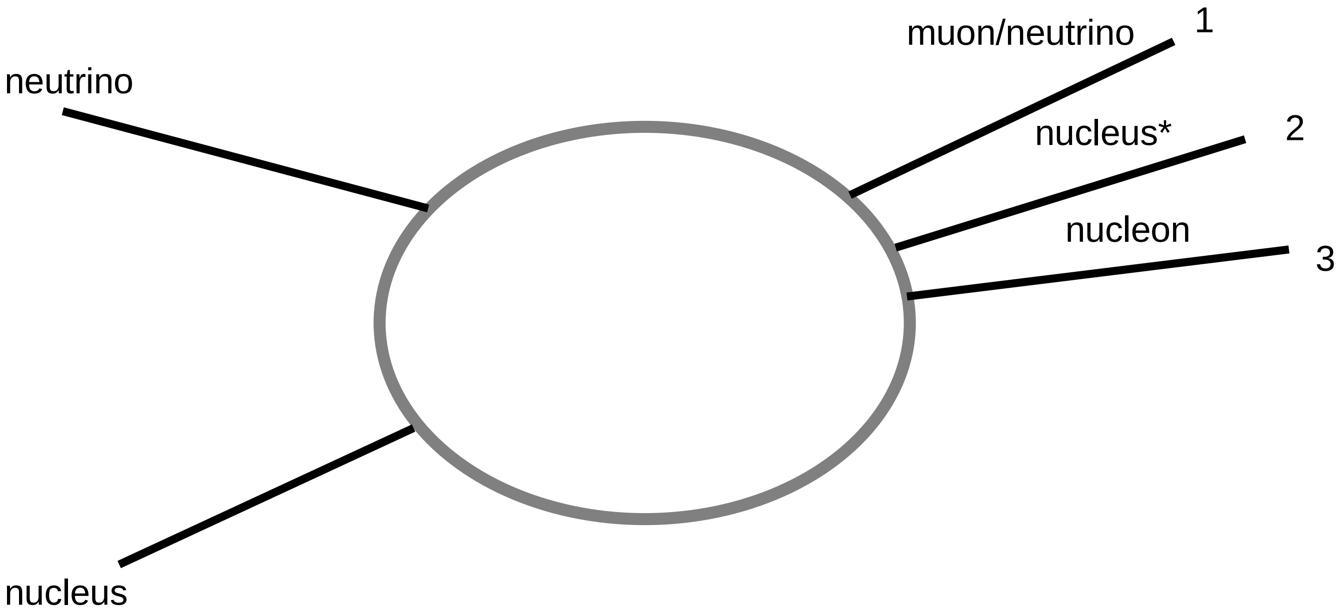
What do Monte Carlo neutrino event generators need?

Do they need to model…



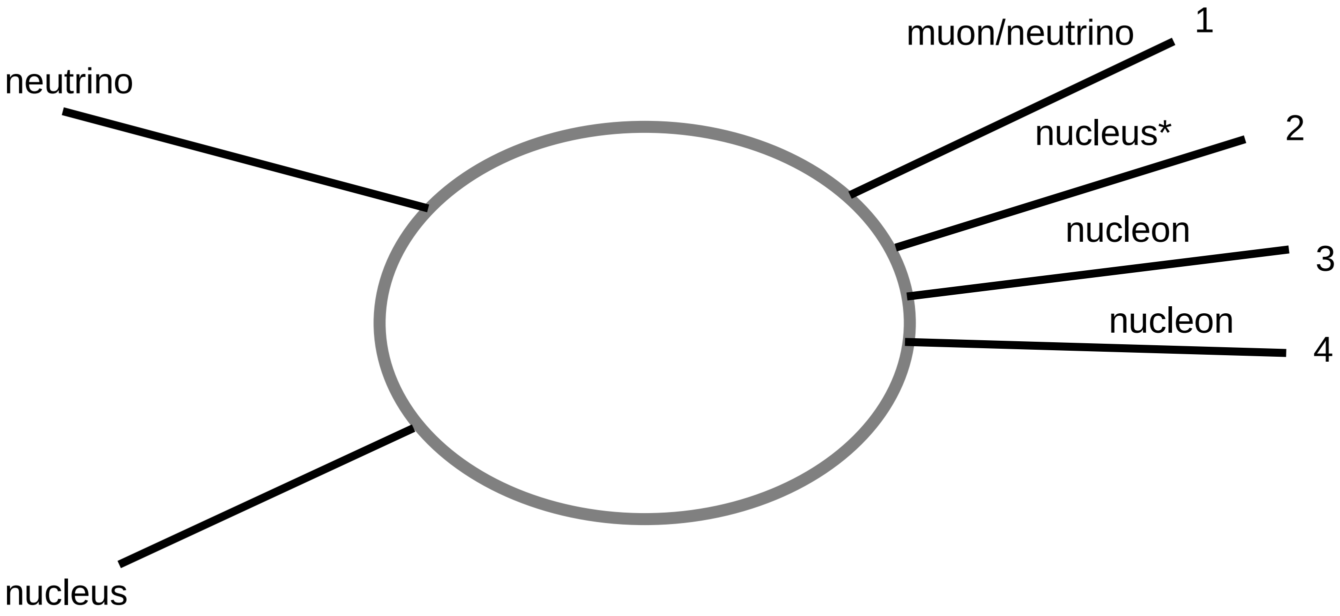
...elastic scattering?
(medium difficult)

Do they need to model…



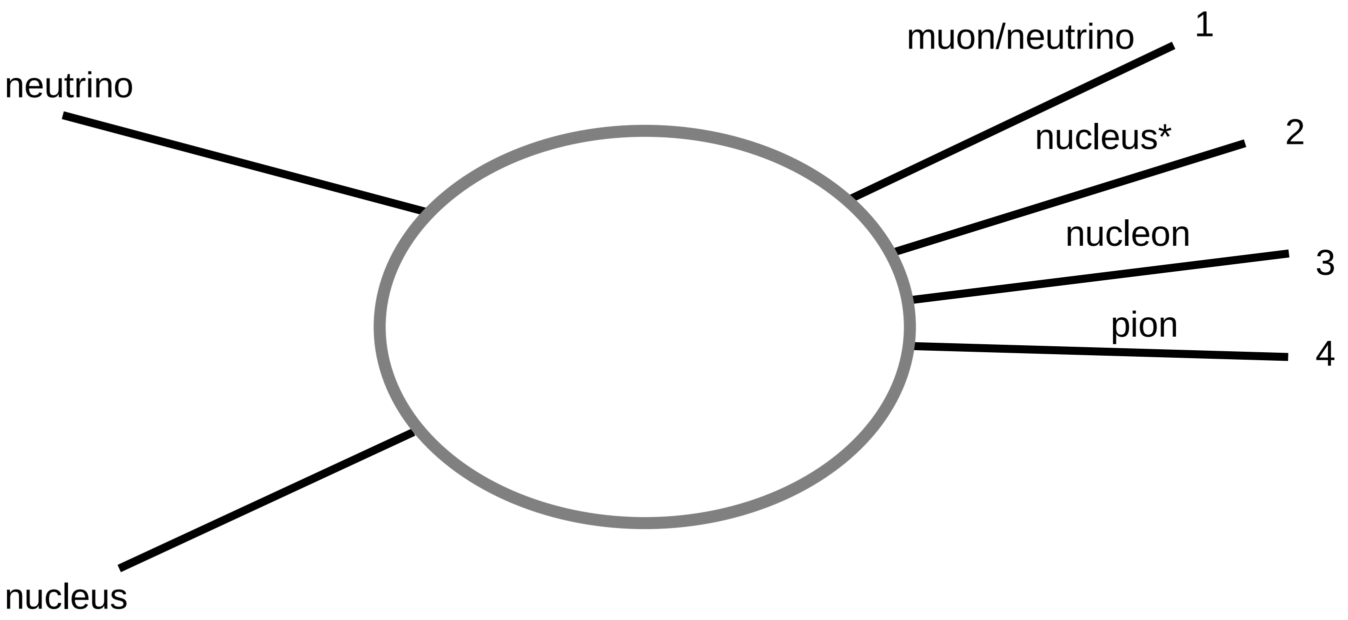
...quasielastic scattering?
(difficult)

Do they need to model…



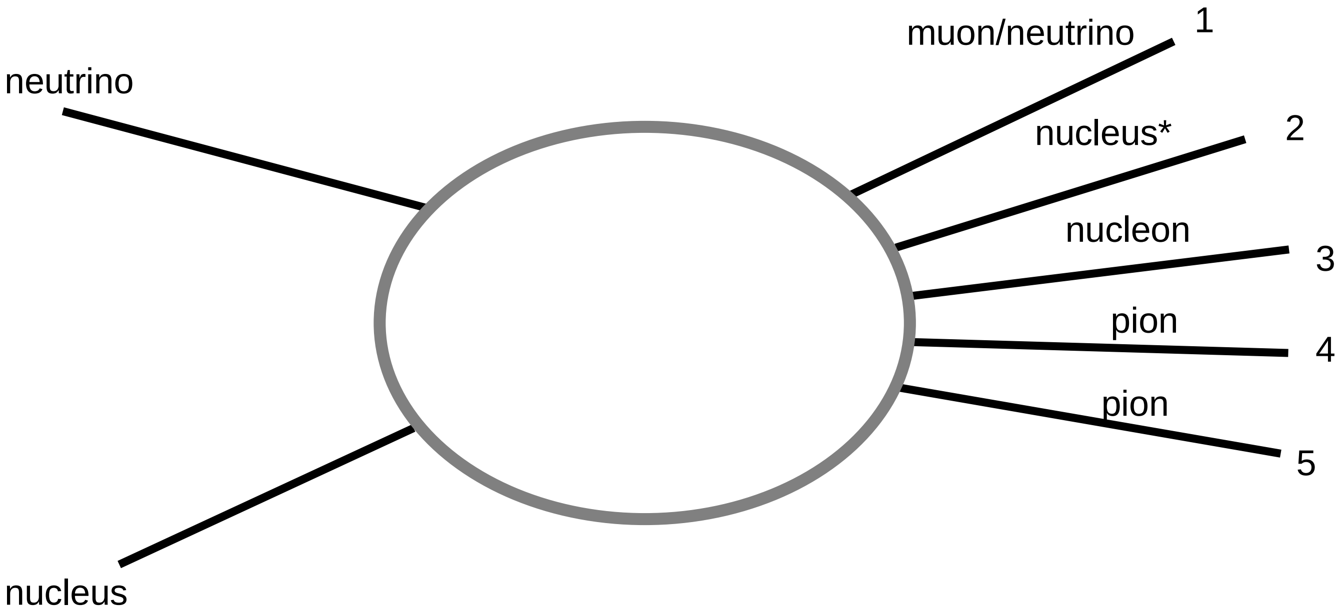
...2N knockout?
(very difficult)

Do they need to model…



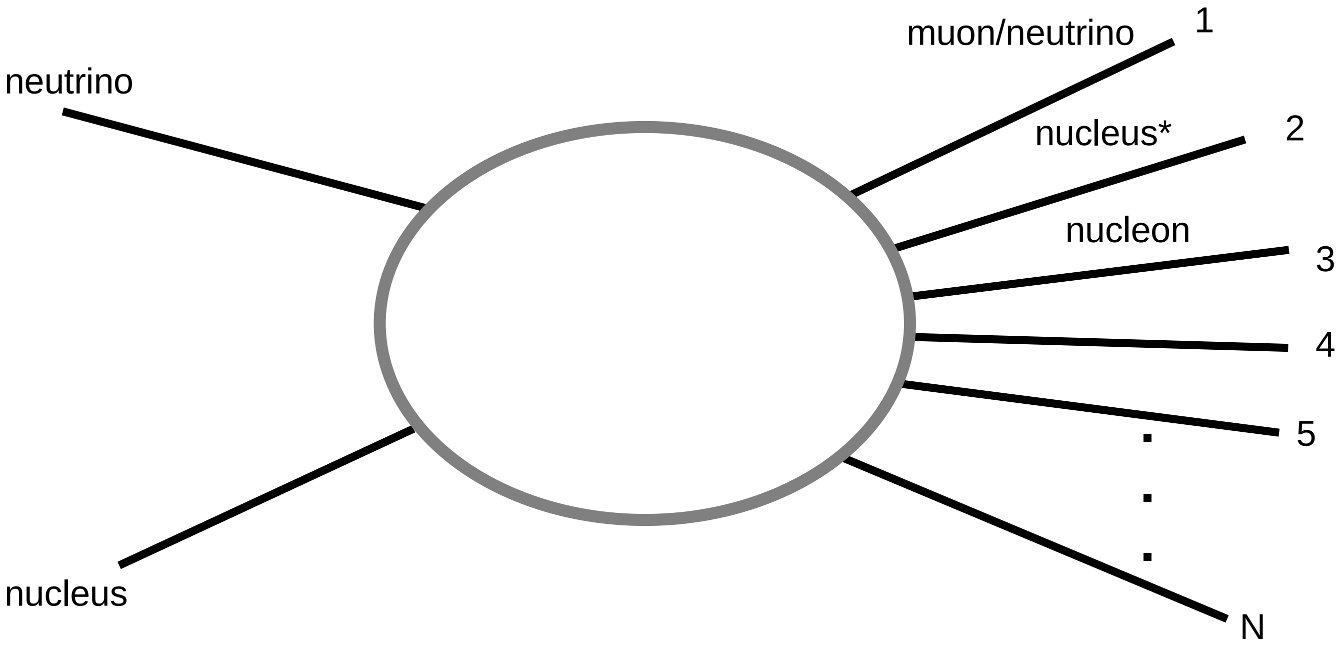
...single-pion production?
(very very difficult)

Do they need to model…



...two-pion production?
(extremely difficult, impossible?)

Do they need to model…



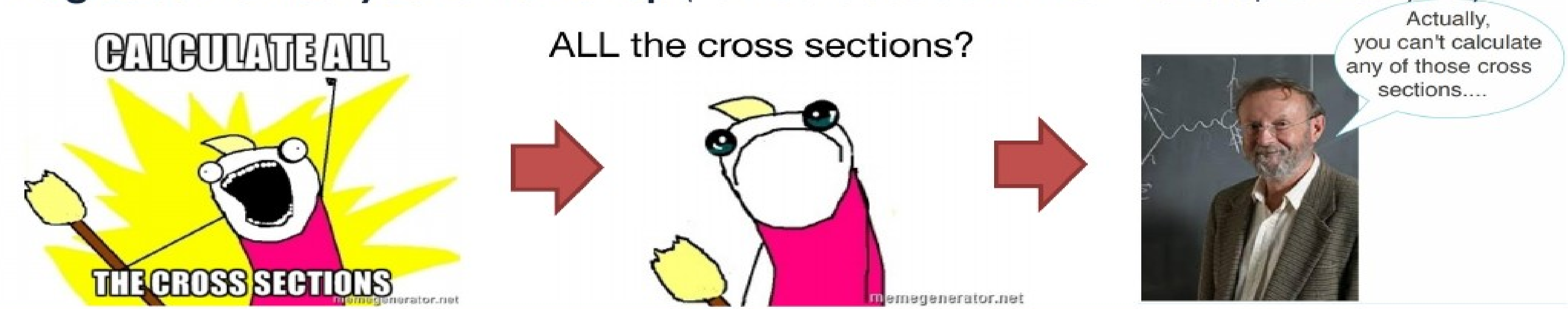
...more complex scenarios?
(impossible)

Semi-inclusive cross sections?

In the generators we (mostly) do this

(And so do most microscopic models)

Progression of last year's workshop (from G. Perdue's GENIE ECT* workshop talk last year)



What **we can actually model** with an acceptable level of accuracy:

What **we can actually model** with an acceptable level of accuracy:

1. **Inclusive** cross sections: no hadrons detected

What **we can actually model** with an acceptable level of accuracy:

1. **Inclusive** cross sections: no hadrons detected
2. **Exclusive 1 proton knockout** cross sections: the full kinematic is known and we’re sure that there is only 1 proton in the final state. (Note: neutrino experiments are not exclusive.)

What **we can actually model** with an acceptable level of accuracy:

1. **Inclusive** cross sections: no hadrons detected
2. **Exclusive 1 proton knockout** cross sections: the full kinematic is known and we're sure that there is only 1 proton in the final state. (Note: neutrino experiments are not exclusive.)
3. **Antineutrino-proton and neutrino-deuterium** cross sections: see works by Donnelly, Van Orden, Moreno, et al.

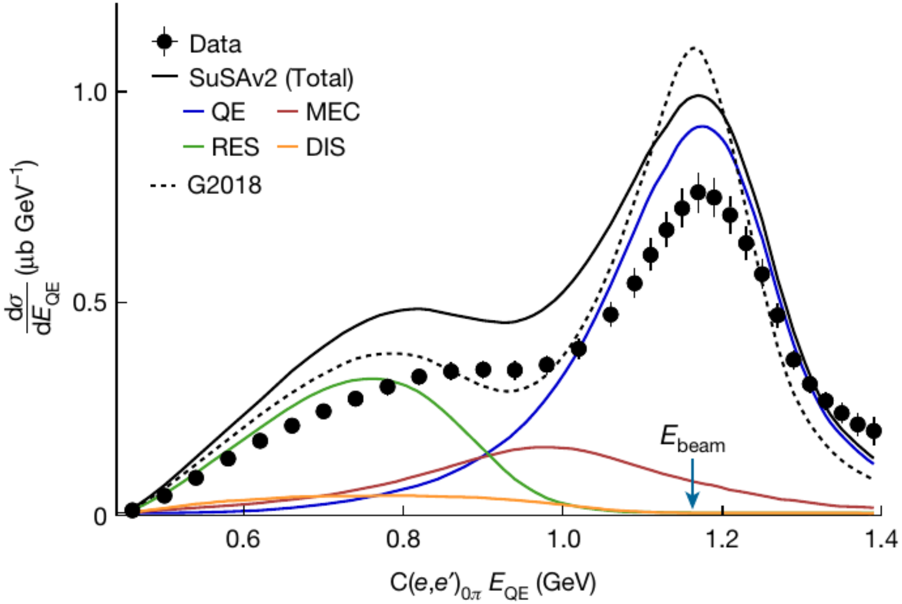
Article

Electron-beam energy reconstruction for neutrino oscillation measurements

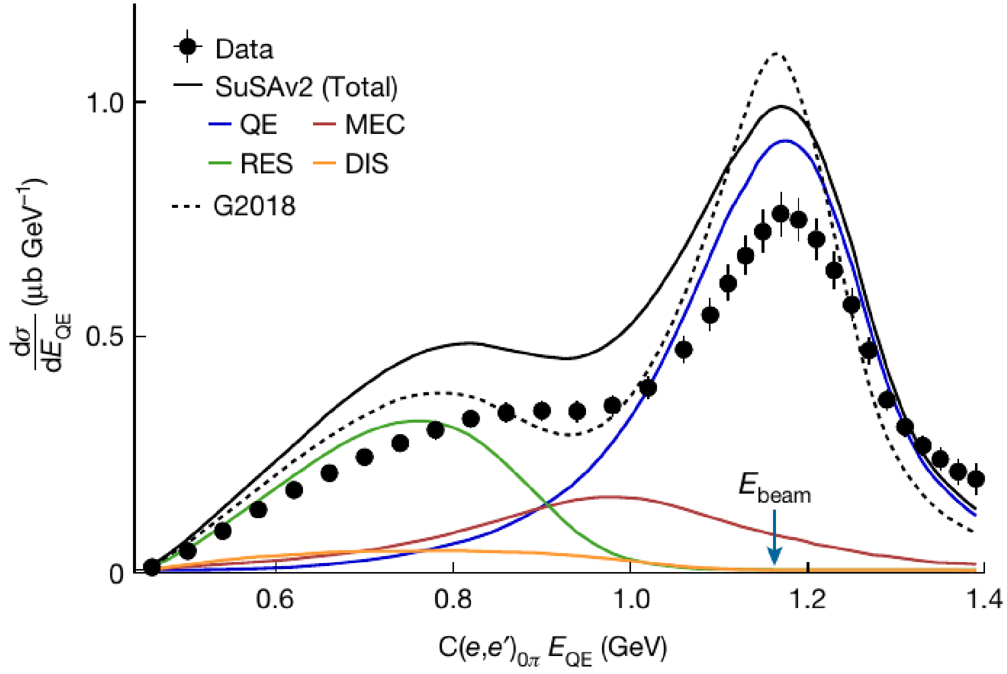
https://doi.org/10.1038/s41586-021-04046-5

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*



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

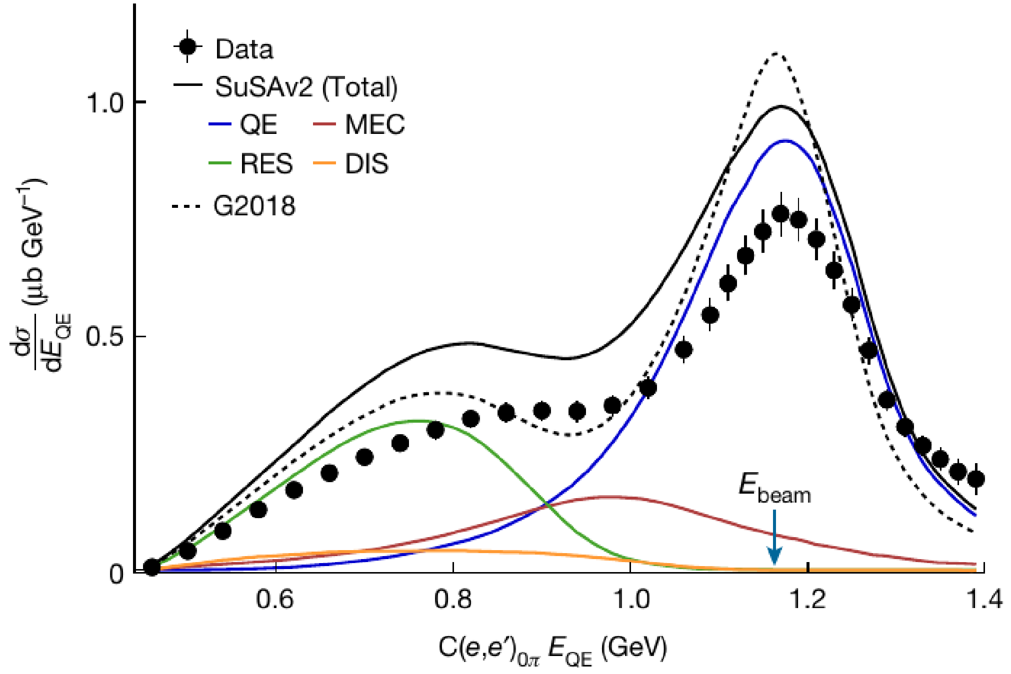


Ebeam = 1.159, and angles 15° ≤ θe ≤ 45°

(I’ll focus the discussion 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? Possible explanations:

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

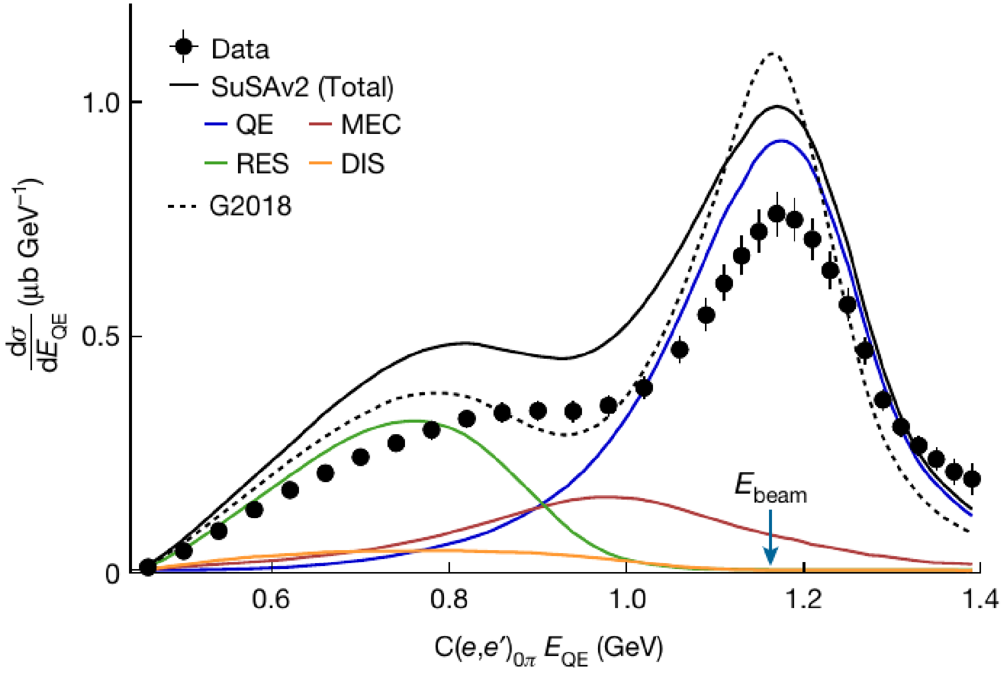


Ebeam = 1.159, and angles 15° ≤ θe ≤ 45°

(I'll focus the discussion 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? Possible explanations:
+ This is not an inclusive experiment, but for this data set, it's almost inclusive in the QE peak...

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



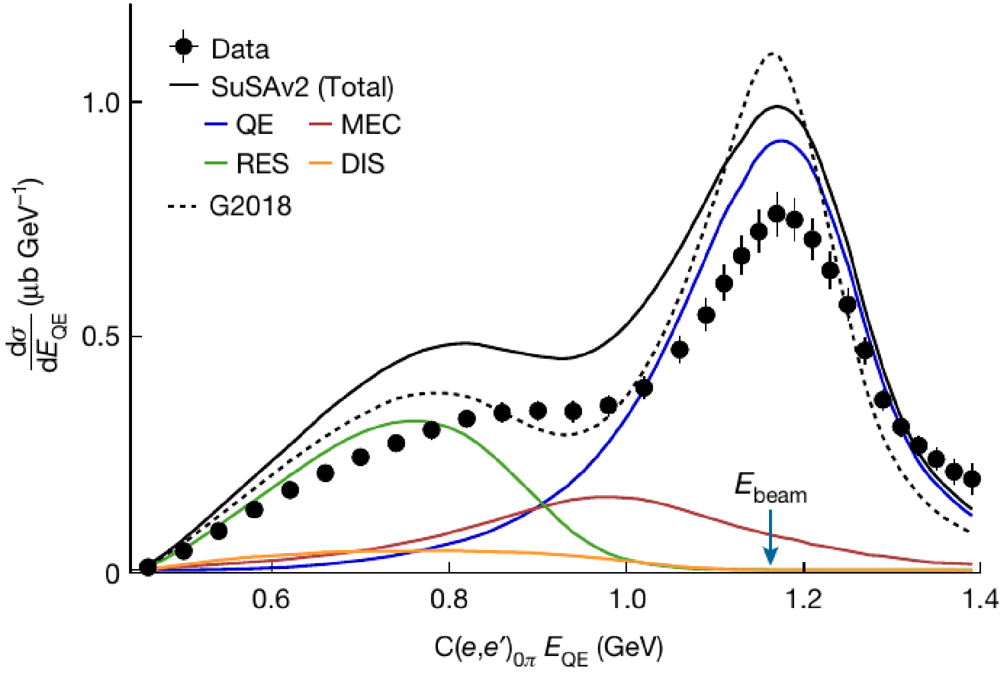
Ebeam = 1.159, and angles 15° ≤ θe ≤ 45°

(I'll focus the discussion 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? Possible explanations:
+ This is not an inclusive experiment, but for this data set, it's almost inclusive in the QE peak...

+ The cross section is dominated by forward scattering angles:

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

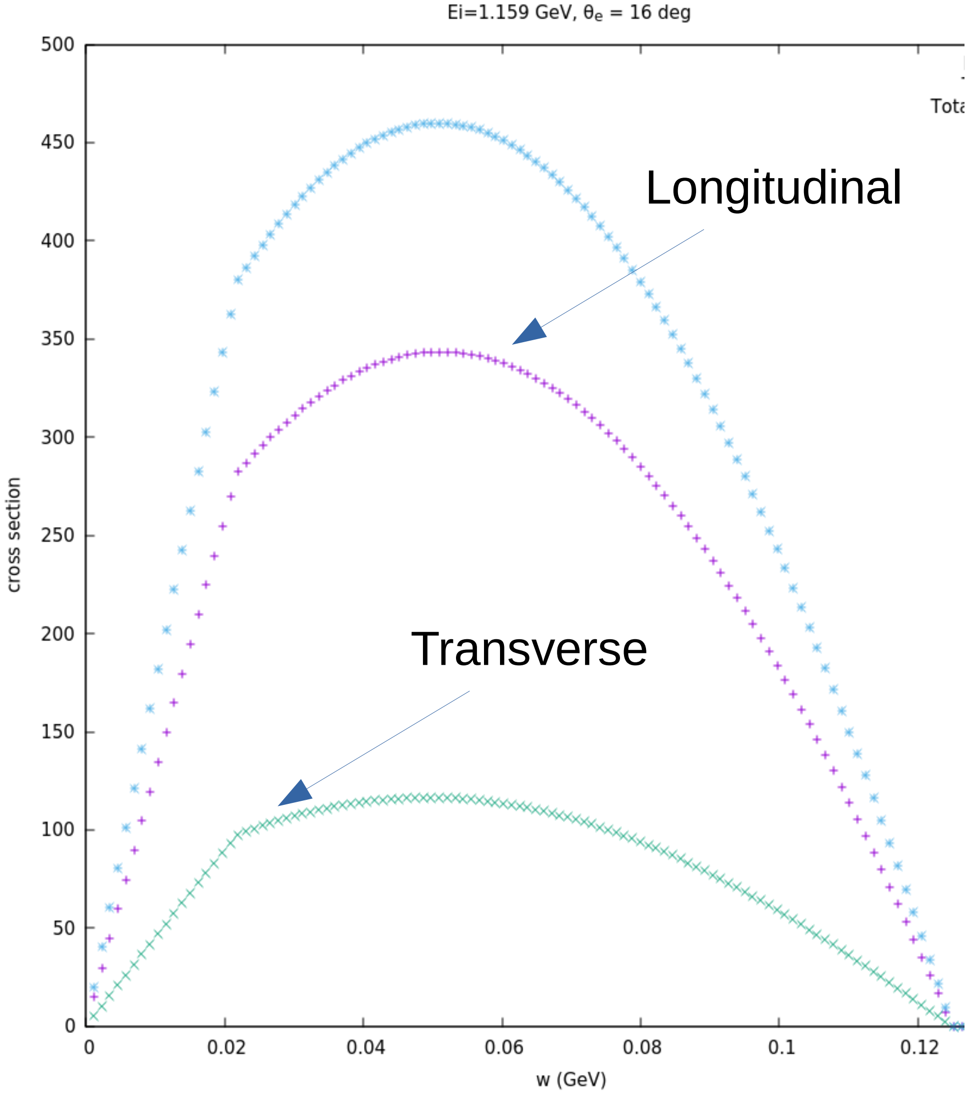


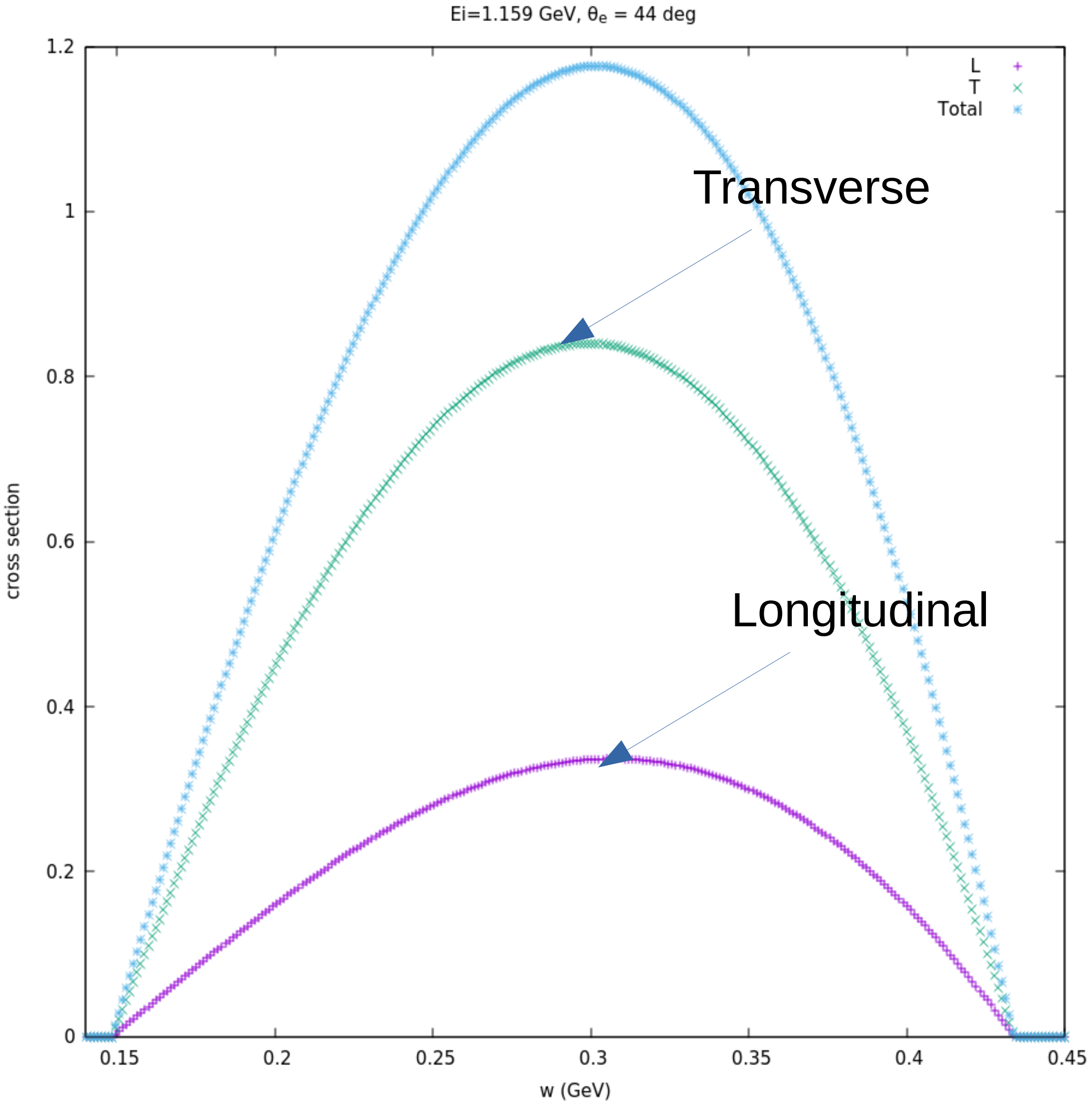
Ebeam = 1.159, and angles 15° ≤ θe ≤ 45°

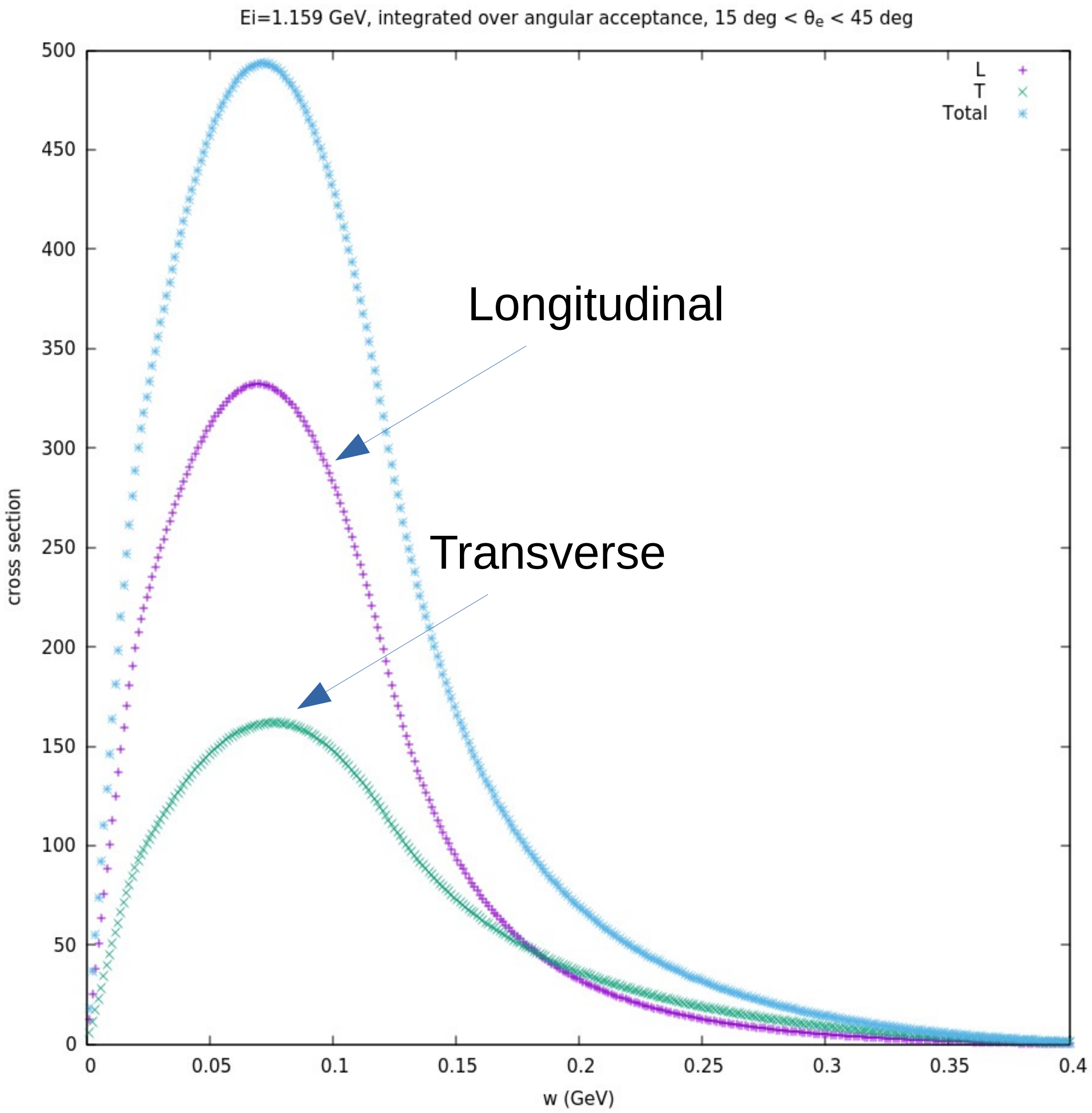
(I’ll focus the discussion on the QE peak.) So far, SuSAv2+MEC has proven to be able to reproduce quite well all inclusive (e,e’) data.

So what’s going on here? Possible explanations:
+ This is not an inclusive experiment, but for this data set, it’s almost inclusive in the QE peak...

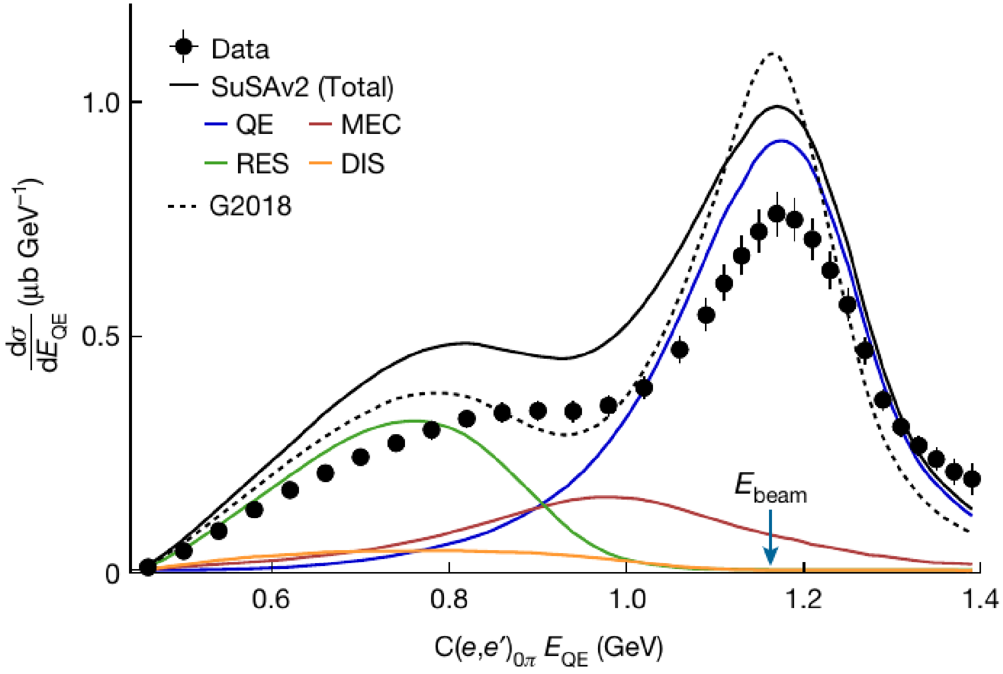
+ The cross section is dominated by forward scattering angles:
++ L response plays a very important role. SuSAv2 has some troubles to describe L and T responses at the same time (JPG:NPP 47 (2020) 124001)


Ei=1.159 GeV, θe = 16 deg
cross section
w (GeV)
Tota
Longitudinal
Transverse
0
50
100
150
200
250
300
350
400
450
500
0
0.02
0.04
0.06
0.08
0.1
0.12


Ei=1.159 GeV, θe = 44 deg
cross section
w (GeV)
L
T
Total
Transverse
Longitudinal
0
0.2
0.4
0.6
0.8
1
1.2
0.15
0.2
0.25
0.3
0.35
0.4
0.45


Ei=1.159 GeV, integrated over angular acceptance, 15 deg < θe < 45 deg
L
T
Total
Longitudinal
Transverse
cross section
w (GeV)
500
450
400
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

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

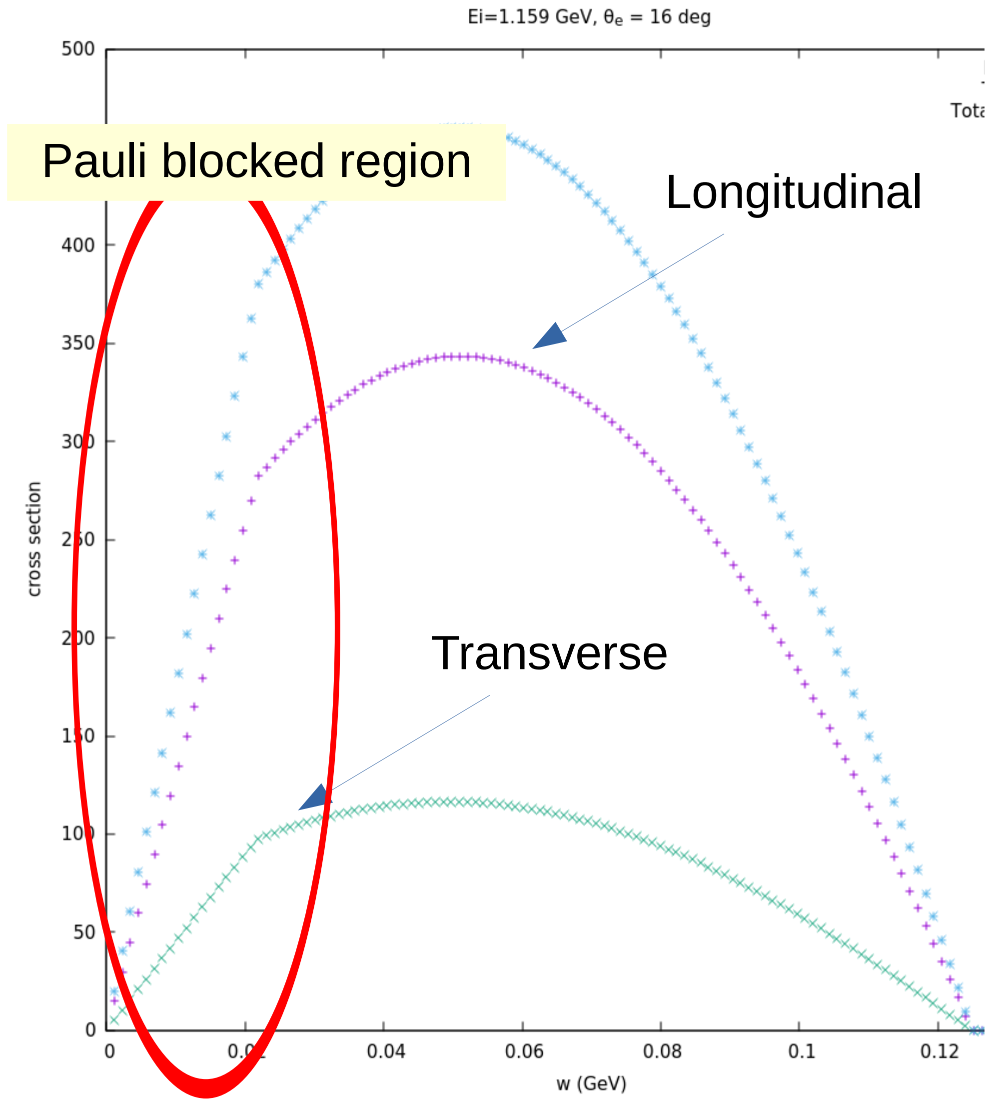


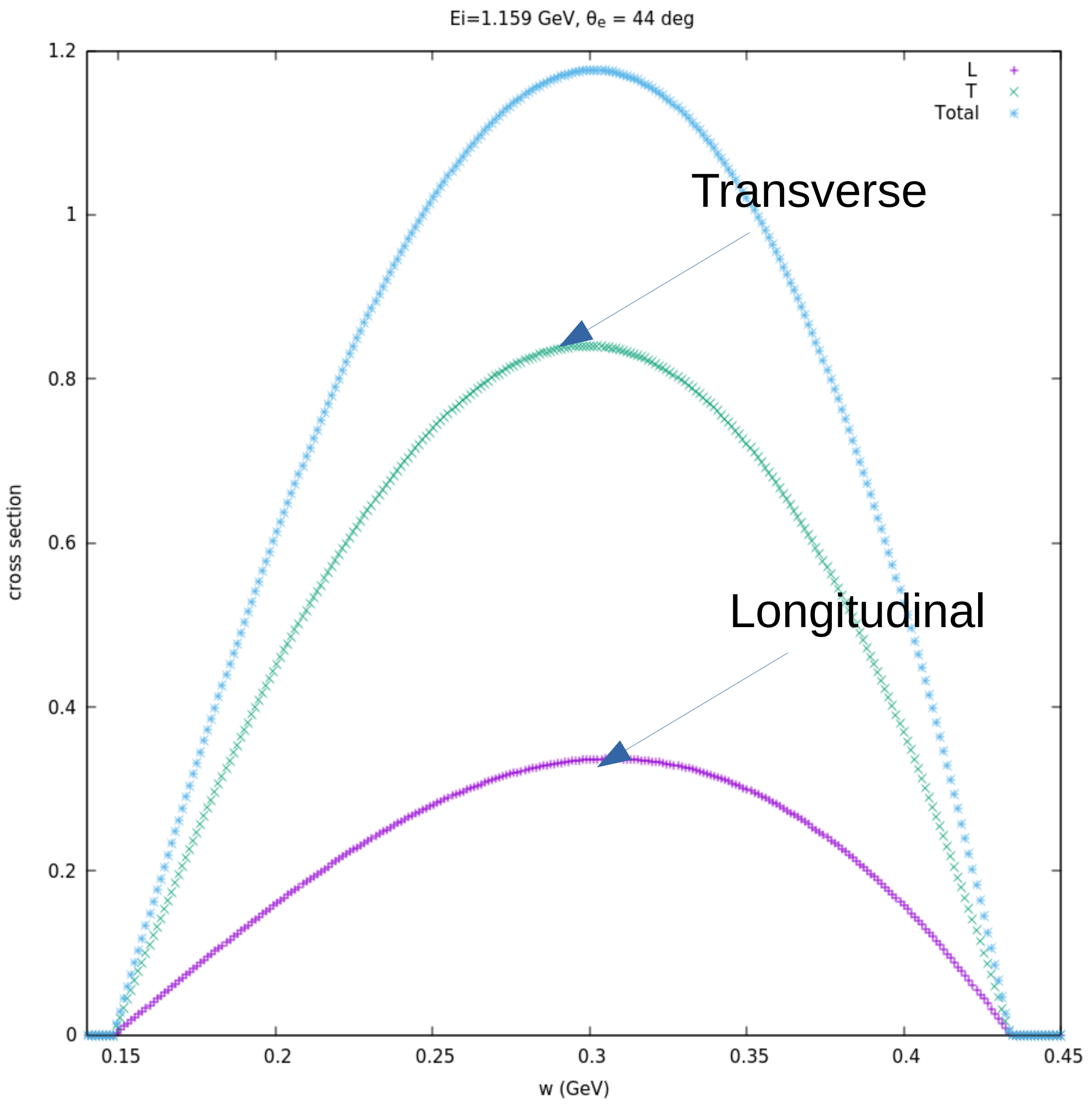
Ebeam = 1.159, and angles 15° ≤ θe ≤ 45°

(I'll focus the discussion on the QE peak.) So far, SuSAv2+MEC has proven to be able to reproduce quite well all inclusive (e,e') data.

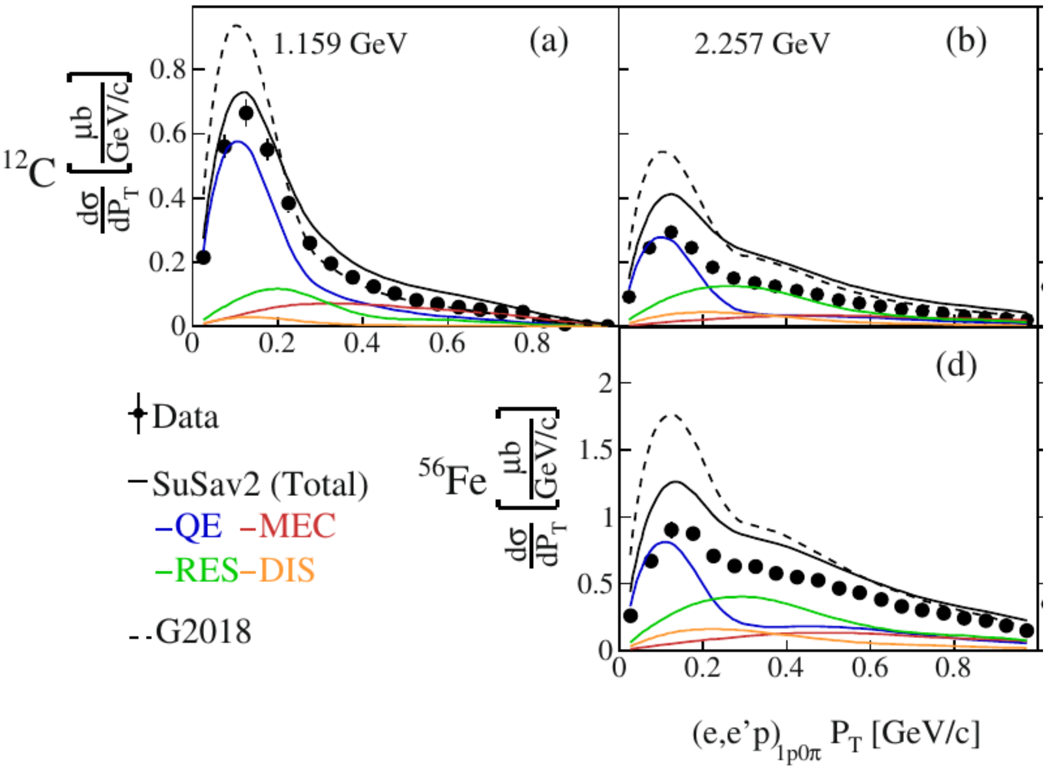
So what's going on here? Possible explanations:
+ This is not an inclusive experiment, but for this data set, it's almost inclusive in the QE peak...

+ The cross section is dominated by forward scattering angles:
  ++ L response plays a very important role. SuSAv2 has some troubles to describe L and T responses at the same time (JPG:NPP 47 (2020) 124001)
  ++ There is a significant contribution from regions where Pauli blocking plays a role. This is a dangerous region.


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


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

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



This is not inclusive data.

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

Better to use (realistic) models that provide information on the final hadron(s)
as well as a good inclusive cross section.

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]

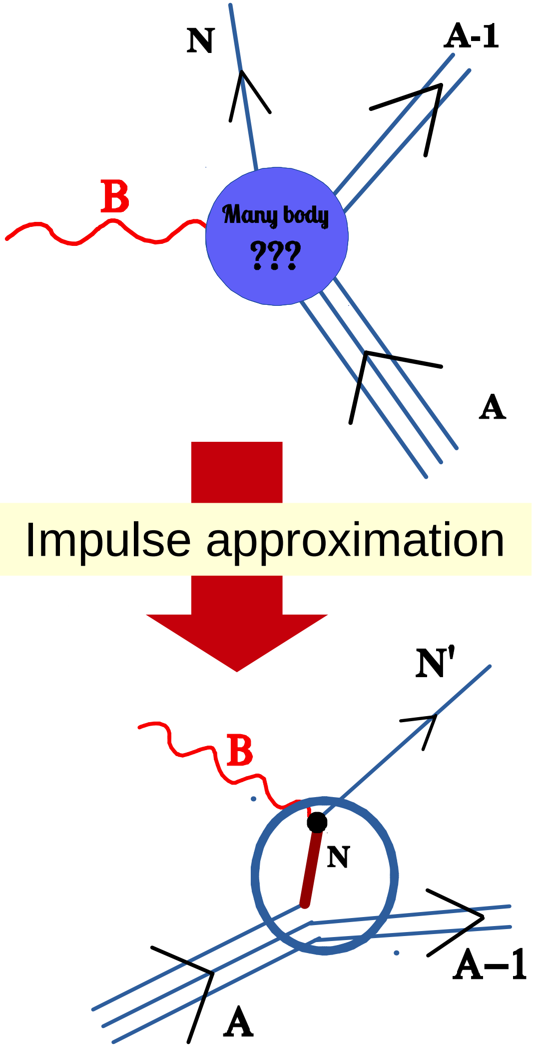
Overview of the nuclear model: Relativistic Distorted-Wave Impulse Approximation (RDWIA).

(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.

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



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

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 exclusive cross sections: 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.

+ Inclusive cross sections: 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]

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

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

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]

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

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

→

CASCADE

NEUT cascade is fed with the rROP events

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]

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

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

→

CASCADE

NEUT cascade is fed with the rROP events

↓

Signal definition

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

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]

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

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

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).

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]

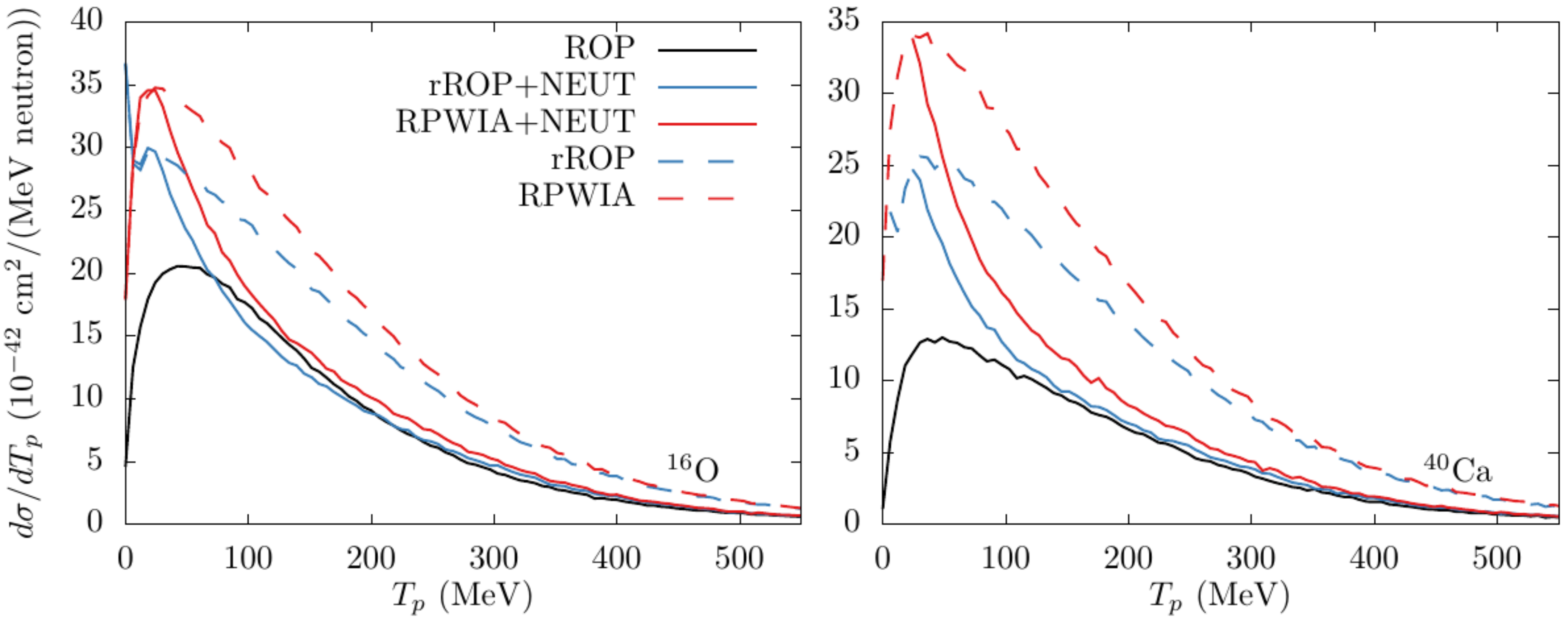
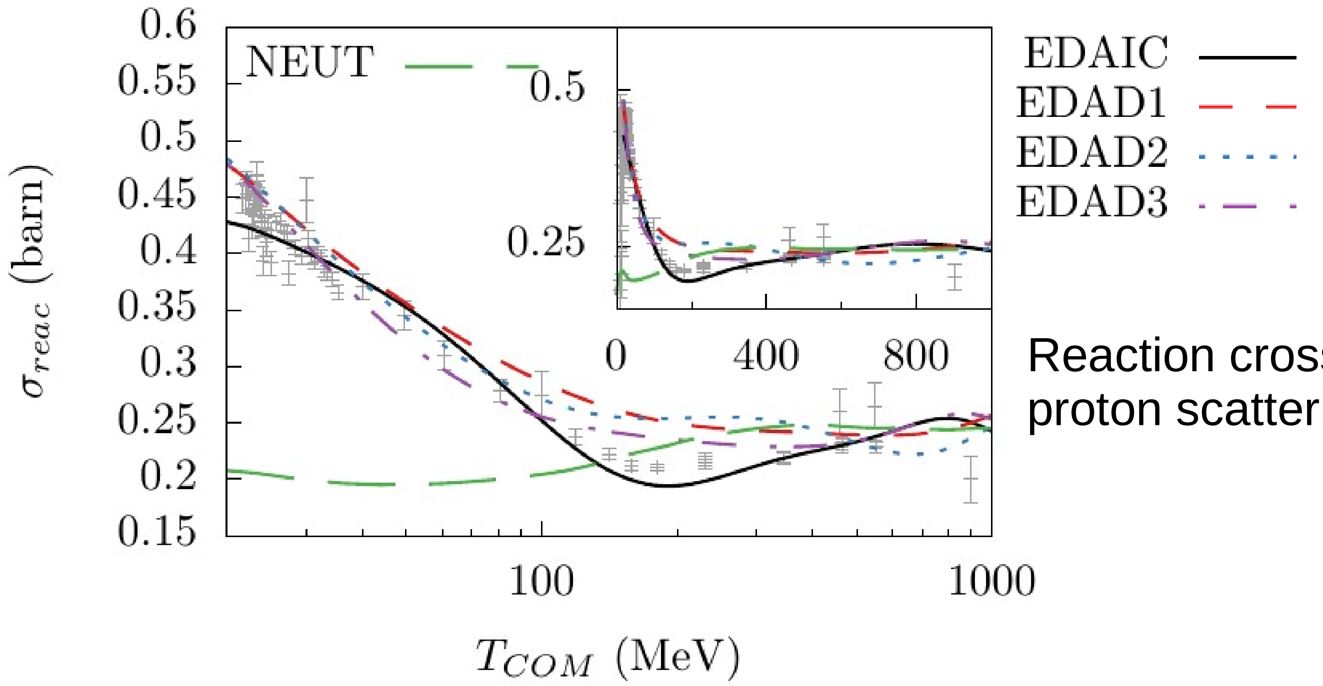


FIG. 7. Cross section in terms of the leading protons kinetic energy averaged over the T2K flux. All results include a cut in missing energy to isolate elastic events. ROP results are compared to the NEUT results when using rROP or RPWIA as input to the cascade. The results of the models before application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

PRC 105, 054603 (2022)

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]



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.

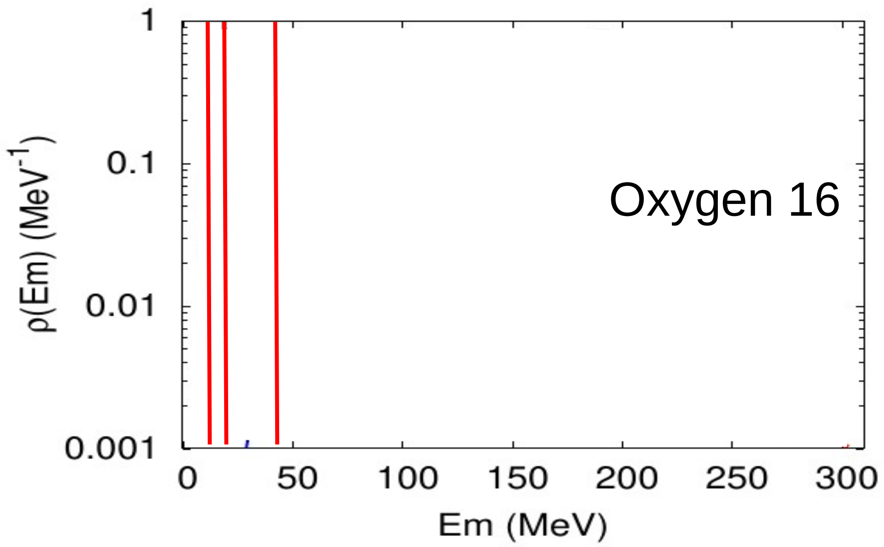
Latest improvements in the model (on the 1 particle–1 hole sector):

+ More realistic energy profile for the shells.

+ Two-body current contribution.

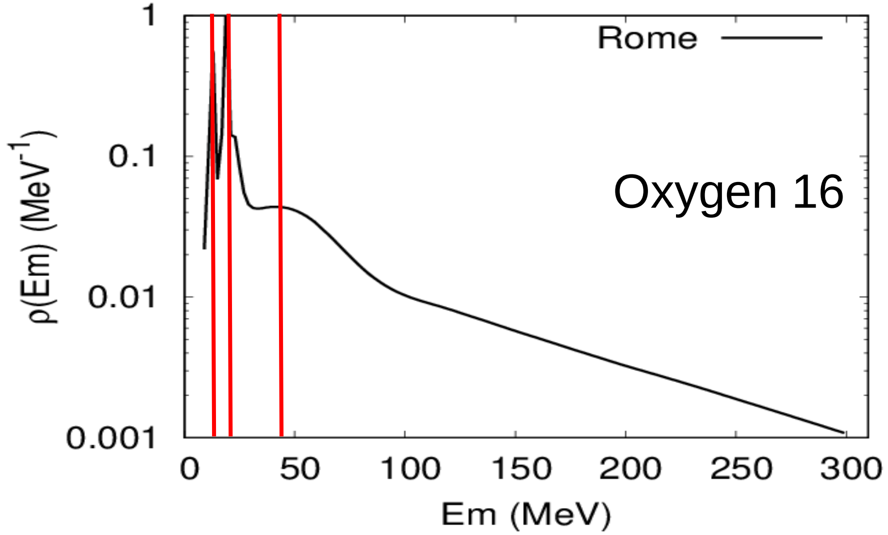
We can now reproduce the **Longitudinal and Transverse EM responses** simultaneously.

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.

+ Two-body current contribution.

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]

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

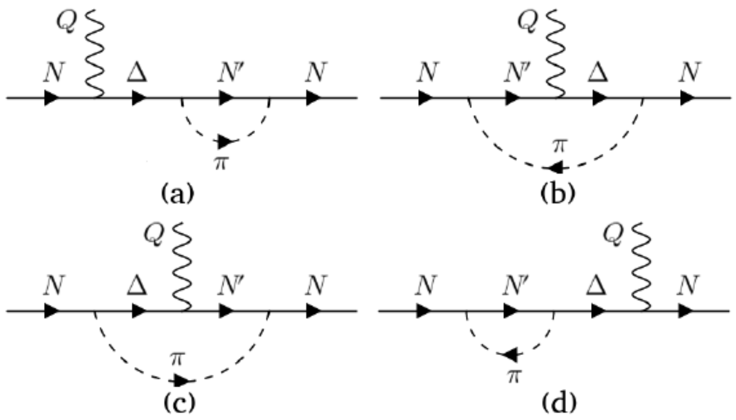


FIG. 1. Delta contributions.

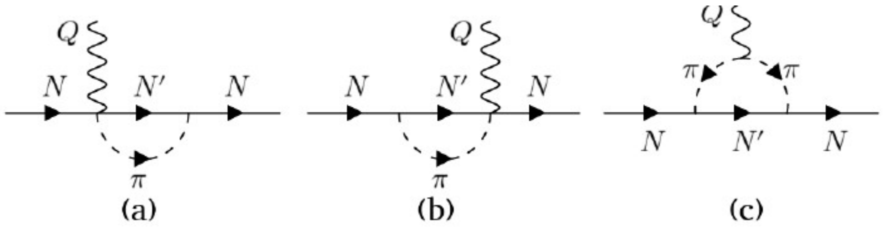
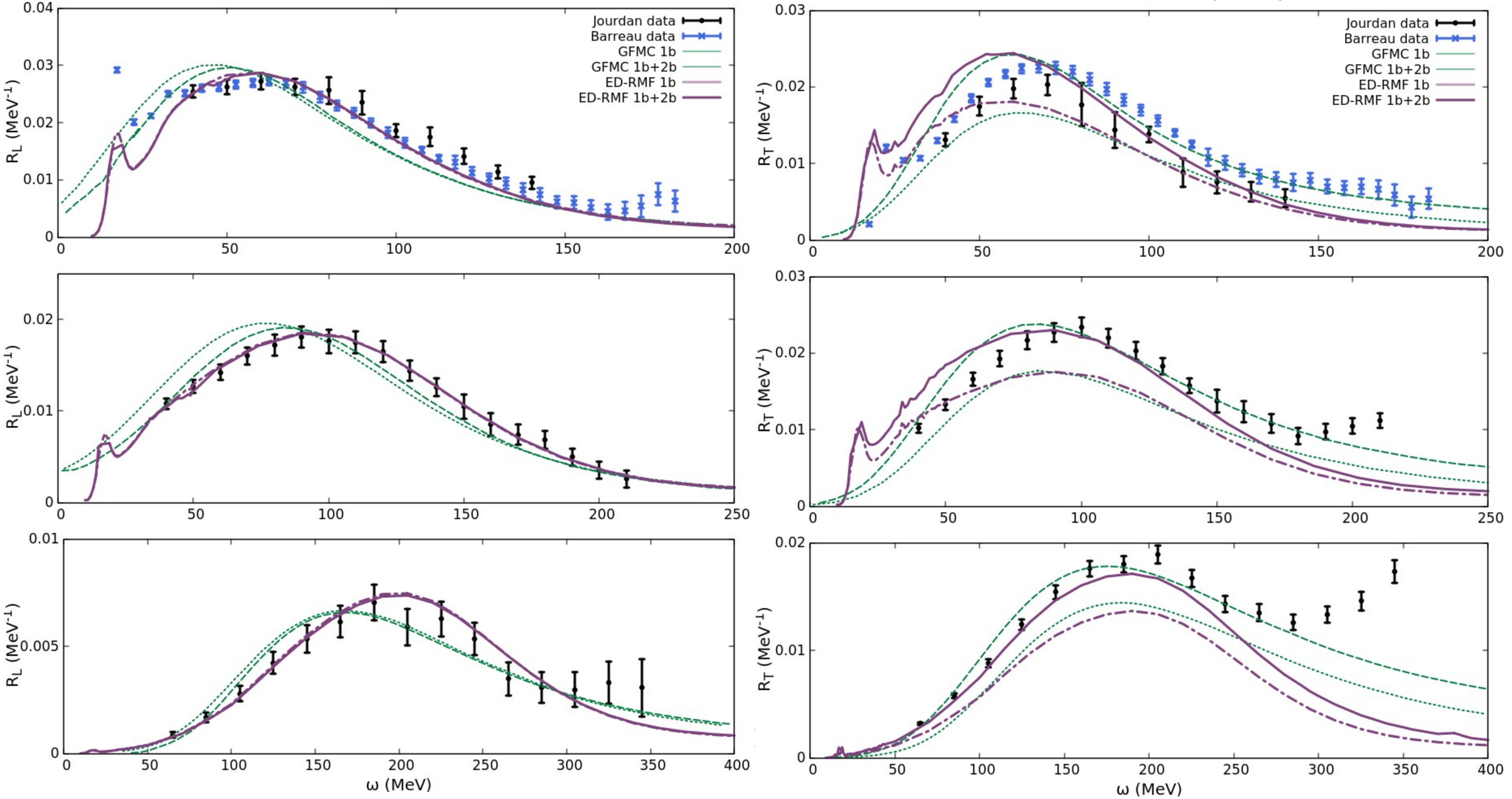


FIG. 2. Background contributions: seagull or contact [CT, (a) and (b)] and pion-in-flight [PF, (c)].

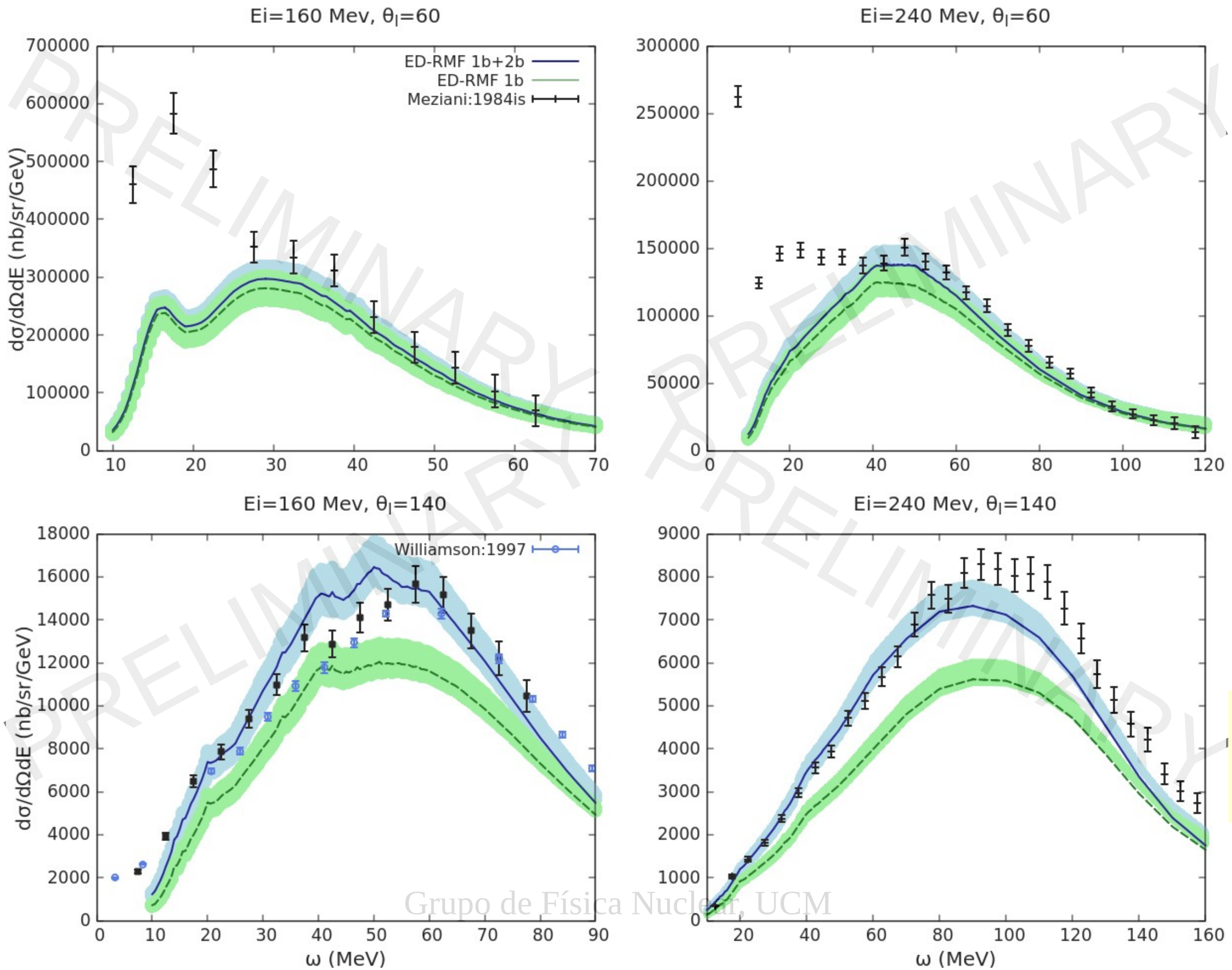
arXiv:2203.09996 [nucl-th]

Carbon 12 responses

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

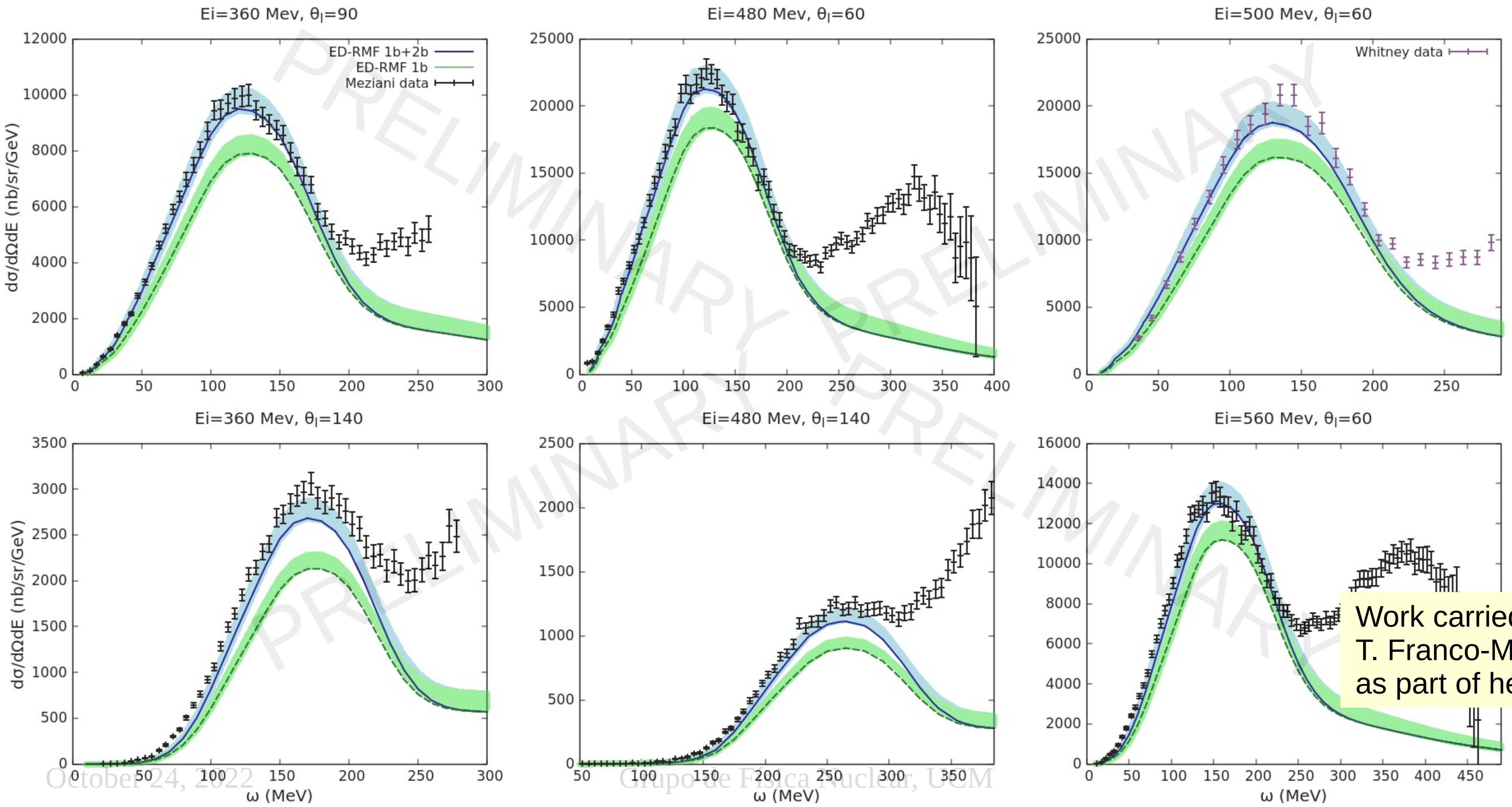


Calcium 40 cross sections



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

Calcium 40 cross sections



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

Some interesting examples

where a proper quantum mechanical treatment of nuclear effects is relevant

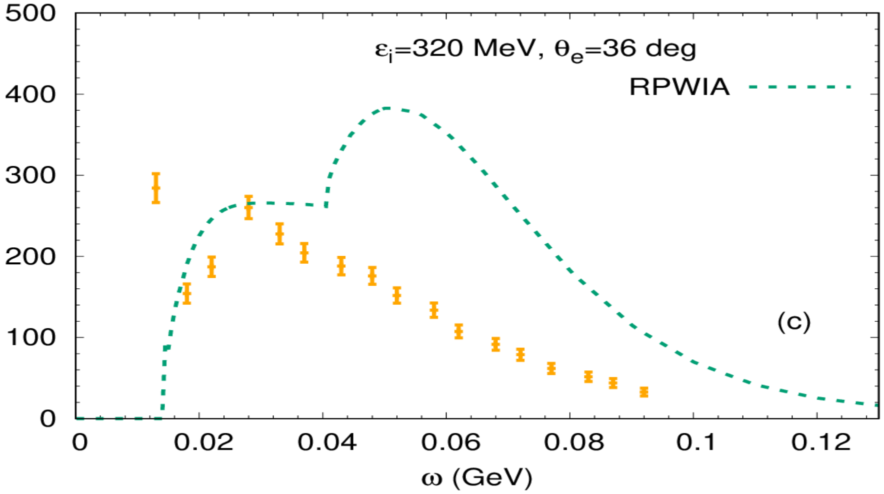
PHYSICAL REVIEW C **100**, 045501 (2019)

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

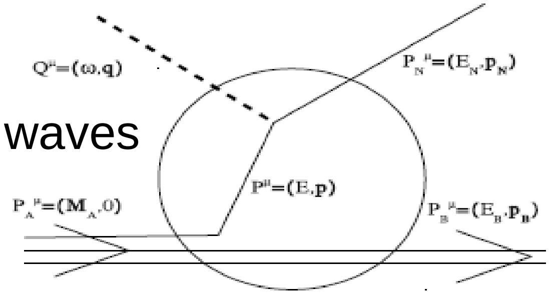
R. González-Jiménez,[1,*] A. Nikolakopoulos,[2,†] N. Jachowicz,[2,‡] and J. M. Udías[1,§]

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

Inclusive electron scattering **at low q:**

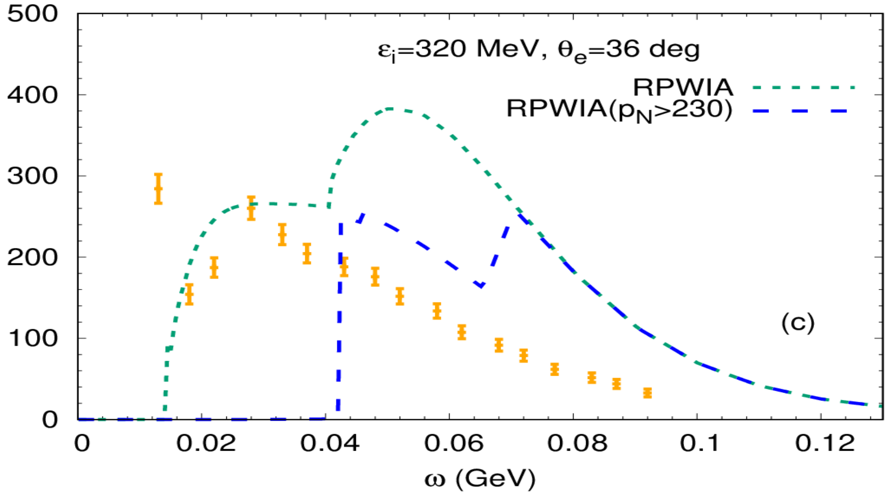


Plane waves

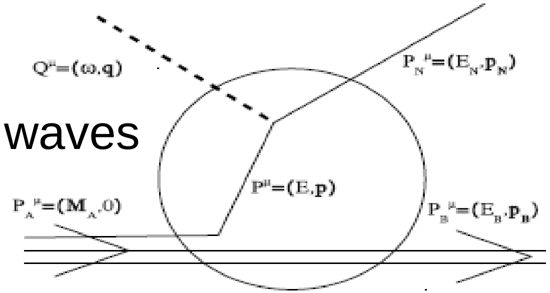


Phys. Rev. C **100** 045501 (2019)

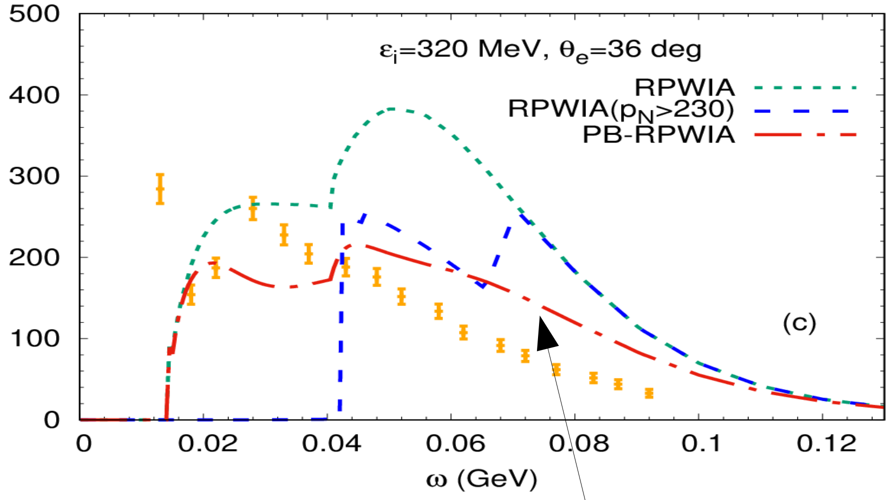
Inclusive electron scattering **at low q:**

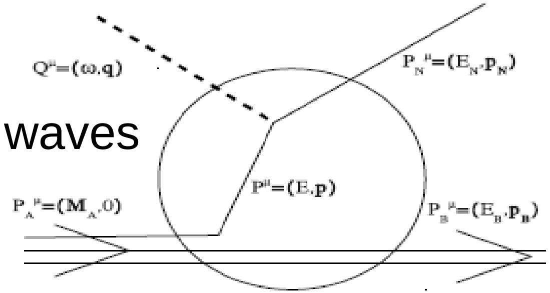


Plane waves



Inclusive electron scattering **at low q:**





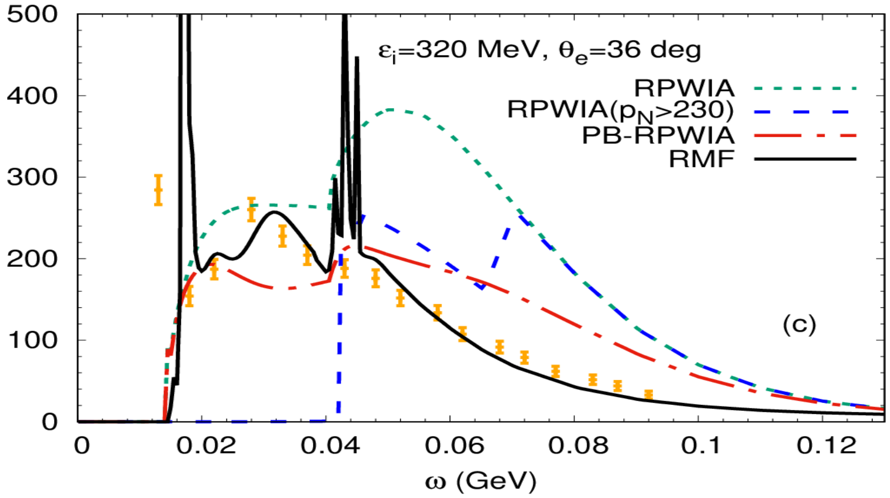
Plane waves

Orthogonalization

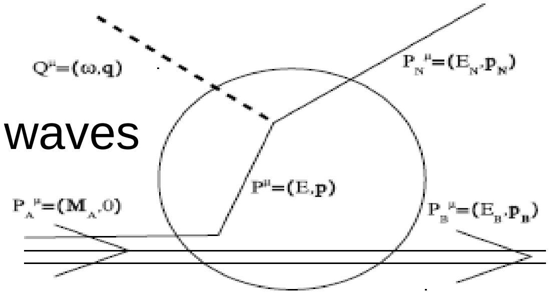
$$|\Psi^{s_N}(\mathbf{p}_N)\rangle = |\psi^{s_N}_{pw}(\mathbf{p}_N)\rangle - \sum_{\kappa,m_j} [C^{m_j,s_N}_{\kappa}(\mathbf{p}_N)]^\dagger \, |\psi^{m_j}_{\kappa}\rangle$$

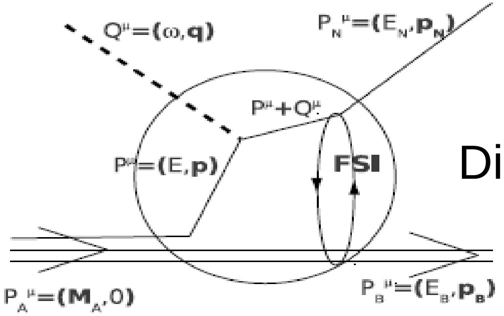
Phys. Rev. C **100** 045501 (2019)

Inclusive electron scattering **at low q:**



Plane waves

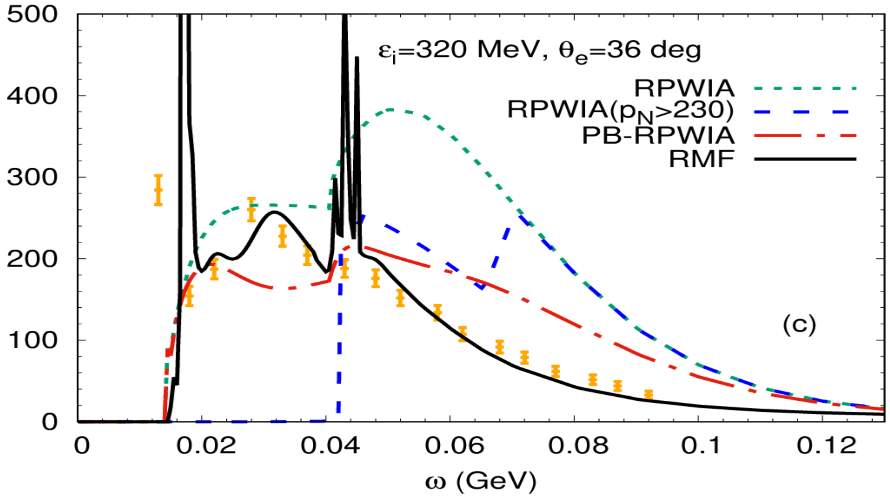




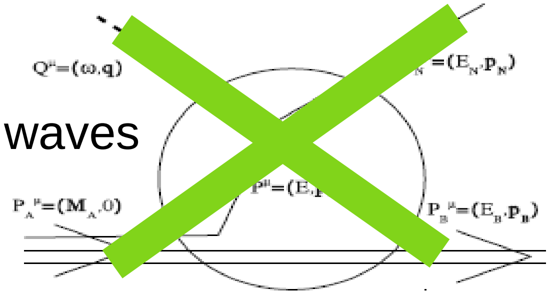
Distorted waves

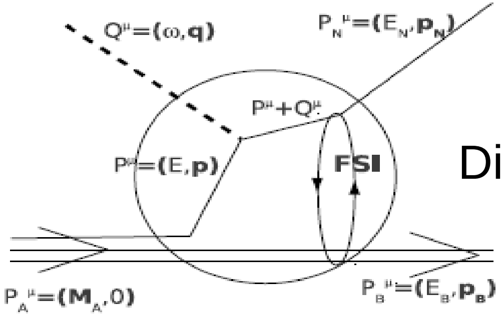
Phys. Rev. C **100** 045501 (2019)

Inclusive electron scattering **at low q:**



Plane waves

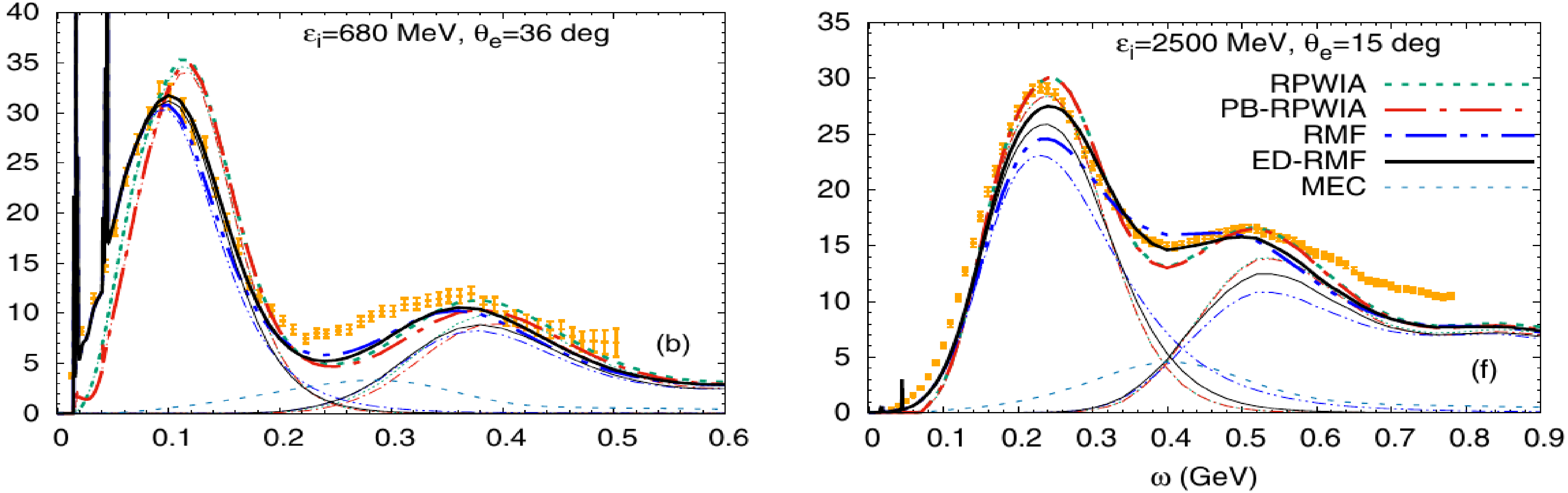




Distorted waves

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:

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

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

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

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

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

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

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

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

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]

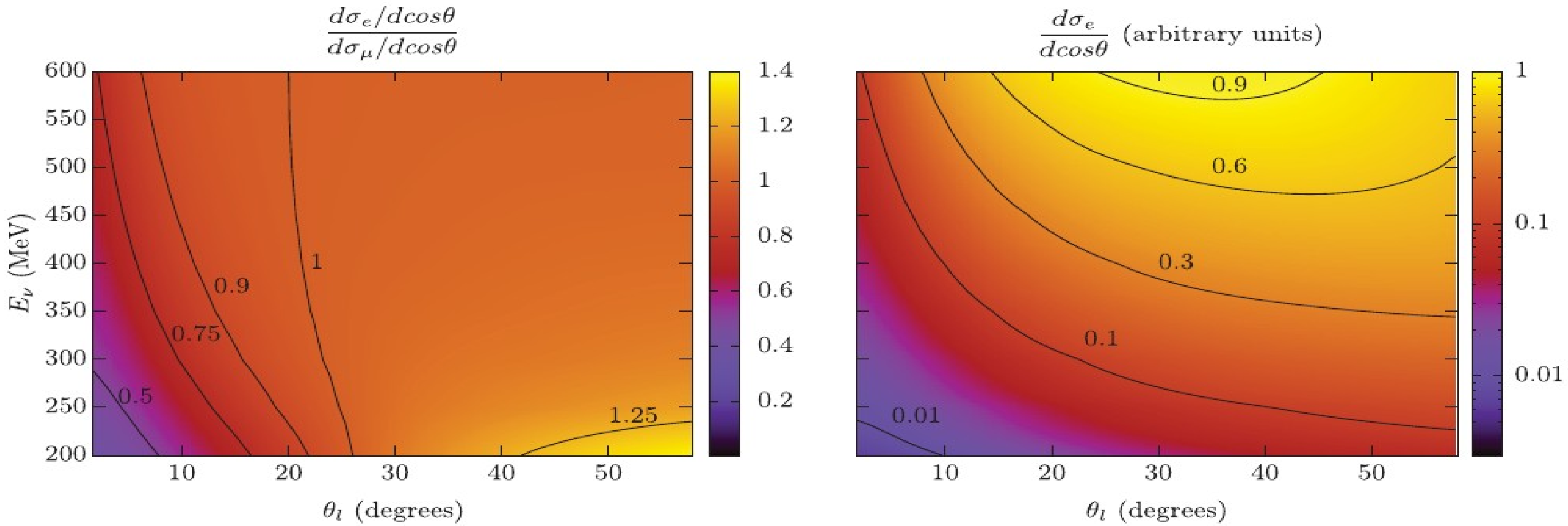


FIG. 4. Ratio of ^{12}C cross sections as a function of incoming energy and lepton scattering angle, combined with relative strength of the cross section at the same kinematics (normalized such that the maximum in this kinematic region is 1). Results shown here were obtained within the CRPA approach,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

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]

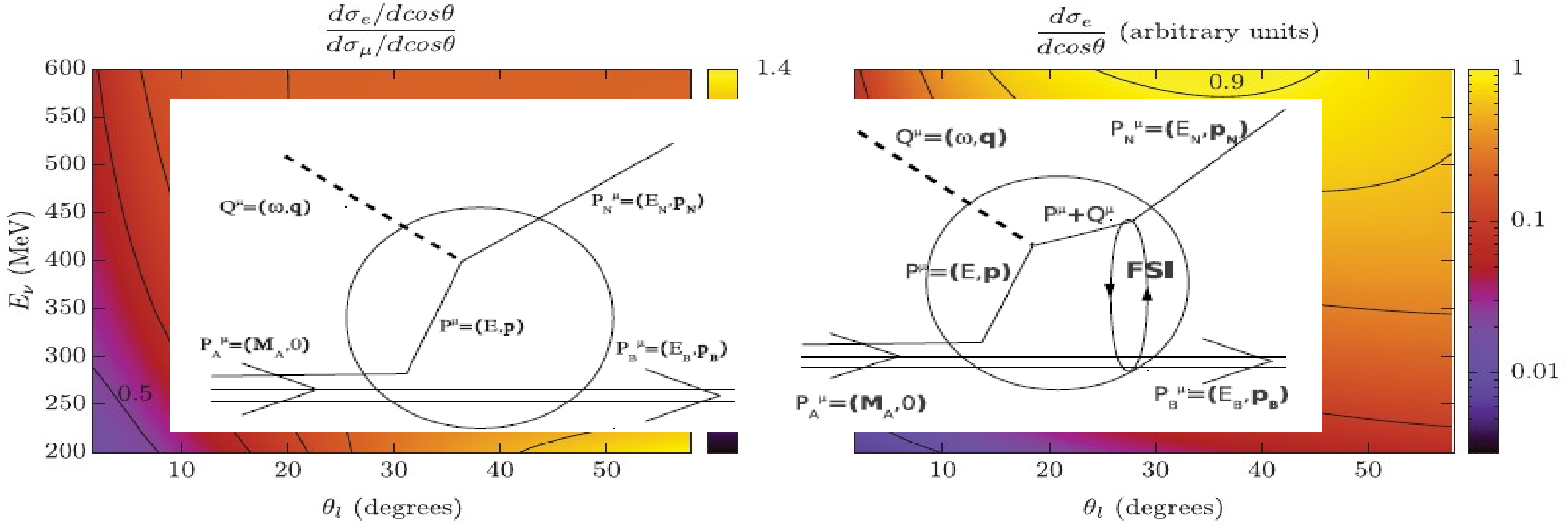


FIG. 4. Ratio of ^{12}C cross sections as a function of incoming energy and lepton scattering angle, combined with relative strength of the cross section at the same kinematics (normalized such that the maximum in this kinematic region is 1). Results shown here were obtained within the CRPA approach,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

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

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]

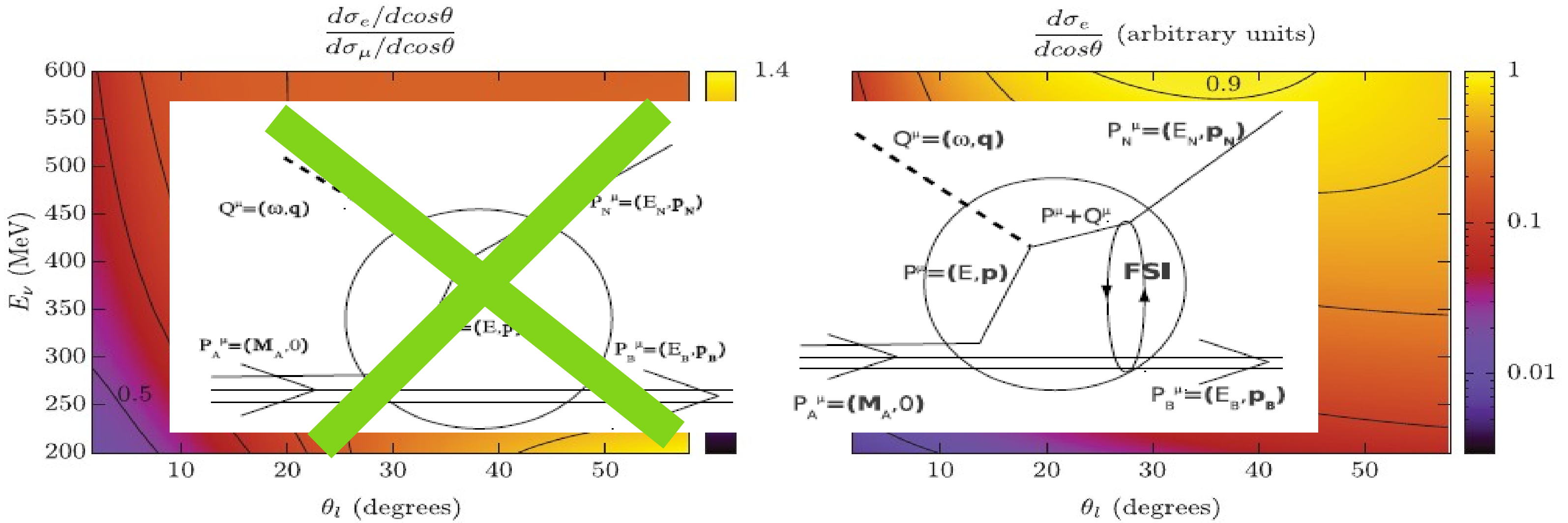


FIG. 4. Ratio of ^{12}C cross sections as a function of incoming energy and lepton scattering angle, combined with relative strength of the cross section at the same kinematics (normalized such that the maximum in this kinematic region is 1). Results shown here were obtained within the CRPA approach,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

Semi-inclusive cross sections

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

J. M. Franco-Patino,[1,2,3] R. González-Jiménez,[4] S. Dolan,[5] M. B. Barbaro,[2,3,6] J. A. Caballero,[1,7] G. D. Megias,[1,8] and J. M. Udias[4]

arXiv:2207.02086v1 [nucl-th]

arXiv:2207.02086v1 [nucl-th]

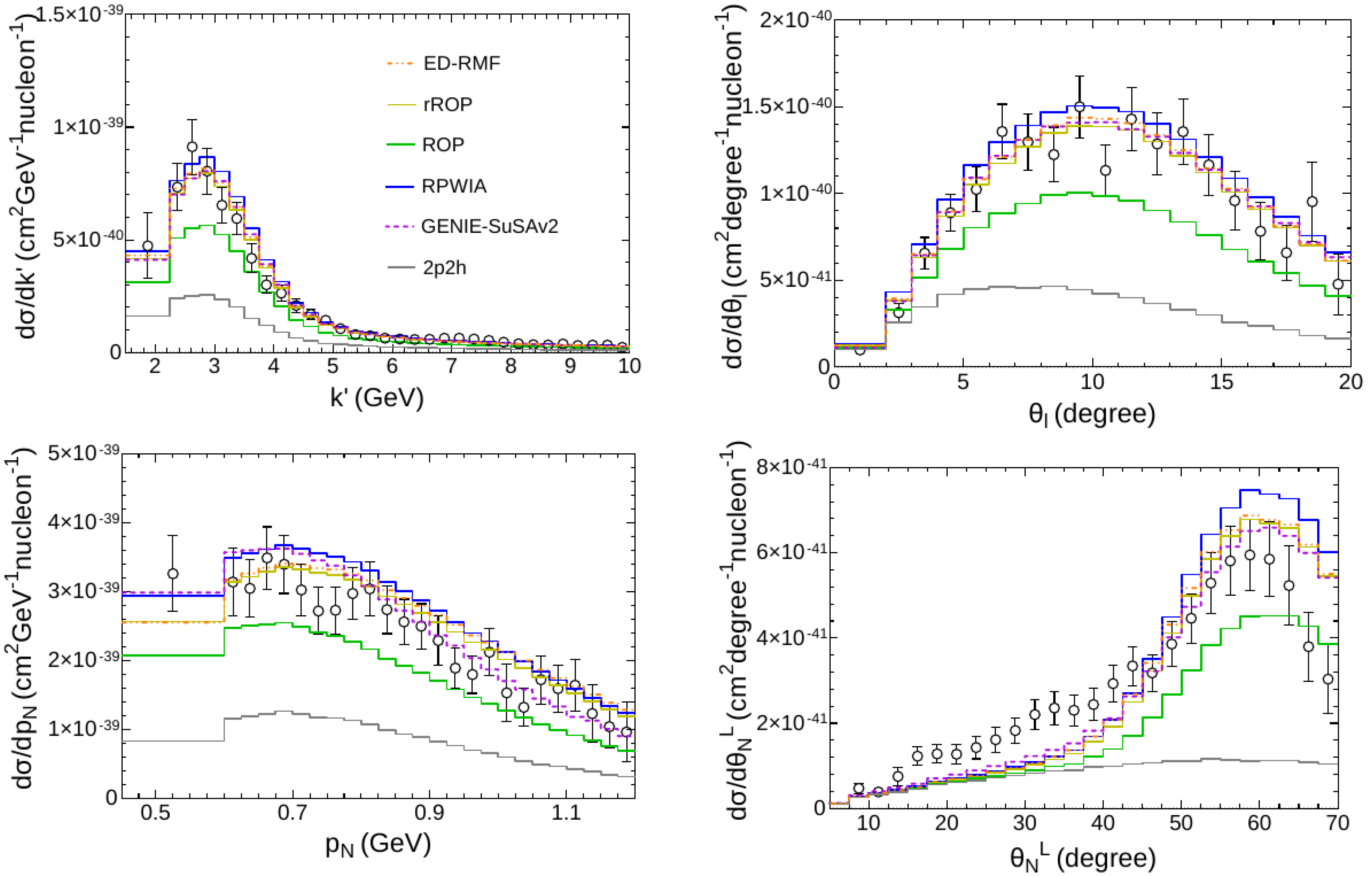


Figure 10: MINERνA semi-inclusive ν_μ–^{12}C cross section as function of the final muon momentum and scattering angle (top) and as function of the final proton momentum and polar angle (bottom). All curves include the 2p2h contribution (also shown separately), evaluated using the implementation in GENIE of the SuSAv2-2p2h model.

arXiv:2207.02086v1 [nucl-th]

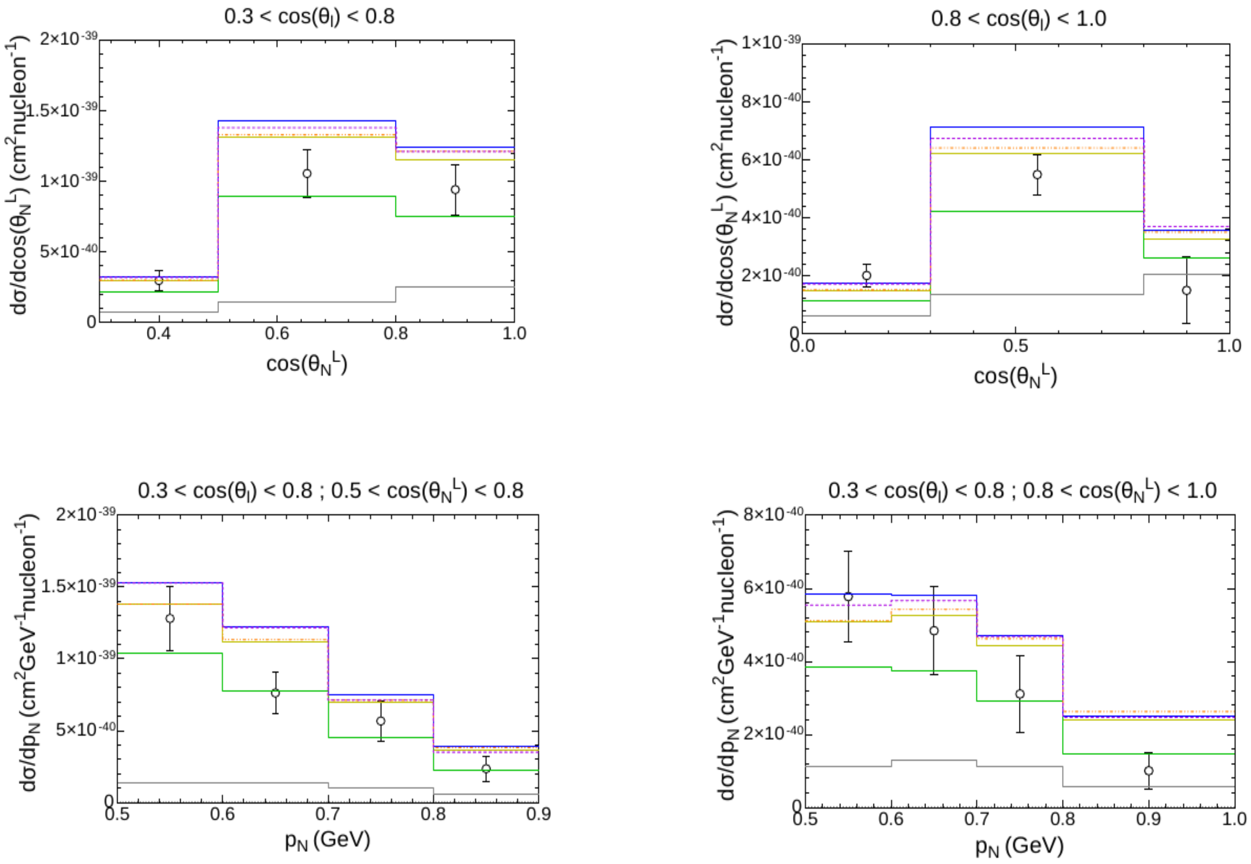


Figure 4: T2K CC0π semi-inclusive ν_μ–^{12}C cross section with protons in the final state with momenta above 0.5 GeV as function of the final proton and muon kinematics. All curves include the 2p2h contribution (also shown separately), evaluated using the implementation in GENIE of the SuSAv2-2p2h model.

Summary and Conclusions:

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

++ Using as input realistic models that provide good inclusive results as well as information on the final hadrons.

++ Benchmarking the cascade model by comparing the "only-1-proton-in-the-final-state signal" with the predictions from ROP models. Tuning the cascade if necessary to match.

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

+ 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.

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

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

A. Nikolakopoulos,[1,*] R. González-Jiménez,[2] N. Jachowicz,[3] and J. M. Udías[2]

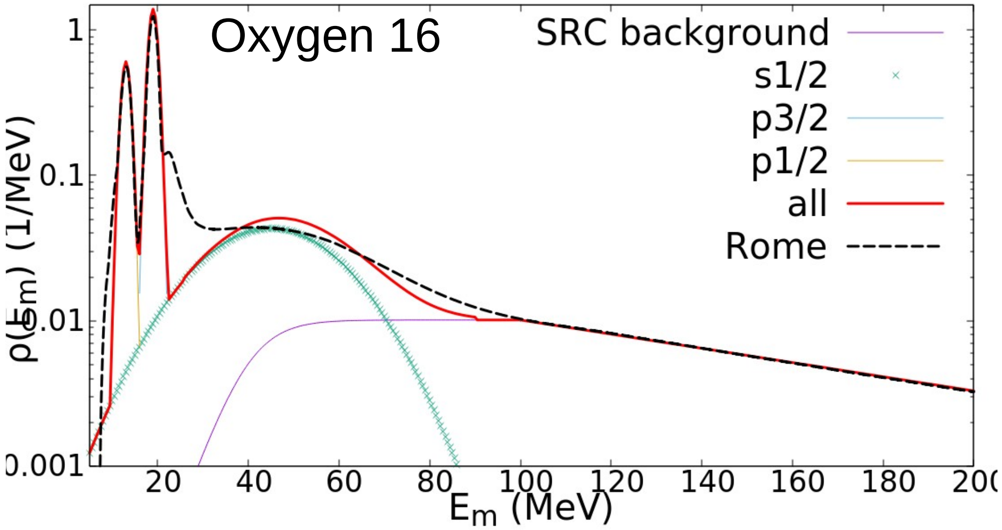
https://arxiv.org/abs/2210.12144

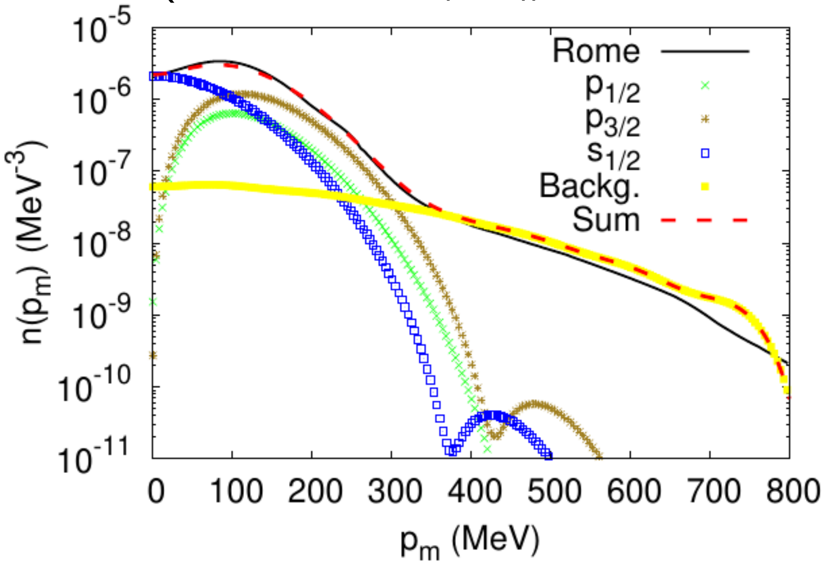
Today on the arXiv!!

Thanks for the attention

Backup slides

Missing energy and momentum distributions from the Rome spectral function (O. Benhar et al. NPA 579, 493 (1994); PRD 72, 053005 (2005)) and the shell model we use (PRC 105, 025502 (2022)):





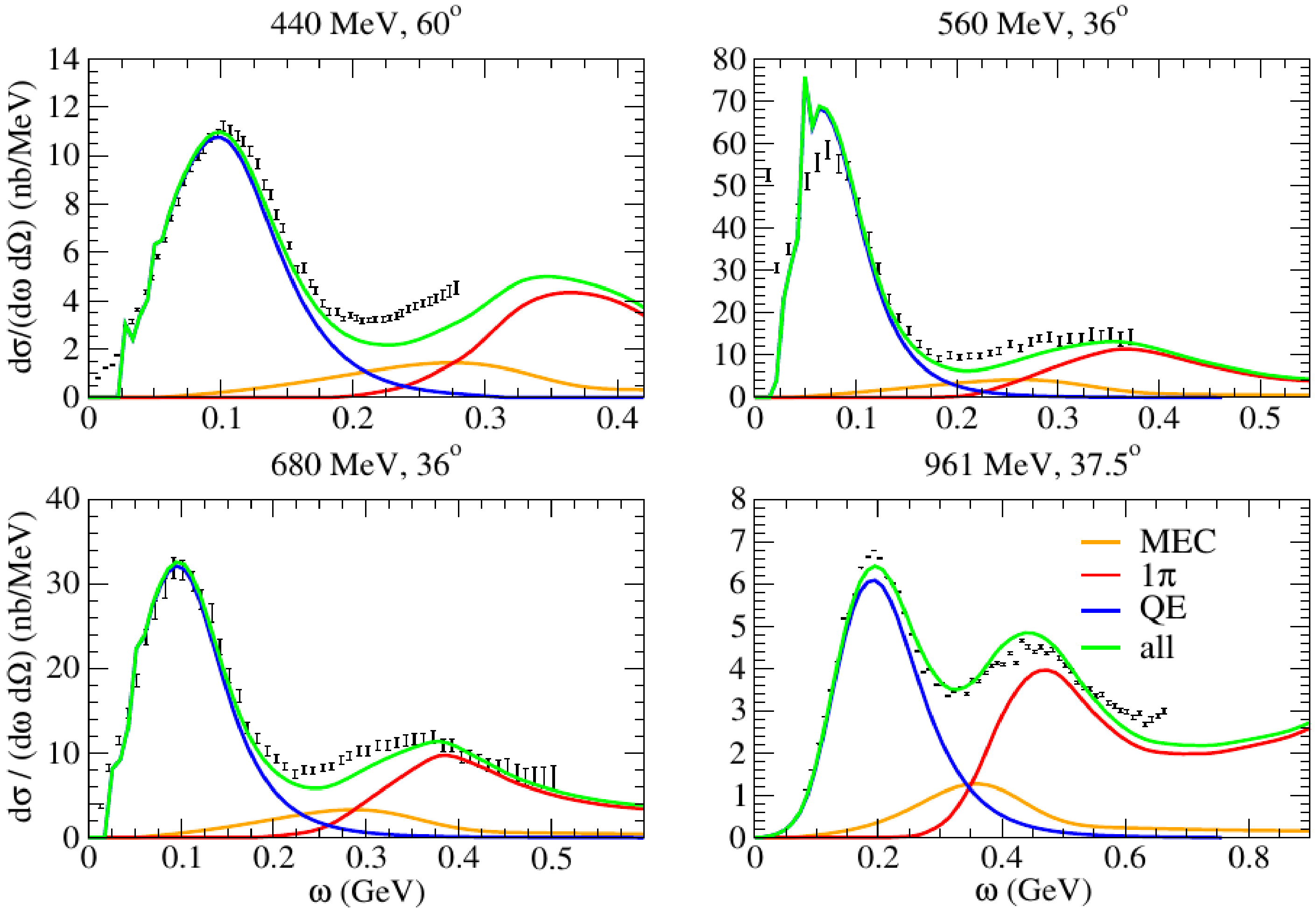
E_m (MeV)	Shells	^{16}O
$0 - 16.5$	$p_{1/2}$	1.51
$16.5 - 25$	$p_{3/2}$	3.47
$25 - 100$	$s_{1/2}$ + backg.	2.22
	$s_{1/2}$	1.62
	backg.	0.60
$100 - 300$	backg.	0.80

$$n(p_m) = \int dE_m S(E_m, p_m)$$

$$\int d^3\mathbf{p}_m n(p_m) = 8$$

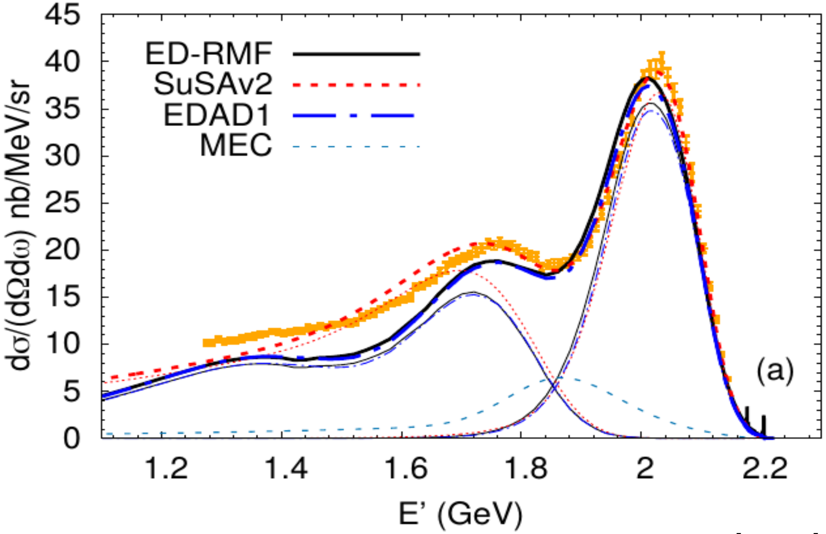
TABLE: Correspondence between missing energy regions and shells in oxygen. The last column are the occupation numbers.

Inclusive cross sections

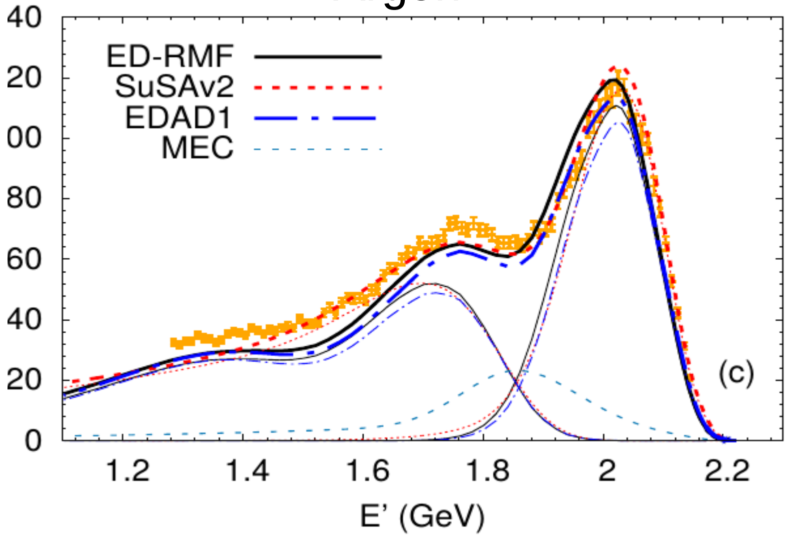

440 MeV, 60°
560 MeV, 36°
680 MeV, 36°
961 MeV, 37.5°
dσ/(dω dΩ) (nb/MeV)
dσ / (dω dΩ) (nb/MeV)
ω (GeV)
MEC
1π
QE
all

PRC 101, 015503 (2020)

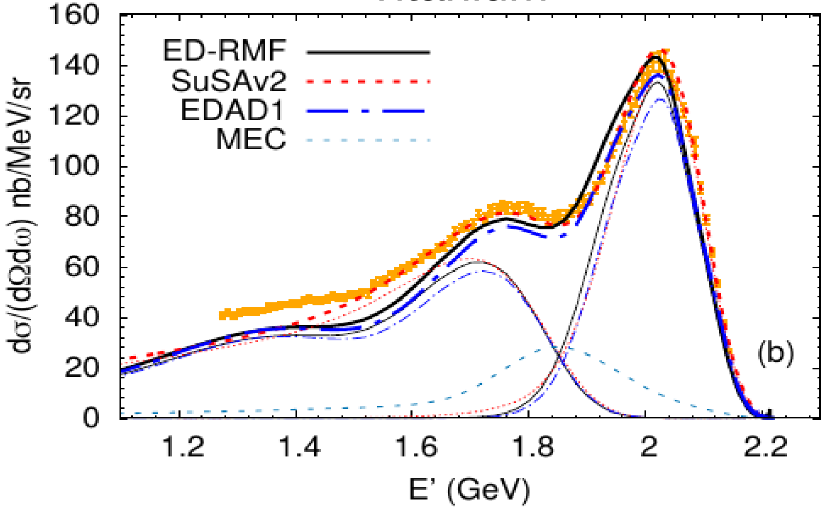
Carbon



Argon



Titanium



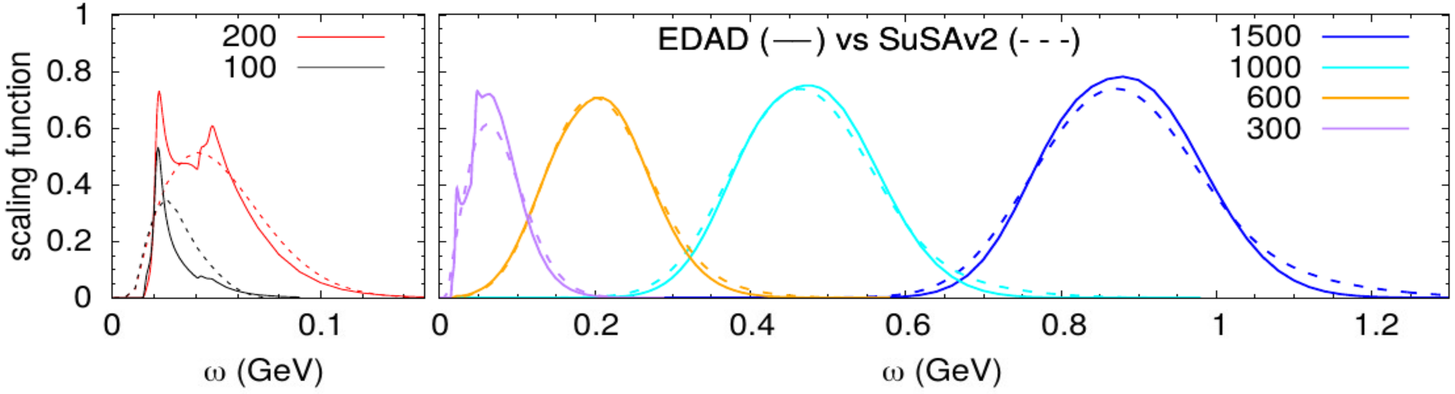
Recent JLab data.

E_i = 2222 MeV

θ_e= 15.541 deg

Constraining the quasielastic response in inclusive lepton-nucleus scattering

R. González-Jiménez,[1] M.B. Barbaro,[2] J.A. Caballero,[3] T.W. Donnelly,[4]
N. Jachowicz,[5] G.D. Megias,[3,6] K. Niewczas,[7,5] A. Nikolakopoulos,[5] and J.M. Udías[1]



The SuSAv2 QE response is very similar to that from a model that solves the (Dirac) wave equation in presence of a real energy-dependent optical potential.

Both approaches satisfactorily agree with inclusive data for the QE peak.

Exclusive cross sections

PHYSICAL REVIEW C, VOLUME 64, 024614

Relativistic mean field approximation to the analysis of ^{16}O$(e,e'p)^{15}$N data at $|Q^2| \leqslant 0.4$ (GeV/c)^2

J. M. Udías,[1] J. A. Caballero,[2,3] E. Moya de Guerra,[3] Javier R. Vignote,[1] and A. Escuderos[3]
[1]*Departamento de Física Atómica, Molecular y Nuclear, Universidad Complutense de Madrid, E-28040 Madrid, Spain*
[2]*Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, Apdo. 1065, E-41080 Sevilla, Spain*
[3]*Instituto de Estructura de la Materia, CSIC Serrano 123, E-28006 Madrid, Spain*
(Received 6 December 2000; revised manuscript received 9 April 2001; published 17 July 2001)

We use the relativistic distorted wave impulse approximation to analyze data on ^{16}O$(e,e'p)^{15}$N at $|Q^2| \leqslant 0.4$ (GeV/c)^2 that were obtained by different groups and seemed controversial. Results for differential cross sections, response functions, and A_{TL} asymmetry are discussed and compared to different sets of experimental data for proton knockout from $p_{1/2}$ and $p_{3/2}$ shells in ^{16}O. We compare with a nonrelativistic approach to better identify relativistic effects. The present relativistic approach is found to accommodate most of the discrepancy between data from different groups, smoothing a long standing controversy.

Set (b)

beam energy was $\varepsilon = 580$ MeV, the outgoing proton kinetic energy $T_F = 160$ MeV, and the transfer momentum and energy: $|\vec{q}| = 570$ MeV/c and $\omega = 170$ MeV $[|Q^2| = 0.3\ (\text{GeV}/c)^2]$. The missing energy resolution was 1.3 MeV, which made not possible to resolve the $(5/2^+, 1/2^+)$ doublet at an excitation energy $E_x = 5.3$ MeV in ^{15}N from the $3/2^-$ state at $E_x = 6.3$ MeV.

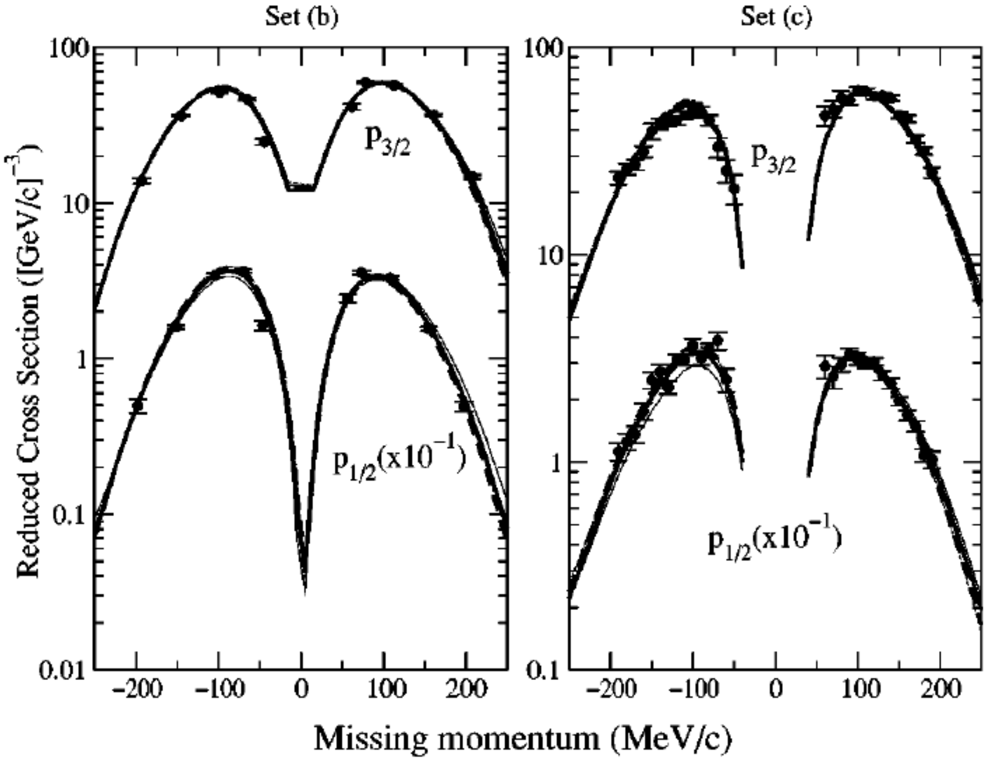


Figure: NLSH-P relativistic bound proton wave function and EDAI-O optical potential have been used.

Set (c)

and energy-transfer values centered at $(\omega, |\vec{q}|) = (90$ MeV, 460 MeV/$c)$, i.e., close to the center of the quasielastic peak at $|Q^2| \simeq 0.2\ (\text{GeV}/c)^2$. The experiment covered a missing momentum range from 30 to 190 MeV/c. The missing energy resolution was about 180 keV, which made it possible to resolve the $(5/2^+, 1/2^+)$ doublet from the $3/2^-$ state.

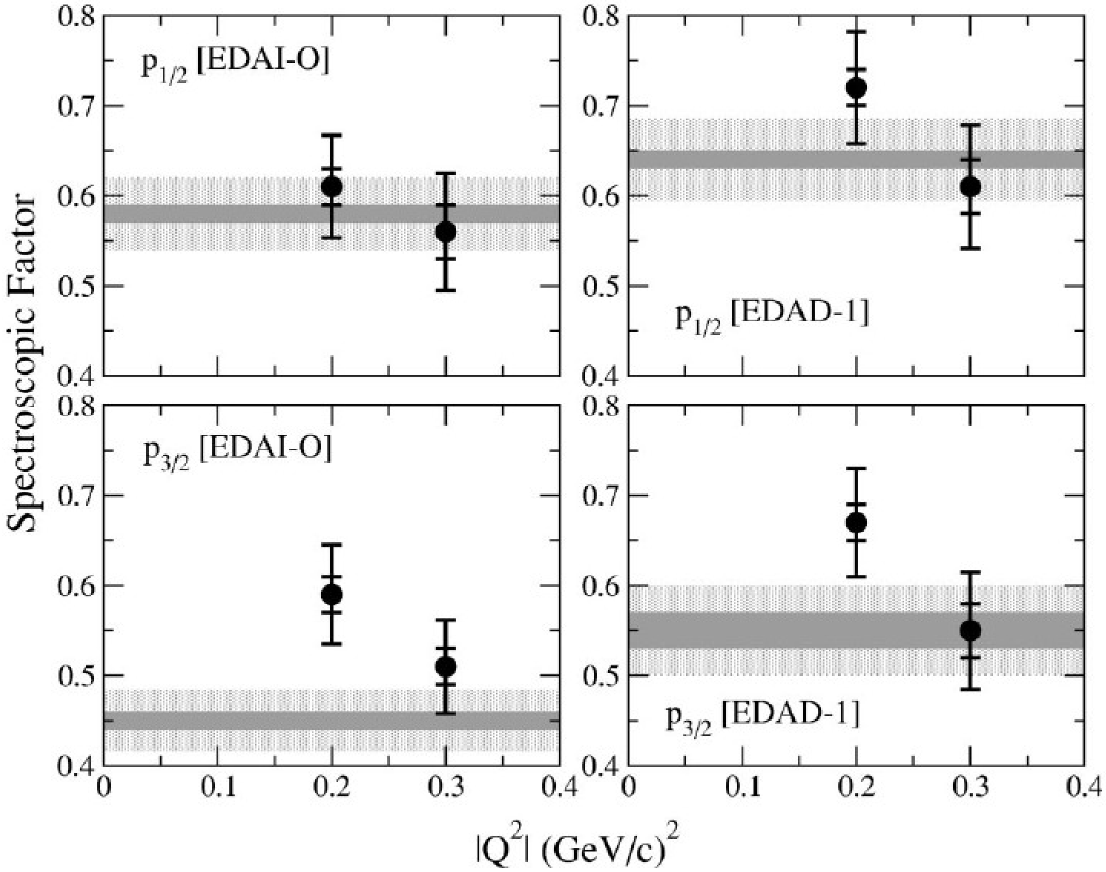


FIG. 4. Spectroscopic factors derived within the fully relativistic approach from the low-Q^2 data discussed in this work with NLSH-P wave function, CC2 current operator, and EDAI-O (left) or EDAD-1 (right) optical potentials. The inner error bars include statistical errors only, the outer one includes also the additional systematic error in the reduced cross sections for each experiment. The bands covering the whole $|Q^2|$ range correspond to the value obtained from the data set (a) [23], while the dots at $|Q^2| = 0.2$ $(\mathrm{GeV}/c)^2$ and 0.3 $(\mathrm{GeV}/c)^2$ correspond to the data set (c) [22] and set (b) [21], respectively.

PRC 49, 955 (1994)
Experiment at NIKHEF

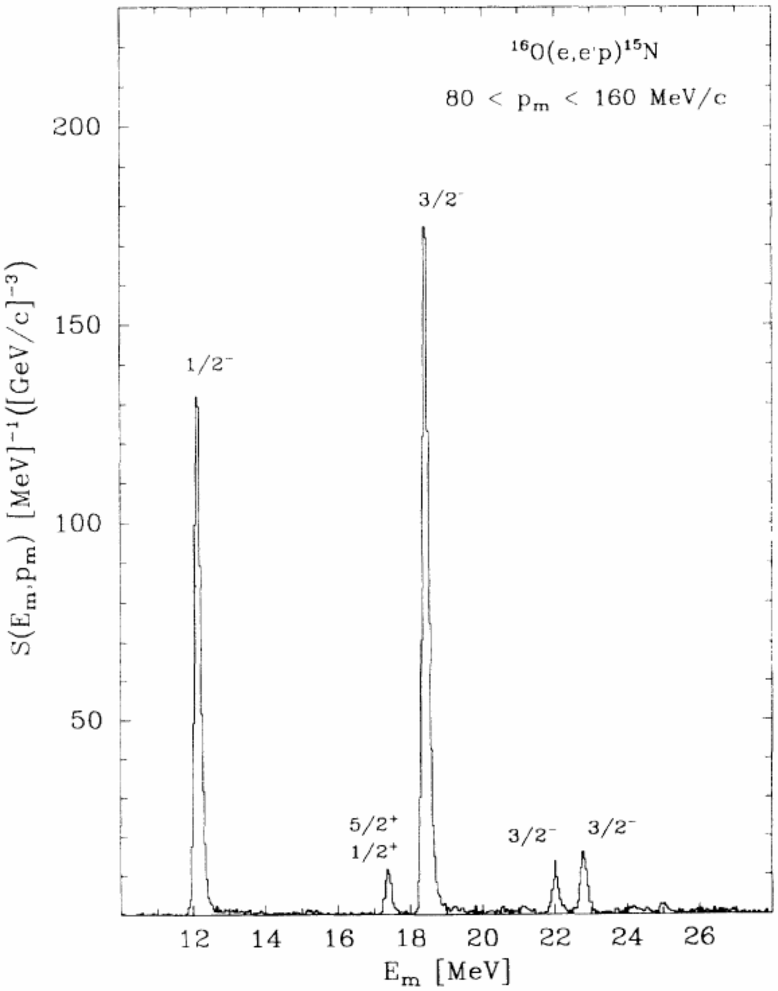


FIG. 1. $^{16}O(e,e'p)^{15}N$ missing energy spectrum for the kinematics centered about $\mathbf{p}_m = 120$ MeV/c.

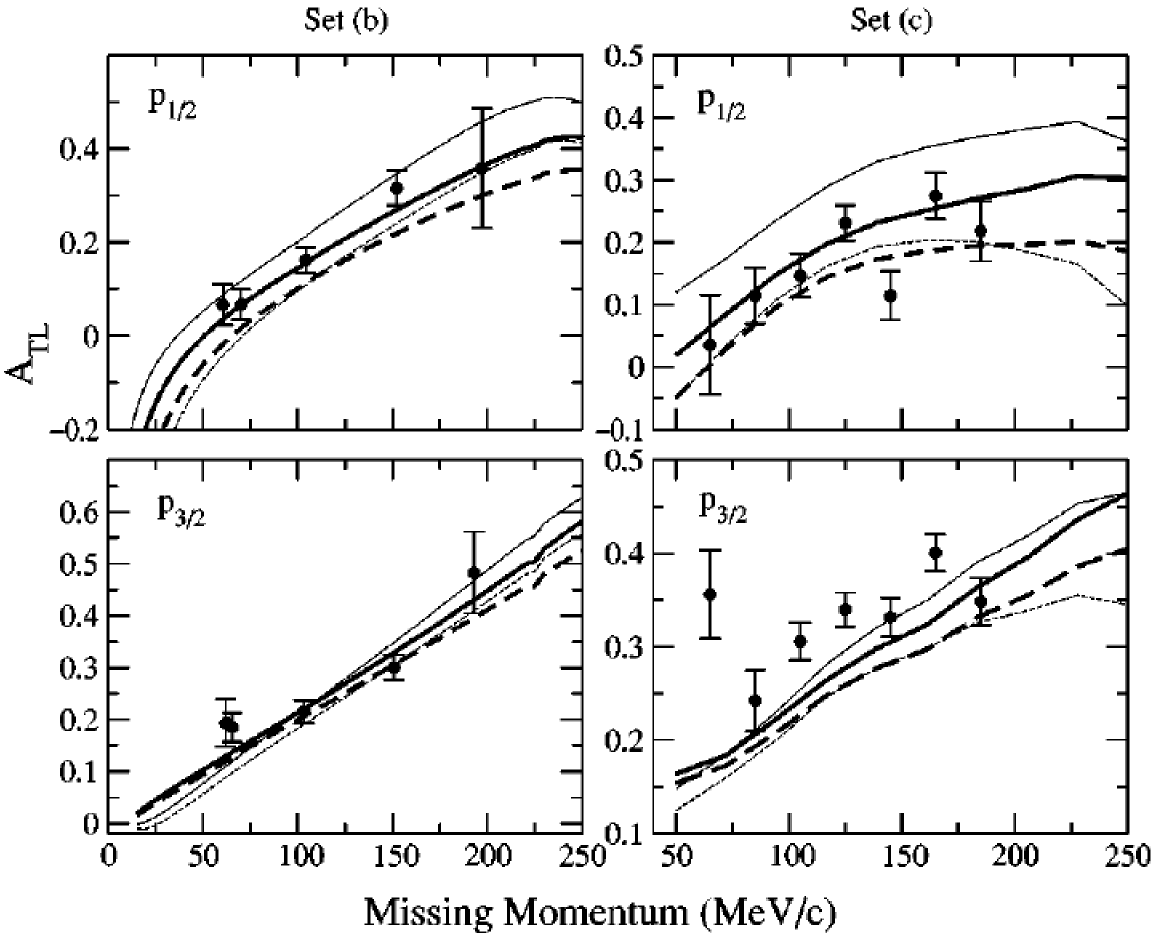


FIG. 6. Same as Fig. 5 for the A_{TL} asymmetry. We recall that this observable is independent on the spectroscopic factor.